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Reduced contact resistance and Improved surface morphology for Ohmic Contacts on AlGaN/GaN based Semiconductors employing KrF Laser Irradiation

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ABSTRACT

We employ excimer laser annealing for ohmic contact formation to n and p type gallium nitride. Laser annealing facilitates the achievement of reduced sheet resistance in the contact formed, essential for high performance GaN light emitting diodes (LEDs) and heterostructure field-effect transistors (HFET) applications. The laser irradiation of the *n*-GaN layers led to increased nitrogen vacancies at surface, which promoted tunneling currents and achieved a lower resistive n-contact. In p-contact, laser irradiation increased the effective hole concentration and similarly resulted in decreased contact resistivity. The lowest specific contact resistance measured using the transmission line method was 2.4×10^{-7} Ω cm², and 3.2×10^{-4} Ω cm² for n and p contacts respectively. Good surface morphology was also obtained. Forward current also increased due to the reduced ohmic contact resistance, and improved electrical characteristics for enhanced carrier conduction.

INTRODUCTION

GaN-based materials have received considerable attention for widespread applications in photonic and electronic devices. Forming low resistive, thermally stable and uniform ohmic contacts to wide bandgap semiconductors such as GaN is still a challenge. Contact properties limit the overall performance of optical and electronic devices. The presence of the insulating native oxide at the metal/semiconductor interface results not only in poor interfacial structures but also in an increase of effective schottky barrier height to act as a barrier for the carrier to transport from the metal to the semiconductor.[1,2] High temperature thermal annealing during device processing is widely used to remove the native oxide on the GaN surface.[3] However, surface roughness and decomposition during RTP results in poor performance and reliability of the devices due to the nonuniform current flow at the damaged interface.

In this work, we report the materials and electrical properties of metal contacts formed by laser annealing (LA). In particular, we have employed Ti (35 nm)/Al(150 nm) deposited on n-GaN and Cr (5nm)/Au (5nm) spreading layer, deposited on p-GaN by electron beam evaporation to form the n and p contacts for light emitting diode.

RESULTS AND DISCUSSION

Fig. 1(a) is a schematic illustration of the GaN layer on sapphire substrate, after mesa definition. Laser annealing was carried out in purging N_2 ambient using a 248nm pulsed KrF excimer laser. A systematic study of annealing conditions on contact properties changes was performed. Laser irradiation using single and multiple pulses at various laser fluences in the range of 0.12 to 0.5Jcm^{-2} was carried out to study the effects of repeated irradiation on Ti/Al and Cr/Au. Fig. 1(b) is an optical micrograph of a typical LED after laser annealing of both n and p contacts. Fig. 2 shows the bright field cross sectional TEM images of GaN evaporated with Ti/Al contacts after (a) RTP and (b) laser annealing. TEM is performed to investigate the morphological changes in Ti/Al with annealing. The Ti/Al, after laser annealing, remains visible and distinct above the atomically sharp GaN surface, but after RTP, it shows signs of layer breakdown and discontinuity.

Fig. 3 shows secondary ion mass spectroscopy (SIMS) profiles of Ti/Al on GaN after RTP and laser annealing at an optimal laser fluence of 0.5Jcm^{-2}. Rapid out and in-diffusion of Al and Ti atoms to the GaN surface occurred for the RTP sample. They diffused to react with GaN and penetrated beyond the GaN interface. For laser annealed sample, less observable diffusion occurred and contacts maintained well defined layers. Fig.4 shows the XRD plot for Ti/Al on GaN. RTP consumed Al and caused a dip in Al peak, and transformed Al to form low resistive Ti-Al compounds. The sample laser annealed at 0.5Jcm^{-2} containing the largest amount of Al and Al_3Ti had the lowest resistance. The peaks of Al_2O_3 overlap strongly at ~41.7° in RTP sample. RBS spectra shows after RTP, Ti and Al thickness increase and yield reduced since the interface between Ti and GaN is indistinct. Fig. 5 shows the *I-V* characteristics for Ti/Al contacts after laser irradiation and RTP. The as-deposited Ti/Al contact sample showed rectifying contact behavior over a range of voltages. However, the annealed sample showed linear *I-V* behavior, indicating that good ohmic contacts were formed on the *n*-GaN layers. Improved ohmic characteristics were observed with laser annealing energy. Interfacial reactions tend to form N vacancies, resulting in increased tunneling current across the GaN/metal interface, creating good ohmic contacts.

For p-contact on GaN, SIMS revealed interdiffusion of Cr and Au atoms occurring in GaN during RTP [Fig. 6]. The grain boundaries between Au atoms served as quick diffusion channels for out-diffusion of Cr atoms to the surface. Cr diffused to react with GaN. Au could also diffuse into the Cr layer, where it forms an unstable Ga–Au phase, which further deteriorates the adhesion of the contact on the GaN surface, thereby causing degradation in electrical characteristics. In fig. 7, XRD was employed to identify the phase formed by interfacial reactions of Cr/Au contacts. A dip in Cr peak is identified in the RTP sample. This is probably due to the consumption of Cr to form Cr-N or Cr_2O_3, as a result of Cr outdiffusion to the surface.

Reflectivity and transmissivity properties of the spreading contact on p-GaN contact are further evaluated in Fig. 8 and 9. The reflectance of RTP annealed Cr/Au contact was higher than laser annealed contacts. This is possibly due to oxidation at the contact surface, resulting in contact discontinuities and increased reflectivity. The transmission properties of laser annealed CrO-Au at 120 mJ cm^{-2} was comparable to RTP in the 475nm to 510nm blue-green light emission region. They both achieved ~80% transmissivity at a wavelength of 470 to 510nm. The annealed p contact exhibits excellent ohmic characteristic as shown in Fig 10. Fig 10 inset reveals observes reduced contact sheet resistance from 0.45 ohms per square to 0.15 ohms per square with increasing laser energy. Reduction in contact resistance was quantified using the linear transmission line method (TLM). The specific contact resistance was then determined from plots of the measured resistance versus the spacing between the TLM contacts as shown in Fig 11. The specific contact resistance measured was 3.2×10^{-4} Ω cm² and 3.6×10^{-3} Ω cm² for laser annealed and RTP contacts respectively.Lower contact resistivity is attributed to minimal reaction of GaN with Cr/Au during the short duration irradiation and laser annealing could also increase the hole concentration of p-GaN, leading to a decrease in contact resistivity.

Bright green emission was clearly observed from LEDs at a wavelength of 510nm, with an injection current of 50mA [Fig. 12]. Fig. 12 shows the room temperature EL spectra taken from the green LED with increasing injection current. The light output from both LEDs increase linearly with injection current.

CONCLUSION

Electrical properties of metal contacts on laser irradiated n and p type GaN were investigated. Laser annealed LEDs show a higher EL intensity as compared to a similar device that has undergone RTP. Contact formation on GaN using pulsed laser irradiation could be timely to meet the demands for reliable ohmic contacts in the integration of III-V semiconductors for future device applications.

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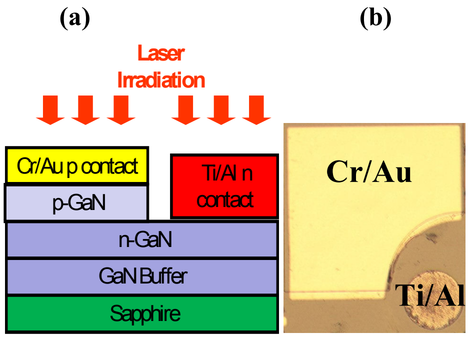

Fig.1.(a) Cross section of LED after mesa definition. (b) Optical micrograph shows contacts on LED after laser annealing. The contact is smooth and stable, with no signs of morphology degradation after laser annealing.

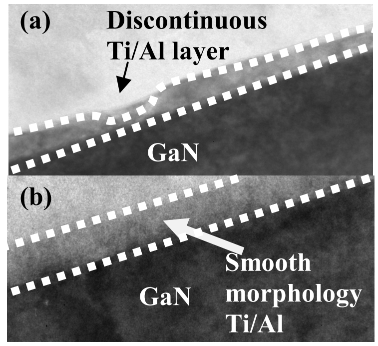

Fig. 2. (a) Disordered Ti/Al and contact interface roughening formed during RTP compared to laser annealing (b). Interfaces remain clearly defined after laser annealing. For RTP contacts, inclusions penetrating through GaN layer were seen.

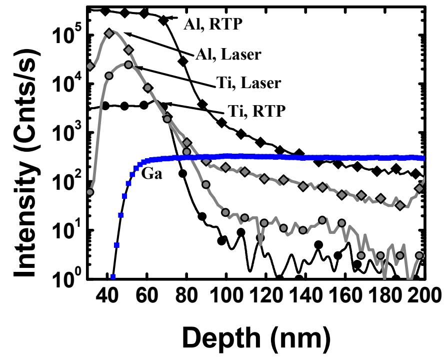

Fig. 3. Depth profiles of Al and Ti contacts on GaN when RTP at 880°C, 30sec and laser annealed at 520mJ cm^{-2}. Significant intermetallic diffusion occurring at Ti/Al interface after RTP is the possible cause of contact degradation.

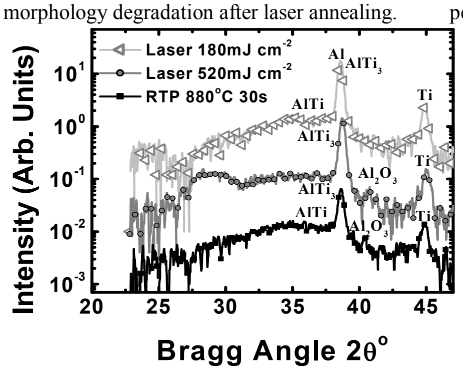

Fig. 4. XRD scans of laser annealed and RTP Ti/Al contacts. Laser annealing at 520mJ cm^{-2} was essential to react Al and Ti to form low resistive Al_3Ti phases for contact resistance reduction.

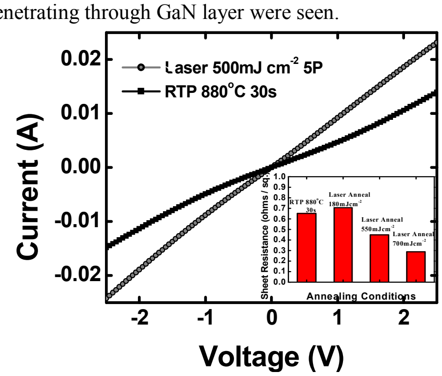

Fig. 5. *I-V* characteristics of Ti/Al contacts after (a) RTP and (b) laser annealing. The slope is steeper with laser annealing, indicating excellent ohmic properties achieved in Ti/Al n-contact.

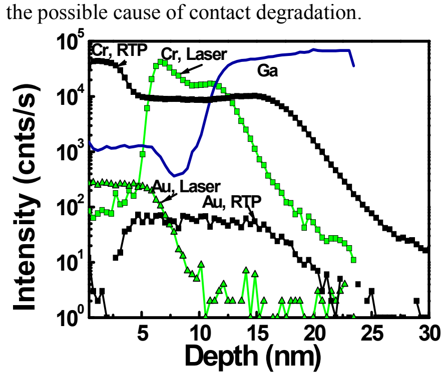

Fig. 6. Profiles of elemental concentration versus depth from the surface of the Cr/Au contact after undergoing rapid thermal anneal at 575°C, 60sec and laser annealing at 120mJ cm^{-2}.

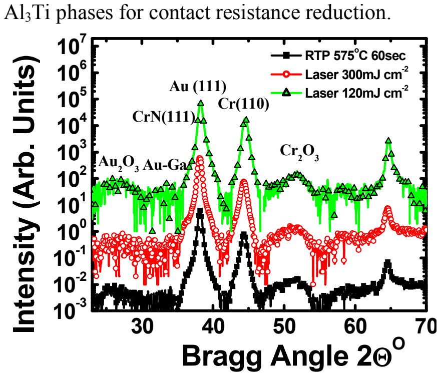

Fig. 7 XRD shows Au-Cr, Au-Ga solid solution due to elemental mixing during RTP.Au peak is higher than Cr, suggesting Cr reactions at surface with oxygen or penetrating into GaN.

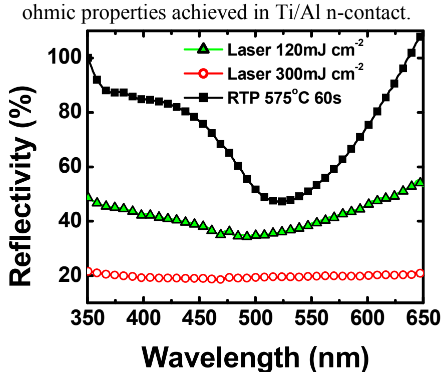

Fig. 8. Plot of reflectivity versus wavelength for laser annealed and RTP current spreading contacts. In the blue-green LED emission wavelength, increased reflectance is observed with RTP.

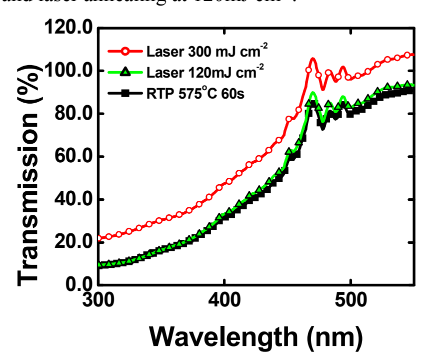

Fig. 9. Tranmissivity versus wavelength for laser annealed and RTP sample suggests excellent transmission properties in the blue-green LED emission after laser annealing.

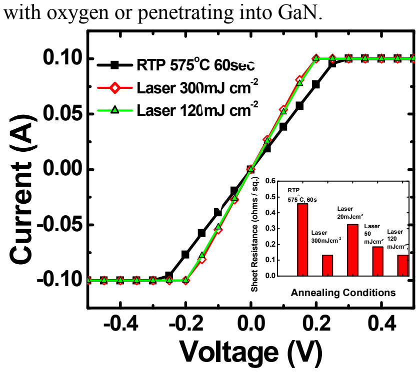

Fig. 10. Comparison of *I-V* characteristics of Cr/Au contacts after (a) RTP and (b) laser annealing. Inset suggests improved sheet resistance and contact properties can be obtained with laser annealing at 120mJ cm^{-2} for p contact.

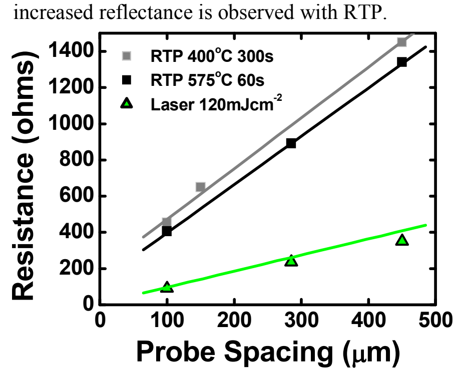

Fig. 11. Plot of resistance versus probe spacing for RTP and laser annealed Cr/Au contacts.Reduced contact resistivity can be achieved with laser annealing, suggesting that a surface conducting layer with a higher doping level of Mg can be formed after laser irradiation.

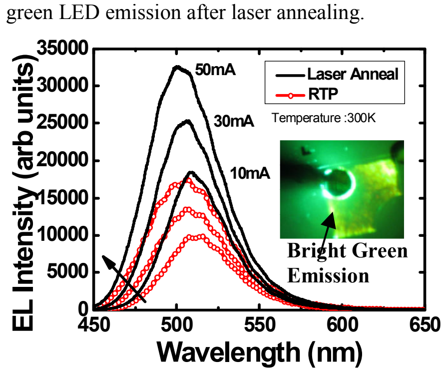

Fig. 12. 2 times improvement in EL intensity with laser annealing. Photographic images at injection current of 50 mA show bright green emissions. Red shift in the EL peak comparing RTP with laser annealed contact is attributed to slightly improved Mg activation in p-GaN.