(1) 25185

Characteristics of low-temperature-grown GaN films on Si(111) substrates

Z. Hassan[1]*, G. L. Chew[1], F. K. Yam[1], K. Ibrahim[1],

M. E. Kordesch[2], W. Halverson[3], P. C. Colter[3]

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

2Department of Physics and Astronomy, Ohio University, Athens, Ohio, U.S.A

[3]Spire Corporation, Bedford, Massachusetts, U.S.A

*Corresponding author: zai@usm.my

Abstract

Gallium nitride (GaN)-based materials have been the subject of intensive research recently for blue and ultraviolet light emission and high temperature/high power electronic devices. Current research activities are mainly focused on epitaxial GaN films grown on sapphire at high temperatures (about 1000°C) for these applications. Silicon is a potential alternative to sapphire as a substrate due to its low cost, high quality and wide availability as well as easy integration with the current silicon technology. In this paper, the characteristics of GaN films grown on Si(111) at 200°C by electron cyclotron resonance (ECR) plasma-assisted metalorganic chemical vapor deposition (PA-MOCVD) are presented. Post deposition analysis revealed high quality crystalline GaN was obtained at this low temperature. Prototype devices (Schottky barrier diodes) based on this low-temperature-grown GaN film have been fabricated and characterized.

PACS: 81.15.Gh; 61.10.-i; 73.61.Ey

Keywords: A1. Characteristics; A3. Plasma-assisted metalorganic chemical vapor deposition; B1. III-V Nitrides

1. Introduction

The wide band gap semiconductors of the nitrides such as GaN, AlN and their alloys, have received enormous attention as ideal materials for optoelectronic and high-temperature/high-power devices due to their unique properties, such as large direct band gap, high breakdown field and high thermal conductivity [1].

Although higher quality GaN films can be produced by growing GaN on substrates like sapphire (Al_2O_3) or silicon carbide (SiC) but due to great interest in commercial growth for large size and a low cost budget, GaN films grown on Si(111) have become of great interest. In application purposes, GaN film grown on Si is expected to be an excellent candidate for the integration of GaN-based optoelectronic devices with Si-based electronic technology.

Current research activities are mainly focused on epitaxial GaN films grown at high temperatures. However, recent studies [2, 3] have shown that amorphous (a-GaN) and microcrystalline GaN (μc-GaN) may also have promise as novel electronic materials. The special attribute of these materials is the ability to deposit inexpensively over large area at low temperatures. The development of device quality films, grown at low temperatures, widens the range of possible substrates that can be used and thus will reduce the cost of technology. Thus, whereas epitaxial GaN films is the choice at present for short wavelength emitters and detectors, the development of low-temperature grown a-GaN and μc-GaN could open up opportunities for large-area devices such as LED arrays, UV detector arrays and high temperature transistors at low cost.

In this paper, we describe the growth and characterization of GaN film grown on Si(111) at 200°C using electron cyclotron resonance (ECR) plasma-assisted metalorganic chemical vapor deposition (PA-MOCVD). Amorphous, microcrystalline and nanocrystalline GaN grown by reactive sputtering has been reported [3, 4, 5]. Since very limited work has been done in this area, it is of utmost importance that the properties of this low-temperature-grown material be investigated to determine their suitability for device applications. Also reported are the characterization results of Schottky diodes fabricated from these GaN films.

2. Experimental

The GaN films were deposited over a range of temperature from 50°C to 650°C on silicon, sapphire and quartz substrates. Selected samples grown at 200°C on Si(111) substrate were used for this study. The ECR-heated plasma reactor, shown schematically in Figure 1, is an aluminum vacuum chamber 20 cm in diameter, 80 cm long, and evacuated by a 10" cryopump and a turbomolecular pump. A pair of solenoid coils form a magnetic "mirror" and a octupole permanent magnet array between the coils provided partial magnetic confinement for the plasma and electron cyclotron resonance conditions for the 2.45 GHz microwaves that ionize and heat the plasma.

The "hybrid polarizer" changes the linearly polarized TE_{01} waveguide mode of the microwaves to a circularly polarized TE_{01} mode. The right-handed circular polarization (RHCP) can propagate as "whistler" waves at plasma densities higher than classical cut-off

(7.4×10^{16} m^{-3} for 2.45 GHz) and is strongly absorbed by parametric decay and electron cyclotron resonance. RHCP microwaves couple more efficiently with the plasma than linearly polarized waves; the polarizer also significantly reduced power reflected back into the magnetron tube by shunting left-handed circularly polarized (LHCP) waves from the plasma chamber into the "dummy" load that is coupled to the "left-hand" port of the hybrid polarizer.

The microwave source is a 2.45 GHz magnetron (AsTex Model AX2107) that provides up to 700 W of power. Forward and reflected power is sampled by a 60 dB directional coupler and diode detectors; the directional coupler is followed by a three-stub tuner to maximize forward power transmission, and, because reflected power is so low, no isolator is necessary to protect the magnetron. The microwaves are coupled to the "right-hand" arm of a hybrid polarizer (Atlantic Microwave Corp. Model WR340) with a transition from square to 9.09 cm diameter circular waveguide at the output end. The flange of the circular waveguide mates with a fused quartz window of 9.09 cm clear aperture and 6.35 mm thickness; the quartz window is the vacuum barrier between the waveguide and end-flange of the reactor chamber. An air-cooled load is coupled to the "left-hand" arm of the hybrid polarizer; this load absorbs LHCP waves that are reflected back from the plasma, quartz window, or the interior of the vacuum chamber. A directional coupler and diode measures LHCP power absorbed by the dummy load.

Nitrogen gas is admitted to the reactor through a variable flow valve that is feedback-controlled by the ion gauge. To provide a source of atomic N, a feedback-controlled ammonia source was installed on the system. The ammonia is metered by a commercial (Unit Instruments Model 1660) mass-flow controller with a maximum flow rate of 20 sccm; valves and piping for by-passing and purging the flow controller were provided to assure cleanliness and safe operation. The ammonia is injected through a central port in the vacuum chamber, between the solenoid magnet coils shown in Figure 1.

Scanning electron microscopy (SEM), energy dispersive x-ray analysis (EDX), and Rutherford backscattering spectrometry (RBS) were used to observe the surface morphology and to identify the elements and contaminants present in the sample. X-ray diffraction (XRD) was used to assess the structure of the deposited films. These data were collected as θ-2θ scans on a Rigaku diffractometer with a wide angle automated goniometer and computer based data acquisition and analysis system. To investigate the electrical characteristics of the GaN/Si heterojunction, Al ohmic contact electrodes were evaporated on the top and bottom surface of the sample, and characterized using current-voltage (I-V) measurements.

The contact metallization pads for the Schottky barrier diodes were deposited by sputtering through a mask. Ti (about 1500 Å thick) was used as the ohmic contact. An annealing treatment at ~400°C in a nitrogen ambient for 5 minutes was carried out after the deposition of the Ti ohmic contacts. Ni or Cr Schottky barriers (about 1000 Å thick) were then deposited to form contacts of area 4.9×10^{-8} m^2. There were no annealing treatments conducted for the Schottky contacts. Both contacts were made on the top surface of the sample. The barrier heights were determined by I-V measurements performed at room temperature.

3. Results and Discussion

The GaN films with thickness of about 0.1 μm are transparent, and exhibit smooth surface morphology, as revealed by scanning electron microscopy (SEM) measurements. EDX measurements confirm the presence of Ga and N in these films. Rutherford backscattering spectrometry (RBS) measurements performed on this sample shows a Ga to N ratio of 1:1. No oxygen is detected in this film. The RBS spectrum is shown in Figure 2. These films showed n-type conduction by thermoelectric power measurements in agreement with those reported for low-temperature-grown amorphous and microcrystalline GaN deposited by reactive sputtering [3].

The 2θ x-ray diffraction (XRD) pattern is shown in Figure 2. 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 c-GaN [1]. In addition to substrate peaks at 58.9° which correspond to Si(222) plane, the pattern shows only a weak (0002) peak from the wurtzite (hexagonal) form of GaN.

The well-known GaN orientation with the c-axis perpendicular to the substrate surface is observed. However, the fact that the XRD patterns do not reveal strong and sharp GaN crystalline peaks and exhibit a broadening centered at the crystalline region could be an indication that these films are a mixed phase of crystalline and amorphous structure. This is probably a signature of the microcrystalline or nanocrystalline phase for GaN.

The average size of the crystallites was determined from the (0002) peak using the Scherrer formula:

$$t = \frac{K\lambda}{\beta \cos\theta} \qquad (1)$$

where t is the crystallite size, K is a constant, which is 0.9, λ is the wavelength of the incident beam, β is the half width of the peak and θ is the diffraction angle of the peak [6]. Using equation (1), the crystallite (grain) size determined by the Scherrer method is about 333 nm, thus confirming the microcrystalline structure of our films.

The current-voltage (I-V) characteristic of this GaN/Si heterojunction is displayed in Figure 4. The Si side was biased positive with respect to the GaN, which is referred as forward biasing here. Rectification behavior was observed for this isotype (n-n) heterojunction. The parameter η is determined by fitting the curves in Fig. 3 for small forward currents to the expression

$$I = I_o \exp(\frac{qV}{nkT}) \qquad (2)$$

The parameter η is found to be 1.6, for I-V measurement performed at room temperature. This characteristic is similar to that observed for a wide variety of isotype heterojunctions such as (n)Ge/(n)GaAs and (n)Ge/(n)Si [7].

The electrical characteristics of Schottky barrier diodes were investigated by I-V measurements at room temperature. The I-V characteristics of ideal Schottky diodes under thermionic emission condition can be written as [8]

$$I = I_o[\exp(\frac{qV}{nkT}) - 1] \qquad (3)$$

$$I_o = AA^*T^2 \exp(\frac{-q\Phi_B}{kT}) \qquad (4)$$

where I is the current through the contact, I_o is the saturation current, V is biased voltage, A is the contact area, k is the Boltzmann's constant, T is the absolute temperature, q is the electron charge, A^* is the Richardson's constant. The theoretical value of the Richardson constant A^* can be calculated using

$$A^* = 4\pi m^* q k^2 / h^3 \tag{5}$$

where h is Plank's constant, and $m^*=0.20m_o$ is the effective electron mass for n-GaN [9]. The value of A^* is found to be 24 $Acm^{-2}K^{-2}$.

In practice, diodes have never satisfied the ideal equation of (3), however, it can be more closely described by the modified equation

$$I = I_o \exp[\frac{qV}{nkT}][1 - \exp(-\frac{qV}{kT})] \tag{6}$$

From equation (6), a straight line will be obtained from the plot of the logarithmic of $I/[1-exp(-qV/(kT))]$ against V, and I_o is yielded from intercept of y-axis.

The forward bias I-V characteristic of Ni/GaN and Cr/GaN Schottky barriers are shown in Figure 5. The barrier heights for Ni and Cr Schottky barriers on GaN, were deduced to be 0.45 and 0.52 eV respectively. From the literature, the Schottky barrier heights varied widely from 0.56-1.15 eV for Ni and 0.53- 0.58 eV for Cr, depending on the measuring methods, doping concentration and quality of the GaN [10, 11, 12].

Conclusion

Characteristics of n-type microcrystalline GaN films grown on Si at a low temperature (200°C) using ECR plasma-assisted MOCVD were investigated. The films of about 0.1μm are transparent and exhibit smooth surface morphology. The XRD spectra identified a microcrystalline structure with crystallites or grain sizes of about 333 nm. Rectification characteristic was observed for this GaN/Si isotype heterojunction structure. Schottky barrier diodes based on these films were achieved and characterized using current-voltage techniques. These results are encouraging for further exploration and development of these low-temperature grown GaN films for electronic and optoelectronic applications.

Acknowledgement

Support from IRPA RMK-8 Strategic Research grant and Universiti Sains Malaysia is gratefully acknowledged.

References

[1] S. Strite, H. Morkoc, J. Vac. Sci. Technol. B10 (1992) 1237.

[2] P. Stumm, D. A. Drabold, Physical Review Letters 79 (4) (1997) 677.

[3] S. Kobayashi, S. Nonomura, T. Ohmori, K. Abe, S. Hirata, T. Uno, T. Gotoh, S. Nitta, Applied Surface Science 113/114 (1997) 480.

[4] K. Abe, S. Nonomura, S. Kobayashi, M. Ohkuubo, T. Gotoh, M. Nishio, S. Nitta, S. Okamoto, Y. Kanemitsu, Journal of Non-Crystalline Solids 227-230 (1998) 1096.

[5] W. T. Young, S. R. P. Silva, J. V. Anguita, J. M. Shannon, K. P. Homewood, B. J. Sealy, Diamond and Related materials 9 (2000) 456.

[6] D. Y. Lee, I. S. Kim, J. S. Song, Jpn. J. Appl. Phys. 41 (2002) 4659.

[7] B. L. Sharma, R. K. Purohit, Semiconductor Heterojunctions (Pergamon Press, New York, 1974) ch.5.

[8] D. K. Schroder, Semiconductor Material and Device Characterization (Wiley-Intersience, New York, 1990) ch.3, p. 130.

[9] A. S. Barker, M. Ilegems, Phys. Rev. B 7 (1973) 743.

[10] A. C. Schmitz, A. T. Ping, M. Asif Khan, Q. Chen, J. W. Yang, I. Adesida, Semiiicond. Sci. Technol. 11 (1996) 1464.

[11] J. D. Guo, F. M. Pan, M. S. Feng, R. J. Guo, P. F. Chou. C. Y. Chang, J. Appl. Phys. 80 (1996) 1623.

[12] E. V. Kalinina, N. I. Kuznetsov, A. I. Babanin, V. A. Dmitriev, A. V. Shchukarev, Diamond and Related Materials 6 (1997) 1528.

List of Figures

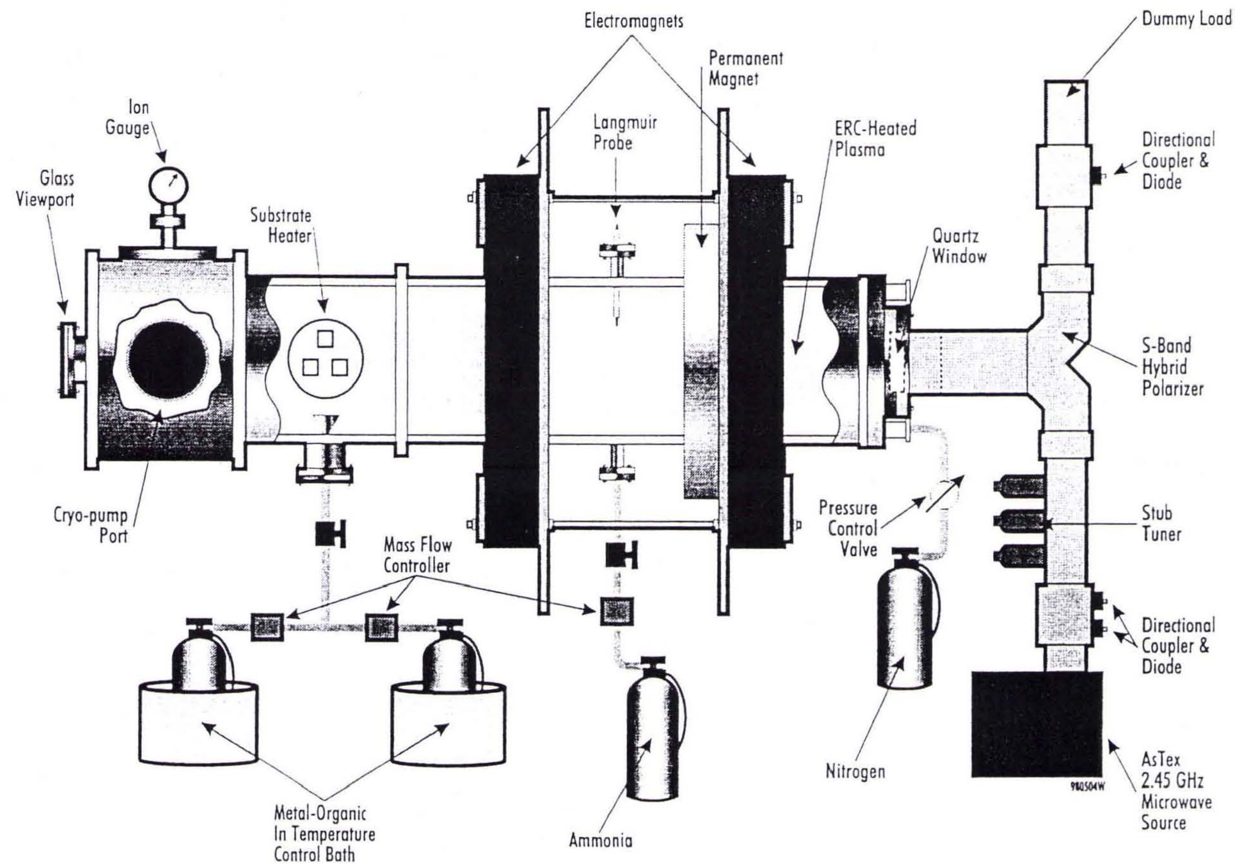

Fig. 1 ECR plasma-assisted MOCVD system

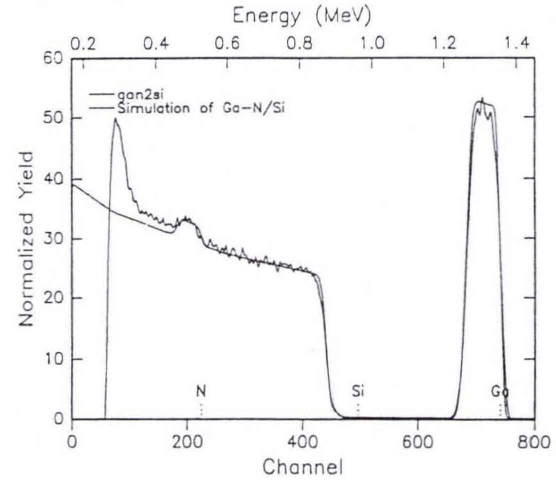

Fig. 2 RBS spectrum of GaN grown on Si (111) at 200°C

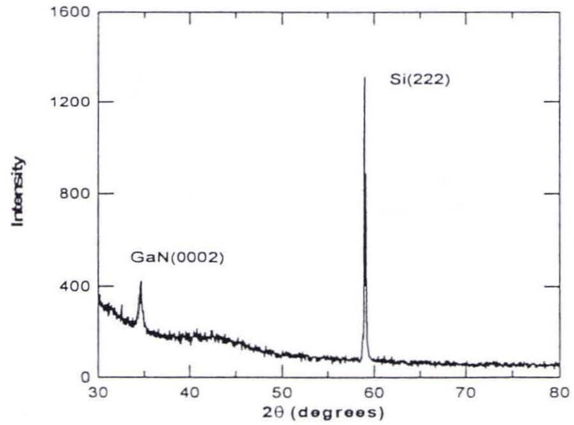

Fig. 3. X-ray diffraction pattern of GaN grown on Si (111) at 200°C

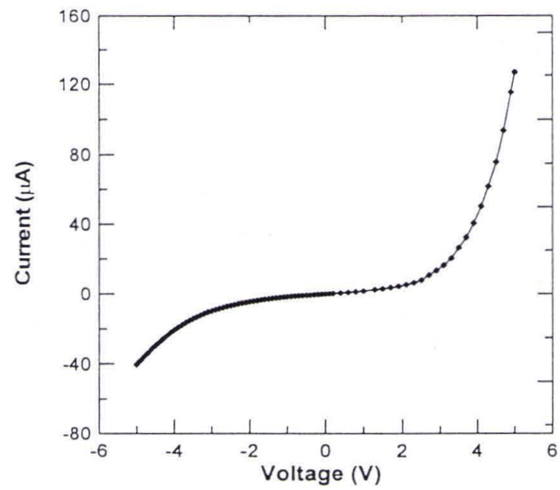

Fig. 4 I-V characteristic for GaN/Si isotype heterojunction

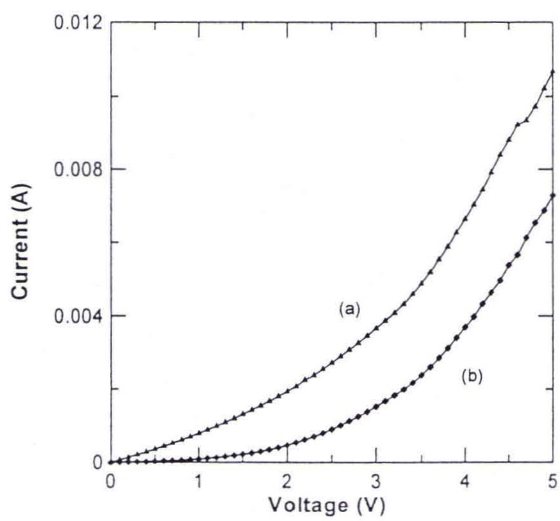

Fig. 5 Forward bias I-V characteristics of

(a) Ni/GaN and (b) Cr /GaN Schottky barriers