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High quality AlN grown on double layer AlN buffers on SiC substrate for deep ultraviolet photodetectors

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High quality AlN epilayers were grown on SiC substrates using double layer AlN buffers growth method by metal organic chemical vapor deposition and exploited as active deep ultraviolet optoelectronic materials through the demonstration of AlN Schottky barrier photodetectors. The grown AlN epilayers have smooth surfaces, low etch-pit density, narrow width of x-ray rocking curves, and strong band edge photoluminescence emission with low impurity emissions. AlN Schottky photodetectors are shown to possess outstanding features including extremely low dark current and high breakdown voltage. © *2012 American Institute of Physics*.
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Aluminum nitride (AlN) can be used for the development of optoelectronic devices such as deep ultraviolet (DUV) emitters and detectors active in the spectral range down to 200 nm due to its wide band gap ($\sim$ 6.1 eV), and its outstanding properties such as thermal and chemical stability.[1] However, due to the lack of a lattice matched substrate, AlN is grown heteroepitaxially on sapphire or silicon carbide (SiC) substrate. As a result, the heteroepitaxial AlN layer contains a high density of threading dislocations.[2] At the same time, DUV photodetectors need extremely high quality AlN with low dislocation densities for the reduction of dark current. Thus, the growth methods for producing high quality AlN are widely sought to exploit its outstanding properties in the device applications. Many efforts have been made in order to improve the crystalline quality of AlN and to decrease the dislocation density,[3–13] for example, using gallium as a surfactant during the growth of AlN epilayers,[3] high temperature growth at 1400 °C,[4] migration enhanced epitaxy,[5,6] use of alternating V/III ratio,[7] nitridation of the substrate,[8] and epitaxial lateral overgrowth.[9] Further improvement of AlN epilayers quality is still needed to improve the performance of AlN-based devices.

In this Letter, we report on the growth of AlN layers on Si-face 4 H-SiC substrate using a double layer AlN buffers growth method and exploitation of pure AlN for Schottky barrier photodetector fabrication. The material quality of AlN epitaxial layers was studied using atomic force microscopy (AFM), etch-pit density (EPD) measurements, x-ray diffraction (XRD), and photoluminescence (PL). The I–V characteristics of fabricated photodetectors are presented and discussed. The results suggested that one effective way for achieving DUV optoelectronic devices with improved performance is to use a double layer AlN buffers growth method.

Undoped AlN of about 1.0 μm thick were grown on Si-face 4 H-SiC substrate by metal organic chemical vapor epitaxy (MOCVD). Trimethylaluminium, trimethylgallium (TMGa), and ammonia were used as sources for aluminium, gallium, and nitrogen, respectively with H_2 as a carrier gas. The double layer AlN buffers growth method is initiated by a 15 nm low temperature (900 °C) AlN buffer layer (buffer 1) grown at 50 mbar followed by a second 100 nm AlN buffer layer (buffer 2) at 1050 °C grown at 50 mbar, and finally a 1.0 μm thick high temperature (1350 °C) AlN layer grown at 30 mbar. During the growth of all high temperature AlN epilayers, TMGa was introduced into the gas stream. Using gallium as surfactant during the growth of AlN is an effective method to release tensile strain and to prevent crack formation in thick AlN epilayers.[3] The insets of Figure 1 show the layer structure of a (a) conventional AlN epilayer grown on single AlN buffer and (b) improved AlN epilayer grown on double layer AlN buffers utilized for Schottky photodetector fabrication. Using double layer AlN buffers growth method is effective in decreasing full width at half maximum (FWHM) for the (105) and (002) reflections, indicating a reduction in threading dislocation density in AlN epilayers.

In order to fabricate AlN based Schottky and p-i-n deep UV photodetectors according to the conventional photodetector structures, we need AlN with reasonable good conductivity (p- and n- type). However, it is quite difficult to achieve highly conductive AlN epilayer. Therefore, to overcome the challenging requirement of a good conducting n-type (or p-type) contact layer for the formation of a Schottky photodetector based on AlN, we utilized highly conductive SiC substrate as the n-contact layer and the high quality AlN epilayer grown on the SiC substrate as an active layer. AlN/n-SiC hybrid Schottky barrier photodetectors were fabricated by depositing Pt (10 nm) Schottky contacts on AlN epilayers. Ohmic contact was formed on the SiC substrate side by e-beam evaporation of 150 nm Ni and 50 nm Au, followed by a rapid thermal annealing at 950 °C for 60 s, and the fabrication procedure has been outlined in a previous paper.[14] DUV PL was employed to investigate the optical properties of AlN epilayers. AlN on (001) SiC with very high crystalline quality and surface morphology is obtained as assessed by AFM, XRD, and EPD measurements.

Figure 1 compares the *in situ* optical reflectance curves of AlN epilayers grown by single AlN buffer (Figure 1(a)) and double layer AlN buffers (Figure 1(b)). A small signal can be seen during buffer 1 growth in both spectra. It is noted

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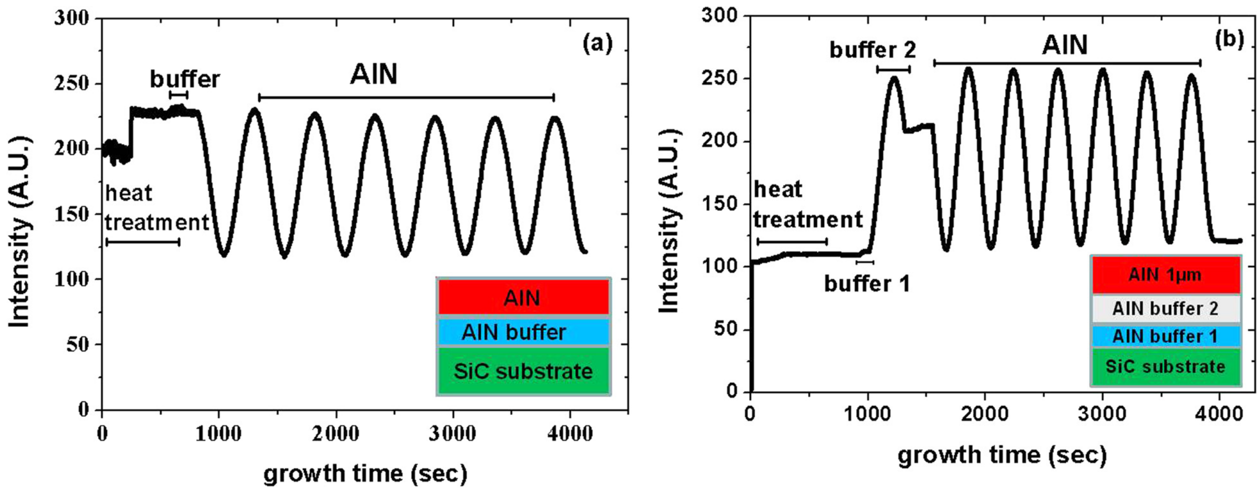

FIG. 1. *In situ* optical reflection curve during the growth of AlN epilayer by (a) single buffer AlN growth method and (b) double layer AlN buffers growth method. Inset: Schematic layer structure of single and double layer AlN buffers growth methods.

that the initial stages of AlN epilayer growth on single and double AlN buffers has a distinct difference where a strong peak is observed during the growth of buffer 2 in Figure 1(b), which is absent in Figure 1(a). An oscillation of the reflectivity intensity with large and almost equal amplitude is clearly observed during the growth of the high temperature AlN epilayer indicating a smooth surface in both Figures 1(a) and 1(b).

The surface quality of AlN epilayers, assessed by AFM is shown in Figure 2(a). Crack-free and very flat surface whose root-mean-square roughness is 0.4 nm is observed in a scanned area of $10\,\mu\text{m} \times 10\,\mu\text{m}$. In order to determine the quality of AlN epilayer, EPD studies are performed using a KOH solution, which is a selective etchant of AlN over GaN and AlGaN.[15] After etched in a 15% KOH solution at 60 °C for 15 min, the samples are cleaned and measured by AFM, and the results are shown in Figure 2(b). An average EPD of $1 \times 10^7\,\text{cm}^{-2}$ is obtained, which is less than the AlN grown on sapphire[16] and SiC.[17]

In general, the presence of defects and impurities will decrease the UV to visible rejection ratio and increase the leakage current. In Figure 3, the room temperature (300 K) PL emission spectrum shows that AlN epilayers emit predominantly the band-edge emission, and virtually no impurity transitions in the near UV and visible region, indicating very high optical quality. The dominant emission line at 5.89 eV is due to the recombination of free excitons.[18–20]

The detectors suffer from the high dislocation densities in the heteroepitaxial nitride structures. For example, threading dislocations have been identified as a path for reverse-bias leakage currents. The dislocations also have negative impact on photodetectors by influencing the dark current and

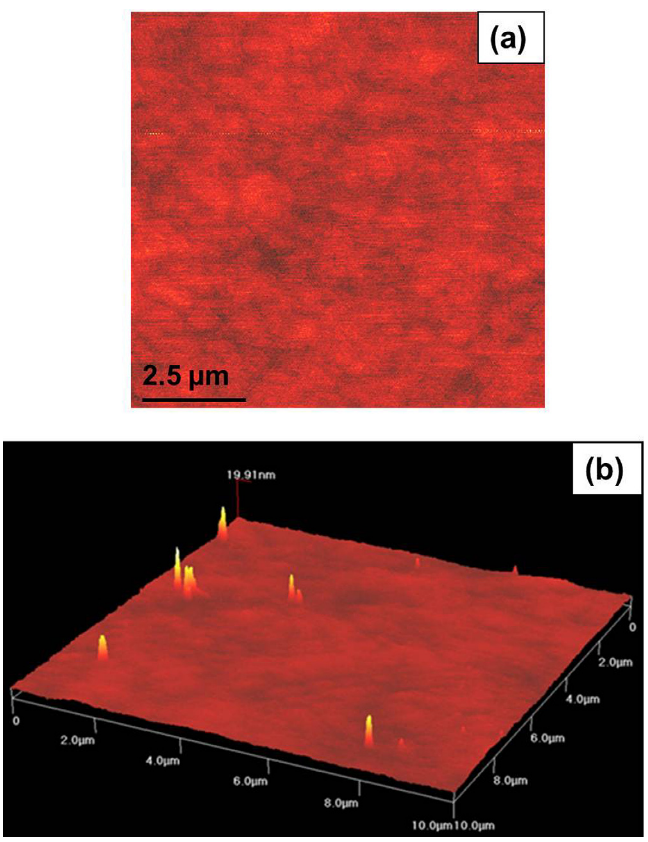

FIG. 2. (a) $10\,\mu\text{m} \times 10\,\mu\text{m}$ AFM image of AlN epilayer grown on (001) SiC. Smooth surface with root-mean-square roughness 0.4 nm and (b) $10\,\mu\text{m} \times 10\,\mu\text{m}$ AFM image of KOH-etched AlN epilayer used to evaluate the etch-pit density.

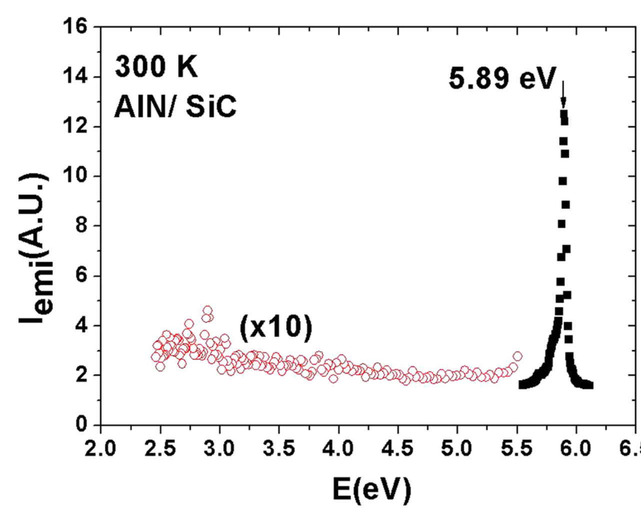

FIG. 3. Room temperature (300 K) photoluminescence spectrum of an AlN epilayer used in this study.

photoresponse.[21] As the rocking curve width is sensitive to dislocations, XRD was used to determine the overall quality of the AlN epilayers. In addition, the type of dislocation information that can be extracted from symmetric or asymmetric curves is different. Figures 4(a) and 4(b) show, respectively, the rocking curves of ω scans of symmetric plane (002) and asymmetric plane (105) of AlN epilayer used in this study. The results show that the FWHM of the (002) reflection peak is very narrow (~40 arcsec), while the (105) reflection peak (~200 arcsec). In comparison, the FWHM of the (002) reflection peak is (~118 arcsec), and the (105) reflection peak (~235 arcsec) for AlN epilayer grown with a single AlN buffer. The density of screw dislocations is estimated using the methodology described by Zhang *et al.*[22] to be $3 \times 10^6\,\mathrm{cm}^{-2}$ for the AlN with double buffer and $3 \times 10^7\,\mathrm{cm}^{-2}$ for AlN with a single buffer. This indicates a good improvement in the crystalline quality of the AlN epilayers.

In spite of the recognition of its outstanding physical properties, so far there have been few demonstrations of AlN as an active DUV optoelectronic device material[23–25] due to the lack of high quality AlN epilayers in the past. The 1.0 μm AlN epilayer was utilized to fabricate Schottky photodetector. The fabricated devices exhibit a peak responsivity at 200 nm, a sharp cutoff wavelength around 208 nm. No photoresponses from SiC substrate were observed. The conduction and valance band offsets between AlN and SiC,

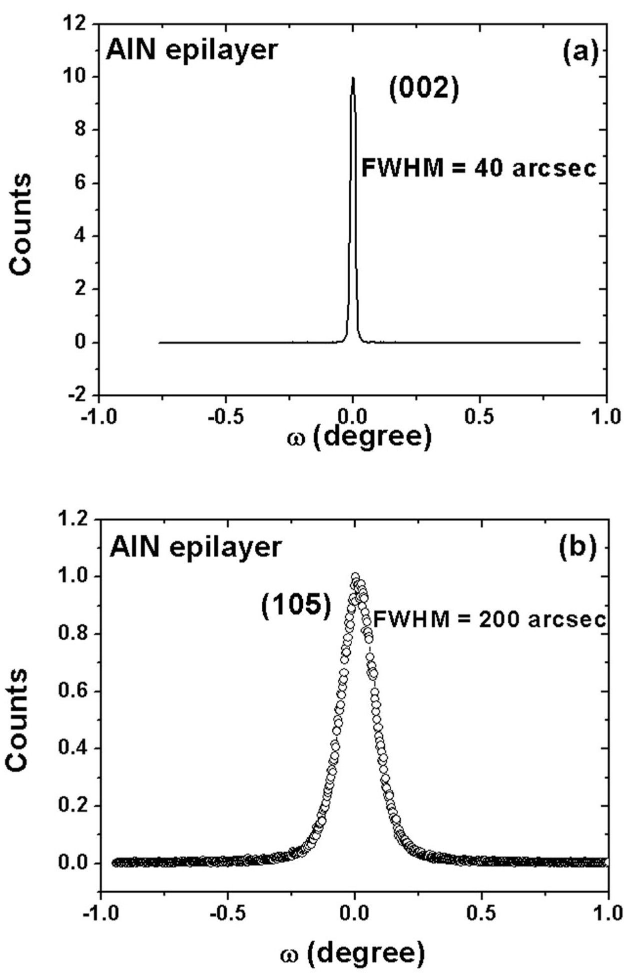

FIG. 4. X-ray diffraction ω scan (rocking curves) of the (a) symmetric plane (002) and (b) asymmetric plane (105) of an AlN epilayer used in this study.

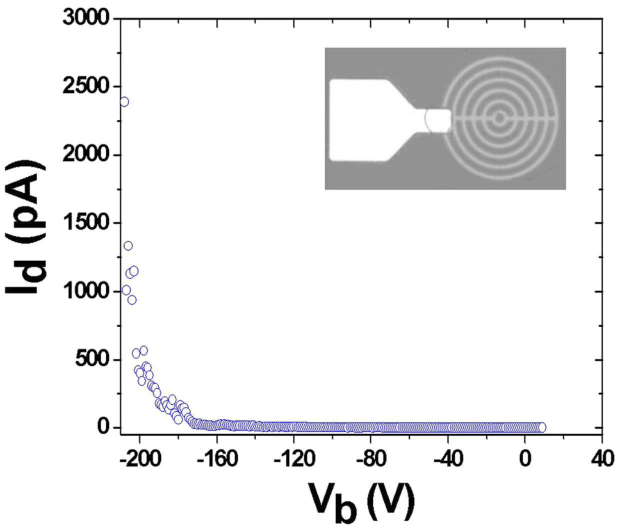

FIG. 5. I–V characteristic and the optical microscopy image of a fabricated photodetector with a device size of 100 μm in diameter.

which were estimated to be around 1.3 and 1.7 eV, respectively,[26] generally prevents the collection of photogenerated carriers in the lower bandgap contact layer (SiC).[27] Therefore, the cutoff wavelength and peak responsivity of the photodetector are solely determined by the AlN epilayer.

The inset of Figure 5 shows the optical microscopy image of a fabricated photodetector with a device size of 100 μm in diameter. The resulting devices exhibited extremely low dark currents and very high breakdown voltages. Figure 5 shows the current-voltage (I-V) curve of the device. The dark current is below 10 fA up to -50 V bias voltage. This dark current is in pA range up to -200 V. The device also exhibited a reverse breakdown voltage around 210 V. The low dark current and high breakdown voltage show the high quality of our AlN epilayers.

In summary, using double layer AlN buffers growth method enables the growth of very high quality AlN epilayers on SiC substrates by MOCVD. The potential of using these AlN epilayers as active DUV material is exploited through the demonstration of AlN Schottky photodetectors. The AlN Schottky photodetectors are shown to possess outstanding features including extremely low dark current and high breakdown voltage.

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