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Electrical characterization of Schottky contacts to N-polar GaN

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ABSTRACT

The Schottky barrier heights of several metals (Cu, Au, Pd, Ni, and Pt) to N-polar GaN were extracted using current–voltage and capacitance–voltage measurements. The dependence of barrier height on metal was found to vary linearly with the electronegativity of the metal as predicted by the metal-induced gap states (MIGS)-and-electronegativity model. However, the magnitude of the barrier heights are lower than those predicted by the MIGS model for GaN and lower than the experimentally measured barrier heights for Ga-polar GaN. It is likely that the polarization-induced charge at the N-polar GaN surface is responsible for the reduced barrier height.

1. Introduction

High-electron-mobility-transistor (HEMT) device structures based in the wurtzite III–N semiconductor system rely on the spontaneous and piezoelectric polarization of the material to induce two dimensional fixed sheet charges at abrupt interfaces [1]. Depending on the polarity of the III–N crystal, interfaces between two materials can form either a positive or negative sheet charge. The sign and magnitude of the induced charge not only influence the position and properties of two-dimensional electron gases (2DEGs) in HEMTs, but also can affect the properties of metal/semiconductor contacts, both ohmic [2,3] and Schottky [3–5]. While a majority of the HEMT research has been performed on metal-polar (0 0 0 1) III–N systems, the recent investigation of N-polar $(0\,0\,0\,\bar{1})$ III–N heterostructures has produced HEMTs with excellent device properties [6–11]. Metal/semiconductor contacts are an integral part of any device, so it is necessary to characterize and understand the properties of contacts for device design and fabrication. While N-polar III–N device structures continue to receive great attention, there have only been a few reports to date characterizing the properties of Schottky contacts to N-polar GaN, which used Pt [3,4] and Ni [5] as the metals. Here we compare the properties of Ti, Cr, Cu, Au, Pd, Ni, and Pt metal contacts to N-polar GaN and show that the Schottky barrier height is dependent on the electronegativity of the metal as predicted by the metal-induced gap states (MIGS)-and-electronegativity model. The barrier heights are smaller than those typically found for Ga-polar GaN, which is consistent with Ga-polar results presented here and with other reports that compare the two crystal polarities [3–5].

2. Experiment

N-polar GaN films were grown by plasma-assisted molecular-beam epitaxy on a C-face 6H–SiC substrate. A schematic of the device structure is shown in Fig. 1. A 50 nm AlN nucleation layer was grown first, followed by a 500 nm n^+-GaN layer doped with Si to approximately 10^{18} cm^{-3} for ohmic contact formation and a 500 nm n-GaN layer doped with Si to approximately 10^{17} cm^{-3} for Schottky contact formation. The fabrication of the structure began with creating circular mesas in the n-GaN layer by etching down to the n^+-GaN using a Cl_2/BCl_3/Ar etch in an inductively-coupled plasma system. Ohmic contacts to the n^+-GaN were then defined by optical lithography and deposited by e-beam evaporation. The Ti/Al/Ni/Au (20/100/10/50 nm) metallization was annealed at 830 °C for 30 s to create the ohmic contact. The gap between the ohmic contact and n-GaN mesa edge was 5 μm as shown in Fig. 1. The contact resistance was measured to be <1.5 Ω mm via the circular transfer length method. After ohmic fabrication, Schottky contacts were deposited by e-beam evaporation on top of the n-GaN mesas. The contacts were either 50 or 100 μm in diameter, and there was a 5 μm gap between the edge of the Schottky contact and the edge of the mesa. Samples were treated with a low power O_2 plasma descum to remove residual photoresist, followed by a 30 s 10:1 buffered HF dip, rinsed with deionized H_2O, and dried with N_2 before being loaded into the e-beam evaporation chamber. For Ti, Cr, Ni, Pd, and Pt contacts, 20 nm of the metal was deposited followed by a 100 nm Au

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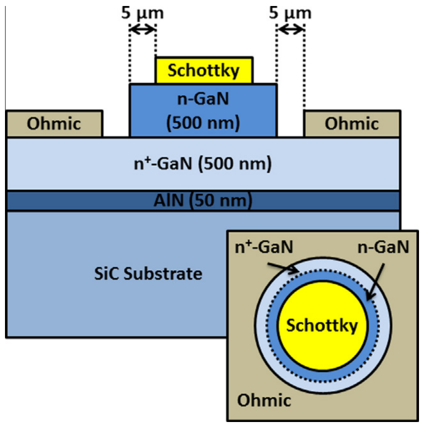

Fig. 1. Side and top view schematic of Schottky contact test structure.

capping layer. For Cu and Au, 50 nm of the metal was deposited with no Au capping layer. For comparison, some Schottky contacts were also made to Ga-polar GaN using the same layer structure and fabrication process as the N-polar structure with the exception of the ohmic contact formation step, where a Ti/Al/Ni/Au (20/200/40/50 nm) metallization was annealed at 900 °C for 30 s.

Current–voltage (*I–V*) characteristics of the Schottky contacts were measured at room temperature using an HP4145B semiconductor parameter analyzer. The *I–V* characteristics were modeled by the following equations assuming thermionic emission and neglecting series resistance [12]:

$$I = I_s(e^{qV/nkT})(1 - e^{-qV/kT}) \tag{1}$$

and

$$I_s = AA^*T^2 e^{-q\Phi_B^{IV}/kT}, \tag{2}$$

where q is the electron charge, V is the applied voltage, n is the ideality factor, k is Boltzmann's constant, T is temperature, A is the contact area, A^* is Richardson's constant, and Φ_B^{IV} is the effective Schottky barrier height. The value for A^* was taken to be 26 A/cm^2/K^2 for GaN [13], assuming an effective electron mass of 0.2 [14]. Both the 50 and 100 µm diameter contacts were used for the I–V measurements and typically nine of each were measured. The value of n and Φ_B^{IV} can be extracted from the slope and y-intercept, respectively, of the $\log[I/(1-e^{-qV/kT})]$ vs. V plot. By using a $\log[I/(1-e^{-qV/kT})]$ vs. V plot, voltage values of less than $3kT$ and reverse bias can be used to fit the data [12]. An example of an I–V and an $I/(1-e^{-qV/kT})$–V plot is shown in Fig. 2a and b, respectively, for two different metallizations with a diameter of 100 µm. As shown in Fig. 2b, an excellent fit (dotted line) is observed between the data (solid line) and Eq. (1) showing linearity to −1 V. The linear correlation coefficient (R^2) was at least 0.999 for each fit. From the extracted values of n and Φ_B^{IV}, a flat-band barrier height, Φ_{BF}, can be calculated from the following relationship [15]:

$$\Phi_{BF} = n\Phi_B^{IV} - (n-1)(kT/q)\ln(N_C/N_D), \tag{3}$$

where N_D is the donor concentration and N_C is the effective density of states in the conduction band. Using this method, the barrier height calculated from the *I–V* measurements is defined at zero electric field.

Capacitance–voltage (*C–V*) measurements were also performed to extract the barrier height using an Agilent E4980A LCR meter. Measurements were performed at a frequency of 1 MHz at room temperature. The *C–V* characteristics were modeled using the following equation [13]:

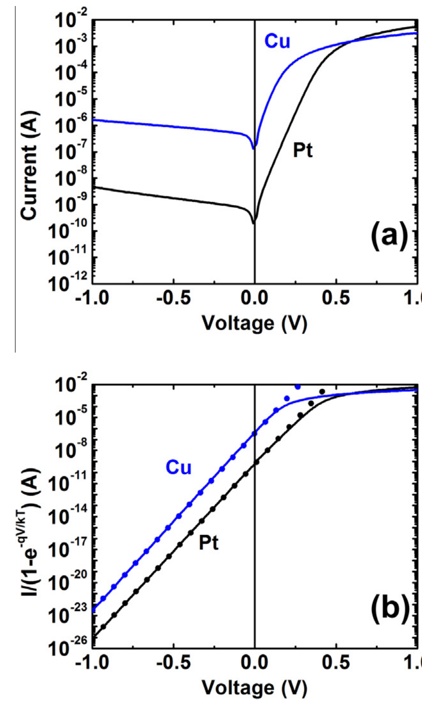

Fig. 2. (a) Log (current) vs. voltage and (b) $\log[I/(1-e^{-qV/kT})]$ vs. voltage plots of a representative Pt and Cu Schottky contact. The dotted lines are fits used to extract the barrier heights and ideality factors.

$$\frac{C}{A} = \sqrt{\frac{q\varepsilon_s N_D}{2(V_{bi} - V - kT/q)}}, \tag{4}$$

where ε_s is the semiconductor permittivity ($10.4\varepsilon_o$, where ε_o is the permittivity of vacuum) and V_{bi} is the built-in potential. A linear fit to the $(A/C)^2$ vs. V plot provides N_D and V_{bi} from the slope and x-intercept, respectively. The Schottky barrier height, Φ_B^{CV}, can then be found from the following equation [13]:

$$\begin{aligned}\Phi_B^{CV} &= V_{bi} + (kT/q)\ln(N_C/N_D) \\ &= V_i + kT/q + (kT/q)\ln(N_C/N_D),\end{aligned} \tag{5}$$

where V_i is the x-intercept from the linear fit to the $(A/C)^2$ vs. V plot. At least six 100 µm diameter contacts were measured for each metallization and the R^2-value for each linear fit to the $(A/C)^2$ vs. V plot was at least 0.999. An example of a $(A/C)^2$-V plot with a linear fit is shown in Fig. 3 for Cu and Pt metallizations. For the N-polar n-GaN layer, N_D was calculated to be 5×10^{16} cm^{-3} – 6×10^{16} cm^{-3} from the *C-V* measurements.

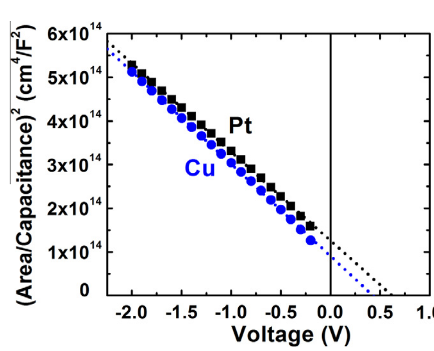

Fig. 3. An (area/capacitance)^2 vs. voltage plot of a representative Pt and Cu Schottky contact. The dotted lines are fits used to extract the barrier heights.