GaN avalanche photodiodes grown on m-plane freestanding GaN substrate

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M-plane GaN avalanche *p-i-n* photodiodes on low dislocation density freestanding m-plane GaN substrates were realized using metal-organic chemical vapor deposition. High quality homoepitaxial m-plane GaN layers were developed; the root-mean-square surface roughness was less than 1 Å and the full-width-at-half-maximum value of the x-ray rocking curve for $(10\bar{1}0)$ diffraction of m-plane GaN epilayer was 32 arcsec. High quality material led to a low reverse-bias dark current of 8.11 pA for 225 μm^2 mesa photodetectors prior to avalanche breakdown, with the maximum multiplication gain reaching about 8000. © *2010 American Institute of Physics*. [doi:10.1063/1.3432408]

Ultraviolet (UV) photodetectors find use in numerous applications in the defense, commercial, and scientific arenas. Many of these applications require high sensitivity, low-noise, and visible- or solar-blind detection. Current high-sensitivity UV detectors, such as photomultiplier tubes (PMTs), present high detectivity due to their large internal gain (typically 10^6). However, these detectors are not without their drawbacks: they are bulky, fragile glass vacuum tubes that require large biases (typically 1000 V) to operate effectively.[1] Thus, there is interest in developing semiconductor based alternatives; however silicon and silicon-carbide based alternatives require additional filtering to operate in the UV making them less favorable.[2]

III-nitride based ultraviolet avalanche photodiodes (APDs) are the most promising semiconductor based candidate to replace PMTs due to their inherent large tunable bandgap ($3.4 < Al_xGa_{1-x}N < 6.2$ eV) and ability to use avalanche gain mechanisms to achieve low noise internal gain.[3] GaN, with a band gap of 3.4 eV, grown on lattice-mismatched sapphire substrates has shown high performance visible-blind UV detection.[4] However, growing on conventional substrates like sapphire and SiC results in up to a 13% lattice mismatch which leads to dislocation densities on the order of 10^9 cm^{-2}.[5] This increases the leakage current, disrupts the electric field distribution, results in premature breakdown, and limits the avalanche gain—all of which make it challenging to grow high performance GaN-based APDs.

Recently, m-plane freestanding (FS) GaN substrates with very low dislocation densities ($<10^6$ cm^{-2}) have become commercially available from a number of suppliers. Homoepitaxial growth of GaN on these substrates should not suffer from lattice-mismatch problems and can thus be used to grow low dislocation density devices.[6] The unconventional m-plane orientation is interesting for avalanche devices since the ionization coefficients perpendicular to the m-planes in III-nitrides[7] are expected to be larger than that for the more conventional c-plane orientation.[3] This should lead to higher avalanche gain for m-plane APDs. To date, high performance m-plane light emitting diodes[8,9] and laser diodes[10,11] have been demonstrated using m-plane FS-GaN substrates. However, there are no reports of GaN APDs grown on m-plane FS-GaN substrates.

This paper reports the development of high quality epitaxial growth on m-plane FS-GaN substrates and the resulting demonstration of m-plane GaN APDs. The initial *n*-type m-plane FS-GaN substrates had a thickness of 330 μm and carrier concentration of 2.7×10^{17} cm^{-3}. Before growth, the surface and crystalline quality of the as-received substrates was investigated by atomic force microscopy (AFM) and x-ray rocking curves (XRC), respectively. A root-mean-square (RMS) roughness of 1.0 Å from 2×2 μm^2 AFM scan and full-width-at-half-maximum (FWHM) value of 28 arcsec from the XRC for $(10\bar{1}0)$ diffraction of m-plane FS-GaN substrate were indicative of high crystalline quality of the substrates.

The GaN epitaxial material used in this study was grown in an AIXTRON 200/4-HT horizontal-flow low-pressure metal-organic chemical vapor deposition (MOCVD) reactor using trimethylgallium (TMGa) and ammonia (NH_3) as the group-III and group-V sources, respectively. Bis(cyclopentadienyl)magnesium (DCpMg) and silane (SiH_4) were used as *p*-type and *n*-type dopant sources, respectively. Hydrogen (H_2) was used as the carrier gas and the growth pressure was 100 mbar.

Before growing the device structure, effect of different MOCVD conditions were investigated for high quality growth of 2 μm thick unintentionally doped homoepitaxial m-plane GaN layers. Initial attempts at homoepitaxy of GaN on m-plane FS-GaN substrates resulted in poor surface morphology with three dimensional pyramidal islands. Thus, surface pretreatment was studied. It was realized that a short desorption at high temperature can improve surface morphology of GaN epilayers. This short desorption before starting the growth remove any contaminations including oxygen or silicon impurities that may exist on the surface of m-plane FS-GaN substrates.

The effect of the molar ratio of NH_3 to TMGa (V/III ratio) and growth temperature on the growth quality of homoepitaxial m-plane GaN were investigated. Figures 1(a) and 1(b) present the surface morphology of two homoepitaxial m-plane GaN layers grown at a fixed growth temperature of 1135 °C and V/III ratios of 1500 and 2500, respectively. The surface morphology of GaN epilayers is strongly affected by the V/III ratio. Stripelike features are observed

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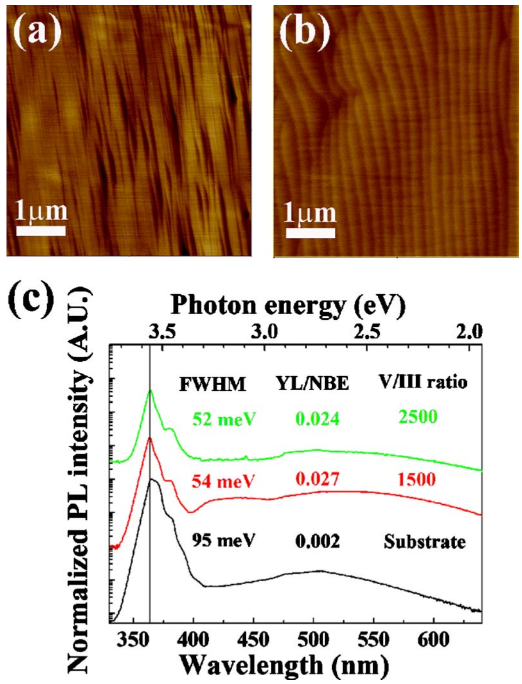

FIG. 1. (Color online) AFM image of 2 μm homoepitaxial m-plane GaN grown at 1135 °C, and V/III=(a) 1500, and (b) 2500, (c) room temperature PL spectra of FS-GaN substrate and homoepitaxial m-plane GaN grown at V/III=1500 and 2500.

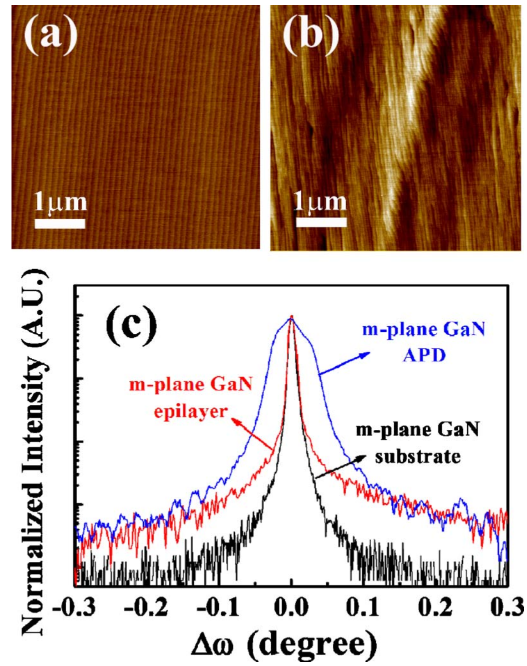

FIG. 2. (Color online) AFM image of (a) 2 μm homoepitaxial m-plane GaN grown at 1150 °C and V/III=2500, and (b) m-plane GaN APD. (c) $(10\bar{1}0)$ XRCs of FS-GaN substrate, homoepitaxial GaN layer, and m-plane GaN APD.

on the surface of the layer grown at the lower V/III ratio (1500) resulting in a RMS roughness of 2.4 Å [seen in Fig. 1(a)]. However, a flat surface with well-aligned atomic steps [seen in Fig. 1(b)] is observed for layers grown at higher V/III ratio (2500) resulting in a RMS of about 1.0 Å. This stripelike feature can be attributed to anisotropic in-plane growth character of the nonpolar m-plane GaN surface due to large different adatom sticking coefficients at various low index step edges, which can be controlled by V/III ratio.[12] The room temperature photoluminescence (PL) spectra of these homoepitaxial layers are shown in Fig. 1(c). The PL spectra are dominated by near-band-edge (NBE) peaks at 3.41 eV accompanied by longitudinal optical phonon replicas and a weak yellow luminescence (YL) peaks around 2.8 eV. The FWHM value of the NBE peak and the YL/NBE intensity ratio for the layer grown at V/III=2500 are 52 meV and 0.024, respectively, which are slightly smaller than those for the layer grown at V/III=1500. The $(10\bar{1}0)$ XRC FWHM values of GaN layers grown at V/III ratio of 1500 and 2500 were 280 arcsec and 75 arcsec, respectively, which indicate higher GaN crystalline quality is achieved at higher V/III ratio.

Effects of growth temperature on surface morphology and crystalline quality of homoepitaxial GaN layers were studied. An atomically smooth surface with very well-aligned atomic steps without any dislocation termination on the surface was achieved for GaN epilayer grown at 1150 °C [Fig. 2(a)]. The RMS roughness of the surface is less than 1.0 Å similar to the initial m-plane FS-GaN substrates surface. $(10\bar{1}0)$ XRD FWHM value of homoepitaxial GaN layer is 32 arcsec, which is comparable to that of the underlying m-plane FS-GaN substrate.

Prior to the growth of the complete APD structure, a 2 μm unintentionally doped homoepitaxial m-plane GaN layer was grown on the m-plane FS-GaN substrate using the aforementioned optimized growth conditions. This template layer preserves the high crystalline quality and surface morphology prior to device growth. The APD structure [inset of Fig. 3(a)] is composed of 1 μm thick *n*-GaN, 200 nm thick *i*-GaN, and 285 nm thick *p*-GaN. The carrier concentrations of these layers were calibrated via independent growths. Hall-effect measurements at room temperature determined the carrier concentration in *i*-GaN, *n*-GaN, and *p*-GaN as $3-4\times10^{16}$, $1-2\times10^{19}$ cm^{-3}, and $1-2\times10^{18}$ cm^{-3}. The 5×5 μm^2 AFM RMS surface roughness and the $(10\bar{1}0)$ XRC FWHM of m-plane GaN APD was 2.5 Å [Fig. 2(b)] and 151 arcsec [Fig. 2(c)], respectively. Dopants incorporation in GaN layers leads to increase in crystal imperfection and increase XRC FWHM and RMS roughness in comparison with GaN epilayer.[13] These low values confirm high quality growth of m-plane GaN APD.

Following the growth, 225 μm^2 circular mesas were defined via photolithography and dry etching. A thin *p*-type transparent contact layer [Ni(30 Å)/Au(30 Å)] was evaporated on top of the mesas via standard lift-off and annealed at 500 °C for 10 min under ambient air to achieve Ohmic *p*-type contact. This was followed by deposition of a thick *n*-type Ohmic contact [Ti (400 Å)/Au (1200 Å)/Ti (200 Å)] which was also deposited as a protective contact over the thin Ni/Au *p*-type layer to facilitate contacting the devices. The entire array was then passivated with 300 nm thick SiO_2 to help reduce surface leakage and prevent surface breakdown. Finally, windows were opened in SiO_2 via dry etching to allow contacting the devices for testing.

Current-Voltage (I-V) characteristics under reverse bias were measured using a HP4155A semiconductor parameter analyzer. The dark current [Fig. 3(a)] remains below the measurement limit up to a reverse bias of 30 V, then increases gradually until reaching a reverse bias of 84 V, where

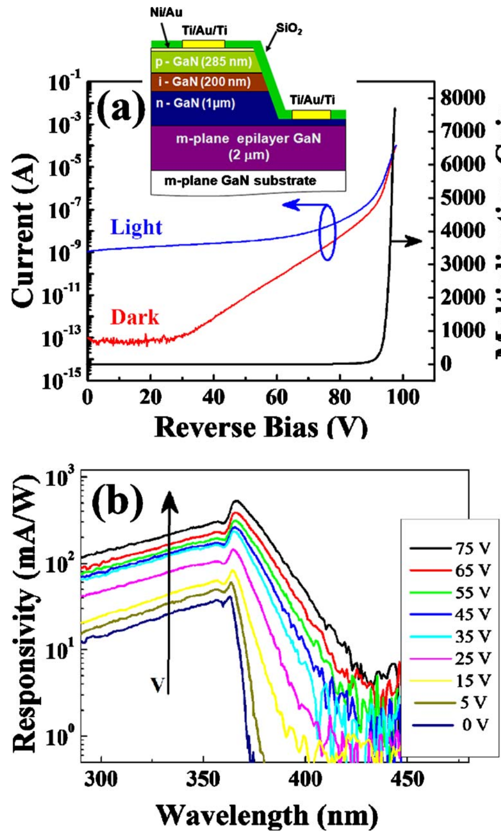

FIG. 3. (Color online) (a) I-V characteristics and gain of 225 μm^2 areas m-plane GaN APDs. Dark current and photocurrent are shown on the left axis; gain is shown on the right axis. The inset shows a cross-sectional diagram of the device structure. (b) Responsivity measurements with increasing reverse bias voltage (V).

it rapidly increases. At a reverse bias of 50 V, the device exhibits a dark current and dark current density of 8.11 pA and 3.6×10^{-6} A/cm^2, respectively. This current density is two orders of magnitude lower than the reported value of 6.4×10^{-3} A/cm^2 for conventional GaN APDs on c-plane sapphire.[14] This significant reduction in leakage current is due to the development of high quality homoepitaxial growth on low defect density FS-GaN substrates.

To confirm the visible-blind response of these devices, the spectral response was measured as a function of reverse bias [Fig. 3(b)] under front-illumination. By increasing reverse bias voltage, the responsivity increases for wavelengths near the GaN band-edge (364 nm) whereas the visible response remains below the noise floor. The responsivity at 0 V and 75 V is 41.5 mA/W and 523.0 mA/W corresponding to external quantum efficiency of 14.2% and 177.0%, respectively. With increasing reverse bias, a slight redshifting at the band absorption edge is observed. This effect can be attributed to the Franz–Keldysh effect in multiplication region, due to an increasing absorption coefficient under high electric fields.[15]

The photocurrent was extracted by measuring the I-V characteristics under white light illumination using a xenon lamp coupled onto the top of the device through an UV fiber-optic cable.[3] Figure 3(a) shows the I-V characteristics in darkness and under illumination—the difference of these two curves represents the photocurrent. The gain characteristics of several devices were determined by measuring the light and dark I-V curves under reverse bias and subtracting them to obtain the photocurrent. The gain was determined by normalizing the photocurrent at the onset of multiplication, which was determined as 25 V by calculating the reverse bias value corresponding to unity gain.[13] Devices showed reproducible avalanche multiplication. At a reverse bias of 84 V, a very sharp increase in gain is observed reaching a maximum gain of about 8000 at a reverse bias of 97 V, for the 225 μm^2 circular device as shown in Fig. 3(a). This gain is higher than that of achieved for front-illuminated GaN APDs grown on c-sapphire,[3] or c-plane FS-GaN[16] substrates. However, similar to previous works on c-plane FS-GaN[17] optimization of device structure for front-illumination can enhance the gain significantly. Considering the fact that ionization coefficients along $[10\bar{1}0]$ direction is higher than that of along [0001] direction in III-nitrides,[7] achieving high gain m-plane GaN APD is promising by further improvement of design and fabrication processing.

In summary, high quality homoepitaxial m-plane GaN layers were grown on m-plane FS-GaN substrates by applying optimized MOCVD conditions. These optimized conditions led to atomically smooth GaN layers with well-ordered atomic steps, an RMS roughness of 1.0 Å, and high crystalline quality (XRC-FWHM of 32 arcsec). m-plane GaN APDs grown on these low dislocation density template revealed low dark current 8.11 pA (dark current density of 3.60 $\times10^{-6}$ A/cm^2) and a high maximum multiplication gain of about 8000.

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