CONTACT RESISTANCE OF InGaN/GaN LIGHT EMITTING DIODES GROWN ON THE PRODUCTION MODEL MULTI-WAFER MOVPE REACTOR

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ABSTRACT

We report both the device fabrication and characterization of InGaN/GaN single quantum well LEDs grown on sapphire substrates using multi-wafer MOVPE reactor. To improve current spreading of the LEDs, a self-aligned process is developed to define LED mesa that is coated with a thin, semi-transparent Ni/Au (40 Å/40 Å) layer. A detailed study on the ohmic contact resistance of Ni/Cr/Au on *p*-GaN versus annealing temperatures is carried out on transmission line test structures. It was found that the annealing temperatures between 300 to 500 ^{o}C yield the lowest specific contact resistance r_c (0.016 Ω-cm^2 at a current density of 66.7 mA/cm). Based on the extracted r_c from the transmission line measurement, we estimate that the contact resistance of the *p*-type GaN accounts for ~ 88% of the total series resistance of the LED.

INTRODUCTION

The III-V nitride semiconductor materials system has become increasingly popular among the applications of UV/blue light emitting diodes (LEDs), laser diodes (LDs) and high-temperature electronic devices due to its large direct bandgap energy (3.4 eV for GaN at room temperature). Even though the potentials of III-V nitrides were well known for more than three decade, it was only until 1992 with the realization of Mg doped *p*-GaN film after the thermal annealing [1] could the realization of high brightness blue/green InGaN/GaN quantum well(s) LED [2] and the recent demonstrations of long-lifetime pulsed and CW blue LDs [3] be achieved. Despite the commercialization of LEDs, the low *p*-type doping concentration (and hence high *p*-type resistivity) in GaN still limits the device performance in two ways: first it reduces the current spreading in the LED. This causes most of the light to emit in the active region directly underneath the *p*-type contact, and is therefore blocked by the *p* contact. Secondly, low *p*-type doping results in a rather high and non-linear contact resistance. While the current spreading problem has been effectively resolved by depositing a thin semi-transparent metal layer on top of the *p*-GaN cap layer, high contact resistance is still a problem to be tackled. In the present work, we report the successful growth of single quantum well

InGaN/GaN LEDs on multi-wafer MOVPE reactor with high thickness uniformity and the development of a self-aligned LED fabrication process that incorporates a thin current spreading layer. We also present detailed studies on the variation of contact resistance r_c of Ni/Cr/Au on *p*-doped GaN layer versus annealing temperature.

EXPERIMENT

The InGaN/GaN LED samples were first grown on the Aixtron production model multi-wafer MOVPE reactor. The structures consist of 1.5 µm *n*-GaN layer, a thin InGaN quantum well (4-8 nm), and a 0.5 µm *p*-GaN cap layer, all grown on 2-inch (0001) sapphire substrates. The growth uses standard precursors including TMGa and TMIn for Group III and NH_3 for Group V elements, and silane and $MgCp_2$ are used for n-type and p-type dopant sources, respectively. The un-intentionally doped GaN is *n*-type with carrier concentration ~ 1-3x10^{17}/cm^3. The *p*-type GaN with hole concentration of ~5x10^{17}/cm^3 are routinely achieved after post-growth annealing. The thickness uniformity across the diameter of a 2-inch wafer was evaluated using spectral reflectometry measurement in the range of 670 to 1100 nm.

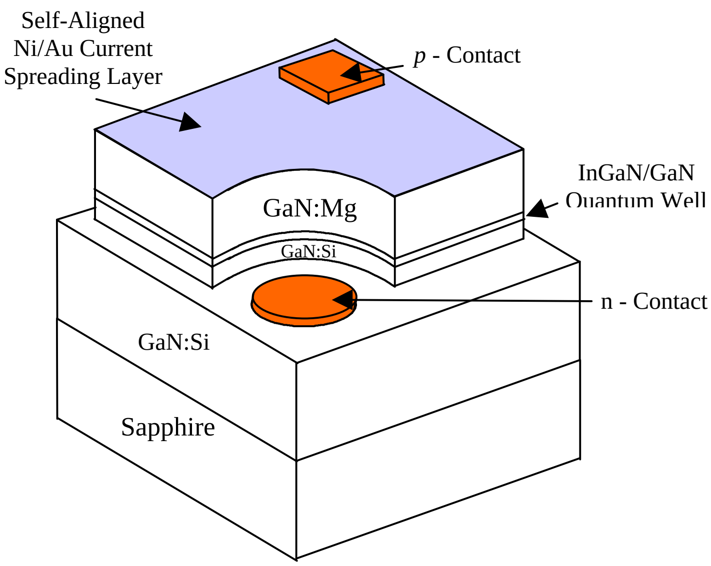

Fig. 1(a) The schematics of self-aligned InGaN/GaN LED structure. Note that a thin Ni/Au layer is deposited on top of the LED mesa to improve the current spreading.

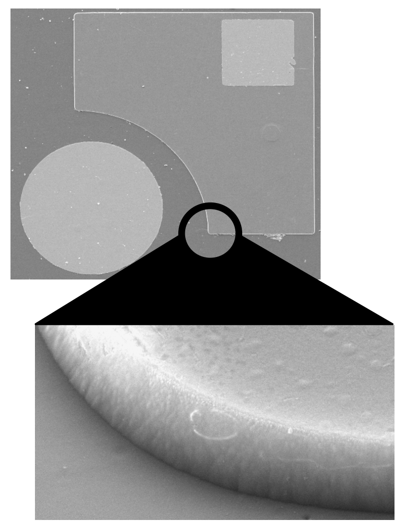

Fig. 1(b) SEM of a typical LED structure with a magnified view of the edges of mesa after RIE etching.

The process flow for fabricating a LED with a structure shown in **Fig. 1(a)**, is described as follows. First, a thin current spreading layer consists of Ni/Au (40 Å/40 Å) was deposited on the entire wafer using electron beam evaporation. The estimated optical absorption due to the current spreading layer is ~ 38% [4]. The sample is thermally annealed at 500^{o}C under N_2 ambient for 100 seconds. The LED mesa is then defined by a photoresist pattern. This is followed by ion milling to remove all except the current spreading layer, and Reactive Ion Etching (RIE) in a mixture of Cl_2 and BCl_3 to remove the GaN all the way to the *n*-layer. In this way, the current spreading layer and the mesa are formed in a self-aligned way. **Figure 1(b)** shows the SEM micrographs of the RIE etched surface around the LED mesa. Both the

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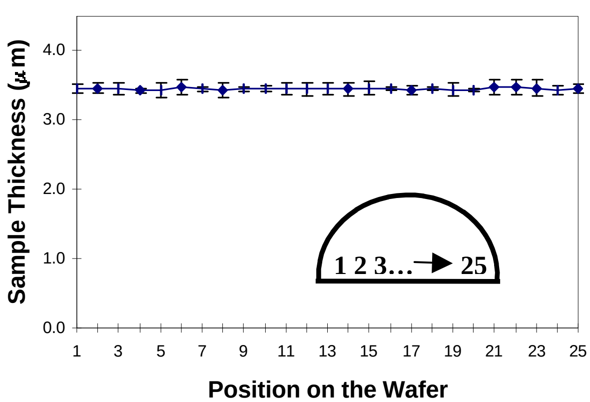
bottom and lateral surfaces of the etched mesa appear to be very smooth. Finally, Ni/Cr/Au (150 Å/150 Å/1200 Å) were e-beam evaporated to form both *n* and *p*-type contact pads. LEDs without current spreading layer are also fabricated for comparison. By varying the In composition and the thickness of the InGaN quantum well, LED emission from 420 to 490 nm were obtained.

To investigate the contact resistance to *p*-type GaN, a rectangular shaped, mesa isolated transmission line (TL) structure was fabricated. The width of the TL pattern is 300 µm while the spacing between adjacent Ni/Cr/Au contacts are varied from 5 to 50 µm at increments of 5 µm. The TL pattern is defined using RIE etching similar to the LED mesa etching. The wafer was then diced into several pieces each containing 4 TL patterns and was subsequently annealed at temperatures from 300°C to 600°C for 100 seconds. The TL structures are measured at constant current and the specific contact resistance r_c's were extracted using standard technique [5]. These experimental results will be discussed in the next section.

RESULTS AND DISCUSSIONS

Figure 2 shows a typical reflectance spectrum and the thickness nonuniformity across the diameter of a 2-inch LED sample. The thickness of *n*-GaN layer for this particular LED sample is ~ 3 µm. The epilayer thickness, d is calculated from $d = [\lambda^2/(2n\Delta\lambda)]$, where $\Delta\lambda$ is the wavelength separation between successive reflectance peak, and n is the refractive index of the GaN epilayer. The thickness shown in **Fig. 2** are averaged using $\Delta\lambda$ from 5 successive reflectance peaks. Thickness nonuniformity of less than < 1% is observed across the entire 2-inch wafer. The uniformity result we obtained on a typical LED device layer agrees reasonably well with Aixtron's own evaluation on 2-inch single-layer GaN wafer [6]. **Figure 3(a)** shows the current vs. voltage of the same LED wafer with and without the addition of the current spreading layer. It can be seen that the incorporation of current spreading layer has drastically reduced the spreading series resistance of the LED, which is caused by the high resistive *p*-GaN cap layer. With the current spreading layer, the operating voltage of the LED at 20 mA is reduced to 5 V or below. The use of self-alignment process for forming both the mesa and



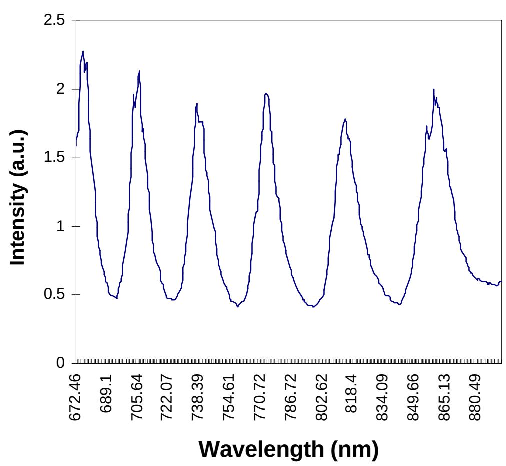


Fig. 2 Thickness uniformity across the diameter of a 2-inch LED wafer. A typical reflectance spectrum is also shown here.

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current spreading layer ensures maximum current spreading of a LED. Microscope observation shows that uniform emission from the entire LED mesa except the *p*-contact pad is achieved. The measured series resistance of 9.19x10^4 μm^2 LED is ~26 Ω. **Figure 3(b)** shows the emission spectrum of a typical LED we fabricated. For this particular device, the emission peak is ~ 490 nm and the FWHM is ~ 50 nm.

Owing to the low carrier concentration of the *p*-type GaN and the relative large barrier height between the metal and *p*-GaN, the I-V characteristics of the TL are non-linear. That is, the contact resistance depends on the measurement current. **Figure 4** shows a typical resistance vs. contact separation at two current levels. **Figure 5** shows the extracted r_c for Ni/Cr/Au system at different measurement currents for samples annealed at different temperatures. In all cases, the value of r_c decreases monotonically with increasing current density (current/unit length) in the TL pattern and then approaches a saturation value. The specific contact resistance, r_c is seen to decrease monotonically with increasing current. The optimal annealing temperature is observed to be 300-500^{o}C. Further increase in the annealing temperature at 600^{o}C and above results in an increase of r_c. This phenomenon is likely caused by the formation of nitrogen vacancy that occurs when samples are subjected to high temperature treatments. The nitrogen vacancy in turn compensates the acceptor dopants at the metal/*p*-GaN interface. Several groups have already reported similar findings on these issues [7,8,9]. In addition, the presence of the high resistive Ni_3N and Ni_4N phases at the metal-semiconductor interface at the annealing temperature greater than 500 ^{o}C can also result in higher contact resistance [10]. The r_c measurement results are summarized in **Table I**. The lowest r_c we obtained is about 0.016 Ω–cm^2 (the resistivity of the TL sample extracted is on the average of 4.05 ± 0.15 Ω-cm). The values r_c we obtained are similar to previously reported data on Ni/*p*-GaN system [11,12]. The lowering of r_c due to thermal annealing below 600 ^{o}C is not clear at this stage. Earlier studies had suggested that thermal annealing of Ni/*p*-GaN helps to removes the contaminants at the

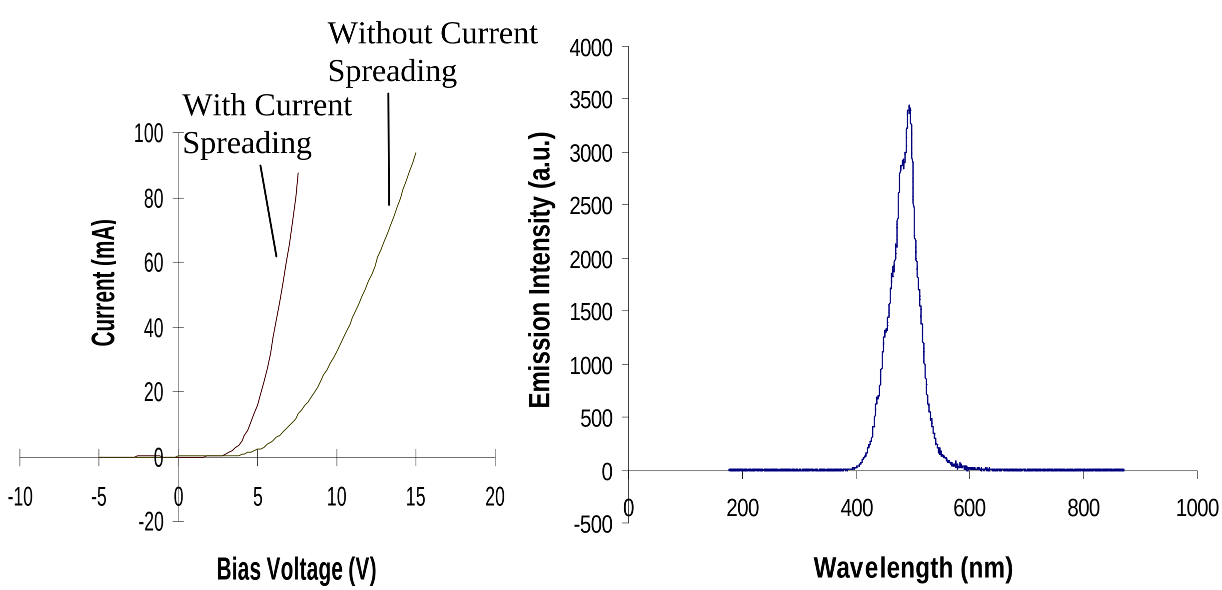

Fig 3 (a) The I-V of the LED with and without the current spreading layer; and (b) the emission spectrum of the LED.

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interface resulting in lowering of r_c [12]. Recent results on the lowering of r_c by aqua regia etching of *p*-GaN has strongly suggested that surface oxide plays a paramount role on the specific contact resistance to *p*-type GaN [13].

From the LED I-V, the extracted series resistance is 26 Ω measured between 40 to 80 mA. The current density of the LED operating at 60 mA corresponds to an average current density of ~ 31.3 mA/cm for the TL measurement. From **Fig. 5**, the corresponding r_c extracted from the TL measurement is 0.021 Ω–cm^2. The estimated contact resistance of the LED is therefore ~ 22.9 Ω. Based on this estimate, over 88 % of the series resistance of the LED

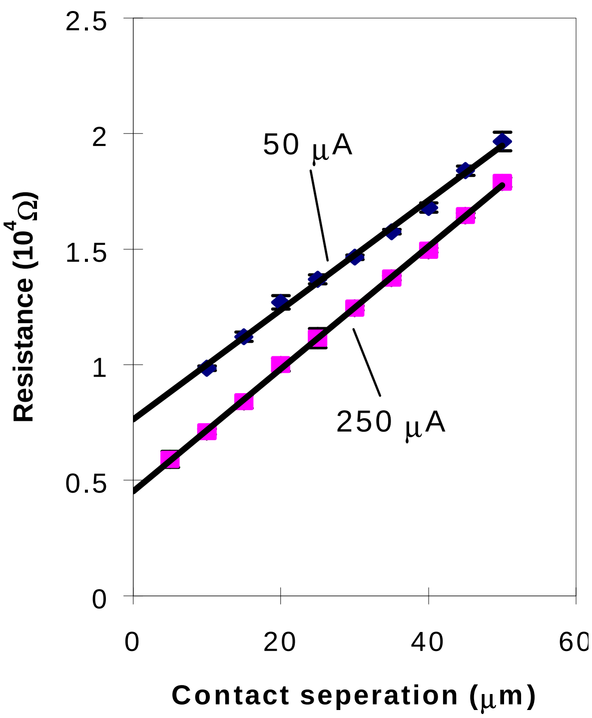

Fig. 4 The measured resistance versus spacing of the TL test pattern at two different measurement currents.

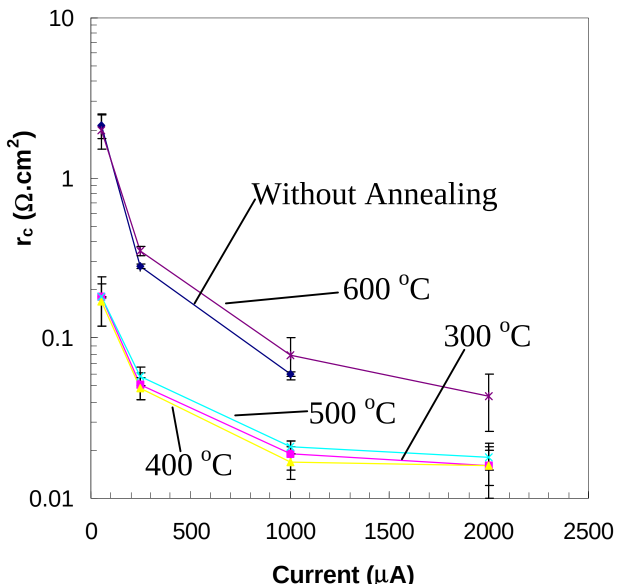

Fig. 5 The extracted r_c measured at different current levels and annealing temperatures. The width of the rectangular TL pattern is 300 μm.

	Specific Contact Resistance (Ω - Sqr. cm)									
Current (μA)	No Annealing	Std. Dev.	300 Deg. C	Std. Dev.	400 Deg. C	Std. Dev.	500 Deg. C	Std. Dev	600 Deg. C	Std. Dev
50	2.13	0.38	0.18	0.06	0.17	0.05	0.18	0.012	1.98	0.47
250	0.28	0.01	0.051	0.01	0.049	0.007	0.058	0.008	0.34	0.024
1000	0.06	0.002	0.019	0.004	0.017	0.004	0.021	0.002	0.078	0.023
2000			0.016	0.006	0.016	0.004	0.018	0.004	0.043	0.017

Table I The extracted average r_c and the corresponding standard deviations from the TL test pattern at different current levels for samples under different annealing temperatures.

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originates from the *p*-GaN contact resistance.

CONCLUSION

We report highly uniform growth (thickness nonuniformity < 1%) of InGaN/GaN LED on 2-inch sapphire substrate using a multi-wafer MOVPE reactor. A self-aligned LED fabrication process is developed to incorporate a thin Ni/Au metal for improved current spreading of the LED device. It is also found that the annealing temperatures between 300-500 ^{o}C significantly reduce the contact resistance of as-deposited Ni/Cr/Au metals on *p*-type GaN. Specific contact resistance in the range of 0.016 to 0.021 Ω–cm^2 is achieved at annealing temperatures between 300^{o}C to 500^{o}C.

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