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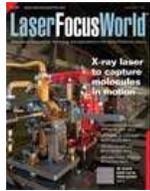
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Volume 45 Issue 9  
September, 2009

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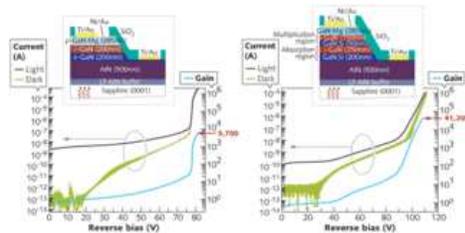
## ULTRAVIOLET DETECTORS: Nitrides push performance of UV photodiodes

*Nitrides offer considerable advantages over other materials for ultraviolet detection. Recently, they proved useful for creating the world's first UV single-photon detectors with efficiencies to 20%—detectors that could enable quantum computing and data encryption.*

**CAN BAYRAM and MANIJEH RAZEGHI**

Development of wide-bandgap [III-nitride semiconductors](#) has been a subject of intense focus since the 1990s, primarily driven by the quest for blue lasers and high-brightness light-emitting diodes (LEDs). In parallel, III-nitrides have been studied extensively for use in [ultraviolet \(UV\) photodetectors](#) because they offer intrinsic visible- or solar-blind detection, which would eliminate the need for expensive and efficiency-limiting optical filters to remove out-of-band visible or solar photons. Such detectors would be well suited for [numerous applications](#) in the defense, commercial, and scientific arenas, including covert space-to-space communications, early missile-threat detection, chemical and biological threat detection and spectroscopy, flame detection and monitoring, UV environmental monitoring, and UV astronomy.

Despite the advantages of III-nitride-based photodetectors, however, photomultiplier tubes (PMTs) still dominate in many of these applications. Photomultipliers can provide high sensitivity using internal electron-multiplication gain (typically  $\sim 10^6$ ), and a degree of visible- or solar-blindness with careful selection of photocathode material. But PMTs are also bulky and fragile, and require large biases (typically 1000 V) to operate effectively. Therefore, a compact, highly sensitive semiconductor-based photodetector would be a welcome alternative.



**FIGURE 1.** Traditional PIN APD devices (left) don't measure up to SAM-APD devices (right), whose gain enhancement is made possible through the use of the separate absorption and multiplication (SAM) regime.

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In principle, it is possible to achieve this goal with III-nitrides by taking advantage of avalanche multiplication under high electric fields—typically 2.7 MV/cm. With proper design, this can correspond to an external reverse bias of less than 100 V.<sup>1</sup>

### Back is better

Despite the relative ease of growing front-illuminated gallium nitride

(GaN) APDs, back-illuminated GaN APDs have proved to be more advantageous.<sup>2</sup> In a back-illuminated (p-doped) intrinsic (n-doped) (PIN) GaN structure, in which photons reach the n-type layer first, most holes are injected into the high-gain multiplication region (see Fig. 1, left). This enables higher gain and better overall performance because with GaN, near the critical field strength, the impact-ionization coefficient of the hole is higher than the impact-ionization coefficient of the electron. In addition, the integration of APD arrays with read-out electronics is easier in a back-illumination scheme.

Besides higher gain, a back-illuminated APD generates less noise. Because ionization events are initiated only by holes, statistical variation in the avalanche process is reduced as the holes traverse the multiplication region. In a normal back-illuminated device structure, the absorption of photons is not limited to the n-type layer, and a portion of the photons is absorbed in the multiplication region itself. This means that gain is not necessarily hole-initiated since electrons can be generated by photons absorbed in the multiplication region. Electron contribution to gain results in lower gain and higher noise than should otherwise be possible.

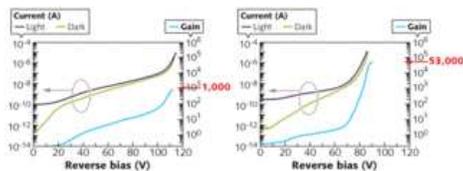
One way to overcome this limitation is to insert a thin n-type separation region between the absorption and multiplication regions to create a separate absorption and multiplication APD (SAM-APD) structure. The use of SAM regions is a common approach to reducing multiplication noise and enhancing gain through impact-ionization engineering. Gallium nitride avalanche photodiodes designed this way allow for nearly pure injection of holes into the multiplication region, and benefit from the higher ionization coefficient by offering lower noise performance and higher gain (see Fig. 1, right).<sup>3</sup>

### More measures for performance

In addition to impact-ionization engineering, carefully controlling material quality and doping can also enable better performance.

The breakdown voltage of APDs is largely determined by electric-field buildup in the device and the voltage at which the critical electric field is reached. Because the dark current tends to increase with voltage, reducing the breakdown voltage can be advantageous for achieving higher gains. For a given multiplication width, the primary limitation on the electric-field buildup is the low carrier concentration of the p-GaN layer.

The p-GaN quality is low for two reasons. First is a tradeoff in growth conditions because conditions that maximize magnesium (Mg) incorporation can degrade GaN quality. Second, the high activation energy of Mg requires that it be incorporated into the lattice at a level almost 100 times higher than the desired carrier concentration—which leads to a disruption of the GaN lattice.



**FIGURE 2.** Introducing  $\delta$ -doping reduces breakdown voltage and increases gain in linear mode, as shown by comparing conventional bulk- (left) and  $\delta$ -doped (right) SAM-APDs.

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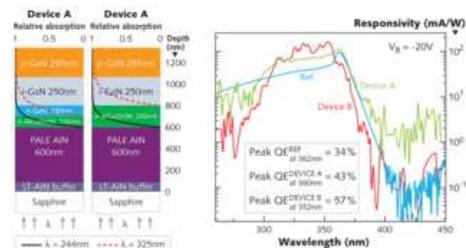
To overcome this and realize a high-quality p-GaN, we have investigated the use of a novel  $\delta$ -doping technique.<sup>4</sup> Compared to regular bulk p-type doping,  $\delta$ -doped p-GaN layers have demonstrated higher structural and electrical quality. By incorporating  $\delta$ -doped p-GaN into a SAM-APD structure, we have produced devices with superior performance.

Comparing conventional and  $\delta$ -doped SAM-APDs makes clear that  $\delta$ -doping reduces breakdown voltage and increases gain in linear mode (see Fig. 2). Our work produced maximum gain of 53,000 at 91 V—a factor of 50 higher than in the conventionally doped device. The enhanced performance is a result of better material quality and electric-field confinement in the multiplication region. A major issue for UV back-illuminated GaN APDs is low diffusion length in the n-GaN below the active region. This limits hole injection from the n-layer where most of the absorption occurs, and leads to low quantum efficiencies—which eventually restricts single-photon detection efficiency in Geiger-mode operation. It is possible to improve external quantum efficiency (EQE) (at low voltages when gain is unity) by using aluminum (Al) in the n-layer to help shift absorption toward the i-GaN region. It is difficult to see avalanche gain in such devices because the propagation of dislocations from the n-AlGa(In)N (aluminum gallium indium nitride) layer into the multiplication region increases in dark current significantly. We noticed that the breakdown and avalanche gain characteristics of AlGaN APDs suffered for similar reasons. And, we demonstrated back-illuminated GaN/AlGa(In)N heterojunction APDs—which have a hard avalanche breakdown,

reliable avalanche gain, and inherently high EQE (see Fig. 3).<sup>5</sup> Using AlGaIn for the n-layer increased the quantum efficiency from 34% to 57%.

### Single-photon detection

Many applications can benefit from—and some actually require—UV detectors with single-photon detection capabilities. In APDs it is possible to realize single-photon detection by using Geiger-mode operation, which entails operating the APDs well above the breakdown voltage and using pulse-quenching circuitry. When the electric field is high enough that a single charge carrier injected into the multiplication layer triggers a self-sustained avalanche, the current will flow until the avalanche is externally quenched. By developing a back-illuminated Geiger-mode APD, we have realized Geiger-mode APDs with a SPDE of 23% and a dark-count rate below 10 kHz (our measurement limit).<sup>6</sup>



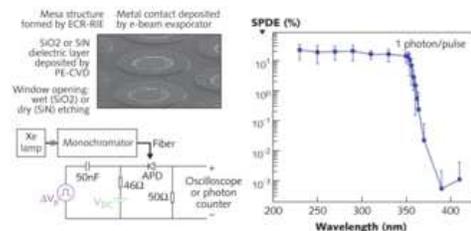
**FIGURE 3.** A back-illuminated PIN APD uses 100-nm-thick GaN on 100-nm-thick AlGa(In)N (Device A), and 200-nm-thick AlGa(In)N as an n-layer (Device B). The quantum-efficiency and responsivity curves of a reference device using 200-nm-thick GaN compares with an APD using AlGa(In)N.

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We measured the pulse detection efficiency of a fabricated GaN APD at different photon fluxes (photons/pulse) by varying the incident optical power. At high photon fluxes, the pulse detection efficiency was 100% and approached the SPDE value as we reduced the number of photons per pulse. In the 625  $\mu\text{m}^2$  area devices, we reached SPDE of 20% between 350 and 230 nm—which includes the so-called solar-blind range. Below the bandgap, we measured a sharp cutoff and a high visible light-rejection ratio (more than  $10^4$ ; see Fig. 4)

### Implications

Ultraviolet detection is important—many biological agents, including anthrax, luminesce in UV. Scattering of short-wavelength light in the atmosphere enables non-line-of-sight secure communications in rugged terrains, whereas strong reflection/absorption of UV at ionosphere promises secure space-to-space communications. Our highest performing UV GaN APDs demonstrated ruggedness and efficiency with gains of 53,000 and EQE of 57%. As the performance of GaN APDs is further enhanced, applications such as UV single-photon detection can emerge.



**FIGURE 4.** A fabricated GaN APD (upper left) uses pulsed quenching circuitry (lower left) for Geiger-mode operation. SPDE varies according to the wavelength of the photon source (right).

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Realization of the world's first UV single-photon detectors (SPDs) with efficiencies as high as 20% could enable quantum computing and data encryption in the near future. Compared with PMTs or superconducting single-photon detectors, the use of Geiger-mode APDs presents key advantages such as lower operation voltages, much reduced sizes, and no need for cooling to very low temperatures. This in turn may enable the fabrication of more-compact, lower power, and all-solid-state APD/CMOS integrated arrays.

### ACKNOWLEDGMENTS

The authors acknowledge valuable collaboration with J. L. Pau of Universidad Autonoma de Madrid; R. McClintock at Center for

Quantum Devices of EECS Department and Prof. M. P. Ulmer at Department of Physics and Astronomy, both at Northwestern University; D. Silversmith of the Air Force Office of Scientific Research; and the collaboration of Dr. Ferechteh H. Hosseini and her group at Nanovation (France).

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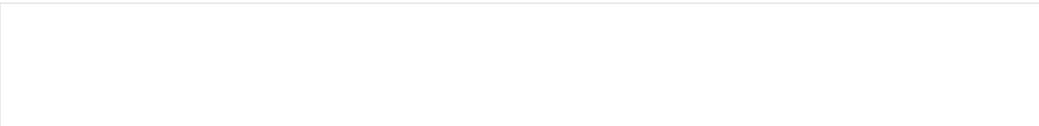
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