High quantum efficiency back-illuminated GaN avalanche photodiodes

C. Bayram,[1] J. L. Pau,[1] R. McClintock,[1] M. Razeghi,[1,a)] M. P. Ulmer,[2] and D. Silversmith[3]
[1]*Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208, USA*
[2]*Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[3]*Air Force Office of Scientific Research, Arlington, Virginia 22203, USA*

(Received 10 October 2008; accepted 7 November 2008; published online 26 November 2008)

Back-illuminated avalanche photodiodes (APDs) composed of heterojunctions of either *p*-GaN/*i*-GaN/*n*-AlGaN or *p*-GaN/*i*-GaN/*n*-GaN/*n*-AlGaN were fabricated on AlN templates. At low voltage, an external quantum efficiency of 57% at 352 nm with a bandpass response was achieved by using AlGaN in the *n*-layer. Dependency of gain and leakage current on mesa area for these heterojunction APDs were studied. Back-illumination via different wavelength sources was used to demonstrate the advantages of hole-initiated multiplication in GaN APDs. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3039061]

Ultraviolet (UV) detectors have numerous applications in scientific, medical, and military areas that require high sensitivity and benefit from internal gain.[1] Currently available high gain detectors include photomultiplier tubes, which are bulky, fragile, and costly, and silicon based detectors, which require external filtering for visible-blind UV detection. Avalanche photodiodes (APDs) combine the advantages of high speed, high sensitivity, and large gain in a small device. Wide bandgap semiconductors such as (Al)GaN and SiC make it possible to realize APDs that offer a reliable, robust, and compact alternative to current UV detectors.[1,2] AlGaN also provides the unique possibility of tuning the bandgap in a wide range from 364 to 200 nm.[3]

A major issue for UV back-illuminated GaN APDs is the low diffusion length in the *n*-GaN below the active region. This limits the hole injection from the *n*-layer where most of the absorption occurs and leads to low quantum efficiencies,[4] which eventually restrict the single photon detection efficiency in Geiger-mode operation.[5] Improving the external quantum efficiency (EQE) (at low voltages when gain is unity) of these APDs can be accomplished by introducing aluminum into the *n*-layer to help shift the absorption toward the *i*-GaN region. Using a similar approach, the EQE of GaN/AlGaN photodiodes was improved up to 70% in another work.[6] However, the observation of avalanche gain in such device is difficult due to the significant increase in the dark current as a consequence of the propagation of dislocations from the *n*-AlGa(In)N layer into the multiplication region.[7] The breakdown and avalanche gain characteristics of AlGaN APDs were observed to suffer for similar reasons.[8,9] In this work, we report on back-illuminated GaN/AlGa(In)N heterojunction APDs, which possess a hard avalanche breakdown, reliable avalanche gain, and inherently high EQE.

The samples were grown in an AIXTRON 200/4-HT horizontal flow, low pressure metalorganic chemical vapor deposition (MOCVD) reactor. First, a transparent AlN template layer via pulsed atomic layer epitaxy (PALE) was grown. Then, high quality *n*-$Al_{0.24}Ga_{0.76}$(In)N was realized via optimization of MOCVD growth parameters. Indium was used in this layer to enhance the mobility of adatoms and observed to improve the AlGa(In)N surface quality.[10] High quality AlN template was used as we determined that it significantly improves the AlGaN regrowth quality as well as GaN quality.[11] A typical ($1\times 1\ \mu m^2$) atomic force microscopy image of optimized surface is given in the inset of Fig. 1. Root-mean-square roughness of 1.66 Å was achieved. No significant indium incorporation was observed via (0002) x-ray diffraction (XRD). This layer was doped *n*-type with silane (SiH_4) to achieve a carrier concentration of $3.2\times 10^{18}\ cm^{-3}$ with a Hall mobility of 49 $cm^2/V\ s$ and a resistivity of 0.04 Ω cm.

Counting all the reflections at air-sapphire, sapphire-AlN, AlN–AlGa(In)N, and AlGa(In)N–GaN interfaces under back-illumination, the reflection losses were calculated to be 11%. Transmission measurement of 200-nm-thick *n*-AlGa(In)N on 600-nm-thick AlN/sapphire is shown in Fig. 1. A cutoff wavelength of 313 nm is close to the 24% Al content calculated from XRD.

On top of this layer, the *i*-GaN active region and *p*-GaN capping layer were grown. The *i*-GaN active region had a carrier concentration of $\sim 10^{16}\ cm^{-3}$. For higher APD performance,[12] the *p*-GaN was grown by our optimized delta-doping technique.[11] The full heterojunction APD struc-

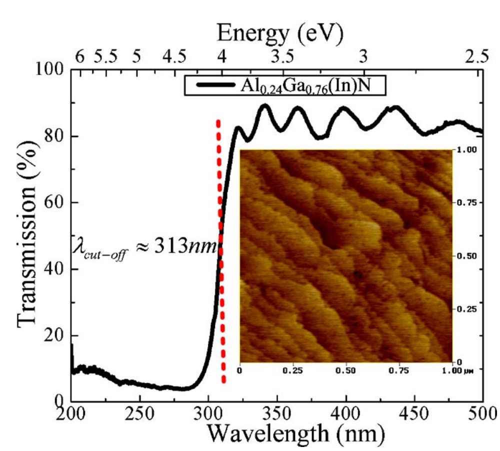

FIG. 1. (Color online) Transmission spectrum for *n*-$Al_{0.24}Ga_{0.76}$(In)N on AlN/sapphire showing sharp cutoff at 313 nm and Fabry–Pérot oscillations. The inset shows ($1\times 1\ \mu m^2$) atomic force microscopy image of optimized surface: root-mean-square roughness is 1.66 Å and height scale is 3 nm.

a)Electronic mail: razeghi@eecs.northwestern.edu.

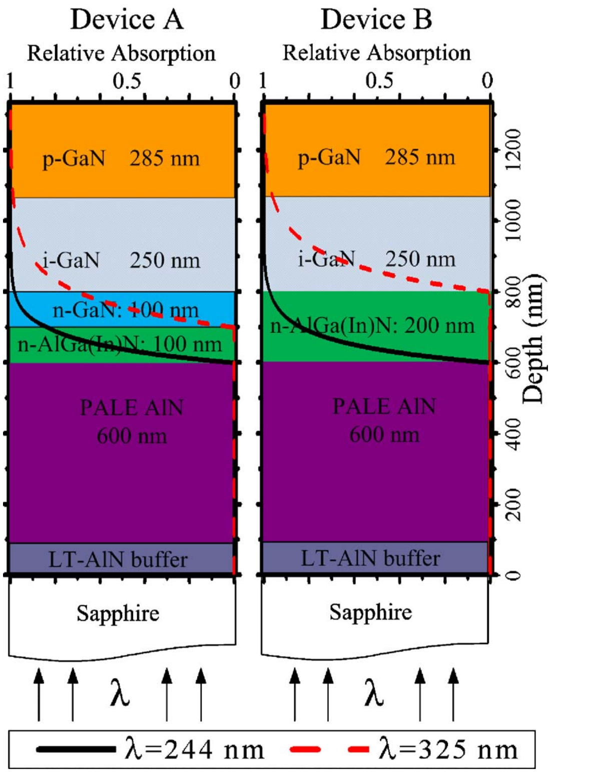

FIG. 2. (Color online) The basic structures of the devices are depicted. Top axis: relative absorption of 244 nm (solid line) and 325 nm (dashed line) light. Right axis: depth (nm). AlN template was grown via PALE technique.

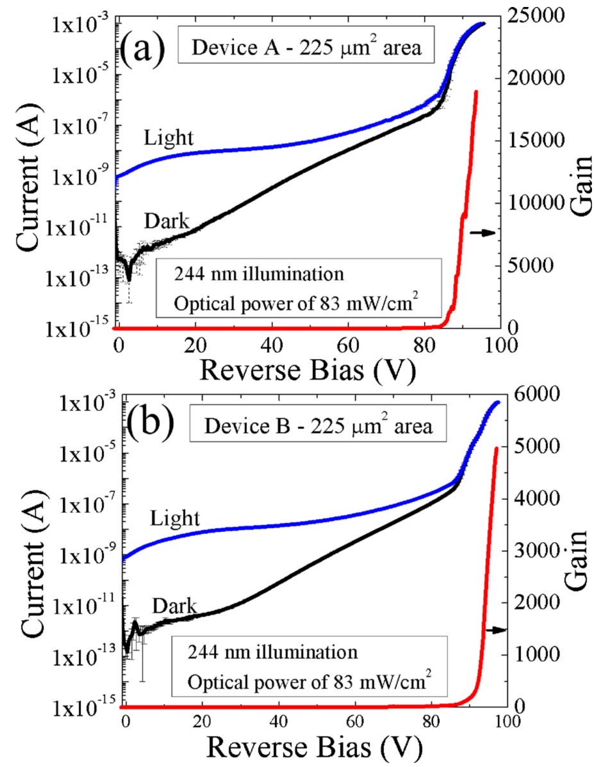

FIG. 4. (Color online) *I-V* curves for circular devices (225 μm^2 mesa area under dark and 244 nm illumination, as well as gain curves of (a) device A and (b) device B. Standard deviation is shown as ordinate bars on the data points.

ture is given in Fig. 2. Two different designs, devices A and B, were used, which differ only in the *n*-layer. These devices were then processed into various sized APDs using standard fabrication techniques.

In order to study the quantum efficiency, spectral responsivity measurements were realized under back-illumination using a xenon arc lamp and monochrometer.[4] Before the onset of gain (−20 V), peak responsivities of 126 mA/W at 360 nm and 163 mA/W at 352 nm were achieved by devices A and B, respectively. These correspond to EQEs of 43% and 57%, respectively. For comparison, a reference homojunction APD was also fabricated.[4] This device only exhibited a peak responsivity of 99 mA/W at 362 nm (corresponding to an EQE of 34%). The spectral responses of these devices are given in Fig. 3. For homojunction GaN APDs, shorter-wavelength photons are more likely to be absorbed closer to the AlN interface and thus less likely to diffuse into the depletion region. AlGa(In)N as *n*-layer shifts the absorption toward the depletion region and thus enhances the EQE. In addition to affecting the EQE, the *n*-$Al_{0.24}Ga_{0.76}$(In)N layer introduces a short wavelength cutoff due to its absorption edge at 313 nm. This, combined with the 365 nm wavelength cutoff of *i*-GaN, gives a bandpass spectral response between 313 and 365 nm and improves the EQE of GaN APDs in that range (as seen in Fig. 3).

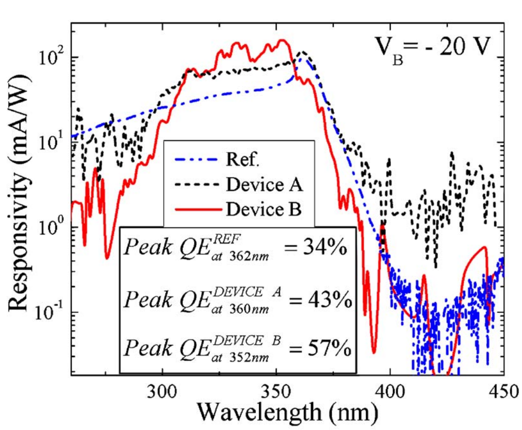

FIG. 3. (Color online) Spectral responses for reference homojunction device, device A, and device B (at reverse bias of 20 V, taken as unity gain). The enhancement in EQE through using *n*-AlGaN is observed.

Choosing the AlGa(In)N composition to have a cutoff wavelength of 313 nm enables us to use a 325 nm HeCd laser to cause absorption in only the GaN layers or to use a 244 nm laser to cause absorption in both the GaN and AlGa(In)N layers (see Figs. 1 and 2). To begin with, we used the 244 nm laser (optical power=83 mW/cm^2) to study gain characteristics.

The gain characteristics were determined by measuring the dark and light *I-V* curves under reverse bias and subtracting to obtain the photocurrent.[4] The gain is then determined by normalizing the photocurrent by the value at the onset of gain. The onset of gain is determined to be at −20 V, establishing the photocurrent value corresponding to unity gain. Figures 4(a) and 4(b) display the light and dark current curves along with the resulting gain of circular 225 μm^2 device of structures A and B, respectively. The breakdown occurs around 83 V, corresponding to electric field strength of 2.7 MV/cm—close to theory[13] and our previous experimental observations.[4,5] Device A achieves almost four times higher gain than device B. As both *n*-layers are where the majority of 244 nm light is absorbed (Fig. 2), this higher gain in device A should be due to higher diffusion length in GaN

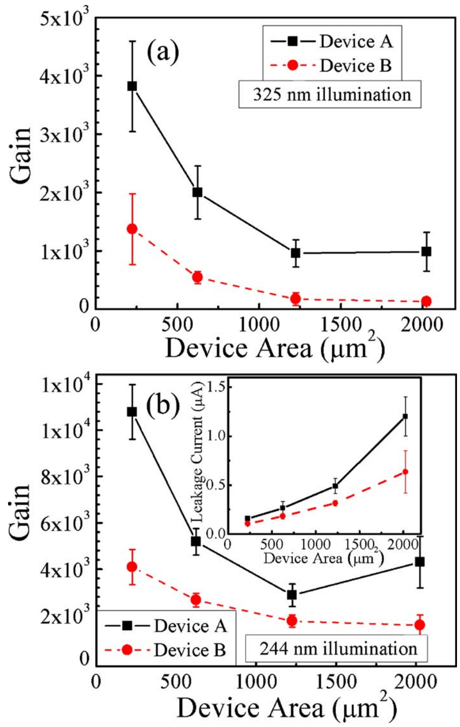

FIG. 5. (Color online) Average gain vs device area for devices A and B under (a) 325 nm and (b) 244 nm illuminations. The inset in (b) shows leakage current dependency on device area for the two designs. Standard deviation is shown as ordinate bars on data points.

than in AlGa(In)N, leading to higher hole injection from the *n*-layer.

Next, gain characteristics of circular mesas ranging in area from 225 to 2025 μm^2 were studied under both illumination wavelengths. An illumination power of 8.1 mW/cm^2 was used for 325 nm source. Fifteen devices of each mesa area were measured. The average gain and standard deviation are plotted in Figs. 5(a) and 5(b) for 325 and 244 nm illuminations, respectively. The average gain was strongly dependent on the device area. The smallest devices showed the highest gain, whereas gain decreased as the area increased. The average gain was observed to be stabilized for devices larger than 1225 μm^2. We attribute this to a more uniform distribution of dislocations for larger area devices. The leakage current, averaged over 50 devices across the sample, is plotted with respect to device area in the inset of Fig. 5(b). It increases almost linearly with increasing mesa area, confirming an increase in the number of dislocations per device. We attribute the lower leakage of device B to the higher resistivity of the thicker *n*-AlGa(In)N layer. Both devices achieved higher gain with 244 nm illumination than with 325 nm, proving hole-initiated multiplication provides higher gain.[14] Sample B, with its thicker AlGa(In)N layer, had lower gain than sample A. This was expected considering that sample B enabled more light absorption in the intrinsic layer eliminating the selective injection of holes into the multiplication region.

In summary, back-illuminated GaN/AlGa(In)N ultraviolet heterojunction APDs with high quantum efficiencies were demonstrated. Below the onset of gain, a maximum EQE of 57% was achieved between 313 and 365 nm. This improved efficiency primarily arises from the use of AlGa(In)N as the *n*-layer allowing photons to be absorbed within the *i*-GaN eliminating carrier loss due to the AlN interface and diffusion processes. However, hole-initiated multiplication is shown to reach higher gain than electron-initiated multiplication. As a result, higher EQE APDs did not achieve higher gain. Combining gain and responsivity measurements, a trade-off between gain and EQE can be achieved by adjusting the ratio of GaN and AlGa(In)N in the *n*-layer.

[1] E. Monroy, F. Omnes, and F. Calle, Semicond. Sci. Technol. **18**, R33 (2003).
[2] J. C. Campbell, S. Demiguel, F. Ma, A. Beck, X. Guo, S. Wang, X. Zheng, X. Li, J. D. Beck, M. A. Kinch, A. Huntington, L. A. Coldren, J. Decobert, and N. Tscherptner, IEEE J. Sel. Top. Quantum Electron. **10**, 777 (2004).
[3] D. Walker, X. Zhang, A. Saxler, P. Kung, J. Xu, and M. Razeghi, Proc. SPIE **2999**, 267 (1997).
[4] K. Minder, J. L. Pau, R. McClintock, P. Kung, C. Bayram, M. Razeghi, and D. Silversmith, Appl. Phys. Lett. **91**, 073513 (2007).
[5] J. L. Pau, R. McClintock, K. Minder, C. Bayram, P. Kung, M. Razeghi, E. Munoz, and D. Silversmith, Appl. Phys. Lett. **91**, 041104 (2007).
[6] W. Yang, T. Nohova, S. Krishnankutty, R. Torreano, S. McPherson, and H. Marsh, Appl. Phys. Lett. **73**, 1086 (1998).
[7] A. Krost, J. Blasing, F. Schulze, O. Schon, A. Alam, and M. Heuken, J. Cryst. Growth **221**, 251 (2000).
[8] R. McClintock, A. Yasan, K. Minder, P. Kung, and M. Razeghi, Appl. Phys. Lett. **87**, 241123 (2005).
[9] P. Kung, A. Yasan, R. McClintock, S. R. Darvish, K. Mi, and M. Razeghi, Proc. SPIE **4650**, 199 (2002).
[10] T. M. Al tahtamouni, A. Sedhain, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **92**, 092105 (2008).
[11] C. Bayram, J. L. Pau, R. McClintock, and M. Razeghi, J. Appl. Phys. **104**, 083512 (2008).
[12] C. Bayram, J. L. Pau, R. McClintock, and M. Razeghi, Appl. Phys. Lett. **92**, 241103 (2008).
[13] R. McClintock, K. Mayes, A. Yasan, D. Shiell, P. Kung, and M. Razeghi, Appl. Phys. Lett. **86**, 011117 (2005).
[14] G. E. Stillman and C. M. Wolfe, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1977), Vol. 12.