Mat. Res. Soc. Symp. Vol. 639 © 2001 Materials Research Society

Low Resistance Optically Transparent Contacts to p–type GaN Using Oxidized Ni/Au and ITO for LED Application

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ABSTRACT

We report on a high transparency low resistance contact to p-GaN composed of a thin oxidized Ni/Au bilayer overcoated with indium tin oxide (NiO/Au/ITO). The NiO/Au/ITO layer shows a specific contact resistivity, ρ_c, of 1.8 x 10^{-3} Ω-cm^2 that is nearly ten times lower than conventional Ni/Au annealed under N_2. Measurements on fully processed LEDs with a NiO/Au/ITO current spreading layer (CSL) show an operating voltage of around 4 V at 20 mA that is comparable to LEDs fabricated with a conventional Ni/Au CSL and a dramatic improvement over the previous ITO data. LED top surface light emission through the NiO/Au/ITO CSL is shown to be greater than that from LEDs with a conventional semi-transparent Ni/Au CSL. Taken together, these results demonstrate the feasibility of using NiO/Au/ITO as a CSL for high performance GaN LEDs.

INTRODUCTION

GaN has demonstrated its great potential for application in a variety of light emitting semiconductor devices operating in the green to ultraviolet wavelength region including light emitting diodes (LEDs) and laser diodes. However, due to its wide band gap and the low doping level of p-GaN, low resistance ohmic contact to p-GaN is difficult to achieve. In addition, due to high resistivity in the p-GaN cap layer itself, carriers flowing from the top contact are not uniformly distributed in the lateral direction. This current crowding under the p-contact yields a device of low efficiency with non-uniform light emission. The introduction of an optically transparent CSL allows more homogeneous current injection to the active layer and, thereby, more efficient generation and emission of photons across the device. Thus, fundamental improvement in the CSL can significantly enhance the performance of GaN-based LEDs. It is important to note that an effective CSL must therefore concurrently possess three basic characteristics: low sheet resistance, low contact resistance to p-GaN, and high optical transparency at the wavelength of application.

Conventional GaN-based LEDs currently employ as a CSL a thin, semi-transparent Ni/Au bilayer. Around 40 Å of each metal are typically deposited and subsequently annealed under N_2. These contacts exhibit ρ_c values of around 1-2 x 10^{-2} Ω-cm^2 [1]. Ho *et al* measured the level of optical transmission through a Ni/Au (100 Å /50 Å) bilayer on BK-7 glass, annealed at 500ºC under N_2, as only around 30-35% between 400-500 nm [2]. While this amount of transparency may be enhanced by decreasing the metal thicknesses, these layers may be too thin to accommodate the high lateral current densities anticipated for the next generation of larger area LEDs.

Two groups have recently published promising results in the effort to develop improved CSL systems for p-GaN. Ho *et al* reported that by oxidizing a thin bilayer of Ni/Au under air or water vapor, record low levels of ρ_c can be achieved while increasing transparency. They measured $\rho_c = 2 \times 10^{-4}\ \Omega\text{-cm}^2$ for a Ni/Au (100 Å /50 Å) bilayer annealed at 500ºC in air and 60-70% transparency for the same film on a BK-7 glass substrate [2]. They described further reduction of ρ_c for their oxidized Ni/Au (NiO/Au) contacts could be obtained by decreasing the metal thicknesses to 50 Å each [3]. But device reliability again must be closely examined since the best performing layers are the thinnest (<100 Å total) and therefore most prone to damage by high lateral current density. Margalith *et al* recently demonstrated an LED employing high transparency indium tin oxide (ITO) as the CSL [4]. ITO exhibits good sheet resistance (around 12-15 Ω/sq. for 2000Å is typical), has good transparency of >80% over the visible wavelength region, and is a well established material for optoelectronic application. But the GaN-based LEDs fabricated with ITO p-contacts required much higher operating voltage (V_{op}) levels of around 7.5 V at 20 mA compared to LEDs of identical design but with conventional thin Ni/Au layers that had V_{op} of 4 V or less due to the large barrier height between ITO and p-GaN.

In this paper, we describe a hybrid CSL composed of a composite stack of a NiO/Au layer overcoated with ITO. We demonstrate that this contact system effectively exploits the low ρ_c characteristic of the NiO/Au, the enhanced lateral current carrying capability of the thicker ITO, and high optical transparency compared to conventional Ni/Au.

EXPERIMENT

The wafers used in the experiment had a standard LED structure and were grown by Metalorganic Vapor Phase Epitaxy on 2-inch diameter (0001)-oriented sapphire. The structure (bottom to top) consists of an n-GaN buffer layer, a 3 μm Si-doped n-GaN layer, an InGaN/GaN MQW active layer composed of undoped InGaN wells and Si-doped GaN barriers, a Mg-doped 100 nm p-AlGaN layer, and a 0.5 μm Mg-doped p-GaN cap.

Prior to metal deposition, the samples were rinsed in acetone, methanol, and deionized water. The Ni/Au bilayer was electron beam evaporated sequentially. Following Ni/Au deposition and lift-off, the samples were annealed at 500ºC in a water vapor atmosphere for 2 minutes. ITO was deposited by reactive sputtering using an ITO target in an oxygen enriched atmosphere at a substrate temperature of 300ºC. ITO patterning was achieved by etching away undesired ITO with dilute hydrochloric acid at a temperature of around 50ºC.

A conventional design was used for the demonstration LEDs. The 300 μm square p-mesa was created by reactive ion etching and then covered by the CSL. A 100 μm square p-contact pad was deposited on top of the CSL at the same time as the n-contact. These contacts were electron beam evaporated, composed of 300 Å of Ti and 1200 Å of Al subsequently annealed at 500ºC under N_2.

RESULTS AND DISCUSSION

Contact Resistivity

In order to measure the ρ_c value of the NiO/Au/ITO contact we prepared circular transmission line (CTL) test structures. The pattern consisted of a circular inner contact of 110 μm diameter surrounded by a large area contact pad with a gap of variable spacing. The gap ranged from 10 to 25 μm by 5 μm increments. The Ni/Au bilayer had metal layer thicknesses of 40 Å each. 0.5 μm of ITO was deposited. Figure 1 shows the I-V characteristics of these NiO/Au/ITO contacts. Multiple test structures for each gap spacing were measured, all showing linear I-V behavior. From these data, the total series resistance was extracted for each spacing. For each gap value, the total series resistance, R_s, between the two contacts is described by [5]

$$R_s = \rho_c/2\pi[L_T/L + L_T/(L+d) + \ln(1+d/L)] \qquad (1)$$

where L is the inner contact radius, d is the gap spacing, and

$$L_T = (\rho_c/\rho_s)^{1/2} \qquad (2)$$

where ρ_s is the sheet resistance.
If $2\pi(L+d) >> d$, the following approximation can be used [5]:

$$R_s = (\rho_s/2\pi L)(d + 2L_T) \qquad (3)$$

A least squares curve fitting analysis of the data using this equation (a plot is shown in Figure 2) yielded a value for $\rho_c = 1.8 \times 10^{-3}\ \Omega\text{-cm}^2$, an order of magnitude lower than the value typically reported for conventional thin Ni/Au annealed under N_2 [1].

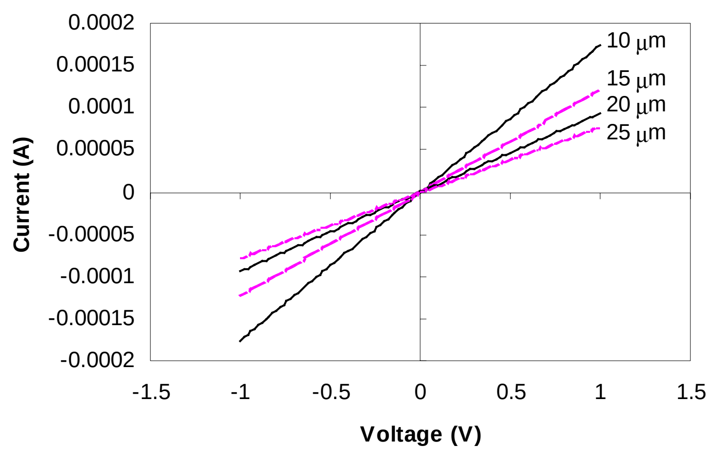

Figure 1. The I-V behavior of the CTL test structures with NiO/Au/ITO contact layers for gap spacings of 10, 15, 20 and 25 μm.

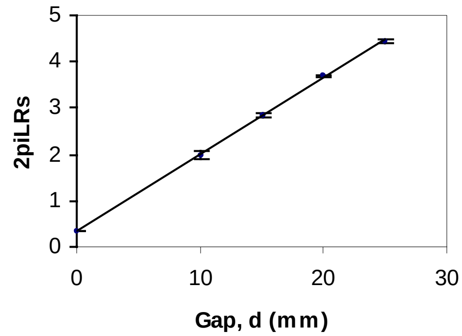

Figure 2. The plot of total series resistance between contacts, R_s, in the CTL test structure as a function of contact spacing, d.

Demonstration LED

For the LEDs, the CSL covering the p-mesa surface was composed of 25 Å each of Ni and Au, overcoated with a 0.2 μm ITO layer. An isometric schematic drawing of a completed LED is shown in Figure 3.

We compared the performance characteristics of an LED with the NiO/Au/ITO CSL to an LED of similar design but with a CSL of thin Ni/Au (20 Å /90 Å) annealed under N_2. Figure 4 shows a comparison of the I-V curves for both LEDs. Both exhibit comparable V_{op} characteristics of around 4 V at 20 mA, much lower than the V_{op} exhibited by the previously reported LED with an ITO CSL. Figure 5 shows a comparison of the L-I curves for the two LEDs where the emitted light is measured from the top surface of each device. The emitted intensity of the LED with the NiO/Au/ITO CSL is consistently higher than the conventional Ni/Au LED clearly demonstrating its enhanced transparency. We performed low magnification microscopic inspection of the two LEDs while operating under a range of driving currents to evaluate uniformity of luminescence. This study revealed that at currents at or above 5 mA, emission appeared equally uniform across both device surfaces. But at lower driving currents, the LED with the NiO/Au/ITO CSL exhibited more homogeneous illumination. Figure 6 illustrates this comparison for the cases of 5 mA and 2 mA of driving current.

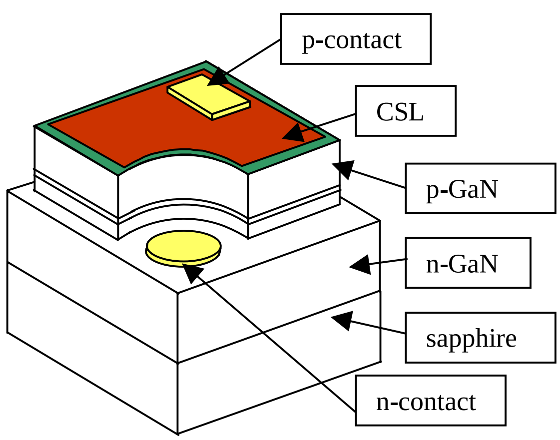

Figure 3. An isometric schematic drawing of a completed LED. The CSL (NiO/Au/ITO) covers the p-mesa (300 μm square). The p-contact pad sits on top of the CSL (100 μm square, Ti/Al). The n-contact pad is also composed of Ti/Al.

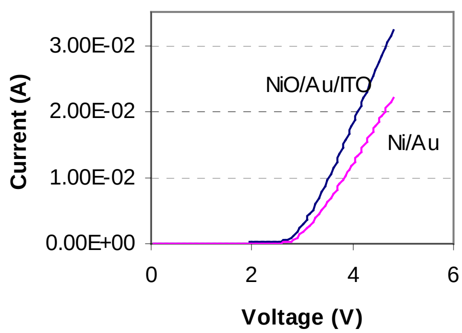

Figure 4. The I-V behavior comparison of two LEDs of similar design: (a) with the NiO/Au/ITO CSL; (b) with a thin Ni/Au (20 Å /90 Å) CSL annealed under N_2.

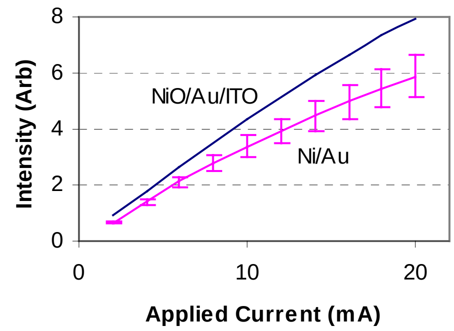

Figure 5. Comparison of the L-I characteristics of the two LEDs of Figure 4: (a) with the NiO/Au/ITO CSL; (b) with a thin Ni/Au (20 Å /90 Å) CSL annealed under N_2.

(a) NiO/Au/ITO CSL **(b) Ni/Au CSL**

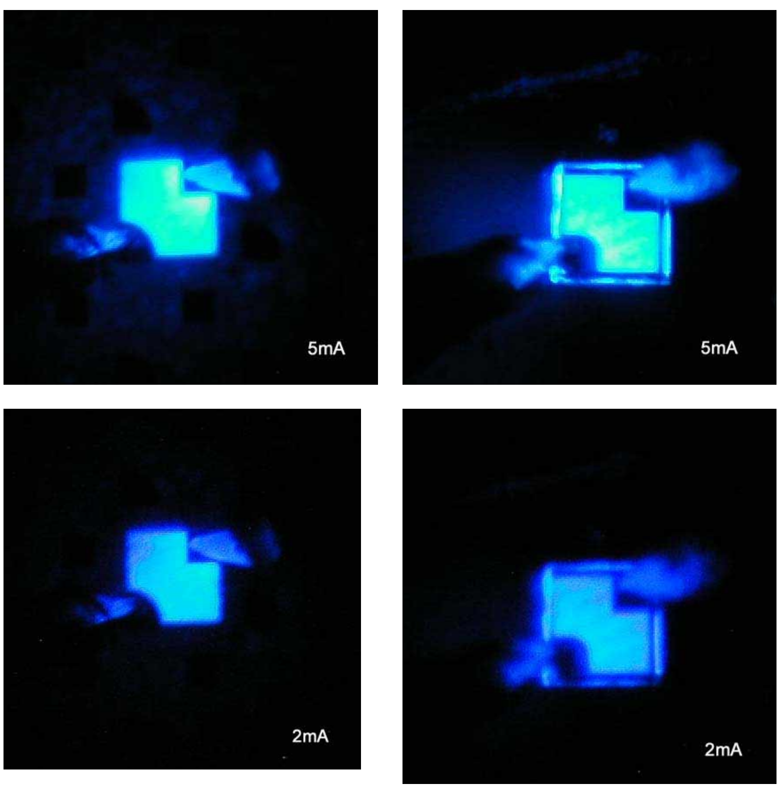

Figure 6. A comparison of the uniformity of luminescence from the two LEDs of Figure 4 under driving currents of 5 mA and 2 mA: (a) with the NiO/Au/ITO CSL; (b) with a thin Ni/Au (20 Å /90 Å) CSL annealed under N_2..

CONCLUSIONS

In summary, we have demonstrated that a hybrid NiO/Au/ITO CSL exhibits reduced contact resistivity, comparable operating voltage, and enhanced optical transparency in comparison to a conventional semi-transparent Ni/Au CSL. These characteristics in addition to its higher current carrying capacity make the NiO/Au/ITO contact system ideal for the next generation of large area GaN-based LEDs.

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