High quantum efficiency back-illuminated GaN avalanche photodiodes

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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. 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 $n$-AlGaN/$n$-GaN interfaces under back-illumination, the reflection losses were calculated to be 11%. Transmission measurement of 200-nm-thick $n$-AlGaN on 600-nm-thick AlN on sapphire is shown in Fig. 1. A cutoff wavelength of 313 nm is close to the 24% Al content calculated from XRD.7

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 $1\times 10^{18}$ cm$^{-3}$, and a Hall mobility of 49 cm$^2$/Vs and a resistivity of 0.04 $\Omega$ cm.8 Counting all the reflections at air-sapphire, sapphire-AlN, AlN–AlGaN, and AlGaN–GaN interfaces under back-illumination, the reflection losses were calculated to be 11%. Transmission measurement of 200-nm-thick $n$-AlGaN on 600-nm-thick AlN on sapphire is shown in Fig. 1. A cutoff wavelength of 313 nm is close to the 24% Al content calculated from XRD.7

In this work, we report on back-illuminated GaN/AlGaN/N heterojunction APDs, which possess a hard avalanche breakdown, reliable avalanche gain, and inherently high EQE.9 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$_{0.76}$N ($n$-AlGaN) 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 AlGaN/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 ($1\times 10^2$ $\mu$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 x-ray diffraction (XRD). This layer was doped $n$-type with silane (SiH$_4$) to achieve a carrier concentration of $1\times 10^{18}$ cm$^{-3}$ with a Hall mobility of 49 cm$^2$/Vs and a resistivity of 0.04 $\Omega$ cm.8,10

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The full heterojunction APD structure is shown in Fig. 1. Transmission spectrum for AlGaN/N on AlN on sapphire showing sharp cutoff at 313 nm and Fabry–Perot oscillations. The inset shows ($1\times 10^2$ $\mu$m$^2$) atomic force microscopy image of optimized surface: root-mean-square roughness is 1.66 Å and height scale is 3 nm.

FIG. 1. (Color online) Transmission spectrum for $n$-Al$_{0.24}$Ga$_{0.76}$N on AlN/sapphire showing sharp cutoff at 313 nm and Fabry–Perot oscillations. The inset shows ($1\times 10^2$ $\mu$m$^2$) atomic force microscopy image of optimized surface: root-mean-square roughness is 1.66 Å and height scale is 3 nm.
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. 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. 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).

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. 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 $\mu$m$^2$ 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 and our previous experimental observations. 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.
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.