Microelectronic Engineering 93 (2012) 100–104

Contents lists available at SciVerse ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Temperature-dependent electrical properties of (Pt/Au)/Ga-polarity GaN/Si(1 1 1) Schottky diode

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ARTICLE INFO

Article history:
Received 8 April 2011
Received in revised form 1 August 2011
Accepted 30 November 2011
Available online 28 December 2011

Keywords:
III–V Semiconductors
Schottky diode
Metal contacts

ABSTRACT

We report on temperature dependent electrical properties of (Pt/Au)/Ga-polarity GaN/Si(1 1 1) Schottky diode using current–voltage characteristics in the temperature range of 200–375 K. The basic diode parameters, such as zero-bias Schottky barrier height (ϕ_{B0}) and ideality factor ('n') were extracted from I–V using standard thermionic emission (TE) theory. The estimated ϕ_{B0} and 'n' are found to be 0.50 eV and 3.2 for 200 K, 0.78 eV and 1.4 for 375 K. The calculated series resistance (R_s) by Cheung's method shows unusual behavior with increasing temperature. The R_s value exhibits by diode at 200 K is about 534 Ω, which then decreases to 132 Ω for 300 K and thereafter increases to 154 Ω at 375 K, respectively. It was seen that ϕ_{B0}, 'n' and R_s are strongly temperature dependent. There is also a linear correlation between ϕ_{B0} and 'n' due to the inhomogeneities of the barrier heights (BHs). The estimated Richardson's constant (A^*) from intercepts at the ordinate of linear fit to the conventional activation energy plot is about $\sim 5.57 \times 10^{-3}$ A cm^{-2} K^{-2},which is much lower than the known value of n-type GaN (26.4 A cm^{-2} K^{-2}). Such behavior is also attributed to barrier inhomogeneities at the contact interface. In order to prove the same, results have been interpreted based on the assumption of Gaussian distribution (GD) over the BHs. We calculated the mean barrier height ($\bar{\Phi}$) is 1.04 eV and standard deviation (σ_s) to be 145 mV. In addition to this, obtained A^* from the modified Richardson plot $\ln(J_s/T^2) - (e^2\sigma_0^2/2k^2T^2)$ *versus* $1/T$ is 27.62 A cm^{-2} K^{-2}, which is in good agreement with the theoretical value of GaN.

1. Introduction

Gallium nitride (GaN) has great potential applications at high temperature, high frequency and in high power electronic devices due to its remarkable properties like wide band gap (3.44 eV at room temperature) [1], high break down field 3×10^6 V/cm [2] and high electron saturation velocity 2×10^7 cm/s [3]. Device applications include light emitting diodes (LEDs) [4], laser diodes (LDs) [5], photo-diodes [6], hetero-junction field-effect transistors (HJFETs) [7] and high-electron mobility transistors (HEMTs) [8]. Schottky contacts are fundamental units for semiconductor electronic industry. Due to the technical importance of metal contacts to semiconductors, a full understanding of current transport mechanism between contact interfaces in harsh environments is still a challenging problem. In addition, the change in surrounding temperature effect the determination of main diode parameters, such as Schottky barrier height (SBH), ideality factor 'n' and series resistance (R_s). Hence, it is important to analyze the behavior of electrical properties at metal–semiconductor interface in wide temperature range. The temperature dependent current–voltage (I–V) characteristics give a better picture of the conduction mechanism, and allow understanding of different aspects involved in the current transport mechanism [9].

Extensive work has been carried out by many researchers on temperature dependent electrical properties of metal–semiconductors contacts [10–21]. Lucolano et al. [10] studied temperature dependent electrical properties of Pt Schottky contact to GaN annealed at 400 °C. They reported barrier inhomogeneity at metal–semiconductor interface, correlated to the nanoscale electrical characterization of the barrier. Huang et al. [11] investigated current transport mechanism in Au/Ni/GaN Schottky diode using I–V characterization technique in the temperature ranging from 27 °C to 350 °C, and reported the effective Richardson's constant is about 24.08 A cm^{-2} K^{-2} from the modified Richardson plot. Tekeli et al. [13] investigated inhomogeneous behavior of I–V–T characteristics in Ni/Au contact on $Al_{0.3}Ga_{0.7}N$/AlN/GaN hetero-structures in the temperature range of 295–415 K. They also estimated Richardson's constant value to be about 34.25 A cm^{-2} K^{-2} from the modified Richardson plot, which is close to the A^* value of undoped $Al_{0.3}Ga_{0.7}N$. Yildirim et al. [18] reported I–V and C–V characteristics of Ni/n-GaN Schottky diode in the temperature range of 80–400 K. Recently Subramaniyan et al. [21] measured I–V characteristics of (Ni/Au)-InAlGaN/GaN Schottky barrier diode in the temperature

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0167-9317/$ - see front matter
doi:10.1016/j.mee.2011.11.019

range of 295–473 K and the results were interpreted based the on the assumption of Gaussian distribution (GD) of barrier heights. They obtained experiment Richardson's constant and reported which is to theoretical value (29.1 A cm^{-2} K^{-2}) from modified Richardson plot for InAlGaN/GaN Schottky barrier diode.

In the present work, we have been investigating temperature-dependent electrical properties of Au/Pt/Ga-polarity GaN/Si(1 1 1) Schottky rectifier in the temperature ranging from 200 K to 375 K. ϕ_{B0} and 'n' were extracted from I–V characteristics using thermionic emission (TE) theory, where as R_s was estimated by Cheung's method [22] and observed that they were strongly temperature dependent.

2. Experimental details

In this work, we used 1 μm unintentionally doped n-type Ga-polarity GaN ($\sim 2 \times 10^{16}$ cm^{-3}) grown on Si(1 1 1) using plasma-assisted molecular beam epitaxy (MBE). First, the Si(1 1 1) substrate was cleaned by dipping into the HF for 1 min to remove native oxide on Si surface and dried with N_2 gas, and then immediately transferred into a chamber and pumped down and heat the substrate at 540 °C for 60 min at 1×10^{-8} Torr pressure in the treatment chamber. The de-oxidation is done by heating the substrate at 850 °C for 60 min at 1×10^{-9} Torr pressure in the growth chamber. The removal of the oxide was verified by the reflection high-energy electron diffraction (RHEED) pattern of (7×7). The substrate temperature was then lowered to 640 °C and the Si substrate was soaked for 1 min in Al (2 monolayer) at an overpressure of 2×10^{-7} Torr. The Al soaking is conducted to avoid the nitridation of the Si surface because nitridation may result in the formation of amorphous Si_3N_x, which is obviously not conducive to subsequent epitaxial growth. After the Al soaking, nitridation on the surface was done at 730 °C for 5 min to form the AlN nucleation layer and then buffer layer AlN (80 nm) was grown sequentially at low (770 °C) and high temperatures (830 °C). Finally, Ga-polarity GaN film was grown at 780 °C. Ohmic metals for n-type GaN Ti/Al (20 nm/100 nm) were deposited on a portion of the sample using electron beam evaporation system, under a pressure of 3×10^{-6} Torr. Prior to Schottky metal deposition, Ohmic samples were annealed using rapid thermal annealing system at 600 °C for 3 min in the presence of N_2 in a quartz tube furnace at atmospheric pressure. The Schottky contact was formed by the deposition of Pt/Au (20 nm/100 nm) with 1 mm diameter, through a mask of circular dots. The Schematic view of our sample structure with Ohmic and Schottky contacts is shown in Fig. 1. First we observed I–V and capacitance–voltage (C–V) characteristics at room temperature using Keithley measure unit (Model No. 236) and Boonton capacitance meter (1 MHz, Model No. 7200), respectively. The carrier concentration obtained from the C–V characteristics was $\sim 4.62 \times 10^{16}$ cm^{-3}. The I–V characteristics as a function of temperature for Schottky diode were measured in steps of 25 K from 200 K to 375 K. Cooled cryostat with liquid nitrogen was used for temperature dependent measurement.

3. Results and discussion

Fig. 2 shows the semi-logarithmic plot of forward and reverse bias current density–voltage (J–V) characteristics of Au/Pt/Ga-polarity GaN Schottky diode as function of temperature in steps of 25 K in the temperature range of 200–375 K. Total eight Pt/Au Schottky contacts were performed on Ga-polarity GaN/Si(1 1 1) structure grown by MBE. In all the cases we observed similar I–V and C–V characteristics measured at room temperature and the exhibited diode parameters were almost similar for all samples. Only one diode is used for temperature dependent characterization. The measured reverse leakage current density at $-1V$ is 4.13×10^{-3} A cm^{-2} for 200 K and 6.17×10^{-2} A cm^{-2} for 375 K, respectively. The leakage current density values for each temperature grade are given in Table 1. It is observed that the leakage current density increases with increase in temperature and consisted SBH inhomogeneity. The origin of leakage current is probably due to deep level impurity or edge leakage currents [23,24]. Zhang et al. [23] investigated leakage current mechanisms in GaN film grown by MBE and suggested that reverse leakage current is dominated by the emission of a electron from a trap state near the metal–semiconductor interface into a continuum of states associated with each conductive dislocation. Hsu et al. [24] reported screw dislocations acts as a passageway of excess leakage current in GaN film grown by MBE. Our further study is on investigation of deep level defects in (Pt/Au)-Ga-polarity GaN system. The current density of metal–semiconductor contact having series resistance (R_s) dominated by TE is given as [25,26]:

$$J = J_s\left[\exp\left\{\frac{q}{nkT}(V - IR_s)\right\} - 1\right] \quad (1)$$

where $J_s = A^*T^2\exp(-q\phi_{B0}/kT) = I_s/A$ is the reverse saturation current density derived from the plot $I/[1-\exp(-qV/kT)]$ *versus* V (figure is not shown here) plot is a straight line and intercepts the current axis at $V = 0$ using experimental data reported in Fig. 2, from which the SBH was defined in terms of TE and is given by

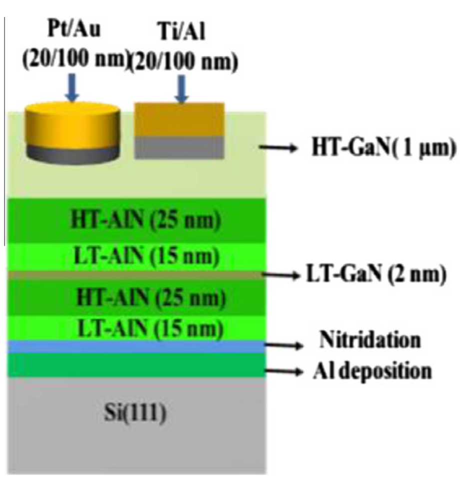

Fig. 1. Schematic view of our sample structure with Ohmic and Schottky contacts on Ga-polarity GaN grown by MBE on Si(1 1 1).

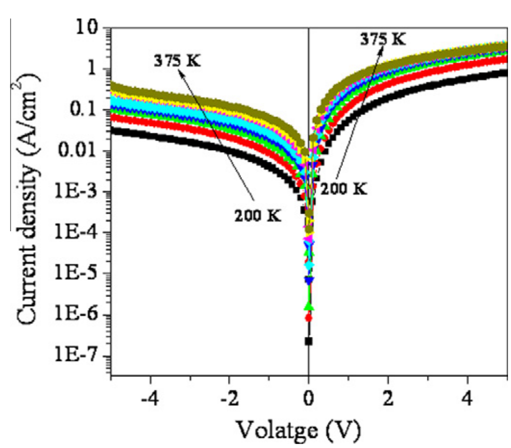

Fig. 2. Semi-logarithmic current density–voltage (J–V) characteristics of a (Pt/Au)/Ga-polarity GaN/Si(1 1 1) Schottky diode in the temperature ranging from 200 K to 375 K.

Table 1
Leakage current density, zero-bias SBH (ϕ_{B0}) ideality factor 'n' and series resistance R_s of Au/Pt/Ga-polarity GaN/Si(1 1 1) Schottky diode in temperature range of 200–375 K.

Temperature (K)	Leakage current density at −1 V (A/cm^2)	Zero-bias SBH (ϕ_{B0}) (eV)	Ideality factor 'n'	Series resistance R_s (Ω)
200	4.13×10^{-3}	0.50 (±0.003)	3.2 (±0.02)	534 (±0.3)
225	8.86×10^{-3}	0.54 (±0.005)	3.1 (±0.01)	247 (±0.2)
250	1.43×10^{-2}	0.59 (±0.006)	2.7 (±0.03)	161 (±0.4)
275	2.01×10^{-2}	0.62 (±0.005)	2.5 (±0.02)	135 (±0.3)
300	2.65×10^{-2}	0.66 (±0.004)	2.2 (±0.01)	132 (±0.1)
325	3.92×10^{-2}	0.68 (±0.003)	1.9 (±0.03)	138 (±0.2)
350	4.67×10^{-2}	0.72 (±0.007)	1.6 (±0.05)	143 (±0.2)
375	6.17×10^{-2}	0.78 (±0.005)	1.4 (±0.03)	154 (±0.2)

$$\phi_{B0} = \frac{kT}{q} \ln\left(\frac{A^*T^2}{J_s}\right) \tag{2}$$

where A is the diode area, A^* is the effective Richardson's constant and it is assumed to be 26.4 A cm^{-2}K^{-2} for n-GaN [27], k is Boltzmann's constant, T is the absolute temperature and q is the electron charge. The estimated SBH of (Pt/Au)-Ga-polarity GaN Schottky diode is about 0.50 eV for 200 K and 0.78 eV for 375 K, for each temperature the SBH values can be seen in Table 1. In addition, the values of SBH of (Pt/Au)-Ga-polarity GaN Schottky diode calculated from the J–V characteristics show an unusual behavior with the increase in temperature. Such temperature dependence is an obvious disagreement with the reported negative temperature coefficient of the barrier height or forbidden band gap of a semiconductor [13]. The difference between the two zero-bias barrier heights of two successive measured temperatures is due to the reduction or enhancement of doping level and free carrier concentration near the metal/semiconductor interface with temperature [28]. The ideality factor 'n' can be estimated from the slope of the linear region of forward bias J–V characteristics and can be written from Eq. (1) as,

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln J}\right) \tag{3}$$

'n' is a measure of consistency of TE for a diode and the value of 'n' for an ideal diode should be unity. However for real diodes it is usually greater than unity. The extracted ideality factor for each measured temperature is shown in Table 1. A significant improvement in the value of ideality factor 'n' from 3.2 to 1.4 was observed. Interestingly, the zero-bias SBH was increasing with temperature, whereas ideality factor 'n' was found decrease with temperature. The increase of 'n' with decreasing temperature is due to, when the current flows across the metal/semiconductor interface in a temperature activated process, the electrons at low temperatures are able to surmount the lower barrier and the current transport will be dominated by the current flowing through the patches of lower SBHs [29–34].

The semi-logarithmic forward bias J–V characteristics are linear in low bias (Fig. 2), but deviated from linearity due to R_s effect at high voltage. Hence, R_s is a very important factor and it deviates ϕ_{B0} and 'n' considerably at low temperatures from accuracy of determination. The series resistance of the Au/Pt/Ga-polarity GaN Schottky diode was evaluated from forward J–V characteristics in the temperature range of 200 K to 375 K using a method developed by Cheung and Cheung [22]. Fig. 3 shows the experimental characteristic plot of $dV/dln(I)$ *versus* I for different temperatures of Au/Pt/GaN Schottky diode. The extracted R_s from the slope of these curves for each temperature is given in Table 1 and we observed an unusual behavior in R_s with increasing temperature. The R_s values increase abnormally at low temperatures due the lack of free charge carriers [25] and decrease gradually with increasing

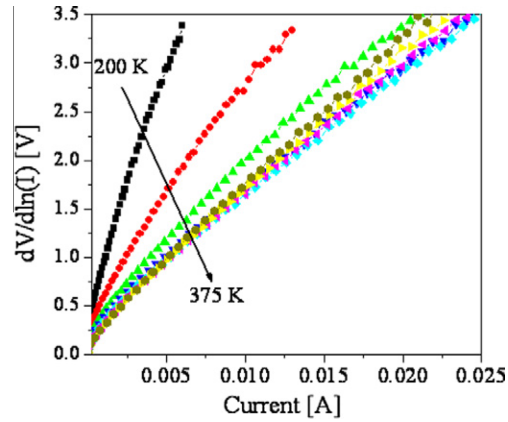

Fig. 3. Characteristics plot of $dV/d\ln(I)$ *versus* I for Ga-polarity GaN Schottky diode at different temperatures.

temperature up to 300 K, there after gradually increase from 325 K to 375 K. According to Lin [35], the increase of R_s with increasing temperature after 325 K is due to decrease in electron mobility with increasing temperature and the increase of effective density states in the conduction band with increasing temperature may lead to increase in the energy difference between the conduction band minimum and the Fermi level and decrease in the probability of tunneling. A similar effect was obtained through simulation and experiments of the forward I–V curves of Si Schottky diodes [36,37].

Fig. 4 shows the activation energy plot also called conventional Richardson plot. The estimated effective SBH at 0 K and Richardson's constant from the slope and intercepts of linear fit for $\ln(J_s/T^2)$ *versus* $1/T$ plot are 0.11 eV and 5.57×10^{-3} A cm^{-2}K^{-2}, respectively. Our A^* value similar to Richardson's value is reported by Zhou et al. for bulk GaN [12] and its value is almost four orders of magnitude lower than the theoretical value of GaN (26.4 A cm^{-2}K^{-2}) due to the existence of the barrier inhomogeneities and potential fluctuations between metal/semiconductor interface, which consist of low and high barrier areas [17,37–42]. According to Horvarth [42] the low value of A^* obtained by the temperature dependence of I–V characteristics is due to the lateral inhomogeneity of BHs.

Another proof of inhomogeneity of BHs in Pt/Au Schottky contact on Ga-polarity GaN is the ideality factor which may increase with decrease in temperature over the distribution of low SBHs.

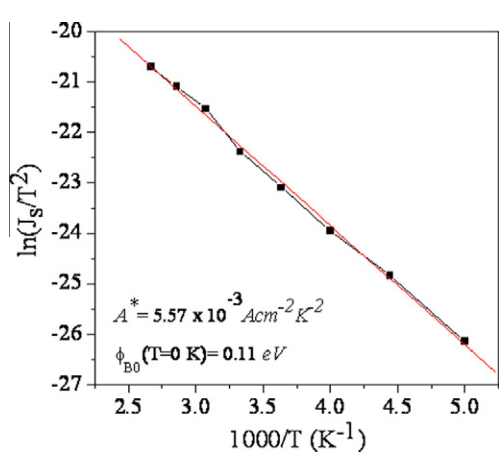

Fig. 4. The plot of $\ln(J_s/T^2)$ *versus* $1/T$ for (Pt/Au)/Ga-polarity GaN/Si(1 1 1) Schottky diode.

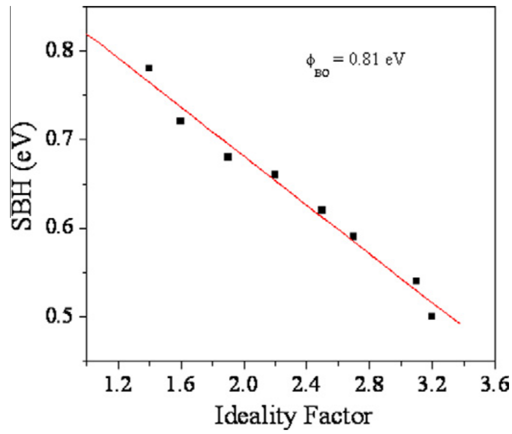

Fig. 5. Plot of zero-bias barrier height *versus* ideality factor.

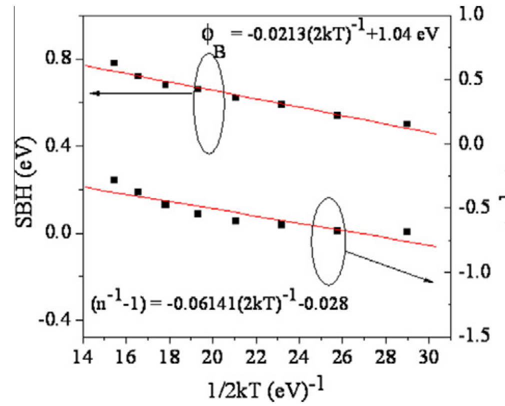

Fig. 6. The plot of ϕ_{B0} and '*n*' *versus* $1/kT$ of a Ga-polarity GaN Schottky diode according to Gaussian distribution theory.

Schmitsdorf et al. [43] found a linear correlation between experimental ϕ_{B0} and '*n*' by using the Tung's [44] theoretical approach. Fig. 5 shows the plot of experimental ϕ_{B0} *versus* n of Ga-polarity GaN Schottky diode. As seen in Fig. 5, there is a linear relationship between the experimental BHs and ideality factor of our Schottky contact and which is explained by the lateral inhomogeneities of BHs in the Schottky diodes as in [13,30,33]. The extrapolation to $n = 1$ of linear fit to the plot (Fig. 5) gives the effective BH which is approximately 0.81 eV. Thus, it is noticed that, there is a significant decrease in the value of ϕ_{B0} and an increase in the value of '*n*' especially at a low temperature probably due inhomogeneities of BHs.

In order to explain the SBH inhomogeneity at metal/semiconductor interface, we assume a model of lateral SBH distribution with Gaussian distribution (GD) over the BHs proposed by Werner and Guttler [31], and the characterized by mean barrier height ($\bar{\Phi}$) and standard deviation σ_s is given by:

$$\phi_{ap} = \bar{\Phi}(T = 0) - \frac{q\sigma_0^2}{2kT} \quad (4)$$

$$\left(\frac{1}{n_{ap}} - 1\right) = \rho_2 - \frac{q\rho_3}{2kT} \quad (5)$$

where $\bar{\Phi}$ and σ_s are linearly bias dependent of GD parameters, such that $\phi_{B0} = \bar{\Phi} + \rho_2 V$ and standard deviation $\sigma_s = \rho_{so} + \rho_3 V$, where ρ_2 and ρ_3 are voltage coefficients which depend on temperature and quality of the voltage deformation of barrier distribution. The temperature dependence of σ_s is usually small and can be neglected [45]. The plot ϕ_{B0} *versus* $1/2kT$ is a straight line (Fig. 6) and it is the first evidence of the GD of BHs. The values of $\bar{\Phi}$ and σ_s extracted from the intercepts and slope of linear fit are 1.04 eV and 145 mV at a zero-bias, respectively. The structure with the best rectifying performance presents the barrier homogeneity with lower value of standard deviation. It was seen that the value of σ_s is not small compared with mean BH value and it indicates the barrier inhomogeneity at the interface between metal and semiconductor [13]. In Fig. 6 the plot of $(1/n_{ap} - 1)$ *versus* $1/2kT$ is straight line that gives the voltage coefficients ρ_2 and ρ_3 from the intercept and slope, >respectively. The obtained values of $\rho_2 = -0.028$ V and $\rho_3 = -0.061$ V, respectively.

Fig. 7 is the plot between $\ln(J_s/T^2) - (e^2\sigma_0^2/2k^2T^2)$ *versus* $1/T$ is called the modified Richardson's plot which has an excellent linearity over the whole temperature range when compared to conventional Richardson's plot. The estimated mean BH ($\bar{\Phi}$) and A^* from slope and intercept of linear fit are 1.06 eV and 27.62 A cm^{-2} K^{-2}, respectively. As it can be observed that, the mean BH is in good agreement with the value of BH (1.06 eV) estimated from ϕ_{B0} *versus* $1/2kT$ (Fig. 7). While the effective Richardson's constant (A^*) is 27.62 A cm^{-2} K^{-2}, which is in excellent agreement with the known theoretical value 26.4 A cm^{-2} K^{-2} of GaN.

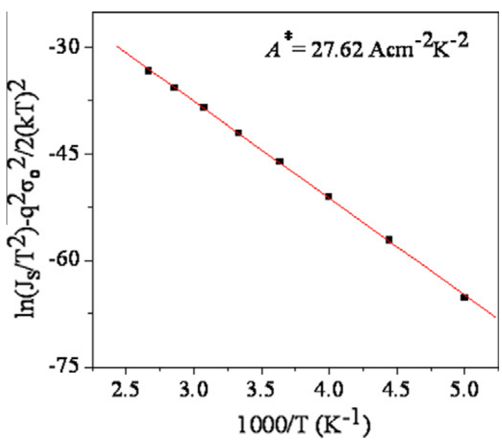

Fig. 7. The modified Richardson plot of $\ln(J_s/T^2) - (q^2\sigma_0^2/2(kT)^2)$ *versus* $1/T$.

4. Summary

The detailed analysis of temperature-dependent electrical properties of Au/Pt/Ga-polarity GaN/Si(1 1 1) Schottky diode has been done in the temperature range of 200 K to 375 K. We estimated the basic diode parameters such as ϕ_{B0}, '*n*' and R_s from the experimental *J–V–T* characteristics. The SBH increases whereas '*n*' decreases with increasing temperature. We found the abnormal behavior of R_s with increasing temperature. The R_s value decreases from 534 Ω to 132 Ω (200–300 K) and then increased to 154 Ω (375 K). The basic diode parameters are strongly temperature dependent, such anomalous behavior of the SBHs and '*n*' is attributed to spatial variations of the barrier heights at metal and semiconductor interface. The effective Richardson's constant (A^*) calculated from the modified Richardson's plot $\ln(J_s/T^2) - (e^2\sigma_0^2/2k^2T^2)$ *versus* $1/T$ is about 27.62 A cm^{-2}K^{-2}, which is very close to the known theoretical value of GaN (26.8 A cm^{-2}K^{-2}). (Pt/Au)-Ga polarity GaN/Si(1 1 1) Schottky barrier diode have been successfully explained on the basis of thermionic emission with the Gaussian distribution of the barrier heights.

Acknowledgements

This research was supported by Basic Science Research (No. 2010-0023852) and Leading Foreign Research Institute Recruitment Program (No. 2010-00218) through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (MEST). Also, this work was supported by the National Research Foundation of Korea Grant funded by the Korean Government (MEST) (NRF-M1AWA001-2010-0026292).

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