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Research Article

Optimum Barrier Height for SiC Schottky Barrier Diode

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The study of barrier height control and optimization for Schottky barrier diode (SBD) from its physical parameters have been introduced using particle swarm optimization (PSO) algorithm. SBD is the rectifying barrier for electrical conduction across the metal semiconductor (MS) junction and, therefore, is of vital importance to the successful operation of any semiconductor device. 4H-SiC is used as a semiconductor material for its good electrical characteristics with high-power semiconductor devices applications. Six physical parameters are considered during the optimization process, that is, device metal, mobile charge density, fixed oxide charge density, interface trapped charge density, oxide thickness, and voltage drop across the metal-semiconductor contact. The optimization process was performed using a MATLAB program. The results show that the SBD barrier height has been optimized to achieve a maximum or minimum barrier height across the contact, in addition to the ability of controlling the physical parameters to adjust the device barrier height.

1. Introduction

The successful operation of any semiconductor device is of vital importance. The barrier height reflects the mismatch in the energy position of semiconductor majority carrier band edge and the metal Fermi level across the MS interface. The ability to control the magnitude of this barrier height is crucial for the advancement of future electronic devices to higher functionality and smaller physical dimensions. Several researches in the literature studied the barrier height control during manufacturing process [1–5]. SiC material offers superior material properties such as large breakdown electric field, large band gap, high electron saturated velocity, and high thermal conductivity. This makes it a viable semiconductor for high-voltage application and high-temperature operation with reduced power loss. 4H-SiC is used for its advantage with high-power applications [6–8]. This paper proposes an optimization technique for controlling and optimizing the SBD barrier height to achieve the required device physical parameters during the design time.

2. Theoretical Description

The structure of Schottky barrier diode (SBD) is illustrated schematically in Figure 1. In SiC, the device regions, where electrons and holes behave as bulk carriers, the Poisson equation can be described as follows [9]:

$$\frac{d^2V(x)}{dx^2} = \frac{q}{\varepsilon}\left(N_A^-(x) - N_D^+(x) + n(x) - p(x)\right), \quad (1)$$

where (p) and (n) are the densities of holes and electrons and N_D, N_A are the densities of ionized donors and acceptors; the holes and electrons densities are [9]

$$p(0) = p_{po}\exp(-\beta\psi_s),$$
$$n(0) = n_{po}\exp(\beta\psi_s). \quad (2)$$

The electric field at the surface is

$$\xi_s = \frac{\sqrt{2}kT}{qL_D}F\left(\beta\psi_s, \frac{n_{po}}{p_{po}}\right). \quad (3)$$

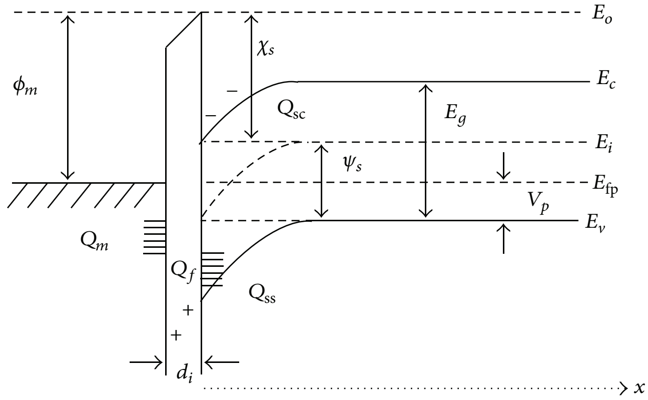

FIGURE 1: Energy band diagram of p-type SBD.

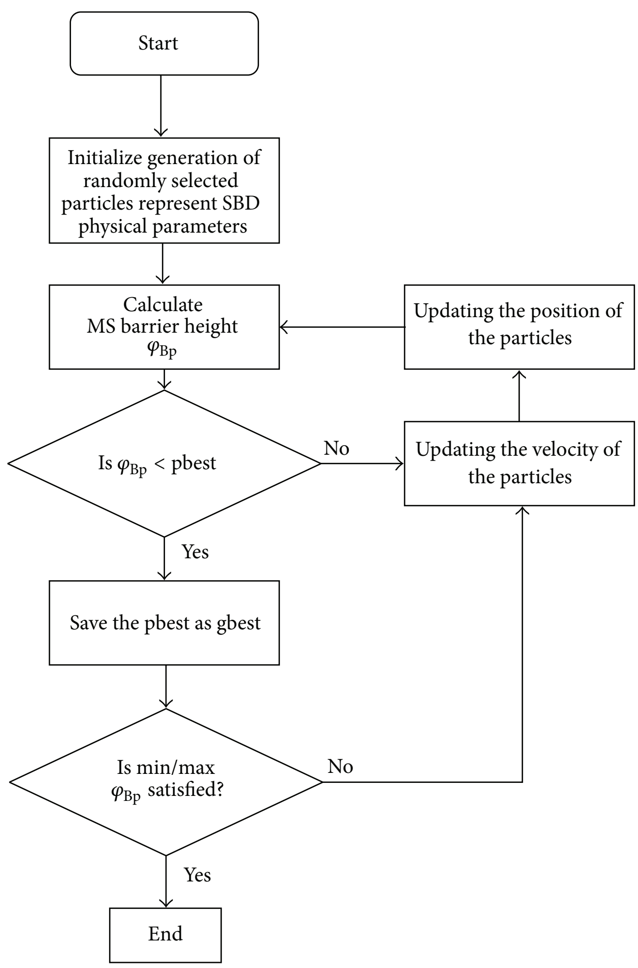

FIGURE 2: PSO flowchart.

The space charge per unit area required to produce this field is

$$Q_{sc} = -\varepsilon_s \xi_s = \frac{\sqrt{2}\varepsilon_s kT}{qL_D} F\left(\beta\psi_s, \frac{n_{po}}{p_{po}}\right). \quad (4)$$

Barrier Height Calculation. The voltage drop across the oxide layer can be obtained by the application of Gauss's law to the metal and semiconductor surfaces as follows:

$$\Delta V_i = \frac{d_i}{\varepsilon_i} Q_t, \quad (5)$$

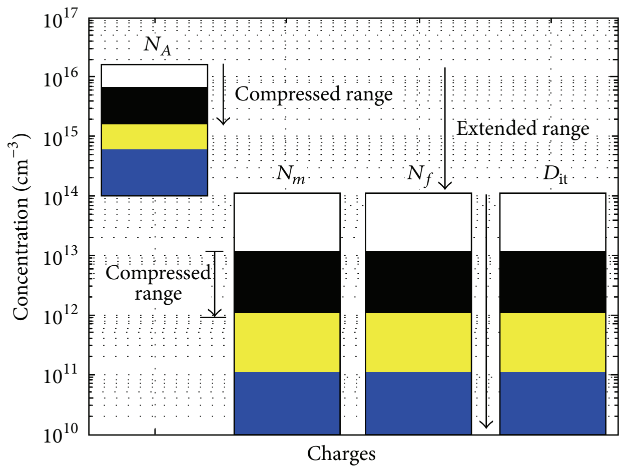

Figure 3: The range of charges used during the optimization process.

Table 1: Device physical parameters during the optimization process.

Parameter	Extended range	Compressed range	Comments
ϕ_m	3.5 : 5.1 eV	3.5 : 5.1 eV	For available metals
N_A	$1E14:1E16$	$1E15:1E16$	
N_m	$1E10:1E14$	$1E12:1E13$	
N_f	$1E10:1E14$	$1E12:1E13$	
D_{it}	$1E10:1E14$	$1E12:1E13$	
d_{ox}	$1E-8:1.5E-7$	$5E-8:1.1E-7$	

Table 2: Metal used and corresponding metal work function.

Metal	Sc	Al	Ti	Mo	Ca
ϕ_m (eV)	3.5	4.1	4.4	4.69	5.1

where ε_i is the permittivity of the interfacial layer, d_i is the thickness of interfacial layer, and Q_t is described as

$$Q_t = Q_{ss} + Q_{sc} + Q_m + Q_f, \quad (6)$$

where Q_{ss} is the surface states charge density, Q_{sc} is the space charge density, Q_m is the mobile charge density, and Q_f is the fixed oxide charge density [10]. Consider

$$Q_{ss} = -q^2 D_{it} (\phi_B + \phi_s + \phi_o), \quad (7)$$

where D_{it} is the interface trapped charge density, ϕ_B is the barrier height, ϕ_s is image force barrier lowering, and ϕ_o is the energy level at the surface. Consider

$$\begin{aligned} Q_f &= q \times N_f, \\ Q_m &= q \times N_m, \end{aligned} \quad (8)$$

where N_f is the density of the fixed oxide charge and N_m is the density of the mobile charge. Another relation of ΔV can be obtained by inspection of the energy band diagram in Figure 1. Consider

$$\Delta V_i = E_g - \phi_m + \chi_s - \psi_s - v_p - V. \quad (9)$$

The device surface potential ψ_s can be easily calculated; the barrier height of SBD can be described as follows:

$$\phi_B = \psi_s + v_p. \quad (10)$$

3. Optimization Process

PSO is a population-based stochastic optimization technique [11–14], inspired by social behaviour of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as genetic algorithm (GA) [15]. The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. It requires only primitive mathematical operators and is computationally inexpensive in terms of both memory requirements and speed. In reality, PSO and GA techniques are too similar, and by making some changes to GA, you have your PSO algorithm. At the beginning, the PSO algorithm randomly initializes a population (called swarm) of individuals (called particles). Each particle represents group of device physical parameters. The particles evaluate their position relative to a goal of the iteration. In each iteration, every particle adjusts its trajectory (by its velocity) toward its own previous best position, and toward the previous best position attained by any member of its topological neighbourhood. If any particle's position is

Table 3: Optimization results for the first section.

Results	V	ϕ_m (eV)	N_A (cm^{-3})	N_m (cm^{-3})	N_f (cm^{-3})	D_{it} (cm^{-3})	d_{ox} (cm)	ϕ_B (V)
Maximize	0.7	4.4	4*E*15	4*E*12	8*E*13	6*E*11	9*E* − 8	**3.328**
Minimize	0.6	4.1	4*E*15	8*E*10	8*E*12	4*E*13	2.5*E* − 7	**0.028**

Table 4: Optimization results for the second section.

Results	V	ϕ_m (eV)	N_A (cm^{-3})	N_m (cm^{-3})	N_f (cm^{-3})	D_{it} (cm^{-3})	d_{ox} (cm)	ϕ_B (V)
Maximize	0	3.5	8*E*14	6*E*11	2*E*11	8*E*13	5*E* − 8	**3.328**
Minimize	0	4.4	4*E*15	2*E*11	2*E*11	8*E*13	2.5*E* − 7	**0.029**
Maximize	1	5.1	6*E*14	4*E*10	4*E*10	1*E*12	1.5*E* − 7	**3.328**
Minimize	1	4.4	8*E*10	8*E*10	1*E*13	4*E*13	1.5*E* − 7	**0.028**
Maximize	0	3.5	1*E*15	1*E*12	8*E*13	6*E*11	2*E* − 7	**3.328**
Maximize	0	4.1	8*E*15	4*E*13	2*E*11	1*E*12	3*E* − 7	**3.328**
Maximize	0	4.4	6*E*15	8*E*10	6*E*11	1*E*13	2*E* − 7	**3.328**
Maximize	0	4.69	4*E*15	1*E*12	4*E*10	4*E*13	2*E* − 7	**3.328**
Maximize	0	5.1	1*E*15	4*E*13	1*E*12	8*E*12	1.5*E* − 7	**3.328**
Maximize	1	3.5	6*E*14	2*E*11	8*E*13	4*E*10	1*E* − 8	**3.328**
Maximize	1	4.1	1*E*16	4*E*12	8*E*13	6*E*11	9*E* − 8	**3.328**
Maximize	1	4.4	1*E*15	8*E*13	1*E*12	2*E*11	7*E* − 8	**3.328**
Maximize	1	4.69	8*E*15	1*E*13	4*E*13	1*E*12	1*E* − 8	**3.328**
Maximize	1	5.1	6*E*15	8*E*13	6*E*11	8*E*10	7*E* − 8	**3.328**

close enough to the goal function, it is considered as having found the global optimum and the recurrence is ended. In our optimization, 40 particles are used in PSO, which is a balance between the accuracy required in searching for the global optimum and time consumed. This procedure, whose flowchart is shown in Figure 2, iterates a predefined number of consecutive particles. The iteration particle is updated by the following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. When a particle takes part of the population as its topological neighbours, the best value is a local best and is called lbest. After finding the two best values, the particle updates its velocity and positions as follows:

$$\begin{aligned} v &= v + c_1 \cdot \text{rand} \cdot (\text{pbest} - \text{present}) \\ &\quad + c_2 \cdot \text{rand} \cdot (\text{gbest} - \text{present}) \\ \text{present} &= \text{present} + v, \end{aligned} \tag{11}$$

where v and is the particle velocity present is the current particle (solution). pbest and gbest are defined as stated before. rand is a random number between 0 and 1. c_1, c_2 are learning factors. Usually, $c_1 = c_2 = 2$ [12].

The device physical parameters used in the optimization process and its limits values are demonstrated in Table 1. The charges' range is indicated in Figure 3. The metals used and its corresponding metal work function values are illustrated in Table 2.

4. Optimization Results

Optimization process is divided into three sections. The first section is a complete optimization of the entire extended range of physical parameters to achieve a maximum or minimum SBD barrier height. The second optimization fixes the applied voltage parameter to minimum value (0) V and maximum value (1) V with the entire range of metals. The third optimization used a compressed range of physical parameters for each metal in the entire range of the metal work function. Table 3 shows the optimization results of the first section, which indicates the device physical parameters to achieve a maximum and minimum SBD barrier height. Optimization process is performed with constant applied voltages and added separately maximization for each metal in the entire band, which is indicated in Table 4. Table 5 illustrates the results of the third section which include the optimization process for each metal with constant voltage values and using the compressed range of the physical parameters. The demonstrated results show that these optimization procedures can control, maximize, or minimize the device barrier height to specific value related to the application requirements.

5. Conclusion

The barrier height for 4H-SiC SBD has been calculated from its device physical parameters using an iterative solution. This calculation includes the effect of the oxide charge density in the interfacial device layer, oxide thickness, metal type, doping concentration of 4H-SiC, and the external applied voltage. The device physical parameters are optimized using PSO to achieve a maximum or minimum barrier height with

Table 5: Optimization results for the third section.

Results	V	ϕ_m (eV)	N_A (cm^{-3})	N_m (cm^{-3})	N_f (cm^{-3})	D_{it} (cm^{-3})	d_{ox} (cm)	ϕ_B (V)
Maximize	0	3.5	$7E15$	$4E12$	$1E12$	$1E13$	$7.5E-7$	**3.328**
Minimize	0	3.5	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**2.42**
Maximize	0	4.1	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**2.94**
Minimize	0	4.1	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**1.79**
Maximize	0	4.4	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**2.92**
Minimize	0	4.4	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**1.47**
Maximize	0	4.69	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**2.9**
Minimize	0	4.69	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**1.16**
Maximize	0	5.1	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**2.83**
Minimize	0	5.1	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**0.73**
Maximize	1	3.5	$6E15$	$2E12$	$3E12$	$9E12$	$9.5E-8$	**3.32**
Minimize	1	3.5	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**137**
Maximize	1	4.1	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**3.09**
Minimize	1	4.1	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**0.73**
Maximize	1	4.4	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**2.47**
Minimize	1	4.4	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**0.42**
Maximize	1	4.69	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**1.88**
Minimize	1	4.69	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**0.028**
Maximize	1	5.1	$1E16$	$1E12$	$1E12$	$1E13$	$1.1E-7$	**3.328**
Minimize	1	5.1	$1E15$	$1E13$	$1E13$	$1E12$	$1.1E-7$	**0.028**

several conditions. The paper concluded that the SBD barrier height can be controlled by changing the metal type and the concentration range of both the oxide charges and thickness.

References

[1] B. Studer, "Barrier height control of Pd_2 Si/Si Schottky diodes using diffusion from doped Pd," *Solid-State Electronics*, vol. 23, no. 11, pp. 1181–1184, 1980.

[2] S. Fujieda, "Control of GaAs Schottky barrier height by formation of a thin off-stoichiometric GaAs interlayer grown by low-temperature molecular beam epitaxy," *Applied Physics Letters*, vol. 61, no. 3, pp. 288–290, 1992.

[3] D. Spaltmann, J. Guerts, N. Esser, D. R. T. Zahn, W. Richter, and R. H. Williams, "Control of Schottky barrier height of Ag/Mn/n-GaAs(110) diodes with Mn interlayer thickness," *Semiconductor Science and Technology*, vol. 7, no. 3, article 344, 1992.

[4] S. D. Lin and C. P. Lee, "Hole Schottky barrier height enhancement and its application to metal-semiconductor-metal photodetectors," *Journal of Applied Physics*, vol. 90, no. 11, pp. 5666–5669, 2001.

[5] H. Umezawa, N. Tatsumi, S.-I. Shikata, K. Ikeda, and R. Kumaresan, "Increase in reverse operation limit by barrier height control of diamond Schottky barrier diode," *IEEE Electron Device Letters*, vol. 30, no. 9, pp. 960–962, 2009.

[6] M. E. Levinshtein, T. T. Mnatsakanov, P. Ivanov et al., "'Paradoxes' of carrier lifetime measurements in high-voltage SiC diodes," *IEEE Transactions on Electron Devices*, vol. 48, no. 8, pp. 1703–1710, 2001.

[7] D. T. Morisette and J. A. Cooper Jr., "Theoretical comparison of SiC PiN and Schottky diodes based on power dissipation considerations," *IEEE Transactions on Electron Devices*, vol. 49, no. 9, pp. 1657–1664, 2002.

[8] M. Tayel and A. El-Shawarby, "The influence of doping concentration, temperature, and electric field on mobility of silicone carbide materials," in *Proceedings of the IEEE International Conference on Semiconductor Electronics (ICSE '06)*, pp. 651–655, Kuala Lumpur, Malaysia, December 2006.

[9] M. Sze, *Physics of Semiconductor Devices*, John Wiley & Sons, New York, NY, USA, 2009.

[10] J. Campi, Y. Shi, Y. Luo, F. Yan, and J. H. Zhao, "Study of interface state density and effective oxide charge in post-metallization annealed SiO_2-SiC structures," *IEEE Transactions on Electron Devices*, vol. 46, no. 3, pp. 511–519, 1999.

[11] J. Kennedy, R. C. Eberhart, and Y. Shi, *Swarm Intelligence*, Academic Press, 2001.

[12] F. T. S. Chan and M. K. Tiwari, *Swarm Intelligence: Focus on Ant and Particle Swarm Optimization*, I-Tech Education and Publishing, Rijeka, Croatia, 2007.

[13] R. Poli, W. B. Langdon, and O. Holland, "Extending particle swarm optimisation via genetic programming," in *Proceedings of the 8th European Conference on Genetic Programming (EuroGP '05)*, pp. 291–300, Lausanne, Switzerland, April 2005.

[14] H. Zhang and M. Ishikawa, "Particle swarm optimization with diversive curiosity—an endeavor to enhance swarm intelligence," *IAENG International Journal of Computer Science*, vol. 35, no. 3, 2008.

[15] Z. Michalewiez, *Genetic Algorithms + Data Strcture = Evolution Programs*, Springer, New York, NY, USA, 1996.