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Enhanced Non-Uniformity Modeling of 4H-SiC Schottky Diode Characteristics Over Wide High Temperature and Forward Bias Ranges

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ABSTRACT A practical model, adequate for full reproduction of inhomogeneous Schottky diodes' forward characteristics over wide high-temperature and bias ranges, is proposed. According to this *p*-diode model, the Schottky contact current is considered to flow through *m* parallel-connected internal diodes, each with stable, constant barrier height and specific series resistance (both main model parameters). The value of *m*, required to reproduce the entire electrical forward behavior of a non-uniform Schottky contact, is directly connected to a particular model parameter (p_{eff}), used to define the inhomogeneity degree. The *p*-diode model was tested on forward characteristics measured for both Ni and commercial Ti Schottky diodes on 4H-SiC, which exhibited varying degrees of inhomogeneity. Excellent replication of experimental curves was achieved for all investigated samples, even those with obvious irregularities, such as "humps", explained in the model by the series resistances' influence. In the case of m = 1, the proposed model does not produce identical results with the conventional model of a homogeneous Schottky contact if $p_{eff} \neq 0$. The value of this parameter indicates how much of an inhomogeneous contact's area is essentially used for current conduction.

INDEX TERMS Schottky diode, parallel conduction, inhomogeneity, non-uniformity parameter, silicon carbide.

I. INTRODUCTION

Modeling the inhomogeneous Schottky interface usually assumes the presence of multiple tiny zones (patches) with different barrier heights on the contact surface, which contribute variably to the total current according to the thermionic emission transport mechanism [1]–[19]. This parallel conduction theory is, thus, the cornerstone of all current non-uniformity models [3]–[13]. The most prominent assumes a Gaussian distribution of patches on a Schottky contact's surface [1], [5], [6], [12], [14]. While this approach was proven adequate for modeling devices over limited temperature ranges, it was quickly demonstrated that, at cryogenic temperatures, it is "in significant error" [7]. In order to explain these discrepancies, Tung introduced the "pinch-off" effect which accounted for zones with areas lower than the space charge region on the Schottky contact and offered a perfected model equation.

Currently, almost all literature contributions pertaining to non-uniform contacts adhere to either one of these approaches. However, with the popularization and rapid development of wide-bandgap Schottky diodes, the maximum operating temperature for these devices was extended to well over the limits of silicon, allowing assessment of electrical behavior over very high domains.

Under these conditions, the attempt to characterize devices at elevated temperatures with the devoted models has revealed glaring limitations in practicality and parameter interpretation [1], [3], [8]–[11], [13]. Specifically, it was empirically determined that, for wide enough investigated temperature intervals, the parameters produced by Tung's model have important variations and are only locally impactful, encumbering the extraction and deconvolution processes. Furthermore, the "pinch-off" effect alone is unable to explain Schottky structure ideality factors above 1.20 [13], leading to the need to consider multiple divergent distributions of patches [10] or limiting the fitting process to only the exponential portion of forward curves [9].

In order to offer an application-oriented solution for modeling high-temperature-capable Schottky diodes, we've also introduced a model based on the well-established parallel conduction macroscopic concept which assumes current flow through discrete diode-patches. It successfully fitted the exponential portion of inhomogeneous Schottky diodes' forward behavior over wide ranges [3], [4]. A comparative evaluation of this model and the Gaussian distribution approach was presented in [16], proving the former's adequacy for wide-temperature-range characterization.

In this article, we propose essential extensions to our previous model in order to enable it to fully reproduce experimental Schottky diode forward characteristics. By considering the parallel-patches' resistive effects, it is able to account for bias-dependent inhomogeneity impact. Additionally, it assumes regular ideality factor variations under 1.03 for each component diode, minimizing the number of required parameters.

II. MODEL

Our proposed *p*-diode model considers that the total forward current (I_F) flows through m ideal parallel connected Schottky diodes, with the following voltage (V_F) variation:

$$I_F = \sum_{i=1}^{m} I_{F,i} = \sum_{i=1}^{m} I_{S,i}\left[\exp\left(\frac{V_F - R_{S,i}I_{F,i}}{nV_{th}}\right) - 1\right], \quad (1)$$

where $I_{S,i}$ is saturation current:

$$I_{S,i} = A_n A_S T^2 \exp\left(\frac{-\Phi_{Bn,i}}{V_{th}} - p_{eff,i}\right). \quad (2)$$

A_n is Richardson's constant (146 A/K^2cm^2 for 4H-SiC), A_S is the nominal Schottky contact area, and V_{th} is the thermal voltage. Each parallel diode has a specific effective barrier height ($\Phi_{Bn,i}$) and a series resistance ($R_{s,i}$). $p_{eff,i}$ are non-uniformity parameters which quantitatively assess the Schottky contact inhomogeneity degree [3]. Saturation currents together with associated series resistances can be determined, for some of the parallel diodes using the Cheung method [18]. Linear regressions of $\ln(I_{S,i})$ as functions of temperature should be performed in order to deconvolute the values of $\Phi_{Bn,i}$ and $p_{eff,i}$.

It should be noted that our proposal considers as distinctive, to the overall Schottky diode, a quasi-constant ideality factor (n), with a value close to unity (a maximum up to 1.03, due to effects such as image force lowering [7], [8], [13]). An n noticeably above this limit would indicate non-uniformity effects within the associated patch itself, which contradicts model premises.

While a microscopic-oriented approach would impose that m is the total number of zones on the inhomogeneous contact [7], our concept is focused on practical device behavior. As such, m is considered the lowest number of regions on the contact surface, with different Schottky barrier heights, which is sufficient to account for most of the non-uniform device's forward current.

Specifically, $p_{eff,i}$ indicates how much the area of diode i deviates from A_S [3], [4], with higher values corresponding to smaller surfaces. Therefore, diodes with high p_{eff} can only contribute significant current if their specific barrier height is low. Furthermore, $R_{S,i}$ is also proportional with $p_{eff,i}$, limiting $I_{F,i}$ at high bias voltages. As temperature increases, it is expected that conduction will be overtaken by diodes with lower p_{eff}. In order to contain only terms that appreciably influence overall current, (1) only considers zones which have their parameters sortable in a specific way: descending in respect to $p_{eff,i}$ and $R_{S,i}$, and ascending in respect to $\Phi_{bn,i}$. Contact regions which cannot be classified in such a manner aren't impactful to conduction. Thus, distinctive to our proposed *p*-diode model, the value of m is closely tied to $p_{eff,i}$ (and, implicitly, $R_{S,i}$) distribution, over the temperature and forward bias ranges of interest. The model is operational especially in the elevated temperature domain at which the "pinch-off" effect is negligible [3], [13].

If a single term ($m = 1$) is sufficient, the expression reverts to the conventional thermionic emission equation, corresponding to a uniform Schottky contact, with a temperature-independent barrier height and constant quasi-unitary ideality factor. In this case, from (1), a simplified expression is obtained:

$$I_F \cong A_n A_S T^2 \exp\left(\frac{-\Phi_{Bn}}{V_{th}} - p_{eff}\right)\left[\exp\left(\frac{V_F - R_S I_F}{nV_{th}}\right) - 1\right]. \quad (3)$$

Parameterizing a practical inhomogeneous Schottky diode using the proposed *p-diode* model should consider setting a fitting accuracy threshold between experimental and model-calculated forward curves. Goodness-of-fit can be quantitatively assessed through the coefficient of determination (R^2). It provides a measure of how well experimental data are replicated by the model, based on the proportion of total variation of outcomes explained by the model [13]. In this work, when modeling our experimental samples, m was increased until R^2 exceeded the value of 99.95%.

III. RESULTS AND DISCUSSION

In order to validate the proposed model, Schottky diodes were fabricated on *n*-doped 4H-SiC wafers with 8 μm epitaxial layers and approx. $10^{16} cm^{-3}$ doping density.

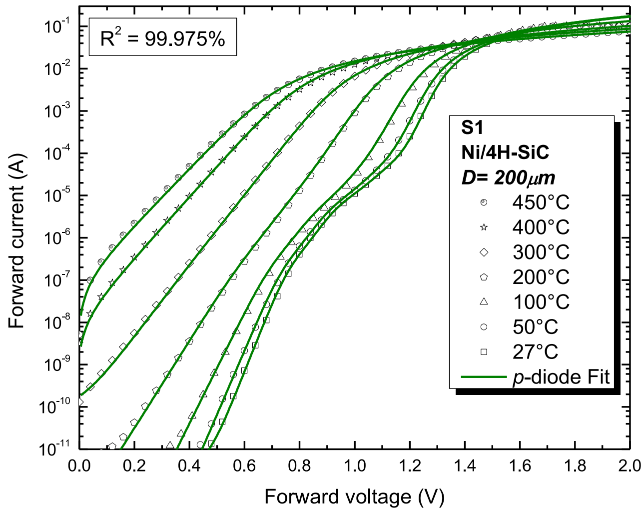

FIGURE 1. Experimental (symbols) and calculated (lines) forward characteristics of sample S1. The R^2 value confirms strong matching.

The Schottky metal was Ni, deposited in circular windows with different diameters and annealed at 800°C for 5-8 min. in inert atmosphere. Devices were packaged in TO39 capsules [17]. Forward characteristics with temperature were acquired up to 450°C using a Keithley 4200 Semiconductor Characterization System [17].

Experimental data for a sample (S1), selected due to strongly visible inhomogeneity are presented in Fig. 1. The curves, measured below 200°C, exhibit pronounced abnormal behavior with two discernable exponential portions.

Thus, two parallel diodes (m = 2) were initially considered for parameterizing the characteristics in Fig. 1. Saturation currents and $R_{S,i}$ values for considered devices (named Dp1 and Dp4), were determined [18] from the portions of the forward characteristics where their impact is predominant (low-bias/low-temperature and high-bias/high-temperature, respectively). Using only m = 2, the "hump", visible on the characteristics between 0.7 V and 1.1 V, up to 200°C, was poorly fitted. Therefore, two additional intermediary diodes (Dp2 and Dp3) were necessary, yielding a final m = 4. Parameters for these diodes were estimated using an iterative process until the R^2 threshold was exceeded ($R^2 = 99.975\%$). Fitted curves (with m = 4), also presented in Fig. 1 (lines), show an excellent agreement with experimental data. For each diode (Dp1-4), the extracted barrier height, non-uniformity parameter and ideality factor are given in Table 1. It can be observed that all these parameters are rigorously constant over the entire temperature and bias range. Hence, the negligible impact of potential "pinch-off" is confirmed, together with the quasi-ideal electrical behavior for each of the parallel diodes.

R_S, normally exhibits temperature dependency (Fig. 2a), due to changes in carrier mobility with temperature [13]. The normalized areas (to the nominal area of S1) calculated as $\exp(-p_{eff})$ [3], corresponding to Dp1-4, are illustrated in Fig. 2b.

TABLE 1. Fitting parameters for sample S1.

Parallel diode	Φ_{Bn} [V]	p_{eff}	n
Dp1	0.936	15.80	1.03
Dp2	1.064	13.60	
Dp3	1.296	9.60	
Dp4	1.585	0.96	

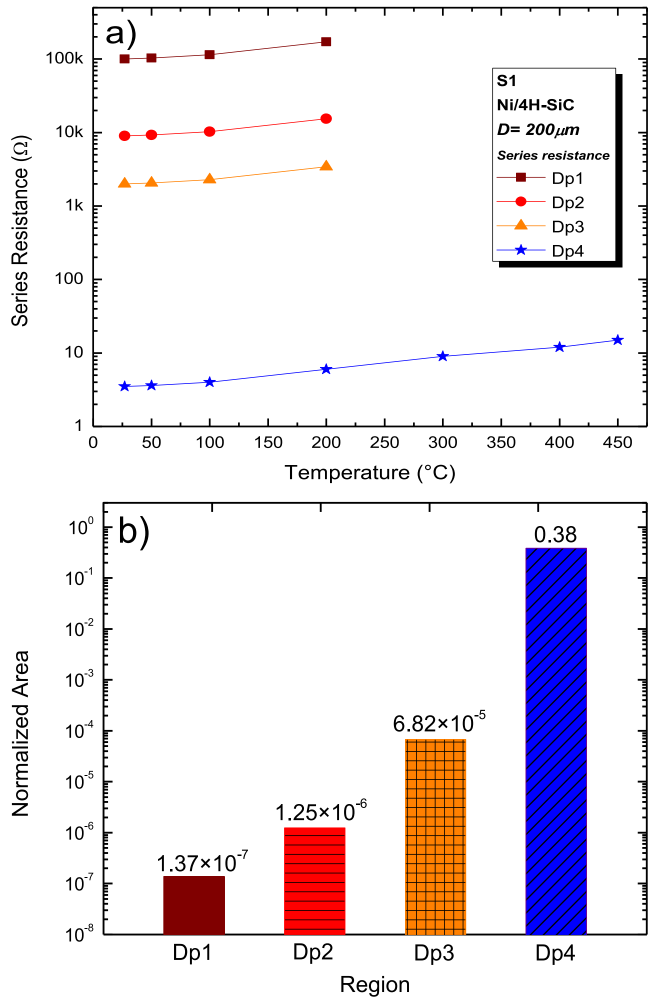

FIGURE 2. a) R_S temperature variation and b) Normalized areas, for Dp1-4.

The percentage contributions of Dp1-4 to total current at 100°C are depicted in Fig. 3a. Individual forward characteristics for every parallel diode are illustrated in Fig. 3b, alongside that of the overall Schottky contact, calculated with the *p*-diode model. In order to analyze each diode's influence, the bias range is split into 5 domains (Fig. 3). The lowest area diodes (Dp1, Dp2) are responsible for nearly all of the total current at voltages up to 0.6 V (domain I – Figs. 3). Their current contributions are constant and different for each diode due to the difference in barrier height. In second domain, Dp1's series resistance becomes significant. The effect of $R_{S,1}$ can be considered an apparent increase in barrier:

$$\Phi_{Bn1,app} = \Phi_{Bn1} + R_{S,1} I_{F,1}. \tag{4}$$

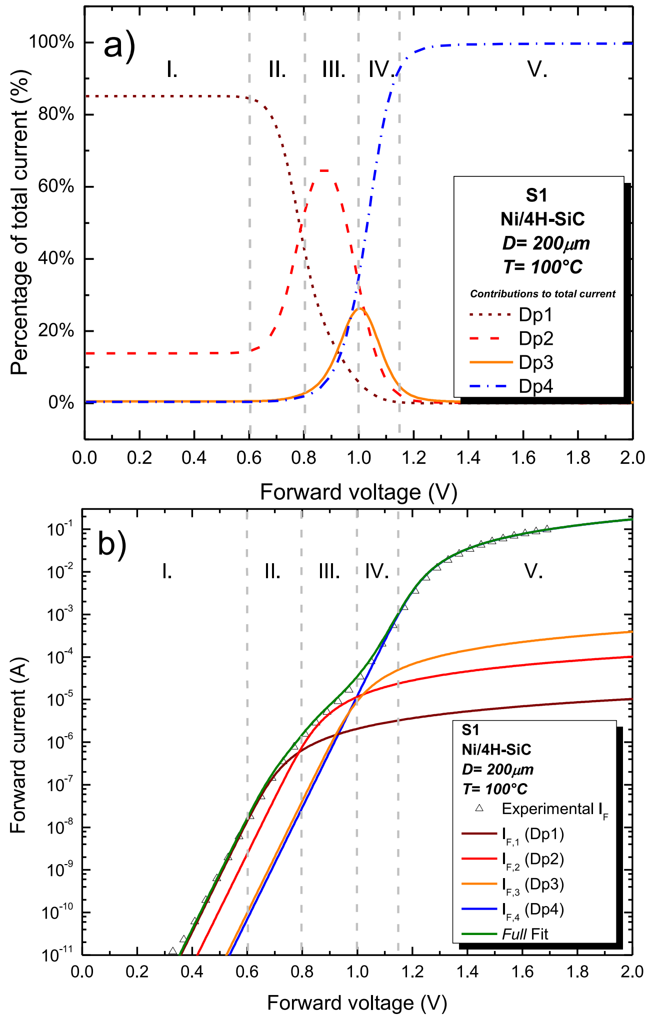

FIGURE 3. **a) Diode percentage current contributions and b) Individual forward characteristics of Dp1-4 and the overall Schottky diode, at 100°C for sample S1.**

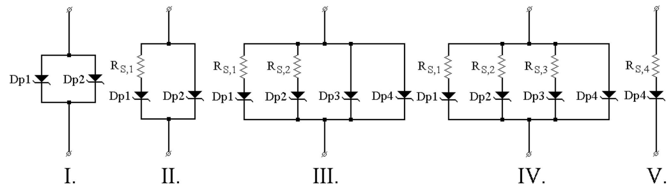

FIGURE 4. **S1 electrical behavior equivalent circuits in the distinctive bias ranges evinced in Fig. 3.**

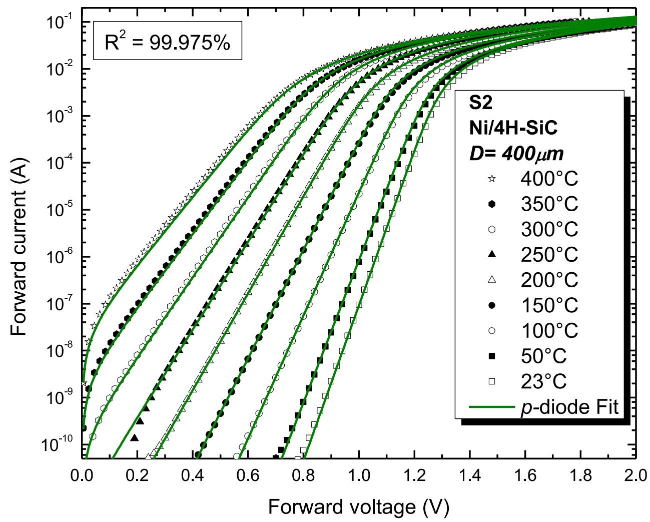

FIGURE 5. **S2 forward characteristics: experimental and calculated by (3).**

Thus, the influence of Dp1 on overall current decreases with bias. Dp2's percentage contribution increases while Dp3 and Dp4 currents remain negligible in this bias zone (II – Fig. 3).

In contrast, all parallel diodes contribute noticeably in the middle of the V_F range (domains III and IV). $R_{S,2}$ becomes significant in domain III, while, in region IV, the impact of $R_{S,3}$ is also relevant. Therefore, the contribution to total current progressively decreases for Dp2 in both domains and for Dp3 only in IV (Fig. 3a).

Dp4, with the highest area, rules conduction above 1.15 V (domain V.). In fact, at higher temperatures, only Dp4 gives off most of S1's current. This explains why, above 200°C, the characteristics apparently become uniform (Fig. 1) and m = 1 is sufficient to model forward curves, with S1 diode parameters corresponding to those of Dp4. Diodes Dp1-3 no longer impactfully affect current flow through the Schottky structure. In the 200°C – 450°C temperature range, 38% of the contact area is responsible for current flow (Fig. 2b).

The electrical behavior of the parallel diodes is summarized in Fig. 4 by equivalent circuits for each of the five abovementioned bias domains. Due to their tiny size, Dp1-Dp3 associated series resistances are notably higher (Fig. 2a). As voltage increases, the ohmic behavior of these regions becomes predominant and limits current flow (Figs 3, 4). This explains the "hump" in the 0.6 V – 1.2 V range that can be observed on curves up to 200°C (Fig. 1).

In contrast with S1, the curves of sample S2, represented in Fig. 5, were chosen due to their much more uniform shape. In this case, the simplified equation (3) can very accurately fit (indicated by the high R^2 – Fig. 5) full measurements for S2 (Fig. 5). The extracted barrier height ($\Phi_{Bn} = 1.596$ V), is very close to the one of Dp4 (Table 1). R_S increases slightly with temperature from 7 Ω to 9 Ω. Noteworthy, $p_{eff} = 1.38$ was extracted with the model-specific method described in [3]. This value means that approx. 25% of the contact area for S2 supplies almost the entire current.

In order to further validate our *p*-diode model, other samples were fabricated, in industrial conditions, on *n*-doped 4H-SiC wafers with 6 μm epitaxial layers, using 100 nm thick Ti layer as Schottky contact [20]. These devices were packaged, in TO39 capsules, just like our fabricated Ni/4H-SiC samples, allowing for measurements up to 400°C.

Forward characteristics for one such sample (S3) are shown in Fig. 6. It can be seen that the exponential portion is distinguishable until just 300°C. Up to this point,

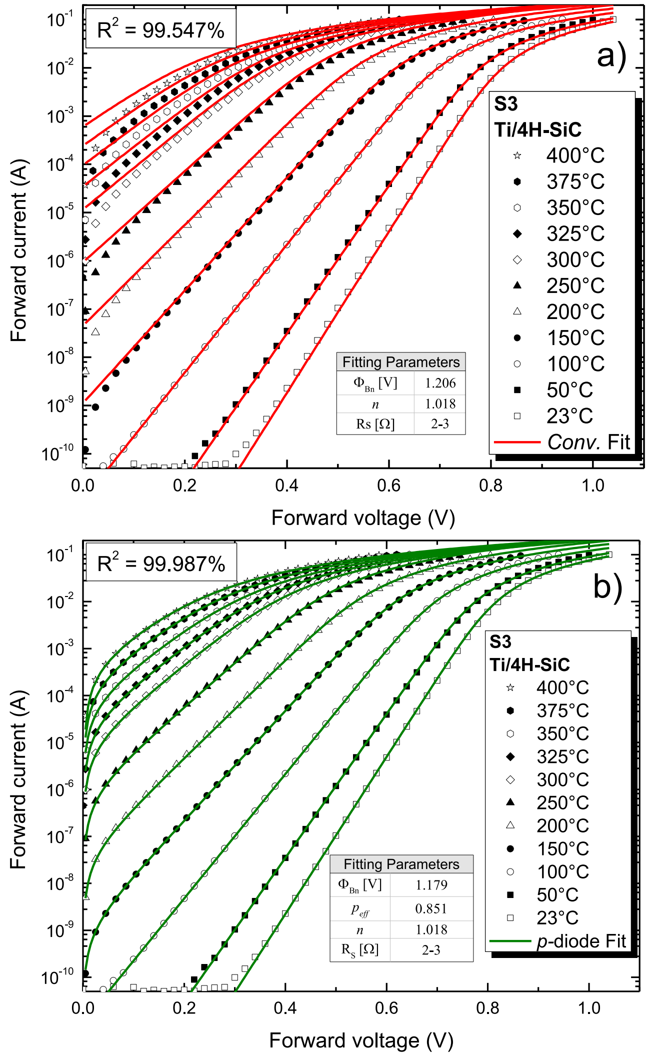

FIGURE 6. Forward characteristics of sample S3: experimental data (symbols) and calculated (lines) using a) the conventional method and b) the proposed model. Fitting parameters are given in the inset tables.

Φ_{Bn}, n and R_S were determined from experimental data, for every temperature, with the standard method [18]. Hence, (3) was used, with $p_{eff} = 0$, which means current flows uniformly through the entire Schottky contact area [2]–[4], [18]. Very slight temperature dependence was extracted for these parameters. Curves, calculated by (3), with the average values for Φ_{Bn} and n, are compared with experimental data in Fig. 6a. For R_S, values determined at each temperature were employed. Good agreement can be observed up to around 200°C, only. At higher temperatures, calculations overestimate the real diode current. The results are remarkable, as they seem to offer a clear reasoning for limiting the operation temperature for commercial devices to 175°C.

The electrical forward curves of Ti/4H-SiC samples can be precisely replicated up to 400°C using the proposed enhanced model, as illustrated in Fig. 6b.

An excellent agreement is observed, using (3) and extracted parameters given in Fig. 6b. This notable conformity is obtained due to the nonzero p_{eff} value, which suggests a certain degree of Schottky contact inhomogeneity. Thus, only approx. 43% of the entire contact area is responsible for current conduction through the device. The rest of the Schottky contact surface should be covered by regions with barrier heights higher than $\Phi_{Bn} = 1.179$ V, (obtained for S3 – Fig. 6b). Extracting the values of these barriers is not possible for the S3 sample from measurements up to 400°C, due to negligible contribution to total current. Even above this temperature, the impact of the higher barrier zones would be shunted by the series resistance over the full bias domain.

IV. CONCLUSION

A model adequate for replicating inhomogeneous Schottky diodes' forward characteristics over wide high temperature and bias ranges was proposed. According to this p-diode model, the Schottky contact current is considered to flow through a few parallel-connected internal diodes, each with a stable and constant barrier height, near-unitary ideality factor and specific series resistance. Distinctive model parameters, $p_{eff,i}$, define the inhomogeneity degree and their distribution directly impacts the number of parallel diodes (m) necessary to reproduce the electrical behavior of a non-uniform Schottky contact. The series resistance effect also plays a major role in establishing the value of m.

The p-diode model was verified on measured forward characteristics of devices with both Ni and Ti Schottky contacts on 4H-SiC, which exhibited varying degrees of inhomogeneity. Accurate reproduction of experimental curves was achieved for all investigated samples, even one with visible irregularities (sample S1). In such situations, the model requires at least two parallel diodes (m = 2) in order to replicate the forward characteristics' shape at low and high bias, respectively. Eventual "humps" present on measured curves at medium V_F voltages can be accounted for in our model by adding intermediary parallel diodes (usually no more than two), with their series resistance effects.

Samples where good agreement between fitted curves and measurements was obtained using only $m = 1$, exhibited much more uniform Schottky contacts. Here, p_{eff} was a valuable indicator of how much of an inhomogeneous contact's area is actually used for conduction. A fully uniform Schottky contact would yield $p_{eff} = 0$, corresponding to current flowing through all the nominal area. In such situations, the proposed model provides identical results with the conventional model of a homogeneous Schottky contact.

It is evinced that modeling a commercial Schottky diode's (S3) forward characteristics with the conventional method and our proposed approach produce different outcomes. On the one side, the consecrated technique would point out that the device's electrical behavior becomes unreliable after a certain temperature threshold, comparable to that of silicon based components (mostly rated under 175°C). On the other side, our proposed p-diode model was able to completely replicate the commercial sample's forward characteristics up to 400°C, indicating that the device can operate predictably even at such high temperatures. Further exploration of these conclusions should represent a distinct direction for research focus in the field of high-temperature-capable SiC-Schottky diodes (and even devices on other wide-bandgap materials).

Thus, the proposed model parameters offer valuable insight on the practical performances of the devices. They have concrete structure-related meaning, making them easily interpretable.

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