AIP Journal of Applied Physics

Dependence of Ni/AlGaN Schottky barrier height on Al mole fraction

D. Qiao, L. S. Yu, S. S. Lau, J. M. Redwing, J. Y. Lin, and H. X. Jiang

Citation: Journal of Applied Physics **87**, 801 (2000); doi: 10.1063/1.371944
View online: http://dx.doi.org/10.1063/1.371944
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/87/2?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 87, NUMBER 2 15 JANUARY 2000

Dependence of Ni/AlGaN Schottky barrier height on Al mole fraction

D. Qiao,[a)] L. S. Yu, and S. S. Lau
Department of Electrical and Computer Engineering, University of California, San Diego, California 92093-0407

J. M. Redwing
Epitronics/ATMI, 21002 North 19 Ave., Suite 5, Phoenix, Arizona 85027

J. Y. Lin and H. X. Jiang
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

(Received 16 August 1999; accepted for publication 13 October 1999)

The dependence of the Schottky barrier height of Ni/$Al_xGa_{1-x}N$ contact on the Al mole fraction up to $x=0.23$ was studied. The barrier heights were measured by $I-V$, capacitance–voltage, and the internal photoemission method. The Al mole fractions were estimated from the AlGaN band gap energies measured by photoluminescence. In the range of $x<0.2$ a linear relationship between the barrier height and Al mole fraction was obtained. This was consistent with the slope predicted by the Schottky rule. For $x=0.23$, the measured barrier height was lower than predicted. We believed this was due to crystalline defects at the Ni/AlGaN interface. © *2000 American Institute of Physics.* [S0021-8979(00)03302-8]

I. INTRODUCTION

Recently AlGaN/GaN heterostructure field effect transistors have been studied extensively for applications in high temperature and high frequency electronic devices.[1,2] The Schottky barrier height of a metal on AlGaN is an important parameter for device design. A large barrier height leads to small leakage currents and high breakdown voltages,[3] thus improving the noise level[4] and the high voltage performance of the device. In contrast to the case for GaAs, the published experimental barrier heights for various metals on n-GaN appear to increase with an increasing metal work function[5] and the barrier height, $q\phi_b$ follows the Schottky rule

$$q\phi_b=\Phi_m-\chi, \tag{1}$$

where Φ_m is the work function of the metal, and χ is the electron affinity of the semiconductor (GaN, χ=4.2 eV). Since the electron affinity of AlGaN decreases with increasing Al mole fraction, the Schottky barrier height of a metal on AlGaN should increase with increasing Al mole fraction in accordance with Eq. (1). The Schottky barrier height of Au[6] and Re[7] on $Al_xGa_{1-x}N$ have been investigated using $I-V$ and capacitance–voltage ($C-V$) measurements. The results indeed indicate a general increase of barrier height with the Al mole fraction x. However, there were significant differences between the $I-V$ and $C-V$ results due to nonideal behaviors of Schottky contact. In this article, we report the dependence of the Schottky barrier height of Ni on AlGaN with an Al mole fraction x in the range between 0 and 0.23. The Schottky barrier height was determined using both electrical and internal photoemission methods. The Al mole fraction of the AlGaN layer was determined by photoluminescence (PL).

[a)]Electronic mail: dqiao@ucsd.edu

II. EXPERIMENTS

The AlGaN samples for this study were grown in a metalorganic vapor phase epitaxy system. The structure of the samples consisted of a 1.0 μm n-type ($\sim 1\times 10^{17}\,cm^{-3}$) $Al_xGa_{1-x}N$ layer on top of a 0.1 μm AlN insulating buffer layer on a n-type SiC (6H) on axis substrate. The GaN ($x=0$) samples consisted of a 1.5 μm n-GaN layer grown on top of a 3.5 μm undoped GaN buffer layer on a (0001) sapphire substrate. The GaN and AlGaN samples were first cleaned with organic solvents, followed by etching in a HCl:HF:H_2O solution, and loaded in an e-beam evaporator equipped with dry pumps. The conventional photolithographic lift-off technique was used to define the Schottky diodes with two different configurations as shown in Fig. 1. A bilayer of Al (710 Å, top layer) Ti (300 Å) was deposited on n-$Al_xGa_{1-x}N$ wafers, followed by annealing in a N_2 ambient at 850 °C for 40 s to form ohmic contacts. 1000 Å of Ni was deposited on the samples as Schottky contacts. For $I-V$ and $C-V$ measurements, the diodes had a donut configuration with a 125 μm diameter Schottky contact in the center [see Fig. 1(a)]. This configuration gives a relatively low series resistance due to the small spacing ($\sim$40 μm) between the outer ohmic contact ring and the Schottky contact dot in the center. For internal photoemission measurements the diodes had the configuration shown in Fig. 1(b). The ohmic contacts were two metal stripes on the sides and the Schottky contacts were 1 mm diameter Ni ($\sim$1000 Å thick) dots. A thin Au layer ($\sim$1200 Å) was deposited on top of the Ni Schottky contact to facilitate Au wire bonding.

The $I-V$ and $C-V$ characteristics were measured with an HP4155A semiconductor parameter analyzer and an HP 4284A LCR meter in parallel mode. The $C-V$ measurement frequency was set at 100 kHz which satisfied the parallel model condition as discussed in a previous article.[8] The photoemission measurement setup consisted of a halogen lamp

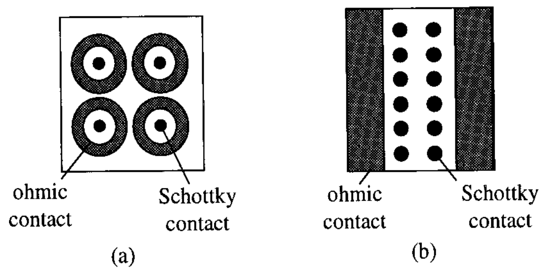

FIG. 1. Schematic diagrams of the configurations of the Schottky diodes (a) for $I-V$ and $C-V$ measurement and (b) for internal photoemission measurement.

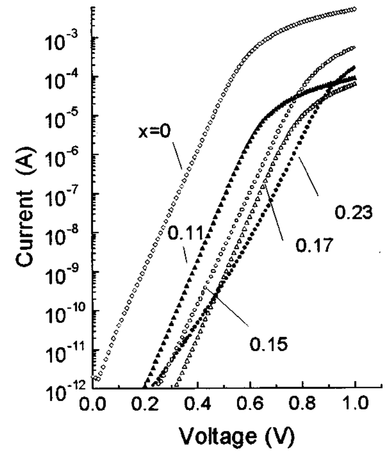

FIG. 2. $I-V$ characteristics of the Ni/AlGaN Schottky diodes with different Al mole fraction; $x=0$, 0.11, 0.15, 0.17, and 0.23.

as the light source and a monochromator (ISA, model HR-320). The monochromatic light was chopped at a frequency 338 Hz and focused on the Schottky diode from the backside. The photocurrent of the Schottky barrier was measured using a lock-in amplifier (EG & G, model 5209). The details of the photocurrent response measurements were reported in a previous article.[9]

The band gap energies of AlGaN samples were measured by PL. The Al mole fractions, x, were calculated using the following equation:

$$E_g^{(\mathrm{AlGaN})}=E_g^{(\mathrm{GaN})}(1-x)+E_g^{(\mathrm{AlN})}x-bx(1-x), \qquad (2)$$

where $E_g^{(\mathrm{AlGaN})}$, $E_g^{(\mathrm{GaN})}(=3.42\,\mathrm{eV})$ and $E_g^{(\mathrm{AlN})}(=6.2\,\mathrm{eV})$ are the band gap energies of AlGaN, GaN, and AlN, respectively, x the Al mole fraction, and b the direct gap bowing parameter. For PL measurements, excitation pulses with a pulse width of about 7 ps at a repetition rate of 9.5 MHz were provided by a picosecond UV laser system. This UV laser consists of a yttrium–aluminum–garnet laser (coherent Antares 76) with a frequency doubler which pumps a cavity-dumped dye laser (coherent 702-2CD) with Rhodamine 6G dye solution. A second frequency doubler after the dye laser provides tunable photon energy up to 4.5 eV. The laser output after the second doubler has an average power of about 20 mW. A single-photon counting detection system was used to record the PL spectra.

III. RESULTS AND DISCUSSION

Figure 2 shows typical measured $I-V$ curves of Ni/AlGaN Schottky diodes with five different x values.

The experimental $I-V$ characteristics were analyzed using the following equations:

$$I=I_s\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \qquad (3)$$

$$I_s=AA^*T^2\exp\left(-\frac{q\phi_b}{kT}\right), \qquad (3a)$$

where $q\phi_b$ is the barrier height, n the ideality factor, A the device area, V the applied voltage, T the temperature, and A^* the effective Richardson constant. The theoretical value of the effective Richardson constant is given by $A^*=2\pi qm^*k^2/h^3$, where h is the Plank constant and m^* the electron effective mass for AlGaN. Apparently there has not been any reported experimental results of the electron effective mass in AlGaN in the literature, we estimated m^* for $Al_xGa_{1-x}N$ with different x by a linear interpolation from the theoretical value of $m^*=0.35\,m_0$ for AlN[10] and $m^*=0.22\,m_0$ for GaN. From Eq. (3) it can be seen that the plot of $\ln I$ vs V should be a straight line when $V>3\,kT$. From this straight line the ideality factor, n, and the saturation current, I_s, can be determined. Using the Richardson constants, calculated from the electron effective mass of AlGaN with different x, the barrier height $q\phi_b$ was deduced from the saturation current, I_s, using Eq. (3a) at room temperature. It should be emphasized that the barrier height obtained from the $\ln I$ vs V plot is valid only when the thermionic mechanism is the only mechanism of carrier transport across the interface. This suggests an ideality factor, n, of one. It becomes larger than one when other carrier transport mechanisms, such as tunneling are involved.[11] It is generally accepted that when $n\leqslant 1.2$, the thermionic model still applies and the $I-V$ characteristics can be analyzed accordingly.

It can be seen from Fig. 2 that the $I-V$ curves of samples with x ranging from 0 to 0.17 were linear for more than six decades in the semilogarithmic scale and with an ideality factor very close to one (see Table I). These results indicate that thermionic emission is the primary transport mechanism in these diodes and that Eq. (3) can be used to deduce the Schottky barrier heights reasonably well. The series resistance of these diodes was found to be about 250–500 Ω, causing bending of the curves at high voltages. The Schottky barrier heights obtained from $I-V$ measurement suggest that $q\phi_b$ increases with x. The results are summarized in Table I. However, for the sample with $x=0.23$ the $\ln I$ vs V curve deviated from a straight line at small forward voltages (see Fig. 2), suggesting that there are components of the current other than the thermionic current, possibly defect assisted tunneling or other leakage current, existing in these samples. As a result, a rather large ideality factor of 1.37 was obtained for these diodes (see Table I).

$C-V$ measurements were also used to determine the barrier heights. The relationship between the capacitance C and the applied voltage V in a Schottky barrier is given by[12]

TABLE I. Schottky barrier height of Ni/AlGaN/SiC with different Al mole fraction.

Sample No.	Energy band gap (eV)	Al mole fraction (x)	Doping concentration $(cm^3)^b$	Ideality $(n)^b$	Barrier height $q\phi_b$ (eV) $(I-V)^b$	$(C-V)^b$	Photo[c]
1[a]	3.42	0	1.5×10^{17}	1.12	0.84	1.00	0.97
2	3.65	0.11	3.5×10^{16}	1.13	0.94	1.24	1.25
3	3.72	0.15	1.6×10^{16}	1.21	1.04	1.26	1.29
4	3.76	0.17	4.7×10^{16}	1.15	1.11	1.36	1.33
5	3.87	0.23	1.4×10^{17}	1.37	1.02	1.30	1.27

[a]All data in this row are the average values for Ni/GaN/SiC and Ni/GaN/sapphire Schottky diodes.
[b]All data in these columns are average values of 15–20 diodes. The standard deviation was about 0.05.
[c]All data in this column are average values of 3–5 diodes. The standard deviation was about 0.05.

$$\frac{1}{C^2}=\frac{2(V_{bi}-kT/q-V)}{A^2qN_d\epsilon_s}, \tag{4}$$

where V_{bi} is the built-in potential, and ϵ_s the dielectric constant of the semiconductor. The barrier height and the doping concentration can be deduced from a linear plot of $1/C^2$ vs V. Figure 3 shows the typical $C-V$ curves for Ni Schottky barriers on n-AlGaN with three different Al mole fractions. The Schottky barrier heights and doping concentration obtained by $C-V$ measurements are also listed in Table I. Listed values obtained by $C-V$ and $I-V$ measurements were the average values of 15–20 diodes. The standard deviation was about 0.05 for both n and the barrier heights.

Internal photoemission measurement is a more accurate and direct method of determining the barrier height. The principle of the photoemission method can be found in standard text books.[12] In our experiment, a monochromatic light with a photon energy $h\nu$, is used to illuminate the metal gate of a Schottky barrier, generating hot electrons in the metal. When these hot electrons diffuse into the depletion region of the Schottky barrier, they are attracted by the built-in electrical field in the barrier, thus causing a photocurrent across the Schottky diode.[9] According to Fowler's theory,[13] the relationship between the photocurrent, R, per photon and the incident photon energy, $h\nu$, is given by[12–14]

$$R\sim(h\nu-q\phi_b)^2, \tag{5}$$

where $q\phi_b$ is the barrier height. This relationship is valid for $h\nu-q\phi_b>3\,kT$ and up to several tenths of an electron volt in magnitude.[11,13] Therefore, the measurement of the photocurrent per photon as a function of the incident photon energy provides a straightforward method to determine the Schottky barrier height. Figure 4 shows a typical curve of the square root of photocurrent per incident photon vs incident photon energy for Ni diodes on $Al_{0.11}Ga_{0.89}N$ grown on a SiC substrate (sample No. 2). The barrier heights obtained by internal photoemission measurement are also listed in Table I. The results were the average of about ten measurements of 3–5 diodes for each sample. The standard deviation of the barrier height was about 0.05. It was observed that the barrier heights obtained by $C-V$ measurement are in better agreement with those obtained by internal photoemission, whereas those obtained by $I-V$ measurements are lower by about 0.2 eV. This is indicative of the fact that there are other transport mechanisms involved.

PL spectra of AlGaN/SiC with different Al mole fractions are shown in Fig. 5. The peak positions of the spectra were taken to be the band gap energies of AlGaN, as indicated by arrows in Fig. 5. Using Eq. (2), the Al mole fractions were deduced from band gap energies and listed in the Table I. In Eq. (2) the parameter b is the direct band gap bowing factor. The most recently reported value of b was 1.3 ± 0.2 eV.[15] The values of $b=1.0\pm0.3$ eV[16] and $b=0$ eV[17] have also been reported in the literature. We chose a value of one in our calculation because it gave the most consistent results for x when compared with the results obtained by other methods, such as the energy dispersive x-ray method.

Figure 6 shows the Schottky barrier heights of Ni on

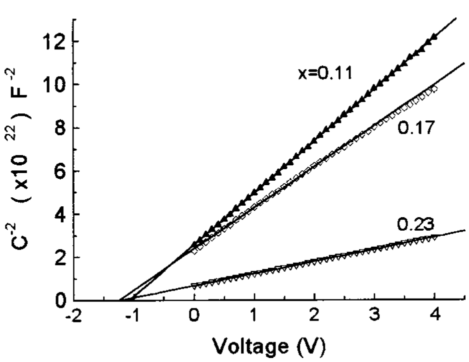

FIG. 3. $C-V$ characteristics of the Ni/AlGaN/SiC Schottky diodes with different Al mole fraction; $x=0.11$, 0.17, and 0.23.

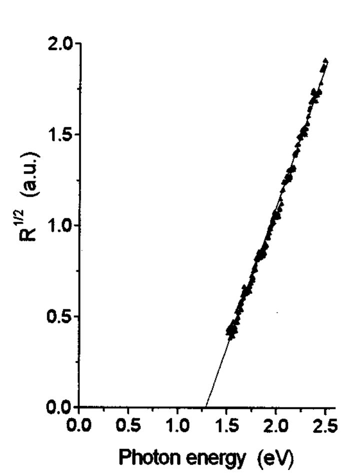

FIG. 4. Typical relationship between the square root of the photocurrent per photon and the incident photon energy for sample No. 2 ($x=0.11$).

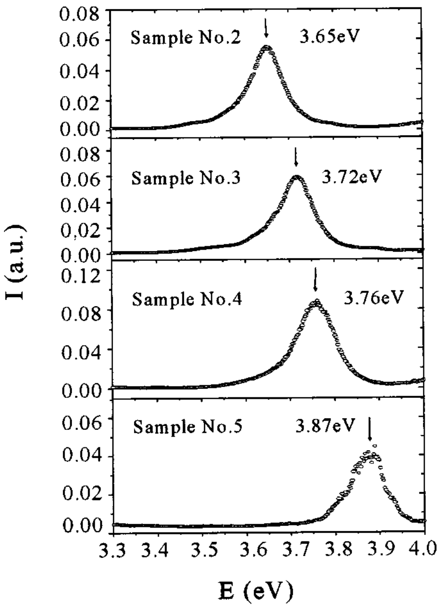

FIG. 5. PL spectra for AlGaN with different Al mole fractions. The arrows indicate the PL peak position, which was taken as the band gap energy.

n-$Al_xGa_{1-x}N$ contacts obtained by $C-V$ and photocurrent measurements as a function of Al mole fraction. It can be seen that for $x<0.2$, the barrier heights have a linear dependence on the Al mole fraction x and follow the line predicted using Eq. (1) (solid line), which was calculated assuming a linear dependence of the electron affinity on x for $Al_xGa_{1-x}N$ (χ_{GaN}=4.2 eV and χ_{AlN}=2.05 eV[18]) and Φ_m of Ni (5.15 eV).[12] The barrier height for the sample with $x=0.23$ was lower than the expected value of ~1.4 eV and the $I-V$ characteristics were not well behaved. We believe that the crystalline quality of this sample was inferior to the other samples and that interfacial states were present causing the contact to behave more in line with the Bardeen model rather than the Schottky model.[19]

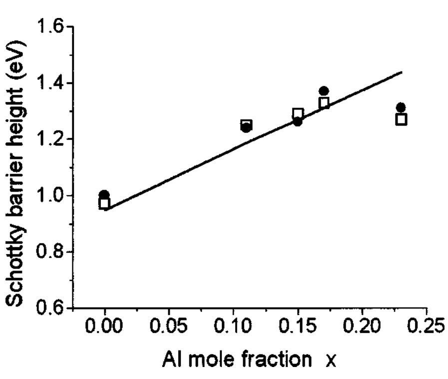

FIG. 6. The dependence of the barrier heights of the Ni/AlGaN/SiC Schottky diodes on the Al mole fraction. Results from $C-V$ measurements are depicted by solid dots (•). Results from internal photoemission measurements are depicted by empty squares (□). The solid line represents the predicted values using Eq. (1). The results obtained by $I-V$ measurements are not shown here.

IV. SUMMARY

The dependence of the barrier height of the Ni $Al_xGa_{1-x}N$ Schottky contact on the Al mole fraction up to $x=0.23$ was studied. Barrier heights were measured by $I-V$, $C-V$, and internal photoemission methods. The Al mole fractions were estimated from the AlGaN band gap energy which was measured by PL. In the range of $x<0.2$, a linear relationship between the barrier height and the Al mole fraction was obtained in reasonably good agreement with the Schottky rule. The barrier height for the sample with $x=0.23$ was smaller than the predicted value. This deviation from the Schottky rule is believed to has been caused by a high density of interface defects in samples with high Al mole fractions.

ACKNOWLEDGMENTS

The work at UCSD and KSU was supported by BMDO (Dr. Kepi Wu), monitored by the U.S. Army Space and Missile Defense Command, and by the National Science Foundation, NSF. Partial financial assistance for the work at Epitronics was provided by BMDO (Dr. Kepi Wu).

[1] M. Asif Khan, M. S. Shur, and Q. Chen, Appl. Phys. Lett. **68**, 3022 (1996).
[2] Y. F. Wu, B. P. Keller, S. Keller, D. Kapolnek, P. Kozodoy, S. P. Denbaars, and U. K. Mishra, Solid-State Electron. **41**, 1569 (1997).
[3] X. Z. Dang, R. Welty, D. Qiao, P. M. Asbeck, S. S. Lau, E. T. Yu, K. S. Boutrous, and J. M. Redwing, Electron. Lett. **35**, 602 (1999).
[4] M. E. Levinshtein, S. L. Rumyantsev, R. Gaska, J. W. Yang, and M. S. Shur, Appl. Phys. Lett. **73**, 1089 (1998).
[5] S. E. Mohney and S. S. Lau, in *GaN and Related Materials II*, edited by S. J. Pearton, (Golden and Breach, New York, 1998).
[6] M. Rezaul, H. Khan, H. Nakayama, T. Detchprohm, K. Hiramatsu, and N. Sawaki, Solid-State Electron. **41**, 287 (1997).
[7] L. Zhou, A. T. Ping, K. Boutros, J. Redwing, and I. Adesida, Electron. Lett. **35**, 745 (1999).
[8] Q. Z. Liu, L. S. Yu, F. Deng, S. S. Lau, J. M. Redwing, N. R. Perkins, and T. F. Kuech, Appl. Phys. Lett. **70**, 1275 (1997).
[9] L. S. Yu, Q. J. Xing, D. J. Qiao, S. S. Lau, K. S. Boutros, and J. M. Redwing, Appl. Phys. Lett. **73**, 3917 (1998).
[10] K. Kim, W. R. L. Lambrecht, B. Segall, and M. V. Schilfgaarde, Phys. Rev. B **56**, 7363 (1997).
[11] L. S. Yu, Q. Z. Liu, D. J. Qiao, S. S. Lau, and J. M. Redwing, J. Appl. Phys. **84**, 2099 (1998).
[12] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981), Chap. 5.
[13] R. H. Fowler, Phys. Rev. **38**, 45 (1931).
[14] C. R. Crowell, W. G. Spitzer, L. E. Howarth, and E. E. Labate, Phys. Rev. **127**, 2006 (1962).
[15] H. Angerer, D. Brunn, F. Freudenberg, O. Ambacher, and M. Stutzmann, Appl. Phys. Lett. **71**, 1504 (1997).
[16] Y. Koide, H. Itahoh, M. R. H. Khan, K. Hiramatu, N. Sawaki, and I. Akasaki, J. Appl. Phys. **61**, 4540 (1987).
[17] D. K. Wickenden, C. B. Bargeron, W. A. Bryden, J. Miragliotta, and T. J. Kisternmacher, Appl. Phys. Lett. **65**, 2024 (1994).
[18] M. W. Wang, J. O. McCaldin, J. F. Swenberg, T. C. McGill, and R. J. Hauenstein, Appl. Phys. Lett. **66**, 1974 (1995).
[19] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts*, 2nd ed. (Oxford Science, Oxford, 1988), p. 15.