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Effect of Temperature Annealing on Electrical and Optical Properties of Ni/Ag/ITO p-Type contacts to p-GaN for Blue Light-Emitting Diodes Applications

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Abstract—The transmittance of thin metal contacts on p-GaN plays a crucial role in the performance of conventional GaN based light emitting diodes (LEDs).In this paper, the effect of temperature annealing on electrical and optical properties of Ni/Ag/ITO (3/2/100 nm) contacts were studied and investigated. Ni/Ag/ITO multi layer metals were deposited on patterned TLM structures at average base pressure of ~ 2 x 10^{-6} torr on metal organic chemical vapor deposition (MOCVD) grown LED structure with top p-GaN (2 x 10^{17} cm^{-3}) by electron beam evaporation. The size of TLM pads were 200 x 200 µm^2 with a gap spacing of 5, 10, 15, 20, 25, 30 and 35 µm, respectively. The as-deposited Ni/Ag/ITO contacts show non-linear current-voltage (I-V) characteristics. However, the I-V characteristics of the annealed contacts in the temperature range of 500 ^{0}C to 600 ^{0}C in N_2+O_2 ambient for 5 min. in rapid thermal annealing system (RTA) become linear i.e. ohmic. The lowest specific contact resistance (ρ_c) was obtained ~ 1.9 x 10^{-2} Ω-cm^2 for contacts annealed at 500 ^{0}C and highest (1.02 x 10^{-1} Ω-cm^2) for as-deposited. The transparency of as-deposited Ni/Ag/ITO film was measured using) spectrophotometer and found 0-3% in the wavelength range of 350-550 nm. The highest transparency of the contacts was 85.8 %, when the contact was annealed at 550 ^{0}C at wavelength of 460 nm. On the other hand, transparency was ~ 83.5 % and ~ 81% for contacts annealed at 500 ^{0}C and 600 ^{0}C, respectively. High resolution X-ray diffraction (HRXRD) was performed to analyze the transmittance of the contacts. The increase in transparency of Ni/Ag/IT contacts is attributed to increase in the crystalline property of the contacts during annealing and confirmed by increase in intensity counts of diffraction peak ITO (222)in XRD measurements.

Index Terms—p-GaN, transparent contacts, rapid thermal annealing, transmittance and XRD.

I. INTRODUCTION

The InGaN/GaN multi-quantum wells (MQWs) based light-emitting diodes (LEDs) with lateral geometries are very attractive due to their wide applications such as full color display, back lighting, traffic lights and solid-state lightings [1]-[3]. To fabricate these LEDs, GaN epi-layers were grown on c-plane (0001) oriented sapphire substrates due to their low cost compared to silicon carbide (SiC) and gallium nitride (GaN).Due to insulating properties of sapphire, n and p-contacts are formed on same plane. This leads to current-crowding phenomenon and limits their light output efficiency[4]-[6]. The current crowding is a strong function of the resistance components such as the contact and cladding layer [4],[7], [8]. Further, another major issue with p-GaN is its high activation energy (~ 170 meV) of Mg, due to which Mg is not easily free from Mg-H complex, which occurs during growth of p-GaN. Due to the highresistivity of p-GaN, the current is not spread uniformly over the entire p-GaN surface. Therefore, to enhance the current spreading performance of GaN-basedLEDs, various metal schemes such as Ni/Au, indium tin oxide (ITO), Ni/ITO,Ni/Au/ITO, Pt/ITO etc. were used [9]-[16].In these metal schemes, thin Ni/Au metal scheme (Ni < 10 nm) is widely used as current spreading layer on p-GaN. The major drawback of this metal scheme is its reliability and low transmittance (~ 60-70%) in wavelength range of 450-550 nm. However, the transparency of these contacts maybe increased further by reducing the thicknesses of Ni and Au metals but reliability becomes a major issue. On the other hand, ITO has good transparency (> 80 %) in wavelength range of 450-550 nm [12],[17]. The major issue with ITO based contacts is to form low resistance contacts to p-GaN. The ITO based contacts on p-GaN has high specific contact resistance of 10^{-1} Ω-cm^2 [18], [19].

In this paper, we report the electrical and optical properties of Ni/Ag/ITO (3/2/100 nm) metal contacts to p-GaN as a function of annealing temperature. The crystalline properties of contacts were measured using high resolution X-ray diffraction (HRXRD) system. From XRD measurements, the change in transmittance of the contacts is also discussed. Scanning electron microscopy (SEM) was used to measure the surface morphologies of the contacts.

II. EXPERIMENT DETAILS

In this study, InGaN/GaN MQWs LED samples were grown on c-plane (0001) oriented 2” sapphire substrates in metal organic chemical vapour deposition (MOCVD) system (Thomas Swan 3”x2” CCS). The single side polished ~ 430

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μm-thick sapphire substrates were used to grow GaN layers. The epitaxial structure consisted of ~ 25 nm GaN buffer layer, 2μm-thick undoped GaN layer, ~ 2 μm-thick Si-dopedn-GaN layer, 5-period InGaN/GaN (~ 3 nm/10 nm) MQWs as active layers, followed by a ~ 30 nm thick Mg-doped AlGaN electron blocking layer and 0.15 μm-thick Mg-doped p-GaN layer.Trimethylindium (TMIn), trimethylgallium (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, grown wafer was thermally annealedin rapid thermal annealing system (RTA). The detailed epi-layer properties are described elsewhere [20]. Fig. 1 shows the schematic diagram of LED structure used in present study.

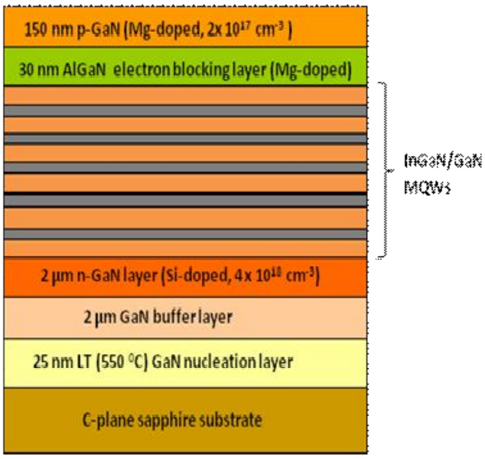

Fig. 1 Schematic diagram of LED structure used in this study.

The specific contact resistances (SCR) of contactswere measured using transmission line model (TLM) [21]. First, grown LED wafer was diced into small pieces of size ~ 1 cm x 1cm. The diced samples were then cleaned by acetone, methanol, 2-propanal and de-ionized water sequentially. After rinsing, the samples were dried in high purity N_2. After cleaning the samples, the linear TLM pads of size 200 x 200 μm^2 and a gap spacing of 5, 10, 15, 20, 25, 30 and 35 μm were formedon samples using ultra violet (UV)photolithography.The patterned samples were then loaded intothe chamber of e-beam systemfor deposition of Ni/Ag/ITO (3/2/100 nm) metals. In this experiment, VST TFDS 462B,electron beam evaporator was used to deposit these materials. Along with patterned TLM samples, glass substrates were also coated with these metals to measure the transmittance of these metal contacts. Prior to loading these samples in the chamber of e-beam system, samples were pre-etched in HCl and de-ionized water solution in ratio of 1:1 for 40 s to remove native oxidation on p-GaN surface. These metal layers were deposited on patterned TLM structures with average vacuum of ~ 2 x 10^{-6} torr. The TLM structures were then realized by lift-off process using ultrasonic bath. Fig. 2 shows the SEM image of fabricated TLM structures after lift-off process. The contacts were then annealed in the temperature range of 500 ^{0}C to 600 ^{0}C for 5 min in N_2+O_2 ambient in RTA system (AnnealSys As-One 100). The current-voltage (I-V) of contacts was measured using DC probe station (Ecopia EPS 1000). The transmission spectra of deposited films were measured by spectrophotometer (Ocean optics USB4000).The crystalline properties of as-deposited and annealed Ni/Ag/ITO metal contacts were measured using HRXRD system (Rigaku Smart Lab). The surface morphologies of the contacts were measured and discussed using SEM (JEOL 5700).

III. RESULTS AND DISCUSSIONS

Fig. 3 shows the room temperature I-V characteristics of as-deposited and annealed Ni/Ag/ITO (3/2/100 nm) contacts, measured between two adjacent TLM pads with a gap spacing of 10 μm. From graph, it is clear that as-deposited contacts slightly non-linear I-V characteristics i.e rectified. On the other hand, I-V of annealed contacts becomes linear i.e ohmic. The non-linear I-V behaviour of as-deposited contacts may be probablydue to large Schottky barrier height (SBH) between p-GaN and Ni interface [22]. The SCR of these contacts were then determined from a plot of the measured resistances versus the contact spacing between the TLM pads. The least square method was used to fit a straight line to the experimental data. The SCR (ρ_c) was then calculated using relation, $\rho_c \sim R_c x W x L_T$, where R_C is the contact resistance, W the width of TLM pad and L_T is the transfer length. The calculated ρ_c for as-deposited Ni/Ag/ITO contacts and annealed contacts were 1.02 x10^{-1} Ω-cm^2,1.95x10^{-2} Ω-cm^2 (500 ^{0}C), 4.67 x10^{-2} Ω-cm^2 (550 ^{0}C), and2.24 x10^{-2} Ω-cm^2 (600 ^{0}C), respectively and shown in Fig. 4.On theother hand, the possible cause of linear behavior of annealed contacts may be due to reduction of SBH after annealing. It may be explained as; during annealing it is high probability that Ni is converted into NiO (which is a p-type semiconductor with high hole concentration and due to which SBH is reduced between p-GaN and Ni interface)[19], [23], [24]. The Ag-Ga solid solution that produces deep acceptor like Ga vacancies during annealing may be another possible cause of lower ρ_c in combination of NiO [19], [25].

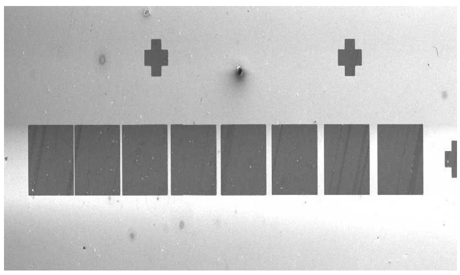

Fig. 2SEM image of fabricated TLM structures.

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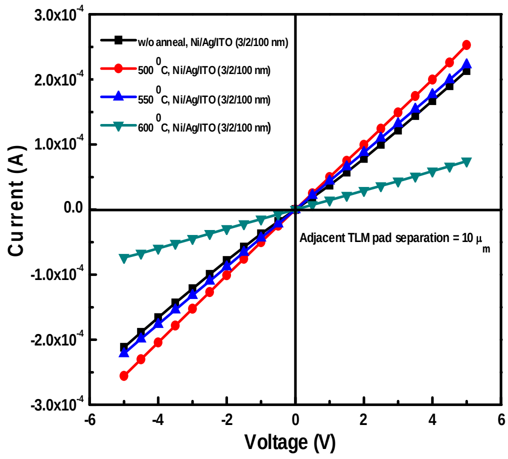

Fig. 3 Room temperature I-V characteristics of as-deposited and annealed Ni/Ag/ITO (3/2/100 nm) p-contacts using TLM pads with gap spacing of 10 µm.

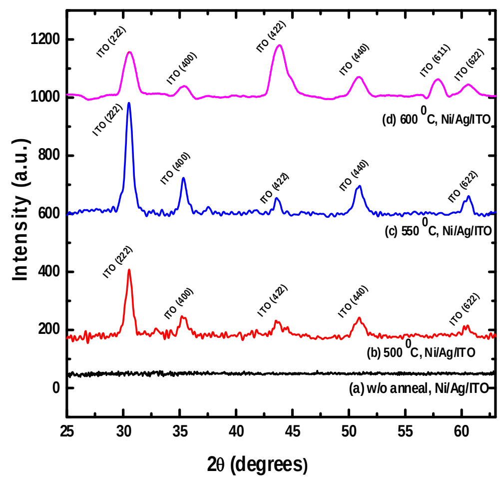

Fig. 6 XRD spectraof as-deposited and annealed Ni/Ag/ITO (3/2/100 nm) p-contacts.

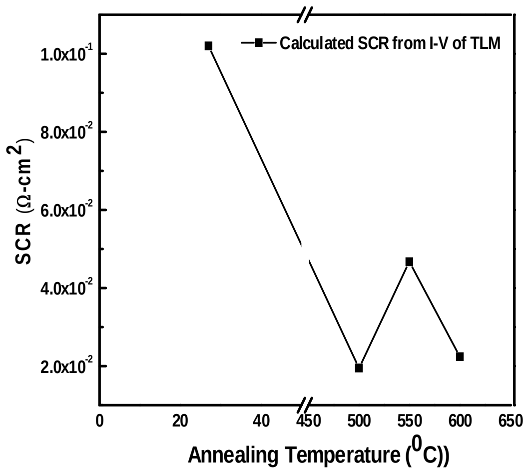

Fig. 4SCR of Ni/Ag/ITO (3/2/100 nm) p-contacts as a function of annealing temperature.

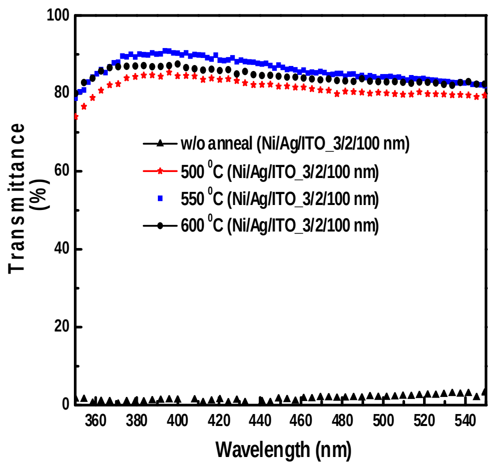

Fig. 5 Optical transmittance of as-deposited and annealed Ni/Ag/ITO (3/2/100 nm) p-contactsas a function of wavelength.

Transmittance of metal contacts plays an important role in performance of top emitting GaN LEDs. The optical transmittance of as-deposited and annealed Ni/Ag/ITO films was measured using spectrophotometer. Fig. 5 Shows measured room temperature optical transmittance of Ni/Ag/ITO film as a function of wavelength. The transmittance of as-deposited Ni/Ag/ITO was less than 3% in the wavelength range of 350-550 nm. Such low transmittance of as-deposited Ni/Ag/ITO film was attributed to amorphous structure of the ITO film because the amorphous film has large numbers of smaller grains in the film and due to which,scattering of incident of light is very high [26].The transmittance of the Ni/Ag/ITO metal film increases as the annealing temperature was raised to 500 ^{0}C. The transmittance was ~ 81% around wavelength ~ 460 nm. The transmittance of the Ni/Ag/ITO was further increased when annealing temperature was raised to 550 ^{0}C. The transmittance of the film was increased to ~ 85.8 % at wavelength ~ 460 nm. Further, when annealing temperature was increased to 600 ^{0}C, the transmittance was slightly decreasedto ~ 83.7 % (Ni/Ag/ITO) at wavelength 460 nm. The increase in transmittance of Ni/Ag/ITO film after annealing may be attributed to increase in crystalline properties of ITO. To analysis the reason behind in increase of transmittance of metal film, X-ray diffraction (XRD) was performed. Fig. 6 shows the x-ray scattering intensity as a function of diffraction angle (2θ) of as-deposited and annealed Ni/Ag/ITO metal films. The XRD pattern of as-deposited Ni/Ag/ITO film did not show any diffraction peak (Fig. 6 a), indicating the amorphous structure of Ni/Ag/ITO metal film [24]. On the other hand, film annealed at 500 ^{0}C showsfive major diffraction peaks (Fig. 6 b), which indicates the change of film structure from amorphous to crystalline. The five major peaks represent ITO (222), ITO (400), ITO (422), ITO (440) and ITO (622) [27], [28]. The most intense peak was ITO (222), indicates that crystallinity of the Ni/Ag/ITO film was improved and the grain size became larger at higher annealing temperature. Similarly,

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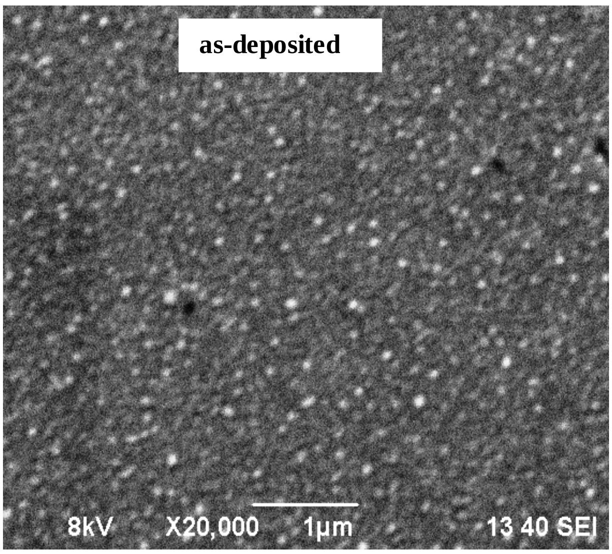
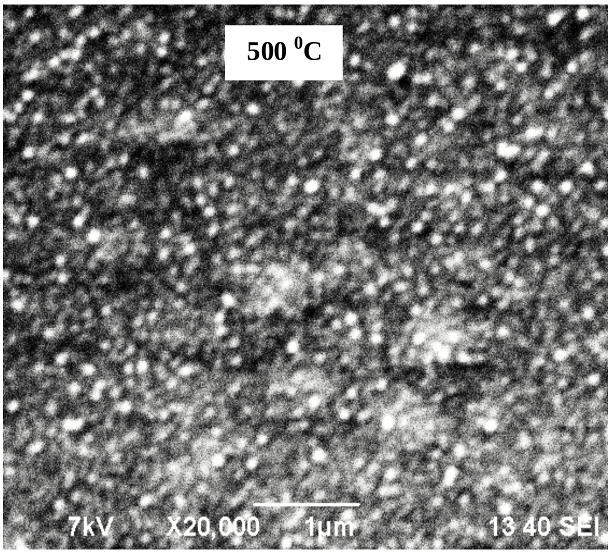
Fig. 6 c shows the x-ray diffraction pattern of 550 ^{0}C annealed Ni/Ag/ITO film. Again five major diffraction peaks with high intensity counts and less broaden with respect to 500 ^{0}C annealed Ni/Ag/ITO film, indicates that crystallinity of the Ni/Ag/ITO film was further improved and the grain size became larger at higher annealing temperature (550 ^{0}C). Fig. 6 d shows the diffraction pattern of 600 ^{0}C annealed Ni/Ag/ITO film. From diffraction pattern, six major diffraction peaks namely ITO (222), ITO (400), ITO (422), ITO (440), ITO (611) and ITO (622) were observed. The two diffraction peaks ITO (222) and (422) have almost same intensity counts. It is also clear that diffraction peaks not only became broaden but also intensity counts were decreased. This indicates that crystallinity of the Ni/Ag/ITO film became slightly poor and therefore, the transmittance of film was slightly decreased.

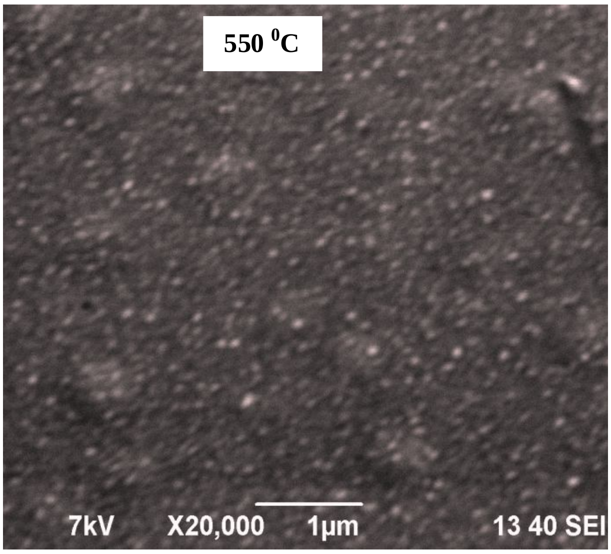
Further, the surface morphology of as-deposited and annealed Ni/Ag/ITO contacts was analyzed using SEM. Fig. 7 shows the SEM images of as-deposited and annealed Ni/Ag/ITO contacts. It is clear from Fig. 7 (a) the crystalline size in ITO film is very small and due which boundary scattering is very large. Due to this, the transmittance of the film is very low in the 350-550 nm range of wavelength. From SEM image Fig. 7 (b), it is clear that the crystalline size in the annealed (500 ^{0}C) ITO film is much larger, which indicates that film is converted from amorphous to crystalline. Thus, the increase in crystalline property of film, the transmittance of the film is increased because the crystalline size in ITO film is large hence boundary scattering is small.Figs. 7 (c) and 7 (d) show the SEM images of Ni/Ag/ITO film annealed at 550 ^{0}C and 600 ^{0}C, respectively. The further improvement of transmittance of film annealed at 550 ^{0}C may be attributed to further improvement of crystalline size in ITO film. On the other hand, slightly decrease in transmittance of film annealed at 600 0C may be attributed to voids between grains.



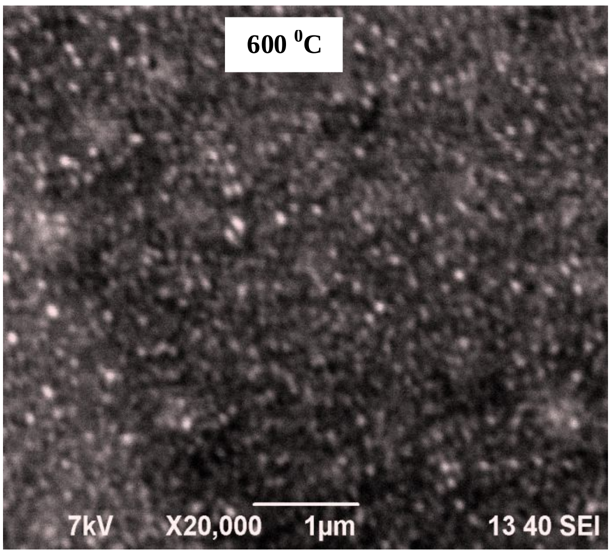
(a)



(b)



(c)



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(d)

Fig. 7SEM images of Ni/Ag/ITO contacts; (a) as-deposited (b) 500 ^{0}C (c) 550 ^{0}C and (d) 600 ^{0}C.

Conclusion

In conclusion, effect of temperature annealing on electrical and optical properties e-beam deposited Ni/Ag/ITO contacts to p-GaN has been investigated. The I-V characteristics of as-deposited Ni/Ag/ITO contacts show the non-linear behavior. On the other hand, the annealed contacts show the linear behavior.The lowest ρ_c was obtained ~ 1.95 x10^{-2} Ω-cm^2 for annealed contacts at 500 ^{0}C and highest for as-deposited. It is observed that after annealing in the range of 500 ^{0}C - 600 ^{0}C, the crystalline properties of the Ni/Ag/ITO film was improved. The crystalline properties of the films were confirmed by increase in intensity counts of diffraction peak ITO (222).The highest transmittance was ~ 85.8 % at 460 nm and confirmed by highest intensity counts of diffraction peak of ITO (222) in XRD measurement. The increase in transmittance of Ni/Ag/ITO was also explained by surface morphologies of SEM images. The grainsizein ITO film after annealing is increased and due to which scattering of incident light is reduced.

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