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AlGaN/GaN Schottky barrier diodes on silicon substrates with various Fe doping concentrations in the buffer layers

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ABSTRACT

This study demonstrated AlGaN/GaN Schottky barrier diodes (SBDs) for use in high-frequency, high-power, and high-temperature electronics applications. Four structures with various Fe doping concentrations in the buffer layers were investigated to suppress the leakage current and improve the breakdown voltage. The fabricated SBD with an Fe-doped AlGaN buffer layer of 8×10^{17} cm^{-3} realized the highest on-resistance (R_{ON}) and turn-on voltage (V_{ON}) because of the memory effect of Fe diffusion. The optimal device was the SBD with an Fe-doped buffer layer of 7×10^{17} cm^{-3}, which exhibited a R_{ON} of 31.6 mΩ-cm^2, a V_{ON} of 1.2 V, a breakdown voltage of 803 V, and a buffer breakdown voltage of 758 V. Additionally, the low-frequency noise decreased when the Fe doping concentration in the buffer layer was increased. This was because the electron density in the channel exhibited the same trend as that of the Fe doping concentration in the buffer layer.

1. Introduction

GaN-based devices are highly suitable for high-frequency, high-power, and high-temperature electronics applications [1–3] because GaN-based materials demonstrate several high-level electronic and material properties such as a wide bandgap, a high breakdown electrical field, high saturation velocity, and high thermal stability [4]. Recently, GaN-based Schottky barrier diodes (SBDs) capable of high-speed and low-loss operation have been preferentially developed as unipolar devices [5–7]. Such devices have a Baliga's figure of merit (FOM) >100 times higher than those of Si-based devices. In addition, GaN-based devices grown on Si substrates have been extensively developed because of advantages such as a large wafer size and low cost [8–9]. Several methods have been reported to improve the breakdown voltage (V_{BR}) of GaN-on-Si devices; for example, the inclusion of intentional dopants such as carbon (C) and iron (Fe), which enable strong semi-insulating buffers without impairing the crystal quality of epitaxial layers [10–11]. The high-power performance of such devices can be attributed to the strong semi-insulating buffer, which improves the breakdown characteristics and minimizes buffer leakage [10–11].

In this study, AlGaN/GaN SBDs on Si (111) substrates with four Fe doping concentrations in the buffer layer were investigated to further improve the breakdown voltage and current-voltage (I–V) characteristics. The four Fe-doped concentrations used in the AlGaN buffer layer were 5×10^{17}, 6×10^{17}, 7×10^{17}, and 8×10^{17} cm^{-3}. Moreover, the reverse recovery characteristics and low-frequency noise measurements of the AlGaN/GaN SBDs are discussed in detail in this paper.

2. Experiment

Cross sections of the proposed AlGaN/GaN SBDs fabricated with the four Fe doping concentrations in the AlGaN buffer layer are shown in Fig. 1. The structures of the AlGaN/GaN SBDs were grown on 6-inch Si (111) wafers by using metalorganic chemical vapor deposition. Fig. 1 shows that each wafer consisted of a 300 μm thick unintentionally-doped (UID) AlN buffer layer, a 4 μm thick $Al_{0.25}Ga_{0.75}N$ buffer layer, a 300 nm thick UID GaN channel layer, a 18 nm thick UID $Al_{0.25}Ga_{0.75}N$ layer, and a 1.5 nm thick GaN top layer. In this study, the Fe doping concentrations of the $Al_{0.25}Ga_{0.75}N$ buffer layer were 5×10^{17} (structure A), 6×10^{17} (structure B), 7×10^{17} (structure C), and 8×10^{17} cm^{-3} (structure D), which represented the nominal doping levels introduced into the buffer layer during epitaxial growth.

The devices were processed through conventional optical lithography and the lift-off process. SBD fabrication was initiated through mesa isolation by using the reactive ion etching system with BCl_3 and Cl_2 combination gases. Cathode ohmic contacts were prepared through the electron beam evaporation of a multilayered Ti/Al/Ni/Au (25/130/25/200 nm) sequence followed by rapid thermal annealing at 850 °C for 30 s in a nitrogen ambient. Subsequently, 20-μm-long anode fingers

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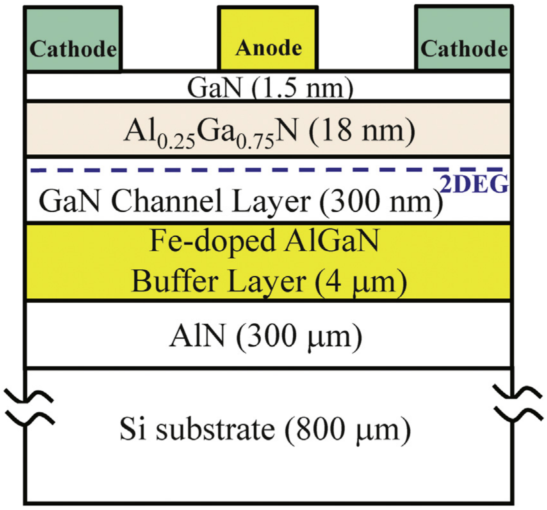

Fig. 1. Cross sections of the proposed AlGaN/GaN SBDs fabricated with the four Fe doping concentrations in the AlGaN buffer layer. In this study, the Fe doping concentrations of the $Al_{0.25}Ga_{0.75}N$ buffer layer were 5×10^{17} (structure A), 6×10^{17} (structure B), 7×10^{17} (structure C), and 8×10^{17} (structure D) cm^{-3}.

with widths of 100 μm were formed through Ni/Au (25/200 nm) evaporation and the lift-off process. The anode-to-cathode contact distance (L_{AC}) was 20 μm. Hall measurements of the two-dimensional electron gas (2DEG) mobility (μ_{2DEG}), sheet resistance (R_{SH}), and sheet carrier concentration (n_{Hall}) were employed to characterize structures A–D with various Fe-doped AlGaN buffer layers. The μ_{2DEG} values of 1356, 1314, 1268, and 1170 cm^2/V-s associated with the n_{Hall} values of 1.85×10^{13}, 1.86×10^{13}, 1.94×10^{13}, and 2.24×10^{13} cm^{-2} were obtained from structures A–D, respectively. Additionally, the R_{SH} values were 499, 510, 507, and 477 Ω/square for structures A–D, respectively. The results of this study suggested that high Fe doping concentrations in the buffer layer can increase n_{Hall} in the 2DEG channel and decrease μ_{2DEG}. The increase in n_{Hall} was probably caused by the improved semi-insulating buffers that resulted from the increased F doping concentration.

I–V characterization and reverse recovery performances were evaluated on all the diodes by grounding the cathode and biasing the anode from −1000 to 5 V by using an Agilent B1505 and a PQR-6000 diode tester. The low frequency noise measurement setup in this study consisted of a control unit with a vector signal analyzer (Agilent N9010A), a dynamic signal analyzer (Agilent 35670A), a precision spectrum analyzer (Agilent E444xA), and a signal source analyzer (Agilent E5052B) that were attached directly to the wafer and biased using a direct current (DC) source (Agilent 4142B).

3. Results and discussion

Fig. 2(a) shows the forward I–V characteristics for AlGaN/GaN SBDs with different Fe-doped AlGaN buffer layers at room temperature. The DC characteristics of the AlGaN/GaN SBDs are listed in Table 1. The on-resistance (R_{ON}) and turn-on voltage (V_{ON}) at a current density of 1 A/cm^2 normalized to the active area are shown in Fig. 2(a). The R_{ON} values were 29.1, 29.9, 31.6, and 60.0 mΩ-cm^2 for structures A–D, respectively, at 300 K. In addition, The V_{ON} values were 1.2, 1.2, 1.2, and 1.8 V for structures A–D, respectively. The fabricated SBD with an Fe-doped AlGaN buffer layer of 8×10^{17} cm^{-3} realized the highest R_{ON} and V_{ON} because of the memory effect and the epitaxial growth effects of Fe doping such as the upward diffusion of Fe atoms during growth [12–13]. Additionally, the memory effect of Fe diffusion increased the traps in the epitaxial layer, thereby introducing a trade-off in forward I-V performance [14].

By using a theoretical I–V relationship, the Schottky barrier heights (SBHs) and ideality factors (n) in the various SBDs can be determined from Fig. 2. The I–V relationship is expressed as follows [15]:

$$J = A^{**}T^2 \exp\left(-\frac{\Phi b}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right] \quad (1)$$

where A^{**}, the effective Richardson constant, is 26.04 A cm^{-2} K^{-2} for n-GaN; J is the current density; T is the measurement temperature in Kelvin; Φb is the SBH; n is the ideality factor and k is Boltzmann's constant. The ideality factors determined using from Eq. (1) were 2.64, 2.53, 2.64, and 2.66 for structures A–D, respectively. Additionally, the extracted SBHs were 0.71, 0.73, 0.72, and 0.76 eV for structures A–D, respectively. These results revealed that with the exception of structure D, n and the SBH did not undergo significant changes when the Fe doping concentration in buffer layer was increased.

The reversed I–V characteristics of the devices for the four structures are shown in Fig. 2(b). The reversed currents of the SBDs at −40 V for the Fe-doped AlGaN buffer layers in structures A–D were 2.88×10^{-3}, 2.67×10^{-3}, 5.97×10^{-4}, and 7.23×10^{-5} mA/mm, respectively. The results indicated that the increased Fe doping concentration in the AlGaN buffer layer effectively suppressed the reversed leakage current.

The reverse breakdown and buffer breakdown characteristics of the SBDs with various Fe-doped AlGaN buffer layers are shown in Fig. 3(a) and (b). The breakdown voltage (V_{BR}) is defined at the leakage current

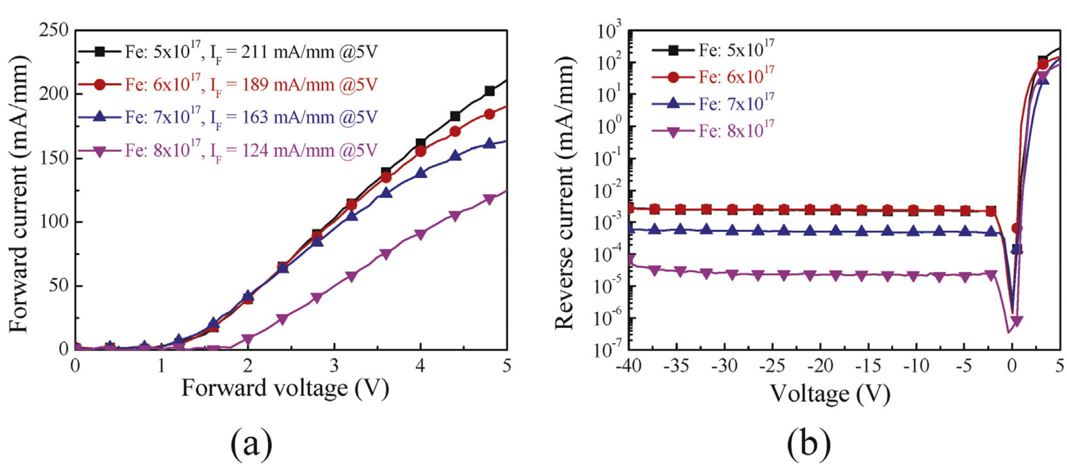

Fig. 2. (a) Forward I–V characteristics of the SBDs with various Fe-doped AlGaN buffer layers. (b) Reverse I-V characteristics of the SBDs with various Fe-doped AlGaN buffer layers.

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