The Leakage Current of the Schottky Contact on the Mesa Edge of AlGaN/GaN Heterostructure

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***Abstract*—A test structure, which is called the ridge-furrow structure, is used to evaluate the leakage current of the Schottky contact on the mesa edge of an AlGaN/GaN heterostructure. The mesa edge leakage currents were measured at different temperatures from 300 to 500 K and analyzed. The conduction-band-edge energy distribution at the mesa edge is simulated by the Integrated Systems Engineering Technology Computer-Aided Design. Based on the simulation results, the electric field strength can be obtained as a function of reverse bias voltage. The mesa edge leakage current is found to agree with the predicted characteristics, which is based on the Frenkel–Poole emission model. Therefore, we believe that the Frenkel–Poole emission dominates the mesa edge leakage at temperatures between 300 and 500 K.**

***Index Terms*—AlGaN/GaN, characteristic electric field strength, Frenkel–Poole, leakage current, mesa edge, ridge-furrow structure.**

I. Introduction

An AlGaN/GaN heterostructure field-effect transistor (HFET) is attracting much attention as a promising candidate for high-power, high-temperature, high-breakdown, and high-frequency electronic devices, and remarkable achievements were made in the recent years [1]–[4]. However, an excessive leakage current of the reverse-biased Schottky gate contact is identified as a key indicator of poor device reliability. The basic mechanisms of a gate leakage current [5], [6] and a leakage current reduction [5], [7], [8] have been the subjects of several investigations. Tan *et al.* [5] reported that the gate leakage current of a conventional HFET should consist of surface, bulk, and mesa edge leakage components. With the help of a guarded surface leakage test structure, the surface and bulk leakage currents are separated, and the mesa edge leakage can be avoided. Zhang *et al.* [6] analyzed the leakage current mechanisms in the Schottky contacts to both n-GaN and AlGaN/GaN at different temperatures and concluded that tunneling current dominates at temperature below 150 K, whereas the Frenkel–Poole emission dominates at temperature higher than 250 K. Xiao *et al.* [7] and Shiu *et al.* [8] reported that the AlGaN/GaN HFETs with implantation isolation show much reduced gate leakage current than those with mesa etching isolation. However, to date, no attempt has been made to analyze the mesa edge leakage current of an AlGaN/GaN heterostructure and its mechanism, although similar analysis has been reported in InAlAs/InGaAs heterostructure [9]. In this letter, a test structure called ridge-furrow structure (similar to that in [9]) is used to evaluate the mesa edge leakage current. The results show that the mesa edge leakage current can play an important role in an AlGaN/GaN HFET. In addition, for the first time, we observe that the mesa edge leakage current obeys the Frenkel–Poole emission law from room temperature to 500 K, similar to the bulk leakage current reported in [6].

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II. Experimental Details

The test structures were fabricated on an unintentionally doped $Al_{0.15}Ga_{0.85}N$/GaN (25 nm/2.5 μm) heterostructure grown by metal–organic chemical vapor deposition on a sapphire substrate (the GaN layer consisted of high-resistivity lower layer 2.3 μm and high-quality upper layer 200 nm). Mesas were formed by using chlorine and inductively coupled plasma (ICP) etching. Sputtered Ti/Al/Ni/Au (20/130/50/150 nm) ohmic contacts were annealed at 900 °C for 30 s. The contact resistance of the ohmic contacts was extracted as 2.1 Ω mm, and the 2-D electron gas (2DEG) sheet resistance was 453 Ω/sq. The Ni/Au (50/100 nm) Schottky contacts were formed by an e-beam evaporation and were annealed at 400 °C for 1 min.

The Schottky metals usually cover the mesa edge sidewalls in order to connect the gate on the surface of an AlGaN to a pad on the etched surface of a GaN in an HFET device. The objective of the ridge-furrow structure, shown in Fig. 1, is to evaluate the mesa edge leakage current. The 2DEG is grounded by the ohmic contact metals. The measured leakage current contains four components, namely, the bulk AlGaN leakage current, the bulk GaN leakage current, the mesa edge leakage current, and the surface leakage current. The surface leakage component can be ignored because it is usually several orders lower than the other components if the bias voltage is not too high [5]. Both the bulk AlGaN leakage current (I_{AlGaN}) and the bulk GaN leakage current (I_{GaN}) can be estimated from the normal circle dot Schottky contact structure (radius = 40 μm, without mesa edge sidewalls), and we assume that I_{AlGaN} and I_{GaN} are area (not perimeter) related. The linear current density of the mesa edge leakage current $(J_{\Gamma\mathrm{mesa}})$ per unit length (in amperes per micrometer) can be expressed as

$$J_{\Gamma\mathrm{mesa}} = (I_{\mathrm{total}} - I_{\mathrm{AlGaN}} - I_{\mathrm{GaN}})/l_{\mathrm{mesa}} \quad (1)$$

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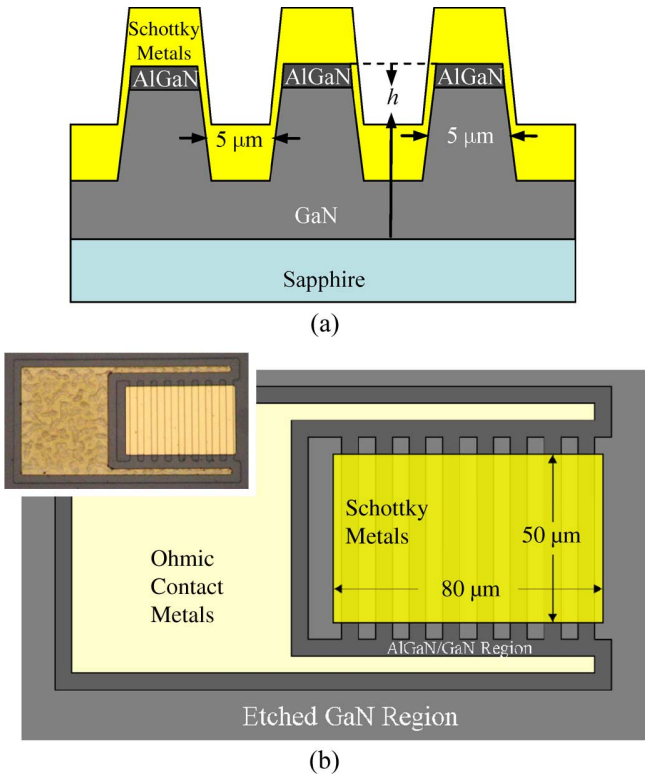

Fig. 1. (a) Cross section and (b) top schematic views of ridge-furrow structure (the inset shows the photograph of the structure).

where l_{mesa} is the total edge length of the following structure:

$$l_{\mathrm{mesa}} = 16 \times 50\ \mu\mathrm{m}. \tag{2}$$

III. Results and Discussion

Fig. 2 shows both the forward and reverse I–V characteristics of the three components of a ridge-furrow structure shown in Fig. 1. Both I_{AlGaN} and I_{GaN} were assumed area dominant and extracted from the circle Schottky pads (radius $= 40\ \mu$m), whereas $J_{\Gamma\mathrm{mesa}}$ was extracted by using (1) from the test structure. The leakage current of the Schottky contact on etched surface of a GaN (I_{GaN}) is much smaller than that on an AlGaN (I_{AlGaN}) because the electric field in an AlGaN layer under the Schottky metals is much stronger than that in the high-resistant GaN layer. The mesa edge leakage current $(J_{\Gamma\mathrm{mesa}} l_{\mathrm{mesa}})$ is the major part of the leakage current in the ridge-furrow structure. In comparison with I_{AlGaN}, $J_{\Gamma\mathrm{mesa}} l_{\mathrm{mesa}}$ does not increase very rapidly as the reverse bias voltage increases due to a smaller increase of the electric field strength at the mesa edge with respect to the absolute value of higher reverse bias voltage.

To analyze the physical mechanism of $J_{\Gamma\mathrm{mesa}}$, we first simulated the electrostatic potential distribution, or the conduction band energy distribution at the mesa edge, using the Integrated Systems Engineering Technology Computer-Aided Design (Fig. 3, -1 V reverse bias). The height and the angle of the etching ramp are measured from the scanning electron microscope (SEM) photograph after the ICP etching (before evaporating the Schottky metals), whereas the parameters such as the relative dielectric permittivity, band gap, electron affinity,

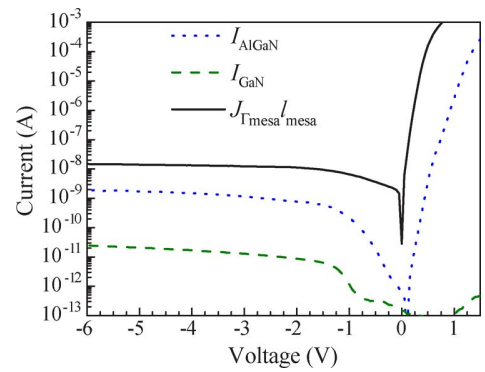

Fig. 2. I–V characteristics of the three components of a ridge-furrow structure: bulk AlGaN leakage current (I_{AlGaN}, dotted line), bulk GaN leakage current (I_{GaN}, dashed line), and the mesa edge leakage current ($J_{\Gamma\mathrm{mesa}} l_{\mathrm{mesa}}$, solid line).

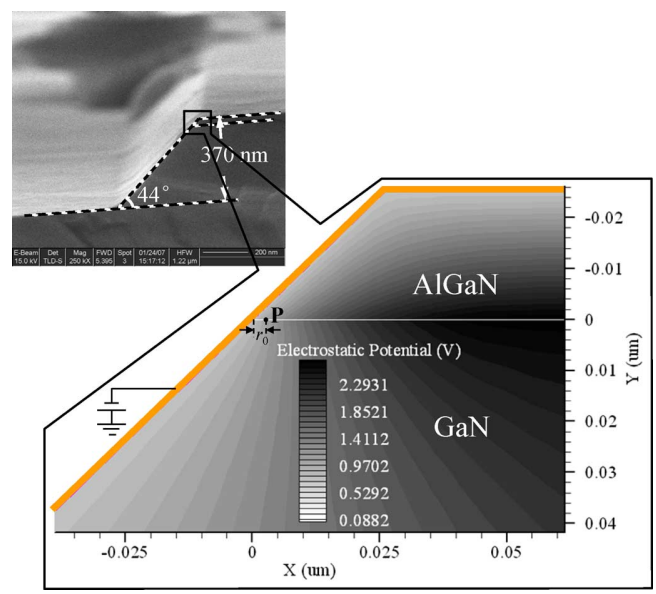

Fig. 3. Electrostatic potential distribution at the mesa edge (reverse bias is -1 V) and the SEM photograph of the etching step (not including the Schottky metals).

and polarization-induced charge could be calculated from the equations in [10] or [11]. The work function of the Schottky metals is defined as 5.0 eV according to [12].

The surface electric field strength is a critical parameter in many compact models of the Schottky leakage current such as the Fowler–Nordheim tunneling and the Frenkel–Poole trap-assisted emission model [5], [6], [13]. However, the electric field strength is a function of position in the area of the mesa edge and reaches the maximum value at the cross line of the mesa edge sidewall and the AlGaN/GaN interface. A characteristic field strength (F_c) should be defined for proper application of the leakage current model. The leakage current from the metals to the GaN should dominate because the AlGaN barrier is higher than the GaN barrier. Only the electric field in the GaN is considered in our analysis. We choose the Frenkel–Poole model because the temperature dependency on leakage current is found in our experiment, and also because there are many traps before and after ICP etching [14]. The traps, which are

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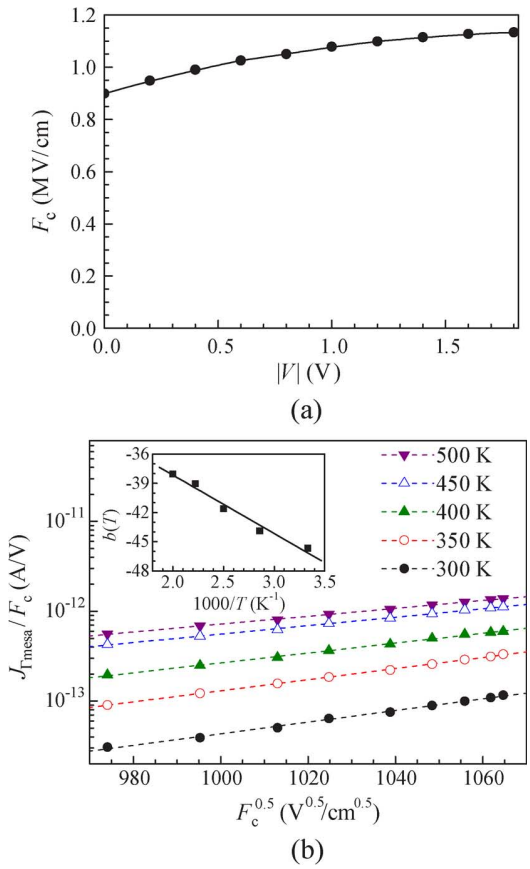

Fig. 4. (a) Characteristic electric field strength F_c as a function of the reverse bias voltage V in the case of the Schottky contact on AlGaN/GaN mesa edge [from simulation results and (3)]. (b) Plot of $J_{\Gamma\mathrm{mesa}}/F_c$ as a function of $F_c^{0.5}$ at different temperatures, where $J_{\Gamma\mathrm{mesa}}$ is the extracted leakage current density at mesa edge [from experimental data and (1)]; the inset shows intercepts $b(T)$ as a function of $1000/T$ to obtain φ_t.

very near to the cross line between the mesa edge sidewall and the AlGaN/GaN interface, should have the greatest effect on the Frenkel–Poole emission. The barrier peak of the electron emitting from such a trap locates at point **P** (Fig. 3), where both the external electric field strength (F_{ext}) in the GaN side and the trap (positive ion) induced electric field strength (F_{ion}) should be

$$F_{\mathrm{ext}}(\mathbf{P}) = F_{\mathrm{ion}}(\mathbf{P}) = F_c = q/4\pi\varepsilon_0\varepsilon_s r_0^2 \tag{3}$$

and they should have approximately opposite direction. (According to the simulation, F_{ext} in the GaN side at point **P** has a direction approximately along the AlGaN/GaN interface.) ε_s is the relative dielectric permittivity of the GaN at high frequency ($\varepsilon_s = 5.35$ [6]), and r_0 is the distance along the AlGaN/GaN interface from the metal–semiconductor interface. As shown in Fig. 4, F_c does not increase very fast as the reverse bias voltage increases.

If the leakage current at the mesa edge $(J_{\Gamma\mathrm{mesa}})$ obeys the Frenkel–Poole emission model [6], it can be expressed as

$$\begin{aligned} J_{\Gamma\mathrm{mesa}} &= CF_c \exp\left[-q(\varphi_t - \sqrt{qF_c/\pi\varepsilon_0\varepsilon_s})/kT\right] \\ &\equiv F_c \exp\left(m(T)\sqrt{F_c} + b(T)\right) \end{aligned} \tag{4}$$

where φ_t is the barrier height for electron emitting from the trap state (usually the energy difference between conduction-band-edge and trap state), C is a constant, and $m(T)$ and $b(T)$, as shown in the following equations, are the slope and intercept of $\ln(J_{\Gamma\mathrm{mesa}}/F_c) \sim \sqrt{F_c}$ line, respectively:

$$\begin{aligned} m(T) &\equiv \sqrt{q/\pi\varepsilon_0\varepsilon_s} \cdot q/kT \\ b(T) &\equiv -q\varphi_t/kT + \ln C. \end{aligned} \tag{5}$$

As shown in Fig. 4(b), a linear dependence of $\ln(J_{\Gamma\mathrm{mesa}}/F_c)$ on $F_c^{0.5}$ and $b(T)$ on 1/T are found, which means that the Frenkel–Poole model matches the AlGaN/GaN mesa edge leakage current. By $b(T) \sim 1000/T$ plot, $q\varphi_t$ is extracted as 0.517 eV. Our results show that the mesa edge leakage current at room temperature or higher temperatures has the same mechanism, i.e., the Frenkel–Poole trap-assisted emission, in comparison with the cases of both the Schottky contact on AlGaN/GaN or bulk GaN [6] and surface leakage current of the Schottky contact on AlGaN/GaN [5].

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