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Research Paper

# Reverse bias-dependence of schottky barrier height on silicon carbide: influence of the temperature and donor concentration

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**Abstract**

The work deals with the dependences of the Schottky barrier height (SBH) on the reverse bias voltage, temperature and on donor concentration of metal/4H-SiC Schottky diodes. Using the tunneling modeling we have shown that the Schottky barrier height on silicon carbide strongly depends on the reverse bias voltage, temperature and doping concentration. At room temperature, the Schottky barrier height increases with increasing the reverse bias voltage at high doping concentration (about $10^{16}$ $cm^{-3}$), while, at low doping concentration (about $10^{15}$ $cm^{-3}$) the Schottky barrier height decreases with increasing the reverse bias voltage. These behaviors are independent of the Schottky barrier lowering effect. That means other effects occur at the barrier and depend on the reverse applied bias. The barrier height increases with increasing temperature and doping concentration under reverse bias conditions. The barrier heights extracted from the Padovani-Stratton formulas are close to the barrier heights extracted from the Tsu-Esaki formula in particular for the thermionic-field emission.

***Keywords***: *Extraction, Schottky Barrier Height, Reverse Bias, Tunneling, Silicon Carbide.*

## 1. Introduction

Silicon carbide is currently of great interest in high voltage power devices. Its properties of high critical field strength, reasonable carrier mobilities, wide band gap, and high thermal conductivity make it a useful material for high frequency, high temperature, and high power devices [1], [2]. However, due to the high electric fields normally encountered in SiC devices, the reverse leakage current of Schottky diodes can be significantly enhanced prior to junction breakdown due to the tunneling mechanism [3]. The high electric fields encountered in SiC and other wide band gap materials lead to significant tunneling through the Schottky barrier thus increasing the leakage current by many orders of magnitude over that predicted by simple thermionic emission (TE) calculations [3-10]. However, the tunneling leakage current, which calculated with the extracted SBH from forward I-V data, is discrepancy of the experimental data [3], [4], [9]. In these works, the authors assume that the barrier height does not depend on the applied bias despite the bias voltage is elevated. According to Rhoderick [11], there are several reasons why the Schottky barrier height ( $\phi_b$ ) may depend on the applied bias such as interfacial layer and effect of the image force. These both factors reduce the barrier height by an amount that depends on the electric field in the semiconductor, and hence on the applied bias. Rhoderick [11] supposed that $\phi_b$ depends linearly on the applied bias V, which is true for small values of forward bias voltage (V), so, the barrier height can be written as.

$$\phi_b = \phi_{b0}(V = 0) + \beta V \quad (1)$$

Where $\phi_{b0}(V = 0)$ is the barrier height at *V*= 0 volts, $\beta$ is the slope of the straight line.

Until the present no one proved experimentally if it is a wrong or a true hypothesis weather in the forward bias or in the reverse bias. The influence of the applied voltage on the *SBH* in the case of forward bias conditions where the predominant mechanism is the thermionic emission does not appear because the magnitude of applied voltage is very small (about 1 V). On the contrary, the magnitude of the reverse applied voltage is very high and thus we can predict that the *SBH* can be influenced by the applied bias. In this paper, we will study the reverse bias dependence of the

Schottky barrier height on Silicon carbide and show the influences of the temperature and donor concentration on the *SBH* under reverse bias conditions. For this purpose we assume the domination of tunneling current for the whole reverse bias, temperature and doping level ranges and we use both models of tunneling: Tsu-Esaki's [12] and Padovani-Stratton's [13] formulas for extracting the *SBH* from reverse *I-V* measurements studied in the literature.

Padovani and Stratton [13] analyzed tunneling currents in Schottky barriers from the standpoint of the field and thermionic-field emission using a one dimensional Wentzel-Kramer-Brillouin (WKB) approximation. However, their analysis ignored image force effects and used a simple parabolic barrier shape.

The field emission current density in the reverse bias applied is expressed by the following equation [13]

$$J_{FE} = \frac{A^* T^2 \pi E_{00} \exp\left[-2q\phi_b^{3/2} / 3E_{00}(\phi_b - V)^{1/2}\right]}{k_B T\left[\phi_b / (\phi_b - V)\right]^{1/2} \sin\left\{\pi k_B T\left[\phi_b / (\phi_b - V)\right]^{1/2} / E_{00}\right\}} \tag{2}$$

Where $E_{00}$ is a constant related to the *WKB* expression for the transmission of the barrier and is given as follows

$$E_{00} = \frac{qh}{2}\sqrt{\frac{N_D}{m_e^* \varepsilon_S}} \tag{3}$$

Where $N_D$ is the semiconductor (*n*-type) doping concentration, $\varepsilon_S$ is the semiconductor permittivity, $A^*$ is the effective Richardson constant, theoretically equal to 146 $A/K^2\ cm^2$ [14]

The thermionic-field emission current density in the reverse bias applied is expressed by the following equation [13]

$$J_{TFE} = \frac{A^* T}{k_B}\sqrt{\pi E_{00} q\left(-V + \frac{\phi_b}{\cosh^2(E_{00}/k_B T)}\right)} \exp\left(\frac{-q\phi_b}{E_0}\right)\exp\left(-\frac{qV}{\varepsilon'}\right) \tag{4}$$

Where

$$\varepsilon' = \frac{E_{00}}{(E_{00}/k_B T) - \tanh(E_{00}/k_B T)} \tag{5}$$

$$E_0 = E_{00}\coth\left(\frac{E_{00}}{k_B T}\right) \tag{6}$$

Field emission occurs for $c_1 > k_B T$ and thermionic field emission for $c_1 < k_B T$ where $c_1$ is given by

$$c_1 = \left\{E_{00}^{-1}\left[\phi_b / (\phi_b - V)\right]^{1/2} + (-0.5qE_{00}V)^{1/2}\right\}^{-1} \tag{7}$$

The Tsu–Esaki expression is the most prominent and almost exclusively used expression to describe tunneling transitions**.** The reverse current density is given by [3], [7], [12], and [15]

$$J_{T\&E} = \frac{A^* T}{k_B}\int_0^\infty T(E)\ln\left(\frac{1+\exp(-q\zeta - E)/k_B T}{1+\exp(-q\zeta - qV - E)/k_B T}\right)dE \tag{8}$$

Where $\zeta$ is the difference between the conduction band and the equilibrium Fermi level, *E* is the electron transversal energy component. *T (E)* is the transmission coefficient. In this work, we use the *WKB* approximation because it offers an analytical solution and it is valid for the Schottky barrier diodes [16].

## 2. Extraction method of the barrier height using the reverse I-V characteristics

For extracting the barrier height ($\phi_b$) from the reverse *I-V* characteristic, we assume that the tunneling process is the dominant mechanism. First, we assume that the $\phi_b$ is independent of the applied bias, and then we extract the values of $\phi_b$ and the effective mass ($m^*$) which verified the best fit of the experimental data. For that, we use the criterion (S) which presents the sum of the squares of the relative differences between the measured and the ideal values. This criterion was proposed for the first time by Osvald [17] for extracting the parameters of Schottky diode from the forward *I-V* characteristic.

$$S = \sum_{i=1}^{N}\left(\frac{I_i^{Th} - I_i^{\exp}}{I_i^{Th}}\right)^2 \tag{9}$$

Where $I_i^{\exp}$ is the ith experimental value, $I_i^{Th}$ is the fitting value of the current, i.e. given by the *Eq*. (8) for $V = V_i$, and *N* is the number of measuring points.

Second, we assume that the $\phi_b$ is dependent on the applied bias and use the theoretical value of the effective mass for 4H-SiC ($m^* \approx 0.2m$) [18-20]. So, we can use the Tsu-Esaki formula or the Padovani-Stratton formulas for extracting the SBH. For that, we can solve numerically the following equations by Newton's method.

$$J_{T\&E}(V_i) = J^i_{exp}(V_i) \tag{10}$$

$$J_{TFE}(V_i) = J^i_{exp}(V_i) \tag{11}$$

$$J_{FE}(V_i) = J^i_{exp}(V_i) \tag{12}$$

Where $J^i_{exp}(V_i)$, is the reverse current density for each bias voltage measurement. The *Eq*. (10) uses the Tsu-Esaki formula and the *Eqs*. (11) And (12) use the Padovani-Stratton formulas.

## 3. Results and discussion

In this study we use the data on silicon carbide (4H-SiC) previously published by several authors. The wafers had an *n*-type epitaxial layer. The type of diode, doping concentration $N_D$, temperature and the forward barrier height for each diode are summarized in the Table 1. As shown in this Table all the semiconductors used in this study are lightly doped and the doping level is varied from $9\text{x}10^{14}$ $cm^{-3}$ to $1.6\text{x}10^{16}$ $cm^{-3}$**.**

**Table 1:** Properties and Characterization of the Diodes Collected from Several Authors.

| Type | $N_D$ ($cm^{-3}$) | T (K) | $\phi_b^{I-V}$ (V) | Reference | Observations |
|---|---|---|---|---|---|
| Ti/4H-$SiC_{ref\ 4}$ | $10^{16}$ | 300 | 1.21 | Furno [4] | Junction termination extension |
| Ni/4H-$SiC_{ref\ 5}$ | $1.6\text{x}10^{16}$, $3.5\text{x}10^{15}$ | 293 | 1.3, 1.5 | Schoen [5] | Boron implant edge termination |
| Ti/4H-$SiC_{ref\ 5}$ | $3.5\text{x}10^{15}$ | 293 | 0.85 | Schoen [5] | Boron implant edge termination |
| Ti/4H-$SiC_{ref\ 5}$ | $1.6\text{x}10^{16}$ | 293-528 | 0.8-? | Schoen [5] | Boron implant edge termination |
| Ti(Ni)/4H-$SiC_{ref\ 6}$ | $3\text{x}10^{15}$ | 301-517 | 1.4-1.47 | Vassilevski [6] | Junction termination extension |
| Ti/4H-$SiC_{ref\ 18}$ | $7\text{x}10^{15}$ | 297-423 | 1.16 | Itoh [18] | Boron implant edge termination |
| Ni/4H-$SiC_{ref\ 21}$ | $6.1\text{x}10^{15}$ | 300-573 | 1.38-1.37 | saxena [21] | Field oxide |
| Ni/4H-$SiC_{ref\ 22}$ | $2\text{x}10^{15}$ | 300 | - | Nigam [22] | JTE, circular diode, area 0.04$mm^2$ |
| Ti/4H-$SiC_{ref\ 23}$ | $2\text{x}10^{15}$-$7.4\text{x}10^{15}$ | 300 | 1.2-1.17 | Ohtsuka [23] | No edge termination |
| Ni/4H-$SiC_{ref\ 24}$ | $2\text{x}10^{15}$ | 359-522 | 1.53 | Ivanov [24] | guard rings: planar *p*–*n* junctions |
| Ni/4H-$SiC_{ref\ 25}$ | $9\text{x}10^{14}$ | 361-470 | 1.12 | Ivanov [25] | protective *p*-type rings |

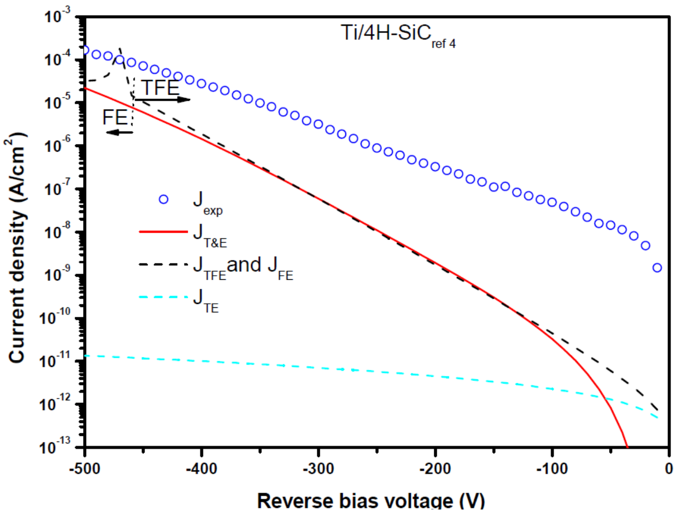



**Fig. 1:** Comparison of Calculating Current Densities (Thermionic Emission, Field Emission, Thermionic Field Emission and Tsu-Esaki's Expression Calculated With $\phi_b^{I-V} = 1.21V$ ) and Experimental Leakage Current For Ti/4H-$SiC_{ref\ 4}$ Schottky Diode. the Experimental Results are From Furno [4].

Fig. 1 shows a comparison of calculating reverse current densities with experimental result obtained for Ti/4H-$SiC_{ref\ 4}$ SD. The calculated reverse current densities are obtained with the extracted barrier height $\phi_b^{I-V} = 1.21V$ from forward I-V measurements. The present result clearly shows the importance of tunneling currents during reverse bias operation of Schottky diodes in high field materials such as SiC. In contrast, and as shown in Fig. 1, it may be noted that thermionic emission theory predicts much smaller voltage dependence. The current densities obtained by the Padovani-Stratton formulas are close to the current density obtained by the Tsu-Esaki formula in particular for the Thermionic field emission. The transition between field and thermionic field emission occurs at approximately - 460 V. However, Fig. 1 shows a strong difference between the slope of the ln(I)-V plots obtained by the tunneling numerical methods and the slope of the experimental ln(I)-V plot. The electron effective mass *m** is the parameter determining the slope of the calculated reverse characteristics as shown in Fig. 2.

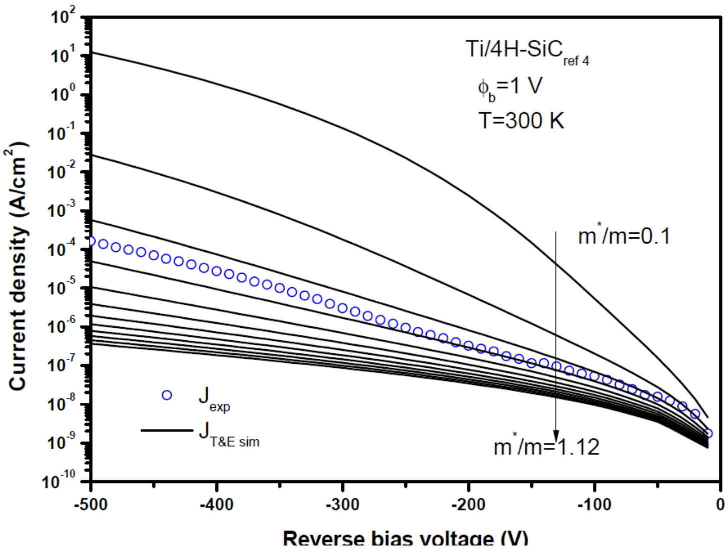



**Fig. 2:** Current Density Calculated with Tsu-Esaki's Expression as A Function of the Reverse Bias Voltage at Various Effective Mass. with $\phi_b$ =1 V, T=300 K.

This result has been mentioned by Furno [4]. However, in this study we have found that the current is decreased when the effective mass is increased because the transmission coefficient is decreased with increasing the effective mass. This behavior is in contradiction with the Furno's results [4]. We explain that by the transfer matrix method used by Furno. In effect, several authors have noted numerical problems in applying this method for the computation of wave functions. These problems are due to the multiplication of matrices with exponentially growing and decaying states. For thick barriers, this leads to rounding errors which eventually exceed the amplitude of the wave function itself [26]. We note here, that, in the case of the forward bias voltage Crowell and Sze [27] found the same behavior as we have obtained.
Assuming no reverse bias-dependence of Schottky barrier height and for determining the best values of ($\phi_b$ , $m^*$) for the fit of the experimental data we search the minimum of the sum of the squares of the relative differences between the measured and the ideal values for various values ($\phi_b$ , $m^*$) as shown in Fig. 3. The extracted values of barrier height and effective mass ($\phi_b$ , $m^*$) for Ti/4H-SiC$_{ref\ 4}$ SD are 1 V and 0.345*m*, respectively. The extracted values ($\phi_b$ , $m^*$) for some diodes are collected in Table 2. As shown in Table 2 a significant difference between the extracted values of the effective mass of 4H-SiC material for different diodes is observed.

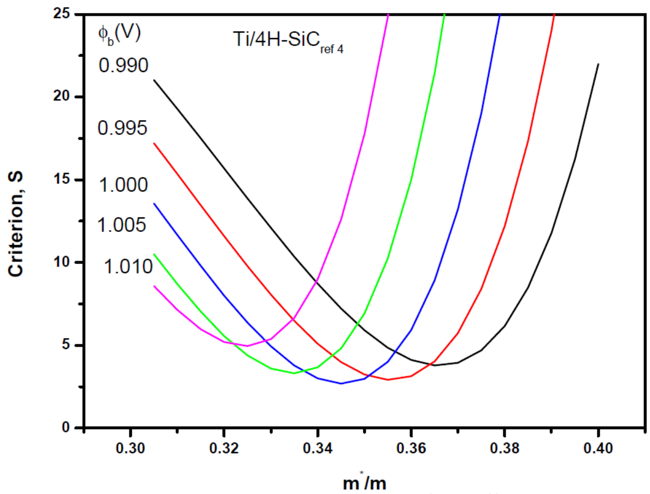



**Fig. 3:** Minimizing of the Sum of the Quadratic Relative Error (S) as A Function of the Effective Mass at Various Schottky Barrier Heights for the Reverse *I-V* Data of the Ti/4H-SiC$_{ref\ 4}$ SD.

**Table 2:** The Fitting Parameters $\phi_b$ and m* Extracted From the Reverse *I-V* Characteristics for Some Diodes at Room Temperature. The Extracted Values are obtained by Using Tsu-Esaki's Expression (*Eq.* (10)) with the Criterion, S, Given by the *Eq.* (9).

| Type | $N_D$ (cm$^{-3}$) | $\phi_b$ (V) | $m^*/m$ |
|---|---|---|---|
| Ti/4H-SiC$_{ref\ 5}$ | 1.6x10$^{16}$ | 0.705 | 0.460 |
| Ti/4H-SiC$_{ref\ 18}$ | 7x10$^{15}$ | 0.840 | 0.435 |
| Ti(Ni)/4H-SiC$_{ref\ 6}$ | 3x10$^{15}$ | 0.900 | 0.200 |
| Ni/4H-SiC$_{ref\ 22}$ | 2x10$^{15}$ | 0.985 | 0.050 |

Fig. 4 shows a comparison between reverse current densities obtained by Tsu-Esaki model calculated with the extracted values reported in Table 2 and the experimental data for several diodes. It can be seen from this figure that the experimental ln(I)–V plots and simulated ln(I)–V plots do not coincide over the entire bias ranges except in the case of the Ti(Ni)/4H-SiC$_{ref\ 6}$ SD, which exhibits an almost total coincidence. The difference in the nature of the experimental ln (I)-V plots and the difference in the effective mass for the same material (4H-SiC) supports the dependence of $\phi_b$ on the bias voltage. Furthermore, the experimental curves have different curvatures which differ from each other. The existing of many different curvatures predicts that the variation of the SBH with bias voltage is not the same for all diodes. Moreover, the coincidence of the experimental and calculated curves for the Ti(Ni)/4H-SiC$_{ref\ 6}$ SD predicts no important variation in the barrier height with the bias voltage and the effective mass ($m^* = 0.2m$) obtained (see Table 2) in this case is equal to the theoretical value.

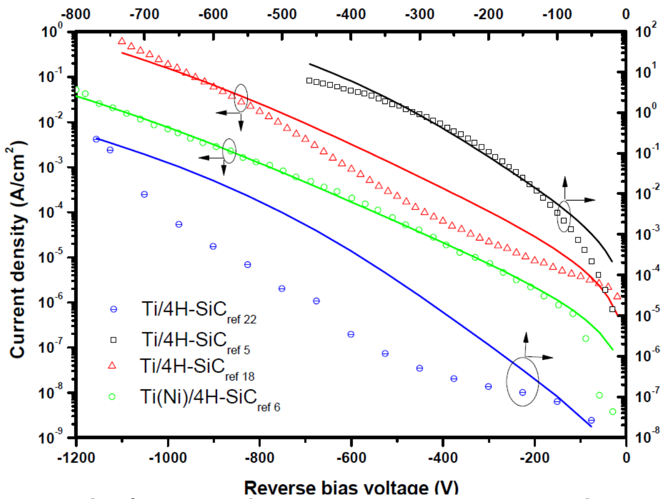



**Fig. 4:** Experimental and Fitted Reverse *I–V* Plots for Some Diodes at Room Temperature. Experimental Data are from the References as Reported in Table 1.

For the reasons discussed above, we assume in the following section reverse bias-dependence of Schottky barrier height and we use the previously extraction method discussed in the section 2. Fig. 5 shows the typical dependence of the extracted value of the barrier height on reverse bias using the Tsu-Esaki model (Eq. (10)) for Ti/4H-SiC$_{ref\ 18}$ SD, at room temperature with and without the Schottky barrier lowering (SBL) effect. A dependence of $\phi_b$ on the reverse bias voltage is clearly observed. Increasing the reverse bias voltage, the barrier height $\phi_b$ first increases then starts to decrease again; it exhibits a maximum value of Schottky barrier height. The reverse bias-dependence of Schottky barrier height is independent of the Schottky barrier lowering (SBL) effect as shown in Fig. 5. This behavior is in contradiction with the Schottky effect theory which predicts a decrease in the barrier height when the reverse bias voltage increases. One possible explanation is that other effects occur at the interface in addition to the Schottky barrier lowering. These effects must be strongly dependent on the reverse applied bias than the Schottky barrier lowering effect.

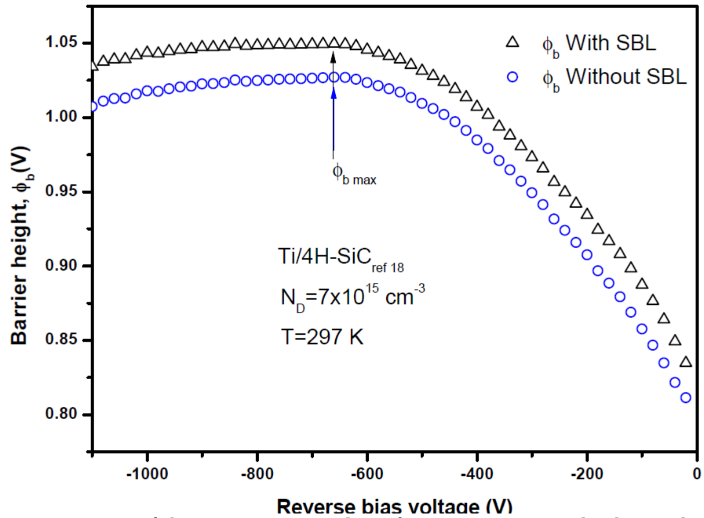



**Fig. 5:** Schottky Barrier Height as A Function of the Reverse Bias Voltage for Ti/4H-Sic$_{ref\ 18}$ Schottky Diode with and Without Schottky Barrier Lowering Effect. The Values of $\phi_b$ Are Extracted By the Tsu-Esaki Model.

The doping concentration dependence of barrier height is depicted in Fig. 6. Fig. 6a shows the barrier height as a function of the reverse bias for Ti/4H-SiC$_{ref\ 23}$ SDs at different doping concentrations (reverse *I-V* data are from the same work [23]). While Fig. 6b shows the barrier height as a function of the reverse bias for Ni/4H-SiC SDs at various doping concentrations (reverse *I-V* data are from several works [5], [6], [21], and [22]). From these figures, we can see two important observations:

First, we can see that the barrier height tends to increase with an increase in the donor concentration, while, several authors [28-31] observed that the barrier height decreases with increasing donor concentration in the case of the forward bias, where the thermionic model is used. Hudait [28] explained this reduction by the barrier height lowering for thermionic field-emission theory, Horváth [29] attributed it to the effect of the interfacial layer and interface states, Noh [30] of his part, attributed this reduction to the Schottky barrier lowering, while, Syrkin [31] explained it by the image force barrier lowering and the value of the surface energy level and the density of surface states.

Second, the barrier height tends to increase with increasing the reverse bias voltage at the high donor concentration (case of Ti/4H-SiC$_{ref\ 23}$ and Ni/4H-SiC$_{ref\ 5}$ SDs with $N_D$ = 7.4x10$^{15}$ cm$^{-3}$, and $N_D$ = 1.6x10$^{16}$ cm$^{-3}$ respectively), while at the low donor concentration the barrier height tends to decrease with increasing the reverse bias voltage (case of Ni/4H-SiC$_{22}$ with $N_D$ = 2x10$^{15}$ cm$^{-3}$). At intermediate doping concentration we can see an intermediate phase which characterized by no significant variation in the barrier height over the entire bias range, as was expected above (case of Ti(Ni)/4H-SiC$_{ref\ 6}$ SD with $N_D$ = 3x10$^{15}$ cm$^{-3}$, and Ti/4H-SiC$_{ref\ 23}$ SD with $N_D$ = 2x10$^{15}$ cm$^{-3}$). The increase in doping concentration leads to a moving of the maximum value of the barrier height from the low reverse bias to the high reverse bias. The value of the barrier height depends on the metal nature as shown in Fig. 7. As shown in this figure the barrier height of the Ni/4H-SiC$_{ref\ 5}$ SD is higher than Ti/4H-SiC$_{ref\ 5}$ SD for the same doping concentration because the metal work function of Ni (5.35 eV) is higher than Ti (4.33 eV). It is also seen from Fig. 6 and Fig. 7 that the barrier heights tend to collect at the lower applied bias for the same type of Schottky contact metal where the doping concentration dependence of the barrier height is weak. This result is in close agreement with the doping dependence of the barrier height obtained from forward bias conditions at slightly doping concentration [31].

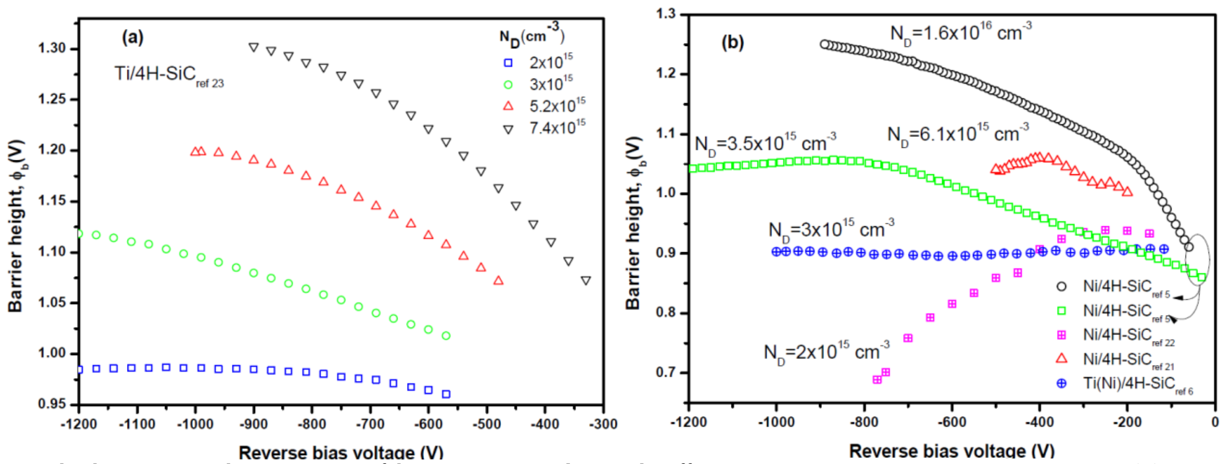



**Fig. 6**: Schottky Barrier Height as a Function of the Reverse Bias Voltage with Different Donor Concentrations at Room Temperature. (A) For Ti/4H-SiC$_{ref\ 23}$ SDs, (B) For Several Metal/4H-SiC$_{ref}$ SDs.

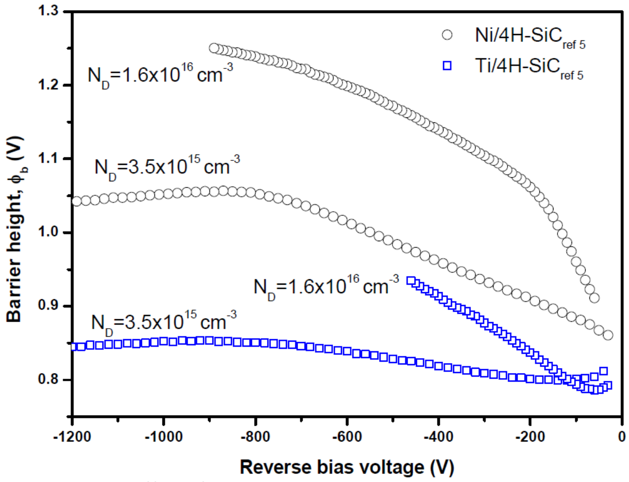



**Fig. 7:** The Effect of the Metal Nature on the Schottky Barrier Height.

Fig. 8 shows the comparison between the $\phi_b$ extracted from the Tsu-Esaki model (Eq. (10)) and the Padovani-Stratton model (Eq. (11) and Eq. (12)). The transition between field and thermionic field emission occurs at approximately -240 V for Ni/4H-SiC$_{ref\ 5}$ SD, and -560 V for Ti/4H-SiC$_{ref\ 18}$ SD. It can be clearly seen from this figure that the values of $\phi_b$ extracted from the Padovani-Stratton model are close to the values extracted from the Tsu-Esaki model, particularly in the case of thermionic field emission. The little discrepancy between them is due to the fact that the Padovani-Stratton formulas do not include any image force lowering of the barrier and they were derived by considering only the first two terms of the Taylor expansion.

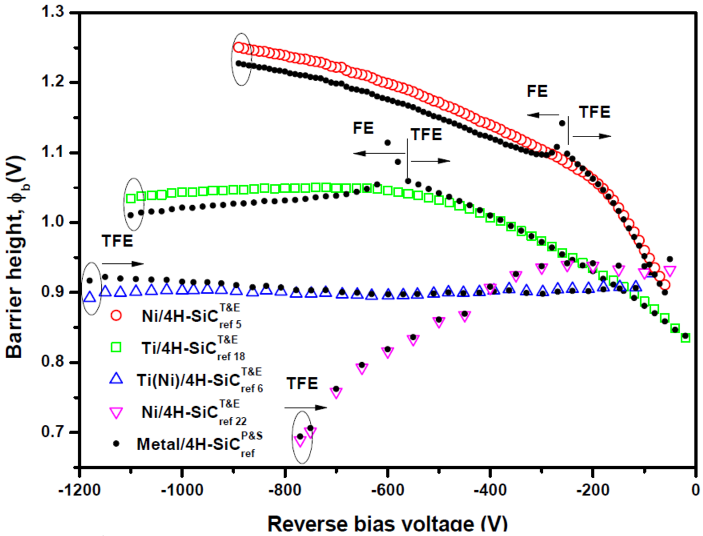



**Fig. 8:** Comparison between the Values of Schottky Barrier Heights Extracted by Tsu-Esaki's Model (with *SBL*) and the Values Extracted by Padovani-Stratton Model.

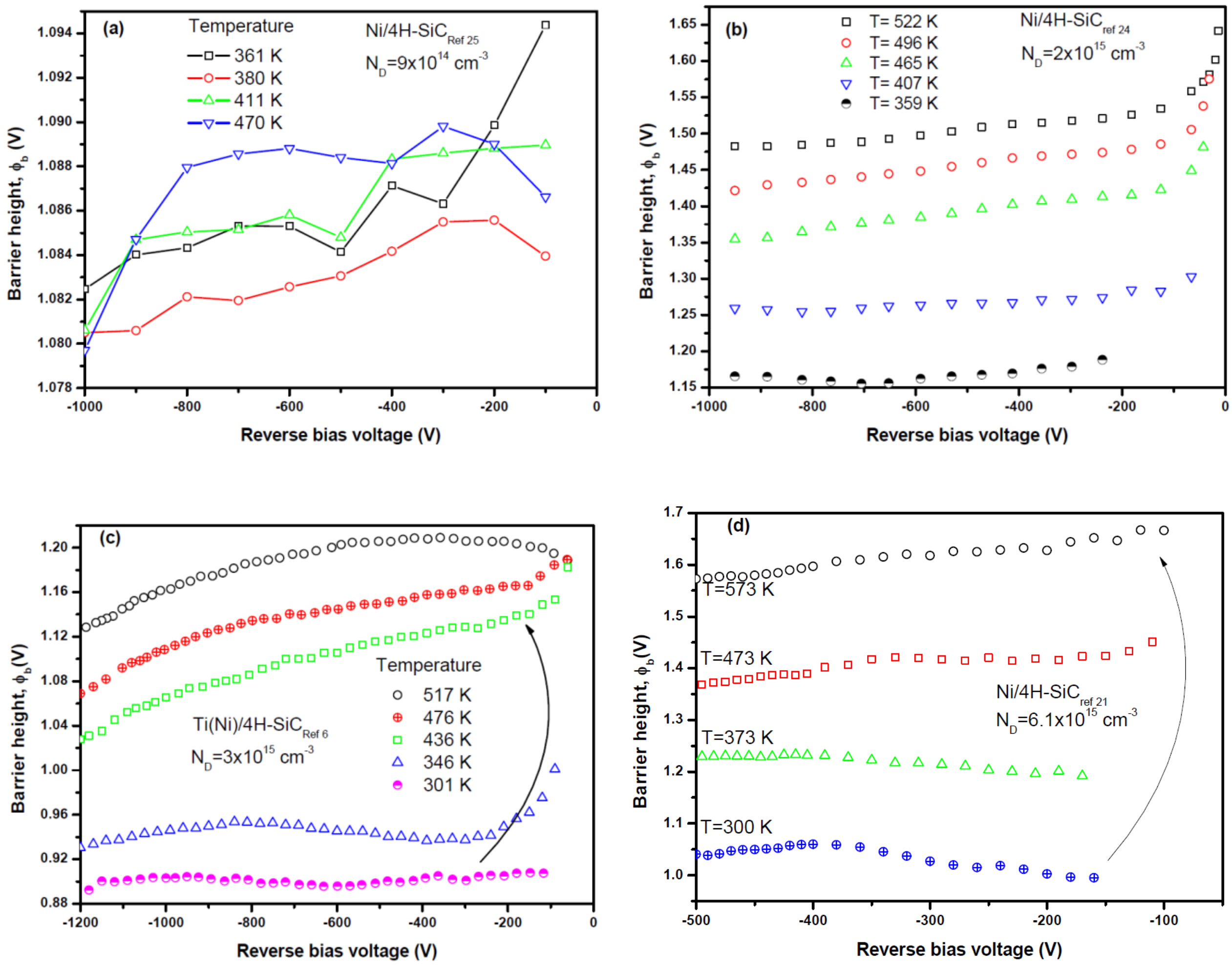
Fig. 9 shows the plots of the extracted barrier height as a function of reverse applied voltage for metal/4H–SiC SDs at different temperatures and doping levels. The increase in temperature leads to an increase in the barrier height, especially, at lower voltages than at higher voltages. As a consequence, the reverse bias dependence is changed and the barrier height tends to decrease with increasing reverse bias in particular at lower doping concentrations (see Fig. 9a, Fig.9b, Fig. 9c and Fig.9d) and the maximum value of the barrier height moves from the high reverse bias to the low reverse bias as shown in Fig. 9e. A reduction in the barrier height value is observed when moving from the forward to the reverse characteristics.

Fig. 10 shows the temperature dependence of the barrier height for metal/4H-SiC SDs, under investigation at different reverse bias. As can be seen from Fig. 10, the experimental barrier height increases linearly with increasing temperature and the slopes are higher for the low bias than for the high bias; the slope is about $1.49\text{x}10^{-3}$ V/K at -500 V and $1.15\text{x}10^{-3}$ V/K at -1200 V for Ti(Ni)/4H-SiC$_{ref\ 6}$. This increase in barrier height with increasing temperature is the same behavior at the forward bias, where the thermionic model is used. The authors attributed this temperature dependence to the barrier height inhomogeneities prevailing at the metal-semiconductor interface [19], [32]-[34].

The Schottky barrier height on SiC is, in general, determined by both the metal work function and the interface states [35]. According to all dependences of barrier height obtained above we can explain them by the combination between the effects of the interfacial layer present in intimate metal/4H-SiC contacts and the surface states density on the metal-semiconductor interface. These both effects have a contrary contribution. The interface layer reduces the barrier height by an amount that depends on the applied bias (increase with increasing applied bias), while the interface states increase the barrier height by an amount that depends on the applied bias, doping concentration and temperature (increase with increasing applied bias, temperature and doping concentration). The total barrier height can be written as

$$\phi_b = \phi_b^{th}(\phi_m,\chi) - \Delta\phi_b^{\mathrm{int-}lay}(V) + \Delta\phi_b^{\mathrm{int-}stat}(V, N_D, T) \tag{13}$$

Where $\phi_b^{th}(\phi_m,\chi)$ is the ideal barrier height defined by the difference between the metal work function ( $\phi_m$ ), and the electron affinity of the semiconductor ( $\chi$ ) .The amount $\Delta\phi_b^{\mathrm{int-}lay}(V)$ is due to the polarization of the interfacial layer between the semiconductor and the metal where the dipole layer will orient toward the metal surface. This type of polarization depends on the proprieties of the layer (dielectric permittivity) and the electric field (applied bias). Under external influences such as temperature or electric field (applied voltage) the neutral states (donor interface traps below the neutral level, $\phi_0$ ) can be lost their electrons and can be ionized with a positive charge. Consequently, it appears a dipole between the interfacial states (positive charge) on the semiconductor and the metal surface (negative charge) and this dipole will orient toward the semiconductor surface. The result of this effect is the amount $\Delta\phi_b^{\mathrm{int-}stat}(V, N_D, T)$ . The interface states increase with increasing doping concentration which leads to the increase in the dipole, and hence increase in the barrier height. At high temperature, in particular, at low doping concentration the amount $\Delta\phi_b^{\mathrm{int-}stat}(V, N_D, T)$ becomes weak dependent on the applied bias because the majority of interface states can be ionized by the effect of temperature, so, the effect of the interfacial layer which depends on applied bias becomes dominant compared with the effect of the interface states and thus the barrier height tends to decrease with increasing reverse bias.



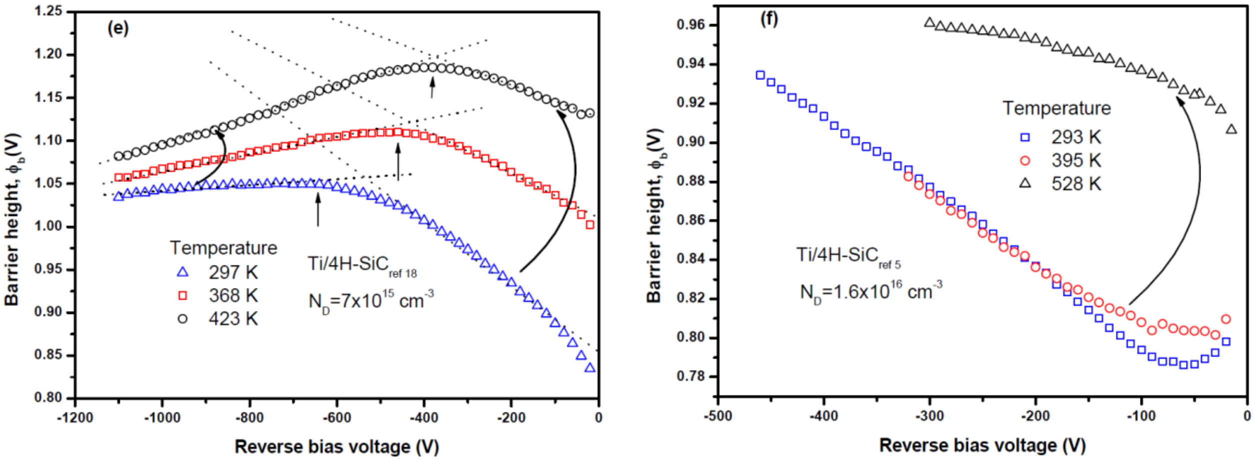



**Fig. 9:** Schottky Barrier Height as a Function of the Reverse Bias Voltage at Different Temperatures and Different Doping Concentration for Several Metal/4H-SiC$_{ref}$ SDs.

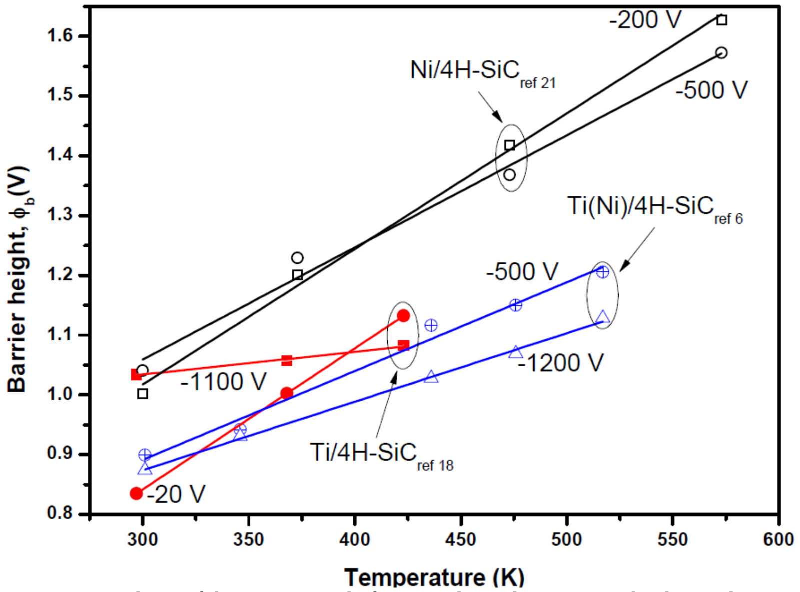



**Fig. 10:** The Temperature Dependence of the Barrier Height for Several Metal/4H-SiC$_{ref}$ Schottky Diodes at Different Reverse Bias.

## 4. Conclusion

The tunneling modeling is used for extracting the Schottky barrier height from reverse *I-V* characteristics. The Schottky barrier height extracted from reverse *I-V* characteristic on silicon carbide exhibits dependences with the reverse applied bias, temperature and doping concentration. At room temperature, the Schottky barrier height increases with increasing the reverse applied bias in the case of high doping concentration and decreases in the case of low doping concentration. This behavior is in contradiction with the behavior predicted by the effect of the image force. That means the existing of other effects which occur at the barrier and depend on the applied bias. The Schottky barrier height increases with increasing temperature and doping concentration. These dependences are due to the combination of the effects of the interfacial layer and interface states. The values of the extracted Schottky barrier height using the Padovani-Stratton model are close to the values of the Schottky barrier height obtained from the Tsu-Esaki model, in particular for thermionic-emission.

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