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Cleiton Marques, Alain Michez, Frédéric Wrobel, S. Kuboyama, Frédéric Saigné, et al.. Physical Explanation for the Higher Sensitivity to Ion-Induced Burnout in SiC Schottky Diodes Compared to Si Schottky Diodes. RADiation Effects on Components and Systems (RADECS), Sep 2024, Maspalomas, Canary Islands, Spain. hal-04715410

HAL Id: hal-04715410

<https://hal.science/hal-04715410v1>

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Document version: Post-print version (Final draft)

Please cite the original version:

C. M. Marques *et al.*, "Physical Explanation for the Higher Sensitivity to Ion-Induced Burnout in SiC Schottky Diodes Compared to Si Schottky Diodes," European Conference on RADiation Effects on Components and Systems (RADECS), 2024.

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Physical Explanation for the Higher Sensitivity to Ion-Induced Burnout in SiC Schottky Diodes Compared to Si Schottky Diodes

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Abstract

SiC has a highly critical electric field, which is promising for power applications. However, by investigating the underlying physical phenomenon, we show that this property is also the main reason for its sensitivity to SEB.

Index Terms

Silicon carbide device, SiC, Schottky diode, TCAD, ECORCE, thermal runaway, critical electric field.

I. INTRODUCTION

Wide bandgap semiconductors, such as silicon carbide (SiC) power devices, have garnered significant interest for applications in harsh environments, particularly in space, due to their superior electrical and thermal properties compared to traditional silicon-based devices [1, 2]. The critical electric field strength of SiC is about 10 times higher than that of silicon. This allows for the use of a voltage-blocking layer (n-epitaxial layer) approximately 10 times thinner and has about 10 times higher donor density for a given breakdown voltage compared to silicon devices. This pushes forward the limits reached by Si-based power electronics, providing devices able to operate in high-temperature, high-power and high-frequency regimes.

However, the susceptibility of SiC Schottky barrier diodes (SBDs) to heavy ions is recognized as a critical issue due to Single Event Burnout (SEB) and large leakage current. Several studies have attempted to explicate these failures, but the explanations remain controversial. S. Kuboyama et al. [3] was the first one to identify the thermal runaway process as a mechanism responsible for the susceptibility of SiC SBDs to heavy ions. A. Javanainen et al. [4] suggested that the damage was induced by high temperatures exceeding the melting point of SiC (3100 K) at the Schottky contact, resulting from enhanced current flow along the ion track attributable to impact ionization. A. Akturk et al. [5] reported that SEB in SiC power devices arises from impact ionization and fast thermal transients, which is completely different from the conduction of parasitic bipolar transistors in silicon power devices. C. Martinella et al. [6] attributed the degradation in leakage current to ion-induced, highly localized energy pulses in SiC power MOSFETs and junction barrier Schottky (JBS) diodes. Finally, C. Peng [7] indicated that heavy ion incidence raises the lattice temperature within SiC devices, with higher bias voltages leading to melting.

As described by these authors, the temperature can reach the SiC melting temperature under high biases applied during irradiation. However, even at lower biases, the temperature increase can potentially damage the Schottky junction due to the lower melting point of Schottky metals, thereby creating leakage paths [4-7].

Despite previous studies, a comprehensive understanding of the primary mechanism responsible for heavy ion-induced degradation in SiC devices is still missing. This work addresses this gap by demonstrating that the high critical electric field, a key advantage of SiC devices, is also the primary factor behind their susceptibility to heavy ion irradiation. To achieve this, we used TCAD simulations to model the physical mechanisms, comparing the behavior of SiC and Si Schottky diodes.

This work received funding from the European Union's Horizon 2020 research and innovation program under grant agreement N° 101008126.

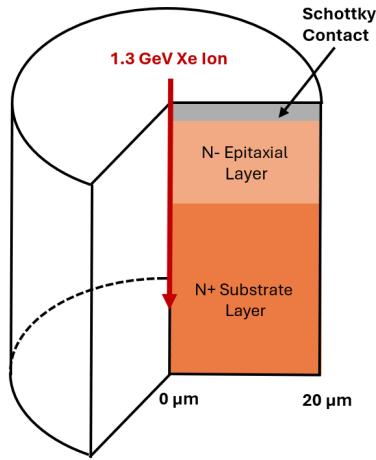


Fig. 1. Cylindrical geometry and structure of the SBD used for simulations.

II. SCHOTTKY DIODE MODELING

Schottky diodes typically have a similar layout. Devices consist of a metal-semiconductor contact (anode) made of platinum, gold, aluminum, titanium or nickel, and an n-type substrate [8]. Fig. 1 illustrates the structure of these devices. The cylindrical or 3D geometry is essential for electrical and thermal coupled simulations, as it enables axial-symmetric charge deposition along the ion track and supports the quantitative analysis of radial heat flow from the track.

Modern SiC SBDs have a structure called as Junction Barrier Schottky (JBS), where p+ regions are placed periodically at the contact to reduce the thermionic emission current under reverse bias conditions. However, their sensitivity is experimentally demonstrated to be similar to the structure showed in Fig. 1 [7].

To model the Schottky diodes, the ECORCE TCAD tool was used [9]. ECORCE applies a drift-diffusion model coupled with the heat equation, allowing for thermodynamic simulations that include lattice temperature. It also features a dynamic mesh generator that optimizes mesh distribution for all modeling steps, providing a high-quality grid, independent of the TCAD user. These capabilities are crucial for understanding the underlying mechanisms while maintaining efficient use of computational resources. This is only available using ECORCE. The electrical and thermal models applied in our simulations align with those utilized in previous studies [10]. Table I provides a detailed overview of these models. The bandgap energy, effective density of states, and intrinsic carrier density are determined by the crystalline material's energy band structure. However, the model expressions do not cover the temperature range up to the melting point of SiC. Considering that they are modeled by simple functions of temperature, they can then be easily extrapolated. This approach has already been validated in previous works [10]. It is important to note that the models must produce values that prevent convergence problems or mathematical issues, generating physically plausible results for meaningful analysis.

The primary goal of this work is to show the main physical mechanisms responsible for heavy ion-induced degradation in SiC while explaining why such degradation is less severe in Si-based devices. To achieve this goal, we modeled Si and SiC SBDs. The parameters related to the device structure are available in Table II. These parameters are chosen to get an electric field in the EPI layer at the lower limit of the critical electric field when biased at nominal conditions: -600 V for the SiC diode and -200 V for the Si diode.

To evaluate the diode response under ion irradiation, a 1.3 GeV Xe ion was injected in the devices, which is widely used in facilities and provides a high Linear Energy Transfer (LET). The ion range, the LET profile, and ion track model follow what was proposed in [10]. It considers the variations in stopping power between Si and SiC. In SiC the initial LET is 61.54 MeV.cm²/mg with a range of 64.4 μm, whereas Si have an initial LET of 58.93 MeV.cm²/mg with a range of 94.5 μm.

III. MAIN MECHANISM OF THERMAL RUNAWAY

During the ion impact, electron-hole pairs are generated along the ion track as illustrated in Fig. 2. At the beginning of the ion track, the electric charge is neutral along the ion path. Because of the electric field applied in the EPI layer, the electrons and holes move in opposite directions. Thus, a positive charge appears near the Schottky contact since electrons are pushed toward the volume of the device and holes cross the Schottky contact at a speed equal to the

TABLE I
ELECTRICAL AND THERMAL MODELS USED FOR SiC [10].

Parameter	Equation	Unit	Remarks
Bandgap energy [11]	$E_g(T) = 3.27 - 6.5 \cdot 10^{-4} \left(\frac{T^2}{T+1300} \right)$	eV	Negative at $T > 6100$ K. Modified to be saturated at $T > 5000$ K with a value of 0.8 eV
Effective density of states in the conduction band [11]	$N_c(T) = 3.25 \cdot 10^{15} (T^{1.5})$	cm^{-3}	
Effective density of states in the valence band [11]	$N_v(T) = 4.8 \cdot 10^{15} (T^{1.5})$	cm^{-3}	
Intrinsic carrier density	$n_i(T) = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2kT}\right)$	cm^{-3}	
Thermal conductivity [11]	$K(T) = \frac{611}{T^{-115}}$	$\frac{\text{W}}{\text{cm K}}$	Values for 6H-SiC are usually used. Experimental data available up to 2300 K.
Electron mobility	See reference [12]		Experimental data available up to 800 K.
Hole mobility	See reference [13]		Experimental data available up to 580 K.
Field dependence of mobility	See reference [14]		Experimental data available up to 730 K for electrons. The same applied for holes.
Impact ionization	See reference [15]		In more details in the section IV.

TABLE II
PARAMETERS OF SBD STRUCTURES.

Parameter		Si	SiC
n- epitaxial layer	thickness (μm)	12.0	3.7
	doping (cm^{-3})	$1 \cdot 10^{15}$	$1 \cdot 10^{16}$
n+ substrate layer	thickness (μm)	108.0	116.3
	doping (cm^{-3})	$1 \cdot 10^{19}$	$1 \cdot 10^{19}$

recombination speed (2.57×10^6 for electrons and 1.93×10^6 cm/s for holes). This charge increases the electric field close to the Schottky contact and reduces it in the volume of the EPI layer (Fig. 3).

When the electric field reaches the critical electric field, the impact ionization is triggered, and additional electron-hole pairs are generated close to the Schottky contact (Fig. 4). Then an increase of temperature appears in the burnout point defined in Fig. 4. After a while, equilibrium is established between the electric field and the enhanced electrical conductivity caused by the electron-hole pairs generated near the Schottky contact. The electric field stabilizes, maintaining this state until all pairs generated by the ion are either collected or recombined.

Fig. 5 shows the SiC properties compared to traditional Si devices. The main difference between the SiC and the Si Schottky diodes is the electric field for which the impact ionization is triggered. For the SiC Schottky diode, it is triggered at 3 MV/cm while it is triggered at 0.3 MV/cm for the Si. So, there is a factor of 10 between the electric field values. Of course, the electric field in the diode will exceed the critical electric field since the equilibrium between electric field and electrical conductivity will be reached at the Schottky contact. The power heat density (Wj) induced by joule effect is given by the product of the electric field (E) by the current density (J). Since J is proportional to E, the power heat density is roughly proportion to E^2 . As a result, it will be approximately 100 times higher in SiC than in Si at the point close to the Schottky contact.

IV. TCAD MODELING RESULTS

This section presents the modeling results comparing the behavior of SiC and Si Schottky diodes under heavy ion irradiation, focusing on the key physical mechanisms responsible for device degradation.

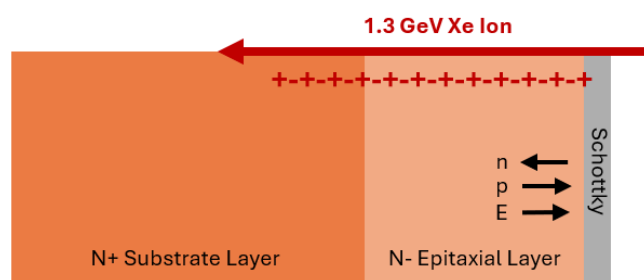


Fig. 2. First step: generation of electron-hole pairs and displacement of charges depending on the electric field.

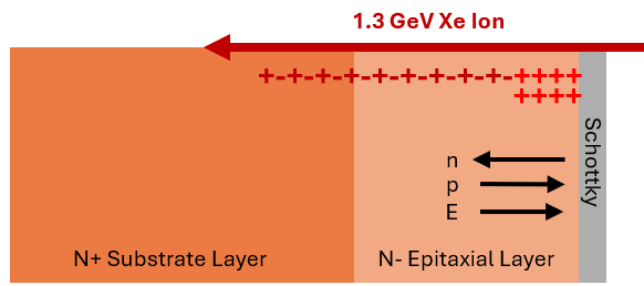


Fig. 3. Second step: charges are separated by the electric field, a high positive charge appears at the contact → the electric field in the EPI layer is reduced → the electric field increases near the Schottky contact → it speeds up the pair separation at this point.

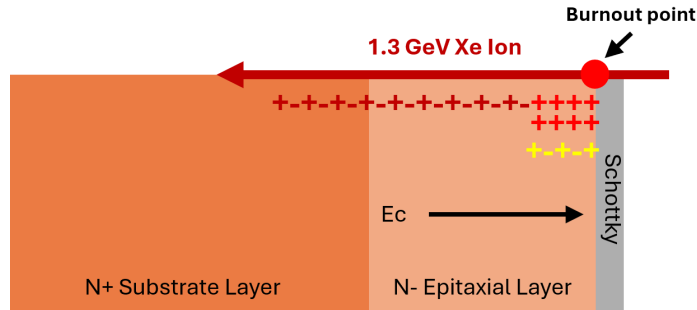


Fig. 4. Third step: the impact ionization is triggered. Additional pairs are generated by impact ionization (yellow) → the electric field is limited when the impact ionization rate is high enough.

A. Impact ionization modeling

In order to effectively apply the main mechanisms presented in the previous section, it is important to understand how the impact ionization on Si and SiC was modeled. Y. Okuto [16] highlighted that for Si the ionization coefficients are functions of electric field strength, position within the junction and temperature. Based on this, we can calculate the impact ionization by:

$$\alpha = a_{300}[1 + c(T - 300)] \varepsilon \exp \left[- \left[\frac{b_{300}[1 + d(T - 300)]}{\varepsilon} \right]^2 \right] \quad (1)$$

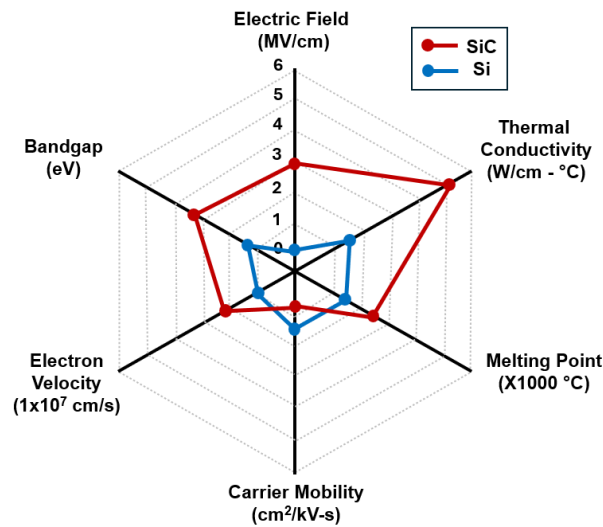


Fig. 5. Chart to compare the Si and SiC properties.

where T is the temperature in kelvin and is the modulus of the electric field. The a300, b300, c and d are constants listed in Table III. a300 and b300 are fitted based on 300K of temperature.

TABLE III
IONIZATION COEFFICIENTS FOR SI AND SiC USED IN ECORCE [15, 16]

Material	Parameter	Value		Unit
		e	h	
Si	a_{300}	0.426	0.243	V^{-1}
	b_{300}	$4.81 \cdot 10^5$	$6.53 \cdot 10^5$	V/cm
	c	$3.05 \cdot 10^{-4}$	$5.35 \cdot 10^{-4}$	K^{-1}
	d	$6.86 \cdot 10^{-4}$	$5.67 \cdot 10^{-4}$	K^{-1}
SiC	a	$\gamma(1.76 \cdot 10^8)$	$\gamma(3.41 \cdot 10^8)$	cm^{-1}
	b	$\gamma(3.30 \cdot 10^7)$	$\gamma(2.5 \cdot 10^7)$	V/cm

The ratio of ionization as a function of the electrical field strength obtained using the expression (1) for Si presented a very good agreement (4% of error) to most practical devices evaluated [16]. For SiC devices, T. Hatakeyama [15] shows that the ionization coefficients need also to include the doping density of the diode layers. Then the impact ionization can be modeled by:

$$\alpha = a \gamma \exp\left(\frac{-b\gamma}{F}\right) \quad (2)$$

$$\gamma = \frac{\tanh\left(\frac{\hbar\omega_{op}}{2k_B T_0}\right)}{\tanh\left(\frac{\hbar\omega_{op}}{2k_B T}\right)} \quad (3)$$

where $\hbar\omega_{op}$ is the optical phonon energy and can be extracted by fitting the temperature dependence of breakdown voltage vs. doping density characteristics () [15]. The a and b are constant with values presented in the Table III. T and T0 are temperature parameters. Finally, using Equation (1) for Si and Equations (2) and (3) for SiC, we can calculate the total impact ionization induced for e-h carries:

$$\alpha_{tot} = \alpha_e e V_e (\alpha_h h V_h) \quad (4)$$

where e is the electron density, h the hole density, and V_{e-h} are the e-h mobility multiply for the modulus of the electric field.

It is important to note that for both Si and SiC, we use the same Equation (4). To demonstrate the results of the ionizing impact, Fig. 6 displays the modeling performed with ECORCE. It shows that the evolution of impact ionization rate in Si, for an electric field range between 0 and 1 MV/cm, is similar than the one in SiC, for a range between 0 and 6 MV/cm.

B. Thermal runaway results

To address the main mechanisms discussed in the Section III, Fig. 7 presents the maximum temperature, electric field, and thermal Joule power density as a function of time for -600 V biased SiC diode (red curves) and -200 V biased Si diode (blue curve). Fig. 7a shows the calculated values of power heat density (Wj) for both diodes, while the Fig. 7b present the electric field in time that reaches its maximum (E_{max}), as follows:

- at t = 547 ps, E_{max} = 0.88 MV/cm, Wj = 3.75 W μm^{-3} for the Si diode.
- at t = 59 ps, E_{max} = 6.2 MV/cm, Wj = 613 W μm^{-3} for the SiC diode.

These values confirm the previous explanation for burnout sensitivity of SiC diode. We can conclude that, for the Si Schottky diode, the impact ionization acts as a protection since it keeps the electric field low and reduces the Joule (heating) effect. For the SiC Schottky diode, when the impact ionization is triggered, it is too late: the electrostatic potential energy that is applied on carriers generated by impact ionization is too high, and the burnout occurs.

It is well known that reducing the bias applied during irradiation mitigate the burnout, so we also display results for the -200 V biases SiC diode (green curves). The SiC and Si diodes have differences in the structure: the EPI layer thickness and doping. To highlight these differences effects, we also display the results for an SiC diode using the same structure parameter than the Si diode: 12 μm thickness and 1015 cm^{-3} doping for the EPI layer (orange curve).

In Fig. 7c. we can observe three operational regions. When the temperature exceeds the melting temperature of SiC we will observe a burnout. If the temperature is between the melting temperature of SiC and the melting

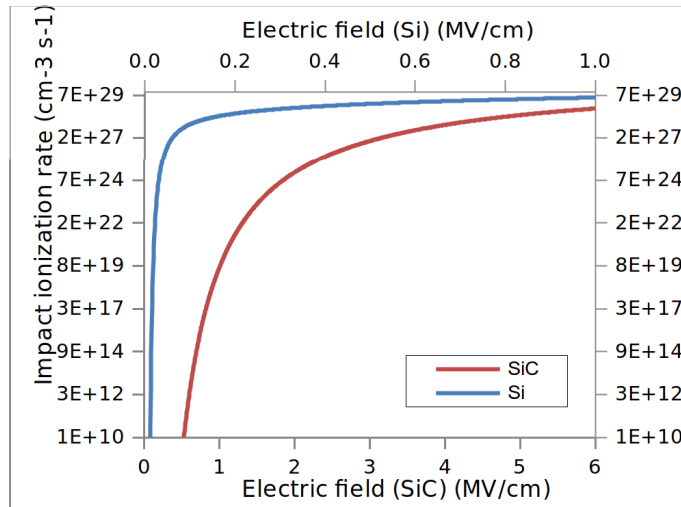


Fig. 6. Impact ionization rate as a function of electric field for Si (blue curve) and SiC (red curve).

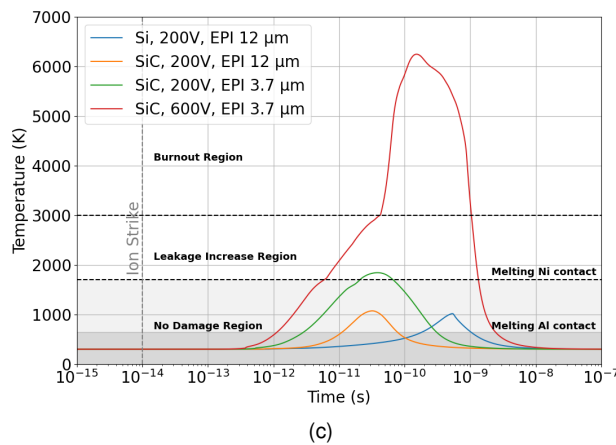
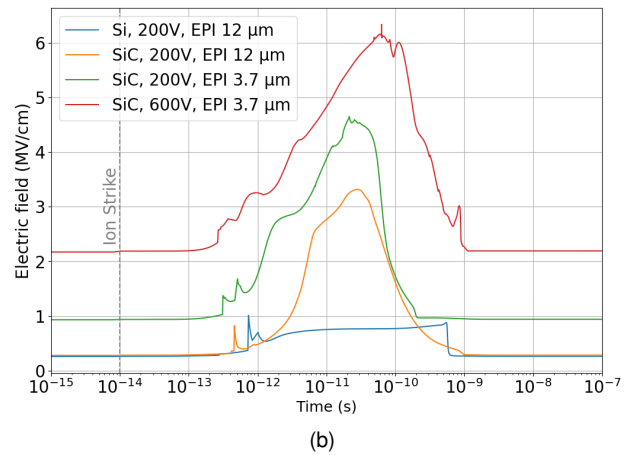
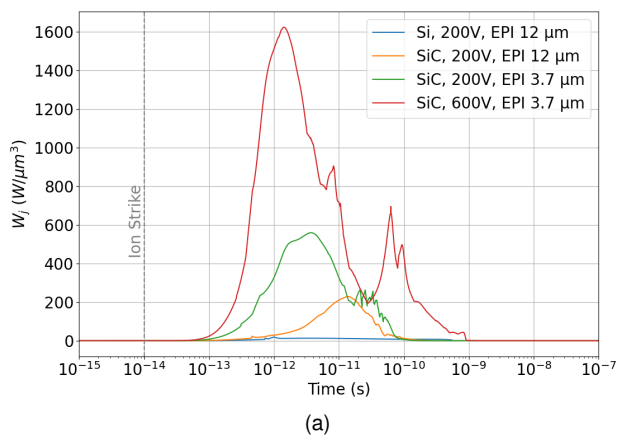


Fig. 7. Simulation results as a function of time: (a) Maximum power heat density, (b) Maximum electric field, and (c) Maximum temperature.

temperature of Schottky contact material, damage will probably occur at the contact, leading to increase of leakage current. Finally, if the temperature remains below the melting point of the Schottky contact material, no damage should occur. The melting temperature limit of the Schottky contact depends on the specific material used.

The temperature for the -200 V biased SiC diodes (green and orange curves) is lower than the one for the -600 V biased SiC diode (red curve) but still high enough to induce damages and induce increase in leakage current (aluminum material). We can observe that both the maximum electric field and the maximum power heat density are also high. This sensitivity of SiC Schottky diodes at low bias voltage has already been highlighted by experiments [3]. However, for a SiC diode using the same structural parameters of the Si device (12 μm thickness and 10^{15} cm^{-3} doping) and considering the many advantages of SiC material, we expected that no damage could occur. It appears that even with these reduced constraints, the temperature still reaches a value that can damage the Schottky material. Finally, as expected, the Si diode shows the lowest temperature, but it occurs later and shorter. We can expect reduced damages even if the temperature is still in the region where leakage increase will occur.

All these effects are consistent with the trends that have been discussed in the literature considering experimental data [1-7]. However, these trends represent only secondary effects generated by the critical electric field. To our knowledge, the main mechanism described in this paper has never been mentioned before.

C. Analysis of the Band-to-Band Tunneling

Another effect that plays a significant role in SiC Schottky diodes and still unresolved is the Band-to-Band tunneling (BBT) [17]. The BBT process occurs when carriers tunneling directly from the valence band to the conduction band, bypassing the traditional thermionic emission mechanism. Normally this effect is dependent on the generation of carriers during the ionization process, together with the applied electric field. However, for SiC SBD, due to the critical electric field, tunneling can occur even without carriers generation by the ionization. In this sense, Fig. 8 presents the correlation between the ionizing impact and BBT, demonstrating the different impacts depending on the structure of the Schottky diodes.

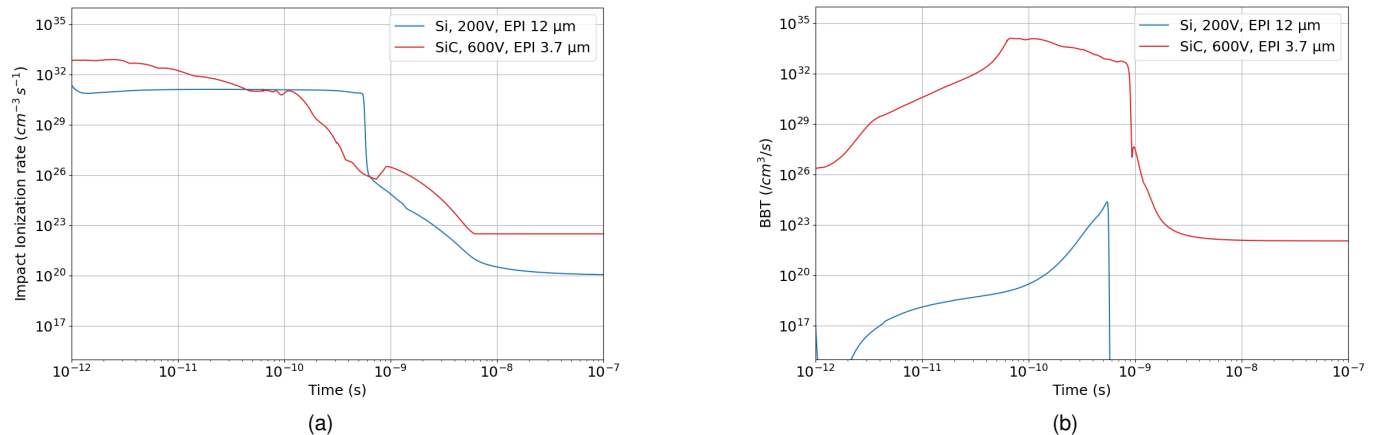


Fig. 8. Impact of Band-to-Band tunneling in Schottky diodes: (a) Impact ionization rate as a function of time and (b) Band-to-Band tunneling as a function of time.

Fig. 8(a) illustrates the maximum impact ionization rate, which coincides with the electric field peak for both Si (547 ps) and SiC (59 ps) diodes. This synchronization of impact ionization rate, the electric field, and the maximum BBT indicates that the peak of carrier generation and carries tunneling occurs when the electric field intensity is at its highest.

However, Fig. 8(b) highlights a notable difference in the behavior of BBT after this peak event. In the Si diode, BBT quickly reduces following the maximum impact ionization rate, which corresponds with the reduction in electric field strength and the subsequent stabilization of the diode. This rapid decline in BBT reflects a self-limiting mechanism in Si devices where impact ionization temporarily increases the carrier density but does not sustain high BBT rates due to the lower electric fields.

In contrast, the SiC diode exhibits a persistent and elevated BBT rate even after the impact ionization peak. This sustained BBT can be attributed to the higher critical electric field inherent in SiC devices and the elevated temperature conditions that are reached during the ionization. The high electric field in SiC maintains the conditions necessary for BBT, leading to continuous tunneling current that exacerbates leakage and increases the likelihood of thermal runaway, which lead to the burnout.

To further understand the interplay between temperature and these mechanisms, Fig. 9 provides an analysis of the impact ionization rate and BBT as functions of temperature. Fig. 9(a) shows that as the impact ionization rate decreases with increasing temperature, the thermal energy input continues to escalate. This reduction in impact ionization is expected because thermal agitation at higher temperatures disperses the carrier energy, reducing the likelihood of the high-energy collisions necessary for ionization.

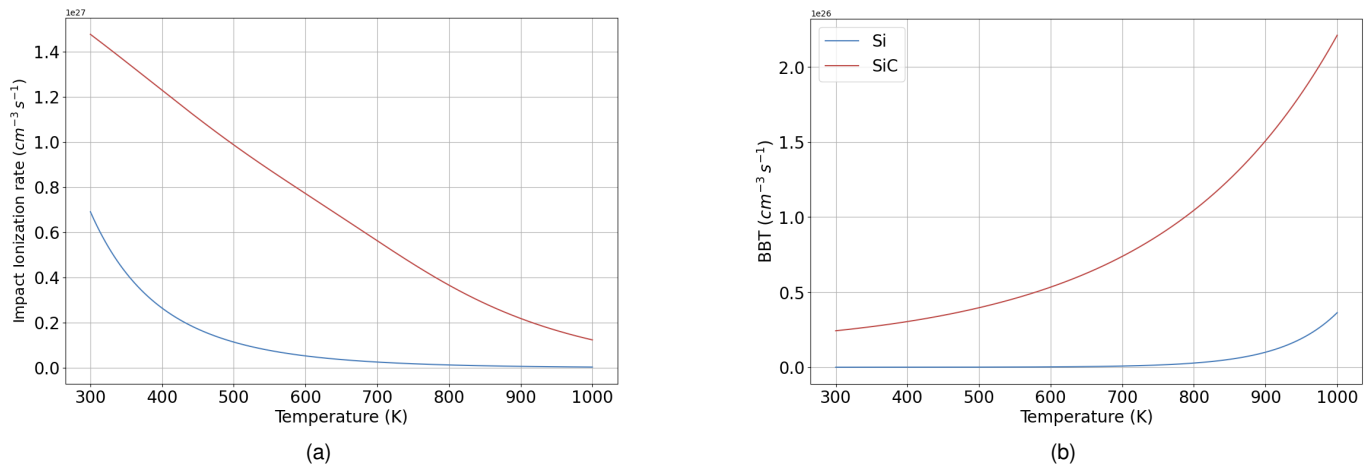


Fig. 9. Impact of the Temperature in Band-to-Band tunneling: (a) Impact ionization rate as a function of temperature and (b) Band-to-Band tunneling as a function of temperature.

V. CONCLUSION

By comparing the physical mechanisms in SiC and Si Schottky diodes through TCAD, this work shows that the critical electric field is the main mechanism responsible for SiC susceptibility under heavy ion irradiation. For the Si Schottky diode, impact ionization acts as a safeguard by maintaining a low electric field and reducing the Joule effect. In the SiC Schottky diode, once impact ionization starts, the electrostatic potential energy is too high, and the burnout is triggered.

The analysis of BBT highlights that it plays a crucial role in the SiC Schottky diodes, distinguishing them significantly from Si diodes. Unlike Si diodes, where BBT diminishes rapidly after impact ionization, SiC diodes exhibit substantial and sustained BBT even after the peak impact ionization event. This persistent BBT in SiC is primarily driven by the high electric fields inherent to SiC, which continuously sustain the conditions necessary for tunneling. In SiC, the critical electric field is much higher than in Si, allowing the diode to maintain a high tunneling rate even in the absence of new carriers generated by ionization. This prolonged BBT leads to continuous leakage current, making SiC diodes vulnerable to thermal runaway.

It can be assumed that similar effects may occur in other wide-bandgap semiconductors. However, properties such as high thermal conductivity and mobility laws may mitigate this issue.

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