Full Length Article

Ohmic contact mechanism for RF superimposed DC sputtered-ITO transparent p-electrodes with a variety of Sn$_2$O$_3$ content for GaN-based light-emitting diodes

Tae Kyoung Kim$^a$, Yeo Jin Yoon$^b$, Seung Kyu Oh$^a$, Yu Lim Lee$^a$, Yu-Jung Cha$^a$, Joon Seop Kwak$^{a,*}$

$^a$ Department of Printed Electronics Engineering, Sunchon National University, Jeonnam 540-742, Republic of Korea
$^b$ Seoul Semiconductor, Seoul Viosys, Gyeonggi 425-851, Republic of Korea

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The dependence of the electrical and optical properties of radio frequency (RF) superimposed direct current (DC) sputtered–indium tin oxide (ITO) on the tin oxide (Sn$_2$O$_3$) content of the ITO is investigated, in order to elucidate an ohmic contact mechanism for the sputtered–ITO transparent electrodes on p-type gallium nitride (p-GaN). Contact resistivity of the RF superimposed DC sputtered-ITO on p-GaN in LEDs decreased when Sn$_2$O$_3$ content was increased from 3 wt% to 7 wt% because of the reduced sheet resistance of the sputtered–ITO with the increasing Sn$_2$O$_3$ content. Further increases in Sn$_2$O$_3$ content from 7 wt% to 15 wt% resulted in deterioration of the contact resistivity, which can be attributed to reduction of the work function of the ITO with increasing Sn$_2$O$_3$ content, followed by increasing Schottky barrier height at the sputtered-ITO/p-GaN interface. Temperature-dependent contact resistivity of the sputtered-ITO on p-GaN also revealed that the ITO contacts with 7 wt% Sn$_2$O$_3$ yielded the lowest effective barrier height of 0.039 eV. Based on these results, we devised sputtered-ITO transparent p-electrodes having dual compositions of Sn$_2$O$_3$ content (7/10 wt%). The radiant intensity of LEDs having sputtered-ITO transparent p-electrodes with the dual compositions (7/10 wt%) was enhanced by 13% compared to LEDs having ITO with Sn$_2$O$_3$ content of 7 wt% only.

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1. Introduction

Gallium nitride (GaN)-based light-emitting diodes (LEDs) have attracted a great deal of attention because of their wide application to backlight units of LCD TVs, interior illumination, horticultural lighting, and as a solid-state lighting source for vehicle headlamps [1–3]. In developing such devices, superior electrical and optical characteristics of transparent conducting oxides (TCOs) like transparent p-electrodes are necessary to maximize external quantum efficiency (EQE) of the GaN-based LEDs. A variety of research for improving the EQE of GaN-based LEDs has been reported by using various TCOs on GaN-based LEDs, such as transparent p-electrodes, that produce low ohmic contact resistivity, high transmittance in visible wavelengths, and low sheet resistance, followed by improving the injection efficiency, light extraction efficiency (LEE), and current spreading [4–6]. Among the various TCOs, indium tin oxide (ITO) is widely used for the transparent p-electrode on p-type GaN in LEDs, because ITO has low resistance and high transmittance in the visible light wavelength range [6–9].

Although radio frequency (RF) sputtered-ITO has superior film quality compared to electron-beam evaporated–ITO [7] in deposition of ITO on a p-GaN in LEDs, electron-beam evaporation of ITO is widely used because of plasma damage during RF sputtering of ITO, followed by deterioration of the electrical properties of LEDs with RF sputtered-ITO transparent electrodes [9,10]. Recently, RF superimposed direct current (DC) sputtered-ITO was reported to produce damage-free sputtered-ITO p-electrodes with low contact resistivity on the p-GaN [10,11]. An RF-superimposed DC sputtering method can control the total flux of ions and electrons near the p-GaN surface through adjusting the discharge voltage and plasma potential by the ratio of the RF and DC power [12].

In this study, we investigated the effect of the tin oxide (Sn$_2$O$_3$) content of RF superimposed DC sputtered-ITO on the electrical and optical properties of GaN-based LEDs with sputtered-ITO transparent p-electrodes, in order to elucidate an ohmic contact mechanism for RF superimposed DC sputtered-ITO contacts on p-GaN. For this
purpose, Sn$_2$O$_3$ content of the RF-superimposed DC sputtered-ITO was varied from 3 wt% to 15 wt%. The results show that the sheet resistance of the sputtered-ITO and the Schottky barrier height decrease when increasing the Sn$_2$O$_3$ content from 3 wt% to 15 wt%, which results in the lowest contact resistivity of the sputtered-ITO contacts with Sn$_2$O$_3$ content of 7 wt%. Furthermore, temperature-dependent contact resistivity of the sputtered-ITO on a p-GaN reveals that the ITO contacts with 7 wt% Sn$_2$O$_3$ content show the lowest effective barrier height.

2. Experiments

The GaN wafer was grown on a sapphire substrate by metal-organic chemical vapor deposition. Subsequently, the epitaxial GaN substrate consisted of a 30 nm thick GaN buffer layer, a 4 μm thick silicon-doped GaN layer, five period indium gallium nitride (InGaN)/GaN multiple quantum wells, and a 0.2 μm thick magnesium(Mg)-doped p-GaN layer. After growth, thermal annealing was performed in a nitrogen atmosphere for 15 min at 725 °C to achieve p-type conductivity of the Mg-doped GaN. A line-transmission line model (L-TLM) of 100 × 50 μm$^2$ was executed via photolithography process. After forming a photoresist pattern on p-GaN, native oxide was removed from the p-GaN surface by using buffered oxide etchant (BOE). Then, a 60 nm thick sputtered-ITO layer was deposited, which included a first layer deposited in an RF (80 W) superimposed DC (40 W) magnetron sputtering system (20 nm), and a second layer deposited in an RF (120 W) magnetron sputtering system (40 nm) using indium oxide (In$_2$O$_3$)–tin oxide targets (97:03, 95:05, 93:07, 90:10, and 85:15 wt%). After depositing the ITO layer on p-GaN, annealing was performed to crystallize the ITO layer by using rapid thermal annealing in a nitrogen ambient for 1 min at 600 °C. Pad metal of chromium (30 nm)–gold (300 nm) was deposited by using electron-beam evaporation. Furthermore, a four-point probe, a Hall-effect measurement, current–voltage (I–V) measurement, ultraviolet–visible spectrophotometry (UV–vis) and X-ray photoelectron spectroscopy (XPS) were used for electrical and optical property measurement of the sputtered-ITO layer on the p-GaN. The carrier transport mechanism of the ITO layer–p-GaN interface was analyzed by using a low-temperature probe station and ultraviolet photoemission spectroscopy (UPS).

3. Results and discussion

First, in order to examine the variety of Sn$_2$O$_3$ content in the RF-superimposed DC sputtered-ITO layers, XPS measurements were performed, as shown in Fig. 1. The intensity of the Sn 3d peaks of the sputtered-ITO layer increased with increasing Sn$_2$O$_3$ content in sputtering targets; meanwhile, those of In 3d and O 1s peaks had not changed much, which indicates that the Sn$_2$O$_3$ content in the sputtered-ITO layers had changed in accordance with the sputtering targets without changing In and O content in the sputtered ITO layers. Then, electrical and optical properties of the 60 nm thick, RF superimposed DC sputtered-ITO layers with a variety of Sn$_2$O$_3$ content were investigated, as shown in Fig. 2. From increasing Sn$_2$O$_3$ content of the sputtered-ITO layers from 3 wt% to 15 wt%, as shown in Fig. 2(a), the sheet resistance of the sputtered-ITO was reduced from 287 to 62 Ω/sq, which is attributed to an increase in carrier concentration when Sn$_2$O$_3$ content increased from 3 wt% to 15 wt%, as shown in Fig. 2(b). The transmittance of the sputtered-ITO layers at a wavelength of 450 nm increased from 73.3% to 76.6% by increasing the Sn$_2$O$_3$ content from 3 wt% to 10 wt%. Further increasing Sn$_2$O$_3$ content to 15 wt% decreased the transmittance slightly, as shown in Fig. 2(c). On the other hand, the transmittance at a wavelength of 2000 nm decreased by increasing the Sn$_2$O$_3$ content, as shown in Fig. 2(d). The optical band gap of the sputtered-ITO layers increased from 3.55 eV to 3.66 eV by increasing the Sn$_2$O$_3$ content from 3 wt% to 15 wt%, as shown in Fig. 2(f), where the optical band gap of the sputtered-ITO layers with a variety of Sn$_2$O$_3$ content was obtained, as shown in Fig. 2(e) through Eq. (1) [13]:

$$a \nu v = A (\nu v - E_g)^n$$

where $a$ is absorption coefficient, $\nu v$ is the photon energy, and $E_g$ is the optical band gap. $A$ is constant, $n = 0.5$ for direct band gap material, and $n = 2$ for indirect band gap material.

The increase in optical bandgap as well as the transmittance at 450 nm by increasing the Sn$_2$O$_3$ content from 3 wt% to 10 wt%, as shown in Fig. 2(c) and (f), can be attributed to increases in carrier concentration of the sputtered-ITO layers by increasing the Sn$_2$O$_3$ content, because the increase in carrier concentration in ITO lay-
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