APPLIED PHYSICS LETTERS **89**, 213510 (2006)

200 nm deep ultraviolet photodetectors based on AlN

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(Received 8 September 2006; accepted 9 October 2006; published online 21 November 2006)

High quality AlN epilayers were grown on sapphire substrates by metal organic vapor deposition and exploited as active deep ultraviolet (DUV) optoelectronic materials through the demonstration of AlN metal-semiconductor-metal (MSM) photodetectors. DUV photodetectors with peak responsivity at 200 nm with a very sharp cutoff wavelength at 207 nm have been attained. The AlN MSM photodetectors are shown to possess outstanding features that are direct attributes of the fundamental properties of AlN, including extremely low dark current, high breakdown voltage, and high DUV to visible rejection ratio and high responsivity. The results demonstrate the high promise of AlN as an active material for DUV device applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2397021]

Considering the requirements and constrains for space applications—reliability, radiation hardness, light weight, and minimal power usage; the next generation of space observatories require order-of-magnitude performance advances in detectors and enabling technologies. AlN appears to be an ideal material for the development of deep ultraviolet (DUV), vacuum UV (VUV), and extreme UV (EUV) detectors because AlN possesses the widest direct energy band gap (∼6.1 eV) among all semiconductors and offers the ability for band gap engineering through the use of alloying and heterostructure design. AlN detectors would help to circumvent many of the limitations imposed by Si technology. The 6.1 eV band gap permits the visible background to be intrinsically suppressed and the detectors to operate at room temperature, which drastically relieve the harsh requirements on optical filters and cooling hardware and greatly simplify the system design. The compact crystal network of AlN inherently provides radiation hardness.

We have previously demonstrated that AlN epilayers with an optical quality comparable to GaN can be grown on sapphire by metal organic chemical vapor deposition (MOCVD).[1–3] Due to its high thermal conductivity and transparency in the DUV spectral range ($\lambda > 200$ nm), AlN epilayers have been widely employed as templates for the development of DUV light emitting diodes (LEDs) with emission wavelengths $\lambda < 300$ nm.[4–9] Several groups have also made significant progress toward the realization of conductive AlGaN alloys with high Al contents.[10–13] Most recently, LED based upon pure AlN with an emission wavelength of 210 nm has been demonstrated.[14] These recent progresses have demonstrated the high promise of AlN as an active material for DUV optoelectronic device applications. Many groups have previously demonstrated UV photodetectors based upon AlGaN alloys with superior performance.[15–26] However, the shortest cutoff wavelength achieved with AlGaN so far is 229 nm.[26] In this letter, we report on the growth and exploitation of pure AlN for DUV photodetector fabrication. We have demonstrated the operation of 200 nm DUV photodetectors through AlN metal-semiconductor-metal (MSM) photodetectors with very high DUV to visible rejection ratio.

Undoped AlN of about 1.5 μm thick were grown by MOCVD on sapphire substrates. The sources of Al and N are trimethylaluminium (TMAl) and blue ammonia, respectively. The typical device fabrication procedures consist of the following steps. First we used photolithography to define the interdigital figures of Schottky contacts area. A Pt (10 nm) layer was deposited using e-beam evaporation to form the Shottky contacts. Bonding pads were then formed by depositing a Au (200 nm) layer. Finally, the wafer was polished and thinned to about 100 μm and diced to discrete devices, which were bonded onto device holders for characterization. The system for the spectral responses and *I-V* characteristics measurements consists of a deuterium light source, monochromator, source meter, and electrometer. The light source was dispersed by the monochromator to obtain light with different wavelengths.

For UV detector applications, the presence of impurities will decrease the UV to visible rejection ratio. We employed deep UV photoluminescence (PL) spectroscopy to investigate the optical properties of AlN epilayers. Figure 1 shows a typical room temperature PL emission spectrum of an undoped AlN epilayer under a 197 nm DUV laser excitation. The PL spectrum was collected in a surface emission mode and the average excitation power density at 197 nm is on the order of 100 W/cm^2. The spectrum consists of a very strong band edge emission line with no visible impurity transitions, ensuring very good optical quality and high purity of the material. The dominant emission line at 5.98 eV is due to the recombination of free excitons, which have a binding energy of about 80 meV in AlN.[1–3]

In general, the presence of high density of dislocations will also degrade the performance of detectors such as high leakage currents. We use x-ray diffraction (XRD) measurements to evaluate the crystalline quality. For wurtzite AlN, high density of screw dislocations will result in a broadening of the full width at half maximum (FWHM) of symmetric x-ray ω scans, such as the (002) rocking curve. However, the majority of dislocations in AlN are of edge type, which pri-

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0003-6951/2006/89(21)/213510/3/$23.00

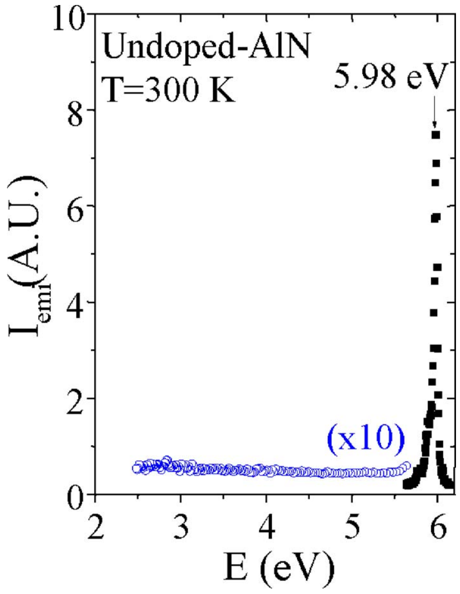

FIG. 1. Room temperature photoluminescence spectrum of an AlN epilayer used in this study.

marily distort the asymmetric planes, such as (102). Figures 2(a) and 2(b) show, respectively, the XRD ω scans (rocking curves) of symmetric plane (002) and asymmetric plane (102) of an AlN epilayer used in this study.[27,28] The results show that the FWHM of the (002) reflection peak is quite narrow ($\sim$50 arc sec), while the (102) reflection peak ($\sim$1200 arc sec) is broader than those of high quality GaN epilayers grown on sapphire ($<$400 arc sec). The estimated screw and edge dislocation densities were about 5×10^7 and 4×10^9 cm^{-2}, respectively, which indicates that there is still a lot of room for further improvement in terms of the edge dislocation density reduction.

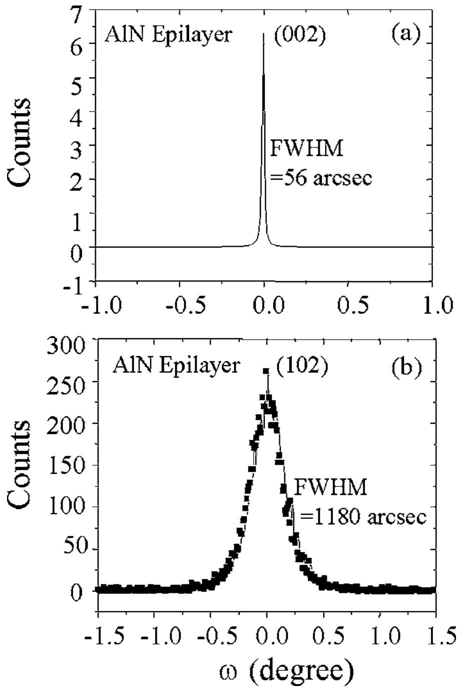

FIG. 2. X-ray diffraction ω scans (rocking curves) of the (a) symmetric plane (002) and (b) asymmetric plane (102) of an AlN epilayer used in this study.

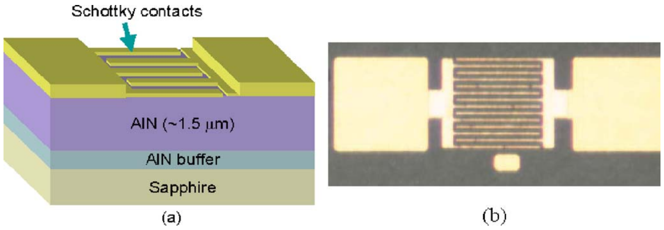

FIG. 3. (a) Device layer structure employed in this study and (b) the optical microscopy image of a fabricated photodetector with a device size of 80 $\times$80 μm^2 and 2 μm/4 μm finger width/spacing.

The device layer structure employed in this study is schematically shown in Fig. 3(a), which utilizes an undoped AlN epilayer as an active layer. Figure 3(b) shows the optical microscopy image of a fabricated device with a size of 80 $\times$80 μm^2 and 2 μm/4 μm finger width/spacing. The typical *I-V* characteristics of AlN epilayer based MSM detectors are shown in Fig. 4. The devices exhibit a very low dark current (the displayed dark current was about 100 fA at a bias voltage of 200 V). The devices also exhibit virtually no sign of breakdown up to a bias voltage of 200 V (our system limit). These characteristics are direct attributes of the outstanding material properties of AlN, including large energy band gap, dielectric constant, and mechanical strength.

The spectral responses have been measured at different bias voltages, and an example is shown in Fig. 5. These AlN MSM detectors exhibit a peak responsity of 200 nm, an extremely sharp cutoff wavelength around 207 nm, and more than four orders of magnitude of DUV to UV/visible rejection ratio as probed by our system setup. The detector responsivity increases almost linearly with the bias voltage, as illustrated in the inset of Fig. 5. The responsivity varies from 0.1 to about 0.4 A/W when the bias voltage is increased from 0 to 100 V. This linear increase of responsivity with bias has been previously observed in an AlN MSM photodetector grown by magnetron reactive sputtering deposition on GaN substrate.[29] The data of Fig. 5 suggest that MSM detector has gain, which may be attributed to the presence of dislocations or deep level defects in the epilayers and its mechanism remains to be investigated. Nevertheless, this is so far the shortest cutoff wavelength achieved for semiconductor detectors.

Previous work has shown that the AlGaN photodetectors significantly outperform GaN photodetectors in the VUV

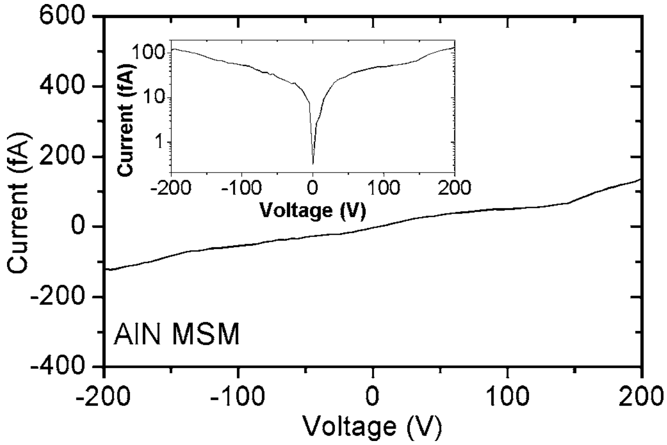

FIG. 4. *I-V* characteristic of an AlN MSM photodetector.

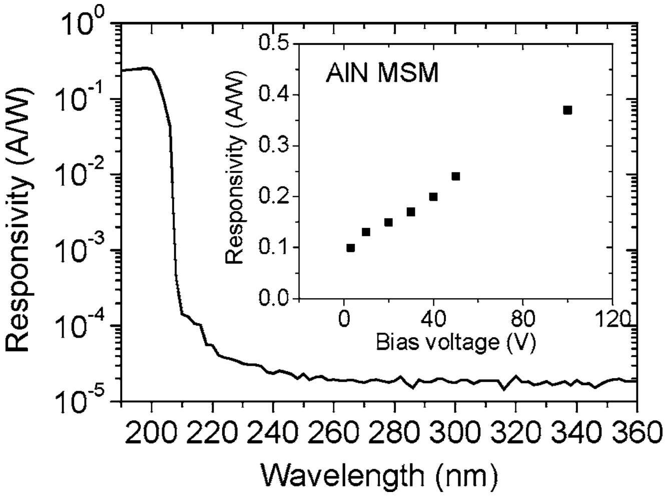

FIG. 5. Spectral response of an AlN MSM detector at 30 V. The inset shows the detector responsivity as a function of the applied bias.

spectral region due to the larger energy band gap of AlGaN than GaN.[30] Since AlN has the largest energy band gap among the AlGaN alloys, our results obtained here thus point to the high promise of AlN based photodetectors for DUV, VUV, and EUV detection applications. Due to the scarcity of published data on Schottky contacts formation on AlN, we believe that much improvement in device performance can be attained if further efforts were devoted to optimizing the contact schemes and surface preparation conditions. Nonetheless, the results obtained so far have demonstrated the extraordinary benefits of AlN as an active material for DUV, VUV, and EUV detector applications.

In summary, we have carried out the growth of high quality AlN epilayers on sapphire substrates by MOCVD and exploited its potential as an active DUV material through the demonstration of AlN MSM photodetectors. The AlN MSM photodetectors exhibit peak responsivity of 200 nm and a very sharp cutoff wavelength at around 207 nm. AlN MSM DUV detectors are also shown to possess outstanding features including extremely low dark current, high breakdown voltage, and high DUV to visible rejection ratio.

This work is supported by NASA (Contract No. NNG06LA43C) The authors are grateful to Drs. Q. Sun-Paduano and D. Weybarne of Air Force Lab (Hanscom, AFB) for XRD measurements.

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