SiC SCHOTTKY BARRIER RECTIFIERS - THEORY AND PRACTICE

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The direct current characteristics of real packaged SiC Schottky barrier rectifiers in the light of up to date knowledge on the reveal subject are presented in this paper. The theory on SiC Schottky barrier rectifier from literature is collected in the text. For comparison the characteristics of SiC Schottky diodes fabricated in research laboratories and reported in literature are also presented. The investigated diodes were intended to work with the maximal forward current of 1 A and the maximal reverse voltage of 600 V. The measured characteristics of four diodes are in a harmony with characteristics presented in product data sheets for room temperature. In the forward current range for which the diodes are intended to work that is for current from 1 mA to 1 A, the I-V characteristics of the diodes are almost identical. The ideality factor ranges from about 1.12 to about 1.17 and is within the range reported in relevant literature. The calculated series resistance at nominal current of 1 A is about of 0.45 Ω. However, there are very different values of reverse leakage currents, although these values are within the range guaranteed by the producer. On the other hand, the forward I-V characteristics below the voltage of 0.75 V and the reverse I-V characteristics below the voltage of 600 V have large discrepancies. The measured reverse I-V characteristics are different from the commonly shown characteristics in papers.

1. INTRODUCTION

The inherent properties of silicon carbide (SiC) as large breakdown electric field strength, large saturated electron drift velocity, reasonably high electron mobility, and high thermal conductivity makes it an attractive candidate in many applications. SiC-based semiconductor electronic devices and circuits have been developed for use in high-temperature, high-power, and/or high-radiation condition under which conventional semiconductors (Si, GaAs) cannot adequately work [1-3].

The expected applications of SiC electronics range from high-voltage switching in public electric power distribution and electric motor drives, to more powerful mi-

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crowave radar and communication, to controls for more fuel-efficient jet aircraft and automobile engines [2-6].

The wide bandgap energy and as a result of it low intrinsic carrier concentration of SiC allow SiC device to maintain functionality at much higher temperatures than Si. The high breakdown field and high thermal conductivity of SiC, coupled with high operational junction temperature, permit extremely high-power densities and efficiencies to be realised in SiC devices. As a result of these properties the most beneficial SiC-based electronics applications are in the area of high-temperature and high-power device operation [2,5].

The advantages Schottky contact include an ease of fabrication and high-switching--speed capability due to the absence of minority carrier injection effects observed in p-n junction devices [1]. SiC high breakdown field and wide energy bandgap permit operation of SiC Schottky diodes at much higher voltages (i.e., kilovolt) and current densities (kA/cm^2) than is practical with silicon-based Schottky diodes. A drawback of the wide bandgap semiconductor diodes is that they require larger forward bias voltage (~1 V) to reach the turn-on state where significant current begins flowing, and this can lead to an increase in on-state power dissipation. However, the high breakdown strength of SiC results in smaller diode drift layers, as compared to Si, for a given blocking voltage, thus reducing the drift region resistance (100 times) and as the result of it reducing the forward voltage drop for the high density current. This benefit should greatly overcome SiC on-state voltage disadvantages for the low density current in most high-power systems [2,7]. Finally, the thermal impedance of the packages is reduced by SiC the high thermal conductivity that helps in spreading the heat laterally [8].

Although there are about 170 known polytypes of SiC, only two (4H-SiC and 6H--SiC) are available commercially. 4H-SiC is preferred over 6H-SiC for vertical power devices because of its higher vertical (a-axis) electron mobility. A variety of prototype SiC devices have been successfully fabricated on both 6-H and 4-H polytypes. The prototype SiC devices have demonstrated excellent area-normalised performance, often well beyond 10 times the theoretical power density of Si power electronics. However, the presence of micropipe crystal defects has thus prevented scale-up of small-area prototypes to large areas that can deliver high operating currents [2-8].

Electronic systems operating in the 600-1200 V range currently utilise silicon (Si) PiN diodes, which tend to store large amount of minority carrier charge in the forward-biased state. The stored charge has to be removed by carrier recombination before the diode can be turned off. The prime benefits of the SiC Schottky Barrier Diode (SBD) lie in its ability to switch faster (at least two times) with almost zero reverse recovery charge even at high junction temperature operation than the comparable silicon PiN diodes (Si SBDs are not viable in the 600 V range) [9].

The increasing number of portable applications is primarily driving miniaturisation in electronics. As a result, manufacturers of Switch Mode Power Supplies (SMPS)

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have to increase the power density in their products. This can be achieved by reducing the size of passive components (by increasing the switching frequency) and by reducing the power losses and the corresponding cooling effort (heat sink and/or fan). To achieve these goals, the main semiconductor power components must achieve a significant reduction of switching power losses. For this reason, unipolar semiconductor devices are replacing bipolar devices. The input stage of an off-line AC-DC power supplies SMPS used in computer and telecom application usually requires devices rated in the range of 500-600 V. Today's Si and GaAs Schottky barrier diodes have a maximum blocking voltage of 250 V. Therefore SiC Schottky diodes which offer high rated voltages up to 1200 V and additionally a very low specific on-resistance should be used in this area [10-12].

Besides, in such power supplies the AC input sees a large inductive (transformer) load, which causes the power factor to be substantially lower than 1. A Power Factor Correction (PFC) circuit allows the AC input line to see near-unity power factor, as required by new legal requirements. Boost converters are usually used to realise such active PFC circuits. The SiC SBDs offer many advantages in this respect: reduced switching losses in the diode and the MOSFET, higher junction temperature operation up to 175°C, reduction in the number of MOSFETs by 50%, faster switching up to 500 kHz to reduce the EMI filter size and other passives, and reduction or elimination of the active or passive snubber [10-11]. Therefore, according to experts from Cree Inc. and Infineon Technologies AG, one of the biggest applications for SiC SBDs in the near future will be in the power factor correction and SMPS circuits. Further they expect powerful cost reduction of SiC devices over the next years [10-11].

Besides, the on-resistance of SiC SBDs increases with temperature due to the reduction in the electron mobility at elevated temperatures. This results in the negative temperature coefficient of large forward current at constant voltage and allows to place in parallel more than one die in a package without any unequal current sharing problem [10-12]. The higher breakdown electric field strength of SiC than of Si and GaAs enables the potential use of SiC SBDs in 600-2000 V [10].

2. OUTLINE OF SCHOTTKY BARRIER DIODE THEORY

In the case of high mobility semiconductors, such as silicon, gallium arsenide, and silicon carbide at relatively low doping levels, the thermionic emission theory is usually used to describe current flow across the Schottky barrier interface [1]:

$$J = J_S \left[\exp\left(qV / nkT \right) - 1 \right] \tag{1}$$

$$J_S = A^* T^2 \exp\left(-q\Phi_B / kT \right) \tag{2}$$

where T is the absolute temperature, q is the electron charge, k is the Boltzmann

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constant, n is the ideality factor and V is the applied voltage. The term J_S refers to the saturation current density of the Schottky barrier, A^* is the effective Richardson constant whose value for N-type SiC is experimentally determined to be 140 A/cm^2 K^2 and is in good agreement with the theoretically calculated value of 146 A/cm^{2}K^2, $q\Phi_B$ is the Schottky barrier height in [eV] [13]. The Schottky barrier height can be calculated from the saturation current I_S determined by an extrapolation of the log (I) versus V curve to V = 0. The current axis intercept for the straight-line portion of this semilog plot at V = 0 is given by I_S [29]. Unfortunately, in the case of SiC diodes with Schottky barrier diode inhomogeneity it is almost impossible to determine the adequate saturation current. Then, the SiC Schottky barrier height is commonly calculated from the capacitance-voltage measurements. From the plot of C^{-2} versus V when the diode is reverse biased, the intercept on the voltage axis gives the diffusion potential V_i. Then the barrier height $q\Phi_B$ can be extracted using the relationship [29-30]:

$$\Phi_B = V_i + kT / q + V_o \quad (3)$$

where V_o is the difference between the Fermi level and the conduction band for n--type material. The built-in potential $V_{bi} = V_i + kT/q$ is related to the barrier height by the relationship:

$$\Phi_B = V_{bi} + V_o \quad (4)$$

The expression kT/q is 0.026 eV at the temperature of 300 K.

When a forward bias is applied, the first term in the square brackets of Eq. 1 becomes dominant and the current flow across the Schottky barrier under forward conduction is given by [1]:

$$J_F = J_S \exp (qV_{FB} / nkT) \quad (5)$$

where V_{FB} is the voltage drop across the Schottky barrier.

The Schottky barrier power rectifier is made by growing an epitaxial n-type layer upon a thick highly doped (N+) substrate. A thick lightly doped epitaxial drift layer must be used for the semiconductor region to support the reverse blocking voltage. The ohmic contact is provided on the backside of the substrate while the Schottky contact is formed on the front side of the lightly doped epi-layer. Although, several different metals have been employed to form Schottky barrier diodes on SiC, nickel (Ni) and titanium (Ti) are the most commonly utilised metals. The diode current flows through the drift layer producing a resistive voltage drop. It should be noted that there is no modulation of the drift region resistance in these devices due to the negligible minority carrier injection. The forward voltage drop (on-state voltage drop V_F) of a Schottky barrier power rectifier is an important parameter and is primarily determined by the metal-semiconductor barrier height (which determines the knee voltage), and the series resistance of the diodes. Using Eq. 2 and 3 and including the resistive voltage drop, it can be shown that the total forward voltage in the Schottky

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rectifier will be given by [1,14]:

$$V_F = (nkT/q)\ ln\ (J_F / A^*T^2) + n\Phi_B + R_S J_F \tag{6}$$

where R_S is the total series resistance per cm^2, which is referred to as the specific series resistance (expressed in Ωcm^2) of the rectifier. It includes contributions from the drift region, the substrate, and cathode contact resistance and the anode metallisation resistance. The resistance of the substrate can be significant in low voltage rectifiers for which the drift layer resistance becomes small. The contribution from the substrate can be made smaller by increasing its doping level and reducing its thickness. Neglecting the substrate and contact resistance, the series resistance for a specified breakdown voltage is [1]:

$$R_S \approx \rho_{epi}\ t_{epi} = t_{epi} / q\mu_n N_D = 4V_{BR}^2/\mu_n e_S E_{CR}^3 \tag{7}$$

where ρ_{epi} is the epilayer resistivity, t_{epi} is the epilayer thickness, μ_n is the electron mobility, N_D is the donor concentration, ε_S is the semiconductor electric constant ($\varepsilon_S=\varepsilon_{RS}\varepsilon_0$, ε_{RS}= 9.7 for SiC), and E_{CR} is the semiconductor critical electric field as a week function of the drift region doping N_D (E_{CR}= 3 MeV/cm for 4H-SiC at N_D = 10^{17} cm^{-3}) [2].

As the breakdown voltage of Schottky rectifier is increased, R_S increases, which in turn increases the forward voltage drop according to Eq. 6. The calculated forward voltage drop of a 4H-SiC SBD at 100 A/cm^2 as a function of the breakdown voltage for different barrier heights does not increase up to a voltage of 2000 V, beyond which a rapid increase is observed, mainly due to the increase a R_S [13]. In general the forward voltage drop of experimental SiC Schottky rectifiers has agreed well with thermionic emission theory [15-20].

When a reverse voltage is applied to the Schottky rectifier, the voltage is supported across a depletion layer, which extends into the semiconductor. The depletion region thickness (W) at a reverse bias (V_R) below the breakdown voltage of the diode is given by [1]:

$$W\ (V_R) = [(2\varepsilon_s / qN_D)\ (V_R + V_{bi})]^{1/2} \tag{8}$$

where V_{bi} is the built-in potential of the metal-semiconductor contact.

This depletion width can be used to calculate the capacitance per unit area of the Schottky barrier diode [1]:

$$C\ (V_R) = \varepsilon_s / W\ (V_R) \tag{9}$$

The key parameters of power Schottky rectifier are breakdown voltage, forward voltage drop, reverse leakage current, power dissipation, and switching time. Depending on the application, different parameters become more or less important relative to others. The breakdown voltage (V_{BR}) of a SBD depends on the semiconductor critical field, epilayer doping, epilayer thickness, and device edge termination [14]:

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$$V_{BR} = \varepsilon_S E_{CR} / 2qN_D \tag{10}$$

The basic reverse leakage current mechanisms of a Schottky rectifier are thermionic emission, thermionic field emission, field emission, and generation in the depletion region. In addition to these basic mechanisms, surface leakage and defect related leakage may occur. In real devices current caused by more than one of these mechanisms occurs. The dominant mechanism depends on the Schottky barrier height, temperature, and applied bias. Thermionic emission reverse leakage current is also affected by image-force barrier height lowering. The image-barrier height lowering can be described by [14]:

$$\Delta\Phi_B = (qE_m/4\pi\varepsilon_S)^{1/2} \tag{11}$$

where $\Delta\Phi_B$ is the image-barrier height lowering, and E_m is the electric field at the metal-semiconductor interface. The thermionic emission reverse leakage current density, including the image-force barrier height lowering may be written as:

$$J_R = A^*T^2 \exp[-q\Phi_B / kT] \exp[q\Delta\Phi_B / kT] \tag{12}$$

Experimentally, the reverse leakage current of both 6H and 4H SiC Schottky rectifiers have a larger magnitude than expected by thermionic emission and a stronger voltage dependence than predicted by image-force barrier height lowering [22]. Thus, other reverse current mechanisms also must be considered. Thermionic field emission and field emission are tunnelling mechanisms and are typically not considered to contribute to the reverse leakage current of moderately and lightly doped Si Schottky rectifiers. However, because of the large critical field of SiC, the large reverse voltage is applied and the probability of thermionic field emission and field emission in SiC Schottky diodes increases [23]. The difference between thermionic field emission and field emission is that thermionic field emission is the tunnelling of electrons thermally excited above the Fermi level of the metal while field emission is the tunnelling of electrons at the Fermi level of the metal. The magnitude and voltage dependence of the tunnelling current has been calculated and compared with experimental SiC Schottky rectifiers reverse leakage currents. These calculations agree relatively with the experimental data and suggest that thermionic field emission and field emission must be considered as significant [23]. The metal-semiconductor-tunnelling barrier may be approximated as a triangular potential barrier. The relationship between tunnelling current density and electric field for the triangular barrier may be expressed in terms of the electric field and the zero bias Schottky barrier height [24]:

$$J_T \propto E_m^2 \exp[-8\pi(2m^*)^{1/2}\Phi_B^{3/2} / 3hqE_m] \tag{13}$$

where m^* is the electron effective mass, and his the Planck constant.

The reverse leakage current caused by the charge carriers generation in the depletion region may be exprressed as:

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$$J_G = qn_iW / 2\tau_r \tag{14}$$

where n_i is the intrinsic carrier concentration, and τ_r is the carrier lifetime within the depletion region. The large bandgap of SiC makes n_i very small ($\sim 10^{-7} cm^{-3}$) and the generation of reverse leakage current in the depletion can be ignored [24].

Experimental results show stronger temperature dependence at low electric fields than at large electric fields suggesting that the reverse leakage current is due to region both thermionic field emission and field emission. At small electric fields, the reverse leakage current appears to be dominated by the thermionic field emission but at large electric fields the field emission becomes more significant [22]. For example, a numerical calculation of the total tunnelling current including the image force lowering of the barrier height for a Schottky barrier with a barrier of 1.1 eV has been done by J.Crofton and S.Sriram [24]. Their results shows that when the voltage is increased from 200 V to 400 V, the leakage current increases about four orders of magnitude.

3. STATE OF ART OF INDUSTRIAL PRODUCTS

3.1. Measurement procedures

We measured capacitance-voltage and current-voltage characteristics of four SiC Schottky rectifier commercially available samples purchased from Cree Inc.-Power Products. The rectifiers named CSD01060 have typical packages TO-220-2 and are intended to applications including switch mode power supplies, power factor correction and motor control. The main electrical characteristics taken from Cree preliminary data sheet of these diodes are given in Tab. 1. The capacitance-voltage characteristic (C-V) measurements were performed for a reverse bias voltage in the range from 0 to 20 V for 1 MHz and 100 kHz measuring frequency using a Keithley 590 CV Analyzer. The current voltage characteristic (I-V) measurements were performed using a measuring tester composed of Analysing Digital Storage Characteriscope System Type TR-4607-1 and Characteriscope Standard Measuring Unit Type Tr-4607- made in Hungary. For I-V characteristics, the voltage was varied from 0 to 4 V in the forward direction, and from 0 to - 1000 V in reverse, but the current was limited to 4A in the forward direction and to 0.4 mA in the reverse to avoid a destruction of devices. All measurements were done at the room temperature. The 1-V measuring tester worked in pulse mode, consequently a power dissipation in the tested diodes was slight. Therefore we believe that a temperature influence on 1-V characteristics was negligible.

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Table 1. Main electrical characteristics of Schottky barrier diodes CSD01060.
Tabela 1. Główne parametry prostowniczych diod Schottky'ego o symbolu CSD01060.

Parameter	Type	Max
DC and repetitive peak reverse voltage [V]		600
Average forward current [A] T_C=150°C		1
Repetitive peak forward surge current [A], T_C=25°C		5
Power dissipation [W] T_C=25°C		21.4
Operating junction temperature [°C]		175
Forward voltage [V] I_F=1A, T_J=25°C	1.6	1.8
Reverse current [μA] V_R=600V, T_J=25°C	20	100
Total capacitance [pF] V_R=0V, T_J=25°C, f=1MHz	80	

3.2. Results and discussion

The measured current-voltage characteristics of the presented four diodes, labelled as A, B, C, D are shown for forward bias in the Figs. from 1 to 3 and for reverse bias in the Figs. from 4 to 6. The characteristics are shown in various arrangements of co-ordinates and for various current and voltage ranges to make their analysis easier. In the Fig. 1 with lin (I) - lin (V) co-ordinates you can see that the forward characteristics of all diodes are almost identical up to about a bias voltage of 2 V. The threshold voltage where significant current begins to flow is about 1 V and the forward voltage drop for nominal current of 1 A is about 1.5 V. However, for the higher current (much above the nominal current) the characteristics of the individual diodes are very divergent, what means that for the same currents the forward voltage drops are different. We think that this is a result of differente series resistances for high current densities in the measured diodes.

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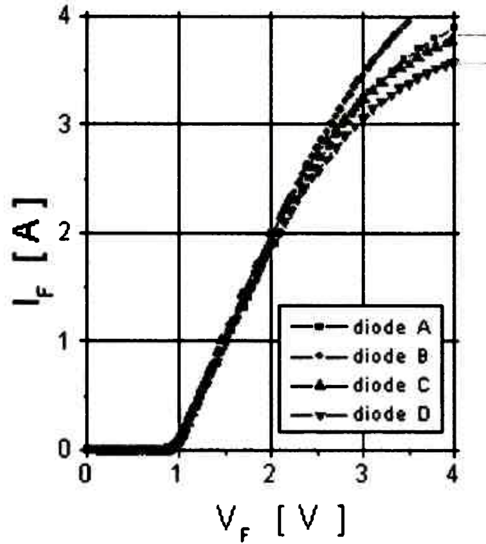

Fig.1. Forward current-voltage characteristics of real SiC Schottky barrier rectifiers.
Rys.1. Charakterystyki prądowo-napięciowe rzeczywistych, prostowniczych diod Schottky'ego z SiC dla kierunku przewodzenia.

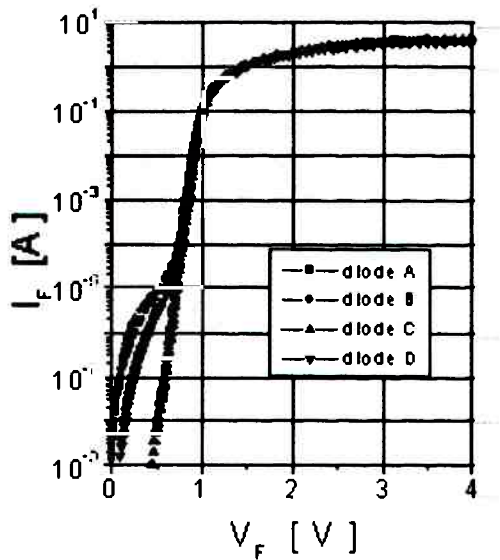

Fig.2. Forward current-voltage characteristics from Fig. 1 in log (I) – lin (V) co-ordinates.
Rys.2. Charakterystyki prądowo-napięciowe z Rys. 1 w układzie współrzędnych log(I) - lin(V).

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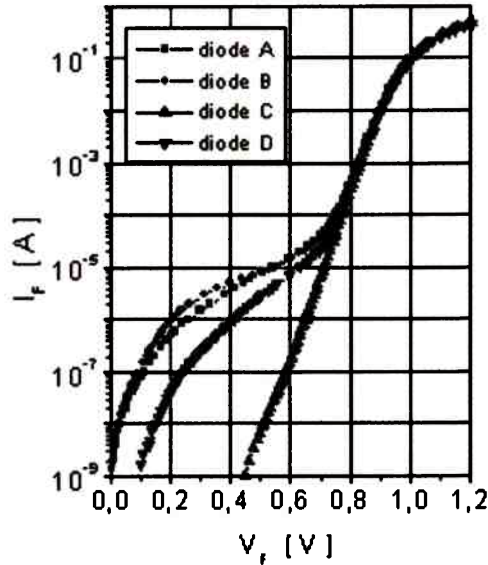

Fig.3. Forward current – low voltage characteristics from Fig. 1 in log (I) – lin (V) co-ordinates

Rys.3. Charakterystyki prądowo-napięciowe z Rys. 1 w układzie współrzędnych log(I) - lin(V) dla małych wartości napięć.

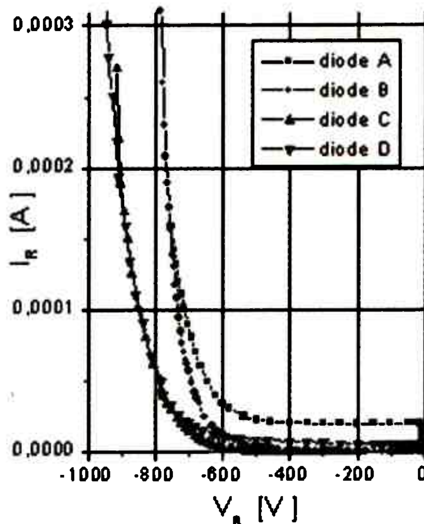

Fig.4. Reverse current-voltage characteristics of real SiC Schottky barrier rectifiers.

Rys.4. Charakterystyki prądowo-napięciowe rzeczywistych, prostowniczych diod Schottky'ego z SiC dla kierunku wstecznego.

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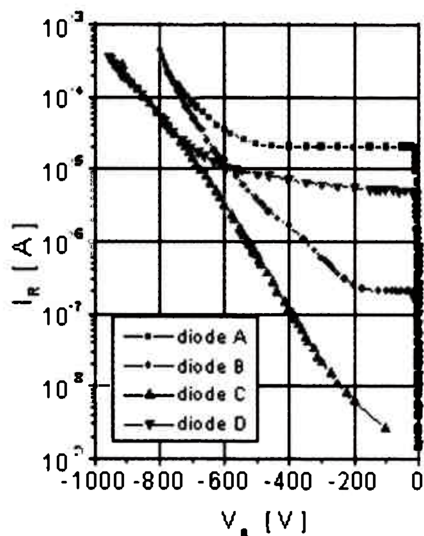

Fig.5. Reverse current-voltage characteristics from Fig. 4 in log (I) – lin (V) co-ordinates.
Rys.5. Wsteczne charakterystyki prądowo-napięciowe z Rys. 4 w układzie współrzędnych log(I) - lin(V).

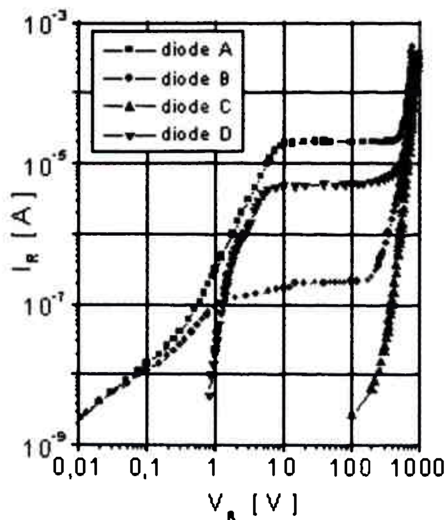

Fig.6. Reverse current-voltage characteristics from Fig. 4 in log (I) – log (V) co-ordinates.
Rys.6. Wsteczne charakterystyki prądowo-napięciowe z Rys. 4 w układzie współrzędnych log(I) - log(V).

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For example, for the current of 3.5 A, the forward voltage drop is 3.03 V for the diode B and 3.75 V for the diode D respectively. Further, in the Fig. 3 with log (I) – lin (V) co-ordinates you can see that the forward characteristics of diodes are very diverse below a bias voltage of about 0.75 V.

According to the thermionic current model of Schottky barrier diode for forward bias (Eq.1) the log (I) – lin (V) plot should be a straight line extending over many orders up to a high current density where the series resistance causes its bending. In our case, only the I-V plot of the diode C remains a straight line over seven orders of magnitude as shown in Figs. 2-3. The other diodes (A, B, and D) have the log (I) –lin (V) plots with the linear region extending only on two orders of magnitude from the current of 10^{-4} A to the current of 10^{-2} A. Indeed, the low forward voltage region up to a voltage of aboute 0.75 V exhibits the higher current than that expected using the thermionic-emission model. This excess current is clearly shown in the range of 10^{-9} A – $5x10^{-5}$ A. Such anomalous current-voltage characteristics of SiC Schottky barrier diodes have been reported by many researchers and many phenomena have been shown to cause deviation from the ideal Schottky interface behaviour [25-27].

In our opinion, the best convincing explanation such anomalous is reported by M. Bhatnagar and co-workers [22] who studied an effect of surface inhomogeneities on the electrical characteristics of SiC Schottky contacts. They presented a model based upon the presence of localised defects in the epitaxial layer at the SiC/metal interface, which result in lowering of the Schottky barrier height (SBH) in localised region. Then, two regions of the SiC/metal interface are identified. The hight-SBH region is the defect free SiC/metal interface where the barrier height is chosen to be equal to the value obtained by the C-V measurements on the actual SiC Schottky contacts. The region where lowering of the barrier height occurs is identified as the low-SBH region. The contributions to the forward current from the high-SBH and low-SBH regions are indicated by I_{FH} and I_{FL} respectively. At very low forward biases, most of the current flows through the low-SBH region and the total forward current is approximately equal to I_{FL}. However, at higher forward biases, the voltage drop across the epitaxial layer resistance becomes large for the low-SBH region due to its higher current density and thus I_{FL} tends to saturate much faster than to I_{FH}. This results in the total forward current becoming approximately equal to I_{FH} for higher bias voltages (above the voltage of 0.75 V in our case). According to this model, it is obvious that a shape of I-V characteristics with surface inhomogeneities should be dependent on a difference in the barrier height of the high-SBH and the low-SBH regions and the ratio of the area of the low-SBH region to the total diode area. Further, it is concluded that at those higher forward biases, the on-state behaviour of the Schottky contact with the Schottky barrier height inhomogeneity is identical to that of the defect-free device [22].

The I-V plot shapes of our diodes A, B, D for low forward bias voltage indicate that the individually tested diode exhibits a various difference in the barrier height

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of the high-SBH and the low-SBH regions and the ratio of the area of the low-SBH region to the total diode area.

Further to explain unusually high reverse leakage current observed in SiC Schottky rectifiers M. Bhatnagar and co-workers (22) assumed in their model that a small region of the low-SBH contact is surrounded by a large area contact with higher SBH. Thus, the potential distribution under the low-SBH region for reverse bias would be different from the case where the entire contact was a low-SBH contact. So, the potential profile under the low-SBH region would tend to be similar to that under the high-SBH region and this would result in a pinch-off of the low-SBH region. Based on this model the numerical simulations show that even for a Schottky barrier height inhomogeneity with a small difference in the barrier height of the high-SBH and the low-SBH regions and small ratio of the area of the low-SBH region to the total diode area, the reverse leakage current is dominated by the current through the low-SBH region. Then localised lowering of the barrier height can significantly affect the reverse I-V characteristic [22]. On the contrary, the simulations show that the effect of the presence of the Schottky barrier height inhomogeneity on the forward characteristics is very small even for a large value of the difference in the barrier height of the high-SBH and the low-SBH regions (such as 0.4 V).

Base parameters of the tested diodes determined from measurements of I-V and I-V characteristics are shown in Tab. 2. The deviation of the forward log (I)-V curve from linearity is $\Delta V = IR_S$, allowing series resistance R_S to be determined according to $R_s = \Delta V/I$ [29]. Using this relation for the curves shown in the Fig. 2 we calculated R_S of all tested diodes for the current of 1 A and 3 A. The series resistances range from 0.42 Ω to 0.50 Ω ($\Delta R_S \approx$ +/- 10%) and from 0.52 Ω to 0.60 Ω for the current of 1 A and of 3 A, respectively. The increase of series resistance with the increase of current may be caused by a decrease of carrier mobility in the drift region. It is known that the drift region carrier mobility decreases when the junction current density and/or the temperature increase [13]. The ideality factor n for the current range from 10^{-3} A to 10^{-2} A where the log (I)-V curve is linear we calculated using the expression derived from Eq. 1 [30]:

$$n = (q / kT)(\sigma V / \sigma \ln J) = (q / kT)\,(V' - V'') / (\ln I' / I'') \qquad (15)$$

As you can see in the Tab. 2 the ideality factor is from 1.117 to 1.165. The ideality factor values for Schottky 6H-SiC and 4H-SiC n-type diodes that you can meet in other papers ranges from 1.0 to 1.2 [14, 20, 28, 31].

As we do not know the Fermi level of examined diodes, we calculated from the capacitance-voltage measurements the built-in potential $V_{bi} = V_i + kT/q$ that is related to the barrier height by the relationship: $\Phi_B = V_{bi} + V_o$. The plot of C^{-2} versus V we performed on base the measured C-V characteristics for 100 kHz. A difference between the C-V characteristics for 100 kHz and the C-V characteristics for 1 MHz was negligible. It means there were not series resistance effects on the C-V charac-

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teristics. As you can see in Tab. 2 the calculated built-in potential is approximately 1.68 V. D. J. Morrison with co-worker calculated that V_o is 109 mV for 4H-SiC with N_D = 2.1 x 10^{17} cm^{-3} at room temperature [17]. When we assume in our examined diodes N_D = 2.1 x 10^{16} cm^{-3} at room temperature and use the relationship $V_o = (kT/q)$ ln (N_C/N_D) where the N_C is effective density of state in the conduction band, the V_o will be 169 mV and $q\Phi_B$ approximately will be 1.85 eV.

Much work has been done to determine barrier heights of metal-semiconductor contacts realised on 6H and 4H polytypes of SiC [16, 20-21, 26, 29, 31-34]. Usually, SiC Schottky contacts have been realised by depositing Ni, Pt, Co, Al, Ti, Au, Ti/Au, and Ni_2Si. In general, studies have shown a discrepancy between the barrier height values obtained by current-voltage and capacitance-voltage measurements, the latter always being larger about of 0.2 eV. According to C. Raynaud and co-workers [20] the discrepancy between C-V and I-V analyses may be explained by the presence of Schottky barrier height inhomogeneity [20]. A model with the presence of two barriers in parallel they have used shows that the barrier height by C-V method is in general close to the highest barrier height, where as the barrier height by I-V method is in general close to the lowest one. D. J. Morrison and co-workers have examined an influence of different pre-metallization surface preparation procedures on the key parameters of Ni / 4H-SiC Schottky barrier structures [34]. They have obtained Schottky barrier heights by C-V method in the range from 1.26 to 1.78 eV. In other papers you can find the values of Schottky barrier heights for the Ni /4H-SiC contacts ranging in such limits [13, 20-21, 28, 26, 32-34].

In the Figs. 4-6 you can see that the reverse current-voltage characteristics of tested diodes present a very different shapes. The reverse leakage current rapidly increases for the reverse voltage higher than of 600 V. For the reverse voltage of 100 V (Fig. 5) the reverse leakage current is 3 nA, 200 nA, 5 µA, and 20 µA for the diodes named C, B, D, and A respectively. With the exception of the diode C, in the remaining diodes the phenomenon of a reverse current saturation appears. But, the current flowing as a result of this phenomenon is not the saturation current J_S of the Schottky barrier that is usually used in the thermionic emission theory [Eq. 2]. We suggest that this current saturation is the result of the mentioned above pinch-off effect of the low-SBH region and the different values of the current for various diodes mean that a different level of the Schottky barrier height inhomogeneity occurs. The voltage up to which the low-SBH region current dominates is about 200 V for the diode B and about 500 V for the diodes A and D. Moreover, in the Fig. 6 you can see that in the diodes A and B a near ohmic reverse leakage flows for low voltage up to about 1 V. In the case of the diode C, the low-SBH region current does not occur for the measured voltage region. Then, we can say that this diode is a surface SBH inhomogeneity-free sample. For higher reverse voltage where the low-SBH region current does not dominate, the shapes of log (I) – lin (V) are similar what suggests that in this voltage range the same carrier transport mechanism occurs for all tested diodes. The slop of the plots suggests an exponential behaviour at higher reverse voltages.

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Table 2. Parameters of SiC Schottky barrier diodes determinal from measurements of I-V and C-V characteristics.
Tabela 2. Parametry prostowniczych diod Schottky'ego wyznaczone na podstawie zmienionych charakterystyk prądowo- i pojemnościowo- napięciowych.

Parameter	Diode A	Diode B	Diode C	Diode D
n	1.165	1.153	1.117	1.143
R_S [Ω] I_F = 1 A	0.47	0.46	0.42	0.50
R_S [Ω] I_F = 3 A	0.56	0.52	0.55	0.60
C [pF] V_R=0V f = 100 kHz	81.6	85	71.7	69.2
V_{bi} [V]	1.71	1.68	1.68	1.68
I_R [μA] V_R = 100 V	20	0.2	0.003	5

We have compared the reverse I-V characteristic of our diode C with such characteristics obtained by other researchers. When the reverse voltage increased from 400 V to 800 V the reverse leakage increased by a factor of 600 for our diode C, by a factor 100 for Ni Schottky diodes on $1.6x10^{16}$ cm^{-3} doped 10 μm thick n-type 4H-SiC measured by K.J. Schoen [14], and by a factor 20 for Ti/Al Schottky diodes on $1x10^{16}$ cm^{-3} doped 10 μm thick n-type 4H-SiC measured by R. Raghunathan [31]. But when the reverse voltage increased from 200 V to 400 V the reverse leakage increased by a factor of 15 for our diode C, by a factor 170 for those diodes measured by K.J. Schoen [14], and by a factor 5 for those diodes measured by R. Raghunathan [31]. However, according to J. Crofton's [23] numerical simulations, including the reverse tunnelling current and the image force lowering of the barrier height obtained for Pt Schottky diodes on $3x10^{16}$ cm^{-3} doped n-type 6H-SiC, the current should increase by a factor 750 in the voltage range from 200 V to 400 V. On the other hand, according to L. Zheng analytic calculation [27], based on both the thermionic emission and tunnelling processes including also image barrier lowering for the same diodes, the current should increase by a factor 50 in the same voltage range.

In conclusion we can assume that many various earlier mentioned physical phenomena control the reverse current flow in SiC Schottky barrier diodes. A participation of the different carrier transport mechanisms in total reverse current flow depends on many material, structural and technological factors. In the end we tried to correlate the tested diodes characteristics shown in the figures and in the tables but we do not see any correlation between the individual parameters.

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4. CONCLUSIONS

The I-V characteristics of tested diodes for the forward bias below 0.75 V and the reverse bias below 600 V have large discrepancies. These discrepancies show the existence of Schottky barrier contact inhomogeneities in three among four investigated diodes. The mentioned discrepancies, however, do not limit most of applications of tested rectifiers. The characteristics shown in the figures and in the tables do not indicate any correlation between the individual parameters of the diodes. Comparing the reverse I-V characteristics of our surface SBH inhomogeneity-free C diode with such characteristics obtained by other researchers we can see many differences in current-voltage dependencies. Usually in the case of weekly doped semiconductors the reverse current contribution from tunneling is negligible but it is known that SiC has a high dislocation density, much higher than that in Si or GaAs. Because of many defects near the surface region, electron can go through the Schottky barrier by defect-assisted tunneling enhancing the tunneling probability. The linear log(I)-lin(V) relationship for the diode C (Fig.5) indicates that the defect-assisted tunneling current is predominant in the reverse leakage current.

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DIODY PROSTOWNICZE SCHOTTKY'EGO Z WĘGLIKA KRZEMU TEORIA I PRAKTYKA

Abstrakt

W artykule przedstawiono stałoprądowe charakterystyki handlowo dostępnych, prostowniczych diod Schottky'ego wykonanych z węglika krzemu (SiC) oraz omówiono mechanizmy przepływu prądu zgodnie z obecnym stanem wiedzy w tej dziedzinie. Dla porównania przedstawiono dostępne w literaturze charakterystyki diod Schottky'ego z SiC wytworzonych w laboratoriach badawczych. Badane diody przewidziane są do pracy z maksymalnym prądem przewodzenia wynoszącym 1 A i z maksymalnym napięciem wstecznym wynoszącym 600 V. Zmierzone w temperaturze pokojowej parametry czterech diod spełniają wymagania zawarte w karcie katalogowej producenta. W istotnym dla pracy tego typu prostownika przedziale wartości natężenia prądu tj. od 1 mA do 1 A, charakterystyki I-V tych diod są prawie identyczne. Współczynnik idealności badanych diod wynoszący od 1.12 do ~ 1.17 mieści się w przedziale który podawany jest w literaturze. Określona rezystancja szeregowa diod dla prądu 1 ampera wynosi ~ 0.45 Ω. Natomiast, dla polaryzacji wstecznej badane diody mają bardzo różne wartości prądu upływu, chociaż mieszczą się one w granicach gwarantowanych przez producenta. Generalnie, dla napięć poniżej 0.75 V w kierunku przewodzenia oraz dla napięć poniżej 600 V dla kierunku wstecznego, zmierzone charakterystyki I-V zdecydowanie różnią się między sobą i są istotnie inne od tych prezentowanych zwykle w publikacjach.

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