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Ohmic contact behavior of aluminum-doped zinc oxide with carbon-doped *p*-GaP epilayer for AlGaInP LEDs applications

Ming-Chun Tseng [a], Dong-Sing Wuu [a, e], Chi-Lu Chen [b], Hsin-Ying Lee [c], Ray-Hua Horng [b, d, *]

[a] Department of Materials Science and Engineering, National Chung Hsing University, Taichung, 402, Taiwan, ROC
[b] Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung, 402, Taiwan, ROC
[c] Department of Photonics, National Cheng Kung University, Tainan, 701, Taiwan, ROC
[d] Institute of Electronics, National Chiao Tung University, Hsinchu, 300, Taiwan, ROC
[e] Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, 701, Taiwan, ROC

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ABSTRACT

Aluminum-doped zinc oxide (AZO) thin films used for ohmic contact layers on carbon-doped GaP window layers (*p*-GaP:C) of AlGaInP light-emitting diodes were fabricated and characterized. AZO thin films with different Zn:Al cycle ratios (15:1, 20:1, and 25:1) were deposited on *p*-GaP:C window layers through atomic layer deposition. The contact characteristics of the AZO thin films on *p*-GaP:C were considerably changed from Schottky contact to ohmic contact after rapid thermal annealing (RTA) at 350 °C for 1 min. The most favorable specific contact resistance of AZO/*p*-GaP:C was evaluated using a circular transmission line model as 6.3×10^{-3} Ω/cm^2. Angle-resolved X-ray photoelectron spectroscopy was employed to understand the ohmic contact behavior of AZO/*p*-GaP:C. After RTA, Zn atoms in the AZO thin films notably diffused into the *p*-GaP:C layers and Ga atoms diffused out of the *p*-GaP:C layer. Therefore, the Ga vacancies were occupied by Zn atoms, which increased the doping concentration in the near-surface region of *p*-GaP:C and reduced the depletion region width of the semiconductor region. Thus, numerous carriers were able to tunnel through the reduced Schottky barrier and those carriers produced the ohmic contact behavior between the AZO and *p*-GaP:C.

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1. Introduction

Quaternary $(Al_{1-x}Ga_x)_{0.5}In_{0.5}P$ alloy materials grown through metal-organic chemical vapor deposition for light-emitting diode (LED) application in the visible spectrum from red ($x = 0$, $E_g = 1.85$ eV) to green ($x = 0.53$, $E_g = 2.25$ eV) have received considerable attention. These materials have been widely used in extremely bright optical products, such as traffic lights, full-color displays, and TV panel backlights [1,2]. Recently, the epilayer quality levels of some AlGaInP-based material systems have been substantially improved through epitaxial techniques; the internal quantum efficiency of AlGaInP-based LEDs has reached approximately 100% [3,4]. However, AlGaInP-based LEDs exhibit low external quantum efficiency (EQE) caused by large differences in the sharp refractive index between the GaP window layer ($n \approx 3.5$) and air ($n \approx 1$) or epoxy ($n \approx 1.5$). Because low EQE is a serious obstacle to application of such LEDs, researchers are motivated to maximize EQE from the active layers of LED devices. Various wide-bandgap materials such as GaP [5,6] and AlGaAs [7] offer satisfactory levels of thickness and electrical conductivity to serve as window layers and uniformly spread injection currents from opaque metal contacts.

A popular approach to this problem is to apply an auxiliary transparent conductive layer (TCL) on the *p*-type window layer to enhance the current-spreading effect and light extraction efficiency (LEE). This TCL can be fabricated from materials such as indium tin oxide (ITO) and Al-doped zinc oxide (AZO) thin film. However, devices that cover their window layers with TCLs fabricated from ITO or AZO tend to exhibit poor ohmic characteristics. The high contact resistance degrades the electrical characteristics of AlGaInP-based LEDs. Therefore, the thermal diffusion of AuBe atoms into the near-surface region of an Mg-doped *p*-GaP window layer before TCL deposition can improve a device's ohmic

* Corresponding author. Institute of Electronics, National Chiao Tung University, 1001 University Road, Hsinchu, 300, Taiwan, ROC.
E-mail address: rhh@nctu.edu.tw (R.-H. Horng).

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characteristics by improving contact resistance between ITO/*p*-GaP:Mg [8] or AZO/*p*-GaP:Mg [9]. It is possible to produce an LED device with a thick *p*-GaP window layer, and to use thermal diffusion of AuBe atoms to improve the device's ohmic characteristics, but such production would be costly. To reduce contact resistance and production cost, and to improve optical absorption, output power, and EQE, a manufacturer can insert a thin carbon-doped GaP contact layer between the TCL and *p*-GaP:Mg [10].

Recently, current-spreading ITO thin film layers have shown promise for enhancing LEE in GaN-based and AlGaInP-based LEDs because ITO offers excellent conductivity and optical transparency [11]. However, indium is a chemically unstable, toxic, and rare metal; its high price and low thermal stability are serious obstacles to its applications in LEDs. Therefore, alternative TCL materials must replace ITO. AZO is widely used in optoelectronic devices because it has superior thermal stability, favorable electronic and optical properties in the visible wavelength region, and a lower fabrication cost than that of ITO [12]. AZO can be used in the current-spreading layers of GaN-based LED devices [13]. Until now, few articles in the literature have investigated AZO thin films as current-spreading layers in direct contact with *p*-GaP:C for thin-film AlGaInP LED applications.

In this work, the ohmic contact formation mechanisms of AZO thin films with different Zn:Al cycle ratios that were grown onto the thin carbon-doped GaP cap layers of AlGaInP LED devices through atomic layer deposition (ALD) are compared and described in detail.

2. Experimental details

AlGaInP LED epilayers were grown on *n*-type GaAs substrates through metal-organic chemical vapor deposition. Each structure consisted of a GaInP etching stop layer, an n^+-GaAs contact layer, *n*-cladding AlGaInP, GaInP-AlGaInP MQWs, *p*-cladding AlGaInP, a *p*-GaP:Mg window layer, a carbon-doped p^+-GaP ohmic contact layer. The epilayers were transferred to silicon substrates with mirror structures through twice wafer-transfer technique, as shown in Fig. 1a. Each AZO thin film was deposited on a *p*-side-up thin-film AlGaInP LED with a specific Zn:Al cycle ratio (15:1, 20:1, or 25:1) by using ALD. The deposition temperature and growth pressure were 200 °C and 0.6 Torr, respectively. Diethylzinc [$Zn(C_2H_5)_2$, DEZn], trimethylaluminum [$Al(CH_3)_3$], and deionized water were used as Zn, Al, and O precursors for depositing the AZO thin films at a growth rate of 0.14 nm/cycle. The ZnO film was doped with Al by introducing the Al precursor into the reaction chamber once during every 15, 20, or 25 cycles of DEZn injections. The depth profiles of the AZO thin film grown on the *p*-GaP:C before and after RTA at 350 °C were obtained through secondary ion mass spectrometry (SIMS, mode: CAMECA IMS-6f). The interfacial chemical state characteristics of AZO/*p*-GaP:C were measured through X-ray photoelectron spectroscopy (XPS) using an Al kα X-ray source with a resolution energy of 0.1 eV. Angle-resolved XPS (ARXPS) was employed to examine the atomic composition of sample surfaces with different takeoff angles of 15°, 45°, and 90°. The current-voltage (I–V) characteristics of AZO/*p*-GaP:C were measured at room temperature using an Agilent 4155B semiconductor parameter analyzer. The contact characteristics of AZO thin films with different Zn:Al cycle ratios (15:1, 20:1, and 25:1) deposited on the *p*-GaP:C were evaluated by circular transmission line model (CTLM). Fig. 1b shows the contact geometry of CTLM which has inner radius (r_0) of 100 μm and gap spacing (d) between inner and outer circle were 25, 50, 100, 150, 200, 250, 300 and 350 μm, respectively. The total resistance, R_T between the contacts for each CTLM structure follows the equation [14]:

$$R_T = \frac{R_s}{2\pi}\left[\left(\ln\frac{r_1}{r_1 - d}\right) + L_T\left(\frac{1}{r_1} + \frac{1}{r_1 - d}\right)\right] \tag{1}$$

where R_s is the sheet resistance of the material, r_1 is the radius of the outer circular contact, d is the gap spacing, and L_T is the transfer length. Since $r_1 \gg d$, Equation (1) can be simplified to

$$R_T = \frac{R_s}{2\pi r_1}(d + 2L_T) \tag{2}$$

The values of L_T and R_s can be obtained from a y-axis intercept and the slope of the plot made between the R_T verses the gap spacing, respectively. The value of specific contact resistance (ρ_c) can be obtained as shown below:

$$\rho_c = (L_T)^2 \times R_s \tag{3}$$

3. Results and discussion

Fig. 2 shows the contact characteristics and CTLM results of AZO thin films fabricated with different Zn:Al cycle ratios (15:1, 20:1, and 25:1). The contact characteristic of pad-to-pad measurement is used CTLM pattern with distance of 350 μm. The schematic diagram of contact characteristics for pad-to-pad measurement is shown in the insert of Fig. 2a. The I–V behavior as-deposited AZO/*p*-GaP:C structures was measured and found to be nonlinear (Schottky contact), which was shown in Fig. 2a. The devices (consisting of AZO thin films deposited onto *p*-GaP:C layers) were annealed at 350 °C for 1 min under a N_2 ambient. After annealing, the contact behaviors of AZO/*p*-GaP:C changed from Schottky contact to ohmic contact, which was shown linear I-V characteristics. AZO thin films in contact with *p*-GaP:C cap layers exhibit various contact properties. To study such contact properties, a CTLM was used to evaluate the specific contact resistance (ρ_c) and sheet resistance (R_s) values. The resistance versus distance relation of AZO thin film measured

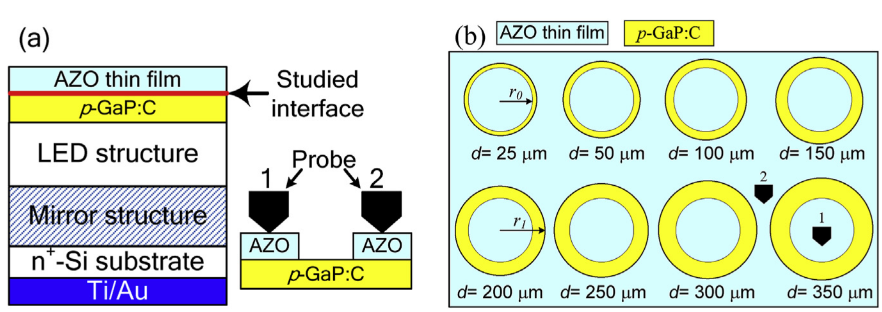

Fig. 1. (a) Schematics of AlGaInP-based LED structure with AZO contact layer and studied interface and (b) contact geometry of the CTLM contact pads.

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