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New study of the abnormal behavior of the low temperature dependence of the current in inhomogeneous Schottky diode

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ABSTRACT

In this study, we show clearly why unexpected observations have been reported in the current–voltage curves of Schottky diodes, containing barrier inhomogeneities generated by using the analytical results based on a Gaussian distribution model of barrier heights. The Chand's calculations have shown that the current (saturation current) at low temperatures may exceed the current (saturation current) at high temperatures when the effective barrier height is calculated from an appropriate integral with integration limits $-\infty$ and $+\infty$. In this new study, we show that the method followed by Chand to remove these anomalies is not accurate enough. We prove that the origin of these anomalies stems from the nature of a proper function $f(\phi)$ that moves to the negative barrier heights and takes large value of the integral at low temperatures than at high temperatures when it has large standard deviation (σ) and the discrepancies are not due to the integration limits as Chand concluded. In order to obtain results consistent with the thermionic emission–diffusion theory, the standard deviation must have lower values.

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KEY WORDS: Schottky diodes; inhomogeneity; Gaussian distribution; integration limits

1. INTRODUCTION

Analysis of the experimental *I–V* characteristics of Schottky barrier diodes (SBDs) based on thermionic emission theory usually reveals an abnormal decrease in the barrier height (BH) ϕ and an increase in the ideality factor n with the decrease in temperature [1–16]. The nature and origin of the decrease in the BH and increase in ideality factor with the decrease in temperature and all of the electrical anomalies in the SBDs may be attributed to the presence of Schottky BH inhomogeneity. Two approaches are generally proposed in the literature to model the current–voltage–temperature (*I–V–T*) characteristics of inhomogeneous Schottky barrier contacts. These models are proposed by Tung [17, 18] and Werner [2].Tung [17, 18] considers in his model the presence of locally non-uniform regions or patches with relatively lower or higher barriers with respect to an average BH. The interaction of the high barrier and low barrier is described with the help of the so called saddle point. However, in Werner's model [2], the BH is supposed to be distributed according to a Gaussian type function, which will usually lead to an apparent BH that is both temperature and bias dependent. In the literature, many authors [19–21] have used the Tung model, and others [2–16] have used the Werner model to analyze experimental current–voltage–temperature data. The ballistic electron emission microscopy studies have also supported the existence of Gaussian distribution of BHs in Schottky diodes [22–27]. The analysis of the experimental *I–V–T* characteristics using Werner's model is based on the extraction of the parameters of the BH distribution with the mean value ($\overline{\phi}$) and the standard deviation (σ). Many authors have studied the analytical *I–V–T* curves using experimental values of

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$\overline{\phi}$ and σ [28–39]. However, these analytical studies exhibit some several abnormal behaviors such as excess of the current at low temperatures than the current at high temperatures [31] and the appearance of the negative apparent BH when the effective BH is calculated from an appropriate integral with integration limits $-\infty$ and $+\infty$ [32, 38].

In his letter, and in order to eliminate the excess of the current at low temperatures compared with the current at high temperatures, Chand [31] proposed to reduce the limits of integral to 0 and $2\overline{\phi}$ because in real Schottky diodes, the maximum BH cannot exceed the semiconductor energy bandgap, and the lowest it can be is close to zero. By doing this, Chand found results consistent with the thermionic emission–diffusion (TED) theory. However, Chand did not provide an accurate enough explanation of his results. This work will reveal exactly why the discrepancies have been observed in the analytical results based on a Gaussian distribution model of barrier inhomogeneities. Before we show our methodology, we prefer to summarize Chand's approach used to remove the discrepancies.

The total current across an inhomogeneous Schottky diode can be expressed as [2, 28, 31]

$$I = \int i(V, \phi)\ \rho(\phi)\ d\phi \tag{1}$$

where $i(V, \phi)$ is the current at a bias V for a barrier of height ϕ and $\rho(\phi)$ is the normalized distribution function giving the probability of occurrence for BH ϕ. The implicit assumption is that there are a number of parallel diodes of different BHs, each contributing to the current independently. In the case of a Gaussian distribution of BHs with mean ($\overline{\phi}$) and standard deviation (σ), the distribution function $\rho(\phi)$ is given by [1, 2]

$$\rho(\phi) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{\left(\phi - \overline{\phi}\right)^2}{2\sigma^2}\right) \tag{2}$$

The current $i(V, \phi)$ through a Schottky barrier at a forward bias 'V' based on TED theory is expressed as [40]

$$i(V,\ \ \phi) = A_d A^{**} T^2 \exp\left[-\frac{q\phi}{kT}\right]\left[\exp\left\{\frac{q(V - iR_s)}{kT}\right\} - 1\right] \tag{3}$$

where A_d, A^{**}, T, q, k, and R_S are the diode area, the effective Richardson constant, the temperature, the electronic charge, the Boltzmann constant, and the diode series resistance, respectively. Substituting $i(V, \phi)$ and $\rho(\phi)$ in Eq. (1) and performing integration from $-\infty$ to $+\infty$ for values of ϕ, one obtains [6, 12, 31]

$$I = I_S\left[\exp\left(\frac{q(V - R_s I)}{kT}\right) - 1\right] \tag{4}$$

with I_S and ϕ_{ap} given by

$$I_S = A_d A^{**} T^2 \exp\left[-\frac{q\phi_{ap}}{kT}\right] \tag{5}$$

$$\phi_{ap} = \overline{\phi} - \frac{\sigma^2 q}{2kT} \tag{6}$$

2. CHAND'S APPROACH

Starting from Eqs. (4), (5), and (6) Chand ([31]) performed the I–V characteristics of inhomogeneous Schottky diodes with Gaussian distribution of BHs and found that the I–V–T characteristics intersect and the currents at low temperatures are higher than the currents at high temperatures as shown in Figure 1. The curves are calculated using $A^{**} = 1.12 \times 10^6\ \mathrm{A\ m^{-2}\ K^{-2}}$, $A_d = 7.87 \times 10^{-7}\ \mathrm{m^2}$ (for a diode with a 1 mm diameter), $R_S = 20\ \Omega$, $\overline{\phi} = 0.8$ V, and $\sigma = 0.08$ V.

The TED theory, however, predicts less current at low temperatures through the diode. This observation is thus inconsistent with the TED theory. Chand [31] concluded that the origin of these anomalies is the saturation current (I_S), which itself contains anomalies. Using Eqs. (5) and (6), Chand

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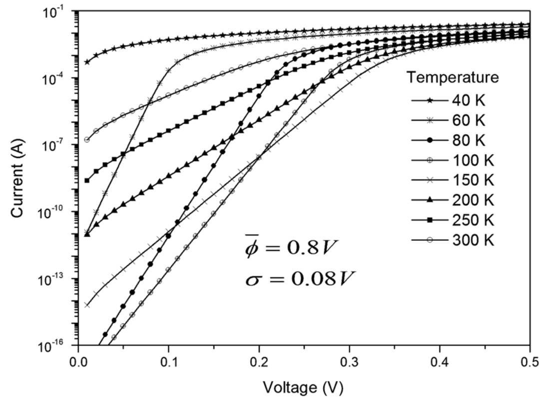

Figure 1. Simulated *I–V* curves of Schottky diodes using Eq. 4 for various temperatures with $\overline{\phi} = 0.8$ V, $\sigma = 0.08$ *V*, and series resistance $R_S = 20\,\Omega$. Clearly, the curve shows high current at very low temperatures [31].

found that the saturation current (I_S) first decreases from its value at room temperature and then starts to increase again below certain transition temperature as shown in Figure 2.

To remove these anomalies, Chand thought that the problem lies in the limits ($-\infty$ to $+\infty$) taken in the integration of Eq. (1). In real Schottky diodes, the maximum BH cannot exceed the semiconductor energy bandgap, and the lowest it can be is close to zero, depending upon the type of semiconductor and the work function of the metal used [31]. Analytical solution using Eqs. 2 and 3, for the total current through all barriers lying symmetrically around $\overline{\phi}$ in the range 0–2$\overline{\phi}$, Eq. (1) yields [31]

$$I = I_S^{'}\left[\exp\left(\frac{q(V - R_s I)}{kT}\right) - 1\right] \tag{7}$$

where the modified saturation current I_S now becomes

$$I_S^{'} = I_S\left(\frac{erf(f1) - erf(f2)}{2}\right) \tag{8}$$

and the error function arguments f_1 and f_2 are given as

$$f_1 = \left(\frac{\sigma^2 q}{kT} + \overline{\phi}\right)\frac{1}{\sigma\sqrt{2}} \tag{9}$$

$$f_2 = \left(\frac{\sigma^2 q}{kT} - \overline{\phi}\right)\frac{1}{\sigma\sqrt{2}} \tag{10}$$

Taking Eq. (8), Chand found that the saturation current decreases when the temperature decreases as

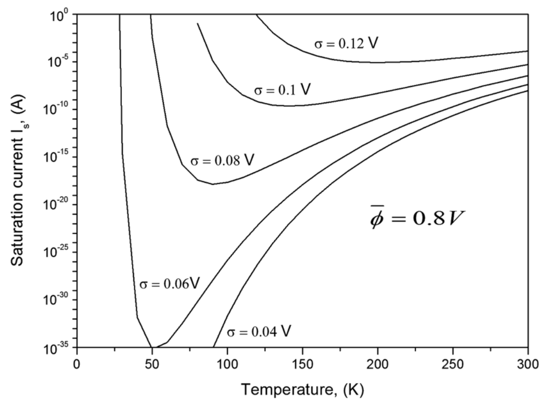

Figure 2. Variation of I_S as a function of *T* for various values of σ for a diode area of 1 mm diameter $\overline{\phi} = 0.8$ V. I_S first decreases with decreasing *T* up to a particular *T* below which it increases with a further decrease of *T* [31].

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shown in Figure 3. However, the curves of the total current are steeper and thus intersect other curves at higher temperatures (see figure 4 of [31]).The author tried to eliminate this effect by generating *I–V* curves for lower temperatures with an ideality factor greater than unity. By this method, Chand could resolve the unusual behavior of the current at low temperatures and reduced the limits of integral between 0 and $2\overline{\phi}$. Note here, that Osvald [32] confirmed later Chand's results, but he shows that the crossing of low temperature *I–V* curves with high-temperature curves is not the result of the difference in ideality factors for single curves but is caused by the different apparent BHs at different temperatures.

3. OUR METHOD

For our part, we will follow another simple technique, and we will show that Chand's reason is not built on a solid enough scientific base and that the limits of the integral are not the origin of those anomalies.

Equation 1 can be rewritten as [12]

$$I = A_d A^{**} T^2 \left\{ \int \rho(\phi) \ \exp(-q\phi/kT) \ d\phi \right\} \{ \exp[q(V - R_S I)/kT] - 1 \} \tag{11}$$

where the saturation current I_S can be given as

$$I_S = A_d A^{**} T^2 \frac{1}{\sigma\sqrt{2\pi}} \left\{ \int f(\phi) \ d\phi \right\} \tag{12}$$

where the proper function $f(\phi)$ is a function of temperature and the mean BH and standard deviations are given as

$$f(\phi) = \exp\left(-\frac{\left(\phi - \overline{\phi}\right)^2}{2\sigma^2} - \frac{q\phi}{kT} \right) \tag{13}$$

The calculation of the saturation current value (presented by Eq. (12)) is based mainly on the calculation of the integral of the proper function $f(\phi)$. Mathematically, the integral of such function $f(\phi)$ equals to the geometric area of the region in the (ϕ, f) plane bounded by the graph of f, the ϕ-axis, and the vertical lines $\phi = a$ and $\phi = b$, where a and b are the two integration limits.

Figure 4 shows the curve of the function $f(\phi)$ against the BH (ϕ) at various temperatures with $\overline{\phi} = 0.8$ V and standard deviation $\sigma = 0.08$ V. It is clear that when the temperature decreases, the curves of the function $f(\phi)$ are moved to the negative BHs and the areas (integrals) bounded by the curves decrease when $f(\phi)$ is in the positive BHs and the areas start to increase at low temperatures when the curves are in the negative BHs. It is for this reason that the saturation current follows the same behavior as the value of the area bounded by the curve (Figures 2 and 4). If we take the limits of the integral from 0 to $2\overline{\phi}$ as Chand did, we deform completely the value of the area (integral), and we take only the area bounded by the tails of the curves. This deformed area decreases with decreasing temperature as shown in Figure 4(b). The decrease in deformed area leads to the decrease in the saturation current as Chand found (Figure 3).

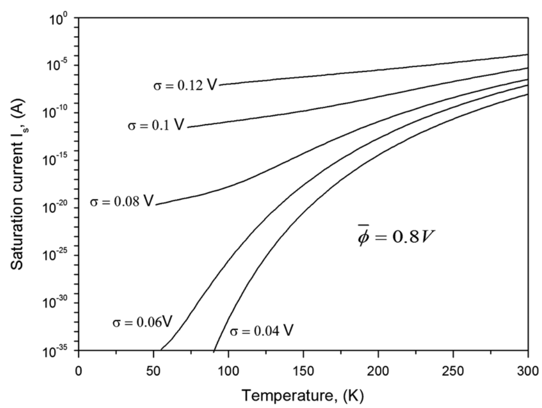

Figure 3. Modified saturation current I_S calculated using Eq. (8) with same parameters as those used to calculate I_S shown in Figure 2. Clearly, I_S now continuously decreases with the decrease of T [31].

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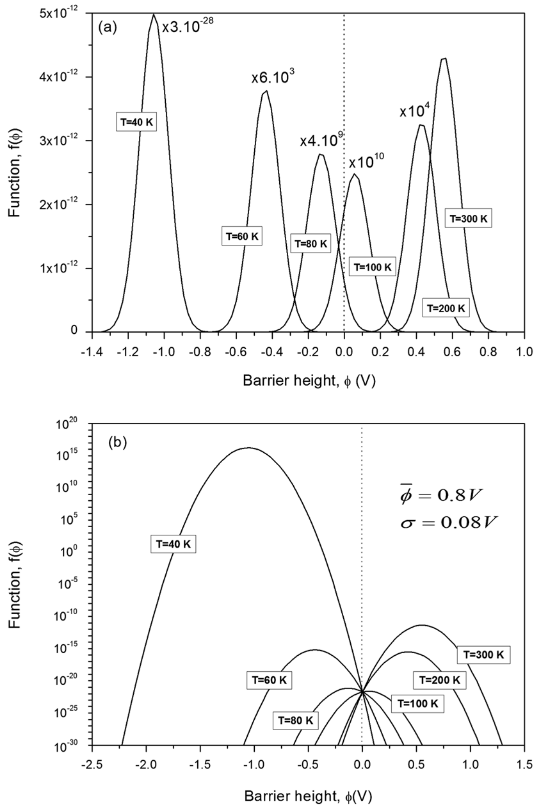

Figure 4. Plots of the proper function $f(\phi)$ as a function of the barrier height at various temperatures: (a) linear scale and (b) semi-logarithmic scale. In order to conserve the same scale in the linear scale, we must weight $f(\phi)$ by different multipliers.

In order to keep the curve of $f(\phi)$ in the positive BHs and does not move to the negative BHs at low temperatures, the standard deviation must have lower values as shown in Figure 5. It is clear from this figure that the function $f(\phi)$ moves to the positive BHs when the function $f(\phi)$ is calculated with smaller values of standard deviations. Low values of the standard deviation have been reported by the ballistic electron emission microscopy studies; 0.03, 0.04 [25], 0.02 [23], and 0.013–0.022 V [26] at room temperature and ~0.011–0.021 V [27] in the temperature range of 129–252 K. Additionally, the mean BH and standard deviation are dependent on temperature [27].

Figure 6 shows the simulated *I–V* curves of Schottky diodes using Eq. (4) for various temperatures with $\overline{\phi} = 0.8$ V, series resistance $R_S = 20\,\Omega$ at low value of standard deviation $\sigma = 0.03$ V. Clearly, the

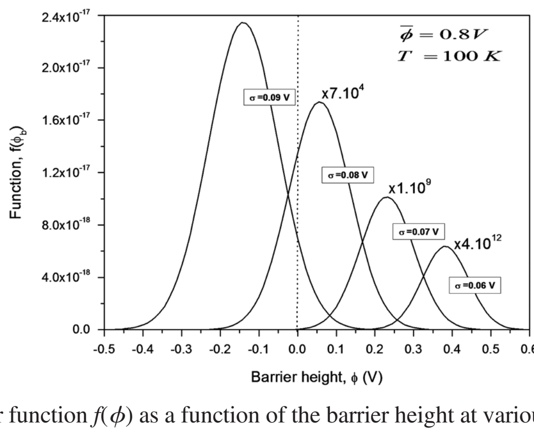

Figure 5. Plots of the proper function $f(\phi)$ as a function of the barrier height at various standard deviations with $\overline{\phi} = 0.8$ V and $T = 100$ K. In order to conserve the same scale, we must weight $f(\phi)$ by different multipliers.

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curves at low temperatures do not intersect the curves at high temperatures in the linear region. However, the 40 K plot still overlaps that of the 60 K plot at approximately ($V \approx 0.59$ V, $I \approx 2 \times 10^{-7}$ A). This intersection is caused by the temperature dependence of the Schottky diode parameters such as the BH, the ideality factor, and the series resistances. In real Schottky diodes, these parameters must change with temperature.

We also note that when the mean BH ($\overline{\phi}$) decreases, the curve of the function $f(\phi)$ moves to the negative BHs at low temperatures as shown in Figure 7.

It is noted, for example, in the case of the temperature 300 K in Figure 4(a), that the entire area between the curve of the function $f(\phi)$ and the horizontal ϕ-axis is bounded between 0.3 and 0.8 V. Figure 8 shows the ln(I)–V characteristics simulated by Eq. (1) at different integration ranges of BHs. So, we can reduce the limits of integral (0–2$\overline{\phi}$) to (0.3–0.8 V).

The analytical Eq. (6), which has been obtained by assuming the total current spread in the semiconductor substrate, is still under investigation because the use of this equation for analysis of the experimental I–V characteristics of SBDs based on thermionic emission theory leads to high standard deviation, which leads to the abnormal analytical results. We suggest to avoid the use of this method for extracting the BH distribution with mean BH and standard deviation, and it is better to extract them directly from the most realistic and most general approach proposed in [37] where the first part of the series resistance pertains to the particular small diodes (R_P) and a second part of the resistance (R_C) belongs to the region in which the total current is already homogeneous and is common to all particular diodes.

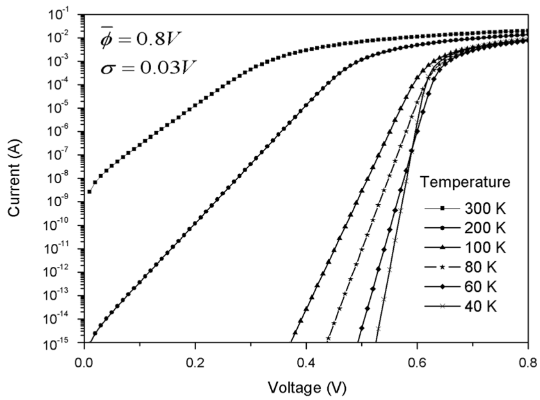

Figure 6. Simulated I–V curves of Schottky diodes using Eq. (4) for various temperatures with $\overline{\phi} = 0.8$ V, $\sigma = 0.03$ V, and series resistance $R_S = 20\,\Omega$. Clearly, the curves at low temperature do not intersect the curves at high temperature.

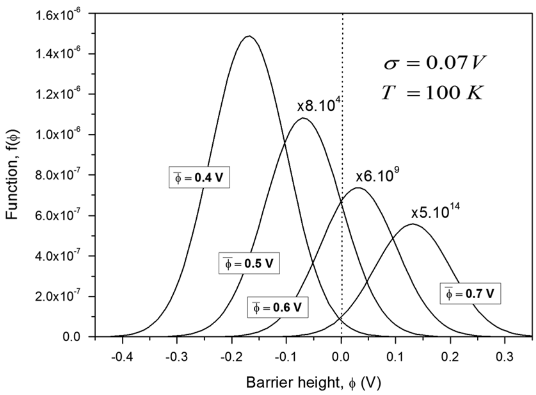

Figure 7. Plots of the proper function $f(\phi)$ as a function of the barrier height at various mean barrier heights with $\sigma = 0.07$ V and $T = 100$ K. In order to conserve the same scale, we must weight $f(\phi)$ by different multipliers.

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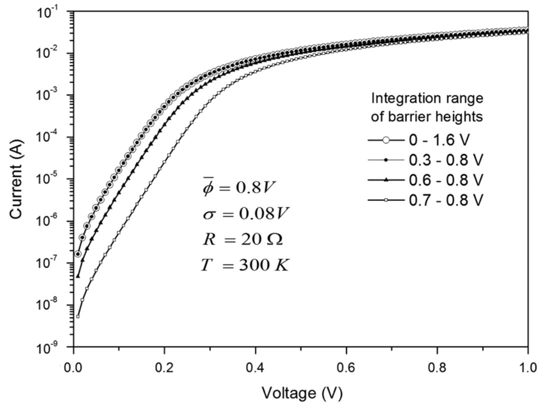

Figure 8. The ln(I)–V plots obtained by numerical integration over different barrier height ranges.

4. CONCLUSION

In the present work, we have used a simple technique to show why, at very low temperatures, the Schottky diodes based on a Gaussian distribution model of BHs exhibit higher analytical saturation current than at high temperatures. A proper function containing the standard deviation is responsible for this abnormal behavior. In order to obtain results consistent with the thermionic emission–diffusion theory, the standard deviation must have lower values.

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REFERENCES

1. Song YP, Van Meirhaeghe RL, Laflere WH, Cardon F. On the difference in apparent barrier height as obtained from capacitance-voltage and current-voltage-temperature measurements on Al/p-InP Schottky barriers. *Solid State Electron* 1986; **29**:633–638.
2. Werner JH, Gőttler HH. Barrier inhomogeneities at Schottky contacts. *J Appl Phys* 1991; **69**:1522–1533.
3. Chand S, Kumar J. Current-voltage characteristics and I barrier parameters of Pd2Si/p-Si(lll) Schottky diodes in a wide temperature range. *Semicond Sci Tech* 1995; **10**:1680–1688.
4. McCafferty PG, Sellai A, Dawson P, Elabd H. Barrier characteristics of PtSi/p-Si Schottky diodes as determined from I–V–T measurements. *Solid-State Electronics* 1996; **39**:583–592.
5. Chand S, Kumar J. Evidence for the double distribution of barrier heights in Pd2Si/n-Si Schottky diodes from I –V –T measurements. *Semicond Sci Tech* 1996; **11**:1203–1208.
6. Chand S, Kumar J. On the existence of a distribution of barrier heights in Pd2Si/Si Schottky diodes. *J Appl Phys* 1996; **80**:288–294.
7. Hudait MK, Krupanidhi SB. Doping dependence of the barrier height and ideality factor of Au/n-GaAs Schottky diodes at low temperatures. *Physica B* 2001; **307**:125–137.
8. Hattab A, Perrossier JL, Meyer F, Barthula M, Osten HJ, Griesche J. Schottky barrier inhomogeneities at contacts to carbon-containing silicon/germanium alloys. *Mater Sci Eng B* 2002; **89**:284–287.
9. Biber M. Low-temperature current–voltage characteristics of MIS Cu/n-GaAs and inhomogeneous Cu/n-GaAs Schottky diodes. *Physica B* 2003; **325**:138–148.
10. Abay B, Çankaya G, Güder HS, Efeoglu H, Yogurtçu YK. Barrier characteristics of Cd/p- GaTe Schottky diodes based on *I–V –T* measurements. *Semicond Sci Tech* 2003; **18**:75–81.
11. Acar S, Karadeniz S, Tugluoglu N, Selçuk AB, Kasap M. Gaussian distribution of inhomogeneous barrier height in Ag/p-Si (1 0 0) Schottky barrier diodes. *Appl Surf Sci* 2004; **233**:373–381.
12. Sellai A, Dawson P. Yield in inhomogeneous PtSi–n-Si Schottky photodetectors. *Nucl Instrum Meth Phys Res A* 2006; **567**:372–375.
13. Karatas S, Temirci C, Akar MC, Türüt A. Temperature dependence of the current–voltage characteristics of the Al/Rhodamine-101/p-Si (100) contacts. *Appl Surf Sci* 2006; **252**:2209–2216.
14. Aydın ME, Yıldırım N, Türüt A. Temperature-dependent behavior of Ni/4H-*n*SiC Schottky contacts. *J Appl Phys* 2007; **102**:043701 (7pp).
15. Toumi S, Ferhat-Hamida A, Boussouar L, Sellai A, Ouennoughi Z, Ryssel H. Gaussian distribution of inhomogeneous barrier height in tungsten/4H-SiC (000-1) Schottky diodes. *Microelectron Eng* 2009; **86**:303–309.
16. Latreche A, Ouennoughi Z, Sellai A, Weiss R, Ryssel H. Electrical characteristics of Mo/4H-SiC Schottky diodes having ion-implanted guard rings: temperature and implant-dose dependence. *Semicond Sci Tech* 2011; **26**:085003 (9pp).
17. Tung RT. Electron transport at metal-semiconductor interface: general theory. *Phys Rev B* 1992; **45**:13509–13523.
18. Tung RT. Recent advances in Schottky barrier concepts. *Mater Sci Eng* 2001; **R 35**:1–138.
19. Roccaforte F, La Via F, Raineri V, Pierobon R, Zanoni E. Richardson's constant in inhomogeneous silicon carbide Schottky contacts. *J Appl Phys* 2003; **93**:9137–9144.
20. Gammon PM, Pérez-Tomás A, Shah VA, Vavasour O, Donchev E, Pang JS, Myronov M, Fisher CA, Jennings MR, Leadley DR, Mawby PA. Modelling the inhomogeneous SiC Schottky interface. *J Appl Phys* 2013; **114**:223704.
21. Boussouar L, Ouennoughi Z, Rouag N, Sellai A, Weiss R, Ryssel H. Investigation of barrier

DOI: 10.1002/jnm

inhomogeneities in Mo/4H–SiC Schottky diodes. *Microelectron Eng* 2011; **88**:969–975.
22. Palm H, Arbes M, Schulz M. Fluctuation of Au-Si (100) Schottky barrier height. *Phys Rev Lett* 1993; **71**:2224–2227.
23. Vanalme GM, Van Meirhaeghe RL, Cardon F, Van Daele P. A ballistic electron emission microscopy (BEEM) study of the barrier height change of Au/n-GaAs Schottky barriers due to reactive ion etching. *Semicond Sci Tech* 1997; **12**:907–912.
24. Detavernier C, Van Meirhaeghe RL, Donaton R, Maex K, Cardon F. Ballistic electron emission microscopy study of barrier height inhomogeneities introduced in Au/n-Si Schottky contacts by a HF pretreatment. *J Appl Phys* 1998; **84**:3226–3231.
25. Im HJ, Kaczer B, Pelz JP, Choyke WJ. Ballistic electron emission microscopy study of Schottky contacts on 6H- and 4H-SiC. *Appl Phys Lett* 1998; **72**:839–841.
26. Vanalme GM, Goubert L, Van Meirhaeghe RL, Cardon F, Van Daele P. A ballistic electron emission microscopy study of barrier height inhomogeneities introduced in Au/III-V semiconductor Schottky barrier contacts by chemical pretreatments. *Semicond Sci Tech* 1999; **14**:871–877.
27. Zhu S, Van Meirhaeghe RL, Detavernier C, Cardon F, Ru GP, Qu XP, Li BZ. Barrier height inhomogeneities of epitaxial CoSi2 Schottky contacts on n-Si (100) and (111). *Solid State Electron* 2000; **44**:663–671.
28. Dobrocka E, Osvald J. Influence of barrier height distribution on the parameters of Schottky diodes. *Appl Phys Lett* 1994; **65**:575–577.
29. Chand S, Kumar J. Effects of barrier height distribution on the behavior of a Schottky diode. *J Appl Phys* 1997; **82**:5005–5010.
30. Chand S, Kumar J. Simulation and analysis of the I-V characteristics of a Schottky diode containing barrier inhomogeneities. *Semicond Sci Tech* 1997; **12**:899–906.
31. Chand S. An accurate approach for analysing an inhomogeneous Schottky diode with a Gaussian distribution of barrier heights. *Semicond Sci Tech* 2002; **17**: L36–L40.
32. Osvald J. New aspects of the temperature dependence of the current in inhomogeneous Schottky diodes. *Semicond Sci Tech* 2003; **18**:L24–L26.
33. Chand S. On the intersecting behaviour of current–voltage characteristics of inhomogeneous Schottky diodes at low temperatures. *Semicond Sci Tech* 2004; **19**:82–86.
34. Chand S, Bala S. A comparative study of numerical and analytical methods of simulating inhomogeneous Schottky diode characteristics. *Semicond Sci Tech* 2005; **20**:1143–1148.
35. Chand S, Bala S. Analysis of current–voltage characteristics of inhomogeneous Schottky diodes at low temperatures. *Appl Surf Sci* 2005; **252**:358–363.
36. Osvald J. Series resistance influence on intersecting behaviour of inhomogeneous Schottky diodes I–V curves. *Solid-State Electronics* 2006; **50**:228–231.
37. Osvald J. Influence of lateral current spreading on the apparent barrier parameters of inhomogeneous Schottky diodes. *J Appl Phys* 2006; **99**:033708 (5pp).
38. Rouag N, Boussouar L, Toumi S, Ouennoughi Z, Djouadi MA. On the difference in the apparent barrier height of inhomogeneous Schottky diodes with a Gaussian distribution. *Semicond Sci Tech* 2007; **22**:369–373.
39. Osvald J. Numerical study of electrical transport in inhomogeneous Schottky diodes. *J Appl Phys* 1999; **85**:1935–1942.
40. Rhoderick EH. Metal-semiconductor Contacts (2nd edn), Oxford: Clarendon, 1978.

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