Performance enhancement of GaN ultraviolet avalanche photodiodes with *p*-type *δ*-doping

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(Received 13 May 2008; accepted 30 May 2008; published online 17 June 2008)

High quality *δ*-doped *p*-GaN is used as a means of improving the performance of back-illuminated GaN avalanche photodiodes (APDs). Devices with *δ*-doped *p*-GaN show consistently lower leakage current and lower breakdown voltage than those with bulk *p*-GaN. APDs with *δ*-doped *p*-GaN also achieve a maximum multiplication gain of 5.1×10^4, more than 50 times higher than that obtained in devices with bulk *p*-GaN. The better device performance of APDs with *δ*-doped *p*-GaN is attributed to the higher structural quality of the *p*-GaN layer achieved via *δ*-doping. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2948857]

Ultraviolet (UV) detectors have numerous applications in scientific, medical, and military areas that require high sensitivity and internal gain. Current high gain detectors such as photomultiplier tubes are bulky, fragile, and costly, whereas silicon based detectors require external filtering for visible-blind UV detection. Avalanche photodiodes (APDs) based on wide bandgap materials such as (Al)GaN and SiC offer a reliable, robust, and compact alternative to current UV detectors.[1] AlGaN also provides the unique possibility of tuning the bandgap in a wide range from 364 to 200 nm.

Impact ionization in GaN has been studied, and it has been determined that back-illuminated GaN APDs have better performance than front-illuminated devices due to the higher ionization coefficient for holes in GaN.[2] By improving the material quality and controlling the device area, uniform breakdown and gain have been obtained.[3] Using separate absorption and multiplication (SAM) regions, the multiplication gain of GaN APDs is recently improved in a linear-mode operation.[4] Moreover, the Geiger mode operation of back-illuminated GaN APDs has been demonstrated with a single photon detection efficiency as high as 20%.[5]

The breakdown voltage of these devices is largely determined by the 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 in achieving higher gains. For a given multiplication width, the primarily limitation on the electric field buildup is the low carrier concentration of the *p*-GaN layer.

A number of groups have recently worked to improving *p*-type GaN through *δ*-doping.[6,7] However, improving GaN-based optoelectronic devices through this technique requires more attention as device parameters are involved in their optimization. The *p*-GaN quality is low due (1) to tradeoffs in growth conditions since those at which Mg incorporation is maximized may degrade GaN quality and (2) to the fact that the high activation energy of Mg requires that the Mg incorporation in the lattice be almost 100 times higher than the desired carrier concentration, leading to a disruption of the GaN lattice.[8] Thus, the performance of *p-n* junction based optoelectronic devices based on GaN (especially APDs for which high reverse bias, good electric field uniformity, and low leakage current are required) is severely affected by the lower quality of the *p*-GaN. In this work, we characterize *p*-type GaN layers grown by using a *δ*-doping technique and compare them to regular bulk *p*-type doping. These *δ*-doped *p*-GaN layers are then incorporated into SAM APD structures to evaluate their performance.

The samples are grown in an AIXTRON 200/4-HT horizontal flow, low pressure metalorganic chemical vapor deposition reactor. Trimethylgallium (TMGa), trimethlyaluminum (TMAl), and bis(cyclopentadienyl)magnesium (DCpMg) are the metal-organic cation precursors for Ga, Al, and Mg sources, respectively. Ammonia (NH_3) is used as the nitrogen source. Hydrogen is used as the carrier gas in all doping studies and in the growth of the APDs.

For the *p*-type doping studies, *p*-GaN is grown on a 600-nm-thick AlN template grown on sapphire. The *δ*-doping profile is implemented as follows: (1) a specific thickness of GaN is deposited normally to grow the GaN period, (2) the TMGa flow is then stopped and the crystal surface is allowed to nitridize, and finally (3) the DCpMg flow is introduced for a specific Mg flow time. The dopant flow is then stopped and TMGa resumed so that the cycle can repeat as the next GaN period is grown.[9] For bulk *p*-type doped samples, TMGa and DCpMg are supplied together.

In order to optimize the hole concentration and material quality of the delta-doped GaN, we have varied the GaN period from 3 to 15 nm, nitridation time from 15 to 120 s, and Mg flow time from 15 to 75 s. After growth, all layers are annealed in a rapid thermal annealing system under N_2 for 30 s at 1000 °C for Mg activation. The structural crystalline quality of these layers is then characterized by x-ray diffraction (XRD) the optical characteristics by photoluminescence (PL), and the electrical properties by Hall measurement. We have found the optimum GaN period to be 10 nm followed by a 30 s nitridation and doped through a 60 s Mg flow time, leading to a carrier concentration of 9.4×10^{17} cm^{-3}. This doping concentration results in a Debye length of 13 nm at room temperature (RT), which is higher than the period of the GaN, allowing us to assume that the hole concentration is uniformly distributed across the layer.

Bulk *p*-GaN layers are also grown under different growth conditions for the sake of comparison. Table I sum-

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TABLE I. Comparison of bulk- and δ-doped p-GaN layers: growth temperature (T_G), growth pressure (P), carrier concentration (p), Hall mobility (μ_H), and XRD (002) FWHM.

Sample	p-GaN	T_G (°C)	P (mbar)	p (cm^{-3})	μ_H ($cm^2/V\,s$)	FWHM (arc sec)
A	Bulk-	1100	100	5.2×10^{15}	130	279
B	Bulk-	1020	100	7.5×10^{16}	28.8	238
C	Bulk-	1020	200	1.4×10^{18}	5.4	457
D	δ-	1100	100	9.4×10^{17}	2.5	312

marizes the characterization results. Samples A and D are bulk and δ-doped p-GaN samples, respectively, otherwise grown under the same conditions. By optimizing the pulsing scheme, at high growth temperature (1100 °C) and low pressure (100 mbars), high quality δ-doped p-GaN with two orders of magnitude higher hole concentration than bulk p-GaN can be achieved. Sample B is grown at lower temperatures and at 100 mbars; it achieves higher doping due to better Mg incorporation. At low temperatures, by increasing the pressure to 200 mbars, sample C achieves the same doping concentration as the δ-doped p-GaN grown at 100 mbars. However, the comparison of XRD full width at half maximum (FWHM) of sample C (457 arc sec) and sample D (312 arc sec) suggests that, at the same doping level, the structural quality of the δ-doped p-GaN is significantly higher.

RT PL of samples A, C, and D is shown in Fig. 1. The spectrum of sample A is dominated by 3.41 eV GaN band-edge emission, and no clear traces of the 2.91 eV Mg-related peaks are found due to the low Mg incorporation level. The spectrum of sample B is nearly identical to that of sample A and is thus not shown. Sample C shows a broad emission band centered at 2.91 eV. This band has been previously observed in bulk-doped p-GaN and has been attributed to doping related deep level centers.[10] The delta-doped sample (sample D) shows a strong emission at 3.41 eV, corresponding to the GaN band edge, however, 2.91 eV is still present. An additional line can also be found at 3.29 eV. The 3.29 eV line is believed to be due to transitions between the conduction band and the Mg shallow acceptor level; RT observance of the shallow Mg acceptor level indicates higher quality material.[6,7,10] The calculated activation energy based on this peak is 127 meV. This value is lower than the typical magnesium activation energy (~200 meV) expected for bulk p-GaN.[11,12]

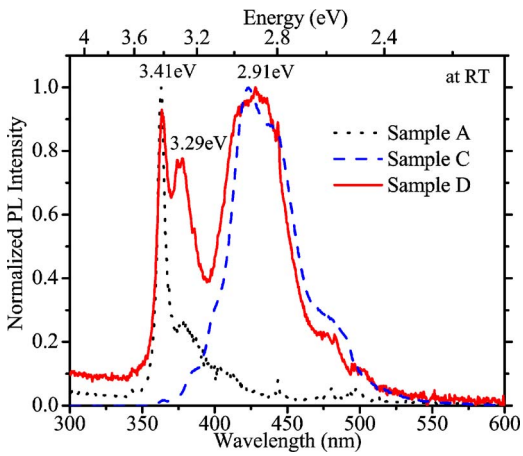

FIG. 1. (Color online) RT normalized PL intensity of different p-GaN layers (after annealing): samples A, C, and D.

It is known that the activation energy of the dopants is affected by the average distance between ionized acceptors.[12,13] The overlap of the Coulomb potentials of the ionized acceptors and screening of the Coulomb potential by free carriers could be responsible for the decreased Mg activation energy observed via PL. By concentrating the Mg dopants into a very thin layer, the acceptor activation energy is expected to decrease, obeying

$$\Delta E(N_A^-) = \Delta E_{A,0} - f\frac{q^2}{4\pi\varepsilon_s}(N_A^-)^{1/3}, \quad (1)$$

where N_A^- is the acceptor concentration, ε_s is the dielectric constant for GaN, $\Delta E_{A,0}$ is the activation energy when overlap of the ionized dopants is negligible, and f is a geometric factor given by $\Gamma(2/3)(4\pi/3)^{1/3}$.[11,12,14] Using this calculation, the acceptor energy E_A in δ-doped p-GaN is predicted to be 125 meV close to the activation energy determined by PL (127 meV).

The advantage of δ-doping for the improved p-GaN quality is twofold: (1) It allows effective doping at higher growth temperature and lower growth pressure due to the increase in mobility of adatoms, resulting in higher quality GaN and (2) assists in decreasing the activation of the Mg atoms by accumulation of dopants in a plane.

The optimized delta doping used for sample D is then applied to the growth of SAM APDs in order to determine the suitability of delta-doped p-GaN as a replacement of the bulk-doped p-GaN with best performance in the SAM APD device. The SAM APD structure is as follows: 285 nm p-GaN/150 nm i-GaN/50 nm n-GaN/250 nm i-GaN/200 nm n-GaN on 600 nm AlN/sapphire (c-plane). N-GaN doping is 1.5×10^{18} cm^{-3}, and residual concentration for the undoped GaN is 10^{16} cm^{-3}. More details related to fabrication[3] and measurement setup[4] can be found elsewhere. Circular diodes with 625 μm^2 mesas are studied.

Dark currents of 32 diodes are measured at a reverse bias of 40 V and taken as a figure of merit. The delta-doped samples present an average dark current of 24 pA, a factor of 4 lower than the minimum dark current obtained in bulk-doped samples. This reduction shows the important role of the p-GaN layer on the origin of the leakage current and confirms the better quality of the delta-doped samples.

The current-voltage (I-V) characteristics under reverse bias are measured in darkness and under illumination using a Xe lamp filtered with a 360 nm bandpass filter (Fig. 2). The optical power on the diode is 11 nW. The light and dark I-V curves are measured alternatively three times in a row to ensure consistent device operation. To calculate the multiplication gain, we normalize the photocurrent, i.e., the differ-

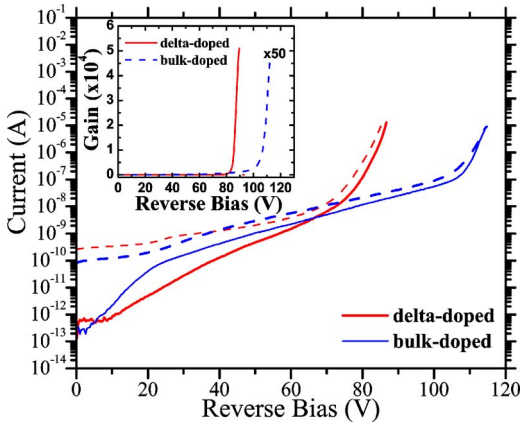

FIG. 2. (Color online) Current-voltage (*I-V*) characteristics in darkness (solid) and under illumination (dashed) of 625 μm^2 area GaN SAM APDs for bulk (blue) and δ-doped (red) *p*-GaN. Inset displays the calculated multiplication gain for both devices.

ence between light and dark currents, by its value at pinch-off (1 nA). External quantum efficiency is calculated to be 32% at 360 nm.

The breakdown voltage of the δ-doped SAM APD is 75 V, whereas that of the bulk-doped is 110 V. The difference in breakdown voltage is primarily due to the better confinement of the electric field related to higher *p*-doping afforded by the delta-doped *p*-GaN. The one dimensional simulation of the electric field (shown in Fig. 3) verifies the average electric field at the breakdown voltages as

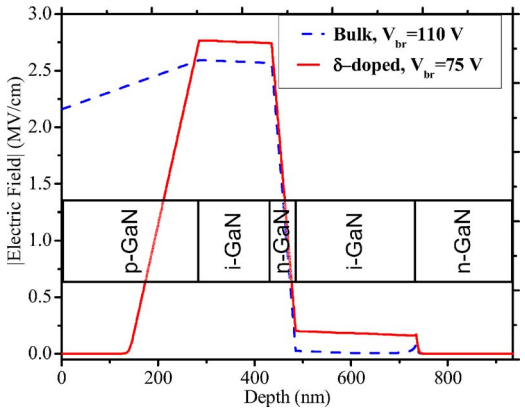

FIG. 3. (Color online) Electric field profile in SAM APD devices with bulk ($p=7.5\times10^{16}$ cm^{-3}) and δ-doped ($p=9.4\times10^{17}$ cm^{-3}) *p*-GaN, both biased at their breakdown voltages (V_{br}).

2.7 MV/cm (for δ-doped APD) and 2.6 MV/cm (for bulk-doped APD), close to their theoretical value.[2] In the delta doped device, after breakdown, the avalanche multiplication reached a maximum value of 5.1×10^4, more than 50 times higher than that of the bulk-doped devices (Fig. 2 inset). The improvement of the *p*-GaN quality enables higher gains in larger area devices. This gain value for these 625 μm^2 area devices is still higher than that in the smaller area GaN SAM APDs grown with conventional bulk *p*-GaN doping,[4] thus emphasizing the importance of the high quality δ-doped *p*-layer.

In conclusion, high quality δ-doped *p*-GaN is introduced in ultraviolet back-illuminated SAM APDs. Higher gains and lower leakage currents are achieved with lower breakdown voltage with respect to bulk-doped GaN devices. This is attributed to the higher *p*-GaN quality achieved via the use of the δ-doping technique. This doping is also expected to enhance the performance of other optoelectronic devices.

The authors would like to acknowledge the Fulbright Association and the Spanish Ministry of Education and Science for supporting one of the authors (J.L.P.).

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