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GaN based Light Emitting Diode with Enhanced Optical Output and Improved Luminescence by employing Excimer Laser Irradiation in contact formation

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ABSTRACT

We report on the fabrication of laser annealed p contact on p-GaN surface for enhanced light extraction from light emitting diodes (LEDs). At an optimal laser fluence (120mJ cm^{-2}), laser irradiation increased the effective acceptor concentration in GaN, improved the activation efficiency of Mg dopants and increased the hole concentration. This resulted in lower contact resistivity and increased hole injection efficiency, leading to a lower turn on voltage (V_T) for the LEDs. In addition, improved output power and quantum efficiency were achieved. The light output from the LEDs with laser annealed p contacts shows ~2.3 times higher electroluminescence (EL) intensity at an injection current I_{inj} of 50 mA in the 470nm blue light region. In addition, at a fixed bias of 5V, the LED's,with laser annealed contact, compared to RTA, improved I_{inj} from 25.4mA to 71.9mA.

INTRODUCTION

GaN based light emitting diodes (LEDs) have attracted significant attention for use in solid state lighting[1]. The high efficiency of LEDs has provided substantial energy savings and environmental benefits in a number of applications[2]. A thermally stable and highly transparent low resistivity electrode is important for the fabrication of high brightness GaN based LED. The conventional p-type multilayer metal contact formed by rapid thermal annealing (RTA) induces thermal damage such as GaN decomposition, interfacial discontinuity leading to spiky interfaces within the LED structures, which often results in higher contact resistivity. In addition, low doping levels of p-GaN further create difficulties in achieving a good ohmic electrical characteristic important to device performance.

In this work, we present a new metallization scheme to reduce the contact resistance and enhance current injection into the LED for improved light extraction. We propose using excimer laser annealing to thermally anneal the Cr/Au contact formed on the p-GaN surface. Consequently, the resulting p-ohmic contact had improved light transmittance, thermal stability and surface morphology.

DEVICE FABRICATION

LED layers comprising AlGaN/GaN/InGaN were epitaxially grown on (111) substrates by a low pressure chemical vapor deposition system. Fig. 1(a) details a cross section illustration of the GaN layers after mesa definition. Fig. 1(b) shows an optical micrograph of a typical LED with an emission area of 300 by 300μm^2. Fig. 1(c) and (d) show the TEM micrographs of the Au/Cr/p-GaN interface after RTA and laser annealing respectively. Disordered interfacial metal alloy formed during RTA, possibly contributed to increased contact sheet resistance. Fig. 2 summarizes the key process steps adopted in the LED device fabrication. To examine the effectiveness of laser annealing in enhancing hole injection current I_{inj} and EL of GaN based LEDs, various laser annealing conditions were explored. Single and multiple pulses at various laser excitation energies in the range of 20 to 120 mJ cm^{-2} are considered. Following the fabrication, the processed LED devices were characterized and the current/voltage (*I-V*) plots from laser annealed and RTA contacts' were obtained. The EL spectra were also recorded from the fabricated devices to compare the light output intensities. Fig. 3 shows XRD rocking curve of the starting LEDs layers on bulk Si. The GaN (0002), AlN (0002), buffer AlGaN (0002) reflections,and the well defined superlattice fringes created by the InGaN/GaN MQWs are shown.

RESULTS AND DISCUSSION

Secondary ion mass spectroscopy (SIMS) depth profiles of Au/Cr/GaN contacts annealed using RTA and laser are obtained in Fig. 4. For the RTA contact, significant interdiffusion of atoms occurred. The long diffusion tails on Ga, Au and Cr are clear indicators about the dissolution of the atoms. It is conceivable that grain boundaries of Au film served as quick diffusion channels for out-diffusion of Cr atoms to the surface. 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 properties (increased resisitivity). In Fig. 5, rutherford backscattering (RBS) further confirms Cr segregation to the contact surface, outdiffusing after RTA. This is due to high reactivity of Cr with oxygen. Transmissivity of the p-GaN contacts were further evaluated. The transmission properties of laser annealed Cr-Au at 120 mJ cm^{-2} was slightly higher than RTA in the 470nm blue light region. They both achieved close to ~80% transmissivity at a λ of 470nm.

The annealed contacts exhibit good ohmic characteristic. Fig 7 inset compares and shows that multiple pulses of 120 mJ cm^{-2} laser irradiation reduced the specific contact resistivity to 9.72 × 10^{-5} ohm cm^2 as compared to contact formed by RTA (3.43 × 10^{-4} ohm cm^2). Reduction in contact resistance was quantified using the linear transmission line method. *I-V* characteristics of the LED devices with RTP and laser annealed contacts are shown in Fig.7. At a forward bias of 5V, I_{inj} improved from 25.4mA to 71.9mA when comparing RTA and laser annealing at 120 mJ cm^{-2}. It is further observed that laser annealing leads to a lower V_T. Fig.8 compares the effectiveness of various laser energies in p contacts formation. From the *I-V* characteristics, at a forward bias of 5V, I_{inj} improved with a higher laser annealing energy. A summary of I_{inj} at various annealing conditions is plotted in Fig. 9. Bright blue-green emission was clearly observed from LEDs at a wavelength of 470nm, at I_{inj} of 60mA[Fig. 10]. Fig. 11 shows the room temperature EL spectra taken from the blue LED with increasing I_{inj}. The laser annealed LEDs show smaller amount of EL peak blue shift from 478nm to 477nm as I_{inj} is increased from 10mA to 60mA as compared to RTA sample. The light outputs from both LEDs increase linearly with increase in injection current. EL peak position of RTA and laser annealed LEDs are 474.8nm and 477.3nm respectively. Red shift observed is due to changes in Mg concentration during annealing. Comparing a similar fabrication procedure on sapphire substrate [Fig. 12], bright green emission was observed at I_{inj} of 50mA.

CONCLUSION

In conclusion, a metallization scheme consisting laser annealed p contacts was developed for enhanced transmission and lower contact resistivity. LEDs with laser annealed contacts show improved EL intensity. Laser annealing brought about several advantages in contact formation over RTA: (i) reduction of native oxide on p-GaN, and (ii) formation of a more intimate contact between contact and p-GaN with improved dopant activation properties. The contact formation on GaN using a pulsed laser irradiation could be promising for the integration of III-V for future device applications.

REFERENCE

[1] E. F. Schubert and J. K. Kim, Science **308**, 1274 (2005).
[2] J.K Sheu *et al.*, *Applied Physics Letters*, vol. 88, 113505(2006).

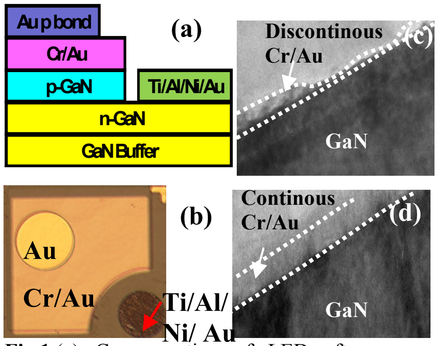

Fig.1.(a) Cross section of LED after mesa definition. (b) Optical micrograph showing completed LED device. (c) Disordered metal alloy and contact interface roughening formed during RTA compared to laser annealing (d)

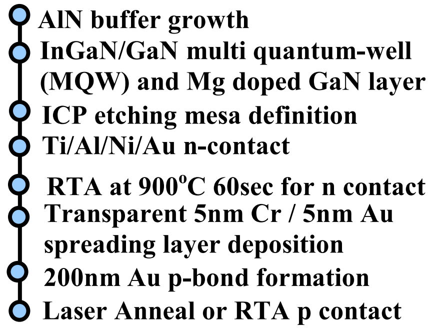

Fig. 2. Experimental procedure adopted for LED fabrication. The devices were fabricated using standard photolithography, dry etching and metal evaporation. Devices had Au as p-bond ,(5nm/5nm) Cr/Au spreading layer, and Ti/Al/Ni/Au n pad.

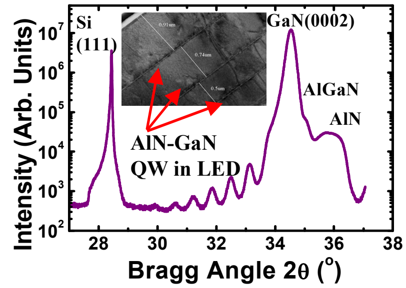

Fig. 3. HRXRD spectra of the LED structures grown on bulk Si(111). The superlattice fringes are clearly resolved and represent high-crystalline quality GaN material for LED fabrication. TEM in inset shows distinct interfaces in GaN/InGaN.

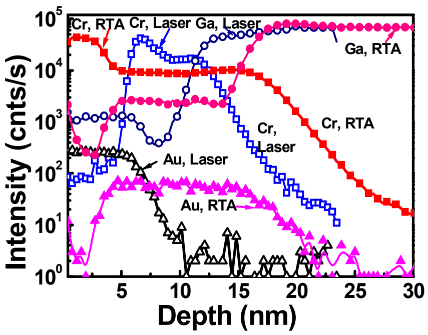

Fig. 4. Comparison of elemental depth profiles after undergoing RTA at 575°C, 60sec and laser annealing at 120mJ cm^{-2}. Au and Cr indiffusion and Cr and Ga out-diffusion were observed after RTA shown by the long diffusion tail

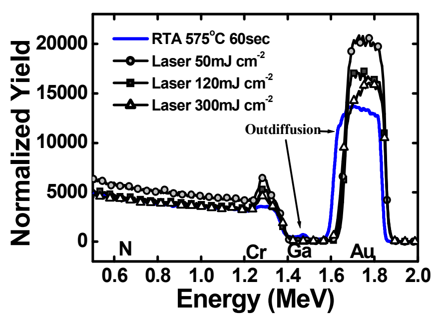

Fig. 5. RTP sample shows thickening of Cr/Au layer with Cr RBS yield reduced. This indicates observable Cr diffusion and spreading throughout the layers from low Cr yield. A good quality Cr remains after laser annealing at 50-300mJcm^{-2}.

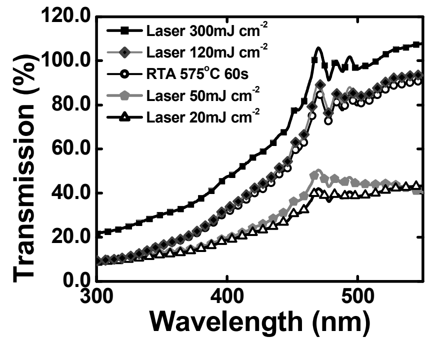

Fig. 6. Transmission spectra comparison for Au/Cr after laser annealing at various irradiation energies and RTA at 575°C, 60sec. At a wavelength of 470nm, improvement in transmissivity is observed at high laser fluences.

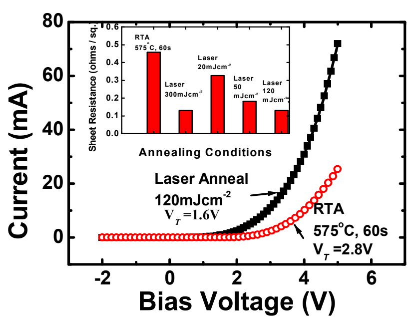

Fig. 7. *I-V* characteristics of the blue LED devices comparing RTA and laser annealing at optimized laser fluence. Inset compares sheet resistance of various metallization schemes.

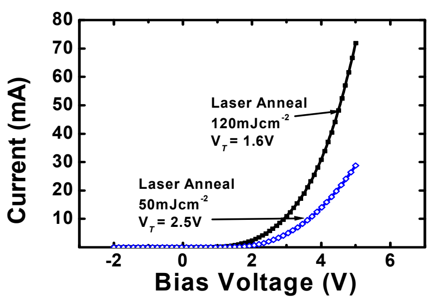

Fig. 8. *I-V* characteristics of LEDs comparing laser annealing at 50mJ $cm^{-2}$and 120mJ cm^{-2} .Improvement in V_T is observed with increasing laser energy. V_T is reduced from 2.5V to 1.8V.

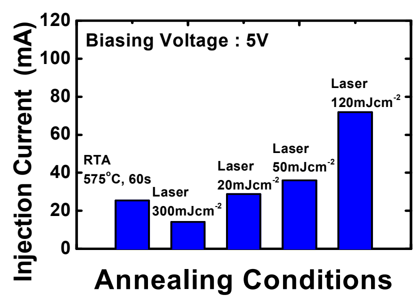

Fig. 9. Summary of I_{inj} at a forward bias of 5V under various annealing conditions. Improvement in I_{inj} from 25.4mA to 71.9mA is observed when laser annealing is employed at optimal fluence.

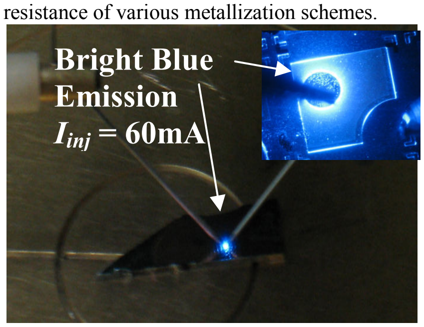

Fig. 10. Photographic images of the LEDs at injection current of 60 mA. Strong and bright blue light output is achieved due to the high transmittance of Cr-Au current spreading layer.

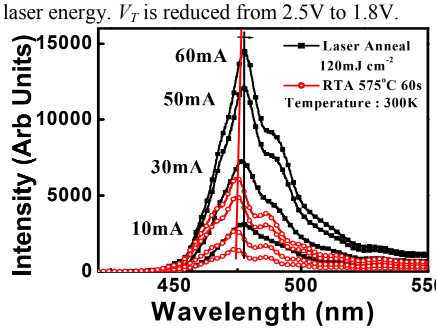

Fig. 11. With I_{inj} at 60mA, 2.3 times improvement in EL intensity and red shift in EL peak position is observed in LED with laser annealed contact. This is due to improved Mg activation with laser anneal.

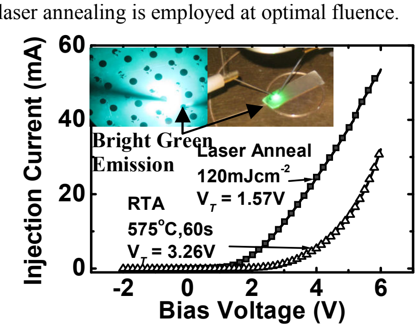

Fig. 12. *I-V* characteristics of the bright green LED devices on sapphire substrate. Improvement in I_{inj} is obtained with laser annealing. Bright green emission is shown at I_{inj} of 50mA.