High barrier height GaN Schottky diodes: Pt/GaN and Pd/GaN

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Platinum (Pt) and palladium (Pd) Schottky diodes on *n*-type GaN grown by metalorganic chemical vapor deposition were achieved and investigated. Aluminum was used for ohmic contacts. Barrier heights were determined to be as high as $\Phi_B=1.13$ eV by the current–voltage ($I-V$) method and $\Phi_B=1.27$ eV by the capacitance–voltage ($C-V$) method for the Pt/GaN diode, and $\Phi_B=1.11$ eV, $\Phi_B=0.96$ eV, and $\Phi_B=1.24$ eV by $I-V$, activation energy ($I-V-T$), and $C-V$ methods for the Pd/GaN diode, respectively. The ideality factors were obtained to be $n\sim1.10$. © *1996 American Institute of Physics.* [S0003-6951(96)00909-8]

GaN is a promising semiconductor for high-temperature, high-frequency, and high-power device applications. The study of Schottky barrier contacts on GaN has great importance for these applications. Recently progress in material growth has been impressive and high quality GaN becomes available for such a study.

Schottky barrier contacts on GaN using gold (Au) have been reported.[1,2] According to the Schottky–Mott model, the barrier height equals the difference between metal work function and electron affinity of semiconductor χ (for GaN $\chi=4.1$ eV).[3] The work functions of Pt, Pd, and Au are 5.65, 5.12, and 5.1 eV, respectively.[4] Pt and Pd are expected to form good Schottky contacts on GaN. Ohmic contacts on *n*-type GaN using aluminum (Al) have been reported in several papers.[1,2,5–7]

In this letter we report experimental results of Schottky barrier contacts on *n*-type GaN Pt and Pd. The GaN films used in this study were grown on sapphire using metalorganic chemical vapor deposition (MOCVD). The details of the growth and crystal properties have been previously reported.[8,9] The films were *n* type with thickness of about 4 μm, sheet resistance of about 1 KΩ/square, carrier concentration of about 10^{17} cm^{-3}, and Hall mobility of about 200 cm^2/V s at room temperature. The metals (about 3000 Å thick) were deposited via conventional electron-beam evaporation with base pressure up to 10^{-7} Torr. The Schottky and ohmic contact patterns with different dot sizes (diameters =100, 200, and 400 μm on mask) were formed using photolithography and liftoff techniques. The distance between the adjacent Schottky and ohmic contact dots (from center to center) is about 650 μm. Before the evaporation, samples were dipped in diluted buffered oxide etch (BOE: H_2O =1:10) for about 30 s to remove possible oxide on the surfaces. There were no annealing treatments conducted for all contacts.

Al was used for the ohmic contact. Without annealing treatment, Al/GaN contacts show good ohmic behavior. $I-V$ characteristics of a typical Al/GaN contact (measured from Al dot to Al dot) are shown in Fig. 1. The resistance is on the order of kiloohms and it is determined essentially by the sheet resistance of GaN. It is consistent with the calculation result of $R=L/(\mu_n NqS)$, where L is the length, S the area, μ_n the electron mobility, N the ionized donor density, and q the electron charge.

We used three methods to measure the barrier height: $I-V$, $C-V$, and activation energy ($I-V-T$).[10] $I-V$ characteristics of Pt/GaN and Pd/GaN Schottky diodes are shown in Figs. 2 and 3(a). The leakage current density was generally less than 10^{-9} A/cm^2 at low bias voltage.

For thermionic emission and $V>3kT/q$, the general diode equations are[11]

$$J=J_0 \exp(qV/nkT), \quad (1)$$

$$J_0=A^*T^2 \exp(-\Phi_B/kT), \quad (2)$$

where J_0 is the saturation current density, n the ideality factor, k Boltzmann's constant, T the absolute temperature, A^* the effective Richardson coefficient, and Φ_B the barrier

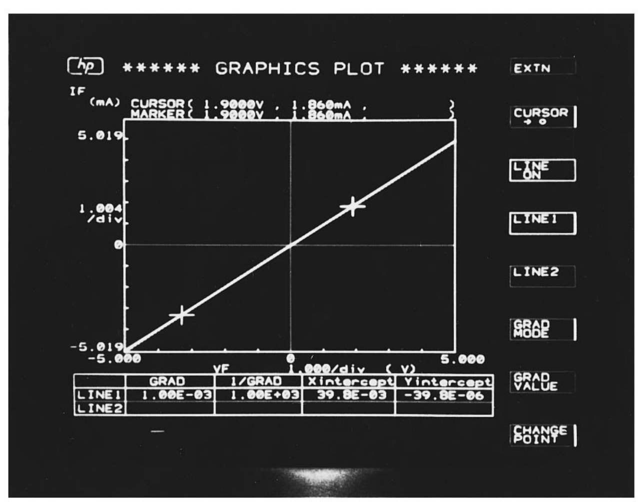

FIG. 1. $I-V$ characteristics of Al/GaN ohmic contacts (measured from Al dot to Al dot, $S=1.39\times10^{-3}$ cm^2).

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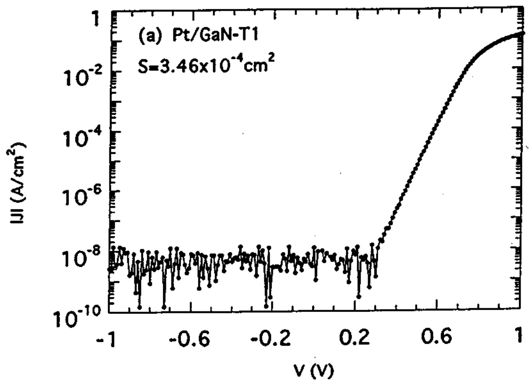

FIG. 2. *I–V* characteristics of Pt/GaN Schottky diodes. The measured contact area is 3.46×10^{-4} cm^2. *I* does not appear to be zero at $V=0$ because of noise.

height. J_0 can be obtained in the plot of $\log J$ vs V. $J_0=3.47\times10^{-13}$ A/cm^2 for Pt/GaN-T1 in Fig. 2 and $J_0=6.65\times10^{-13}$ A/cm^2 for Pd/GaN-D3 at room temperature. In the *I–V* method Φ_B was determined from Eq. (2) at room temperature with theoretical value $A^*=24$ A cm^{-2} K^{-2} [based on $A^*=4\pi m^* qk^2/h^3$ and $m^*\approx0.20m_0$ (Ref. 12)], $\Phi_B=1.13$ eV for Pt/GaN-T1 and $\Phi_B=1.11$ eV for Pd/GaN-D3. In the *I–V–T* method Φ_B and A^* were determined via a plot of $\ln(I_0/ST^2)$ vs $1/T$ (Fig. 3) based on Eq. (2), $\Phi_B=0.96$ eV, and $A^*=0.04$ A cm^{-2} K^{-2}. The measured

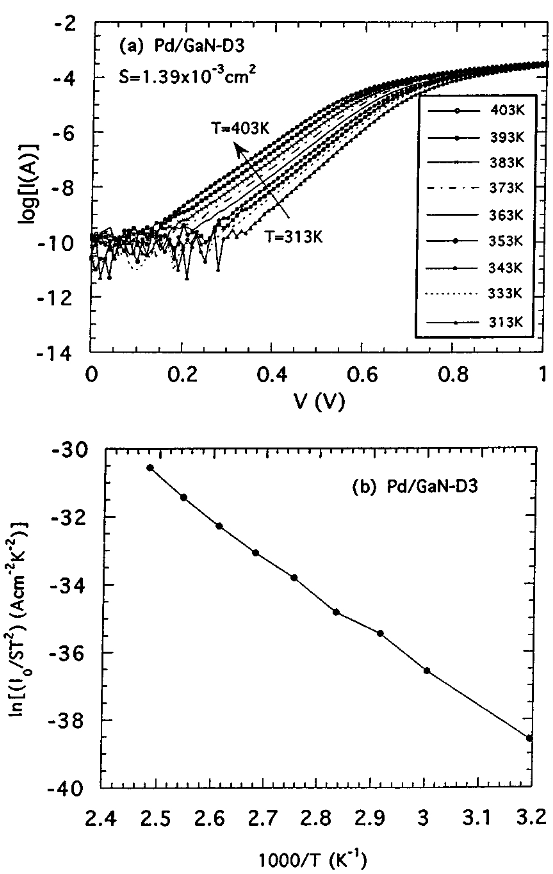

FIG. 3. Thermal activation energy method (Pd/GaN-D3). (a) *I–V* characteristics at various temperatures. (b) Plot of $\ln(I_0/ST^2)$ vs $1/T$ with linear fit of $y=-3.19-11.11x$. $\Phi_B=0.96$ eV and $A^*=0.04$ A cm^{-2} K^{-2}.

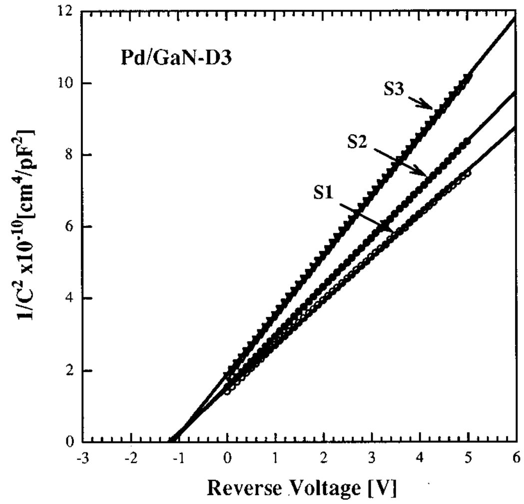

FIG. 4. *C–V* characteristics of Pd/GaN-D3 Schottky diodes with three different contact areas ($S_1=9.50\times10^{-5}$ cm^2, $S_2=3.46\times10^{-4}$ cm^2, $S_3=1.39\times10^{-3}$ cm^2). $N\approx1.11\times10^{17}$ cm^{-3}, $V_{bi}=1.16$ V, and $\Phi_B=1.24$ eV.

value of A^* is much smaller than the theoretical value. Hacke *et al.*[1] reported a measured value of $A^*=0.006$ A cm^{-2} K^{-2} from Au/GaN.

C–V measurements were performed at a frequency of 1 MHz. The *C–V* relationship for a Schottky barrier is[11]

$$(1/C)^2=(2/\epsilon qNS^2)(V_{bi}-V-kT/q), \tag{3}$$

where ϵ is the permittivity (for GaN $\epsilon=9.5\epsilon_0$).[12] $\Phi_B=q(V_{bi}+V_n)$, where $V_n=(kT/q)\ln(N_c/N)$, $N_c=2.60\times10^{18}$ cm^{-3} based on $N_c=2(2\pi m^* kT/h^2)^{3/2}$. From a measured plot of $1/C^2$ vs V (Fig. 4), $N\approx1.11\times10^{17}$ cm^{-3}, $V_{bi}=1.16$ V, and $\Phi_B=1.24$ eV.

The results of barrier height, ideality factor, ionized donor density (from the Hall measurement), and breakdown voltage are summarized in Table I. The breakdown voltage was arbitrarily taken to be the voltage at which the reverse current exceeded 1 mA. It was found that Schottky contact (barrier height) relates to carrier concentration of GaN. If the carrier concentration is $\sim10^{18}$ cm^{-3} or higher, the contact will be ohmic instead of Schottky contact. This is in agreement with the reported results of Au/GaN in which a good Schottky contact refers to $N=6.6\times10^{16}$ cm^{-3},[1] and a leaky one with $N=3\times10^{18}$ cm^{-3}.[2] The high carrier concentration might cause a tunneling effect at the interface. The barrier height of Au/GaN is close to the result of Hacke *et al.*[1] The

TABLE I. Summary of characteristics of GaN Schottky diodes.

Diodes	Barrier height, Φ_B (eV)			Ideality factor, n	Carrier density (cm^{-3})	Breakdown voltage (V)
	I–V	*C–V*	*I–V–T*			
Pd/GaN-D1	1.11	1.24	—	1.20	9.4×10^{16}	−55
Pd/GaN-D2	1.05	1.30	—	1.02	1.4×10^{17}	−72
Pd/GaN-D3	1.11	1.24	0.96	1.09	1.2×10^{17}	−35
Pt/GaN-T1	1.13	1.27	—	1.10	9.4×10^{16}	−45
Pt/GaN-T2	0.89	1.12	—	1.05	1.2×10^{17}	−85
Pt/GaN-T3	0.52	—	—	2.96	4.3×10^{17}	−7
Au/GaN	0.88	—	—	1.06	7.0×10^{16}	−2

dependence of barrier height on the difference between the metal work function and the electron affinity of the semiconductor was not observed.

The values of the barrier height measured by the I–V method are always lower than those obtained by the C–V method in our measurements. This was also found in the GaAs (Au/GaAs) Schottky contact.[13] The reason might be partly due to the image-force barrier lowering effect.[10] The current distribution on the contact dots may not be uniform which can cause error in area S in the I–V method. The low Φ_B and small A^* found by the $I-V-T$ method in one sample is a further suggestion of the possibility of nonuniform current distribution in the diodes.

In conclusion, good Schottky diodes on n-type GaN with Pt and Pd were achieved and investigated. Ohmic contacts were obtained using Al. Barrier heights were determined to be as high as $\Phi_B=1.13$ eV by the I–V method and $\Phi_B=1.27$ eV by the C–V method for the Pt/GaN diode, and $\Phi_B=1.11$ eV, $\Phi_B=0.96$ eV, and $\Phi_B=1.24$ eV by I–V, I–V–T, and C–V methods for the Pd/GaN diode, respectively.

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