OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 1, No. 10, October 2007, p. 523 - 527

Comparative study of characteristics in Ni, Ag and Ni/Ag metal contact schemes on n-type InN layer

L. S. CHUAH*, Z. HASSAN, H. ABU HASSAN
Nano-Optoelectronics Research and Technology Laboratory, School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia

In this work, the structure of the InN films has been determined by means of conventional XRD phase analysis $\omega/2\theta$ scan. Characteristics of the as-deposited (Ni, Ag, and Ni/Ag) metal contact on indium nitride (InN) have been studied. Specific contact resistivity, ρ_c (SCR) was determined using transmission line method (TLM). The bilayer contact produced the lowest SCR. For this reason, different annealing temperatures (400 °C-700 °C) in nitrogen gas ambient and durations (1-30 minutes) are investigated for Ni/Ag metal contacts, as thermally stable metal-semiconductor contacts are essential for high quality devices. Annealing in nitrogen gas ambient is believed to avoid nitrogen vacancies which act as donors. The electrical behavior of each condition is compared. For relatively different annealing temperatures, substantial difference of the SCR values is observed between different durations samples. Scanning electron microscopy (SEM) measurements were carried out on the as-deposited, and annealed contacts where the surface morphology of each of these conditions was compared.

(Received August 8, 2007; accepted August 15, 2007)

Keywords: Specific contact resistivity, Indium nitride, Ohmic contact, Annealing

1. Introduction

Among III-nitride semiconductor materials, indium nitride (InN) is an attractive material for long-wavelength optoelectronic and high-speed electronics devices, because of the narrowest direct band-gap energy and superior carrier-transport characteristics over a wide range of temperature. However, the growth of InN has been less studied as compared with those of other III-nitride semiconductor materials such as gallium nitride (GaN) and aluminium nitride (AlN), because of the low thermal stability of InN.

InN can form continuous alloys with GaN and permits light emitting wavelengths from blue to green and far into the red region. Recently however, band gap energies smaller than 1.9 eV have been reported [1-2], namely, in the range of 0.7 –1.0 eV. Corresponding wavelengths are compatible with the wavelengths used in optical communication. If InN of high crystalline quality and with direct band gap energies of 0.65 – 0.9 eV could be grown, it could have a major impact on the optical communication industry.

An ohmic contact is defined as a metal-semiconductor contact that has a low resistance. The resistance should be so low that the voltage drop across the contact is negligible as compared to the drop across other parts of the semiconductor structure. The contact must be stable at temperature through which the device will be heated during processing or to which it will be heated during its usage. High quality, low resistance and stable ohmic contacts are necessary for reducing parasitic resistance and improve over-all performance of the electronic and optoelectronic semiconductor devices. The carrier across the contact are transported by one or more of the three mechanisms: (i) The thermionic emission, (ii) Field emission or tunneling, and (iii) Thermionic field emission. If the Schottky barrier at the contact is thick, tunneling can not take place and thermionic emission dominates. The contact is rectifying. On the other hand if the barrier is thin, tunneling takes place and contact is ohmic. The thickness of the barrier is related to the width of the depletion layer in the semiconductor. The depletion width is inversely proportional to the free carrier concentration in the semiconductor near the junction. If the barrier is wide at the bottom and thin near the top, the carrier need be excited thermally only up to the thin region and they tunnel through. It requires lesser energy than and occurs at lower temperatures then the thermionic emission.

As the semiconductor device technology advances, more stringent requirements are needed for the fabrication of ohmic contacts with very low resistance (reducing knee voltage and resistive heating), good thermal stability (ensuring dependable high temperature performance), and flat surface morphology (hence good edge acuity for short channel devices). It is widely known that parasitic resistances, in the form of contact resistance, significantly affect the overall performance of the electronic and optical devices. The large voltage drop across the semiconductor/metal interface at the ohmic contacts will seriously lead to the loss of device performance and reliability. Therefore, high quality, thermally stable contacts to InN-based materials are essential for the fabrication of reliable, efficient, high performance devices and circuits.

To date, reliable ohmic contacts on InN have not been extensively studied yet. To the best of our knowledge, characteristics of the as-deposited (Ni, Ag, and Ni/Ag) metal contact on InN have not been studied so far. Although InN as a semiconductor was first proposed a long time ago [3], it has been difficult to grow it with good crystal quality due to its large lattice mismatch (~25% with sapphire) [4], the high equilibrium vapour pressure of nitrogen [5], and its low growth temperature [4]. Only in 2000, InN, grown by the most popular growth techniques, metalorganic vapour-phase epitaxy (MOVPE) and molecular beam epitaxy (MBE), with sufficient crystalline quality has been achieved. The lowest carrier concentration of 3.49×10^{17} cm^{-3} and the highest mobility of 2050 cm^2/Vs have been achieved in MBE grown InN [4]. It has been noticed that high n-type carrier concentration is a common feature of InN, and it is assumed to be due to nitrogen vacancies [6].

Thus far, few studies using Hg, Ti, Al or Ni have been carried out regarding metal contacts on InN [7-8]. Large lattice mismatch with the substrates, high carrier concentration, and rough surface morphology turn out to be difficult obstacles in the quest for an ohmic contact. 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.

It is widely known that the application of thermal treatment is vital in achieving ohmic contact upon metal deposition to the bandgap semiconductor since there are very few as-deposited metals, which have ohmic behaviour. In fact, thermal treatment has been used to study the thermal stability in many metal-semiconductor contacts as well as to improve or optimize the electrical properties of the contacts. Thermally stable metal-semiconductor contacts are essential for the realization of high quality devices.

In this paper, characteristics of the as-deposited (Ni, Ag, and Ni/Ag) metal contact on InN have been studied. Specific contact resistivity (SCR) was determined using transmission line method (TLM). The bilayer contact produced the lowest SCR. For this reason, different annealing temperatures (400°C-700°C) and durations (1-30 minutes) of Ni/Ag metal contacts are investigated, as thermally stable metal-semiconductor contacts are essential for high quality devices. The electrical behavior of each condition was compared. Surface morphology of the samples was compared by using scanning electron microscopy (SEM).

2. Experimental

In this study, the commercially sourced unintentionally doped n-InN/GaN sample grown on sapphire (Al_2O_3) was used. The structure of the films has been determined by means of conventional XRD phase analysis $\omega/2\theta$ scan. Prior to the metal deposition, the samples were cleaned using the standard procedure. Samples were dipped into a mixture of NH_4OH: H_2O: 1: 20 for 5 min, then rinsed with de-ionised (DI) water. Subsequently, the samples were dipped into a mixture of HF: H_2O (1: 50) for 20 seconds then rinsed with de-ionised water. 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.

The metal contacts Ni (300 nm), Ag (100 nm) and Ni (300 nm)/Ag (300 nm) was deposited onto the InN through a metal mask by using thermal evaporation. For bilayer contacts, Ni was then sputtered onto the InN through a metal mask, followed by the Ag capping layer. Characteristics of the as-deposited (Ni, Ag, and Ni/Ag) metal contact on InN have been studied by current-voltage (I-V) measurements.

The transmission line method (TLM) pads were 2mm (W, width) ×1 mm (d, length) in size, and the spacings, l, between the pads were 0.3, 0.4, 0.6, 0.9 and 1.3 mm. The specific contact resistivities, ρ_c were determined from the plot of the measured resistances against the spacings between the TLM pads. The linear-square method was used to fit a straight line to the experimental data.

The bilayer contact produced the lowest SCR by transmission line method (TLM). For this reason, different annealing temperatures (400°C-700°C) in nitrogen gas ambient and durations (1-30 minutes) of Ni/Ag metal contacts are investigated, as thermally stable metal-semiconductor contacts are essential for high quality devices. The Ni/Ag samples were annealed under flowing nitrogen gas environment in a furnace at temperatures ranging from 400°C-700°C for different durations. Heat treatment was carried out again after performing current-voltage (I-V) measurements for the subsequent annealing to investigate the thermal stability of the contacts. Finally, surface morphology of the samples was compared by using scanning electron microscopy (SEM).

3. Results and discussion

Fig. 1 shows X-ray diffraction (XRD) phase analysis scan of $InN/GaN/Al_2O_3$. The intensity data was collected by performing ω (sample angle) - 2θ (detector angle) scan at a range of different values. The peaks at about 31.14° and 34.38° correspond to (0002) and (0002) diffraction peaks of InN and GaN films with wurtzite structure, respectively. The peak characteristic of sapphire (0006) substrate was observed around 42°.

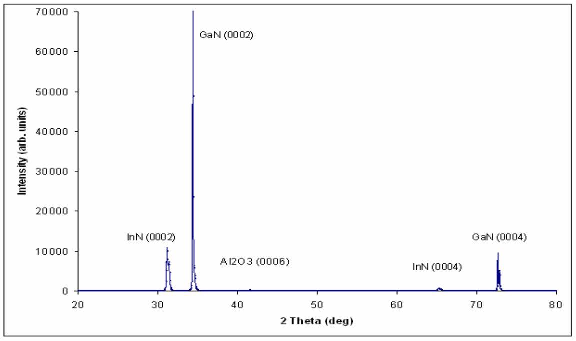


Fig. 1. X-ray diffraction scan of $InN/GaN/Al_2O_3$.

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

$$R_i = \frac{R_{sh} l_i}{W} + \frac{2 R_{sk} L_t}{W} \quad (1)$$

$$R_i = \frac{R_{sh} l_i}{W} + 2 R_c \quad (2)$$

where W is the width of the 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, and $2R_c$ is yielded from the intercept at y-axis. The intercept at x-axis, will give L_x, where

$$L_x = \frac{2 R_{sk} L_t}{R_{sh}} \approx 2 L_t \quad (3)$$

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 [9], which leads to $\rho_c = R_c W L_t$.

From Fig. 2, the as-deposited of Ni, Ag and Ni/Ag exhibited nearly *I-V* behavior. We selected Ni as the key contact element, because Ni is second higher work function metal, and has a work function of 5.15 eV. Metal Ag was selected because it is second lower work function metal, and has a work function of 4.26 eV. The initial investigation revealed that SCR for the as-deposited samples of Ni, Ag and Ni/Ag are determined to be 29.3 × 10^{-2} Ω-cm^2, 30.5 × 10^{-2} Ω-cm^2, and 6.3 × 10^{-2} Ω-cm^2 respectively. For the as-deposited case, the bilayer contact produced the lowest SCR. We believe that the lower contact resistance of the Ni/Ag contact with lower work function of Ag is due to a new phase with lower work function.

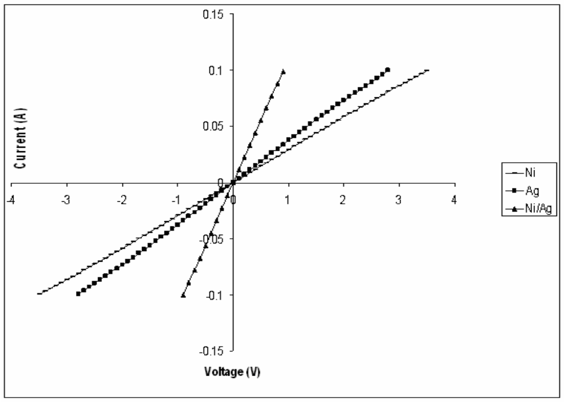


Fig. 2. The as-deposited of Ni, Ag and Ni/Ag exhibited Nearly I-V behavior.

For this reason, different annealing temperatures (400 °C-700 °C) and durations (1-30 minutes) are investigated for the Ni/Ag metal contacts. In this study, heat treatments for Ni/Ag contacts could be divided into low (400 °C), moderate (500-600 °C) and elevated (700 °C) annealed temperatures. The Ni/Ag contact resistivities measured in this study are summarized in Table 1. Annealing in nitrogen gas ambient is believed to avoid nitrogen vacancies which act as donors. Besides the annealed in nitrogen gas, annealing was conducted in an oxygen and nitrogen mixed gas ambient as reported by Y. Koide et al. [10]. This is to remove hydrogen atoms contained in Mg-doped GaN epilayers.

Table 1. The specific contact resistivities at different annealing temperatures and times for Ni/Ag contacts.

Annealing Temperature	Specific Contact Resistivities (Ω cm^2)		
Low Temperature	Time / (cumulated time)		
	5 min	10 min/(15 min)	15 min/(30 min)
400°C	5.9 x 10^{-2}	4.1 x 10^{-2}	3.5 x 10^{-2}
Moderate Temperature	Time / (cumulated time)		
	2 min	5 min/(7 min)	-
500°C	5.8 x 10^{-2}	8.6 x 10^{-2}	-
600°C	6.6 x 10^{-2}	Sch.	-
Elevated Temperature	Time / (cumulated time)		
	1 min	2 min/(3 min)	-
700°C	5.9 x 10^{-2}	Sch.	-

Sch. : Schottky behavior

Fig. 3 shows the I-V characteristics of Ni/Ag contacts of samples thermally treated at 400°C under annealing durations of 15 minutes (cumulated 30 minutes). 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 5 minutes (cumulated 7 minutes), Ni/Ag contacts showed slight non-linear *I-V* characteristic behavior with a small potential barrier, as seen in Fig. 3. 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.

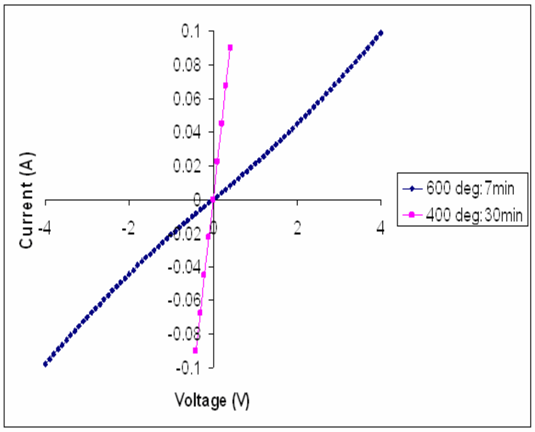
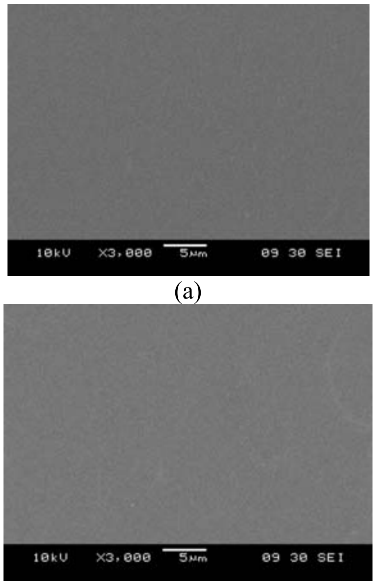
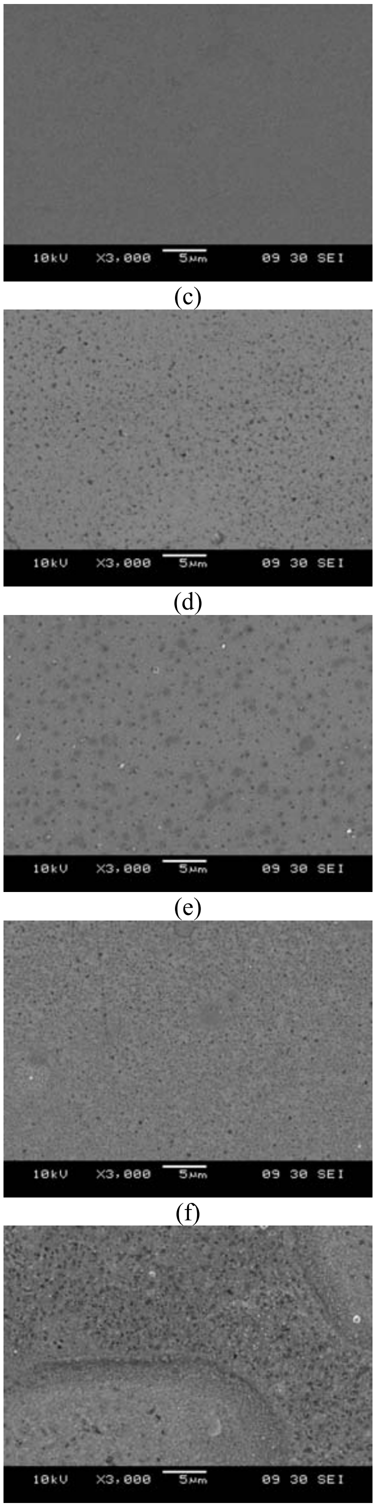


Fig. 3. The I-V characteristics of Ni/Ag contact of samples annealed at 400 °C and 600 °C for 30 and 7 min, respectively.



(a)

(b)



(c)

(d)

(e)

(f)

(g)

Fig. 4. SEM images of the as-deposited samples of (a)Ni, (b)Ag, (c) Ni/Ag contacts; Images of the Ni/Ag contacts annealed at different temperatures: (d) sample annealed at 400°C for total 30 minutes; (e) sample annealed at 500°C for total 7 minutes (f) sample annealed at 600 °C for total 2 minutes; (g) sample annealed at 700 °C for total 1 minutes. Scale bar indicates 5 μm.

When the samples were thermally treated at low temperatures, i.e. 400 °C, substantial difference of the SCR values was observed between samples under 5 min, 10 min and 15 min annealing durations. For annealing durations of 15 min (cumulated 30 minutes), SCR values obtained was found to be lower as compared to the other annealed durations in Table 1. When samples were annealed at 600°C for 7 min and 700 °C for 3 min, Schottky contacts were observed. Nevertheless, it is possible to observe that the resistance of the sample is smaller as a result of annealing at 400 °C (30 min) than for the unannealed sample. Resistance decreases more after annealing at 700 °C (1 min). It is known that annealing improves ohmic contacts due to a metal–semiconductor intermixing and the resistance starts to decrease [11].

Lately it has been reported that InN can be transformed into In_2O_3 by annealing in nitrogen [12] or air [13]. The source of oxygen was attributed to dioxygen contaminations in the N_2 gas. Although the samples were annealed in nitrogen ambient, a certain amount of oxygen could be present in the furnace which would lead to the formation of oxide compounds in the samples under high annealing temperature. Formation of oxide compounds in GaN has been claimed and reported by E. F. Chor [13].

Fig. 4 shows the SEM images of the as-deposited and annealed treated contacts samples. Generally, no agglomeration or “ball-up” was observed from the SEM images for all of the samples. In addition, the surface morphology of the annealed contacts was not significantly changed with different annealing temperatures. Only pores were observed from the SEM images after annealing as shown in Fig. 4. The pore size distribution is relatively uniform on contact after annealing. We believe that the pore size of the Ni/Ag layer occurs during the heating process from the compressive stress due to the difference of the thermal expansion coefficients between Ni, Ag and InN.

4. Conclusions

Characteristics of the as-deposited (Ni, Ag, and Ni/Ag) metal contact on indium nitride (InN) have been studied. The thermal stability, electrical behavior of Ni/Ag contacts at various annealing temperatures (400 °C – 700 °C) has been investigated. For 15 min annealing durations (cumulated 30 minutes) at 400 °C, SCR values obtained was found to be lower as compared to other treatment durations. On the other hand, both samples treated at 600°C and 700 °C, showed deterioration after the subsequent 5 minutes (cumulated 7 minutes) and 2 minutes (cumulated 3 minutes) thermal treatment was introduced. SEM images indicated that little difference of surface morphology was observed for all the samples regardless of the annealing temperatures, durations and treatments.

Acknowledgement

The support from Universiti Sains Malaysia is gratefully acknowledged. The authors would like to thank Mr Sin Yew Keong for the SEM measurements.

References

[1] J. Wu, Yu M. Walukiewicz, J. W. Ager III, E. E. Haller, H. Lu, W. J. Schaff, Y. Saito, Y. Nanishi, Appl. Phys. Lett. **80**, 3967 (2002).
[2] T. Matsuoka, H. Okamoto, M. Nakao, H. Harima, E. Kurimoto, Appl. Phys. Lett. **81**, 1246 (2002).
[3] F. Fischer, F. Schro¨ ter: Ber. Dtsch. Chem. Ges. **43**, 1465 (1910).
[4] A. G. Bhuiyan, A. Hashimoto, A. Yamamoto, J. Appl. Phys. **94**, 2779 (2003).
[5] O. Ambacher, M. S. Brandt, R. Dimitrov, T. Metzger, M. Stutzmann, R. A. Fischer, A. Miehr, A. Bergmajer, G. Dollinger, J. Vac. Sci. Technol. B **14**, 3532 (1996).
[6] N. Miura, H. Ishii, A. Yamada, M. Konagai, Y. Yamauchi, A. Yamamoto, Jpn. J. Appl. Phys. **36**, L256 (1997).
[7] W. J. Schaff, H. Lu, J. Hwang, H. Wu: Growth of InN for Heterojunction Field Effect Transistor Applications by Plasma Enchanced MBE (IEEE, New York, 2000) p. 225.
[8] J. Wu, W. Walukiewicz, Yu K. M., J. W. Ager, E. E. Haller, Lu H., W. J. Schaff, Y. Saito, Y. Nanishi, Appl. Phys. Lett. **80**, 3967 (2002).
[9] G. K. Reeves, H. B. Harrison, IEEE Electron Device Letters, Vol. EDL-3, 111 (1982).
[10] Y. Koide, T. Maeda, T. Kawakami, S. Fujita, T. Uemura, N. Shibata, M. Murakami, J. Elec, Mat. **28**, 341 (1999).
[11] V. T. Rangel-Kuoppa, S. Suihkonen, M. Sopanen, H. Lipsanen, Jpn. J. of Appl. Phys. 36 (2006).
[12] E. Kurimoto, M. Hangyo, H. Harima, M. Yoshimoto, T. Yamaguchi, T. Araki, Y. Nanishi, K. Kisoda, Appl. Phys. Lett. **84**, 212 (2004).
[13] E. F. Chor, D. Zhang, H. Gong, G. L. Chen, T. Y. F. Liew, J. Appl. Phys. **90**, 1242 (2001).

---

*Corresponding author: chuahleesiang@yahoo.com