Improvement of electrical and optical properties of *p*-GaN Ohmic metals under ultraviolet light irradiation annealing processes

S. W. Chae
Department of Electronics Engineering, Korea University, Seoul 136-701, Korea and LM Development Team, Samsung Electro-Mechanics Co., Suwon 443-743, Korea

S. K. Yoon
LM Development Team, Samsung Electro-Mechanics Co., Suwon 443-743, Korea

J. S. Kwak and Y. H. Park
Department of Material Sciences and Metallurgical Engineering, Sunchon National University, Chonnam 540-712, Korea

T. G. Kim[a)]
Department of Electronics Engineering, Korea University, Seoul 136-701, Korea

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We report the improvement of electrical and optical properties of *p*-GaN Ohmic metals, ZnNi(10 nm)/Au(10 nm), by ultraviolet (UV) light irradiation. After UV light irradiation, the specific contact resistance of *p*-GaN decreased slightly from 2.99×10^{-4} to $2.54\times10^{-4}\ \Omega\,\text{cm}^2$, while the transmittance of the contact layer increased form 75% to 85% at a wavelength of 460 nm. In addition, the forward voltage of InGaN/GaN light-emitting diode chip at 20 mA decreased from 3.55 to 3.45 V, and the output power increased form 18 to 25 mW by UV light irradiation. The low resistance and high transmittance of the *p*-GaN Ohmic metals are attributed to the reduced Shottky barrier by the formation of gallium oxide and the increased oxidation of *p*-Ohmic metals, respectively, due to ozone generated form oxygen during UV light irradiation. © *2006 American Vacuum Society.* [DOI: 10.1116/1.2183192]

I. INTRODUCTION

GaN-based white light-emitting diodes (LEDs) have drawn a great deal of attention because of their wide spectrum of applications to back-lighting units for liquid-crystal displays, car interiors, and solid-state lightings.[1] However, despite of these possible applications, white LEDs have many weaknesses which must be solved before it can be substituted for the conventional fluorescent lamp. The most critical problem is the output power of white LED.

One of the primary reasons for the low efficiency from the conventional InGaN LEDs is the low light extraction efficiency due to poor transparency of a broad-contact electrode on *p*-GaN. To enhance the external quantum efficiency, transparent *p*-type Ohmic contacts with low contact resistances must be developed. Many researchers[2–7] have reported various development schemes for *p*-GaN Ohmic electrodes with low resistance and high transmittance. However, because of the high contact resistance due to wide band gap energy and low *p*-doping concentration of GaN, many technical barriers must be overcome in the development of such *p*-type electrodes. The metals with large work functions such as Ni,[2] Pt,[3] Pd,[4] Ru, and Ir[5] have been used for the *p*-GaN Ohmic contacts; however, these materials are very absorptive against short wavelengths (i.e., 460 nm) of light, leading to low transmittance.

To solve these problems, the transparent conducting oxides (TCOs) such as indium tin oxide (ITO), ZnO, etc., have been investigated as the alternative *p*-GaN Ohmic metal. Kim *et al.*[6] and Margalith *et al.*[7] reported that ITO would be effective in increasing the light output of LEDs, due to its higher transmittance; however, this process could incur a significantly large voltage penalty because of high specific contact resistance of ITO in the range of $\sim10^{-1}\ \Omega\,\text{cm}^2$. Therefore, these materials are weak alternatives for *p*-GaN Ohmic metal because of their higher contact resistance than conventional metals with large work functions.

In this work, we propose an approach based on low-temperature UV light irradiation annealing processes to enhance the transmittance and to decrease the contact resistance of *p*-GaN Ohmic metals. First, the effect of UV light irradiated annealing on the electrical and optical properties of InGaN/GaN LEDs with ZnNi/Au (Ref. 8) and Ni/Au *p*-GaN Ohmic metals is investigated, and then, the effect of UV light irradiation on the performance of InGaN/GaN blue LEDs with *p*-type ZnNi/Au electrodes is evaluated.

II. EXPERIMENT

1.5 μm thick *p*-GaN layers ($5\times10^{17}\ \text{cm}^{-3}$) grown by metal organic chemical vapor deposition (MOCVD) were ultrasonically degreased by using trichloroethylene, acetone, methanol, and de-ionized (DI) water for 5 min in each step and were N_2 blown. Prior to lithography, the GaN samples were treated with a buffered oxide etch (BOE) solution for 5 min and rinsed in DI water for 20 min. The transfer length method (TLM) patterns, defined by the standard photolithographic technique, were used to measure the specific contact

[a)]Electronic mail: tgkim1@korea.ac.kr

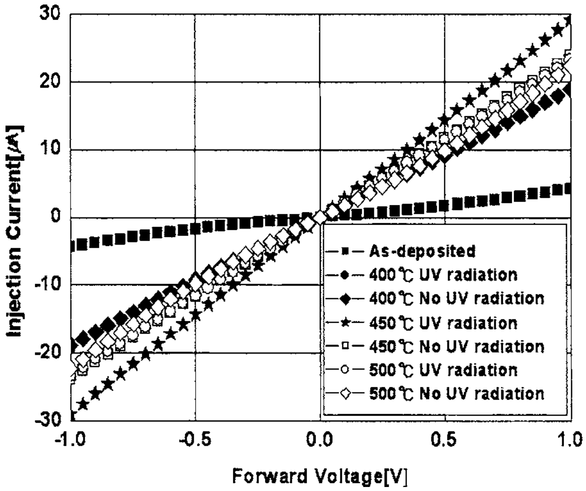

FIG. 1. *I-V* curves of ZnNi/Au metal films under various conditions of thermal annealing and UV light irradiation.

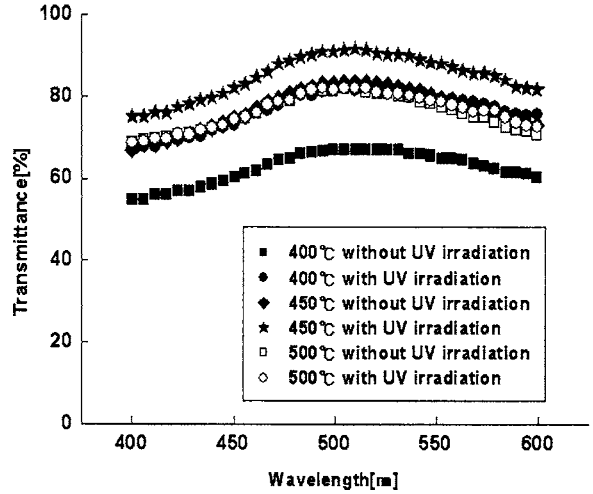

FIG. 2. Light transmittance curves for the ZnNi/Au metal films under various conditions of thermal annealing and UV light irradiation.

resistance. The pattern size was fixed to $150\times500\ \mu m^2$, while the spacing varied from 5 to 25 μm. Prior to metal deposition, all the samples were treated in a diluted HCl solution for 1 min and deposited with ZnNi/Au (10 nm/10 nm). The composition of Zn/Ni compound was Zn=10% and Ni=90%, respectively, and sequentially deposited from Zn/Ni and Au by electron beam evaporation. To constitute the Ohmic contact materials, some of the samples were rapid thermal annealed (RTA) with a 365 nm under 50 W ultraviolet lamp. RTA was carried out for 5 min at various temperatures in air ambient. Current-voltage (*I-V*) characteristics were measured by using a parameter analyzer (HP 4155A), and the transmittance were evaluated by using a spectrophotometer and the beam analyzer (NST BL-200). In addition, the optical properties of InGaN/GaN multiple-quantum-well (MQW) LEDs were examined in LED tester of Opto Company, Japan.

III. RESULTS AND DISCUSSION

First, to understand the effect of UV light irradiation on the electrical and optical properties of ZnNi/Au electrodes, we prepared seven as deposited ZnNi/Au films annealed at 400, 450, and 500 °C with and without UV irradiation. The power of UV light irradiation was fixed at 50 mW. Figure 1 shows the *I-V* curves of ZnNi/Au metal films under various conditions of thermal annealing and UV light irradiation. In Fig. 1, a nonlinear curve is shown for the as-deposited sample; however, it turns into a linear curve with both increasing annealing temperature and irradiation of UV light for ZnNi/Au contacts. For the samples with UV light irradiation, the slopes of *I-V* curves become larger than those without UV light irradiation at a given annealing temperature. In particular, the electrical properties of the samples exposed to UV light in the annealing temperatures of 400–500 °C were considerably improved. The specific contact resistance was determined from the plots of the measured resistance as a function of the spacing between the TLM pads. The least-squares method was used to fit a straight line to the experimental data.[9] Typical specific contact resistance of ZnNi/Au electrodes was $2.55\times10^{-4}\ \Omega\,cm^2$ when they were annealed at 450 °C under 50 mW UV light irradiation, while that of the ZnNi/Au after annealing at 450 °C without UV light irradiation was $2.99\times10^{-4}\ \Omega\,cm^2$. Figure 2 shows the magnitude of the light transmittance through the ZnNi/Au electrodes against emission wavelength for different annealing temperatures with or without UV light irradiation. ZnNi/Au electrodes under UV light irradiation were more transparent to light of wavelengths from 400 to600 nm than those without UV light irradiation at the same annealing temperatures. All ZnNi/Au films exhibit transmittance higher than 70% under UV light irradiation in the visible range, regardless of the annealing temperature. In particular, transmittances of ZnNi/Au films at 460 nm were as high as 75% and 85% under UV light irradiation for the samples annealed at 400 and 450 °C, respectively, while those of ZnNi/Au films at 460 nm under no UV light irradiation were 65% and 75% at the same annealing temperatures.

Then, to investigate the effect of UV light irradiation on the performance of practical LEDs with *p*-type ZnNi/Au electrodes, we fabricated three InGaN/GaN blue LEDs with different types of *p*-type Ohmic contacts, i.e., ZnNi/Au (10 nm/10 nm) films with and without UV light irradiation, and a Ni/Au (10 nm/10 nm) film without UV light irradiation. All samples were annealed at a temperature of 450 °C, and a 50 mW UV light irradiation was used. Figure 3 shows the *I-V* characteristics for the three InGaN/GaN LEDs described above. The inset of Fig. 3 shows a typical emission spectrum from the LEDs with ZnNi/Au electrodes under UV light irradiation, where the center wavelength was 460 nm. By comparison of the slopes among the three InGaN/GaN blue LEDs, the lowest forward-bias voltage was ~3.45 V at 20 mA from the InGaN/GaN LED with ZnNi/Au electrodes under UV light irradiation. For reference, the forward-bias voltages of the InGaN/GaN LEDs with ZnNi/Au and Ni/Au without UV irradiation were measured to be 3.55 and

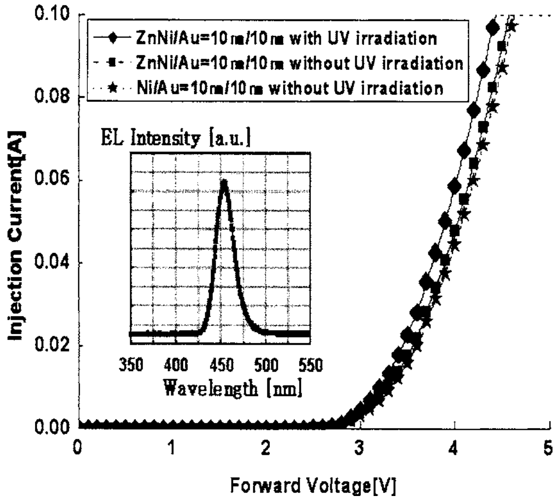

FIG. 3. *I-V* characteristics of InGaN/GaN blue LEDs fabricated with ZnNi/Au electrodes, with or without UV light irradiation, and with Ni/Au film without UV light irradiation for a fixed annealing temperature of 450 °C. The inset shows the emission spectrum taken at 25 mW, whose peak wavelength is 460 nm.

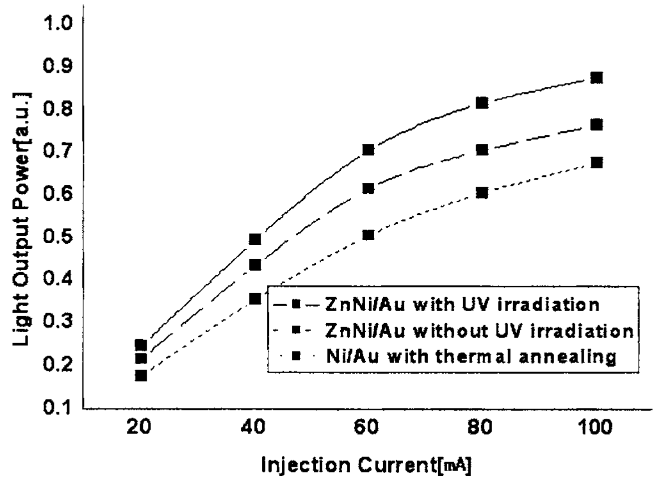

FIG. 4. Light-output power vs current curve for InGaN/GaN blue LEDs with ZnNi/Au electrodes with UV light irradiation, and the ones with ZnNi/Au and Ni/Au electrodes without UV light irradiation. All samples are annealed at a temperature of 450 °C.

3.60 V, respectively. These results are well consistent with those for the specific contact resistance described in Fig. 1.

Figure 4 shows the characteristics of the light-output power versus current (*L-I*) curve for the three InGaN/GaN LEDs. The output power increases with injection current for all samples up to 100 mA. By comparison, InGaN/GaN LEDs with ZnNi/Au electrodes under UV light irradiation recorded the highest output power up to 100 mA while the InGaN/GaN LEDs with ZnNi/Au electrodes without UV light irradiation marked the second highest output power, followed by the InGaN/GaN LEDs with Ni/Au electrodes. The output power at 20 mA from the InGaN/GaN blue LEDs with ZnNi/Au electrodes under UV light irradiation was enhanced from 18 to 25 mW, as compared to that from the InGaN/GaN blue LEDs with Ni/Au electrodes under no UV light irradiation, at the same annealing temperature of 450 °C. These improvements are thought to be due to the role of O_3 radical (ozone) generated from oxygen during UV irradiation. Since ozone is more reactive than oxygen, it is likely that ozone promotes the oxidation of *p* electrode and forms more gallium oxide than oxygen does, increasing Ga vacancies at the surface of *p*-GaN at the same annealing temperature. These Ga vacancies are assumed to serve as deep acceptors, lowering the schottcky barriers.[10] However, further investigations such as x-ray photoelectron spectroscopy (XPS) are required to clarify the origin. On the other hand, the increase of transmittance in *p*-GaN electrode, probably due to sufficient oxidation of electrode, is thought to be the main reason for the higher light-output power of the InGaN/GaN blue LEDs at low forward-bias voltage.

IV. CONCLUSIONS

We investigated the effect of UV light irradiated annealing on the electrical and optical properties of InGaN/GaN LEDs with ZnNi/Au and Ni/Au *p*-GaN Ohmic metals, in order to make highly transparent and low resistance Ohmic contacts to *p*-type GaN ($p=5\times10^{17}$ cm^{-3}). The specific contact resistances of the ZnNi/Au electrodes were as low as 2.55×10^{-4} Ω cm^2 with UV light irradiation and 2.99 $\times10^{-4}$ Ω cm^2 without UV light irradiation. The light transmittance was also measured to be higher than 85% with UV light irradiation and 75% without UV light irradiation at a wavelength of 460 nm. That is, by applying UV light irradiation to ZnNi/Au films at a fixed annealing temperature of 450 °C, the specific contact resistance was decreased by ~20%, and the transmittance of *p* electrode was increased by ~10%. Regarding the InGaN/GaN LED chip performance, the forward voltage of the chip at 20 mA was decreased from 3.55 to 3.45 V, and the output power was enhanced form 18 to 25 mW by UV light irradiation.

ACKNOWLEDGMENT

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