(2)

A Comparative Study of the Electrical Characteristics of Metal-Semiconductor-Metal (MSM) Photodiodes Based on GaN Grown on Silicon

Y.C.Lee[1], Z. Hassan[1], F. K. Yam[1], M. J. Abdullah[1], K. Ibrahim[1],

M. Barmawi[2], Sugianto[2], M. Budiman[2], and P. Arifin[2]

[1]School of Physics, Universiti Sains Malaysia, Penang, Malaysia

[2]Lab. of Electronic Materials Physics, Department of Physics,

Institute Technology Bandung, Indonesia

E-mail: zai@usm.my

25186

ABSTRACT

High quality GaN films are usually produced at high growth temperatures (>1000°C) with the use of substrates such as sapphire (Al_2O_3) or silicon carbide (SiC). Therefore, for a low production cost purpose, there has been a growing interest in producing lower growth temperatures GaN films as well as GaN based devices with low cost substrates such as silicon. Growth of GaN onto silicon substrates offers a very attractive opportunity to incorporate GaN devices onto silicon-based integrated circuits. The development of device quality films grown at low temperatures could also open up opportunities for large area devices such as UV detector arrays at low cost.

In this paper, we report on the electrical characterization of metal-semiconductor-metal (MSM) photodiodes fabricated on GaN grown on silicon by electron cyclotron resonance (ECR) plasma-assisted metalorganic chemical vapor deposition (PA-MOCVD) with different growth temperatures (200°C and 600°C). Electrical characterization were carried out by using current-voltage (I-V) measurements to study the electrical characteristics of the fabricated device. Structural analysis of the GaN samples used for the photodiodes fabrication were performed by using x-ray diffraction (XRD), atomic force microscopy (AFM), scanning electron microscopy (SEM), and energy dispersive x-ray analysis (EDX) to analyze the crystalline quality of the samples used for photodiodes fabrication.

PACS: 61.10.-i; 61.43.Dq; 68.55.-a; 73.40.Sx

Keywords: A1. Characterization, A1. Crystalline Structure, B1. III-V Nitrides,
B3. Photodiodes.

INTRODUCTION

Galium nitride (GaN), a wide and direct bandgap semiconductor is a vastly studied semiconductor material due to its potential as an excellent candidate for the application in optoelectronic and high power/temperature electronic devices [1]. Great attention have been received in recent years for the development of visible-blind ultraviolet (UV) photodetectors based on III-V nitride which have application in both civil and military industries such as engine control, flame sensing, source calibration, solar UV monitoring, UV astronomy, secure space-to-space communications, and missile plume detection [2].

GaN grown on silicon (Si) based photodetectors are still very few especially of those grown at low temperature due to the large quantities of defect densities which is attributed to the high lattice and thermal mismatch of Si and GaN. Therefore more work has to be done to investigate its significance for the application in device fabrication as GaN films grown on Si is expected to be an excellent candidate for the integration of GaN-based optoelectronic devices with Si-based electronic technology [3]. Moreover the advantage of low temperature grown films is the capability to deposit the material inexpensively over large areas, which could open up opportunities for the development of low cost and large-area devices such as UV detector arrays.

Photodetectors in the form of metal-semiconductor-metal (MSM) structure are subjected to keen interest among various kind of detectors due to its many attractive features like the ease of fabrication, low dark current, large bandwidth, small capacitance, and the suitability for integration in an optical receiver [4].

In this paper, we report on the comparative study of the electrical characteristics of the MSM photodiodes based on ECR PA-MOCVD grown GaN at growth temperatures of 200°C and 600°C. Structural analysis of the GaN samples used for the photodiodes fabrication was also carried out by using x-ray diffraction (XRD), atomic force microscopy (AFM), scanning electron microscopy (SEM), and energy dispersive x-ray analysis (EDX) to analyze its crystalline quality.

EXPERIMENTAL

GaN films grown on Si(100) at 200°C and 600°C by ECR PA-MOCVD were used for this study. Details of the reactor and growth technique have been described elsewhere [5]. The two samples used for the detector fabrication have a transparent GaN epitaxial layer of about 0.5μm thick and are unintentionally doped n-type. The unintentionally doped n-GaN samples used in this study are most commonly thought to be nitrogen vacancies [6] but until recent investigation, it has been revealed that nitrogen vacancies are high energy defects in n-type GaN [7] and their high formation energy makes it very unlikely that they would form during growth of undoped or n-type GaN, and instead, the proposed idea in explaining the actual cause of unintentional n-type doping are unintentional impurities such as oxygen and silicon [8].

The structure of the MSM photodiodes consist of two interdigitated Schottky contact (electrode) with fingers width of 230µm, finger spacing of 400µm, and the length of each electrode was about 3300 µm. It consists of 4 fingers at each electrode.

X-ray diffraction (XRD) was used to assess the structure of the deposited layers. These data were collected on a Rigaku diffractometer with a wide angled automated goniometer and computer based data acquisition and analysis system. Scanning electron microscopy (SEM), atomic force microscopy (AFM), and energy dispersive x-ray analysis (EDX) were used to observe the surface morphology and to identify the elements present in the samples.

Nickel (Ni) Schottky contacts were deposited on the GaN samples by thermal evaporation where the pattern of metallization was defined by using a metal mask. Prior to metal contact deposition, the GaN sample which was grown at 600°C was cleaned in boiling aqua regia ($HCl:HNO_3 = 3:1$) as a way to etch away surface contaminants and native oxides. Then it was followed by thermal annealing at 400°C in flowing nitrogen environment for 10 minutes. As the existence of a thin contamination layer cannot be totally ruled out upon cleaning unless the samples are cleaved in an ultra-high vacuum condition [9], thus annealing the Ni-GaN at 400°C in flowing nitrogen environment for 10 minutes was done as a way to remove the contamination layer from the GaN/Ni interface [10] and also to reduce the leakage current, increase the Schottky barrier height, and to improve the uniformity of the barrier height [11]. For the GaN sample grown at 200°C, the method of cleaning prior to contact deposition was the same but the aqua regia solution was not at its boiling point, instead it was at room temperature. The sample was soaked inside the aqua regia solution for about 1 minute. The reason for the slight differences in cleaning treatment was mainly due to the amorphous like structure of the sample grown at 200°C, which might have a lower thermal and chemical stability.

RESULTS AND DISCUSSIONS

Figure 1 shows the x-ray diffraction spectra of GaN samples grown on Si(100) substrates. For the GaN sample grown at 200°C, the peaks at 33.4° and 69.6° correspond to Si(200) and Si (400) planes respectively, with the (400) peak intensity much higher than the intensity of the (200) peak by a few hundred times. We suggest that the GaN samples grown at 200°C were amorphous in nature due to the absence of a diffraction pattern which indicate a crystalline phase of GaN. However, for the GaN samples grown at 600°C, we observed the (0002) peak for GaN at 34.6° which suggest the existence of a crystalline or microcrystalline phase due to the low intensity of this peak. X-ray diffraction peaks for GaN should be observed at around 32.3°, 34.6° and 36.8° which correspond to $(10\bar{1}0)$, (0002) and $(10\bar{1}1)$ planes of the hexagonal crystalline GaN. With the absence of strong and sharp GaN crystalline peaks and a broadening centered at the crystalline region for films grown at 600°C, we would conclude that this could be an indication of a mixed phase of crystalline and amorphous structure, and therefore, we would suggest that this could be a sign of microcrystalline phase in the GaN samples grown at 600°C.

The transparent GaN films have a thickness of about 0.5μm and exhibit smooth surface morphology. The measured root mean square (rms) surface roughness by AFM (Figure 2) on a $2\times2\mu m^2$ was 1.86nm for GaN grown at 200°C and 4.95nm for GaN grown at 600°C. Here, we suggest that the formation of small grains (microcrystallites) on the substrate surface at this temperature was the main cause of the increase in roughness for the GaN samples grown at 600°C. Finally, the presence of Ga and N in these GaN samples is confirmed with EDX measurements.

Figure 3 and 4 illustrates the I-V characteristics of the photodiodes based on GaN grown at 600°C and 200°C respectively. In these graphs, a) is the dark current while b) is the current under illumination condition (photocurrent). The amorphous GaN photodiode shows a very small fluctuation in the dark current which is nearly constant with the applied bias, with a magnitude of about 0.18μA at 10V much smaller when compared to the dark current characteristics of the photodiode based on GaN grown at 600°C or the microcrystalline GaN, which has a magnitude of about 18μA at 10V. This behaviour is most probably due to the resistive nature of amorphous GaN under dark condition. The conductivity of the amorphous GaN photodiode rises drastically under illumination (white light photoresponse) without any sign of saturation commonly observed in typical MSM photodiodes [12].

The lack of saturation for the dark current and photocurrent characteristics of the photodiode based on the microcrystalline GaN was also observed. The lack of current saturation in Schottky contacts is commonly attributed to various factors like image force lowering, tunneling mechanism which is more substantial during reverse bias, generation of electron-hole pairs in the depletion region which is more pronounced at low temperature, and the dependency of the barrier height on the electric field strength in the barrier as a result of the existence of an interfacial layer between the metal and the semiconductor. We still can assume that there is a negligible thickness of interfacial layer at the interface of the microcrystalline GaN/Ni Schottky contact as it has been annealed to remove any possible interfacial/contamination layer, but we cannot ruled out the existence of a contamination layer at the amorphous GaN since it was cleaned in a slightly different condition. Thus according to Ref. [9], the reverse current of a Schottky contact with a fairly thick contamination layer may actually be greater than that of a Schottky contact with a very thin contamination layer. This can be observed in the amorphous GaN based photodiode under illumination when compared to the microcrystalline-based photodiode under the same condition. A large magnitude of leakage current can mainly be attributed to a high amount of defect densities usually found in GaN materials [13 -16] especially for those grown on Si substrates due to the existence of defect generated trap-assisted tunnel current [17] which enhances the dark current. This can be seen in the drastic rise in the current magnitude for both of the samples under illumination.

In addition, the drastic rise in current without saturation at elevated biasing (>~5V) when illuminated in the amorphous GaN photodiode is unexpected. Usually typical MSM photodiodes under dark condition will normally have a flat band pattern in their dark current characteristics, which are almost independent of the bias voltage at further biasing or in other words, the dark current at first rise with voltage and then become saturated. When illuminated, typical photodiodes will behave the same, with a flat band pattern but at a higher magnitude of saturation current. This could be due to the highly resistive nature of the amorphous GaN under dark condition. Thus, when illuminated, the change in the resistivity allows electrical conduction to occur at a normal behaviour.

The other factor which is responsible for the large increase in the magnitude of the dark current after being illuminated, may be attributed to the contribution from the n-type Si substrate to the current transport mechanism of the Schottky contacts due to the absence of a buffer layer between the substrate and the GaN film. Usually, structural properties of nitride compounds can be improved by a two-step growth method where monocrystalline GaN epilayers are grown on top of a thin AlN buffer/nucleation layer [18]. J. L. Pau et al has stated that the role of the AlN buffer layer is not only to improve the crystalline quality, but also to electrically insulate the epitaxial film from the conductive Si substrate [19].

CONCLUSION

The electrical characteristics of MSM photodiodes based on unintentionally doped n-type amorphous GaN grown at 200°C and microcrystalline GaN grown at 600°C on Si substrates were investigated. The photodiode based on amorphous GaN tends to be very resistive at dark condition and normal conduction can only take place with the assistance of light illumination. The high dark current characteristics of the MSM photodiode based on microcrystalline GaN can be attributed to factors like high defect densities present in the GaN samples which generate a high value of trap-assisted tunnel current as well as leakage current and some contributions from the silicon substrates. The structural analysis of the GaN films showed that these films exhibit smooth surface morphology, as revealed by scanning electron microscopy (SEM), and atomic force microscopy (AFM) measurements.

ACKNOWLEDGEMENT

This work was conducted under AUN/SEEDNet and IRPA RMK-8 Strategic Research grant. The authors wish to thank M. E. Kordesch (Ohio University) and Spire Corporation for providing the samples in our study. The support from Universiti Sains Malaysia is gratefully acknowledged.

REFERENCES

[1] S. Strite and H. Morkoc, J. Vac. Sci. Technol. B 10 (1992) 1237.

[2] Eva Monroy, Fernando Calle, Jose Luis Pau, Elias Munoz, Franck Omnes, Bernard Beaumont, and Pierre Gibart, Mat. Res. Soc. Symp., Vol. 622 (2000) T3.7.1.

[3] Z. M. Zhao, R. L. Jiang, P. Chen, D. J. Xi, Z. Luo, R. Zhang, B. Shen, Z. Z. Chen, and Y. D. Zheng, Appl. Phys. Lett., 74(3) (2000) 444.

[4] Eva Monroy, Fernando Calle, Jose Luis Pau, Elias Munoz, Franck Omnes, Bernard Beaumont, and Pierre Gibart, Mat. Res. Soc. Symp., Vol. 622 (2000) T3.7.4.

[5] Z. Hassan, M. E. Kordesch, W. M. Jadwisienzak, H. J. Lozykowski, W. Halverson, P. C. Colter, Mat. Res. Soc. Symp. Proc. 536 (1999) 245.

[6] S. Strite and H. Morkoc, J. Vac. Sci. Technol. B 10 (1992) 1243.

[7] J. Neugebauer, C. G. Van de Walle, Phys. Rev. B 50 (1994) 8067.

[8] J. Neugebauer, C. G. Van de Walle, Proc. ICPS-22, World Scientific, Singapore, (1995) 2327.

[9] E. H. Rhoderick and R. H. Williams, Metal-Semiconductor Contact, 2nd ed. (Oxford University Press, New York, 1998).

[10] Hidenori Ishikawa, Setsuko Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike, and Masanori Murakami, J. Appl. Phys. 81 (3) (1997) 1318.

[11] T. Sawada, Y. Ito, K. Imai, K. Suzuki, H. Tomozawa, and S. Sakai, Appl. Surf. Sci. 159-160 (2000) 449.

[12] Kwok K. Ng, Complete Guide To Semiconductor Devices, 2nd ed. (Wiley-IEEE Press, New York, 2002) ch. 60, p. 472.

[13] S. Tomiya, K. Funato, T. Asatsuma, T. Hino, S. Kijima, T. Asano, and M. Ikeda, Appl. Phys. Lett. 77 (2000) 636.

[14] T. L. Tansley, E. M. Goldys, M. Godlewski, Zhou and H. Y. Zuo, in: GaN and Related Materials, edited by Stephen J. Pearton, (Gordon and Breach Science, Netherlands, 1997) ch. 8, p. 251.

[15] W. Gotz, N. M. Johnson, D. P. Bour, C. Chen, H. Liu, C. Kuo, and W. Imler, Mater. Res. Soc. Symp. Proc. 395 (1996) 443.

[16] P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo, and K. Miyake, J. Appl. Phys. 76 (1994) 304.

[17] J. C. Carrano, T. Li, P. A. Grudowski, C. J. Eiting, R. D. Dupuis, and J. C. Campbell, Appl. Phys. Lett. 72(5) (1997) 542.

[18] T. L. Tansley, E. M. Goldys, M. Godlewski, Zhou and H. Y. Zuo, in: GaN and Related Materials, edited by Stephen J. Pearton, (Gordon and Breach Science, Netherlands, 1997) ch. 8, p. 253-255.

[19] J. L. Pau, E. Monroy, M. A. Sanchez-Garcia, E. Calleja, E. Munoz, Mater. Sci. Eng. B93 (2002) 159.

List of figure captions:

Fig. 1. X-ray diffraction spectra of GaN grown on Si at (a) 200°C and (b) 600°C

Fig. 2. Atomic force microscopy images of GaN grown on Si at (a) 200°C and (b) 600°C

Fig. 3. The I-V characteristics of the MSM photodiode based on the GaN/Si sample grown at 200°C under (a) dark (coincident with the x-axis) and (b) illumination.

Fig 4. The I-V characteristics of the MSM photodiode based on the GaN/Si sample grown at 600°C under a) dark and b) illumination.

Set of original figures:

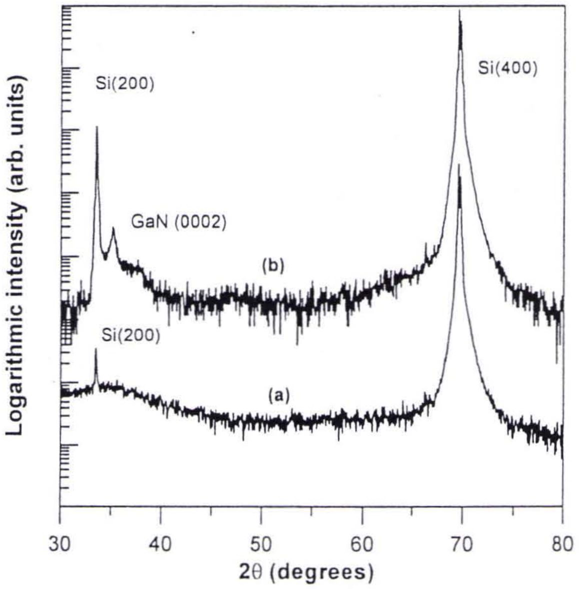
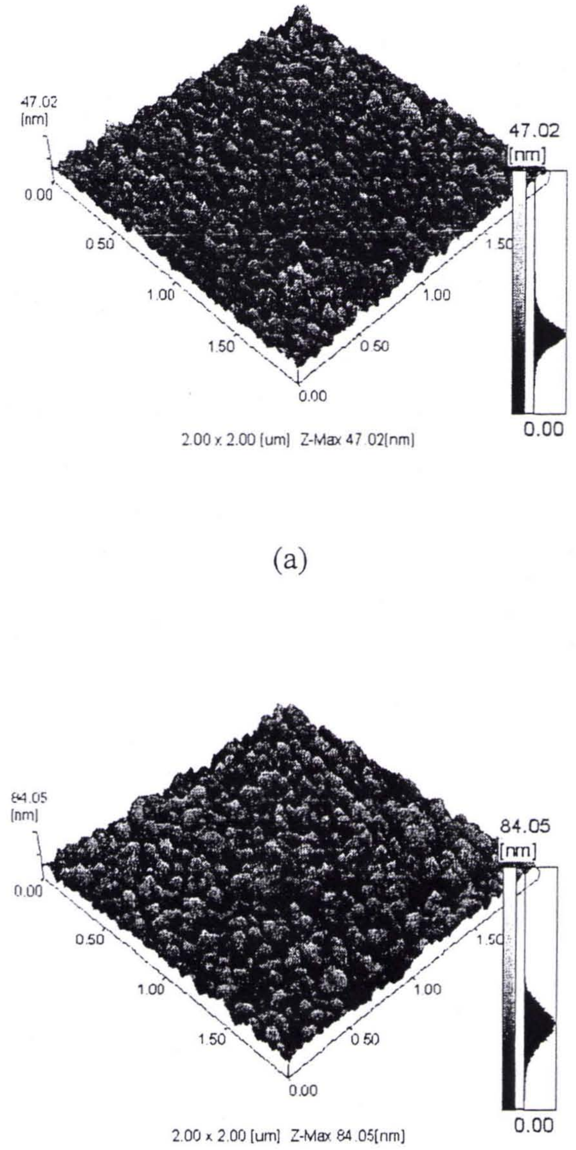


Fig. 1. X-ray diffraction spectra of GaN grown on Si at (a) 200°C and (b) 600°C



(a)

(b)

Fig. 2. Atomic force microscopy images of GaN grown on Si at (a) 200°C and (b) 600°C

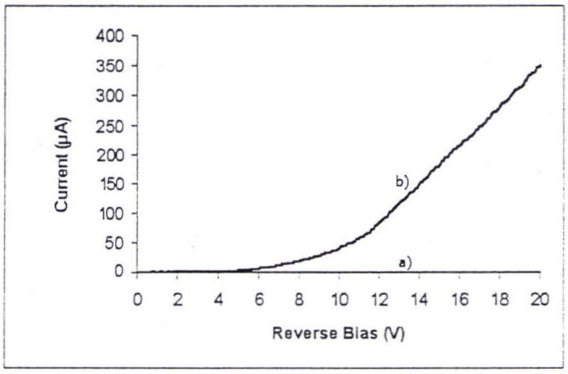


Fig 3. The I-V characteristics of the MSM photodiode based on the GaN/Si sample grown at 200°C under (a) dark (coincident with the x-axis) and (b) illumination.

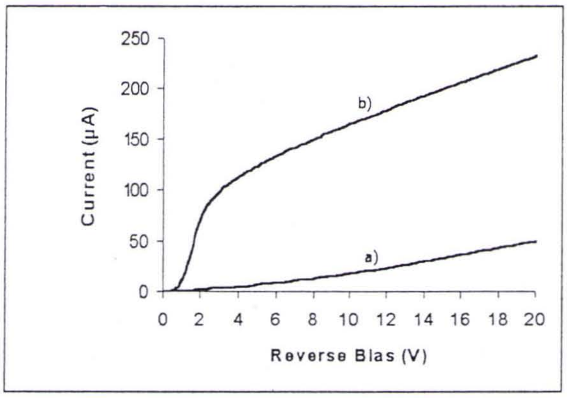


Fig 4. The I-V characteristics of the MSM photodiode based on the GaN/Si sample grown at 600°C under a) dark and b) illumination.