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Intersection of 4H-SiC Schottky diodes *I–V* curves due to temperature dependent series resistance

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Abstract

We theoretically and experimentally analyzed the non-obvious intersections of Schottky diode *I–V* curves measured at different temperatures caused by increasing the series resistance of the diode with increasing temperature. We considered a homogeneous diode and an inhomogeneous diode with two ways of influencing the *I–V* curve by the series resistance. In each case we developed a numerical method that enabled anticipation of the *I–V* intersection point. We studied the Ni/Au/4H-SiC diode for which such an intersection was measured. For homogeneous diodes and temperature interval 300–400 K we found a voltage dispersion of intersection points of only ∼0.002 V, which is in accordance with experimental observations and suppositions in the literature that the curves intersect at almost the same *I–V* point. Even for an inhomogeneous diode with a common series resistance we obtained a dispersion of the intersection voltage of only ∼0.02 V which is hardly discernible by the common visualization of the *I–V* curves. The largest dispersion of intersection points was obtained for an inhomogeneous diode composed of non-interacting diode patches.

Keywords: Schottky barrier, *I–V* curves intersection, 4H-SiC, inhomogeneous Schottky diode

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

1. Introduction

Thermionic emission (TE) theory does not anticipate crossing of Schottky diode *I–V* curves measured at different temperatures. At low forward voltages the current is driven by the TE and increases with increasing temperature. At higher voltages, a series resistance starts to have an overwhelming influence on the current and the *I–V* curve converges to a linear shape. For an even higher voltage the current has approximately the same value regardless of the measuring temperature.

This is valid for the constant value of the series resistance when changing the temperature. The currents at high forward voltage may differ in frequent cases when the series resistance is caused prevalently by a semiconductor bulk. The series resistance value decreases in this case with increasing temperature and the asymptotic current value may increase with temperature, e.g. in [1, 2], where it was explained by activation of the B acceptors and/or improvement of ohmic resistance at higher temperature.

Recently we obtained seemingly an anomalous effect. By measuring the temperature dependence of Ni/Au/4H-SiC Schottky diodes *I–V* we obtain the intersection of the *I–V* curves [3]. This effect has already been observed in many previous studies, namely in 4H-SiC Schottky diodes, but has been left virtually without mention. Generally the crossing of the *I–V* curves also has been studied theoretically, but in those studies the reason of the *I–V* curve intersection was other than increasing the series resistance with the temperature. Chand and Bala [4] studied inhomogeneous diodes and observed the crossing of the *I–V* curves measured at low temperatures up to 100 K with *I–V* curves measured at higher temperatures. Latreche and Ouennoughi [5] carried out recently a similar study in which this effect has been confirmed, but the physical interpretation of the effect was rather different. Osvald and

Horváth [6] simulated by the drift-diffusion approximation I–V curves of n-Si Schottky diodes with a p-type surface inversion layer in the temperature region 80–320 K. The intersection of the I–V curves appeared already in the linear section of the semi-logarithmic I–V curves.

The intersection of the Schottky diodes I–V curves of SiC diodes measured at different temperatures was observed by Funaki *et al* [7]. A similar effect was measured in [8] in Al/Ti/4H-SiC diodes. Intersection point in the voltage region where series resistance drives the current was observed also in [9] at Ni/4H-SiC and Pt/4H-SiC diodes and (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN/SiC Schottky barrier diode [10]. The authors found the increase of the series resistance with increasing temperature (approximately linear) but did not study the effect more in detail. The same behavior has been observed in a wide temperature range study of I–V curves of Pd/n-Si/4H-SiC diodes [11]. Increasing the series resistance with increasing temperature was also found as the reason of the I–V curves of Ni/SiO_2/p-Si/Al metal insulator semiconductor (MIS) diode intersection [12] and also in heterostructures based on GaN [13]. The intersection of the I–V curves was also observed also in the Schottky diode on AlGaN/GaN structure [14]. The authors analyzed the effect and extracted the temperature dependence of the series resistance of the I–V curves. Series resistance increased with increasing temperature and the temperature dependence was approximately linear. The intersection of I–V curves at approximately the same point was established at low temperatures also in Al/SiO_2/p-Si (MIS) Schottky diodes [15, 16]. Series resistance also increased in this case with increasing temperature. Such a temperature dependence of the current was observed also in hybrid organic–inorganic poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)/silicon heterojunctions where it was explained by filling the traps in the intersection point with further decrease of current [17].

An existence of the intersection point in the I–V curves where the current is constant whatever the temperature is, enables to prepare the diode which stabilizes the current flowing through it. And certainly, it is also necessary to know what will be the value of the stabilized current and what will be a possible drift of the current with temperature at the voltage responding to the stabilizing point. This is the aim of a theoretical analysis of the intersection behavior of the Schottky diode I–V curves measured at different temperatures at the conditions of series resistance increase with temperature. We analyze the situation in the case of homogeneous as well as inhomogeneous barrier height. Finally, we apply our developed method to our recently published experimental results [3].

2. Theory, results and discussion

A recently published study [3] reported temperature dependence of the I–V curves measured in temperature region 308–353 K. At voltages in excess of the intersection voltage the I–V curves change position. At a higher temperature, the current through the diodes was lower. It is clear that the reason for this position change is increasing the series resistance of the diodes with increasing temperature, which is, in principle, metallic temperature dependence of the resistance. What is especially peculiar is the fact that at first sight it seems that the curves cross at almost the same I–V point. This is also an object of this study—to verify this assumption and derive theoretically a procedure by which we could anticipate the voltage and current at which the I–V curves intersect when the series resistance of the diode increases with increasing temperature.

We analyze the conditions which could lead to such behavior. Firstly, we will study homogeneous Schottky diodes with a sharp barrier height and then also inhomogeneous barriers, especially with Gaussian barrier height distribution (BHD).

2.1. Homogeneous barrier

According to TE theory the current flowing through the Schottky diode also taking into account an influence of the series resistance may be expressed as

$$I = AA^{*}T^{2}\exp\left(-\frac{q\varphi}{kT}\right)\left[\exp\left(\frac{q\left(V-RI\right)}{kT}\right)-1\right] \tag{1}$$

where A is the diode area, A^{*} is the Richardson constant, φ is the barrier height and R is the series resistance. We will study forward direction for voltages $V > 3kT/q$ where the component 1 can be omitted. We can then write for the current

$$I = AA^{*}T^{2}\exp\left(-\frac{q\varphi}{kT}\right)\exp\left(\frac{q\left(V-RI\right)}{kT}\right). \tag{2}$$

In further considerations the diode area will be 1×10^{-6} m^2 and the Richardson constant of the n-type 4H-SiC will be used 146×10^{4} A m^{-2} K^{-2}. We are interested in deriving an expression which determines the intersection point for two I–V curves measured at different temperature with known series resistances at both temperatures. The result will be more general, if we have an expression of how the series resistance of the diode changes with the temperature. That is why in further considerations, we will use approximate temperature dependence of the series resistance to obtain a more universal solution. We took our experimental results [3], where the series resistance was evaluated and we simulate this temperature dependence of the resistance as a linear function of the temperature

$$R\left(T\right) = R\left(T_0\right)\left(1+\alpha\Delta T\right), \tag{3}$$

where α is the temperature coefficient of resistance and in our case has the value 0.0915 Ω K^{-1}. We should now find the common I–V point for which we can write the following equations

$$I = AA^{*}T_1^{2}\exp\left(-\frac{q\varphi}{kT_1}\right)\exp\left(\frac{q\left(V-R\left(T_1\right)I\right)}{kT_1}\right), \tag{4}$$

$$I = AA^{*}T_2^{2}\exp\left(-\frac{q\varphi}{kT_2}\right)\exp\left(\frac{q\left(V-R\left(T_2\right)I\right)}{kT_2}\right). \tag{5}$$

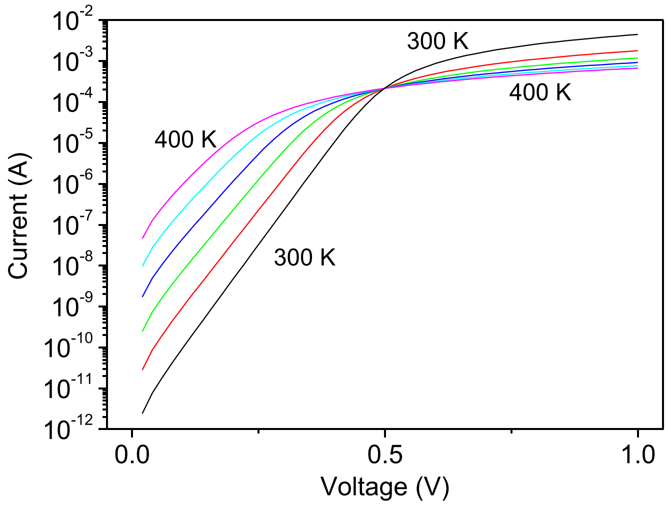

Figure 1. Simulated I–V curves of 4H-SiC diode with $\varphi = 1$ V, the series resistance $R = 100\ \Omega$ and temperature between 300 and 400 K step 20 K.

Table 1. I–V curves intersection voltage and currents calculated for every temperature combination in the 300–400 K interval.

		Intersection current (A)					
Intersection voltage (V)	T (K)	300	320	340	360	380	400
	300		2.10×10^{-4}	2.11×10^{-4}	2.11×10^{-4}	2.12×10^{-4}	2.12×10^{-4}
	320	0.498		2.11×10^{-4}	2.12×10^{-4}	2.12×10^{-4}	2.13×10^{-4}
	340	0.498	0.498		2.12×10^{-4}	2.13×10^{-4}	2.13×10^{-4}
	360	0.498	0.498	0.499		2.13×10^{-4}	2.14×10^{-4}
	380	0.498	0.498	0.499	0.500		2.14×10^{-4}
	400	0.498	0.499	0.499	0.500	0.500	

We have assumed that the barrier height does not change with the temperature, which is physically sound, regardless of the experimental results which prevalently do not fulfill this hypothesis. It is not possible to find the common current I from these equations analytically since it is not possible to isolate the current I from the equations. That is why it is necessary to solve it numerically. We created the inverse function $V = V(I)$. Certainly, also voltages on the diodes must be equal in the intersection-point

$$V = \frac{1}{q}\left(kT_1\left(\ln I - \ln A - \ln A^* - 2\ln T_1\right)\right) + \varphi + R\left(T_1\right)I, \quad (6)$$

$$V = \frac{1}{q}\left(kT_2\left(\ln I - \ln A - \ln A^* - 2\ln T_2\right)\right) + \varphi + R\left(T_2\right)I. \quad (7)$$

After some manipulation and elimination of the voltage V we obtain the equation for the current I

$$k\ln I\left(T_1 - T_2\right) - 2\left(T_1\ln T_1 - T_2\ln T_2\right) = qI\left(R\left(T_2\right) - R\left(T_1\right)\right), \quad (8)$$

that can be solved by iteration or by the Newton–Raphson method.

We show the result on the 4H-SiC diode. We assumed barrier height was $\varphi = 1$ V and the series resistance at the temperature 300 K $R(300) = 100\ \Omega$. The curves were simulated for the temperature region 300–400 K with the step 20 K. The curves generated by equation (2) are in figure 1. It is seen that the curves intersect at almost the same I–V point with $V \sim 0.5$ V. The calculated intersection voltages and currents for each combination of the temperatures between 300 and 400 K are in table 1.

The calculated intersection voltages are within the range of 0.498–0.500 V. This is the difference that cannot be seen in the figure and is commonly evaluated as it would be the same I–V point.

2.2. Inhomogeneous barrier—each diode patch with its own series resistance

If the I–V curve does not have the linear part in semi-logarithmic plot and has a concave character it is very probable that the barrier is not homogeneous and is composed of small barrier patches with different barrier height [18]. It is reasonable to assume that the current flows through the single barrier patches which have their own series resistance and such barriers are connected in parallel. This approach is suitable for diodes prepared on moderately doped semiconductors. By evaluation of such barriers it is assumed in the majority cases that the barrier height of small diode patches has Gaussian BHD [18, 19]. The total current flowing within such a diode can be written as [19]

$$I = A\int_{0}^{2\varphi_0} \rho(\varphi) j(V,\varphi)\,\mathrm{d}\varphi \tag{9}$$

where

$$\rho(\varphi) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_0)^2}{2\sigma^2}\right) \tag{10}$$

is Gaussian BHD with the mean barrier height φ_0 and standard deviation σ,

$$j(V,\varphi) = A^*T^2 \exp\left(-\frac{q\varphi}{kT}\right) \exp\left(\frac{q(V - r(T)j(V,\varphi))}{kT}\right) \tag{11}$$

is the barrier height current density and $r = RA$ may be referred as a resistance of the unity area of the diode. We have again assumed that $V > 3kT/q$. Integration should be in principle done up to an infinite barrier height, but the barrier heights higher than the mean barrier height have lower statistical abundance and even more, current exponentially decreases with the barrier height increase. That is why it is enough to integrate to the barrier twice as high as the mean barrier height. Since it is again not possible to separate $j(V,\varphi)$ in the equation, it must be solved numerically, e.g. by the Newton–Raphson method. The intersection point condition $I_1 = I_2$ may be then rewritten as

$$\begin{aligned} &AA^*T_1^2 \int_{0}^{2\varphi_{01}} \frac{1}{\sigma_1\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{01})^2}{2\sigma_1^2}\right) \exp\left(-\frac{q\varphi}{kT_1}\right) \exp\left(\frac{q(V - r_1(T)j(V,\varphi))}{kT_1}\right) \mathrm{d}\varphi \\ &= AA^*T_2^2 \int_{0}^{2\varphi_{02}} \frac{1}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{02})^2}{2\sigma_2^2}\right) \exp\left(-\frac{q\varphi}{kT_2}\right) \exp\left(\frac{q(V - r_2(T)j(V,\varphi))}{kT_2}\right) \mathrm{d}\varphi, \end{aligned} \tag{12}$$

where φ_{01}, φ_{02} and σ_1, σ_2 are the mean barrier heights and standard deviations, respectively at two different temperatures. Here we assume a general case where BHD may in principle change its parameters with the temperature.

After some manipulation and isolation of the voltage of the intersection point we get expression for the voltage for which the current flowing through the diode at different temperatures is the same

$$\begin{aligned} V = \frac{kT_1T_2}{q(T_2-T_1)} \Bigg[&\ln \int_{0}^{2\varphi_{02}} \exp\left(-\frac{(\varphi-\varphi_{02})^2}{2\sigma_2^2}\right) \\ &\times \exp\left(-\frac{q\varphi + r_2(T)j(V,\varphi)}{kT_2}\right) \mathrm{d}\varphi \\ &- \ln \int_{0}^{2\varphi_{01}} \exp\left(-\frac{(\varphi-\varphi_{01})^2}{2\sigma_1^2}\right) \\ &\times \exp\left(-\frac{q\varphi + r_1(T)j(V,\varphi)}{kT_1}\right) \mathrm{d}\varphi - 2(\ln T_1 - \ln T_2) \Bigg]. \end{aligned} \tag{13}$$

In the beginning, the current density $j(V,\varphi)$ is resolved iteratively for both temperatures for certain initial voltage. The new voltage is then calculated in accordance with equation (13) and new currents are calculated according to equation (12). The process is repeated until the difference between the two consecutive solutions of V is lower than a given accuracy.

This procedure enables to calculate the voltage at which two *I–V* curves of the Schottky diode with the known temperature dependence of the series resistance and measured at two arbitrary temperatures intersect. It can be seen that the position of the intersection point is in both cases independent of the diode area. We again generated *I–V* curves of inhomogeneous diode corresponding to the temperatures between 300 and 400 K (figure 2). The mean barrier height $\varphi_0 = 1$ V, the standard deviation BHD $\sigma = 0.1$ V and the series resistance $R = 100\ \Omega$. The curves visually intersect again close to each other, but the dispersion of the intersection points is already visible. The intersection points calculated according to our procedure for every couple of *I–V* curves from the temperature interval are shown in table 2.

2.3. *Inhomogeneous barrier—total current spread after crossing the barrier and common series resistance*

Finally, we develop the same procedure for the diode prepared on highly doped semiconductor where we expect a total current spreading in the semiconductor and we can model the diode as a parallel diode patches having the common series resistance. We assume again Gaussian BHD with the same BHD parameters: the mean barrier height $\varphi_0 = 1$ V, the standard deviation $\sigma = 0.1$ V and the series resistance $R = 100\ \Omega$. Now we can write for the currents flowing through the diode at two different temperatures T_1 and T_2, which should be equal in the intersection point

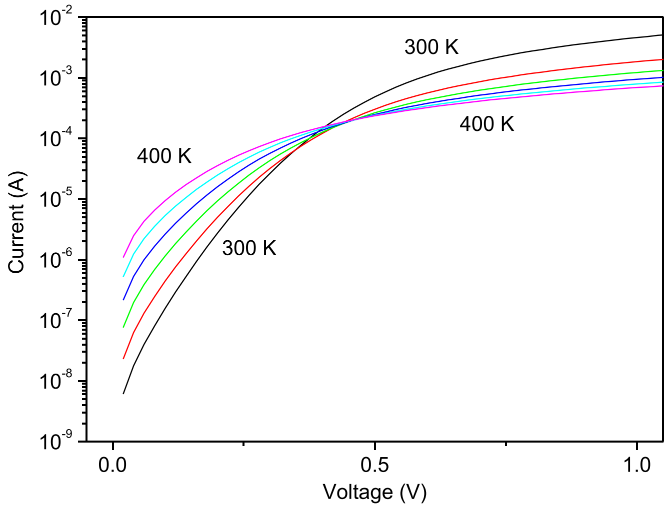

Figure 2. Simulated I–V curves of inhomogeneous 4H-SiC Schottky diode with $\varphi_0 = 1$ V, $\sigma = 0.1$ V, total series resistance $R = 100\ \Omega$ and temperature between 300 and 400 K step 20 K. It was assumed that every barrier patch has its own resistance.

Table 2. Calculated I–V curves intersection voltages and currents of inhomogeneous 4H-SiC Schottky diode with $\varphi_0 = 1$ V, $\sigma = 0.1$ V, total series resistance $R = 100\ \Omega$ for every temperature combination in the 300–400 K interval.

		Intersection current (A)					
Intersection voltage (V)	T (K)	300	320	340	360	380	400
	300		6.36×10^{-5}	1.01×10^{-4}	1.28×10^{-4}	1.47×10^{-4}	1.61×10^{-4}
	320	0.347		1.51×10^{-4}	1.70×10^{-4}	1.83×10^{-4}	1.91×10^{-4}
	340	0.375	0.421		1.89×10^{-4}	1.96×10^{-4}	2.03×10^{-4}
	360	0.391	0.433	0.450		2.05×10^{-4}	2.09×10^{-4}
	380	0.401	0.440	0.456	0.464		2.13×10^{-4}
	400	0.407	0.444	0.459	0.467	0.472	

$$AA^*T_1^2 \int_0^{2\varphi_{01}} \frac{1}{\sigma_1\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{01})^2}{2\sigma^2}\right) \exp\left(-\frac{q\varphi}{kT_1}\right) \exp\left(\frac{q\left(V-R(T_1)I\right)}{kT_1}\right) \mathrm{d}\varphi$$
$$= AA^*T_2^2 \int_0^{2\varphi_{02}} \frac{1}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{02})^2}{2\sigma^2}\right) \exp\left(-\frac{q\varphi}{kT_2}\right) \exp\left(\frac{q\left(V-R(T_2)I\right)}{kT_2}\right) \mathrm{d}\varphi. \tag{14}$$

Using numerically calculated current I we obtain an expression for the intersection voltage V as

$$V = \frac{kT_1T_2}{q(T_2-T_1)} \left[\ln \int_0^{2\varphi_{02}} \frac{1}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{02})^2}{2\sigma^2}\right) \times \exp\left(-\frac{q\varphi+R(T_2)I}{kT_2}\right) \mathrm{d}\varphi - \ln \int_0^{2\varphi_{01}} \frac{1}{\sigma_1\sqrt{2\pi}} \exp\left(-\frac{(\varphi-\varphi_{01})^2}{2\sigma^2}\right) \times \exp\left(-\frac{q\varphi+R(T_1)I}{kT_1}\right) \mathrm{d}\varphi - 2\left(\ln T_1 - \ln T_2\right) \right]. \tag{15}$$

In figure 3 there are again generated appropriate I–V curves and calculated voltages and currents of intersection points. The calculated values of the voltage and current at the intersection point for each temperature combination between 300 and 400 K are in table 3. We can see that the dispersion of the voltage and current of intersection points is much lower than in the case of so called non-interacting diodes where every barrier patch has its own series resistance. It is quite understandable since the onset of the series resistance driven part of the I–V curve is much steeper than in the situation when the current through single barrier patches is driven by the series resistance of the single patches which in this approach depend on its barrier height abundance in the distribution.

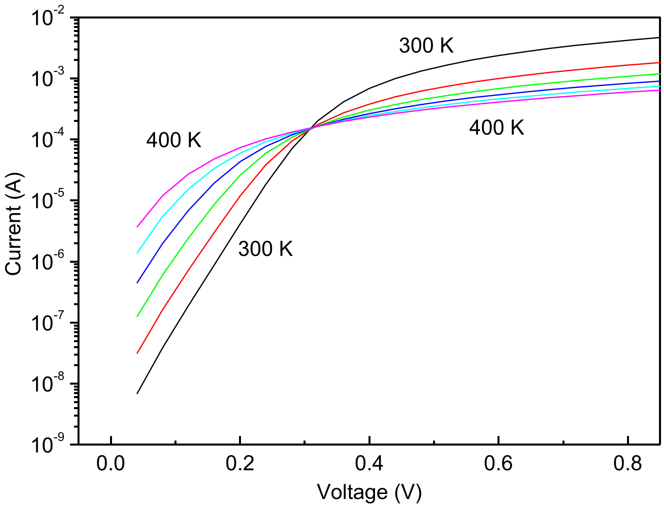

Figure 3. Simulated I–V curves of inhomogeneous 4H-SiC Schottky diode with $\varphi_0 = 1$ V, $\sigma = 0.1$ V, total series resistance $R = 100\ \Omega$ and temperature between 300 and 400 K step 20 K. The assumption of common series resistance has been used.

Table 3. Calculated I–V curves intersection voltages and currents of inhomogeneous 4H-SiC Schottky diode with $\varphi_0 = 1$ V, $\sigma = 0.1$ V and common series resistance $R = 100\ \Omega$ for every temperature combination in the 300–400 K interval.

		Intersection current (A)					
Intersection voltage (V)	T (K)	300	320	340	360	380	400
	300		1.47×10^{-4}	1.52×10^{-4}	1.55×10^{-4}	1.59×10^{-4}	1.62×10^{-4}
	320	0.289		1.56×10^{-4}	1.59×10^{-4}	1.63×10^{-4}	1.66×10^{-4}
	340	0.290	0.293		1.63×10^{-4}	1.66×10^{-4}	1.69×10^{-4}
	360	0.291	0.294	0.297		1.69×10^{-4}	1.72×10^{-4}
	380	0.292	0.296	0.299	0.302		1.74×10^{-4}
	400	0.293	0.297	0.301	0.305	0.308	

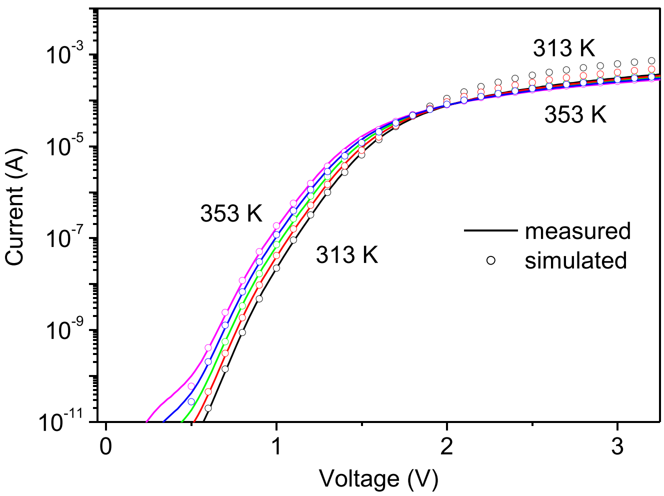

Figure 4. I–V curves of Au/Ni/4H-SiC Schottky diodes measured at temperatures 313–353 K.

We now illustrate the procedure also on the experimental results [3] shown in figure 4. The I–V curves had no linear part in semi-logarithmic representation. The evaluation of the curves assuming the barrier height inhomogeneity showed that the I–V curves could have been simulated with the Gaussian BHD. The BHD extracted of the I–V curves measured from 313 to 353 K at the assumption of non-interacting diode patches are in table 4. The calculated intersection points are given in table 5. Comparison with figure 1 shows that the calculated voltages at the intersection point (~1.7–1.9 V) is lower than ~2 V measured in the experiment. This is because the calculation of the intersection points is carried out for simulated BHD of the I–V curves and the simulation curves intersect at lower voltages than experimental. It is necessary to hold in mind that the approximation of Gaussian BHD is still only an approximation and as it seen in high forward voltage the fitting is relatively good for Schottky contact driven part of the curves, but not so good for Ohmic part of the curves. But the overall accuracy is satisfactory.

Table 4. Gaussian BHD parameters from the I–V curves shown in figure 1.

T (K)	φ (V)	σ (V)	R (Ω)
313	2.440	0.244	1800
323	2.366	0.234	3010
333	2.318	0.228	4039
343	2.287	0.224	4808
353	2.265	0.223	5411

It is seen that the intersection point shifts for higher temperatures to higher voltages for all our cases studied. We

Table 5. Calculated intersection points of Ni/Au/4-SiC Schottky diodes *I–V* curves measured between 313 and 353 K.

		Intersection current (A)				
Intersection voltage (V)	T (K)	313	323	333	343	353
	313		3.61×10^{-5}	4.11×10^{-5}	4.57×10^{-5}	5.06×10^{-5}
	323	1.708		4.73×10^{-5}	5.18×10^{-5}	5.72×10^{-5}
	333	1.732	1.767		5.74×10^{-5}	6.39×10^{-5}
	343	1.751	1.789	1.821		7.19×10^{-5}
	353	1.772	1.814	1.856	1.904	

may divide the total resistance of the Schottky diode R_d at every voltage into the series combination (sum) of the resistance of the Schottky diode itself (resistance of the TE process at the Schottky contact) R_{TE} that is voltage dependent and decreases with temperature and the series resistance R_s itself, which is assumed to be voltage independent and is formed by the resistance of the quasi-neutral part of the semiconductor, resistance of the Ohmic contact and resistance of outer connections. At the intersection point the sum of these two components is equal for both intersecting curves. The intersection point will not shift in temperature if $\Delta R_{TE}(\Delta T) = -\Delta R_s(\Delta T)$, i.e. increase of the series resistance will be compensated by the same decrease of the TE process resistance or in other words, derivative of resistance of the TE process according the temperature (which could be influence in principle only by the barrier height) plus derivative of the series resistance according to the temperature should be zero. The shift of the intersection point to higher voltages with increasing temperature in our results should be a result of the increase of the series resistance with temperature not compensated enough by sufficient decrease of the resistance of the metal semiconductor contact itself.

3. Conclusion

We have analyzed the intersection of Schottky diode *I–V* curves measured at different temperatures which is caused by increasing the diode series resistance with increasing temperature. We treated the case of the homogeneous diode as well the inhomogeneous diode with common series resistance or so called non-interacting diode patches. We derived the numerical procedure for assessment of the intersection *I–V* points—voltage as well as current of the crossing. The presumption of the method consists in knowing the series resistance of the diode at studied temperatures, or more general, temperature dependence of the series resistance.

We have shown that in the case of homogeneous barrier and linear increase of the series resistance with temperature the *I–V* curves intersect practically in the same *I–V* point (we found for the specific diode dispersion of 0.002 V). The intersection points also gave very low dispersion for the inhomogeneous diode with the common series resistance—dispersion lower than 0.02 V. The highest dispersion of the intersection points was obtained for inhomogeneous diodes which were simulated by the parallel combination of diode patches with their own resistance. This could have been expected since the single diode patches have different series resistance according to their abundance in BHD and the voltage interval where the series resistance starts to drive the current through the single patches is wider.

Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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