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Effect of Temperature Annealing on Electrical and Optical Properties of Ni/Au/ITO Contacts to p-type GaN

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Abstract: *The effect of annealing temperatures on Ni/Au/ITO contacts on p- type GaN (2 x $10^{17}/cm^3$) has been studied. The Ni/Au/ITO (1.5/1/50 nm) metal layers were prepared by electron beam evaporation technique at the base pressure of 1.2 x 10^{-6} torr. The current-voltage (I-V) characteristics of as-deposited and annealed Ni/Au/ITO contact at annealing temperature of 400 ^{0}C exhibit the rectified behavior. However, I-V characteristics of contacts becomes linear after thermal annealing of Ni/Au/ITO contacts in the temperature range of 500 ^{0}C - 600 ^{0}C. Transparency of as-deposited Ni/Au/ITO film was increased from 24 % to 87.86 % at 470 nm for contact annealed at 600 ^{0}C in N_2+O_2 ambient. The contact resistivity of as-deposited Ni/Au/ITO contact was reduced from 2.14 x 10^{-1} Ω-cm^2 to 1.97 x 10^{-2} Ω-cm^2 for sample annealed at 600 ^{0}C in rapid thermal annealing system in N_2+O_2 ambient for 5 min.*

Keywords: *p-GaN, Ni/Au/ITO contact, rapid thermal annealing and transmittance.*

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I. Introduction

The III-nitrides are highly promising materials for development of optoelectronic devices such as light emitting diodes (LEDs) and laser diodes (LDs) in the wavelength range of 400-550 nm [1, 2]. The one major issue with these devices is a large voltage drop at metal/semiconductor interface. The large voltage drop has an adverse impact on device performance such as low efficiency, device failure etc. The low resistance contacts on n-GaN can be easily formed with low specific contact resistance of the order of 10^{-5}-10^{-7} Ω-cm^2 using Ti/Al based metal schemes [3, 4]. On the other hand, contacts on p-GaN have still an issue. For improvement of ohmic properties of contacts on p-GaN, various metallization schemes and chemical surface treatments were used [5-14]. The low specific contact resistance to p-GaN with resistivity in the range of 10^{-3} Ω-cm^2 - 10^{-4} Ω-cm^2 with high transmittance (> 80 %) is essential for development of high brightness and high efficiency LEDs. The thin Ni/Au metal scheme [15-17] is commonly used as transparent ohmic contact to p-GaN because of the relatively good values of specific contact resistance 10^{-3} Ω-cm^2 - 10^{-4} Ω-cm^2 and its optical transparency (> 70%). Though, the contact resistance may be improved by increasing the thicknesses of Ni and Au metal layers, but it will reduce the optical transmittance of contact. Also, thin metal layers could not spread the current effectively into the active region. However, the transparency of Ni/Au metal layers can be increased by reducing the thicknesses of these metal layers, but the contact reliability could become an issue, when the contact layer thickness becomes too thin. Though, the indium tin oxide (ITO) has good transparency (> 80%) in the visible region (450-550 nm) but it has non-ohmic behavior with high contact resistance [18-19] and due to which, it could not be suitable material for formation of low resistance with high transparent ohmic contact on p-GaN. Horng *et a*l. have reported that Ni/ITO has also form good ohmic contact on p-GaN [20]. Kim *et a*l. have reported that Ni/Au/ITO (2/3/200 nm) have also form good ohmic contact on p-GaN [21]. Therefore, to get low resistance ohmic contact with high optical transparency on p-GaN, the combination of thin layers of Ni/Au metals along with ITO layer may be good option because Ni/Au form good ohmic contact and ITO would be provide better reliability after annealing in the temperature range of 400 - 600 ^{0}C in N_2+O_2 ambient.

In this article, we deposited Ni/Au/ITO (1.5/1/50 nm) metal layers on p-GaN by electron beam evaporation at the base pressure of 1.2 x 10^{-2} torr. The contacts were then annealed in the temperature range of 400-600 ^{0}C in N_2+O_2 ambient to see the impact of annealing temperatures on its specific contact resistance. In addition, the effects of annealing temperatures on transmittance of Ni/Au/ITO films in the visible range of 400 - 550 nm were also studied.

II. Experimental Work

In this study, epitaxially grown LED structure was used. The LED structure was grown by metal organic chemical vapor deposition (MOCVD) technique on 400 µm thick c-plane sapphire substrate. The LED structure consists of a ~ 25 nm GaN nucleation layer, 2 µm thick undoped GaN, ~ 2 µm thick n-GaN (Si-doped), an active region, ~ 30 nm AlGaN (Mg-dope) electron blocking layer and 150 nm p-GaN (Mg-doped). The active region consists of five 3 nm/10 nm InGaN/GaN quantum wells embedded between n-GaN and p-GaN layers. Trimethylindium (TMIn), gallium (TMGa), trimethylalumium (TMAl) and ammonia (NH_3) were used as the source materials of In, Ga, Al and N, respectively. Bicylopentadienyl magnesium (CP_2-Mg) and silane (SiH_4) were used as the p-type and n-type dopants. For activation of Mg, wafer was annealed at 700 ^{0}C for 1 min in N_2 ambient in rapid thermal annealing system (As-One 100). The holes concentration was 2 x 10^{17}/cm^3 and holes mobility was 5 cm^2/V.s.

For measurement of contact resistivity, circular transmission line method (CTLM) was used. The inner circular pads with radius of 85 µm were separated by gap spacing of 25, 30, 35, 40 and 45 µm. The circular contacts pads were defined by standard photolithography. Prior to deposition of metal films, the CTLM patterned samples were dipped into HCl and H_2O chemical solution in the ratio of 1:1 for 40 s and then rinsed in de-ionized water for 1 min before loading samples in to the chamber to remove the native oxide. The patterned samples were deposited with Ni (15 A^0), Au (10 A^0) and ITO (500 A^0) metals in sequence by electron beam evaporator at the base pressure of 1.2 x10^{-6} torr. For measurement of optical properties of Ni/Au/ITO films, glass substrates were also coated with these metal layers along with these CTLM patterned samples. After deposition of metal layers, circular pads were realized by lift-off process. In addition, a Ni/Au (5/5 nm) metal contact was also deposited on p-GaN for comparison of surface morphology of Ni/Au metal film with Ni/Au/ITO after annealing at 550 ^{0}C for 5 min in N_2+O_2 ambient. To study the effect of annealing temperature of Ni/Au/ITO contacts to p-GaN, CTLM patterned samples were heat treated under N_2+O_2 ambient condition in the range of 400 ^{0}C - 600 ^{0}C for 5 min in a rapid thermal anneal system (As-One 100). The contacts were characterized using circular transmission line model (CTLM). Current-voltage (I-V) measurements were performed by applying a voltage ramp from - 5 V to + 5 V and measured the resultant current. The light transmittance of annealed Ni/Au/ITO films were measured using by USB4000 (Ocean optics) spectrophotometer.

III. Results And Discussions

Fig. 1 shows the current-voltage characteristics of Ni/Au/ITO contact to p-GaN of as deposited and annealed in the temperature range of 400 ^{0}C - 600 ^{0}C. It is clear that as deposited Ni/Au/ITO film to p-GaN exhibited nonlinear I-V characteristics. However, the electrical properties of contacts are considerably improved after annealing at temperature in the range of 400 ^{0}C - 600 ^{0}C. The sample annealed at 400 ^{0}C still shows nonlinear characteristics. However, samples annealed at 500 ^{0}C, 550 ^{0}C and 600 ^{0}C exhibit the linear I-V characteristics i.e. contacts become ohmic after annealing in the temperature range of 500 ^{0}C - 600 ^{0}C. The contact resistivities of the contacts were plotted as function of the annealing temperature, as shown in fig. 2. The specific contact resistances of these contacts were measured from plots of the measured resistances versus the spacing between the CTLM pads. The least square method was used to fit a straight line to the experimental data. The specific contact resistance of as-deposited Ni/Au/ITO contact on p-GaN was obtained 2.14 x 10^{-1} Ω-cm^2. The specific contact resistance was decreased to 7.22 x 10^{-2} Ω-cm^2 for contact annealed at 500 ^{0}C in N_2+O_2 ambient. The specific contact resistance was further reduced to1.69 x 10^{-2} Ω-cm^2 for the sample annealed at 550 ^{0}C. The specific contact resistance of sample annealed at 600 ^{0}C has slightly higher (1.97 x 10^{-2} Ω-cm^2) compared to sample annealed at 550 ^{0}C. The decrease in specific contact resistance at higher temperatures may be attributed to formation of NiO layer at metal/p-GaN interface during rapid thermal annealing process [13-14, 21]. Also, during thermal annealing, there is possibility of indium atoms from ITO layer diffuse into Au layer and form In-Au solid solution [21]. The interface layer NiO behaves as p-type semiconductor with high holes concentration [17-21]. The slightly increase in contact resistance at 600 ^{0}C may be attributed to lower contact area of film to p-GaN surface at higher temperature compared to contact annealed at lower temperature.

In addition to the electrical properties of Ni/Au/ITO contacts to p-GaN, the optical properties of the film are also important for fabrication of high brightness GaN LEDs emitting emission in the wavelength range of 450-470 nm. The optical transmittance as a function of wavelength of samples annealed in the temperature range of 400 ^{0}C - 600 ^{0}C were plotted in fig. 3. It is clear that, as the annealing temperature was increased from 400 ^{0}C to 600 ^{0}C, the transmittance was increased from 76.6 % to 87.86%. This value is higher than the value reported for p-GaN [19]. The increase in transmittance may be attributed to improvement of crystalline quality of ITO and lower thickness of Ni because Ni behaves like an opaque in the visible region. Therefore, the thickness of Ni plays an important role in the transparency of Ni/Au, Ni/ITO and Ni/Au/ITO contacts on p-GaN. If the thicknesses of Ni and Au are less than 3 nm, then the transparency of as-deposited Ni/Au/ITO film will be dominated mainly by the optical properties of ITO. Therefore, lower thickness of Ni is essential for higher transmittance in the wavelength range of 450-550 nm for Ni based transparent ohmic contacts on p-GaN. Since, the Ni/Au/ITO film was deposited at near room temperature and therefore, it has very low transparency ~ 24 % around 470 nm. The transparency was significantly improved after thermal annealing in N_2+O_2 ambient at higher temperature. During thermal annealing, the concentration of oxygen vacancy in ITO film was reduced by compensation via heat treatment in N_2+O_2 ambient [5].

To see the effect of annealing temperature on surface morphology of Ni/Au/ITO contacts, scanning electron microscopy (SEM) was performed. Fig. 4 shows the SEM images of as-deposited and annealed Ni/Au/ITO contacts in the range of 400-600 ^{0} C in N_2+O_2 ambient conditions. From SEM images, the surface morphologies of as-deposited and annealed contacts were almost similar. Therefore, it is clear from SEM images that Ni/Au/ITO contact on p-GaN has good surface morphology even after annealing at higher temperatures. To compare the surface morphologies of Ni/Au/ITO with commonly used Ni/Au (5/5 nm) transparent contacts on p-GaN, the SEM image of Ni/Au (5/5 nm) contact, annealed at 550 ^{0}C in N_2+O_2 ambient was also performed (fig. 5). From SEM image, it is clear that the surface morphology of annealed Ni/Au contact is much roughed compared to Ni/Au/ITO contact. It was also observed that the adhesion of thin Ni/Au contacts on p-GaN becomes poor, however the Ni/Au/ITO contacts had very good adhesion even after annealing in the temperature range of 400 - 600 ^{0}C in N_2+O_2 ambient.

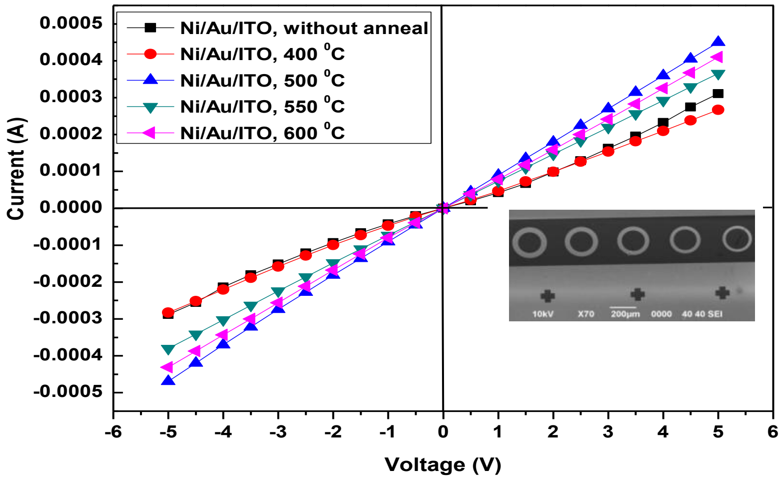

Fig. 1. Current-voltage characteristics of Ni/Au/ITO (1.5/1/50 nm) contacts to p-GaN annealed in the temperature range 400 ^{0}C to 600 ^{0}C in N_2+O_2 ambient conditions.

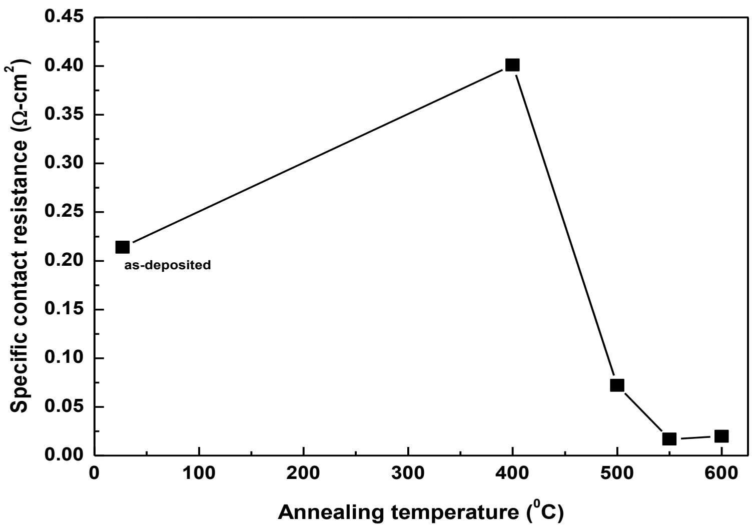

Fig. 2. Effect of annealing temperatures on specific contact resistance of Ni/Au/ITO contacts to p-GaN in N_2+O_2 ambient conditions in the temperature range of 400 ^{0}C to 600 ^{0}C.

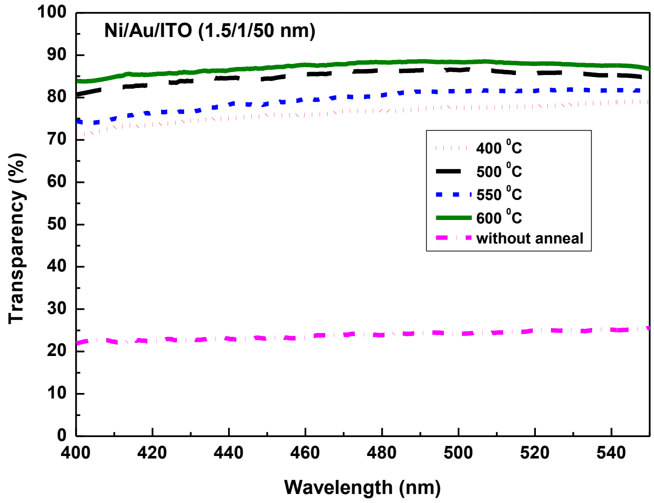

Fig. 3. Optical transmittance of as-deposited and annealed Ni/Au/ITO (1.5/1/50 nm) films as a function of wavelength in the temperature range 400 ^{0}C to 600 ^{0}C in N_2+O_2 ambient conditions.

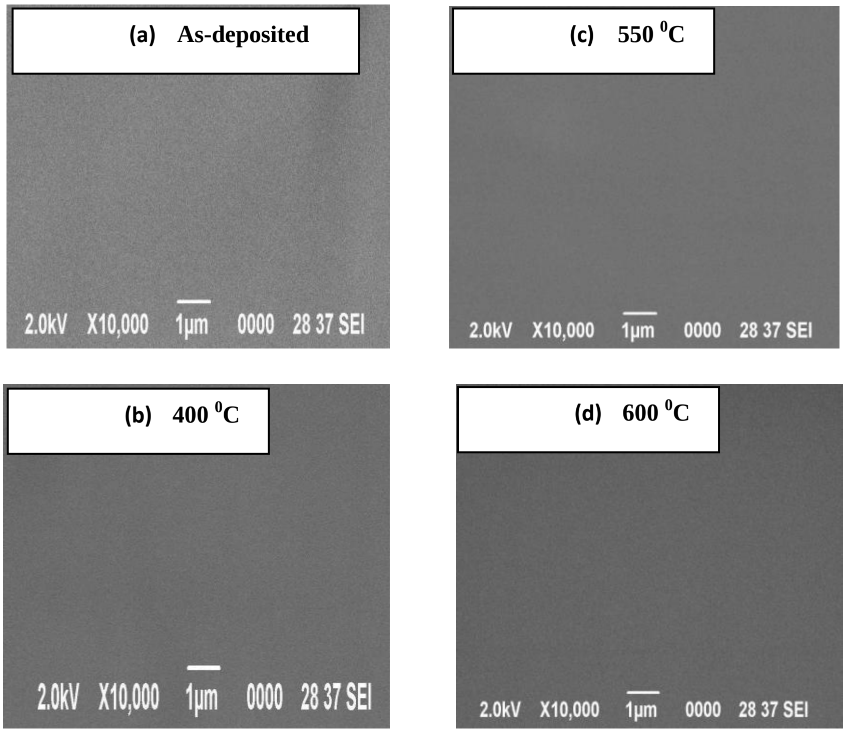

Fig. 4. SEM images of Ni/Au/ITO (1.5/1/50 nm) contacts (a) as-deposited (b) contact annealed 400 ^{0}C in N_2+O_2 ambient (c) contact annealed 550 ^{0}C in N_2+O_2 ambient (d) contact annealed 600 ^{0}C in N_2+O_2 ambient.

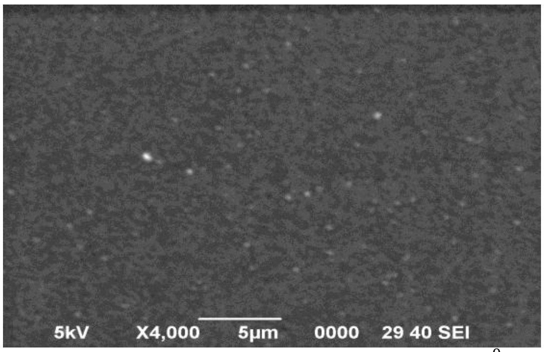

Fig. 5. SEM image of Ni/Au (5/5 nm) contact annealed at 550 ^{0}C in N_2+O_2 ambient.

IV. Conclusion

The electrical and optical properties of Ni/Au/ITO (1.5/1/50 nm) contacts on p-GaN have been investigated as a function of annealing temperature in N_2+O_2 ambient condition. The sample annealed at 550 ^{0}C in N_2+O_2 ambient to p-GaN shows the lowest specific contact resistance of 1.69 x 10^{-2} Ω-cm^2 with optical transparency of 80.1%. The highest transparency of Ni/Au/ITO film was obtained ~ 87.86 %, when the film was annealed at 600 ^{0}C in N_2+O_2 ambient for 5 min, with slightly higher contact resistance of 1.97 x 10^{-2} Ω-cm^2. The formation of NiO layer at metal/p-GaN interface is responsible for formation of ohmic contacts on p-GaN. Moreover, Ni/Au/ITO contact has better adhesion, stability and high transparency compared to commonly used thin Ni/Au bi-metal contact on p-GaN. Therefore, Ni/Au/ITO metal layers could be applicable as a high transparent ohmic contact to p-type GaN for fabrication of GaN LEDs in the emission wavelength of 450-550 nm.

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