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Effects of strained InGaN interlayer on contact resistance between *p*-GaN and indium tin oxide

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Indium tin oxide (ITO), with its transparency and strong adhesion to GaN, has been used as a replacement for Ni/Au as a contact on *p*-GaN. However, ITO suffers from high contact resistance on *p*-GaN. In this work, low contact resistance between ITO and the *p*-GaN layer was consistently achieved using various strained InGaN layers as the interface layers between ITO and *p*-GaN layer. The doping of InGaN, whether *n* type or *p* type, has a relatively weak effect on the contact resistance as long as the thickness of the InGaN layer is adequately controlled. The secondary-ion-mass spectroscopy depth profile reveals that the *n*-type InGaN strained contact layer was also heavily doped with Mg. Results of this study demonstrate that the piezoelectric field between InGaN and *p*-GaN is important in reducing the barrier height of Ohmic contact. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2737122]

GaN-based semiconductors are of great importance in fabricating visible and ultraviolet light-emitting diodes (LEDs).[1] In order to improve the light output power of LEDs, the contact resistance must be reduced and the transmission efficiency of the *p*-contact metal layer increased to achieve high-performance nitride-based LEDs. However, obtaining Ohmic contacts on *p*-GaN is difficult because of the wide band gap and the high work function of *p*-GaN and because of the absence of metals having a work function that exceeds that of *p*-GaN. Most conventional nitride-based LEDs use semitransparent Ni/Au on Mg-doped GaN as the *p*-contact material. However, the transmittance of such a semitransparent Ni/Au (5 nm/8 nm) contact is only around 60%-75%. This problem can be solved using transparent indium tin oxide (ITO), instead of Ni/Au, as the contact material. ITO is a hard and chemically inert transparent material with high electrical conductivity and low optical absorption coefficient. The adhesion between ITO and GaN is also strong. These characteristics make ITO an attractive material for fabricating GaN-based LEDs. However, a good Ohmic contact has also been demonstrated to be difficult to achieve when ITO is deposited on *p*-GaN.[2–5]

In this work, LEDs with InGaN strained contact layers (SCLs) of variously doped InGaN strained contact layers on the LEDs with ITO as transparency contact layer (TCL) were compared, and various thicknesses between the *p*-GaN layer and the ITO layer were also compared.

All of the samples used in this work are grown on (0001)-oriented sapphire using a low-pressure metal organic chemical vapor deposition reactor. The gallium, aluminum, indium, and nitrogen sources are trimethylgallium, trimethyaluminum, trimethylindium, and ammonia (NH_3), respectively. Bicyclopentadienylmagnesium (Cp_2Mg) and silane (SiH_4) are the *p*-type and *n*-type dopants, respectively. The epilayer structures of all samples comprise a 25-nm-thick low-temperature GaN buffer layer grown at 550 °C, followed by a 1.5-μm-thick undoped *u*-GaN layer grown at 1050 °C, a 1.5-μm-thick highly conductive *n*-type GaN:Si layer grown at 1050 °C, a five-period InGaN/GaN multiple-quantum-well (MQW) region grown at 760 °C, a 0.2-μm-thick *p*-type AlGaN:Mg grown at 950 °C, a 0.5-μm-thick *p*-type GaN:Mg layer at 950 °C, and 50-Å-thick heavy GaN:Mg-doped layer. Finally, various strained contact layers serve as an Ohmic contact layer. Two experiments, using different dopants and strained contact layers of different thicknesses, were performed to understand how the SCL affects the Ohmic contact between *p*-GaN and the ITO as TCL. In experiment A, 20-Å-thick undoped InGaN, p^+-InGaN and n^+-InGaN were used as the SCLs. In experiment B, 0-, 20-, 40- and 60-Å-thick n^+-InGaN layers were used as the strained contact layer. The as-grown samples were then furnace annealed at 750 °C in N_2 ambient to activate the Mg dopant.

In the device process procedure, wafers were partially etched until the *n*-GaN layer was exposed. Then, the 2000-Å-thick ITO TCL was evaporated onto the SCL to serve as a *p*-electrode. Finally, Cr/Pt/Au (20 nm/50 nm/2 μm) metals were deposited on the *p*-electrodes and the *n*-electrodes as bonding pads. The processed wafer was then ground and polished down to 90 μm for chipping. The dimensions of the LED dies used in this study are $300 \times 360\ \mu m^2$.

First, the LEDs with various dopant SCLs were fabricated to investigate the role of the InGaN SCLs with different dopants. As shown in Table I, LEDs with a 20-Å-thick undoped, heavily Si-doped, and heavily Mg-doped InGaN strained contact layer were compared with those without the SCL. The forward voltages of the LEDs with undoped, heavily Si-doped, and heavily Mg-doped InGaN strained contact layers are 3.28, 3.26, and 3.27 V, respectively, at a

TABLE I. Forward voltage of LED at driving current of 20 mA using strained InGaN contact layer with various dopants.

Strained contact layer	Thickness (Å)	V_f (V)
NA	0	3.58
n^+-InGaN:Si	20	3.26
p^+-InGaN:Mg	20	3.27
Undoped InGaN	20	3.28

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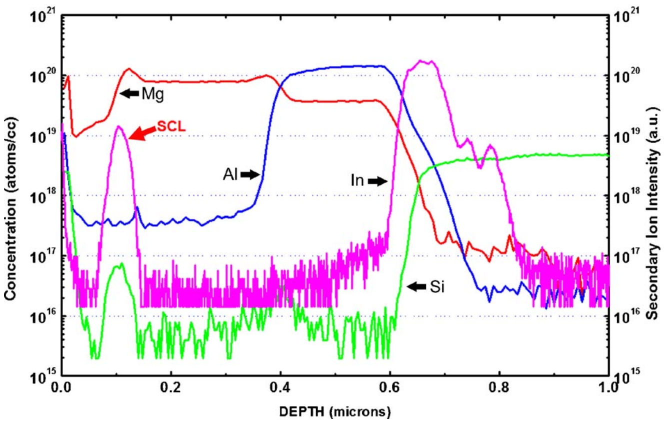

FIG. 1. (Color online) Depth profile of SIMS of a 0.1-μm-thick undoped GaN on the strained contact layer with standard LED structure.

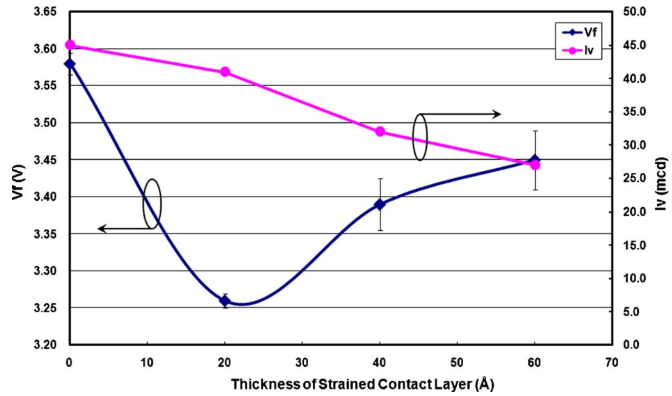

FIG. 2. (Color online) Forward voltage and electrical photoluminance intensity of LED at a driving current of 20 mA as a function of thickness of n^{+}-InGaN.

driving current of 20 mA. But the forward voltage of LED without SCL was as high as 3.58 V at a driving current of 20 mA. Comparing the LEDs with and without InGaN SCL, the forward voltage is about 0.3 V lower. These results reveal that if the SCL were added on the LED and the thickness is small enough that the strain cannot be relieved, regardless of the dopant type of the strained layer the forward voltage can be reduced. The forward voltage of LEDs did not vary with the types of dopant. We believe that the dopant type of the SCLs was less important than the thickness of SCLs.

In order to investigate the role of dopant in SCLs, a 0.1-μm-thick low-temperature grown undoped GaN was placed on the heavily Si-doped SCL with a standard LED structure to verify the doping concentration of the thin SCL. The secondary-ion-mass spectroscopy (SIMS) depth profile is shown in Fig. 1; the Si doping concentration was $6\times10^{16}\ \text{cm}^{-3}$ and the Mg doping concentration was $8\times10^{19}\ \text{cm}^{-3}$ in the SCL, indicating that in the SCL, the doping concentration of Si was much lower than that of Mg, which diffused out of the heavily Mg-doped layer. The SIMS depth profile reveals that even the heavily Si-doped and undoped InGaN SCL were p^{+}-type InGaN, which were formed by the diffusion of Mg from a heavily Mg-doped layer. Previously, Sheu *et al.*,[6] Margalith *et al.*,[2] and Lin *et al.*[4] reported that the ITO layer exhibits good Ohmic contact with the n-type GaN but poor Ohmic contact with the p-type GaN. The results of the SIMS indicate that the mechanism of good Ohmic contact does not only involve the ITO film's forming an Ohmic contact with the n-type InGaN film and tunneling to the p-type GaN film.

The thickness of the InGaN SCL varied among 0, 20, 40, and 60 Å. As presented in Fig. 2, the thickness was varied from 0 to 20 Å and the forward voltage of the LEDs at the driving current of 20 mA decreased from 3.58 to 3.26 V, which lowered the voltage to 0.32 V. As the thickness was varied from 20 through 40 to 60 Å, the forward voltage increased from 3.26 through 3.39 to 3.45 V, respectively. These results indicate that the InGaN SCL can significantly reduce the resistivity of the Ohmic contact. If the thickness of the InGaN SCL is increased, then the forward voltage of the LED at a driving current of 20 mA increases, since the strain in the InGaN layer is relaxed. However, since the band gap of InGaN is equal to or less than 2.67 eV, the InGaN layer absorbs the light emitted from InGaN/GaN MQW, and the increase in the thickness of the InGaN layer reduces the luminance intensity.

Figure 3 is the band diagram of the ITO/p-InGaN/p-GaN heterointerface near the surface of LEDs, where $\Delta\Phi$, $\Delta\Phi'$, and $\Delta\Phi''$ are the image-force-induced (IFI) lowering item without SCL, with SCL, and with strain relaxed SCL, respectively. The main mechanisms of the mediate metal-semiconductor Ohmic contact are thermionic emission electrons, thermionic field emission electrons, and tunneling electrons, as presented in Fig. 3(a). The item of $q\Phi_B$ is the barrier height at the interface without IFI

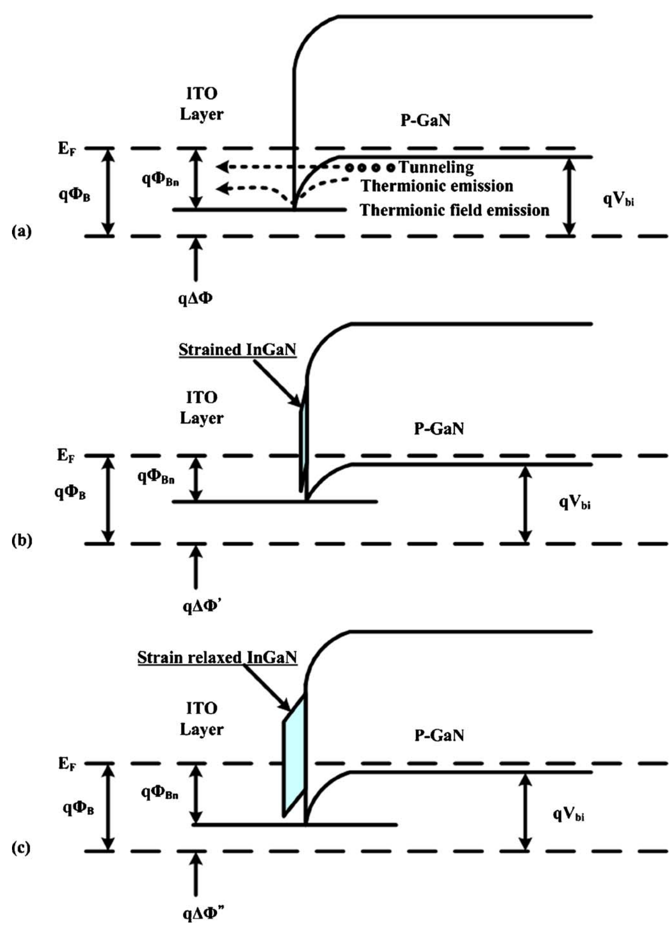

FIG. 3. (Color online) Band diagrams of p-InGaN/p-GaN heterointerface near the surface: (a) without InGaN strained contact layer, (b) with strained InGaN contact layer, and (c) with relaxed InGaN contact layer.

lowering item, which is simply the difference between the metal work function and the electron affinity. Since the electric field at the metal-semiconductor interface produces an image force that reduces the barrier height, $\Delta\Phi$, the IFI lowering item, is given by

$$\Delta\Phi = \sqrt{\frac{qE}{4\pi\varepsilon_s}}, \qquad (1)$$

where E is the piezoelectric field at the metal-semiconductor interface and ε_s is the semiconductor permittivity. Finally, the barrier height with IFI lowering item $q\Phi_{Bn}$ is given by $q\Phi_{Bn}=q\Phi_B-\Delta\Omega$. If an InGaN/GaN heterostructure is present close to the surface, large band bending occurs because of both the large piezoelectric polarization field and the electric field associated with the ionized acceptors at the surface depletion layer. Because a large piezoelectric polarization field formed at the InGaN/GaN layer, the IFI lowering factor, $\Delta\Phi'$, becomes large, hence lowering the metal-semiconductor barrier, $q\Phi_{Bn}$, below that without the SCL. In the article of Takeuchi *et al.*,[7] theoretical results showed that the induced piezoelectric field in a strained $Ga_{0.87}In_{0.13}N$ layer is expected to be 1.1 MV/cm. From Eq. (1), we can estimate the IFI lowering item to be about 0.35 eV; this value agrees with the results in Fig. 2. When the SCL becomes thicker, the piezoelectric field E will decrease due to strain relaxation and the IFI lowering item will become smaller. The heavily doped InGaN near 10^{19} cm^{-3} also reduces the surface depletion layer. Therefore, the tunneling barrier becomes thinner as shown in Fig. 3(b), dramatically reducing the contact resistance.[8]

If the thickness of the InGaN contact layer exceeds the critical thickness, then the strain-induced piezoelectric field disappears because of the lattice relaxation, reducing the IFI lowering factor, $\Delta\Phi''$, and causing the barrier height of the metal-semiconductor to exceed that of the thinner InGaN SCLs. Thickening the InGaN SCL also reduces the tunneling current by increasing the tunneling barrier. Additionally, the potential spike at the InGaN/GaN heterointerface disturbs the transportation of holes, as presented in Fig. 3(c). Therefore, the contact resistance increases with the SCL thickness, because the strain gradually relaxes as the thickness increases.

This study investigated the InGaN SCLs with various dopants and thicknesses. Experimental results indicate that even when various dopants are used in the strained InGaN films to form the contact layer, the Mg doping level is extremely high, even in the heavily Si-doped InGaN SCLs. Additionally, the thickness of the InGaN SCLs is more important than the dopant in the InGaN SCLs. We believe that the piezoelectric field between the strained InGaN layer and the *p*-GaN layer, which lowers the energy barrier at the surface, is important.

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[1] S. Nakamura, T. Mukai, and M. Senoh, Appl. Phys. Lett. **64**, 1687 (1994).
[2] T. Margalith, O. Buchinsky, D. A. Cohen, A. C. Abare, M. Hansen, S. P. DenBaars, and L. A. Coldren, Appl. Phys. Lett. **74**, 3930 (1999).
[3] R. H. Horng, D. S. Wuu, Y. C. Lien, and W. H. Lan, Appl. Phys. Lett. **79**, 2925 (2001).
[4] Y. C. Lin, S. J. Chang, Y. K. Su, T. K. Tsai, C. S. Chang, S. C. Shei, C. W. Kuo, and S. C. Chen, Solid-State Electron. **47**, 849 (2003).
[5] K. M. Chang, J. Y. Chu, C. C. Cheng, and C. F. Chu, Phys. Status Solidi A **2**, 2920 (2005).
[6] J. K. Sheu, Y. K. Su, G. C. Chi, M. J. Jou, C. C. Liu, and C. M. Chang, Solid-State Electron. **43**, 2081 (1999).
[7] T. Takeuchi, S. Sota, M. Katsuragawa, M. Komori, H. Takeuchi, H. Amano, and I. Akasaki, Jpn. J. Appl. Phys., Part 2 **36**, L382 (1997).
[8] K. Kumakura, T. Makimoto, and N. Kobayashi, Jpn. J. Appl. Phys., Part 1 **42**, 2254 (2003).