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

Grace Huiqi Wang, T. Sudhiranjan, Ting Chong Wong, Xincai Wang, Hong Yu Zheng, Taw Kuei Chan, T. Osipowicz, and Yong Lim Foo.
Institute of Materials Research & Engineering, Agency for Science, Technology and Research, 3 Research Link, Singapore.
Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore.
Phone: +65 6514-1520, Fax: +65 6774-1042, Email: wanghq@imre.a-star.edu.sg

**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 (120µm 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 3.4 mAm to 3.9mAm.

**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 form unstable Ga–Au phase, which further deteriorates the adhesion of the contact on the GaN surface, thereby causing degradation in electrical properties (increased resistivity). In Fig. 5, rutherford backscattering (RBS) 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 was 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 \(\lambda\) of 470nm.

The annealed contacts exhibit good ohmic characteristic. Fig. 7 compares and shows that multiple pulses of 120 mJ cm\(^{-2}\) laser irradiation reduced the specific contact resistivity to 

\[9.72 \times 10^4\ \text{ohm cm}\]

compared to contact formed by RTA. 

\[3.43 \times 10^4\ \text{ohm cm}\]

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].

**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 resistivity). 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 was 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 \(\lambda\) of 470nm.

In conclusion, a metallization scheme consisting laser annealed p contacts was developed for enhanced transmission and lower contact resistivity. EL peaks from laser annealed contacts show higher 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**


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**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 formation 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 LED layers on bulk Si. The GaN (0002), AIN (0002), buffer AlGaN (0002) reflections, and the well defined superlattice fringes created by the InGaN/GaN MQWs are shown.
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 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 cm². 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 50-300mJ cm².

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 $V_I$ is observed with increasing laser energy. $V_I$ 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.