Schottky barrier on *n*-type GaN grown by hydride vapor phase epitaxy

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(Received 4 June 1993; accepted for publication 31 August 1993)

A Schottky barrier on unintentionally doped n-type GaN grown by hydride vapor phase epitaxy was obtained and characterized. Using vacuum evaporated gold as the Schottky barrier contact and aluminum for the ohmic contact, good quality diodes were obtained. The forward current ideality factor was $n \sim 1.03$ and the reverse bias leak current below 1×10^{-10} A at a reverse bias of -10 V. The barrier height ϕ_{Bn} was determined to be 0.844 and 0.94 eV by current-voltage and capacitance measurements, respectively.

GaN, having a 3.39 eV direct band gap at room temperature, is being used in optoelectronic devices such as light emitting diodes performing in the blue and ultraviolet regions. But until recently, it has been difficult to fabricate good quality single-crystal films with which the properties of the Schottky barrier can be studied. In the past, electrical measurements such as current-voltage tests have been done on n-type GaN obtained by N^+ or Be^+ ion implantation,[1,2] but the quality of such crystals precluded detailed analysis to obtain fundamental electrical properties of the Schottky barrier on GaN. Recently, good quality bulk single crystals of GaN have been successfully grown using hydride vapor phase epitaxy (HVPE) on which such electrical measurements can be done.[3,4]

Schottky contacts in this study are made using as-grown, unintentionally doped GaN crystals fabricated by HVPE. In the HVPE chamber, HCl is reacted with Ga at 850 °C to form GaCl gas which is transported to the growth zone and reacted with NH_3. The carrier gas is N_2. The reaction takes place at 1090 °C forming GaN and NH_4Cl and the GaN is deposited on a substrate. The HVPE-GaN crystals used are grown on metalorganic chemical vapor deposition (MOCVD)-grown GaN on an AlN buffer layer on sapphire. The GaN layers tested were c faced (0001) and 100–400 μm thick. The GaN films grown by this method show excellent crystalline, electrical, and optical properties. In particular, the Hall mobility is 1920 $cm^2\,V^{-1}\,s^{-1}$ at its maximum at 120 K. The details of the growth method and crystal properties have been previously reported.[3,4] The nature of the donor included unintentionally in the crystal remains unclear and requires further study.

Before metallization, the samples were cleaned in boiling aqua regia for ten minutes then in organic solvents and alcohol with ultrasonic agitation. In a vacuum of about 3×10^{-6} Torr, 99.999% pure gold was evaporated through a stainless-steel mask pattern of holes to form contacts of area 3.71×10^{-4} cm^2. Aluminum was evaporated to form ohmic contacts on the perimeter of the crystal face as done by Amano *et al.*[5] for connection to the n layer of GaN p-n junctions.

The Schottky barrier diodes were checked for their rectifying behavior and quality with current-voltage (I-V) tests. For contacts on visibly pit or crack-free surfaces (40 $\times$magnification), the reverse bias leak current was generally very small—on the order of 1×10^{-10} A or lower at a reverse bias voltage of -10 V. This is near the lower detection limit and resolution of the equipment used. In many samples, strong breakdown was not observed up to a reverse bias of -100 V (Fig. 1).

The forward bias characteristics were studied in detail to determine the ideality of the diode. The diode equation for $V_f > 3kT/q$ is well known to be

$$I = I_0 \exp\left[q\left(\frac{V - IR_s}{nkT}\right)\right], \tag{1}$$

where n is the ideality factor, R_s is the series resistance in the device and the other variables have their usual meanings. A plot of the natural log of current versus forward bias voltage for small forward currents where the effect of series resistance is small and can be neglected yields an ideality factor $n \sim 1.03$ indicating current flow by diffusion of electrons over the Schottky barrier (Fig. 2). The ideality of the contact is further corroborated by the extremely low reverse bias leak current at high applied reverse voltage indicating minimal recombination in the depletion region.

I-V measurements at various temperatures were also done to determine the barrier height and effective Richardson coefficient. If it is assumed that the diode is nearly ideal ($n \sim 1$), a plot of $\ln I/e^{qV/kT}$ vs I in forward bias yields I_0 as a function of temperature at the y intercept (Fig. 3). From thermionic emission theory, the saturation current is given by $I_0 = S\,A^*T^2 \exp(-\phi_{Bn}/kT)$, where S is the diode cross-sectional area and A^* the effective Richardson coefficient. An activation energy plot of I_0/ST^2 vs $1/T$ yields the barrier height ϕ_{Bn} and the effective value A^* (Fig. 4). The barrier height was found to be $\phi_{Bn} = 0.844$ eV and

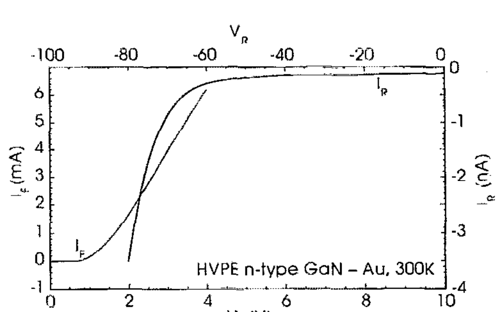

FIG. 1. Forward and reverse bias I-V characteristics. The contact area is 3.71×10^{-4} cm^2.

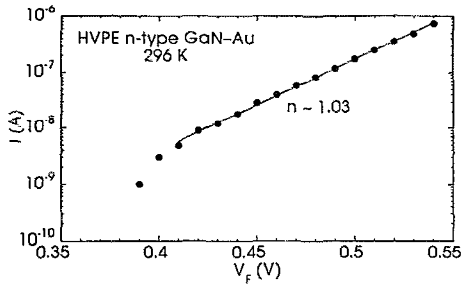

FIG. 2. Forward bias *I-V* characteristics indicating current flow primarily by thermionic emission.

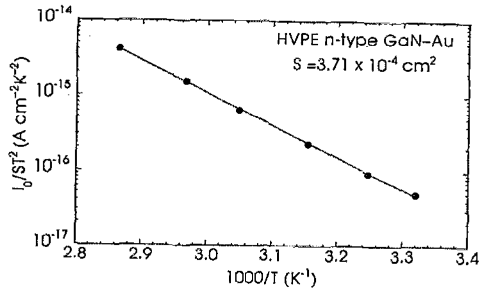

FIG. 4. Activation energy plot using the saturation current as a function of temperature from the forward bias *I-V* characteristics.

$A^*=0.006\ \mathrm{A\ cm^{-2}\ K^{-2}}$ by means of *I-V* tests varying the temperature. The built-in potential can be deduced from the barrier height since $V_i=\phi_{Bn}/q-V_n$ where the difference in the energies between the bottom of the conduction band and the Fermi level is given by $V_n=(E_C-E_F)/q$ and $V_n=kT/q\ln(N_C/N_D)$. The density of states in the conduction-band edge is given by $N_C=2(2\pi m_n^* kT/h^2)^{3/2}$, where m_n^* is the effective mass of electrons in GaN taken to be $m_n^*=0.22\pm0.03$ in units of the electron mass m_0.[6] At 296 K, $N_C=2.53\times10^{18}\ \mathrm{cm^{-3}}$ and $V_n=0.09$ V, thus the built in potential $V_i=0.754$ V based on the *I-V* measurements.

The electron affinity χ_s of the semiconductor for a Schottky barrier on a *n*-type semiconductor is related to the work function of the metal and the barrier height by $\chi_s=\phi_m-\phi_{Bn}$. The relationship is not so simple in practice because of charges often existing at the junction caused by surface states, metal induced gap states, or chemical reactions at the interface. However, for a stable ionic-bonded semiconductor like GaN, the relationship may have more validity. Taking $\phi_m=5.1$ eV for gold,[7] $\chi_s=4.26$ eV based on the *I-V* measurements.

Capacitance-voltage (*C-V*) measurements were done to further determine the nature of the depletion region in the Schottky barrier. Capacitance was measured by applying a dc sweep back and forth between -8 and 2 V with a 1 MHz, 20 mV rms testing signal. The capacitance voltage relationship for a Schottky barrier with a negligible oxide layer between the metal and the semiconductor is given by[8]

$$C=S\left[\frac{\epsilon_S q N_d}{2(V_i-V-kT/q)}\right]^{1/2}, \tag{2}$$

where S is the diode cross-sectional area, ϵ_S is the permittivity of the semiconductor, and V is the applied voltage. Using the measured relationship between $1/C^2$ and the applied voltage V shown in Fig. 5, the ionized donor density N_d and the built-in potential V_i were determined. The dielectric constant for GaN in the condition where the electric field is perpendicular to the "*c* face" is taken to be $\epsilon_S/\epsilon_0=9.5$.[9] From *C-V* measurements, $N_d=6.6\times10^{16}$ $\mathrm{cm^{-3}}$. The x intercept V_0 (at $1/C^2=0$) is related to the built in potential via $V_0=V_i-kT/q$.

If the barrier height is assumed not to depend on the electric field in the junction (i.e., neglecting the effect of an imaging force), then $\phi_{Bn}=q(V_0+V_n)+kT$. Thus, from Fig. 5, the x intercept is $V_0=0.82$ V, the built-in voltage $V_i=0.85$ V and the barrier height $\phi_{Bn}=0.94$ eV determined by *C-V* measurements. If the same analysis and arguments used to determine the electron affinity for the *I-V* results are applied here, $\chi_s=4.16$ eV based on the capacitance test.

When comparing the values obtained for ϕ_{Bn}, 0.94 and 0.84 eV by *C-V* characteristics and *I-V-T* characteristics, respectively, the effects of an insulating layer or charges existing at the semiconductor-metal interface must be considered.[8] Most Schottky diodes have a thin oxide or insulating layer at the metal-semiconductor junction unless all the processing is done in a vacuum. In the case of *C-V* measurements, an interface layer of 10 Å or so can significantly enlarge the value V_0 determined at $1/C^2=0$ and the measured barrier potential.[8] Also, deep levels occurring in the GaN band gap can affect capacitance measurements if they emit carriers to the conduction band at a rate comparable to the testing signal frequency of the capacitance meter.[8,10] For the sample characterized in Figs. 2–5, vari-

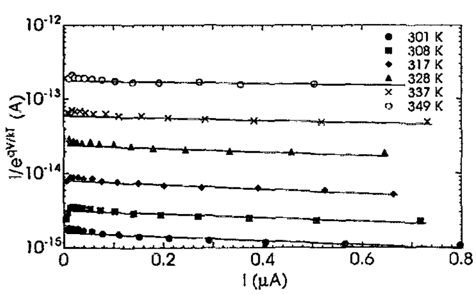

FIG. 3. Plot to determine the saturation current based on forward bias *I-V* characteristics at various temperatures.

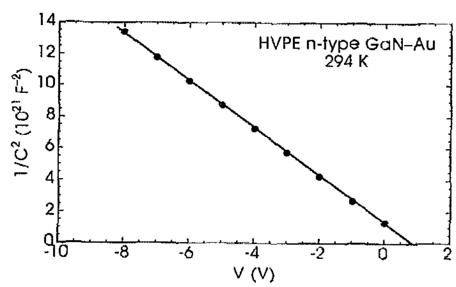

FIG. 5. Capacitance-voltage characteristics of the GaN-Au diode.

TABLE I. Summary of GaN and GaN-Au Schottky barrier characteristics from current-voltage (I-V) and capacitance-voltage (C-V) test results.

	I-V tests	C-V tests
Ionized donor density N_D (cm^{-3})	···	6.6×10^{16}
Ideality factor n	~1.03	···
Built-in potential V_i (V)	0.754	0.85
Barrier height ϕ_{Bn} (eV)	0.844	0.94
Electron affinity χ_s (eV)	4.26	4.16

ation of capacitance with temperature showed that there is negligible interference caused by deep levels to the capacitance measurements done at room temperature; however, the deep level structure in GaN continues to be studied.

The effective value of the Richardson coefficient that was obtained in this analysis, 0.006 A cm^{-2} K^{-2}, is very small compared to that determined theoretically based on the effective mass, 26 A cm^{-2} K^{-2}, via $A=4\pi m^*qk^2/h^3$.[8] This would indicate the presence of a barrier through which the electrons must tunnel. The ideality factor n, however, is near unity indicating that the potential in the insulating layer remains constant with voltage. Rhoderick[10] showed that for very thin insulating layers on silicon, charged states which exist in equilibrium with the metal tend to hold the barrier height constant, thus the ideality factor n remains low. The present tests indicates that a very thin barrier exists at the junction through which the electrons must tunnel, but the potential drop across it remains fairly constant with applied voltage. The electric potential across this layer, or charges it contains, is a probable cause of the difference in the measured barrier heights by capacitance and current-voltage techniques.

A Schottky diode on n-type GaN with gold was achieved and characterized using capacitance- and current-voltage techniques. The ideality factor is nearly unity indicating current flow by thermionic emission in forward bias. The barrier height and built-in potential of the junction, and the electron affinity and ionized donor concentration of GaN are summarized in Table I.

Acknowledgement for the support of portions of this research is gratefully extended to the Japan Society for the Promotion of Science, the SDIO/IST-Office of Naval Research and the North Carolina Japan Center. The encouragement from Dr. J. T. Glass is also greatly appreciated.

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