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Evaluating AlGaN/AlN/GaN heterostructure Schottky barrier heights with flat-band voltage from forward current-voltage characteristics

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Both circular and rectangular Ni Schottky contacts on AlGaN/AlN/GaN heterostructures have been fabricated. Both of the Schottky barrier heights were measured by internal photoemission. The flat-band voltage (V_0) for the AlGaN/AlN/GaN heterostructure Schottky contacts was analyzed and obtained from the forward current-voltage (I-V) characteristics. Based on the forward I-V characteristics and with the obtained flat-band voltage, the Schottky barrier heights for the circular and rectangular diodes have been analyzed and calculated by self-consistently solving Schrodinger's and Poisson's equations. The evaluated Schottky barrier heights for the prepared circular and rectangular Ni Schottky diodes agree well with the photocurrent measured results. © *2011 American Institute of Physics*. [doi:10.1063/1.3643139]

AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) have been the state-of-the-art candidates for high-voltage and high-power operations at microwave frequency due to the improvement of the transport properties and electron mobility.[1,2] The Schottky barrier height of the GaN-related HFETs is essential to device performance and reliability. A large barrier height leads to small leakage current and high breakdown voltage,[3] thus improving the noise level[4] and power performance of the device. The Schottky barrier engineering for the traditional AlGaN/GaN HFETs has been systematically investigated and can be obtained by internal photoemission[5] or with an iterative calculation by self-consistently solving Schrodinger's and Poisson's equations from forward current-voltage (I-V) characteristics.[6] However, the AlGaN/AlN/GaN heterostructures are currently the mainstream material structures for AlGaN/GaN HFETs; so far, few papers on the precise evaluation for the Schottky barrier height of the AlGaN/AlN/GaN Schottky diodes has been published due to the complexity of the structure. Thus, it is necessary to obtain a simple and universal approach of evaluating AlGaN/AlN/GaN heterostructure Schottky barrier heights.

In this letter, both circular and rectangular AlGaN/AlN/GaN diodes were fabricated. The Schottky barrier heights of the two AlGaN/AlN/GaN diodes were first measured by internal photoemission. Based on the forward I-V characteristics, the flat-band voltage V_0 was analyzed and obtained. Then with the flat-band voltage and based on the forward I-V characteristics, the AlGaN/AlN/GaN heterostructure Schottky barrier heights have been analyzed and calculated by self-consistently solving Schrodinger's and Poisson's equations. Finally, the evaluated flat-band Schottky barrier heights of the two AlGaN/AlN/GaN diodes were compared with the photocurrent measured results.

The heterostructure layer was grown by molecular beam epitaxy (MBE) on a (0001) sapphire substrate (see Ref. 2 for a more detailed material structure description). Both circular and rectangular AlGaN/AlN/GaN diodes were fabricated. The device processing was also the same as that in Ref. 2. For the circular device, the Ohmic contact was a ring with an inside diameter of 600 μm and an outside diameter of 700 μm, and for the rectangular device, it was rectangular with 100 μm wide and 50 μm long. The specific resistivity of the Ohmic contacts was measured to be 7×10^{-5} Ω cm^2. The Schottky contacts consisted of Ni/Au (60 nm/160 nm) were formed by e-beam evaporation. The Schottky contact was circular with a diameter of 300 μm for the circular device and was rectangular with 100 μm wide and 20 μm long for the rectangular device. The space between the Ohmic and Schottky contact was 100 μm for the rectangular device. Capacitance-voltage (C-V) measurements were performed at room temperature using an Agilent B1520A at 1 MHz, and I-V measurements were also performed at room temperature using an Agilent B1500A semiconductor parameter analyzer. The photoemission measurements were performed with a femtosecond laser and optical fiber as a light source, a monochromator (Acton, model sp2150i), and a lock-in amplifier (Stanford research systems, model SR830DSP).

Figs. 1(a) and 1(b) show the photocurrent spectra of the circular and rectangular AlGaN/AlN/GaN diodes, respectively. According to Fowler's theory,[7] the relationship between the photocurrent per photon, R, and the incident photon energy hν is given by[5,7]

$$R \sim (h\nu - q\phi_b)^2, \tag{1}$$

where $q\phi_b$ is the Schottky barrier height. This relation is valid when $(h\nu - q\phi_b) > 3$ kT. Therefore, the Schottky

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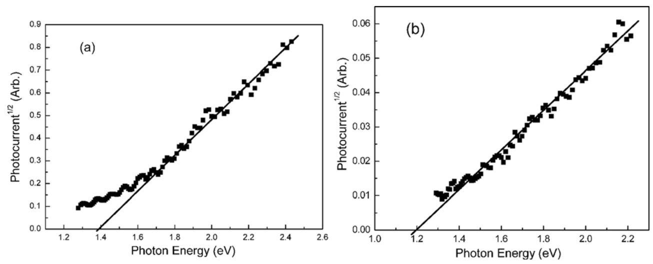

FIG. 1. Photoemission measurement curves for the circular AlGaN/AlN/GaN diode (a) and the rectangular one (b).

barrier height can be obtained from the linear relationship of the square root of the photocurrent per photon versus the incident photon energy. With the photoemission measurements, the Schottky barrier heights of the circular and rectangular diodes were determined to be 1.39 eV and 1.20 eV, respectively.

The measured C-V curves for the circular and rectangular AlGaN/AlN/GaN heterostructure Schottky diodes are shown in Figs. 2(a) and 2(b), respectively. By C-V curves integration,[8] the two dimensional electron gas (2DEG) sheet carrier density (n_{2D}) under the Schottky contact metals at zero bias was calculated to be 5.63×10^{12} cm^{-2} and 5.70×10^{12} cm^{-2} for the circular and rectangular diodes, respectively.

Figs. 3(a) and 3(b) show the measured forward I-V curves of the circular and rectangular AlGaN/AlN/GaN heterostructure Schottky diodes, respectively. Figure 4(a) shows the band diagram of the AlGaN/AlN/GaN heterostructure at zero bias. Since the AlN layer is only 0.5 nm thick, the AlGaN/AlN/GaN heterostructure Schottky diode can be visualized as two diodes back-to-back in series (Fig. 4(a)) by introducing the effective conduction-band offset ($\Delta E_{C,\ eff}$).[6,9] The left diode (diode 1) represents the Schottky contact between the Schottky metals and the AlGaN barrier layer. The right diode (diode 2) represents the effective Schottky contact between the 2DEG and the AlGaN barrier layer.[6] The reverse saturation current of the two diodes can be expressed by[6]

$$I_{S1} = SA^*T^2\exp(-q\phi_{b1}/\mathrm{k}T), \tag{2}$$

$$I_{S2} = SA^*T^2\exp(-q\phi_{b2}(0)/\mathrm{k}T), \tag{3}$$

where $q\phi_{b1}$ is the Schottky barrier height at zero bias, $q\phi_{b2}(0)$ is the Schottky barrier height of diode 2 at zero bias, S is the Schottky contact area, A^* is the effective Richardson constant, k is Boltzmann's constant, and T is the temperature.

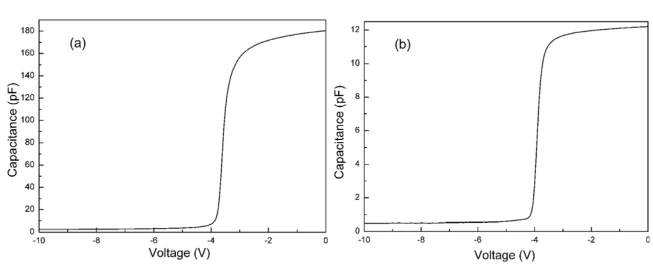

FIG. 2. The measured C-V curves for the circular AlGaN/AlN/GaN diode (a) and the rectangular one (b).

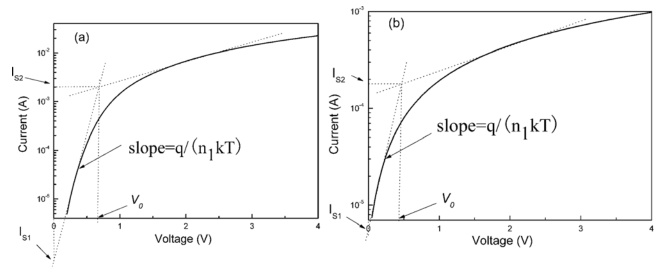

FIG. 3. The measured forward I−V curves for the circular AlGaN/AlN/GaN diode (a) and the rectangular one (b).

From the slope of the I-V curves (as shown in Fig. 3), the following equation can be obtained:

$$(\ln I_{S2} - \ln I_{S1})/V_0 = q/(KTn_1), \tag{4}$$

where V_0 is the voltage value at the intersection of the two fitted dot-lines as shown in Fig. 3, and n_1 is the ideality factor of diode 1. The above parameters of I_{S1}, I_{S2}, V_0, and n_1 can be determined with Fig. 3,[6] and their values for these parameters corresponding to the circular and rectangular diodes are shown in Table I. From Eqs. (2)–(4), n_1 can also be expressed as

$$n_1 = V_0/(\phi_{b1} - \phi_{b2}(0)). \tag{5}$$

It is well known that the barrier height of a Schottky barrier diode is electric field dependent,[10] and when the electric field is zero, the Schottky barrier height is denoted ϕ_{BF}. The relationship between the Schottky barrier height (ϕ_{b1}) at zero bias and the one (ϕ_{BF}) at zero electric field obeys[6]

$$\phi_{BF} = n_1\phi_{b1} - (n_1 - 1)\phi_{b2}(0). \tag{6}$$

Substituting Eq. (5) into Eq. (6), the following expression can be obtained:

$$\phi_{BF} = \phi_{b2}(0) + V_0. \tag{7}$$

According to Eq. (7), and with the definition of the flat-band voltage in Ref. 6, the bias V_0 corresponding to the intersection of the two fitted dot-lines in forward I-V characteristics is the flat-band voltage for the Schottky contacts on AlGaN/AlN/GaN heterostructures as shown in Fig. 4(b). Furthermore, the determination of the $\phi_{b2}(0)$ for the circular and rectangular diodes is as follows.

As shown in Fig. 4(a), $\phi_{b2}(0)$ and $\Delta E_{C,\ eff}$ obeys

$$\phi_{b2}(0) = \Delta E_{C,\mathrm{eff}} - E_F, \tag{8}$$

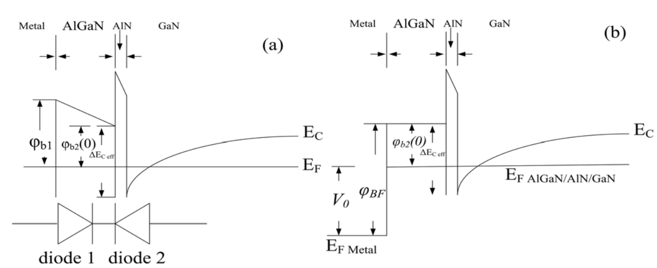

FIG. 4. Conduction band diagram of the AlGaN/AlN/GaN heterostructure at zero bias (a) and under flat-band voltage (b).

TABLE I. The calculated and measured parameters for the circular and rectangular AlGaN/AlN/GaN diodes.

	I_{S1} (A)	I_{S2} (A)	n_1	$\Delta E_{C,\,eff}$ (eV)	ϕ_{b1} (eV)	$\phi_{b2}(0)$ (eV)	V_0 (V)	ϕ_{BF} (eV)	Φ_B (Photo) (eV)
Circular diode	1.06×10^{-6}	1.81×10^{-3}	3.62	0.942	0.88	0.687	0.692	1.38	1.39
Rectangular diode	1.56×10^{-5}	3.86×10^{-4}	5.77	0.942	0.77	0.684	0.484	1.17	1.20

where E_F is the Fermi level in the AlGaN/AlN/GaN heterostructure. Both $\Delta E_{C,\,eff}$ and E_F at zero bias can be calculated by self-consistently solving Schrodinger's and Poisson's equations which is based on the known n_{2D} and the polarization charge density in the AlN/GaN interface ($\sigma_{AlN/GaN}$).[11] Assuming the degree of relaxation of the AlN layer to be 0,[12] the $\sigma_{AlN/GaN}$ was calculated to be 6.41×10^{13} cm^{-2} based on the Al content of 1.[12,13]

In order to calculate the value of ϕ_{BF}, the value of $\phi_{b2}(0)$ is first assumed to equal to a given value (0-1 eV or more). From Eq. (7), the value of ϕ_{BF} can be obtained with the known value of V_0, and using the known value of n_1, the value of ϕ_{b1} can be calculated by Eq. (6). With the obtained values of n_{2D}, ϕ_{b1} and $\sigma_{AlN/GaN,}$ the values of E_F and $\Delta E_{C,\,eff}$ at zero bias can be calculated by self-consistently solving Schrodinger's and Poisson's equations.[6,11] With Eq. (8), the new $\phi_{b2}(0)$ is obtained. We then replace the initial $\phi_{b2}(0)$ by the new calculated value and operate iteratively the above process until the difference between the latest $\phi_{b2}(0)$ and the prior $\phi_{b2}(0)$ value is less than a specified value.[6] With this iterative calculation, the values of ϕ_{b1}, ϕ_{BF}, and $\phi_{b2}(0)$ for the circular and rectangular diodes have been determined and summarized in Table I.

As seen from Table I, the values of the flat-band Schottky barrier heights ϕ_{BF} for the circular and rectangular diodes obtained with the above approach are 1.38 eV and 1.17 eV, respectively. Both of them are in good agreement with the ones obtained by photocurrent measurements. Thus, it is shown that this approach for evaluating AlGaN/AlN/GaN heterostructure Schottky barrier heights with flat-band voltage from forward I-V characteristics is valid. Compared with the approach for evaluating AlGaN/GaN heterostructure Schottky barrier heights reported in Lv *et al.*'s literature[6] (in which the thermionic emission model is involved), the approach described in this paper is less involved in any specific carrier transport models; as a result, the approach with flat-band voltage for evaluating AlGaN/AlN/GaN heterostructure Schottky barrier heights is more universal.

In summary, both circular and rectangular AlGaN/AlN/GaN Schottky diodes were fabricated. The Schottky barrier heights of the two AlGaN/AlN/GaN diodes were first measured by internal photoemission. With the flat-band voltage V_0 obtained from the forward I-V characteristics, and by self-consistently solving Schrodinger's and Poisson's equations, the Schottky barrier heights of the circular and rectangular AlGaN/AlN/GaN diodes have been determined based on the forward I-V characteristics, and the evaluated flat-band Schottky barrier heights for the two diodes agree well with the ones obtained by photocurrent measurements. This demonstrates that a simple and universal approach for evaluating AlGaN/AlN/GaN heterostructure Schottky barrier heights with flat-band voltage from forward I-V characteristics is developed and determined.

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