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# Interpretation of some physical parameters of SiC Schottky interfaces manufactured by diffusion welding technology

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**Abstract.** The goal of this paper is to show some new problems introduced by the diffusion welding technology for SiC Schottky structures concerning the current transport through the metal–semiconductor interface using classical thermionic-diffusion theory. The experimental results show clearly that the classical Schottky current model parameters like Richardson coefficient, on-state series resistance and ideality factor differ from their usual values. The calculations show that the current transport, based on classical description of the ideal Schottky interface, does not give a true picture of the situation at the interface. Namely, during the manufacturing process, between the metal and semiconductor appears an extra thin silica layer, which, we guess, has an influence on the electrical charactersitics of the device.

**Key words:** SiC, diffusion welding technology, current transport, Schottky interface.

## 1. INTRODUCTION

The classical method of analysing the forward $U$–$I$ characteristics in a temperature range between 300–700 K gives the possibility to extract the Schottky diode parameters such as the saturation current ($J_S$), barrier height ($\Phi_b$), the ideality factor ($\eta$), the effective area Richardson constant ($A^{**}$), and the series on-resistance ($R_{sp}$) [1]. For sputtering-type Schottky contacts all these parameters seem to be in good qualitative accordance with the classical thermionic-emission and diffusion-drift theory of the current transport. Unfortunately, for the Schottky contacts, obtained with the diffusion-welded (DW) technology, a disparity between measurement results and parameters, predicted by the ideal Schottky–Mott physical model, exists.

Recently we reported experimental results of the DW Al Schottky contacts for p-and n-type SiC epilayers on the basis of $U$–$I$ measurements [2]. For the experiment a $p^0$-6H-SiC substrate from Cree Research Inc. Al-doped $(N_a \sim 5\times10^{17})$ cm$^{-3}$ and $n^0$-$n^-$ 4H-SiC epistructure with $n^-$ nitrogen doping $(N_a \sim 1\times10^{15}\ \text{cm}^{-3})$ from Sterling Semiconductor Inc were used. We discovered some unusual values and dependencies of some basic Schottky parameters during the characterization of the Schottky interface.

In this paper we make an attempt to find the main reasons for disparity of the parameters, defined by classical Schottky–Mott theory, and parameters, measured in Schottky contacts, manufactured using DW technology.

## 2. MODELLING

To clear up the reasons of the disparity of parameters of the classical theory and those obtained from the experiments, a PSPICE environment based simulator was developed and used to determine the basic parameters of Schottky diodes.

Theoretically, the ideal Schottky junction is described by the following $U$–$I$ equation [1]:

$$J = J_S[\exp(qV/kT) - 1], \tag{1}$$

where

$$J_S = A^{**}T^2 \exp\{-q(\Phi_b - \Delta\varphi_{bi})/\text{kT}\}, \tag{2}$$

$\Phi_b - \Delta\varphi_{bi}$ is the effective barrier height $\Phi_e$, $A^{**}$ is the modified Richardson coefficient, which takes into account the effective mass of the reflected electrons able to overflow the barrier and electrons of phonon scattering at the maximum barrier height, $q$ is the electron charge, $k$ is the Boltzmann constant, $T$ is the absolute temperature, and $V$ is the applied voltage.

The $U$–$I$ characteristic of the realistic non-linear junction, used also in equivalent circuit models for Schottky junctions, will get finally the following form (–1 in Eq. (1) is neglected):

$$J = J_S \exp(qV/\eta kT), \tag{3}$$

where $\eta$ is the idality factor.

The simplified non-linear model of the Schottky diode, available in PSPICE environment, is shown in Fig. 1.

The $U$–$I$ equation for the model writes as follows:

$$I = K_{inj}I_D + K_{gen}I_{GR} - I_B, \tag{4}$$

where $I_D$ is the diffusion current, $I_{GR}$ the generation/recombination current, $I_B$ the breakdown current, and $K_{inj}$ and $K_{gen}$ are the empirical coefficients introduced by PSPICE. The diffusion current writes as follows:

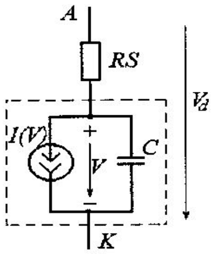



**Fig. 1.** Nonlinear Schottky model in PSPICE environment; *RS* is the series resistivity of the device and can be handled as on-state resistivity, $V_d$ is applied voltage, *C* is the barrier capacitance, *I*(*V*) is the voltage-dependent current generator (which describes the *U–I* behaviour of the Schottky interface), *A* is the anode and *K* is the cathode of the Schottky diode.

$$I_D = I_S\left[\exp\left(\frac{qV}{NkT}\right) - 1\right], \tag{5}$$

where saturation current $I_S$ is defined at room temperature (300 K) and $N$ is the injection coefficient.

The saturation current is given by (according to emission-diffusion theory)

$$I_S = KT\exp(-\Phi_b q/kT), \tag{6}$$

where $K$ is an empirical coefficient.

The breakdown and tunnelling currents, because of simplicity of interpretation of the results, are neglected. In case of high-level forward currents the on-state reistivity $R_S$ has to be taken into account as well:

$$R_S = \frac{1}{S_j}\int_{x_1}^{x_2}\rho(x)\,dx + \frac{\rho_B}{4r} + R_C. \tag{7}$$

Here $\rho_B/4r$ is the additional term of bulk resistivity defined under the contact area with radius $r$, and $R_C$ is the contact resistivity and $S_j$ is the junction area.

The temperature dependence of saturation current is given through the temperature dependence of the barrier height of the Schottky junction and of the width of the band-gap.

Finally, the current can be expressed as

$$I = I_S\left(e^{\frac{V - IR_s}{\eta kT/q}} - 1\right). \tag{8}$$

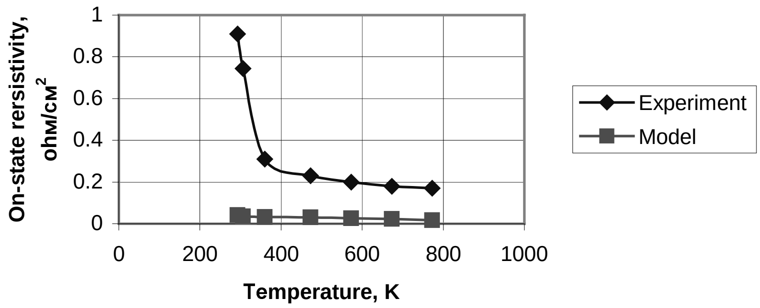
## 3. INTERPRETATION AND DISCUSSION

In this paper we focus on on-state resistivity. The behaviour of other Schottky junction parameters will be discussed later elsewhere.

Figure 2 shows the calculated on-state resistivity values depending on the temperature for n- and p-type SiC Schottky interfaces using theoretical and experimental data. It is, of course, slightly speculative to compare structures with different polytypes (4H- and 6H-SiC) to make conclusions about interface behaviour. But on basis of our previous papers (e.g., [3]), where we have observed some unexpected behaviour of p-SiC Schottky structures, we can state that the properties of the interface are mainly defined by the type of conductivity of the epilayer are not by the polytype itself (6H- or 4H-).

Figure 2a shows strong discrepancy between measured and simulated results for p-type (6H-) SiC Schottky structures. Such a discrepancy has not been observed in the contacts, manufactured with traditional sputtering technology [4]. Therefore we can conclude that the p-type Schottky interfaces, manufactured with DW technology, have a more complicated structure as compared to tradi-

(a)




(b)

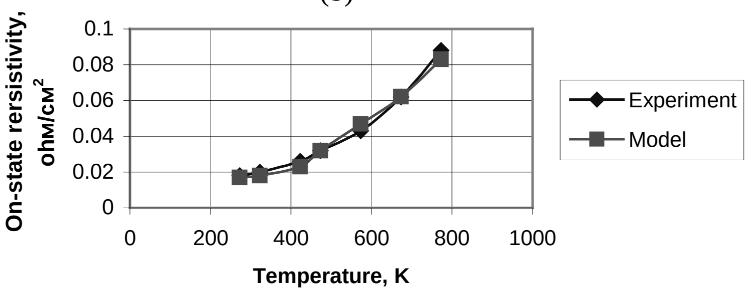



**Fig. 2.** The dependence on temperature of the on-state resistivity of the interfaces for 6H-p (a) and 4H-n-type (b) SiC Schottky structures.

tional ones. Taking into account the specific features of the DW technology we assume that a thin amorphous (silica) layer (thickness about 2 nm) between the metal and SiC epilayer surface will be introduced during the manufacturing process. This silica layer forms together with metal and SiC a sandwitch-type structure for the current transport and the barrier height should be treated in a different way. The thin silica layer seems to shortcut the junction. The tunnelling current transport appears instead of the traditional diffusion-drift or thermionic-emission transport already at very low current values and therefore the calculated model parameters, based on ideal Schottky junction theory, become wrong.

Figure 2b shows clearly that for the n-type (4H-) SiC structures the theoretical and experimental curves match each other very well. Thus we can conclude that the Schottky junction, manufactured with DW technology, form in case of the n-type substrate an interface, which is more close to the ideal junction than in case of the p-type. It seems also that for n-type epilayers the metallization technology has different influence as compared to the p-type epilayer. The silica shortcut phenomenon can not be proved. However, the Richardson coefficient, which is an important characteristic of the Schottky barrier current transport, deviates strongly from its traditional value. It means that also in this particular case an additional current mechanism is introduced. But this time the tunnelling takes place through the traps and dislocations generated by the technology and the silica shortcut layer influence is not clearly observed.

In both cases the Schottky interfaces, manufactured with DW technology, have different properties as compared with Schottky contacts, manufactured using traditional technologies.

## 4. CONCLUSIONS

Taking into account the physical nature of each parameter responsible for the deviation and carrying out the analytic matching of calculated and experimental characteristics, we have determined the possible reasons of disparity between the experimental data and data from the simulations. Thus, with relative high probability we can state that the realization of Schottky contacts using the DW technology creates an additional amorphous layer between the aluminium and silicon carbide boundary, which introduces also the stronger tunnelling phenomenon of charge carriers inside the interface.

The approach proposed in this work introduces the possibility to improve the focus of the investigations and to eliminate the revealed imperfections or use these imperfections to increase the quality of analysis of device operation.

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# Difusioonkeevituse teel valmistatud SiC Schottky siirete füüsikaliste parameetrite interpreteerimine

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Töö eesmärgiks on näidata mõne uue probleemi olemasolu difusioonkeevitatud SiC Schottky siirete voolutranspordi kirjeldamisel klassikalise termilise emissiooni ja difusioontriiviteooria baasil. Uuringud näitasid, et difusioonkeevitusega valmistatud kontaktide puhul omandavad klassikalised voolutransporti iseloomustavad suurused nagu Richardsoni tegur, päritakistus ja *U*–*I*-kõverate ideaalsustegurid väärtusi, mis ei ole seletatavad klassikalisest teooriast ning ideaalsest me-pooljuhi kontaktist lähtudes. Tulemuste erinevus ideaalsest kontaktist tuleneb ilmselt sellest, et difusioonkeevituse tehnoloogia puhul tekib metalli ja pooljuhi vahele üliõhuke amorfse pooljuhi kiht, läbi mille ei ole laengukandjate liikumine klassikalise termodifusioonteooria põhjal enam kirjeldatav. Selle tulemusena kaotavad klassikalise tähenduse ka eelnimetatud voolutransporti kirjeldava ideaalse mudeli parameetrid.