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**HIGH ENERGY DENSITY DIELECTRICS FOR PULSED  
POWER APPLICATIONS**

**Richard L.C. Wu and Kevin R. Bray**

**K Systems Corporation**

**SEPTEMBER 2008**

**Final Report**

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---

JEFFERY T. STRICKER  
Program Manager  
Energy and Power Systems Branch  
Energy/Power/Thermal Division

//Signature//

---

JOSEPH A. WEIMER, Chief  
Energy and Power Systems Branch  
Energy/Power/Thermal Division

//Signature//

---

DEREK M. LINCOLN, Major, USAF  
Deputy Chief  
Energy/Power/Thermal Division  
Propulsion Directorate

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**K SYSTEMS CORPORATION**  
1522 Marsetta Drive • Beaver Creek, Ohio 45432-2733  
Phone: (937) 429-5151 • Fax: (937) 429-1122

November 7, 2008

Ms. Susan Wapelhorst  
AFRL/RZOB, Area B, Bldg. 18, 1950 Fifth St.  
WPAFB, OH 45433-7251

Subject: Final Report for K Systems Corporation Contract No. FA8650-04-C-2415

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Should you have any questions, please contact Dr. Richard L.C. Wu (Program Manager of this program).

Thank you very much.

Sincerely,

Richard L.C. Wu, PhD  
Vice President  
K Systems Corporation  
1522 Marsetta Drive  
Beaver Creek, OH 45432  
Tel. (937) 429-5151/255-6933  
Fax (937) 429-1122  
e-mail: rlwu@aol.com

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## Foreword

This research and development work entitled “High Energy Density Dielectrics for Pulsed Power Capacitors” was funded by the AF/OSD SBIR Phase II Program under K Systems Corporation Contract No. FA8650-04-C-2415 with the Energy and Power Systems Branch, Energy, Power, and Thermal Division, Propulsion Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH.

The original program objectives for the aluminum nitride research included:

- (1) Optimize key manufacturing process steps: AlN films, AlN-coated aluminum oils/metallized polymer films. Processes will be optimized to achieve maximum adhesion of AlN, highest AlN dielectric strength and good thermal stability.
- (2) Design and construct prototype AlN deposition system using dual magnetron reactive sputtering technique for simultaneous deposition of AlN films on both sides of capacitor grade aluminum foils/metallized polymer films.
- (3) Design and construct prototype high energy density AlN capacitors by rolling under controlled environmental conditions.
- (4) Characterize and test AlN capacitors under various environmental conditions: develop understanding of the mechanisms of failure. Demonstrate capacitor capabilities with respect to equivalent series resistance (ESR), dissipation factor (DF), Frequency response, and temperature characteristics. The Military Standard Test Methods for Electronic and Electrical Component Parts (MIL-STD-202F) will be performed and, in particular they will include tests for humidity, thermal shock and high voltage conditions.

Aluminum nitride films were deposited on multiple substrates, including thin metal foils and polymers compatible with rolled capacitor technologies. Simple parallel plate capacitor structures were utilized to optimize the dielectric properties. At the conclusion of the original contract, an enhancement and extension were authorized to address unanticipated complications and overcome technical obstacles.

The objectives for the enhancement include:

- (1) Increase the deposition rate of aluminum oxynitride dielectrics deposited from pulsed magnetron reactive sputtering.
- (2) Modify the web-handling system to produce lengths of AlON on foil.
- (3) Construct multilayer capacitor structures for high volume efficiency utilizing the scanner in the web-handling system.
- (4) Improve the AlON capacitor energy density using the multilayer stacked construction.

(5) Improve the efficiency of the operation by depositing both dielectric and metal electrode in one process.

(6) Investigate the thickness and materials of the metal electrode for self-clearing and high temperature applications.

(7) Demonstrate prototype packaged multilayer AlON capacitors.

Aluminum nitride films were deposited on multiple substrates, including thin metal foils and polymers compatible with rolled capacitor technologies. Stacked multilayer capacitor structures have been developed using in-situ processing.

As a result of the work done during this program, seven manuscripts have been submitted and published, and eleven presentations were given at professional conferences.

We would like to thank Ms. Sandra Fries-Carr and Mr. Joseph Weimer, Air Force Research Laboratory (AFRL), Propulsion Directorate, Energy and Power Systems Branch, Wright-Patterson Air Force Base, Ohio, for their interest and support of this program.

Dr. Richard L.C. Wu, Chief Scientist, was the Principle Investigator, and Dr. Kevin R. Bray, Senior Process Engineer, conducted the research and film characterization.

The period of performance was from February 17, 2004 to August 31, 2008.

## Summary

Aluminum oxynitride (AlON) capacitors exhibit several promising characteristics for high energy density capacitor applications in extreme environments. Dielectric constants in the range of 9 and dielectric strength in excess of  $650 \text{ V}/\mu\text{m}$  have been demonstrated in our SBIR Phase II program, resulting in material energy densities greater than  $14 \text{ J/cc}$ . The dielectric properties remain stable from cryogenic temperatures of  $-200 \text{ }^\circ\text{C}$  to temperatures above  $400 \text{ }^\circ\text{C}$ . Stacked capacitor devices have been developed and packaged. The high energy density and wide temperature stability make AlON an attractive candidate for many military, space and commercial applications.

## 1. Introduction

Capacitors are key components in all forms of electronic devices. Military systems utilize millions of capacitors and consider them key components due to their susceptibility for failure. Future needs for weapons systems and aircraft performance require the development of compact, high energy density capacitors for pulsed power and extreme environment applications. Compact, high performance capacitors are the enabling technology for the More Electronic Aircraft (MEA), Directed Energy Weapons (DEW), Directed Energy Attack Aircraft (DE ATAC), Unmanned Combat Aerial Vehicles (UCAV), High Power Microwave (HPW), Electric Propulsion Power Conditioning, Space Based Laser (SBL), and Space Plane Power Management and Distribution (PMAD). Available state-of-the-art (SOTA) dielectric materials include polymer films such as polypropylene (PP), polyester (PET) and polyvinylidene fluoride (PVdF) [1]. Polymer film capacitors dominate current pulsed power and AC applications. Polymers are used for most AC applications because of their non-polar nature and low dielectric losses. Key drawbacks to polymer films include their low operating temperature, typically  $\sim 100$  °C [1], and their large volume-to-weight ratio, which compromises energy storage density.

Most polymers also have a dielectric constant ( $k$ ) in the range of 2 – 4, although  $k$  for PVdF is from 10 – 12 [1]. These low  $k$  values make it difficult to obtain the high energy density required for future military applications. Polymer breakdown voltage is typically in the range of 550 V/ $\mu\text{m}$  [1]. Energy density ( $u_v$ ) depends linearly on dielectric constant ( $k$ ) and on the square of the dielectric breakdown strength ( $E_B$ ) of a capacitor as shown in Equation 1,

$$u_v = \frac{1}{2} k \epsilon_0 E_B^2 \quad (1)$$

where  $\epsilon_0$  is the permittivity of free space. Increasing the breakdown voltage increases the energy density more rapidly than increasing the dielectric constant. Energy densities between 3 and 10 J/cc are typical for current SOTA polymer dielectric materials. Improved dielectric materials for capacitors are needed to meet the military's future power applications. Materials with a higher dielectric constant, greater dielectric breakdown strength and superior thermal stability are needed to improve capacitor performance to meet emerging needs.

Crystalline aluminum nitride (AlN) is a semiconductor with one of the largest known bandgaps (6.2 eV) [2,3] with dielectric strength between 400 and 550 V/ $\mu\text{m}$  [4] and thermal conductivity of 320 W/mK [3]. Amorphous AlN retains many of the crystalline properties and the insulating properties and high resistivity in conjunction with the high breakdown strength make amorphous AlN a desirable material for high density power applications. Thin AlN films have been deposited using a wide range of processes including MOCVD [5,6], RF and DC magnetron sputtering [4,7,8,9,10], and pulsed laser deposition [3,10]. Film structures from amorphous to epitaxial crystals have been obtained by varying deposition parameters and substrates [11].

Pulsed DC sputter deposition produces faster deposition rates than other deposition methods and also results in less substrate heating and thermal stressing of the films [9]. The aluminum target does not experience the same target poisoning that occurs during  $\text{Al}_2\text{O}_3$  sputtering, making the AlN process easier to control and reproduce [8]. Aluminum oxynitride (AlON) also exhibits a stable magnetron sputtering deposition process. Thin amorphous  $\text{Al}_2\text{O}_3$  films have shown

breakdown strength  $\sim 500$  V/ $\mu\text{m}$  [12]. Oxynitride films improve upon this parameter. In this work, the material and dielectric properties of DC sputtered amorphous AlN and AlON are further investigated.

Aluminum nitride and aluminum oxynitride dielectrics were successfully developed in our initial SBIR phase II program. Aluminum oxynitride (AlON) capacitors exhibit several promising characteristics for high energy density capacitor applications in extreme environments. Dielectric constants in the range of 9 and dielectric strength in excess of 600 V/ $\mu\text{m}$  have been measured, resulting in material energy densities greater than 14 J/cc. The dielectric properties remain stable from cryogenic temperatures of  $-200$  °C to temperatures above 400 °C. The high energy density and wide temperature stability make AlON an attractive candidate for many military, space and commercial applications. In the initial phase of this program, films are grown using pulsed DC reactive magnetron sputtering processing with a  $\text{N}_2/\text{O}_2$  reactive gas mixture. One key barrier to producing commercially viable AlON capacitors is the relatively low deposition rate of less than 1 Å/s. We investigated altering the gas composition to increase the deposition rate by replacing the  $\text{N}_2/\text{O}_2$  gas mixture with different constituents. Both the oxygen and nitrogen species are needed to produce high quality films. The addition of oxygen to the nitrogen plasma improved the dielectric properties, but decreased the deposition rate.

Low deposition rates, problems with the aluminum foil scanner and new power conditioning applications that take advantage of the wide temperature properties necessitate additional experimentation to overcome these challenges. Improvements in the deposition rate and an increase in the volumetric efficiency of the AlON capacitors are needed to enhance the feasibility of AlON devices. Therefore, an enhancement program was implemented to investigate techniques to increase the sputter deposition rate through the addition of an inert gas to the reactive mixture. It also explored the influence of a different reactive gas mixture on the growth rate. Nitrous oxide ( $\text{N}_2\text{O}$ ) is commonly used in the semiconductor industry to deposit nitrogen doped oxide films. Thus, nitrous oxide and nitrogen were used as the sputtering gas.

In addition, a multilayer capacitor stack structure was deposited on wafers and other substrates using an in-situ process and was evaluated for increased volumetric efficiency for power conditioning applications. Several packaged AlON capacitors have been manufactured and tested at high temperatures.

## 2. Program Objectives

The original program objectives for the aluminum nitride research include:

- (1) Optimize key manufacturing process steps: AlN films, AlN-coated aluminum foils/metallized polymer films. Processes will be optimized to achieve maximum adhesion of AlN, highest AlN dielectric strength and good thermal stability.
- (2) Design and construct prototype AlN deposition system using dual magnetron reactive sputtering technique for simultaneous deposition of AlN films on both sides of capacitor grade aluminum foils/metallized polymer films.
- (3) Design and construct prototype high energy density AlN capacitors by rolling under controlled environmental conditions.
- (4) Characterize and test AlN capacitors under various environmental conditions: develop understanding of the mechanisms of failure. Demonstrate capacitor capabilities with respect to equivalent series resistance (ESR), dissipation factor (DF), Frequency response, and temperature characteristics. The Military Standard Test Methods for Electronic and Electrical Component Parts (MIL-STD-202F) will be performed and, in particular they will include tests for humidity, thermal shock and high voltage conditions.

The objectives for the enhancement include:

- (1) Increase the deposition rate of aluminum oxynitride dielectrics deposited from pulsed magnetron reactive sputtering.
- (2) Modify the web-handling system to produce lengths of AlON on foil.
- (3) Construct multilayer capacitor structures for high volume efficiency utilizing the scanner in the web-handling system.
- (4) Improve the AlON capacitor energy density using the multilayer stacked construction.
- (5) Improve the efficiency of the operation by depositing both dielectric and metal electrode in one process.
- (6) Investigate the thickness and materials of the metal electrode for self-clearing and high temperature applications.
- (7) Demonstrate prototype packaged multilayer AlON capacitors.

### 3. Dual Ion Beam Deposition System

The unique Dual Ion Beam Source deposition system has been modified for aluminum nitride pulsed magnetron reactive sputtering deposition. The ion beam sources were replaced with 4" diameter magnetron sputtering guns with 1/4" thick 99.999% pure Al targets. The RF power supplies were replaced with pulsed DC power supplies with a range up to 5 kW power and pulse frequencies up to 350 kHz. Research grade Ar, N<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub>O gases are available for sputtering. The aluminum foil scanner plate used for DLC deposition is also being utilized for AlN film growth. The scanner is equipped with substrate cooling/heating capabilities ranging from 5 °C to 40 °C. A class 100 clean room enclosure houses the entire deposition system. Figure 1 shows the deposition systems in the clean room facilities.

For individual small substrates, a copper plate was designed for substrate mounting. The temperature is monitored via a thermocouple attached to the backside of the mounting plate. A schematic of the deposition system is shown in Figure 2. The Dual Ion Beam Source deposition system was further modified for use in this enhancement. The scanner apparatus was replaced with a precision sample transfer manipulator, shown in Figure 3. The manipulator allowed the use of both sputter sources in the chamber, one for dedicated conductive metal electrode deposition and the other for insulating dielectric layers. Our dual sputter source deposition system and scanner provides us the ability to deposit multilayer capacitor stacks in-situ without outside process steps such as etching. The sputter deposition allows the deposition of both conductive metal electrode films and insulating dielectric layers in the same apparatus without breaking vacuum. This in-situ processing will improve the interfaces between the layers and reduce damage and defects from exposure to air and additional processing steps. Insulating substrates are needed for multilayer stacks. Initial experiments utilized glass plates and subsequently oxidized silicon wafers with 1 μm SiO<sub>2</sub> were used as substrate material.

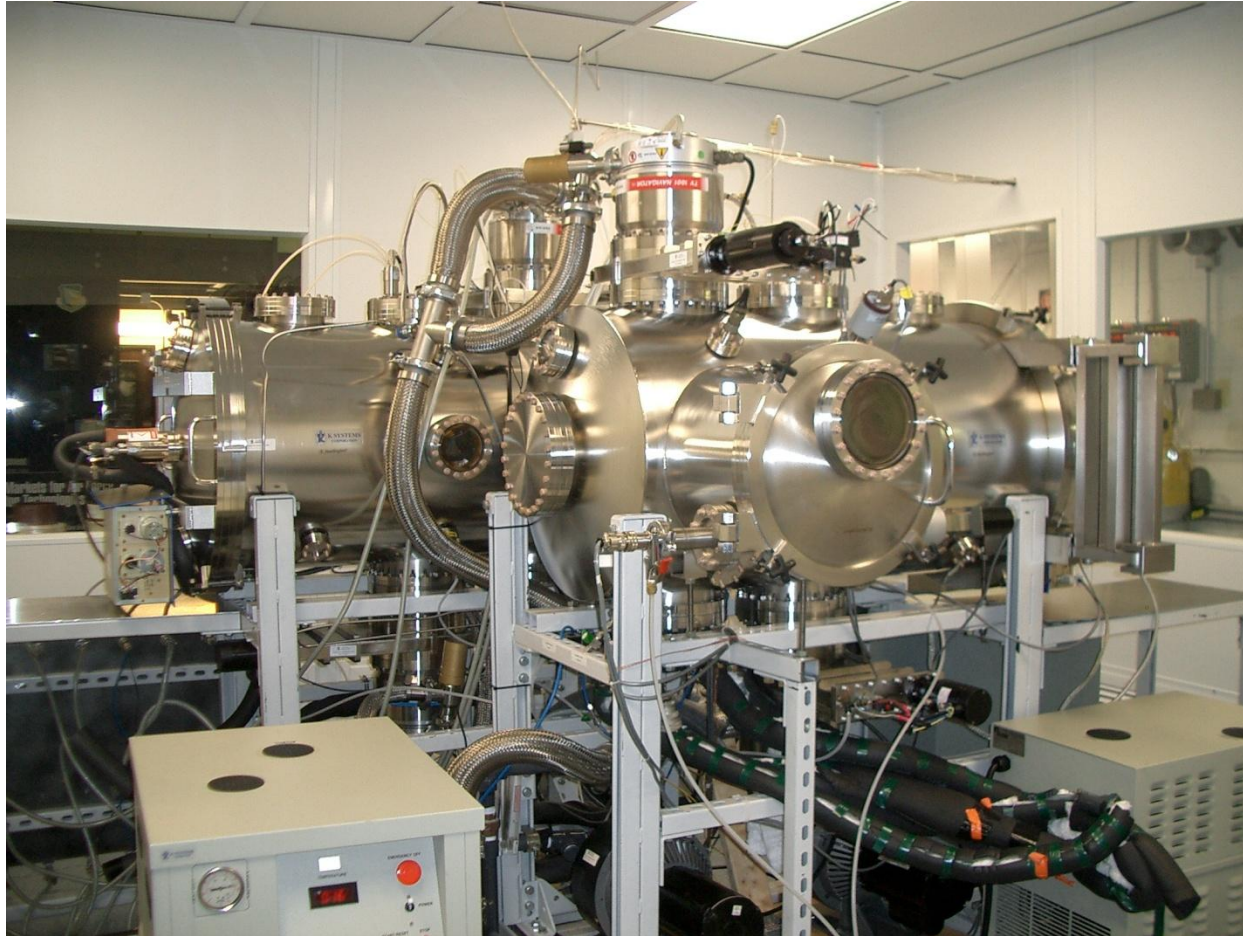


Figure 1. Dual Ion Beam Deposition System

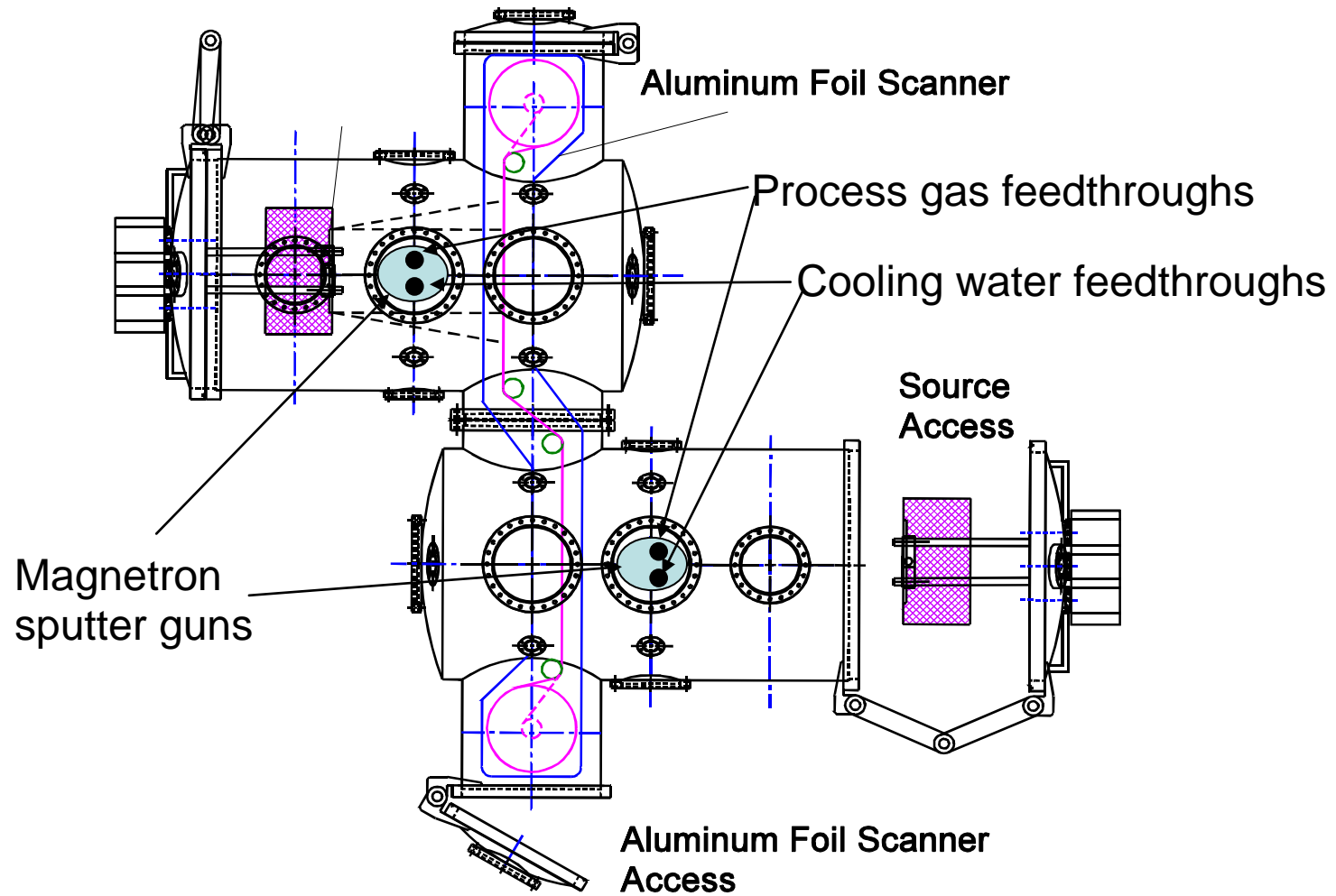


Figure 2. Schematic of Dual Ion Beam Deposition System

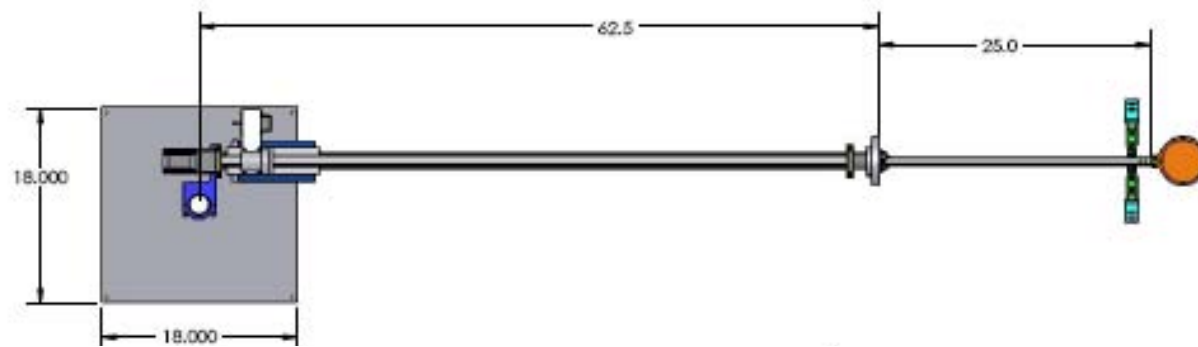


Figure 3. Schematic of Precision Sample Transfer Manipulator

## 4. Aluminum Nitride Deposition from N<sub>2</sub>/O<sub>2</sub>

### 4.1 Process Optimization

The process parameters for AlN deposition were optimized to maximize dielectric performance. The effects of DC power, gas mixture, pulse frequency, target-to-substrate spacing, and process pressure were examined. A statistical process optimization procedure was employed to identify key input parameters.

Genichi Taguchi used orthogonal tables in experiments designed to improve quality control. The purpose of orthogonal design is to study the relationship between process parameters (input parameters) and their corresponding output functions by selecting certain representative combinations of input parameter level settings. By following the orthogonal table, a maximum amount of information can be obtained using the least number of experiments.

#### 4.1.1 Taguchi Analysis

A set of process optimization experiments was performed. Table 1 lists the input parameters examined and the resulting properties. DC power, pulse frequency and process pressure were varied in the analysis. The one factor plots from the analysis are shown in Figure 4 – 12. The most significant effects were observed in relation to the breakdown strength. Both the DC power and frequency influenced this parameter. No significant effects were observed for the dielectric constant and the dissipation factor.

Table 1. Taguchi Analysis Parameters and Results

| Sample | Run | Power (W) | Frequency (kHz) | Pressure (mTorr) | k     | HV (V/micron) | DF     | Rate (Å/s) |
|--------|-----|-----------|-----------------|------------------|-------|---------------|--------|------------|
| AlN060 | 1   | 1000      | 50              | 10               | 7.12  | 445           | 0.0241 | 1.36       |
| AlN055 | 2   | 1000      | 150             | 12.5             | 8.30  | 402           | 0.0317 | 1.50       |
| AlN057 | 3   | 1000      | 250             | 15               | 7.48  | 527           | 0.0363 | 1.67       |
| AlN054 | 4   | 1500      | 50              | 15               | 10.36 | 513           | 0.0543 | 2.45       |
| AlN061 | 5   | 1500      | 150             | 10               | 10.17 | 393           | 0.0313 | 2.35       |
| AlN052 | 6   | 1500      | 250             | 12.5             | 8.43  | 270           | 0.0217 | 2.73       |
| AlN058 | 7   | 2000      | 50              | 12.5             | 8.05  | 349           | 0.0178 | 3.01       |
| AlN056 | 8   | 2000      | 150             | 15               | 6.93  | 424           | 0.0139 | 2.34       |
| AlN053 | 9   | 2000      | 250             | 10               | 9.77  | 200           | 0.0159 | 3.51       |

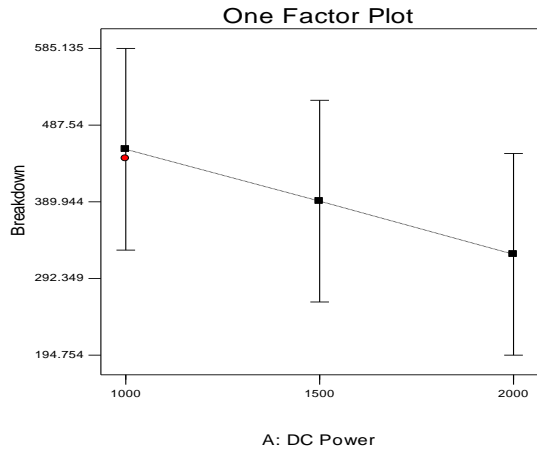


Figure 4. Breakdown Voltage vs. DC Power

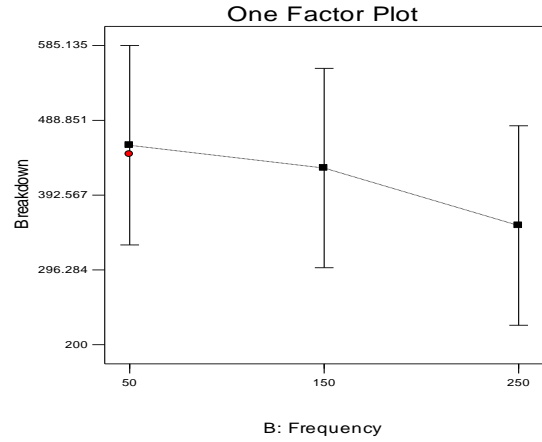


Figure 5. Breakdown Voltage vs. Frequency

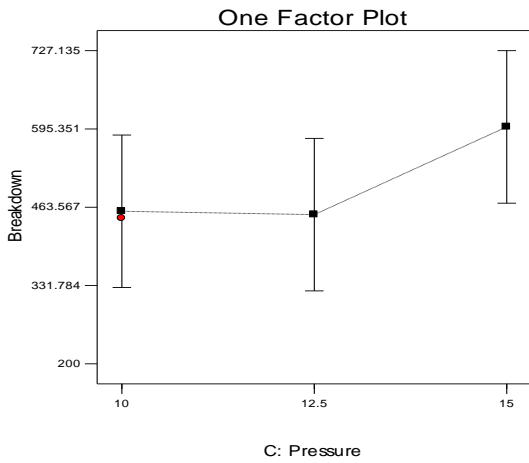


Figure 6. Breakdown Voltage vs. Pressure

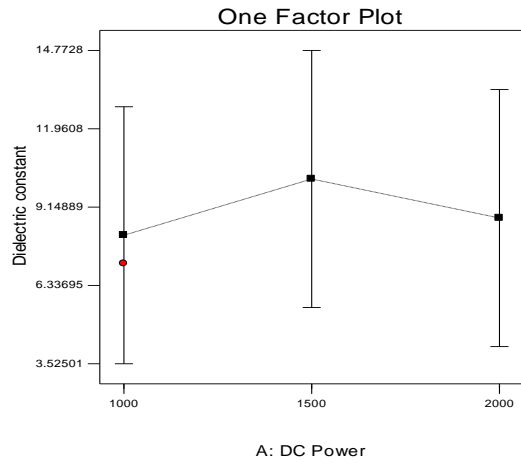


Figure 7. Dielectric Constant vs. DC Power

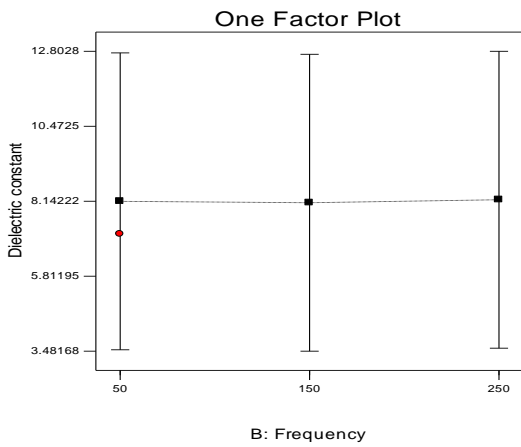


Figure 8. Dielectric Constant vs. Frequency

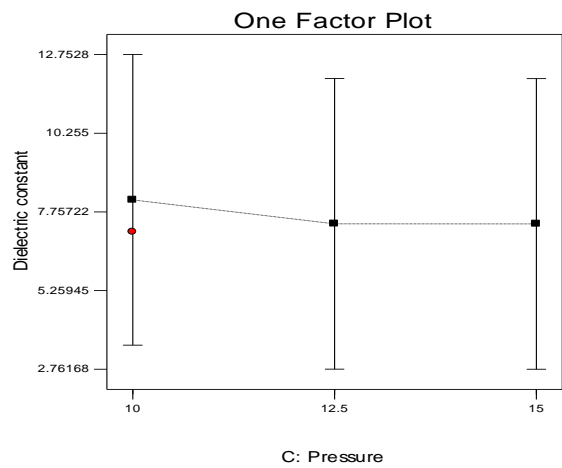


Figure 9. Dielectric Constant vs. Pressure

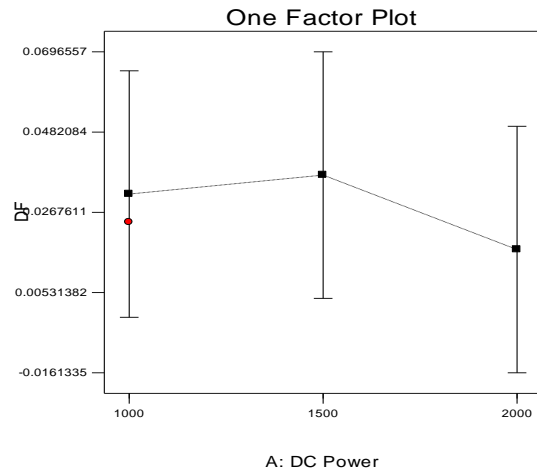


Figure 10. Dissipation Factor vs. DC Power

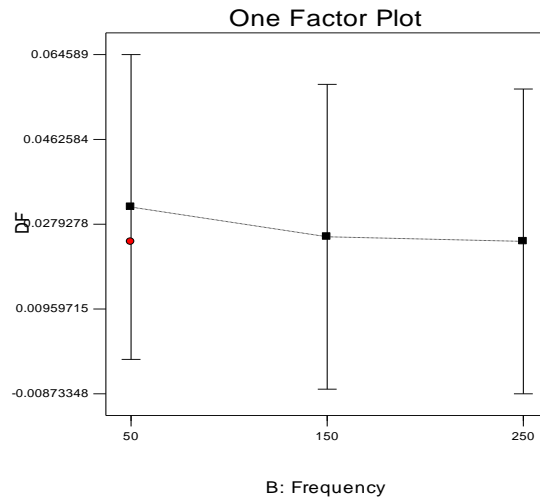


Figure 11. Dissipation Factor vs. Frequency

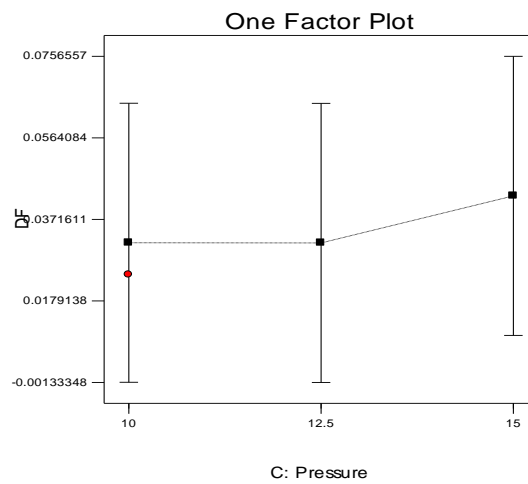


Figure 12. Dissipation Factor vs. Pressure

#### 4.1.2 Gas Composition

Initial aluminum nitride films were deposited from pure nitrogen plasma. The capacitance and dissipation factor exhibited significant frequency dependence and additional studies were undertaken to examine the effects of process gas composition. Figure 13 shows the capacitance and dissipation factor plotted vs. frequency for films deposited from pure nitrogen plasma and an N<sub>2</sub>:O<sub>2</sub> mixture. The aluminum nitride deposition was optimized to stabilize the capacitance and dissipation factor with respect to frequency. The addition of oxygen improves the frequency stability of the capacitance. It also lowers the dissipation factor by an order of magnitude. The addition of oxygen also had the adverse effect of decreasing the deposition rate. Argon was also mixed in the system to increase the sputtering rate. This raised the deposition rate, but the film quality was degraded and argon was removed from the process.

#### 4.1.3 Breakdown Strength

Dielectric breakdown strength is one of the most critical film properties for high power density devices. Examination of deposition parameters including DC power, deposition pressure and pulse frequency determined that DC power was the most significant process input into film breakdown. Figure 14 plots breakdown strength vs. DC Power for different N<sub>2</sub>:O<sub>2</sub> gas ratios. The breakdown strength increases with increasing power initially, achieves a maximum and then decreases at higher powers. The optimal DC power to achieve the maximum breakdown can be shifted by altering the N<sub>2</sub>:O<sub>2</sub> ratio. Maximum breakdown strength of ~600 V/μm has been measured. This is consistent with increasingly energetic particles sputtered from the target with increasing power. As more energetic material reaches the substrate, it is capable of diffusing and adhering to the optimal location. As the power increases beyond the optimal setting, the particles arrive at the surface too rapidly, and there is not sufficient time for diffusion before the subsequent layer deposits. Increased power during film growth also results in a higher aluminum fraction in the deposited film. Increased DC power has also been shown to increase micro voids in the dielectric. The higher metal content or the increased void concentration creates defect sites that breakdown under lower applied voltage.

## Capacitance and Dissipation Factor vs. Frequency

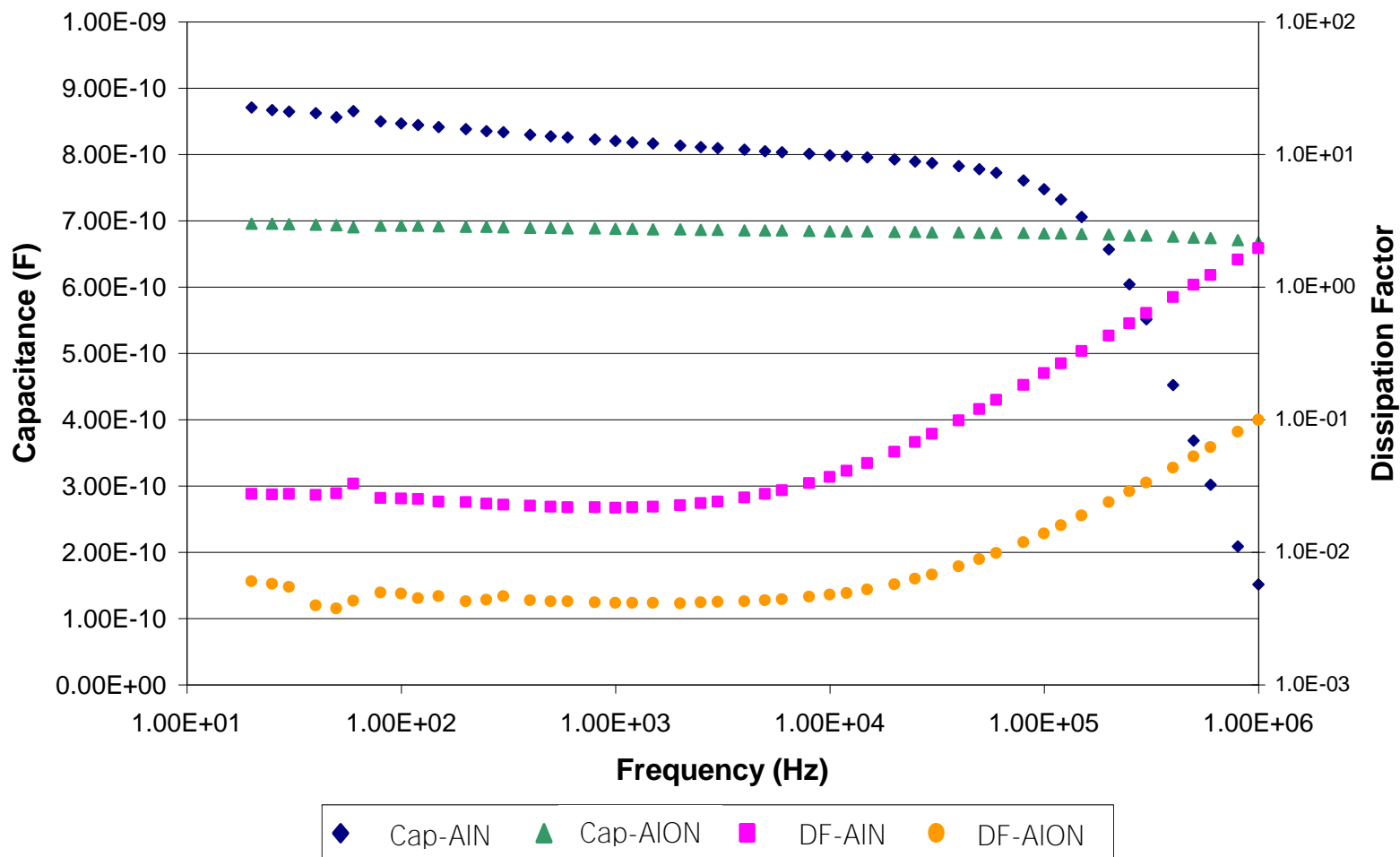


Figure 13. Capacitance and Dissipation Factor vs. Frequency from N<sub>2</sub> and N<sub>2</sub>:O<sub>2</sub> Plasmas

# Breakdown Voltage vs. DC Power

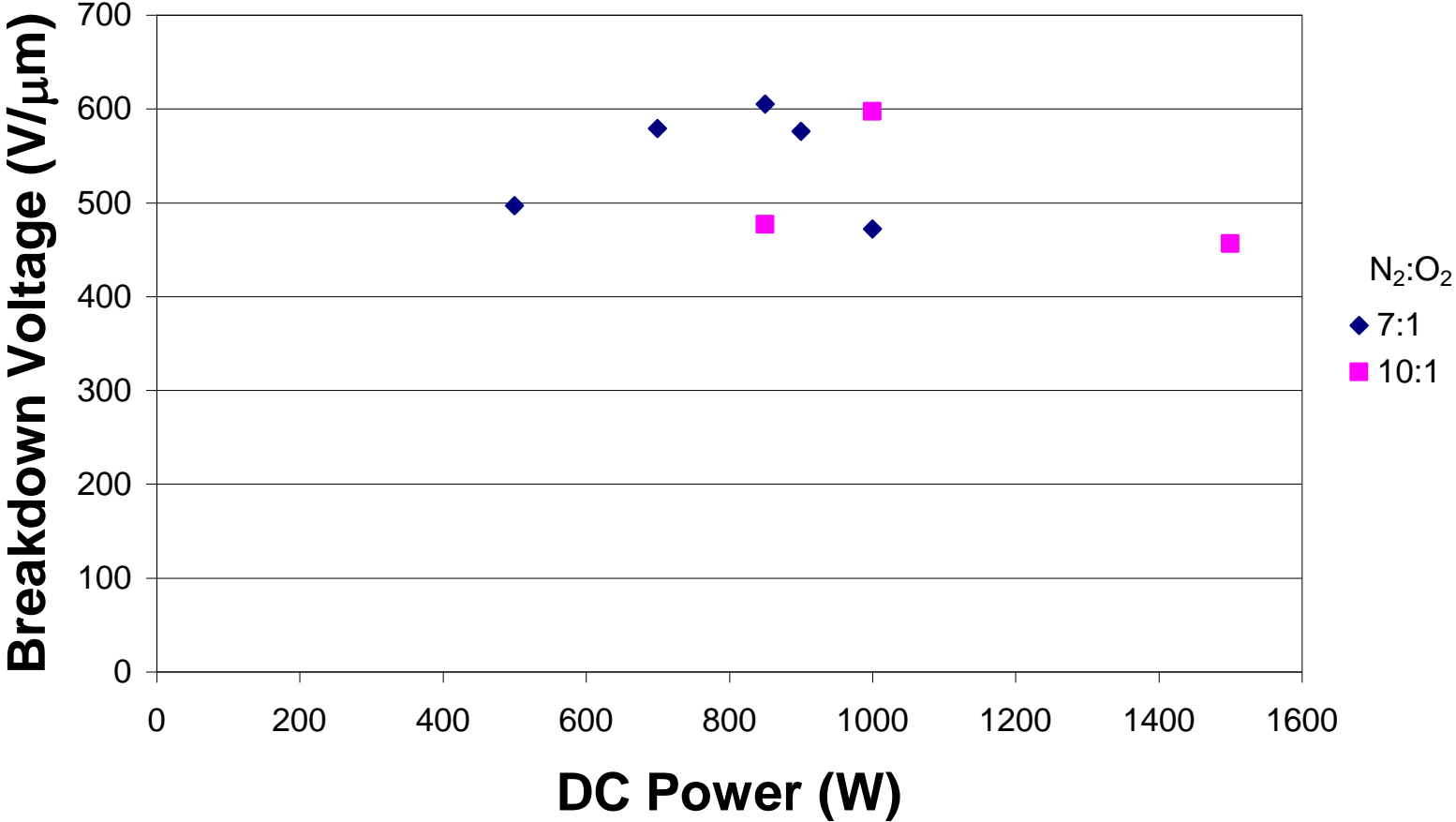


Figure 14. Breakdown Voltage vs. DC Power at various N<sub>2</sub>:O<sub>2</sub> Ratios

## 4.2 Chemical Composition

Energy Dispersive X-ray Spectroscopy (EDS) and Rutherford Backscattering Spectroscopy (RBS) were used to evaluate the chemical composition of our AlN and AlON films and to identify impurities and contaminants. Figure 15 shows the EDS spectrum of AlN096, deposited from pure nitrogen plasma. Table 2 lists the elemental composition of the film. Although no oxygen was introduced into the process, residual gas in the deposition chamber was incorporated in the film. The high concentration of carbon observed in our previous report was eliminated by thoroughly flushing the gas lines. The Al:N ratio is ~1:1, with a slight excess of Al. RBS analysis of the same sample reports the same results as shown in Fig. 16, the RBS composition vs. depth profile. Al, O and N are observed, with a uniform distribution throughout the film.

The results change dramatically when oxygen is intentionally added to the process. Figure 17 is the EDS spectrum for AlN112, deposited with a 10:1 ratio of N:O. The oxygen completely replaces the nitrogen in the film and an AlO compound is formed. Although evaluation of the spectrum does not indicate any nitrogen in the film, closer inspection indicates a shoulder on the oxygen peak from a small amount of nitrogen. The RBS spectrum in Fig. 18 confirms both of these results. The sample is primarily AlO, with an Al:O ratio of ~1:2, and ~7% N present. The standard heats of formation for crystalline AlN and Al<sub>2</sub>O<sub>3</sub> are -318 kJ/mol and -1675.7 kJ/mol respectively. The formation of aluminum oxide is ~5X more thermodynamically favorable than aluminum nitride. Although reactive sputtering does not operate at thermodynamic equilibrium, the heats of formation indicate any excess oxygen will displace nitrogen in the films.

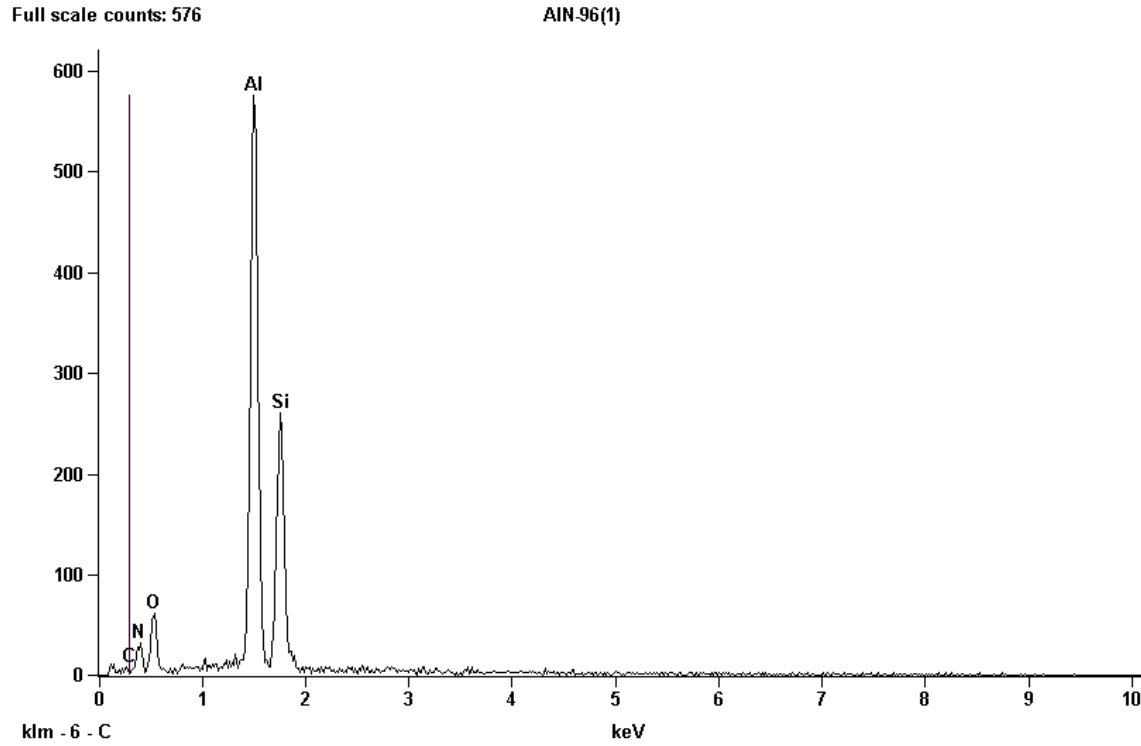


Figure 15. EDS Spectrum of AlN Film

Table 2. Elemental Composition of AlN Film from EDS

| SAMPLE NO.    | ATOM CONCENTRATION % |          |          |           |
|---------------|----------------------|----------|----------|-----------|
|               | <i>C</i>             | <i>N</i> | <i>O</i> | <i>Al</i> |
| <i>AlN096</i> | 0.00                 | 35.73    | 23.54    | 40.73     |

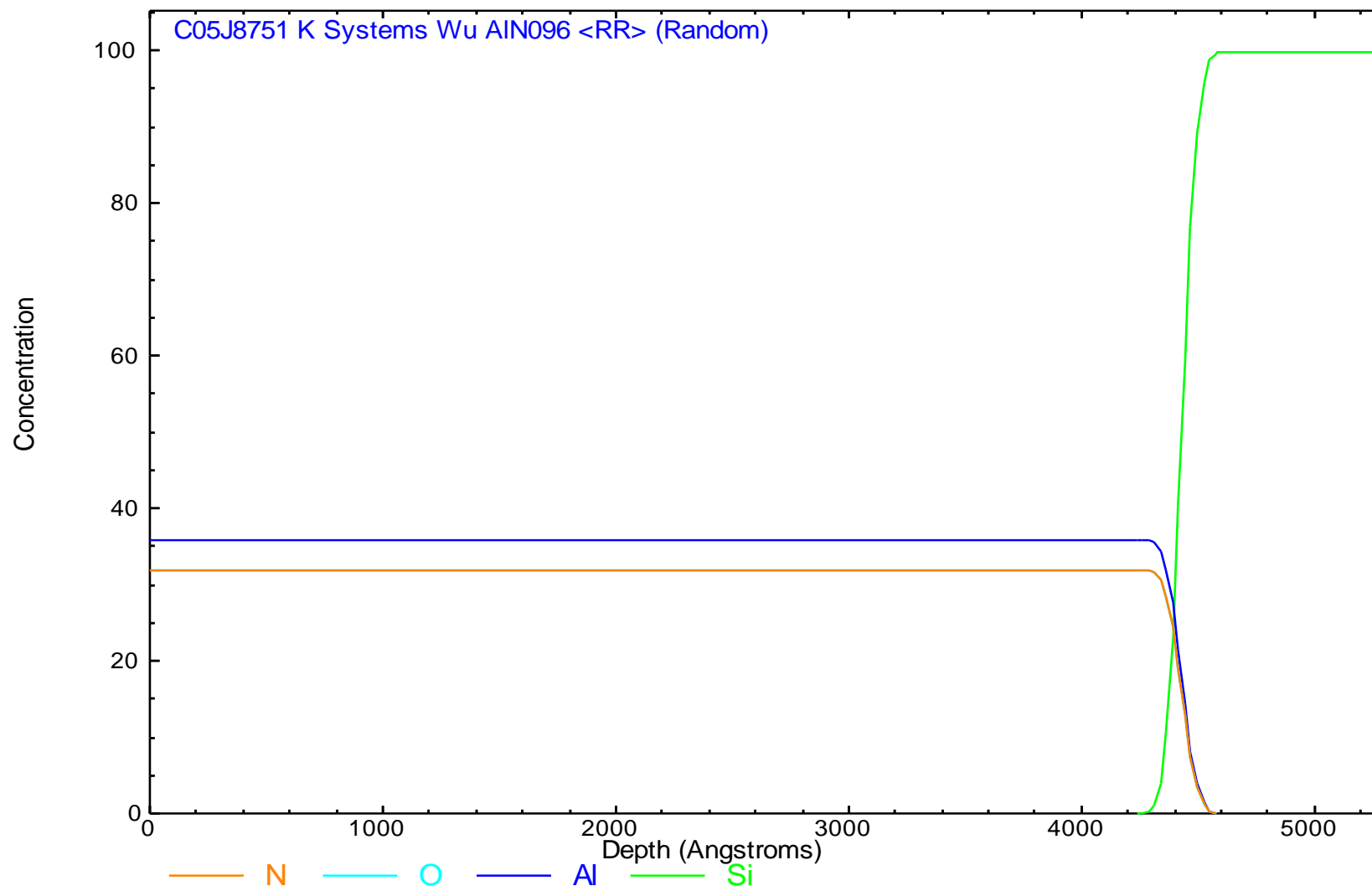


Figure 16. RBS Spectrum of AlN Film

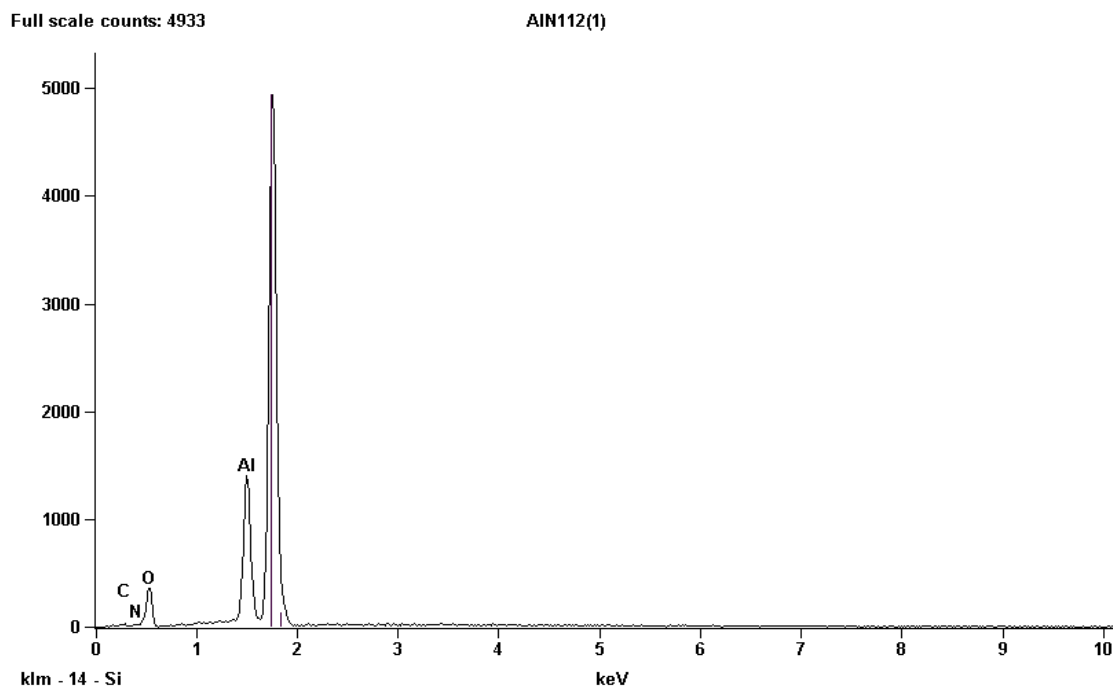


Figure 17. EDS Spectrum of AION Film

Table 3. Elemental Composition of AION Film from EDS

| SAMPLE NO.    | ATOM CONCENTRATION % |          |          |           |
|---------------|----------------------|----------|----------|-----------|
|               | <i>C</i>             | <i>N</i> | <i>O</i> | <i>Al</i> |
| <i>AIN112</i> | 18.90                | 0.00     | 56.06    | 25.04     |

# Charles Evans & Associates

Figure \_\_\_\_\_

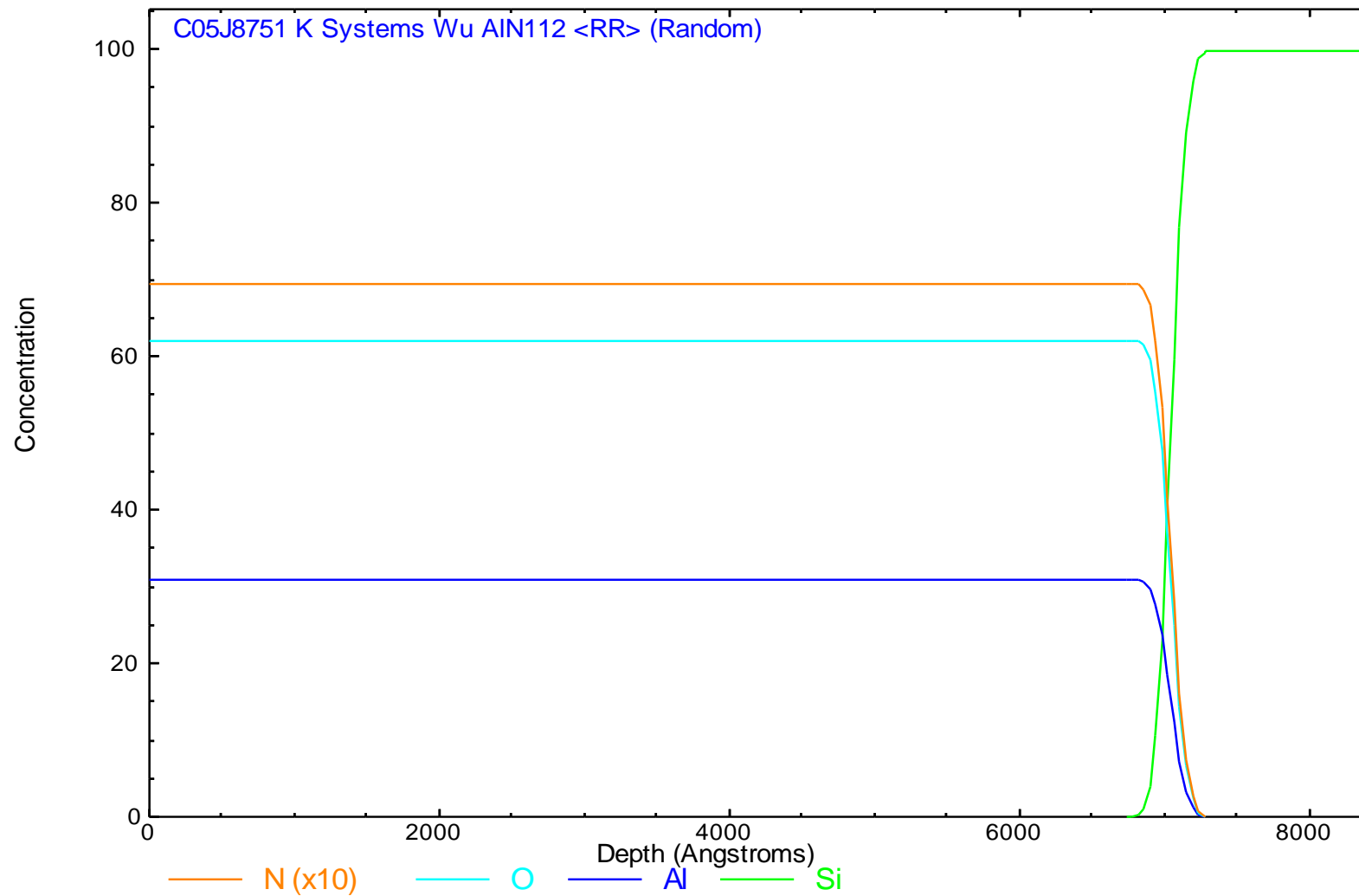


Figure 18. RBS Spectrum of AlON Film

### 4.3 Aluminum Nitride Deposition

Aluminum nitride deposition runs were conducted on numerous substrates and utilizing a wide variety of process settings. DC power ranged from 500 W to 2000 W, with pressures between 5 mTorr and 20 mTorr. Films were deposited on metallized silicon wafers, metallized glass, aluminum foil, and metallized polymers. Nitrogen plasma with argon and oxygen dilution was also examined. The target-to-substrate distance was varied from 3" to 6". Active substrate cooling was also investigated. Deposition times were adjusted to achieve 5000-Å-films. Appendix A summarizes the deposition conditions for each experimental run from the initial aluminum nitride investigation.

### 4.4 Film Thickness and Surface Characterization

A Dektak 3ST surface profilometer was utilized to measure the film thickness across the deposited films. A portion of each Si or glass substrate was masked with a thin strip of stainless steel foil or high temperature tape to create a thickness step. Multiple step height measurements across the entire sample were averaged to obtain the reported film thickness.

An Olympus optical microscope with integrated digital camera and a Scanning Electron Microscope (SEM) were employed to image the surface structure of the AlN films deposited on a variety of substrates. Optical surface images at magnifications from 100X to 1000X were obtained. Figure 19 shows a typical SEM image of an AlN film on silicon. The surface is smooth and amorphous. Figures 20 and 21 are optical images of films deposited on glass and FPE polymer. Some small surface defects were observable, but large pinholes were not present in the majority of the samples. Good adhesion was observed on all of the substrates investigated without any surface pretreatments.

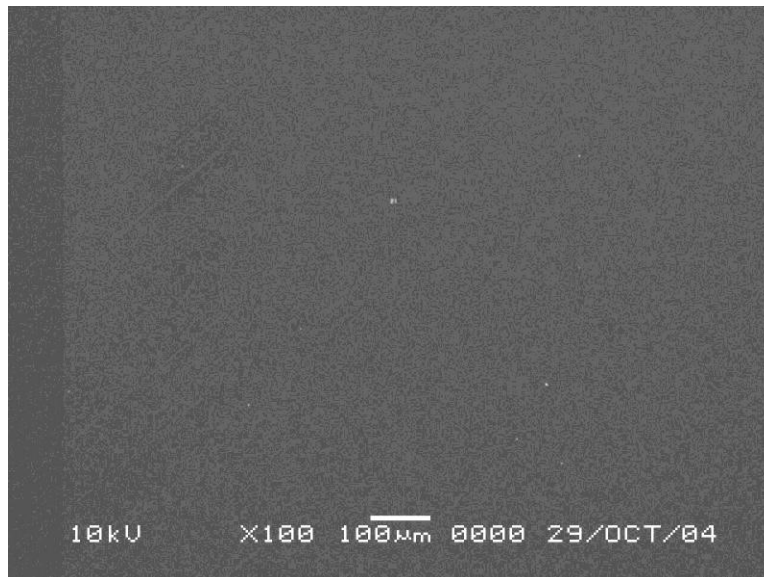


Figure 19. SEM Micrograph of AlN on Si

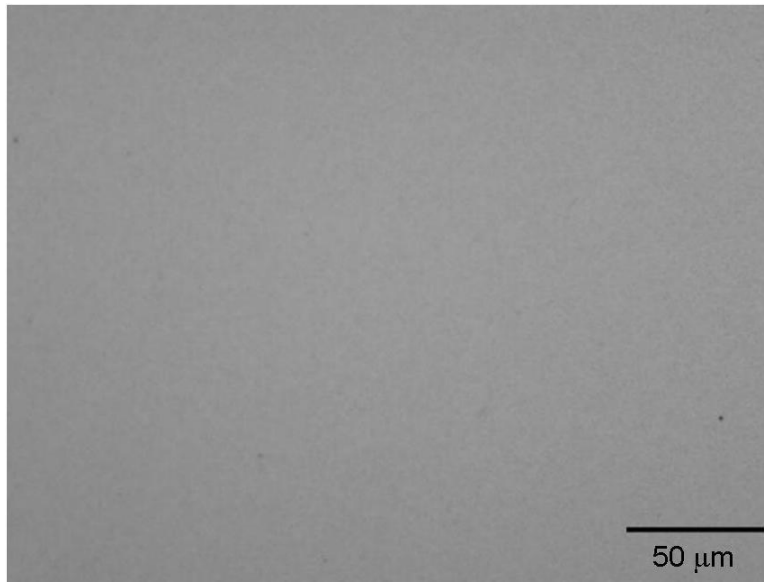


Figure 20. Optical Micrograph of AlN on Glass

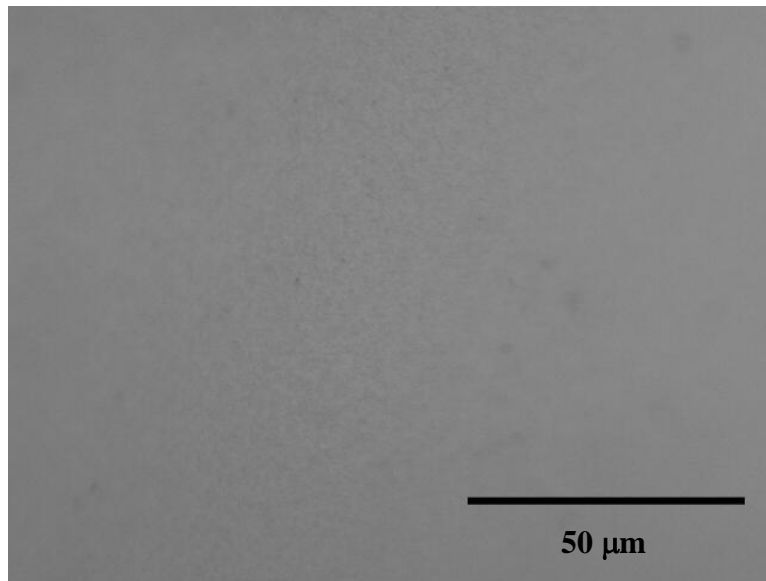


Figure 21. Optical Micrograph of AlN on FPE

#### 4.5 Dielectric Properties

Extensive dielectric properties of AlN films have been characterized at K Systems facilities in the AFRL/RZPE Capacitor Research Center, WPAFB, OH. The characterizations include: (1) spot check, (2) frequency characterization, (3) insulation resistance and (4) dielectric breakdown. Values of the dielectric constant and dissipation factor are obtained from the spot checks and frequency analysis. The resistance is calculated from the AC frequency measurements and the DC IR measurements. Breakdown voltage was determined by applying a voltage stepped in

regular increments to a capacitor for a set time duration and measuring the resulting current until complete breakdown occurs. Steps of 5 V and 10 V were applied for 3 or 5 seconds in typical tests. The average dielectric constant at 1 kHz is ~9, with a dissipation factor of ~ 0.005 and a breakdown voltage of ~600 V/ $\mu\text{m}$ . Appendix B summarized the dielectric results. “Film” refers to the film thickness measured by profilometry or estimated from the deposition rate. “HV” is the actual breakdown voltage. Blank cells in the table could not be measured.

#### 4.5.1 Atmospheric Stability

The stability of the capacitance and dissipation factor with respect to atmospheric exposure was also measured as a function of frequency. Figures 22 and 23 plot capacitance and dissipation factor vs. frequency for AlN112, deposited in January, 2005. The film was originally measured directly after deposition. It was then allowed to sit on the desktop open to the laboratory atmosphere for six months. The second trace on the plots is the frequency response after this six month exposure. The capacitance remains constant with frequency for both measurements. There is approximately a 6% change in the capacitance value, reflecting a small change in the dielectric constant. The dissipation factor is equivalent below ~5 kHz, and then there is a minor change with the aged film showing a slightly lower value at higher frequencies.

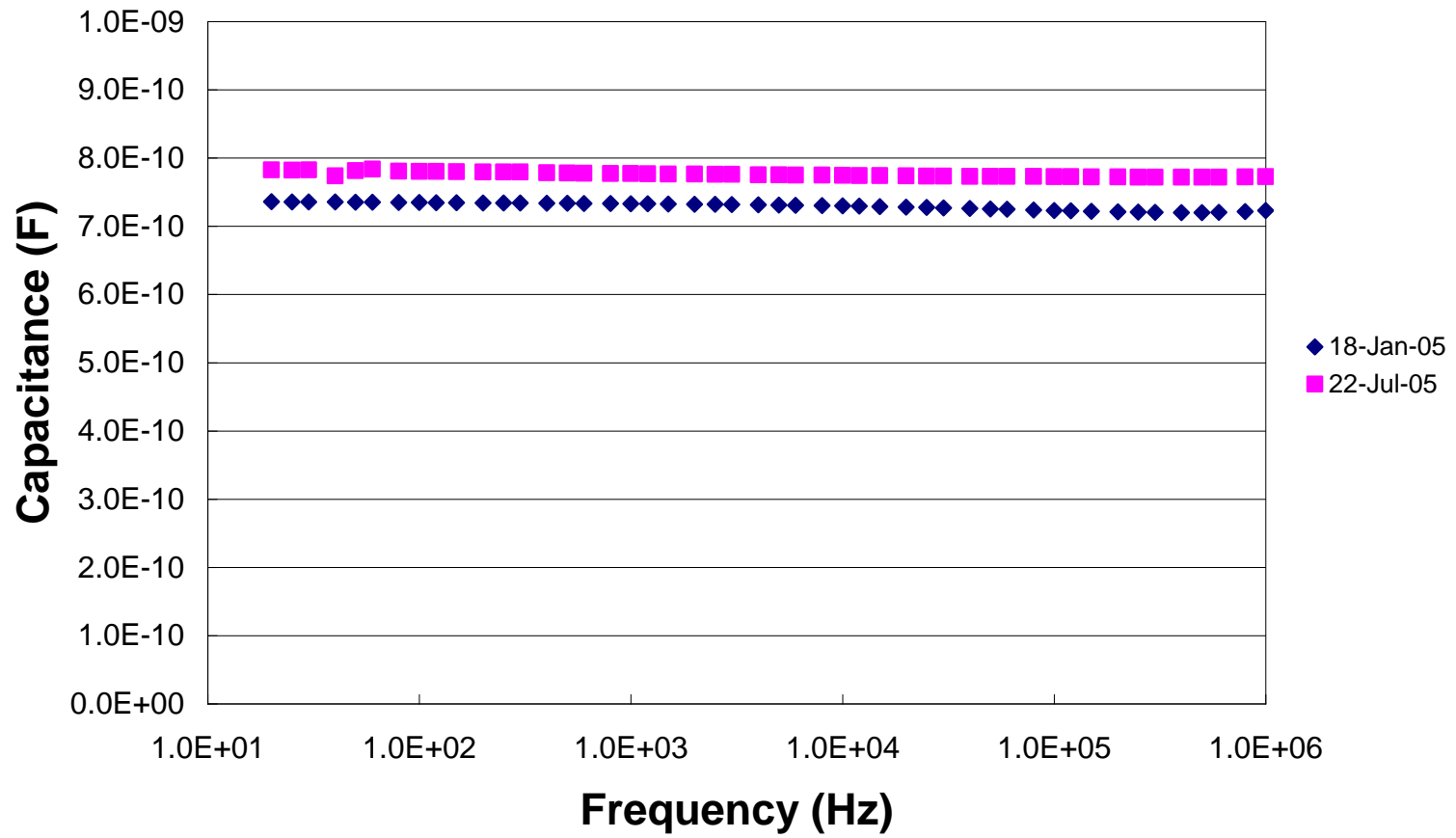


Figure 22. Effects of Atmospheric Exposure on the Capacitance

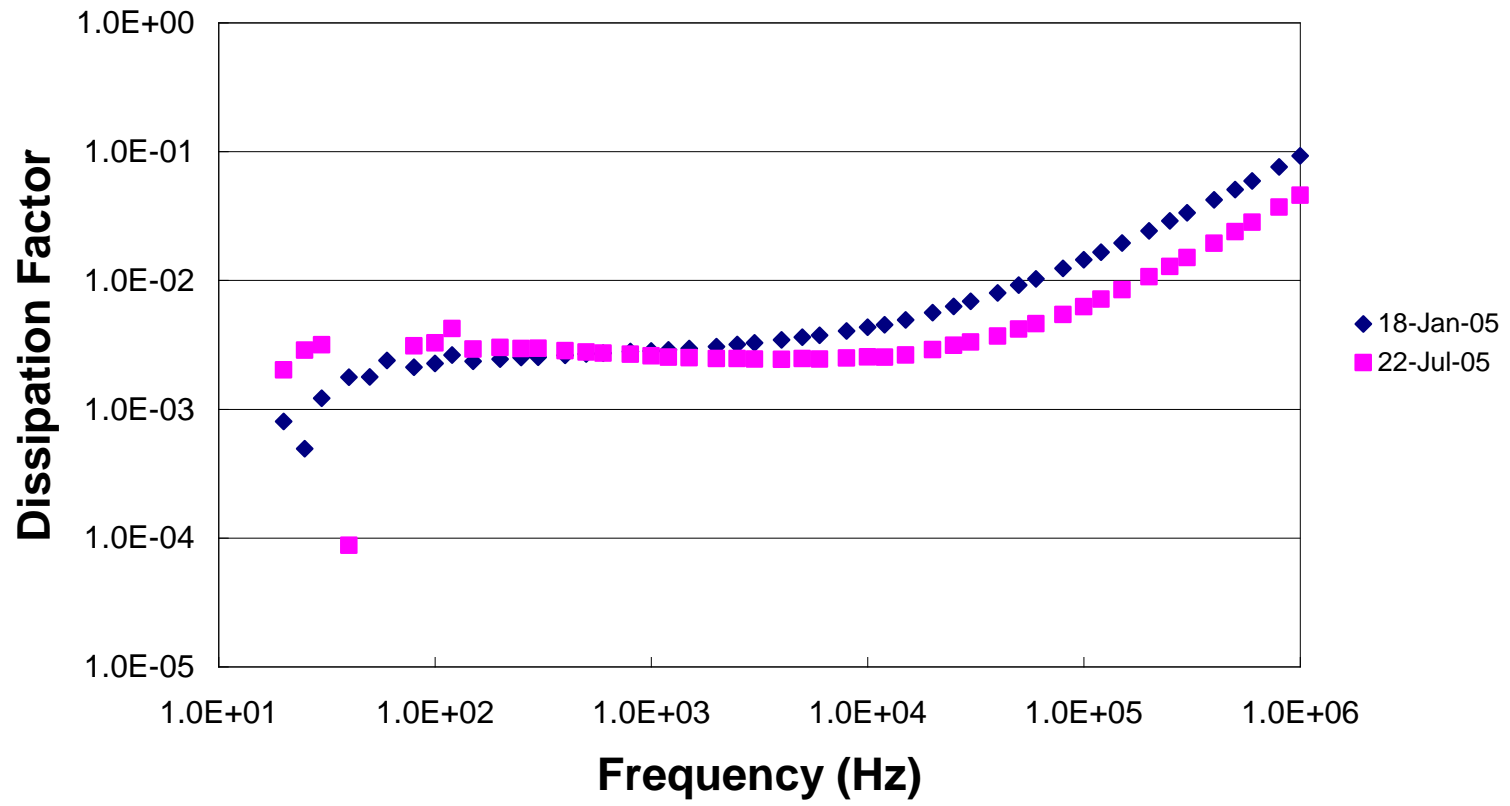


Figure 23. Effect of Atmospheric Exposure on Dissipation Factor

#### 4.5.2 Substrate Materials

Aluminum oxynitride films have been deposited on a variety of substrates including both rigid materials such as glass and silicon and flexible substrates such as polymers and thin metal foils. The ability to deposit AION films on flexible substrates is important for constructing rolled capacitor devices. Polymer films along with aluminum, stainless steel and titanium metal foil substrates were investigated. Initial polymer testing utilized Mylar, a polyester film. Previous work on DLC capacitors had utilized Mylar as a substrate. But the AION sputter deposition involves a higher energy deposition than the DLC process. The Mylar material was consistently burned and warped during deposition. We then turned our attention to a high temperature polymer, fluorine polyester (FPE). Results with this material were much more successful. We were able to deposit 5000 Å AION films on 5- $\mu\text{m}$ -thick FPE substrates. The high temperature properties of FPE were able to withstand the intense plasma beam. Dielectric constants of  $\sim 9$  and DF  $\sim 0.005$  were observed at 1 kHz on all substrates. Figure 24 shows the capacitance and dissipation factor for films grown on a variety of substrates. The capacitance remains independent of the substrate material for all the materials examined. Below 5 kHz, the dissipation factor behaves similarly for each substrate. The metallized glass and metal foil substrates continue to exhibit comparable behavior to 1 MHz. The sample on FPE begins to deviate from the other materials around 5 kHz.

The initial substrate smoothness also has a considerable influence on the breakdown strength. Figure 25 plots the leakage current vs. applied field for 5000-Å-thick films deposited on thin stainless steel and titanium foils under identical deposition conditions. The film on the stainless steel foil shows over 200 V/ $\mu\text{m}$  increase in the breakdown field strength compared to the film on the titanium. Examination of the film surfaces using optical microscopy, shown in Figures 26 and 27, helps explain these dramatic differences. The stainless steel foil is much smoother than the titanium. The initial roughness of the titanium results in local areas where the AION is thinner than estimated, resulting in preferential breakdown sites at lower fields. Films grown on other smooth substrates, including silicon, glass, and FPE, exhibit dielectric strengths of  $\sim 600$  V/ $\mu\text{m}$ .

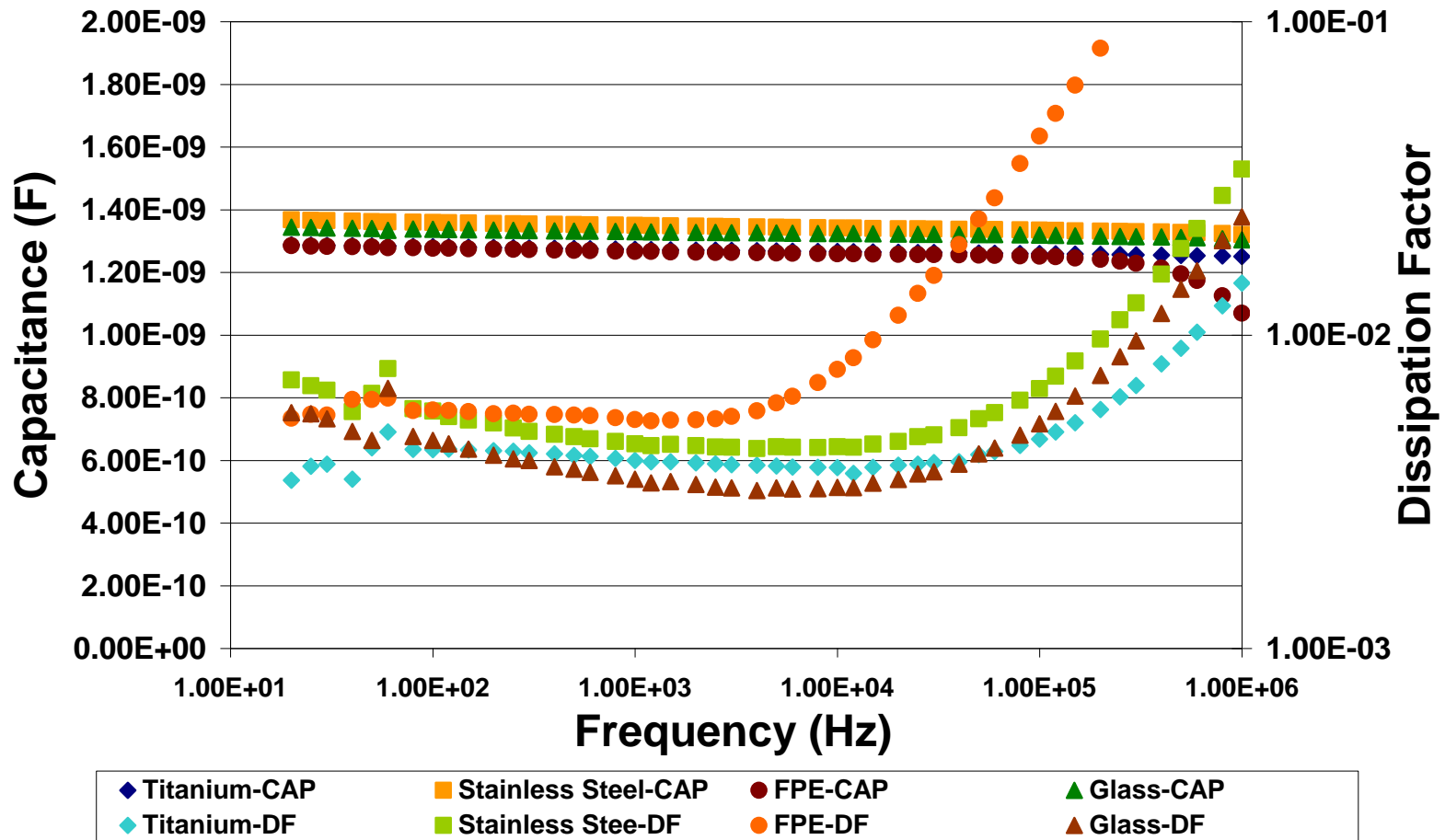


Figure 24. Effects of Substrate on Capacitance and Dissipation Factor

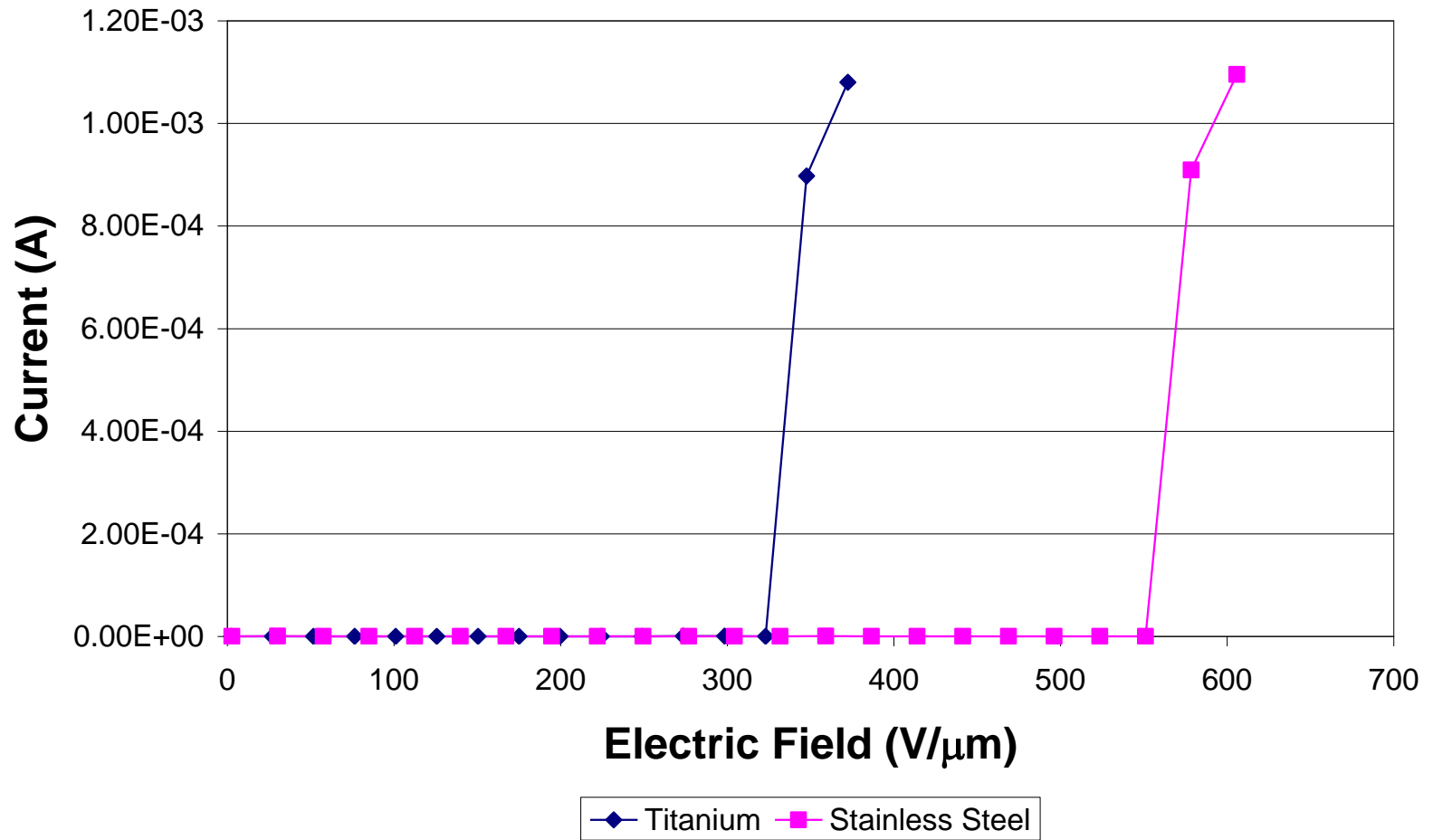


Figure 25. Effects of Substrate on Breakdown Strength



Figure 26. Optical Micrograph of AlON on Stainless Steel Foil



Figure 27. Optical Micrograph of AlON on Titanium Foil

## 5. Aluminum Foil Scanner Characterization

### 5.1 Deposition Uniformity

The dual ion beam deposition system is equipped with a scanner system for depositing dielectric films directly onto spooling aluminum foil or polymer films. The film thickness distribution was examined across the exposed scanner deposition area. Figures 28 and 29 show the vertical and horizontal thickness distribution in Source One while Figures 30 and 31 show the same information in Source Two. The vertical distribution is approximately constant for greater than two inches in both chambers, and then slowly begins to decrease. The horizontal growth profiles in both chambers are very similar. The data fit reasonably with a second order polynomial. The equations for the data fits shown in Figures 29 and 31 are very similar, indicating good reproducibility between the two chambers. The thickness distribution equations were utilized to calculate the average deposition rate across the scanner area. The scan speed necessary to coat 5000 Å uniformly across a moving foil was determined from the average deposition rate.

Figure 32 plots the capacitance vs. frequency for samples deposited in both Source One and Source Two in different deposition runs. The data is reproducible and falls within  $\pm 10\%$  deviation. This suggests the film quality is similar in both deposition chambers.

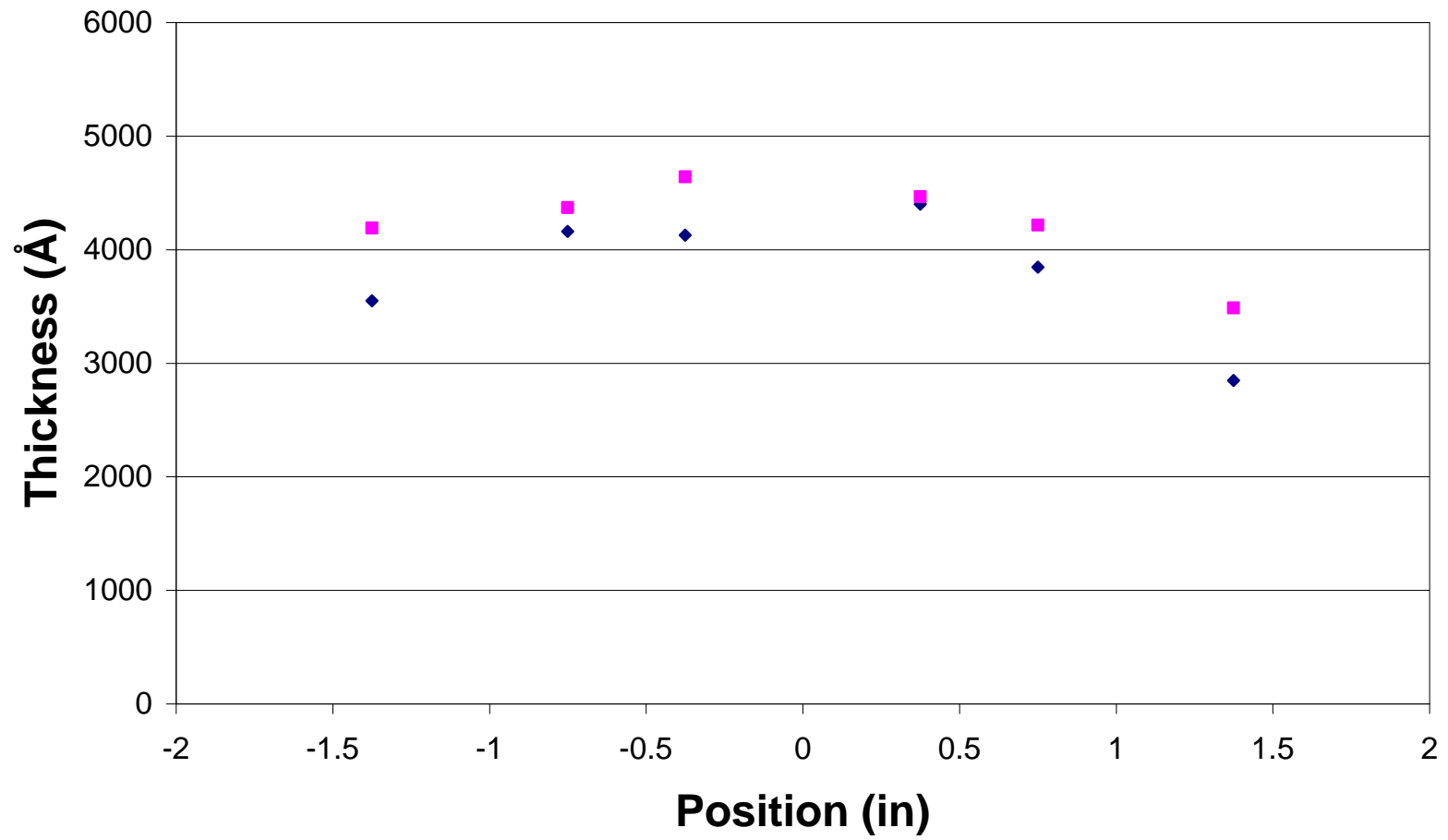


Figure 28. Vertical Deposition Distribution in Source One

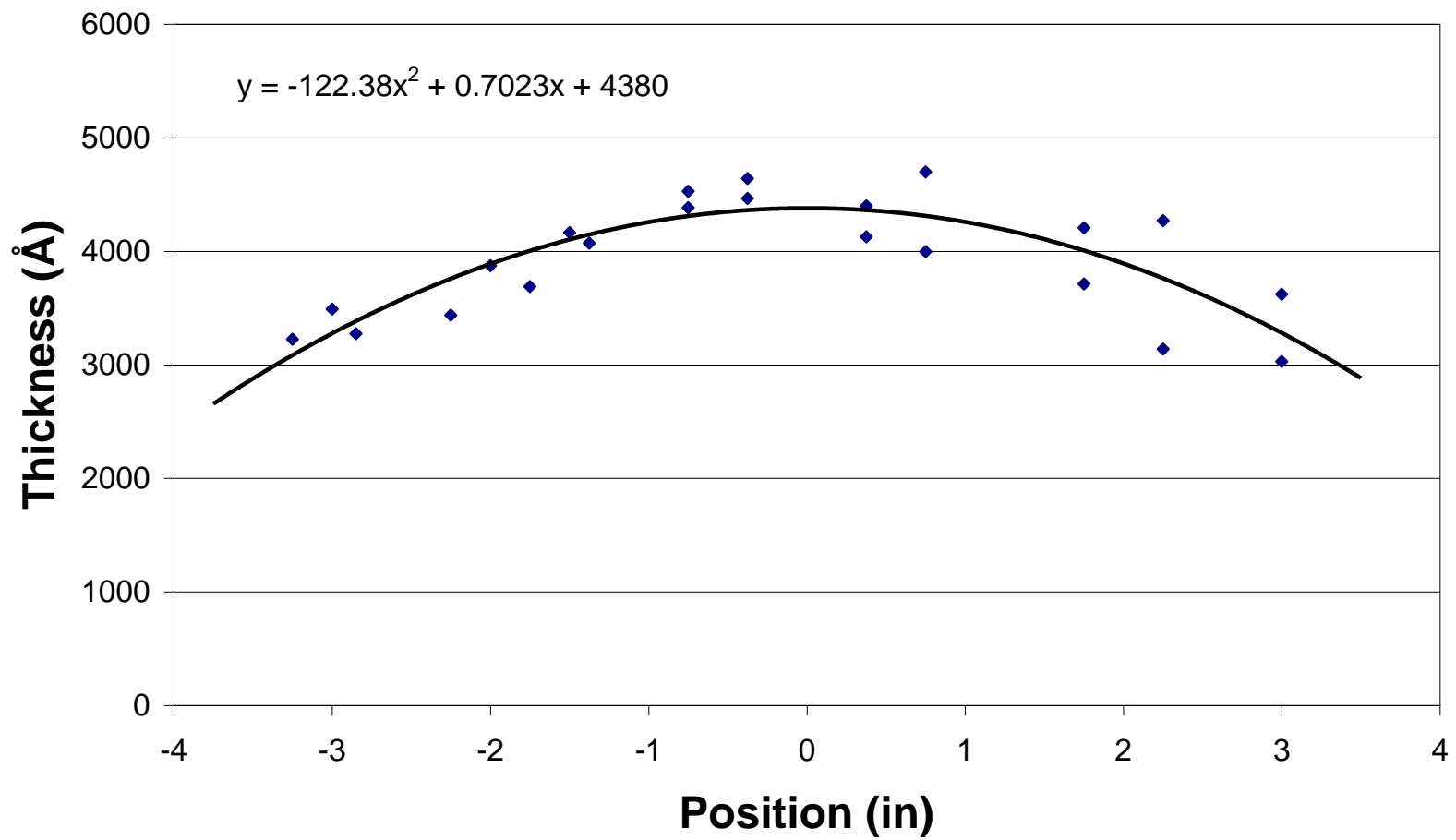


Figure 29. Horizontal Deposition Distribution in Source One

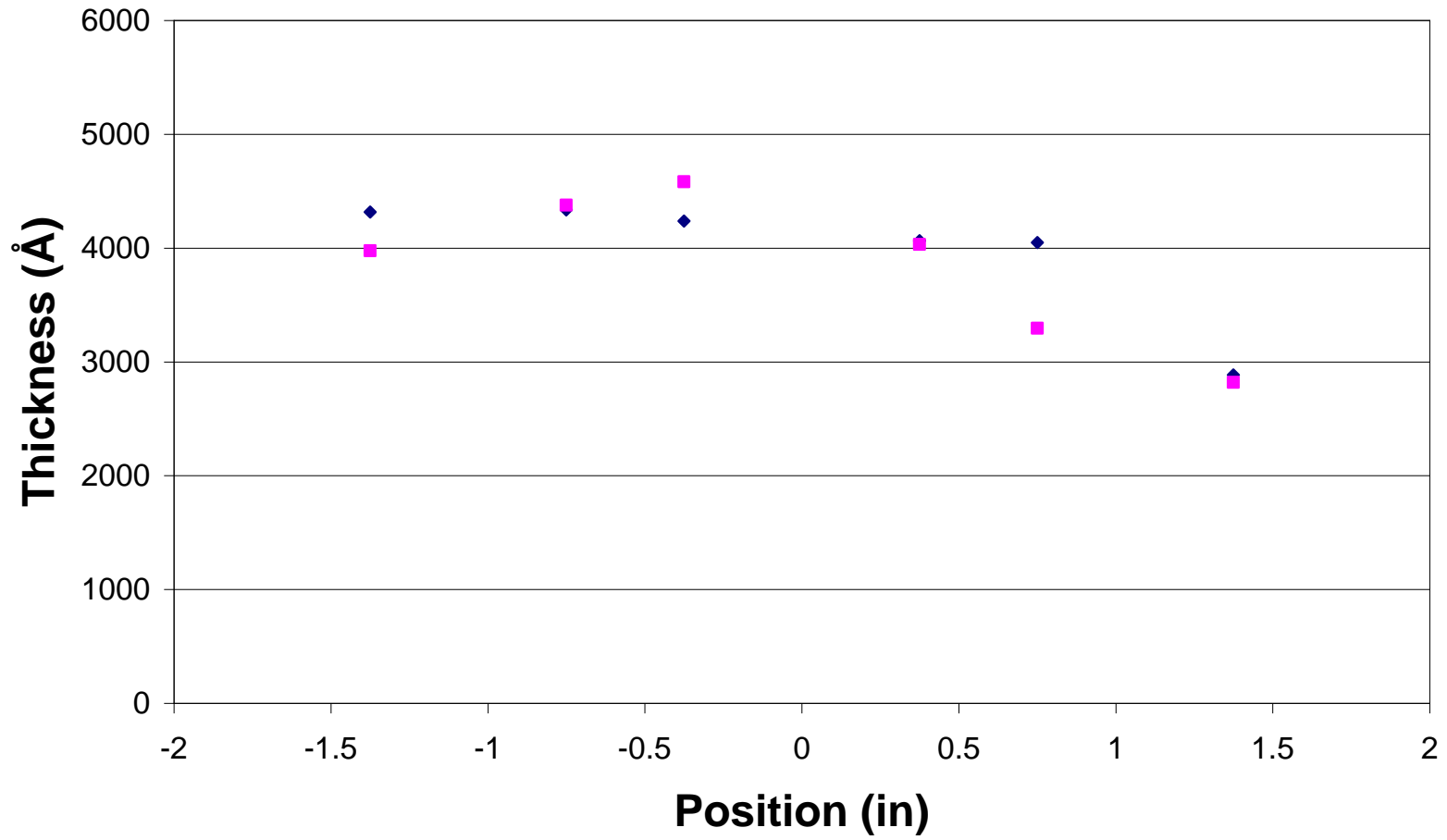


Figure 30. Vertical Deposition Distribution in Source Two

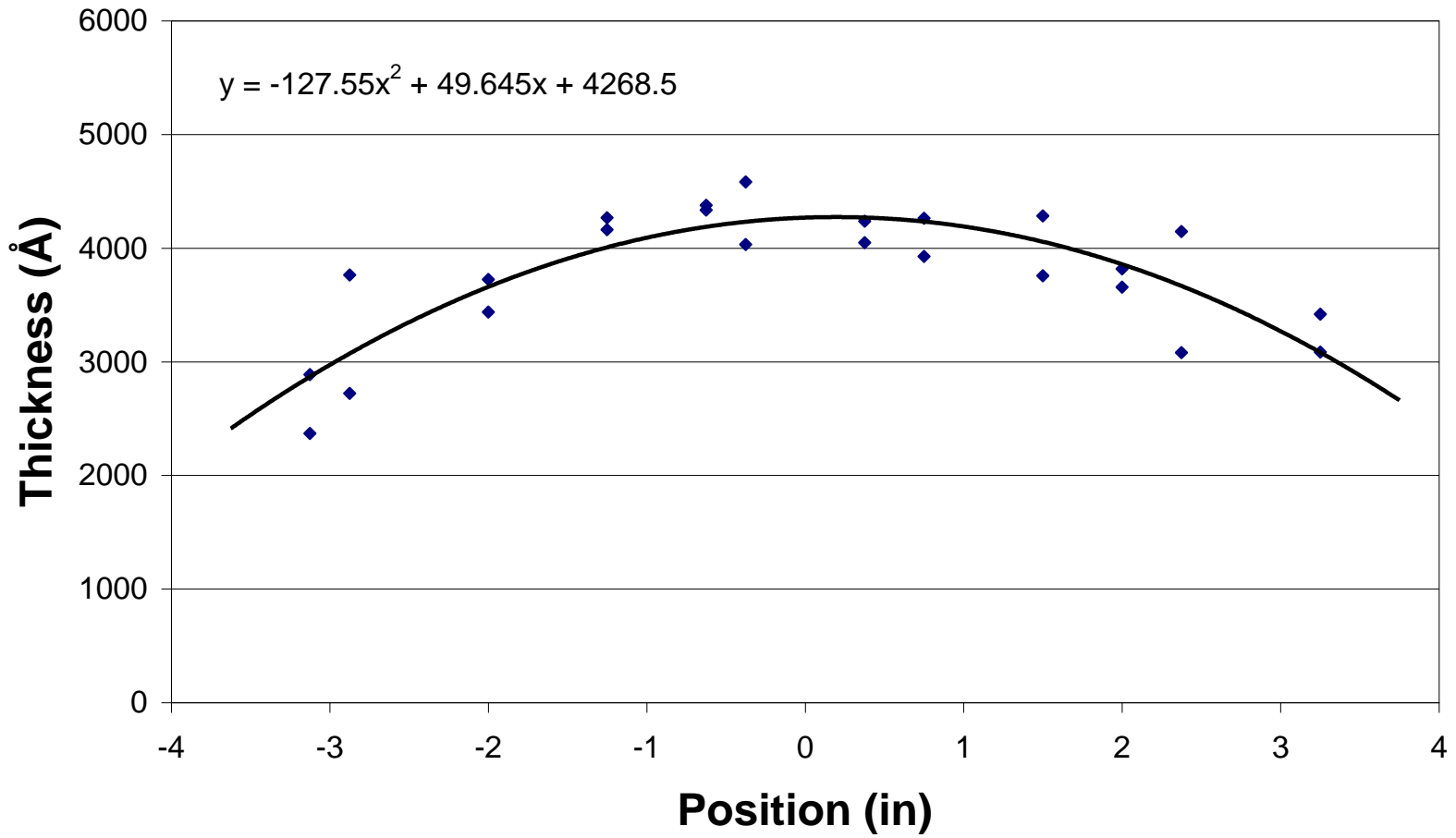


Figure 31. Horizontal Deposition Distribution in Source Two

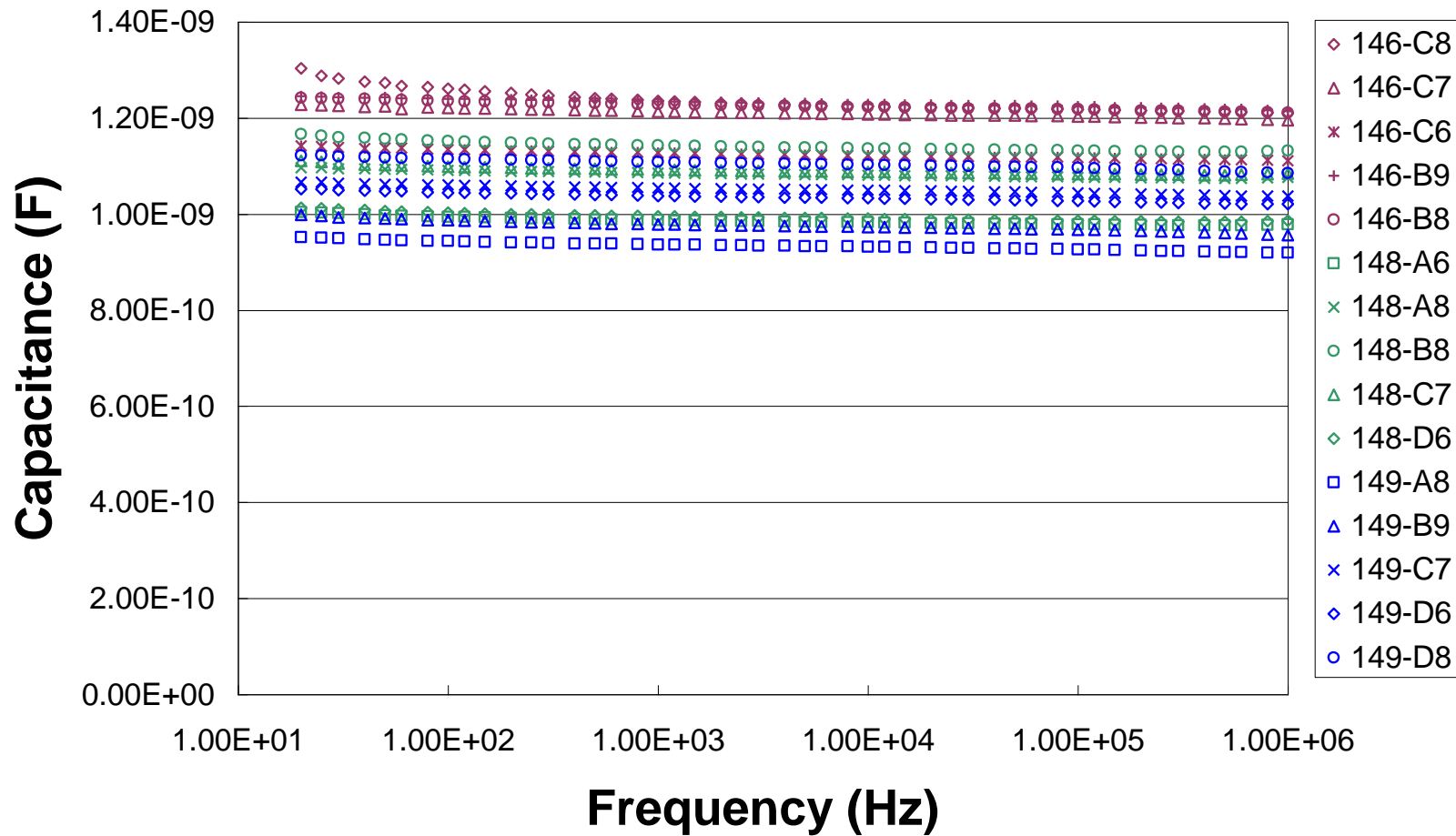


Figure 32. Comparison of Capacitance Values from the Dual Sources in Different Runs

## 5.2 Aluminum Foil Scanning

Operation of the Aluminum Foil Scanner was investigated with various DC power levels, scanner speeds and film tensions. Both single and double-sided deposition onto aluminum foil was examined. Table 4 summarizes the deposition conditions and scanner settings studied. Several observations can be drawn from analyzing the data. First, the foil broke in all depositions with the tension set higher than 1 lb. Lowering the tension introduces other problems into the system as the foil does not remain rigid and would sag away from the back plate, creating thickness variations across the foil. Even with  $T = 1.0$  lb, the foil still broke when the DC power was greater than 500W. Actively cooling the foil during deposition does not improve the ability of the scanner to operate. Cooled foils broke under similar conditions as uncooled material. The scanning speed did not appear to influence the ability of the foil to withstand the plasma and films were successfully deposited on scanning foil with speeds from 0.5 in/min to 4.0 in/min. Lengths up to 18 inches were coated, using up to 70 deposition passes. Once stable process conditions are obtained, the scanner is capable of producing longer lengths of material. The scanner apparatus needs to be redesigned to prevent the foil from sagging to support deposition under the optimal process conditions.

Table 4. Scanner Parameters for AlON Deposition

| <u>DC power (W)</u> | <u>Scan Speed (in/min)</u> | <u>Tension (lb)</u> | <u>DepPress (mTorr)</u> | <u># of Scans</u> | <u>Gas ambient N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>Sides</u> | <u>Frequency (kHz)</u> | <u>Distance (inch)</u> | <u>Broke ?</u> | <u>Length (in)</u> | <u>Cooled ?</u> |
|---------------------|----------------------------|---------------------|-------------------------|-------------------|---|--------------|------------------------|------------------------|----------------|--------------------|-----------------|
| 850                 | 0.14                       | 4.0                 | 11.5                    | 1                 | 7:1:0   | 2            | 50                     | 5                      | Y              | 0.5                | N               |
| 850                 | 1.40                       | 4.0                 | 11.5                    | 1                 | 7:1:0   | 2            | 50                     | 5                      | Y              | 2.6                | N               |
| 850                 | 1.4                        | 2.0                 | 11.5                    | 1                 | 7:1:0   | 2            | 50                     | 5                      | Y              | 17.0               | N               |
| 850                 | 2.8                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 2            | 50                     | 5                      | Y              | -0.0               | N               |
| 850                 | 2.8                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 2            | 50                     | 5                      | Y              | -4.5               | N               |
| 850                 | 2.8                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 2            | 50                     | 5                      | Y              | -2.0               | N               |
| 850                 | 1.4                        | 2.0                 | 11.5                    | 1                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 11.4               | N               |
| 850                 | 2.8                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -1.0               | N               |
| 850                 | 2.8                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -12.1              | N               |
| 850                 | 3.5                        | 2.0                 | 11.5                    | 2                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -4.0               | N               |
| 850                 | 3.5                        | 2.0                 | 11.5                    | 3                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 16.6               | N               |
| 850                 | 3.5                        | 2.0                 | 11.5                    | 3                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 3.9                | N               |
| 850                 | 3.5                        | 2.0                 | 11.5                    | 4                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -3.0               | N               |
| 850                 | 3.5                        | 2.0                 | 11.5                    | 4                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -9.3               | Y               |
| 850                 | 3.5                        | 1.0                 | 11.5                    | 5                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 11.1               | N               |
| 500                 | 3.5                        | 1.0                 | 11.5                    | 45                | 7:1:0   | 1            | 50                     | 5                      | N              | 6.0                | N               |
| 600                 | 1.0                        | 1.0                 | 11.5                    | 3                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 6.1                | N               |
| 500                 | 2.0                        | 1.0                 | 11.5                    | 32                | 7:1:0   | 1            | 50                     | 5                      | N              | 12.0               | N               |
| 500                 | 0.5                        | 1.0                 | 11.5                    | 16                | 7:1:0   | 1            | 50                     | 5                      | N              | 12.0               | N               |
| 500                 | 0.5                        | 2.0                 | 11.5                    | 3                 | 7:1:0   | 1            | 50                     | 5                      | Y              | 6.7                | N               |
| 500                 | 4.0                        | 1.0                 | 11.5                    | 70                | 7:1:0   | 1            | 50                     | 5                      | N              | 18.0               | N               |
| 500                 | 4.0                        | 1.0                 | 11.5                    | 15                | 7:1:0   | 2            | 50                     | 5                      | Y              | 76.0               | N               |
| 500                 | 4.0                        | 2.0                 | 11.5                    | 11                | 7:1:0   | 1            | 50                     | 5                      | Y              | 23.0               | N               |
| 600                 | 4.0                        | 1.0                 | 11.5                    | 4                 | 7:1:0   | 1            | 50                     | 5                      | Y              | -8.2               | N               |

## 6. Aluminum Oxynitride Deposition from N<sub>2</sub>O

### 6.1 Process Optimization

The process parameters for AlON deposition were further optimized to maximize dielectric performance and improve deposition rate. Nitrous oxide (N<sub>2</sub>O) is commonly used in the semiconductor industry to deposit nitrogen doped oxide films. Reactive sputtering with N<sub>2</sub>O has been used to introduce nitrogen into metal oxide films [13,14]. The double bonded nitrogen in N<sub>2</sub>O has a bond strength of ~ 450 kJ/mol compared to the triple bond strength of ~950 kJ/mol in N<sub>2</sub>. It is also easier to break the nitrogen-oxygen bond in N<sub>2</sub>O than the oxygen-oxygen bond in O<sub>2</sub> [15]. The weaker bond strengths in N<sub>2</sub>O result in a more reactive gas mixture with both oxygen and nitrogen present. The more reactive nitrogen species may increase the nitrogen content in the films, increasing the deposition rate and the dielectric strength. The effects of DC power, gas mixture, pulse frequency, target-to-substrate spacing, and process pressure were examined. A statistical process optimization procedure was employed to identify key input parameters.

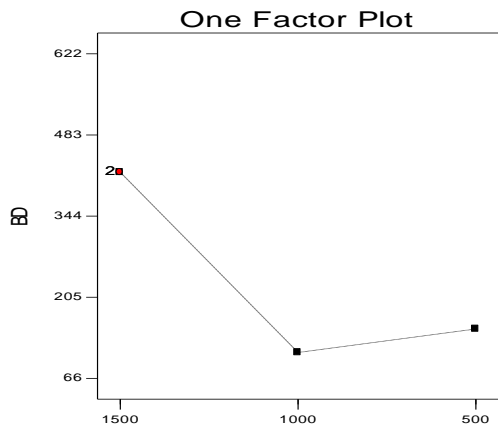
#### 6.1.1 Taguchi Analysis

Genichi Taguchi used orthogonal tables in experiments designed to improve quality control. The purpose of orthogonal design is to study the relationship between process parameters (input parameters) and their corresponding output functions by selecting certain representative combinations of input parameter level settings. By following the orthogonal table, a maximum amount of information can be obtained using the least number of experiments.

Nitrous oxide was as an alternative reactive gas to improve the deposition rate. Table 5 lists the input parameters examined and the resulting properties. DC power, pulse frequency, reactive gas ratio and process pressure were varied in the analysis. The one factor plots from the analysis are shown in Figure 33 – 47. The most significant effects were observed in relation to the breakdown strength and deposition rate. DC power is the most significant influence for both these parameters. Higher power improves both properties. Dissipation factor also improved at higher power. The frequency also effected the dissipation. Lower frequency lowered the dissipation factor. Although lower frequency slightly lowered the breakdown voltage, the 50 kHz setting was selected as the optimal setting due to the better dissipation and only modest decrease in breakdown. No significant effects were observed for the dielectric constant.

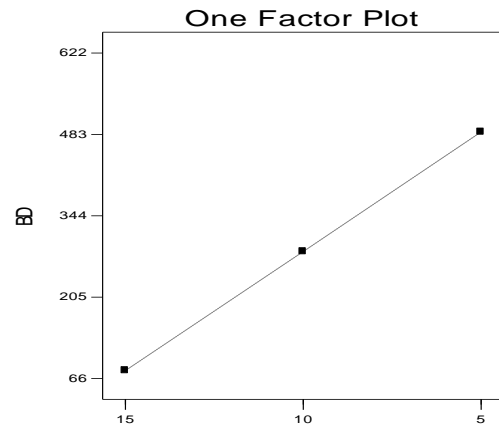
Table 5. Taguchi Analysis Parameters and Results for Nitrous Oxide

| SAMPLE | RUN | POWER | PRESSURE | GAS RATIO                          | FREQUENCY | K    | DF     | BD     | RATE    |
|--------|-----|-------|----------|------------------------------------|-----------|------|--------|--------|---------|
|        |     | (W)   | (mTorr)  | (N <sub>2</sub> :N <sub>2</sub> O) | (kHz)     |      |        | (V/μm) | (Å/sec) |
| AIN270 | 1   | 500   | 10       | 9                                  | 50        | 9.23 | 0.0121 | 114    | 1.30    |
| AIN271 | 2   | 1000  | 5        | 9                                  | 150       | 8.45 | 0.0077 | 398    | 1.00    |
| AIN279 | 3   | 1000  | 15       | 1                                  | 50        |      |        |        | 0.91    |
| AIN280 | 4   | 1000  | 10       | 0                                  | 250       | 8.75 | 0.0134 | 349    | 0.76    |
| AIN274 | 5   | 1500  | 15       | 9                                  | 250       | 7.73 | 0.0073 | 419    | 1.16    |
| AIN275 | 6   | 500   | 15       | 0                                  | 150       | 9.85 | 0.0091 | 66     | 0.33    |
| AIN281 | 7   | 500   | 5        | 1                                  | 250       | 9.31 | 0.0115 | 459    | 0.26    |
| AIN282 | 8   | 1500  | 5        | 0                                  | 50        | 7.27 | 0.0032 | 622    | 1.67    |
| AIN278 | 9   | 1500  | 10       | 1                                  | 150       | 7.12 | 0.0038 | 403    | 2.41    |



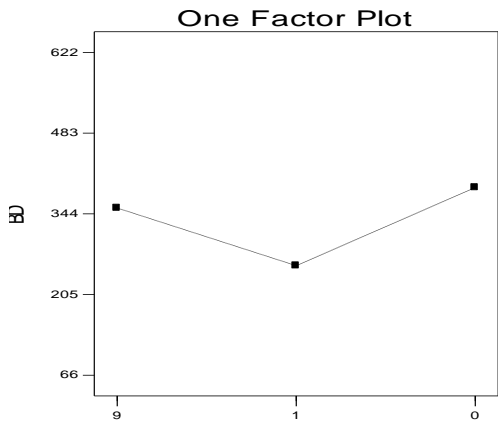
A: DC Power

Figure 33. Breakdown Voltage vs. DC Power



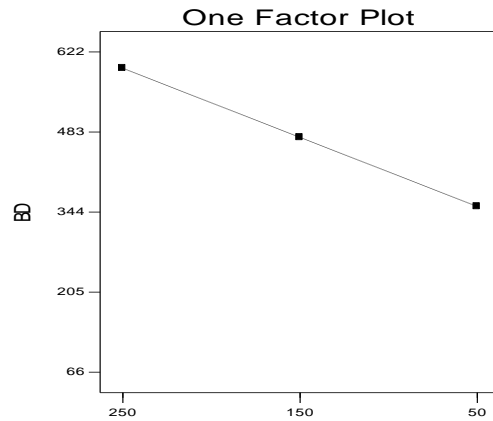
B: Pressure

Figure 34. Breakdown Voltage vs. Pressure



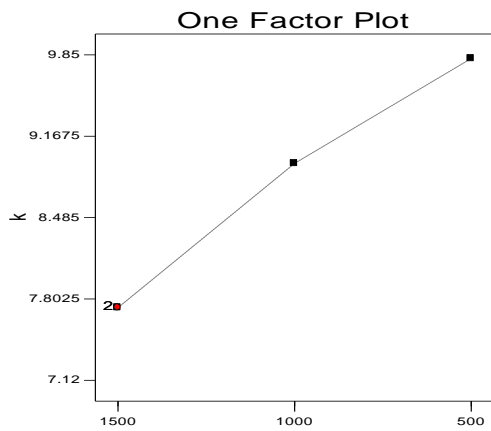
C: Gas Ratio

Figure 35. Breakdown Voltage vs. Gas Ratio



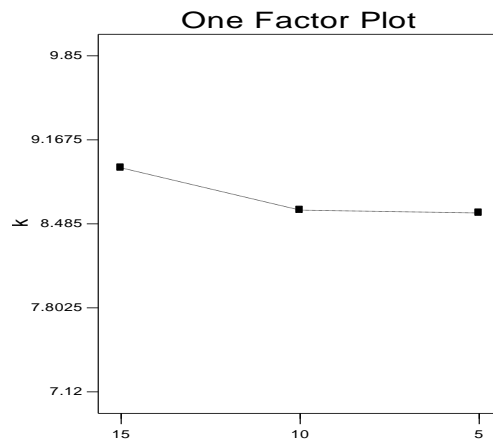
D: Frequency

Figure 36. Breakdown Voltage vs. Frequency



A: DC Power

Figure 37. Dielectric Constant vs. DC Power



B: Pressure

Figure 38. Dielectric Constant vs. Pressure

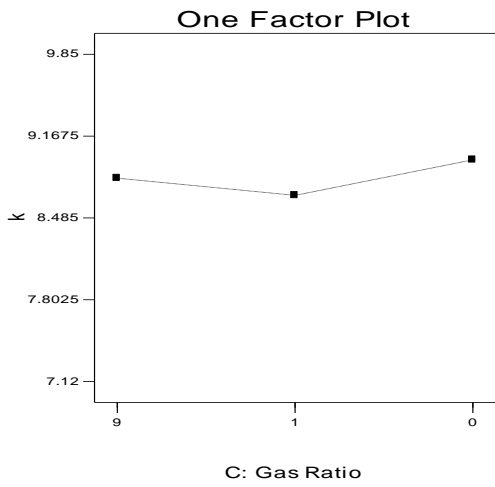


Figure 39. Dielectric Constant vs. Gas Ratio

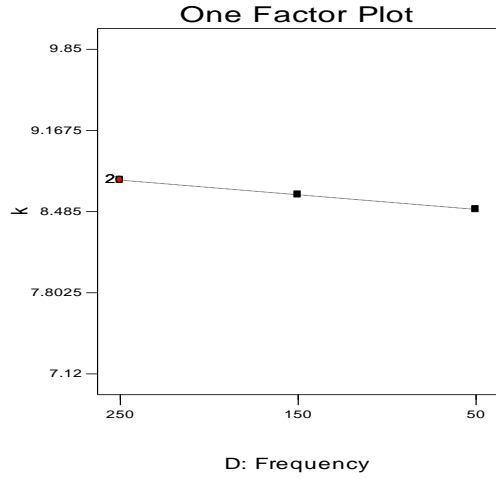


Figure 40. Dielectric Constant vs. Frequency

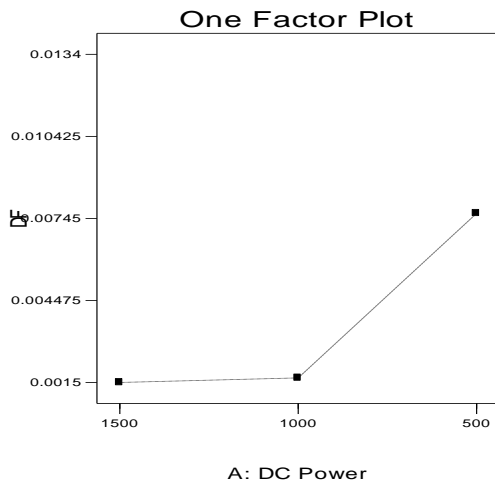


Figure 41. Dissipation Factor vs. DC Power

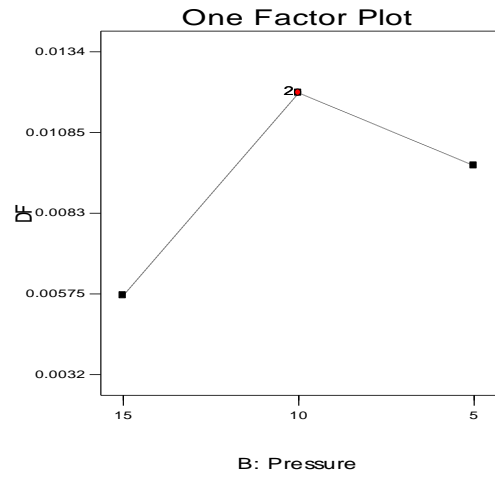


Figure 42. Dissipation Factor vs. Pressure

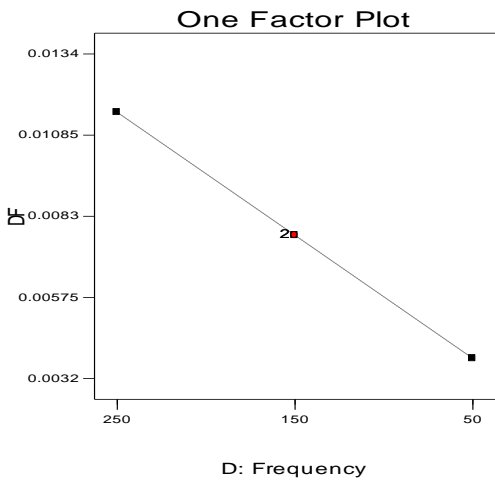


Figure 43. Dissipation Factor vs. Frequency

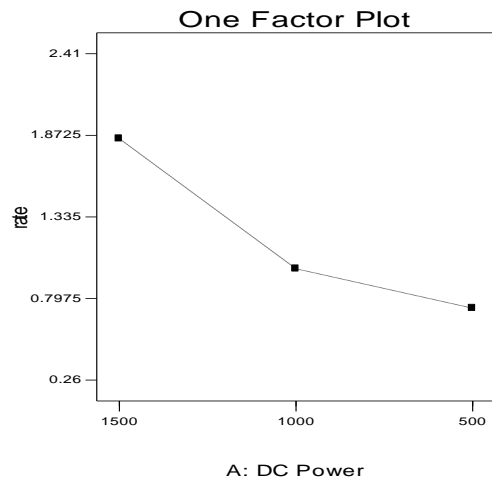
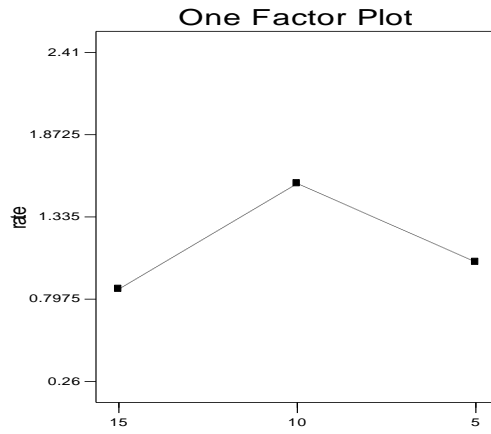
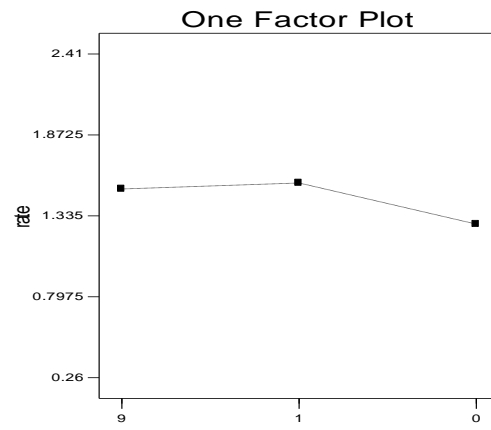


Figure 44. Deposition Rate vs. DC Power



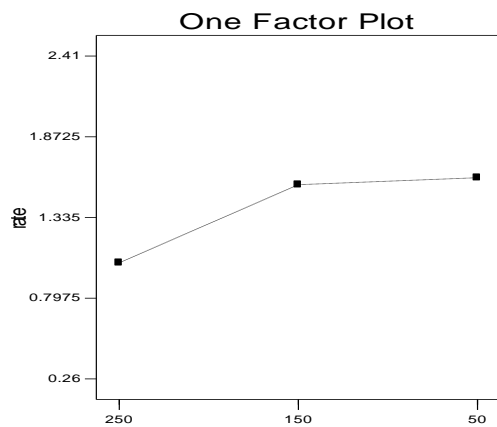
B: Pressure

Figure 45. Deposition Rate vs. Pressure



C: Gas Ratio

Figure 46. Deposition Rate vs. Gas Ratio



D: Frequency

Figure 47. Deposition Rate vs. Frequency

### 6.1.2 Aluminum Oxynitride Deposition

Nitrous oxide ( $\text{N}_2\text{O}$ ) is a more reactive species than nitrogen ( $\text{N}_2$ ) and oxygen ( $\text{O}_2$ ) due to its weaker bonding energy.  $\text{N}_2\text{O}$  was utilized as the source for both the oxygen and nitrogen species in the oxynitride material. This modification in the deposition chemistry increased the deposition rate by a factor of two under conditions producing optimal dielectric properties. The dielectric properties of the films remained the same when grown from  $\text{N}_2\text{O}$  or  $\text{N}_2/\text{O}_2$ . Figure 48 compares the deposition rate from deposition in  $\text{N}_2\text{O}$  and  $\text{N}_2/\text{O}_2$ . Figures 49, 50, and 51 compare the capacitance, dissipation factor, and breakdown strength of  $\text{N}_2\text{O}$  and  $\text{N}_2/\text{O}_2$  films. These dielectric properties are comparable between the two gas mixtures. The differences in the capacitance in Figure 49 are due to difference in the film thickness resulting from the higher deposition rate with  $\text{N}_2\text{O}$ . The dielectric constant is similar for both films. The increased rate with steady dielectric properties prompted a transition to  $\text{N}_2\text{O}$  chemistry for further deposition.

Aluminum nitride deposition runs were conducted on numerous substrates and utilizing a wide variety of process settings. DC power ranged from 500 W to 2000 W, with pressures between 5 mTorr and 20 mTorr. Films were deposited on metallized silicon wafers, metallized glass, aluminum foil, and silicon dioxide. Nitrous oxide plasma with nitrogen dilution was also examined. The target-to-substrate distance was initially set at 5 inches. Deposition times were adjusted to achieve 5000 Å films. Appendix C summarizes the deposition conditions for each experimental run.

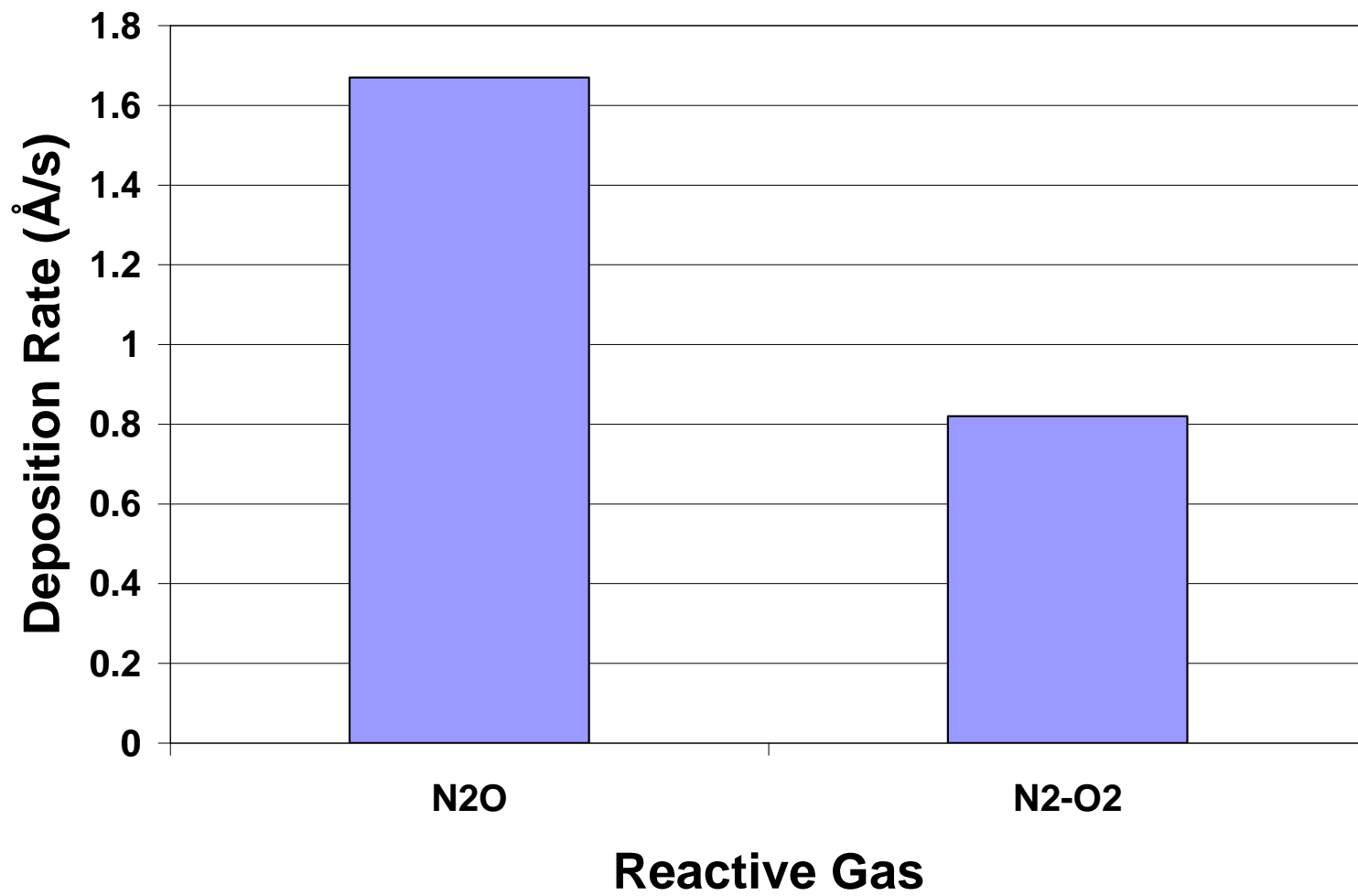


Figure 48. Deposition Rate Comparison for Reactive Gases

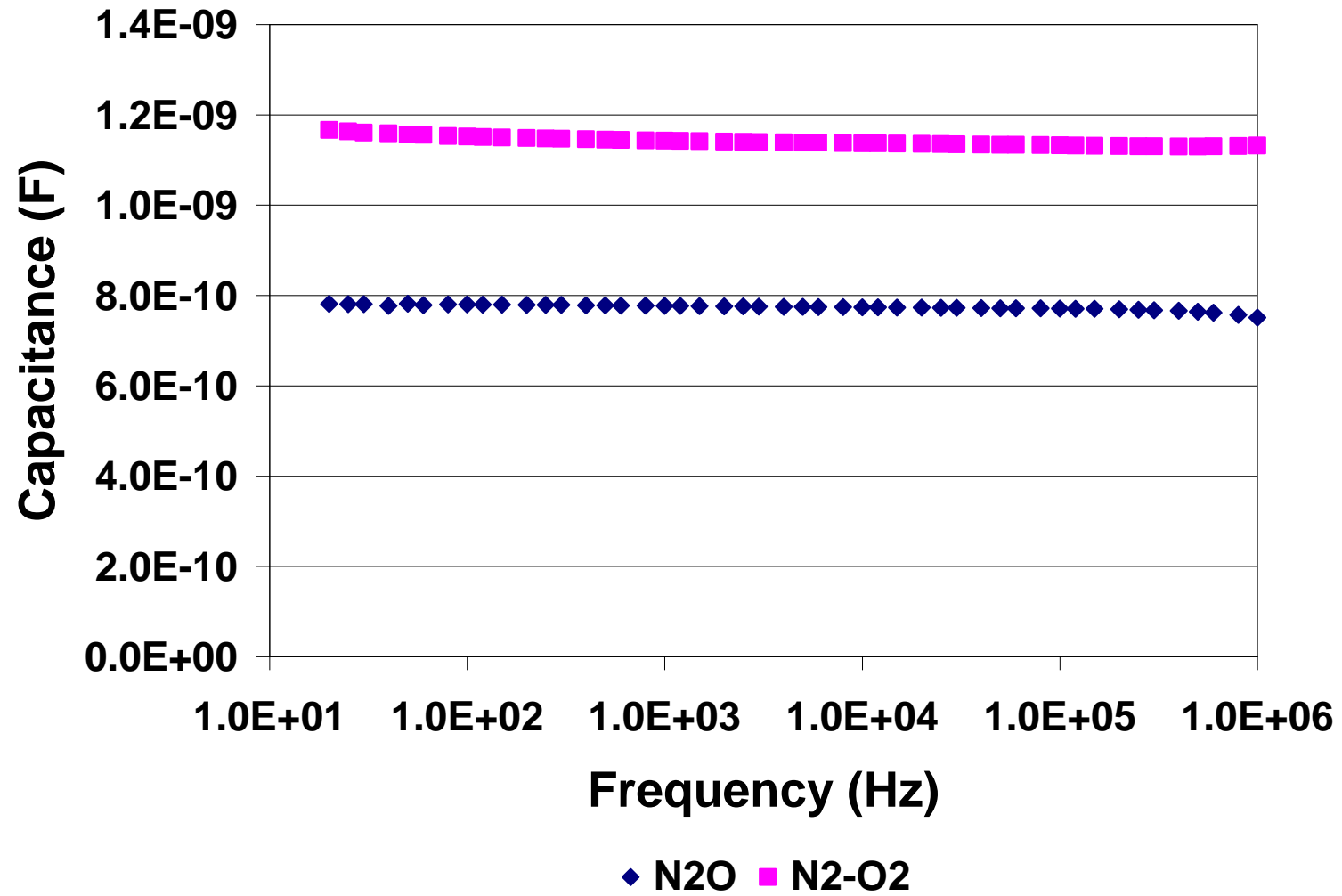


Figure 49. Capacitance Comparison for Reactive Gases

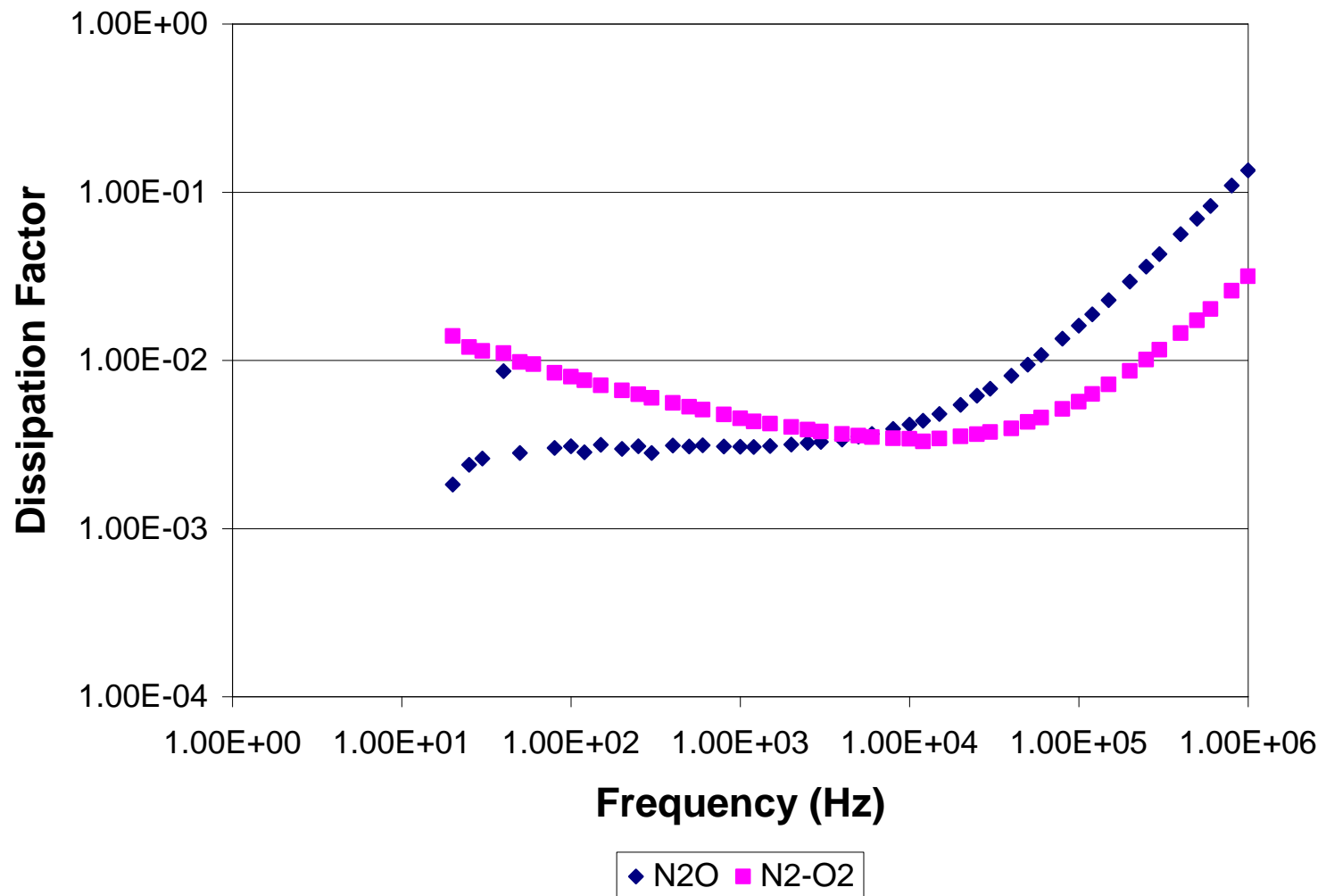


Figure 50. Dissipation Factor Comparison for Reactive Gases

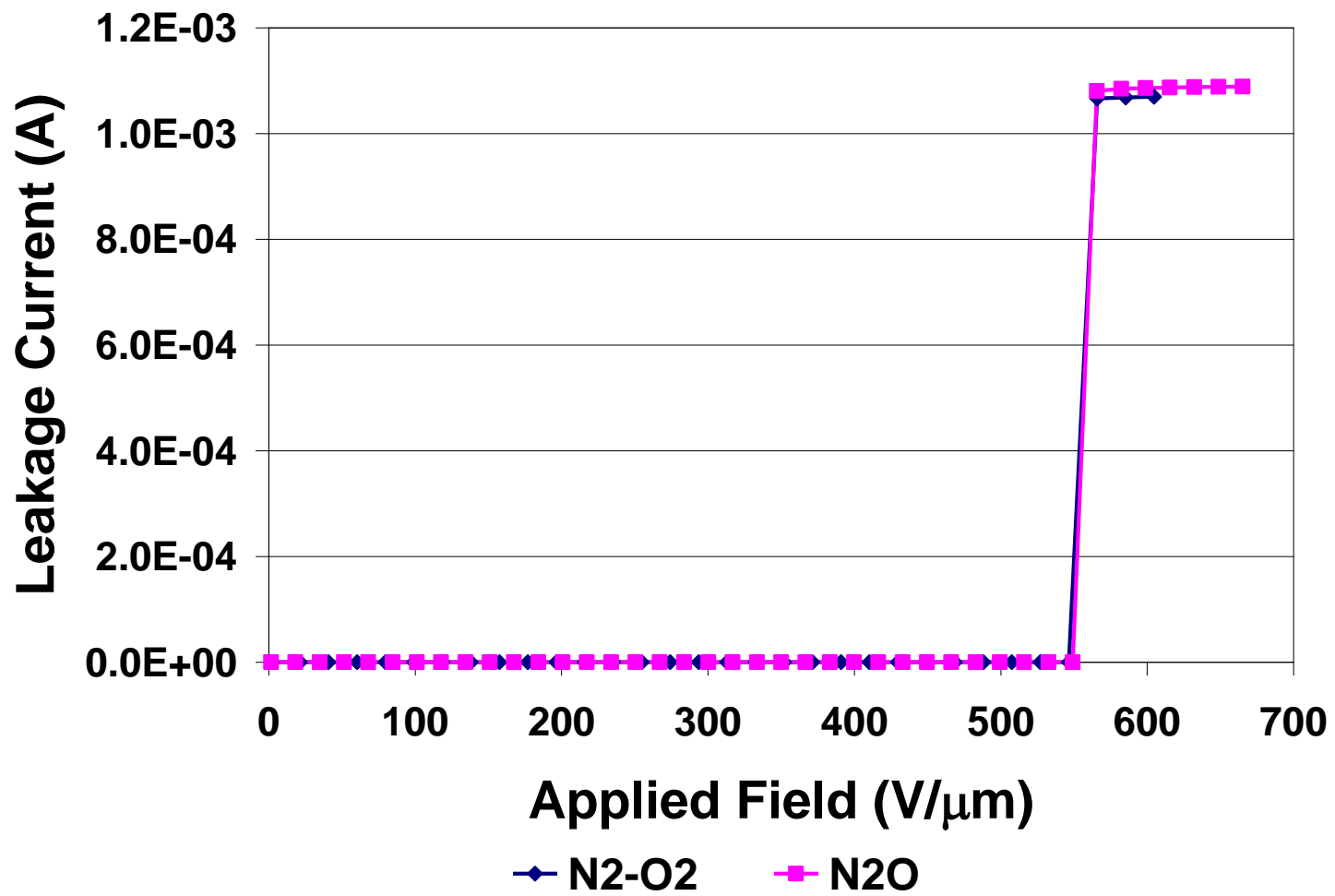


Figure 51. Breakdown Strength Comparison for Reactive Gases

### 6.1.3 Multilayer Devices

Nitrous oxide ( $N_2O$ ) reactive gas at 5 mTorr chamber pressure and 1500 W DC power provided the optimal dielectric properties. The aluminum foil scanner was modified to mask areas for multilayer capacitor deposition. Openings were created in the foil and the scanner positioned the openings over stationary substrates. Alternating metal, dielectric and metal layers were deposited in the same chamber. Targets were cleaned with Ar plasma for 30 - 45 minutes between dielectric and metal depositions. Devices with up to eight dielectric layers were constructed. Layer alignment was a critical issue with this deposition design. The foil mask was not under stress during the deposition. This allowed the foil to sag and created an undesirable offset between the layers. In extreme cases, the offset was sufficiently large that the layers did not overlap and there was no capacitance. We replaced the scanner with a precision transfer arm to repeatably position substrates in the requisite position behind stationary masks. The precision placement allowed capacitors with up to ten layers to be successfully deposited.

For the in-situ stacked layer processing, shadow masks were placed in the chamber. To reduce the edge distortion around the masks, the sputter sources were moved closer to the substrates. The shadow mask configuration for capacitor deposition allows some film spread beyond the edge of the mask. Often this spread can be so wide the entire electrode is coated by the dielectric and no contact can be made. The influence of the source-to-substrate separation on the dielectric spreading was examined with the distance varying from 1.75 to 4 inches. The best resolution was achieved at 4 inches, so that distance was maintained for the subsequent deposition runs. This resulted in an increase in the deposition rate from  $\sim 1.5 \text{ \AA/s}$  to  $\sim 2.5 \text{ \AA/s}$ . We examined different size masks to limit the influence of the dielectric spread on device performance. The capacitor active area was also reduced. This created larger electrode contacts that could be successfully connected for device testing, although it also had the deleterious effect of reducing the device capacitance.

## 6.2 Film Thickness and Surface Characterization

A Dektak 3ST surface profilometer was utilized to measure the film thickness across the deposited films. A portion of each Si or glass substrate was masked with a thin strip of stainless steel foil or high temperature tape to create a thickness step. Multiple step height measurements across the entire sample were averaged to obtain the reported film thickness. Some small surface defects were observable, but large pinholes were not present in the majority of the samples. Good adhesion was observed on all of the substrates investigated without any surface pretreatments.

## 6.3 Dielectric Properties

Extensive dielectric properties of AlN films have been characterized at K Systems facilities in the AFRL/RZPE Capacitor Research Center, WPAFB, OH. The characterizations include: (1) spot check, (2) frequency characterization, (3) insulation resistance and (4) dielectric breakdown. Values of the dielectric constant and dissipation factor are obtained from the spot checks and

frequency analysis. The resistance is calculated from the AC frequency measurements and the DC IR measurements. Breakdown voltage was determined by applying a voltage stepped in regular increments to a capacitor for a set time duration and measuring the resulting current until complete breakdown occurs. Steps of 5 V and 10 V were applied for 3 or 5 seconds in typical tests. A complete list of results is tabulated in Table B-1 in Appendix B. “Film” refers to the film thickness measured by profilometry or estimated from the deposition rate. “HV” is the actual breakdown voltage or the highest measured voltage before loss of capacitance. Blank cells in the table could not be measured.

## 6.4 Clearing

Thin aluminum electrodes of 100 Å or less were deposited to form capacitor structures. The thin metal allows the capacitor to clear to increase the breakdown voltage. Figure 52 plots the leakage current through the capacitor and the capacitance vs. the applied voltage for two single layer devices. The leakage increases relatively smoothly until there are some sharp spikes around 350 V and 450 V. The capacitance remains constant with voltage until 350 V and 450 V respectively. A significant drop in capacitance is observed at these voltages which correspond with the spikes in the leakage current.

Figure 53 shows optical images of the capacitor surface after applied voltages from 0 V to 350 V. Images (a) – (f) depict the surface from as deposited to 250 V. No effects from the voltage are visible. One major clearing site is visible in Figure 53(g) at 300 V, but it does not affect the overall capacitance of the device as seen in Figure 52. As the voltage is ramped further, another clearing event is observed (not shown) immediately adjacent to the previous site and most apparently resulting from damage during the previous clearing and not inherent defects in the material. The breakdown test continued from 350 V and the capacitor lost contact almost immediately. Figure 53(h) displays the capacitor after the final 350 V biasing. Two different types of features are visible, the large clearing damage in Fig. 53(g) with an adjacent clearing and thin intertwined defects that propagate from the edge of the underlying bottom electrode. These smaller clearing defects spread across the whole edge of the electrode almost simultaneously, in contrast to the larger clearings which occur as individual identifiable events. This suggests that the large clearings (Fig. 53(g)) are caused by a defect or pinhole in the dielectric which resulted in self-healing of the capacitor with no significant loss of capacitance. The smaller, more rapid clearing concentrated on the edge of the electrode results from the enhanced electric field effect in the device. This rapid clearing isolates the electrode from the contacts, resulting in an open circuit. The loss of the capacitor transpires at  $\sim 650$  V/ $\mu\text{m}$ , but the dielectric has still not physically broken down under this voltage.

Thinner metal electrodes were also examined. A 50-Å-aluminum electrode did not provide sufficient continuity for the capacitor to hold charge. High temperature titanium was also evaluated. The sputtering process did not produce a uniform metal film and a different approach may be needed for commercial metallization.

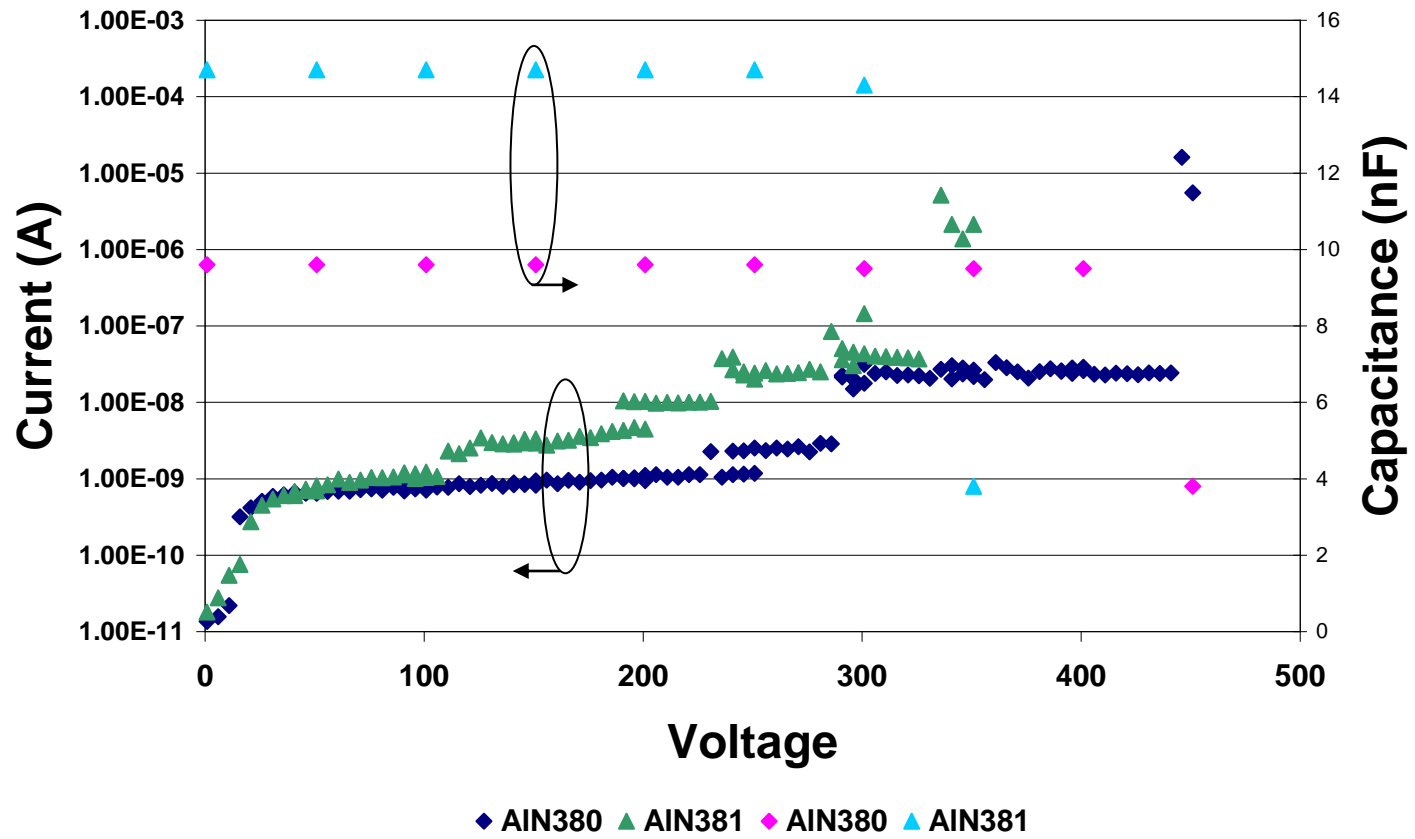


Figure 52. Capacitance and Leakage vs. Applied Voltage



Figure 53. Optical Images of Capacitor Surface after Applied Voltage from 0 V to 350 V

## 6.5 Electrode Thickness

The effects of the electrode thickness on device performance and clearing are an important consideration. Comparisons of breakdown tests for capacitors with 100 Å, 200 Å and 300 Å aluminum electrodes are shown in Figure 54. The clearing, discernable by the increased leakage current, originates at lower voltages for the thicker electrodes. The thicker electrodes also display higher leakage than the thinner electrodes, indicative of more powerful clearing events. Figure 55 plots the capacitance vs. voltage for the same capacitors in Fig. 54. Due to the more energetic clearing, the 300-Å-electrode device begins losing significant capacitance between 200 V and 250 V. The 200-Å-electrode device first declines about 10 % of the capacitance around 200 V. This corresponds with the high energy clearing seen at around 180 V, but the capacitance remains stable after those events until above 250 V. The 100-Å-electrode capacitor maintains its value to above 300 V. As with the 200-Å-capacitor, there is about 10 % loss in capacitance due to isolated clearing around 280 V prior to the primary clearing events.

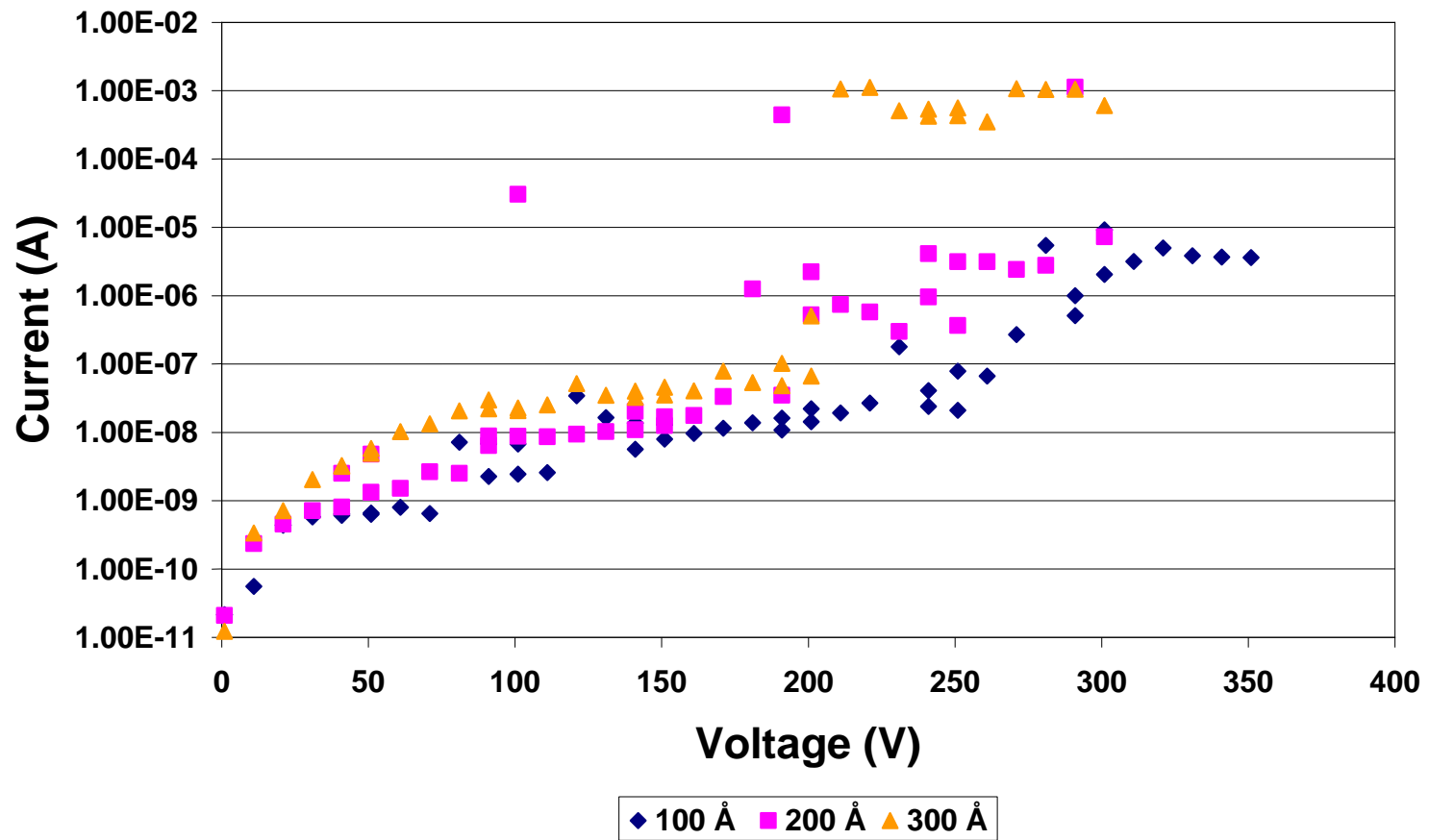


Figure 54. Effect of Electrode Thickness on Capacitor Leakage and Clearing

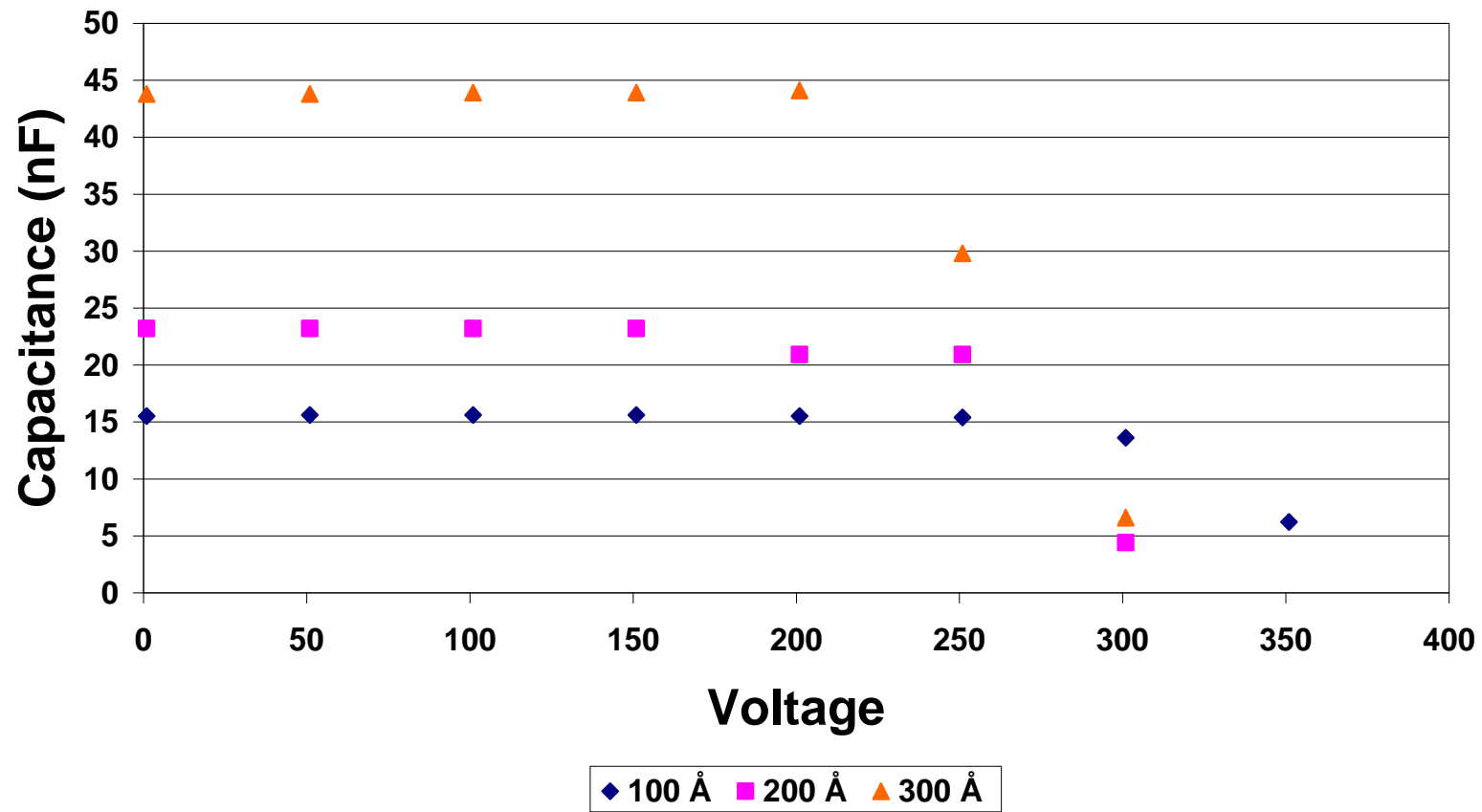


Figure 55. Capacitance vs. Voltage for Different Electrode Thicknesses

## 6.6 Heavy Edge

Heavy edge contacts have also been examined to reduce the effects of sharp edges on the loss of the electrode contact during breakdown testing. Initial assessment of the heavy edge capacitors revealed extremely good properties. Closer examination disclosed that the large area of the heavy edge pads was creating a pathway through the silicon dioxide substrate and not through the AlON. All heavy edge results on SiO<sub>2</sub> are suspect. Heavy edge tests on glass substrates did not show any significant improvement over standard designs. ANSYS modeling has been done to study the effects of the electrode edge. Results show a strong electric field enhancement at the edge of the electrode. Putting a heavy edge to reduce the step over the dielectric edge does not reduce the field enhancement. The field effect of the edge and not the physical step of the electrode is responsible for the loss of the electrode during clearing events. A heavy edge will improve the contact for packaging and improve high current carrying capabilities.

## 6.7 Electrode Metal

Aluminum and titanium were evaluated as AlON capacitor electrodes. Electrodes were deposited using magnetron sputtering with shadow masks to produce the desired pattern. Aluminum has been the standard metal in capacitor evaluations. It has remained stable up to 400 °C and produced dissipation factors as low as 0.003. A minimum thickness of ~75 Å has been reached with aluminum. Thinner layers are not conductive when deposited in our apparatus or the electrodes are not visible to make contact. Figure 56 shows an optical image of an AlON capacitor with aluminum electrodes. The metallization is uniform and smooth.

Titanium is a high temperature metal which is desirable for capacitor application above the operating temperature of aluminum. It is more difficult to sputter titanium than aluminum. Figure 57 is an optical micrograph of a capacitor with titanium electrodes. The ~50-Å-thick metal has not completely coalesced. 100-Å-thick electrodes also exhibited the same island behavior. For optimal capacitor performance the electrode thickness needs to remain in the 100-Å-regime. Although thick contacts for heavy edge structures showed coalesced films, these metals are too thick to be used for the active capacitor contacts. Titanium may still be a potential electrode material for high temperature capacitors, but more experimentation with the deposition parameters or even a different deposition process may be needed.

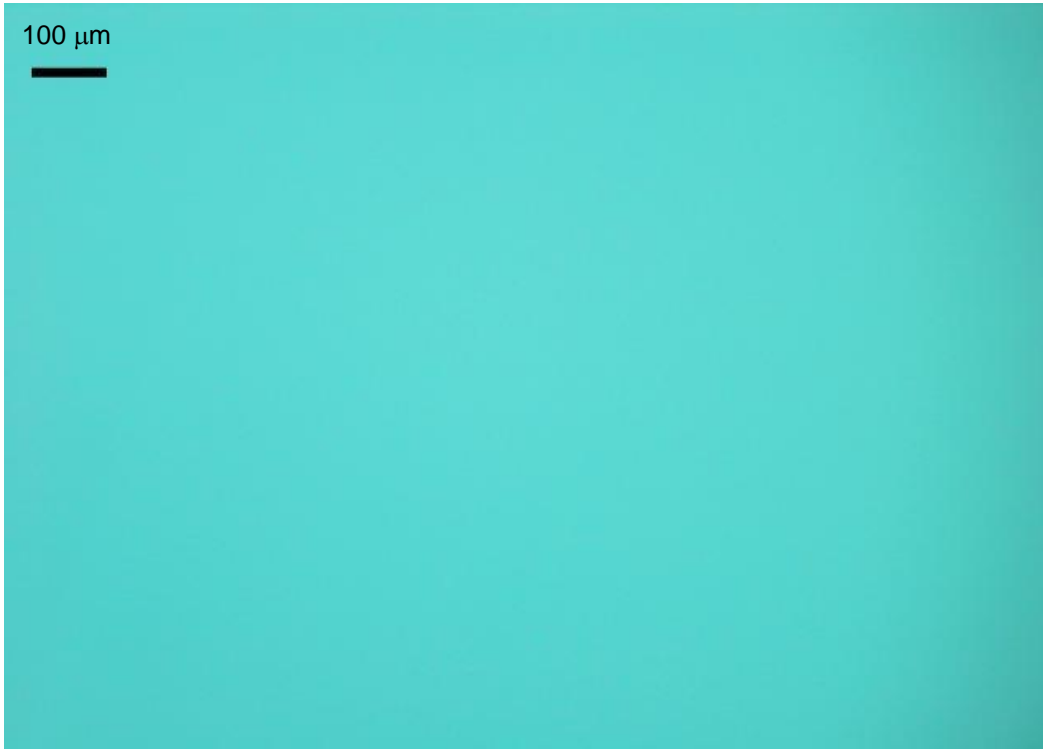


Figure 56. Optical Image of AION Capacitor with Aluminum Electrodes



Figure 57. Optical Image of AION Capacitor with Titanium Electrodes

## 6.8 Temperature Stability

Dielectric thermal stability is a critical issue for capacitor performance in extreme conditions. Figure 58 plots the capacitance vs. frequency for AION capacitors under both elevated and cryogenic temperature exposure. The capacitance remains constant with frequency and is stable with increasing temperature to 300 °C. As the temperature is increased above 300 °C, the capacitance increases at low frequencies, while above 5 kHz no temperature effects are observed up to 400 °C. The capacitance also remains stable under cryogenic conditions, with no variations observed down to -200 °C. Two different capacitors with different capacitances were tested for the high temperature and cryogenic evaluation. When capacitors are heated in ambient air, Figure 59, the capacitance at low frequency begins to increase around 250 °C but still remains constant at high frequencies. At 1 kHz, a dielectric constant of ~9 is achieved.

The dissipation factor was also evaluated under the same temperature conditions. Stronger temperature dependence was observed. At room temperature, the dissipation factor is ~0.003 at 1 kHz. Under vacuum conditions, shown in Figure 60, significant increases in DF begin above 200 °C while in air, Figure 61, increases are observed around 150 °C. Again, the temperature primarily influences the properties below 5 kHz. No change in the dissipation factor is observed under cryogenic conditions. The difference between film performance in vacuum and in ambient air at elevated temperatures may be related to the atmospheric boundary layer present on the surface. Interactions with particulates in the atmospheric boundary layer over the top electrode may begin to alter the electric field as the temperature increases. The boundary layer is more pronounced in atmospheric air compared to vacuum environment and the temperatures effects are seen at lower temperatures. The temperature effects on both capacitance and dissipation factor are reversible. The original values for both the capacitance and dissipation factor are reacquired after returning the material back to room temperature and are stable after multiple temperature cycles. The high and low temperature values are also repeatably obtained on each temperature cycle. This indicates the observed capacitance and dissipation shifts are not caused by a chemical reaction, but by reversible interactions between the atmosphere and the surface.

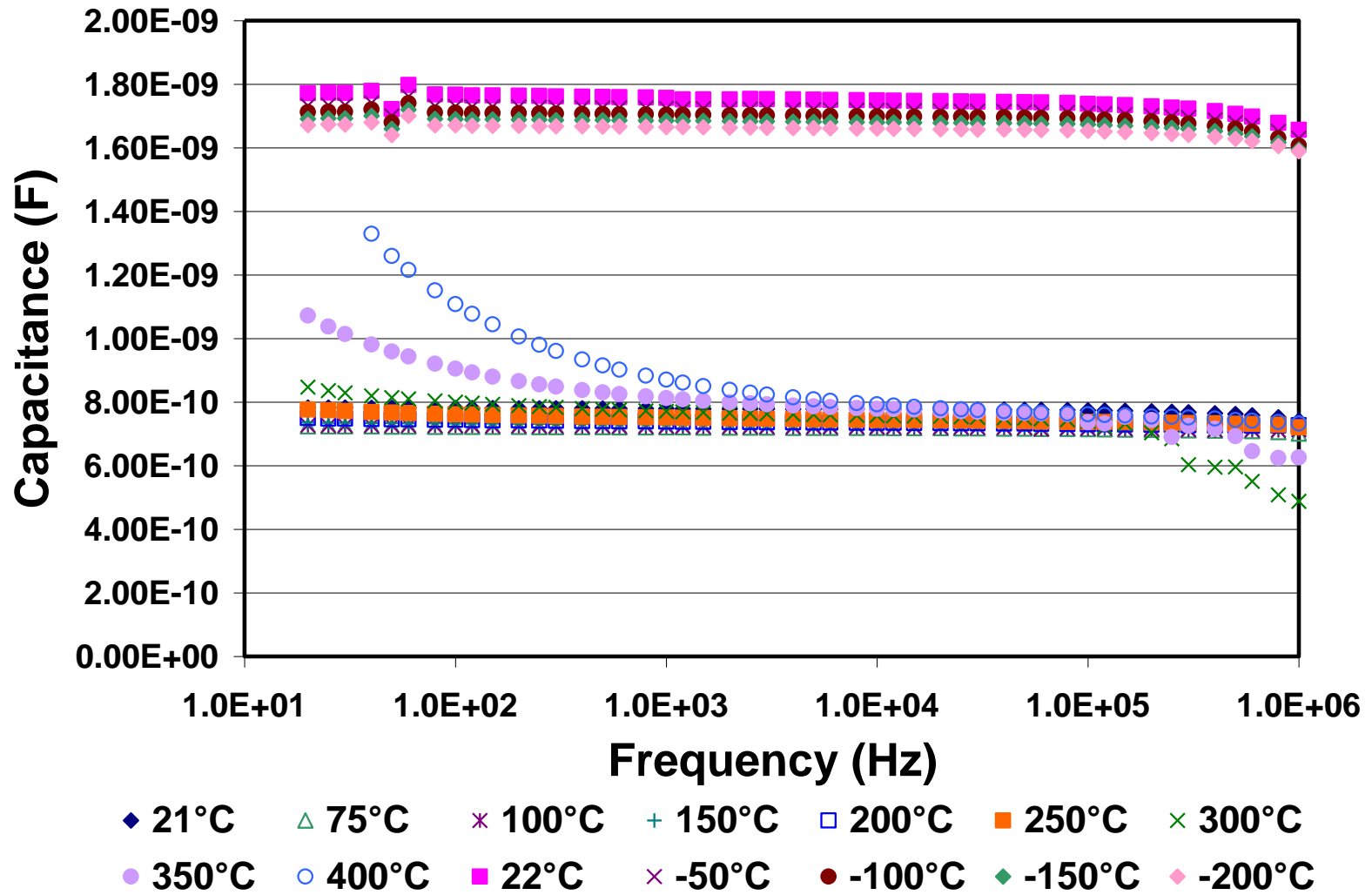


Figure 58. Capacitance vs. Frequency at Various Temperatures in Vacuum

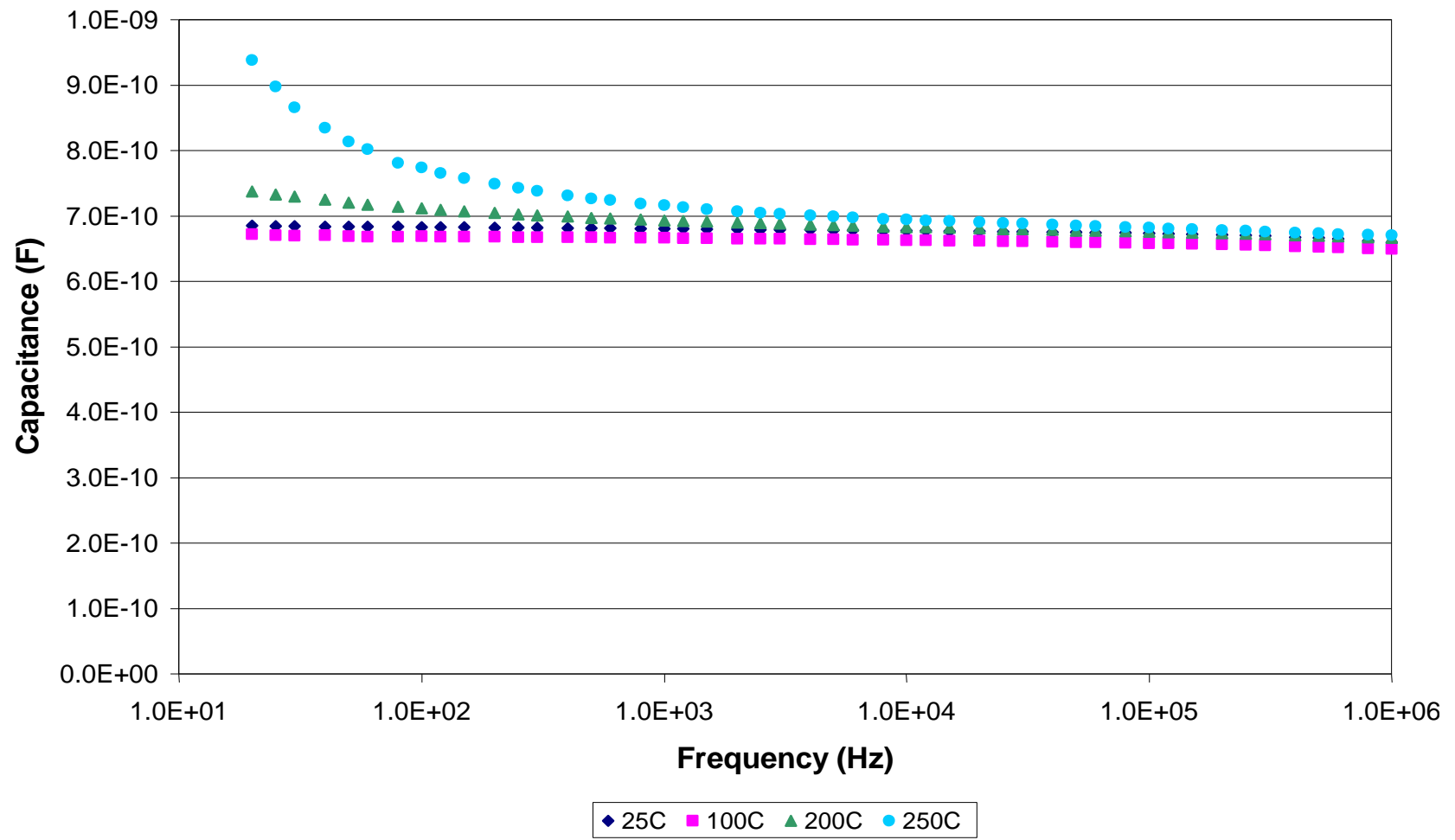


Figure 59. Capacitance vs. Frequency at Various Temperatures in Air

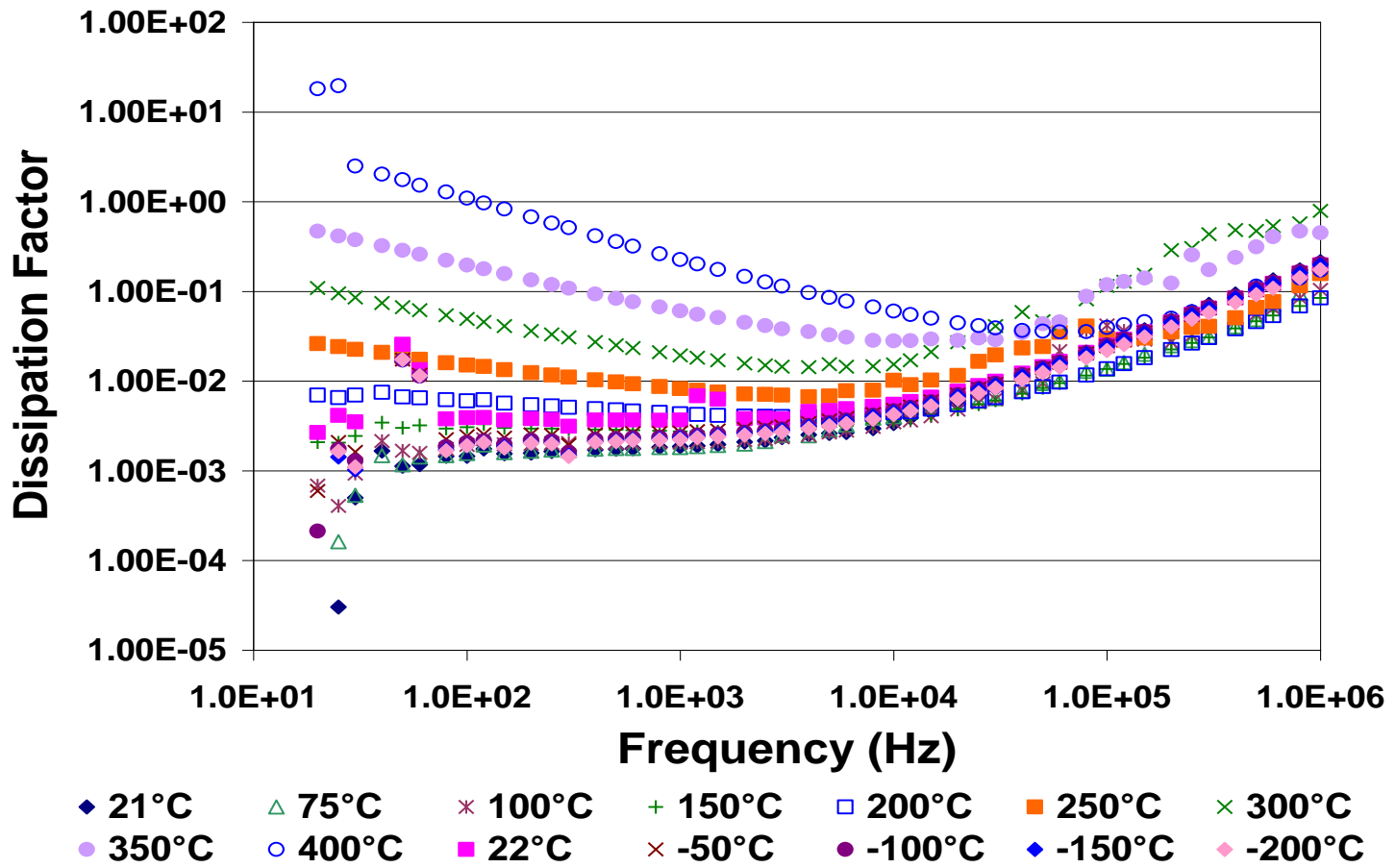


Figure 60. Dissipation Factor vs. Frequency at Various Temperatures in Air

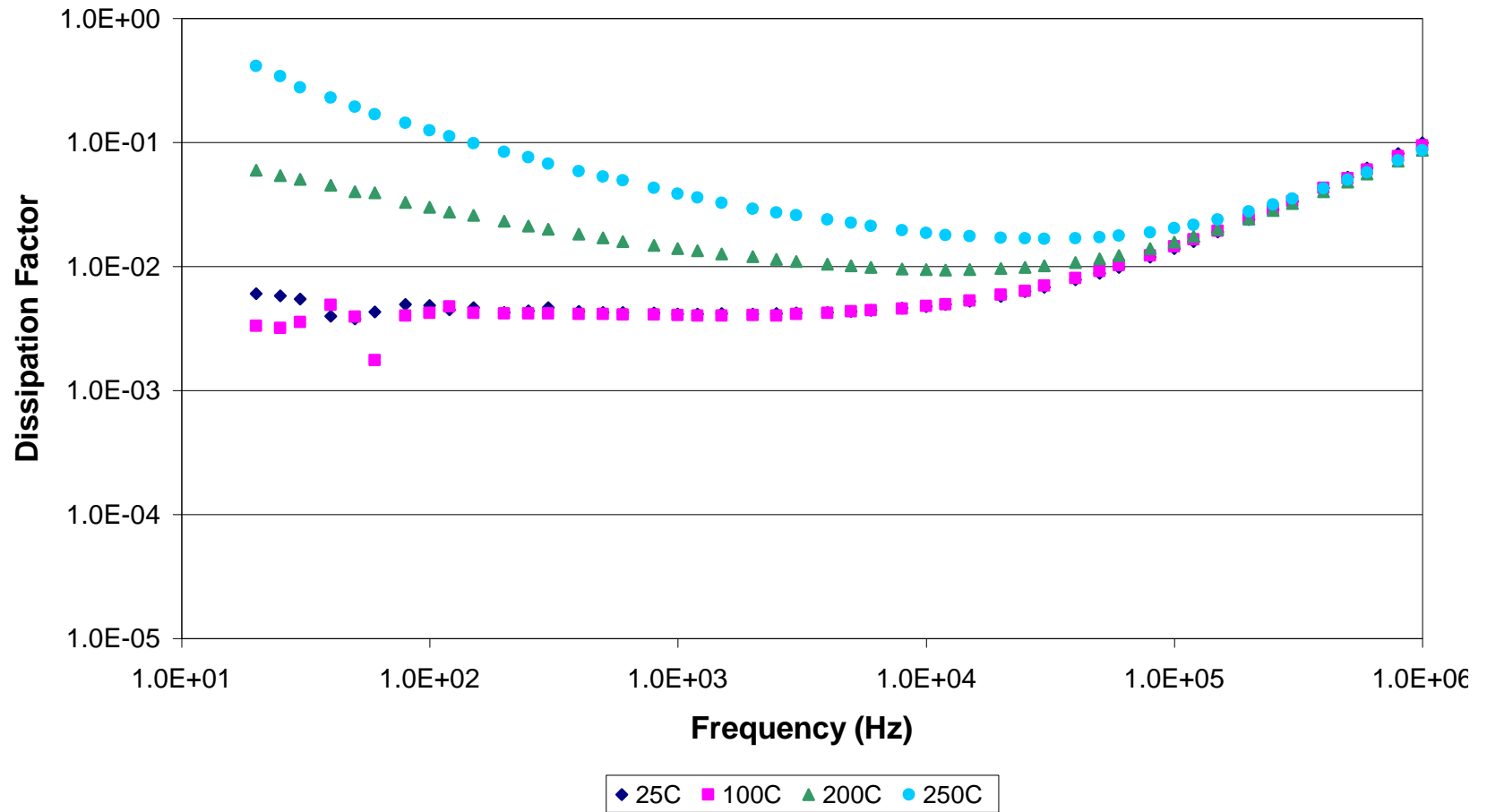


Figure 61. Dissipation Factor vs. Frequency at Various Temperatures in Air

## 6.9 Multilayer Capacitors

Multilayer capacitors with one to ten dielectric layers have been fabricated using in-situ processing. Figure 62 is a cross-sectional schematic of a three layer structure. The capacitance at 1 kHz is plotted vs. layers in Figure 63. A precision transfer arm to position substrates for metal and dielectric deposition allowed repeatable sample processing. Attempts at measuring hard breakdown strength of the multilayer structures were not very successful. Clearing events removed the electrodes and created an open circuit. Breakdown values were taken from the loss of capacitance observed from the clearing. Initial results do indicate AION is suitable for stacked capacitor designs

### 6.9.1 Thermal Properties

Temperature testing was conducted to observe insulation resistance under applied voltage. Figure 64 plot IR data for 25 °C to 300 °C for one layer devices at 50 V, 100 V and 200 V. The devices maintain a reproducible trend under each voltage applied. Comparisons of one and two layer devices at 100 V and 50 V are shown in Figures 65 and 66. At low temperature, there is some variation between the one and two layer device at 100 V, but at 50 V and at high temperatures, they behave similarly. Figure 67 is an Arrhenius plot of the leakage current data. Two distinct regions are discernible. At low temperature (<125 °C), the leakage remains constant with increasing temperature, while at higher temperature, a thermally activated component, with an activation energy of 0.7 eV, is observed. Annealing the samples in air or vacuum before measurements did not influence the performance.

### 6.9.2 Packaged Devices

Majelac Technologies, PA, packaged two, five and ten layer capacitors. We tested the capacitance and the insulation resistance at 100 V for these packaged devices from room temperature to 250 °C. Figure 68 shows the change in capacitance with temperature. The capacitance of the five layer device varies less than 3 % up to 200 °C. The two layer sample is slightly less stable and varies almost 10 % over the same range. There is significant clearing in the ten layer capacitor which reduced the capacitance ~70 % initially, but after these events, the capacitance remained stable to 180 °C. Each capacitor tested lost capacitance above 200 °C. This may be an artifact of the conductive epoxy that was used to connect the electrodes to the package leads. Testing of the dielectric material shows the capacitance is stable to 400 °C. Some oxidation of the aluminum bond pads may occur due to oxygen in the epoxy material. Gold bond pads were deposited to investigate this theory. The same epoxy bonding systems was examined with gold bond pads on the capacitors. The capacitors maintained continuity in the measurement up to 250 °C. This reinforces the initial testing which shows AION is stable to 400 °C.

The insulation resistance (IR) was also measured. The IR for two and five layer device remained above 1000 MΩ at 100 V and 200 °C. The ten layer capacitor exhibited much lower IR, near 1 MΩ at the same conditions. The lower resistance with the increased layers may result from difficulties in closely masking the wafer during deposition. A gap is maintained between the

substrate and the mask to allow the substrate to move. But this gap also decreases the precision of the layer alignment. Improved process equipment should improve the alignment and increase the resistance of higher layer devices. Aluminum oxynitride appears an excellent potential for high temperature high capacitance devices, but processing and packaging challenges still exist to produce commercially viable AlON capacitors.



Figure 62. Cross-sectional Schematic of Stacked Multilayer Structure

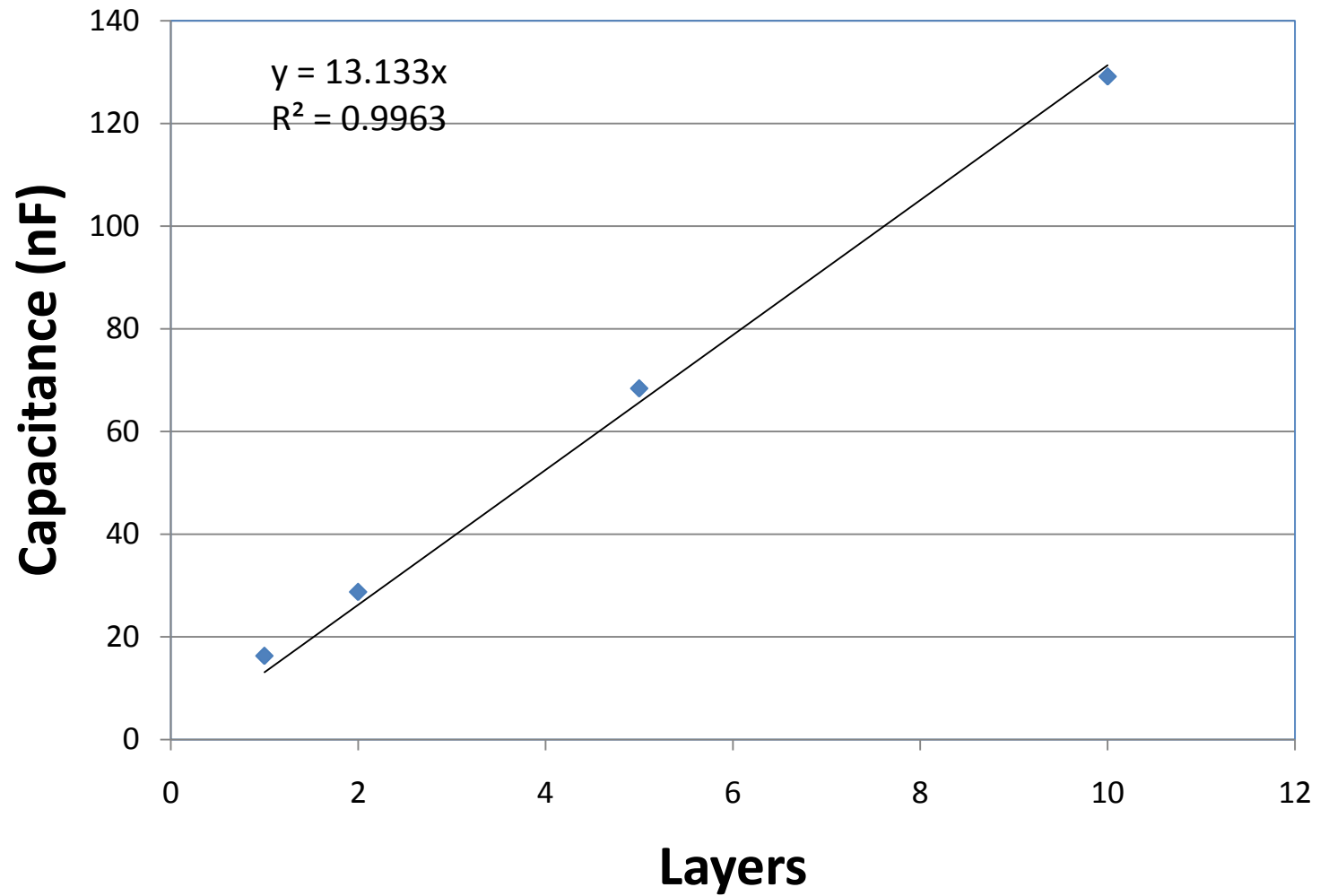


Figure 63. Capacitance vs. Layers for Multilayer Devices

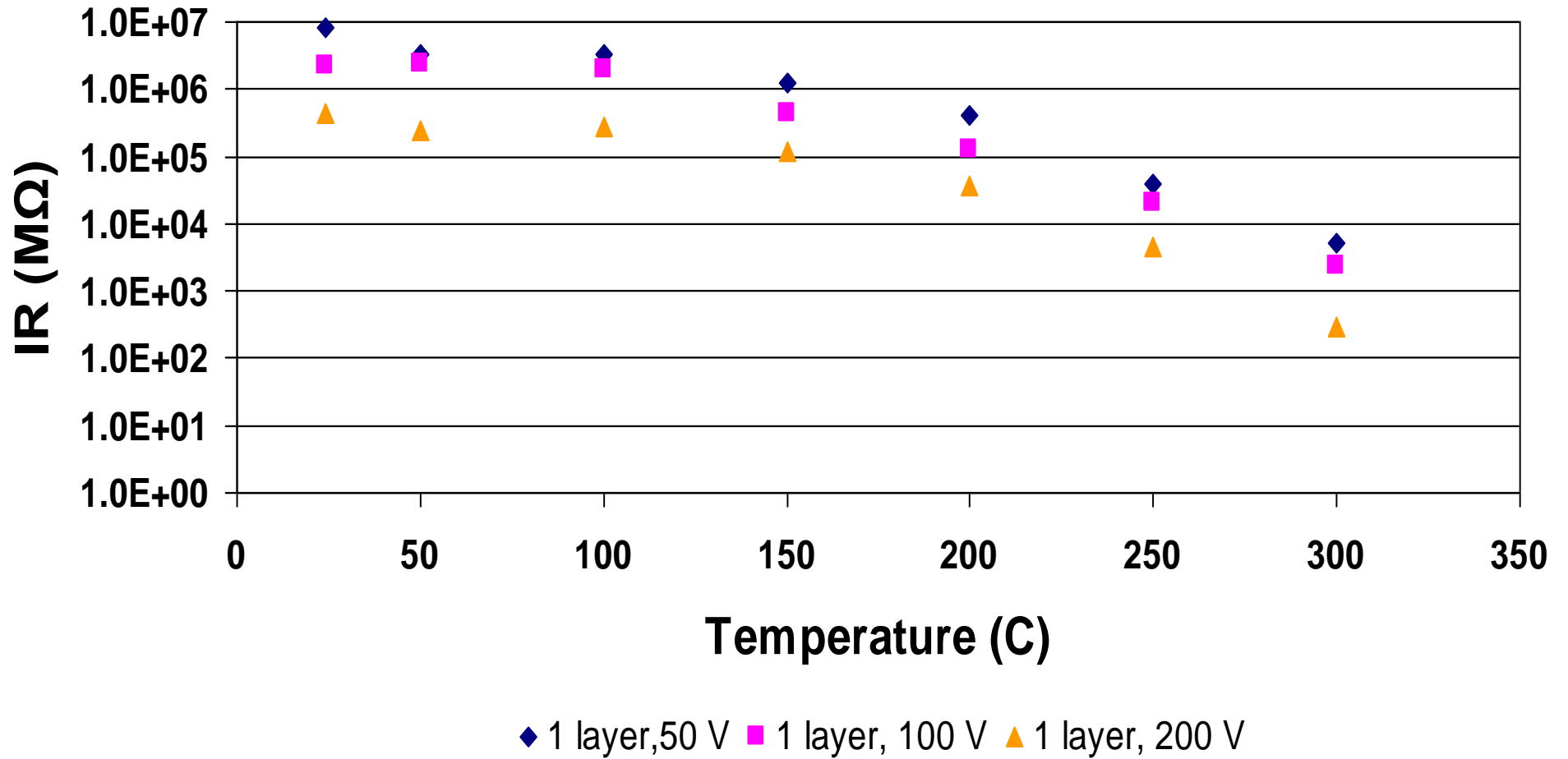


Figure 64. Insulation Resistance vs. Temperature at Various Voltages for a 1 Layer Device

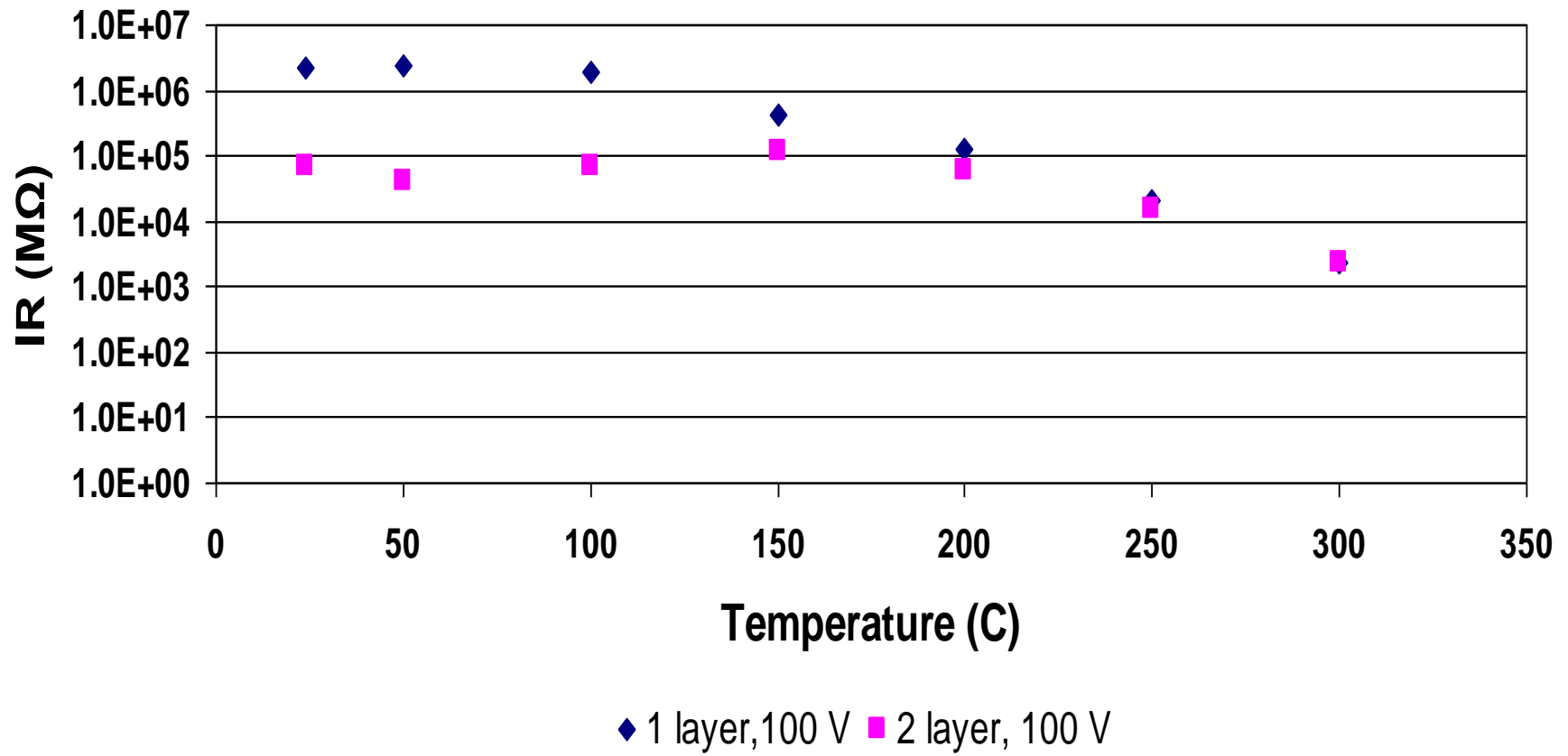


Figure 65. Insulation Resistance vs. Temperature at 100 V for 1 and 2 Layer Devices

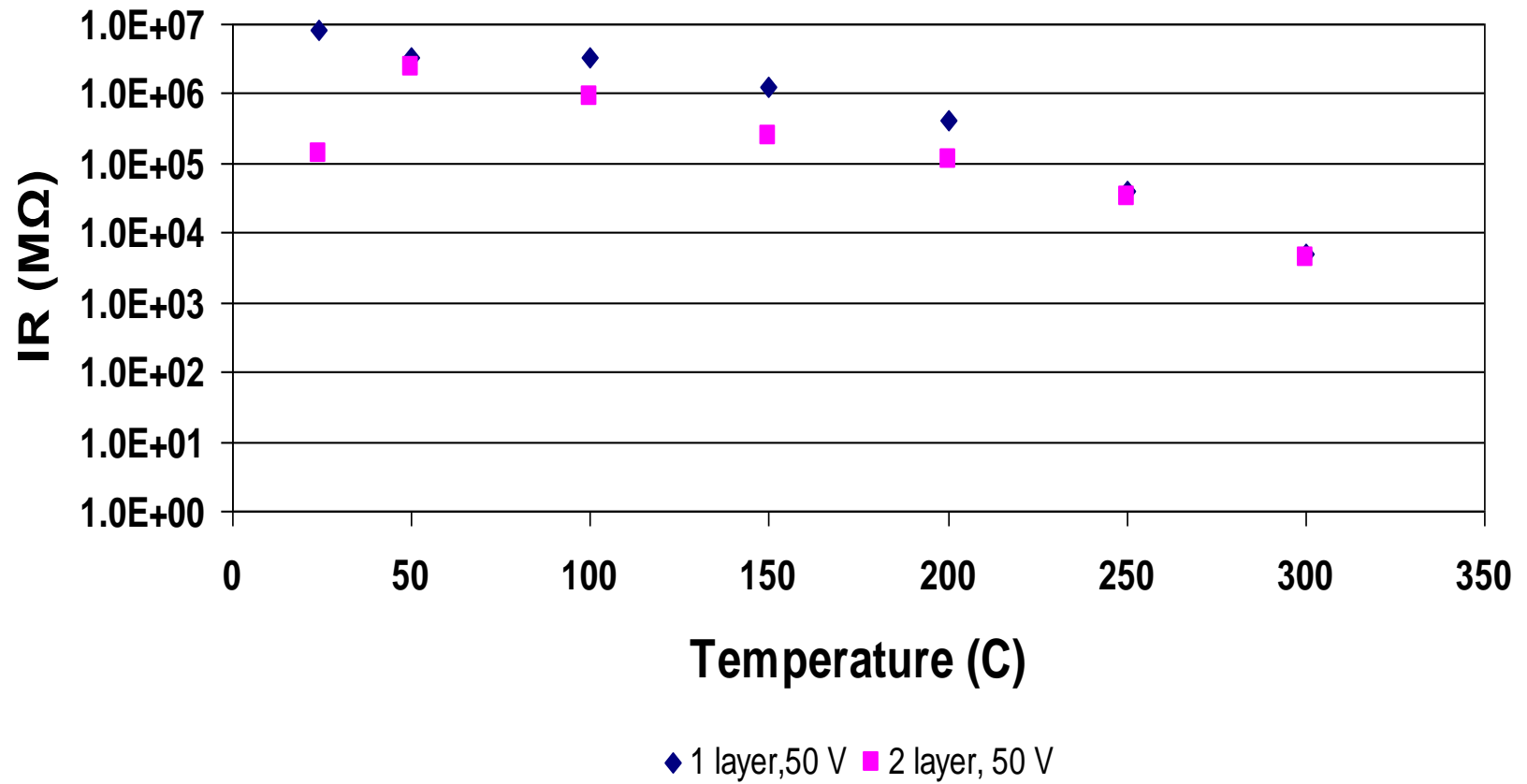


Figure 66. Insulation Resistance vs. Temperature at 50 V for 1 and 2 Layer Devices

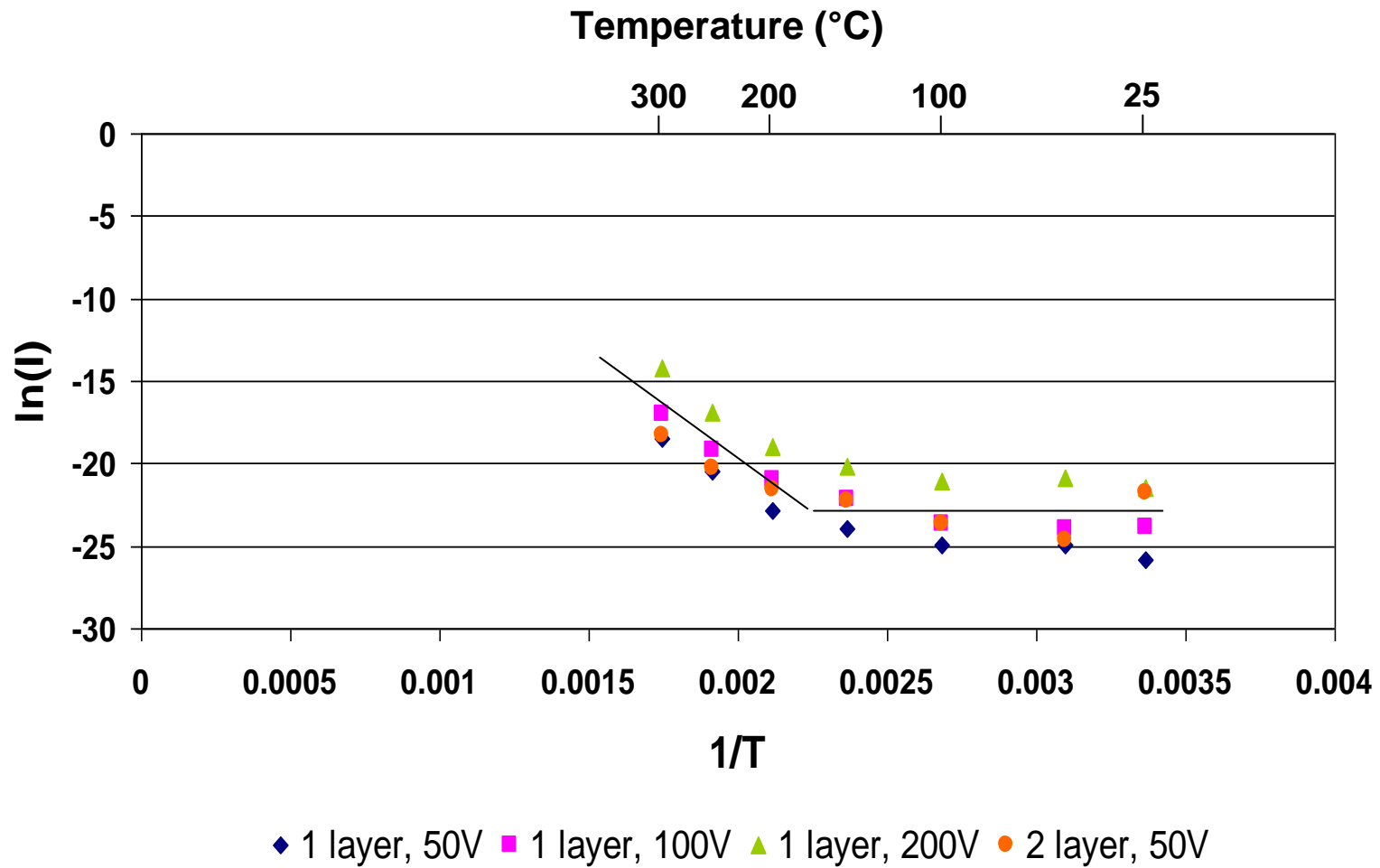


Figure 67. Arrhenius Plot of Leakage Current Data

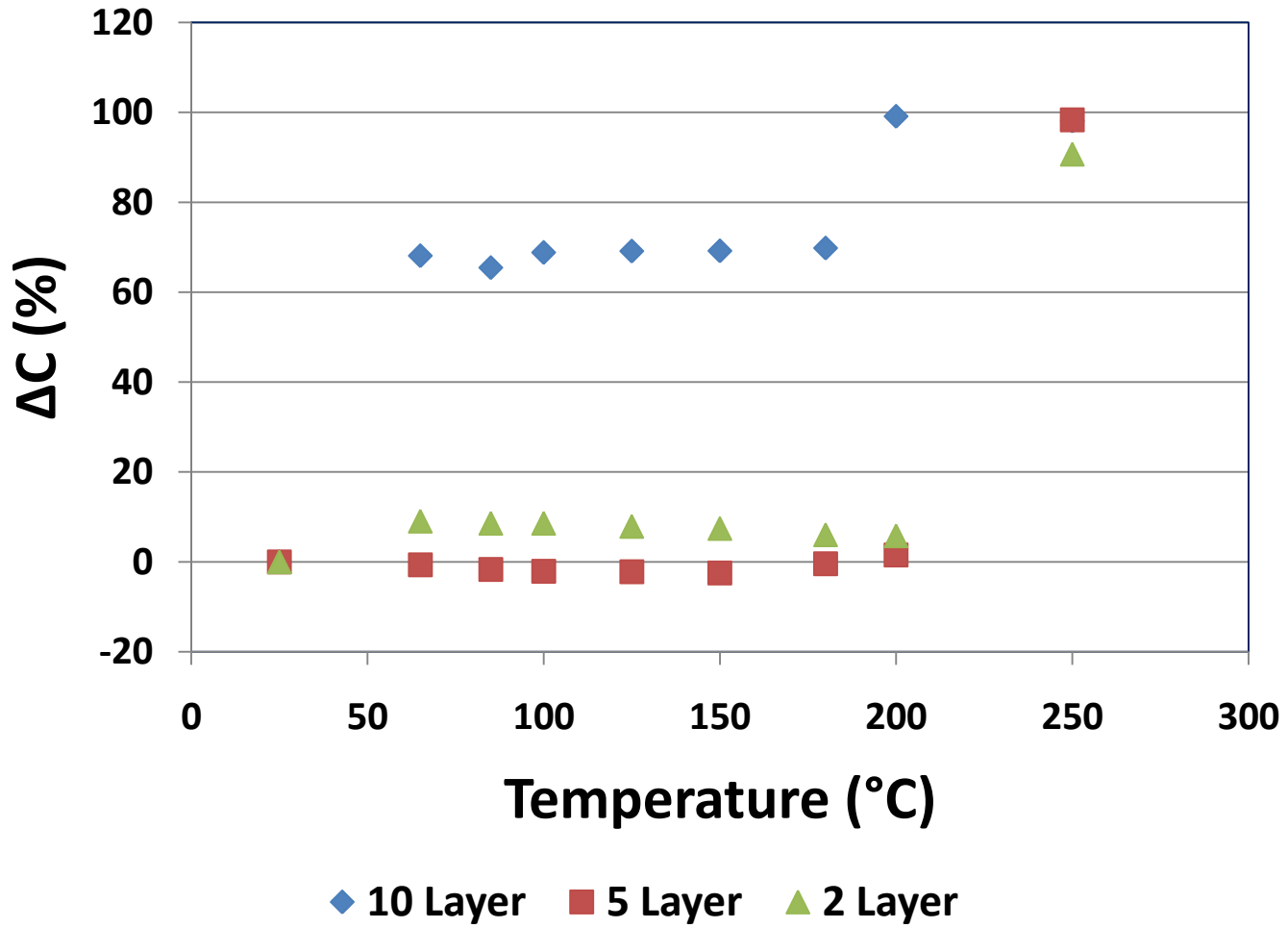


Figure 68. Temperature Stability of Packaged Capacitors

## 7. Discussion

The objective of this project was to develop high energy density aluminum nitride capacitors. The material was characterized in terms of its dielectric breakdown strength and dissipation factor. Aluminum nitride and aluminum oxynitride dielectric films were studied. The dielectric properties of the oxynitride material were superior to the nitride films. A dielectric constant of  $\sim 9$  was achieved, with a dissipation factor  $\sim 0.005$  and a breakdown voltage  $>600$  V/ $\mu\text{m}$ . These values result in a material energy density  $\sim 15$  J/cc. The films also exhibit excellent thermal stability from  $-200$  °C to  $400$  °C. The films remained amorphous and were free of pin-hole defects and were successfully deposited onto thin metal and polymer materials.

Another goal of the project was to simultaneously coat two sides of foil or polymer utilizing our custom designed web handling scanner system. We experienced difficulty in attaining this accomplishment. The high intensity plasma sputtering beam caused the aluminum foil to break under the tension of rolling. The foil did not maintain close contact with the scanner back plate, which allowed the plasma to overheat the foil. Better contact would transfer the heat away from the foil and reduce the stress during deposition. A set of process conditions was identified using lower DC power and tension where deposition was successful on foil, but it was not at the optimal conditions for dielectric performance. Several polymers were also examined. The majority could not withstand the plasma and melted. A high temperature polymer, FPE, was able to withstand the beam, but was not available in sufficient quantity to attempt deposition utilizing the web handler. Thin titanium and stainless steel foils were also investigated. Both showed superior strength than aluminum foil, but again we could not attempt to roll these foils.

In order to improve the rolled foils, we initiated an AF/OSD SBIR Phase II Enhancement program with the goal of modifying the scanner. The enhancement also examined techniques to improve the deposition rate, making the AlON deposition more economical. We also investigate a new stacked multilayer capacitor design to improve the volumetric energy density of our capacitors.

The deposition rate for AlON sputtering was improved by replacing the nitrogen/oxygen reactive gas mixture with nitrous oxide. Nitrous oxide bond strength is not as high as nitrogen and oxygen, resulting in a larger dissociation fraction in the plasma. Similar dielectric constant, dissipation factor and breakdown strength are obtained with  $\text{N}_2\text{O}$  as with  $\text{N}_2/\text{O}_2$ .

Multilayer capacitor devices have been deposited using the sample manipulator to align the dielectric and metal layers. The capacitance increases linearly with increasing layers. In-situ processing allowed both the metal and dielectric layers to be processed without exposing the sample to atmospheric contamination. Packaged multilayer devices have been operated up to  $250$  °C. Minimal change in capacitance is observed in packaged multilayer capacitors at high temperatures. The bond material to connect the electrodes to the package leads is critical for high temperature performance.

## **8. Conclusions**

High quality aluminum oxynitride dielectric films for high energy density capacitor applications have been developed. The deposition rate for reactive sputtering AlON films has been increased 2x by switching from a  $N_2/O_2$  chemistry to an  $N_2O$  chemistry. Capacitors with up to ten layers have been constructed and packaged. The capacitance increases linearly with increasing stacked layers. Films have been tested up to 400 °C. Aluminum oxynitride appears an excellent potential for high temperature, high capacitance devices, but processing and packaging challenges still exist to produce commercially viable AlON capacitors.

## **9. Deliverables**

- (1) Two (2) -10 feet Length of AlON coated aluminum foil/metalized polymer.
- (2) Two (2) -Three-layer AlON stacked capacitors.
- (3) Six (6) packaged capacitor devices  
  
Two (2) Stacked AlON capacitors with two (2) dielectric layers (0.04  $\mu\text{F}$ , 200 V)  
Two (2) Stacked AlON capacitors with five (5) dielectric layers (0.075  $\mu\text{F}$ , 100 V)  
Two (2) Stacked AlON capacitors with ten (10) dielectric layers (0.195  $\mu\text{F}$ , 80 V)
- (4) Quarterly progress reports covering the period 17 February, 2004 to 31 August 2008
- (5) A final report detailing the work performed.

## 10. Technical Publications and Presentations

### 10.1 Publications

- (1) “Aluminum Nitride Dielectrics for High Energy Density Capacitors”, R.L.C. Wu, J. Lawson, M. Samiee, P.B. Kosel, S.F. Adams, S. Fries-Carr and J. Weimer, Proceedings of 2004 National Space & Missile Materials Symposium, Seattle, Washington, (2004).
- (2) “Advanced Dielectrics for Pulsed Power Capacitor Devices”, S. Fries-Carr, S. Adams, J. Weimer, R.L.C. Wu, H. Kosai, K. Bray, T. Furmaniak, E. Barshaw, S. Scozzie, R. Jow, R. Garrison, F. Warnock, Proceeding of 2004 SAE International Conference on Power & Thermal Technologies for Directed Energy Applications 2004-01, 3216, (2004).
- (3) “Aluminum Nitride Dielectrics for High Energy Density Capacitors”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, and J. Weimer, Advances in Electronic and Electrochemical Ceramics, Ceramic Transactions 179, F. Dogan and P. Kumta, editors, 45-55, (2006).
- (4) “Aluminum Oxynitride Dielectrics for High Power, Wide Temperature Capacitor Applications”, K.R. Bray, R.L.C. Wu, S. Fries-Carr and J. Weimer, CARTS USA 2006, Proceedings of the 26<sup>th</sup> Symposium for Passive Components, 161-170, (2006).
- (5) “Aluminum Oxynitride Dielectrics for High Energy Density Capacitor Applications”, K.R. Bray, R.L.C. Wu, S. Fries-Carr and J. Weimer, “, Proceedings of the International Symposium on Advanced Dielectrics and Electronic Devices, Materials Science and Technology 2006, 647-656, (2006).
- (6) “Multilayer Aluminum Oxynitride Capacitors for Higher Energy Density, Wide Temperature Applications” K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, CARTS USA 2007, Proceeding of the 27<sup>th</sup> Symposium for Passive Components, 371-379 (2007).
- (7) “Aluminum Oxynitride Capacitors for Multilayer Devices with Higher Energy Density and Wide Temperature Properties”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, CARTS USA 2008, Proceeding of the 28<sup>th</sup> Symposium for Passive Components, 51-61 (2008).

### 10.2 Presentations

- (1) “Advanced Dielectrics for Pulsed Power Capacitor Device”, S. Fries-Carr, S. Adams, J. Weimer, R.L.C. Wu, H. Kosai, K. Bray, T. Furmaniak, E. Barshaw, S. Scozzie, R. Jow, R. Garrison, F. Warnock, was presented at the 2004 SAE International Conference on Power & Thermal Technologies for Directed Energy Applications, Reno, Nevada, Nov. 2-4, (2004).
- (2) “Aluminum Nitride Dielectrics for High Energy Density Capacitors”, R.L.C. Wu, J. Lawson, M. Samiee, P.B. Kosel, S.F. Adams, S. Fries-Carr and J. Weimer was presented

- at the 2004 National Space & Missile Materials Symposium, Seattle, Washington, (2004).
- (3) “Aluminum Nitride Dielectrics for High Energy Density Capacitors”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, was presented at 30<sup>th</sup> Dayton-Cincinnati Aerospace Sciences Symposium of the American Institute of Aeronautics and Astronautics, Dayton, OH, March 8 (2005).
  - (4) “Aluminum Nitride Dielectrics for High Energy Density Capacitors”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, was presented at the 107<sup>th</sup> Annual Meeting & Exposition of The American Ceramic Society, Baltimore, Maryland, April 10-13, (2005).
  - (5) “Aluminum Oxynitride Dielectrics for High Power, Wide Temperature Capacitor Applications”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, was presented at the 31<sup>st</sup> Dayton-Cincinnati Aerospace Sciences Symposium of the American Institute of Aeronautics and Astronautics, Dayton, OH, March 7, (2006).
  - (6) “Aluminum Oxynitride Dielectrics for High Power, Wide Temperature Capacitor Applications”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, was presented at CARTS USA 2006, the 26th Symposium for Passive Components, Orlando, FL, April 3-6, (2006).
  - (7) “Aluminum Oxynitride Dielectrics for High Energy Density Capacitor Applications”, K.R. Bray, R.L.C. Wu, S. Fries-Carr, J. Weimer, was presented at the Materials Science and Technology 2006 Conference and Exhibition, Cincinnati, OH, October 15-19, (2006).
  - (8) “Multilayer Aluminum Oxynitride Capacitors for Higher Energy Density, Wide Temperature Applications” K.R. Bray, R.L.C. Wu, S. Fries-Carr, and J. Weimer, was presented at the 32nd Dayton-Cincinnati Aerospace Sciences Symposium, Dayton, OH, March 6, (2007).
  - (9) “Multilayer Aluminum Oxynitride Capacitors for Higher Energy Density, Wide Temperature Applications” K.R. Bray, R.L.C. Wu, S. Fries-Carr, and J. Weimer, was presented at CARTS USA 2007, Albuquerque, NM, March 26-29, (2007).
  - (10) “Aluminum Oxynitride Capacitors for Multilayer Devices with Higher Energy Density and Wide Temperature Properties” K.R. Bray, R.L.C. Wu, S. Fries-Carr, and J. Weimer, was presented at the 33rd Dayton-Cincinnati Aerospace Sciences Symposium, Dayton, OH, March 4, (2008).
  - (11) “Aluminum Oxynitride Capacitors for Multilayer Devices with Higher Energy Density and Wide Temperature Properties” K.R. Bray, R.L.C. Wu, S. Fries-Carr, and J. Weimer, was presented at CARTS USA 2008, Newport Beach, CA, March 17-20, (2008).

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## APPENDIX A

Table A-1. AlN Deposition Conditions

| <u>Sample#</u> | <u>DepTemp</u><br><u>(C)</u> | <u>DepPress</u><br><u>(mTorr)</u> | <u>DepTime</u><br><u>(hr)</u> | <u>Gas</u><br><u>ambient</u><br><u>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC</u><br><u>power</u><br><u>(W)</u> | <u>Frequency</u><br><u>(kHz)</u> | <u>Distance</u><br><u>(inch)</u> |
|----------------|------------------------------|-----------------------------------|-------------------------------|---|---|----------------------------------|----------------------------------|
| AIN003         | 25-75                        | 7.5                               | 1.50                          | 1:0:0   | 500                                     | 0                                | 3                                |
| AIN004         | 25-75                        | 11.0                              | 1.00                          | 1:0:0   | 900                                     | 250                              | 3                                |
| AIN006         | 25-75                        | 3.7                               | 0.50                          | 1:0:0   | 900                                     | 250                              | 3                                |
| AIN007         | 25-75                        | 5.5                               | 0.50                          | 1:0:0   | 600                                     | 250                              | 3                                |
| AIN008         | 25-75                        | 9.0                               | 0.42                          | 1:0:0   | 900                                     | 250                              | 3                                |
| AIN009         | 25-75                        | 9.0                               | 0.5                           | 1:0:0   | 700                                     | 250                              | 3                                |
| AIN010         | 25-75                        | 5.0                               | 0.50                          | 1:0:0   | 900                                     | 250                              | 4                                |
| AIN011         | 25-75                        | 3.0                               | 0.50                          | 1:0:0   | 800                                     | 250                              | 4                                |
| AIN012         | 25-147                       | 10.0                              | 0.67                          | 1:0:0   | 900                                     | 150                              | 4                                |
| AIN013         | 25-87                        | 10.0                              | 0.67                          | 1:0:0   | 500                                     | 250                              | 4                                |
| AIN014         | 25-87                        | 7.0                               | 0.75                          | 1:0:0   | 900                                     | 50                               | 4                                |
| AIN015         | 10-92                        | 7.0                               | 1.00                          | 1:0:0   | 500                                     | 150                              | 4                                |
| AIN016         | 13-105                       | 7.0                               | 1.00                          | 1:0:0   | 700                                     | 250                              | 4                                |
| AIN017         | 9-126                        | 7.0                               | 0.67                          | 1:0:0   | 1000                                    | 250                              | 4                                |
| AIN018         | 13-52                        | 7.0                               | 0.67                          | 1:0:0   | 500                                     | 250                              | 4                                |
| AIN019         | 40-131                       | 4.5                               | 0.75                          | 1:0:0   | 1000                                    | 50                               | 4                                |
| AIN020         | 40-94                        | 4.5                               | 0.75                          | 1:0:0   | 700                                     | 150                              | 4                                |
| AIN021         | 10-108                       | 15.0                              | 0.58                          | 1:0:0   | 1000                                    | 250                              | 4                                |
| AIN022         | 8-64                         | 15.0                              | 0.58                          | 1:0:0   | 1000                                    | 50                               | 4                                |
| AIN023         | 29-144                       | 10.0                              | 0.75                          | 1:0:0   | 900                                     | 50                               | 4                                |
| AIN024         | 26-79                        | 10.0                              | 0.75                          | 1:0:0   | 700                                     | 150                              | 4                                |
| AIN025         | 25-74                        | 7.0                               | 0.75                          | 1:0:0   | 1000                                    | 150                              | 4                                |
| AIN026         | 25-114                       | 7.0                               | 0.75                          | 1:0:0   | 900                                     | 250                              | 4                                |
| AIN027         | 24-82                        | 15.0                              | 0.67                          | 1:0:0   | 700                                     | 250                              | 4                                |
| AIN028         | 26-88                        | 15.0                              | 0.67                          | 1:0:0   | 900                                     | 150                              | 4                                |
| AIN029         | 24-106                       | 10.0                              | 0.67                          | 1:0:0   | 1000                                    | 250                              | 4                                |
| AIN030         | 28-84                        | 10.0                              | 0.67                          | 1:0:0   | 700                                     | 150                              | 4                                |
| AIN031         | 28-84                        | 7.0                               | 0.83                          | 1:0:0   | 1000                                    | 150                              | 4                                |
| AIN032         | 28-84                        | 7.0                               | 0.83                          | 1:0:0   | 700                                     | 50                               | 4                                |

Table A-1. AlN Deposition Conditions (continued)

| <u>Sample#</u> | <u>DepTemp</u><br><u>(C)</u> | <u>DepPress</u><br><u>(mTorr)</u> | <u>DepTime</u><br><u>(hr)</u> | <u>Gas</u><br><u>ambient</u><br><u>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC</u><br><u>power</u><br><u>(W)</u> | <u>Frequency</u><br><u>(kHz)</u> | <u>Distance</u><br><u>(inch)</u> |
|----------------|------------------------------|-----------------------------------|-------------------------------|---|---|----------------------------------|----------------------------------|
| AIN033         | 28-84                        | 10.0                              | 0.75                          | 1:0:0   | 1000                                    | 250                              | 4                                |
| AIN034         | 28-84                        | 10.0                              | 0.75                          | 1:0:0   | 700                                     | 150                              | 4                                |
| AIN035         | 24-80                        | 10.0                              | 0.58                          | 1:0:0   | 1000                                    | 250                              | 4                                |
| AIN036         | 24-72                        | 10.0                              | 0.58                          | 1:0:0   | 700                                     | 150                              | 4                                |
| AIN037         | 24-75                        | 10.0                              | 0.50                          | 1:0:0   | 2000                                    | 250                              | 5                                |
| AIN038         | 24-49                        | 10.0                              | 0.50                          | 1:0:0   | 1000                                    | 150                              | 5                                |
| AIN039         |                              | 7.0                               |                               | 1:0:0   | 2000                                    | 150                              | 5                                |
| AIN040         |                              | 7.0                               | 0.50                          | 1:0:0   | 1500                                    | 250                              | 5                                |
| AIN041         |                              | 7.0                               | 0.50                          | 1:0:0   | 2000                                    | 150                              | 5                                |
| AIN042         |                              | 7.0                               | 0.33                          | 1:0:0   | 1500                                    | 250                              | 5                                |
| AIN043         | 16-20                        | 7.0                               | 0.17                          | 1:0:0   | 1500                                    | 250                              | 6                                |
| AIN044         | 18-24                        | 10.0                              | 0.33                          | 1:0:0   | 1500                                    | 250                              | 6                                |
| AIN045         | 16-                          | 15.0                              | 0.17                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN046         | 16-19                        | 10.0                              | 0.17                          | 1:0:0   | 1000                                    | 150                              | 6                                |
| AIN047         | 11-54                        | 15.0                              | 0.17                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN048         | 18                           | 10.0                              | 0.58                          | 1:0:0   | 1000                                    | 150                              | 6                                |
| AIN049         | 17-34                        | 15.0                              | 0.33                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN050         | 19-28                        | 15.0                              | 0.67                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN051         | 19-28                        | 16.0                              | 0.50                          | 3:0:1   | 2000                                    | 50                               | 6                                |
| AIN052         | 24-70                        | 12.5                              | 0.67                          | 1:0:0   | 1500                                    | 250                              | 6                                |
| AIN053         | 24-66                        | 10.0                              | 0.50                          | 1:0:0   | 2000                                    | 250                              | 6                                |
| AIN054         | 22-56                        | 15.0                              | 0.67                          | 1:0:0   | 1500                                    | 50                               | 6                                |
| AIN055         | 22-28                        | 12.5                              | 0.67                          | 1:0:0   | 1000                                    | 150                              | 6                                |
| AIN056         | 24-58                        | 15.0                              | 0.50                          | 1:0:0   | 2000                                    | 150                              | 6                                |
| AIN057         | 24-84                        | 15.0                              | 0.67                          | 1:0:0   | 1000                                    | 250                              | 6                                |
| AIN058         | 24-84                        | 12.5                              | 0.50                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN059         | 24-84                        | 12.5                              | 0.50                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN060         | 24-84                        | 10.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN061         | 24-84                        | 10.0                              | 0.50                          | 1:0:0   | 1500                                    | 150                              | 6                                |
| AIN062         |                              |                                   |                               |   |   |                                  |                                  |
| AIN063         | 20-22                        | 20.0                              | 0.67                          | 1:0:0   | 700                                     | 25                               | 6                                |
| AIN064         | 20-40                        | 20.0                              | 0.67                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN065         | 30-35                        | 20.0                              | 0.67                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN066         | 30-35                        | 20.0                              | 0.67                          | 1:0:0   | 850                                     | 5                                | 6                                |
| AIN067         | 10-20                        | 25.0                              | 0.50                          | 1:0:0   | 850                                     | 25                               | 6                                |
| AIN068         | 10-50                        | 25.0                              | 0.67                          | 1:0:0   | 2000                                    | 25                               | 6                                |
| AIN069         | 20-24                        | 15.0                              | 0.67                          | 1:0:0   | 850                                     | 50                               | 6                                |
| AIN070         | 20-30                        | 15.0                              | 0.67                          | 1:0:0   | 1500                                    | 50                               | 6                                |

Table A-1. AlN Deposition Conditions (continued)

| <u>Sample#</u> | <u>DepTemp</u><br><u>(C)</u> | <u>DepPress</u><br><u>(mTorr)</u> | <u>DepTime</u><br><u>(hr)</u> | <u>Gas</u><br><u>ambient</u><br><u>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC</u><br><u>power</u><br><u>(W)</u> | <u>Frequency</u><br><u>(kHz)</u> | <u>Distance</u><br><u>(inch)</u> |
|----------------|------------------------------|-----------------------------------|-------------------------------|---|---|----------------------------------|----------------------------------|
| AIN071         | 28-32                        | 15.0                              | 0.67                          | 1:0:0   | 1000                                    | 25                               | 6                                |
| AIN072         | 30-56                        | 15.0                              | 0.04                          | 1:0:0   | 2500                                    | 50                               | 6                                |
| AIN073         | 12-16                        | 15.0                              | 0.75                          | 1:0:0   | 700                                     | 5                                | 6                                |
| AIN074         | 18-20                        | 15.0                              | 0.75                          | 1:0:0   | 700                                     | 5                                | 6                                |
| AIN075         | 11-36                        | 15.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN076         | 18-21                        | 15.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN077         |                              | 25.0                              | 0.75                          | 1:0:0   | 1000                                    | 5                                | 6                                |
| AIN078         |                              | 25.0                              | 0.75                          | 1:0:0   | 1000                                    | 5                                | 6                                |
| AIN079         |                              | 15.0                              | 0.50                          | 1:0:0   | 2000                                    | 50                               | 6                                |
| AIN080         |                              | 15.0                              | 0.75                          | 1:0:0   | 1000                                    | 250                              | 6                                |
| AIN081         | 5-44                         | 15.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN082         | 4-61                         | 15.0                              | 0.75                          | 1:0:0   | 850                                     | 25                               | 6                                |
| AIN083         | 2-38                         | 20.0                              | 0.75                          | 1:0:0   | 850                                     | 5                                | 6                                |
| AIN084         | 2-44                         | 20.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN085         | 3-47                         | 15.0                              | 0.42                          | 1:0:2   | 1500                                    | 50                               | 6                                |
| AIN086         | 3-38                         | 20.0                              | 0.33                          | 1:0:1   | 1000                                    | 150                              | 6                                |
| AIN087         | 22-82                        | 20.0                              | 0.50                          | 1:0:0   | 850                                     | 25                               | 6                                |
| AIN088         | 22-129                       | 20.0                              | 0.50                          | 1:0:0   | 1500                                    | 150                              | 6                                |
| AIN089         | 22-98                        | 25.0                              | 0.75                          | 1:0:0   | 1000                                    | 50                               | 6                                |
| AIN093         | 24-147                       | 15.0                              | 0.50                          | 1:0:0   | 2000                                    | 50                               | 5                                |
| AIN094         | 22-106                       | 15.0                              | 0.75                          | 1:0:0   | 850                                     | 25                               | 5                                |
| AIN095         | 24-122                       | 20.0                              | 0.75                          | 1:0:0   | 850                                     | 25                               | 4                                |
| AIN096         | 24-100                       | 20.0                              | 0.75                          | 1:0:0   | 850                                     | 25                               | 5                                |
| AIN097         | 40-120                       | 10.0                              | 0.67                          | 1:0:0   | 900                                     | 50                               | 4                                |
| AIN098         | 38-120                       | 10.0                              | 0.67                          | 1:0:0   | 900                                     | 50                               | 5                                |
| AIN099         | 26-82                        | 7.0                               | 0.75                          | 1:0:0   | 700                                     | 250                              | 4                                |
| AIN100         | 26-68                        | 7.0                               | 0.75                          | 1:0:0   | 700                                     | 250                              | 5                                |
| AIN101         | 29-114                       | 3.0                               | 1.00                          | 1:0:0   | 800                                     | 250                              | 4                                |
| AIN102         | 29-113                       | 3.0                               | 1.00                          | 1:0:0   | 800                                     | 250                              | 5                                |
| AIN103         | 30-116                       | 5.0                               | 0.75                          | 1:0:0   | 850                                     | 150                              | 4                                |
| AIN104         | 30-88                        | 5.0                               | 0.75                          | 1:0:0   | 850                                     | 150                              | 5                                |
| AIN105         | 30-94                        | 7.5                               | 0.75                          | 1:0:0   | 900                                     | 300                              | 5                                |
| AIN106         | 29-69                        | 5.0                               | 0.75                          | 1:0:0   | 600                                     | 25                               | 5                                |
| AIN107         | 26-90                        | 10.0                              | 1.00                          | 1:0:0   | 750                                     | 150                              | 5                                |
| AIN108         | 28-86                        | 10.0                              | 1.00                          | 1:0:0   | 750                                     | 150                              | 5                                |
| AIN109         | 26-100                       | 21.0                              | 0.75                          | 2:1:0   | 1000                                    | 25                               | 5                                |
| AIN110         | 25-92                        | 12.0                              | 1.00                          | 5:1:0   | 850                                     | 25                               | 5                                |
| AIN111         | 25-92                        | 16.5                              | 1.00                          | 10:1:0  | 700                                     | 25                               | 5                                |
| AIN112         | 25-92                        | 16.5                              | 1.00                          | 10:1:0  | 1000                                    | 25                               | 5                                |

Table A-1. AIN Deposition Conditions (continued)

| <u>Sample#</u> | <u>DepTemp<br/>(C)</u> | <u>DepPress<br/>(mTorr)</u> | <u>DepTime<br/>(hr)</u> | <u>Gas<br/>ambient<br/>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC<br/>power<br/>(W)</u> | <u>Frequency<br/>(kHz)</u> | <u>Distance<br/>(inch)</u> |
|----------------|------------------------|-----------------------------|-------------------------|---|-----------------------------|----------------------------|----------------------------|
| AIN113         | 28-155                 | 12.0                        | 1.00                    | 23:1:0  | 2000                        | 50                         | 5                          |
| AIN114         | 30-102                 | 12.0                        | 0.83                    | 23:1:0  | 850                         | 50                         | 5                          |
| AIN115         | 36-116                 | 5.0                         | 0.50                    | 0:1:0   | 850                         | 50                         | 5                          |
| AIN116         | 35-108                 | 3.0                         | 1.25                    | 0:1:0   | 500                         | 150                        | 5                          |
| AIN117         | 35-110                 | 3.0                         | 1.25                    | 0:1:0   | 700                         | 250                        | 5                          |
| AIN118         | 32-133                 | 11.0                        | 1.50                    | 10:1:0  | 850                         | 25                         | 5                          |
| AIN119         | 32-138                 | 11.0                        | 1.50                    | 10:1:0  | 1500                        | 150                        | 5                          |
| AIN120         | 26-104                 | 10.0                        | 0.80                    | 1:(10:1:0)  | 850                         | 50                         | 5                          |
| AIN121         | 26-96                  | 10.0                        | 0.80                    | 1:(10:1:0)  | 1000                        | 25                         | 5                          |
| AIN122         | 26-96                  | 10.0                        | 0.80                    | 1:(10:1:0)  | 1000                        | 50                         | 5                          |
| AIN123         | 26-96                  | 10.0                        | 0.80                    | 1:(10:1:0)  | 850                         | 50                         | 5                          |
| AIN124         | 26-96                  | 10.5                        | 1.00                    | 20:1:0  | 850                         | 25                         | 5                          |
| AIN125         | 26-96                  | 10.5                        | 1.00                    | 20:1:0  | 1000                        | 50                         | 5                          |
| AIN126         | 32-118                 | 10.0                        | 1.00                    | 1(10:1:0)   | 850                         | 50                         | 5                          |
| AIN127         | 34-88                  | 10.0                        | 1.00                    | 1(10:1:0)   | 850                         | 250                        | 5                          |
| AIN128         | 36-130                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN129         | 36-110                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN130         | 34-127                 | 11.5                        | 2.00                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN131         | 35-100                 | 11.5                        | 2.00                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN132         | 29-112                 | 11.5                        | 2.00                    | 7:1:0   | 700                         | 50                         | 5                          |
| AIN133         | 29-77                  | 11.5                        | 2.00                    | 7:1:0   | 500                         | 50                         | 5                          |
| AIN134         | 37-113                 | 13.0                        | 1.50                    | 12:1:0  | 850                         | 50                         | 5                          |
| AIN135         | 38-95                  | 13.0                        | 1.50                    | 12:1:0  | 850                         | 25                         | 5                          |
| AIN136         | 37-120                 | 21.0                        | 1.50                    | 20:1:0  | 850                         | 25                         | 5                          |
| AIN137         | 36-92                  | 21.0                        | 1.50                    | 20:1:0  | 700                         | 25                         | 5                          |
| AIN138         | 33-135                 | 16.5                        | 1.75                    | 10:1:0  | 1000                        | 50                         | 5                          |
| AIN139         | 33-124                 | 16.5                        | 1.75                    | 10:1:0  | 1200                        | 50                         | 5                          |
| AIN140         | 34-133                 | 11.5                        | 1.75                    | 7:1:0   | 1000                        | 50                         | 5                          |
| AIN141         | 36-98                  | 11.5                        | 1.75                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN142         | 34-122                 | 16.5                        | 2.00                    | 10:1:0  | 1000                        | 50                         | 5                          |
| AIN143         | 29-101                 | 16.5                        | 2.00                    | 10:1:0  | 1000                        | 25                         | 5                          |
| AIN146         | 35-137                 | 11.5                        | 1.75                    | 7:1:0   | 900                         | 50                         | 5                          |
| AIN147         | 36-102                 | 11.5                        | 1.75                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN148         | 36-135                 | 11.5                        | 1.75                    | 7:1:0   | 900                         | 50                         | 5                          |
| AIN149         | 36-98                  | 11.5                        | 1.75                    | 7:1:0   | 900                         | 50                         | 5                          |
| AIN150         | 28-114                 | 11.5                        | 1.75                    | 7:1:0   | 900                         | 50                         | 5                          |
| AIN151         | 28-114                 | 11.5                        | 1.75                    | 7:1:0   | 900                         | 50                         | 5                          |
| AIN152         | 35-103                 | 11.5                        | 0.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN153         | 35-103                 | 11.5                        | 0.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN154         | 18-110                 | 11.5                        | 1.00                    | 7:1:0   | 850                         | 50                         | 5                          |

Table A-1. AlN Deposition Conditions (continued)

| <u>Sample#</u> | <u>DepTemp<br/>(C)</u> | <u>DepPress<br/>(mTorr)</u> | <u>DepTime<br/>(hr)</u> | <u>Gas<br/>ambient<br/>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC<br/>power<br/>(W)</u> | <u>Frequency<br/>(kHz)</u> | <u>Distance<br/>(inch)</u> |
|----------------|------------------------|-----------------------------|-------------------------|---|-----------------------------|----------------------------|----------------------------|
| AIN155         | 18-110                 | 11.5                        | 1.00                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN156         | 32-55                  | 11.5                        | 0.17                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN157         | 32-55                  | 11.5                        | 0.17                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN158         | 33-97                  | 11.5                        | 0.58                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN159         | 33-97                  | 11.5                        | 0.58                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN160         | 32-102                 | 11.5                        | 2.17                    | 7:1:0   | 850                         | 50                         | 6                          |
| AIN161         | 32-102                 | 11.5                        | 2.17                    | 7:1:0   | 850                         | 50                         | 6                          |
| AIN162         | 29-113                 | 11.5                        | 2.50                    | 7:1:0   | 1000                        | 50                         | 5                          |
| AIN163         | 29-113                 | 11.5                        | 2.50                    | 7:1:0   | 1000                        | 50                         | 5                          |
| AIN164         |                        | 11.5                        | 2.17                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN165         |                        | 11.5                        | 2.17                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN166         | 29-108                 | 11.5                        | 1.75                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN167         | 29-108                 | 11.5                        | 1.75                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN168         | 29-106                 | 11.5                        | 1.42                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN169         | 29-106                 | 11.5                        | 1.42                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN174         | 30-160                 | 10.0                        | 2.00                    | 0:3:2   | 1500                        | 50                         | 5                          |
| AIN175         | 30-100                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN176         | 30-100                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN177         | 34-118                 | 11.5                        | 1.25                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN178         | 34-118                 | 11.5                        | 1.25                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN179         | 34-122                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN180         | 34-122                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN181         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN182         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN196         | 30-120                 | 15.5                        | 1.00                    | 7:1:3   | 850                         | 50                         | 5                          |
| AIN197         | 30-120                 | 19.5                        | 1.00                    | 7:1:5   | 850                         | 50                         | 5                          |
| AIN198         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN199         | 30-120                 | 5.5                         | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN200         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN201         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN202         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN203         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN204         | 30-120                 | 9.0                         | 1.67                    | 7:1:7   | 850                         | 50                         | 5                          |
| AIN205         | 30-120                 | 7.0                         | 1.67                    | 7:1:3.5   | 850                         | 50                         | 5                          |
| AIN206         | 30-120                 | 11.5                        | 1.00                    | 7:1:0   | 1000                        | 50                         | 5                          |
| AIN207         | 30-120                 | 11.5                        | 1.00                    | 7:1:0   | 1000                        | 50                         | 5                          |

Table A-1. AlN Deposition Conditions (continued)

| <u>Sample#</u> | <u>DepTemp<br/>(C)</u> | <u>DepPress<br/>(mTorr)</u> | <u>DepTime<br/>(hr)</u> | <u>Gas<br/>ambient<br/>N<sub>2</sub>:O<sub>2</sub>:Ar</u> | <u>DC<br/>power<br/>(W)</u> | <u>Frequency<br/>(kHz)</u> | <u>Distance<br/>(inch)</u> |
|----------------|------------------------|-----------------------------|-------------------------|---|-----------------------------|----------------------------|----------------------------|
| AIN208         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN209         | 30-120                 | 6.0                         | 1.67                    | 7:1:7   | 850                         | 50                         | 5                          |
| AIN210         | 30-120                 | 9.0                         | 1.92                    | 7:1:7   | 850                         | 50                         | 5                          |
| AIN211         | 30-120                 | 13.0                        | 1.75                    | 7:1:14  | 850                         | 50                         | 5                          |
| AIN214         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN215         | 30-120                 | 9.0                         | 1.42                    | 7:1:7   | 850                         | 50                         | 5                          |
| AIN216         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN217         | 30-120                 | 9.0                         | 1.33                    | 7:1:7   | 850                         | 50                         | 5                          |
| AIN218         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN219         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN220         | 30-120                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN222         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN223         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN224         | 30-120                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN225         | 30-120                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN226         | 30-120                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN227         | 30-120                 | 11.5                        | 1.50                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN228         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN229         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN230         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN231         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN232         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN233         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN234         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN235         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN236         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN237         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN238         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN239         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN240         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |
| AIN241         | 30-120                 | 11.5                        | 1.67                    | 7:1:0   | 850                         | 50                         | 5                          |

## APPENDIX B

Table B-1. Dielectric Properties of AlN Films

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>Rp (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|----------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN003         | Si               | 10513           | 0.02449   | 0.47            | 29.12          | 13.89          | 0.00           | 279       | 7.86     | 6.72E+02        | 265.39     | 1.95                 |
| AlN004         | Si               | 11067           | 0.01048   | 0.46            | 38.44          | 33.17          | 2740000.00     | 480       | 8.10     | 1.75E+15        | 433.73     | 3.07                 |
| AlN006         | Si               | 5840            | 0.01753   | 1.26            | 10.35          | 7.21           |                |           | 11.76    | 1.21E+03        |            | 3.24                 |
| AlN007         | Si               | 4967            | 0.01339   | 1.32            | 9.47           | 8.97           |                |           | 10.52    | 1.42E+03        |            | 2.76                 |
| AlN008         | Si               | 2859            | 0.02283   | 1.68            | 4.13           | 4.15           |                |           | 7.67     | 2.47E+03        |            | 1.91                 |
| AlN009         | Si               | 2937            | 0.01202   | 1.70            | 7.82           | 7.78           |                |           | 7.99     | 2.41E+03        |            | 1.63                 |
| AlN010         | Si               | 3672            | 0.00951   | 1.47            | 11.69          | 11.41          |                |           | 8.61     | 1.93E+03        |            | 2.04                 |
| AlN011         | Si               | 3623            | 0.00839   | 1.84            | 10.33          | 10.32          |                |           | 10.65    | 1.95E+03        |            | 2.01                 |
| AlN012         | Si               | 5294            | 0.00580   | 0.99            | 27.70          | 27.66          | 445000.00      | 180       | 8.39     | 5.94E+14        | 340.04     | 2.21                 |
| AlN013         | Si               | 3380            | 0.01889   | 1.59            | 8.44           | 5.29           | 2232.00        | 125       | 8.60     | 4.67E+12        | 369.79     | 1.41                 |
| AlN014         | Si               | 5235            | 36.76350  | 1.82            | 0.00           | 0.00           |                |           | 15.23    | 1.35E+03        |            | 1.94                 |
| AlN015         | Si               | 4861            | 0.01103   | 1.16            | 13.10          | 12.40          |                |           | 9.04     | 5.80E+09        |            | 1.35                 |
| AlN016         | Si               | 7504            | 0.00552   | 0.73            | 33.06          | 39.73          | 4350.00        | 185       | 8.71     | 4.10E+12        | 246.54     | 2.08                 |
| AlN017         | Si               | 5534            | 0.01936   | 1.10            | 8.95           | 7.46           | 38.80          |           | 9.75     | 4.96E+10        |            | 2.31                 |
| AlN018         | Si               | 3329            | 0.03129   | 1.82            | 5.63           | 2.80           | 41600.00       | 20        | 9.68     | 8.83E+13        | 60.08      | 1.39                 |
| AlN021         | Si               | 4716            | 0.05958   | 1.06            | 0.26           | 2.52           |                |           | 8.01     | 1.50E+03        |            | 2.25                 |
| AlN022         | Si               | 6709            | 0.01359   | 0.71            | 16.71          | 16.41          | 64500.00       | 257.5     | 7.66     | 6.80E+13        | 383.83     | 3.19                 |
| AlN023         | Si               | 4599            | 0.01677   | 1.10            | 8.83           | 8.59           | 77600.00       | 105       | 8.12     | 1.19E+14        | 228.29     | 1.70                 |
| AlN024         | Si               | 4750            | 0.17573   | 1.26            | 1.26           | 0.72           | 8980.00        |           | 9.59     | 1.34E+13        |            | 1.76                 |
| AlN025         | Si               | 5709            |           | 1.04            | 0.13           | 0.00           |                |           | 9.54     | 1.24E+03        |            | 2.11                 |
| AlN026         | Si               | 5950            | 0.03129   | 1.82            | 5.63           | 2.80           |                |           | 17.30    | 1.19E+03        |            | 2.20                 |
| AlN027         | Si               | 3158            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.32                 |
| AlN027         | Foil             | 3158            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.32                 |
| AlN028         | Si               | 6986            | 0.05825   | 1.60            | 1.73           | 1.71           | 9980.00        | 141.667   | 17.83    | 1.01E+13        | 202.79     | 2.91                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>Rp (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|----------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN028         | Foil             | 6986            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 2.91                 |
| AlN029         | Si               | 4337            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.81                 |
| AlN029         | Foil             | 4337            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.81                 |
| AlN030         | Si               | 4167            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.74                 |
| AlN030         | Foil             | 4167            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.74                 |
| AlN031         | Si               | -               | -         | -               | -              | -              | -              | -         | -        | -               | -          | -                    |
| AlN032         | Si               | -               | -         | -               | -              | -              | -              | -         | -        | -               | -          | -                    |
| AlN033         | Si               | 5663            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 2.10                 |
| AlN034         | Si               | 3800            | -         | -               | -              | -              | -              | -         | -        | -               | -          | 1.41                 |
| AlN037         | Si               | 7207            | 0.01776   | 0.73            | 13.36          | 12.20          | 2340.00        | 271       | 8.46     | 2.30E+12        | 376.02     | 4.00                 |
| AlN037         | Foil             | 7207            | 0.01099   | 0.78            | 17.46          | 18.58          | 68000.00       | 127.667   | 8.98     | 6.67E+13        | 177.14     | 4.00                 |
| AlN038         | Si               | 2932            | 0.0157    | 1.542           | 6.64           | 6.572          |                |           | 7.23     |                 |            | 1.63                 |
| AlN039         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN040         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN041         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN042         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN043         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN044         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN045         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN046         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN047         | Foil             |                 |           |                 |                |                |                |           |          |                 |            |                      |
| AlN048         | Foil             | 2803            | 0.0351    | 1.725           | 2.68           | 2.633          | 16350          | 90.00     | 7.73     | 4.12E+13        | 321.11     | 1.33                 |
| AlN049         | Foil             | 4783            | 0.0424    | 1.555           | 2.49           | 2.413          | 5000           | 140.00    | 11.89    | 7.39E+12        | 292.73     | 3.99                 |
| AlN050         | Foil             | 7522            | 0.0675    | 0.804           | 3.39           | 2.932          | 13550          | 375.00    | 9.67     | 1.27E+13        | 498.57     | 3.13                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AIN051         | Foil             | 8504            | 0.0297    | 0.752           | 7.24           | 7.140                     | 67166.67       | 333.33    | 10.22    | 5.58E+13        | 391.99     | 4.72                 |
| AIN052         | Foil             | 6544            | 0.0217    | 0.806           | 9.91           | 9.100                     | 32400          | 176.67    | 8.43     | 3.50E+13        | 269.96     | 2.73                 |
| AIN052         | Si               | 6544            | 0.0305    | 0.832           | 6.27           | 6.265                     | 18550          | 277.50    | 8.70     | 2.00E+13        | 424.04     | 2.73                 |
| AIN053         | Foil             | 6323            | 0.0159    | 0.967           | 11.60          | 10.332                    | 59266.67       | 126.25    | 9.77     | 6.63E+13        | 199.67     | 3.51                 |
| AIN054         | Foil             | 5882            | 0.0543    | 1.102           | 2.76           | 2.659                     | 12182.75       | 301.67    | 10.36    | 1.46E+13        | 512.89     | 2.45                 |
| AIN055         | Foil             | 3609            | 0.0318    | 1.438           | 3.89           | 3.480                     | 17793.33       | 145.00    | 8.30     | 3.49E+13        | 401.77     | 1.50                 |
| AIN056         | Foil             | 4219            | 0.0319    | 1.027           | 4.99           | 4.852                     | 15800          | 178.75    | 6.93     | 2.65E+13        | 423.68     | 2.34                 |
| AIN057         | Foil             | 4017            | 0.0363    | 1.166           | 3.78           | 3.759                     | 12833.33       | 211.67    | 7.48     | 2.26E+13        | 526.96     | 1.67                 |
| AIN058         | Foil             | 5416            | 0.0178    | 0.930           | 9.71           | 9.606                     | 13766.67       | 189.00    | 8.05     | 1.80E+13        | 349.00     | 3.01                 |
| AIN059         | Foil             | 5459            | 0.0198    | 0.936           | 8.73           | 8.579                     | 35175          | 162.50    | 8.17     | 4.55E+13        | 297.67     | 3.03                 |
| AIN060         | Foil             | 3681            | 0.0241    | 1.210           | 5.62           | 5.466                     | 8069.25        | 163.75    | 7.12     | 1.55E+13        | 444.82     | 1.36                 |
| AIN061         | Foil             | 4231            | 0.0313    | 1.504           | 3.42           | 3.386                     | 17750          | 166.25    | 10.17    | 2.97E+13        | 392.91     | 2.35                 |
| AIN062         |                  | Aborted         |           |                 |                |                           |                |           |          |                 |            |                      |
| AIN063         | Foil             | 2304            | 0.2844    | 3.503           | 0.16           | 0.160                     |                |           | 12.90    |                 |            | 0.96                 |
| AIN063-2       | Foil             | 2304            | 0.0600    | 1.958           | 1.39           | 1.354                     |                |           | 7.21     |                 |            | 0.96                 |
| AIN064         | Foil             | 4029            | 0.1577    | 1.551           | 0.66           | 0.651                     | 534.6667       | 21.67     | 9.99     | 9.38E+11        | 53.78      | 1.68                 |
| AIN064-2       | Foil             | 4029            | 0.0794    | 1.177           | 1.71           | 1.702                     | 534.6667       | 21.67     | 7.58     | 9.38E+11        | 53.78      | 1.68                 |
| AIN065         | Foil             | 3017            | 0.3423    | 6.038           | 0.08           | 0.077                     | 11.5           | 15.00     | 29.12    | 2.69E+10        | 49.72      | 1.26                 |
| AIN065-2       | Foil             | 3017            | 0.1766    | 1.968           | 0.46           | 0.458                     | 11.5           | 15.00     | 9.49     | 2.69E+10        | 49.72      | 1.26                 |
| AIN067         | Foil             | 2533            | 0.3163    | 11.978          | 0.04           | 0.042                     | 263.5          | 52.50     | 48.51    | 7.35E+11        | 207.24     | 1.41                 |
| AIN067-2       | Foil             | 2533            | 0.2619    | 3.754           | 0.16           | 0.162                     | 263.5          | 52.50     | 15.20    | 7.35E+11        | 207.24     | 1.41                 |
| AIN068         | Foil             | 6387            | 0.2092    | 1.919           | 0.41           | 0.397                     | 13200          | 267.50    | 19.59    | 1.46E+13        | 418.82     | 2.66                 |
| AIN068-2       | Foil             | 6387            | 0.0767    | 1.095           | 2.89           | 1.896                     | 13200          | 267.50    | 11.18    | 1.46E+13        | 418.82     | 2.66                 |
| AIN069         | Foil             | 2878            | 0.1559    | 1.957           | 0.53           | 0.521                     | 9003.333       | 166.67    | 9.00     | 2.21E+13        | 579.16     | 1.20                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AIN069-2       | Foil             | 2878            | 0.0401    | 1.377           | 2.94           | 2.886                     | 9003.333       | 166.67    | 6.33     | 2.21E+13        | 579.16     | 1.20                 |
| AIN070         | Foil             | 6012            | 0.0842    | 0.895           | 2.27           | 2.112                     | 14466.67       | 338.75    | 8.60     | 1.70E+13        | 563.49     | 2.50                 |
| AIN070-2       | Foil             | 6012            | 0.0422    | 0.803           | 4.94           | 4.700                     | 14466.67       | 338.75    | 7.72     | 1.70E+13        | 563.49     | 2.50                 |
| AIN071         | Foil             | 3479            | 0.3115    | 5.065           | 0.11           | 0.101                     | 980.5          | 62.50     | 28.17    | 1.99E+12        | 179.67     | 1.45                 |
| AIN071-2       | Foil             | 3479            | 0.1393    | 2.470           | 0.50           | 0.462                     | 980.5          | 62.50     | 13.74    | 1.99E+12        | 179.67     | 1.45                 |
| AIN072         | Foil             |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AIN073         | Foil             | 2993            | 0.3053    | 8.720           | 0.06           | 0.060                     | 541            | 107.50    | 41.72    | 1.28E+12        | 359.17     | 1.11                 |
| AIN073-2       | Foil             | 2993            | 0.1359    | 3.732           | 0.35           | 0.314                     | 541            | 107.50    | 17.86    | 1.28E+12        | 359.17     | 1.11                 |
| AIN073         | Si               | 2993            | 0.1891    | 2.718           | 0.31           | 0.310                     |                |           | 13.01    | 2.36E+03        |            | 1.11                 |
| AIN074         | Foil             | 2822            | 0.0499    | 1.799           | 1.81           | 1.772                     | 13133.33       | 55.00     | 8.12     | 3.29E+13        | 194.93     | 1.05                 |
| AIN074-2       | Foil             | 2822            | 0.0476    | 1.767           | 1.95           | 1.892                     | 13133.33       | 55.00     | 7.97     | 3.29E+13        | 194.93     | 1.05                 |
| AIN074         | Si               | 2822            | 0.1559    | 2.622           | 0.46           | 0.389                     |                |           | 11.83    | 2.51E+03        |            | 1.05                 |
| AIN075         | Foil             | 4666            | 0.1117    | 1.707           | 0.84           | 0.834                     | 2783.333       | 200.00    | 12.74    | 4.22E+12        | 428.63     | 1.73                 |
| AIN075-2       | Foil             | 4666            | 0.0624    | 1.484           | 1.73           | 1.720                     | 2783.333       | 200.00    | 11.07    | 4.22E+12        | 428.63     | 1.73                 |
| AIN076         | Foil             | 4693            | 0.1204    | 1.504           | 0.93           | 0.878                     | 2250           | 171.67    | 11.29    | 3.39E+12        | 365.77     | 1.74                 |
| AIN077         | Foil             | 5270            |           |                 |                |                           |                |           |          |                 |            | 1.95                 |
| AIN078         | Foil             | 4387            |           |                 |                |                           |                |           |          |                 |            | 1.62                 |
| AIN079         |                  | 4285            |           | Sent to NASA    |                |                           |                |           |          |                 | 2.38       |                      |
| AIN080         |                  | 2696            |           | Sent to NASA    |                |                           |                |           |          |                 | 1.00       |                      |
| AIN081         | Si               | 4258            | 0.0762    | 1.273           | 1.64           | 1.641                     |                |           | 8.67     |                 |            | 1.58                 |
| AIN081         | Glass            | 4534            | 0.2247    | 1.853           | 0.39           | 0.382                     | 1350           | 90.00     | 13.43    | 2.10E+12        | 198.50     | 1.68                 |
| AIN082         | Glass            | 3479            | 0.2383    | 2.563           | 0.27           | 0.261                     | 1282.667       | 81.67     | 14.25    | 2.61E+12        | 234.72     | 1.29                 |
| AIN083         | Glass, Si        | 3671            |           |                 |                |                           |                |           |          |                 |            | 1.36                 |
| AIN084         | Glass, Si        | 4114            |           |                 |                |                           |                |           |          |                 |            | 1.52                 |
| AIN085         | Foil             | 1743            | 0.1157    | 1.436           | 0.98           | 0.958                     | 910.4          | 68.33     | 4.00     | 3.69E+12        | 392.12     | 1.16                 |
| AIN085         | Si               | 1743            | 0.3288    | 2.446           | 0.21           | 0.198                     | 4739.5         | 85.00     | 6.81     | 1.92E+13        | 487.76     | 1.16                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN086         | Foil             | 1645            | 0.2351    | 3.351           | 0.23           | 0.202                     |                |           | 8.81     | 4.30E+03        |            | 1.37                 |
| AlN086         | Glass            | 1867            | 0.1207    | 1.950           | 0.68           | 0.676                     |                |           | 5.82     | 3.79E+03        |            | 1.56                 |
| AlN086         | Si               | 1645            | 0.2383    | 2.563           | 0.27           | 0.261                     |                |           | 6.74     | 4.30E+03        |            | 1.37                 |
| AlN087         | Foil             | 2127            | 0.0623    | 2.542           | 1.05           | 1.005                     |                |           | 8.64     | 3.32E+03        |            | 1.18                 |
| AlN087         | Glass            | 1874            | 0.1327    | 3.153           | 0.39           | 0.380                     |                |           | 9.45     | 3.77E+03        |            | 1.04                 |
| AlN087         | Si               | 2127            | 0.1293    | 3.258           | 0.60           | 0.378                     |                |           | 11.08    | 3.32E+03        |            | 1.18                 |
| AlN088         | Foil             | 3417            | 0.0604    | 1.213           | 2.24           | 2.174                     | 15000          | 123.33    | 6.62     | 3.10E+13        | 360.94     | 1.90                 |
| AlN088         | Glass            | 4444            | 0.3315    | 2.089           | 0.23           | 0.230                     | 2720           | 172.50    | 14.84    | 4.33E+12        | 388.13     | 2.47                 |
| AlN088         | Si               | 3417            | 0.6772    | 7.100           | 0.03           | 0.033                     | 1310           | 190.00    | 38.78    | 2.71E+12        | 556.04     | 1.90                 |
| AlN089         | Glass            | 4559            | 0.6344    | 3.686           | 0.07           | 0.068                     | 179.6667       | 192.50    | 26.86    | 2.79E+11        | 422.21     | 1.69                 |
| AlN089         | Si               | 3609            | 0.9365    | 12.897          | 0.01           | 0.013                     |                |           | 74.41    | 1.96E+03        | 0.00       | 1.34                 |
| AlN093         | Foil             | 5576            | 0.0343    | 0.860           | 5.73           | 5.396                     | 19296.67       | 198.33    | 7.66     | 2.45E+13        | 355.71     | 3.10                 |
| AlN093         | Glass            | 6386            | 0.0179    | 0.787           | 11.57          | 11.321                    | 274780         | 279.00    | 8.04     | 3.04E+14        | 436.87     | 3.55                 |
| AlN093         | Si               | 5576            | 0.0737    | 0.935           | 3.50           | 2.310                     | 2720           | 265.00    | 8.33     | 3.45E+12        | 475.27     | 3.10                 |
| AlN094         | Foil             | 3849            | 0.0303    | 1.026           | 5.64           | 5.120                     | 58566.67       | 190.00    | 6.31     | 1.08E+14        | 493.67     | 1.43                 |
| AlN094         | Glass            | 4175            | 0.0602    | 1.219           | 2.20           | 2.170                     | 15233.33       | 120.00    | 8.14     | 2.58E+13        | 287.41     | 1.55                 |
| AlN094         | Si               | 3849            | 0.0644    | 1.267           | 2.05           | 1.949                     | 8043.333       | 233.33    | 7.80     | 1.48E+13        | 606.26     | 1.43                 |
| AlN095         | Glass            | 5858            | 0.2040    | 1.120           | 0.74           | 0.697                     | 7537.6         | 216.67    | 10.48    | 9.10E+12        | 369.89     | 2.17                 |
| AlN095         | Si               | 5212            | 0.1376    | 1.141           | 1.02           | 1.014                     | 20275          | 245.00    | 9.50     | 2.75E+13        | 470.04     | 1.93                 |
| AlN096         | Foil             | 3837            | 0.2976    | 0.934           | 0.61           | 0.573                     | 9100           | 85.00     | 5.73     | 1.68E+13        | 221.51     | 1.42                 |
| AlN096         | Glass            | 4189            | 0.4314    | 3.502           | 0.11           | 0.105                     | 2061           | 96.67     | 23.45    | 3.48E+12        | 230.74     | 1.55                 |
| AlN096         | Si               | 3837            | 0.8998    | 10.520          | 0.02           | 0.017                     | 1310           | 170.50    | 64.53    | 2.41E+12        | 444.32     | 1.42                 |
| AlN097         | Foil             | 5051            | 0.0427    | 0.809           | 4.69           | 4.613                     | 58550          | 54.00     | 6.53     | 8.19E+13        | 106.92     | 2.10                 |
| AlN097         | Si               | 5051            | 0.2221    | 1.420           | 0.52           | 0.505                     | 4103.333       | 66.00     | 11.46    | 5.74E+12        | 130.68     | 2.10                 |
| AlN098         | Foil             | 3113            | 0.0726    | 1.272           | 1.73           | 1.724                     | 33300          | 75.00     | 6.33     | 7.56E+13        | 240.90     | 1.30                 |
| AlN098         | Si               | 3113            | 0.4824    | 4.580           | 0.07           | 0.072                     | 6263.333       | 40.00     | 22.79    | 1.42E+13        | 128.48     | 1.30                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>Rp (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|----------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN099         | Glass            | 4963            | 0.0489    | 1.060           | 3.17           | 3.075          | 2746677        | 100.00    | 8.41     | 3.91E+15        | 201.48     | 1.84                 |
| AlN099         | Si               | 5320            | 0.0170    | 0.979           | 9.61           | 9.592          | 4675000        | 0.00      | 8.32     | 6.21E+15        | 0.00       | 1.97                 |
| AlN100         | Glass            | 4417            | 0.0265    | 1.231           | 4.99           | 4.877          | 2275000        | 252.50    | 8.69     | 3.64E+15        | 571.62     | 1.64                 |
| AlN100         | Si               | 4091            | 0.0186    | 1.019           | 8.73           | 8.376          | 7110710        | 288.33    | 6.66     | 1.23E+16        | 704.80     | 1.52                 |
| AlN101         | Glass            | 8023            | 0.0250    | 0.659           | 9.70           | 9.668          | 2259500        | 421.25    | 8.45     | 1.99E+15        | 525.09     | 2.23                 |
| AlN101         | Si               | 9081            | 0.0501    | 0.610           | 5.40           | 5.203          | 956250         | 441.25    | 8.86     | 7.44E+14        | 485.92     | 2.52                 |
| AlN102         | Glass            | 5227            | 0.0256    | 0.823           | 7.77           | 7.555          | 901666.7       | 323.33    | 6.88     | 1.22E+15        | 618.58     | 1.45                 |
| AlN102         | Si               | 6939            | 0.0563    | 0.710           | 4.80           | 3.986          | 5010000        | 326.67    | 7.87     | 5.10E+15        | 470.79     | 1.93                 |
| AlN103         | Foil             | 4181            | 0.0305    | 1.181           | 4.59           | 4.416          |                |           | 7.89     |                 |            | 1.55                 |
| AlN103         | Si               | 4181            | 0.0303    | 1.278           | 4.18           | 4.104          |                |           | 8.54     |                 |            | 1.55                 |
| AlN104         | Foil             | 4456            | 0.0321    | 1.408           | 4.44           | 3.519          |                |           | 10.03    |                 |            | 1.65                 |
| AlN104         | Si               | 4456            | 0.0351    | 1.436           | 3.39           | 3.159          | 4365000        | 167.50    | 10.23    | 6.92E+15        | 375.90     | 1.65                 |
| AlN105         | Glass            | 4598            | 0.0097    | 1.359           | 12.26          | 12.124         | 28809.33       | 48.33     | 9.99     | 4.43E+13        | 105.13     | 1.70                 |
| AlN105         | Si               | 4289            | 0.0105    | 1.400           | 10.85          | 10.819         | 2442588        | 46.25     | 9.60     | 4.03E+15        | 107.83     | 1.59                 |
| AlN106         | Glass            | 3138            | 0.0104    | 2.336           | 6.55           | 6.531          | 233963.3       | 17.50     | 11.72    | 5.27E+14        | 55.78      | 1.16                 |
| AlN106-A       | Glass            | 2237            | 0.0140    | 2.227           | 5.15           | 5.108          | 806133.3       | 36.67     | 7.96     | 2.55E+15        | 163.91     | 0.83                 |
| AlN106         | Si               | 3075            | 0.0107    | 2.500           | 5.08           | 5.927          | 15.915         | 12.50     | 12.29    | 3.66E+10        | 40.65      | 1.14                 |
| AlN107         | Glass            | 5025            | 0.0375    | 1.300           | 3.39           | 3.264          | 18822.25       | 92.50     | 10.45    | 2.65E+13        | 184.08     | 1.40                 |
| AlN107         | Si               | 4287            | 0.0131    | 1.290           | 9.81           | 9.424          | 301166.7       | 70.00     | 8.84     | 4.97E+14        | 163.30     | 1.19                 |
| AlN108         | Glass            | 5010            | 0.0177    | 1.130           | 7.98           | 7.935          | 51875          | 158.33    | 9.05     | 7.32E+13        | 316.02     | 1.39                 |
| AlN109         | Foil             | 2042            | 0.0641    | 3.573           | 0.74           | 0.695          |                |           | 11.66    |                 |            | 0.76                 |
| AlN109-A       | Foil             | 2042            | 0.0114    | 2.927           | 5.16           | 4.779          | 166000         | 25.00     | 9.55     | 5.75E+14        | 122.46     | 0.76                 |
| AlN109         | Si               | 2042            | 0.1071    | 3.910           | 0.39           | 0.380          | 169333.3       | 55.00     | 12.76    | 5.86E+14        | 269.41     | 0.76                 |
| AlN110         | Foil             | 1713            | 0.0078    | 2.466           | 8.33           | 8.310          | 860000.6       | 60.00     | 6.75     | 3.55E+15        | 350.22     | 0.48                 |
| AlN110-A       | Foil             | 1713            | 0.0064    | 2.532           | 9.90           | 9.875          |                |           | 6.94     |                 |            | 0.48                 |
| AlN110         | Si               | 1713            | 0.0113    | 2.804           | 5.11           | 5.022          | 701.25         | 80.00     | 7.68     | 2.89E+12        | 466.96     | 0.48                 |
| AlN111         | Glass            | 3420            | 0.0108    | 1.274           | 15.91          | 11.564         | 177148         | 180.00    | 6.96     | 3.66E+14        | 526.39     | 0.95                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN112         | Glass            | 5094            | 0.0042    | 0.715           | 54.62          | 53.442                    | 382670         | 304.00    | 5.82     | 5.31E+14        | 596.78     | 1.42                 |
| AlN112-A       | Glass            | 5132            | 0.0055    | 0.849           | 37.72          | 34.352                    | 3793333        | 310.00    | 6.97     | 5.22E+15        | 604.03     | 1.43                 |
| AlN113         | Glass            | 13436           | 0.0072    | 0.356           | 59.88          | 61.978                    | 392833.3       | 330.00    | 7.66     | 2.07E+14        | 245.61     | 3.73                 |
| AlN113-A       | Glass            | 13316           | 0.0054    | 0.326           | 91.82          | 89.955                    | 10654750       | 540.00    | 6.94     | 5.66E+15        | 405.53     | 3.70                 |
| AlN114         | Glass            | 3867            | 0.0082    | 1.354           | 12.26          | 14.361                    | 1607667        | 170.00    | 8.37     | 2.94E+15        | 439.65     | 1.29                 |
| AlN114         | Mylar            | 3867            | 0.0060    | 1.323           | 21.49          | 20.132                    | 3462325        | 176.00    | 8.18     | 6.33E+15        | 455.16     | 1.29                 |
| AlN115         | Glass            | 1485            |           |                 |                |                           |                |           |          |                 |            | 0.82                 |
| AlN116         | Glass            | 1141            |           |                 |                |                           |                |           |          |                 |            | 0.25                 |
| AlN117         | Glass            | 980             |           |                 |                |                           |                |           |          |                 |            | 0.22                 |
| AlN118         | Glass            | 3497            | 0.0062    | 1.384           | 25.05          | 18.574                    | 2.61E+05       | 166.67    | 7.73     | 5.28E+14        | 476.63     | 0.65                 |
| AlN119         | Glass            | 7410            | 0.0038    | 0.609           | 63.78          | 69.021                    | 4.52E+06       | 338.00    | 7.22     | 4.31E+15        | 456.14     | 1.37                 |
| AlN120         | Glass            | 3111            | 0.0105    | 1.416           | 10.99          | 10.675                    | 7.40E+04       | 180.00    | 7.04     | 1.68E+14        | 578.67     | 1.08                 |
| AlN121         | Glass            | 5359            | 0.0135    | 1.220           | 10.26          | 9.659                     | 3.20E+05       | 202.50    | 10.45    | 4.22E+14        | 377.90     | 1.86                 |
| AlN122         | Glass            | 4901            | 0.0090    | 1.228           | 14.96          | 14.356                    | 1.30E+05       | 167.50    | 9.62     | 1.88E+14        | 341.77     | 1.70                 |
| AlN123         | Glass            | 4459            | 0.0109    | 1.460           | 10.12          | 10.020                    | 2.54E+05       | 152.86    | 10.41    | 4.03E+14        | 342.81     | 1.55                 |
| AlN124         | Glass            | 5754            | 0.0062    | 1.011           | 25.70          | 25.415                    | 1.72E+06       | 162.00    | 9.30     | 2.11E+15        | 281.53     | 1.60                 |
| AlN125         | Glass            | 6304            | 0.0076    | 0.822           | 25.59          | 25.334                    | 2.30E+05       | 110.00    | 8.29     | 2.58E+14        | 174.50     | 1.75                 |
| AlN126         | Glass            | 4463            | 0.0205    | 1.470           | 6.20           | 5.283                     | 8.67E+05       | 230.00    | 10.48    | 1.37E+15        | 515.38     | 1.24                 |
| AlN127         | Glass            | 3724            | 0.0161    | 1.438           | 7.02           | 6.871                     | 3.75E+05       | 140.00    | 8.56     | 7.11E+14        | 375.92     | 1.03                 |
| AlN128         | Glass            | 2561            | 0.0040    | 2.082           | 19.71          | 19.149                    | 5.43E+05       | 155.00    | 8.52     | 1.50E+15        | 605.35     | 0.47                 |
| AlN129         | Glass            | 2704            | 0.0072    | 2.090           | 10.73          | 10.644                    | 1.06E+06       | 141.67    | 9.03     | 2.78E+15        | 523.95     | 0.50                 |
| AlN130         | Glass            | 2672            | 0.0040    | 1.361           | 29.56          | 29.257                    | 1.68E+06       | 142.14    | 5.81     | 4.45E+15        | 531.93     | 0.37                 |
| AlN131         | Glass            | 3281            | 0.0052    | 1.432           | 22.78          | 21.424                    | 1.12E+06       | 194.38    | 7.51     | 2.41E+15        | 592.46     | 0.46                 |
| AlN132         | Glass            | 2533            | 0.0039    | 1.941           | 19.23          | 20.858                    | 1.82E+05       | 146.67    | 7.86     | 5.08E+14        | 579.02     | 0.35                 |
| AlN133         | Glass            | 1882            | 0.0087    | 3.011           | 6.46           | 6.080                     | 2.35E+05       | 93.57     | 9.06     | 8.83E+14        | 497.24     | 0.26                 |
| AlN134         | Glass            | 2950            | 0.0042    | 1.321           | 30.49          | 28.878                    | 1.27E+06       | 170.00    | 6.23     | 3.04E+15        | 576.22     | 0.55                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (A/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN135         | Glass            | 2612            | 0.0154    | 1.533           | 9.31           | 6.755                     | 1.34E+05       | 90.00     | 6.40     | 3.63E+14        | 344.63     | 0.48                 |
| AlN136         | Glass            | 4576            | 0.0176    | 0.997           | 14.11          | 9.078                     | 1.20E+06       | 192.00    | 7.29     | 1.85E+15        | 419.63     | 0.85                 |
| AlN137         | Glass            | 4313            | 0.0635    | 1.680           | 1.92           | 1.492                     | 4.42E+01       | 193.33    | 11.58    | 7.24E+10        | 448.26     | 0.80                 |
| AlN138         | Glass            | 3981            | 0.0047    | 1.191           | 28.82          | 28.325                    | 1.17E+06       | 206.67    | 7.58     | 2.07E+15        | 519.13     | 0.63                 |
| AlN139         | Glass            | 4487            | 0.0100    | 0.957           | 40.27          | 16.606                    | 3.94E+05       | 216.67    | 6.86     | 6.20E+14        | 482.85     | 0.71                 |
| AlN140         | Glass            | 3389            | 0.0051    | 1.256           | 44.41          | 24.965                    | 2.91E+06       | 160.00    | 6.81     | 6.06E+15        | 472.12     | 0.54                 |
| AlN141         | Glass            | 2928            | 0.0106    | 1.541           | 10.28          | 9.753                     | 1.45E+06       |           | 7.21     | 3.50E+15        |            | 0.46                 |
| AlN142         | Glass            | 6527            | 0.0080    | 0.692           | 29.92          | 28.906                    | 3.67E+05       | 156.67    | 7.22     | 3.97E+14        | 240.01     | 0.91                 |
| AlN143         | Glass            | 5933            | 0.0210    | 0.760           | 11.78          | 9.952                     | 3.91E+05       | 180.00    | 7.21     | 4.66E+14        | 303.38     | 0.82                 |
| AlN146         | Glass            | 5198            | 0.0048    | 1.185           | 28.92          | 27.756                    | 1.48E+06       | 218.33    | 9.85     | 2.01E+15        | 420.07     | 0.83                 |
| AlN147         | Glass            | 3629            | 0.0101    | 1.252           | 16.23          | 12.631                    | 2.02E+06       | 166.00    | 7.26     | 3.94E+15        | 457.46     | 0.58                 |
| AlN148         | Glass            | 5142            | 0.0036    | 1.081           | 41.85          | 41.220                    | 6.08E+05       | 291.00    | 8.89     | 8.36E+14        | 565.91     | 0.82                 |
| AlN149         | Glass            | 5103            | 0.0037    | 1.017           | 41.82          | 42.133                    | 9.78E+05       | 294.00    | 8.29     | 1.35E+15        | 576.11     | 0.81                 |
| AlN150         | Polyester        | Mylar burned    |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN151         | Foil             | 5125            | 0.0043    | 1.257           | 29.19          | 29.206                    | 1.00E-06       | 1.00      | 10.30    | 1.38E+03        | 1.95       | 0.81                 |
| AlN152         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN153         | Glass            | 1986            | 0.0153    | 4.004           | 2.67           | 2.606                     | 9.75E+04       | 60.00     | 12.71    | 3.47E+14        | 302.14     | 0.83                 |
| AlN154         | Glass            | 3330            | 0.0075    | 2.082           | 10.43          | 10.195                    | 9.89E+03       | 114.17    | 11.08    | 2.10E+13        | 342.88     | 0.92                 |
| AlN155         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN156         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN157         | Glass            | 732             | 0.0855    | 12.525          | 0.17           | 0.149                     | 3.34E+01       | 23.71     | 14.66    | 3.22E+11        | 323.86     | 1.22                 |
| AlN158         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN159         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN160         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AlN161         | Glass            | 3499            | 0.0053    | 1.347           | 22.37          | 22.299                    | 1.64E+06       | 190.00    | 7.53     | 3.31E+15        | 543.08     | 0.45                 |
| AlN162         | Polyester        | 4686            | 0.0026    | 1.003           | 62.13          | 60.166                    | 9.98E+05       | 170.00    | 7.51     | 1.50E+15        | 362.76     | 0.52                 |
| AlN163         | Glass            | 4686            | 0.0061    | 0.853           |                |                           |                |           |          |                 |            |                      |
| AlN164         | Foil             | 6396            | 0.0293    | 1.338           |                |                           |                |           |          |                 |            |                      |
| AlN165         | Foil             | 6396            | 0.0137    | 1.604           | 7.53           | 7.261                     | 6.91E+04       | 76.67     | 16.39    | 7.64E+13        | 119.87     | 0.82                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>R<sub>p</sub> (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|---------------------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AIN166         | Polyester        | 5166            |           |                 |                |                           |                |           |          |                 |            |                      |
| AIN167         | Polyester        |                 |           |                 |                |                           |                |           |          |                 |            |                      |
| AIN168         | Polyester        | 4182            | 0.0354    | 1.500           | 5.04           | 3.000                     | 6.01E+02       | 10.00     | 10.03    | 1.02E+12        | 23.91      | 0.82                 |
| AIN169         | Polyester        | 4182            |           |                 |                |                           |                |           |          |                 |            | 0.82                 |
| AIN174         | Glass            | 10000           | 0.0766    | 1.652           | 1.99           | 1.258                     |                |           | 26.42    |                 |            | 1.39                 |
| AIN175         | FPE              | 4920            | 0.0134    | 1.494           | 8.28           | 7.973                     |                |           | 11.75    |                 |            | 0.82                 |
| AIN176         | FPE              | 4920            | 0.0131    | 1.331           | 8.97           | 9.111                     | 1.88E+06       | 10.00     | 10.47    | 2.70E+15        | 20.33      | 0.82                 |
| AIN177         | FPE              | 3474            | 0.0126    | 1.404           | 9.34           | 8.999                     | 0.00E+00       | 0.00      | 7.79     | 0.00E+00        | 0.00       | 0.77                 |
| AIN177         | Glass            | 3474            | 0.0149    | 1.434           | 7.49           | 7.467                     | 1.14E+05       | 110.00    | 7.97     | 2.31E+14        | 316.62     | 0.77                 |
| AIN178         | FPE              | 3474            | 0.0138    | 1.449           | 8.32           | 7.984                     | 1.07E+06       | 101.67    | 8.05     | 2.18E+15        | 292.63     | 0.77                 |
| AIN178         | Glass            | 3474            | 0.0066    | 1.527           | 16.93          | 15.744                    | 7.65E+04       | 80.00     | 8.48     | 1.56E+14        | 230.27     | 0.77                 |
| AIN179         | FPE              | 5320            | 0.0069    | 1.277           | 14.93          | 18.029                    | 5.92E+05       | 228.33    | 10.86    | 7.86E+14        | 429.20     | 0.89                 |
| AIN179         | Glass            | 5320            | 0.0276    | 1.397           | 4.59           | 4.136                     | 4.94E+03       | 203.75    | 11.88    | 6.56E+12        | 383.01     | 0.89                 |
| AIN180         | FPE              | 4612            | 0.0079    | 1.397           | 11.10          | 14.451                    | 9.27E+04       | 140.00    | 10.30    | 1.42E+14        | 303.56     | 0.77                 |
| AIN180         | Glass            | 4612            | 0.0080    | 1.438           | 13.97          | 13.828                    | 2.57E+05       | 165.00    | 10.60    | 3.93E+14        | 357.76     | 0.77                 |
| AIN181         | FPE              | 4920            | 0.0074    | 1.397           | 16.35          | 15.383                    | 2.12E+05       | 145.00    | 10.99    | 3.04E+14        | 294.72     | 0.82                 |
| AIN181         | Foil             | 4920            | 0.0060    | 1.309           | 20.45          | 20.176                    | 4.42E+05       | 181.67    | 10.30    | 6.35E+14        | 369.24     | 0.82                 |
| AIN182         | FPE              | 4920            | 0.0125    | 1.329           | 9.82           | 9.611                     | 1.15E+06       | 156.67    | 10.45    | 1.65E+15        | 318.43     | 0.82                 |
| AIN182         | Foil             | 4920            | 0.0114    | 1.341           | 10.69          | 10.434                    | 1.01E+05       | 186.67    | 10.55    | 1.45E+14        | 379.40     | 0.82                 |
| AIN196         | Glass            | 2330            | 0.0569    | 3.288           | 0.88           | 0.851                     |                |           | 12.25    |                 |            | 0.65                 |
| AIN197         | Glass            | 2205            | 0.0318    | 2.879           | 1.77           | 1.737                     |                |           | 10.15    |                 |            | 0.61                 |
| AIN198         | Glass            | 4011            | 0.0042    | 1.605           | 23.44          | 23.389                    |                |           | 10.29    |                 |            | 0.67                 |
| AIN199         | Glass            | 3766            | 0.0040    | 1.421           | 28.07          | 27.937                    |                |           | 8.55     |                 |            | 0.63                 |
| AIN200         | S.S.             | 4000            |           |                 |                |                           |                |           |          |                 |            | 0.67                 |
| AIN201         | Ti               | 4000            |           |                 |                |                           |                |           |          |                 |            | 0.67                 |
| AIN202         | S.S.             | 3698            | 0.0054    | 1.253           | 24.65          | 23.382                    |                |           | 7.41     |                 |            | 0.62                 |
| AIN203         | Ti               | 3698            | 0.0040    | 1.279           | 32.54          | 31.096                    |                |           | 7.56     |                 |            | 0.62                 |
| AIN204         | Glass            | 5033            | 0.0054    | 1.147           | 27.70          | 25.600                    | 1.01E+05       | 130.00    | 9.23     | 1.42E+14        | 258.30     | 0.84                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>Rp (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|----------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AIN205         | Glass            | 4737            | 0.0059    | 1.098           | 24.71          | 24.403         | 2.19E+05       | 213.33    | 8.32     | 3.27E+14        | 450.38     | 0.79                 |
| AIN206         | S.S.             | 3698            | 0.0054    | 1.668           | 17.76          | 17.606         | 1.87E+07       | 40.00     | 9.00     | 3.57E+16        | 118.53     | 1.03                 |
| AIN207         | Ti               | 3401            | 0.0062    | 1.655           | 15.63          | 15.596         | short          |           | 9.00     | short           |            | 0.94                 |
| AIN208         | Glass            | 3471            | 0.0053    | 1.683           | 18.06          | 17.919         | 2.39E+05       | 133.33    | 9.34     | 4.86E+14        | 384.14     | 0.58                 |
| AIN209         | Glass            | 6162            | 0.0097    | 0.818           | 20.76          | 20.093         | 1.44E+06       | 252.00    | 8.06     | 1.65E+15        | 408.99     | 1.03                 |
| AIN210         | Glass            | 6318            | 0.0063    | 0.881           | 28.93          | 28.663         | 2.44E+05       | 133.33    | 8.90     | 2.73E+14        | 211.03     | 0.92                 |
| AIN211         | Glass            | 6710            | 0.0657    | 0.858           | 2.98           | 2.823          | 1.79E+03       | 180.00    | 9.20     | 1.88E+12        | 268.25     | 1.07                 |
| AIN214         | Glass            | 5249            | 0.0131    | 1.370           | 9.89           | 8.857          | 9.43E+02       | 86.67     | 11.49    | 1.27E+12        | 165.12     | 0.87                 |
| AIN215         | Glass            | 6471            | 0.0371    | 1.060           | 4.09           | 4.047          | 2.07E+03       | 80.00     | 10.97    | 2.26E+12        | 123.62     | 1.27                 |
| AIN216         | Glass            | 3426            | 0.0052    | 1.525           | 20.10          | 19.892         | 4.59E+04       | 155.71    | 8.35     | 9.48E+13        | 454.57     | 0.57                 |
| AIN217         | Glass            | 5764            | 0.0246    | 1.041           | 6.29           | 6.201          | 2.81E+04       | 160.00    | 9.60     | 3.45E+13        | 277.57     | 1.20                 |
| AIN218         | Glass            | 5532            | 0.0034    | 1.048           | 44.25          | 44.177         | 2.24E+05       | 132.50    | 9.27     | 2.86E+14        | 239.54     | 0.92                 |
| AIN219         | SS               | 5532            |           |                 |                |                |                |           |          |                 |            | 0.92                 |
| AIN220         | Glass            | 4182            | 0.0043    | 1.285           | 29.42          | 28.967         | 4.71E+04       | 210.00    | 8.59     | 7.96E+13        | 502.15     | 0.77                 |
| AIN222         | Glass            | 6017            | 0.1454    | 0.986           | 1.71           | 1.110          |                |           | 9.49     |                 |            | 1.00                 |
| AIN223         | Glass            | 3947            |           |                 |                |                |                |           |          |                 |            | 0.66                 |
| AIN224         | Ti               | 4055            | 0.0048    | 1.311           | 26.32          | 25.346         | 3.77E+06       | 140.00    | 8.50     | 6.57E+15        | 345.23     | 0.75                 |
| AIN225         | S.S              | 3647            | 0.0048    | 1.458           | 22.82          | 22.580         | 2.14E+06       | 202.00    | 8.50     | 4.15E+15        | 553.90     | 0.68                 |
| AIN226         | Glass            | 4183            | 0.0075    | 1.299           | 16.47          | 16.304         | 1.46E+03       | 162.50    | 8.68     | 2.47E+12        | 388.51     | 0.77                 |
| AIN227         | Glass            | 3768            | 0.0047    | 1.305           | 26.48          | 26.158         |                |           | 7.86     |                 |            | 0.70                 |
| AIN228         | Glass            | 5384            | 0.0051    | 0.957           | 34.22          | 32.343         | 5.70E+04       | 185.00    | 8.23     | 7.48E+13        | 343.63     | 0.90                 |
| AIN229         | Glass            | 4532            | 0.0067    | 1.140           | 22.38          | 20.832         | 5.98E+03       | 156.67    | 8.26     | 9.32E+12        | 345.67     | 0.76                 |
| AIN230         | S.S              | 4157            | 0.0057    | 1.279           | 22.30          | 21.944         | 1.67E+06       | 186.00    | 8.50     | 2.84E+15        | 447.45     | 0.69                 |
| AIN231         | S.S              | 3816            | 0.0056    | 1.394           | 20.91          | 20.309         | 6.58E+05       | 170.00    | 8.50     | 1.22E+15        | 445.55     | 0.64                 |
| AIN232         | Glass            | 4709            | 0.0053    | 1.121           | 27.04          | 26.875         | 1.43E+05       | 130.00    | 8.44     | 2.15E+14        | 276.07     | 0.78                 |
| AIN233         | Glass            | 4555            | 0.0058    | 1.206           | 23.13          | 22.942         | 2.67E+04       | 158.00    | 8.78     | 4.14E+13        | 346.87     | 0.76                 |

Table B-1. Dielectric Properties of AlN Films (continued)

| <u>Sample#</u> | <u>Substrate</u> | <u>Film (Å)</u> | <u>Df</u> | <u>Cap (nF)</u> | <u>Rp (MΩ)</u> | <u>Rp (MΩ)</u> | <u>IR (MΩ)</u> | <u>HV</u> | <u>k</u> | <u>ρ (Ω-cm)</u> | <u>V/μ</u> | <u>DepRate (Å/s)</u> |
|----------------|------------------|-----------------|-----------|-----------------|----------------|----------------|----------------|-----------|----------|-----------------|------------|----------------------|
| AlN234         | S.S              | 4834            |           |                 |                |                |                |           |          |                 |            |                      |
| AlN235         | S.S              | 4496            |           |                 |                |                |                |           |          |                 |            |                      |
| AlN236         | FPE              | 5209            | 0.0061    | 1.081           | 24.41          | 24.035         | 2.22E+06       | 235.00    | 9.00     | 3.01E+15        | 451.16     | 0.87                 |
| AlN237         | FPE              | 4847            | 0.0058    | 1.162           | 23.72          | 23.559         | 4.33E+05       | 250.00    | 9.00     | 6.32E+14        | 515.82     | 0.81                 |
| AlN238         | Glass            | 4386            | 0.0052    | 1.231           | 24.68          | 24.786         | 7.86E+05       | 238.00    | 8.63     | 1.27E+15        | 542.68     | 0.73                 |
| AlN239         | Glass            | 4268            | 0.0048    | 1.327           | 26.55          | 24.837         | 2.59E+06       | 267.50    | 9.05     | 4.29E+15        | 626.83     | 0.71                 |

## APPENDIX C

Table C-1. AION Deposition Conditions Using N<sub>2</sub>/O<sub>2</sub>

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :O <sub>2</sub> :Ar | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN245  | 30-120       | 11.5             | 1.50         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN246  | 30-120       | 11.5             | 2.00         | 1      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN247  | 30-120       | 11.5             | 2.00         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN248  | 30-120       | 11.5             | 2.00         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN249  | 30-120       | 11.5             | 2.00         | 1      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN250  | 30-120       | 11.5             | 2.00         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN251  | 30-120       | 11.5             | 2.00         | 3      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN252  | 30-120       | 11.5             | 2.00         | 3      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN254  | 30-120       | 11.5             | 1.50         |        | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN255  | 30-120       | 11.5             | 1.00         | 1      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN256  | 30-120       | 11.5             | 1.00         | 3      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN257  | 30-120       | 11.5             | 2.00         | 4      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN258  | 30-120       | 11.5             | 2.00         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN259  | 30-120       | 11.5             | 2.00         | 1      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN260  | 30-120       | 11.5             | 2.00         | 2      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN261  | 30-120       | 11.5             | 2.00         | 6      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN262  | 30-120       | 11.5             | 2.00         | 8      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN263  | 30-120       | 11.5             | 2.00         | 4      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN264  | 30-120       | 11.5             | 2.00         | 7      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN265  | 30-120       | 11.5             | 2.00         | 8      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN266  | 30-120       | 11.5             | 2.00         | 3      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN267  | 30-120       | 11.5             | 2.00         | 4      | Al    | N  | 7:1:0  | 850          | 50              | 5               |
| AIN268  | 30-120       | 11.5             | 2.00         | 8      | Al    | N  | 7:1:0  | 850          | 50              | 5               |

Table C-2. AlON Deposition Conditions Using N<sub>2</sub>O

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN270  | 30-120       | 10.0             | 1.50         | 1      | Al    | N  | 9:1  | 500          | 50              | 5               |
| AIN271  | 30-120       | 5.0              | 1.50         | 1      | Al    | N  | 9:1  | 1000         | 150             | 5               |
| AIN272  | 30-120       | 15.0             | 1.50         | 1      | Al    | N  | 1:1  | 1000         | 50              | 5               |
| AIN273  | 30-120       | 10.0             | 1.50         | 1      | Al    | N  | 0:1  | 1000         | 250             | 5               |
| AIN274  | 30-120       | 15.0             | 1.00         | 1      | Al    | N  | 9:1  | 1500         | 250             | 5               |
| AIN275  | 30-120       | 15.0             | 1.25         | 1      | Al    | N  | 0:1  | 500          | 150             | 5               |
| AIN276  | 30-120       | 5.0              | 1.67         | 1      | Al    | N  | 1:1  | 500          | 250             | 5               |
| AIN277  | 30-120       | 5.0              | 1.25         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN278  | 30-120       | 10.0             | 1.25         | 1      | Al    | N  | 1:1  | 1500         | 150             | 5               |
| AIN279  | 30-120       | 15.0             | 1.50         | 1      | Al    | N  | 1:1  | 1000         | 50              | 5               |
| AIN280  | 30-120       | 10.0             | 1.50         | 1      | Al    | N  | 0:1  | 1000         | 250             | 5               |
| AIN281  | 30-120       | 5.0              | 2.33         | 1      | Al    | N  | 1:1  | 500          | 250             | 5               |
| AIN282  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN285  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN286  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN287  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN288  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN289  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN290  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1000         | 50              | 5               |
| AIN291  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1000         | 50              | 5               |
| AIN293  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN294  | 30-120       | 5.0              | 0.80         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN295  | 30-120       | 5.0              | 0.80         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN296  | 30-120       | 5.0              | 0.80         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN297  | 30-120       | 5.0              | 0.80         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN298  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN299  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN300  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |

Table C-2. AlON Deposition Conditions Using N<sub>2</sub>O (continued)

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN301  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN302  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN303  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN304  | 30-120       | 10.0             | 0.58         | 1      | Al    | N  | 1:1  | 1500         | 50              | 5               |
| AIN305  | 30-120       | 10.0             | 0.58         | 1      | Al    | N  | 1:1  | 1500         | 50              | 5               |
| AIN306  | 30-120       | 10.0             | 0.58         | 1      | Al    | N  | 1:1  | 1500         | 50              | 5               |
| AIN307  | 30-120       | 10.0             | 0.58         | 1      | Al    | N  | 1:1  | 1500         | 50              | 5               |
| AIN308  | 30-120       | 10.0             | 0.67         | 1      | Al    | N  | 1:1  | 1500         | 50              | 5               |
| AIN309A | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN309B | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN310  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN311  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN314  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN315  | 30-120       | 5.0              | 0.75         | 2      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN316  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN317  | 30-120       | 5.0              | 0.75         | 2      | Al    | N  | 0:1  | 1500         | 50              | 5               |
| AIN318  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN319  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN320  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN321  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN322  | 30-120       | 5.0              | 0.75         | 3      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN323  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN324  | 30-120       | 5.0              | 0.75         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN325  | 30-120       | 5.0              | 0.75         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN326  | 30-120       | 5.0              | 0.75         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |

Table C-2. AlON Deposition Conditions Using N<sub>2</sub>O (continued)

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN327  | 30-120       | 5.0              | 0.83         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN328  | 30-120       | 5.0              | 0.92         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN329  | 30-120       | 5.0              | 0.92         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN330  | 30-120       | 5.0              | 0.92         | 4      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN331  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN332  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN333  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN334  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN335  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN336  | 30-120       | 5.0              | 0.92         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN337  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN338  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN339  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN340  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN341  | 30-120       | 5.0              | 0.92         | 2      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN342  | 30-120       | 5.0              | 0.95         | 2      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN343  | 30-120       | 5.0              | 0.92         | 3      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN344  | 30-120       | 5.0              | 0.92         | 3      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN345  | 30-120       | 5.0              | 0.92         | 1      | AL    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN346  | 30-120       | 5.0              | 0.92         | 2      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN347  | 30-120       | 5.0              | 0.92         | 2      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN348  | 30-120       | 5.0              | 0.92         | 2      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN349  | 30-120       | 5.0              | 1.50         | 2      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN350  | 30-120       | 5.0              | 0.92         | 2      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN351  | 30-120       | 5.0              | 0.92         | 2      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN353  | 30-120       | 5.0              | 0.92         | 1      | Ti    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN354  | 30-120       | 5.0              | 0.92         | 2      | Ti    | N  | 0:1  | 1500         | 50              | 4               |
| AIN355  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |

Table C-2. AlON Deposition Conditions Using N<sub>2</sub>O (continued)

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN356  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN357  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN358  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN359  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN360  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN361  | 30-120       | 5.0              | 0.45         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN362  | 30-120       | 5.0              | 0.45         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN363  | 30-120       | 5.0              | 0.45         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN364  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN365  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN366  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN367  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN368  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN369  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN370  | 30-120       | 5.0              | 0.92         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN371  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN372  | 30-120       | 5.0              | 1.83         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN373  | 30-120       | 5.0              | 1.33         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN374  | 30-120       | 5.0              | 0.67         | 1      | Al    | Y  | 0:1  | 1500         | 50              | 4               |
| AIN375  | 30-120       | 5.0              | 1.33         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN376  | 30-120       | 5.0              | 1.33         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN377  | 30-120       | 5.0              | 1.33         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN378  | 30-120       | 5.0              | 1.33         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN379  | 30-120       | 5.0              | 1.00         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN380  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN381  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN382  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN383  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN384  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN385  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |

Table C-2. AlON Deposition Conditions Using N2O (continued)

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN386  | 30-120       | 5.0              | 0.50         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN387  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN388  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN389  | 30-120       | 5.0              | 0.67         | 2      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN390  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN391  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN392  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN393  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN394  | 30-120       | 5.0              | 0.50         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN395  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN396  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN397  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN398  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN399  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN400  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN401  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN405  | 30-120       | 5.0              | 0.55         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN406  | 30-120       | 5.0              | 0.50         | 1      | Al    | N  | 0:1  | 1500         | 50              | 1.75            |
| AIN407  | 30-120       | 5.0              | 0.67         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN408  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN409  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN410  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN411  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN412  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN413  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |

Table C-2. AlON Deposition Conditions Using N<sub>2</sub>O (continued)

| Sample# | DepTemp (°C) | DepPress (mTorr) | DepTime (hr) | Layers | Metal | HE | Gas ambient N <sub>2</sub> :N <sub>2</sub> O | DC power (W) | Frequency (kHz) | Distance (inch) |
|---------|--------------|------------------|--------------|--------|-------|----|--|--------------|-----------------|-----------------|
| AIN414  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN415  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN416  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN417  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN418  | 30-120       | 5.0              | 0.92         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN419  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN421  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN422  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN423  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 3               |
| AIN424  | 30-120       | 5.0              | 0.92         | 4      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN425  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN426  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN427  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN428  | 30-120       | 5.0              | 0.92         | 10     | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN429  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN430  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN431  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN432  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN433  | 30-120       | 5.0              | 0.92         | 1      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN434  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN435  | 30-120       | 5.0              | 0.92         | 5      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN436  | 30-120       | 5.0              | 0.92         | 10     | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN442  | 30-120       | 5.0              | 0.92         | 2      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN443  | 30-120       | 5.0              | 0.92         | 3      | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN444  | 30-120       | 5.0              | 0.92         | 10     | Al    | N  | 0:1  | 1500         | 50              | 4               |
| AIN445  | 30-120       | 5.0              | 0.92         | 10     | Al    | N  | 0:1  | 1500         | 50              | 4               |

## APPENDIX D

Table D-1. Dielectric and Electrical Properties

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV     | k     | ρ(Ω-cm□) | V/μm   | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|--------|-------|----------|--------|---------------|
| AlN245  | Glass     | 4320     | 2      |        |          |                     |                     |          |        |       |          |        | 0.80          |
| AlN246  | Glass     | 5760     | 1      | 0.0138 | 2.994    | 3.85                | 3.848               | 1.17E+06 | 355.00 | 10.82 | 3.66E+15 | 616.32 | 0.80          |
| AlN247  | Glass     | 5760     | 2      | 0.0546 | 8.486    | 0.34                | 0.344               |          |        | 10.23 |          |        | 0.80          |
| AlN248  | Glass     | 5760     | 2      | 0.0557 | 7.068    | 0.40                | 0.404               |          |        | 8.52  |          |        | 0.80          |
| AlN249  | Glass     | 5760     | 1      |        |          |                     |                     |          |        |       |          |        | 0.80          |
| AlN250  | Glass     | 5760     | 2      | 0.0689 | 8.627    | 0.27                | 0.268               |          |        | 10.03 |          |        | 0.80          |
| AlN251  | Glass     | 5760     | 3      | 0.0127 | 7.788    | 1.59                | 1.609               |          |        | 10.76 |          |        | 0.80          |
| AlN252  | Glass     | 5760     | 3      | 0.0083 | 14.326   | 1.34                | 1.335               |          |        | 11.95 |          |        | 0.80          |
| AlN254  | Glass     | 4556     |        |        |          |                     |                     |          | 276.67 |       |          | 607.26 | 0.84          |
| AlN255  | Glass     | 2880     | 1      |        |          |                     |                     |          |        |       |          |        | 0.80          |
| AlN256  | Glass     | 2880     | 3      |        |          |                     |                     |          |        |       |          |        | 0.80          |
| AlN257  | Glass     | 5760     | 4      | 0.0591 | 14.322   | 0.19                | 0.188               |          |        | 11.10 |          |        | 0.80          |
| AlN258  | Glass     | 5760     | 2      | 0.0433 | 14.461   | 0.26                | 0.254               |          |        | 13.45 |          |        | 0.80          |
| AlN259  | Glass     | 5760     | 1      | 0.0124 | 1.753    | 7.35                | 7.344               |          |        | 12.54 |          |        | 0.80          |
| AlN260  | Glass     | 5760     | 2      | 0.0110 | 3.985    | 3.62                | 3.623               |          |        | 8.64  |          |        | 0.80          |
| AlN261  | Glass     | 5760     | 6      | 0.0188 | 23.831   | 0.36                | 0.356               |          |        | 11.75 |          |        | 0.80          |
| AlN262  | Glass     | 5760     | 8      |        |          |                     |                     |          |        |       |          |        | 0.80          |
| AlN263  | Glass     | 5760     | 4      | 0.0294 | 8.563    | 0.63                | 0.633               |          |        | 9.95  |          |        | 0.80          |
| AlN264  | Glass     | 5760     | 7      | 0.0473 | 26.233   | 0.14                | 0.128               |          |        | 11.61 |          |        | 0.80          |
| AlN265  | Glass     | 5760     | 8      | 0.1478 | 39.095   | 0.03                | 0.028               |          |        | 12.23 |          |        | 0.80          |
| AlN266  | Glass     | 5760     | 3      | 0.1478 | 39.095   | 0.03                | 0.028               |          |        | 12.23 |          |        | 0.80          |
| AlN267  | Glass     | 5760     | 4      | 0.0000 | 0.000    | 0.00                |                     |          |        | 0.00  |          |        | 0.80          |
| AlN268  | Glass     | 5760     | 8      | 0.0271 | 24.358   | 0.24                | 0.241               | 2.17E+05 | 270.00 | 11.32 | 5.28E+15 | 468.75 | 0.80          |
| AlN270  | Glass     | 5760     | 1      | 0.0902 | 91.921   | 0.24                | 0.019               |          |        | 16.62 |          |        | 0.80          |
| AlN271  | Glass     | 7009     | 1      | 0.0121 | 0.823    | 16.10               | 15.924              | 2.57E+04 | 80.00  | 9.23  | 2.59E+13 | 114.15 | 1.30          |
| AlN272  | Glass     | 5409     | 1      | 0.0077 | 0.977    | 21.46               | 21.189              | 1.99E+05 | 215.00 | 8.45  | 2.59E+14 | 397.52 | 1.00          |
| AlN273  | Glass     |          | 1      |        |          |                     |                     |          |        |       |          |        |               |
| AlN274  | Glass     |          | 1      |        |          |                     |                     |          |        |       |          |        |               |
| AlN275  | Glass     | 4181     | 1      | 0.0073 | 1.157    | 18.95               | 18.785              | 1.38E+05 | 175.00 | 7.73  | 2.34E+14 | 418.60 | 1.16          |
| AlN276  | Glass     | 1500     | 1      | 0.0091 | 4.106    | 4.25                | 4.243               | 2.68E+04 | 10.00  | 9.85  | 1.26E+14 | 66.67  | 0.33          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV     | k    | ρ(Ω-cm□) | V/μm   | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|--------|------|----------|--------|---------------|
| AIN277  | Glass     | 1762     | 1      | 0.0641 | 3.272    | 0.76                | 0.759               | 0.00E+00 | 0.00   | 9.21 | 0.00E+00 | 0.00   | 0.29          |
| AIN278  | Glass     | 8278     | 1      | 0.0267 | 0.574    | 10.53               | 10.401              | 0.00E+00 | 0.00   | 7.59 | 0.00E+00 | 0.00   | 1.84          |
| AIN279  | Si        | 10853    | 1      | 0.0038 | 0.411    | 103.09              | 102.571             | 5.89E+05 | 437.50 | 7.12 | 3.83E+14 | 403.11 | 2.41          |
| AIN280  | Si        | 4932     | 1      |        |          |                     |                     |          |        |      |          |        | 0.91          |
| AIN281  | Si        | 4104     | 1      | 0.0134 | 1.333    | 8.99                | 8.910               | 1.53E+06 | 143.33 | 8.75 | 2.64E+15 | 349.25 | 0.76          |
| AIN282  | Si        | 2180     | 1      | 0.0115 | 2.673    | 5.27                | 5.198               | 2.04E+05 | 100.00 | 9.31 | 6.62E+14 | 458.77 | 0.26          |
| AIN285  | Glass     | 6027     | 1      | 0.0032 | 0.755    | 65.55               | 65.426              | 9.65E+05 | 375.00 | 7.27 | 1.13E+15 | 622.17 | 1.67          |
| AIN286  | Glass     | 2672     | 1      | 0.0056 | 1.924    | 14.84               | 14.802              | 2.29E+06 | 77.50  | 8.22 | 6.04E+15 | 290.02 | 0.89          |
| AIN287  | Glass     | 7708     | 1      | 0.0042 | 0.601    | 65.53               | 63.427              | 3.53E+05 | 353.33 | 7.40 | 3.24E+14 | 458.40 | 2.57          |
| AIN288  | Glass     | 2416     | 1      | 0.0077 | 2.551    | 7.80                | 8.061               |          |        | 9.85 |          |        | 0.81          |
| AIN289  | Glass     | 2315     | 1      | 0.0065 | 2.154    | 11.53               | 11.456              | 6.16E+03 | 50.00  | 7.97 | 1.88E+13 | 215.95 | 0.77          |
| AIN290  | Glass     |          | 1      |        |          |                     |                     |          |        |      |          |        |               |
| AIN291  | Glass     | 1818     | 1      |        |          |                     |                     |          |        |      |          |        | 0.50          |
| AIN293  | Glass     | 5492     | 1      |        |          |                     |                     |          |        |      |          |        | 1.53          |
| AIN294  | Glass     | 3840     | 1      |        |          |                     |                     |          |        |      |          |        | 1.28          |
| AIN295  | Glass     | 3113     | 1      |        |          |                     |                     |          |        |      |          |        | 1.08          |
| AIN296  | Glass,Si  | 2802     | 1      |        |          |                     |                     |          |        |      |          |        | 0.97          |
| AIN297  | Glass,Si  | 3993     | 1      |        |          |                     |                     |          |        |      |          |        | 1.39          |
| AIN298  | Oxide     | 3094     | 1      | 0.0067 | 1.717    | 13.88               | 13.748              | 1.33E+06 | 110.00 | 8.49 | 3.04E+15 | 355.53 | 0.86          |
| AIN299  | Oxide     | 5154     | 1      | 0.0058 | 1.053    | 26.53               | 26.155              | 1.98E+06 | 270.00 | 8.68 | 2.72E+15 | 523.84 | 1.43          |
| AIN300  | Oxide     | 3734     | 1      | 0.0069 | 1.628    | 14.20               | 14.141              |          |        | 9.72 |          |        | 1.04          |
| AIN301  | Oxide     | 5979     | 1      | 0.0063 | 1.004    | 25.46               | 25.284              | 1.43E+06 | 184.00 | 9.59 | 1.69E+15 | 307.73 | 1.66          |
| AIN302  | Oxide     | 3504     | 1      |        |          |                     |                     |          |        |      |          |        | 1.06          |
| AIN303  | Oxide     | 5519     | 1      | 0.0062 | 1.034    | 24.79               | 24.746              | 5.25E+06 | 147.50 | 9.12 | 6.72E+15 | 267.26 | 1.67          |
| AIN304  | Si        | 4085     | 1      | 0.0030 | 1.287    | 41.39               | 41.281              | 2.34E+06 | 160.00 | 8.41 | 4.04E+15 | 391.69 | 1.95          |
| AIN305  | Si        |          | 1      |        |          |                     |                     |          |        |      |          |        |               |
| AIN306  | Si        | 4313     | 1      | 0.0070 | 1.192    | 19.32               | 19.150              | 3.08E+06 | 160.00 | 8.22 | 5.05E+15 | 370.99 | 2.05          |
| AIN307  | Si        |          | 1      |        |          |                     |                     |          |        |      |          |        |               |
| AIN308  | Si        | 4483     | 1      | 0.0086 | 1.288    | 14.59               | 14.397              | 2.18E+06 | 160.00 | 9.23 | 3.43E+15 | 356.89 | 1.87          |
| AIN309A | Oxide     | 4880     | 1      | 0.0034 | 1.074    | 43.30               | 43.236              | 3.61E+06 | 150.00 | 8.38 | 5.22E+15 | 307.38 | 1.63          |
| AIN309B | Oxide     | 4902     | 1      | 0.0068 | 1.247    | 18.89               | 18.825              | 4.84E+06 | 160.00 | 9.77 | 6.98E+15 | 326.37 | 1.63          |
| AIN310  | Oxide     | 2767     | 1      |        |          |                     |                     |          |        |      |          |        | 0.92          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV | k     | ρ(Ω-cm□) | V/μm | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|----|-------|----------|------|---------------|
| AlN311  | Oxide     | 3197     | 1      |        |          |                     |                     |          |    |       |          |      | 1.07          |
| AlN314  | Oxide     | 5000     | 1      | 0.0155 | 25.705   | 0.41                | 0.400               | 1.02E+06 |    | 9.00  | 3.29E+16 |      | 1.85          |
| AlN315  | Oxide     | 5000     | 2      | 0.0105 | 36.983   | 0.45                | 0.408               | 2.26E+06 |    | 6.48  | 1.46E+17 |      | 1.85          |
| AlN316  | Oxide     | 5000     | 1      | 0.0115 | 25.669   | 0.55                | 0.539               | 9.03E+05 |    | 8.99  | 2.91E+16 |      | 1.85          |
| AlN317  | Oxide     | 5000     | 2      | 0.0169 | 43.091   | 0.23                | 0.219               |          |    | 7.55  | 6.45E+04 |      | 1.85          |
| AlN318  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 2.08          |
| AlN319  | Oxide     | 5000     | 1      | 0.0145 | 26.022   | 0.43                | 0.423               |          |    | 9.12  |          |      | 1.85          |
| AlN320  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.85          |
| AlN321  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.85          |
| AlN322  | Oxide     | 5000     | 3      | 0.0203 | 75.355   | 0.11                | 0.104               | 2.44E+06 |    | 8.80  | 2.36E+17 |      | 1.85          |
| AlN323  | Oxide     | 5000     | 1      | 0.0117 | 22.142   | 0.63                | 0.615               | 2.93E+03 |    | 7.76  | 9.44E+13 |      | 1.85          |
| AlN324  | Oxide     | 5000     | 3      |        |          |                     |                     |          |    |       |          |      | 1.85          |
| AlN325  | Oxide     | 5000     | 3      | 0.0244 | 124.758  | 0.05                | 0.052               | 7.88E+02 |    | 14.57 | 7.63E+13 |      | 1.85          |
| AlN326  | Oxide     | 4300     | 1      | 0.0141 | 54.974   | 0.23                | 0.205               | 1.00E-06 |    | 16.56 | 3.75E+04 |      | 1.59          |
| AlN327  | Oxide     | 5000     | 1      | 0.0127 | 42.861   | 0.30                | 0.293               |          |    | 15.01 |          |      | 1.67          |
| AlN328  | Oxide     | 5000     | 3      | 0.0550 | 98.043   | 0.03                | 0.030               |          |    | 11.45 |          |      | 1.52          |
| AlN329  | Oxide     | 5000     | 3      | 0.0131 | 132.908  | 0.09                | 0.091               |          |    | 15.52 |          |      | 1.52          |
| AlN330  | Oxide     | 5000     | 4      | 0.1422 | 165.202  | 0.01                | 0.007               |          |    | 14.47 |          |      | 1.52          |
| AlN331  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN332  | Oxide     | 5000     | 2      | 0.0123 | 66.209   | 0.20                | 0.196               |          |    | 11.60 |          |      | 1.52          |
| AlN333  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN334  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN335  | Oxide     | 5000     | 1      | 0.0744 | 37.568   | 0.06                | 0.057               |          |    | 13.16 |          |      | 1.52          |
| AlN336  | Oxide     | 5000     | 3      |        | 38.000   |                     |                     |          |    | 4.44  |          |      | 1.52          |
| AlN337  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    | 0.00  |          |      | 1.52          |
| AlN338  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    | 0.00  |          |      | 1.52          |
| AlN339  | Oxide     | 5000     | 1      |        | 33.000   |                     |                     |          |    | 11.56 |          |      | 1.52          |
| AlN340  | Oxide     | 5000     | 2      |        | 33.000   |                     |                     |          |    | 5.78  |          |      | 1.52          |
| AlN341  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    | 0.00  |          |      | 1.52          |
| AlN342  | Oxide     | 5000     | 2      | 0.0100 | 92.000   | 0.00                | 0.173               |          |    | 16.11 |          |      | 1.46          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV | k     | ρ(Ω-cm□) | V/μm | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|----|-------|----------|------|---------------|
| AlN343  | Oxide     | 5000     | 3      | 0.0100 | 115.000  |                     | 0.138               |          |    | 13.43 |          |      | 1.52          |
| AlN344  | Oxide     | 5000     | 3      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN345  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN346  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN347  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN348  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN349  | Oxide     | 7500     | 2      |        |          |                     |                     |          |    |       |          |      | 1.39          |
| AlN350  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN351  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN353  | Oxide     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN354  | Oxide     | 5000     | 2      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN355  | Oxide     | 5000     | 1      | 0.0242 | 16.293   | 0.41                | 0.404               | 1.21E+05 |    | 14.27 | 1.56E+15 |      | 1.52          |
| AlN356  | Oxide     | 5000     | 1      | 0.0139 | 33.002   | 0.35                | 0.346               | 2.51E+04 |    | 28.90 | 3.24E+14 |      | 1.52          |
| AlN357  | Oxide     | 5000     | 1      | 0.0153 | 15.819   | 0.66                | 0.656               | 3.29E+04 |    | 13.85 | 4.25E+14 |      | 1.52          |
| AlN358  | Oxide     | 5134     | 1      | 0.0075 | 7.913    | 2.69                | 2.687               | 7.35E+05 |    | 7.12  | 9.24E+15 |      | 1.56          |
| AlN359  | Glass     | 5000     | 1      | 0.0335 | 4.811    | 0.99                | 0.988               | 5.03E+05 |    | 4.21  | 6.49E+15 |      | 1.52          |
| AlN360  | SiO2      | 5000     | 1      |        | 24.000   |                     |                     |          |    | 21.02 |          |      | 1.52          |
| AlN361  | Glass     | 2500     | 1      |        |          |                     |                     |          |    |       |          |      | 1.54          |
| AlN362  | Glass     | 2500     | 1      |        |          |                     |                     |          |    |       |          |      | 1.54          |
| AlN363  | Glass     | 2500     | 1      |        |          |                     |                     |          |    |       |          |      | 1.54          |
| AlN364  | Glass     | 10000    | 1      | 0.0088 | 2.084    | 8.76                | 8.636               | 2.37E+04 |    | 4.09  | 1.36E+14 |      | 1.52          |
| AlN365  | Glass     | 10000    | 1      | 0.0000 |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN366  | Glass     | 10000    | 1      | 0.0124 | 2.901    | 4.41                | 4.414               | 2.24E+02 |    | 5.70  | 1.29E+12 |      | 1.52          |
| AlN367  | Glass     | 5000     | 1      | 0.0093 | 5.139    | 3.36                | 3.314               | 1.30E+03 |    | 5.05  | 1.49E+13 |      | 1.52          |
| AlN368  | Glass     | 10000    | 1      | 0.0080 | 5.578    | 3.57                | 3.577               |          |    | 10.96 |          |      | 1.52          |
| AlN369  | Glass     | 10000    | 1      | 0.0190 | 7.770    | 1.07                | 1.076               |          |    | 15.27 |          |      | 1.52          |
| AlN370  | Glass     | 5000     | 1      | 0.0098 | 12.283   | 1.35                | 1.327               |          |    | 12.07 |          |      | 1.52          |
| AlN371  | Glass     | 5000     | 1      |        |          |                     |                     |          |    |       |          |      | 1.52          |
| AlN372  | Glass     | 14550    | 1      | 0.0669 | 3.554    | 0.98                | 0.669               | 5.77E+02 |    | 10.16 | 2.28E+12 |      | 2.20          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV     | k     | ρ(Ω-cm□) | V/μm   | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|--------|-------|----------|--------|---------------|
| AIN373  | Glass     | 10000    | 1      | 0.0314 | 11.578   | 0.46                | 0.437               | 6.82E+01 |        | 22.75 | 3.92E+11 |        | 2.08          |
| AIN374  | Glass     | 5000     | 1      |        |          |                     |                     |          |        | 11.30 | 4.58E+12 |        | 2.08          |
| AIN375  | Glass     | 10000    | 1      |        |          |                     |                     |          |        |       |          |        | 2.08          |
| AIN376  | Glass     | 10000    | 1      |        |          |                     |                     |          |        |       |          |        | 2.08          |
| AIN377  | Oxide     | 5000     | 1      |        |          |                     |                     |          |        |       |          |        | 1.04          |
| AIN378  | Oxide     | 5000     | 1      |        |          |                     |                     |          |        |       |          |        | 1.04          |
| AIN379  | Oxide     | 9000     | 1      | 0.0084 | 8.383    | 2.25                | 2.249               | 1.08E+05 |        | 8.20  | 1.24E+15 |        | 2.50          |
| AIN380  | Oxide     | 6000     | 1      | 0.0075 | 10.420   | 2.04                | 2.024               | 1.14E+05 | 440.00 | 7.76  | 1.73E+15 | 733.33 | 2.50          |
| AIN381  | Oxide     | 6000     | 1      | 0.0123 | 13.845   | 0.94                | 0.932               | 1.01E+05 | 350.00 | 9.03  | 1.75E+15 | 583.33 | 2.50          |
| AIN382  | Oxide     | 6067     | 1      | 0.0147 | 13.833   | 0.80                | 0.785               |          |        | 9.12  |          |        | 2.53          |
| AIN383  | Oxide     | 6067     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN384  | Oxide     | 6067     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN385  | Oxide     | 6067     | 1      | 0.0191 | 14.239   | 0.59                | 0.584               |          |        | 9.39  |          |        | 2.53          |
| AIN386  | Oxide     | 4538     | 1      | 0.0390 | 17.268   | 0.24                | 0.236               |          |        | 8.51  |          |        | 2.52          |
| AIN387  | Oxide     | 6067     | 1      | 0.0199 | 12.266   | 0.66                | 0.651               |          |        | 8.09  |          |        | 2.53          |
| AIN388  | Oxide     | 6067     | 1      | 0.0182 | 16.209   | 0.55                | 0.539               |          |        | 10.68 |          |        | 2.53          |
| AIN389  | Oxide     | 6067     | 2      | 0.0341 | 30.338   | 0.16                | 0.154               |          |        | 10.00 |          |        | 2.53          |
| AIN390  | Oxide     | 6067     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN391  | Oxide     | 6067     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN392  | Oxide     | 6067     | 1      | 0.0310 | 14.043   | 0.38                | 0.366               |          |        | 9.26  |          |        | 2.53          |
| AIN393  | Oxide     | 6067     | 1      | 0.0292 | 15.766   | 0.35                | 0.345               |          |        | 10.39 |          |        | 2.53          |
| AIN394  | Oxide     | 4538     | 1      | 0.0688 | 23.077   | 0.10                | 0.100               |          |        | 11.38 |          |        | 2.52          |
| AIN395  | Oxide     | 5000     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN396  | Oxide     | 5000     | 1      | 0.0723 | 10.843   | 0.20                | 0.203               |          |        | 6.73  |          |        | 2.53          |
| AIN397  | Oxide     | 5000     | 1      | 0.0130 | 25.545   | 0.48                | 0.481               |          |        | 8.75  |          |        | 2.53          |
| AIN398  | Oxide     | 5000     | 1      | 0.0282 | 13.645   | 0.43                | 0.414               |          |        | 8.47  |          |        | 2.53          |
| AIN399  | Oxide     | 5000     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AIN400  | Oxide     | 5000     | 1      | 0.0109 | 41.419   | 0.35                | 0.352               |          |        | 22.50 |          |        | 2.53          |
| AIN401  | Oxide     | 5000     | 1      | 0.0369 | 10.907   | 0.43                | 0.395               |          |        | 5.93  |          |        | 2.53          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ)  | HV     | k     | ρ(Ω-cm□) | V/μm   | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|----------|--------|-------|----------|--------|---------------|
| AlN405  | Oxide     | 5000     | 1      |        |          |                     |                     |          |        |       |          |        | 2.53          |
| AlN406  | Oxide     | 6000     | 1      | 0.0298 | 10.619   | 0.56                | 0.503               | 8.59E+04 | 250.00 | 6.00  | 1.72E+15 | 416.67 | 3.33          |
| AlN407  | Oxide     | 3600     | 1      | 0.0413 | 24.132   | 0.17                | 0.160               | 1.00E+05 | 220.00 | 8.18  | 3.34E+15 | 611.11 | 1.50          |
| AlN408  | Oxide     | 4950     | 2      | 0.0500 | 30.400   | 0.18                | 0.105               |          |        | 7.08  |          |        | 1.50          |
| AlN409  | Oxide     | 4868     | 1      | 0.0470 | 21.000   |                     | 0.161               | 9.46E+04 | 200.00 | 9.63  | 2.33E+15 | 410.85 | 1.48          |
| AlN410  | Oxide     | 4868     | 1      | 0.0189 | 14.943   | 0.58                | 0.565               | 8.72E+04 |        | 6.85  | 2.49E+16 |        | 1.48          |
| AlN411  | Oxide     | 4950     | 1      | 0.0621 | 9.727    | 0.27                | 0.264               | 0.00E+00 |        | 6.80  | 0.00E+00 |        | 1.50          |
| AlN412  | Oxide     | 4950     | 1      | 0.0311 | 18.438   | 0.29                | 0.278               | 8.72E+04 |        | 8.59  | 2.11E+15 |        | 1.50          |
| AlN413  | Oxide     | 4950     | 1      | 0.0459 | 19.277   | 0.18                | 0.180               | 6.97E+05 |        | 8.98  | 1.69E+16 |        | 1.50          |
| AlN414  | Oxide     | 4950     | 1      | 0.0229 | 15.387   | 0.45                | 0.452               | 0.00E+00 |        | 7.17  |          |        | 1.50          |
| AlN415  | Oxide     | 4950     | 1      |        |          |                     |                     |          |        |       |          |        | 1.50          |
| AlN416  | Oxide     | 5700     | 1      | 0.0407 | 15.863   | 0.25                | 0.246               |          |        | 8.51  |          |        | 1.73          |
| AlN417  | Oxide     | 4950     | 2      | 0.0358 | 41.538   | 0.12                | 0.107               | 1.14E+06 | 170.00 | 9.68  | 5.53E+16 | 343.43 | 1.50          |
| AlN418  | Oxide     | 4950     | 3      | 0.2345 | 53.439   | 0.02                | 0.013               |          |        | 8.30  |          |        | 1.50          |
| AlN419  | Oxide     | 4950     | 2      | 0.0212 | 55.890   | 0.14                | 0.135               |          |        | 13.03 |          |        | 1.50          |
| AlN421  | Oxide     | 8250     | 2      | 1.3876 | 20.309   | 0.01                | 0.006               |          |        | 9.86  |          |        | 2.50          |
| AlN422  | Oxide     | 8250     | 1      | 0.0458 | 21.484   |                     |                     |          |        |       |          |        | 2.50          |
| AlN423  | Oxide     | 8250     | 5      |        |          |                     |                     |          |        |       |          |        | 2.50          |
| AlN424  | Oxide     | 4950     | 4      |        |          |                     |                     |          |        |       |          |        | 1.50          |
| AlN425  | Oxide     | 4950     | 2      | 0.0733 | 26.944   | 0.08                | 0.081               |          |        | 6.98  |          |        | 1.50          |
| AlN426  | Oxide     | 4950     | 5      | 0.0886 | 87.812   | 0.02                | 0.020               |          |        | 8.40  |          |        | 1.50          |
| AlN427  | Oxide     | 4950     | 5      | 0.0555 | 99.049   | 0.03                | 0.029               | 6.44E+05 | 80.00  | 9.47  | 7.61E+16 | 161.62 | 1.50          |
| AlN428  | Oxide     | 4950     | 10     | 0.0863 | 202.287  | 0.01                | 0.009               | 2.90E+03 |        | 9.67  | 6.85E+14 |        | 1.50          |
| AlN429  | Oxide     | 4950     | 5      | 0.0424 | 81.319   | 0.05                | 0.046               |          |        | 8.42  |          |        | 1.50          |
| AlN430  | Oxide     | 4950     | 5      | 0.0522 | 75.832   | 0.04                | 0.040               | 9.86E+05 | 115.00 | 13.46 | 6.27E+16 | 232.32 | 1.50          |
| AlN431  | Oxide     | 4950     | 2      | 0.0338 | 43.869   | 0.11                | 0.107               | 4.86E+05 |        | 19.47 | 1.24E+16 |        | 1.50          |
| AlN432  | Oxide     | 3650     | 1      | 0.0384 | 23.086   | 0.18                | 0.180               |          |        | 15.11 |          |        | 1.11          |
| AlN433  | Oxide     | 4443     | 1      | 0.0516 | 16.310   | 0.19                | 0.189               | 4.26E+05 |        | 13.00 | 6.04E+15 |        | 1.35          |
| AlN434  | Oxide     | 4620     | 2      | 0.0316 | 28.762   | 0.17                | 0.175               | 8.76E+05 |        | 11.92 | 2.39E+16 |        | 1.40          |
| AlN435  | Oxide     | 4620     | 5      | 0.0465 | 68.399   | 0.05                | 0.050               | 4.27E+05 |        | 11.34 | 2.91E+16 |        | 1.40          |
| AlN436  | Oxide     | 4620     | 10     | 0.0652 | 129.140  | 0.02                | 0.019               | 6.98E+05 |        | 10.70 | 9.52E+16 |        | 1.40          |

Table D-1. Dielectric and Electrical Properties (continued)

| Sample# | Substrate | Film (Å) | Layers | Df     | Cap (nF) | R <sub>p</sub> (MΩ) | R <sub>p</sub> (MΩ) | IR (MΩ) | HV | k     | ρ(Ω-cm□) | V/μm | DepRate (Å/s) |
|---------|-----------|----------|--------|--------|----------|---------------------|---------------------|---------|----|-------|----------|------|---------------|
| AlN442  | Oxide     | 4620     | 2      | 0.0353 | 13.805   | 0.33                | 0.326               |         |    | 6.67  |          |      | 0.92          |
| AlN443  | Oxide     | 4620     | 3      | 0.2021 | 26.087   | 0.03                | 0.030               |         |    | 8.41  |          |      | 0.92          |
| AlN444  | Oxide     | 4620     | 10     | 0.2687 | 107.366  | 0.01                | 0.006               |         |    | 10.38 |          |      | 0.92          |
| AlN445  | Oxide     | 4620     | 10     |        |          |                     |                     |         |    |       |          |      | 0.92          |