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Reduced Contact Resistance and Improved Surface Morphology of Ohmic Contacts on GaN Employing KrF Laser Irradiation

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We employ excimer laser annealing for ohmic contact formation to n- and p-type GaN layers grown on sapphire substrates. The laser irradiation of the n-GaN layers led to increased nitrogen vacancies at the nitride surface, which promoted tunneling currents with a less resistive n-contact. For p-GaN layer, the laser irradiation increased the effective hole concentration that resulted in a reduced contact resistivity. The lowest specific contact resistance measured using the transmission line method was about 2.4×10^{-7} and $3.2 \times 10^{-4}\ \Omega\,\mathrm{cm}^2$ for n- and p-contacts, respectively. Laser irradiation also resulted in a comparatively good surface morphology as compared to rapid thermal annealing, which in turn improved the transmittance of contacts for light extraction from active layers. It was found out that both the electrical and optical characteristics of the p-GaN contacts exhibited a good thermal stability and an improved transmittance in the blue–green spectral range. An increased forward current with a reduced ohmic contact resistance in such high thermal stable contacts enable the fabrication of GaN light emitting diodes.

1. Introduction

Forming low resistance thermally stable and uniform ohmic contacts to wide band gap semiconductors such as gallium nitride (GaN) and related materials are desirable for high performance levels in photonic and electronic device applications. Despite significant progress being made in the growth and processing technology of light emitting diodes (LEDs), several technical obstacles remain to be solved to improve the electrical efficiency of devices. Among these are the p-type doping of GaN and AlGaN, and the ohmic contacts to such nitride layers. Excimer laser irradiation has been exploited for the fabrication process of GaN based devices including LEDs, laser diodes, and high power transistors due to the advantage of short duration and selective area processes.[1)] Numerous studies have shown that the structural, optical and electrical characteristics of GaN films were not severely degraded by the laser irradiation.[2,3)] Laser annealing enables the achievement of excellent interfacial characteristics between the metal contacts and GaN surface, and can lead to a reduction in contact resistance due to increased hole concentration in p-GaN.[1,4)] High contact resistivity usually results in high operation voltage and increases the LED junction temperature, eventually leading to degradation of nitride devices.

Laser annealing is a promising technique to achieve a low contact resistivity in both n- and p-contacts. The irradiation of a laser pulse with high energy density and low wavelength onto GaN leads to the thermal decomposition of GaN into metallic Ga and nitrogen gas.[5)] The decomposed metallic Ga can form a Ga oxide layer with oxygen in the air ambient. The residual Ga can be removed chemically, thus, metal contacts can be formed on the clean surface of the laser-irradiated GaN films. This is highly desirable in contacts formation, as the presence of insulating native oxides at the metal/semiconductor interface often results in poor interfacial contact and lead to an increase of effective Schottky barrier height for the carrier transport from metal to semiconductor.[6,7)] This limits the overall performance of photonic devices. In this context, laser annealing can be applied on p-GaN surface to achieve higher levels of device performances and it is desirable to probe the properties of such laser irradiated contacts in GaN.

In this paper, we report on the demonstration of metal contacts formed by excimer laser annealing for LED applications. The change of contact resistivity with laser irradiation was examined for ohmic contacts on both n- and p-type GaN. In particular, we have employed Ti (35 nm)/Al (150 nm) for n-contact formation and Cr (5 nm)/Au (5 nm) current spreading layer for p-contact. For metal contacts on n-type GaN, the laser irradiation leads to a decreased Schottky barrier heights and contact resistivities due to the generation of nitrogen vacancies.[1)] Although in p-type GaN, nitrogen vacancies produced by the laser irradiation could compensate the p-type doping in the near surface region, however, with optimized laser annealing conditions, we could increase the hole concentration of p-type GaN, thus, leading to a decrease in contact resistivity. In order to explore the effects of laser irradiation on the surface chemistry of GaN, transmission electron microscopy (TEM), time-of-flight secondary ion-mass spectrometry (ToF-SIMS), and X-ray diffraction (XRD) techniques were employed. The influence of laser irradiation and rapid thermal processing (RTP) on the metal contacts and its impact on LED performance will be further discussed.

2. Laser Irradiation Experiment

The film quality of contact and metal–GaN interfaces after laser irradiation depends on its initial thickness, the laser-pulse energy density and the number of pulses irradiated. Under appropriate laser conditions, laser irradiation treatment could improve the film quality and surface state of the GaN material.[8)] It is known that excimer laser irradiation on GaN surface could induce the interdiffusion of surface atoms and yield surface recrystallization.[9)] At a lower energy density of 250 mJ/cm^2, only the surface melts and metallic intermixing occurs. The laser irradiation induced atomic diffusion was expected to induce intermixing between metal contact and GaN, eliminate structural defects such as vacancies and misfit dislocations or threading dislocations.

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As a result, laser irradiation treatment under appropriate conditions could reduce the number of nonradiative recombination centers[9] and improve the overall crystalline film quality. It is known that a laser pulse with high energy density could lead to thermal decomposition of GaN into metallic Ga and nitrogen gas.[5] In the high energy density range, (600 mJ/cm^2), whole GaN layers may be melted and total surface damage was observed. An incident laser fluence of 600 mJ/cm^2 is also known to correspond to the threshold fluence incident through the sapphire substrate for laser liftoff of GaN.[10]

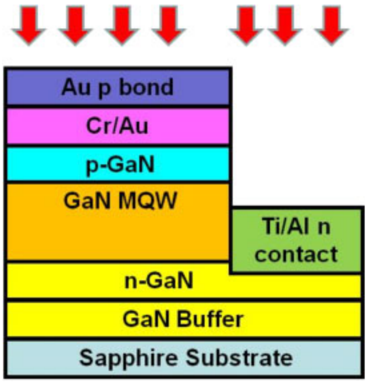
Excimer laser irradiation ($\lambda = 248$ nm; full width at half maximum of the pulse = 23 ns) at room temperature was carried out under continuous purified N_2 purging on the metal layers. Laser annealing using multiple pulses (1, 2, 5, and 10 pulses at an optimal fluence of 0.45 J cm^{-2}) and various fluences (0.12 to 0.5 J cm^{-2}) were performed to study the effect of repeated irradiation on contact formation on GaN.

3. Contact Processing

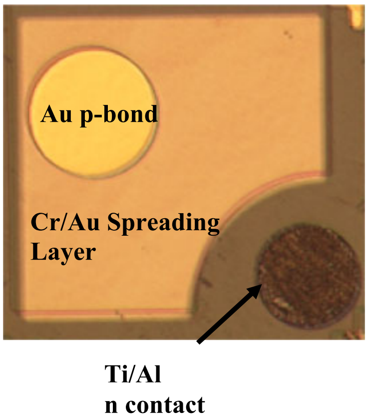
In the present study, a standard InGaN/GaN LED structure is grown epitaxially on the *c*-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD) technique. The mesa structures were patterned using reactive ion etcing (RIE) using BCl_3/Cl_2 at 6 °C. Figure 1(a) is a schematic illustration of the GaN layers on sapphire substrate, after mesa definition. The mesas were approximately 500 nm deep and were used to prevent current crowding as well as to isolate contact pads. Figure 1(a) details a cross section illustration of the GaN layers after mesa isolation. After patterning and definition of the p-GaN surface, fabrication of LEDs was carried out with the metallic contacts.

Prior to deposition of the metal films, all the samples were exposed to Ar plasma for 60 s in the RIE chamber. Then Ti (35 nm)/Al (150 nm) structures were deposited by electron beam evaporation. The samples were then laser annealed in N_2 ambient. Transparent p-contact electrodes Cr (5 nm)/Au (5 nm) were then deposited by electron beam evaporation. The Au (200 nm) p bond was then defined by lithography to contact the p-contacts and reduce the contact resistance and enable p-electrode probing. As a first demonstration in examining the impact of laser annealing in enabling an enhancement in hole injection current, various laser annealing conditions were explored. Single and multiple laser pulses at various laser excitation energies in the range of 20 to 500 mJ cm^{-2} are considered. Below 380 mJ cm^{-2}, the laser energy could not sufficiently achieve p-ohmic characteristic in the p-contact. Hence, RTP at 575 °C for 30 s was further employed to obtain an ohmic characteristic in the electrode.

Laser irradiation using single and multiple pulses at various laser fluences in the range of 0.12 to 0.5 J cm^{-2} was carried out to study the effects of repeated irradiation on Ti/Al for n-contacts and Cr/Au for p-contacts on GaN. Figure 1(b) is an optical micrograph of a typical LED after laser annealing of both n- and p-contacts. Figure 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. Surface roughness and decomposition during RTP results in poor performance and reliability of the contacts formed, due to the nonuniform current flow at the damaged interface.



(a)



(b)

Fig. 1. (Color online) (a) A schematic of cross section of GaN based LED structure grown on sapphire substrate. Ti/Al multi layer was deposited onto the n-GaN surface as the exposed n-type GaN layer by e-beam evaporation and lift-off process. Semitransparent p-type contact layers were then deposited, consisting of 5 nm Cr and 5 nm Au. This is followed by 200 nm Au p bond formation. (b) Optical micrograph shows n- and p-contacts formed on LED after laser annealing. The contact is smooth and stable, with no signs of morphology degradation after laser annealing, this indicates the thermal stabilities of the contacts to laser annealing.

4. Results and Discussion

Figure 3 shows SIMS profiles of Ti/Al on GaN after RTP and laser annealing at an optimal laser fluence of 0.5 J cm^{-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. Furthermore, the Rutherford back scattering (RBS) spectra from RTP-treated samples show increased Ti and Al thickness with a diordered interface between Ti and GaN. Comparing rapid thermal annealed Ti/Al contacts and laser annealed contacts, laser annealing maintained a Ti-richer Ti/Al contact. This improved the overall conductivity of the contact formed, and showed an improved electrical performance.

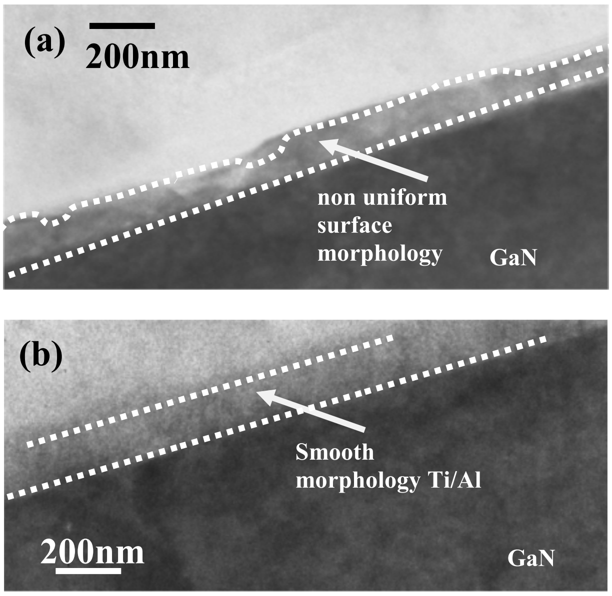


Fig. 2. Bright field cross-sectional TEM images obtained from the top region of the contact/LED interface shows (a) disordered Ti/Al and contact interface roughening formed during RTP compared to laser annealing (b). Interfaces remain clearly defined after laser annealing. For RTP contacts, non-uniform evolutions of discrete array of Cr penetrating through GaN layer were seen.

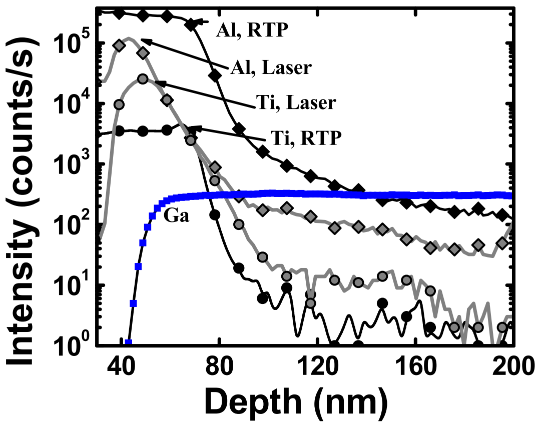


Fig. 3. (Color online) SIMS depth profiles of Al and Ti contacts formed on GaN comparing annealing with RTP at 880 °C, 30 s and laser annealing at 520 mJ cm^{-2}. As-deposited Al-Ti on GaN was used as reference sample for SIMS. The interdiffusion of gallium, titanium and aluminium becomes apparent when the sample undergoes RTP. For the laser annealed sample, the metallic contacts remain in their as-deposited state, with less observable diffusion. Significant intermetallic diffusion occurs at Ti/Al to GaN interface. This could be the main cause that leads to contacts with poorer ohmic characteristics.

Prior work performed on Ti/Al showed that the reaction products formed following laser annealing could be affected strongly by the relative amounts of Ti and Al.[11,12] Since Ti (002) has $2\theta = 38.422°$, while Al(111) has $2\theta = 38.473°$, they have very close diffraction angles and thus form a wide peak at $2\theta \sim 38°$. Laser annealing at 500 mJ cm^{-2} was essential to react Al and Ti to form low resistive Al_3Ti and other intermetallic phases for contact resistance reduction. (Al_3Ti $2\theta = 39.252°$) Kinetic considerations and XRD spectra shown in Fig. 4 suggest that the Ti and Al will

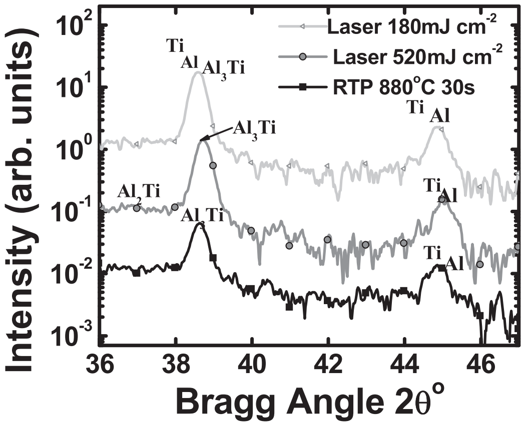


Fig. 4. Glancing angle irradiation XRD spectra of laser annealed and RTP annealed Ti/Al contacts. Since Ti(002) has $2\theta = 38.422°$, while Al(111) has $2\theta = 38.473°$, they have very close diffraction angles and thus form a wide peak at $2\theta \sim 38°$. Laser annealing at 520 mJ cm^{-2} was essential to react Al and Ti to form low resistive Al_3Ti and other intermetallic phases for contact resistance reduction. Al_3Ti has $2\theta = 39.252°$.

react to form Al_3Ti before possible reaction with Ga occurs, since diffusion in the metal is several orders of magnitude greater than that in GaN. Other studies have revealed that Al_3Ti is the primary phase formed in the contact metallization following laser annealing.[13] Any excess Ti in the Ti/Al multilayer was reasonably assumed to be located at the metal semiconductor interface following the formation of Al_3Ti phase. This Ti could later react with GaN to form a complex $Ti_{1-x}Ga_xN$ alloy which could affect the electrical properties of the contact. The XRD spectrum shows that RTP consumes Al and results in a dip in the Al peak. Al forms low resistive phases during the reaction with Ti, and this explains the reduction in contact resistance after annealing. The sample laser annealed at 0.5 J cm^{-2} contains the largest amount of Al and Al_3Ti and had the lowest resistance.

Figure 5 shows the current–voltage (I–V) characteristics for Ti/Al contacts after laser irradiation and RTP. The elemental thickness ratio of Ti and Al affects the metallurgical and electrical properties. The as-deposited Ti/Al contact sample showed rectifying contact behavior over a range of voltages. It is believed that a proper reaction interface is critical to achieving a successful ohmic contact. The annealed sample showed linear I–V behavior, indicating that good ohmic contacts were formed on the n-GaN layers. Interfacial reactions tend to form nitrogen vacancies through the preferential loss of nitrogen atoms, resulting in increased tunneling current across the GaN/metal interface, creating good ohmic contacts. Carrier concentrations were further deduced from the samples. It is noteworthy that the bulk electron concentration of the n-type GaN increased by laser irradiation, as compared to RTP. The carrier concentration, deduced by Hall measurements, in laser irradiated n type GaN was $\sim 6.4 \times 10^{18}$ cm^{-3}, while that in RTP sample was $\sim 9.4 \times 10^{17}$ cm^{-3}. Improved ohmic characteristics were observed with increasing laser annealing energy. The Ti/Al contacts did not become ohmic until the laser annealing energy reached at least 500 mJ cm^{-2}. The XRD data showed that the Al_3Ti phase did not form to any great extent until the Ti/Al multilayer was laser-annealed at 520 mJ cm^{-2}. These

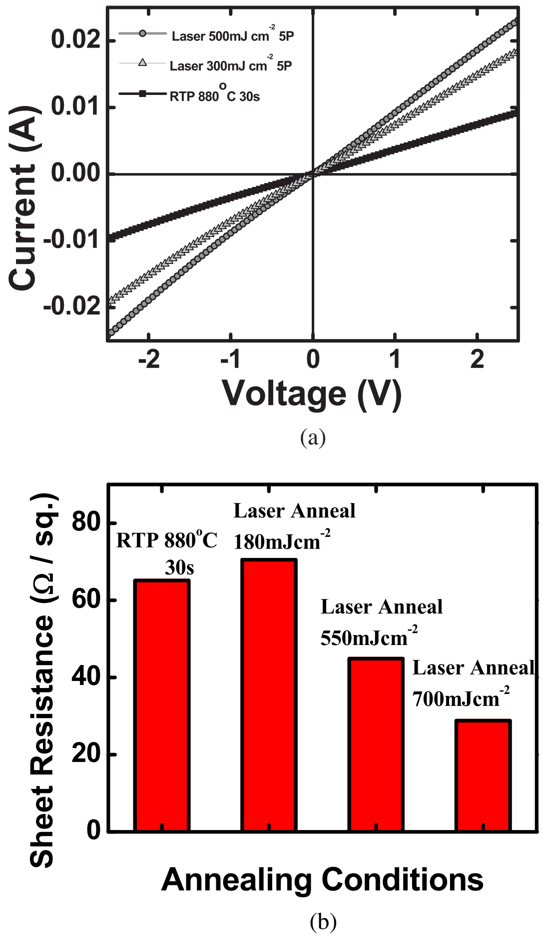


Fig. 5. (Color online) (a) *I–V* characteristics of Ti/Al contacts after RTP and laser annealing. The slope is steeper with laser annealing at enhanced laser energies, indicating excellent ohmic properties achieved in Ti/Al n-contact. (b) A comparison of sheet resistance further indicates laser annealing of Ti/Al contact at 520 mJ cm^{-2} would sufficiently achieve a low sheet resistance for LED n contact fabrication.

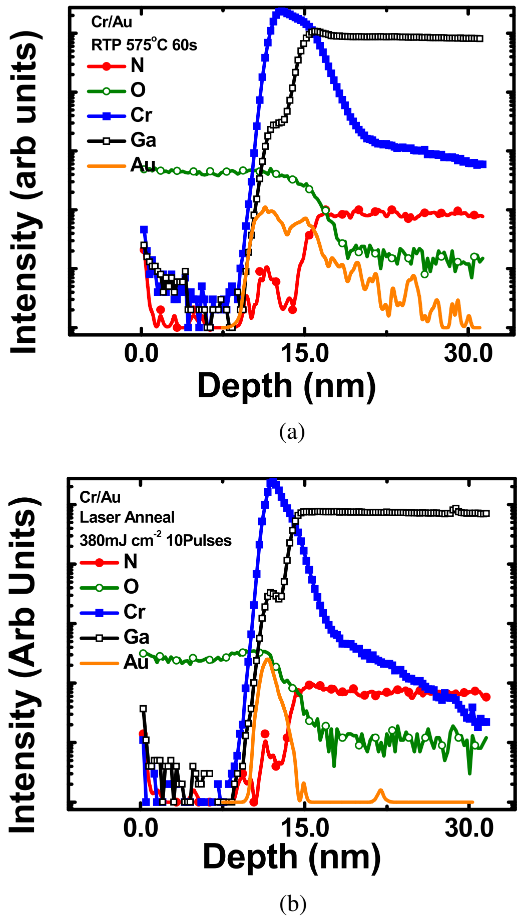


Fig. 6. (Color online) SIMs profiles of elemental concentration versus depth from the surface of the Cr/Au contact after undergoing (a) rapid thermal process at 575 °C, 60 s and (b) laser annealing at 120 mJ cm^{-2}. As-deposited Cr–Au on GaN was used as reference sample for SIMS. Microstructural change of the Cr/Au contact observes the original interface of the Cr–Au on GaN was abrupt after laser annealing. Whereas, RTP caused layer thickening of the Cr and Au and suggested that Au diffused through the grain boundaries and reacted with Cr. Similarly Ga atoms outdiffused from GaN and dissolved in the Au–Cr solid solution.

results suggest that the formation of the Al_3Ti phase is somehow critical to the ohmic behavior of the Ti/Al contact on GaN.

For p-contact on GaN, the SIMS data revealed significant interdiffusion of Cr and Au atoms occurring in GaN during RTP [Fig. 6(a)]. In the as-deposited state, the original interface of Cr/Au contact on p-type GaN was abrupt and a number of grain boundaries existed due to the lattice mismatch between Cr and GaN. When Cr/Au was annealed using RTP, interdiffusion between the Au and Cr layer takes place. The grain boundaries between Au atoms probably served as quick diffusion channels for out-diffusion of Cr atoms to the surface. Cr diffused to react with GaN. In addition, Au atoms diffuse to GaN to react with both Cr and GaN substrate. Au could also diffuse beyond 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. RTP caused layer thickening of the Cr and Au [Fig. 6(a)] and suggested interatomic movements through the grain boundaries. Formation of Cr–Au solid solution at the grain boundary of Cr film resulted in the evolution of discrete array of Cr, resulting in the non-uniform surface morphology after RTP. However, laser annealing [Fig. 6(b)] avoided the discrete Cr formation due to the lower penetration depth of the laser in inducing the morphological changes.

The annealed p-contact further exhibits excellent ohmic characteristic as shown in Fig. 7. We observed a reduced contact sheet resistance from 18 to 5 Ω/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 the plots of the measured resistance versus the spacing between contacts. The specific contact resistance measured was 3.2×10^{-4} and 3.6×10^{-3} Ω cm^2 for laser annealed and RTP contacts respectively. Based on prior work on the activation of Mg or Be dopants in p-type GaN, it was suggested that the laser irradiated p-type GaN could have a higher activation efficiency.[1] The hole concentration of the p-type GaN was found to be $\sim 7.8 \times 10^{17}$ cm^{-3} from Hall Measurements while that of the RTP sample was $\sim 1.9 \times 10^{17}$ cm^{-3}. It was found that acceptor concentration was increased after laser irradiation and this was consistent with our understanding that laser irradiation could lead to a higher activation efficiency of Mg dopants in GaN.

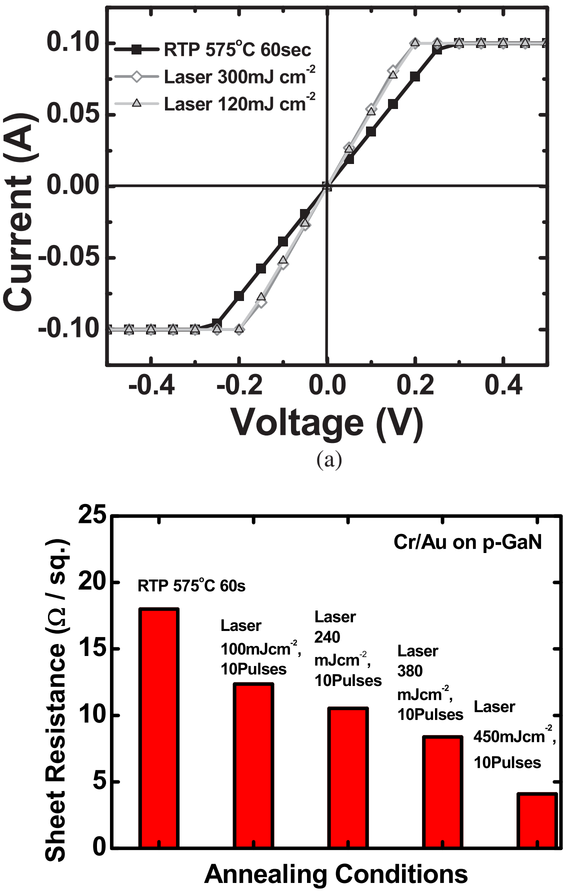


Fig. 7. (Color online) (a) Comparison of *I–V* characteristics of Cr/Au contacts after RTP and laser annealing. TLM patterns were measured on metallic contacts deposited on p-GaN and not on the LED devices. (b) Variation of ohmic contact sheet resistance with annealing conditions suggests improved sheet resistance and contact properties, which can be obtained from laser annealing at 450 mJ cm^{-2} for p-contact.

Lower contact resistivity observed here, could be 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. One possible reason suggested was the removal of hydrogen atoms from Mg–H bonds by the formation of H_2O at the GaN surface.[1] As the reactivity of hydrogen to oxygen was higher than to Mg or Be, hydrogen in the p-type GaN could react with oxygen from the air ambient and surface Ga oxide layer. Another reason proposed was the laser annealing, which was rapid enough to make the Mg–H bond unstable, helping Mg atoms to act as acceptors. Since the laser pulse width is a very short duration,[14] it was convincible that the increase in hole concentration of the p type GaN after laser irradiation could originate from the photo induced breaking of Mg–H bonds. However, in the case of RTP, when the Cr/Au contact on the p-type GaN was annealed, N vacancies predominantly existed at the surface region of the p-type GaN. This could decrease the hole concentration of the p-type GaN via the compensation of holes with electrons generated from the N vacancies. As a result, the barrier for hole injection from metal to p-type GaN increased, resulting in increase of contact resistivity due to decrease of net concentration of

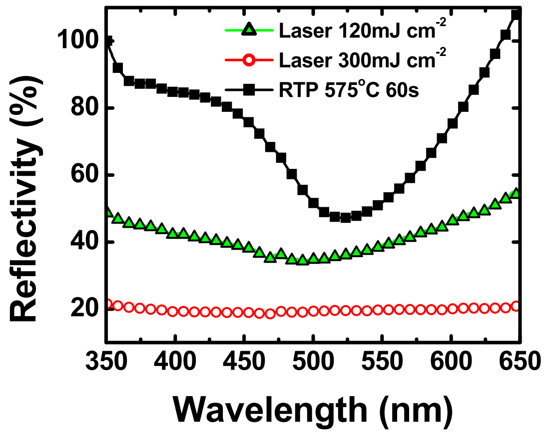


Fig. 8. (Color online) Plot of reflectivity versus wavelength for laser annealed and RTP current spreading p-contacts. In the green LED emission wavelength at 510 nm, the increased reflectance is observed with RTP. Contact discontinuity and morphological transformations could be attributable to the increased reflectance characteristics observed with RTP.

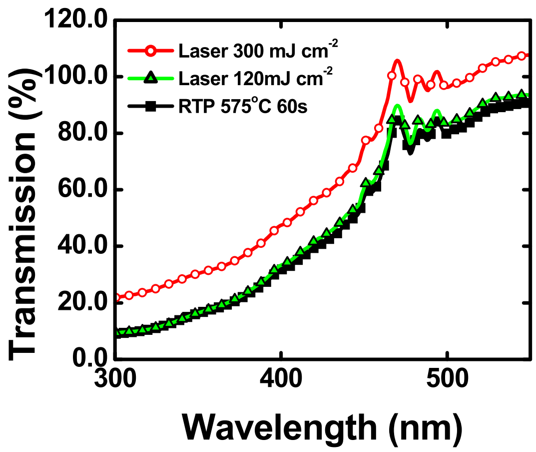


Fig. 9. (Color online) Normalized transparency spectra for laser-annealed and RTP Cr–Au contacts suggesting comparable transmission properties in the green LED emission after RTP or laser irradiation. The average transparency was ~80% within the green light spectral range. Thermal annealing by RTP results in slight degradation in the transparency of the film which may be related to metallic oxidations and interdiffusion. Oxidized contact could have resulted in the overall drop in transmittance. In addition, metal layers thickening, observed in SIMS, could lead to light transmission reduction.

holes, and this increased the effective Schottky barrier height. As a result, a lower ohmic contact resistivity could be obtained in the laser irradiated sample.

Reflectivity and transmissivity properties of the current spreading contact on p-GaN are further evaluated in Figs. 8 and 9. The reflectivity 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 510 nm green light emission region. They both achieved ~80% transmissivity at a wavelength of 510 nm. Bright green emission was clearly observed from LEDs at a wavelength of 510 nm, with an

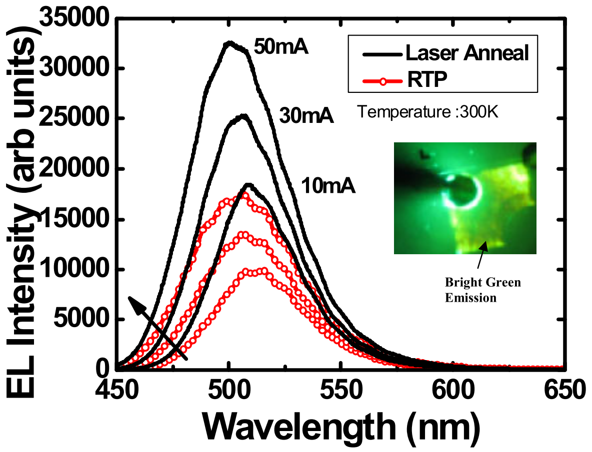


Fig. 10. (Color online) EL spectra of LEDs taken at room temperature. About two-fold improvement in EL intensity with laser annealing is seen in our study. Photographic images at injection current of 50 mA show bright green emissions. A small red shift in the EL peak in RTP-treated compared to laser-annealed contact is attributed to slightly improved Mg activation in p-GaN.

injection current of 50 mA (Fig. 10). Figure 10 shows the room-temperature electroluminescence (EL) spectra taken from the green LED with increasing injection currents. The light output was detected by using a photodiode placed in close vicinity to the device top. The electroluminescence intensity from both LEDs increase linearly with injection current as evident from integrated EL intensity. The EL spectra of the LEDs with laser-annealed contacts show enhanced light emission as compared to LED chips with contacts processed by RTP.

5. Conclusions

Electrical properties of metal contacts formed using laser irradiation were investigated. A KrF excimer laser pulse onto Ti/Al n-GaN and Cr/Au p-GaN led to the formation of ohmic contact with reduced contact resistivity. The metallic Ga decomposed from GaN by the laser irradiation and was transformed into Ga oxide, playing a role in promoting outdiffusion of N atoms. N vacancies were produced, resulting in good ohmic contact. For p-type GaN, the laser irradiation increased the Mg acceptor concentration and activation efficiency of dopants via Mg–H dissociation during the short duration nanosecond laser pulse. This resulted in reduction in contact resistivity of the oxidized Cr/Au contact. The lowest specific contact resistance measured using the transmission line method was 2.4×10^{-7} and $3.2 \times 10^{-4}\,\Omega\,\mathrm{cm}^2$ for n- and p-contacts, respectively. Contact formation on GaN using pulsed laser irradiation could meet the demands for reliable ohmic contacts in the integration of III–V semiconductors for future device applications.

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