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Ohmic metal contact to InGaN

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In this work, InGaN/GaN/AlN is growth on Si (111) substrate by plasma-assisted molecular beam epitaxial (MBE). Structural characterization such as X-ray diffraction (XRD) is usually employed for analysis of these materials. The structure and electrical stability of the contacts at various annealing temperatures (400 °C - 600 °C) were investigated. Specific contact resistivity (SCR), ρ_c was determined using transmission line method (TLM). The measurement is carried out on the annealed Ti/Al contact where the electrical behaviors of each of these conditions are compared. For relatively different annealing temperatures, substantial differences of the SCR values are observed between different duration samples. This study has resulted in producing contacts from the Ti/Al metallization scheme with the lowest specific contact resistivity of $\rho_c = 0.46\ \Omega cm^2$ after annealing in nitrogen for 30 minutes at 600 °C. However, this ρ_c is still considerably high for optimum device performance whereby the region of ideal contact is within 10^{-2} -10^{-4} Ωcm^2.

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1. Introduction

The III-nitrides form a continuous alloy system with direct band gap ranging from 6.2 eV (AlN) to 0.7 eV (InN) with 3.4 eV for GaN [1-3]. Consequently, the growth and physics of GaN-based materials have attracted tremendous scientific attention. GaN-based materials receive great deal of attention because of the potential applications for optoelectronic devices operating in the whole visible spectral range and in electronic devices such as high temperature, high power, and high frequency transistor.

Traditionally, the heterostuctures of the conventional III-V compounds such as GaAs, GaP and InP are commonly grown by metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) techniques. However, the growth of GaN-based materials has been mainly performed using MOCVD, particularly, the GaN-based commercial optoelectronics devices, which are light emitting diodes and laser diodes. In contrast, MBE grown GaN-based optoelectronics devices are relatively lagged behind; this is attributed to the unavailability of suitable source of active nitrogen species. Nevertheless, with the development of efficient and reliable nitrogen plasma sources for MBE recently, the quality of the GaN-based epilayer has been improved tremendously.

In our previous paper [4] we have studied the dark-current characteristics of Ni contacts on porous AlGaN-based uV photodetector.

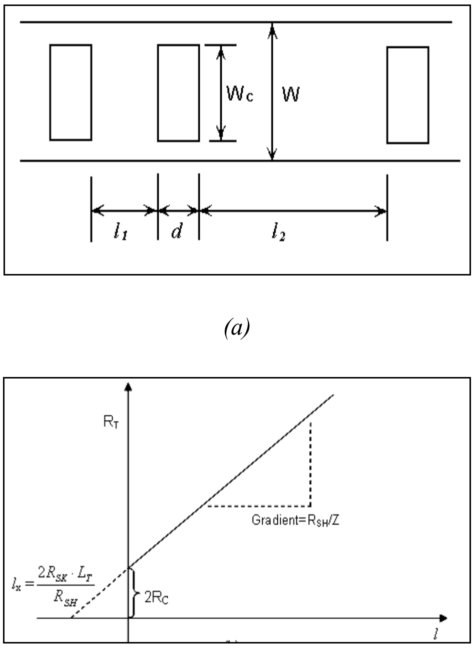
The structural properties of InGaN have recently attracted great attention because they are involved in many applications: high-temperature electronics, light emitters and detectors operating in the blue and ultra-violet wavelength range. Despite comprehensive studies performed in harnessing the fullest potential of GaN semiconductors, ohmic contacts with a very reliable and low resistance are yet to be achieved especially with InGaN. In order to produce efficient and stable device, issues such as metallization schemes, surface preparations, methods of deposition and heat treatments on InGaN semiconductors have to be considered carefully.

Although GaN are no longer uncommon, plenty of researches are still being undertaken to improve and optimize the electrical performance by creating suitable recipes for ohmic contact system. The main objective of this work would be to produce an ohmic contact on InGaN with low resistance and good thermal stability.

1.1 Ohmic contact and specific contact resistivity (SCR)

Transmission line model (TLM) can be divided into 2 test structures which are linear TLM structure and circular TLM structure. The transmission line model (TLM) offered a convenient method for determining ρ_c for planar ohmic contacts. To find ρ_c requires a more detailed evaluation of the nature of the current flow into and out of the contacts. An early two-dimensional current flow analysis in diffused semiconductor resistors revealed current crowding at the contacts. Therefore, current crowding was taken into account in order to extract the specific contact resistivity. When current flows from the semiconductor to the metal, it sees the resistances ρ_c and R_{sh} being the sheet resistance of the semiconductor layer choosing the path of least resistance.

The measurements of the specific contact resistivity were made using the TLM method that has been widely used in the characterization of ohmic contacts to semiconductors. The pattern used and resistance versus the gap spacing l are depicted in Fig. 1. The transmission line method (TLM) pads were 2mm (W, width) ×1 mm (d, length) in size, and the spacing, l, between the pads was 0.3, 0.4, 0.6, 0.9 and 1.3 mm. The specific contact resistivity, ρ_c was determined from the plot of the measured resistances against the spacing between the TLM pads. The linear-square method was used to fit a straight line to the experimental data.



(a)

(b)

Fig. 1 (a) The transmission line pattern (b) the typical graph showing the variation of the resistance with respect to the gap distance [5].

Resistance, R_i, between two contacts with spacing l_i, is given by:

$$R_i = \frac{R_{sh} l_i}{W_C} + \frac{2R_{sk} L_t}{W_C} \tag{1}$$

$$R_i = \frac{R_{sh} l_i}{W_C} + 2R_C \tag{2}$$

where W_C and d are the width and breadth of the contact pad, R_c is resistance due to contact, R_{sh} is sheet resistance of the semiconductor layer outside the contact region, R_{sk} is the sheet resistance of the layer directly under the contact, and L_t is the transfer length.

The plot of R_i as a function of l_i will produce a straight line with a slope of R_{sh}/W_C, and $2R_C$ is yielded from the intercept at y-axis. The intercept at x-axis, will give L_x, where

$$L_x = \frac{2R_{sk} L_t}{R_{sh}} \approx 2L_t \tag{3}$$

with the assumption that $R_{sh}=R_{sk}$. On the other hand, the assumption of an electrically long contact d >> L_t enabled the relationship $\rho_c = R_{sh} L_t^2$ to be invoked, which leads to $\rho_c = R_c W L_t$, where ρ_c is the specific contact resistivity (Morkoc, 1999).

2. Experimental

The III-V nitrides heterostructure, which is InGaN/GaN/AlN was grown on Si (111) substrate using Veeco model Gen II MBE system. The MBE grown InGaN/GaN/AlN heterostructure thin film was characterized by a variety of tools. High resolution XRD (PANalytical X'pert Pro MRD) with a Cu-Kα_1 radiation source (λ= 1.5406 Å) was used to assess and determine the crystalline quality epilayers, as well as indium composition of InGaN.

Before the metallization process, InGaN wafer is cleaned by the following steps; first, the removal of native oxide in $NH_4OH:H_2O$ = 1:20 solution, follow by dipping in a $HF:H_2O$ = 1:50 solution, subsequently, boiling aqua regia ($HCl:HNO_3$ = 3:1) is used to chemically etch and clean the samples. Wafer is then rinsed with distilled water and blown dry with compressed air.

Proper surface cleaning is imperative to achieve intimate contact between metal and semiconductor, since GaN surface could form a thin Ga_2O_3 native oxide upon exposure to air. In the context of contact technology, the presence of native oxides or organic residues can increase the contact resistance of ohmic contacts and can lead to non-idealities in rectifying contacts.

The structure and electrical stability of the contacts at various annealing temperatures (400 ^{o}C-600 ^{o}C) were investigated. Specific contact resistivity (SCR), ρ_c was determined using transmission line method (TLM). The measurement is carried out on the annealed Ti/Al contact where the electrical behaviors of each of these conditions are compared. For this work, heat treatments for Ti/Al contacts could be divided into low (400°C), moderate (500°C) and elevated (600°C) annealed temperatures. In this work, different annealing temperatures (400°C-600°C) and durations (1-30 minutes) are investigated for the Ti/Al metal contacts.

3. Results and discussion

Fig. 2 shows the EDX spectra obtained for $In_{0.47}Ga_{0.53}N/GaN/AlN/Si$. The corresponding atomic composition of the elements (the element concentration), detected in film is tabulated in Table 1.

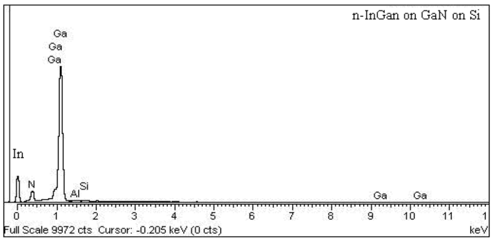


Fig. 2. EDX spectrum of the sample.

Table 1. Elements detected in the InGaN filmd by EDX and their corresponding weight and atomic composition.

Sample	Element	Weight composition (%)	Atomic composition (%)
InGaN/GaN/AlN/Si	N	18.33	8.04
	Al	0.45	0.66
	In	32.04	26.50
	Si	12.34	28.54
	Ga	36.84	36.26

Fig. 3. shows the 2θ XRD spectra of the sample grown by MBE. The XRD measurement confirmed that the heterostructure of III-nitrides were epitaxially grown on Si (111). These can be seen from the presence of the peaks at 34.59°, 36.09°, 72.96° and 76.50°, which correspond to GaN (0002), AlN (0002), GaN (0004) and AlN (0004) respectively, in addition, a weak peak appears at 32.99° that can be attributed to InGaN (0002). The positions of the peaks and the corresponding crystal planes as well as the relative intensity are compiled in Table 2.

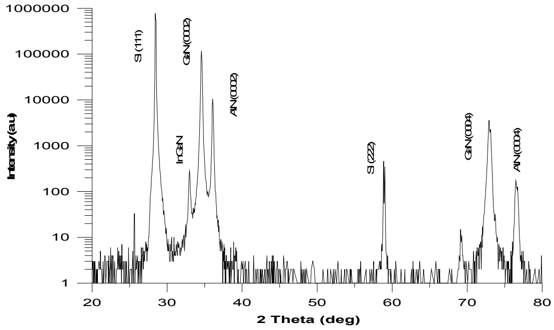


Fig. 3. XRD spectra of the InGaN/GaN/AlN/Si sample.

Table 2: The 2θ XRD peak positions of different crystal planes and their relative intensity.

2θ Peak position (°)	Crystal Plane
28.475	Si (111)
32.986	InGaN
34.593	GaN (002)
36.092	AlN (002)
58.914	Si (222)
72.964	GaN (004)
76.500	AlN (004)

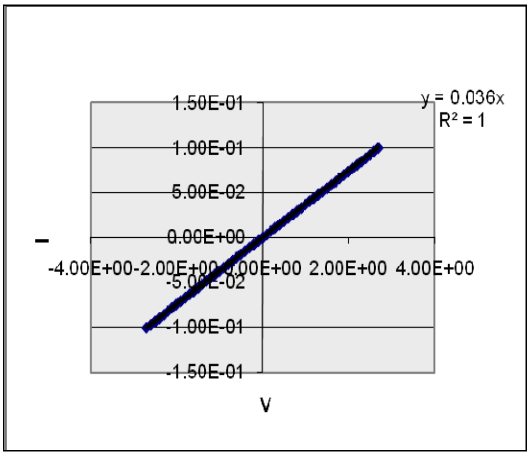
From Fig. 3 and Table 2, the intensity of InGaN is found to be relatively low, which it is approximately three orders of magnitude smaller than GaN, and this indicates that the thickness of InGaN epilayer was very thin. The modeling of the ω/2θ XRD spectra showed that the thicknesses of the GaN and InGaN were 200 and 8 nm, respectively, in addition, the simulated result also revealed that the indium molar fraction of InGaN epilayer was 0.47. It is well known that InGaN materials are difficult to be grown, particularly InGaN with high indium fraction. The difficulties in growing high quality InGaN materials can be attributed to a number of problems, for instances, the large difference in interatomic spacing between InN and GaN results in a solid phase miscibility gap [6], the relatively high vapor pressure of InN as compared to the vapor pressure of GaN [7] as well as the difference of formation enthalpies for InN and GaN which causes a strong indium surface segregation on the growth front. Moreover, InGaN deposition is complicated by thermodynamic instability of InN, at higher growth temperature, InN will tend to dissociate faster than it can be adsorbed [8].

The Ti/Al contact resistivities are summarized in Table 3. I-V characteristics of Ti/Al contacts of samples thermally treated at 400°C under annealing durations of 15 minutes (cumulated 30 minutes) is shown in Fig. 4 (a). Ohmic behavior is observed. This particular annealing temperature was chosen to present the I-V characteristics because this is the optimum annealing temperature which produced the lowest SCR. Therefore, it is expected that a thermionic diffusion mechanism is the reason the electron cross the barrier. Lowering the contact resistance and improving linearity may come from a more intimate contact of metal with semiconductor or any new phases having lower work function. Intimate contact leads to more current flow across the interface by breaking up some of the interfacial contamination between metal and semiconductor. Possible new compounds reduce the potential offset at the metal/semiconductor interface by forming a layer of a compound with lower work function.

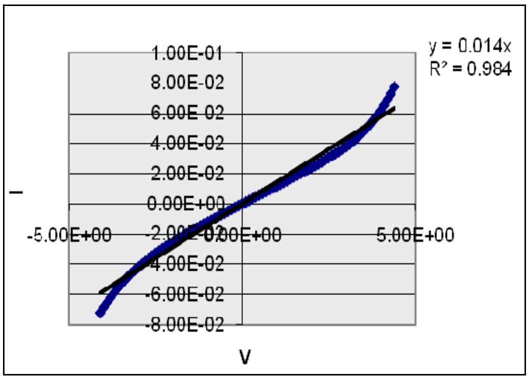
On the other hand, for the sample treated at 600 °C under annealing durations of 10 minutes (cumulated 15 minutes), Ti/Al contacts showed slight non-linear I-V characteristic behavior with a small potential barrier, as seen in Fig. 4 (b). It is known that rough morphology affects the quality, homogeneity, and reliability of ohmic I-V characteristic behavior. The non-ohmic contact (schottky contact) could then be to rough morphology. It is also possible that GaInN is formed between the substrate and the epilayer, due to N reacting with In and Ga. It is known that GaN has stronger bonds than InN; therefore, it is also likely that Ga with react with N at high temperature. High temperature annealing may degrade homogeneity possibly caused by spiking of metals between themselves or between metal and semiconductor due to the differences in thermodynamic properties of materials.

Table 3. The specific contact resistivity at different annealing temperatures and times for Ti/Al contact.

Annealing Temperature	Specific Contact Resistivity (Ωcm^2)		
As deposited	4.47 × 10^{-1}		
Low Temperature	Time / (cumulated time)		
	5 min	10 min / (15 min)	15 min / (30 min)
400 ^{0}C	9.99 × 10^{-1}	8.72 × 10^{-1}	8.40 × 10^{-1}
Moderated Temperature	Time / (cumulated time)		
	5 min	10 min / (15 min)	15 min / (30 min)
500 ^{0}C	7.70 × 10^{-1}	6.25 × 10^{-1}	5.44 × 10^{-1}
Elevated Temperature	Time / (cumulated time)		
	5 min	10 min / (15 min)	15 min / (30 min)
600 ^{0}C	8.23 × 10^{-1}	6.83 × 10^{-1}	4.60 × 10^{-1}



(a)



(b)

Fig. 4. The I-V characteristic of Ti/Al contact of samples annealed at (a) 400 °C (b) 600 °C for 20 and 15 min, respectively.

4. Conclusions

Ti/Al contacts were fabricated using sputtering method on n-type InGaN semiconductors to determine the capability of this specific contact to serve as ohmic contact. Then, the as-deposited contacts were thermal annealed at a temperature ranging from 400 °C to 600 °C. The samples were annealed in ambient which includes nitrogen ambient. The duration of the annealing process were also varied to analyze the change of ohmic characteristics as the annealing duration is set 30 minutes. This study has resulted in producing contacts from the Ti/Al metallization scheme with the lowest specific contact resistivity of $\rho_c = 4.60\times10^{-01}$ Ωcm^2 after annealing in nitrogen for 30 minutes at 600°C. However, this ρ_c is still considerably high for optimum device performance whereby the region of ideal contact is within 10^{-2} - 10^{-4} Ωcm^2.

Acknowledgements

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