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Modeling and Simulation of Silicon Carbide (SiC) Based Bipolar Junction Transistor

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***Abstract*— Silicon Carbide (SiC) is a promising material for high voltage and high temperature applications due to their low conduction losses and fast switching capability. This paper focuses on the simulation of static and switching characteristics of SiC Bipolar Junction Transistor (BJT developed by TranSiC) rated at 600V and 6A at different temperatures. SiC BJT is modeled in MATLAB using Ebers-Moll equations. The Ebers-Moll parameters taken for modeling SiC are: parasitic capacitances (C_{BC} and C_{BE}), the forward current gain β_F , the early voltage and the saturation current (I_s). Comparison was made between the SiC BJT and a 1200 V Si insulated gate bipolar transistor (IGBT). The simulation results are verified with experimental data. It is found that SiC BJT has much smaller conduction and switching losses than the Si IGBT.**

***Index Terms*—SiC, Si IGBT, Losses, Ebers moll Equation**

I. INTRODUCTION

SiC is a wide band gap semiconductor that possesses extremely high thermal, chemical, and mechanical stability. It has the advantage of high thermal conductivity, high breakdown electric field, and saturated carrier velocity compared to other semiconductor materials, which makes it an ideal material for power devices. Among the SiC devices, SiC BJT is a promising high power switching device. BJTs based on 4H-SiC have the advantage of no gate oxide and low on-resistance due to two-sided high-level injection, which is preferable in high temperature conditions. The power transistors for 600 V and above based on Si have either a relatively high specific on resistance or significant switching power losses, which both result in high power dissipation. In addition, the maximum allowed operating temperature of Si power devices is typically 125

°C, which cannot satisfy the demand of an increasingly dense power electronics system design such as the traction inverter used in electric vehicle [1].Compared to other bipolar devices, like IGBT and GTO, BJT does not have the junction voltage needed to overcome in order to conduct current. Also, the process complexity is reduced greatly as compared to SiC MOSFETs, rendering the SiC BJT a promising high power switching device [2]. This paper describes the characterization of SiC BJT and its temperature dependency through DC measurements. In this paper, the static and switching characteristics of SiC BJT are simulated using MATLAB. Comparisons are carried out with a state-of-the-art Si IGBT with the emphasis on total losses.

II. CONSTRUCTION OF SIC BJT

SiC BJT is suited for high temperature and high power applications due to their low conduction losses and fast switching capability. A schematic cross-section of 4H-SiC based NPN BJT is shown in Fig.1. A three layer epitaxy (NPN type structure) has been grown in a single continuous growth step. The emitter layer is composed of two steps with different doping concentration. The emitter and base mesa structures have been defined by ICP (Inductively Coupled Plasma) etching using SiO_2 as a mask. Aluminum ions have been implanted to form the low resistance base contact. Another aluminum implantation has been introduced to define the Junction Termination Extension (JTE) to suppress the surface electric field. The implants have been

activated at 1650°C. A thermal oxide under N_2O environment has been grown for passivation. The emitter and base contact metals are Ni and Ni/Ti/Al respectively while bottom collector

contact is based on Ni/Au. The top pad metallization is aluminum.

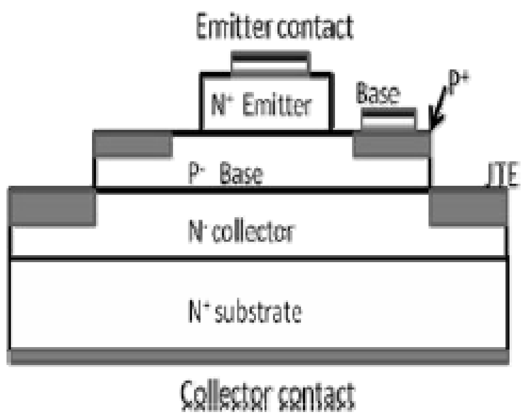

Fig. 1 Schematic cross-section and terminals of SiC BJT

The terminals of SiC BJT (BITSiC 1206) developed by Transic company is shown in Fig.2.

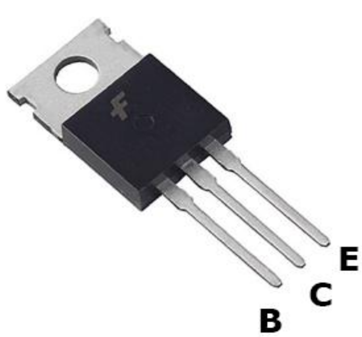

Fig.2. Terminals of BITSiC 1206

III. MODELING OF SIC BJT

SiC BJT (BITSiC 1206) is modeled in MATLAB using Ebers –Moll equations [7,8]. The most important Ebers-Moll parameters which differentiates Si and SiC BJT devices are: parasitic capacitances (C_{BC} and C_{BE}), the forward current gain β_F , the early voltage and the saturation current (I_s).

1. Parasitic Capacitance

This capacitance governs the switching behavior of the transistor which arises between the different doping layers in the transistor. The simulated parasitic capacitance curves are shown in Figs. 3 and 4.

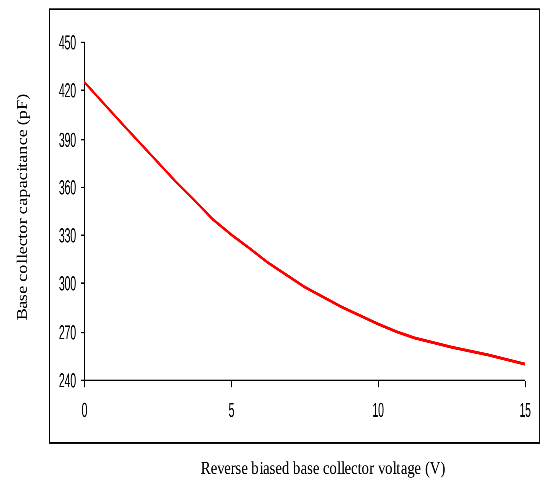

Fig.3 Simulated base collector capacitance as function of reverse biased base collector voltage

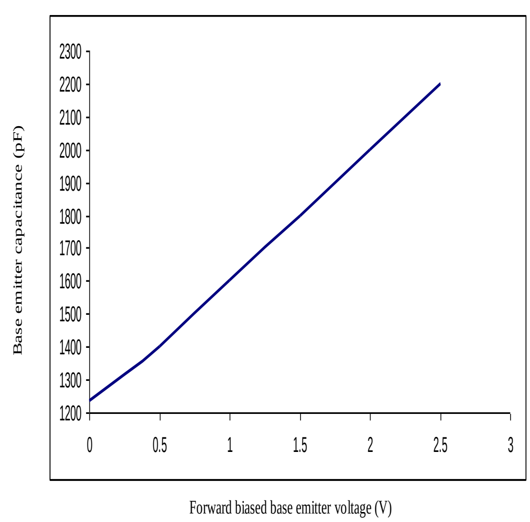

Fig.4.Simulated base emitter capacitance as a function of forward biased base –

emitter voltage

From the simulated graphs, it is obvious that the base-collector capacitance (C_{BC}) at zero voltage is about 425pF and the base-emitter capacitance

(C_{BE}) is about 1233pF which closely match with the manufacturer's datasheet values (C_{BC} = 400pF and C_{BE} = 1500pF).

2. Early Voltage

In a bipolar transistor, the width of the base is reduced if the collector emitter voltage is increased. A smaller width of the base allows a large collector current passing through the transistor. The early voltage is measured by obtaining the output characteristics of the transistor for different values of base current. The set of current lines obtained from the output characteristics are extended into the second quadrant and gathered in one single point on the V_{CE} axis and this point is referred as the early voltage [3, 4].To measure the early voltage, a voltage is applied to the base-emitter junction resulting in a base current. This result in collector current flowing through the transistor. Thereafter two different values of collector-emitter voltages are applied and the corresponding collector currents are measured. The collector-emitter voltages with the corresponding collector current are presented in Table I.

Table I Simulated values of V_{CE} and I_C for calculating early voltage

V_{CE}(V)	I_C(A)
5.00	2.85
3.56	2.34

The early voltage is obtained as 6.25V.

3. Forward Current Gain (β_F)

The forward current gain is the ratio between the collector current and the base current. It is not a constant parameter but depends on the collector current. The collector voltage V_{CC} is set to 10V and the base current is swept until the collector current reached 5A.The simulated forward current gain as a function of the collector current is shown in Fig.5. The graph shows SiC

BJT's ability to remain at relatively high gain at high collector current. This is an advantage compared to a Si BJT which loses a lot of its gain at high collector currents.

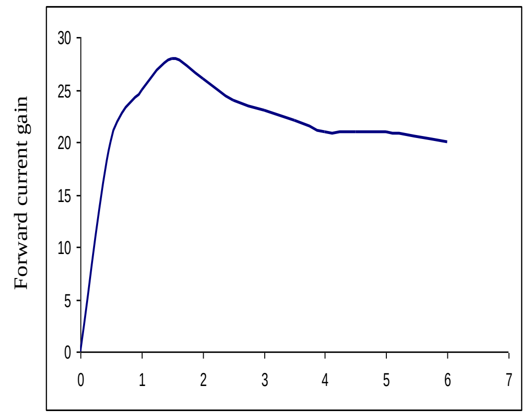

Fig.5 Simulated forward current gain as function of collector current

4. Saturation Current (I_s)

Saturation current is defined as the current flowing through a PN junction when the junction has been saturated. It is calculated using the equation which is given by

$$Is = Iso\left(1+\frac{V_{CE}}{V_A}\right) \qquad (1)$$

where, I_{SO} represents the saturation current when V_{CE} = 0 V, V_{CE} represents the collector –

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emitter voltage, V_A represents the early voltage.

The saturation voltage of a SiC PN junction is somewhere about 2.5-3V. The zero voltage saturation current is calculated by applying the saturation voltage to the base emitter junction. Then the resulting collector current is measured and I_{SO} is calculated using

$$I_{SO} = e^{\ln(I_C) - V_{BE}/V_t} \qquad (2)$$

For I_C = 3.87mA, V_{BE} = 2.688V and the threshold voltage V_t = 25.85mA, the zero voltage saturation current is about 2.68×10^{-48} A. The modeled parameters of SiC BJT are used to obtain the static and dynamic characteristics and the values are listed in Table 4.5. Modeling of current gain and parasitic capacitances are important which determines the switching behavior of SiC BJT.

Table II Parameters of SiC BJT

Parameter	Simulated Values	Data sheet values
Base Emitter capacitance (C_{BE}) with V_{BE} = 0V and Fs = 100kHz	1233pF	1500pF
Base-Collector capacitance (C_{BC}) with V_{BE} = 0V and f_s = 100kHz	425pF	400pF
Early voltage (V_A)	6.25V	5.85V
Saturation current (I_S)	2.68×10^{-48}A	1.29×10^{-49}A
Forward current gain (For V_{CE} = 5V and I_C = 2A)	20	20

Using the device parameters shown in Table 4.5, the SPICE code for obtaining the characteristics of SiC BJT in LTSPICE is given as

.model BitSiC1206 NPN (IS = 1.5e-48 BF = 20 NF = 1 ISE = 2.2e-26 NE = 2 BR = 0.55 RB = 0.26 RC =0.06 XTI = 3 XTB = -1.1 EG = 3.2 TRC1 = 4e-3 + CJE = 1233pF VJE = 2.9 MJE = 0.5 CJC = 425pF VJC = 2.9 MJC = 0.5)

The model includes a temperature dependent collector resistance, which is an important feature that is not available in all SPICE versions. The parameters IS, BF, NF, ISE and NE are important for modeling the current gain and its dependence on the collector current accurately; XTI, XTB and EG model the temperature dependence of the current gain. RC and TRC1 model the on-resistance of the BJT and thus the value of V_{CE} (SAT). The parameters CJE, VJE and MJE model the base-emitter capacitance. CJC, VJC and MJC model the base-collector capacitance which is important for the switching speed [2].The output characteristics of SiC BJT are obtained for different junction temperatures using LTSPICE as shown in Figs 6 and 7 .Switching characteristics are obtained by taking into account the parasitic inductances for the TO-258 package provided by the manufacturer (L_C = 10nH, L_E = 20nH and L_B = 25nH).

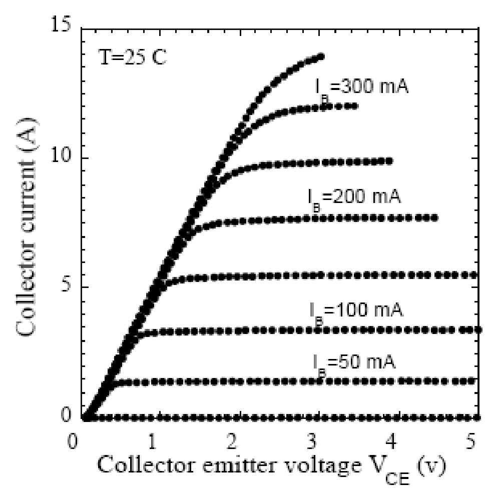
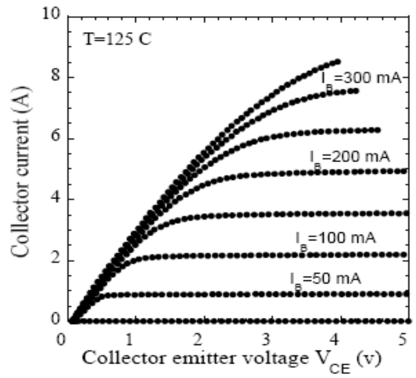


Fig.6. VI characteristics of SiC BJT at



25°C

Fig.7. VI characteristics of SiC BJT at 125°C

IV.COMPARISON OF SiC BJT AND Si IGBT

A state-of-the-art 1200V Si IGBT has been selected for compring with SiC BJT and the output characteristics of both the devices are shown in Fig.8.

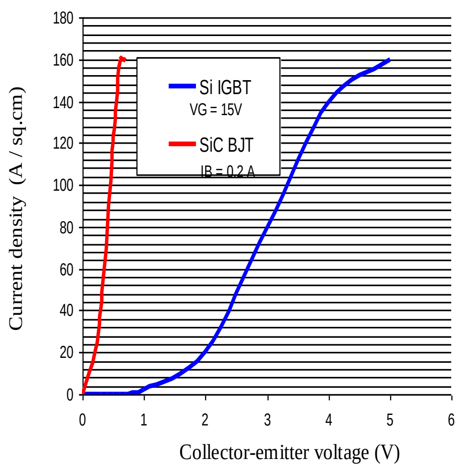


Fig.8.Output characteristics comparison between SiC BJT and Si IGBT

The IGBT has a forward voltage drop of 3.3V at collector current density J_C = 100A/cm^2 while the forward voltage of the SiC BJT is only 0.59V much smaller than the Si IGBT. This means the conduction losses in the SiC BJT will be much smaller than that of Si IGBT.

1. *Calculation of conduction and switching losses*

SiC BJT is a fast switching device having very little stored charge during forward conduction and virtually negligible storage time delay during turn-off compared to a Si power BJT. It has a small tail current which enables significantly lower turn-off switching losses compared to a Si IGBT. The attractive feature of SiC BJT is that it is basically free of second breakdown and has a square reverse biased safe operating area. The design of driver circuit for SiC BJT is crucial since it requires an on-state base current of at least 400mA [5,6]. The high dynamic base current is achieved by employing a fast IC driver IXDN509 and a external base resistor with a capacitor in parallel. Although the driver loss of SiC BJT is much higher than Si IGBT, all other losses including the turn-on, turn-off, and conduction loss of SiC BJT are much smaller than Si IGBT, making the total loss of SiC BJT much lower than Si IGBT as shown in Fig.9.

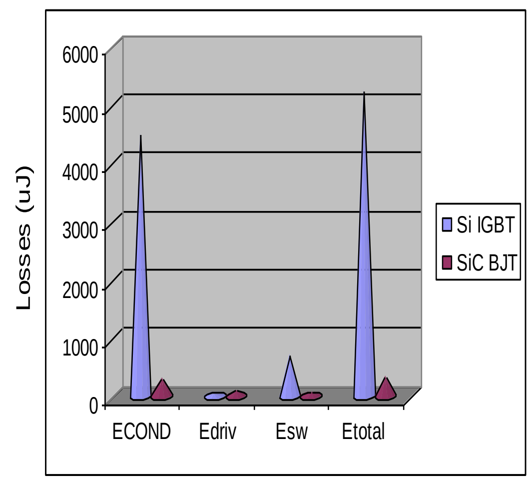


Fig.9 Loss comparison of Si IGBT and SiC BJT

The loss comparison shown in Fig.9 confirms that SiC BJT has much lower conduction and switching losses than Si IGBT. Moreover, a square RBSOA makes the SiC BJT more

attractive for hard switching applications. Although the loss penalty of driving a BJT with a base current is large compared to the IGBT driving loss, the total loss in the SiC BJT is much smaller than that of the Si IGBT[10.11]. This makes the 1200V SiC BJT more attractive for switching applications than the 1200V Si IGBT.

V.CONCLUSION

The modeling of SiC BJT parameters has been carried out in MATLAB and LTSPICE. Comparison is made between SiC and Si based switches in terms of conduction and switching losses. It shows that the SiC BJT has resulted in reduced switching loss and higher efficiency. Moreover, a square RBSOA makes the SiC BJT more attractive for hard-switching applications. Although the loss of driving a BJT with a base current is large compared to the IGBT driving loss, the total loss in the SiC BJT is much smaller than that of the Si IGBT. This makes the 1200 V SiC BJT more attractive for switching applications than the 1200 V Si IGBT.

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