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Temperature-dependent contact resistivity of radio frequency superimposed direct current sputtered indium tin oxide ohmic contact to *p*-type gallium nitride

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ABSTRACT

The temperature-dependent contact resistivity of radio frequency (RF) superimposed direct current (DC) sputtered indium tin oxide (ITO) contacts to p-type gallium nitride (*p*-GaN) films as well as the temperature-dependent sheet resistivity of *p*-GaN films were investigated to understand the carrier transport mechanism of the sputtered ITO ohmic contacts to *p*-GaN. As the measurement temperature was decreased from 400 to 200 K, the contact resistivity increased by three orders of magnitude. Furthermore, the sheet resistivity of the *p*-GaN increased linearly with exp $(1/\text{Temperature(T)})^{1/4}$ from 200 to 340 K, indicating variable-range hopping (VRH) conduction via the Mg-related deep level defect (DLD) band. Based on the VRH conduction model, the effective barrier height between the sputtered ITO and the DLD band were calculated to be 0.12 eV, which is sufficiently low to explain the formation of the low contact resistivity of the RF superimposed DC sputtered ITO contacts to *p*-GaN (~10^{-2} Ω-cm^2).

1. Introduction

In early research, to improve the efficiency of gallium nitride (GaN)-based light-emitting diodes (LEDs), the activation of magnesium (Mg)-doped GaN by post-growth thermal annealing in nitrogen ambient was demonstrated. On the other hand, p-type gallium nitride (*p*-GaN) showed poor conductivity due to the limited current spreading by the low concentration of carriers. Therefore, it is important to deposit a conducting layer on *p*-GaN to spread the current uniformly. This conductive film should not only form ohmic contacts to *p*-GaN, but also be transparent to the light emitted from the active layer. To fabricate good ohmic contact to *p*-GaN, many study groups began to focus on materials and methods [1–5]. Ohmic contact materials were mostly pure single layer or multilayers metal. This satisfied the conductivity and current spreading for ohmic contacts. On the other hand, GaN based LEDs require electrical conductivity and optical transparency.

Transparent conducting oxides (TCO), such as zinc oxide and indium tin oxide (ITO) have been studied widely to overcome this problem [6–10]. Among the various TCOs, ITO is used widely as a transparent electrode on *p*-GaN in LEDs, because ITO is a well-known TCO with a sheet resistivity of ~5.2×10^{-4} Ω-cm and a high transmittance of more than 85% in the visible wavelength range [6–8]. On the other hand, due to plasma damage in the ITO sputtering process, electron-beam evaporated ITO is commonly used to make a transparent electrode on GaN-based top emission LEDs despite its relatively low film quality. Recently, radio frequency (RF) superimposed direct current (DC) sputtered ITO contacts to *p*-GaN were reported to yield a low contact resistivity of ~10^{-2} Ω-cm^2, which is low enough to be used as a transparent electrode on *p*-GaN in LEDs [11]. The benefit of the RF superimposed DC sputtering method is that the discharge voltage and plasma potential during sputtering can be adjusted by the ratio of the RF and DC power, which can control the total flux of ions and electrons near the *p*-GaN surface. For example, Kim et al. reported that the discharge voltage decreased with increasing RF portion in RF superimposed DC sputtering, which reduced the deposition rate of ITO films [12]. Adjusting the discharge voltage using the ratio between the RF and DC power was reported to be important for obtaining a low contact resistivity in the sputtered ITO films on *p*-GaN in LEDs [11]. This suggests that damage-free sputtered ITO films on *p*-GaN with a high transparency and low contact resistivity can be fabricated by RF superimposed DC sputtering.

Because a precise understanding of the carrier transport mechanism in RF superimposed DC sputtered ITO/*p*-GaN interfaces is very important for the formation of transparent electrodes on *p*-GaN in LEDs, this study examined the temperature-dependent contact resistivity of RF superimposed DC sputtered ITO contacts to *p*-GaN films as well as the temperature-dependent sheet resistivity of the *p*-GaN films. The results show that carrier transport at the interface between the sputtered ITO and *p*-GaN can be dominated by carrier flow from the ITO films directly to the dense deep level defect (DLD) band in *p*-GaN.

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2. Experimental

The sample structures were grown on sapphire substrate by metalorganic chemical vapor deposition (MOCVD). The sapphire substrates were cleaned in chemical clean solutions of trichloroethylene, acetone, methanol, and distilled water for 5 min in each step before being loaded into the MOCVD system. Subsequently, the GaN buffer layer, Si-doped GaN layer, indium gallium nitride/GaN multiple quantum wells, and Mg-doped *p*-GaN layer were grown on the cleaned sapphire substrate. In this study, bis-(cyclopentadienyl)-magnesium was used as a p-type dopant source. After growth, thermal annealing in a nitrogen atmosphere was performed for 15 min at 725 °C to achieve p-type conductivity of the Mg-doped GaN, where the hole concentration was 2×10^{17} cm^{-3}.

The temperature dependence of the contact resistivity and sheet resistance were performed in a cryostat using a circular transmission line model (CTLM) [13,14]. The CTLM patterns on *p*-GaN were defined using a standard photolithographic technique. The outer circle radius was 150 μm and the spacing between the inner and the outer radius were varied from 5 to 50 μm. Before being loaded into the vacuum chamber, the samples were cleaned in a buffered hydrofluoric acid solution, rinsed in deionized water and dried with nitrogen. Subsequently, the 60 nm thick ITO films were deposited in a RF superimposed DC magnetron sputtering system, where the RF power was 80 W and the DC power was 40 W. After sputter deposition of the ITO films, rapid thermal annealing at 600 °C for 1 min in nitrogen ambient was performed to yield a low contact resistivity. Finally, the Cr(30 nm)/Au(800 nm) layers were deposited onto the ITO to reduce the resistance between the Au-coated tungsten probe and the ITO film, particularly at a low measurement temperature.

The electrical properties measured by low temperature probe station in the temperature range from 200 to 400 K, which temperature in the thermostat was maintained constant with an accuracy of 1 K, and manual probe station (HP-4145B) at room temperature.

3. Results and discussion

First, to verify the formation of ohmic contacts for the RF superimposed DC sputtered ITO films on *p*-GaN, the current voltage (I–V) characteristics and total resistance were measured as a function of the gap spacing, as shown in Fig. 1. The I–V curve of the RF superimposed DC sputtered ITO films on *p*-GaN was linear for all gap spacings, indicating the formation of good ohmic contacts. The contact resistivity (ρ_c) and sheet resistance (R_s) can be obtained through a plot of the total resistance (R_T) as a function of the gap spacing (d) using the following equation [15]:

$$R_T = R_s/2\pi L\ (d + 2L_T\ )C \tag{1}$$

where L is the contact inner circle radius (150 μm), L_T is the transfer length with the relation of $L_T = (\rho_C/R_S)^{\ 1/2}$ and C is the correction factor. The inset in Fig. 1 shows the linear regression fits of the total resistance vs. the gap spacing measured at room temperature, which leads to a contact resistivity of 1.6×10^{-2} Ω-cm^2 and a sheet resistance of 2.5×10^5 Ω/sq. The contact resistivity of the RF superimposed DC sputtered ITO films on *p*-GaN was low enough to be used as a transparent electrode on *p*-GaN in the LEDs.

To investigate the carrier transport mechanism for the RF superimposed DC ITO ohmic contacts to *p*-GaN, the I–V curves at a gap spacing of 10 μm in the CTLM were measured as a function of temperature from 200 to 400 K, as shown in Fig. 2. The I–V curve became steeper with increasing measurement temperature, which suggests that the carrier transport at the ITO/*p*-GaN interface is dependent on the measurement temperature. The contact resistivity and sheet resistance of *p*-GaN were also calculated as a function of the measurement temperature from the I–V curves for all gap spacings at each measurement temperature. As shown in Fig. 3, the contact resistivity decreased by three orders of magnitude when the measurement temperature was increased from 200 to 400 K, which confirms that the carrier transport phenomena is closely related to the measurement temperature.

According to the classical metal–semiconductor contact theory, carrier transport at the metal–semiconductor contact can account for thermionic emission (Eq. 2-1), thermionic field emission (Eq. 2-2) or field emission (Eq. 2-3) [16]:

$$\rho_C = k/(qA^{**})\ \exp((q\varphi_B)/kT) \tag{2 – 1}$$

$$\rho_C \approx \exp((q\varphi_B)/E_{00}\ ) \tag{2 – 2}$$

$$\rho_C \approx \exp\left((q\varphi_B)/\sqrt{(N_A\ )}\right) \tag{2 – 3}$$

where k is the Boltzmann constant, $A^{*\,*}$ is the Richardson constant, φ_B is the Schottky barrier height, E_{00} is the tunneling parameter, and N_A is the carrier concentration. Eqs. (2-1) and (2-2) indicate that carrier transport at the ITO/*p*-GaN interface is not dominated by thermionic emission and thermionic field emission because the Schottky barrier height (φ_B) between ITO and *p*-GaN should be greater than 2.5 eV considering

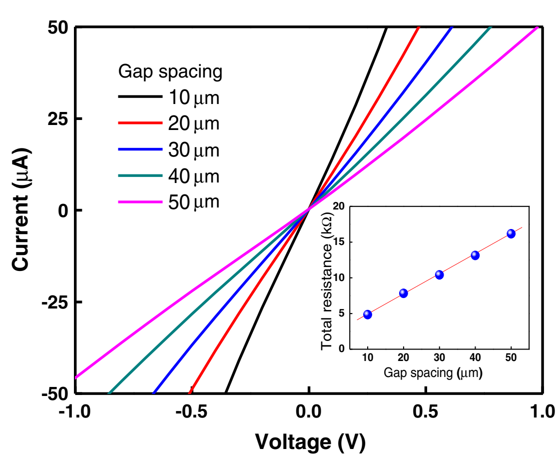

Fig. 1. Variation of I–V characteristics for the RF superimposed DC sputtered ITO contacts to *p*-GaN as a function of gap spacing, which are measured at room temperature. The inset shows variation of total resistance as a function of gap spacing from 10 to 50 μm.

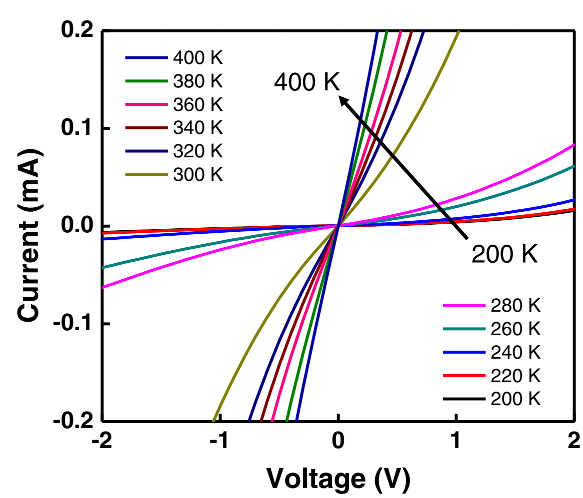

Fig. 2. Variation of I–V curves for the RF superimposed DC sputtered ITO contacts to *p*-GaN as a function of measurement temperature. The gap spacing was 10 μm.

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