Current-Voltage Temperature characteristics of Au/n-Ge (100) Schottky diodes

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Abstract

The variation in electrical characteristics of Au/n-Ge (100) Schottky contacts have been systematically investigated as a function of temperature using current–voltage (I–V) measurements in the temperature range 140–300 K. The I–V characteristics of the diodes indicate very strong temperature dependence. While the ideality factor n decreases, the zero-bias Schottky barrier height (SBH) (Φ_B) increases with increasing temperature. The I-V characteristics are analyzed using the thermionic emission (TE) model and the assumption of a Gaussian distribution of the barrier heights due to barrier inhomogeneities at the metal-semiconductor interface. The zero-bias barrier height Φ_B versus 1/2kT plot has been used to show evidence of a Gaussian distribution of barrier heights and values of $\overline{\Phi}_B$ = 0.615 eV and standard deviation $\dagger_{s0}$ = 0.0858 eV for the mean barrier height and zero-bias standard deviation have been obtained from this plot, respectively. The Richardson constant and the mean barrier height from the modified Richardson plot were obtained as 1.37 Acm^{-2}K^{-2} and 0.639 eV, respectively. This Richardson constant is much smaller than the reported of 50 Acm^{-2}K^{-2}. This may be due to greater inhomogeneities at the interface.

Keywords: Schottky contacts, current-voltage-temperature, Schottky barrier height, Gaussian distribution, inhomogeneities

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1. Introduction

Metal-semiconductor (MS) contacts are the most widely used rectifying contacts in the electronic industry. The performance and reliability of a Schottky diode (SD) is drastically influenced by the interface quality between the deposited metal and semiconductor surface [1]. Therefore, MS interfaces are an essential part of virtually all semiconductor electronic and optoelectronic devices. The Schottky barrier height (SBH) is one of the most interesting properties of a MS interface as it controls the electron transport across the MS interface, and is of vital importance to the successful operation of any semiconductor device [2]. It is often found that the current-voltage (*I-V*) characteristics of MS contacts usually deviate from the ideal thermionic emission (TE) current model [3]. Analysis of the *I-V* characteristics of Schottky barrier diodes (SBDs) based on TE theory usually reveals an abnormal decrease in the barrier height and an increase in the ideality factor with decreasing temperature [4,5]. The standard TE theory fails to explain this result as it expects the SBH variation to be controlled only by the variation of band gap with temperature [6]. SBH in Schottky contacts is likely to be a function of the atomic structure, and the atomic inhomogeneities at MS interface which are caused by grain boundaries, defects, multiple phases, etc. [7]. Contaminants due to undesirable reaction products at the MS interface may act directly to introduce inhomogeneties or they may simply promote inhomogeneity through the generation of defects [8]. Schottky diodes with low SBH have found applications in devices operating at cryogenic temperatures as infrared detectors and sensors in thermal imaging [9,10,11,12]. Therefore, analysis of *I-V* characteristics of Schottky diodes at room temperature only does not give detailed information about their conduction process or the nature of barrier formation at the MS interface. The temperature dependence of the *I-V* characteristics allows us to understand different aspects of conduction mechanisms [13].

To the best of our knowledge there has been no report on the electrical transport characteristics of germanium (Ge) Schottky contacts at low temperatures. Therefore an attempt has been made to study the current transport characteristics of Au/n-Ge (100) Scottky diodes in the temperature range 140 – 300 K. In this study, the *I-V* characteristics of Au/n-Ge (100) Schottky diodes were measured in the 140 – 300 K temperature range. The temperature dependent barrier characteristics of Au/n-Ge (100) contact were interpreted on the basis of a thermionic emission mechanism with Gaussian spatial distribution of the barrier heights around a mean value due to barrier height inhomogeneities prevailing at the MS interface.

2. Experimental procedures

Schottky barrier diodess were fabricated on Sb-doped (100) n-type Ge substrate with doping concentration of 2.5×10^{15} cm^3. The substrate was sequentially degreased with organic solvents like trichloroethylene, acetone and methanol by ultrasonic agitation for 5 minutes in each stage followed by rinsing in deionized water. The native oxide on the surface was etched in a mixture of H_2O_2 (30%):H_2O (1:5) for 1 minute. After rinsing in deionized water the sample was blown dry using N_2. Immediately after cleaning the sample was inserted into a vacuum chamber where 100 nm thick AuSb (0.6%) was deposited by resistive evaporation as a back ohmic contact, followed by annealing at 350°C in Ar ambient for 10 minutes to minimize the ohmic contact's resistivity. Before contacts deposition, the sample was again chemically cleaned as described above. Au Schottky contacts were deposited by vacuum resistive evaporation through a mechanical mask. These contacts were deposited under vacuum with a pressure below 10^{-6} Torr. The contacts were (0.60 ± 0.05) mm in diameter and 30 nm thick. Thickness of the contacts was measured during deposition by an INFICON XTC 751-001-G1 crystal thickness monitor. After contact fabrication, current-

voltage (*I-V*) measurements were performed in a He cryostat in the temperature range 140 – 300 K.

3. Results and discussions

3.1 The current-voltage characteristics as a function of temperature

The *I-V* relation for a MS diode, based on the TE theory can be expressed as [1,14]

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

where *I* is the measured current, *V* is the applied voltage, *q* is the electronic charge, *n* is the ideality factor that describes the deviation from the ideal diode equation for reverse bias as well as forward bias, *k* is the Boltzmann's constant, *T* is the absolute temperature in Kelvin, I_s is the saturation current derived from the straight line intercept of ln *I* at zero-bias and is given by

$$I_s = AA^*T^2 \exp\left(-\frac{q\Phi_B}{kT}\right)$$
(2)

where *A* is the SD area, A^* is the effective Richardson constant and Φ_B is the apparent barrier height at zero-bias, which can be obtained from Eq. (2)

$$\Phi_B = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_s}\right)$$
(3)

The ideality factor is determined from the slope of the linear region of the plot of natural log of forward current versus forward bias voltage and is given by

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right)$$
(4)

Typical forward bias *I-V* characteristics of Au/n-Ge (100) Schottky contacts measured in the 140 – 300 K temperature range are shown in Fig. 1. These curves indicate a very strong temperature dependence of the Schottky diodes. The *I-V* characteristics deviate from ideality at low temperature (140 – 200 K), which is due to the effect of other current transport

processes like generation-recombination of carriers in space charge region [14] and tunneling of electrons through the barrier. At temperatures above 220 K, thermionic emission becomes the dominant process. We have performed the least squares fit of Eq. (1) to the linear part of the intermediate forward bias region of the measured *I-V* plots (Fig. 1), by assuming that this region consisted of TE current [1]. From these fits, the experimental values of Φ_B and *n* are determined.

Φ_B and *n* plots as a function of temperature for the Au/n-Ge (100) SBDs are presented in Fig. 2. The SBH shows a decrease with decrease in temperature, while the ideality factor increase with decrease in temperature. This depicts that both parameters exhibit strong temperature dependence. This temperature dependence can be attributed to the discontinuities at the interface which may exist even for well controlled fabrication of samples [15]. Since current flow across a MS interface is a temperature activated process [9,10,13,16], the current transport will be dominated by current flowing through nanometer scale interfacial patches of small regions with lower SBH and a larger ideality factor [13]. As a result of inhomogeneities, charge transport across the interface is no longer dominated by TE. Furthermore, many models have been devolved to explain the inhomogeneity in the barrier [9,17,18]. A potential fluctuation model was proposed by Tung [9] to explain the inhomogeneity in SBHs which show a larger deviation from the classical TE theory at low temperature. From the potential fluctuation model, at sufficiently low temperatures, a large number of patches may be present and consequently high current flowing through these patches. As the temperature increases, more electrons have sufficient energy to surmount the higher barrier [7,15].

3.2 Analysis of inhomogeneous barrier height

In order to describe the abnormal behaviour, i.e. the decrease in the SBH with decrease in temperature, a spatial distribution of the SBH at the MS interface of Schottky contacts was

suggested by Werner and Guttler [6,19] to be a Gaussian distribution $P(\Phi_B)$ with a standard deviation ($\dagger_s$) around a mean SBH ($\overline{\Phi}_B$) as:

$$P(\Phi_B) = \frac{1}{\dagger_s \sqrt{2f}} \exp\left[-\frac{\left(\Phi_B - \overline{\Phi}_B\right)^2}{2\dagger_s^2}\right] \tag{5}$$

where $\dfrac{1}{\dagger_s \sqrt{2f}}$ is the normalization constant of the Gaussian barrier distribution. The Gaussian distribution of the SBH yields the following expression for experimental apparent SBH at zero-bias [20,21]:

$$\Phi_B = \overline{\Phi}_B(T=0) - \frac{q\dagger_{s0}^2}{2kT} \tag{6}$$

where $\overline{\Phi}(T=0)$ and $\dagger_{s0}$ are the mean SBH and its standard deviation at zero-bias ($V = 0$), respectively. The temperature dependence of $\dagger_{s0}$ is usually small and can be neglected [22]. The variation of experimental apparent ideality factor with temperature in this model is given by [19]:

$$\left(\frac{1}{n} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT} \tag{7}$$

where ρ_2 and ρ_3 are the voltage coefficients that depict the voltage deformation of the barrier height distribution.

The experimental Φ_B vs $\dfrac{1}{2kT}$ and $\left(\dfrac{1}{n} - 1\right)$ vs $\dfrac{1}{2kT}$ plots obtained by means of data extracted from Fig. 1 are shown in Fig. 3.

The temperature dependence of the SBH Au/n-Ge (100) Schottky diodes (Fig. 3) depicts one Gaussian distribution with $\overline{\Phi}_B(T=0) = 0.615$ eV and $\dagger_{s0} = 0.0858$ eV in the 140 – 300 K. In this temperature range, the ideality factor shows some linearity with temperature in two regions. The voltage coefficients have been obtained as $\rho_{21} = $ -0.454 and $\rho_{31} = $ -0.028 in the 180 – 300 K range, $\rho_{22} = $ 0.182 and $\rho_{32} = $ -0.0437 in the 140 – 180 K range. The standard

deviation is a measure of barrier homogeneity. The lower value of $\dagger_{s0}$ indicates a more homogenous SBH [22]. When comparing $\overline{\Phi}_B(T=0)$ and $\dagger_{s0}$ parameters, it is seen that the standard deviation is 13 % of the mean zero-bias SBH. This value $\dagger_{s0}$ is not small compared to $\overline{\Phi}_B(T=0)$ and this indicates large inhomogeneity at interface of Au/n-Ge (100) structures. Hence, this inhomogeneity and potential fluctuations affect low temperature *I-V* characteristics.

To determine the barrier height in another way, Eq. (2) can be written as

$$\ln\left(\frac{I_s}{T^2}\right) = \ln\left(AA^*\right) - \frac{q\Phi_B}{kT} \tag{8}$$

The Richardson constant is usually determined from the intercept of $\ln\left(\dfrac{I_s}{T^2}\right) vs \dfrac{1000}{T}$ plot.

Fig. 4 shows the conventional energy variation of $\ln\left(\dfrac{I_s}{T^2}\right) vs \dfrac{1000}{T}$ (labeled y_1) for Au/n-Ge (100) Schottky diodes. The experimental data shown, fit asymptotically to a straight line at higher temperatures. Since the conventional Richardson plot deviates from linearity at low temperatures due the barrier inhomogeneity, it can be modified by combining Eq. (2) and (6) which yields

$$\ln\left(\frac{I_s}{T^2}\right) - \left(\frac{q^2\dagger_{s0}^2}{2k^2T^2}\right) = \ln\left(A^{**}A\right) - \frac{q\overline{\Phi}_B}{kT} \tag{9}$$

Fig. 4 shows the modified $\ln\left(\dfrac{I_s}{T^2}\right) - \left(\dfrac{q^2\dagger_{s0}^2}{2k^2T^2}\right) = \ln\left(A^*A\right) - \dfrac{q\overline{\Phi}_B}{kT}$ plot (labeled y_2) for Au/n-Ge (100) Schottky diodes. The modified plot gives $\overline{\Phi}_B(T=0)$ = 0.639 eV and modified Richardson constant, $A^{**} = 1.37$ Acm^{-2}K^{-2}. The value of $\overline{\Phi}_B(T=0)$ has almost the same value as the mean SBH obtained from $\Phi_B vs \dfrac{1}{2kT}$ plot at higher temperatures in Fig. 3. The

modified Richardson constant is much smaller than the reported of 50 $Acm^{-2}K^{-2}$ [23]. This may be due to greater inhomogeneities at the interface.

4. Summary and conclusions

The *I-V-T* characteristics of Au/n-Ge (100) Schottky contacts fabricated using the resistive evaporation system were measured in the 140-300 K range. While the zero-bias SBH (Φ_B) increases with increasing temperature, the ideality factor *n* decreases with increasing temperature. This observation has been attributed to barrier inhomogeneities explained by assuming a Gaussian distribution of SBHs due to barrier inhomogeneities that prevail at interface. In order to obtain evidence of a Gaussian distribution of SBHs, we have plotted

$\Phi_B \, versus \, \dfrac{1}{2kT}$ graphs, and from which the values of $\overline{\Phi}_B(T=0) = 0.615$ eV and $\dagger_{s0} = 0.0858$

eV for mean SBH and standard deviation, respectively, have been obtained. In the modified

$\ln\left(\dfrac{I_s}{T^2}\right) - \left(\dfrac{q^2\dagger_{s0}^2}{2k^2T^2}\right) vs \dfrac{1000}{T}$ plot, the values of $\overline{\Phi}_B(T=0)$ and A^{**} were obtained as 0.639 eV

and 1.37 $Acm^{-2}K^{-2}$, respectively.

References

[1] E.H. Rhoderick, R.H. Williams, Metal-Semiconductor Contacts, Claredon Press, Oxford, University Press, Oxford, (1988) 19.

[2] V. Janardhanam, A. Ashok Kumar, V. Rajagopal Reddy, P. Narasimha Reddy, J. Alloys Compd 485 (2009) 467.

[3] E. Gur, S. Tuzemen, B. Kolic, C. Coskun, J. Phys. Condens. Matter. 19 (2007) 1966206.

[4] I. Dokme, S. Altindal, Semicond. Sci. Technol. 21 (2006)1053.

[5] S. Karatas, S. Altindal, M. Cakar, Physica B 357 (2005) 386.

[6] J.H. Werner, H.H. Güttler, J. Appl. Phys. 73 (1993) 1315.

[7] F.E. Cimili, M. Sa lam, H. Efeo lu, A. Türüt, Physica B 404 (2009) 344.

[8] R. F. Schmitsdorf, T.U. Kampen, W. Mönch, J. Vac. Sci. Technol. B 15 (1997) 1221.

[9] R.T. Tung, Phys. Rev. B 45 (1992) 13509.

[10] R.T. Tung, J.P. Sullivan, F. Schrey, Mater. Sci. Eng. B 14 (1992) 266.

[11] S. Chand, J. Kumar, Appl. Phys. A 63 (1996) 171.

[12] S. Chand, Semicond. Sci. Technol. 17 (2002) 136.

[13] Ö. Faruk Yüksel, Physica B 404 (2009) 1993.

[14] S.M. Sze, Physics of Semiconductor Devices, 2nd ed., John Wiley & Sons, New York, 1981.

[15] M.B. reddy, A.A. Kumar, V. Jamardhanam, V.R. Reddy, P.N. Reddy, Current. Appl. Phys. 9 (2009) 972.

[16] A. Gümü , A. Türüt, N. Yalçin, J. Appl. Phys. 91 (2002) 245.

[17] J.D. Levine, J. Appl. Phys. 42 (1971) 3991.

[18] F.A. Padovani, R. Stratton, Solid-State Electron. 9 (1996) 695.

[19] J.H. Werner, H.H. Güttler, J. Appl. Phys. 69 (1991) 1522.

[20] Y.P. Song, R.L. Van Meirhaeghe, W.H. Laflere, F. Cardon, Solid-State Electron. 29

(1986) 633.

[21] S. Chand, S. Bala, Appl. Surf. Sci. 252 (2005) 358.

[22] V. Janardhanam, A.A. Kumar, V.R. Reddy, P.N. Reddy, J. Alloys Cmpd 485 (2009) 467.

[23] H.B. Yao, C.C. Tan, S.L. Liew, C.T. Chua, R. li, R.T.P. Lee, S.J. Lee, D.Z. Chi,

International Workshop on Junction Technology Proc. (2005) 85.

Figure captions

Fig. 1. Experimental forward-bias current-voltage characteristics of a Au/n-Ge (100) Schottky contact in the temperature range 140 – 300 K.

Fig. 2. Temperature dependence of ideality factor and barrier height for Au/n-Ge (100) Schottky contact in the temperature range 140 – 300 K.

Fig. 3. Temperature dependence of barrier height (Φ_B) and ideality factor (1/n   1) for Au/n-Ge (100).

Fig. 4. Richardson's plot of $\ln\left(\dfrac{I_s}{T^2}\right)$ *versus* $\dfrac{1000}{T}$ and modified $\ln\left(\dfrac{I_s}{T^2}\right) - \left(\dfrac{q^2 \dagger_{s0}^2}{2k^2 T^2}\right)$ *versus* $\dfrac{1000}{T}$.
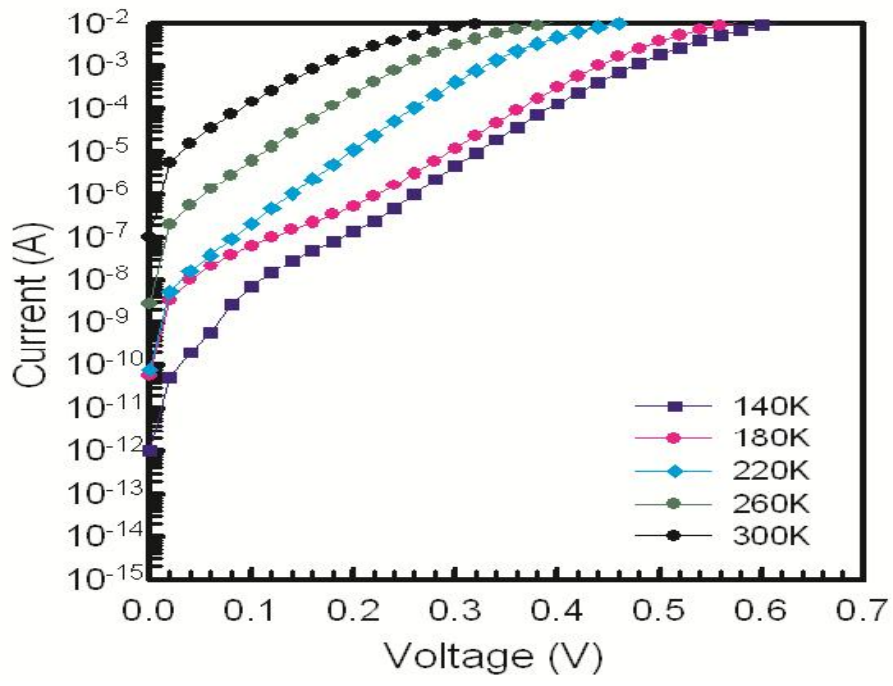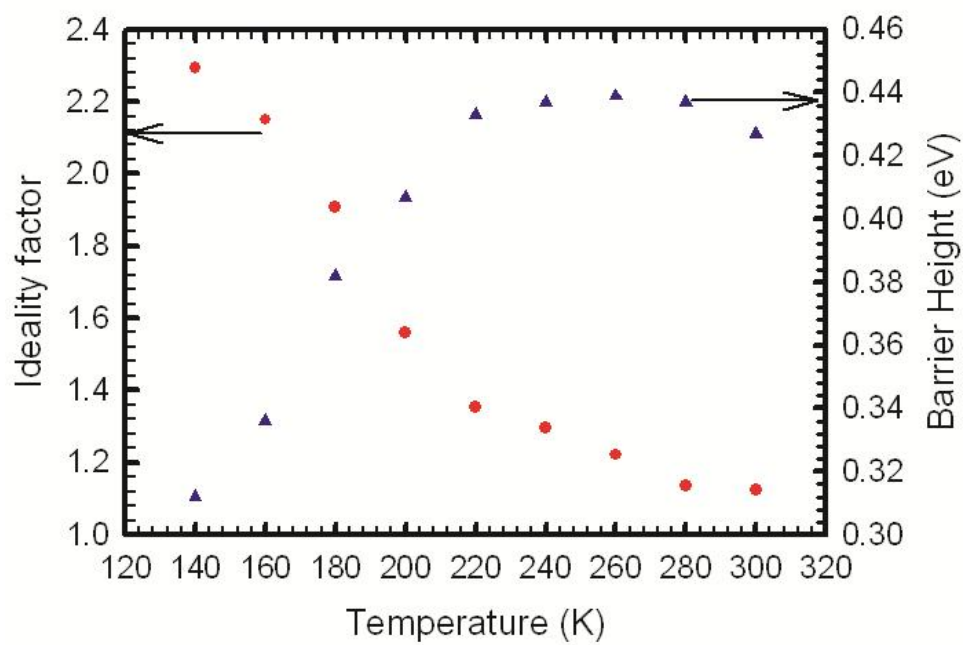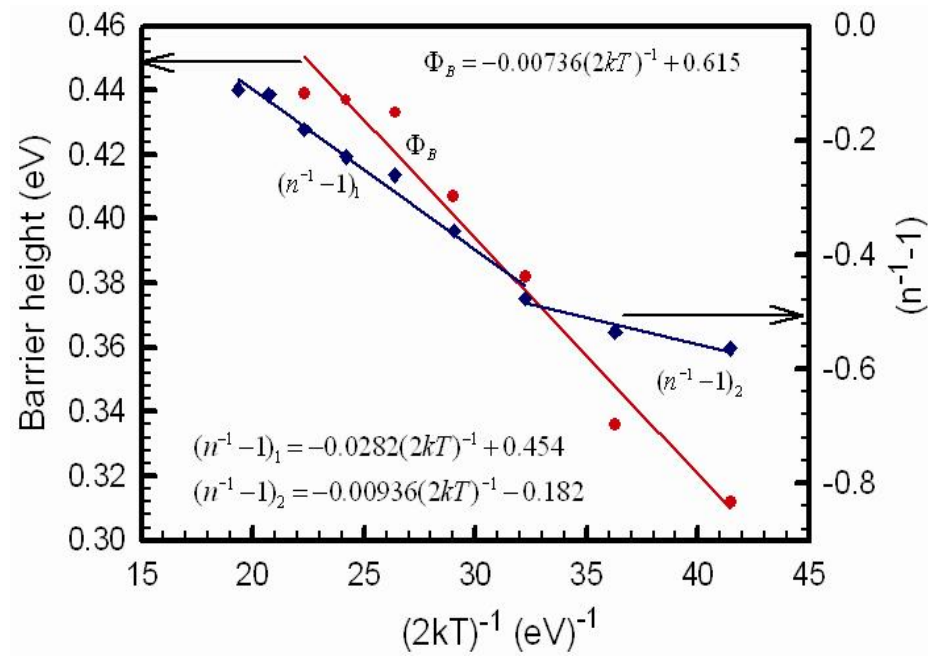
Fig. 1.

Fig. 2

Fig. 3.

$$\Phi_B = -0.00736(2kT)^{-1} + 0.615$$

$$(n^{-1}-1)_1 = -0.0282(2kT)^{-1} + 0.454$$

$$(n^{-1}-1)_2 = -0.00936(2kT)^{-1} - 0.182$$

Fig. 4.