Investigation of GaN-based avalanche photodiodes

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Abstract

GaN-based avalanche photodiodes (APDs) have become of increased interest in the UV detection arenas. However, numerous material-, fabrication-, and design-related problems are exactly settled before GaN-based APDs can be commercialized. In this study, we, first, discussed recent development of the GaN-based APDs. Then front- and back-illumination (respectively realizing electron and hole initial impact-ionization) p-i-n heterostructure devices with various mesa diameters were fabricated. The device with a diameter of 40 μm exhibited a multiplication gain of ~680, at reverse bias of ~76 V corresponding to the magnitude of the electric field of ~ 3 MV/cm by experiment indicating and simulation verifying. To confirm the origin of dark current under different reverse bias, the dark current-voltage characteristic of various sized mesa devices were performed. The dark current could be linearly fitted to the device diameter (or circumference) implied that the surface leakage along the mesa sidewall was the dominant component of the dark current. At zero bias, the spectral peak responsivity reached ~ 0.14A/W for front illumination, and ~ 0.152A/W for back illumination at a wavelength of 358 nm. The positive breakdown voltage coefficient from the temperature-dependent current-voltage characteristics was 0.02 V/K.

Key words: avalanche photodiodes, dark current, breakdown voltage coefficient, responsivity

1. INTRODUCTION

Ultraviolet (UV) radiation detection presents numerous applications such as flame detection, chemical/biological sensing and optical communication[1-3]and scientific research. High sensitivity (quantum efficiency), low noise (dark current) and high speed are desired to meet these special applications. Up to now, these needs have almost been dominated by photomultiplier tubes (PMT) and Si-enhanced ultraviolet detectors. However, relative high operation voltage, bulky, frangible and complex for PMT and low rejection ratio of ultraviolet/visible for Si UV devices are their drawbacks to meet those special applications. In parallel, the investigation of photocurrent gain in semiconductor photodetectors has already been driven in the field of semiconductor technology. Moreover, impact ionization in APDs is one of the most effective gain mechanisms, capable of delivering gain factors. Therefore GaN-based avalanche photodiodes (APDs) combined internal gain due to impact ionization with special material properties such as direct and tunable wide band gap, intrinsic rejection of the visible spectrum, high bond strength, high breakdown field and exceeding chemical stability and superior radiation hardness for durable operation in caustic environments have presented themselves as the most suitable alternative for PMTs and Si-enhanced UV devices for UV-detection applications.

In GaN material and its alloys, it suffers from the lack of native substrate, usually, sapphire, SiC or silicon serves as the

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International Symposium on Photoelectronic Detection and Imaging 2009: Material and Device Technology for Sensors, edited by Xu-yuan Chen, Yue-lin Wang, Zhi-ping Zhou, Qing-kang Wang, Proc. of SPIE Vol. 7381, 73810Y · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.835325

substrate, but all of them induce large strain as well as high dislocation densities in the epilayers due to the lattice mismatch and thermal expansion coefficient. Those defects locate in the band gap can affect the electrical and optical properties[4]. They are attributed to the trap-assisted tunneling current resulting in increasing the dark current at a moderate reverse bias. They are attributed to the existence of microplasmas effects in GaN-based APDs prior to onset of avalanche breakdown which is a dominant factor resulting in their degraded performance[5]. They are also attributed to reduce the overall UV quantum efficiencies of AlGaN photodetectors[6]. Now, the majority of the epitaxial structures reported for III-N UV photodetectors are grown by metalorganic chemical vapor deposition (MOCVD) by inserting a buffer layer (low-temperature AlN or thicker GaN layer) to improve the material quality.

Although there have been a few reports on the development and characterization of GaN-based visible- or solar-blind APDs, most of them are p-i-n[7-10] or Schottky[11] APDs, in which several problems exist as follows: 1) larger dark current determined by structural parameters of devices, for example, the dark current increasing with the diameter of devices 2) lower internal quantum efficiency due to the absorption and short diffusion length of minority carrier in the n-GaN layer for back-illuminated p-GaN/i-GaN/n-GaN/AlN APDs as well as the quality of epitaxial material; 3) small diameter of devices , usually, ranging from 10um to 40um limited by the defects, but for Si or InGaAs APDs, there exits a diameter of ~1 mm device; 4) the lack of theoretical investigation in GaN-based material hindering the development of simulation of GaN-based APDs and investigation of high-field properties of carrier transport; 5) the immature material technology resulting in the impossibility of fabricating devices with special and complex structure to improve their multiplication characteristics and suppress excess noise. For example, it has been found that the separate absorption and multiplication (SACM) structure and heterostructure are common approaches to reduce multiplication noise and enhance gain through impact ionization engineering in Si, Ge or InGaAs APDs. There are fewer reports on the GaN-based APDs with SACM [12]or hereojunction structure[10], but the fact that these special structure can improve devices characteristics also is confirmed in GaN-based APDs.

However, there are few reports on back-illumination heterojunction GaN-based APDs mainly due to the material quality. Back illumination favors separate hole and electron initiated multiplication, which yields superior gain and noise characteristics. In addition, back-illumination allows easier integration and packaging through flip-chip technology as required for the production APDs arrays. In this paper, we report on the fabrication and characterization of back-illumination heterojunction GaN-based APDs.

2. EXPERIMENTAL

P-i-n samples were grown by metal-organic chemical-vapor deposition on double side polished c-plane sapphire substrates with inserting AlN layers to control lattice mismatched defects. The structure consists of a 0.7um $Al_{0.33}Ga_{0.67}N$: Si n-type AlGaN followed by an unintentionally doped 180 nm GaN and capped with a 150 nm GaN :Mg p-type region. Carrier concentration in these layers were estimated by recombined Hall measurements and capacitance-voltage results with the values of 1×10^{16} cm^{-3} and 3×10^{18} cm^{-3} for electron concentration in the i-GaN and n- $Al_{0.3}Ga_{0.7}N$ layers, respectively, and 2×10^{17} cm^{-3} for the hole concentration in the p-GaN layer. An 200 Å/200 Å multilayer Ni/Au was evaporated in order to form p-contact.

Various sized mesas ranging in diameter from 40 um to 90 um with the increment of 10 um were defined via standard photolighography technology and inductively coupled etching (ICP) under Cl_2, BCl_3 and Ar plasmas, optimizing the ratio of Cl_2 to BCl_3 to assure ideal etched morphology and fewer induced defects. After etched down to n-type layer, Ti/Al/Ti/Au contacts were deposited via thermal evaporation and left in an acetone solution for the lift-off process, followed by annealing at 750 ^oC for 60s under N_2 ambience in a rapid thermal annealing system. Then, a 3000Å thick Si_3N_4 was deposited via plasma enhanced chemical vapor deposition for passivation. Finally, 200 Å/3000Å thick Cr/Au interconnect metal was deposited and lifted off to connect the pads and measurement devices. Finally, the structure of samples is given in Fig.1.

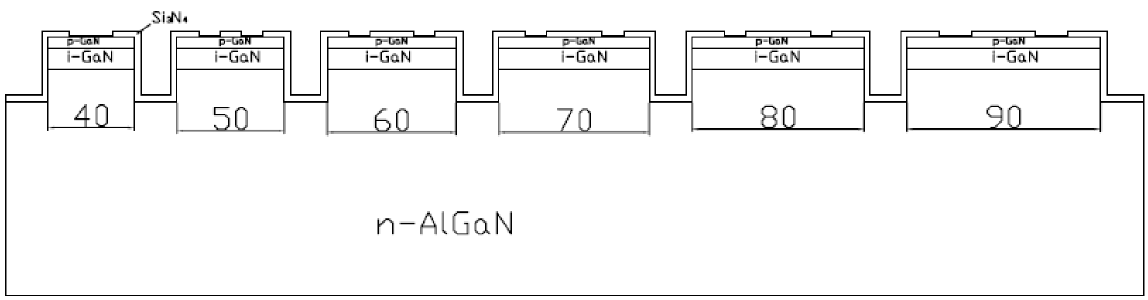

Fig.1 the simple cross structure of various sized diameter of GaN-based APDs

3. RESULTS AND DISSCUSSION

3.1 The dark Current-Voltage characteristics

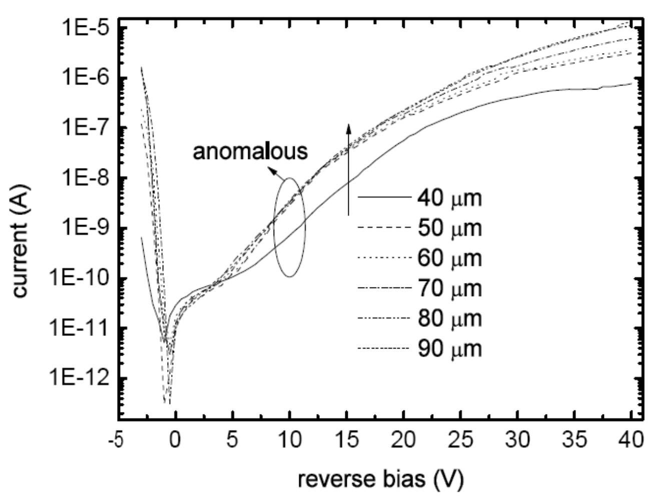

Fig.2 the dark current of various sized diameter devices

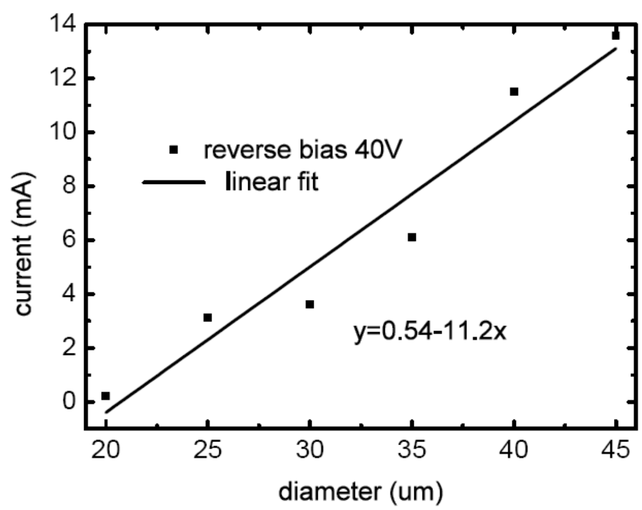

Fig.3 Reverse dark current versus device diameter at reverse bias of 40V

The dark current-voltage (I-V) characteristics under reverse bias were measured using a keithley236 semiconductor parameter analyzer for different mesa diameter; this primarily allowed for the study of the dark current as a function of the mesa area or diameter to find the study of the dark current. As shown in fig.3, the reverse dark current rapidly increases with the increase of reverse bias. In addition, the I-V measurement exhibited the anomalous current, and there is not a linear log (I)-V curve. Yamaguchi et al[13] reported an anomalous current that was caused by deep traps in the vicinity of the sidewall in Si p-n junctions. Dr. Guo[14] also found anomalous current in SiC APDs for different passivation processes. The dark current versus devices diameter at reverse bias of ~ 40 V is shown in Fig.4. The fact that dark current could be linearly fitted to the device diameter (or circumference) implied that the surface leakage along the mesa sidewall was the dominant component of the dark current. Therefore, it is reasonable to conclude that the surface leakage is dominant dark current component at low and moderated bias for our devices, and effective surface treatment and passivation technology or different passivation process should be introduced.

3.2 Multiplication Characteristics

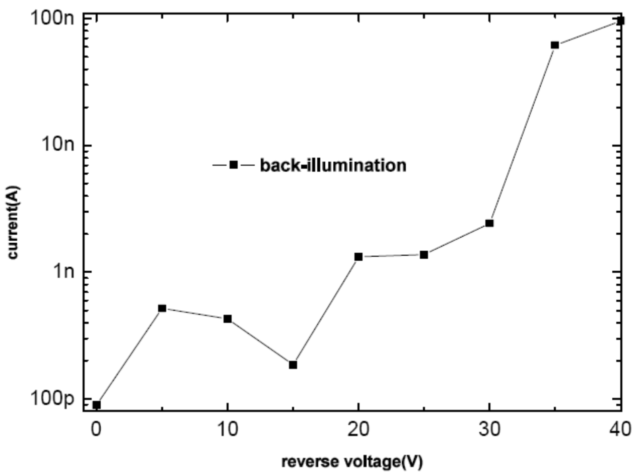

Fig.4 photocurrent of device under back illumination by modulated UV LED using a lock-in amplifier and resistor.

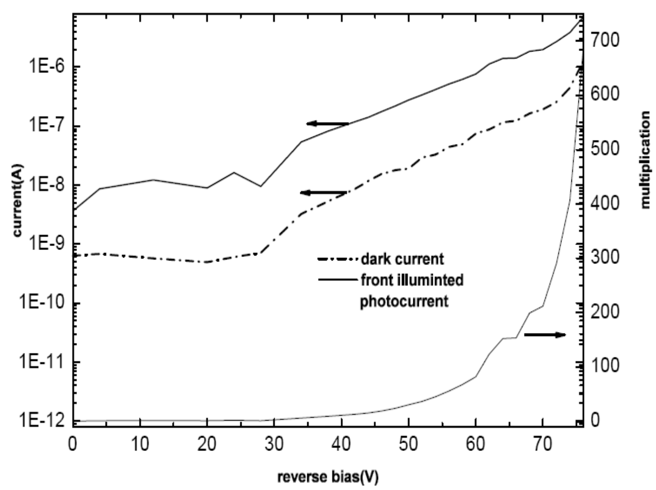

Fig.5 the dark current (dot line),front-illumination photocurrent and multiplication curves at different voltage.

When illuminated from the substrate using chopping LED, the photocurrent was measured using a resistor and lock-in amplifier. As given in fig.4, the photocurrent does not significantly increase with increasing reverse bias until at a bias of 35 V. Also, R. McClintock et. al [8] reported that ionization events started at voltages above 50 V for holes and 70 V for electrons in the i-200 nm samples, while for i-150 nm samples, 35 V and 65 V, corresponding to expected electric field of close to 2 MV/cm and 1.8 MV/cm. Then avalanche gain is defined as the difference between the primary multiplied current and the multiplied dark current, normalized by the difference between the primary unmultiplied current and the unmultiplied dark current. In this paper, the normalized value of photocurrent is chosen at bias of 20 V as the unity gain reference point, since there is no significant photocurrent multiplication. The photocurrent gain was calculated according to

$$M = \frac{I'_{ph} - I'_{d}}{\left(I_{ph} - I_{d}\right)_{-20V}}$$

Where $I_{ph}^{'}$ and $I_{d}^{'}$ are multiplied photo- and dark- currents, respectively, whereas I_{ph} and I_{d} are unmultiplied photo- and dark current at bias of 20V. Fig.5 shows the reverse current in both dark and back-illumination using a Xe lamp conditions for devices with a diameter of ~40 μm. The maximum value of multiplication gain is ~680 at a reverse bias of 76 V, corresponding to an electric field of 3 MV/cm calculated by combining single abrupt junction approximation with current-voltage measurement results. An important indicator of avalanche gain is a positive temperature coefficient of the breakdown voltage. As the temperature increases, so does carrier scattering, owing to carrier-phonon interaction. Therefore, a higher electric field intensity value is required to accelerate the carriers to initiate impact ionization; this results in a positive temperature coefficient. The temperature-dependent current-voltage (I-V-T) characteristic (not shown in this paper) shows the monotonic increase in the breakdown voltage with increasing temperature-as is expected for impact ionization. For T>200 K, the temperature coefficient of breakdown-voltage variation of our APDs devices is (dV_B/dT) ≈0.02 V/K.

3.3 Photoresponse characterization

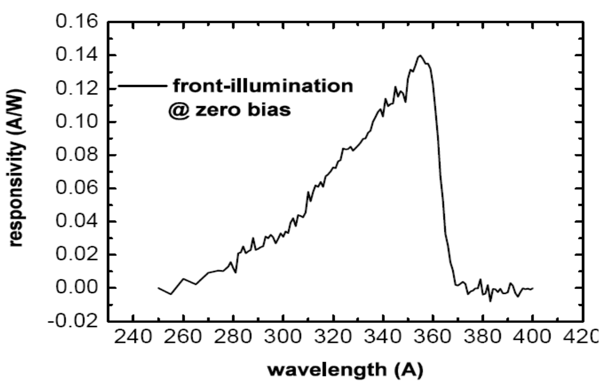

Fig.6(a) responsivity *v.s* wavelength at zero bias for a device with diameter of ~20 μm under front illumination

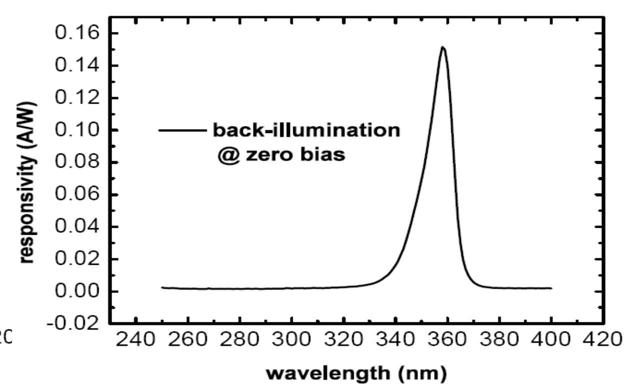

Fig.6(b) responsivity *v.s* wavelength at zero bias for a device with diameter of ~20 μm under back illumination

The photoresponse characteristics of the GaN-based APDs with mesa diameter of ~40 μm were measured and analyzed. The light source which was provided by a 350-W Xe arc lamp was focused by a lens and dispersed through a monochrometer. Figure 6(a) and (b) respectively show the measured spectral responsivities of devices at front- and back-illumination at zero reverse bias. It is the simple device from measurement to measurement. The spectral peak responsivity reached ~0.14 A/W for front illumination, and ~0.152 A/W for back illumination at a wavelength of 358 nm. For front-illumination as shown in fig.6 (a), the responsivity ranges are broad, from 280 nm to 370 nm, and exhibit and abrupt spectral cutoff. This is due to the fact that GaN is a direct semiconductor and has a sharp cutoff edge at the band edge. However, for back-illumination, as shown in fig.6 (b), the responsivity ranges are narrower than that of front illumination. The fact confirms that a layer of AlGaN serves as the “window” for ultraviolet illuminated on the substrate and makes the absorption directly occur in the active layer (undoped-GaN). In this way, the external quantum efficiency of p-i-n UV photodetectors can be effectively improved. C.Bayram and coworkers[10] fabricated and measured back-illumination GaN-based APDs with p-GaN/i-GaN/n-AlGaN and p-GaN/i-GaN/n-GaN/n-AlGaN. The results were that an external quantum efficiency (EQE) of 57% at 352 nm with a bandpass response was achieved by using AlGaN in the n-layer, at low voltage. Using this simple approach, the GaN/AlGaN photodiodes was improved up to 70% in another work[15].

4. CONCLUSION

In conclusion, we have discussed the fabrication and measurement of front- and back-illumination GaN-based APDs. A multiplication gain of devices with diameters of 40 μm exhibited of ~680, at reverse bias of ~76 V. Experiment indicates and simulation verifies that the magnitude of the electric field at the onset to avalanche gain is ~ 3 MV/cm. The dark current could be linearly fitted to the device diameter (or circumference) implied that the surface leakage along the mesa sidewall was the dominant component of the dark current, which is obtained by I-V characteristics of different diameter devices. At zero bias, The spectral peak responsivity reached ~0.14 A/W for front illumination, and ~0.152 A/W for back illumination at a wavelength of 358 nm. The positive breakdown voltage coefficient from the temperature-dependent current-voltage characteristics is 0.02 V/K, which indicated that the increase of dark current with increasing reverse bias induced by avalanche effect not by the Zener tunneling effect.

ACKNOWLEGEMENT

The authors would like to thank Professor Degang Zhao for giving GaN-based p-i-n material in State key laboratory on Integrated Optoelectronics, Institute of semiconductors, Chinese Academy of Science Beijing , China. Also We thank Hui Qiao, Guoqing Xu, Shijia Liu ,Nili Wang, Kaihui Chu, Xiangyang Liu, and Yidang Tang for their important works.

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