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High transparency low resistance oxidized Ni/Au–ZnO contacts to p-GaN for high performance LED applications

Sung-Pyo Jung[*, 1], **Chien-Hung Lin**[1], **Hon Man Chan**[1], **Zhiyong Fan**[2], **J. Grace Lu**[1, 2], and **Henry P. Lee**[1]

[1] Department of Electrical Engineering and Computer Science
[2] Department of Chemical Engineering and Material Science, Henry Samueli School of Engineering, University of California, Irvine, USA

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This paper presents high-transparency low-resistance contact on p-GaN using oxidized Ni/Au–ZnO : Al_2O_3(2 wt%) for high-performance GaN-based light-emitting diodes (LEDs) applications. It is shown that oxidized Ni/Au–ZnO contact to p-GaN yields an operating voltage of around 4.7 V at 20 mA compared to 4.1 V of a reference oxidized Ni/Au(5 nm/5 nm)–Ni/Au(20 nm/120 nm) sample without the ZnO : Al_2O_3(2 wt%) layer. Enhancement of transmittance of about 60% at the wavelength of 450 nm over a conventional N_2-annealed semi-transparent Ni/Au(5 nm/5 nm) contact is measured on glass substrates.

1 Introduction

Recent development of GaN-based optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs) has attracted considerable attention due to their wide applications ranging from display, solid-state lighting to optical storage [1]. However, owing to the high resistivity of p-GaN, the injected current does not spread uniformly in an LED device: a thin semi-transparent Ni/Au (<10 nm) current spreading layer (CSL) is needed for this purpose at the expense of reduced light extraction (transparency of 30–40%) due to optical absorption [2]. The introduction of thin oxidized Ni/Au contact having enhanced optical transmittance of 60–75% in the wavelength range of 400–500 nm has partially alleviated this problem [3, 4]. But oxidized Ni/Au CSL is known to suffer from poor reliability compared to N_2-annealed Ni/Au contact [5].

One way to overcome this deficiency is to use a thicker transparent and conductive layer such as indium tin oxide (ITO) for current spreading. Although direct contact of ITO on p-GaN shows the Schottky contact behavior [6], enhanced light extraction LEDs has been reported using oxidized Ni/Au-ITO and Ni/ITO contacts with V_f (operating voltage) comparable to conventional LEDs [7, 8]. In addition, ITO on LED employing a tunnel junction has been investigated and showed superior optical and electrical performance over conventional N_2-anneled Ni/Au CSL design [9]. Recently, Al-doped ZnO (AZO), which has similar electrical and optical properties in the visible wavelength range as ITO, but is non-toxic, cheaper, and has high temperature stability [10], has been explored as a low resistance and high transparent contact to p-GaN [11]. In this paper, we report the fabrication process and electrical/optical characteristics of oxidized Ni/Au-AZO contact to p-GaN on LED-like test structures.

[*] Corresponding author: e-mail: jungs@uci.edu, Phone: 1-949-824-4861, Fax: 1-949-824-4861

2 Experiment

Commercial graded InGaN MQW LED epi-wafers grown on sapphire substrates, with a peak emission wavelength of 450 nm prepared by AXT, Inc. are used in this work. Before any deposition, the samples are rinsed with acetone, methanol, de-ionized water, methanol, acetone, and isopropyl alcohol consecutively. Both thin Ni/Au(5 nm/5 nm) and thicker Ni/Au(10 nm/10 nm) are deposited on p-GaN using e-beam evaporation. The samples are then oxidized at 500 °C in oxygen ambient to form NiO with embedded Au matrix [3]. The deposition of AZO is carried out using a Perkin-Elmer 2400A RF sputtering system. The sputtering target used in this experiment is an 8-inch Al_2O_3 doped (2 wt%) ZnO provided by Super Conduct Materials, Inc. The RF power is 200 W and the background chamber pressure is below 5×10^{-7} Torr. The O_2 and Ar flow rate of 0.5 and 4.8 SCCM are used, respectively, and the sputtering is carried out at the pressure of 5 mtorr and a d.c. bias of 650 Volts.

The thickness of AZO is chosen to be $3\lambda/4n$ to minimize optical reflection. Using $n = 2.05$ for AZO and λ at 450 nm, the AZO thickness is designed to be 160 nm. The electrical resistivity and sheet resistance of AZO are measured using Four Point Probe method. The samples are patterned and etched into circular dots with a diameter of 500 µm using a wet etching process. Finally, the samples are annealed at 500 °C in N_2 ambient. A reference sample of oxidized Ni/Au(5 nm/5 nm)–Ni/Au(20 nm/120 nm) is also prepared for comparison. Parallel sets of samples are prepared on BK-7 glass substrates under identical process conditions for optical transmission measurement.

3 Results and discussions

Figure 1 shows the resistivity of AZO-on-Si_3N_4 coated silicon test samples before and after annealing at 400 °C and 500 °C in O_2 and N_2 ambient. The resistivity value of $1–3 \times 10^{-3}$ Ω cm is achieved at 500 °C in N_2 ambient for 10 minutes after sputtering. For 160 nm-thick AZO, this corresponds to a sheet resistance of 60–180 Ω/□, which is higher than ~60 Ω/□ for oxidized Ni/Au(5 nm/5 nm). The resistivity of AZO is still higher than the lowest reported value of ~10^{-4} Ω cm [10]. This suggests a need to further lower the resistivity of AZO through process optimization, or to use a thicker AZO layer. Figure 2 shows the AFM images of as-deposited Ni/Au(5 nm/5 nm), oxidized Ni/Au(5 nm/5 nm), and oxidized Ni/Au (10 nm/10 nm) on p-GaN prior to AZO deposition. The surface roughness RMS values are 0.722, 3.301, and 3.488 nm, respectively. Considerable roughening of Ni/Au can be seen after the oxidation process.

The electrical behavior of the contact is evaluated using a wafer-level probing technique that does not require full fabrication of the LED [12]. In this method, localized damage is first made by applying a high voltage (70–80 V) between two sharp probes (2 and 3). This allows probes 2 and 3 to make contact

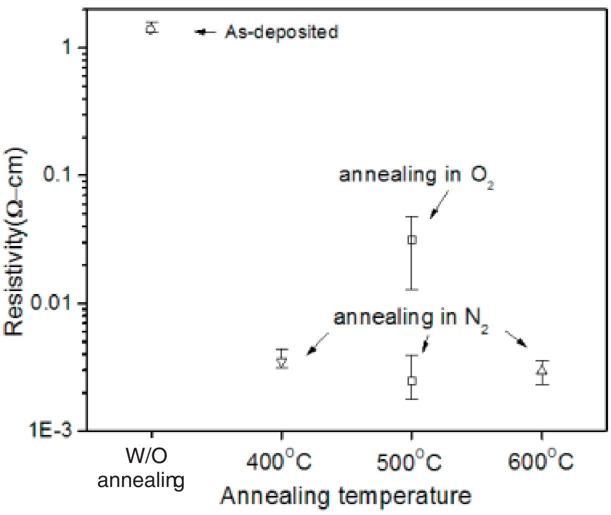

Fig. 1 Resistivity of AZO as a function of annealing condition.

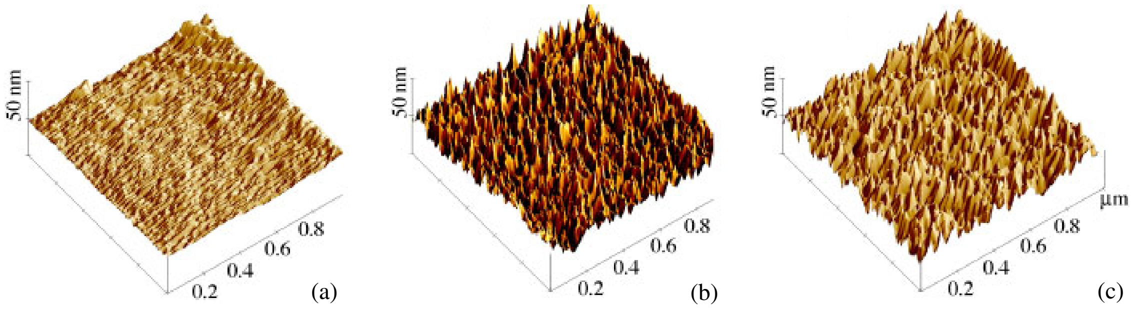

Fig. 2 (online colour at: www.pss-a.com) (a) As-deposited Ni/Au (5 nm/5 nm) on GaN; (b) oxidized Ni/Au (5 nm/5 nm) on GaN; and (c) oxidized Ni/Au (10 nm/10 nm) on GaN. The roughness RMS for (a), (b), and (c) are 0.722, 3.301, and 3.488 nm, respectively.

with the low-resistance n-GaN layer. The *I–V* characteristics of the p–n diode directly below the circular dot is then made between contact 1 and 2 as shown in the inset of Fig. 3. Figure 3 shows the *I–V* results of oxidized Ni/Au(5 nm/5 nm)–AZO(160 nm) and oxidized Ni/Au(10 nm/10 nm)–AZO(160 nm) samples after annealing in N_2 together with the reference sample, oxidized Ni/Au(5 nm/5 nm)–Ni/Au(20 nm/ 120 nm) without AZO layer. The operating voltage for oxidized Ni/Au(5 nm/5 nm)–AZO(160 nm) is 5.5 V at 20 mA. The V_f for oxidized Ni/Au(10 nm/10 nm)–AZO(160 nm) is 4.7 V at 20 mA, which is higher compared to 4.1 V for the reference sample. The reason for increase in V_f is not understood at this stage. It could have been caused by sputtered-induced damage on a roughened oxidized Ni/Au surface during AZO deposition. Uniform light emission is obtained from both oxidized Ni/Au-AZO samples after annealing in N_2.

The measured optical transmission spectra of various test structures deposited on BK-7 glass slides are shown in Fig. 4(a). Transmittance as high as 62–73% in the wavelength of 400–500 nm is achieved for the oxidized Ni/Au(5 nm/5 nm)–AZO(160 nm) annealed at 500 °C in N_2. This is comparable to the transmittance of oxidized Ni/Au(5 nm/5 nm) [4] and agrees well with the simulated values using TFCalc.

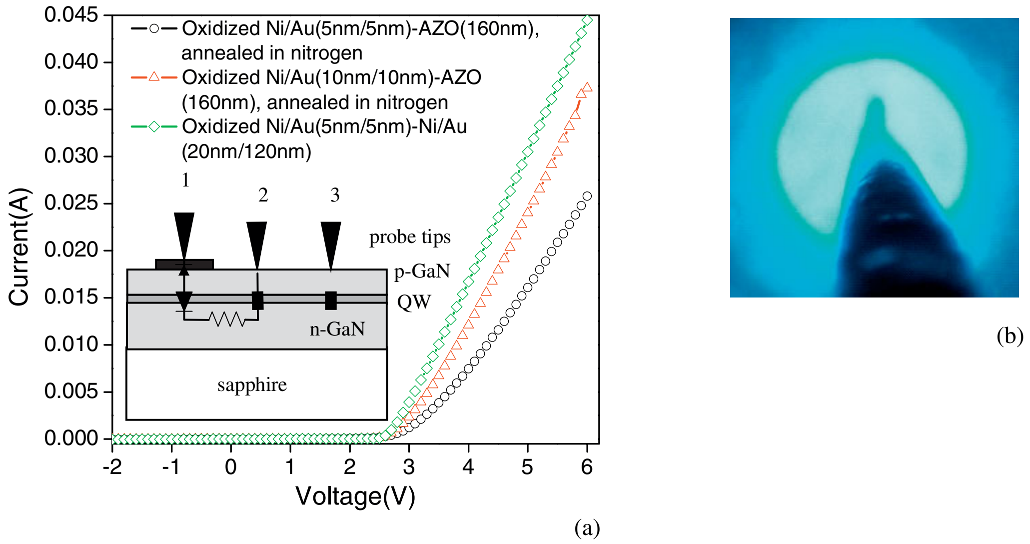

Fig. 3 (online colour at: www.pss-a.com) (a) *I–V* characteristics of LEDs with thin oxidized Ni/Au(5 nm/5 nm)–AZO(160 nm), thicker oxidized Ni/Au (10 nm/10 nm)–AZO (160 nm) contact, and oxidized Ni/Au(5 nm/5 nm)–Ni/Au (20 nm/120 nm) contact measured between probe 1 and 2. (b) The emission image of the LED with oxidized Ni/Au–AZO contact.

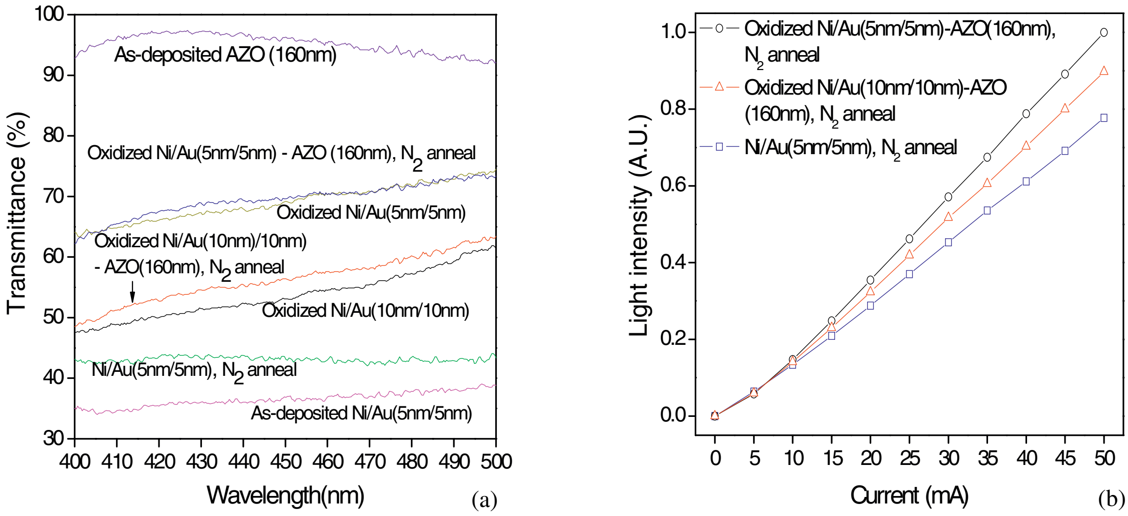

Fig. 4 (a) A comparison of transmission spectra for various samples deposited on BK-7 glass substrates. (b) Light intensities versus applied current for different contact structures deposited on GaN.

Compared to conventional N_2-annealed Ni/Au(5 nm/5 nm) CSL, transmittance enhancement of about 60% at the wavelength of 450 nm is achieved. Figure 4(b) shows the light intensities of different contact structures versus applied current. The improvement of light output intensity up to approximately 29% using oxidized Ni/Au (5 nm/5 nm) with AZO compared to the reference sample is observed at 50 mA. Higher percentage improvement of light intensity is expected at higher injection current.

4 Conclusion

In summary, we report a new high transparency low resistance contact consisting of oxidized Ni/Au-AZO on GaN LED test structures. Our results demonstrate the applicability of such contact structures for LED application. However, further process optimization is needed to reduce the operation voltage.

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