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MACROMODELING WITH SPICE OF SiC SCHOTTKY DIODE

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ABSTRACT
This paper presents a SiC Schottky diode model including static and dynamic features implemented as a parameterized block constructed from SPICE Analog Behavioral Modeling (ABM) controlled sources. The parameters for this block are easy to extract, even from readily available diode data sheet information. This model can easily simulate the diode's reverse recovery and power losses behavior over all temperatures from 0C° to 175C°.
Keywords: Power Diode; Reverse Recovery;Silicon Carbide Schottky (SiC); Temperature effect ;Modeling; PSpice;ABM.

I. INTRODUCTION

The semiconductor industry has a well-established history of "smaller, faster, and cheaper." Improving performance and reducing device cost while shrinking packaging size is fundamental to virtually every semi-conductor product type. For power products, improved performance is measured by increased efficiency and power density, higher power handling capability, and wider operating temperature range. Such improvements depend largely on the desirable characteristics of power components used, such as low switching and conduction losses, high switching frequency, stable electrical characteristics over a wide temperature range, high operating temperature, and high blocking voltage. As silicon power components approach their theoretical limits, compound semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), provide the capability to dramatically improve these parameters.

Efficient device models are required to evaluate the performance of SiC Schottky diodes in different applications and guide system design. Although several models have been developed for SiC Schottky diodes, most of them are based on device physics or based on experiments [1] [2]. For the former, usually a number of device parameters (which are usually known only by designers) are required to solve the model, and sometimes the model itself is complicated, and difficult to solve or time consuming. For the latter, a variety of experiments are needed. Parameter extractions are also involved and can be rather tough. Accordingly, these models are difficult to be integrated into a system simulation. It is necessary to find some models of SiC Schottky power diodes specialized for system modeling. This work is to address this need.

II. DIODE CHARACTERISTICS

In Fig.1, it is represented the original Schottky Diode model we have implemented. It is composed of a voltage controlled current generator in parallel to the original SPICE diode. The aim of this current generator is to provide a better accuracy in the reverse I-V characteristic. The I-V and reverse current are among the static characteristics of the device. Due to higher level of majority carrier injection in Si diode, this causes a lower voltage drop and hence smaller capacitance to bias the junction for turn-on process. This is the only advantage of Si diode compared to SiC. Here, SiC diode requires a higher voltage to forward bias the device [3]. Apart from that, SiC diode can handle larger reverse voltage as compared to Si.

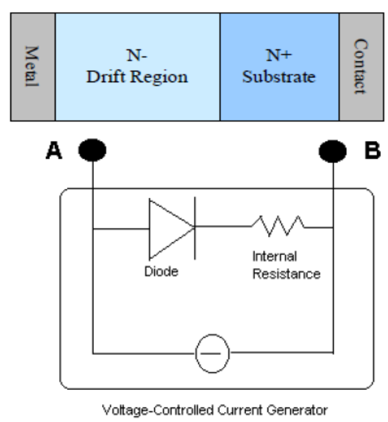

Figure 1: Electric Schottky diode Model

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

$$V_D=V_0+R_D\,I_D \tag{1}$$

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

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

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

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:

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

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 /ºC and Ω / (ºC) ^{n}. This is consistent with the way parameters are extracted from data sheet or measurements.

III. DYNAMIC CHARACTERISTIC

The characteristic that changes with time is inherited in both devices. Si and SiC diodes are compared in terms of the reverse recovery time, reverse recovery current and corresponding switching losses. The comparisons in dynamic characteristics between two devices are tabulated in Table 1. The SiC and Si diodes used are of part number SDP04S60 and SB30-03F respectively [5].

Table 1: Comparison of Dynamic Characteristics

Characteristics	SiC Schottky (SDP 04S60)	Si Schottky (SB30-03F)
Reverse Recovery Time	Unchanged with temperature variation	Increases as temperature increases
Reverse Recovery Current	Negligible	Increases as temperature increases
Switching Losses	Low	Slightly higher

Table 1 show that SiC diode has advantages in all dynamic characteristics. Si diode suffers from higher reverse recovery current and switching losses. This clearly indicates the additional carbide substance in the device may improve switching speed and reduce power dissipation.

Reverse recovery is one of the properties in a diode. It can be a factor in determining the efficiency of the applications. When a diode has been conducting in a forward bias long enough for it to establish steady state, there will be charges due to the presence of minority charge carriers. This charge must be removed to block in reverse direction [6].

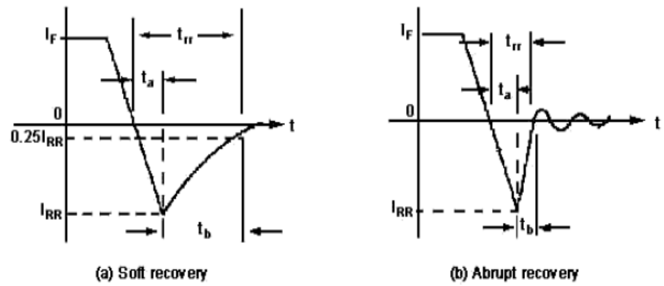

Figure 2: Reverse Recovery Current Characteristic

The characteristic of reverse recovery current experienced by a diode is represented in Figure 2 above. t_{rr} represents the reverse recovery time, I_{rr} is the peak reverse current whilst t_a is the transition time due to charge stored in depletion region of the p-n junction. t_b is the time for the current to relax to zero. The peak reverse recovery current depends on the falling rate of change in current during turn-off. In SiC diode, there will be less or none reverse recovery current due to its ability to immediately remove stored charge [7]. However, there are differences observed during the recovery from the peak values. This is merely reflected from different device's fabrication techniques. Normally, in SiC, the rising currents rate to zero takes a longer time (t_{rr}) as shown in part (a) in Figure 2. This eventually reduces the turn-off speed. In other SiC type, the speed can also be slightly faster due to smaller t_b but with the cost of higher dissipation. This can be seen in part (b) as oscillation exists during the end stage of turn-off time. In addition, if the falling current rate during the beginning of turn-off time is high as in the case of non-schottky diode, the reverse current would also be high, leading to both high power dissipation and lower in turn-off speed [8].

IV. SPICE MODELING

Analog behavior modeling (ABM) is utilized extensively in this model to represent the conductance of the diode based on equations presented in the first part of the paper. ABM itself is a powerful tool available in most SPICE software packages enabling time and frequency domain evaluation of equations or look up tables. Some packages provide block diagram components simplifying the modeling process. The proposed charge control model was implemented using ABM block diagram components as shown in Figure 3.Taking advantage of existing stability, only the modified charge controlled equation was added to the native diode model available in the standard SPICE library. The model is a function of temperature and with a few parameter changes can easily represent a new JBS SiC diode at the respective temperature. The new diode model shown in figure 3 was packaged in a single part for quick archiving into the existing library.

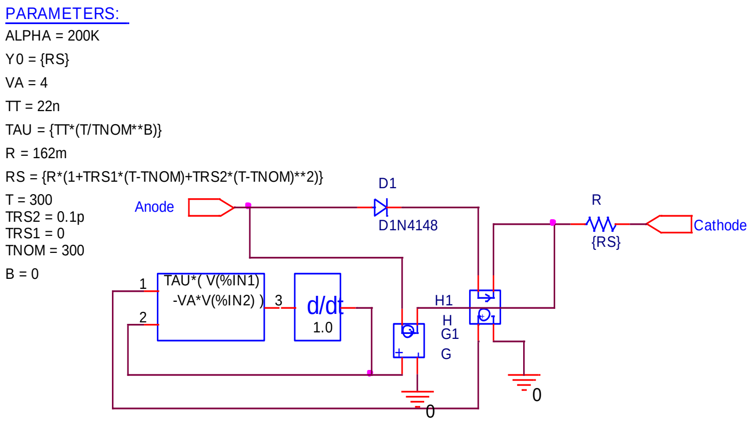

Figure 3: SPICE ABM static and dynamic SiC Schottky Diode Model

Figure 4: SPICE symbol Diode Model inserted in spice library

The first step towards a model is extracting the parameters that describe the behavior of the diode. For all semiconductors, temperature has a significant effect on the material's conductive properties. Silicon carbide increases resistance with increasing temperature and this is observable in the curve trace. At elevated temperatures, the carriers at the junction become excited lowering the junction voltage. These two phenomenons are demonstrated from the collected data and presented in Figure 5 illustrate the thermal influence on conductivity.

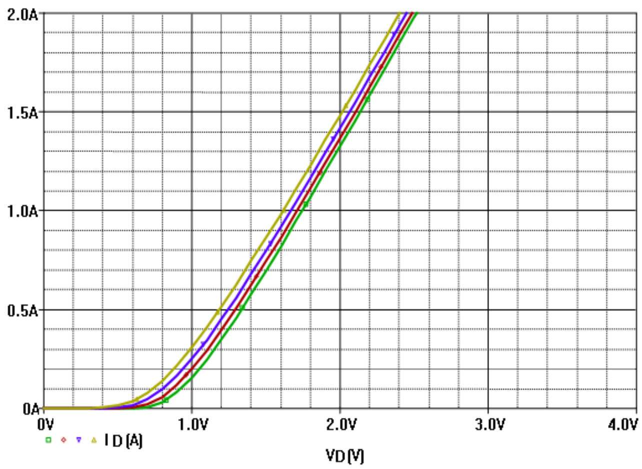

Figure 5: Forward characteristic at T= 25ºC, 75ºC, 125ºC and 175ºC (Yellow to Green)

V. TEST CIRCUIT SIMULATION

The test circuit used for the Pspice simulation of this model is shown in figure. 6

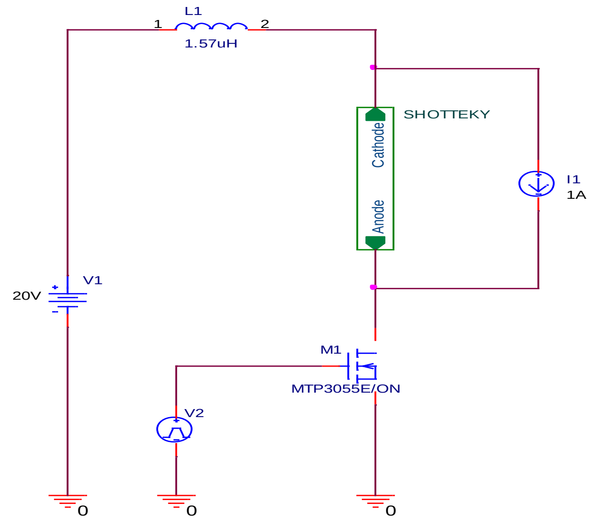

Figure 6: The test circuit used for simulation

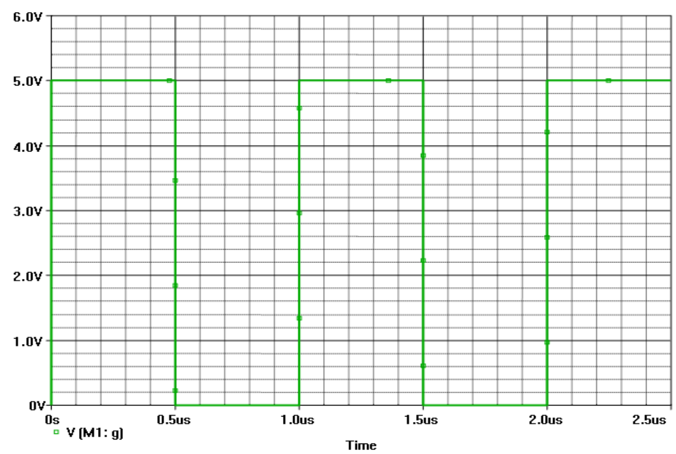

Figure 7: V_2 (Vpulse) Signal

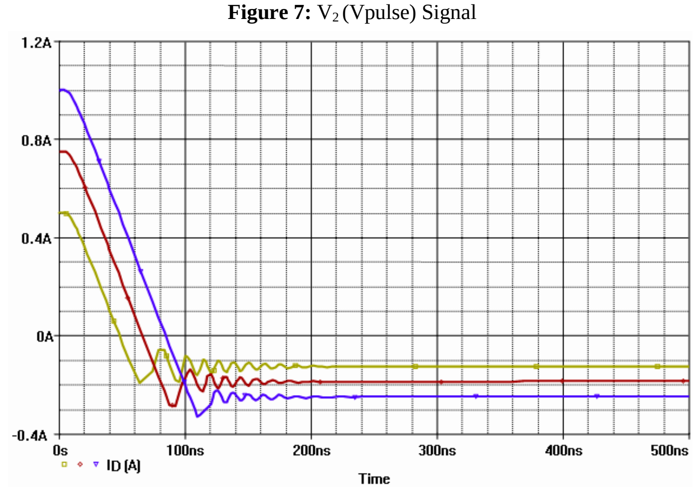

Figure 8: Turn-off Reverse Recovery Current of SiC Diodes for I1 = 0.5A, 0.75 A and 1A (Yellow to Blue)

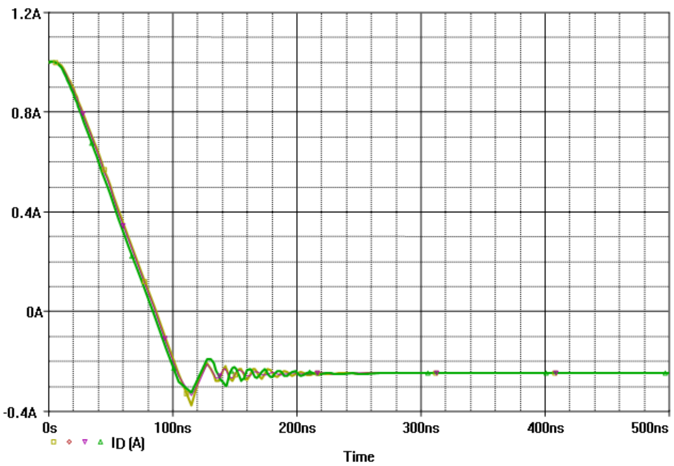

Figure 9: Turn-off transient for I1= 1 A and T = 25 ºC , 75 ºC, 125 ºC and 175 ºC.

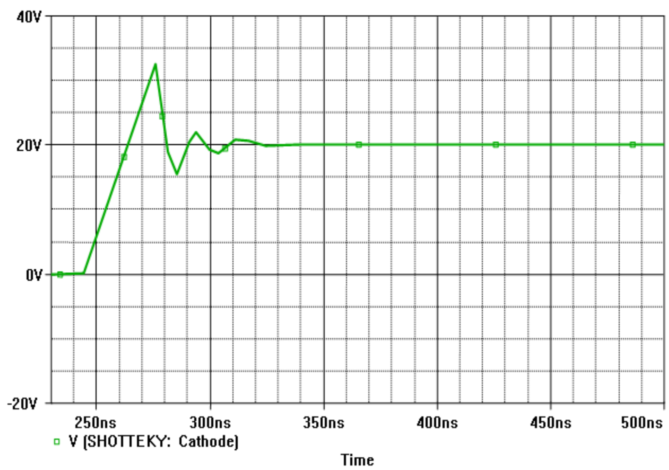

Figure 10: Forward recovery simulations of SiC Shottky

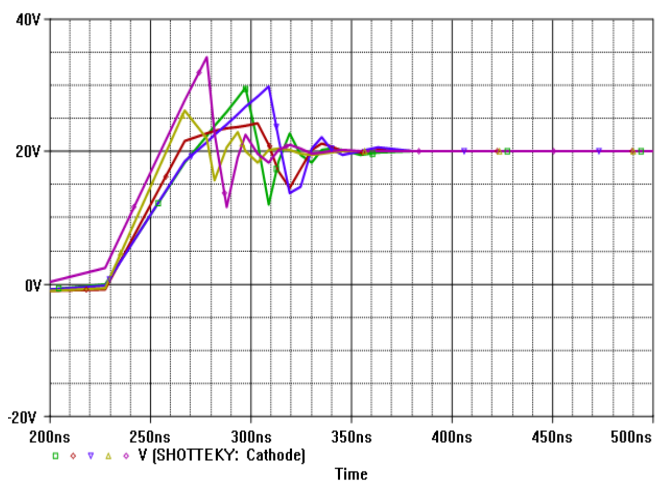

Figure 11: Forward recovery simulations of SiC at T=25°C, 75C°, 125C°, 175C° (Purple to Blue)

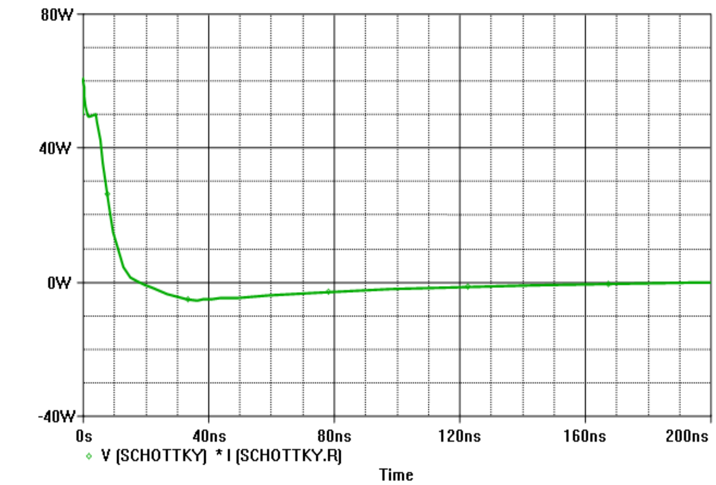

Figure 12: Power Loss during FET Turn-On

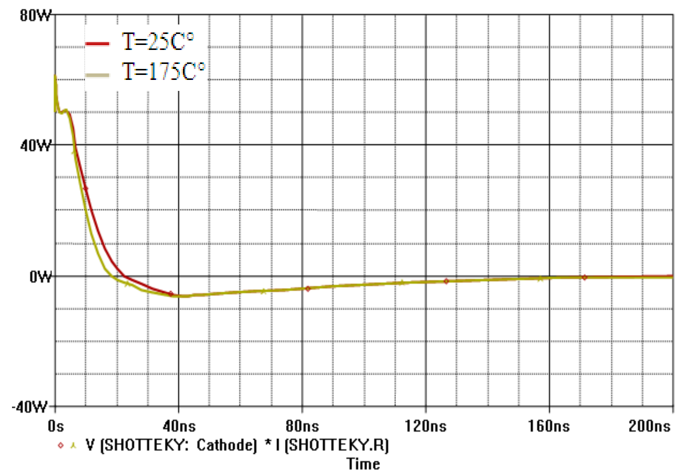

Figure 13: Power Loss during FET Turn-On for T=25C° and T=175C°

VI. Conclusion

A model for SiC Schottky Barrier Diodes based on SPICE ABM has been presented. This model not only described static and dynamic characteristics of SiC Schottky power diodes, but also reflects their dependence on temperature. Thus, they are very useful and effective to estimate the power losses of SiC Schottky diodes and to predict device temperatures. The model was also used to estimate the efficiency of a Si IGBT/SiC Schottky diode hybrid inverter.

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