Temperature dependence on current-voltage characteristics of Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode

C. J. Cheng,[1,a)] X. F. Zhang,[1] Z. X. Lu,[1] J. X. Ding,[1] L. Zhang,[1] L. Zhao,[1] J. J. Si,[1] W. G. Sun,[1] L. W. Sang,[2] Z. X. Qin,[2] and G. Y. Zhang[2]

[1]*Luoyang Optoelectronic Institute, P.O. Box 030, Luoyang, Henan 471009, People's Republic of China*
[2]*School of Physics, Beijing University, 100871 Beijing, People's Republic of China*

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Temperature dependence on electrical characteristics of a Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode is investigated in a temperature range of 198–323 K. The ideality factor decreases from 2.57 to 1.75, while the barrier height increases from 0.75 to 1.14 eV in this temperature range. The ln(I)-V curves at a small forward current are intersectant at 273, 298, and 323 K and are almost parallel at 198, 223, and 248 K. This crossing of the ln(I)-V curves is an inherent property of Schottky diodes, and the almost parallel curves can be well explained by thermionic field emission theory. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2896298]

Wide bandgap III-N materials have been the subjects of great interest mostly because of their applications in blue light emitting diodes and lasers[1] as well as in solar-blind ultraviolet (UV) photodetectors.[2,3] There are many applications for high efficiency solar-blind UV photodetectors, including early missile threat detection and interception, chemical and biological threat detection, UV flame monitoring, and UV environmental monitoring.[4] The solar-blind region corresponds to the strong atmospheric absorption of solar UV in the narrow range of 240–290 nm. This creates a natural low background window for detection of man-made UV sources. The AlGaN material system has a wide direct bandgap, and it is ideally suited in detecting UV light in the solar-blind range. The carrier transport mechanisms of the Schottky barriers can be analyzed by the temperature dependence on electrical characteristics. From the literature, there are a number of reports about the temperature dependence on electrical characteristics of metal/GaN Schottky diodes,[5–9] but there are few reports about that of metal/AlGaN solar-blind UV Schottky photodiodes. Accordingly, in this letter, we report the fabrication of the back-illuminated $Al_{0.45}Ga_{0.55}N$ Schottky photodiode and temperature dependence on electrical characteristics of the device.

The AlGaN Schottky photodiode wafer was grown by metal-organic chemical vapor deposition on both sides of the polished sapphire substrate. The detector structure was designed for back illumination. Triethyl aluminum, triethyl gallium, and ammonia (NH_3) were used as the source materials of Ga, Al, and N, respectively, with H_2 as the carrier gas. Bicyclopeantadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p-type and n-type doping sources, respectively. Deposition was initiated with a 320-nm-thick AlN at 1200 °C, followed by a ten period AlN/$Al_{0.80}Ga_{0.20}N$ (5/5 nm) superlattices topped with a 80-nm-thick undoped $Al_{0.55}Ga_{0.45}N$ layer. Next, a 300-nm-thick Si doped n^+-$Al_{0.55}Ga_{0.45}N$ layer was deposited, forming the n-type contact layer, which preceded a 250 nm-thick unintentionally doped $Al_{0.45}Ga_{0.55}N$ as an active layer. After growing, the sample was examined with both optical and scanning electron microscopes and was found to be crack-free. A schematic diagram of the device structure including the metallic contacts is shown in the inset of Fig. 1.

The fabrication process is as follows. The sample was first cleaned in boiling aqua regia for 10 min to remove the native oxide on the surface. Later, the sample was lithographically patterned into 1 mm diameter circular mesas and etched to the n-type $Al_{0.55}Ga_{0.45}N$ layer using induced coupled plasma etching. Then, a ring contact of Ti (20 nm)/Al (150 nm)/Ti (20 nm)/Au (100 nm) was deposited to n-type $Al_{0.55}Ga_{0.45}N$ and annealed in nitrogen ambient at 650 °C for 150 s to form the Ohmic contacts. Ni/Au (5/300 nm) were deposited to $Al_{0.45}Ga_{0.55}N$ and annealed in nitrogen ambient at 600 °C for 1 min. The current-voltage (I-V) parameters of the device were measured using the Keithley 4200 semiconductor characterization system in the temperature range of 198–323 K.

After processing, we analyzed the current-voltage-temperature (I-V-T) characteristics of the devices. Figure 1 shows the forward I-V characteristics of a Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode measured in a temperature range of 198–323 K. The experimental points are represented by various symbols in the figure. The logarithmic plots of I against V are straight lines at small forward currents where the effect of series resistance is small and can be neglected. At high forward voltage, the graphs are no longer straight lines, which are caused by the voltage drop

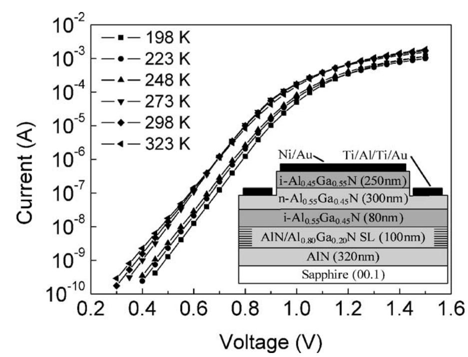

FIG. 1. Forward I-V characteristics of a Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode at various temperatures. The inset shows the cross-sectional schematic diagram of the device structure.

a)Electronic mail: yunengw@yahoo.com.cn.

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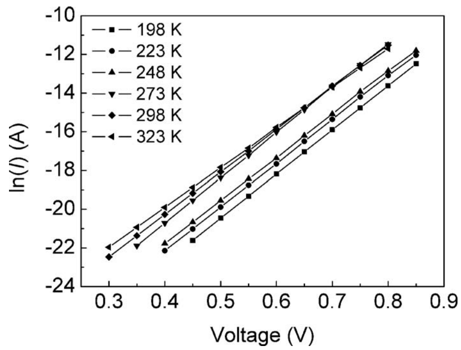

FIG. 2. Plots of ln(I) vs V of the oxidized Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode at a small forward current at different temperatures.

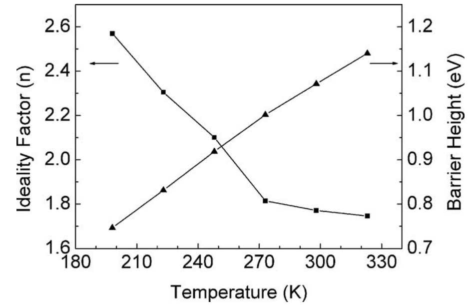

FIG. 3. Temperature dependence of the ideality factor (left scale) and barrier height (right scale) for the oxidized Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode.

across the series resistance. The forward biased I-V relationship shown in Fig. 1 can be given by the following equations based on the thermionic field emission (TFE) model:[10]

$$I = I_0 \exp[q(V - IR_S)/E_0], \quad q(V - IR_S) \gg kT, \tag{1}$$

and

$$E_0 = E_{00} \coth(qE_{00}/kT), \tag{2}$$

where I_0 is the saturation current, V the applied voltage, R_S the series resistance, q the electronic charge, k the Boltzmann constant, T the absolute temperature, and E_{00} the characteristic energy defined by $E_{00}=(qh/4)[N_d/(m_e^*\varepsilon_S)]^{1/2}$, where h is the Plank's constant, N_d the donor concentration, m_e^* the effective mass of the electron, and ε_S the permittivity. $m_e^*=0.337\ m_e$ and $\varepsilon_S=8.72$ for $Al_{0.45}Ga_{0.55}N$ are estimated by a linear extrapolation from the value of $m_e^*=0.48\ m_e$ and $\varepsilon_S=8.5$ for AlN and $m_e^*=0.22\ m_e$ and $\varepsilon_S=8.9$ for GaN, where m_e is the mass of the electron.

A family of ln(I) versus V plots at a small forward current for the different temperatures is shown in Fig. 2. It can be seen from Fig. 2 that the ln(I)-V curves somewhere around the voltage 0.68 V intersect to each other at 273, 298, and 323 K and are almost parallel at 198, 223, and 248 K. This crossing of the ln(I)-V curves where the current is not driven by the series resistance appears as an abnormality compared to the conventional behavior of ideal Schottky diodes, which is an inherent property of any Schottky diodes.[11,12] The almost parallel ln(I)-V curves means that the dominant transport mechanism is TFE, which is in agreement with a theoretical analysis of metal/GaN Schottky diodes with $E_{00}=0.020$ eV reported by Yu *et al.*[5]

The accurate values of E_0 and I_0 are determined from the slope and intercept on the vertical axis in Fig. 2, respectively. From the slope of ln(I) versus V curve at a small forward current, E_0 of 43.84, 44.28, 44.90, 42.70, 45.50, and 48.60 meV are obtained at 198, 223, 248, 273, 298, and 323 K, respectively. The ideality factor n and the barrier height $q\Phi_B$ are obtained from $n=E_0/kT$ and $q\Phi_B=kT\ln(AA^{**}T^2/I_0)$, respectively, where A is the area of the diode and A^{**} is the Richardson constant defined by $A^{**}(\mathrm{A\ cm^{-2}\ K^{-2}})=4\pi qk^2m_e^*/h^3=120(m_e^*/m_e)$.[13] By using an effective mass of $0.337m_e$, the theoretical value of A^{**} is calculated to be 40.44 A $\mathrm{cm^{-3}\ K^2}$. Figure 3 shows the temperature dependence on n and Φ_B. The ideality factor decreases from 2.57 to 1.75, while the barrier height increases from 0.75 to 1.14 eV with increasing temperature. Since the current transport across the metal-semiconductor interface is a temperature-activated process, electrons at a low temperature are able to surmount the lower barrier, and therefore, the current transport will be dominated by the current flowing through the patches of a lower Schottky barrier height and a larger ideality factor. As the temperature increases, more and more electrons have sufficient energy to surmount the higher barrier. As a result, the dominant barrier height will increase with the temperature and bias voltage.[14,15] The ideality factors of 1.75–2.75 far greater than 1 could be caused by the interfacial layer between the metal and semiconductor.[10]

Figure 4 shows the values of E_0 as a function of kT. In the high temperatures of 273, 298, and 323 K, three datum points fall on a straight line, and E_0 increases rapidly with increase in kT. The dashed curve in Fig. 4, which represents the theoretical expression of the thermionic emission (TE) with $n=1.75$, deviates slightly from the experimental datum points at high temperatures. Other three datum points at lower temperatures of 198, 223, and 248 K are off the straight line fitted at high temperatures, and E_0 increases slightly with increase in kT. The solid curve in Fig. 4, which represents the theoretical expression of E_0 with $E_{00}=43.3$ meV, is in good agreement with the experimental datum points at low temperatures. Using the formula for E_{00}, the donor concentration of $1.6\times10^{19}\ \mathrm{cm^{-3}}$ calculated is higher than that of $6.8\times10^{17}\ \mathrm{cm^{-3}}$ obtained from the C-V measurement at room temperature. One possibility of the origin of the difference may be from N vacancies induced by the interfacial reactions between contacts of Ni/Au and $Al_{0.45}Ga_{0.55}N$ annealed in nitrogen ambient at 600 °C for 1 min.

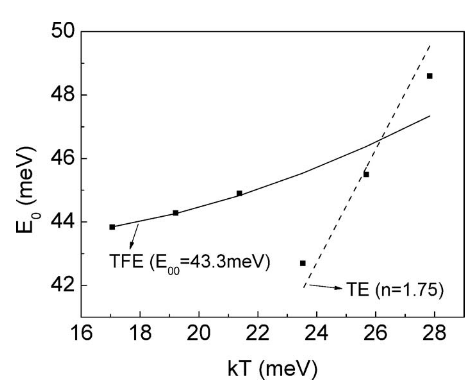

FIG. 4. Experimental values of E_0 as a function of kT for the oxidized Ni/Au–$Al_{0.45}Ga_{0.55}N$ Schottky photodiode. The solid and dashed curves represent the theoretical expression of TFE with $E_{00}=43.3$ meV and TE with $n=1.75$, respectively.

In summary, we report the fabrication and temperature dependence on electrical characteristics of a $Ni/Au-Al_{0.45}Ga_{0.55}N$ Schottky photodiode grown on sapphire by metal-organic chemical vapor deposition. Temperature dependence of the forward *I-V* characteristics of the Schottky photodiode has been investigated. The ideality factor decreases from 2.57 to 1.75, while the barrier height increases from 0.75 to 1.14 eV in a temperature range of 198–323 K. The $\ln(I)$-V curves at a small forward current are intersectant at 273, 298, and 323 K and are almost parallel at 198, 223, and 248 K. This crossing of the $\ln(I)$-V curves appears as an abnormality compared to the conventional behavior of ideal Schottky diodes, which is an inherent property of any Schottky diodes, while the almost parallel curves can be well explained by the TFE theory with a characteristic energy of 43.3 meV.

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