Paper

Comparison of 4H-SiC and 6H-SiC MOSFET *I-V* characteristics simulated with Silvaco Atlas and Crosslight Apsys

Jędrzej Stęszewski, Andrzej Jakubowski, and Michael L. Korwin-Pawlowski

Abstract—A set of physical models describing silicon carbide with fitting parameters is proposed. The theoretical *I-V* output and transfer characteristics and parameters of MOS transistors were calculated using Silvaco Atlas and Crosslight Apsys semiconductor device simulation environments.

Keywords*— *silicon carbide, SiC MOSFET, 4H-SiC, 6H-SiC, Crosslight Apsys, Silvaco Atlas.

1. Introduction

Wide band gap, high breakdown field, high thermal conductivity and low thermal expansion make silicon carbide a very interesting material for high-temperature and high-frequency electronics (e.g., [1, 2]). Selected material parameters of silicon and two hexagonal polytypes of silicon carbide are shown in Table 1.

Table 1
Comparison of basic parameters of silicon, 4H-SiC and 6H-SiC [1, 2]

Parameters	4H-SiC	6H-SiC	Si
$E_{g(300\,\mathrm{K})}$ [eV]	3.23	2.90	1.12
$n_{i(300\,\mathrm{K})}$ [cm^{-3}]	$1.5 \cdot 10^{-8}$	$2.1 \cdot 10^{-5}$	10^{10}
$E_{crit(300\,\mathrm{K})}$ [V/cm]	$2.2 \cdot 10^{6}$	$2.5 \cdot 10^{6}$	$0.25 \cdot 10^{6}$
ε_S	9.66	9.66	11.7
$\mu_{n\max} \perp$ [cm^2/Vs]	947	415	1400
$\mu_{p\max} \perp$ [cm^2/Vs]	124	99	450
V_{SAT} [cm/s]	$2.1 \cdot 10^{7}$	$2 \cdot 10^{7}$	10^{7}

Figure 1 shows the influence of temperature on intrinsic concentration of 4H-SiC and 6H-SiC materials, associated with the temperature-induced band gap narrowing. In the case of 4H-SiC the intrinsic concentration is only one order of magnitude higher at the temperature of 900 K than the intrinsic concentration of silicon at room temperature. That proves very significant, theoretical suitability of silicon carbide as a material for high temperature applications. Moreover SiC is the only wide band-gap semiconductor with native insulator – SiO_2. Figure 2 presents band offsets of 4H-SiC and 6H-SiC compared to silicon [3]. That makes silicon carbide a promising choice for MOSFET devices.

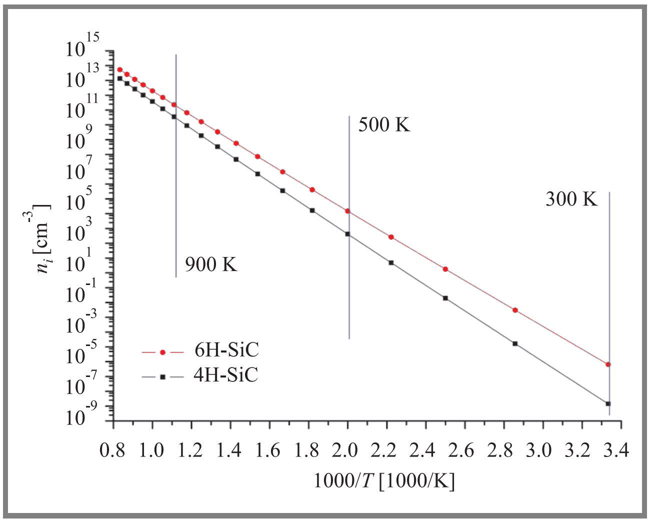

Fig. 1. Simulated influence of the temperature on intrinsic concentration of 4H-SiC and 6H-SiC – temperature-induced band gap narrowing phenomenon taken into account.

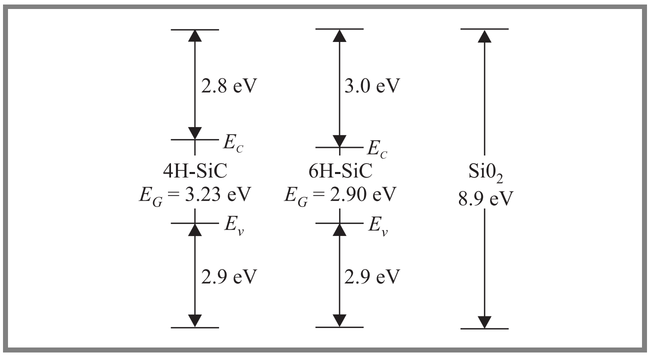

Fig. 2. Band offset of 4H- and 6H-SiC in comparison to silicon dioxide [3].

2. Calculations

In order to obtain accurate calculation results, a variety of physical models with fitting material parameters were implemented in the semiconductor device simulation environments: Silvaco Atlas [4] and Crosslight Apsys [5]. The theoretical *I-V* output and transfer characteristics of 4H-SiC and 6H-SiC NMOSFETs were calculated. Moreover, the influence of the temperature on output characteristics was simulated.

3. Physical model summary

The following models were amongst the most important used:

1) carrier mobility:
   - low electric field – Caughey-Thomas formula,
   - high electric field – FLDMOB model [6];
2) carriers ionization effects:
   - incomplete ionization [7],
   - impact ionization – Selberherr model [8];
3) generation-recombination phenomenon:
   - Auger recombination [9],
   - SRH recombination [10];
4) band gap narrowing:
   - temperature dependence – analytical formula,
   - doping influence – Slotboom model [11].

In all simulations anisotropy of silicon carbide electrical parameters was neglected. It was assumed that the dominant direction of carrier flow is oriented along the transistor channel.

4. Results

Figures 3 and 4 show output and transfer characteristics of 4H-SiC and 6H-SiC NMOS transistor ($N_B = 2 \cdot 10^{17}$ cm^{-3}, $t_{ox} = 10$ nm, $L_{ch} = 1$ μm, $D_{it} = 10^{11}$ cm^{-2}), respectively.

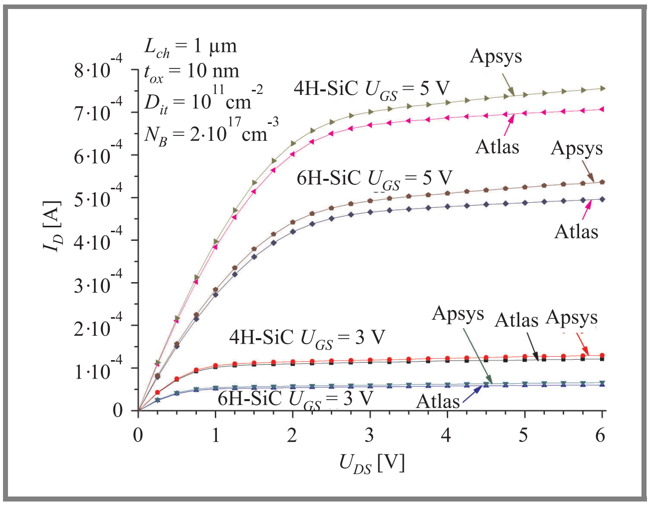

Fig. 3. Simulated output characteristics of 4H-SiC and 6H-SiC NMOSFETs.

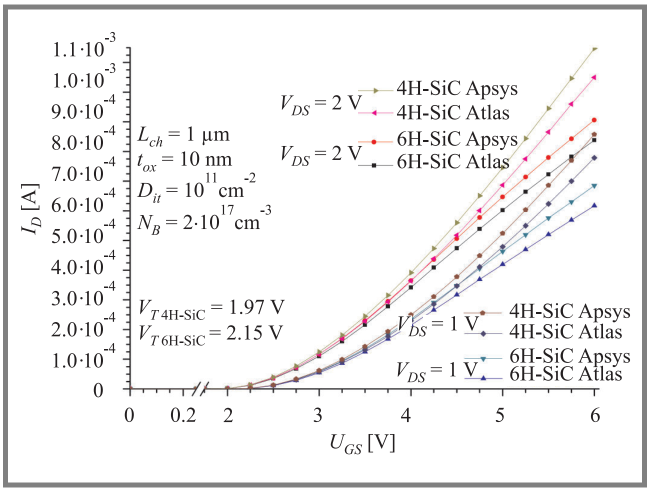

Fig. 4. Simulated transfer characteristics of 4H-SiC and 6H-SiC NMOSFETs.

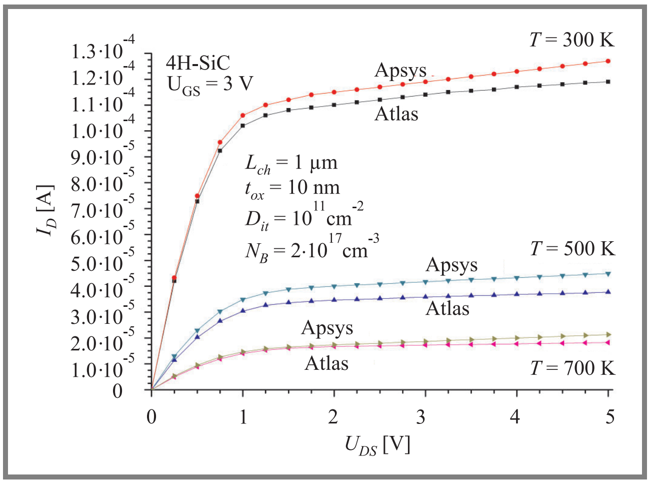

Fig. 5. Simulated influence of temperature on 4H-SiC NMOSFET output characteristics.

The characteristics were calculated using both simulators. The influence of temperature on output characteristics of 4H-SiC NMOSFET is presented in Fig. 5.

5. Discussion and conclusions

Presented results obtained with Silvaco Atlas and Crosslight Apsys show noticeable difference in drain current values. In the case of *I-V* output characteristics, drain current calculated with Apsys is, on the average, 7 to 9% higher, while transfer characteristics exhibit 8 to 11% drain current difference in favor of Apsys. Moreover, simulated drain current at elevated temperatures displays 8 to 18% difference.

Both device simulators – Silvaco Atlas and Crosslight Apsys use the same computational approach: Poisson's equation and electron/hole continuity equations are solved in a coupled manner.

The differences in drain currents obtained with both environments might be caused by the mesh discretization tactics and distinct numerical methods, as well. Possible overestimation of MOSFETs drain current might also be a consequence of the omission of anisotropy in the calculations carried out.

The paper introduces band gap narrowing models (which are generally neglected) to the simulation of silicon carbide devices. The proposed modification is based on Slotboom (doping influence) and analytical (temperature influence) models with appropriate parameters, well known for silicon. Significant influence of temperature-induced band gap narrowing on carrier concentration at elevated temperatures is commonly overlooked. Eventually, it leads to overestimation of SiC device applicability in extremely high temperatures.

Obtaining of reliable simulation results is difficult by significant differences in the values of silicon carbide material parameters reported in various papers. Further studies are needed.

References

[1] *Properties of Advanced Semiconductor Materials GaN, AlN, InN, BN, SiC, SiGe*, M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur, Eds. New York: Wiley, 2001, pp. 31–47.

[2] M. Ruff, H. Mitlehner, and R. Helbig, "SiC devices: physics and numerical simulation", *IEEE Trans. Electron Dev.*, vol. 41, pp. 1040–1053, 1994.

[3] V. V. Afanasev, M. Bassler, G. Pensl, and M. Schultz, "Intrinsic SiC/SiO_2", *Phys. Stat. Sol. A*, vol. 162, no. 1, pp. 321–337, 1997.

[4] *User's Manual*. Atlas, Silvaco, 2002.

[5] *User's Manual*. Apsys, Crosslight, 2000.

[6] I. A. Khan and J. A. Cooper, Jr., "Measurement of high-field electron transport in silicon carbide", *IEEE Trans. Electron Dev.*, vol. 47, pp. 269–273, 2000.

[7] A. A. Lebedev, "Deep level centers in silicon carbide: a review", *Semiconductors*, vol. 33, no. 2, pp. 107–130, 1999.

[8] R. Raghunathan and B. J. Baliga, "Measurement of electron and hole impact ionization coefficients for SiC power semiconductor devices and IC", in *ISPSD'97 IEEE Int. Symp. Pow. Semicond. Dev. IC's*, Weimar, Germany, 1997, pp. 173–176.

[9] A. Galeckas, J. Linnros, V. Grivickas, U. Lindefelt, and C. Hallin, "Auger recombination in 4H-SiC: unusual temperature behavior", in *Proc. 7th Int. Conf. SiC, III-Nitr. Rel. Mater.*, Stockholm, Sweden, 1997, pp. 533–536.

[10] J. P. Bergman, "Carrier lifetimes in SiC, studied by time resolved photoluminescence spectroscopy", *Diam. Rel. Mater.*, vol. 6, pp. 1324–1328, 1997.

[11] U. Lindefelt, "Doping-induced band edge displacements and band gap narrowing in 3C-, 4H-, 6H-SiC, and Si", *J. Appl. Phys.*, vol. 84, no. 5, pp. 2628–2637, 1998.

Jędrzej Stęszewski was born in Warsaw, Poland, in 1978. He received the B.Sc. and M.Sc. degrees in microelectronics from the Faculty of Electronics and Information Technology, Warsaw University of Technology (WUT), in 2004. He is currently preparing his Ph.D. thesis, the same university. His research interests include modeling and characterization or wide band gap materials, silicon carbide in particular.

e-mail: j.steszewski@elka.pw.edu.pl
Institute of Microelectronics and Optoelectronics
Warsaw University of Technology
Koszykowa st 75
00-662 Warsaw, Poland

Michael L. Korwin-Pawlowski received his M.Sc. in electronics from Warsaw University of Technology (WUT), Poland, in 1963, then Ph.D. in electronics engineering from University of Waterloo, Canada, in 1974. He got the MBA Finance diploma in Long Island, USA, in 1993. He joined the Université du Québec en Outaouais in 2004 as a Professor after an over 30 years career in R&D, engineering, marketing and operations management in the international semiconductor and microelectronic industry in Canada, Taiwan, USA, Ireland and France. His current research interests focus on this film technology for fiber optic sensor applications, laser process technology, nanotechnology, photonic sensors and microelectronic device modeling. He is an author or coauthor of 45 publications. He holds 18 of US, French and international patents.

e-mail: Michael.Korwin-Pawlowski@uqo.ca
Université du Qébec en Outaouais
C. P. 1250, succ. Hull
283, boul. Alexandre-Taché
Gatineau (Québec) J8X 3X7, Canada

Andrzej Jakubowski – for biography, see this issue, p. 7.