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Electrical properties of RF-sputtered Zn-doped GaN films and *p*-Zn-GaN/*n*-Si hetero junction diode with low leakage current of 10^{-9} A and a high rectification ratio above 10^5

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ABSTRACT

Zn-doped GaN films have been deposited on Si (100), SiO_2/Si (100), and glass substrates by RF reactive sputtering at 100–400 °C with single cermet targets. The Zn-GaN films deposited with a 10% Zn cermet target showed the good electrical properties, wurtzite structure, and the *p*-type behavior without a thermal annealing process. At room temperature (RT), the 400 °C-deposited film with mobility (μ) of 17.7 cm^2/V·s had the highest hole concentration (n_p) of 6.1×10^{17} cm^{-3} and electrical conductivity of 1.72 S·cm^{-1}. The values of band gap (E_g) for Zn-GaN films were found in the range of 2.83–3.01 eV. Furthermore, to prove the *p*-type behavior of Zn-doped GaN, the *p*-GaN/*n*-Si hetero junction diode was also made by RF reactive sputtering. At room temperature, the device showed the leakage current of 1.65×10^{-9} A at −5 V, the turn-on voltage of ~2.3 V, and the breakdown voltage above −20 V. The high rectification (on/off) ratio of the diode was calculated to be $\sim 1.08 \times 10^5$ at bias of ±5 V and $\sim 2.3 \times 10^5$ at the bias of ±20 V. The electrical characteristics of the diode were also tested at the temperature range of 25–150 °C. By using equations based on the standard thermionic-emission (TE) mode and the Cheungs' method, the barrier height, ideality factor, and series resistance of the diode were also determined.

1. Introduction

The successful investigation of high-quality doping in III-nitride semiconductors by incorporating elements such as Cu, Mg, and Zn has an important role for the development of optoelectronic and electronic devices [1–4]. In recent years, the fabrication of Mg doping and post-growth treatments in GaN and InGaN films have been greatly benefits for developing LEDs or power effect devices [5–7]. High conductivity with the high hole concentration of the *p*-layer will lead to the improvements on the turn-on voltage, breakdown voltage, and leakage current in electronic devices [8,9]. In addition to Mg doping, Zn doping into GaN also has been studied for application in electric device since 1970s. The purpose of adding Zn dopant is to reduce the defect concentration in GaN films [10,11]. Ejder and Fagerstrom reported the Zn-doped GaN grown by the gas-phase epitaxial technique [10]. Their samples were highly compensated and had high resistivity ($\sim 10^8$ Ω.m). The band gap with the existence of Zn was found at ~3.2 eV. Pankove and Hutchby had investigated the photoluminescence of Zn-implanted GaN [11]. At room temperature, the photoluminescence spectrum of Zn-implanted GaN had a peak of 2.87 eV. With the range of $1–20 \times 10^{18}$ cm^{-3} of Zn concentration, the emission efficiency decreased linearly. Chiou et al. studied Zn-implanted GaN samples by angle-dependent X-ray absorption near edge structure (XANES) measurements [12]. By XANES spectral analysis, the Ga–N bonds lying in the bilayer had lower energies than bonds along the c-axis, which was recognized to the polar nature of GaN film. Li et al. reported Mg-doped and Zn-doped GaN powders by direct nitridation of Ga_2O_3 under a flowing NH_3 gas [13]. At room temperature, the Mg-GaN and Zn-GaN powders showed the bright blue-violet emission of ~3.05 and 2.81 eV, respectively. Feng et al. investigated the Zn-doped InGaN grown by MOCVD method [14]. The GaN band edge emission had the relatively weak PL peak at 3.42 eV, while the InGaN band edge emissions due to phase separation spread over a wide range of 2.1–3.1 eV. Tong et al. investigated Zn-doped and high quality $In_xGa_{1-x}N$ ($x \leq 0.3$) grown by low pressure MOCVD technique [15]. The photo emission of Zn-doped InGaN showed a peak at 448 nm, corresponding to blue

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emission. The PL intensity of Zn-doped InGaN film was 30-time higher than that of undoped InGaN film. Zhao et al. reported the low-resistance and high-transmission Ohmic contact to the *p*-GaN by Zn^+ implantation [16]. The lowest specific contact resistance was found to be $5.46 \times 10^{-5}\ \Omega\cdot cm^2$, reaching after $1 \times 10^{16}\ cm^{-2}$ Zn^+ implantation. The transparency of the electrodes was also improved at higher annealing temperature.

All previous papers had Zn-doped GaN and its alloys grown by MOCVD above 800 °C and by the ion implantation technique. The low temperature process at and below 400 °C has not been declared. Furthermore, Zn-doped GaN films to be made by sputtering into the homo-junction or hetero-junction diode also have been rarely reported. In this work, Zn-doped GaN films (Zn ~ 10%) have been deposited at different temperatures on Si (1 0 0), SiO_2/Si (1 0 0), and glass substrates by RF reactive sputtering. The technique of RF reactive sputtering has been chosen as a method to grow the *p*-type Zn-GaN and to fabricate the electric devices with the benefits of lower sputtering temperature, lower equipment cost, and safe working atmosphere without using the toxic metal-organic precursors and ammonia [17–19]. The Si-based electronic devices have been extensively used for its low cost, large wafer size, and easy availability [20–22]. To prove the success of Zn doping in the *p*-type GaN, a totally sputtering-made *p*-Zn-GaN/*n*-Si hetero junction diode was also fabricated. The electrical *I–V* characteristics of devices were determined by thermionic emission (TE) mode at a wide range of testing temperature.

2. Experimental details

Z*n*-doped GaN films were deposited on Si (100), SiO_2/Si (100), and transparent glass substrates by RF reactive sputtering for the considerations of different characterizations. The cermet targets for sputtering were prepared by hot pressing the mixture of Zn, Ga, and GaN powder. The [Zn]/([Zn]+[Ga]) molar ratio in cermet target was kept at 10%. Before sputtering, the chamber pressure was vented to 1×10^{-6} torr by diffusion pump to avoid the oxygen, moisture, and impurities. The substrates were heated at 100–400 °C and the working pressure was kept at 9×10^{-3} torr. The Zn-GaN target was sputtered under RF power of 150 W for 1 h with the mixture of Ar and N_2 gases at a flow rate of 5 sccm for each.

In addition, *p*-Zn-GaN/*n*-Si hetero junction diode was also deposited directly on *n*-Si (1 0 0) substrate by RF sputtering without using a buffer layer. This diode was designed on *n*-Si wafer with the "top-top" electrode configuration. The *n*-Si (1 0 0) wafer had polished surface, sheet resistance of ~1–10 Ω·cm, diameter of 2 inches, thickness of ~550 µm, the carrier concentration of $\sim 10^{15}\ cm^{-3}$, and mobility of $\sim 200\ cm^2/V\cdot s$. The *p*-GaN film as a diode was deposited at 300 °C under RF power of 150 W for 30 min. Pt and Al metals were used to make Ohmic contacts for *p*-Zn-GaN/*n*-Si hetero junction structure by using steel masks. The electrodes were sputtered at 200 °C for 30 min with the pure Al and Pt targets (99,999%) on the tops of *p*-GaN film and *n*-Si (100) substrate, respectively.

The bulk concentration, electrical conductivity, and mobility of Zn-GaN films were measured by Hall measurement (HMS–2000, Ecopia) at room temperature with the magnetic field of 0.51 T. Crystalline phase and growth orientation of Zn-GaN films were analyzed by X-ray diffraction (XRD, D8 Discover, Bruker). Scanning electron microscopy (SEM, JSM–6500F, JEOL) was used to observe the surface morphology of Zn-GaN films. Energy dispersive spectrometer (EDS, JSM–6500F, JEOL) equipped on SEM was used to analyze composition of films. Ultraviolet–Visible (UV–Vis) Spectrometer (V–670, Jasco) was used to determine the absorption spectra for Zn-GaN films grown on glass substrates. Temperature-dependent transport behavior of *p*-GaN/*n*-Si hetero junction diode was determined by using Semiconductor Device Analyzer (Agilent, B1500A) in the temperature range of 25–150 °C. All parameters of diodes were calculated by using the TE mode and Cheungs' method.

3. Results and discussion

3.1. Structural and surface morphological characteristics

Fig. 1 shows XRD patterns of Zn-GaN films deposited at 100–400 °C on Si (100) substrates. XRD results indicated that all Zn-GaN films had a wurtzite structure and were polycrystalline. With the SEM measurement shown later, the thicknesses of all Zn-GaN films were above 2 µm, the effect of substrate on film properties can be minimized.As the growth temperature increased from 100 to 300 °C, the dominant peak contributing from the nonpolar *m*-$(1\,0\,\bar{1}\,0)$ crystalline plane increased its intensity. For the 400 °C-deposited film, the other strong peak from the $(1\,0\,\bar{1}\,1)$ diffraction plane with the peak position at $2\theta = 36.68°$ also appeared. Lattice constant, volume of unit cell, and full-width-half-maximum (FWHM) values for the $(1\,0\,\bar{1}\,0)$ peaks of Z*n*-GaN films are shown in Table 1. FWHM values for the $(1\,0\,\bar{1}\,0)$ peaks were 0.343, 0.281, 0.266, and 0.262° for Zn-GaN films deposited at 100, 200, 300 and 400 °C, respectively. FWHM value decreased while lattice constants of a (Å) and c (Å), and volume of unit cell ($Å^3$) of Z*n*-GaN films increased with the rise in the substrate temperature. Crystallinity of Zn-GaN was greatly improved at higher growth temperature. The other diffraction peaks from the $(1\,1\,\bar{2}\,0)$, $(2\,0\,\bar{2}\,0)$,$(1\,1\,\bar{2}\,2)$, and $(2\,0\,\bar{2}\,1)$ crystal planes with the peak positions at $2\theta = 57.77$, 67.67, 68.84, and 70.25°, respectively, were also observed. By comparing with our previous work, the nonpolar *m*-$(1\,0\,\bar{1}\,0)$ peak position for the undoped 100 °C-GaN film was located at 2θ of 0.32.54°, and the FWHM for the $(1\,0\,\bar{1}\,0)$ peaks was determined at 2θ of 0.336° [23]. In this study, the $(1\,0\,\bar{1}\,0)$ peak position was slightly shifted to the lower angle at $2\theta = 32.4°$ for Zn-doped GaN film due to the large Zn^{2+} size of 0.62 Å replacing the smaller Ga^{3+} size of 0.53 Å. In addition, no second phases and any phase separation had been detected in our sputtered Zn-GaN films, which indicate that the Zn dopant absolutely dissolves into GaN by RF reactive sputtering to form solid solution or the Zn cation replaces

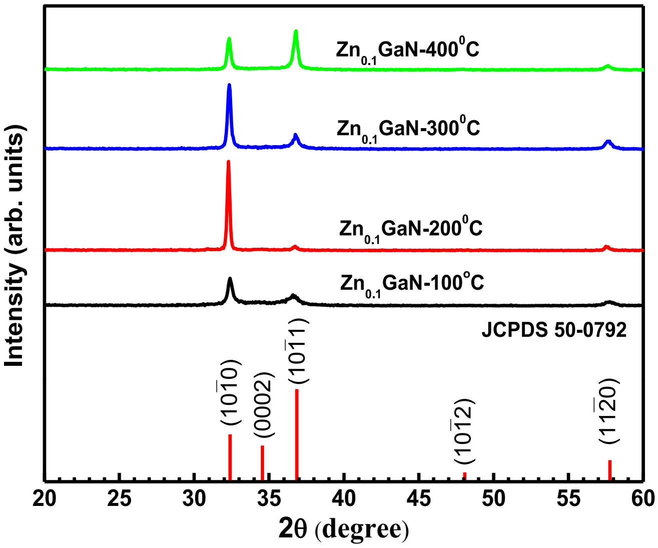

Fig. 1. XRD patterns of the Zn-doped GaN films deposited at 100–400 °C on Si (1 0 0) substrates by RF reactive sputtering.