

Al rich AlGa_N based APDs on single crystal AlN with solar blindness and room temperature operation

Pramod Reddy
Adroit Materials
Cary NC, USA
pramod@adroitmaterials.com

M. Hayden Breckenridge
Department of Materials
Science and Engineering
North Carolina State
University
Raleigh, NC
mhbrecke@ncsu.edu

Andrew Klump
Department of Materials Science
and Engineering
North Carolina State University
Raleigh, NC
ajklump@ncsu.edu

Qiang Guo
Department of Materials Science
and Engineering
North Carolina State University
Raleigh, NC
qguo4@ncsu.edu

Seiji Mita
Adroit Materials
Cary NC, USA
smita@ncsu.edu

Biplab Sarkar
Department of Materials
Science and Engineering
North Carolina State
University
Raleigh, NC
bsarkar@ncsu.edu

Ronny Kirste
Adroit Materials
Cary NC, USA
ronny@adroitmaterials.com

Baxter Moody
Adroit Materials
Cary NC, USA
baxter@adroitmaterials.com

James Tweedie
Adroit Materials
Cary NC, USA
james@adroitmaterials.com

Ramon Collazo
Department of Materials
Science and Engineering
North Carolina State
University
Raleigh, NC
rcollaz@ncsu.edu

Zlatko Sitar
Department of Materials Science
and Engineering
North Carolina State University
Raleigh, NC
sitar@ncsu.edu

Abstract— We demonstrate Al rich AlGa_N based APDs grown on AlN substrates capable of high sensitivity at room temperature with ambient lighting rejection showcasing the advantage over Si and Ge based detectors. APDs are operated in linear gain region with maximum gain exceeding 1100.

Keywords—AlGa_N, APD, solar blindness

I. INTRODUCTION

Development of a compact and efficient avalanche photodiode (APD) operating in deep-UV regime with ambient or visible light rejection capabilities and room temperature operation is of great interest for implementation of next generation bio-chem-detectors, nuclear detectors etc. Al rich ($x > 0.5$) Al_xGa_{1-x}N is an excellent material system with a tunable wide bandgap transparent in the visible region, high breakdown fields ($> 10 \text{ MV cm}^{-1}$) and low leakage currents. Hence avalanche photodiodes (APD) based on Al rich AlGa_N are expected to be solar blind, highly sensitive, smaller, less expensive, and more robust than current UV detectors. However there are many challenges in designing and implementing AlGa_N based APDs including Mg carry forward and compensating defects (C_N and threading dislocations) and dislocation mediated leakage. Specifically, screw dislocations have been demonstrated to be a source of leakage in GaN p-n junctions.[1], [2] Hence implementation on single crystal AlN with threading dislocation density (TDD) $< 10^3 \text{ cm}^{-2}$ is expected to greatly reduce leakage (dark) current.[3] Accordingly, in this work, we demonstrate AlGa_N APDs on AlN substrates with high multiplication gain exceeding 1100, very low dark current ($< 1 \text{ pA}$) at room temperature, with ambient and solar spectra blindness.

II. APD DESIGN

APD design is directed by simulations performed using ATLAS framework (Silvaco). Designing the Al rich AlGa_N based APD requires not only the understanding of the interdependence of the sensitivity of the APD (i.e. magnitude of dark current) and the desired operating voltage as in a typical APD, but also the knowledge of doping behavior, surface electronic properties and ionization coefficients of AlGa_N. Typically, the gain region (p-n junction) has higher doping concentration than π region for higher electric fields that result in increased carrier ionization co-efficient. At sufficiently high ionization coefficient over sufficiently long length scales, avalanche breakdown with large gain is possible. For linear gain region operation, either hole or electron multiplication is necessary. One of the key requirements of AlGa_N based APDs, the APD structure grown on c-plane AlN needs to terminate with Mg doped p-AlGa_N and p-GaN to avoid the effects of Mg “carry forward” or diffusion towards the surface. Hence APD was designed initially as hole multiplication device with the absorption region serving as a charge separation region sending only holes towards the multiplication region. For increased sensitivity, the doping in gain region is designed to ensure avalanche breakdown (gain) dominating over Zener effects (tunneling or “dark current”) within reasonable operating voltage. Typically, very high doping results in Zener or tunneling current leakage and hence lowering sensitivity but ensures lower operating voltages. In contrast, very low doping results in high voltage operation but better sensitivity. However, minimum Si (donor) doping densities in the “ π ” region were constrained by

compensation. Here the compensators namely C_N and vacancy-oxygen complexes are controlled to $\leq 10^{17} \text{ cm}^{-3}$ by chemical potential control[4] where the formation energies of the compensating defects are increased by tuning the metal and nitrogen chemical potentials in the growth environment accordingly and TDD related compensation[5], [6] by growth on single crystal AlN. The thickness of the “ π ” region where most of the photon absorption occurs was 500 nm which is thick enough for >99% of light absorption. Finally, the p-i-n multiplication region was designed to be 45 nm/10 nm/ 45 nm with doping of $5 \times 10^{18} \text{ cm}^{-3}$ in n and $2 \times 10^{19} \text{ cm}^{-3}$ in p with nominally undoped i-region with simulations indicating operation at $\sim 100 \text{ V}$ with very high sensitivity better than $1 \mu \text{Wcm}^{-2}$. Finally, beveled termination is necessary to reduce the surface fields and to reduce edge leakage and to prevent edge breakdown expected in purely vertical etched structures.

III. EXPERIMENTAL

APD structures (diameter of $100 \mu\text{m}$) were grown on AlN single crystal substrate in a vertical, rf-heated low-pressure MOCVD reactor equipped with an open showerhead. A 300 nm thick AlN layer was grown to serve as a template for doped AlGa_{0.65}N growth. The dislocation density (DD) on AlN substrate was $< 10^3 \text{ cm}^{-2}$. The reactor total pressure was kept constant at 20 Torr throughout the growth. Trimethylaluminum (TMA), triethylgallium (TEG), and NH_3 were used as Al, Ga, and N precursors, respectively. SiH_4 and Cp_2Mg were used as the Si and Mg dopant sources respectively. AlGa_{0.65}N layers were grown in H_2 diluent gas. Al mole fraction in strained AlGa_{0.65}N layer on AlN was determined by the relative measurement between AlN and AlGa_{0.65}N peaks. The details of the composition measurement technique are described elsewhere.[7] The ratio of and individual TEG and TMA flow rates were chosen to obtain the required composition shown in Figure 1. The low defect density was achieved under higher NH_3 flows (i.e. N rich conditions) as described in Reddy et al[4]. The Mg doped sample was then activated at 800°C for 20 min in N_2 ambient. Conventional photolithography and reactive ion etching (RIE) using Cl_2 based recipe was employed to etch the mesa into AlGa_{0.65}N with a bevel angle of $\sim 38^\circ$ (shown in Figure 2 where AlGa_{0.65}N on sapphire was characterized). V/Al/Ni/Au based ohmic contact metallization scheme was used for n-contact, and the contact anneal was performed using rapid thermal anneal (RTA) at 850°C for 1 min under N_2 ambient. Standard Ni/Au contact was then deposited on p-GaN, and the contact was annealed at 600°C for 10 mins in air ambient. Both the contact metallization's were achieved using conventional photolithography, e-beam evaporation and lift-off process. I-V measurements were performed using a Keithley 4200 semiconductor parameter analyzer. Illumination for testing was achieved by Hg-Xe lamp.

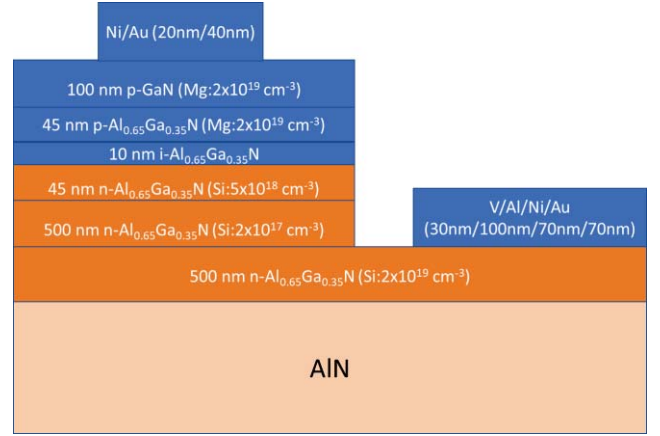


Figure 1: Characterized APD structure with a p-i-n gain medium.

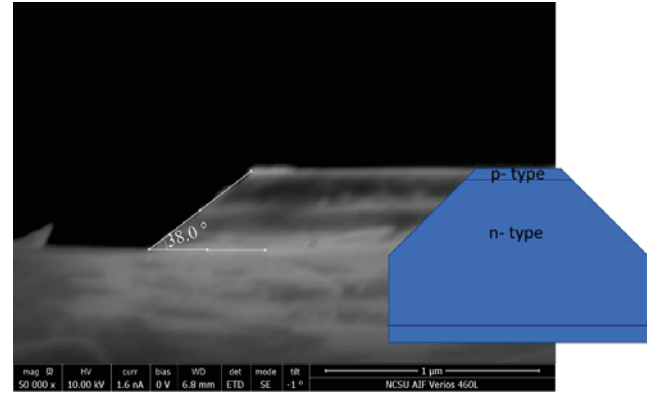


Figure 2: SEM image of the etched mesa structure in AlGa_{0.65}N on sapphire showing beveled edges. A schematic (not to scale) of the APD p-n junction is shown for illustrative

IV. RESULTS AND DISCUSSION

We initially characterized dark current and ambient/white light rejection. The APD reverse biased I-V characteristics in the absence of any above bandgap illumination is shown in Figure 3 at room temperature. Three key performance metrics may be illustrated:

1. The operation was at room temperature.
2. They demonstrate excellent ambient light rejection capability with no perceivable increase in the reverse current under illumination by white LED array in addition to room lighting.
3. The dark current is very low (below $\sim 1 \text{ pA}$) for applied bias $< 25 \text{ V}$ before linear gain region, allowing for very low noise and hence high sensitivity under ambient lighting and at room temperature.

It is obvious that Al rich AlGa_{0.65}N based APDs grown on AlN substrates are capable of very high sensitivity at room temperature operation under ambient lighting which is obviously not possible for Si or Ge based detectors. Figure 3 shows the photocurrent in comparison to dark current through the designed APD. For applied reverse bias $> 25 \text{ V}$, the increase in photo-current is due to ionization gain and exhibits a linear

gain region. It also exhibits a transition to a high linear gain region at higher fields for voltages >150 V. Although the device is still in linear gain region, it already exhibits gains exceeding 1100 as shown in Figure 4. Finally, the estimated gains ionization coefficients employed for simulation and designing the APD was found to lower than the experimentally observed breakdown observed at voltages >250 V. The experimentally observed breakdown fields for $\text{Al}_{0.65}\text{Ga}_{0.35}\text{N}$ was found to be $>10\text{MVcm}^{-1}$.

V. CONCLUSION

We have demonstrated Al rich AlGaIn based APDs grown on AlN substrates with low dark current and high sensitivity at room temperature and under ambient lighting and white LED illumination showcasing the advantage over Si and Ge based detectors. APDs were operated in linear gain region with maximum gain exceeding 1100.

ACKNOWLEDGMENT

Partial financial support from NSF (DMR-1508191, ECCS-1610992, ECCS-1653383), ARO (W911NF-15-2-0068, W911NF-16-C-0101), AFOSR (FA9550-17-1-0225) and DE-SC0011883 is greatly appreciated.

REFERENCES

- [1] S. Usami *et al.*, "Correlation between dislocations and leakage current of p-n diodes on a free-standing GaN substrate," *Appl. Phys. Lett.*, vol. 112, no. 18, p. 182106, Apr. 2018.
- [2] J. W. P. Hsu, M. J. Manfra, R. J. Molnar, B. Heying, and J. S. Speck, "Direct imaging of reverse-bias leakage through pure screw dislocations in GaN films grown by molecular beam epitaxy on GaN templates," *Appl. Phys. Lett.*, vol. 81, no. 1, pp. 79–81, Jun. 2002.
- [3] R. Dalmau *et al.*, "Growth and Characterization of AlN and AlGaIn Epitaxial Films on AlN Single Crystal Substrates," *J. Electrochem. Soc.*, vol. 158, no. 5, pp. H530–H535, May 2011.
- [4] P. Reddy *et al.*, "Point defect reduction in MOCVD (Al)GaIn by chemical potential control and a comprehensive model of C incorporation in GaN," *Journal of Applied Physics*, vol. 122, no. 24, p. 245702, Dec. 2017.
- [5] I. Bryan *et al.*, "Doping and compensation in Al-rich AlGaIn grown on single crystal AlN and sapphire by MOCVD," *Appl. Phys. Lett.*, vol. 112, no. 6, p. 062102, Feb. 2018.
- [6] E. C. H. Kyle, S. W. Kaun, P. G. Burke, F. Wu, Y.-R. Wu, and J. S. Speck, "High-electron-mobility GaN grown on free-standing GaN templates by ammonia-based molecular beam epitaxy," *Journal of Applied Physics*, vol. 115, no. 19, p. 193702, May 2014.
- [7] J. Tweedie *et al.*, "X-ray characterization of composition and relaxation of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($0 \leq x \leq 1$) layers grown on GaN/sapphire templates by low pressure organometallic vapor phase epitaxy," *Journal of Applied Physics*, vol. 108, no. 4, p. 043526, Aug. 2010.

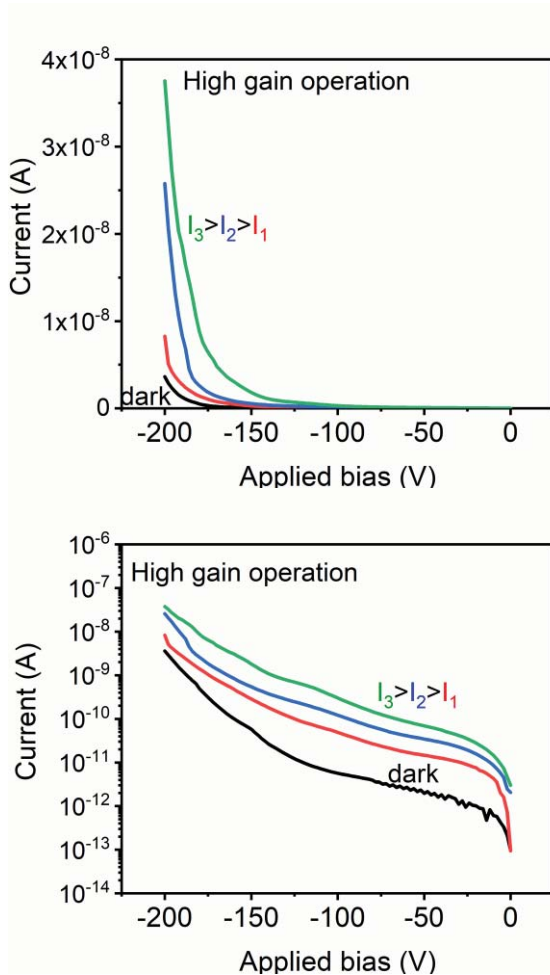


Figure 3: The dark and photo-current on linear and semi-log scales for the APDs shown in Figure 1.

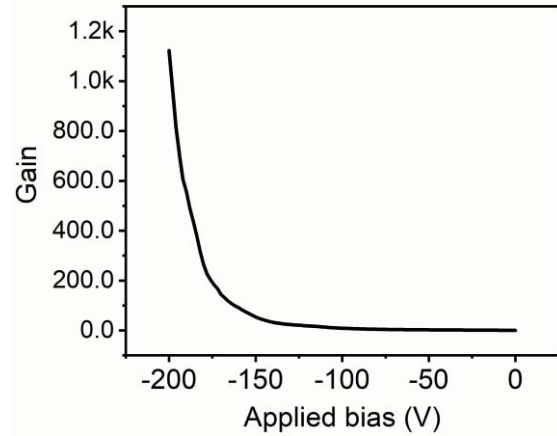


Figure 4: High Gain measured for the APDs shown in Figures 3.