Surface Fermi Level Pinning of Semipolar (1122) n-type GaN Surfaces Grown on m-Plane Sapphire Substrates

Sungmin Jung,1 Sung-Nam Lee,2 Kwang-Soon Ahn,3 and Hyunsoo Kim1,*

1School of Semiconductor and Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Jeonju 561-756, Korea
2Department of Nano-Optical Engineering, Korea Polytechnic University, Siheung, Gyeonggi 429-793, Korea
3School of Chemical Engineering, Yeungnam University, Gyeongsan, Gyeo 712-749, Korea

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The Schottky barrier height and the S-parameter of the semipolar (1122) n-type GaN grown on m-plane sapphire substrate were investigated by using Schottky diodes fabricated with the different work functions of metals including Cu, Pd, and Pt. The Barrier inhomogeneity model applied to temperature dependent current-voltage characteristics of Schottky diodes revealed the mean barrier heights of 0.86, 0.77, and 0.82 eV for the Cu, Pd, and Pt contact, respectively. The extracted S-parameter was nearly zero, indicating a pinning of the surface Fermi level at approximately 0.8 eV below the conduction band. This could be attributed to the substantial crystallographic defects of semipolar GaN as verified from the atomic force microscope and x-ray diffraction measurements.

Keywords: fermi level pinning, semipolar n-GaN, schottky barrier

1. INTRODUCTION

Nonpolar or semipolar GaN semiconductors have become significantly important owing to their potential applications to high-efficiency optoelectronic and electronic devices, especially for the light-emitting diodes (LEDs) with a quantum-confined Stark effect free by eliminating the polarization-induced internal electric fields in the active regions.1-4 The absence of the polarization-induced internal electric fields is also expected to induce the normally-off operation of GaN-based heterojunction field-effect transistors due to the possible control of 2-dimensional electron gas generated at the hetero-interfaces,5 suggesting that the nonpolar or semipolar GaN could be promising for future electronic devices.

In order to develop and fabricate noble GaN-based devices with a nonpolar and semipolar plane, it is essentially required to understand the electrical characteristics of the metal contacts on these GaN surfaces, specifically, the effect of the metals work-function (ΦM) on the Schottky barrier height (SBH, ΦB), namely, the S-parameter defined as dΦB/dΦM, and its corresponding carrier transport mechanism at metal/GaN interfaces.6 For example, the S-parameter of the moderately doped polar c-plane n-GaN surface was reported to be 0.3877 and 0.41,8 indicating that the metal contact on the polar n-GaN surface more likely follows the Schottky-Mott theory than other semiconductors such Si and GaAs. In addition, our group also observed the S-parameter of plasma-treated polar n-GaN to be as low as of 0.17,9 which was attributed to the plasma-induced surface states, which resulted in a surface Fermi-level pinning. However, the S-parameter and corresponding carrier transport mechanism for semipolar n-type GaN surfaces have not yet been reported.

In the present study, we investigated the SBH and the S-parameter of (1122) semipolar n-GaN planes by using Schottky diodes fabricated with metals having different work functions, i.e., Cu (4.65 eV), Pd (5.12 eV), and Pt (5.65 eV). The (1122) semipolar surface was investigated due to its higher In incorporation rate compared to other semipolar planes of (1011), nonpolar (1120) a-plane, and (1010) m-planes,10,11 thus resulting in the fabrication of better light emitters. The current-voltage-temperature (I-V-T) measurements showed anomalous temperature dependence in both the SBH and ideality factor (n), suggesting that the barrier inhomogeneity model should be employed to explain the carrier transport at semipolar n-GaN surfaces instead of the thermionic emission (TE) model. The S-parameter extracted using the barrier inhomogeneity model was nearly zero, indicating a perfect pinning of the surface Fermi level. This could be attributed to the presence of the substantial interface states caused by crystallographic defects.

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*Corresponding author: hskim7@jbnu.ac.kr
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2. EXPERIMENTAL PROCEDURE

Semipolar (11$ar{2}$2) n-GaN (Si-doped) wafers were grown on the m-plane sapphire substrates by the metalorganic chemical vapor deposition (MOCVD) system. The structure is 1.4 µm-thick n-GaN/1.0 µm-thick undoped GaN/m-plane sapphire. The detailed growth procedure can be found elsewhere.[11] Hall-effect measurements revealed the carrier concentration ($N$) of $7.5 \times 10^{17}$ cm$^{-3}$ and the Hall mobility ($\mu$) of 47.9 cm$^2$/V·s$^{-1}$. The atomic force microscope (AFM) and x-ray diffraction (XRD) measurements were also performed to investigate the structural properties of semipolar n-GaN wafers. Schottky diodes were fabricated using a standard photolithographic technique and metal deposition by an e-beam evaporator, as shown in the inset of Fig. 1. For example, firstly, a Ti/Al (30 nm/80 nm) scheme was deposited on the surrounding contact region, followed by rapid thermal annealing at 550°C for 1 min in nitrogen ambient to form an Ohmic contact, yielding the specific contact resistance for the order of low $10^{-4}$ Ω·cm$^2$. A 100 nm thick Cu, Pd, and Pt were then deposited onto the central Schottky region with a diameter of 50 µm. Note that the buffered oxide etchant (BOE) was always used to remove the contamination layer of the n-GaN surface prior to the deposition of metal. The electrical characteristics of the Schottky diode were measured using a parameter analyzer (HP4156A), in which the chuck temperature was changed from 300 to 480 K.

3. RESULTS AND DISCUSSION

Figure 1 shows the semi-logarithmic $I$-$V$ characteristics of the Schottky diodes fabricated with Cu, Pd, and Pt, as measured at 300 K. The inset shows the optical microscopic image of Schottky diodes fabricated with Pd contact. Note that the reverse leakage currents are relatively large (~$5 \times 10^{-7}$ A at −2 V) and the rectification ratio (~1200 at ±2 V) is small for all Schottky diodes, while the forward $I$-$V$ characteristics are less significantly dependent on the Schottky contact, indicating that the electrical characteristics of Schottky diodes fabricated on semipolar n-GaN are relatively poor.

To analyze the Schottky characteristics, an appropriate conduction model should be used according to the tunneling parameter ($E_{00}$), which is given by $E_{00} = (qh/4\pi n(N/e_m^*)^{1/2}$, where $h$ is Planck’s constant, $e$ is the dielectric constant of the semiconductor ($e = 8.9\varepsilon_0$), and $m^*$ the electron effective mass ($m^* = 0.2m_e$). For example, thermionic emission (TE) dominates when $kTqE_{00} > 1$, thermionic field emission (TFE) when $kTqE_{00} \sim 1$, and field emission (FE) when $kTqE_{00} \ll 1$. For the semipolar n-GaN with $N = 7.5 \times 10^{17}$ cm$^{-3}$, the TE model is expected to be valid since the calculated $kTqE_{00}$ value was as large as 2.2, i.e.:

$$I = A A^\ast T^2 \exp\left(-\frac{q\Phi_0}{kT}\right) \left[\exp\left(\frac{q\mu}{n kT}\right)-1\right].$$

where $A$ is the contact area, $A^\ast$ is the Richardson constant, and $\Phi_0$ is the effective SBH. Based on the theoretical fitting using Eq. (1), as illustrated in the solid line in Fig. 1, the effective SBH ($\Phi_0$) was estimated as 0.34, 0.33, and 0.34 eV, and the ideality factor ($n$) was 3.4, 4.6, and 4.0 for the Cu, Pd, and Pt contacts, respectively. It should be noted that the obtained SBHs are much lower than the theoretical prediction, e.g., ~1.1 eV for Pt contact, and the ideality factors are much larger than the unity. This indicates that the pure TE model is not suitable to explain the carrier transport behavior of our samples. To obtain more accurate Schottky parameters and to further analyze the carrier transport properties, $I$-$V$-$T$ measurements were performed for all Schottky diodes in a temperature range of 300 - 480 K, as shown in Fig. 2.

![Fig. 1. The semi-logarithmic $I$-$V$ characteristics of the Schottky diodes fabricated with Cu, Pd, and Pt. The insets show the optical microscopic image of the fabricated Schottky diode.](image1)

![Fig. 2. The semi-logarithmic forward $I$-$V$-$T$ characteristics of all Schottky diodes.](image2)