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Metal induced inhomogeneous Schottky barrier height in AlGaN/GaN Schottky diode

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The dependence of *barrier height inhomogeneity* on the gate metal has been investigated for the AlGaN/GaN Schottky diode. The analysis from the electroreflectance spectroscopy measurement for different types of Schottky gate metals tried (in this case, Au, Pt, Pd, and Ni) reveals that the *surface donor states* of AlGaN/GaN heterostructure strongly depends on the type of Schottky gate metals used, which suggests that barrier height inhomogeneity is strongly dependent on the gate metal. The X-ray photoelectron spectroscopy also reveals a strong correlation between the barrier height inhomogeneity and the gate metal type. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4811756]

Due to its high conductivity and large breakdown fields, the AlGaN/GaN *high electron mobility transistor* (HEMT) is a promising candidate for applications in the area of high power switching. Nevertheless, it is essential to improve the device's breakdown voltage characteristic for successful industrial applications. Such characteristic is strongly affected by internal field strength of the AlGaN barrier, which property in turn depends on the type of Schottky gate metals used. Investigations on various Schottky gate metals have drawn considerable interest for their peculiar properties of *two dimensional electron gas* (2DEG) states,[1] the Fermi level pinning properties,[2] and the associated gate leakage mechanisms.[3,4] It has been also suggested that Schottky gate metals may be responsible for the presence of inhomogeneous barrier heights in the Schottky diodes, which property still remains not fully understood.[5–7] Such is supported by our recent finding, where we have reported that different gate metals for the AlGaN/GaN heterostructure result in the reduction of density of states for the *surface donor states* (SDS).[8] For instance, different energy distributions are observed for the *metal-semiconductor* (M-S) interface states when Au or Ni are used as the gate metal, which suggests that the gate metal at the M-S interface may have a critical role in the Schottky barrier inhomogeneity (SBI).

In this work, we investigate the possible correlations between the M-S interface states and the SBI by considering Au, Pt, Pd, and Ni as Schottky gate metals. For the optical and electrical properties of each device, we have utilized the measurements from the *electro-reflectance spectroscopy* (ER), the ultra-violet photoelectron spectroscopy, the *temperature-dependent current-voltage measurement* (I-V-T), and the *X-ray photoelectron spectroscopy* (XPS). By analyzing these results, we shall discuss on the possible sources of Schottky barrier inhomogeneity.

The AlGaN/GaN HEMT wafer structure was grown by the *metal-organic chemical vapor deposition* (MOCVD). The AlN nucleation layer, $Al_xGa_{1-x}N$ transition layer, 3 μm of GaN buffer, and 25 nm of $Al_{0.27}Ga_{0.73}N$ barrier were deposited on 6 in. Si wafer in (111)-direction. The sheet carrier concentration and the electron mobility of the 2DEG obtained from the Hall measurement were $n_s = 1.03 \times 10^{13}\,\mathrm{cm}^{-2}$ and $\mu_e = 2040\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$, respectively. For the I-V-T measurements, the Schottky diode mesa was etched in a circular shape. A ring-shaped ohmic contact (Ti/Al/Ni/Au alloy) deposited at the surface of GaN was annealed at rapid thermal annealing. Four types of metals, Au, Pt, Pd, and Ni, have been chosen for the Schottky metal candidates. These metals, each with diameter of 100 μm, were deposited over the center of the ring-shaped metallic ohmic contact via the electron beam evaporation technique at the rate of 1 Å/s with the target temperature stabilized at ~90 °C. The Schottky metal and the ohmic contact are separated by 30 μm. For the ER spectroscopy, two separate van der Pauw samples have been fabricated for each Pt and Pd Schottky-gates following the scheme described by Shin *et al.*[8]

For the AlGaN/GaN heterostructure Schottky metal, the changes in the sheet concentration of its SDS or the M-S interface states over the Fermi level have been investigated using the ER spectroscopy. As illustrated in Figure 1, the internal field of the AlGaN barrier gets saturated at the threshold voltages of 4.4, 4.4, 4.2, and 3.6 eV for Au, Pt, Pd, and Ni, respectively. Such results imply a complete depletion of 2DEG at the threshold voltages.[9] As illustrated in Table I, both sheet carrier concentration of 2DEG and the changes in the sheet concentration of the SDS can be estimated from the consideration of AlGaN barrier's internal field obtained from the ER spectroscopy and from the Schottky diode's work function obtained from the UPS.[8] he electron affinity of AlGaN, χ_{AlGaN}, was extracted as 3.07 eV.[8]

From the Table I, it can be readily seen that the sheet carrier concentration of the 2DEG, i.e., revealed by the ER measurement $n_{s,ER}$, decreases with the increase in the reduction of the SDS. Such result supports the argument that Schottky metal changes the SDS into another quantum state, as suggested by Ibbetson *et al.*[1] The reduction of the SDS implies the generated M-S interface states exist below the Fermi level, which can be a leakage path for electrons to tunnel through the AlGaN barrier. Such result hints that different reductions of the SDS, depending on the gate metal in the AlGaN/GaN heterostructure, might have a strong relation

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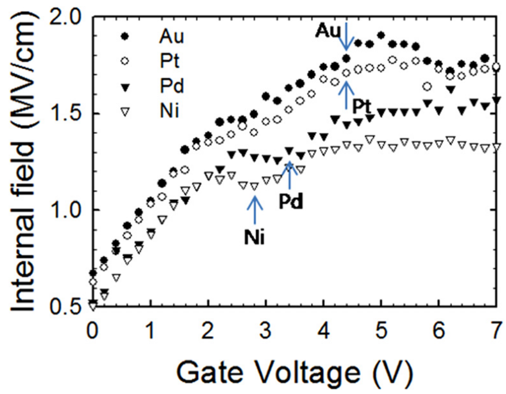

FIG. 1. Internal field in AlGaN barrier with various Schottky metals, Au, Pt, Pd, and Ni, obtained from the fitting of ER spectroscopy to the Franz-Keldysh oscillation formalism. The internal field is saturated which implies that 2DEG is depleted at Vth.

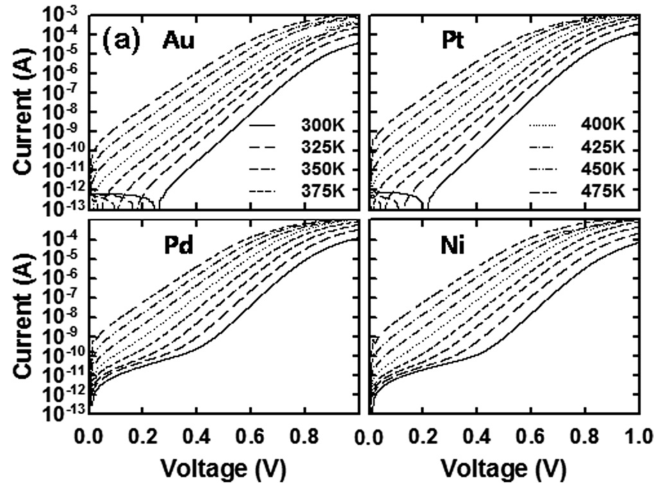

FIG. 2. Measured results of forward I-V-T characteristics of Schottky diodes containing Au, Pt, Pd and Ni.

to the SBI. More specifically, both Au and Pt samples have low densities of deep charge trap states at M-S interface, rendering a higher density of negative polarization charges present at the M-S interface. This, in turn, decreases the reduction of the SDS at the AlGaN surface. On the other hand, both Pd and Ni samples have high densities of shallow trap states at the M-S interface, which results in the lower densities of negative polarization charges. The reduction of the SDS caused by Pd and Ni Schottky metal depositions is therefore higher than that due to Au and Pt metals. This implies the reduction of 2DEG densities, induced by Pd and Ni metals, in the AlGaN/GaN heterostructure is larger than the one induced by Au and Pt metals.

To explore the connection between the M-S interface states and the SBI, the I-V-T measurements were performed under forward bias condition, where the results are shown in Figure 2. Below 400 K, the forward current-voltage shows a critical distinction among different Schottky diodes. For the low voltage regions from 0 to 0.4 V, the diodes with Au and Pt Schottky gate metals yield a low forward leakage current, which is less than 1 pA. In detail, it is thought that the tunneling currents through the AlGaN barrier can be a major cause of the initial forward leakage in the low bias voltage of below 0.2 V. However, in the case of a forward bias voltage over 0.2 V, the energy band deforms and the tunneling current can be suppressed. Therefore, the current reduces to a minimum value in the positive voltage of ~0.25 V for both Au- and Pt-Schottky diodes. For higher levels of forward bias voltages, current can be increased due to the thermionic emission phenomena. Interestingly, in the diodes with Pd and Ni Schottky gate metals, higher levels of forward leakage currents in the same voltage regions are observed, where the leakage current increased from 1 to 100 pA with increased voltages. In both Pd- and Ni-Schottky diodes, it has been suggested that extra tunneling of currents might be caused by the shallow level of metal-semiconductor interface states located just below the conductive dislocation state assigned by Zhang *et al.*[10] Therefore, the leakage current becomes increase further rather than decrease to minimum under forward bias voltage. Due to the uniformity of the AlGaN/GaN epitaxial layer, it can be suggested of the existence of different metal-semiconductor interface states (i.e., different SDS reduction depending on Schottky metal) which determine the leakage mechanism. Except for the curves below 0.4 V at temperatures below 400 K, the curves in I-V-T measurement of Fig. 2 can be explained from the thermionic emission theory of[7]

$$I = I_s \exp\left(\frac{qV}{nkT}\right)\left[1 - \exp\left(-\frac{qV}{kT}\right)\right], \tag{1}$$

where

$$I_s = AA^* T^2 \exp\left(-\frac{q\phi_b}{kT}\right), \tag{2}$$

and I_s is the saturation current, q is the electric charge, T is the relative temperature, k is the Boltzmann constant, n is the ideality factor, ϕ_b is the Schottky barrier height, A is the contact area, and A^* is the effective Richardson constant. What is remarkable is that the ideality factors for AlGaN/GaN diodes at different temperatures are more than 1, as shown in Fig. 3(a). According to the Tung's model,[5] both the ideality factor of more than 1 and its linearity vs. $1000/T$ can be convincing evidence of an inhomogeneous barrier for all (Au, Pt, Pd, and Ni) Schottky diodes. Figure 3(b) shows Schottky barrier heights for AlGaN/GaN diodes at different measurement temperatures. The increase rate of each Schottky barrier heights in accordance with temperature increase (which are 3.8 meV/K for Au, 2.6 meV/K for Pt, 0.74 meV/K for Pd,

TABLE I. Parameters of AlGaN/GaN Schottky diode depending on Schottky metal.

Metal	V_{th} (V)	F_{th} (MV/cm)	$n_{s.ER}$ (cm^{-2})	φ_b (eV)	W (eV)	$\varphi_{b.eff}$ (eV)	$\Delta n_{s.ER}$ (cm^{-2})
Au	4.4	1.86	5.74×10^{12}	1.05	5.09	0.97	1.88×10^{12}
Pt	4.4	1.70	5.60×10^{12}	0.98	4.6	0.55	3.17×10^{12}
Pd	4.2	1.47	4.93×10^{12}	1.08	4.3	0.55	3.73×10^{12}
Ni	3.6	1.21	3.68×10^{12}	0.98	4.5	0.4	5.37×10^{12}

V_{th}: threshold voltage of internal field saturation in AlGaN barrier, F_{th}: threshold internal field of AlGaN barrier, $n_{s.ER}$: sheet carrier density of 2DEG, φ_b: Schottky barrier height, W: work function of each metal, $\varphi_{b.eff}$: effective Schottky barrier height lowering, $\Delta n_{s.ER}$: reduction of SDS.

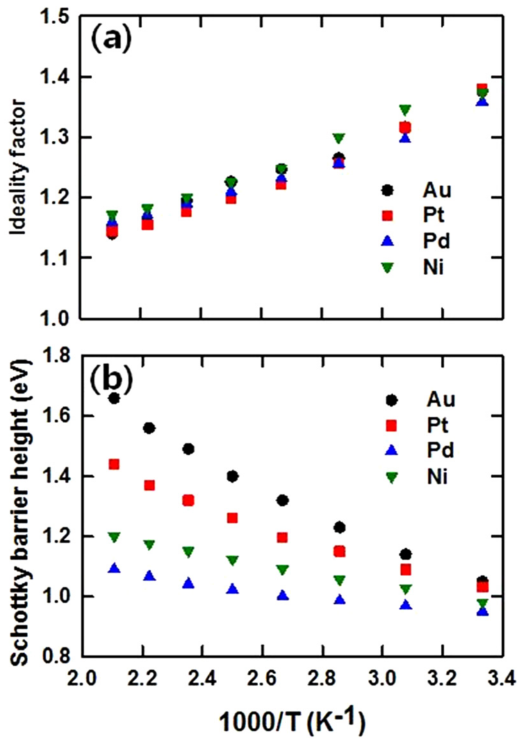

FIG. 3. (a) Ideality factor and (b) Schottky barrier height of each Schottky diodes at different temperatures (300 K-475 K).

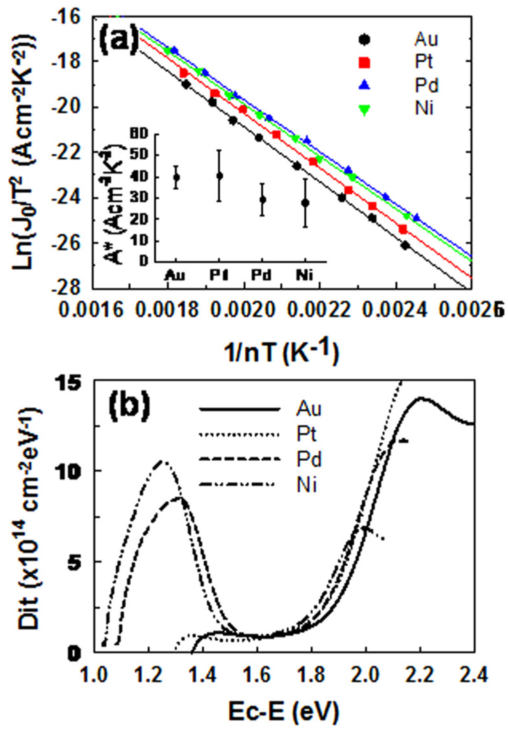

FIG. 4. (a) Modified Richardson plots of $\ln(J_0/T^2)$ vs 1/nT. (extrapolated Richardson constant in inset) and (b) energetic distribution of extracted surface trap density (Dit) of each Schottky diodes at 300 K.

and 0.78 meV/K for Ni) are obviously different from each other. Physically, this implies that the forward-biased (over 0.4 V) electrons in the AlGaN/GaN interface, which migrate through the different inhomogeneous Schottky barriers, involve the thermionic emission mechanism; and, such mechanism is strongly depending on the type of Schottky contact metals used at the gate. In order to confirm the validity of thermionic emission theory, we have calculated the modified Richardson plots of $\ln(J_0/T^2)$ vs $1/nT$,[11] Fig. 4(a). The calculated values for modified Richardson constants are $\sim$34.3 A cm^{-2} K^{-2} for Au sample, $\sim$40.4 A cm^{-2} K^{-2} for Pt sample, $\sim$29.0 A cm^{-2} K^{-2} for Pd sample, and $\sim$27.5 A cm^{-2} K^{-2} for Ni sample, which are very close to the theoretical value of 26.4 A cm^{-2} K^{-2}. By employing the non-equilibrium approach,[12] we have also investigated the presence of surface traps states (D_{it}) at the M-S interface. Figure 4(b) represents the energetic distributions of the surface traps for each of the investigated Schottky contacts. The results were obtained from the forward I-V measurements. These plots clearly indicate variations in the distribution of the surface states in the energy band gap with peak density at 1.44 (for Au sample), 1.35 (for Pt sample), 1.3 (for Pd sample), and 1.25 eV (for Ni sample) from the conduction band energy for different metals. The second trap level of 1.98–2.19 eV at room temperature can be attributed to the mid-band gap trap reported in the literature.[13–15] The levels of D_{it} are $\sim 1.1 \times 10^{14}$ cm^{-2} eV^{-1} for Au sample, $\sim 9.3 \times 10^{13}$ cm^{-2} eV^{-1} for Pt sample, $\sim 8.5 \times 10^{14}$ cm^{-2} eV^{-1} for Pd sample, and $\sim 1.05 \times 10^{15}$ cm^{-2} eV^{-1} for Ni sample, which are similar to order reported values in the literature.[12–15] Conventionally, the origin of the different SBI has been attributed to the fabrication process-induced damage on the semiconductor surface. To investigate the deposition-induced surface damage of M-S interface, after the metal removal by the wet chemical etching, we measured the revealed semiconductor surface morphology by using the *atomic force microscopy* (not shown here). However, there was no evidence that deposition-induced damage has been occurred to M-S surface. Furthermore, there was no discernable difference among surface morphologies of the samples after metal removal. On the other hand, by using XPS, we studied the element composition of M-S interface in each Schottky diodes, as shown in Fig. 5. Through the analysis of XPS spectra, Schottky contact can be divided into two groups; (I) Au and Pt Schottky contact with little or no

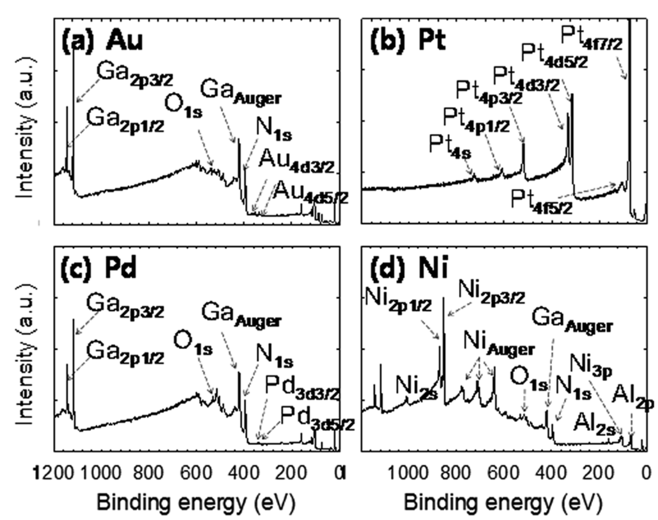

FIG. 5. X-ray photoelectron spectroscopy of (a) Au, (b) Pt, (c) Pd, and (d) Ni Schottky gates. There is oxygen peak (O1s) attributed to Ga-O bonding in Au, Ni, and Pd Schottky diodes.

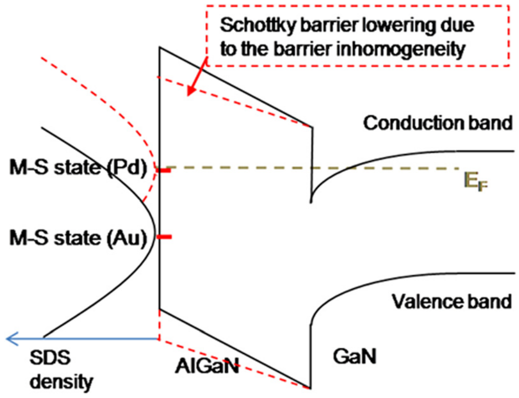

FIG. 6. Schematic figure of Schottky barrier lowering effect correlated with the reduction of SDS density depending on the gate metal.

oxygen peak and (II) Pd and Ni Schottky contact with strong oxygen peak caused by Ga-O bonding. Both Pd and Ni Schottky diodes have more oxygen peaks than the Au Schottky diodes. Interestingly, the Pt Schottky contact has no oxygen peak. Through the analysis, it can be suspected that the Ga-O bonding in the AlGaN/GaN Schottky diode is strongly related to the M-S interface states as well as on the properties of its epitaxial layer. An explanation to the origin of M-S interface state is provided by the "dangling bonds" at the surface of the AlGaN.[16] Jang, *et al.*[17] indicated that V_{Ga}-O or V_{Al}-O might play a role in the production of the M-S interface states, which suggests that the presence of V_{Ga}-O or V_{Al}-O might have an effect on the Schottky barrier by reducing the SDS. So far, the origin of the reduction of SDS has been explained in terms of the interaction between the metal and the semiconductor surfaces which are mediated by the dangling bonds. This is one of the interaction which rearranges the M-S interface as suggested previously by Mohammad.[18] In that regard, it is plausible that the metal-semiconductor interaction mediated dangling bond could reduce the number of dangling bond or fill the empty surface states even in the absence of V_{Ga}-O or V_{Al}-O bonding in the Schottky contacts. Considering the level of the binding energy for the Ga-O bonding reported by Jang *et al.*,[19] it can be suggested that the reduction of the Schottky barrier height on n-type GaN might be affected by the Ga-O bonding, which in turn can vary the transport of electrons. In this report, we have focused on the effects of the dangling bonds at the AlGaN surface and suggested that it can be changed by the Ga-O bonding. We believe the inhomogeneous Schottky barrier height has a strong relation to the reduction of the surface donor states on the AlGaN/GaN heterostructure; and, such result can be attributed to the Ga-O bonding. Furthermore, the strong Oxygen peak in the XPS spectroscopy for the Pd and Ni Schottky contacts suggest that the energy level of the M-S interface states is close to Fermi energy level (Fig. 5). For the case of Au and Pt Schottky contacts, the sparse Ga-O bonding give rise to a weak reduction in the SDS, which suggests that the energy level of M-S interface states is located far from the Fermi energy levels as shown in Fig. 6.

In summary, the origin of metal-induced Schottky barrier inhomogeneity in the AlGaN/GaN Schottky diode has been investigated for Au, Pt, Pd, and Ni Schottky metals. It has been obtained that Schottky gates cause the different internal electric fields in AlGaN barrier. Furthermore, from the thermionic emission theory, Schottky gates induces the different linearity of both the ideality factor and barrier height vs. 1000/T, which can be convincing evidence of an inhomogeneous Schottky barrier. It has been observed that metal-semiconductor interface state related to Ga-O bonding in Schottky metals have noticeable effect on the Schottky barrier inhomogeneity. Our experimental results show that both Schottky barrier inhomogeneity and the reduction in SDS are distinguishably affected by the different type of Schottky metals.

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