

# Radiation Effects in Ultra-Wide Bandgap AlN Schottky Diodes

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**Abstract**—Ultra-wide bandgap AlN Schottky diodes were fabricated by metal organic chemical vapor deposition and tested under gamma-ray and proton radiation conditions. The breakdown voltage and leakage currents were found to be strongly dependent on the temperature and surface area of the diodes. Radiation effects degraded forward currents slightly but had little impact on the crystal quality.

**Keywords**—ultra-wide bandgap, AlN, Schottky diode, MOCVD, high-temperature, gamma ray, radiation.

## I. INTRODUCTION

Extreme temperature and radiation-harsh environments, such as those involving nuclear power, advanced military applications (*e.g.*, electronically guided missiles) or space exploration have created a high demand for more robust electronics. The ultra-wide bandgap (UWBG) semiconductor AlN is a highly promising platform to fill this need. Commanding the largest bandgap  $E_g$  (6.2 eV) out of any semiconductor, AlN has a critical field  $E_c$  of 12 mV/cm, electron and hole mobilities of 1090 and 14 cm<sup>2</sup>/V·s, and a maximum operating temperature of 690°C [1,2]. The ultra-wide bandgap, coupled with the 11.52 eV/atom chemical bond strength and small lattice constants give AlN a natural advantage against impact ionization and lattice displacement, the two most fundamental radiation effects. Furthermore, as radiation hardness is well-known to increase with the bandgap, superior radiation performance can be expected from AlN.

In spite of all the clear promise that AlN shows, there are significant gaps in studies of how AlN behaves in extreme environments. Results are limited primarily due to the lack of high-quality AlN substrates, growing difficulties, and absence of successful *p*-type doping. This lack of understanding is unfortunate, because AlN has a clear advantage over the wildly successful and well-studied wide bandgap (WBG) class of materials such as gallium nitride (GaN) and silicon carbide (SiC). For example, many objective measures, such as Baliga's Figure of Merit (BFoM) and Johnson's Figure of Merit (JFoM), predict that UWBG materials such as AlN can deliver order-of-magnitude improvements on current trends in power electronics. This is because performance quantifiers such as BFoM and JFoM scale with the bandgap of the semiconductor; in particular, BFoM has a sixth-order dependence on the bandgap [3]. Regardless, studies to date on radiation effects in AlN are practically non-existent.

To this end, lateral Pd/*n*-AlN Schottky diodes were fabricated [4,5] by metal organic chemical vapor deposition(MOCVD) on (0001) sapphire substrates and their

current–voltage (I–V) characteristics were studied across varying temperatures, as well as gamma-ray irradiation doses (0-90 MRad) and proton irradiation doses ( $5 \times 10^{15}$  cm<sup>-2</sup>). The protons were at an energy of 3 MeV. Large ideality factors were obtained at forward bias. A negative temperature dependence was observed at reverse breakdown conditions. Our results show that surface states play a large role in the electrical behavior of the device. With increasing gamma radiation doses, forward currents decrease slightly while crystal quality, as determined by high-resolution x-ray diffraction (HR-XRD), shows little degradation. Proton irradiation resulted in little change in forward- and reverse-bias currents until the highest dose, where currents drop to zero.

## II. GROWTH AND FABRICATION

MOCVD growth was used to grow 1 μm-thick AlN layers, doped with Si ( $3 \times 10^{18}$  cm<sup>-3</sup>), on (0001) sapphire substrates. The MOCVD precursors were Trimethylaluminum (TMAI), ammonia (NH<sub>3</sub>), and silane (SiH<sub>4</sub>) for the Al, N, and Si elements. The AlN epilayer was grown at high temperature (~1200°C) while the AlN buffer layer was grown at low temperature [6]. The carrier concentration in the AlN epilayer is  $\sim 10^{15}$  cm<sup>-3</sup>. The crystal quality of the as-grown samples was determined by HR-XRD using a PANalytical X'Pert Pro materials research X-ray diffractometer (MRD) setup, which utilized Cu Kα radiation. Fig. 1(a) shows the (0002) plane rocking curve. The full width at half maximum (FWHM) of the AlN epilayer is 0.16°. Based on the methods found in [7, 8], the estimated defect density is  $>10^9$  cm<sup>-2</sup>. X-ray photoelectron spectroscopy (XPS) measurements were carried out in ultrahigh vacuum ( $<10^{-9}$  Torr) using an Al Kα x-ray source. The XPS analysis confirmed that there was a negligible gallium content present in the as-grown AlN. This result confirms that the sample is indeed AlN instead of AlGaN, which is a common issue with MOCVD growth of AlN.

Fig. 1(b) shows the XPS valence band spectrum of the as-grown AlN sample. The polarization charge on the AlN surface is neutralized by the oppositely-charged surface states, which results in surface band-bending. This is the surface barrier height (SBH) of the AlN sample. At the charge neutrality level, the SBH is equal to  $E_g - E_{VBM}$ . Here,  $E_g$  is the bandgap of AlN and  $E_{VBM}$  is the valence band maximum energy level calculated with respect to the surface Fermi level.  $E_{VBM}$  can be determined by extrapolating a linear fit of the leading edge of the valence band spectrum to the baseline [9]. This results in an SBH of 2.60 eV. The SBH was then used to estimate the surface state density [10-12] and results in a density of  $1.1 \times 10^{14}$  eV<sup>-1</sup>cm<sup>-2</sup>.

This value is comparable to previous AlN data and is larger than values found for GaN [10].

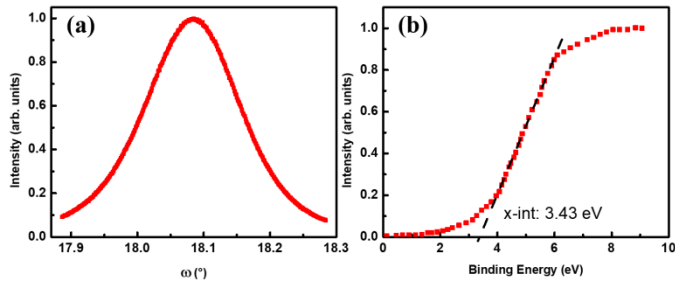


Fig. 1. (a) HR-XRD rocking curve for the (0002) plane in the AlN epilayer. (b) XPS valence band spectrum. Reproduced from [5].

Several AlN Schottky diodes were fabricated by standard lithographic patterning. Ohmic contacts comprised of Ti/Al/Ti/Au stacks were deposited on the AlN epilayers via electron beam evaporation. The ohmic contacts were annealed at 1000°C for 30 s in N<sub>2</sub> ambient. The Schottky contacts were also deposited using electron beam evaporation without annealing. Neither passivation nor field-plating was employed in any device. The devices had circular ohmic contacts with diameters of 400 μm. The Schottky contact used a circular shape with diameter 200 or 300 μm. device is shown in Fig. 2. The distance between the contacts was 200 μm. More details on the fabrication process can be found in [5].

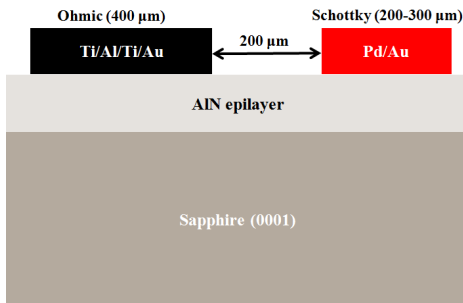


Fig. 2. Side view of the diode. Reproduced from [5].

The I–V characteristics were determined using a Keithley 4200-SCS parameter analyzer on a thermally-controlled probe station. Gamma ray irradiation was carried out using a <sup>60</sup>Co source.

### III. RESULTS AND DISCUSSION

Fig. 3(a) shows the temperature-dependent I–V curves of AlN diodes with 200 μm diameter Schottky contacts. A turn-on voltage of 2.2 V is observed at 305 K, which is similar to previous reported values for AlN [13,14]. As temperature increases, the turn-on voltage decreases from 2.2 to 1.6 V, perhaps owing to high-energy electrons being generated or a slight reduction in AlN bandgap at high temperatures. The off-state current density is ~1 μA/cm<sup>2</sup>. Fig. 3(b) shows the diode ideality factors as a function of temperatures, which show very large values. This implies that the fabricated diodes deviate from the thermionic emission model [15]. Possible causes include lateral non-uniformities at the Schottky-contact interface [13,16], tunneling effects, leakage currents, and defect-related generation and recombination [17]. The temperature dependence of the ideality factor is referred to as

the T<sub>0</sub> anomaly and is related to the lateral inhomogeneity of the Schottky barrier. The T<sub>0</sub> anomaly relates the ideality factor *n* as  $n=1+T_0/T$ , for some constant T<sub>0</sub> related to barrier distribution. An excellent trendline fit between this model and the experimental data can be observed.

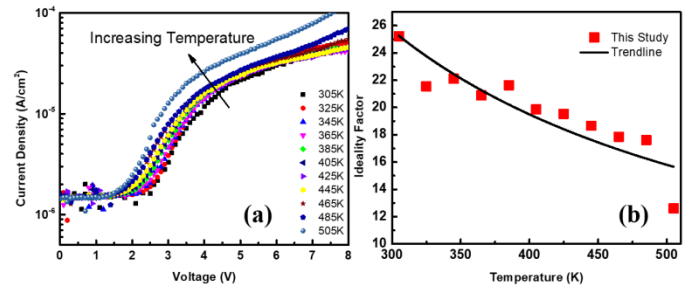


Fig. 3. (a) Forward-bias I–V characteristics of the AlN Schottky diodes, for 305 to 485 K. (b) Temperature dependence of the ideality factor for the AlN Schottky diodes. Reproduced from [5].

For the circular AlN Schottky diodes with 300 μm diameter, it was found that with increasing temperature, the breakdown voltage (V<sub>BD</sub>) decreases (Fig. 4(a) and 4(b)). If impact ionization was the main breakdown mechanism, V<sub>BD</sub> would instead show a positive dependence on temperature, since the phonon scattering-limited mean free path (MFP) is reduced at higher temperatures. A larger electric field would be needed to get enough energy for impact ionization. However, a breakdown mechanism related to surface states has a negative temperature dependence because hopping conduction through surface states is more active at higher temperatures. These results are consistent with the XPS data (Fig. 1(b)) that show a large amount of surface states in the as-grown AlN sample. Surface states in AlN are related to dangling Al bonds and are much more numerous in AlN compared to GaN. Thus, surface leakage through these surface states is a large contributor to device breakdown.

The effect of gamma ray irradiation from 0–90 MRads on the I–V characteristics of the diodes and sample crystallinity was observed for the 300 μm circular diodes at a separation of 200 μm. As the radiation increased, the turn-on voltage of the diodes decreased from 2.2 V at 0 MRads down to 1.8 V at 90 MRads (Fig. 5(a)). Forward currents decreased with increasing radiation. HR-XRD measurements taken after each dose show similar full width half maximum values, not deviating appreciably from 0.16° after irradiation. As the radiation increases from 0 to 90 MRads, there is a slight change in peak position of the XRD results, from 18.08 to 18.02° (Fig. 5(b)). These results indicate little crystal degradation in the bulk. The slight change in peak position can perhaps be a result of experimental setup variations.

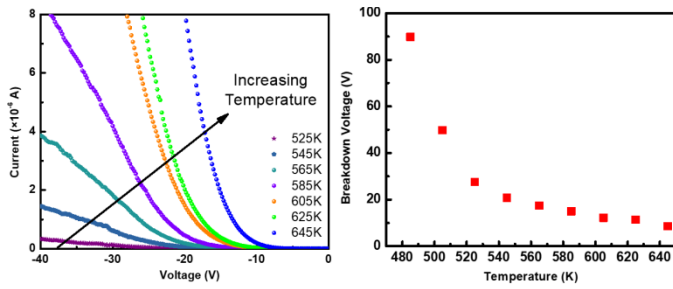


Fig. 4. (a) Reverse bias I-V characteristics at high temperatures, and (b) breakdown voltage as a function of temperature, for the AlN Schottky diodes. Reproduced from [5].

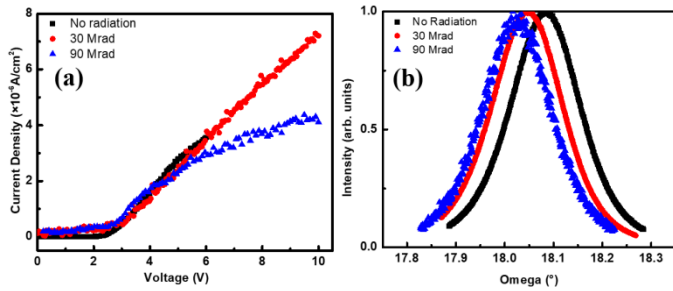


Fig. 5. (a) Forward-bias I-V characteristics before and after gamma ray irradiation, and (b) HR-XRD data before and after gamma ray radiation exposure.

The 300  $\mu\text{m}$  AlN Schottky diodes were further subjected to 3 MeV proton irradiation at doses ranging from  $5 \times 10^9 \text{ cm}^{-2}$  up to  $5 \times 10^{15} \text{ cm}^{-2}$ . Figs. 6(a) and 6(b) show the forward- and reversed-bias currents of the AlN Schottky diodes before and after proton irradiation. The currents do not decay appreciably until suddenly the highest dose of  $5 \times 10^{15} \text{ cm}^{-2}$ , where they drop to zero.

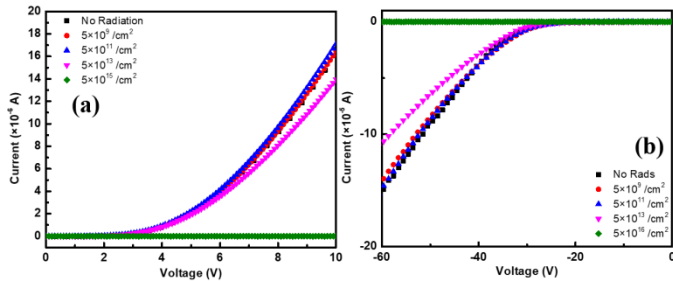


Fig. 6. Forward- (a) and reverse-bias (b) currents before and after proton irradiation for the AlN Schottky diodes.

The proton irradiated AlN Schottky diodes were also subjected to high-temperature tests ranging from 20°C to 120°C, and the results are shown in Figs. 7 and 8. A consistent trend of increasing forward currents and decreasing reverse currents is observed with increasing temperature. As the radiation dose increases up to  $10^{13} \text{ cm}^{-2}$ , there is no appreciable drop in the currents, indicating that radiation bombardment has not hindered the performance. The currents after the  $10^{15} \text{ cm}^{-2}$  are not presented here.

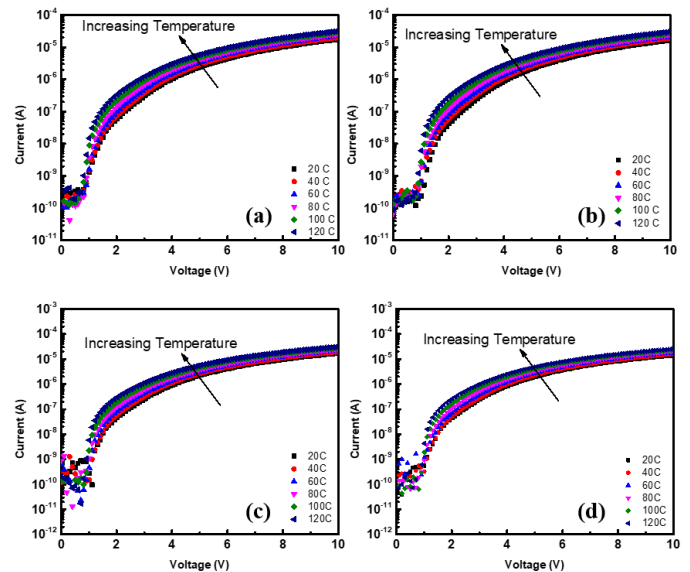


Fig. 7. High-temperature forward-bias I-V tests at various proton radiation doses for the AlN Schottky diodes. (a) After no radiation. (b) After a dose of  $5 \times 10^9 \text{ cm}^{-2}$ . (c) After  $5 \times 10^{11} \text{ cm}^{-2}$ . (d) After  $5 \times 10^{13} \text{ cm}^{-2}$ .

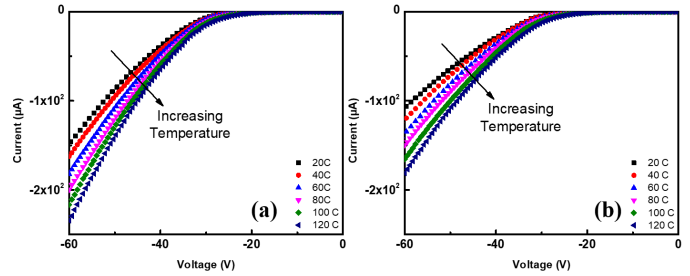


Fig. 8. High-temperature reverse-bias I-V tests at various proton radiation doses of the AlN Schottky diodes. (a) After  $5 \times 10^{11} \text{ cm}^{-2}$ . (b) After  $5 \times 10^{13} \text{ cm}^{-2}$ .

The diode ideality factors for the proton-irradiated devices were calculated as a function of temperature and the results are shown in Fig. 9(a). The ideality factors decrease with increasing temperature, which is consistent with the previous observation. The exact nature of their dependence on proton dose, however, requires further study. The ideality factor for the device after  $10^{15} \text{ cm}^{-2}$  could not be calculated. Shown in Fig. 9(b) is the FWHM values extracted HR-XRD measurements taken for the (0002) and (2024) planes of the AlN devices as a function of their proton radiation exposure. The FWHM values increase with radiation doses, showing a slight decrease in crystalline quality after bombardment.

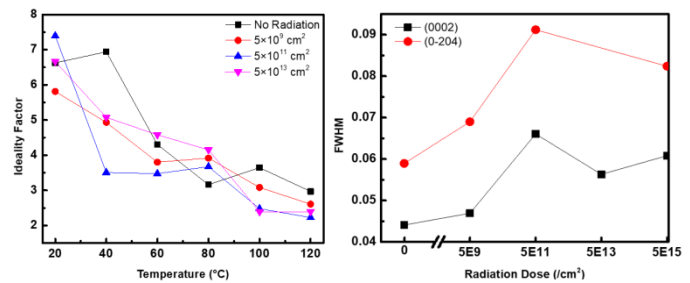


Fig. 9. (a) Diode ideality factors of the irradiated devices as a function of temperature. (b) FWHM values for the (0002) and (2024) planes as a function of proton radiation dose.

#### IV. CONCLUSIONS AND FUTURE WORK

Lateral Pd/n-AlN Schottky diodes were designed and fabricated using MOCVD. The temperature-dependent forward and reverse I-V characteristics were obtained and analyzed. The devices were exposed to gamma ray and proton irradiation. The breakdown voltage showed a negative temperature dependence which, coupled with our XPS data and previous work [5], showed that the electrical property of AlN Schottky diodes is strongly dependent on surface states. Radiation treatments with gamma rays decreased forward currents slightly at the highest dose of 90 MRads. Crystalline quality as determined by HR-XRD showed little degradation after gamma ray irradiation. I-V characteristics improved slightly after subjecting the AlN Schottky diodes to high-temperature settings. Proton bombardment showed a negligible effect on forward- and reverse-bias currents until a dose of  $10^{15}$  cm<sup>-2</sup>, where they abruptly dropped to zero. FWHM values from HR-XRD shows crystal degradation with each proton dose.

Future work will focus on the analysis of the fundamental radiation parameters such as total dose effects, defect energy levels, thermal stabilities, and the roles of pre-existing defects using comprehensive materials characterization methods. The impacts of the surface states on the radiation performance of AlN devices will also be explored.

#### ACKNOWLEDGMENTS

This work is supported by Defense Threat Reduction Agency (DTRA) Young Investigator Program Grant No. HDTRA11710041, supported by Dr. Jacob A. Calkins.

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