Electrical properties of inhomogeneous tungsten carbide Schottky barrier on 4H-SiC

M Vivona\(^1\), G Greco\(^1\), G Belloccchi\(^2\), L Zumbo\(^2\), S Di Franco\(^1\), M Saggio\(^2\), S Rascun\(\`\)a\(^2\) and F Roccaforte\(^1\)

\(^1\) CNR-IMM, Strada VIII n.5 Zona Industriale, I-95121, Catania, Italy
\(^2\) STMicroelectronics, Stradale Primosole 50, I-95121, Catania, Italy

E-mail: marilena.vivona@imm.cnr.it

Received 8 July 2020, revised 8 September 2020
Accepted for publication 1 October 2020
Published 9 November 2020

Abstract

In this paper, the electrical behavior of tungsten carbide (WC) Schottky barrier on 4H-SiC was investigated. First, a statistical current-voltage (I–V) analysis in forward bias, performed on a set of equivalent diodes, showed a symmetric Gaussian-like distribution of the barrier heights after annealing at 700 °C, where a low Schottky barrier height (\(\Phi_B = 1.05\) eV) and an ideality factor \(n = 1.06\) were measured. The low value of the barrier height makes such a WC contact an interesting candidate to reduce the conduction losses in 4H-SiC Schottky diodes. A deeper characterization has been carried out, by monitoring the temperature dependence of the I–V characteristics and the behavior of the relevant parameters \(\Phi_B\) and \(n\). The increase of the barrier height and decrease of the ideality factor with increasing temperature indicated a lateral inhomogeneity of the WC/4H-SiC Schottky contact, which was described by invoking Tung’s model. Interestingly, the temperature dependence of the leakage current under reverse bias could be described by considering in the thermionic field emission model the temperature dependent barrier height related to the inhomogeneity. These results can be useful to predict the behavior of WC/4H-SiC Schottky diodes under operative conditions.

Keywords: semiconductor interface, 4H-SiC, tungsten carbide, electrical characterization, current transport, Schottky device

(Some figures may appear in colour only in the online journal)

1. Introduction

Today, hexagonal silicon carbide (4H-SiC) is recognized as a material of choice to overcome the limits of conventional silicon technology, in terms of power losses reduction and energy efficiency improvement [1]. This relies on the superior physical properties of the 4H-SiC compared to Si, like a wider band gap (3.2 eV), higher breakdown electrical field (3 MV cm\(^{-1}\)), saturation electron velocity (\(2 \times 10^7\) cm s\(^{-1}\)) and thermal conductivity (3.7 W K\(^{-1}\) cm\(^{-1}\)) [2].

Among the 4H-SiC devices, Schottky barrier diodes (SBDs) have reached a mature technological level with a variety of products commercially available by several companies, providing low on-state voltage drop, high breakdown voltage, and high switching speed, combined with the possibility to operate at high temperatures [3].

Since the core of a SBD is the metal/semiconductor interface, in the last two decades several studies have investigated the electrical properties of various metallization schemes for Schottky contacts to 4H-SiC and the current transport through these interfaces [4–7]. Nowadays, in state-of-the-art 4H-SiC commercial devices, the Schottky contact is typically based on titanium (Ti) or molybdenum (Mo), as these metals enable us to obtain low Schottky barrier height values (in the range 1.1–1.2 eV) and can be easily integrated in the manufacturing steps. However, since a further reduction of the conduction losses in SBDs is highly desired in many applications, the reduction of the barrier height (i.e. the device turn-on...
voltage) is one of the current challenges in 4H-SiC SBD technology [8].

In literature, metallization schemes based on low-work-function metals with high melting point (W, Mo, etc) [9–14] or tunable composition have been investigated to optimize the performance of 4H-SiC Schottky diodes. As an example, Stöber et al [12] proposed the use of molybdenum nitride (MoNₓ) Schottky contacts, controlling the barrier height by varying the nitrogen fraction in the reactive sputtering metal deposition. On the other hand, by thermal annealing of a thin tungsten (W) layer, Knoll et al [13] observed the formation of tungsten carbide (WₓC), with a smooth interface morphology, high thermal stability and low turn-on voltage in 4H-SiC diodes. In this context, only a few papers have studied the tungsten carbide barrier material, most of them being limited to structural, morphological and optical characterization of this contact on 6H-SiC [15–17].

The electrical characterization of a contact relies on the study of the Schottky barrier height Φ_B, which governs the forward voltage drop, and the reverse leakage current. The peculiarity of an ideal contact features a barrier height independent of temperature, voltage and measurement method, with the Φ_B value close to that predicted by the Schottky-Mott rule [18]. In contrast, in ‘real’ cases, Schottky contacts on 4H-SiC can exhibit deviations from the ideal behavior, due to interface inhomogeneities related to surface/interface states, defects, processing contaminations, etc [3].

Several studies have discussed the inhomogeneity of Schottky contacts on 4H-SiC based on different metals (Ti, Ni, NiₓSi, W, etc) [19–25]. These studies often invoked Tung’s model [26], which assumes a local lateral inhomogeneity of the Schottky barrier height. Specifically, nanometer-size regions, characterized by a low barrier height value and embedded in a uniform high barrier background, interact with one another with a resulting pinch-off effect on the low barrier height regions [26]. However, the electrical behavior and the homogeneity of tungsten carbide (WC) Schottky contacts on 4H-SiC are still unexplored.

This study reports on the electrical behavior of WC/4H-SiC Schottky contacts. In particular, a temperature-dependent current-voltage characterization (I-V-T) enabled us to get insights on the inhomogeneous nature of the barrier and to explain the forward and reverse conduction mechanisms through the inhomogeneous WC/4H-SiC interface.

### 2. Experimental details

Commercial n-type 4H-SiC wafer, with a 9.5 μm thick epitaxial layer having a nominal doping concentration N_D = 8 × 10^{15} cm^{-3}, was used as a starting material in our study. On this sample, Schottky diodes with an active contact area A = 4.53 × 10^{-2} cm² have been fabricated, using tungsten carbide (WC) as the barrier metal. Before the front-side processing of the wafer, a large-area back-side contact has been fabricated by Ni deposition followed by rapid thermal annealing (RTA) at 950 °C in N₂ [27]. Then, an 80 nm-thick WC layer was deposited by DC magnetron sputtering, and defined by optical lithography and the lift-off process. The relevant electrical parameters of the contacts (ideality factor n and Schottky barrier height Φ_B) were determined by means of current-voltage (I-V) measurements on a set of 40 equivalent diodes, performed in a Karl-Suss MicroTec probe station equipped with a parameter analyzer. The Schottky diodes were characterized both before (as-deposited) and after annealing treatment at 700 °C for 10 min in N₂-atmosphere. For selected samples, the temperature-dependence of both forward and reverse I-V characteristics (I-V-T) was monitored in the range 25 °C–125 °C, to get more insights on the barrier inhomogeneity and leakage mechanisms.

### 3. Results and discussion

Firstly, in order to evaluate the uniformity of the WC/4H-SiC Schottky barrier formation, the distribution of the ideality factor n and barrier height Φ_B was derived from forward I-V characteristics acquired on a set of equivalent diodes fabricated on the wafer, in the as-deposited and annealed samples. Figure 1 reports in a semilog plot the I-V characteristics representative of the average behavior of the as-deposited and annealed WC/4H-SiC tested diodes.

Evidently, the forward I-V curves present a wide linearity region over several decades. Above a certain bias (0.6–0.8 V), the I-V curves start to bend, due to the dominant contribution of the series resistance. After annealing at 700 °C, the forward I-V curves of the WC/4H-SiC diodes exhibit a slight negative voltage shift with respect to the as-deposited case, suggesting a reduction of the barrier height.

By applying the thermionic emission (TE) model [18], the ideality factor n and the Schottky barrier height Φ_B were derived by fitting the linear region of the semilog forward I-V curves, according to the relation:
where $A$ is the diode area, $A^*$ is the theoretical Richardson constant of 4 H-SiC (146 A cm⁻² K⁻²) [20], $k_B$ is the Boltzmann constant, $q$ is the electron charge, $V_F$ is the voltage applied across the metal/semiconductor interface and $T$ is the absolute temperature.

Figure 2 shows the statistical distribution of the barrier height $\Phi_B$ values for the as-deposited and annealed contacts, determined on a set of 40 diodes in different positions of the wafer. Notably, narrow distributions of the $\Phi_B$ values were obtained, thus indicating a good reproducibility of the WC barrier formation process. In the as-deposited contact, an asymmetric distribution of the measured barrier heights was observed, with the barrier value peaked at 1.11–1.12 eV. On the other hand, with the annealing treatment at 700 °C, the barrier heights distribution became more symmetric. In particular, the barrier heights distribution can be fitted to a Gaussian curve (figure 2(b)) centered at 1.075 eV and with a standard deviation of 0.013 eV.

Figure 3 reports the average values of the ideality factor $n$ and Schottky barrier height $\Phi_B$ determined from the forward I-V characteristics of WC/4H-SiC Schottky diodes for the as-deposited and 700 °C annealed contacts. The forward J-V characteristics (with J being the current density) are displayed in figure 4 for five different measurement temperatures (from 25 °C to 125 °C). As predicted by the TE model, the diode forward current increases with increasing the measurement temperature.

The ideality factor $n$ and barrier height $\Phi_B$ determined from these curves are reported in figure 5 as function of the measurement temperature. As can be seen, while the barrier height increases with increasing temperatures, the ideality factor decreases. The temperature dependence of ideality factor $n$ and barrier height $\Phi_B$ indicates that the WC/4H-SiC Schottky contact is characterized by a certain degree of local inhomogeneity. Such a behavior was described by applying Tung’s theory [20].

Accordingly, the inhomogeneity of the metal/semiconductor interface can be explained by considering a distribution of regions (patches) characterized by different low barrier heights and different area, embedded in an ideal high-barrier contact to n-type semiconductor $V_F^{\text{ideal}}$ is given by the difference between the metal work-function ($\Phi_M$) and the semiconductor electron affinity ($X_{\text{SiC}}$), i.e. $\Phi_B^{\text{ideal}} = \Phi_M - X_{\text{SiC}}$. Considering $X_{\text{SiC}} = 3.2$ eV for 4 H-SiC [30], an ideal barrier height $\Phi_B^{\text{ideal}} = 1.7$ eV is expected for the WC/4H-SiC contact, taking into account a work function of 4.9 eV for WC [31]. Clearly, the experimental data determined by the I-V characterization do not match with the theoretical calculations. In fact, in a ‘real’ metal/semiconductor contact the presence of surface states (related to roughness, surface contaminants, residual thin interfacial oxide layers, etc) is responsible for a deviation from the Schottky–Mott rule [17]. Moreover, the metal work function can be also affected by the deposition technique and/or by the annealing treatments.

Figure 2. Statistical distribution of the measured barrier heights in WC/4H-SiC Schottky contacts, extracted from I–V measurements on a set of diodes in the as-deposited sample (a) and after thermal annealing at 700 °C (b).

Figure 3. Average values of ideality factor $n$ and barrier height $\Phi_B$ determined from the forward I–V characteristics of WC/4H-SiC Schottky diodes for the as-deposited and 700 °C annealed contacts.
Figure 4. Forward J-V characteristics acquired at different temperatures ranging from 25 °C to 125 °C with step = 25 °C for the WC/4H-SiC Schottky contact annealed at 700 °C.

Figure 5. Temperature-dependence of ideality factor n and barrier height $\Phi_B$ for the WC/4H-SiC Schottky contact subjected to thermal annealing at 700 °C.

Figure 6. Richardson’s plot $\ln(I_s/T^2)$ vs $1/k_BT$ for determining the effective barrier height $\Phi_B^{\text{eff}}$ and Richardson’s constant $A^{*\text{eff}}$ in the WC/4H-SiC Schottky contact annealed at 700 °C.

allows us to extrapolate the ‘effective’ values of the barrier height and of the Richardson’s constant as slope and y-intercept of a conventional ‘Richardson’s plot’ $\ln I_s/T^2$ vs $q/k_BT$.

Such a plot, reported in figure 6, provides an effective barrier height $\Phi_B^{\text{eff}} = 0.96$ eV, which can be regarded as an average barrier of the patches and is lower than the barrier height derived by the forward I–V curve at room temperature (1.05 eV). On the other hand, an effective Richardson’s constant $A^{*\text{eff}} = 4.7 \text{ A cm}^{-2} \text{K}^{-2}$ can be estimated, which is two orders of magnitude lower that the theoretical value (146 A cm$^{-2}$ K$^{-2}$). Since the y-intercept enables us to determine the product $AA^*$, this result indicates that the effective active area interested by the current transport is smaller than the entire area of the contact, as assumed in the application of the TE model.

In order to quantify the Schottky barrier inhomogeneity, it is useful to compare the plot $n T$ vs $k_BT$ with the ideal case ($n = 1$), as depicted in figure 7(a). As can be seen, the experimental data can be fitted by a straight line parallel to that of the ideal case, allowing to express the ideality factor as $n = 1 + T_0/k_BT$ and calculate the so-called ‘$T_0$ anomaly’, resulting $T_0 = 34$ K for our case. This expression for the ideality factor agrees with the Tung’s formalism for the case where the inhomogeneity can be described with a Gaussian distribution of effective barrier heights related to the low-barrier patches [32].

According to Tung’s approach, the effective barrier $\Phi_B^{\text{eff}}$ of a single low-barrier patch is related to the surrounding uniform high barrier $\Phi_B^0$ background by:

$$I_s = AA^*T^2\exp\left[-q\Phi_B^{\text{eff}}/k_BT\right]$$

allows us to extrapolate the ‘effective’ values of the barrier height and of the Richardson’s constant as slope and y-intercept of a conventional ‘Richardson’s plot’ $\ln I_s/T^2$ vs $1/k_BT$.

Such a plot, reported in figure 6, provides an effective barrier height $\Phi_B^{\text{eff}} = 0.96$ eV, which can be regarded as an average barrier of the patches and is lower than the barrier height derived by the forward I–V curve at room temperature (1.05 eV). On the other hand, an effective Richardson’s constant $A^{*\text{eff}} = 4.7 \text{ A cm}^{-2} \text{K}^{-2}$ can be estimated, which is two orders of magnitude lower that the theoretical value (146 A cm$^{-2}$ K$^{-2}$). Since the y-intercept enables us to determine the product $AA^*$, this result indicates that the effective active area interested by the current transport is smaller than the entire area of the contact, as assumed in the application of the TE model.

In order to quantify the Schottky barrier inhomogeneity, it is useful to compare the plot $n T$ vs $k_BT$ with the ideal case ($n = 1$), as depicted in figure 7(a). As can be seen, the experimental data can be fitted by a straight line parallel to that of the ideal case, allowing to express the ideality factor as $n = 1 + T_0/k_BT$ and calculate the so-called ‘$T_0$ anomaly’, resulting $T_0 = 34$ K for our case. This expression for the ideality factor agrees with the Tung’s formalism for the case where the inhomogeneity can be described with a Gaussian distribution of effective barrier heights related to the low-barrier patches [32].

According to Tung’s approach, the effective barrier $\Phi_B^{\text{eff}}$ of a single low-barrier patch is related to the surrounding uniform high barrier $\Phi_B^0$ background by:
dependence of the reverse I–V characteristics of the diodes. Also studied under reverse bias, monitoring the temperature-conduction mechanism, the WC/4H-SiC contact was found to play the experimental J-V reverse characteristics, measured from the analysis of forward I–V characteristics of figure 7(a), a good agreement with experimental curves is observed when the barrier height of 0.96 eV obtained by the Richardson’s plot of figure 6 is extrapolated for the WC/4H-SiC Schottky contact annealed at 700 °C.

\[
\Phi_{\text{BB}}^{\text{eff}} = \Phi_B^0 - \gamma_i \left( \frac{V_{\text{BB}}}{\eta} \right)^{1/3} \tag{3}
\]

where \( V_{\text{BB}} \) is the band bending and \( \eta = 4.7/\eta^2 \) SiN. The parameter \( \gamma \) takes into account the patch characteristics through the relation \( \gamma = (3\Delta R_0^2/4)^{1/3} \), where \( \Delta \) is the local deviation from the ideal barrier \( \Phi_B^0 \) and \( R_0 \) is the patch radius (assuming a circular geometry) [32]. In general, an inhomogeneous Schottky contact is characterized by a Gaussian distribution of \( \gamma_i \) parameters, whose standard deviation \( \sigma_\gamma \) is related to the standard deviation of the effective barrier distribution \( \sigma_{\Phi_{\text{BB}}} \) by the relations [32, 33]:

\[
T_0 = \frac{q^2 \gamma_0}{3k_B\gamma_0^2 V_{\text{BB}}^{1/3}} = \frac{q^2 \gamma_{\text{BB}}}{3k_B V_{\text{BB}}} \tag{4}
\]

Hence, considering the value \( T_0 = 34 \) K obtained in our case (figure 7(a)), a standard deviation \( \sigma_{\Phi_{\text{BB}}} = 0.12 \) eV can be derived, taking into account the value of \( V_{\text{BB}} \) expressed in eV. Furthermore, in an inhomogeneous Schottky contact, the ideal barrier height \( \Phi_B^0 \) can be determined as the limit to the ideal behavior (\( n = 1 \)) of the so-called Schmitsdorf’s plot (barrier height \( \Phi_B \) versus ideality factor \( n \)) [34]. In particular, from such a plot, reported in figure 7(b), it was possible to determine an ideal barrier height \( \Phi_B^0 = 1.11 \) eV for the WC/4H-SiC contact. This value corresponds to the uniform high barrier background surrounding the patches.

Therefore, it can be concluded that our inhomogeneous WC/4H-SiC Schottky contact can be described by a Gaussian distribution of low barrier patches with an average effective barrier \( \Phi_B^{\text{eff}} = 0.96 \) eV and standard deviation of \( \sigma_{\Phi_{\text{BB}}} = 0.12 \) eV, embedded in a uniform ideal barrier \( \Phi_B^0 = 1.11 \) eV. For the sake of completeness, it is worth mentioning that an electrical characterization extending to lower temperatures could highlight additional effects related to the contact inhomogeneity, as reported by Pierobon et al [35].

In order to get additional insights on the barrier height and current conduction mechanism, the WC/4H-SiC contact was also studied under reverse bias, monitoring the temperature-dependence of the reverse I–V characteristics of the diodes. It is known that the presence of interface inhomogeneities, whose presence was previously observed under forward bias for the WC/4H-SiC interface, can enhance the tunneling contribution to the reverse leakage current [36, 37]. This behavior can be described by the thermionic field emission (TFE) model [38]. In fact, since SiC diodes typically operate at high electric field under reverse bias, a thinning of the potential barrier can occur, thus enabling the electrons to tunnel through with an increase of the leakage current by many orders of magnitude [39]. Therefore, while in Si diodes the reverse current is typically described by the TE model accounting for the image force lowering, the reverse characteristics of 4H-SiC Schottky diodes is better described considering an additional tunneling contribution, that is, using the TFE mechanism [40, 41]. However, there is no consensus in literature on the model describing the reverse characteristics of 4H-SiC Schottky diodes. In fact, while some papers use the classical TFE model [34, 42], whose validity depends on doping concentration and bias range [43], other works include the image force lowering effect in the TFE model to fit the experimental data [37, 44].

In particular, taking into account the doping level and the reverse bias range of our case, the TFE (without force lowering effect) should be the most appropriate model to describe the reverse characteristics.

According to the TFE model, the current density \( J \) can be expressed as:

\[
J = \lambda^* T^2 \left( \frac{q^2 \Phi_0 E_0}{kT} \right)^{1/2} \exp \left( -\left( \frac{\Phi_B}{E_1} \right) \exp \left( \frac{V_R}{E_2} \right) \right) \tag{5}
\]

where \( E_0 = (h/4\pi) \sqrt{N_D/m^*_{\text{SiC}}} \), \( E_1 = E_0 \times \tanh \left( \frac{qE_0}{kT} \right)^{-1} \), and \( E_2 = E_0 \times \left( \frac{qE_0}{kT} - \tanh \left( \frac{qE_0}{kT} \right) \right)^{-1} \), and with \( h \) being the Planck constant, \( m^* \) the effective mass of electron and \( \varepsilon_{\text{SiC}} \) the dielectric constant of the semiconductor.

Firstly, a barrier height value of 1.11 eV was considered in equation (5), which corresponds to the ideal barrier obtained by Schmitz-Dorf’s plot of figure 7(b). However, under this assumption a significant discrepancy between the experimental reverse characteristics and the simulated curves was found for all temperatures. Similar discrepancy was found by considering the effective barrier height of 0.96 eV obtained by the Richardson’s plot of figure 6.

Hence, the barrier inhomogeneity was included in the TFE model, by considering in equation (5) the experimental temperature-dependence of the barrier height. Figure 8 displays the experimental J-V reverse characteristics, measured in the WC/4H-SiC contact annealed at 700 °C, together with the simulated curves according to TFE model including the barrier inhomogeneity. As can be seen in figure 8, a good agreement with experimental curves is observed when the barrier inhomogeneity is included in the TFE model. Specifically, the temperature-dependence of the barrier, with values derived from the analysis of forward I–V characteristics of figure 4, is

![Figure 7](https://example.com/image7.png)

**Figure 7.** (a) nkT versus kT plot expressing the deviation from the ideal case (depicted as solid line), showing the TBB anomaly; (b) \( \Phi_B \) versus \( n \) plot from which the ideal homogeneous \( \Phi_B^0 \) at \( n = 1 \) is extrapolated for the WC/4H-SiC Schottky contact annealed at 700 °C.
considered in the simulated curves reported by dashed lines in figure 8.

From our approach, we can conclude that the temperature dependence of the barrier height, as observed in the forward I-V-T curves, must be taken into account to better describe the current transport at the WC/4H-SiC by the TFE model under reverse bias.

4. Conclusions
In this work, the electrical properties of the tungsten carbide (WC) Schottky barrier on 4H-SiC have been studied. In particular, based on a set of measurements on several diodes, the contacts showed a nearly ideal behavior ($n = 1.06$) and a narrow distribution of the barrier height values upon annealing at 700 °C.

The temperature dependent I-V characterization of the annealed contact revealed an increase of the barrier height and a decrease of the ideality factor with increasing measurement temperature, thus indicating a lateral inhomogeneity of the WC/4H-SiC Schottky contact. This behavior was described with Tung’s model on inhomogeneous barriers. Noteworthy, the temperature dependence of the reverse leakage current could be well described by including the temperature dependent barrier height, measured in forward bias, in the classic thermionic field emission formalism.

The low value of the barrier height (1.05 eV) makes such a WC contact an interesting candidate to reduce the conduction losses in 4H-SiC Schottky diodes. Moreover, the results are useful to predict the behavior of WC/4H-SiC Schottky diodes under operative conditions.

Acknowledgments
The authors would like to acknowledge F Giannazzo (CNR-IMM) for fruitful discussions on these experiments and related results. Part of this research activity has been carried out in the framework of the European ECSEL JU project REACTION (Grant Agreement No. 783158), using the facilities of the Italian Infrastructure Beyond-Nano Upgrade.

References
[1] Kimoto T and Cooper J A 2014 Fundamentals of Silicon Carbide Technology (Singapore: Wiley)
[2] Baliga B J 2005 Silicon Power Devices (Singapore: World Scientific)
[3] Roccaforte F, Brezeanu G, Gammon P M, Giannazzo F, Rascon S and Saggio M 2018 Schottky contacts to silicon carbide: physics, technology and applications Advancing Silicon Carbide Electronics Technology I, ed K Zekentes and K Vasilievsky (Millersville, MD: Materials Research Forum LLC) pp 127–90
[4] Yakimova R, Hemmingsson C, MacMillan M F, Yakimov T and Janzén E 1998 J. Electron. Mater. 27 871
[5] Perrone D, Naretto M, Ferrero S, Scaltrito L and Pirri C F 2009 Mater. Sci. Forum. 647 615–17
[6] Gora V E, Chawanda C, Nyamhere C, Auret F D, Mazunga F, Jaure T, Chibaya B, Omosofo E, Danga H T and Tunhuma S M 2018 Physica B 535 333
[7] Gulnahr M 2014 Superlattices Microstruct. 76 394
[8] Roccaforte F, La Via F, Di Franco S and Raineri V 2003 Microelectron. Eng. 70 524
[9] Weiss R, Frey L and Ryssel H 2001 Appl. Surf. Sci. 184 413
[10] Berthou M, Godignon P, Montserrat J, Millan J and Planson D 2011 J. Electron. Mater. 40 2355
[11] Zhang T, Raynaud C and Planson D 2019 Eur. Phys. J. Appl. Phys. 85 10102
[12] Renz A B et al 2020 Appl. Phys. 127 025704
[13] Stöber L., Konrath J P, Patocka F, Schneider M and Schmid U 2016 IEEE Trans. Electron Dev. 63 578
[14] Knoll L, Teodorescu V and Minamisawa R A 2016 IEEE Trans Electron Dev. 37 1318
[15] Mattheiss L F and Hamann D R 1984 Phys. Rev. B 30 1731
[16] Seng W F and Barnes P A 2000 Mater. Sci. Eng. B 2 B 13
[17] Pereira da Cunha A, Walker T D, Sims R A, Chhaya B, Muntele C I, Muntele I, Elsamadicy A and Ila D 2007 Nucl. Instrum. Methods Phys. Res. B 261 561
[18] Roderick E H and Williams R H 2006 Semiconductor Physical Electronics 2nd edn (New York: Springer)
[19] Werner J H and Güttler H H 1991 J. Appl. Phys. 69 1522
[20] Brezeanu G, Pristavu G, Draghić F, Badila M and Pascu R 2017 J. Appl. Phys. 122 084501
[21] Roccaforte F, La Via F, Raineri V, Pierobon R and Schmid U 2003 J. Appl. Phys. 93 9137
[22] Gammon P M et al 2013 J. Appl. Phys. 114 223704
[23] Pérez R, Mestres N, Montserrat J, Tournier D and Godignon P 2005 Phys. Status Solidi a 202 692
[24] Ferhat Hamida A, Ouennoughi Z, Selall A, Weiss R and Ryssel H 2008 Semicond. Sci. Technol. 23 045005
[25] Dong S X, Bai Y, Tang Y D, Chen H, Tian X L, Yang C Y and Liu X Y 2018 Chin. Phys. B 27 097305
[26] Tung R T 1992 Phys. Rev. B 45 13509
[27] Vivona M, Greco G, Giannazzo F, Lo Nigro R, Rascunà S, Saggio M and Roccaforte F 2014 Semicond. Sci. Technol. 29 075018
[28] Mott N F 1939 Proc. R. Soc. A 171 27
[29] Liu Y, Guo J, Zhu E, Liao L, Lee S L, Ding M, Shakir I, Gambin V, Huang Y and Duan X 2018 Nature 557 696
[30] Davydov S Y 2007 Semiconductors 41 696
[31] Fuji R, Gotoh Y, Liao M Y, Tsuji H and Ishikaw J 2006 Vacuum 80 832
[32] Sullivan J P, Tung R T, Pinto M R and Graham W R 1998 J. Appl. Phys. 70 7403
[33] Iacolano F, Roccaforte F, Giannazzo F and Ranieri V 2007 Appl. Phys. Lett. 90 092119
[34] Schmitsdorf R F, Kampen T U and Mönch W 1997 J. Vac. Sci. Technol. B 15 1221
[35] Pierobon R, Meneghesso G, Zanoni E, Roccaforte F, La Via F and Raineri V 2005 Mater. Sci. Forum. 933 483–85
[36] Bhatnagar M, Baliga B J, Kirk H R and Rozgonyi G A 1996 IEEE Trans. Electron. Dev. 43 150
[37] Zheng L, Joshi R P and Fazi C 1999 J. Appl. Phys. 85 3701
[38] Padovani F A and Stratton R 1966 Solid-State Electron. 9 695
[39] Crofton J and Sriram S 1996 IEEE Trans. Electron. Dev. 43 2305
[40] Treu M, Rupp R, Kapels H and Bartsch W 2001 Mater. Sci. Forum. 353–356 679
[41] Hatakeyama T and Shinohe T 2002 Mater. Sci. Forum. 389–393 1169
[42] Hatakeyama T, Kushibe M, Watanabe T, Imai S and Shinohe T 2003 Mater. Sci. Forum. 831 433–36
[43] Latreche A 2019 Semicond. Sci. Technol. 34 055021
[44] Okino H, Kameshiro N, Konishi K, Shimaand A and Yamada R 2017 J. Appl. Phys. 122 235704