THE DEPENDENCE OF REVERSE RECOVERY TIME ON BARRIER CAPACITANCE AND SERIES-ON RESISTANCE IN SCHOTTKY DIODES

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ABSTRACT

It is well known that reverse recovery time (τ_{rr}) is important when a diode is used in a switching application. It is the time taken to switch the diode from its forward conducting or 'ON' state to the reverse 'OFF' state. As a result, there is reverse current overshoot when switching from the forward conducting state to the reverse blocking state. The time is needed to remove the reverse recovery charge (Qrr) as a Schottky diode is normally measured in nanoseconds, ns. Some diodes exhibit τ_{rr}s of 100p/s. The experimental part consists of the measurements of the reverse recovery time on a special tester – LEMSYS DMS dynamic parameter system – the SiC Schottky diodes C3D10060A are used. In the present work, measuring the results of reverse recovery time depends on additional resistors and condensers connected to the initial diode. It has been shown that the recovery time is mostly determined by the barrier capacitance, and should not depend on the resistance of the base.
Keywords: reverse recovery time, Schottky diode, barrier capacitance, series-on resistance.

1 INTRODUCTION

The theoretical advantages of SiC technology are obvious. It is well known that SiC diodes are the perfect choice in high efficiency, high-voltage applications such as switch-mode power supplies and high-speed inverters. Nowadays, the new technology promises new semiconductor products with a behavior very close to ideal parameters such as forward voltage drops, high operating temperature, ultra low Qrr, low leakage current. The remaining advantage for SiC technology is its ideal dynamic behavior [1]. The low recovery current is the key benefit of using SiC Schottky diodes. When the diode switches from its forward conducting or 'ON' state to the reverse 'OFF', the total charge that must be removed during reverse recovery is denoted by Q_{RR}, i.e. the reverse recovery charge, which leads to an appearance of the reverse current that causes additional loss (switching loss) in the diode (eqn 1):

$$\tau_{rr} \cong \sqrt{\frac{2Q_{RR}}{di/dt}} \tag{1}$$

When the diode has been conducting, a charge is stored at the junction and the bulk of the semiconductor. With reference to Fig. 1, when the diode current becomes negative, the diode continues to conduct. This reverse conduction continues until the negative current sweeps away the charge stored in the junction. At that moment, the diode gains its reverse blocking capability and its voltage charges to the reverse recovery voltage. The time needed for the diode to gain blocking capability is denoted by t_a. An additional time, t_b, is needed to remove the stored charge from the bulk of the semiconductor. Therefore, the total turn-off time is the reverse recovery time of the diode, $\tau_{rr}=t_a+t_b$. The total charge that must be removed during reverse recovery is denoted by Q_{RR}, i.e. the reverse recovery charge. The peak negative current during reverse recovery is denoted by I_{RR}. Fig. 1 provides the relations applied to the diode turn-off. The use of additional load of capacitance and/or resistance must lead to the change in reverse recovery time and current I_{rr}.
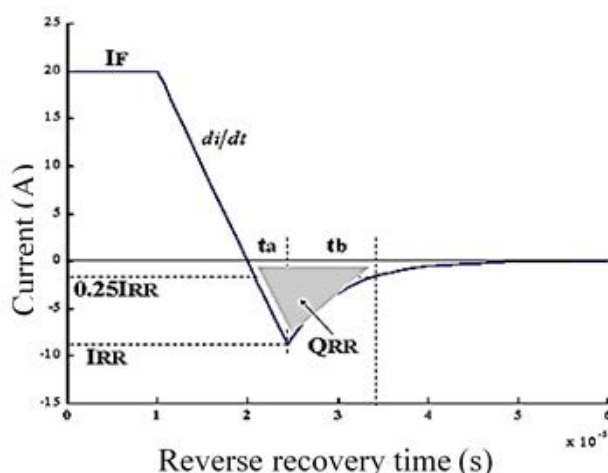
Figure 1: Current during diode turn-off [2].

The aim of this work was to determine which of the key parameters, series-on resistance and/or barrier capacitance should be taken into account when producing the SiC Schottky diodes for use in extreme operating conditions such as radiation rich environments, high frequency etc.

2 MATERIALS AND METHODOLOGY

SiC Schottky diodes that were used for the experiment were commercial purchased Cree SiC Schottky power diodes 600V - C3D10060A. We conducted experiments with different commercial stationary condensers and resistors, connected in series and in parallel to the diode one by one.

To carry out the electrical measurements, we used the following equipment:

- an Agilent B1500A semiconductor device analyser
- a LEMSYS DMS dynamic parameter system
- the generator AFG 3252
- Tektronix
- an Agilent MSOS104A oscilloscope.

Capacitance-voltage (C-V) and current-voltage (I-V) measurements of the diode with different resistors and condensers values have been measured and collected I-V and C-V are presented. Reverse recovery time dependences of the initial diode and diode connected in series and in parallel with different resistors and condensers have been measured. In addition, the measurements result of combined resistor and condenser together connected to the initial diode have been made and shown.

3 RESULTS AND DISCUSSION

Fig. 2 shows the typical views of current-voltage (I-V) characteristics at room temperature for the initial diode and diode with different resistors. The values of resistors used for the experiment are the following: 150mΩ, 220mΩ, 270mΩ, 330mΩ, 390mΩ, 470mΩ, 510mΩ

and 560mΩ. All resistors were metal oxide film resistors with rated output of 1W and rated voltage of 350 V.

As shown in Fig. 2, the I-V exhibits a quite good diode behaviour with different resistor values. The value of series resistance R_S is growing with the increasing of the resistor value connected to the diode. The series-on resistance of a Schottky diode is the sum of the barrier resistance, the resistance due to the epi layer and the resistance due to the substrate. Fig. 3 shows the linear dependence of R_S on the different values of resistors.

As expected the C-V characteristics at room temperature for the initial diode and diode with different resistors showed no changes. The same results were for the I-V characteristics at room temperature for the initial diode and the diode with connected condensers.

Fig. 4 shows the typical C-V dependence at room temperature for the same experiment conditions as for I-V measurements. The condensers used for the experiment were ceramic with the following capacitance: 100pF, 180pF, 270pF, 330pF and 510pF.

As seen from Fig. 4 the capacitance-voltage characteristics are displaced parallel to themselves with the different values of condensers connected to the initial diode.

The typical reverse recovery characteristics for the initial Schottky diode is shown in Fig. 5.

The measurements of the reverse recovery time for the initial diode with resistor or condenser have been made as well. For the demonstration of the results, we have chosen one resistor of 270mΩ and one condenser of 378pF for the reverse recovery time characteristics Fig. 6.

Additionally, combining some resistors together with condensers connected to the initial diode for the measurement of the reverse recovery time are shown in Fig. 7.
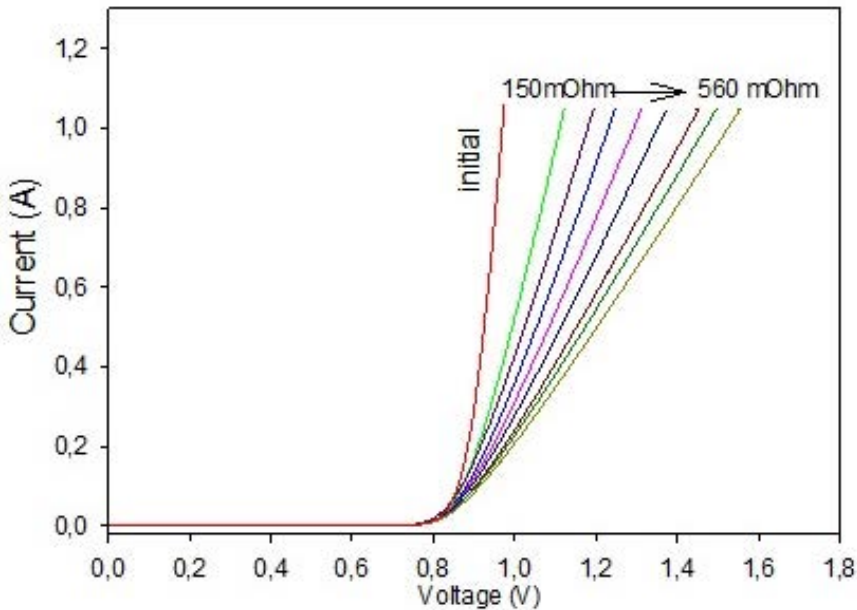

Figure 2:   Current-voltage characteristics for the initial diode and diode measured with different resistors values (from 150mΩ to 560mΩ).
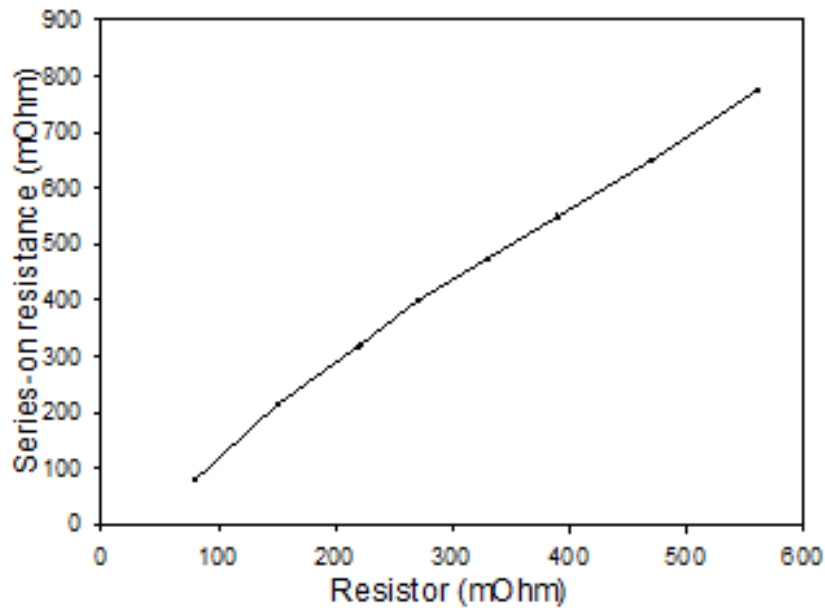
Figure 3: Series-on resistance dependence on different resistor values.
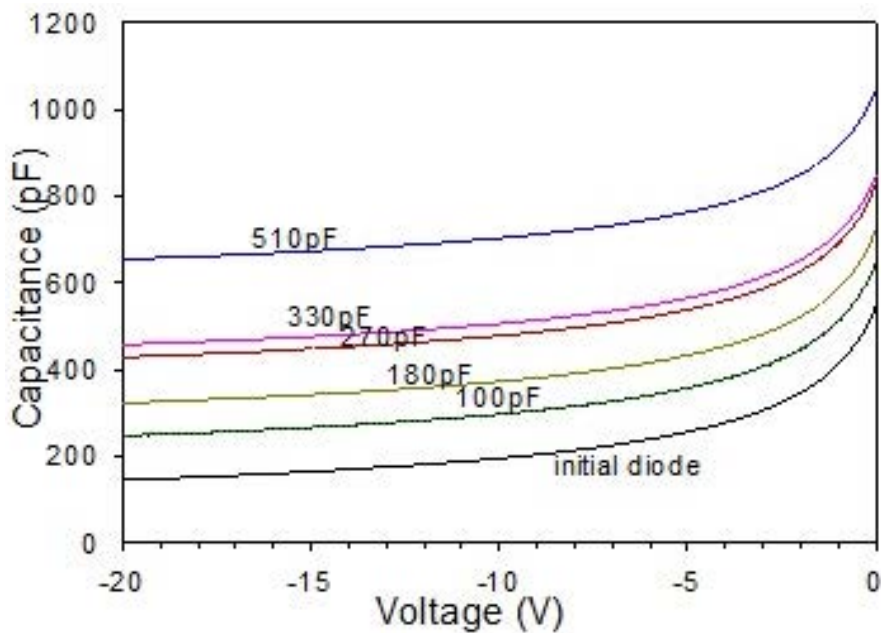

Figure 4:   Capacitance-voltage characteristics for the initial diode and diode with different condensers in parallel (from 100pF to 510pF).
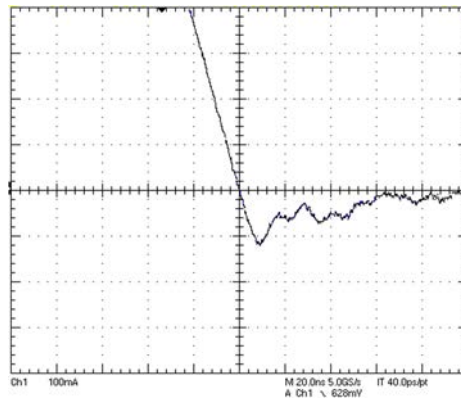
Figure 5: Reverse recovery time characteristic for the initial Schottky diode (I=100mA/div, τ=20ns/div).
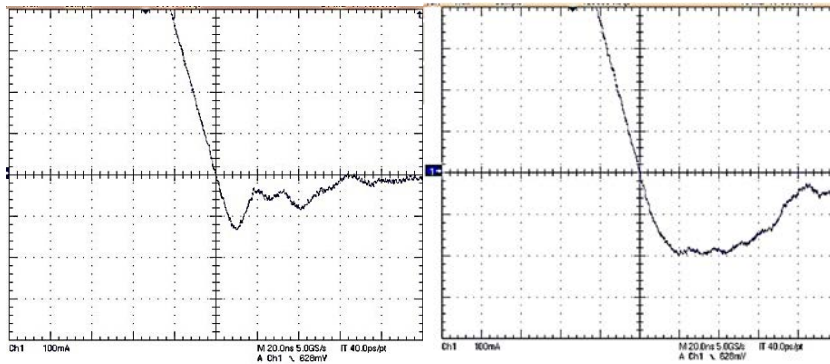

Figure 6: Reverse recovery time for the diode with resistor (270 mΩ) on the left and for the diode with condenser (378 pF) on the right (I=100mA/div, τ=20ns/div).
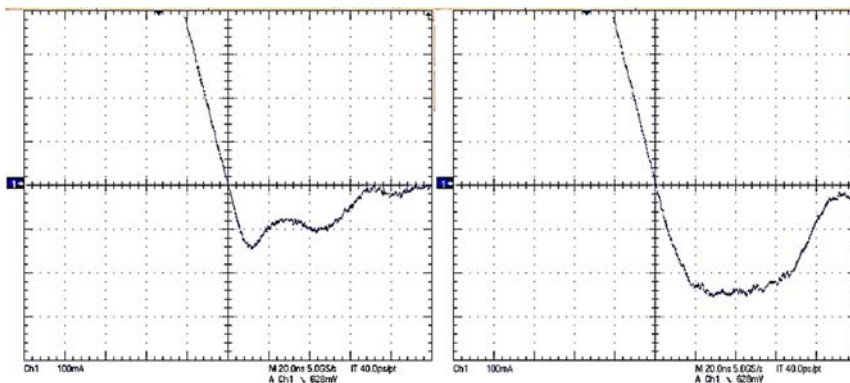

Figure 7: Reverse recovery time for the diode with condenser and resistor (100pF+560 mΩ) on the left and for the diode with condenser and resistor (378 pF+330mΩ) on the right (I=100mA/div, τ=20ns/div).
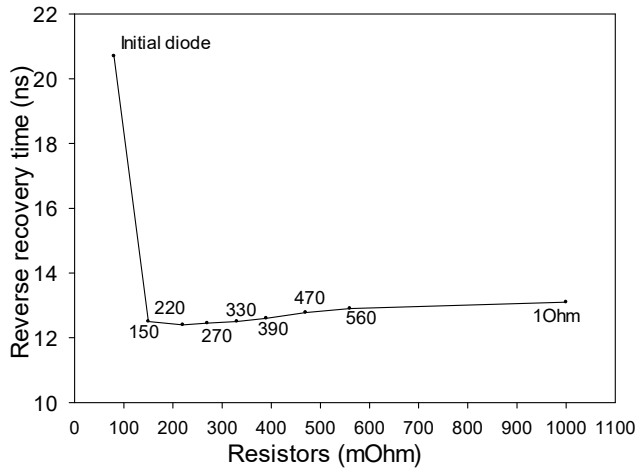
Figure 8:   Reverse recovery time dependence on the initial diode and different values of resistors connected to the diode one by one.
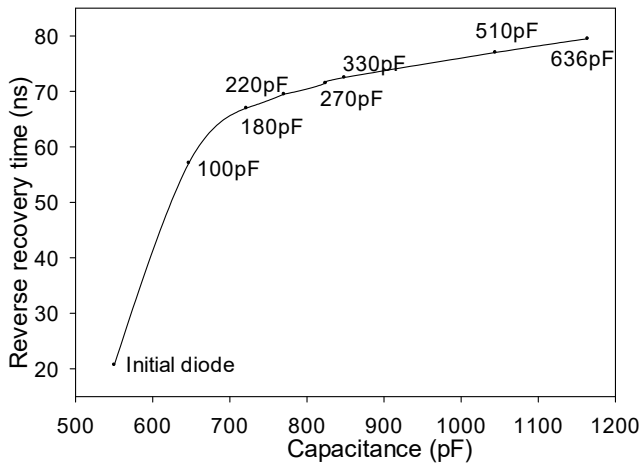

Figure 9:   Reverse recovery time dependence on different values of condensers connected to the diode one by one.

The reverse recovery time dependences with all used values of condensers and resistors shown in Figs 8 and 9. As seen from the Fig. 8 the reverse recovery time drops sharply after the connecting the first resistor and then remains independent on the value of the resistors. As for the Fig. 9, we can see the increasing of the τ_{rr} more than 3 times depending on the capacitance values. This can be easily explained if we imagine the Schottky as a parallel-plate capacitor [3]. The larger value of condenser, the larger the space charge between parallel-plate capacitors, the more time it takes for the diode to remove the total charge from the junction region when reverse recovered.

When combining the resistors and condensers connected to the initial diode, one may note that reverse recovery time is determined by the capacitance of the additional condenser and is independent on the additional resistance (Fig. 10).

The idea of carrying out the work presented in this publication appeared during the research of the degradation of 600V, 4H-SiC Schottky diodes under irradiation with 0.9MeV electrons [4]. Among other characteristics studied during the work, the reverse recovery time (τ_{rr}) was analyzed as a function of the radiation dose. To explain the variation of τ_{rr} with increasing radiation density, the following version was proposed. It is known that the recharge time of barrier capacitance (τ_M) between the two equilibrium states mostly determined by the Maxwell relaxation time expression (eqn 2):

$$\tau_M = \rho \varepsilon \varepsilon_0 , \tag{2}$$

where ρ is the resistivity, ε the dielectric constant, and ε_0 the electric constant. Rewriting the expression as $\tau_M = R_s C_0 \varepsilon \varepsilon_0$, where R_s is series on resistance and C_0 - barrier capacitance at zero bias, we can see that reverse recovery time (τ_{rr}) determined by τ_M is equal to $R_s C_0$. Thus, the change in the reverse recovery time will be determined by the influence of two mutually compensating processes. Specifically, the barrier capacitance becomes lower due to the decrease in the N_d-N_a concentration, on the one hand, and to the increase in R_s because of the decrease in the number of carriers and in their mobility, on the other hand. The latter occurs because the carrier lifetime becomes shorter due to the scattering on additional radiation defects. As a result, the decrease in τ_{rr} at low irradiation doses, when the increase in R_s is not significant yet, is determined by the decrease in C_0. At doses more than 2×10^{16} cm^{-2}, the key influence on the variation of τ_{rr} will be exerted by the increase in R_s and ohmic resistance of n-base.

Since substrate resistance can be considered as an external resistance with respect to the metal-semiconductor junction, and the barrier capacitance can be simplified to a plate capacitor, these quantities can be modulated by external resistors and capacitors. This is what exactly has been done in this paper. Since the results are perfectly illustrated by the graphs presented above, it is possible to make a reliable conclusion that the recovery time is mostly determined by the barrier capacitance and should not depend on the resistance of the base. The initial sharp drop of τ_{rr} when connecting an external resistor can be explained by the instrumental specificity of the measurements. The turn-off curve configuration changes. The Q_{RR} charge remains the same due to the elongation of the t_b branch, but this does not take into account the measurement method (see Figs 1, 6, 7).
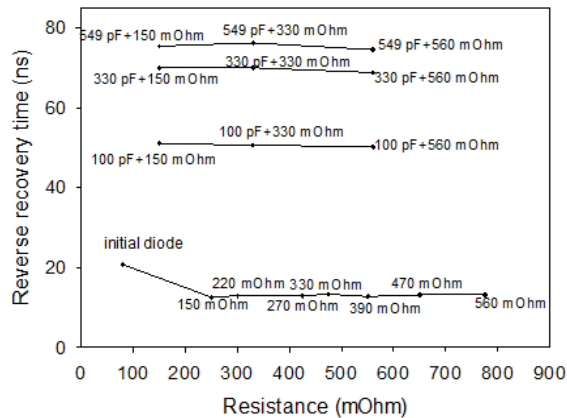

Figure 10: Reverse recovery time dependence on combined resistors and condensers.

4 SUMMARY

The modelling of the diode operation in extreme conditions such as radiation rich environments, high frequency etc. is very important. Conducted experiments with additional resistors and condensers connected to the initial commercial Schottky diode presented here showed that additional capacitance increases reverse recovery time dramatically while additional resistance decreases τ_{rr} by 1.5 times. The reverse recovery time as well as the junction capacitance are very important in high-frequency operation of the diode.

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