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Temperature dependence of electrical behaviour of inhomogeneous Ni/Au/4H–SiC Schottky diodes

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ABSTRACT

Temperature dependence of electrical parameters of Ni/Au/4H–SiC Schottky diodes in a small temperature interval has been studied. Current–voltage characteristics were measured between 35 and 80 °C. I–V curves have not a linear part in semi-logarithmic plot which indicates barrier height inhomogeneity. We analyzed forward part of the I–V curves assuming Gaussian barrier height distribution and parallel connection of diode patches with different barrier heights. Using the least squares method we determined mean barrier height, standard deviation of the barrier height distribution and finally series resistance of the diode as a function of temperature. The extracted barrier height and standard deviation of the distribution decrease with increasing temperature. In contrary the series resistance of the diode increases with increasing temperature. As an interesting feature and a consequence of the series resistance increase with temperature a crossing of the I–V curves in practically the one point of the I–V curve has been observed. At this cross-point the current flowing through the diode is independent of the temperature.

1. Introduction

Silicon carbide (SiC) is under study in recent years as a promising material for high temperature, high frequency and also high power applications. Schottky diodes on 4H–SiC are intensively studied in surface barrier detectors of radiation [1,2]. The properties of contacts of the semiconductor with metals or semiconductors are a main attribute which determines the possibilities to use this semiconductor in device production. This is the reason why Schottky contacts of SiC, especially with 4H–SiC and their temperature dependence is intensively explored [3–5].

Several metallic materials have been studied as a Schottky gate [6–9]. At many of them I–V curves measured do not correspond to an assumption of one sharp Schottky barrier height (SBH) over the area of the contact. One of the features which confirms the possibility of an existence of barrier patches with different SBHs is non-linearity of the forward I–V curve in semi-logarithmic plot.

In majority studies the authors assume statistical distribution of the SBH in the contact. As an appropriate distribution for this case, prevalently Gaussian barrier height distribution (BHD) is used. As was shown by Song et al. [10], if the standard deviation of the BHD is small the I–V curve may even retain its linear shape in the semi-logarithmic plot and a series resistance effect may be visible similar as by sharp barrier height only after flattening of the conduction and valence bands by the forward voltage corresponding to the middle of the BHD.

In spite of the fact that the SBH is according to the theory independent of the semiconductor doping this is not fully approved for inhomogeneous contacts. The main difference between inhomogeneous Schottky contacts on low and highly doped semiconductors is an influence of the series resistance on the I–V curves. For lowly doped semiconductors we may assume that there is not enough current spreading in a semiconductor bulk and every single diode patch has its own resistance of the semiconductor behind the contact patch. On the other hand, for highly doped semiconductors the current spreads in the semiconductor and more approved is an approximation assuming common series resistance for all of the diode patches.

Recently we have studied inhomogeneity of the Ni/Au/4H–SiC contacts [11]. We explored both cases of the series resistance incorporating into the I–V curve simulations. Since the 4H–SiC was low-doped material approach with non-interacting diodes gave reasonable results while it was not possible to model I–V curves by the approach of common series resistance.

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In this work we analyze the temperature dependence of the forward part of I–V curves of 4H–SiC Schottky diodes and the parameters which characterize their inhomogeneity in a relatively small interval of temperatures between 35 and 80 °C.

2. Experiment and theory

The Schottky contacts were prepared on 70 μm thick epitaxial layer of 4H–SiC. The doping was done with nitrogen to the level of 1×10^{14} cm^{-3} given by the producer ETC Catania. The diodes are intended to use as a part of the surface barrier radiation detector. Schottky contacts were formed by evaporation of Ni/Au layer. Samples were standardly cleaned before evaporation in boiling acetone, isopropylalcohol, deionized water and finally dried by nitrogen. Ohmic contact was formed by the Ti/Pt/Au metalization. Diameter of circular diode was 2 mm.

I–V curves of the diodes were then measured in the temperature region 35–80 °C with 5 °C step. Because of the bowing of the I–V curves in semi-logarithmic plot it was not possible to simulate them correctly enough by the expression for thermionic emission.

$$I = AA^{*}T^{2}\exp\left(-\frac{q\varphi}{kT}\right)\exp\left(\frac{qV}{nkT}-1\right), \quad [1]$$

where A is the diode area, A^* is effective Richardson constant, T is temperature, and n is ideality factor. The main known effect which could cause this non-linearity was described by Dobročka and Osvald [12] and consists in SBH inhomogeneity together with the series resistance effect. Bowing of the I–V curve is caused by continuous cutting off with increasing voltage of small barriers by series resistance. Consecutively the slope of the I–V curve decreases with increasing voltage and the curve is not linear.

The temperature dependent I–V curves of the diode are shown in Fig. 1. The shape of the I–V curves indicates that the barrier is probably not homogeneous and a centroid of the current flowing shifts towards higher barrier patches with increasing forward voltage. By evaluating the I–V curves we used the approximation of non-interacting diodes, *i. e.*, we assumed that the Schottky diode consists in many small diode patches with Gaussian BHD each containing its own series resistance. This assumption is supported by low doping concentration of 4H–SiC, which implicates the small current spreading in the semiconductor before the potential barrier. Using the common series resistance approach was not successful similarly as in Osvald *et al.* [11], since it was not possible to fit bowing of the I–V curves. This approach is more appropriate for the structures which have some part of the I–V curve linear in semi-logarithmic plot [5,7,13]. By the BHD distribution, we understand not the BHD at the intimate interface, but effective BHD driving the current flow formed taking into account "proximity effect", by which lower barrier patches are influenced by neighbouring higher barrier patches [14]. The maxima of the low barrier patches are shifted into the semiconductor bulk. Under these assumptions we may treat the diode patches as independent diodes. The single diodes are in parallel as it is shown in Fig. 2. The mathematics describing the total current as a sum of the currents through all the single diode patches is described in detail in Refs. [11,15]. The parameters of the Gaussian BHD are determined directly from the I–V curves and not only interposed through some not fully clear parameters. In brevity, current density flowing through the barrier height φ is

$$j(\varphi) = A^{*}T^{2}\exp\left(-\frac{q\varphi}{kT}\right)\left[\exp\left(\frac{q(V - rj(\varphi))}{kT}\right) - 1\right], \quad [2]$$

$j(\varphi)$ being the barrier current density and $r = RA$ is the area resistance. The total current flowing through the diode taking into account Gaussian BHD will be

$$I = \int_{0}^{2\varphi_0} A\rho(\varphi)j(\varphi)d\varphi, \quad [3]$$

where $\rho(\varphi)$ is the Gaussian BHD

$$\rho(\varphi) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[\frac{(\varphi-\varphi_0)^2}{2\sigma^2}\right], \quad [4]$$

with φ_0 being the mean barrier height and σ the standard deviation.

Integration need not to be done with infinity barrier as an upper integration limit since the current density decreases quickly with increasing barrier height and it is reasonable to integrate only up to double the mean barrier height φ_0. Gaussian BHD $\rho(\varphi)$ modifies the current contribution of different patches according to their count in the diode area A.

To solve the problem we must find three parameters: mean barrier height, standard deviation of the BHD and the area resistance. Experimental curves were fitted with these three parameters using lest squares

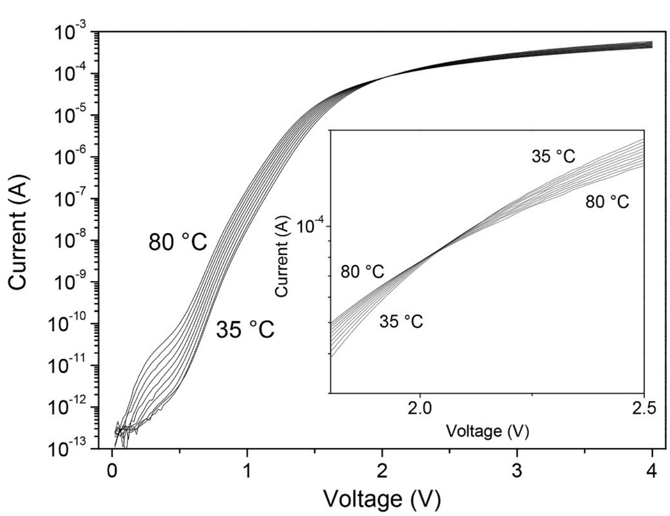

Fig. 1. Measured I–V curves between 35 and 80 °C and common intersection of the I–V curves.

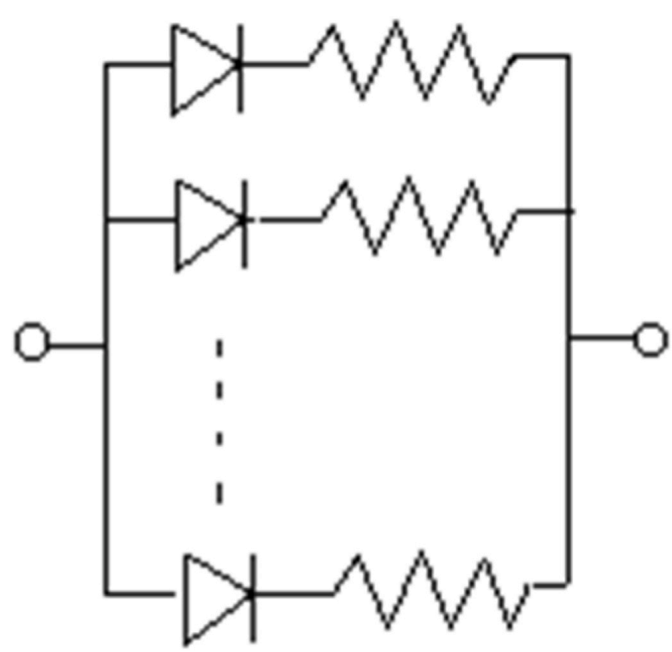

Fig. 2. Equivalent scheme of the parallel connected barrier patches each with its own series resistance.

approximation. The procedure is described more in detail in Ref. [16].

3. Results and discussion

The measured I–V curves together with simulated I–V curves for three temperatures (40, 60 and 80 °C) are shown as an example in Fig. 3. Excellent fit has been obtained for the exponential part of the I–V curves. For lower temperature some deviations occur for resistive part of the I–V curve. This may be caused the fact that the series resistance is not fully constant parameter independent of the applied voltage and changes connected with changing the depletion layer thickness which shrinks with increasing temperature because of higher carrier concentration. This change is higher for lower temperatures when the depletion layer is thicker.

Extracted parameters of the Gaussian BHD and their temperature dependence are shown in Fig. 4 and the series resistance in Fig. 5. It is seen that all three parameters develop monotonously. The mean barrier height and the standard deviation decrease with increasing temperature while series resistance increases with increasing temperature. In principle, the same temperature dependence of these three parameters was obtained by Tuomi *et al.* [5]. The mean barrier height decrease with increasing temperature is in some contradiction to the barrier height increase with temperature in homogeneous diodes. Also Latreche *et al.* [3] obtained the opposite temperature dependence, but their diodes were significantly less inhomogeneous with standard deviation of the BHD only in hundredths of V.

Since the standard deviation of BHD of our diodes lowers with increasing temperature, *i. e.*, BHD starts to be narrower for higher temperatures, the SBH seems to be more homogeneous at higher temperatures. The temperature scale used is relatively small and it is not very probable that some re-organization and homogenization of the interface is underway. In homogeneous diodes the barrier height commonly increases with temperature, which is compensated by decreases of ideality factor which itself has not a physical meaning. In our approach it is expected that the all single barrier patches have ideality factor equal 1. This complementary effect of increasing the barrier height with simultaneous decrease of the ideality factor cannot be used here. Coming out from the assumption of the Gaussian BHD the used mathematics offers the obtained results concerning the temperature dependence of extracted paratemers. Development of the Gaussian BHD with temperature as it was extracted from the measured I–V curves is in Fig. 6. The mean barrier height shifts to the left and the BHD is narrowing with increasing temperature.

The temperature dependence of the series resistance is also an

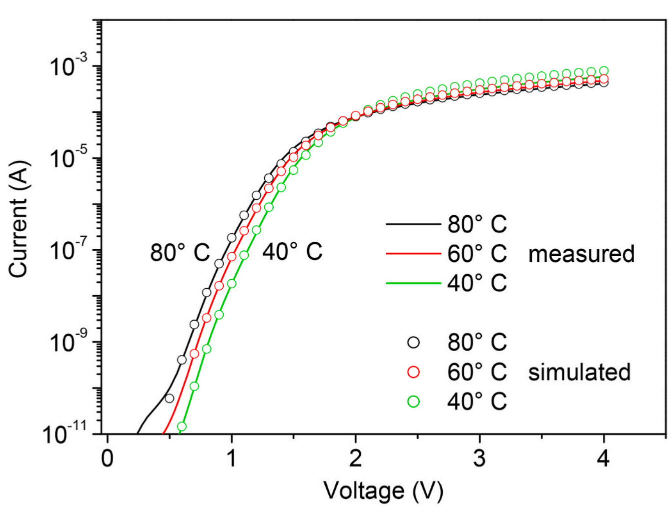

Fig. 3. Measured and simulated I–V curves for three chosen temperatures 40, 60, and 80 °C.

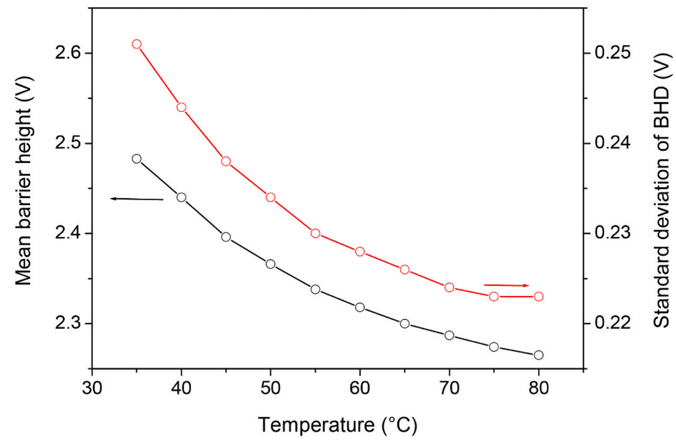

Fig. 4. Temperature dependence of the mean barrier height and standard deviation of the Gaussian barrier height distribution.

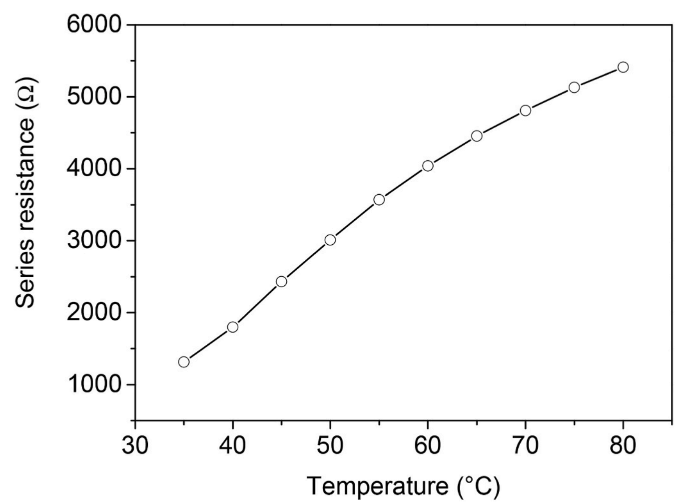

Fig. 5. Temperature dependence of the series resistance.

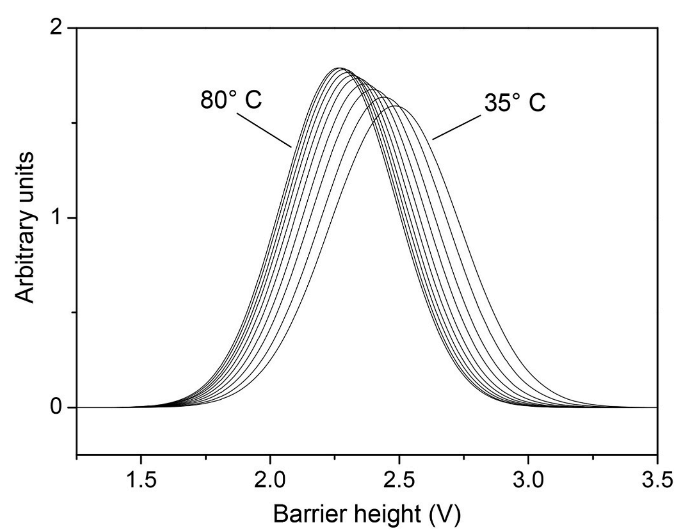

Fig. 6. Development of the Gaussian barrier height distribution with temperature. Temperature step is 5 °C.

interesting point (Fig. 4b). In the inset of Fig. 1 it is seen that all the I–V curves measured at different temperatures intersect at practically one point determining the voltage at which the same current is flowing through the diode independently of the temperature. At voltage behind the intersection point the current through the diode at higher temperatures is lower than the current at lower temperature. A similar situation has been already anticipated by Osvald and Horváth [17] theoretically for Schottky diodes with a thin inversion layer. The reason of this fact was temperature dependent series resistance of the quasi-neutral part of the semiconductor modeled by temperature dependent semiconductor mobility and doping concentration. Experimentally has been this effect of the I–V curve intersection already observed in Al/Ti/4-SiC Schottky diodes in Ref. [18] and by other authors [9,19] but the curves did not cross in one I–V point as it was in our case. The same effect has been experimentally measured also by Saxena et al. [20] and Brezeanu et al. [21] but the effect was not discussed in detail. The effect was also observed by Bolen and Capano in similar small temperature scale [22]. Generally, we may say that this intersection effect occurs often in SiC Schottky diodes. Even more, practical linear dependence of the forward voltage drop in temperature for different currents is used for production of temperature sensors based on SiC Schottky diodes [23]. On the other hand it is necessary to say that the I–V curves were measured at the majority of the mentioned works in much wider temperature intervals. It is clear, that such effect is not connected with barrier height homogeneity and is connected with the series resistance increase with temperature.

The electric conductivity of semiconductors is expected to increase with temperature. There are two mutually competitive influences; charge concentration increase and mobility decrease with increasing temperature. Funaki *et al.* [24] discussed the reason of the series resistance increase with increasing temperature. They approximated it by power expression with coefficient n varying for different temperature regions. As a physical reason of the resistance increase they identified acoustic phonon scattering and intervalley scattering. We may conclude, that charge scattering effect has greater influence on the conductivity and the final conductivity decreases for higher temperature. At the I–V cross-point the current through the diode is temperature independent which could find also some applications.

The situation with the cross-point is the same for homogeneous and inhomogeneous diodes. But an interesting fact is, that if we omit the series resistance in inhomogeneous diodes, as it is frequently done according to the approach of Song *et al.* [10], we also obtain an intersection of the I–V curves at different temperature. It is demonstrated in Fig. 7 where we show a simulation of the I–V curves generated with the BHD extracted from the experimentally measured curve at 40 °C and used also for generation of I–V curves at 60 °C and 80 °C. It is seen that the curves have the common intersection point. But this is only a fiction, in real diode the series resistance is always present. In real inhomogeneous diodes the current at high forward voltage is determined by the series resistance in the same way as in homogeneous diodes. Appropriate I–V curves with the same BHDs but with the series resistance 2250 Ω are also shown in Fig. 7. That is why, the effect we have observed must be caused by increasing the series resistance with increasing temperature. The question remains, why it is observed practically at the same current-voltage point for all the measured temperatures. The explanation may be that at the voltage at which the I–V curves cross practically all the barrier patches which significantly contribute to the current are already closed (BHD distributions are similar) and the series resistance starts to drive the current. Since the series resistance increases with temperature the I–V curves exchange their positions and the I–V curve with the higher current at SBH driven voltage region has lower current in series resistance controlled region.

The consideration of practically the same voltage where the current finishes to be controlled by the barrier height in the case of BHD is based on the fact, that for the current flow the lower part of the BHD is important for the current flow. The barrier patches with the barrier height higher than the mean barrier height have a very low contribution to the whole current.

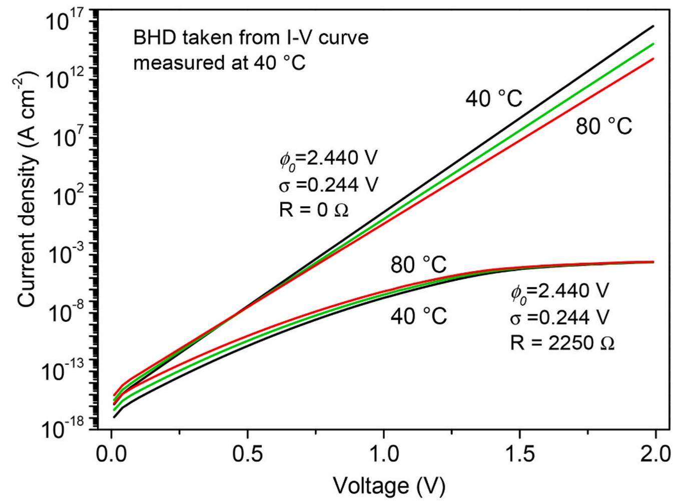

Fig. 7. Intersection point for inhomogeneous I–V curves with omitted series resistance and appropriate I–V curves with real series resistance. The temperatures are 40, 60 and 80 °C.

4. Conclusion

The temperature dependence of the Au/Ni/4H–SiC Schottky diodes I–V curves in relatively small temperature 35–80 °C has been studied. The I–V curves measured at different temperatures had not linear part in semi-logarithmic plot. It was found out that the I–V curves may be very well modeled and simulated as the I–V curves of an inhomogeneous barrier with some statistical distribution of small barrier height patches. Barrier heights of these patches were assumed to fulfill Gaussian BHD. The parameters of these distributions and series resistance of the diode were calculated by the least squares method. Extracted mean barrier height and standard deviation decrease monotonously with increasing temperature. On the other hand the series resistance increases with increasing temperature, which causes crossing of the temperature dependent I–V curves in one point where the current is independent of the diode temperature. Due to the temperature dependence of the series resistance anomalous cross-point of the I–V curves measured at different temperatures has been observed.

CRediT authorship contribution statement

J. Osvald: Software, Methodology, Formal analysis, Conceptualization. **L. Hrubčín:** Investigation, Resources. **B. Zaťko:** Validation, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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