SiC Schottky Diode Electrothermal Macromodel

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Abstract—**This paper presents a SiC Schottky diode model including static, dynamic and thermal features implemented as separate parameterized blocks constructed from SPICE Analog Behavioral Modeling (ABM) controlled sources. The parameters for each block are easy to extract, even from readily available diode data sheet information. The model complexity is low thus allowing reasonably long simulation times to cope with the rather slow self heating process and yet accurate enough for practical purposes.**

Index Terms—**SiC Schottky, self heating, ABM, temperature coefficient, voltage controlled capacitance, RC thermal model.**

I. INTRODUCTION

SiC is becoming fashionable as a base material for power devices [1,2] due to its intrinsic characteristics as wider bandgap, higher critical breakdown field strength and higher thermal conductivity compared to Si. Despite its poorer material quality and much higher price, SiC is finding its way in power applications, being the Schottky diode the most readily available component now in the market. As opposed to Si Schottky diodes that suffer from high leakage currents and relatively poor device reliability and are thus limited to low voltage parts, the wider bandgap and higher critical field of SiC allows for the manufacturing of high voltage devices with much lower leakage currents, even at elevated temperatures. Moreover, being majority carrier devices, SiC Schottky's switch faster than their Si PiN diode counterparts and its switching speed is almost independent of temperature.

For all that, the need of suitable models to use for circuit and system design becomes evident for such parts. Ideally, these models should include both static and dynamic features and also, due to the high temperature operation capability of devices, thermal modeling and especially self heating effects that can substantially affect operation.

Two main approaches are available [3] that include self heating, i.e., Analog Hardware Description Language (AHDL) and SPICE Analog Behavioral Modeling. Although AHDL solution is faster, as the model code is compiled and linked to the simulator, its portability between different simulators is low and user has no direct access to model equations and parameters. On the other side, SPICE ABM model is interpreted by the simulator so it executes slower than AHDL but it has total portability (except for a few syntactic differences) between SPICE simulators that support ABM, while model structure, equations (if any) and parameters are readily available to the user.

In the following paragraphs, we will build the model as three independent blocks for static, dynamic and thermal response that will finally be joined together into a single electrothermal model.

II. STATIC MODEL

The forward *I-V* characteristics will be modeled by means of the standard piece-wise linear (PWL) model [4,5] featuring a d.c. voltage V_0 and a series resistance R_d as follows:

$$V_d = V_0 + R_d \cdot I_d \tag{1}$$

Temperature dependence for V_0 and R_d is introduced at this point as:

$$V_0 = V_{00} + \alpha_V \cdot (T - T_0) \tag{2}$$

$$R_d = R_{d0} + \alpha_R \cdot (T - T_0)^n \tag{3}$$

Where V_0 temperature dependence is assumed linear, which is a good fit in practice, and series resistance is fitted by a power law. If we want a simpler linear model we can make $n = 1$. However, a better fit is generally achieved if n has a value between 2 and 3. For practical purposes, the value 2 can be forced with sufficient approximation. T_0 is the reference (ambient) temperature.

Substituting (2) and (3) into (1) we get for the diode forward drop, including temperature variation:

$$V_d = V_{00} + \alpha_V \cdot (T - T_0) + R_{d0} \cdot I_d + \alpha_R \cdot I_d \cdot (T - T_0)^n \tag{4}$$

This constitutes the model equation. Note that the way equations (2), (3) and (4) are stated, α_V and α_R have dimensions of $V/{}^{\circ}C$ and $\Omega/({}^{\circ}C)^n$. This is consistent with the way parameters are extracted from data sheet or measurements.

Using ABM dependent sources, equation (4) can be modeled as shown in figure 1. *H1* transforms I_d into an equivalent voltage to use at the input of the multiplier *EKrID* modeling the last term in equation (4). The second term is modeled by the *EKV* source, which gain is set to α_V. Source *EKR* models series resistance temperature dependence through its gain that is set to α_R. Temperature equivalent voltage input is passed through a power element *PWR n* before going into *EKR*. Finally, V_{00} is modeled directly by a d.c. voltage source of the same name.

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Switch *Sr0* is included to make the model valid for forward as well as reverse input voltage.

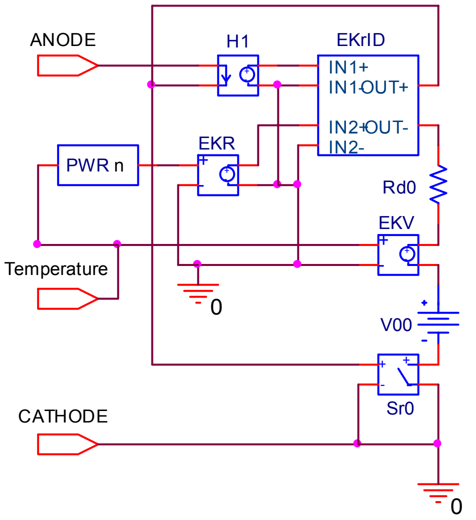

Figure 1. SPICE ABM static Diode Model

The value for R_{d0} could be modeled by the on resistance of *Sr0* but an independent resistor is used instead for reasons that will become clear later. The reverse diode current is simply modeled by *Sr0* off resistance. No further effort is done to improve this point.

III. DYNAMIC MODEL

SiC Schottky diodes, being majority carrier devices, do not have minority carrier stored charge, hence no reverse recovery current. However, junction transition capacitance is heavily voltage dependent so, during voltage transients, there is a displacement current through the diode.

Diode transition capacitance, in fact, is not a function of diode voltage but of voltage applied across the space charge region, i.e., the external diode voltage less the series resistance drop. This last voltage drop may be negligible with reverse bias but is not with forward bias, and this fact has to be taken into account because switching processes cross the boundary between both biases. Diode capacitance as a function of voltage may thus be written as:

$$C_{jT} = f(V_{jT} - V_B) \qquad (5)$$

Where V_{jT} is the voltage across the transition region and V_B is the barrier height at zero applied voltage. The displacement current across this capacitance is:

$$I_{jT} = C_{jT}\, d(V_{jT} - V_B)/dt \qquad (6)$$

To model this displacement current we'll use the ABM circuit shown in figure 2. The voltage at the output of *HI* source is $C_2 \cdot dV_{Copy}/dt$ where C_2 is a reference capacitor (1pF in this case) and V_{copy} (the output voltage of E_{Copy}) is the applied voltage. This term takes into account the displacement current due to the applied voltage change across a 1pF constant capacitor. This value is multiplied at G_{Cap} by the voltage dependent junction capacitance implemented through a table.

The terminal labeled *Internal Anode* has to be connected to the *EKV +* output of the static model, which represents the internal point where the transition region ends, i.e., total diode voltage less series resistance drop. This is the reason why switch *Sr0* does not include R_{d0} as the on state resistance.

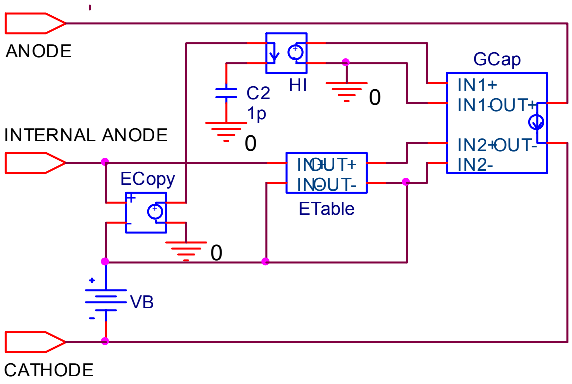

Figure 2. SPICE ABM dynamic model

The V_B voltage source subtracts the built-in barrier voltage. The voltage dependent diode capacitance is implemented via a table whose values may be extracted from measurement or data sheet information. Although the approximation is piece-wise, 4 or 5 points will give sufficient accuracy for the purpose. Finally, even there is some variation of the transition capacitance with temperature [6] it is assumed temperature independent. This is done to simplify the model, because no much data are available on the subject and also because the measurement is very time consuming. The error incurred with such an approximation is assumed to be quite low.

A key issue of the dynamic model is the switching points we choose for *Sr0*. The main question is to make sure that the switch turns off (approximately) when diode current crosses zero because if not, reverse current will flow not because of transition capacitance charging, but of reverse conduction. A good choice for that is $V_{ON} = V_{00}$ and $V_{OFF} \approx ½\, V_{00}$.

IV. THERMAL MODEL

To include self heating in the model, the first we need is the instantaneous power dissipation of the device, i.e., the product of instantaneous device current and voltage. This product is transformed to a current of the same value that is injected into the dynamic thermal model of the packaged device.

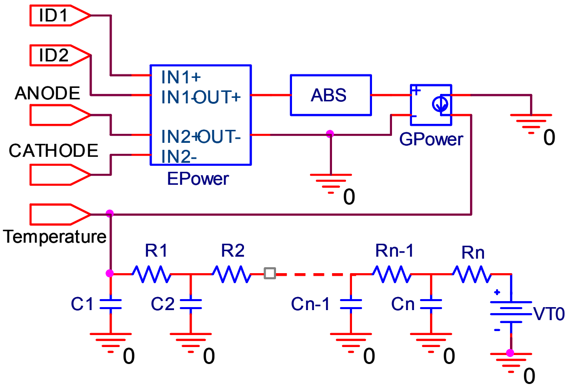

Figure 3. SPICE ABM thermal model

The dynamic thermal model has the form of an RC Cauer network that can be extracted from a single measurement plus some processing [7] or is eventually supplied by the manufacturer in the data sheet.

Figure 3 shows the thermal model. *ID1* and *ID2* sense the device current and must be connected to *H1* output in the static model. *Anode* and *Cathode* are diode external terminals and sense device terminal voltage. *EPower* is the multiplier that gives device power. This value is passed through an absolute value circuit to avoid negative power that could arise from output ringing due to lead or external inductance. Finally, *GPower* converts voltage into current to be injected into the device thermal equivalent circuit. This way of calculating the instantaneous device power may include some reactive power taken and returned by external reactive elements and not really dissipated by the device itself. However this error is assumed to be small and otherwise difficult to avoid.

Thermal RC device model is composed of C_1 to C_n and R_1 to R_n while d.c. source V_{T0} stands for reference (ambient or heatsink) temperature.

V. SIMULATION RESULTS

The part used for simulation is a 4A, 600V SBD in TO220 package. Measurements are performed on three units at four different temperatures, i.e., 25, 70 110 and 150ºC to extract model parameters V_{00}, R_{d0}, α_V and α_R. The results for the fit are shown in tables 1 and 2, along with the regression coefficient to ascertain its goodness. The average of the measured values on the three parts is used in the model.

TABLE I. MEASUREMENT RESULTS FOR V_{00} AND α_V

Part #	$\mathbf{V_{00}+\alpha_V \cdot \Delta T}$	$\mathbf{R^2}$
1	$1024.8 - 0.9354\ \Delta T$	0.9946
2	$1026.9 - 0.9616\ \Delta T$	0.975
3	$1025.4 - 0.9766\ \Delta T$	0.9961

TABLE II. MEASUREMENT RESULTS FOR R_{D0} AND α_R

Part #	$\mathbf{R_{d0}+\alpha_R \cdot \Delta T^2}$	$\mathbf{R^2}$
1	$155.336 + 0.00523\ \Delta T^2$	0.9972
2	$156.424 + 0.00526\ \Delta T^2$	0.9917
3	$155.394 + 0.00531\ \Delta T^2$	0.9957

The values for the transition capacitance have been taken from data sheet using 7 points, from 300V down to 0V. The values for the thermal equivalent circuit come from available data on the package used for the part.

Four different simulations are run: a d.c. simulation to show the modeled d.c. forward characteristics, a repetitive surge current at 50Hz to show how self heating is handled by the model, a turn-off transient at three different *di/dt* values to show the dynamic model coherence and finally a turn-off transient at four different temperatures to show there is no significant change.

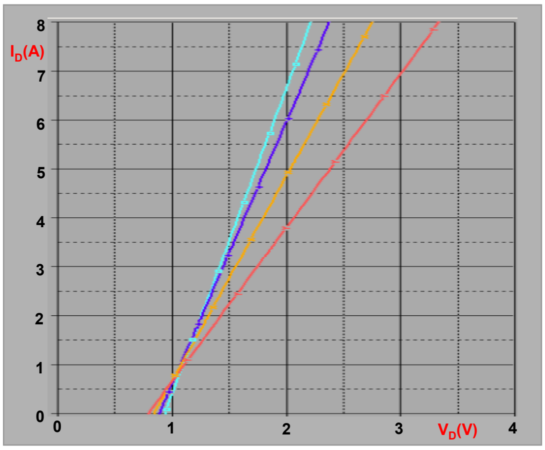

Figure 4. D.C. model output at four temperatures: 25ºC, 75ºC, 125ºC and 175ºC (light blue to red)

Apart from d.c. measurements that give rise to d.c. model, no other experimental measurements have been performed to date to verify the model accuracy, although they will in a near future.

Figure 4 shows the d.c. model output at four temperatures, from 25ºC up to 175ºC. It is not intended to fit any particular part but to give a representation of a typical diode.

To show the model capability to take self heating into account, the second simulation run consists of a three 50Hz period surge current of about six times the average current rating of the diode and is displayed in figure 5.

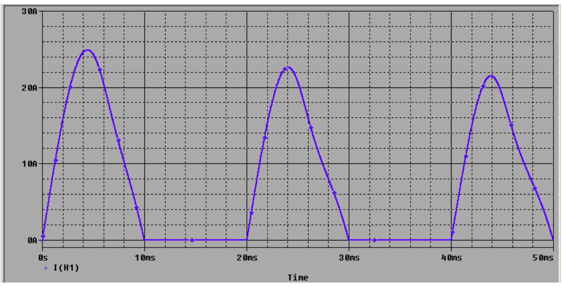

Figure 5. Repetitive surge current to show self heating

Waveform change due to self heating is clearly seen as a decrease in peak current and distortion on the second half period of the signal, increasing with time.

Figure 6 displays the turn-off transient at three different *di/dt*. Red plot is for 950 A/µs, yellow is for 470 A/µs and blue for 340 A/µs. It can be seen the change in peak reverse current from more than 1 A to less than 0.5 A.

Finally, figure 7 displays the 950 A/µs turn-off transient at four temperatures, i.e., 25, 75, 125 and 175ºC. The slight variation is due to changes in forward voltage drop of the diode that in turn lead to slight changes in *Sr0* switching instant. This has to be considered, strictly speaking, as a model flaw.

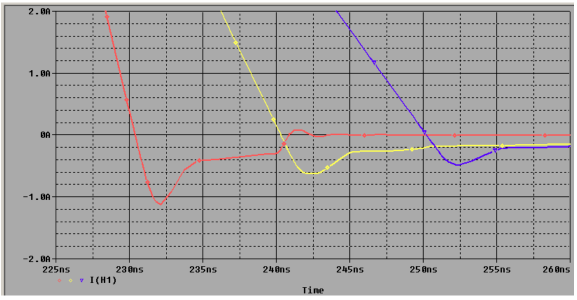

Figure 6. Turn-off transient at three di/dt values of 950, 470 and 340 A/µs.

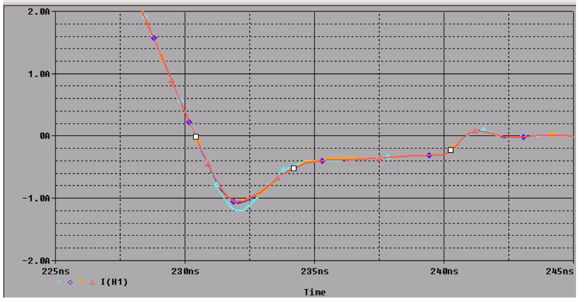

Figure 7. Turn-off transient for di/dt = 950 A/µs and T = 25, 75, 125 and 175 ºC.

VI. CONCLUSIONS

A model for SiC Schottky Barrier Diodes based on SPICE ABM has been presented, its prime advantage being portability and easy access to model parameters.

Parameters used in the model are easily extracted even from data sheet information.

Its coherence with real device behavior has been shown, and further experiments are underway to also proof its accuracy.

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