Journal of Materials and Electronic Devices 1 (2016) 22-26

FYTRONIX
JOURNAL OF
MATERIALS AND ELECTRONIC DEVICES
JMED
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Analysis of current-voltage characteristics of Zn/p-Si (100) Schottky contacts in the temperature range of 290-390 K

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The current-voltage (*I-V*) characteristics of inhomogeneous Zn/*p*-Si Schottky contacts determined in the temperature range 290-390 K. The electronic properties were investigated recording in current-voltage characteristics. The current-voltage characteristics of a Schottky contacts containing barrier inhomogeneities have been used thermionic emission-diffusion theory and assuming a Gaussian distribution of barrier heights. It is shown that the occurrence of a Gaussian distribution of then barrier heights is responsible for the decrease of the apparent barrier height Φ_b, increase ideality factor n and linearity in the activation energy plot at high linearity. $\emptyset_b$ versus 1/*T* plot was drawn to obtain evidence of a Gaussian distribution of the barrier heights, and values of Φ_{bo} =1.51 eV and σ_o = 0.201 V for the mean barrier height and zero-bias standard deviation have been obtained from this plot, respectively. Thus, a modified $\ln\left({}^{I_O}/_{T^2}\right) - q^2\sigma_o^2/2k^2T^2$ versus 1/T plot gives Φ_{bo} (T=0) and A^* as 1.51 eV and 32.61 A cm^{-2} K^{-2}, respectively.

Keywords: Temperature dependence; Gaussian distribution; Schottky contacts

Submission date: 02 November 2016
Acceptance date: 21 December 2016

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1. Introduction

In recent years, current transport with respect to the exact nature of contact in real Schottky contacts has been the main thrust of research. The abnormal behaviour of the Schottky contacts has been attributed to the barrier inhomogeneities present in the Schottky contacts. The current-voltage (*I-V*) characteristics of real Schottky contacts usually deviate from the ideal thermionic emission-diffusion (TED) model, which assumes the junctions to be abrupt with a fixed Schottky barrier height (SBH). These deviations have been explained by assuming the presence of the barrier height inhomogeneities [1]. The rectifying property of metal-semiconductor (MS) contacts was first described by Schottky [2] in the 1930s. The theory of the Schottky diode was then developed and the MS contact has become of the most widely used rectifying contacts in the electronics industry [3]. Recently, spatial barrier inhomogeneities have been described mainly with a Gaussian distribution function [4]. Metal-semiconductor (MS) interfaces are an essential part of virtually all semiconductor electronic and opto-electronic devices. One of most interesting properties of a MS interface is its Schottky-barrier height (SBH), which is a measure of the mismatch of the energy levels for majority carriers across the MS interface. The SBH controls the electronic transport across MS interfaces and is, therefore, of vital importance to the successful operation of any semiconductor devices. Despite the tremendous advances in solid state physics and semiconductor device physics in the past several decades, our knowledge on the basic formation mechanism of the Schottky barrier height has not advanced much beyond a primitive level during the same period time. Many textbooks, chapter, and review articles exist which describe the pervasive confusion and frustration with efforts to unravel the Schottky barrier height mystery in the second half of the 20th century [5-8]. However, there are some surprising developments in the field of Schottky barrier height research very recently, and with the surfacing of some new ideas, the need for a re-examination of the entire Schottky barrier height literature immediately arises [9].

In this work, we have studied the effect of temperature the *I-V* characteristics of Zn Schottky contacts on a *p–type* Si substrate were measured over temperature range of 290-390 K. The temperature dependent characteristics of the Zn/*p*-Si Schottky contacts were interpreted on the basis of the existence of Gaussian distribution of the barrier heights around a mean value due to barrier height inhomogeneities prevailing at the metal-semiconductor interface.

2. Experimental details

The semiconductor substrates used were p-type B-doped Si single crystals, with a (100) surface orientation, 635 μm thick and 100 Ω-cm resistivity. The wafer was chemically cleaned. The native oxide on the front surface of the substrate was removed in HF:H2O(1:10) solution and finally the wafer was rinsed in deionized water for 30 s. Then, low resistivity ohmic back contact to *p*-type Si (100) wafers was made by using Al, followed by a temperature treatment at 570 ºC for 3 min in N_2 atmosphere. The Schottky contacts were formed by evaporation of Zn dots with diameter of about 1.0 mm. Thickness of the *Zn* film was 800-1200 Å. All evaporation processes were carried out in a turbo molecular fitted vacuum coating unit at 10-5 Torr. The *I-V* characteristics of the devices were measured in the temperature range of 290-390 K using a temperature controlled janes vpf-475 cryostat, which enables us to make measurements in the temperature range of 77-450 K, and a Keithly 220 programmable constant current source and a Keithly 199 dmm/scanner under dark conditions.

3. Results and discussion:

3.1.Temperature dependence of the forwar dbias current-voltage characteristics

The *I-V* characteristics obtained at six temperature values for Zn/*p*-Si Schottky contacts are shown that in Fig. 1 the reverse and forward bias *I-V* characteristics of the Zn/*p*-Si Schottky contact at different temperatures, ranging from 290 to 390 K. For each temperature value, ideality factors, *n*, were calculated by means of ln*I-V* graphs for Zn/*p*-Si Schottky contacts. The *I-V* characteristics in Schottky contacts according to the thermionic emission theory, can be expressed as [7]:

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

where I_0 is the saturation current is defined by

$$I_o = A\ A^* T^2 \exp\left(-\frac{q\Phi_{bo}}{kT}\right) \qquad (2)$$

The quantities *A, A*, T, k, q, $\emptyset_b$* and *n* are the diode area, the effective Richardson constant, the absolute temperature, Boltzman constant of 32 $A\ cm^{-2}\ K^{-2}$ for *p-type* Si, electronic charge, the zero-bias barrier height and the ideality factor, respectively. Ideality factor, n, is determined from the slope of the linear region of the forward bias ln*I-V* characteristics through the relation:

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

The semilog forward and reverse bias *I-V* characteristics of Zn/*p*-Si Schottky barrier contacts are shown in the temperature 290-390 K. The ideality factor *n* is not constant with temperature. Similar results have been reported in the literatures [17-21]. High values of n can be attributed to the presence of the interfacial thin native oxide layer, due to the potential drop in the interfacial layer, and abnormal behaviour barrier inhomogeneities present in the Schottky contacts, therefore, to the bias voltage dependence of Schottky barrier height [7,10,11].

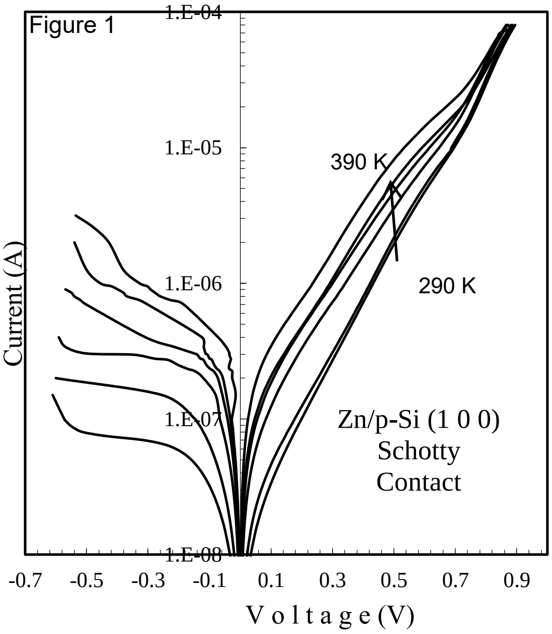

Fig.1: Experimental forward bias current-voltage characteristics of Zn/p-Si(1 0 0) Schottky diode at various temperatures.

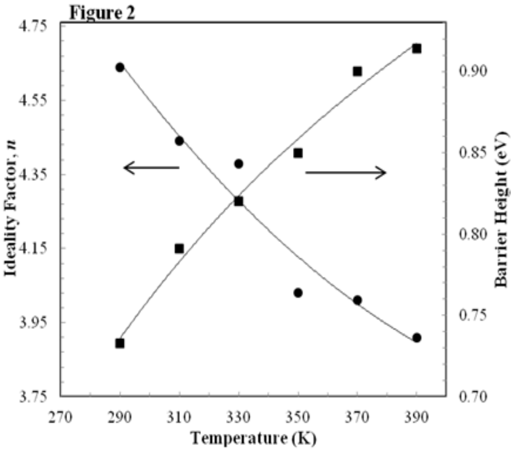

*Fig.2: The change according to Gaussian distribution of barrier height and ideality factor as function of temperature Zn/p-Si(1 0 0) Schottky diod*e.

The formation of such a thin interfacial layer is inevitably during the fabrication of the device by the conventional techniques and before evaporation of *Zn* on the front surfaces of the *p-type* Si substrate [3, 7]. For a sufficiently thick interface layer, the interfaces states are in equilibrium with the *p*-Si and they cannot interact with the metal [3, 15]. In the usual analyses of the experimental data on Schottky contacts, the barrier height $\emptyset_b$ is determined from the extrapolated I_o and is given by:

$$\Phi_b = \frac{kT}{q}\ln\left[\frac{AA^*T^2}{I_0}\right] \qquad (4)$$

The experimental values of barrier height, $\emptyset_b$, and ideality factor, *n*, were determined from intercept and slopes of the forward-bias ln*I*-*V* plot at each temperature (Fig. 2), respectively. The experimental values of $\emptyset_b$and *n* for the device range from 0.733 eV and 4.64 (290 K) to 0.914 eV and 3.91 (at 390 K), respectively. Values of 0.733 and 0.914 eV for $\emptyset_b$were calculated using Eq. (2). The laterally homogeneous barrier height value of 0.733 eV at 290 K that we have obtained for the Zn/*p*-Si Schottky contact is in close agreement with the expected value of 0.78 eV theoretically evaluated by Kampen and Mönch [13] and the value of 0.75 eV of $\emptyset_b$ for the *p*-Si samples at 300 K by Temirci et all [16]. Therefore, as can be seen from Fig. 3, there is a linear relationship between experimental effective barrier height and experimental ideality factor according temperature of Zn/*p*-Si Schottky contact [10, 12, 13, and 14].

3.2. Barrier heights inhomogeneities

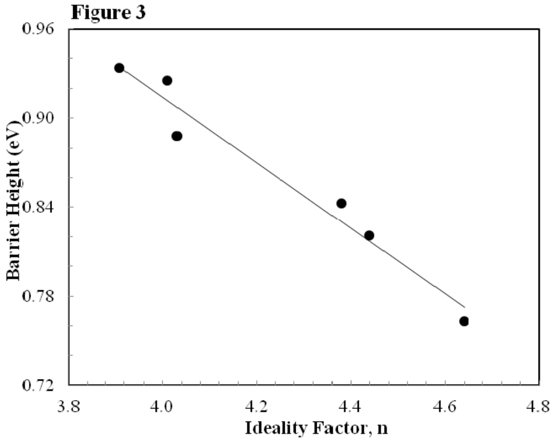

Fig.3: The zero-bias apparent barrier height vs. ideality factor with temperature for a typical Zn/p-Si (1 0 0) Schottky diode.

The abnormal behaviours in this work can be explained using an analytical potential fluctuation model based on spatially inhomogeneous barrier heights at the interface [22-23]. The significant decrease of zero-bias barrier heights and increase of ideality factors are possibly caused by barrier heights (BH) inhomogeneities resulting due to variation in thickness and composition of Si layer, non-uniformity of the interfacial charges, etc. [24-25]. By describing the barrier height inhomogeneities with a Gaussian distribution function and assuming linear bias dependence of both the mean barrier height and standard deviation with coefficient $\emptyset_b$ and σ_s, respectively, get modified n_{ap} and $\emptyset_b$ appear in place of *n* and $\emptyset_b$ [26, 27]. The mean barrier height and standard deviation with coefficient can be expressed in the following from [22, 23];

$$P(\Phi_b) = \frac{1}{\sigma_S\sqrt{2\pi}}\exp\left(-\frac{\left(\Phi_b-\bar{\Phi}_b\right)}{2\sigma_S^2}\right) \qquad (5)$$

Where $\frac{1}{\sigma_S\sqrt{2}}$ is the normalization constant of the Gaussian barrier height distribution. The total current in forward bias V is given then by,

$$I(V) = \int_{-\infty}^{+\infty} I(\Phi_b, V)P(\Phi_b)\,d\Phi \qquad (6)$$

Performing upon integration from -∞ to +∞

$$I(V) = A^*T^2\exp\left[-\frac{q}{kT}\left(\bar{\Phi}-\frac{q\sigma_S^2}{2kT}\right)\right]\exp\left(\frac{qV}{n_{ap}kT}\right)\left[1-\exp\left(-\frac{qV}{kT}\right)\right] \qquad (7)$$

with

$$I_o = A\ A^*\,T^2 \exp\left(-\frac{q\Phi_{ap}}{kT}\right) \qquad (8)$$

where Φ_{ap} and n_{ap} are the apparent barrier height and apparent ideality factor, respectively, and are given by

$$\Phi_{ap} = \bar{\Phi}_{bo}\left(T=0\right) - \frac{q\sigma_o^2}{2kT} \qquad (9)$$

$$\left(\frac{1}{n_{ap}} - 1\right) = \rho_2 - \frac{q\rho_3}{2kT} \qquad (10)$$

It is assumed that the mean SBH $\emptyset_b$ and σ_s are linearly bias dependent on Gaussian parameters, such as $\emptyset_b = \emptyset_{bo} + \rho_2 V$ and standard deviation$\emptyset_s = \emptyset_{so} + \rho_3 V$, where ρ_2 and ρ_3 are voltage coefficients which may depend on T and they quantify the voltage deformation of the barrier height distribution. The temperature dependence of σ_s is usually small and can be neglected [1, 21, 23, 28].

Fitting of the experimental data in Eq.(2) or (8) and in Eq.(3) gives Φ_{ap} and n_{ap}, respectively, which should obey Eq. (9) and (10). Thus, the plot of Φ_{ap} vs $1/T$ (Fig. 4) should be a straight line that gives $\emptyset_{bo}$ and σ_o from the intercept and slope, respectively. The values of 1.51 eV and 0.201 V for $\emptyset_{bo}$ and σ_o (the zero-bias standard deviation), respectively, were obtained from the experimental Φ_{ap} vs $1/T$ plot (Fig. 4). The standard deviation is a measure of the barrier homogeneity. The lower value of σ_o corresponds to more homogeneous BH. Clearly, the diode with the best rectifying performance presents the best barrier homogeneity with the lower value of standard deviation.

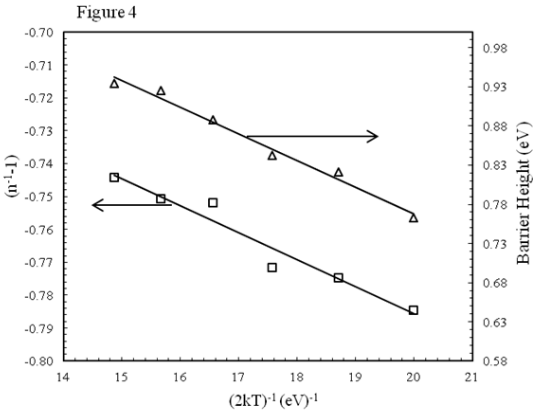

Fig.4: The zero-bias apparent barrier height and ideality factor vs. 1/T curves of a typical Zn/p-Si(1 0 0) Schottky diode according to Gaussian distribution of BHs

It was seen that the value of σ_o = 0.201 V is not small compared to the mean value of $\emptyset_{bo}$=1.51 eV, and it indicates the presence of the interface inhomogeneities. Nevertheless, this inhomogeneity and potential fluctuation dramatically affect low temperature *I-V* characteristics.

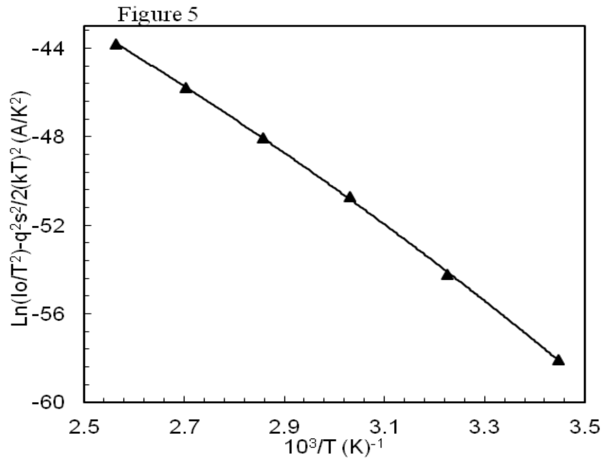

Fig.5: Modified Richardson ln $\left({}^{I_o}/_{T^2}\right) - \left({}^{q^2\sigma_o^2}/_{2k^2T^2}\right)$ *vs. 1/T plot for Zn/p-Si(1 0 0) Schottky diode according to Gaussian distribution of BHs.*

The plot of n_{ap} vs $1/T$ should be a straight line that gives voltage coefficients ρ_2 and ρ_3 from the intercept and slope, respectively (Fig. 4). The values of ρ_2=0.0151 V and ρ_3=0.490 V were obtained from the experimental n_{ap} vs 1/T plot (Figure 4). The linear behavior of this plot demonstrates that the ideality factor does indeed express the voltage deformation of the Gaussian distribution of the Schottky BH. Furthermore, the experimental results of n_{ap} fit very well with theoretical Eq.(10) with ρ_2=0.0151 V and ρ_3=0.490 V. The continuous solid line in Figure 2 represents data estimated with these parameters using Eq (10). Now, combining Eq. (8) and (9), we get;

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\sigma_o^2}{2k^2T^2}\right) = \ln(AA^*) - \frac{q\bar{\Phi}_{bo}}{kT} \qquad (11)$$

A modified $\ln\left({}^{I_o}/_{T^2}\right) - \left({}^{q^2\sigma_o^2}/_{2k^2T^2}\right)$ vs $1/T$ plot according to Eq.(11) should give a straight line with the slope directly yielding the mean $\emptyset_{bo}$ and the intercept (=lnAA^*) at the ordinate determining A^* for a given diode area A. Figure 5 shows this plot. The modified $\ln\left({}^{I_o}/_{T^2}\right) - \left({}^{q^2\sigma_o^2}/_{2k^2T^2}\right)$ versus

$1/T$ plot gives $\emptyset_{bo}$ and A^* as 1.51 eV and 92.95 A/cm^{2}K^2, respectively. As can be seen, the value of $\emptyset_{bo}$ =1.51 eV from this plot is in completely agreement with the value of $\emptyset_{bo}$ =1.51 eV from the plot of Φ_{ap} vs $1/T$.

Conclusions

The forward-bias *I-V* charasteristics of inhomogeneious Zn/*p*-Si Schottky contacts reveal that while the zero-bias barrier height Φ_b decreases the ideality factor *n* increases with decreasing temperature in in the temperature range of 290-390 K. It was shown that the *I-V* characteristics of inhomogeneious Zn/-*p* type Si Schottky contacts in the temperature range of 290-390 K can be interpreted on the basis of the TE mechanism with Gaussian distribution of the BHs of $\emptyset_{bo}$ =1.51 eV and standard deviation of 0.201 V. The experimental results of Φ_{ap} and n_{ap} fit very well with the theoretical equations related to the Gaussian distribution of Φ_{ap} and n_{ap}. Again, the $\ln(I_0/T^2)$ or $\ln(I_{0f}/T^2)$ vs $1/T$ or $1/nT$ plots yield unreasonably the effective Richardson constant although the flat band temperature coefficient was used in the calculation.

Acknowledgment

This work was supported by Kahramanmaraş Sütçü İmam University Commission of Scientific Research Projects under Grant No.2015/3-90M. Authors also thank to Kahramanmaraş Sütçü İmam University.

References:

[1] S. Zhu, R. L. Van Meirhaeghe, C. Detavernier, F. Cardon, G. P. Ru, X. P. Qu, B. Z. Li, Solid-St Elecron., 44 (2000) 663.
[2] W. Schottky, Naturwiss., 26, (1938) 843.
[3] S. M. Sze, Physics of Semiconductor Devices, 2nd Edn. Willey, New York 1981.
[4] S. Chand., Semiconductor Science Technology,17 (2002) 36-l40.
[5] L.J. Brillson, Surface Science Reports, 2 (1982) 123.
[6] W. Mönch, Festkorperprobleme, 26 (1986) 67.
[7] E. H Rhoderick, R. H. Williams, Metal-Semiconductor Contacts, 2nd Edition Clarendon Press, Oxford, 1988
[8] L.J. Brillson, Contacts to Semiconductor, Noyes Publishers, New Jersey, 1993.
[9] T. Tung Raymond., recent advances in Schottky barrier concepts., Materials Science and Engineering R, 35 (2001) 1-138.
[10] J.P. Sullivan, R.T. Tung, M.R. Pinto, W.R. Graham., Journal Applied Physics., 70 (1991) 7403.
[11] H.A. Çetinkara, A. Türüt, D.M. Zengin, Ş. Erel., Applied Surface Science., 207 (2003) 190.
[12] W. Mönch, Semiconductor surfaces and Interfaces, third ed., Springer, Berlin, 2001.
[13] T. U. Kumpen, W. Mönch, Surface Science., 490 (1995) 331-333.
[14] W. Mönch, Journal Vac.. sci. Technol. B, 17 (1999) 1867.
[15] Ş. Karataş, Ş. Altındal, A.Türüt, A. Özmen., Appl. Surf. Sci., 217 (2003) 250.
[16] C. Temirci, B. Bati, M. Sağlam, A. Türüt, Appl. Surface Sci., 172 (2001) 1.
[17] A.K. Ghosh, T. Feng, J.I. haberman, H.P. Maruska., Journal Appl. Phys., 55 (1984) 2990.
[18] R. Hackam, P. Harrop. IEEE trams. Electron Dev., 19 (1972) 1231.
[19] S. Varma, k.V. Rao, S.Kar., Journal Appl. Phys., 56 (1984) 2812.
[20] S. Ashok, J.M. Borrego, R.J. Gutmann., Solid-State Electron., 22 (1979) 621.
[21] S. Kar, K. M. Panchal, S. Bhattacharya, S. Varma., IEEE Trans. Electron Dev., 29 (1982) 1839.
[22] Y.P. Song, R.L. Van Meirhaeghe, W.H. Lafléreand F. Cardon, Solid-St. Electron., 29 (1986) 633.
[23] C.A. Dimitriadis, S. Logothetidis and I. Alexandrou, Appl. Phys. Lett., 66 (1995) 502.
[24] V.W.L. Chin, M.A. Green, J.W.V. Storey., Solid-State Electron, 33, (1990) 299.
[25] H. K. Hanish., Semiconductor-Contacts., Oxford Univ. Press. London, 1983
[26] S. Chand, J. Kumar., In Semiconductor Devices, ed. By K. Lal (Narosa, New Delhi 1996), pp. 196.
[27] S. Chand and J. Kumar, Appl. Phys. A, 63 (1996) 171.
[28] Ş. Karataş, Ş. Altındal, M. Çakar, Physica B, 357 (2005) 386.