Modeling and Switching Simulation Tool of SiC-GTO

M. S. Jadin, M. Z. Sujod and R. M.Taufika Raja Ismail

Abstract — **Power semiconductor devices such as Thyristor, GTO, IGBT and Power MOSFET become important devices in high voltage and high frequency power electronics applications. Recent development in power electronics has made power semiconductor devices larger and more complicated, and therefore, device simulation is necessary to predict their characteristics. From the fundamental equations of semiconductor devices, potential distribution and carrier concentrations can be solved using the Finite Element Method (FEM) [1]. Silicon Carbide (SiC) material has been utilized for power devices, in order to achieve fast switching time and low switching loss. In this study, we analyzed the physical constants and device characteristics of Silicon Gate Turn-off (Si-GTO) thyristor and SiC-GTO. We build a GTO model by set up the boundary conditions, dimensions and adapt a suitable doping profile into the device model. We also compare the switching waveforms of Si-GTO and SiC-GTO. Results show that turn-off time of SiC-GTO is decreased extremely. We use our simulation tools in running all the modeling and switching simulation process.**

Index Terms — **Silicon Carbide, Gate Turn-off Thyristor, Modeling Tool and Finite Element Method.**[1]

I. INTRODUCTION

Gate Turn-off Thyristor (GTO) is known as a self turn-off device controlling high voltage and large current. GTO is favored for direct current power applications because of its independent gate turn-on and off characteristics. A material such as Silicon Carbide (SiC) is being investigated to replace with common silicon for the fabrication of power semiconductor devices. SiC based semiconductor electronic devices and circuits are presently being developed for use in high temperature, high power, and/or high radiation conditions under which conventional semiconductors cannot adequately perform. Silicon Carbide's ability to function under extreme conditions is expected to enable significant improvements to a far-ranging variety of applications and systems. These range from greatly improved high voltage switching for energy savings in public electric power distribution and electric motor drives, to more powerful microwave electronics for radar and communications, to sensors and controls for cleaner burning more fuel efficient jet aircraft and automobile engines. In the particular area of power devices, Silicon Carbide material has been utilized in order to achieve fast switching time and low switching loss [2], [3]. SiC based devices will bring renaissance in high power electronics.

In this paper, we make analysis on physical constants and device characteristics of Si and SiC GTO thyristor and implement Finite Element Method (FEM) for the device model. In order to make an easy way of simulation process, we create the simulation tool.

II. DEVICE MODEL

A.. GTO Thyristor

Fig. 1 shows the periodic structure of GTO thyristor. In this study, we consider only the Ω area and create two dimensional model for the simulation. Γ_1 is a device surface, Γ_2 is mirror surface boundary and Γ_3 is electrode boundary of anode and cathode.

Mohd Shawal Jadin, Muhamad Zahim Sujod and Raja Mohd Taufika Raja Ismail is currently with the Faculty of Electrical & Electronics Engineering, University Malaysia Pahang, 25000 Kuantan, Pahang, Malaysia. (e-mail: shawal@ump.edu.my, zahim@ump.edu.my, rajamohd@ ump.edu.my)

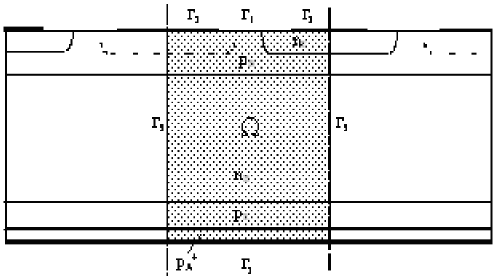

Fig. 1. Periodic structure of GTO Thyristor

In order to implement Finite Element Method (FEM), the Ω area is divided into triangular elements with total of IX × IY nodes. These nodes are also called mesh points. All nodes are numbered from 1 to N. Fig. 2 shows the triangular elements and numbered nodes of the Ω area.

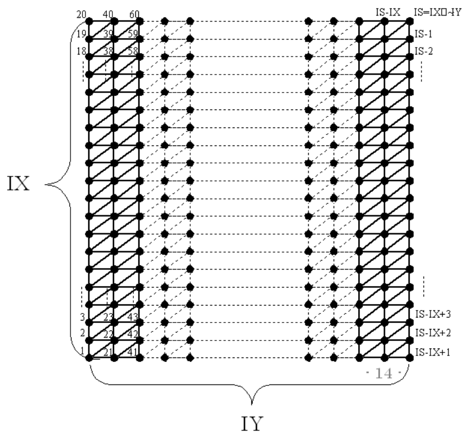

Fig. 2. Triangular elements and numbered nodes for FEM

We create the shape function as shown in Fig. 3, where only **i** node is set to 1 and the others is 0. At the mesh point of 1, the function Φ is defined as,

$$\Phi(x,y)=\frac{a_e+b_e x+c_e y}{2\Delta_e}$$

where;

$$a_e=\begin{vmatrix}x_B & y_B\\ x_C & y_C\end{vmatrix}\quad b_e=-\begin{vmatrix}1 & y_B\\ 1 & y_C\end{vmatrix}\quad c_e=\begin{vmatrix}1 & x_B\\ 1 & x_C\end{vmatrix}$$

$$2\Delta_e=\begin{vmatrix}1 & x_A & y_A\\ 1 & x_B & y_B\\ 1 & x_C & y_C\end{vmatrix}$$

Δ_e is the surface area of the triangular element *e* as shown in Fig 4.

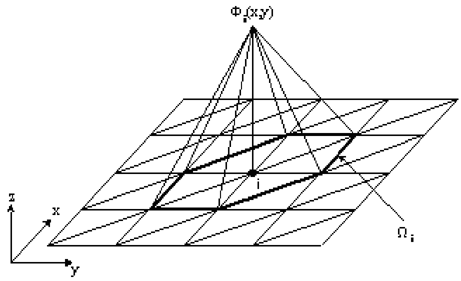

Fig. 3. Shape function

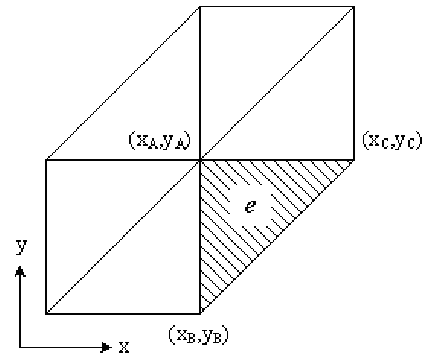

Fig. 4. Triangular element *e*

B. Silicon Carbide

In more than 170 polytypes of SiC known, only two (4H-SiC and 6H-SiC) are commercially available. 4H-SiC is preferred over 6H-SiC for power devices due to its higher electron mobility than that of 6H-SiC. Therefore, 4H-SiC is selected in this comparative study. The value of physical constants used in the model for Si and SiC are given in Table 1. Intrinsic concentrations, n_i of Si and SiC are $1.48\times10^{16}\,m^{-3}$ and $6.00\times10^{19}\,m^{-3}$, respectively. Electron and hole lifetimes of Si and SiC for n base layer are 7.0 μs and 3.0 μs, respectively. Parameters for electron and hole mobility μ are also arranged to smaller values for SiC [4].

III. METHOD OF NUMERICAL ANALYSIS

Basic equations describing internal potential V, hole concentration p and electron concentration n in semiconductor device are given as,

$$\mathrm{div}\,\mathrm{grad}\,V = -(q/\varepsilon)(p - n + N_d) \tag{1}$$

$$q(\partial p/\partial t) = -\mathrm{div}\,\mathbf{J}_p - qR \tag{2}$$

$$q(\partial n/\partial t) = \mathrm{div}\,\mathbf{J}_n - qR \tag{3}$$

where; q = electronic charge
ε = dielectric constant

Equation (1) is known as Poisson's equation. Impurity concentration N_d that is the difference of donor concentration N_D and accepter concentration N_A, $N_D - N_A$, is given for the semiconductor device under consideration. Equations (2) and (3) describe carrier transport. Both hole current density $\mathbf{J_p}$ and electron current density $\mathbf{J_n}$ contain the drift and diffusion components, and depend on V, p and n. Assuming Shockley-Read-Hall recombination model, recombination rate R depends on p and n.

TABLE 1
VALUE OF PHYSICAL CONSTANS FOR SI C USED IN DEVICE SIMULATION

	Si	SiC
Intrinsic concentration $n_i[\mathrm{m}^{-3}]$	1.48×10^{16}	6.00×10^{19}
Carrier lifetime $\tau_o[\mu s]$	7.0	3.0
Minimum electron mobility $\mu_{\min n}[\mathrm{m}^2/\mathrm{Vs}]$	65.0×10^{-4}	50.0×10^{-4}
Maximum electron mobility $\mu_{\max n}[\mathrm{m}^2/\mathrm{Vs}]$	1265×10^{-4}	1000×10^{-4}
Minimum hole mobility $\mu_{\min p}[\mathrm{m}^2/\mathrm{Vs}]$	47.7×10^{-4}	10.0×10^{-4}
Maximum hole mobility $\mu_{\max p}[\mathrm{m}^2/\mathrm{Vs}]$	447.3×10^{-4}	190.0×10^{-4}
Electron ionization coefficient α_n	0.72	0.72
Hole ionization coefficient α_p	0.76	0.76
Reference electron concentration $N_{\mathrm{ref}\,n}[\mathrm{m}^{-3}]$	8.5×10^{22}	2.2×10^{23}
Reference hole concentration $N_{\mathrm{ref}\,p}[\mathrm{m}^{-3}]$	6.3×10^{22}	2.35×10^{23}

IV. DISCRETIZATION USING FINITE ELEMENT METHOD

In order to do a numerical analysis, equations (1), (2) and (3) are transformed into different equations in which the variables V, p and n are defined at the mesh points of the device model that has been numbered from 1 to N. Substituting finite element approximation into these equations and integrating them, we get the following matrix equations.

$$\mathbf{K}^v\mathbf{V} - \frac{\mathbf{q}}{\varepsilon}\mathbf{M}(\mathbf{p} - \mathbf{n} + \mathbf{N_d}) = 0 \tag{4}$$

$$-\mathbf{M}\left(\frac{\partial \mathbf{p}}{\partial \mathbf{t}}\right) + \mathbf{K}^p\mathbf{p} - \mathbf{MR} = 0 \tag{5}$$

$$\mathbf{M}\left(\frac{\partial \mathbf{n}}{\partial \mathbf{t}}\right) + \mathbf{K}^n\mathbf{n} + \mathbf{MR} = 0 \tag{6}$$

$\mathbf{K^v}$, $\mathbf{K^p}$, $\mathbf{K^n}$ and $\mathbf{M}$ are coefficient matrices of N x N dimension. N_d is a constant vector of N x N dimension. $\mathbf{V}$, $\mathbf{p}$, $\mathbf{n}$ and $\mathbf{R}$ are variable vectors of N × 1 dimension. Equations (4), (5) and (6) are valid except for the electrodes such as anode, cathode and gate. For the expression of $\mathbf{J_p}$ and $\mathbf{J_n}$ we use the difference scheme of Scharfetter and Gummel.

Using the Crank-Nicolson method for the time derivatives of equations (5) and (6), these equations become as follows,

$$\frac{-\mathbf{M}(\mathbf{p} - \mathbf{p}^*)}{\Delta\mathbf{t}} + \frac{1}{2}\left(\mathbf{K}^p\mathbf{p} - \mathbf{MR} + \mathbf{K}^{p^*}\mathbf{p}^* - \mathbf{MR}^*\right) = 0 \tag{7}$$

$$\frac{\mathbf{M}(\mathbf{n} - \mathbf{n}^*)}{\Delta\mathbf{t}} + \frac{1}{2}\left(\mathbf{K}^n\mathbf{n} + \mathbf{MR} + \mathbf{K}^{n^*}\mathbf{n}^* + \mathbf{MR}^*\right) = 0 \tag{8}$$

where $\Delta\mathbf{t}$ is the interval of time steps. Suffix * denotes the computed value at one time step before.

V. SIMULATION TOOL

In order to do the modeling and switching simulation of the GTO device, we create a simulation tool as shown in Fig. 5. This simulation tool is developed user friendly, for convenient use. The dimensions and parameters of doping profiles for the GTO model are shown in Fig. 6.

Fig. 5. Simulation tool for the GTO model

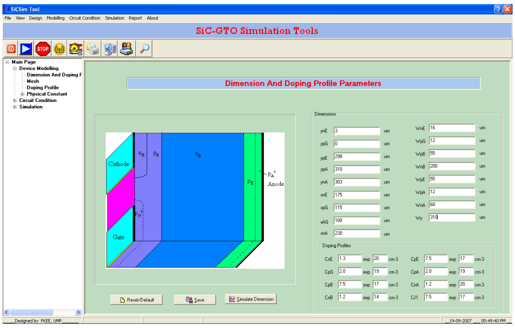

Fig. 6. Dimensions and doping profiles parameters

VI. Result of Doping Profile

Fig. 7 shows the doping profile of two dimensional model of GTO. This GTO is industrial type rating that is 1200V, 90A. Fig. 7 represents one of the 64 units of the GTO

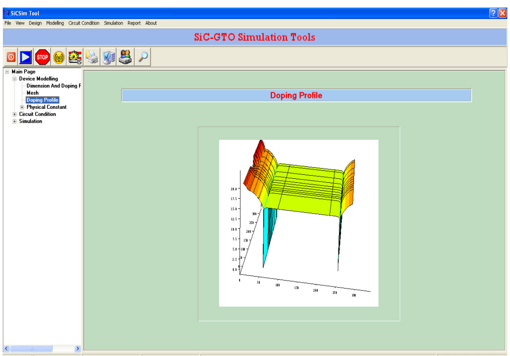

Fig. 7. Doping profile of two dimensional model of GTO

VII. Switching Characteristics

Fig. 8 shows the switching waveforms of Si-GTO and SiC-GTO. In the simulation, we raised anode voltage to 300V, GTOs are turned on (anode current is increased to 30A and anode voltage is decreased to 0V). Then they are turned off by negative gate pulse. Anode current decreased to 0A and anode voltage recovers to 300V. We can see large difference at turn-off switching waveforms. We know that turn-off time of SiC-GTO is better than that of Si-GTO. Turn-on time and turn-off time are shown in Table 2 (All units are in µs). Result show that switching time of SiC-GTO is decreased extremely and the performance of SiC in GTO is the time improvement in storage time, fall time and tail time.

	Si-GTO	SiC-GTO
Turn-on time	0.42	0.63
Delay time	0.20	0.22
Rise time	0.22	0.41
Turn-off time	10.40	1.58
Storage time	3.28	0.34
Fall time	1.07	0.25
Tail time	6.05	0.99
Switching time (µ s)	10.82	2.21

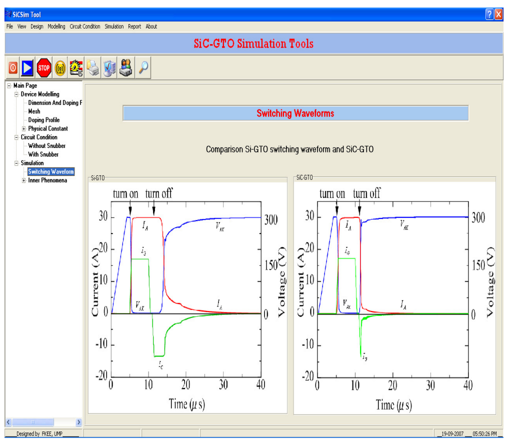

Fig. 8. Switching waveforms of Si-GTO and SiC-GT

VIII. CONCLUSION

From the analysis of physical constants of silicon and silicon carbide, and device characteristics of Gate Turn-off thyristor, we create the modeling device of Si-GTO and SiC-GTO. Using the simulation tool, we show the doping profile of GTO thyristor and compare the switching waveforms of usual Silicon Gate Turn-off Thyristor (Si-GTO) and new Silicon Carbide GTO (SiC-GTO). Turn-off time is smaller in the case of SiC-GTO than in that Si-GTO

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ohd Shawal Jadin received his BSc (Hons) from Universiti Sains Malaysia in Electrical and Electronic Engineering in 2002. From 2002 he held position as a Research Officer in Electrical Power at USM. Awarded MSc degrees from Universiti Sains Malaysia in 2006. From 2006 attached as a lecturer in Faculty of Electrical & Electronic Engineering, Universiti Malaysia Pahang, Pahang, Malaysia. Research interest in Power Electronic & Drives, Expert System and Renewable Energy.

Muhamad Zahim Sujod was born in Kuala Selangor, Selangor in Malaysia, on 11 August 1976. He received his Bachelor Electrical & Electronics Engineering in 2000 and Master Electrical & Electronics Engineering in 2002 from Ehime University, Japan. His research interest includes power electronics, energy conversions, semiconductor devices and renewable energy.

Raja Mohd Taufika Raja Ismail received his B.Eng. from Universiti Teknologi Malaysia (UTM) in Electrical Engineering in 2004. Awarded M.Sc. (Mathematics) degrees from UTM in 2006. From 2006, attached as a lecturer in Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang. Research interest in Applied Mathematics and Computational Engineering.