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# MANUFACTURING METHODS AND TECHNOLOGY ENGINEERING HIGH EFFICIENCY, HIGH POWER GALLIUM ARSENIDE READ-TYPE IMPATT DIODES

## FIFTH QUARTERLY PROGRESS REPORT

1 July 1976 to 30 September 1976

CONTRACT NO. DAAB07-75-C-0045

Prepared By

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work on fabrication of the Confirmatory Samples was initiated. The X and Ku-band wafers were grown. The processing of dice from these wafers was begun.

New equipment has been installed on the production line. A hot-gas bonding unit was installed to facilitate chip mounting. A thermal resistance tester was installed to increase production rates.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The fourth operational life test was completed with no failures in ten devices.

# MANUFACTURING METHODS AND TECHNOLOGY ENGINEERING
# HIGH EFFICIENCY, HIGH POWER GALLIUM ARSENIDE
# READ-TYPE IMPATT DIODES

## FIFTH QUARTERLY PROGRESS REPORT

1 July 1976 to 30 September 1976

CONTRACT NO. DAAB07-75-C-0045

The object of this program is to develop a capability to manufacture High Efficiency, High Power Gallium Arsenide IMPATT Diodes meeting the description and specifications of Section F of the contract and the requirements of SCS-481.

DISTRIBUTION STATEMENT

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Prepared By

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## PURPOSE

The objective of this program is to establish a capability to manufacture high-efficiency, high-power Gallium Arsenide IMPATT diodes at specified rates and yields. There are two diode types; one at X-band, and one at Ku-band which have the nominal characteristics listed below.

| | X-Band | Ku-Band |
|---|---|---|
| Operating Frequency (GHz) | 10.0 ±1.0 | 15.0 ±1.0 |
| Power Output (Watts) | 3.5 min. | 2.5 min. |
| Conversion Efficiency (%) | 20 min. | 20 min. |
| Operating Junction Temperature ($^{o}$C) | 200 max. | 200 max. |

Engineering effort is to be directed toward establishing production processes for both Gallium Arsenide epitaxial wafers and diode fabrication and test. The wafers are to meet the material characterization testing as specified, and the diodes must meet the detailed performance requirements outlined in SCS-481.

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## 1.0 INTRODUCTION

Work on fabrication of the Confirmatory Samples was initiated during the period. The X-band and Ku-band wafers were grown to specifications, completely characterized and delivered to the device fabrication area. Processing of the wafers into dice was begun.

Work on the assembly line included the installation of two new pieces of production equipment. A hot gas die bonder was installed to facilitate bonding of dice into the package by elimination of flux. A new thermal resistance tester was purchased and installed to enhance the production rate for this measurement, which until now had been a limiting factor.

The fourth operating life test was completed. Five X-band diodes completed the test with no failures. Five Ku-band diodes completed the test with no failures.

# 2.0 RESULTS AND ACCOMPLISHMENTS

## 2.1 Wafers Supplied for Confirmatory Samples

Eight wafers were supplied for device fabrication during this period. These were intended to provide materials from which to manufacture diodes for confirmatory samples. The wafers were equally divided between X and Ku-bands and met the preliminary wafer specifications for these bands. The important characteristics of the confirmatory wafers are summarized in Table 2-1.

All of the epitaxial layers were deposited upon highly conducting tellurium-doped substrates which met the specifications given in previous reports. Most of the substrates used had electron concentrations in the range of 1.0 to 1.5 $\times 10^{18} cm^{-3}$ so as to avoid a high incidence of precipitates and other substrate defects.

All substrates were polished to a pregrowth thickness between 280 and 320 micrometers, using bromine in methanol as the polishing compound. The thickness, bow, and taper of each substrate was determined after polishing, using a contactless probe manufactured by the Ade Corporation. This probe is especially suited to pregrowth wafer measurements because it operates by capacitance measurements; therefore it does not damage the wafer in any way.

Wafers were cleaned immediately prior to growth using multiple hot rinses of acetone and methanol. About five micrometers of the surface material were removed chemically in the pregrowth cleaning procedure using 7:2:1 sulfuric acid: hydrogen peroxide: water as a moving etch in a teflon beaker.

The epitaxial layers were deposited using the standard production reactor. This reactor is capable of producing up to three 2.2 x 2.2 wafers simultaneously. A holder constructed to hold

Table 2-1

Read Wafers Supplied for Confirmatory Samples

| Wafer No. | | Buffer | Transit | | Spike | | | | | Contact | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | W | W | $n \times 10^{16}$ | W | $n \times 10^{16}$ | $Q^* \times 10^{12}$ | V* | $x_p$ | $x_o$ | $n_o \times 10^{16}$ | |
| Series | Run | (μm) | (μm) | ($cm^{-3}$) | (mm) | ($cm^{-3}$) | ($c\text{-}cm^{-2}$) | (volts) | (μm) | (μm) | ($cm^{-3}$) | Band |
| 413 | 19A | 4.9 | 4.6 | 0.51 | 50 | 46.0 | 2.5 | 8.9 | 0.24 | 0.19 | 11 | X |
| | 19B | 5.1 | 4.7 | 0.50 | 50 | 45.0 | 2.4 | 8.1 | 0.24 | 0.19 | 12 | X |
| | 20A | 5.2 | 5.1 | 0.49 | 52 | 42.0 | 2.4 | 8.6 | 0.24 | 0.19 | 11 | X |
| | 20B | 5.7 | 5.4 | 0.49 | 52 | 43.0 | 2.4 | 8.1 | 0.24 | 0.19 | 12.5 | X |
| | 28A | 4.5 | 3.5 | 1.03 | 46 | 43.7 | 2.5 | 8.0 | .23 | 0.19 | 11 | Ku |
| | 28B | 4.8 | 3.7 | 1.06 | 46 | 43.1 | 2.4 | 7.9 | .23 | 0.18 | 11 | Ku |
| | 30C | 5.6 | 4.5 | 1.15 | 50 | 42.8 | 2.4 | 8.3 | .25 | 0.20 | 10 | Ku |
| 820 | 10 | 6.5 | 4.3 | 1.10 | 50 | 43.0 | 2.5 | 8.2 | .25 | 0.20 | 9.8 | Ku |

the three wafers coplanar and with maximum symmetry in the vapor stream was used. A photograph of the triple wafer holder is shown in Figure 2-1.

Wafers grown in the triple wafer reactor are designated by the deposition run number, followed by the letters A, B, or C, depending upon wafer position in the holder. The top center position is designated A, the lower left B, and the lower right C. The letter designations are used to describe the wafer position in the triple wafer holder in the production reactor in both single wafer or multiple wafer depositions.

After growth, each wafer was characterized by removing a small profile strip from the right-hand edge. Standard-area aluminum-gold Schottky diodes were formed by photolithography and vacuum evaporation upon the profile strip. Doping profiles were measured on these diodes by C-V profiling. Profiles in depth were by step-etching.

The epitaxial layers deposited included a heavily doped layer five to seven micrometers grown on this polished substrate surface. This was followed by a transit layer, 3.5 to 4.5 micrometers in thickness for Ku-band, or 4.5 to 5.5 micrometers in thickness for X-band. The electron concentrations for the transit layers were centered about $1.05 \times 10^{16} cm^{-3}$ for Ku-band or $5 \times 10^{15} cm^{-3}$ for X-band. The transit layer was followed by the deposition of an avalanche confining spike which, for both bands, was 0.24 micrometers from the surface and had an integrated charge of $2.4 \times 10^{12}$ coulomb $cm^{-2}$.

Two of three wafers grown in particular runs met the preliminary wafer specifications. Each triple wafer holder possesses unique characteristics because of slight deviations from the design dimensions. The one used to grow the confirmatory samples produced two wafers (the A and B position) which were virtually identical. The

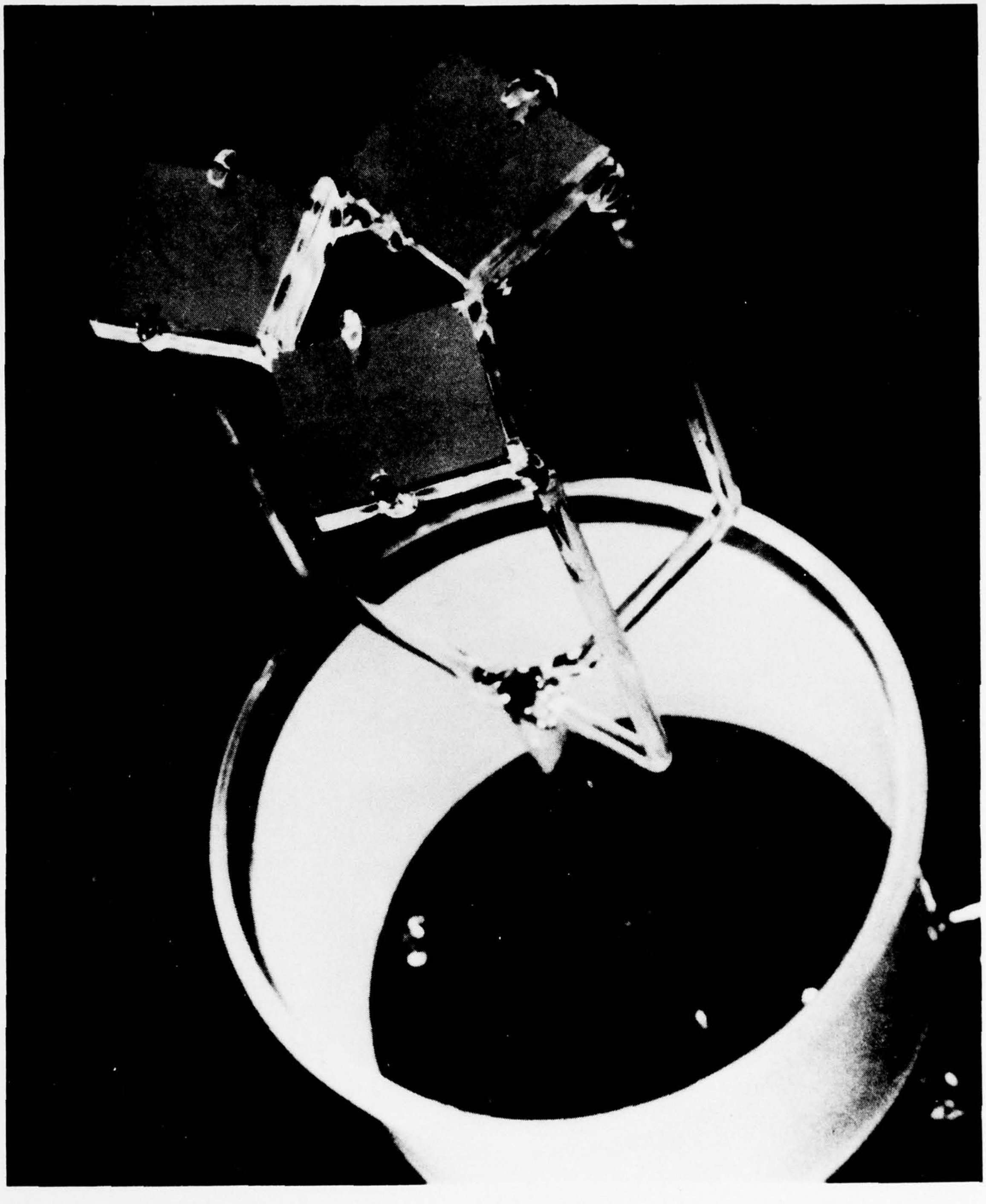

Figure 2-1  Photograph of Triple Wafer Holder

other wafer (the C position) although still within specifications, possessed layers which averaged five to ten percent thinner and five to ten percent higher in doping than the other two. This deviation probably results from a slight temperature difference between the three wafers, and can be minimized by slight modification of the growth equipment.

## 2.2 Dice Fabrication

Fabrication of dice for the Confirmatory Samples was begun during the period. Although four wafers of each type had been scheduled for this activity, only two of each were processed. The others were held pending results from the first group. A small fraction of the resultant dice will be required for fabrication of the diodes.

The wafers were metallized in the production sputtering unit using conditions which have been recently modified to more closely match conditions in the Research Division unit. The power during titanium sputter was increased from 500 W to 700 W, which is required with the larger target in the production unit to achieve the same power density as in the Research unit.

## 2.3 Hot-Gas Chip Bonding

One of the problems in mounting dice using solder is that the dice tend to float on the solder after the tip pressure is removed. A second problem is that flux is usually required to achieve a good flow of the solder. Both of these problems can be eliminated by using the hot gas method of bonding.

In operation, the solder preform and die are placed in the package which is held on a heated stage at a temperature just below the melting point of the solder. The die is held in place using a die collet as in conventional bonding. A jet of heated gas is then directed to the bond area through a nozzle to supply the incremental heat necessary to melt the solder. The heated gas is forming gas which replaces the air to prevent oxidation and also serves as a flux by reducing oxides. When the gas jet is interrupted, the local temperature decreases to its initial value and the solder freezes. The tip pressure is maintained during the freezing which prevents the chip from floating.

The bonding equipment which was purchased and installed is manufactured by Mech-El Industries. In order to evaluate the Mech-El hot gas bonder, four lots (Lots B, C, D, and E) of about ten diodes each were assembled. Lots B and C were assembled using the K&S bonder with 50 and 70 gr, respectively, die collet pressure. These represent the control samples. Lots D and E were assembled using the Mech-El hot gas bonder. The same collet pressures were used, 50 and 70 gr., respectively.

The quality of die bonding of IMPATT diodes is quantitatively measured by the thermal impedance $R_{TH}$ of the device.

Since thermal impedance is area-dependent, the capacitance of all diodes was measured. This was used as an indication of device area variations, assuming the same capacitance per unit area for all devices. This is a reasonable assumption considering that all of the devices came from the same Ku-band wafer, 81844M2.

The mean ($\mu$) and standard deviation ($\sigma$) of thermal impedance and capacitance were calculated for every lot. The results are compiled in Table 2-2. An analysis of the results indicates that there is no significant difference between the two bonders. However, there is a tendency towards lower $R_{TH}$ values at the lower collet pressure for both bonders. Even though the percentage change is quite small, the direction of change is surprising. Higher collet pressure should force out more solder from under the chip, hence better $R_{TH}$ values. One possible explanation would be that

Table 2-2

Thermal Resistance of Diodes from Hot Gas Bonder

| Parameter | | K&S | | H.G. Mech-El | |
|---|---|---|---|---|---|
| | | Lot B | Lot C | Lot D | Lot E |
| C (pF) | μ | 2.01 | 1.98 | 1.95 | 2.00 |
| | σ | 0.13 | 0.10 | 0.18 | 0.18 |
| $R_{TH}$ (°C/W) | μ | 17.4 | 18.2 | 17.8 | 18.6 |
| | σ | 0.57 | 0.85 | 0.69 | 0.8 |

the thin plated heat sink chip (.0020-.0025) bows under pressure and the solder distribution is uneven and thicker at the chip center.

## 2.4 Thermal Resistance Tester

The measurement of thermal resistance was highlighted in the proposal as one of the areas which would limit production rates. The reason for this was that the accurate measurement of thermal resistance is a fairly lengthy two-step process involving first the calibration of the diode breakdown voltage with temperature, and secondly, the use of this calibrated diode thermometer during a pulsed power test to measure the device temperature. Knowing the amount of power dissipated in the device and its temperature, the thermal resistance of the device is calculated. We had been performing the measurement in a multi-station test fixture capable of measuring twelve devices simultaneously. The cycle time was approximately four hours per batch. A doubling of this rate was the minimum required to meet the rate objective of 1000 units/month.

As a first step, the temperature calibration and pulsing portions of the measurement were separated. A twenty-five position fixture was designed and fitted to an oven so that temperature calibration curves could be obtained on twenty-five units simultaneously. Each diode can be individually tested by switching it into a measuring circuit through a rotary switch. This system can be readily expanded for very high production rates. Commercial equipment can be purchased to perform this portion of the measurement at high rates. The pulsing portion of the measurement was then modified so that diodes could be individually tested in succession using a single-position fixture. Knowing the temperature variation of breakdown voltage and the conditions during the pulsing portion of the measurement, the thermal resistance is then calculated.

In order to further improve efficiency, we purchased a thermal resistance tester manufactured by Sage Enterprises. This instrument is designed to perform the pulse portion of the measurement and calculate the answers using a dialed-in value for the temperature calibration factor. The total cycle time for the measurement is nine (9) seconds. Including the manual loading and unloading in a threaded socket, diodes can be measured and recorded at a rate of 50/hour which far exceeds the requirements. This instrument is presently being evaluated for accuracy and repeatability of measurements and for correlation with our existing techniques. The results will be reported in the next quarterly report.

## 3.0 DIODE OPERATING LIFE TESTS

### 3.1 Summary of Requirements

Operating life test requirements of this program specify that diodes periodically be subjected to 1000 hour life tests while operating as oscillators. The tests are to be initiated at the end of the first quarter and repeated quarterly for a total of seven (7) tests. The sample size for each test is five (5) diodes of each type randomly selected from a corresponding wafer. In addition, nine (9) diodes of each type are to be life tested for 1000 hours as a part of the Group B quality Conformance Inspection at the time of confirmatory sample testing and again at the time of pilot run sample testing.

The testing is to be conducted at an ambient temperature of 25°C with the test cavity temperature held below 75°C and the diode junction temperature not exceeding 200°C. To identify failures, the power output must be monitored with failures defined by a 25% decrease in the power output of a diode relative to its initial value. The Group B life testing will be performed with the diode operating within its rated power output, frequency, efficiency, and junction temperature specifications. The quarterly tests will be conducted in such a way as to demonstrate progress toward successfully meeting these test requirements.

Two operating life test stations, one for X-band diodes and one for Ku-band diodes, were designed and constructed to meet the operating life test requirements described. A description of the equipment was presented in the first quarterly report.

### 3.2 Fourth Operating Life Test

During the present period, the fourth operational life test was completed. The five X-band diodes and five Ku-band diodes survived the life test with no failures. There was no degradation of power output during the test. Upon retesting the diodes, at completion of the test, it was found that the diode characteristics repeated their pre-test values quite closely. The test was uneventful with the exception of a power failure at 260 hours which interrupted the test and stopped the clock. The test was successfully restarted after restoration of power. During such a failure, the equipment must be manually reset and restarted to prevent possible diode failures caused by line transients.

The initial and final data for the X-band and Ku-band diodes is given in Tables 3-1 and 3-2. It may be seen that there is practically no change in the operating performance of the diodes. The X-band diodes were operated within the specifications at full rated power. The Ku-band devices were operated at full rated power and met all of the specifications except operating frequency.

## 3.3 Status of Operating Life Test Program

The following is a summary of the results obtained to date during the operating life test program. The fourth life test was the first test which was completed without device failures. This is attributed in large part to improvement in the equipment as discussed in prior reports.

| | X-Band | | Ku-Band | |
|---|---|---|---|---|
| Test Number | Qty. Tested | Failures | Qty. Tested | Failures |
| 1 | 5 | 1 | 5 | 1 |
| 2 | 5 | 1 | 5 | 5* |
| 3 | 5 | 1 | 5 | 0 |
| 4 | 5 | 0 | 5 | 0 |

* System malfunction caused catastrophic failure of all devices.

Table 3-1

## Operating Life Test Data - X-Band Diodes

| | Diode No. | Rack Position | Resistance ($^{o}$C/W) | Junction Temp. ($^{o}$C) | Operating Voltage (Volts) | Operating Current (mA) | Power Out (Watts) | Freq. (GHz) | Dissipated Power (Watts) |
|---|---|---|---|---|---|---|---|---|---|
| Initial | 81610M2-9b | 1 | 11.9 | 172.6 | 58.9 | 270 | 3.5 | 9.0 | 12.4 |
| Final | | | | | 58.8 | 270 | 3.9 | 9.0 | |
| Initial | 81610M2-1b | 2 | 12.2 | 175.9 | 58.8 | 270 | 3.5 | 9.01 | 12.4 |
| Final | | | | | 59.0 | 270 | 3.5 | 9.01 | |
| Initial | 81610M2-5 | 3 | 12.9 | 194.2 | 57.3 | 290 | 3.5 | 9.10 | 13.1 |
| Final | | | | | 57.0 | 290 | 3.8 | 9.09 | |
| Initial | 81610M2-7b | 4 | 13.0 | 199.1 | 56.3 | 300 | 3.5 | 9.24 | 13.4 |
| Final | | | | | 56.5 | 300 | 3.5 | 9.23 | |
| Initial | 81610M2-16 | 5 | 12.7 | 162.5 | 55.1 | 260 | 3.5 | 9.10 | 10.8 |
| Final | | | | | 54.9 | 260 | 3.75 | 9.13 | |

Specification:

$P_o$ = 3.5 W minimum
$f_o$ = 9-11 GHz
$\eta$ = 20% minimum
$T_j$ = 200$^{o}$C maximum

Table 3-2

Operating Life Test Data - Ku-Band Diodes

| | Diode No. | Rack Position | Resistance ($^{o}C/W$) | Junction Temp. ($^{o}C$) | Operating Voltage (Volts) | Operating Current (mA) | Power Out (Watts) | Freq. (GHz) | Dissipated Power (Watts) |
|---|---|---|---|---|---|---|---|---|---|
| Initial | 81830M1E-21 | 1 | 15.7 | 185.2 | 43.8 | 290 | 2.5 | 12.43 | 10.2 |
| Final | | | | | 44.0 | 290 | 2.45 | 12.45 | |
| Initial | 81830M1E-23 | 2 | 15.8 | 189.3 | 43.0 | 300 | 2.5 | 12.25 | 10.4 |
| Final | | | | | 42.9 | 300 | 2.4 | 12.25 | |
| Initial | 81830M1E-3 | 4 | 15.7 | 177.4 | 43.6 | 280 | 2.5 | 12.6 | 9.7 |
| Final | | | | | 43.7 | 280 | 2.42 | 12.63 | |
| Initial | 81830M1E-4 | 5 | 15.4 | 181.2 | 43.6 | 290 | 2.5 | 12.35 | 10.1 |
| Final | | | | | 43.6 | 290 | 2.42 | 12.35 | |
| Initial | 81830M1E-5 | 6 | 15.9 | 188.0 | 42.5 | 300 | 2.5 | 12.50 | 10.2 |
| Final | | | | | 42.1 | 300 | 2.5 | 12.51 | |

Specification:

$P_o$ = 2.5 W minimum
$f_o$ = 14-16 GHz
$\eta$ = 20% minimum
$T_j$ = 200$^{o}$C maximum

## 4.0 CONCLUSIONS

With successful completion of the fourth life test without failures, conformance to most aspects of the specification have been demonstrated. The equipment required for manufacture of the confirmatory samples has been installed on the production line. Assembly of the confirmatory samples has begun.

## 5.0 PROGRAM FOR NEXT INTERVAL

During the next period, we will continue assembly of the confirmatory samples. The evaluation work on the thermal resistance equipment will be completed. Installation of the noise measurement equipment will begin.

## 6.0 IDENTIFICATION OF PERSONNEL

| | |
|---|---|
| Michael Benedek<br>Engineer - Production Processes | 148 Hours |
| Robert Bierig<br>Manager - Semiconductor Research Laboratory and GaAs Material Production | 28 Hours |
| Henri Chalifour<br>Manager - Diode Production | 100 Hours |
| Paul Coletti<br>Supervisor Engineer - Dice Fabrication | 32 Hours |
| William Labossier<br>Research Assistant - Epitaxial Wafer Growth | 122 Hours |
| Andrew Moysenko<br>Associate Research Scientist - Quality Assurance Wafer Growth | 8 Hours |
| Dr. S. F. Paik<br>Manager - Solid State Engineering | 10 Hours |
| Samuel R. Steele<br>Senior Scientist - Manager Materials Laboratory | 112 Hours |
| Basil Vafiades<br>Programs Manager - MMTE Program Manager | 63 Hours |
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