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Comparison of the dynamic behaviour of complementary 6H- and 4H-SiC Schottky structures using numerical simulation

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Abstract. In this paper we compare, using numerical simulation, the dynamic behaviour of complementary Schottky structures based on 6H- and 4H-SiC substrates. Clear differences in the behaviour of these two Schottky structures at different temperatures has been established. The calculations show that the turn-off time is about the same for both Schottky structures, but it varies with the temperature about 1.5 times.

Key words: SiC, Schottky structures, turn-off time, high temperature behaviour, numerical simulation.

1. INTRODUCTION

Silicon carbide (SiC) is an outstanding compound semiconductor material with extremely promising physical properties that makes it an excellent material for high-speed and high-temperature power electronic applications. Metal–semiconductor interfaces play a fundamental role in any semiconductor device. Thus research of different characteristics of the Schottky contact semiconductor structures is very important. Furthermore, some parameters of the 6H- and 4H- polytypes of SiC differ considerably, which influences directly the device characteristics.

In the present paper the turn-off characteristics in complementary SiC Schottky structures with 6H- and 4H- substrates under different temperature conditions are studied using two-dimensional nonisothermal drift-diffusion device simulator DYNAMIT-2DT, developed at TTU Department of Electronics [1,2].

2. DESCRIPTION OF THE MODEL

The simulator solves the Poisson and continuity equations for electrons and holes (holes are negligible in the present case) in semiconductor "electrical solution domain". The boundary conditions at Schottky contact surface are specified in a standard manner, applied in most of the simulators: the boundary potential φ_s (bound with band edge energies E_c and E_v) is shifted from the bulk (neutral) value so that the barrier height for electrons in the metal at the Fermi level equals the effective barrier height and carrier surface concentrations depend slightly on the current density through $j_n = q v_{sn} (n_s - n_{s0})$ -type relations, where j_n is the electron current density, q is the electron charge, v_{sn} is the electron surface velocity, and n_s and n_{s0} are surface concentration of electrons in the actual and thermal equilibrium situations, respectively. The barrier lowering due to the surface electric field (i.e., the Schottky effect) is here not included assuming that the effective (empiric) Φ_{bn} and Φ_{bp} values already include the influence of this effect.

The 100 μm wide structure fragment was selected for simulation, assuming that characteristic lateral scale of the current crowding effect is several times below that limit (Fig. 1). The lateral sides of the fragment are neutral reflecting surfaces (Neumann-type boundary conditions $\partial f / \partial y = 0$). In vertical direction, to reduce the mesh node number, only the $0 \le x \le 100$ μm region was included in "electrical solution". The rest of the 300 μm thick SiC wafer is considered in the

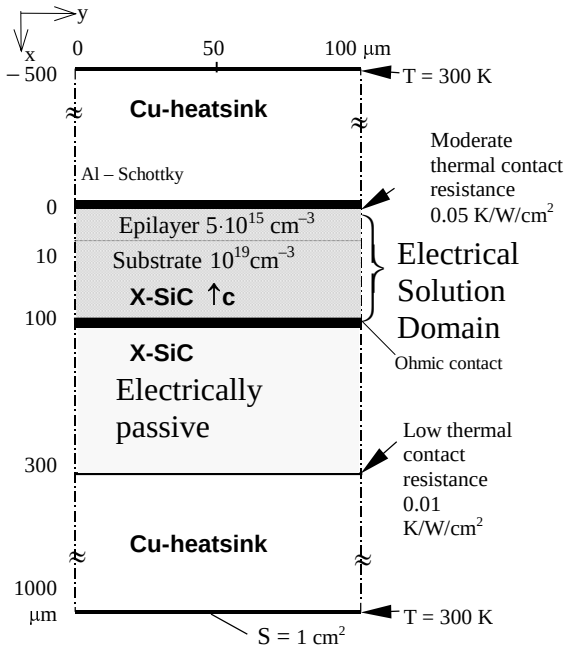

Fig. 1. Description of the electrothermal simulation task (X means either 6H or 4H).

thermal solution only. The change of the contact metal is assumed to take place exactly at the centre of the 100 μm wide simulation fragment (at y = 50 μm). In the present simulation only the abrupt Φ_{bn} (Φ_{bp}) change is analysed considering that this limit case reveals in the clearest way the essential details of the problem. The forward voltage $V < 0$ (n-substrate) and $V > 0$ (p-substrate) is applied to the bottom ohmic contact at $x = 100$ μm, $y =$ 0–100 μm. The Schottky contact is grounded: $V = 0$. The specified Cu heatsink layers model "a nearly ideal cooling package". In contrast to [3,4], part of the cooling is assumed to occur through the upper contact. This choice describes better the reality and also increases temperature changes along the Schottky contact surface.

By default, x-axis is fixed parallel to 6H- or 4H-SiC c-axis and high electron mobility anisotropy is used for 6H-SiC: $\mu_{ny} = 4.8\mu_{nx}$, $\mu_{nx300} = 78.5\ \mathrm{cm}^2/\mathrm{Vs}$ (at $T = 300$ K, $N_d = 2.3\times10^{16}\ \mathrm{cm}^{-3}$), $\mu_n(T) \sim T^{-2.07}$ (according to empirical formulae in [5]); here T is the absolute temperature and N_d is the impurity concentration in the semiconductor epilayer. For 4H-SiC, the mobility values were taken as $\mu_{ny} = 0.89\mu_{nx}$, $\mu_{nx300} = 968.0\ \mathrm{cm}^2/\mathrm{Vs}$ (at $T = 300$ K, $N_d = 2.3\times10^{16}\ \mathrm{cm}^{-3}$) and $\mu_n(T) \sim T^{-1.8}$ [6] (according to empirical formulae in [5]).

3. RESULTS AND DISCUSSIONS

Turn-off processes for complementary 6H- and 4H-Schottky structures were investigated. The stepwise switching process from 5 V forward voltage to 5 V reverse voltage over 0.01 ohm series resistance was assumed to be taking place. The temperature changes have been chosen from 300 up to 900 K. Figure 2 shows the dependence of the switching current on time for the 6H-SiC and Fig. 3 the same function for the 4H-SiC complementary Schottky structures.

Using the 10% rule for determination of the turn-off time (t_{off}), our calculations show that t_{off} for complementary 6H-SiC and n-4H-SiC structures lies between 0.05 and 0.06 ns at room temperature and increases up to the values from 0.07 to 0.08 ns at 900 K. At the same time, the p-4H-SiC has the highest turn-off time (about 0.09 ns) at the room temperature and this value decreases with the temperature increase down to about 0.05 ns. In both cases the temperature influence on the turn-off time has nearly linear character.

It is a clear indication of a different behaviour of p-4H-SiC Schottky structures as compared to other structures. Similar strange behaviour we have observed earlier by the experimental investigations of temperature influence on the U–I characteristics of p-4H-SiC Schottky structures [7].

In the U–I case this strange behaviour can be explained by the mobility of holes in the p-type SiC, which has a relatively weak temperature dependence as compared to electrons, and also by the fact that aluminium doping atoms are not fully ionized. Thus, the increasing temperature influences the turn-off time mainly through the mobility decrease, which in turn causes lower on-state resistance values. The temperature dependence of the barrier height does not play significant role in this process. Due to the fact that the turn-off time can be

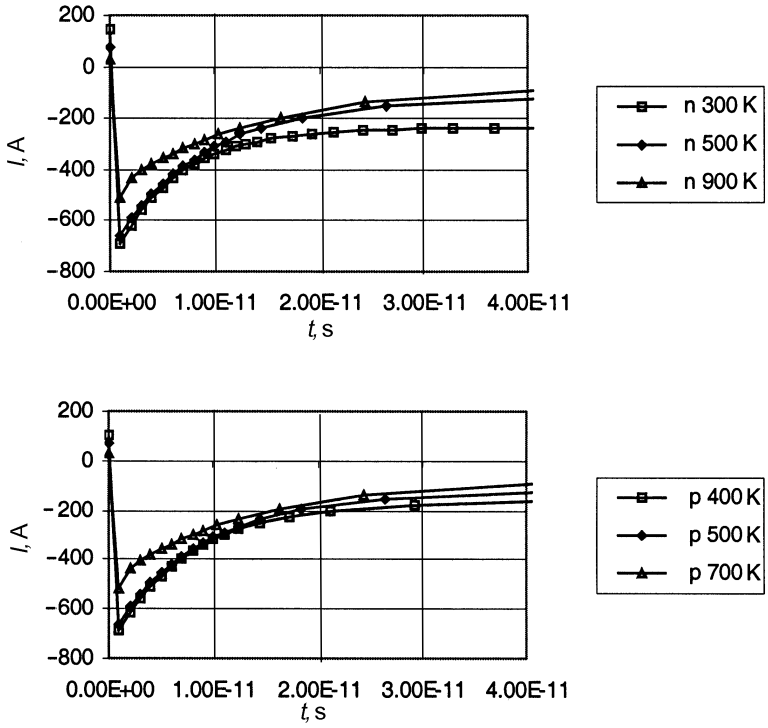

Fig. 2. The current versus time curves for complementary 6H-SiC Schottky structures at different temperatures.

handled as a delay over the Schottky structure, which in first approximation can be described by a simple *RC* chain, we can conclude that the series on-state resistance defines the behaviour of the turn-off time depending on the temperature. Accepting the fact that for all investigated structures the barrier capacity has nearly constant character and there is no charge accumulation of minority carriers in the epilayer, the on-state resistance is the only parameter, which changes the value of the *RC* product and consequently the turn-off time changes in the same way. The decrease of the on-state resistivity is directly defined by the value of mobility of holes over the Schottky structure by increasing temperature.

Our earlier analysis has shown that in p-type silicon Schottky structures the weak, but measurable minority carrier accumulation can be detected in the epilayer near the Schottky depletion layer border [[8]]. We have not observed such a phenomenon for 6H- and 4H-SiC p-type Schottky structures. The explanation leads back to the quick vanishing of the injected charge of the minority carriers (electrons) in an epilayer outside the Schottky interface for SiC structures. The practically close to zero volume of charge accumulation in the p-type epilayer of the Schottky structure results from the drift-diffusion theory of current transport,

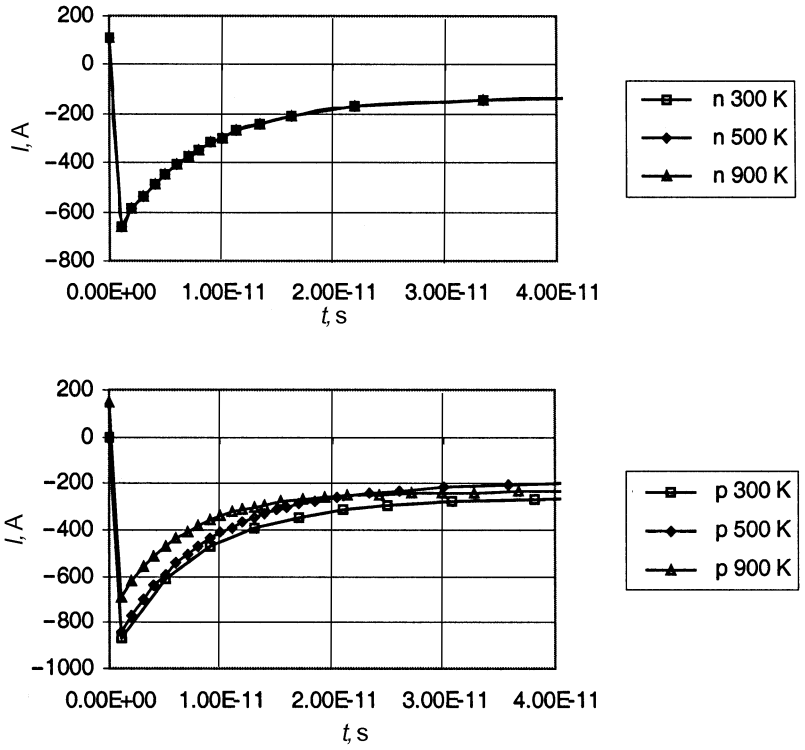

Fig. 3. The current versus time curves for complementary 4H-SiC Schottky structures at different temperatures.

where the minority carriers play significantly smaller role in the SiC epilayer as compared to the Si one and therefore no visible charge accumulation takes place.

4. CONCLUSIONS

A 2D model for the analysis of 6H- and 4H-SiC complementary Schottky structures has been verified. On the basis of our calculations, the turn-off time of the structures has shown nearly linear character under the increase of temperature. The increase of the temperature causes the increase in the turn-off time for 6H-SiC complementary and 4H-SiC n-type Schottky structures. For the 4H-SiC p-type Schottky structures the turn-off time decrease was observed under temperature increase. The reason for such a behaviour can be the decrease of the on-state resistivity under temperature influence. Our calculations show also differences in the behaviour of p-type SiC Schottky structures as compared to similar silicon-based structures. In SiC p-type Schottky structures no minority carrier charge accumulation has been observed in the epilayer outside the Schottky depletion layer.

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REFERENCES

1. Udal, A. Development of numerical semiconductor device models and their application in device theory and design. *Theses of Tallinn Technical Univ*., 1998, No. D12.
2. Kurel, R. and Udal, A. Two-dimensional nonisothermal analysis of current crowding effect at nonuniform SiC Schottky contacts using device simulator DYNAMIT-2DT. In *Proc. 8th Baltic Electronics Conference*. Tallinn, 2002, 51–54.
3. Waldrop, J. R. and Grant, R. Schottky barrier height and interface chemistry of annealed metal contacts to alpha 6H-SiC. Crystal face dependence. *Appl. Phys. Lett*., 1993, **62**, 2685–2687.
4. Kurel, R. and Rang, T. Self-heating phenomenon and current suppressing effect at 6H-SiC Schottky interfaces. In *Proc. 5th NEXUSPAN Workshop on Thermal Aspects in Microsystems Technology*. Budapest, 1998, 88–91.
5. Schaffer, W. J., Negley, G. H., Irvine, K. G., and Palmour, J. W. Conductivity anisotropy in epitaxial 6H and 4H SiC. In *Proc. MRS Spring Meeting*. San Fransisco, 1994, 6 p.
6. Hjelm, M., Nilsson, H.-E., Dubaric, E., Persson, C., Käckell, P., and Petersson, C. S. Full band Monte Carlo simulation of short channel MOSFETs in 4H and 6H-SiC. In *Proc. MRS Spring Meeting.* San Francisco, 1999, 185–190.
7. Korolkov, O., Rang, T., Syrkin, A., and Dmitriev, V. Diffusion welded Al contacts to p-type SiC. In *Silicon Carbide and Related Materials 2002 (ECSCRM2002)*. Trans. Techn. Publ. Ltd, Switzerland, 2003.
8. Rang, T. One-dimensional numerical simulation of complementary power Schottky structures. *IEE Proc*., 1985, **132**, Pt. I, 253–256.

Komplementaarsete 6H- ja 4H-SiC Schottky struktuuride dünaamilise käitumise uurimine numbrilise mudeli abil

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On uuritud komplementaarsete 6H- ja 4H-SiC Schottky struktuuride väljalülitusprotsesse erinevatel temperatuuridel. On näidatud, et p-tüüpi epitaksiaalkihiga Schottky struktuuride väljalülitusaeg näitab temperatuuri kasvades kahanemistendentsi, mis erineb oluliselt teiste uuritud struktuuride väljalülitusaegade käitumisest. Tuleb mainida, et vaatamata temperatuuri peaaegu lineaarsele mõjule väljalülitusajale, on selle faktiline muutus siiski suhteliselt suur (ligi 1,5 korda nii suurenemise kui ka vähenemise suunas).