Red emission of thin film electroluminescent device based on p-GaN

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Abstract

High quality GaN layers doped with Mg were grown on Si(111) substrates using high temperature AlN as buffer layer by using radio-frequency molecular beam epitaxy (RF-MBE). Nickel ohmic contacts and Schottky contacts using indium was fabricated on Mg-doped p-GaN films. The light emission has been obtained from these thin film electroluminescent devices. These thin film electroluminescent devices were operated under direct current bias. Schottky and ohmic contacts used as cathode and anode were employed in these investigations. Alternatively, two Schottky contacts could be probed as cathode and anode. Thin film electroluminescent devices were able to emit light. However, electrical and optical differences could be observed from the two different probing methods. The red light colour could be observed when the potential between the electrodes was increased gradually under forward bias of 8V at room temperature. Electrical properties of these thin film electroluminescent devices were characterized by current–voltage (I–V) system, the barriers heights determined from the I–V measurements were found to be related to the injection luminescence or electroluminescence.

1. Introduction

The wide bandgap semiconductors especially GaN and its alloys have been investigated intensively in the past decades for their practical applications in short wavelength optoelectronic devices and high power/high frequency/high temperature electronic devices. These excellent applications are based on the unique and excellent properties such as wide direct bandgap, strong piezoelectric effects (~0.2 – 0.6 GV/m), high-saturation velocity ($\sim 2.7\times10^4$ cm/s) and high-breakdown field ($\sim 0.2\times10^9$ V/m) [1]. The nitride semiconductors form a continuous alloy system with direct band gaps, ranging from about 0.7 eV (InN) to 6.2 eV (AlN) with 3.4 eV for GaN. Therefore light emitting devices fabricated from III-V nitrides are active at wavelength ranging from infrared to ultraviolet.

Contact technology remains an important factor for most electronic and optical devices in the field of wide band gap semiconductors. To fabricate reliable, efficient, high performance devices and circuit, it is essential to develop high quality and thermally stable contacts to GaN-based material. Generally, making low-resistance ohmic contact is difficult for wide band gap semiconductors, especially for p-type GaN due to difficulty in achieving high carrier concentration ($\sim 10^{18}$ cm^{-3} and above), and the absence of suitable metals which have a work function, larger than band gap and electron affinity of GaN (7.5 eV) [2]. These two obstacles have impeded the fabrication of highly efficient blue light emitting diodes (LEDs) and laser diodes (LDs).

As GaN devices are usually made from hexagonal GaN epitaxial layers, Si (111) can provide the hexagonal template for AlN deposition. According to the literatures, X-ray diffraction (XRD) patterns showed that full width at half maximum (FWHM) of AlN (0002) peak grown on Si (111) substrates was smaller than that grown on Si (100) substrates. XRD results also indicate that the preferred orientation of AlN films on Si (111) substrates is more easily controlled than those on Si (100) substrates. It can be attributed to the more matched lattice template with hexagonal structures of AlN films provided by (111) plane of silicon.

In 1972, the first LED was fabricated by Pankove et al. [3]. Light emitted from the Schottky contacts on p-type GaN films are rarely investigated and explored thus far. In this work, we studied the light emission of electroluminescent device based on p-type GaN grown on Si(111) substrates by radio-frequency molecular beam epitaxy (RF-MBE). Since the device structure requires only two electrodes, the device could have some practical applications such as indicator lamps or display elements.

2. Experimental

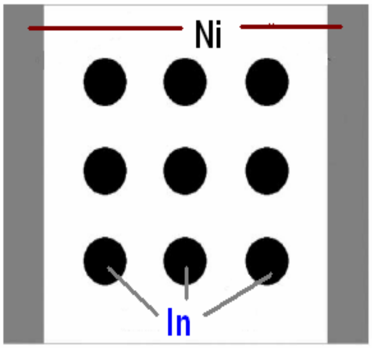
The film growth has been performed in a Veeco Gen II MBE system. Active nitrogen was produced using a Veeco Unibulb inductively coupled plasma source. In situ RHEED measurements were performed using a 15 keV electron gun. The base pressure in the system was below 5×10^{-11} Torr. Three inch n-type Si (111) wafer was used for the substrate of wurtzite p-GaN growth. Prior to loading into MBE chamber, the n-type Si (111) wafers (resistivity < 0.02 ohm-cm) were ultrasonically degreased in solvents and etched in buffered HF. In the preparation chamber, the substrates were outgassed for 10 min at 400 °C prior to growth.

The plasma was operated at typical nitrogen pressure of 1.5×10^{-5} Torr under a discharge power of 300 watts. A few monolayers of Ga were deposited on the substrate for the purpose of removing the SiO_2 by formation of GaO_2. After a few minutes, a reflection high energy electron diffraction (RHEED) reconstruction with prominent Kikuchi lines is then observed that turns into clean Si (111) surfaces at 750 °C.

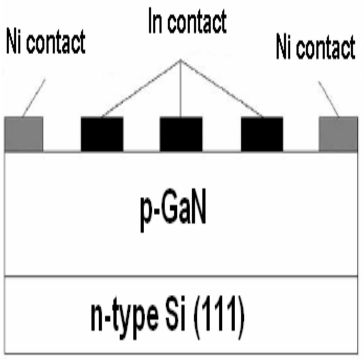
Then a few monolayers of Al is deposited on Si(111) prior to an AlN buffer layer growth. AlN deposition is started by opening both Al (cell at 1120 °C) and N shutters simultaneously. The role of this layer is to improve the crystalline quality of the latter doped GaN layer. For p-type doping, Mg cell temperatures was set at 383 °C. The doping element was provided after 5 min growth of an unintentionally doped GaN layer. Sample was grown with about 0.2 µm AlN buffer layer followed by Mg-doped layer on 0.1 µm GaN.

Using In metal for ohmic contact, Hall effect by Van der Pauw configuration was measured at room temperature. The doping of GaN was also confirmed by hot probe measurements. We obtained a p-type carrier concentration of GaN as high as 4-5 x 10^{18} cm^{-3} by radio-frequency molecular beam epitaxy (RF-MBE) without post-growth acceptor activation.

Prior to the metallization, the native oxide was removed in the NH_4OH: H_2O = 1:20 solution, followed by $HF:H_2O$ = 1:50. Boiling aqua regia ($HCl:HNO_3$ = 3:1) was used to chemically etch and clean the samples. The surface cleanliness is important to ensure good quality contact and to minimize surface contamination. After surface treatment, nickel (Ni) was first deposited onto the p-GaN as ohmic contacts by a sputtering system. The samples with the ohmic contacts were then annealed under flowing nitrogen gas environment in the furnace at 450 °C for 10 min. The ohmic behaviour of the contacts was checked and confirmed by I–V measurement. Subsequent to the ohmic contacts deposition, the indium (In) was coated as Schottky contact using thermal evaporation method. The metal mask which was used for Schottky contacts fabrication consists of an array of dots with diameter of 250 µm. The top and cross section views of the ohmic and Schottky contacts of a typical sample, is shown in Fig. 1.



(a)



(b)

Fig. 1: (a) Top view, and (b) cross section view of ohmic and Schottky contacts of a typical sample.

After the device is fabricated, the electrical property of the device is analyzed by Keithley High-voltage-source-measurement unit for measuring the I-V characteristics. At room temperature, light emission could be observed when power supply is used to apply electrical bias to the contacts of the device. Different probing conditions, for instances, negative (cathode) and positive (anode) terminals of the power supply are connected to Schottky and ohmic contacts, or negative and positive terminals connected to both Schottky contacts, could lead to different optical and electrical characteristics.

For the probing conditions, the first sample (In1), cathode and anode were connected to Schottky and ohmic contacts respectively, whereas for the second sample (In2), two Schottky contacts were probed as cathode and anode. On the other hand, both ohmic contacts were probed as cathode and anode for the third sample (In3).

3. Results and discussions

To determine the exact orientation relationship and the content of the sample, high-resolution PANalytical X'Pert Pro MRD XRD system with a Cu-Kα_1 radiation source (λ = 1.5406 Å) was used. For ω scan of XRD rocking curves (RC), the incident beam is monochromatized and collimated by a Ge (220) four-crystal monochromator, and the diffracted beam optics was the rocking curve-triple axis PreFIX module. Fig. 2 illustrates the XRD phase analysis scan of the GaN film. The intensity data was collected in two dimensions by performing ω (sample angle) - 2θ (detector angle) scan at a range of different values. The pattern reveals the (0002) peak for the plane of hexagonal crystalline GaN at 34.6°. Fig. 3 shows RC $\omega/2\theta$ scans of (0002) plane for GaN and AlN. It can be seen that two intense and sharp peaks corresponding to GaN(0002) and AlN(0002) diffraction peaks are observed at about 17.3° and 18.1°, respectively. The full width at half maximum

(FWHM) of the RC for the GaN (0002) and AlN (0002) peaks are 21.20 arcmin and 18.35 arcmin, respectively.

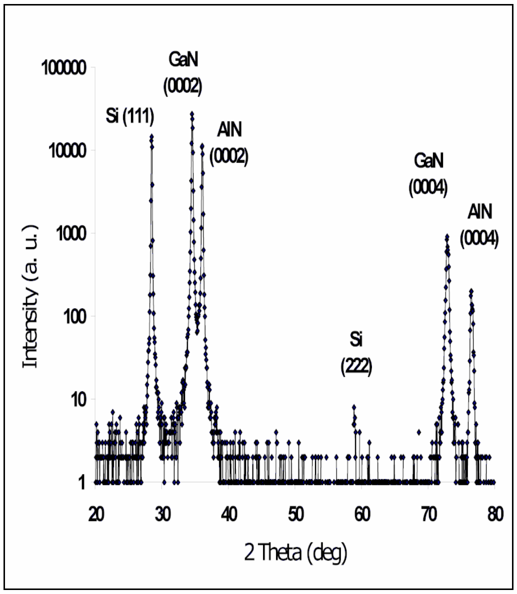


Fig. 2: X-ray diffraction pattern of thin film p-GaN grown on Si(111).

Fig. 4 shows the I-V characteristics of the samples. Sample In1 and In2 exhibited typical Schottky behaviour, whereas In3 showed an ohmic characteristic. Apart from that, it should be noted that for forward bias, generally, the measured current for In2 and In3 samples were relatively high as compared to In1 samples. For In3 samples, the measured current at 3V was about one order of magnitude lower than In1 and In2 samples.

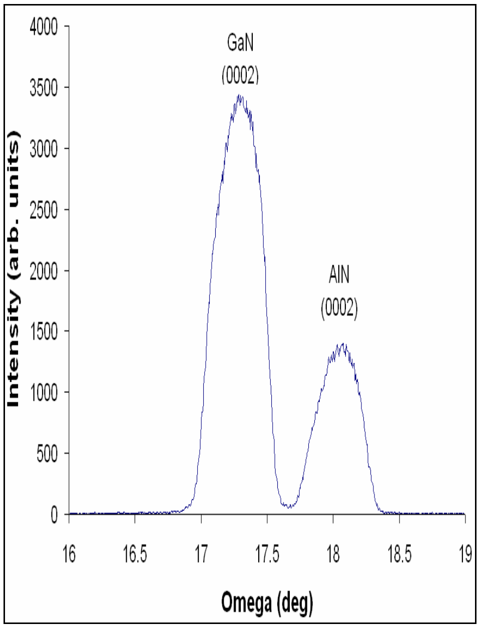


Fig. 3: Rocking curve ω/2θ scans of (0002) plane for GaN and AlN.

With I-V measurements, Schottky barrier height (SBH) can be determined. When V>3kT/q, for thermionic emission, the general diode equations are [5]:

$$I = I_o \exp\{qV/(nkT)\} \qquad (1)$$

$$I_o = A^*AT^2 \exp\{-q\,\Phi_B/(kT)\} \qquad (2)$$

where, n is the ideality factor, I_o is the saturation current, k is the Boltzmann's constant, T is the absolute temperature, Φ_B is the barrier height, A is area of the Schottky contact and A* is the effective Richardson coefficient. The theoretical value of A* can be calculated using

$$A^* = 4\pi m^* qk^2/h^3 \qquad (3)$$

where, h is Planck's constant. For Mg doped p-type GaN, $m^* = 0.80m_o$ is the effective hole mass for GaN. The value of A* is determined to be 103.8 $Acm^{-2}K^{-2}$ [6].

The plot of lnI vs V will give a straight line with a slope of q/(nkT), and the intercept with y-axis will yield I_o, in which barrier height, Φ_B can be obtained using equation (2). The SBH of sample In1 was determined to be 0.55 eV.

For sample involving two Schottky contacts, representing two diodes connected back-to-back, the I-V characteristics of the Schottky contact are more appropriate to be analyzed in the more general form of equation, where it can be used under reverse bias conditions [7,8]

$$I = I_0 \exp(\frac{eV}{nkT})[1 - \exp(\frac{-eV}{kT})] \qquad (4)$$

Equation (4) can be written in the form of

$$\frac{I \exp(eV/kT)}{\exp(eV/kT) - 1} = I_0 \exp(eV/nkT) \qquad (5)$$

Based on equation (5), the plot of In $\{I \exp(qV/\{kT\}) / [\exp(qV/\{kT\})-1]\}$ against V will give a straight line, similarly, I_o is derived from the intercept with y-axis, in which SBH, Φ_B can be calculated using equation (2). The SBH of sample In2 was deduced to be 0.48 eV.

When electrical bias was applied on these samples, light emission was observed for In1 and In2. According to Pankove et al., similar metal/Zn-doped highly resistive i-GaN/undoped n-GaN (M-i-n) structured light emitting devices were reported in early 1970 [3], where the active region was the area underneath the metal contact, and the light was emitted from the cathode. On the other hand, no light emission was found for In3. Sample In1, started to emit red luminescence at the turn-on voltage of 12V. However, for sample In2 such emission was observed at 8V. The red emission from In1 and In2 on Si is bright enough to be observed under room light.

The differential resistance of AlN/Si interface may be responsible for high operating voltage. However, the intermediate layers consisting of the AlN layers are necessary to enhance the quality of GaN on Si. Table 1 shows the probing condition, the emission of red color at different threshold voltages and SBH of the samples.

On the other hand, for In1 and In2, only red light emission was observed for sample at different probing conditions. From the studies, samples were found to be resistive in nature. Under low voltage, the corresponding current level was significantly low, and the number of electrons available for recombination with holes in p-GaN was too small, therefore no emission was found at low electrical bias. On the other hand, under higher voltage, the current level was correspondingly higher, the amount of electrons which were ready for recombination also larger, the probability for recombination became higher and eventually emission was observed.

From the results, it can be noticed that the In samples with lower barrier heights will have light emissions at lower voltages, in which two Schottky contacts were probed as cathode and anode. However, the lowest barrier height does not mean that the sample will be able to start emitting light at the lowest voltage. The ability to emit light at low bias may depend on the type of metal used for Schottky contacts fabrication. The light emitted would be saturated for higher bias due to inherent Joule heating as high current was injected into the device, eventually the metal contact would be damaged and burnt.

The injection luminescence or electroluminescence produced by In1 and In2 could be attributed to the electrons injected from the metal contact under a forward bias into p region created by Mg doping and recombined with holes from emission centres which lead to red emission colors. Column II dopants or impurities, i.e. Mg can either substitute for Ga to form single acceptors or substitute for N to form deeper triple acceptors. Since *a priori* the acceptor can occupy both sites, Mg should be a quadrupole acceptor, which forms four different levels above the valence band [9]. Apart from these levels, there are other deep acceptors, which involve defects associated with Mg doping [10].

To the best of our knowledge, this is the first time the red emission is observed in p-GaN/Si (111). From the literature, the red luminescence (RL) band is sometimes observed in heavily Mg-doped p-type GaN. Nevertheless, the observation of the RL in GaN has been reported by several researchers [11-13]. The origin of this peak could be a result of transition between a $N_{Ga\ site} - Ga_{n\ site}$ deep donor-deep acceptor state. For GaN films grown by MBE, the most common impurity is carbon; it was incorporated into the films from the material sources. Since, the role of the carbon (C) can be amphoteric either on substitutional Ga or N site, therefore, a possible model for this emission could be a result of transition between a $C_{Ga\ site} - Ga_{n\ site}$ deep donor-deep acceptor state. Further studies are needed to clarify this issue. Besides that, the samples may most probably be contaminated by residual Si (from Si substrate). The red luminescence (RL) is rarely observed in n-type GaN photoluminescence (PL) studies. The red emission is characterized by a broad band centred at ~ 1.70 eV.

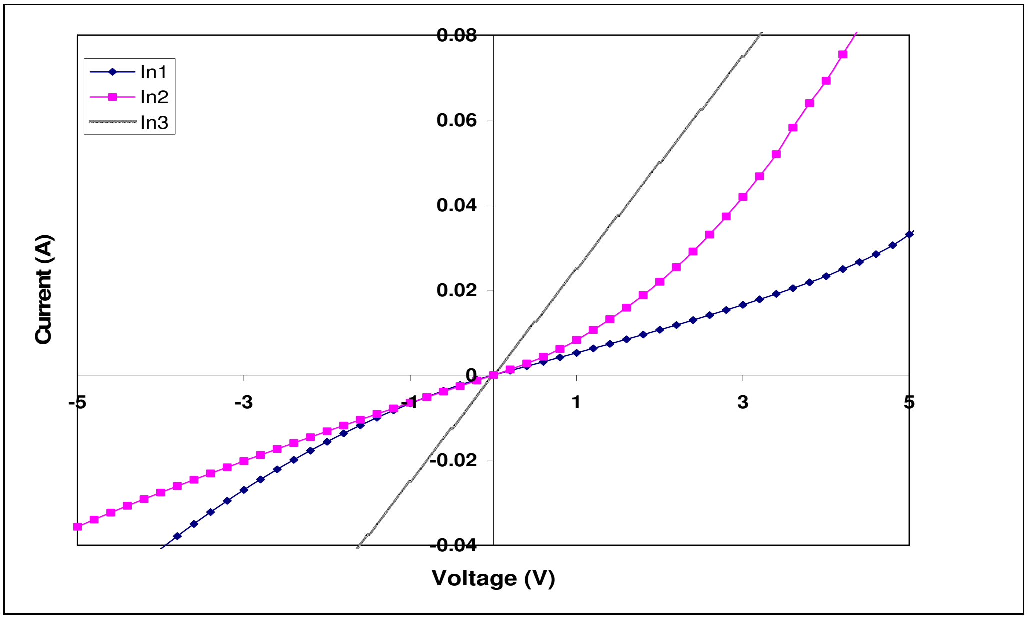


Fig. 4: The I-V characteristics of the sample with Schottky contacts made of In under three different probing conditions.

Table 1: Summary of the probing condition, the threshold voltage and SBH of samples.

Sample	Probing Condition		Color at voltage (V)	SBH (eV)
	Anode	**Cathode**	**Red**	
In1	**Ohmic contact**	**Schottky contact**	**12.0**	**0.55**
In2	**Schottky contact**	**Schottky contact**	**8.0**	**0.48**
In3	**Ohmic contact**	**Ohmic contact**	**-**	**-**

4. Conclusions

Nickel ohmic contacts and Schottky contacts using indium was fabricated on Mg doped p-GaN films. Red light emission colours have been observed from these thin film electroluminescent devices. Lower barrier heights were obtained for samples with both Schottky contacts probed as cathode and anode as compared to the samples where Schottky and ohmic contacts were used as cathode and anode. Contacts of In with lower barrier heights were found to have light emissions at lower voltages. The ability to emit light at low applied bias could be dependent on the type of metal used for Schottky contacts fabrication.

Acknowledgement

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References

[1] Arakawa, Y., IEEE J. Select. Topics Quantum Electron. 8 (2002) 823.

[2] Liu, Q.Z., Lau. S.S., Solid State Electronics 42 (1998) 677.

[3] Pankove, J.I., Miller, E.A., Berkeyheiser, J.E., J. Lumin. 5 (1972) 84.

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

[5] Sze, S.Z., *Physics of Semiconductor Devices*, second ed., John Wiley & Sons, New York, 1989, p. 245.

[6] anlove, J.I., Bloom, S., Harbeke, G., RCA Rev. 36 (1975) 163.

[7] Rhoderick, E.H., Williams, R.H., *Metal–semiconductor Contacts,* second ed., Clarendon Press, Oxford, 1988, p. 39.

[8] Averine, S., Chan, Y.C., Lam, Y.L., Appl. Phys. Lett. 77 (2000) 274.

[9] Pankove, J.I., in: Pearton S.J., (Ed.), *GaN and Related Materials*, Gordon and Breach Science, Netherlands, 1997, p. 1.

[10] Calle, F., Monroy, E., Sanchez, F.J., Munoz, E., Beaumont, B., Haffouz, S., Leroux, M., Gibart, P., Internet J. Nitride Semicond. Res. 3 (1998) 24.

[11] Nakamura, S., Iwasaki, N., Senoh, M., Mukai, T., Jpn. J. Appl. Phys. 31 (1992) 1258.

[12] Gotz, W., Romano, L.T., Krusor, B.S., Johnson, N.M., Appl. Phys. Lett. 69 (1996) 242.

[13] Tansley, T.L., Egan, R.J., Phys. Rev. B 45 (1992) 10942.

[14] Andreani, L.C., Bassani, F., Phys. Rev. B 41 (1990) 7536.

[15] Neugebauer, J., Van de Walle, C.G., Appl. Phys. Lett. 69 (1996) 503.