AlN avalanche photodetectors

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Deep ultraviolet (DUV) avalanche photodetectors (APDs) based on an AlN/n-SiC Schottky diode structure have been demonstrated. The device with a mesa diameter of $\sim$100 μm exhibits a gain of 1200 at a reverse bias voltage of −250 V or a field of about 3 MV/cm. The cut-off and peak responsivity wavelengths of these APDs were 210 and 200 nm, respectively. This is the highest optical gain and shortest cut-off wavelength achieved for III-nitride based DUV APDs. It was also observed that the reverse breakdown voltage increases with decreasing device size, which suggests that the device performance is limited by the presence of dislocations. The breakdown voltage for dislocation-free AlN was deduced to be about 4.1 MV/cm. The present results further demonstrate the potential of AlN as an active DUV material for future optoelectronic device applications .© *2007 American Institute of Physics*. [DOI: 10.1063/1.2823588]

AlN has attracted tremendous interest as a material for deep ultraviolet (DUV) optoelectronic devices because of its ultrahigh direct bandgap. Recent advances in epitaxial growth techniques have made it possible to grow high quality AlN epilayers on different substrates.[1–4] A few active DUV devices based on pure AlN have also been demonstrated, including 210 nm light emitting diodes[5] and 200 nm photodetectors.[6,7] It was shown that AlN based photodetectors possess an extremely low dark (leakage) current with a detectivity that is comparable to that of photomultiplier tubes (PMTs).[7] Due to the intrinsic solar blindness, radiation hardness and high temperature stability, AlN based DUV detectors have applications in many areas of science and technology including secure space communication, hazardous chemical and biological agent detection, and UV radiation monitoring in environment and flame sensing. Furthermore, the outstanding optoelectronic and mechanical properties make AlN a promising candidate for developing detectors operating down to extreme UV region with excellent responsivity where Si based technology have reached their limits.

The highly matured existing PMT technology offers very high sensitivity, low dark current, and internal photocurrent gain greater than 10^6 for radiation detection applications. However, PMTs are bulky, fragile, require high bias voltage (>1000 V), cooling hardware and expensive filters, and are sensitive to magnetic fields. AlGaN based intrinsic solar blind solid state detectors with high internal photocurrent gain can overcome many shortcomings of PMTs by offering compactness, high sensitivity, moderate bias, and ability for chip-level integration with other optoelectronic devices. Many researchers have already demonstrated AlGaN based MSM, Schottky, and p-i-n photodiodes with excellent performances for DUV detection applications.[8–16] However, there are only a few reports on AlGaN based avalanche photodiodes (APDs) with reasonable internal photocurrent gain utilizing either p-i-n or Schottky device structures.[17–20] The shortest cut-off wavelength reported so far is 276 nm for $Al_xGa_{1-x}N$ (x=0.4) based APDs.[17,18] Most of the earlier reported AlGaN based APDs are more close to lateral charge transport devices in which surface defect charge and electric field crowding at electrode edges can degrade the device performance.[21,22] True vertical AlGaN based APDs have not been reported so far. High quality interface and better lattice match (mismatch <1%) between AlN and SiC (Refs. 23 and 24) together with the conductive nature SiC substrate provide the feasibility to build vertical conducting AlN/n-SiC DUV APDs. In these devices, under a high reverse bias, the high electric field across the AlN epilayer accelerates the charge carriers in the vertical direction, during which the charge carriers gain sufficient kinetic energy leading to impact ionization. In this letter, we report on the growth, fabrication, and characterization of vertical conducting AlN Schottky APDs with a large linear mode photocurrent gain.

The layer structure of our DUV APDs consists of an AlN epilayer grown on n-SiC substrate. AlN epilayers of about 0.9 μm were grown on n-type 4H-SiC substrates by metal-organic chemical-vapor deposition. The device fabrication starts with the deposition of Ohmic contact on the SiC substrate side by e-beam evaporating a Ni (200 nm)/Au (50 nm) bilayer, followed by 950 °C annealing for 60 s in N_2. Schottky contact area was defined by evaporating a 6 nm thick Pt layer followed by photolithography and lift-off. Then, a 100 nm SiO_2 passivation layer was deposited by plasma-enhanced chemical-vapor deposition. Schottky bonding pads were formed by evaporating a Ni (40 nm)/Au (160 nm) bilayer after opening window on SiO_2 passivation layer using photolithography and selective area wet etching of SiO_2. The fabricated devices were 100, 50, and 30 μm in diameters. Finally, devices were bonded in ten pin ceramic flat pack for characterization.

Figure 1 shows the schematic layer structure and scanning electron microscopy (SEM) image of a fabricated AlN APDs. The top undoped AlN epilayer serves simultaneously as the light absorption and carrier multiplication layer proving a cut-off wavelength of λ_c=210 nm, which corresponds to the **room temperature** band-edge absorption of 5.96 eV of AlN. Figure 2 shows the reverse biased current-voltage (I-V) characteristics for d=100 μm device under dark (solid line) and DUV (200 nm) light illumination (dotted line). The dark current (I_d) is extremely small and below 10 fA up to a reverse bias (V_b)=−60 V. I_d is about 10 pA around V_b=−180 V. Beyond V_b=−180 V (or E_b=2 MV/cm), I_d increases exponentially with further increasing V_b. These devices exhibit a reverse breakdown voltage (V_B) exceeding

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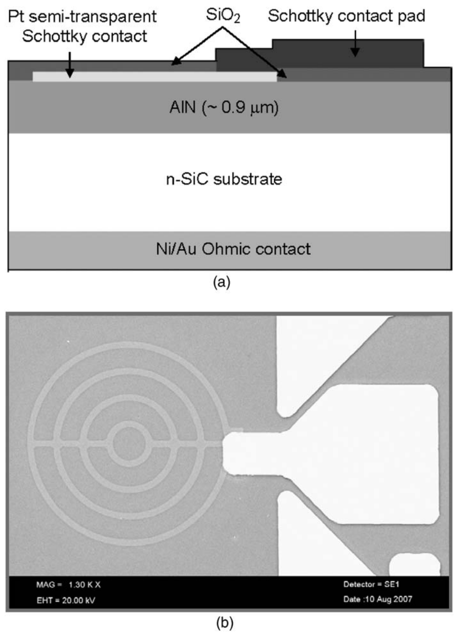

FIG. 1. (a) Schematic layer structure of AlN APDs and (b) SEM image of a fabricated AlN APD with $d=100$ μm in diameter.

-250 V corresponding to a breakdown field (E_B) exceeding 3 MV/cm. Large V_B and small I_d values provide the necessary conditions for the observation of the avalanche effect in these detectors.

The upper curve in Fig. 2 represents the *I-V* characteristic under 200 nm DUV illumination with an incident power density (P_{inc}) of about 0.05 μW/mm^2. The photocurrent (I_{ph}) starts to increase rapidly as V_b increases from 0 V and saturates at around $V_b=-10$ V. This behavior suggests that the 0.9 μm active AlN epilayer is fully depleted up to $V_b=-10$ V. Beyond $V_b=-10$ V, I_{ph} increases slowly up to $V_b=-180$ V. Therefore, I_{ph} at -10 V was taken as unity gain photocurrent. Similar to I_d, I_{ph} also increases exponentially beyond $V_b=-180$ V, which suggests the avalanche multiplication of photogenerated carriers due to the presence of high electric field in the multiplication layer. The electric field at which the avalanche multiplication starts to occur was about 2 MV/cm. A field of about 1 MV/cm for the observation of the onset avalanche gain in $Al_xGa_{1-x}N$ ($x\sim0.4$) based Schottky and *p-i-n* photodetector structures has been previously reported.[17,18] We also estimated the critical field to initiate impact ionization in AlN using the relation $E=V_d/\mu$, where μ is the electron mobility and V_d is the drift velocity, which is given by[25] $V_d=(3E_g/m_e)^{1/2}$, where E_g and m_e are the band-gap energy and electron effective mass of AlN, respectively. With $E_g=6.1$ eV, $m_e=0.48m_0$, and $\mu=135$ cm^2/V s (Refs. 26 and 27), the critical electric field is about 1.9 MV/cm, which agrees very well with our experimentally observed value of 2 MV/cm.

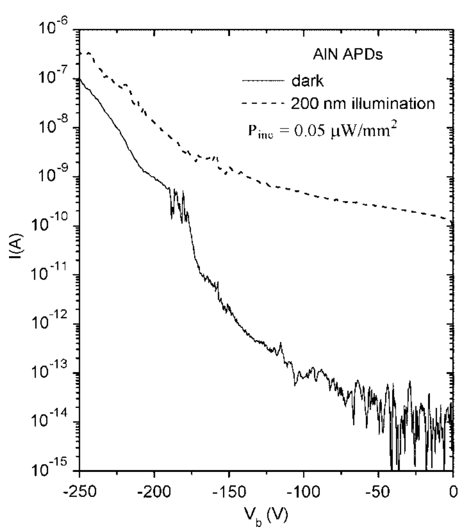

FIG. 2. Reverse *I-V* characteristics of $d=100$ μm diameter AlN APDs in dark and under 200 nm light illumination. The incident power density at 200 nm is 0.05 μW/mm^2.

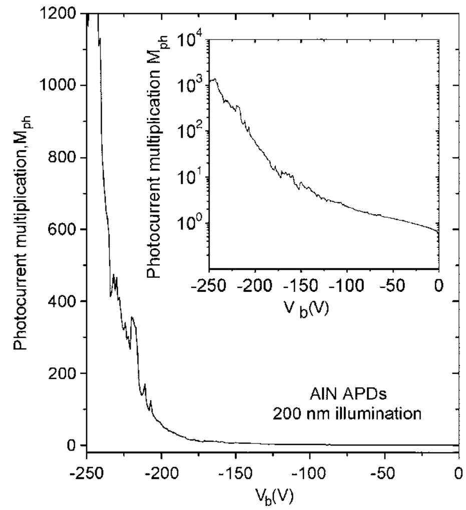

FIG. 3. Photocurrent multiplication or gain of an AlN APD with $d=100$ μm M_{ph} as a function of the reverse bias voltage V_b. M_{ph} increases only slowly at $|V_b|<180$ V, but increases exponentially at $|V_b|>180$ V and reaches about 1200 at $V_b=-250$ V. The inset is the same plot in the semilog scale.

From the *I-V* curves measured under dark and DUV illumination, photocurrent multiplication or gain (M_{ph}) as a function of V_b can be calculated according to

$$M_{\mathrm{ph}}=\frac{(I'_{\mathrm{ph}}-I'_d)}{(I_{\mathrm{ph}}-I_d)}, \qquad (1)$$

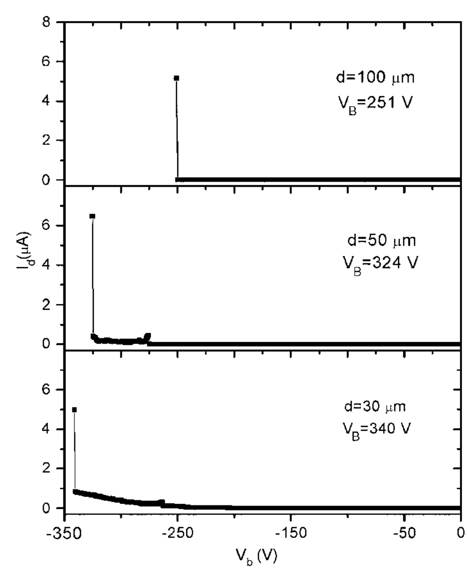

FIG. 4. Reverse bias *I-V* characteristics of AlN APDs with $d=100$, 50, and 30 μm in diameter. The breakdown voltage V_B increases with decreasing device size.

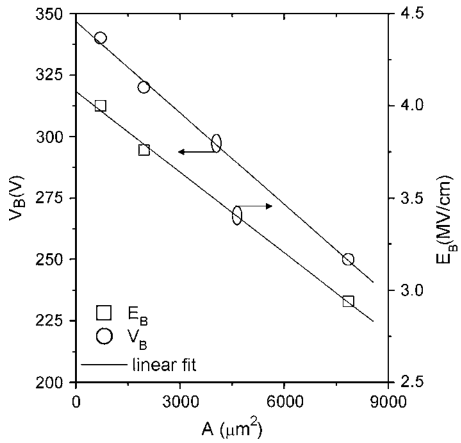

FIG. 5. Reverse breakdown voltage (V_B) and breakdown field (E_B) as functions of the device area $A(=\pi d^2/4)$ for AlN APDs. The solid lines are the linear least square fits of data. The breakdown field of dislocation-free AlN epilyer (E_B at $d=0$) is about 4.1 MV/cm.

where I'_{ph} and I'_d are multiplied photo- and dark currents, respectively, whereas I_{ph} and I_d are primary (unmultiplied) photo- and dark currents at the unity gain region. Figure 3 shows M_{ph} as a function of V_b. M_{ph} does not increase significantly between $V_b=-10$ and -180 V and starts to increase exponentially beyond $V_b=-180$ V and reaches about 1200 at $V_b=-250$ V (which corresponds to an electric field of about 3 MV/cm). These vertical carrier transport photodetectors without mesa etch sidewall precludes the edge related gain mechanism. Furthermore, the exponentially increasing nature of M_{ph} with V_b occurring only at very high reverse field rules out the possibility of photoconductive gain, which may take place even at lower V_b and increases only linearly with applied voltage.[18] Furthermore, we have measured I_d at different temperatures and observed that I_d was temperature dependent, which suggests that the gain mechanism is not related to Zener tunneling.[17] Therefore, the linear mode photocurrent gain observed in our devices is related to the soft avalanche multiplication of carriers due to impact ionization. The results are believed to be related to the better quality of AlN compared to AlGaN alloys, in which alloy scattering reduces carrier mobility.[28] The critical electric field for the onset avalanche is inversely proportional to carrier mobility for a given drift velocity. It may be also related to the advantages of vertical conducting devices, where surface defect charge and carrier scattering by charged dislocations have less severe effects on the device performance. Moreover, the ratio of I_{ph} to I_d is more than four order of magnitude up to $V_b=-100$ V.

We have also studied the variation of V_B with the device size for these photodetectors. The reverse *I-V* characteristics for $d=100$, 50, and 30 μm devices are shown in Fig. 4, which clearly indicate that the breakdown voltage increases with decreasing the device size. This is a direct consequence of the presence of threading dislocations in the device, because the breakdown voltage should be device size independent if the material is defect-free. This point is further elucidated in Fig. 5, which clearly demonstrates that V_B increases almost linearly with decreasing device area $[A=(\pi d^2/4)]$. Since the number of dislocations increases linearly with the device area, the behavior shown in Fig. 5 is related only with the presence of threading dislocations. The result thus suggests that the device performance can be further improved by improving material quality through dislocation reduction and device size and geometry optimization. The breakdown field of dislocation-free AlN epilayers can be obtained by extrapolating V_B to $A=0$, which is about 4.1 MV/cm.

In summary, we have demonstrated the linear mode operation of AlN based APDs which possess the shortest cutoff wavelength of 210 nm. The photocurrent multiplication reached a value of 1200 under -250 V ($E_b=2.8$ MV/cm) reverse bias. Also, the device size dependent breakdown field suggests that Geiger mode operation could be achieved by further reducing the dislocation density and optimizing device size and geometry. These results further demonstrate that AlN is an excellent active DUV material for future DUV optoelectronic device applications.

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[1] J. Li, K. B. Nam, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **81**, 3365 (2002).
[2] K. B. Nam, J. Li, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **81**, 3365 (2003).
[3] J. Li, K. B. Nam, M. L. Nakarmi, J. Y. Lin, H. X. Jiang, P. Carrier, and S. H. Wei, Appl. Phys. Lett. **83**, 5163 (2003).
[4] M. Horita, J. Suda, and T. Kimoto, Appl. Phys. Lett. **89**, 112117 (2006).
[5] Y. Taniyasu, M. Kasu, and T. Makomoto, Nature (London) **441**, 325 (2006).
[6] J. Li, Z. Y. Fan, R. Dahal, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **89**, 213510 (2006).
[7] R. Dahal, T. M. Al Tahtamouni, Z. Y. Fan, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **90**, 263505 (2007).
[8] A. Osinsky, S. Gangopadhyay, B. W. Lim, M. Z. Anwar, M. A. Khan, D. V. Kuksenkov, and H. Temkin, Appl. Phys. Lett. **72**, 742 (1998).
[9] C. J. Collins, U. Chowdhury, M. M. Wong, B. Yang, A. L. Beck, R. D. Dupuis, and J. C. Campbell, Appl. Phys. Lett. **80**, 3754 (2002).
[10] U. Chowdhury, M. M. Wong, C. J. Collins, B. Yang, J. C. Denyszyn, J. C. Campbell, and R. D. Dupuis, J. Cryst. Growth **248**, 552 (2003).
[11] S. Butun, T. Tut, B. Butan, M. Gokkavas, H. Yu, and E. Ozbay, Appl. Phys. Lett. **88**, 123503 (2006).
[12] C. Pernot, A. Hirano, M. Iwaya, T. Detchprohm, H. Amano, and I. Akasaki, Jpn. J. Appl. Phys., Part 1 **39**, 387 (2000).
[13] N. Biyikli, O. Aytur, I. Kimukin, T. Tut, and E. Ozbay, Appl. Phys. Lett. **81**, 3272 (2002).
[14] X. Xin, F. Fan, T. W. Koeth, C. Joseph, J. Hu, and J. H. Zhao, Electron. Lett. **41**, 1192 (2005).
[15] A. Sciuto, F. Roccaforte, S. D. Franco, and V. Raineri, Appl. Phys. Lett. **89**, 081111 (2006).
[16] E. J. Tarsa, P. Kozodoy, J. Ibbetson, B. P. Keller, G. Parish, and U. Mishra, Appl. Phys. Lett. **77**, 316 (2000).
[17] T. Tut, M. Gokkavas, A. Inal, and E. Ozbay, Appl. Phys. Lett. **90**, 163506 (2007).
[18] R. McClintock, A. Yasan, K. Minder, P. Kung, and M. Razeghi, Appl. Phys. Lett. **87**, 241123 (2005).
[19] T. Tut, S. Butan, B. Butan, M. Gokkavas, H. Yu, and E. Ozbay, Appl. Phys. Lett. **87**, 223502 (2005).
[20] J. B. Limbo, D. Yoo, J. H. Ryou, W. Lee, S. C. Shen, R. D. Dupis, M. L. Reed, C. J. Collins, M. Wraback, D. Hanser, E. Preble, N. M. Williams, and K. Evans, Appl. Phys. Lett. **89**, 011112 (2006).
[21] A. Nishikawa, K. Kumakura, and T. Makimoto, Jpn. J. Appl. Phys., Part 1 **46**, 2316 (2007).
[22] M. Mishra, A. V. Sampath, and T. D. Moustakas, Appl. Phys. Lett. **76**, 1045 (2000).
[23] M. O. Aboelfotoh, R. S. Kern, S. Tanaka, R. F. Davis, and C. I. Harris, Appl. Phys. Lett. **69**, 2873 (1996).
[24] C. M. Zetterling, M. Östling, N. Nordell, O. Schön, and M. Deschler, Appl. Phys. Lett. **70**, 3549 (1997).
[25] D. Wood, *Optoelectronic Semiconductor Devices* (Prentice Hall, UK, 1994), pp. 331–332.
[26] V. W. L. Chin, T. L. Tansley, and T. Osotchan, J. Appl. Phys. **75**, 7365 (1994).
[27] S. K. O'Leary, B. E. Foutz, M. S. Shur, U. V. Bhapkar, and L. F. Eastman, Solid State Commun. **105**, 621 (1998).
[28] C. Sevik and C. Bulutay, Appl. Phys. Lett. **83**, 1383 (2003).