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AlN MSM and Schottky photodetectors

R. Dahal, J. Li, Z. Y. Fan, M. L. Nakarmi, T. M. Al Tahtamouni, J. Y. Lin, and H. X. Jiang*

Department of Physics Kansas State University, Manhattan, Kansas 66506-2601, USA

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* Corresponding author: e-mail jiang@phys.ksu.edu, Phone: 1-785-532-1627, Fax: 1-785-532-5636

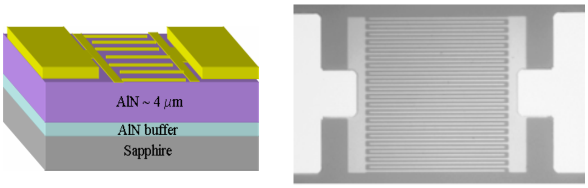
Deep ultraviolet (DUV) AlN Metal-Semiconductor-Metal (MSM) and Schottky barrier photodetectors have been demonstrated by exploiting the epitaxial growth of high quality AlN epilayer on sapphire and n-SiC substrates, respectively. The fabricated photodetectors exhibited peak responsivity at 200 nm with very sharp cut-off wavelength at 207 nm along with extremely low dark current, very high breakdown voltages, high responsivity and high DUV to UV/visible rejection ratio. AlN Schottky barrier detectors show high zero bias responsivity and very high thermal energy limited detectivity at zero bias. These outstanding features are direct attributes of the fundamental material properties and high quality of AlN epilayers. These results demonstrated that AlN could be an excellent candidate as an active material for next generation DUV opto-electronic device applications.

1 Introduction Aluminium nitride (AlN) appears to be very promising material for the development of next generation deep UV (DUV), vacuum UV (VUV) and extreme UV (EUV) photodetectors because of its novel physical characteristics like ultra large direct band gap (~6.1 eV), intrinsic solar blindness, radiation hardness, light weight and minimum power usage. AlN based photodetectors could deliver superior performance in DUV to EUV range by overcoming many limitations like the requirements of cooling hardware, complex filter system to block visible light, which are both associated with the existing Si technology [1, 2]. AlN based photodetectors have a board areas of application including secure space communication, solar EUV flux monitering in ionosphere, missile threat detection, UV radiation monitoring in environment, and biological agent detection. The recent advances in growth techniques have made it possible to grow high quality AlN on different substrates that are suitable to fabricate DUV opto-electronic devices like emitters and detectors [3, 4].

Many research groups have already demonstrated AlGaN based Schottky, p-i-n, and MSM photodetectors grown both on SiC and sapphire substrates with excellent performances [5-8]. Compared to AlGaN based MSM and Schottky photodetectors, AlN based photodetectors are expected to have better performance due to lower dislocation density, reduced alloy scattering of photo-generated carriers and minimal dopping induced defects. We report here the growth, fabrication and characterization of AlN MSM and Schottky photodetectors grown on sapphire and SiC substrates, respectively. These fabricated photodetectors exhibited extremly low dark current, high breakdown voltage, high responsivity, high DUV to UV/visible rejection ratio and very high thermal energy limited detectivity for AlN/n-SiC Schottky photodetector.

2 Experimental

2.1 AlN MSM photodetector fabrication Undoped AlN of about 4 µm in thickness were grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. The sources of Al and N were trimethylaluminum and blue ammonia, respectively. X-ray diffraction (XRD) measurements ensured the better crystalline quality of AlN epilayer with the full width at half maximum (FWHM) of 63 and 437 arcsec for (002) and (102) planes, respectively, which is essential for the better performance of detectors. The device fabrication process consists of the following steps. Photolithography was used to define interdigitized Schottky contact area. After photolithography, the sample was dipped in BOE solution for 30 sec followed by deionized water rinse and then immediately loaded in an e-beam evaporator. A 10 nm Pt was deposited at the base pressure of ~1×10^{-7} Torr. Bonding pads were then formed using photolithography and e-beam

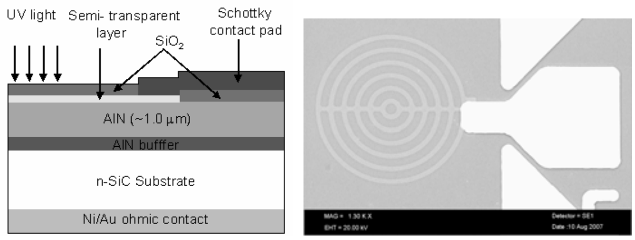


(a) (b)

Figure 1 (a) Systematic layer structure of AlN MSM photodetector and (b) optical miscroscopy image of fabricated MSM photodetector with 80 x 80 μm^2 active area with finger/spacing width 1μm/1μm.

evaporation of 20 nm Pt and 200 nm Au followed by lift-off in photoresist stepper. The schematic layer structure and optical microscopy image of MSM detector are shown in Figs. 1(a) and (b), respectively. Finally, the wafer was back polished, thinned down to ~ 100 μm and diced into discrete devices, which were bonded in 10 pin ceramic flatpack for characterization.

2.2 AlN Schottky photodetector fabrication Undoped AlN epilayers of about 1 μm in thickness were grown on n-type Si-face 4H-SiC by MOCVD. The Hall effect measurement showed the free electron concentration in n-SiC substrate about 10^{19} cm^{-3}. The source gases for aluminum and nitrogen were TMA and NH_3, respectively. Atomic force microscopy (AFM) ensures a very smooth surface morphology of AlN epilayer with a root-mean-square (RMS) value of about 0.6 nm over the scan area of 10 x 10 μm^2. Schottky photodetector fabrication process consists of the following steps. First, the wafer was dipped in BOE solution for 60 sec followed by deionized water rinse and immediately loaded in e-beam evaporator. 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 ^{o}C for 60 sec. Before annealing, 100 nm SiO_2 was deposited on AlN epilayer by plasma enhanced chemical vapor deposition (PECVD) for protection of AlN epilayer during high temperature annealing, which was later removed by wet etching. Photolithography was used to define the semi-transparent Schottky contact area. A 10 nm Pt was deposited by e-beam evaporation on top of AlN epilayer side to form Schottky contacts. Then 100 nm SiO_2 was deposited by PECVD for passivation. Photolithography and selective area wet etching of SiO_2 were used to open window for Schottky contact pad deposition. A Ni (40 nm)/Au (160 nm) bilayer were deposited using e-beam evaporation to form Schottky bonding pad. The schematic layer structure and scanning electron microscope image of fabricated AlN/n-SiC Schottky detector are shown in Figs. 2(a) and (b), respectively. Finally devices were bonded in 10 pin flatpack for characterization. Our measurement system consists of deuterium light source, monochromator, Keithley 2400 source meter and 617 electrometer for spectral response and I-V characteristic measurements.



(a) (b)

Figure 2 (a) Systematic layer structure of AlN/n-SiC Schottky photodetector. (b) SEM image of fabricated Schottky photodetector with 100 μm in diameter.

3 Results and discussion Typical dark *I-V* characteristics of AlN MSM photodetector are shown in Fig. 3. The dark current for these devices are below 100 fA up to a bias voltage of 300 V. The devices showed breakdown voltage greater than 320 V. Beyond 320 V, the dark current increases very sharply which damaged the devices. The inset in Fig. 3 shows the I-V curves in semi-log scale in dark (solid line) and with 200 nm light illumination (-o-o-) up to 200 V applied bias voltage, V_b. The photocurrent at V_b = 10 V is about 0.3 nA which continuously increases and reaches about 1.3 nA at V_b = 200 V. The ratio of photocurrent to the dark current up to V_b = 30 V is about five orders of magnitude for incident power density of 0.05 μW/mm^2. These characteristics are direct attributes of the outstanding material properties of AlN, including large energy band gap and dielectric constant.

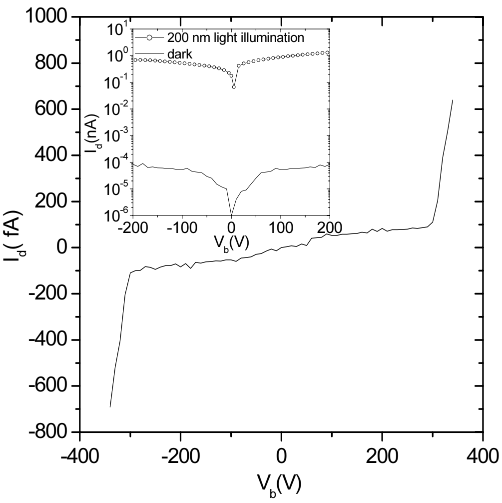


Figure 3 I-V curve of AlN MSM photodetector. The inset is the I-V curves in dark (solid line) and with 200 nm light illumination (-o-) up to V_b = 200 V.

Measurements have also been carried out to study spectral response of these detectors at different bias voltages, and an example is shown in Fig. 4. These AlN MSM detectors exhibit peak responsivity at 200 nm, an extremely sharp cut-off wavelength around 207 nm, and more than four orders of magnitude of DUV to UV/visible rejection ratio. The inset in Fig. 4 shows the peak responsivity as a function of V_b. The responsivity increases from 0.1 to about 0.4 A/W as V_b increases from 3 to 100 V. This linear increase of responsivity with V_b suggests the presence of current gain in AlN MSM detector, which could be related to the dislocation and deep level defects present in AlN epiayer and it is detailed mechanism needs to be investigated.

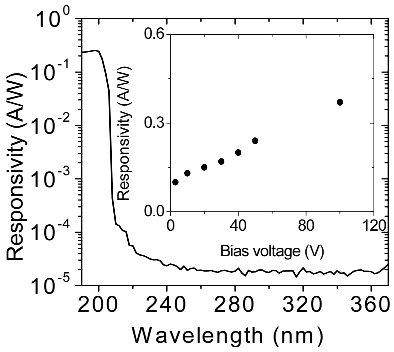
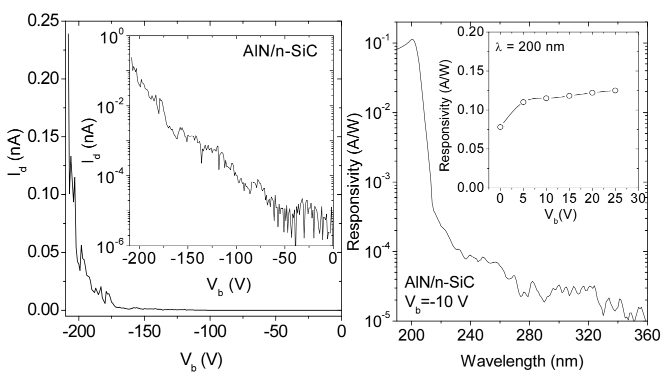


Figure 4 Spectral photoresponse of AlN MSM photodetector at V_b= 30 V The inset illustrates the bias voltage dependent peak responsivity at 200 nm for these detectors.

We have also fabricated and characterized the AlN/n-SiC vertical Schottky photodetectors. Figure 5 (a) shows the typical dark current-voltage (I-V) characteristics of the device. The inset is the same plot in semi-log scale. These devices showed extremly low dark currents (I_d), which is below 10 fA at a reverse bias voltage (V_b) of -50 V. I_d is in pA range up to V_b = -200 V. Beyond -200 V, I_d starts to increase rapidly and the device exhibited a reverse breakdown voltage (V_B) around 208 V. The differential resistance R (= dV/dI) in the range of V_b between 0 and -50 V was in excess of $5x10^{16}$ Ω.



(a) (b)

Figure 5 (a) Typical dark I-V characteristic for AlN/n-SiC detector with d = 100 μm. The inset is the same plot in semi-log scale, (b) spectral photoresponse measured at V_b=-10 V. The inset is the bias dependent peak responsitivity.

Spectral photoresponse of AlN/n-SiC Schottky detectors for diameter d = 100 μm at V_b = -10 V is illustrated in Fig. 5(b). These AlN-based Schottky photodetectors have peak responsivity of 0.12 A/W at wavelength of 200 nm and very sharp cut-off around 210 nm. This is the shortest cut-off wavelength and highest breakdown voltage attained so far for AlGaN based Schottky barrier photodetectors. These cut-off wavelength and peak response wavelength are comparable to those of AlN based MSM photodetectors we discussed earlier. Also, a DUV to near UV rejection ratio of more than four orders of magnitude has been observed. Furthermore, we did not observe photo-response from SiC substrate. This is attributed to the large conduction and valance band offsets at AlN/SiC interface of 1.3 and 1.7 eV, respectively, which prevent the collection of potoexcited carriers in n-SiC contact layer[2]. Similar result has been reported in AlGaN-based inverted heterostructure p-i-n photodiodes [9].

The inset in Fig. 5(b) illustrates the bias voltage dependent peak responsivity at 200 nm from 0 to -25 V. The photovoltaic mode (zero bias) responsivity is 0.078 A/W. The high zero bias responsivity exhibited by AlN/n-SiC hybrid detectors could be related with relatively large depletion of undoped AlN epilayer by built-in potential. The responsivity initially increases by a factor of 1.4 when V_b changes from 0 to -5 V and then it increases slightly as V_b increases from -5 to -25 V. Such a weak V_b dependent responsivity observed in the bias range of -5 to -25 V suggests that the 1 μm thick undoped AlN active layer was almost fully depleted up to V_b = -5 V. This weak V_b dependent photoresponsivity for $|V_b|$ greater than 5 V observed in our AlN/n-SiC Schottky detector is due to the improved material quality of AlN epilayers grown on SiC.

The detectivity performance of solar blind wide band gap semiconductor is thermally limited because the noise current due to background radiation is far less than the noise current due to thermal energy. So, the thermal energy limited specific detectivity is given by $D=R_\lambda (R_0A/4kT)^{1/2}$ where R_λ is the zero bias responsivity, R_0 is differential resistance, k is Boltzmann's constant, A is the detector active area, and T is the absolute temperature [10]. With resistance-area product $R_0A = 3.93x10^{12}$ Ω-cm^2, the room temperature specific detectivity of our AlN/n-SiC hybrid Schottky barrier photodetectors is deduced to be about $1.0x10^{15}$ cmHz$^{1/2}$ W^{-1}, which is one of the highest values reported so far for AlGaN UV photodetectors. This very high detectivity is due to the extremely low leakage current and high zero bias responsivity.

4 Conclusion We have demonstrated AlN based MSM and Schottky photodetectors by exploiting the epitaxial growth of high quality AlN epilayer on sapphire and SiC substrates, respectively. These AlN based detectors showed peak responsivity at 200 nm, cut-off wavelength as short as 207 nm for MSM, high breakdown voltage, and more than four order of magnitude of DUV to UV/visible rejection ratio. Also, AlN/n-SiC Schottky detector exhibited a very high zero bias responsivity of 0.078 A/W and thermal energy limited detectivity of 1.0 x 10^{15} $cmHz^{1/2}$ W^{-1}. These results demonstrate that AlN could be an excellent candidate for next generation DUV opto-electronic device applications.

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