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Performance improvement mechanisms of *i*-ZnO/$(NH_4)_2S_x$-treated AlGaN MOS diodes

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ABSTRACT

The intrinsic ZnO (*i*-ZnO) film was deposited by a vapor cooling condensation system and used as the dielectric layer of the AlGaN metal–oxide–semiconductor (MOS) diodes. Before the deposition of the *i*-ZnO dielectric layer, the AlGaN surface was treated using $(NH_4)_2S_x$ solution. In view of the lattice match of the *i*-ZnO film and the reduced surface state density of the $(NH_4)_2S_x$-treated surface, the quality of the *i*-ZnO/AlGaN interface was improved. According to the experimental results, the *i*-ZnO/$(NH_4)_2S_x$-treated MOS diodes revealed the lower leakage current, the lower interface state density, and the high electrical performances compared with the *i*-ZnO/untreated ones. Furthermore, the X-ray photoelectron spectroscopy and the charge neutrality level model were used to analyze the conduction band offset and the valence band offset of the *i*-ZnO/AlGaN interface. The valence band offset of the *i*-ZnO film contacted with the untreated and the $(NH_4)_2S_x$-treated AlGaN layer was 1.53 eV and 1.96 eV, respectively. The conduction band offset of the *i*-ZnO film contacted with untreated and $(NH_4)_2S_x$-treated AlGaN layers was 0.77 eV and 1.20 eV, respectively. The mechanisms of the enhanced conduction band offset were attributed to the effective reduce of interface states by using the $(NH_4)_2S_x$ surface treatment.

1. Introduction

Recently, in view of the significant progress of epitaxial growth and fabrication techniques [1–4], nitride-based compound semiconductors have been widely and successfully used in the gas sensors [5,6], electronic devices [7,8] and optoelectronic devices [9,10]. To reduce the leakage current and improve the power-handling capacity, the GaN-based metal–oxide–semiconductor high-electron mobility transistors (MOS-HEMTs), in which the gate dielectric layer was inserted between the metal gate and the GaN-based compound semiconductors, were developed. Various gate dielectric layers have been investigated [11–13]. To avoid the possible defects and the surface states caused by the lattice mismatch interface between the gate dielectric layer and the GaN-based semiconductors, the zinc oxide (ZnO) is a promising material due to the advantage of the same wurtize crystalline and the nearly identical lattice constant with the GaN-based semiconductors. Recently, the intrinsic ZnO (*i*-ZnO) film with low carrier concentration and high resistivity was grown at low temperature by our designed vapor cooling condensation system [14,15]. Furthermore, the resulting AlGaN/GaN MOS-HEMTs with *i*-ZnO gate dielectric layer deposited by the vapor cooling condensation system were reported, previously [16]. However, the native oxide resided on the surface of the GaN-based semiconductors led to the formation of high surface state density and Fermi level pinning. To improve the performances of the resulting devices by using the $(NH_4)_2S_x$ surface treatment, not only could native oxide on the surface of the GaN-based semiconductors be completely removed, but also Ga—S bonds were formed and nitrogen-related vacancies occupied as well [17,18]. By using the $(NH_4)_2S_x$ surface treatment, the improved performances of the ZnO-gated AlGaN/GaN MOS-HEMTs were previously demonstrated [19,20]. To investigate the physical mechanisms, the study of the interface state density and the band alignment of the *i*-ZnO/AlGaN interface is an important issue. In this work, the electrical characteristics of the *i*-ZnO/AlGaN MOS diodes with and without the $(NH_4)_2S_x$ surface treatment were measured and compared. Furthermore, the X-ray photoelectron spectroscopy (XPS) measurement was carried out to determine the valence band offset and the conduction band offset of the *i*-ZnO film contacted with the untreated and the $(NH_4)_2S_x$-treated AlGaN layers. A systematic analysis was used to verify the function of the $(NH_4)_2S_x$ surface treatment.

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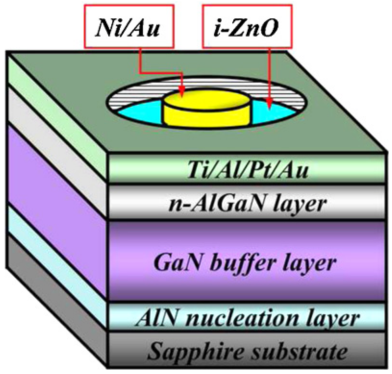

Fig. 1. Schematic configuration of the *i*-ZnO/AlGaN MOS diodes.

2. Device structure and fabrication

Fig. 1 shows the schematic configuration of the *i*-ZnO/AlGaN MOS diodes. The epitaxial layers used in this work were grown on *c*-plane sapphire substrates by a metalorganic chemical vapor deposition system. The epitaxial structure consisted of a 20-nm-thick AlN nucleation layer, a 2-μm-thick GaN buffer layer, and a 0.1-μm-thick $Al_{0.22}Ga_{0.78}N$ layer (referred as AlGaN layer, hereafter) with electron concentration of 6.8×10^{17} cm^{-3}. The ohmic metals of Ti/Al/Pt/Au (25/100/50/150 nm) were deposited by an electron-beam evaporator and the ohmic contact was formed by rapid thermal annealing at 850 °C in N_2 ambient for 2 min [21]. The inner radius and the outer radius of the concentric ohmic contact ring were 150 μm and 400 μm, respectively. Before the deposition of *i*-ZnO film, the $(NH_4)_2S_x$ surface treatment was performed to passivate and completely remove the surface states resided on the AlGaN surface. During the $(NH_4)_2S_x$ surface treatment, the samples were first dipped into the yellow $(NH_4)_2S_x$ solution at 60 °C for 30 min, and the samples were then rinsed with deionized water and blown dry with nitrogen gas. A 50-nm-thick *i*-ZnO film was deposited on the AlGaN layer using the vapor cooling condensation system. During the deposition of the *i*-ZnO film, the samples were attached on the liquid nitrogen-cooled stainless steel plate in the chamber of the vapor cooling condensation system. The sublimated ZnO vapor materials originated from the heated ZnO powder (purity of 99.99%) were deposited and condensed on the cooled AlGaN layer. The electron concentration and mobility of the deposited ZnO films were 7.6×10^{15} cm^{-3} and 3.2 cm^2/V s, respectively. Finally, the circular pattern Ni/Au (20/100 nm) metals with a radius of 100 μm were deposited by an electron-beam evaporator. For the comparison purpose, the *i*-ZnO/untreated AlGaN MOS diodes were fabricated on the same samples by the same fabrication process except the $(NH_4)_2S_x$ surface treatment.

To investigate the function of the $(NH_4)_2S_x$ surface treatment on the *i*-ZnO/AlGaN interfacial property, the band alignment, the conduction band offset, and the valence band offset of the *i*-ZnO/AlGaN interface were analyzed. The epitaxial samples were divided into five groups and cleaned in the chemical solutions of trichloroethylene, acetone, and methanol. Among them, three group samples (referred to as group A, group B, and group C) were maintained in the as-cleaned condition. The other two group samples (referred to as group D and group E) were dipped into the yellow $(NH_4)_2S_x$ solution at 60 °C for 30 min, and then were rinsed with deionized water and immediately blow dried by N_2 gas. The group E samples were maintained in the $(NH_4)_2S_x$-treated condition. An 1-μm-thick *i*-ZnO film was deposited on the group B samples using the vapor cooling condensation system. Moreover, a 5-nm-thick *i*-ZnO film was deposited on the as-cleaned group C samples and the

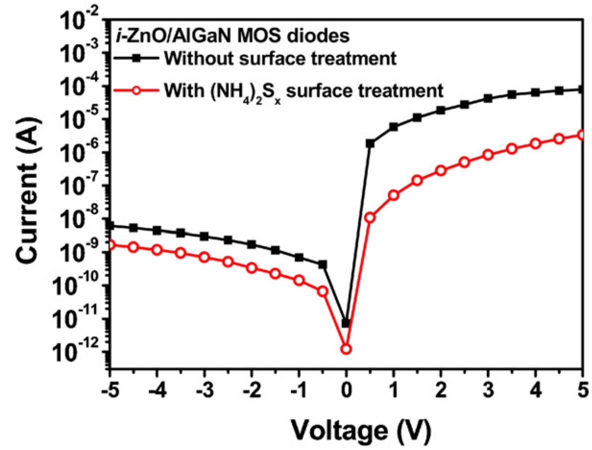

Fig. 2. Current–voltage characteristics of the *i*-ZnO/untreated and the *i*-ZnO/$(NH_4)_2S_x$-treated AlGaN MOS diodes.

$(NH_4)_2S_x$-treated group D samples using the vapor cooling condensation system, respectively. By using the measured XPS spectra, the thick *i*-ZnO film (1 μm) and the thin *i*-ZnO film (5 nm) deposited on AlGaN layers were used to determine the energy of the *i*-ZnO film and the energy of the *i*-ZnO/AlGaN interface, respectively. To avoid possible contamination in the XPS measurement, the five group samples were immediately loaded into the vacuum chamber of the XPS system (ULVAC-PHI, PHI 5000 Versa Probe). The XPS measurements were carried out using a monochromatic Al Kα radiation (1486.6 eV) as the excitation source. The C 1s peak at 284.6 eV was taken as the reference energy. To enhance surface sensitivity, the XPS data were taken at a take-off angle of 45° from the surface.

3. Experimental results and discussion

Fig. 2 shows the current–voltage (*I*–*V*) characteristics of the *i*-ZnO/untreated and the *i*-ZnO/$(NH_4)_2S_x$-treated AlGaN MOS diodes with the 50-nm-thick *i*-ZnO dielectric layer measured by an Agilent 4156C semiconductor parameter analyzer. Compared with the *i*-ZnO/untreated AlGaN MOS diodes, the leakage current of the *i*-ZnO/$(NH_4)_2S_x$-treated AlGaN MOS diodes operated at +5 V was decreased from 7.79×10^{-5} A to 3.39×10^{-6} A. On the other hand, the leakage current of the *i*-ZnO/$(NH_4)_2S_x$-treated AlGaN MOS diodes operated at −5 V was decreased from 6.16×10^{-9} A to 1.68×10^{-9} A. It could be seen that the leakage current of the *i*-ZnO/$(NH_4)_2S_x$-treated MOS diodes was significantly lower than that of the *i*-ZnO/untreated MOS diodes. Fig. 3(a) and (b) shows the high frequency (1 MHz) capacitance–voltage (*C*–*V*) characteristics of the *i*-ZnO/untreated and the *i*-ZnO/$(NH_4)_2S_x$-treated MOS diodes measured by an HP 4284A, respectively. To estimate the interface state density (D_{it}) of the *i*-ZnO/AlGaN MOS diodes, the photo-assisted *C*–*V* measurement was utilized in this work [22]. In general, the inversion layer of the *i*-ZnO/AlGaN MOS diodes was difficult to be achieved because of the extremely low minority carrier generation rate of the GaN-based semiconductors. In the photo-assisted *C*–*V* measurement, the light with energy larger than the bandgap of the GaN-based semiconductors was utilized to generate the electron-hole pairs and to form the inversion layer. In the first measurement procedure, the *i*-ZnO/AlGaN MOS diodes were applied the voltage swept from the accumulation layer (6 V) to the depletion layer (−12 V) in dark. The *i*-ZnO/AlGaN MOS diodes were illuminated by an Xe lamp (selected wavelength of 325 nm) for 60 s and then were applied by a constant bias voltage of −12 V. The generated holes were attracted toward to the *i*-ZnO/AlGaN interface to form the inversion layer by applying a bias voltage