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

Master's Thesis

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SIC SCHOTTKY DIOODI TAASTUMISAJA SÕLTUVUS BARJÄÄRI MAHTUVUSEST JA TAKISTUSEST

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Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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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 a 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), for a Schottky diode is normally measured in nanoseconds, ns. Some diodes exhibit τ_{rr} of 100 ps.

The principle of the formation of the Schottky barrier at the metal-semiconductor contact as well as the current-voltage (I-V), the junction capacitance and the main dynamic characteristics of the Schottky diode were considered.

The experimental part consists of the measurements of reverse recovery time on a special tester LEMSYS DMS QRR 100 A diode measurement system, Keithley's Series 2400 Source Measure Unit (SMU). The commercial purchased Cree SiC Schottky diodes C3D10060A were used. In the present work the measuring results of reverse recovery time depending on additional resistors and condensers connected to the initial diode are presented. It has been shown that the reverse recovery time is mostly determined by the barrier capacitance and should not depend on the resistance of the base.

This thesis is written in English and is 45 pages long, including 6 chapters, 22 figures, 0 tables and 2 appendixes.

Annotatsioon

SiC Schottky dioodi taastumisaja sõltuvus barjääri mahtuvusest ja takistusest

Dioodstruktuuride vastutaastumisaeg (τ_{rr}) on oluline näitaja pooljuhtseadiste ümberlülitamise protsesside hindamisel ja käsitlemisel. Ümberlülitumise kestvus on aeg, mis kuulub dioodstruktuuril päripingelt (*on-state*) ümberlülitumisele vastupingele (*off-state*). Nimetatud protsessi käigus täheldatakse täiendavalt nähtust, mida tuntakse vastuvoolu ülelöögi nime all (*overshoot*), mis pikendab siirdeaega dioodi stabiliseerumiseks püsivale vastupingele. Protsessi füüsikaliseks aluseks on päripingel tekkinud lisalaengu (Q_{rr}) elimineerimine pooljuhtstruktuuri siirde läheduses. Schottky dioodide puhul mõõdetakse seda aega nanosekundides. Mõnedel dioodidel toimub see veel kiiremini, olles näiteks 100ps suurusjärgus.

Käesolevas uurimistöös uuriti firma Cree SiC Schottky C3D10060A dioodi lülitumisprotsesse. Uurimistöös mõõdeti vastutaastusaja (τ_{rr}) sõltuvust skeemi lisatud täiendavast takistusest ja mahtuvusest. Mõõtetulemused näitavad, et vastutaastusaeg (τ_{rr}) on põhiliselt määratud siiski siirde mahtuvusega ja ei sõltu Schottky dioodi enda baasiala takistusest. Magistritöös esitatakse mahtuvus-pinge (*C*-*V*) ja pinge-voolu (*I*-*V*) karakteristikute sõltuvused mahtuvusest.

Lõputöö on kirjutatud inglise keeles; on 45 lehekülge pikk ja jaguneb 6 peatükiks, ning sisaldab 22 joonist, 0 tabelit ja 2 lisa.

List of abbreviations and terms

C-V	Capacitance–voltage Characteristic
I-V	Current–voltage Characteristic
DMS	Diode measurement system
SMU	Source Measure Unit
SB	Schottky Barrier
FL	Fermi level
VSC	Volumetric Space Charge
RRSF	Reverse Recovery Softness Factor
ZBD	Zero bias detector

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List of symbols

A	Area of Schottky contact
A^{**}	Modified Richardson Constant
C_0	Barrier capacitance at zero bias
C_j	Barrier capacitance
C_{geom}	Geometric capacity
C_P	Package capacitance
ε_0	Dielectric constant
ε	Dielectric permeability
η	Ideality factor
f	Frequency
ϕ_B	Barrier height
I	Current
I_{rr}	Reverse recovery current
I_{rrm}	Negative current peak of recovery current
I_{SAT}	Saturation current
I_s	Series current
k	Boltzmann's Constant
L_S	Series inductance
L	Thickness of epi layer
μ_N	Mobility of electrons
N_D	Doping density of the epi layer
N_A	Acceptor concentration
q	Electronic charge
Q_{rr}	Reverse recover charge
R_j	Differential resistance of the transition
R_{epi}	Resistance due to the epi layer

R_{sub}	Resistance of the substrate
R_S	Series resistance
R_C	The resistance of ohmic contacts to the substrate
ρ	Resistivity
ρ_S	Substrate resistivity.
ρ_B	The resistance of spreading from a circular contact to the substrate
S_g	Area of the packing
S_j	Area of junction
T	Temperature
τ_{rr}	Reverse recovery time
t	Time
t_{DIODE}	Conduction time of diode
τ_f	The time needed for the diode to gain blocking capability
τ_s	The time needed to remove the stored charge from the bulk of the semiconductor
τ_{rr}	Reverse recovery time
τ_M	Recharge time of barrier capacitance
V	Voltage
V_I	Internal Contact Potential
V_R	Reverse bias voltage from external voltage source
x_1	Depleted layer
x_2	Substrate layer

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 drop, high operating temperatuure, ultra low Q_{rr}, and low leakage current. The remaining advantage for SiC technology is its ideal dynamic behavior [1]. The low recovery currents 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.

The present work gives an overview of the static and dynamic characteristics of Schottky diode. In view of the particular properties of the Schottky diode there are several parameters that are of key importance when determining the operation of the diode such as series resistance, reverse breakdown, junction capacitance and reverse recovery time. In total, the research of these parameters allows us to determine the key dependencies of the behavior of the Schottky diode.

The purpose of the present Master thesis was to make 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. Schottky diode

Schottky diodes are useful in voltage clamping applications and prevention of transistor saturation due to the higher current density in the Schottky diode. Also, because of the low forward voltage drop in a Schottky diode, less energy is wasted as heat, therefore making them an efficient choice for applications that are sensitive to efficiency. Because of this, they are used in stand-alone photovoltaic systems in order to prevent batteries from discharging through the solar panels at night as well as in grid-connected systems containing multiple strings connected in parallel. Schottky diodes are also used as rectifiers in switched-mode power supplies [2]. In this sense, Schottky's silicon carbide diodes (SiC) have a number of remarkable properties:

- A very small (almost zero!) reverse recovery time of the main charge carriers during switchings;
- Higher breakdown voltage than for silicon instruments;
- High operating temperature (up to 175 ° C);
- High switching frequency (up to 500 kHz), which allows to reduce the filter of electromagnetic interference and the size of other passive components;
- Reduction or elimination of active or passive damper chains.

The main advantage of high-voltage Schottky diodes is their exceptional dynamic characteristics. The charge of reverse recovery (Q_{rr}) of these diodes is extremely low (less than 20 nC), so the junction capacitance does not preserve the charge. In addition, unlike silicon *p-i-n* diodes, the rate of current rise dI/dt does not depend on the magnitude of the forward current and temperature. The diodes operate normally at a maximum transition temperature of 175 ° C. The extremely small value of the Q_{rr} charge of Schottky silicon carbide diodes leads to a decrease in switching losses in typical applications of pulsed power electronics.

In comparison with other semiconductors, carbide-silicon devices are able to function at high temperatures, high power, and are resistant to radiation. All this determines the brilliant prospects of this semiconductor material and devices based on it. Silicon carbide has the following advantages over other semiconductors, for example, silicon or gallium arsenide:

- Two to three times the width of the forbidden band;
- 10 times the electric breakdown field;
- Ability to work at high temperatures, up to 600 ° C;
- Thermal conductivity is 3 times greater than that of silicon, and almost 10 times greater than that of gallium arsenide;
- Resistance to radiation;
- Stability of electrical characteristics under the influence of temperature and time.

The material is resistant to oxidation at temperatures up to 1400 ° C. At room temperature, it does not interact with any acids. This explains the difficulty of manufacturing semiconductor devices, which are based on it [3].

2.1 Current-Voltage (I-V) characteristics

The internal voltage difference between the metal and the semiconductor is called the contact potential, and is usually in the range 0.3 – 0.8 V for typical Schottky diodes. When a positive voltage is applied to the metal, the internal voltage is reduced, and electrons can flow into the metal. Only those electrons whose thermal energy happens to be many times the average can escape, and these “hot electrons” account for all the forward current from the semiconductor into the metal. One important thing to note is that there is no flow of minority carriers from the metal into the semiconductor and thus no neutral plasma of holes and electrons is formed. Therefore, if the forward voltage is removed, current stops within a few picoseconds and reverse voltage can be established in this time. The voltage-current relationship for a barrier diode is described by the law of the junction equation.

The IV characteristic is generally that shown Figure 1. It can be seen that the Schottky diode has the typical forward semiconductor diode characteristic, but with a much lower turn on voltage. At high current levels it levels off and is limited by the series resistance or the maximum level of current injection. In the reverse direction breakdown occurs above a certain level. The mechanism is similar to the impact ionisation breakdown in a $p-n$- junction. In the forward direction the current rises exponentially, having a knee or turn on voltage of around 0.2 V. In the reverse direction, there is a greater level of reverse current than that experienced using a more conventional $p-n$- junction diode. [4]

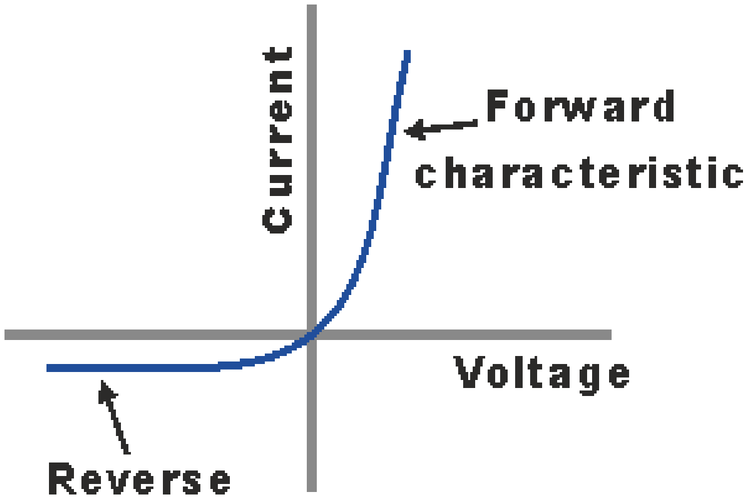

Figure 1. Schottky diode IV characteristic [4].

Silicon Schottky diodes can be produced with several different barrier heights, as shown in the table below, but for practical reasons four main barrier heights are offered: high barrier, medium barrier, low barrier and "zero bias detector (ZBD)" barrier.

The equation that relates the current through a Schottky junction to the voltage across it is:

$$I = I_{SAT}\left(e^{\frac{q(V-IR_S)}{\eta KT}} - 1\right) \quad (1)$$

where k = Boltzmann's constant, 1.38044 x 10^{-23} J/K; q = electronic charge, 1.60206X10^{-19} C; T = Temperature, K; R_S = series resistance, Ω; I_{SAT} = saturation current, A; η = ideality factor (typically 1.0) and

$$I_{SAT} = AA**e^{\left(\frac{q\phi_B}{kT}\right)} \quad (2)$$

where A = area, cm^2 A** = Modified Richardson constant, $(A/K)^2$ $/cm^2$; k = Boltzmann's Constant; T = absolute temperature, K; ϕ_B = barrier height, V. [5]

The use of a guard ring in the fabrication of the diode has an effect on its performance in both forward and reverse directions. Both forward and reverse characteristics show a better level of performance. However the main advantage of incorporating a guard ring into the structure is to improve the reverse breakdown characteristic. There is around a 4:1 difference in breakdown voltage between the two - the guard ring providing a distinct improvement in reverse breakdown. Some small signal diodes without a guard ring may have a reverse breakdown of only 5 to 10 V [4].

2.2 Schottky diode key parameters

The Schottky diode is a majority carrier device. This gives it tremendous advantages in terms of speed because it does not rely on holes or electrons recombining when they enter the opposite type of region as in the case of a conventional diode. By making the devices small the normal RC type time constants can be reduced, making these diodes an order of magnitude faster than the conventional P-N- diodes. This factor is the prime reason why they are so popular in radio frequency applications.

The diode also has a much higher current density than an ordinary P-N- junction. This means that forward voltage drops are lower making the diode ideal for use in power rectification applications.

In view of the particular properties of the Schottky diode there are several parameters that are of key importance when determining the operation of one of these diodes against the more normal P-N- junction diodes.

Forward voltage drop: In view of the low forward voltage drop across the diode, this is a parameter that is of particular concern. As can be seen from the Schottky diode IV characteristic, the voltage across the diode varies according to the current being carried. Accordingly any specification given provides the forward voltage drop for a given current.

Reverse breakdown: Schottky diodes do not have a high breakdown voltage. Figures relating to this include the maximum Peak Reverse Voltage, maximum Blocking DC Voltage and other similar parameter names. If these figures are exceeded then there is a possibility the diode will enter reverse breakdown. It should be noted that the RMS value for any voltage will be $1/\sqrt{2}$ times the constant value. The upper limit for reverse breakdown is not high when compared to normal P-N- junction diodes. Maximum figures, even for rectifier diodes only reach around 100 V. Schottky diode rectifiers seldom exceed this value because devices that would operate above this value even by moderate amounts would exhibit forward voltages equal to or greater than equivalent P-N- junction rectifiers.[4]

Capacitance: The capacitance parameter is one of great importance for small signal RF applications. Typical values of a few picofarads are normal. The Schottky diode can be imagined as a parallel-plate capacitor. The capacitance of this region is determined by the physical dimensions of the junction as well as the doping profile of the semiconductor layer. The thickness of the depletion layer can be affected by the magnitude of an externally-applied voltage: a forward bias will reduce the thickness of the depletion layer, effectively moving the plates of the capacitor closer together; and, a reverse bias voltage increases the thickness of the depletion layer, effectively spreading the parallel plates farther apart. The relationship between reverse bias voltage and diode capacitance is

$$C_J(V_R) = \frac{C_J(0)}{(1-\frac{V_R}{V_I}-\frac{kT}{q})^{\frac{1}{2}}} \quad (3)$$

where $C_J(V_R)$= junction capacitance at reverse bias voltage V_R ; V_R = reverse bias voltage from external voltage source; $C_J(0)$ = junction capacitance with V_R = 0 V; V_I = internal contact potential = ϕ_B -0.15 for n-type silicon k = Boltzmann's constant; T = absolute temperature; q = charge of an electron.[4]

Series Resistance: The series resistance of a Schottky diode is the sum of the resistance due to the epi layer and the resistance due to the substrate. The resistance of the epi is given by the following equation:

$$R_{epi} = \frac{L}{q\mu_N N_D A} \quad (4)$$

where L = thickness of epi in cm μ_N = mobility of electrons for n-type Si (for p-type silicon the mobility of holes would be used) N_D = doping density of the epi layer in atoms/cm^3 A = area of Schottky contact in cm^2. The resistance of the substrate is given by the following equation [4]:

$$R_{sub} = 2 * \rho_S * (A/\pi)^{1/2} \quad (5)$$

Where ρ_S = substrate resistivity in Ω-cm.

Reverse recovery time: This parameter 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. The charge that flows within this time is referred to as the 'reverse recovery charge'. The time for this parameter for a Schottky diode is normally measured in nanoseconds, ns. Some exhibit times of 100 ps. In fact what little recovery time is required mainly arises from the capacitance rather than the majority carrier recombination. As a result there is very little reverse current overshoot when switching from the forward conducting state to the reverse blocking state.

Working temperature: The maximum working temperature of the junction, Tj is normally limited to between 125 to 175°C. This is less than that which can be sued with ordinary silicon diodes. Care should be taken to ensure heat sinking of power diodes does not allow this figure to be exceeded.

Reverse leakage current: The reverse leakage parameter can be an issue with Schottky diodes. It is found that increasing temperature significantly increases the reverse leakage current parameter. Typically for every 25°C increase in the diode junction temperature there is an increase in reverse current of an order of magnitude for the same level of reverse bias. [4]

2.3 Dynamic Characteristics

One of the most important but often neglected limitations of Schottky diodes is the undesired reverse recovery behaviour [6]. The main dynamic parameters of the diode are its time or frequency characteristics: the time of reverse recovery (τ_{rr}), the charge of recovery (Q_{rr}), constant reverse current (I_{rr}). Reverse recovery occurs when the diode switches off while carrying a positive forward current as shown in Figure 2, where the voltage and current waveforms illustrate the turn-on and turn-off transitions of a diode.

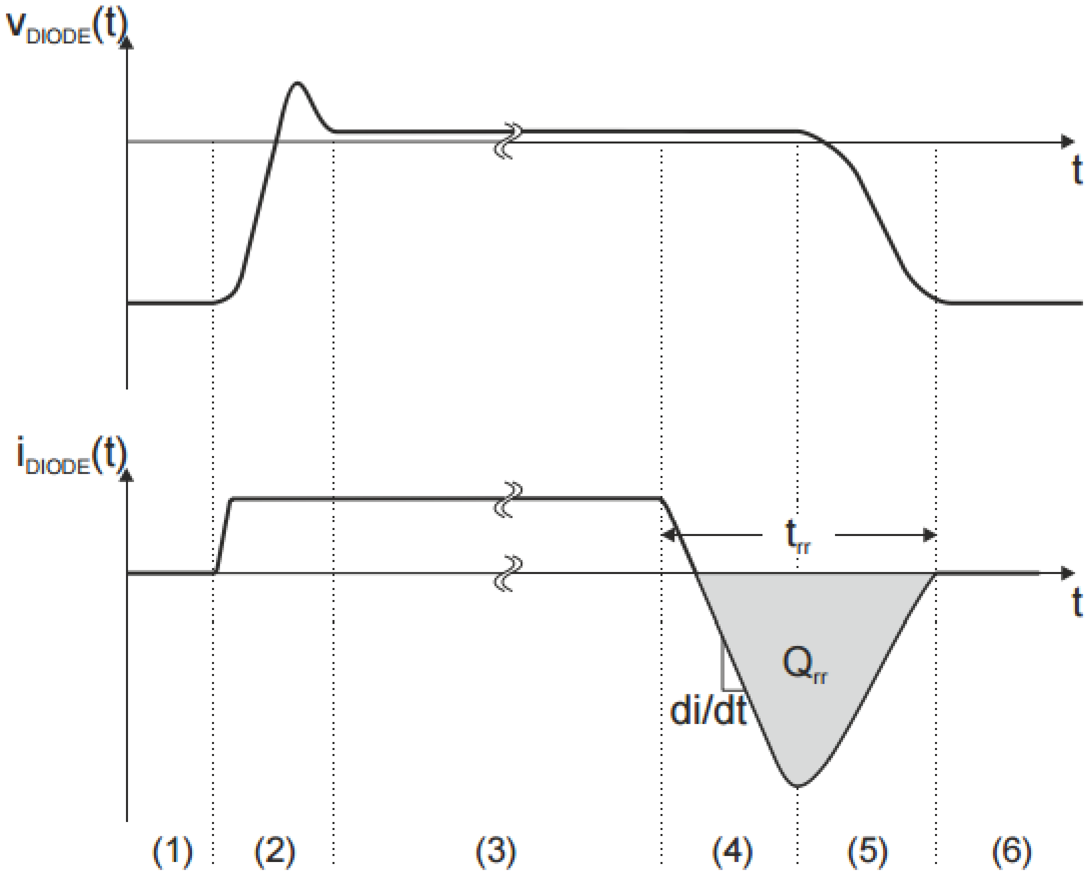

Figure 2. Operation of a diode [7].

The following explains each state of the diode operation in Figure 2. At interval (1), the diode is in the “OFF” state.

- The diode starts to turn on in interval (2). At the end of the turn-on process, the diode becomes forward biased.
- The reverse recovery charge accumulates and is stored while the forward biased diode carries a positive current (3).

- At the start of the turn-off interval (4), the current rolls off to zero then reverses direction. During the negative current, the reverse recovery charge stored in the device recombines.

- In (5), the turn-off process finishes and in (6) the diode is off again.

This recombination process takes time (τ_{rr}) and yields additional power loss. The shaded area in the diagram indicates the reverse recovery charge (Q_{RR}) - the key device parameter for hard commutation ruggedness [6].

The low recovery currents 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 (Eq. 6):

$$\tau_{rr} \cong \sqrt{\frac{2Q_{RR}}{di/dt}} \qquad (6)$$

When the diode has been conducting, a charge is stored at the junction and the bulk of the semiconductor. With reference to Figure 2, 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 τ_f. An additional time, τ_s, 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, $\tau_{rr} = \tau_f + \tau_s$. 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}. Figure 2 provides the relations applied to the diode turn-off [8].

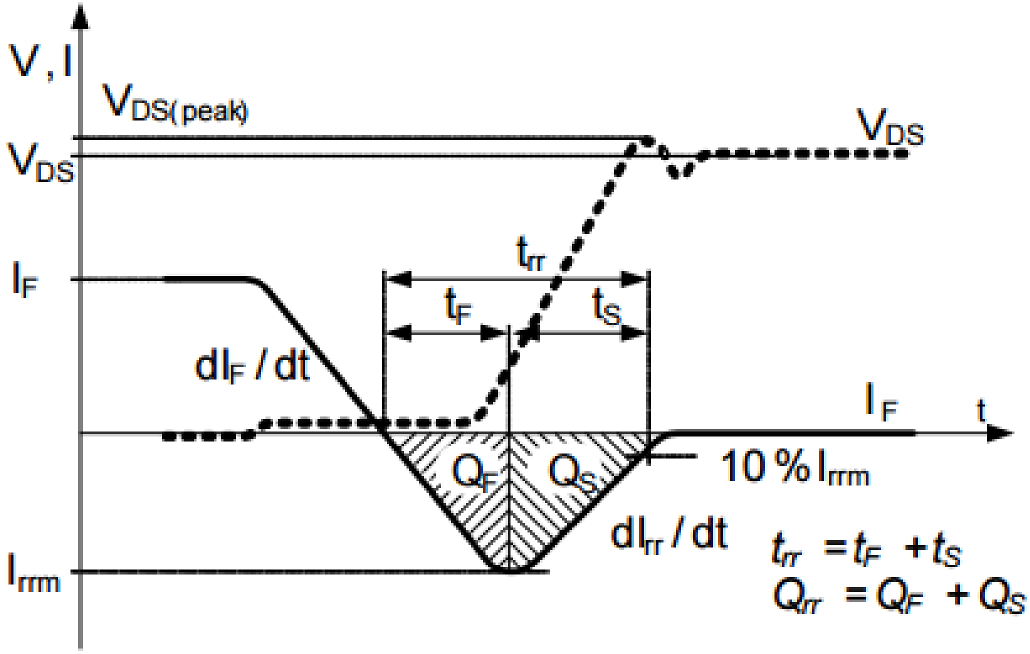

Figure 3. Current during diode turn-off [6].

The diode current rolls off at a constant slope (di/dt) to zero and then reverses the direction. The negative current, also known as reverse recovery current (I_{rr}), finally reaches the negative peak (I_{rrm}) and then goes back up to zero. The reverse recovery process completes at this moment, and the body diode returns to its blocking state. Q_{rr} can be calculated by integrating the shaded area under the negative current curve in the diagram. It can also be approximated by the area of the shaded triangle as in equation (Eq. 7).

$$Q_{rr} = 0.5 \times I_{rrm} \times \tau_{rr} \tag{7}$$

In the half-bridge configuration, when the body diode is in reverse recovery, the direction of the body diode current flow is the same as the top side FET, thus a shoot through occurs. The higher the Q_{rr}, the higher the overshoot. In other words, a device with lower Q_{rr} is less susceptible to a rough hard commutation. Therefore, $Q_{rr}$is a good indicator for a device's hard commutation ruggedness. Since Q_{rr} is undesirable yet unavoidable in many cases, it is important to understand the factors that influence reverse recovery behaviour and Q_{rr}. The following illustrates the relationship between Q_{rr} and its factors.

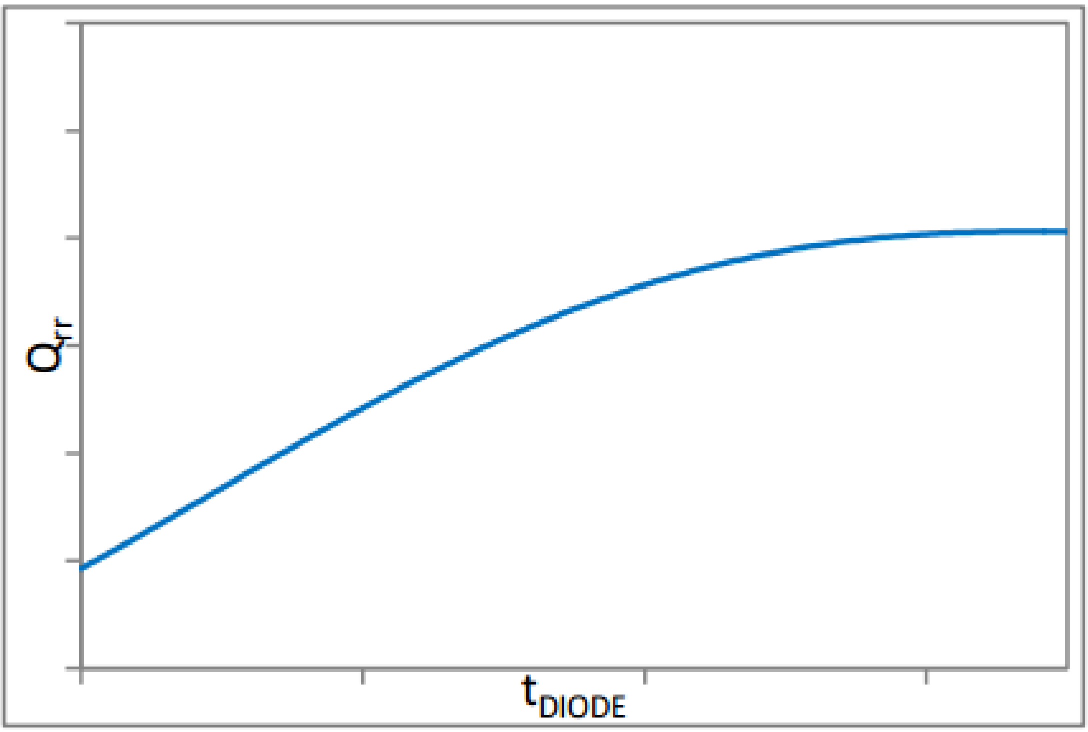

Figure 4. Q_{rr} vs t_{DIODE}(fixed I_{DIODE} and di/dt) [6].

Reverse recovery charge accumulates over time. At a fixed diode conduction current and di/dt, Q_{rr} accumulates in the MOSFET during body diode conduction. The longer the body diode conduction time, the more charge is accumulated until it saturates.

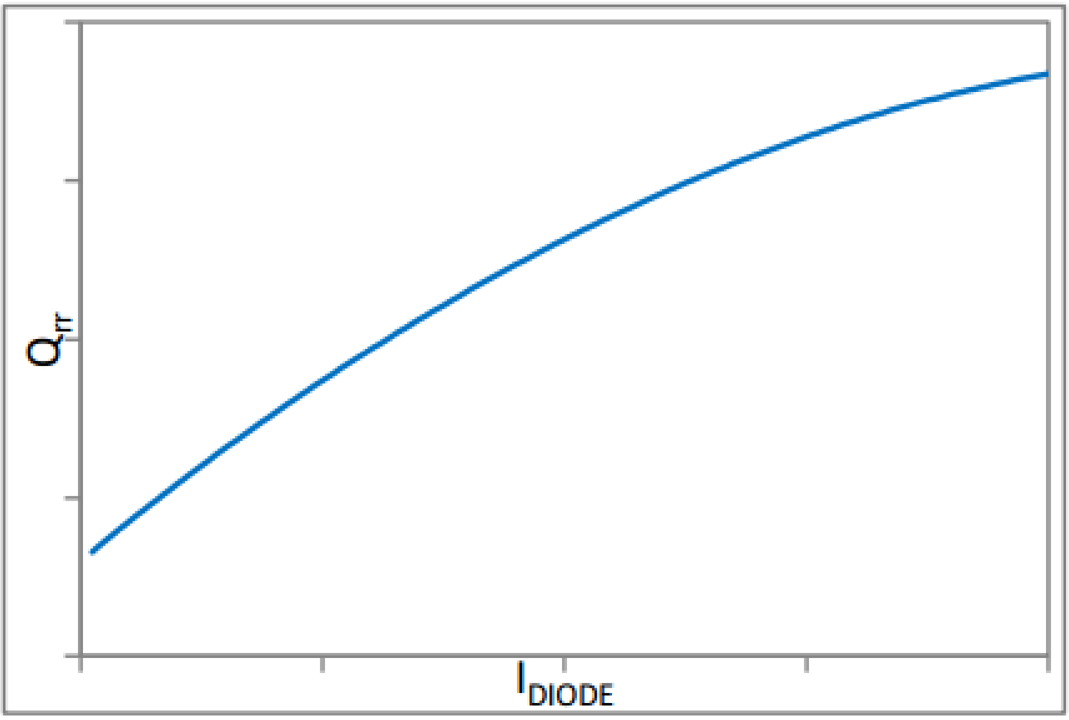

Figure 5. Q_{rr} vs I_{DIODE}(fixed t_{DIODE} and di/dt) [6].

With di/dt fixed, the higher the body diode conduction current, the higher the stored: Q_{rr} in the device.

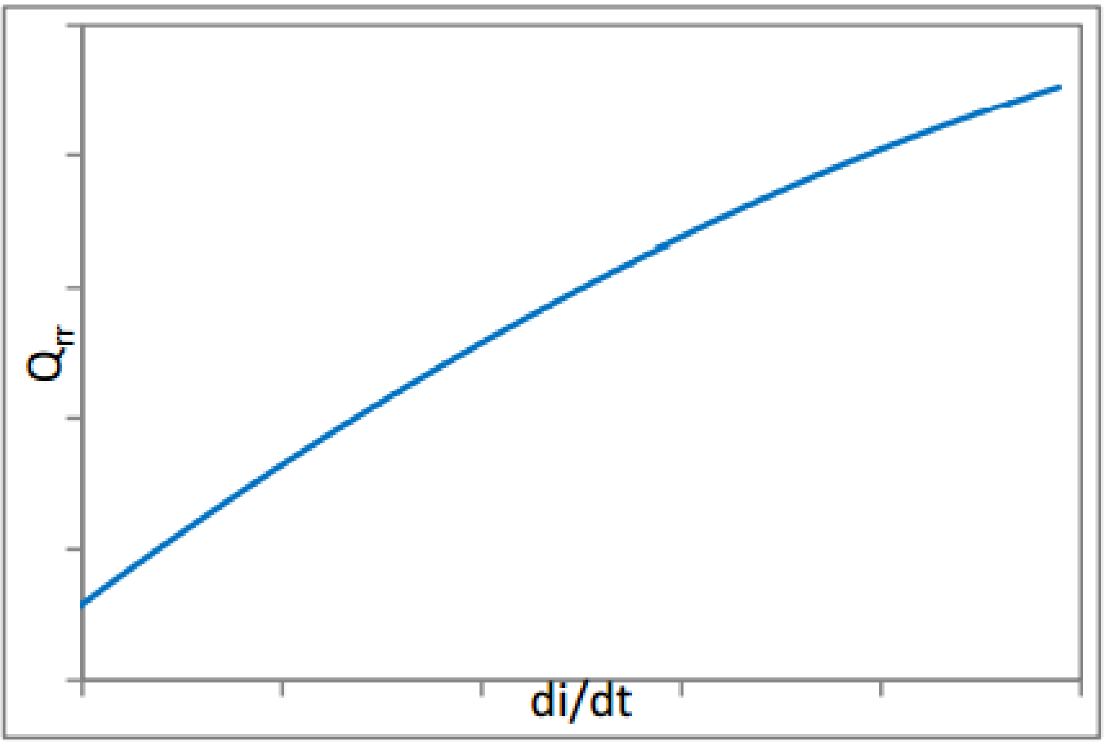

Figure 6. Q_{rr} vs di/dt (fixed t_{DIODE} and I_{DIODE}) [6].

The saturated Q_{rr} also scales with how quickly the current changes. The higher the current slope (di/dt), the higher the Q_{rr}. In other words, if the commutation loop is designed well with very low inductance to allow fast switching, it is inevitable for the MOSFET to experience higher accumulated Q_{rr} [6].

Another parameter that is not always specified on the datasheet is the Reverse Recovery Softness Factor (RRSF) of the diode's I_{rr} waveform. The RRSF is the ratio of the two parts of the reverse recovery current: stored charge removal and the return to zero current. With reference to Fig 3 RRSF is calculated by dividing the time required to remove the stored charge carriers from the diode (τ_f) into the time it takes for the resultant reverse current to fall from its peak negative value (I_{rrm}) back to zero (τ_s). RRSF $= \tau_f/\tau_s$.The Softness ratio equally can be defined as the absolute value in ratio of dI_F/dt slope in the τ_s region divided by the greatest magnitude of dI_R/dt slope (28) in the τ_s region and the parts of the waveform are shown in Figure 7 [9].

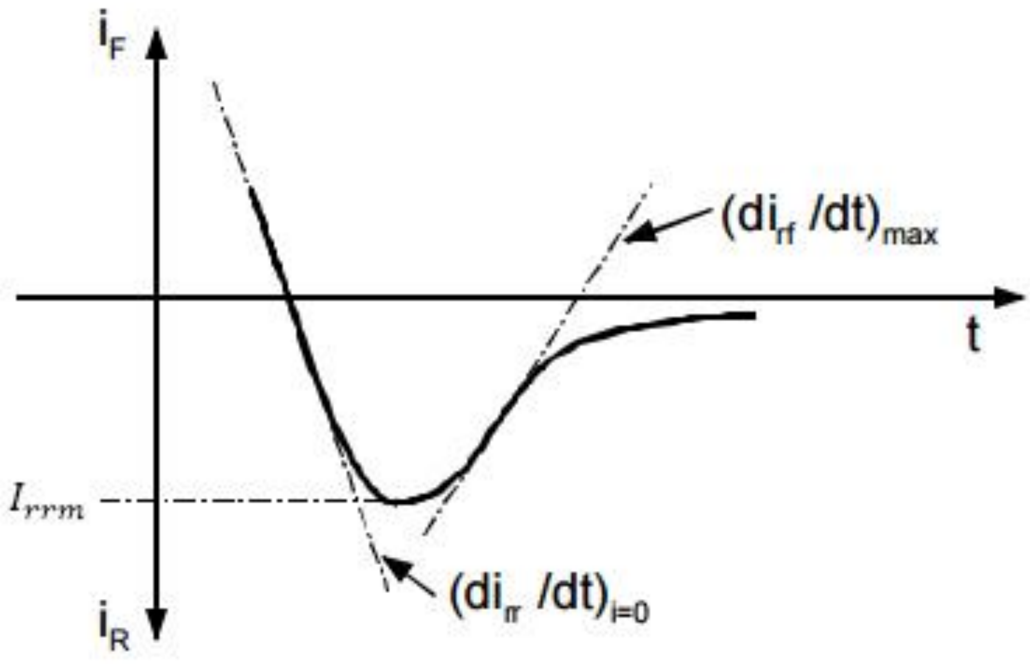

Figure 7. RRSF - Reverse Recovery Softness Factor [9].

The softness of a device's I_{rr} will depend on the lifetime control technique used to reduce Q_{rr}. The softness factor can easily be calculated for diodes that do not have this parameter specified in their data sheets [10] (Eq. 8) .

$$RRSF = \left| \frac{(dI_{rr}/dt)_{max}}{(dI_{rf}/dt)_{i=0}} \right| \quad (8)$$

Abrupt recovery also produces excessive EMI and voltage stress across the diode, which requires snubber circuitry or larger EMI filter components. Soft recovery reduces voltage stress and EMI, without the use of snubbers [10].

3. Equivalent circuit model of Schottky diode

Equivalent circuit models are required in order to represent a particular operating mode of the circuit with the required accuracy. Models used in the large signal mode using simplifications based on the linearization of the circuit in the active area of the device. In models used in circuit analysis in DC mode, capacitance and inductance are not taken into account.

Since charge in the Schottky diode is carried out by the main carriers, the barrier capacitance and the current vary almost instantaneously with the voltage at the junction, and the small signal values of these parameters are valid up to very high frequencies.

A small signal equivalent circuit of a Schottky diode with parasitic elements is based on an equivalent circuit of a diode with a p-n junction, but not taking into account the diffusion capacitance (Figure 8). The circuit includes the barrier capacitance C_j, the differential resistance of the transition R_j, the series resistance R_S; parasitic elements; series inductance L_S, capacitance of contacts to the barrier relative to the package C_P; The geometric capacity, or the capacity of the C_{geom}.

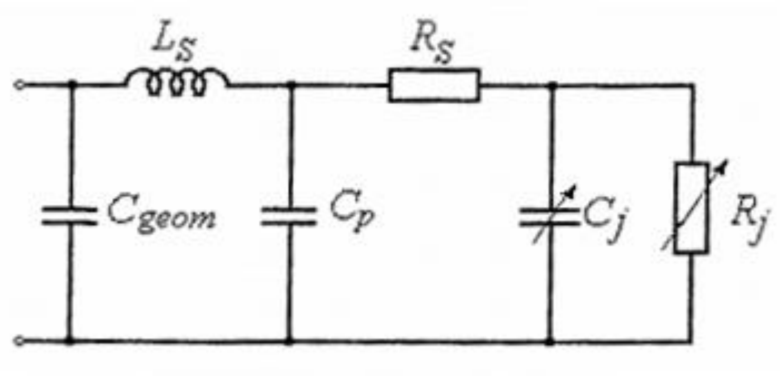

Figure 8. Equivalent circuit of a Schottky diode [11].

The capacitance of the packaging is determined by the dimensions of the device and can be found from the expression $C_{geom} = \varepsilon S_g / L$. The series inductance has a dominant effect on high frequencies and at large bias. The equivalent circuit of a packaged diode is highly dependent on the configuration of the circuit into which it is turned on and on the way it is connected to the circuit. The enclosure always introduces additional losses and reactivity and at the same time can significantly affect the frequency characteristics of the diode. Therefore, the parasitic capacitance and inductance must be reduced as much as possible.

The differential resistance of the transition can be obtained by transforming the expression for the current-voltage characteristic:

$$R_j = \left(\frac{dI}{dV}\right)^{-1} = \frac{\eta kT}{S_j q(I_s+I)} \tag{9}$$

For large forward bias, when the differential resistance decreases, the diode series resistance is comparable to or even dominates.

In the general case, the slope of the current-voltage characteristic will be determined by the sum of two resistances: differential and series resistance. Taking into account the series resistance, the current-voltage characteristic differs from the expression for an ideal diode:

$$I = I_s\left(e^{\frac{V-IR_S}{\eta kT/q}} - 1\right) \tag{10}$$

The series resistance of the diode is determine by the formula:

$$R_s = \frac{1}{S_j}\int_{x_1}^{x_2} \rho(x)dx + \frac{\rho_B}{4r} + R_C \tag{11}$$

Here, the first term is the resistance of the quasi-neutral region, that is, the part of the epitaxial layer located between the depleted layer and the substrate; the second term is the resistance to spreading from a circular contact to the substrate. The last term describes the resistance of ohmic contacts to the substrate. The series resistance depends on the bias voltage, since it is a function of x_1 and x_2. An increase in the bias voltage results in an expansion of the space charge region, and this reduces the magnitude of the series resistance. [11]

4. Materials and methodology

SiC Schottky diodes that were used for the experiment were commercial purchased Cree SiC Schottky power diodes 600V - C3D10060A(Appendix 1). The values of resistors that were used for experiment are following: 150mΩ, 220mΩ, 270mΩ, 330mΩ, 390mΩ, 470mΩ, 560mΩ. . The values of condensers are following: 100pF, 180pF, 220pF, 312pF, 378pF, 412pF, 510pF, 549pF.

Performed experiments were made at normal conditions (room temperature) and based on a model, which consist of SiC Schottky diodes, various resistors and condensers. Passive components were soldered to the pins of SiC Schottky. Reverse recovery time dependences of the initial diode and diode connected in series with different resistors and condensers, respectively, have been measured. Experiments were conducted separetely following three main concepts: diode + resistor, diode + condenser and mixed by using both resistor and condenser at the same time.

To carry out the electrical measurements, we used the following equipment: an Agilent B1500A semiconductor device analyser, a LEMSYS DMS QRR 100 A dynamic parameter system, the generator AFG 3252 , Tektronix TDS5034B and an Agilent MSOS104A oscilloscopes , Keithley's Series 2400 Source Measure Unit (SMU).

For reverse recovery measurement the input parameters for LEMSYS DMS QRR 100 A were the following: short pulse I_F= 20A, dI_F/dt= 100A/us, V_{rr}=100V; where I_F- forward current, V_{rr} – reverse voltage, dIF/dt - the ratio of the amount of current from the time of its occurrence. For capacitance-voltage (C-V) measuring the frequency f=1MHz was used.

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 characteristics were presented.

5. Results and discussions.

5.1 I-V characteristic measurements

For measuring I-V characteristic Keithley's Series 2400 Source Measure Unit (SMU) has been used. Figure 9 shows the typical views of current-voltage (I-V) characteristics at room temperature for the initial diode and diode with different resistors connected in series one by one. The values of resistors used for the experiment were the following: 150mΩ, 220mΩ, 270mΩ, 330mΩ, 390mΩ, 470mΩ and 560mΩ. All resistors were metal oxide film resistors with rated output of 1W and rated voltage of 350 V.

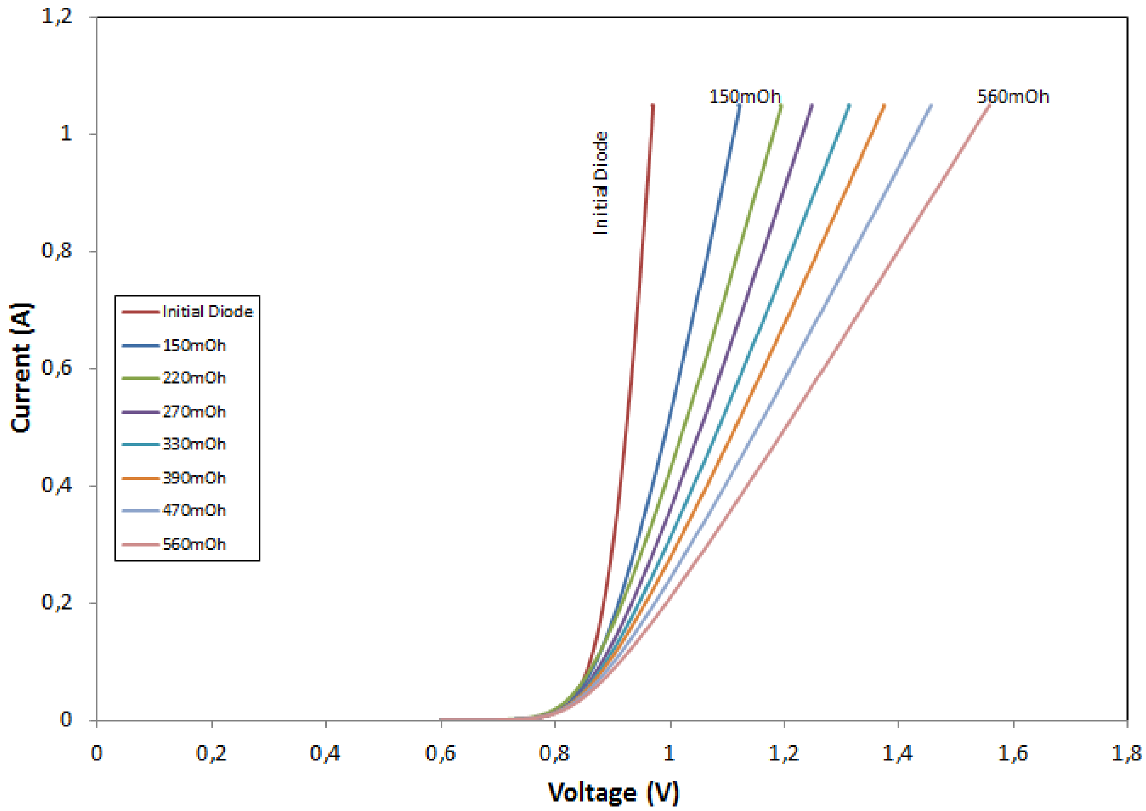

Figure 9. Current-voltage characteristics for the initial diode and diode measured with different resistors values (from 150mΩ to 560mΩ).

As shown, the I-V exhibits a quite good exponential diode behaviour with different resistor values. I-V starts from 0.6V because Schottky diode from 0 to 0.6V behaves as a straight line.

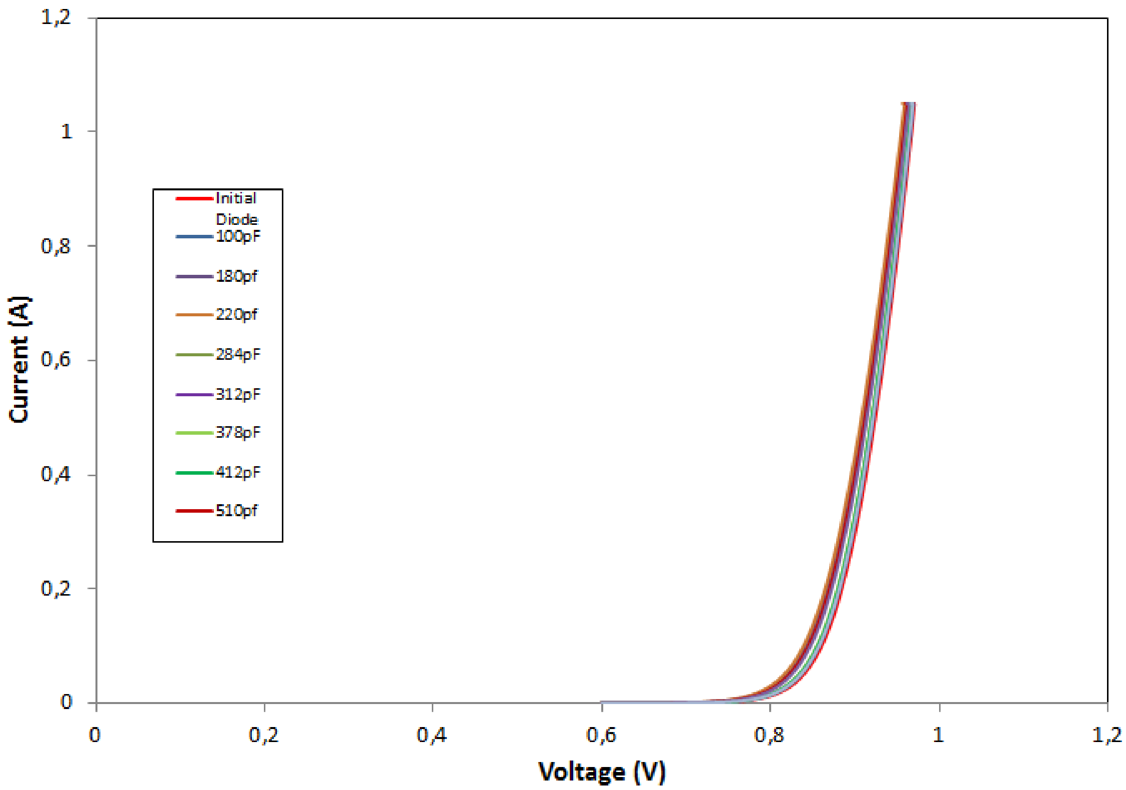

Figure 10. Current-voltage characteristics for the initial diode and diode measured with different condensers values (from 100pF to 510pF).

On Figure 10 shown the behaviour of Schottky diode on applied voltage with additional parallel capacitance. The values of condensers used for the experiment were the following: 100pF, 180pF, 220pF, 284pF, 312pF, 378pF, 412pF and 510pF.

As expected the I-V characteristics at room temperature for the initial diode and diode with different condensers showed no changes.

In order to check how resistance and capacitance effect together on I-V characteristic, resistors and condensers were connected to the initial diode. In order to reduce number of measurements and figure out the whole behaviour of the diode, only 3 values of resistors and condensers were taken. The values for resistors: 150mOhm, 330mOhm, 560mOhm and 100pF, 330pF, 549pF for condensers.

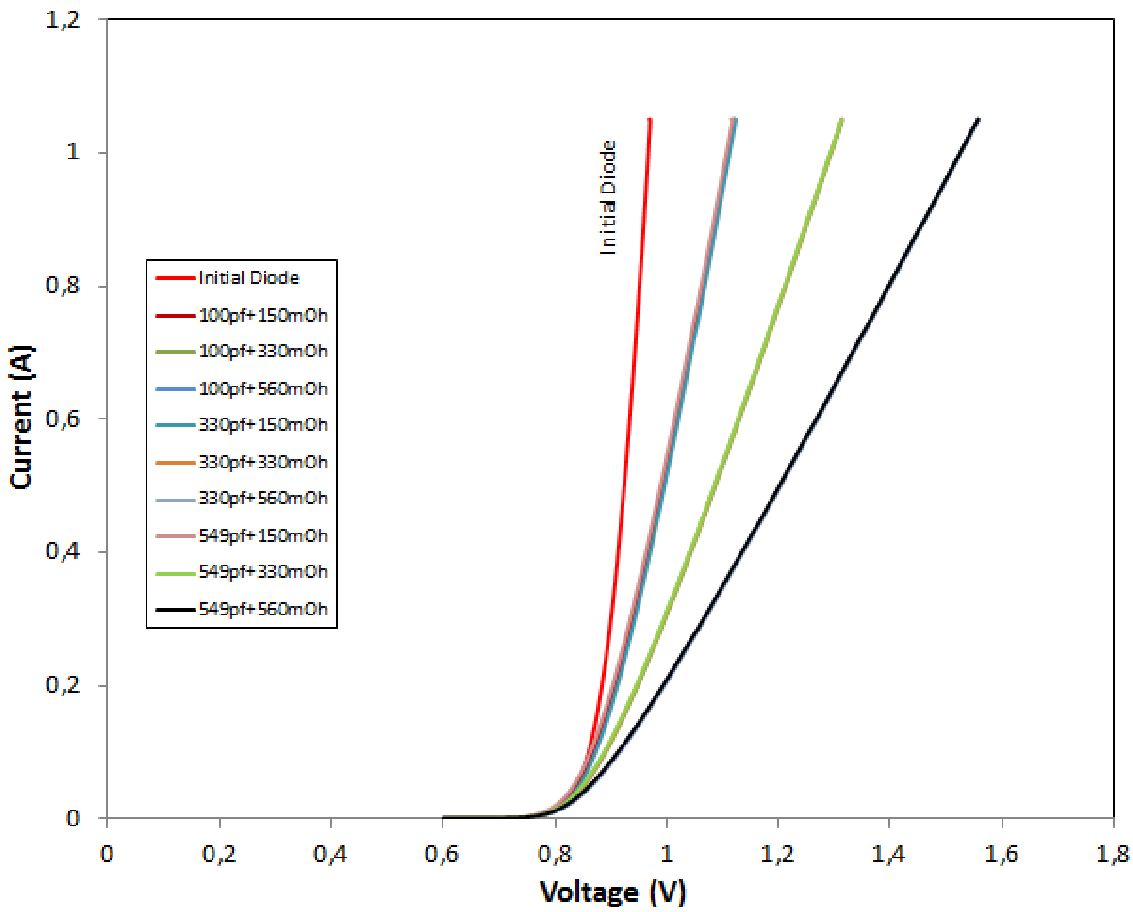

Figure 11. Current-voltage characteristics for the initial diode and diode measured with additional different condensers and resistors values (from 100pF to 549pF and 150mOhm to 560mOhm).

As it shown on Figure 11 additional resistance and capacitance effect on I-V characteristic according the resistance behaviour, similar to Figure 9.

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. Next Figure 12 shows the linear dependence of R_S on the different values of resistors.

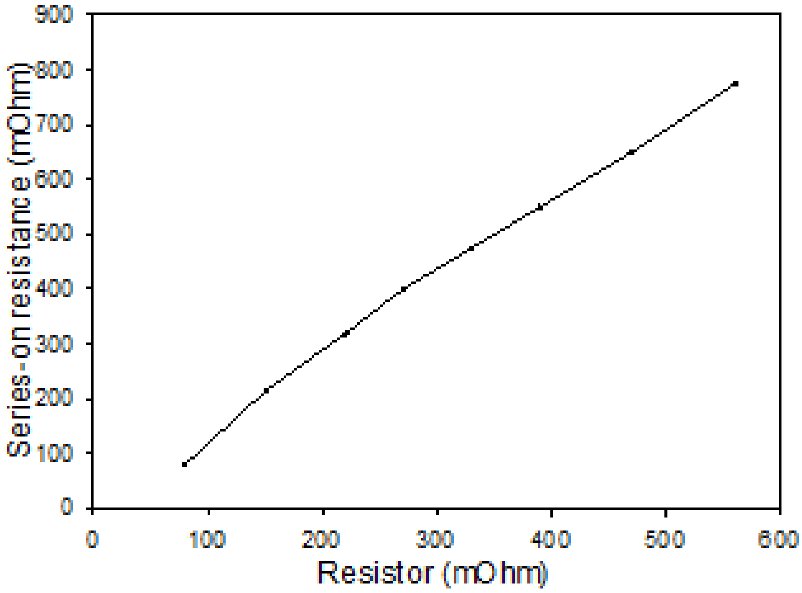

Figure 12. Series-on resistance dependence on different resistor values.

5.2 C-V characteristic measurements.

Capacitance-voltage measurements were made with input frequency f = 1MHz. Figure 13 shows the typical C-V dependence at room temperature and high frequency for the same experiment conditions as for I-V measurements. The condensers used for the experiment were chosen with the following capacitance: 100pF, 180pF, 220pF, 312pF, 378pF, 412pF, 510pF and 549pF.

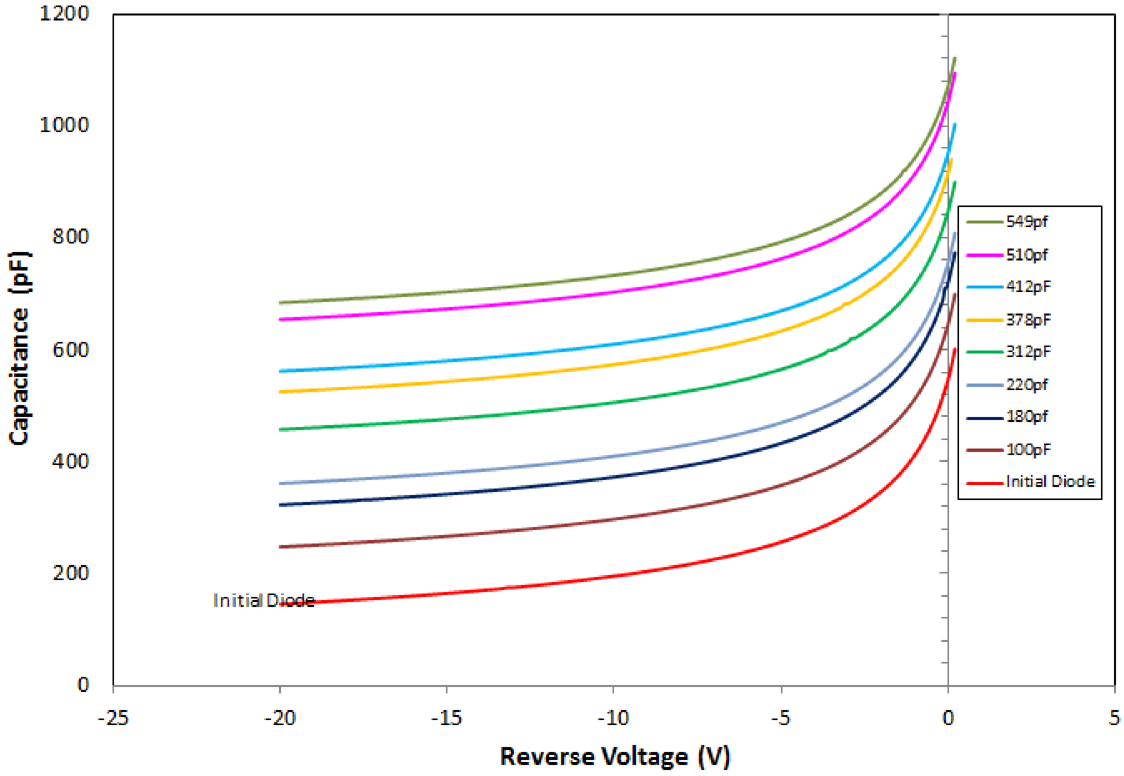

Figure 13. Capacitance-voltage characteristics for the initial diode and diode with different condensers in parallel (from 100pF to 549pF).

As seen from Figure 13 the capacitance-voltage characteristics are displaced parallel to themselves with the different values of condensers connected to the initial diode. It is clear that additional condensers increasing the overall Schottky barrier capacitance, however, the relaxation behaviour not affected.

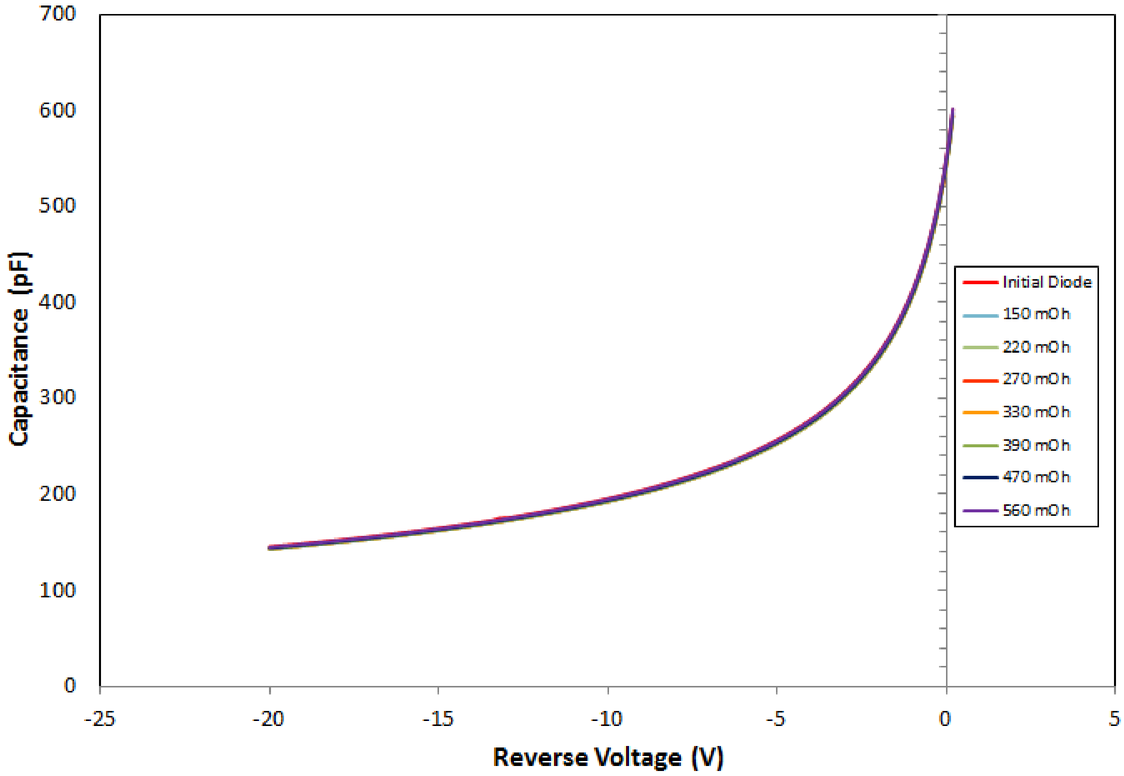

Figure 14. Capacitance-voltage characteristics for the initial diode and diode measured with different resistors values (from 150mOh to 560mOh).

As expected the C-V characteristics at room temperature for the initial diode and diode with different resistors showed no changes. The same behaviour were shown on Fig 10. for the I-V characteristics at room temperature for the initial diode and the diode with connected condensers.

To test the simultaneous effect of resistance and capacitance on the characteristic, I used the same set of resistors and condensers as for measuring the current-voltage characteristic.

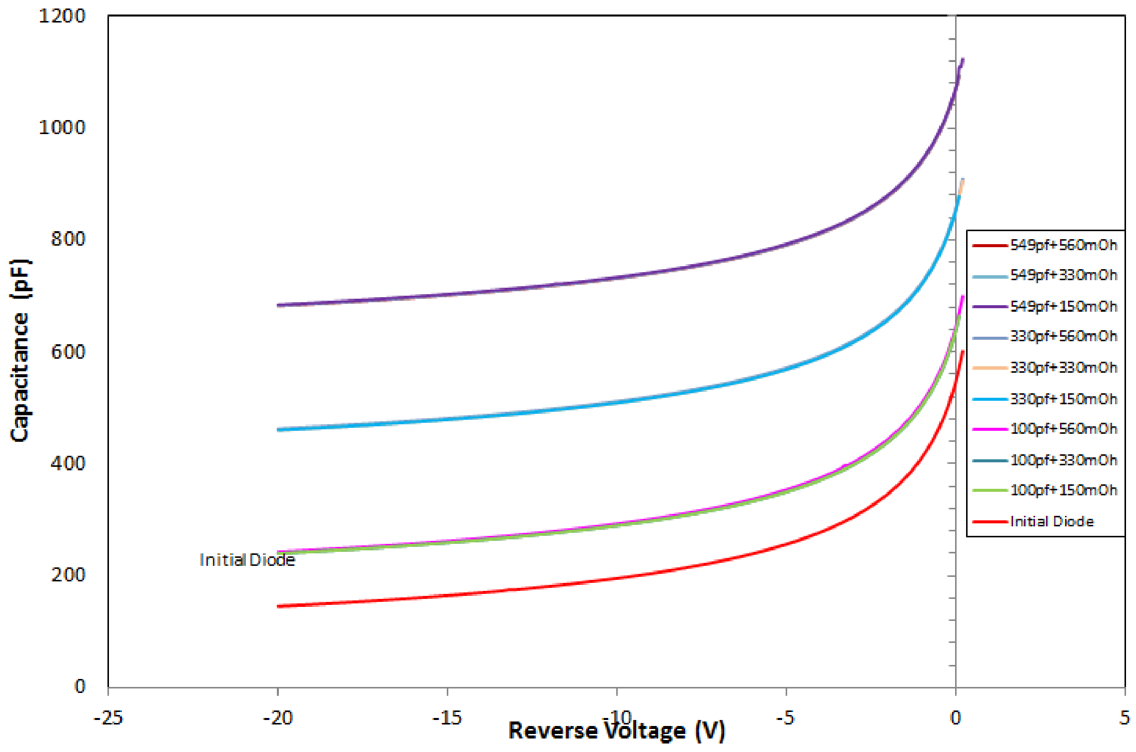

Figure 15. Capacitance-voltage characteristics for the initial diode and diode measured with additional different condensers and resistors values (from 100pF to 549pF and 150mOh to 560mOh).

5.3 Reverse Recovery time measurements

For measuring reverse recovery time were used Dynamical Measuring System-LEMSYS DMS QRR 100 A, the generator AFG 3252, Tektronix TDS5034B and Agilent MSOS104A oscilloscopes. As an input parameters for experiment were set following: short pulse I_F= 20A, dI_F/dt= 100A/ns, V_{rr}=100V; where I_F- forward current, V_{rr} – reverse voltage, dI_F/dt - the the ratio of the amount of current from the time of its occurrence.

The typical reverse recovery characteristics for the initial Schottky diode is shown on Figure 16.

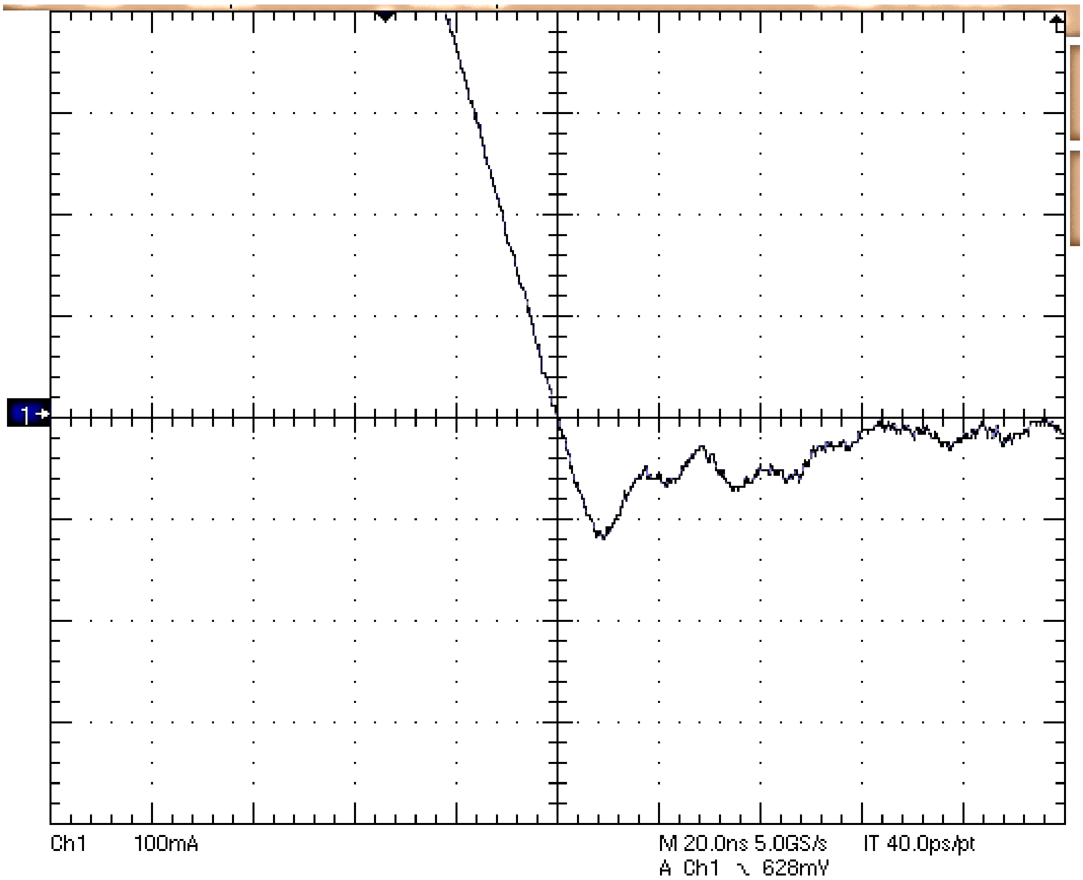

Figure 16. Reverse recovery time characteristic for initial Schottky diode (I=100mA/div, τ=20ns/div).

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, was chosen the set of condensers: 100pF, 378pF, 412pF, 536pF and set of resistors: 150mΩ, 270mΩ, 370mΩ, 560mΩ.

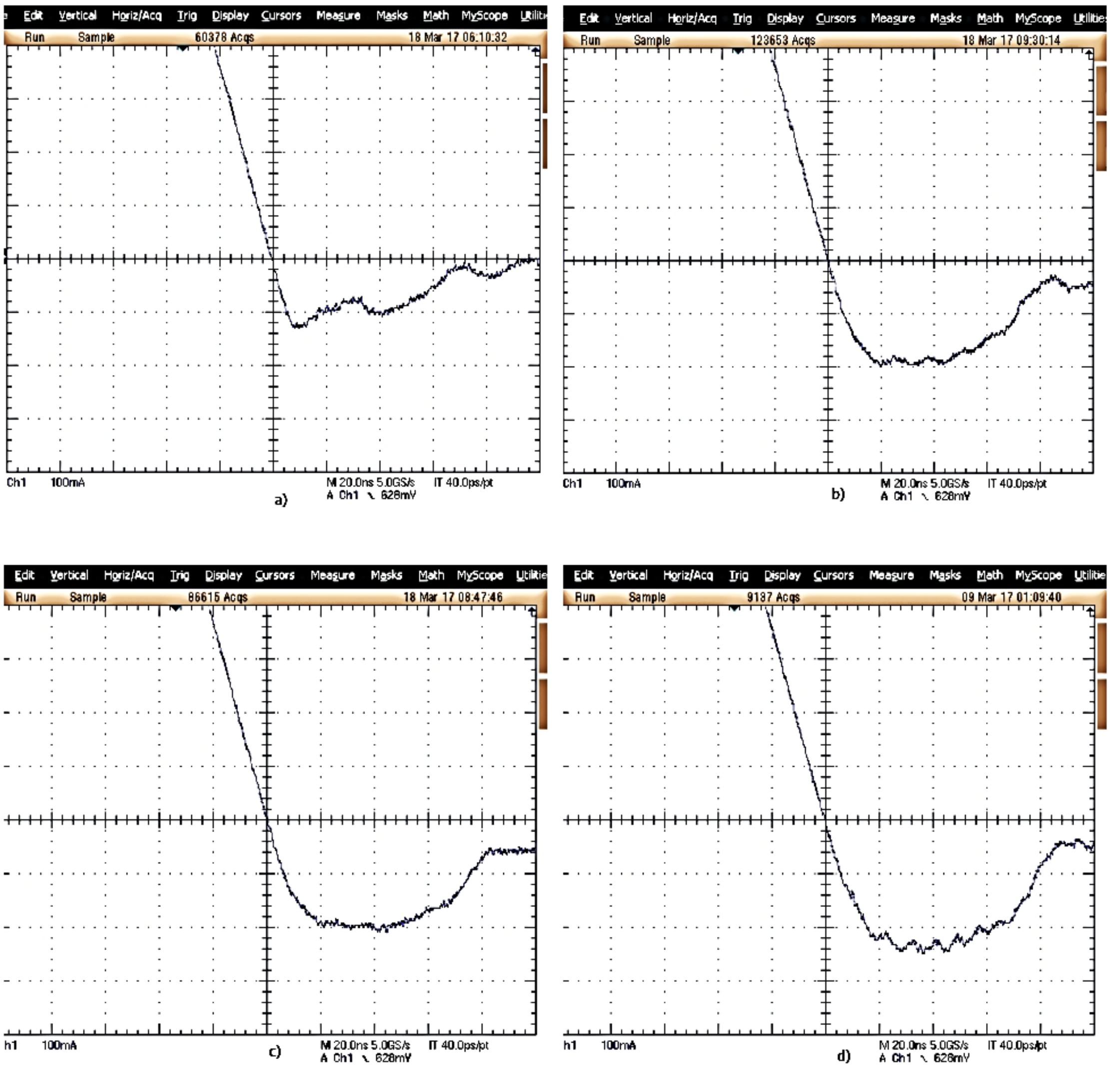

Figure 17. Reverse recovery time for the diode with condensers connected a)100pF, b)378pF, c)412pF, d)536pF (I=100mA/div, τ=20ns/div).

Fig 17, shows that with increasing of capacitance Q_{rr} charge region expands, which directly affects the recovery time, according to (Eq.6). Thus, the bigger Q_{rr} the higher recovery time.

From the Figure 18, it is clear that additional resistance does not increase reverse recovery time compared to additional capacitance. However, additional resistance has an opposite effect, reverse recovery time decreased in comparison to τ_{rr} of initial diode (Figure 20).

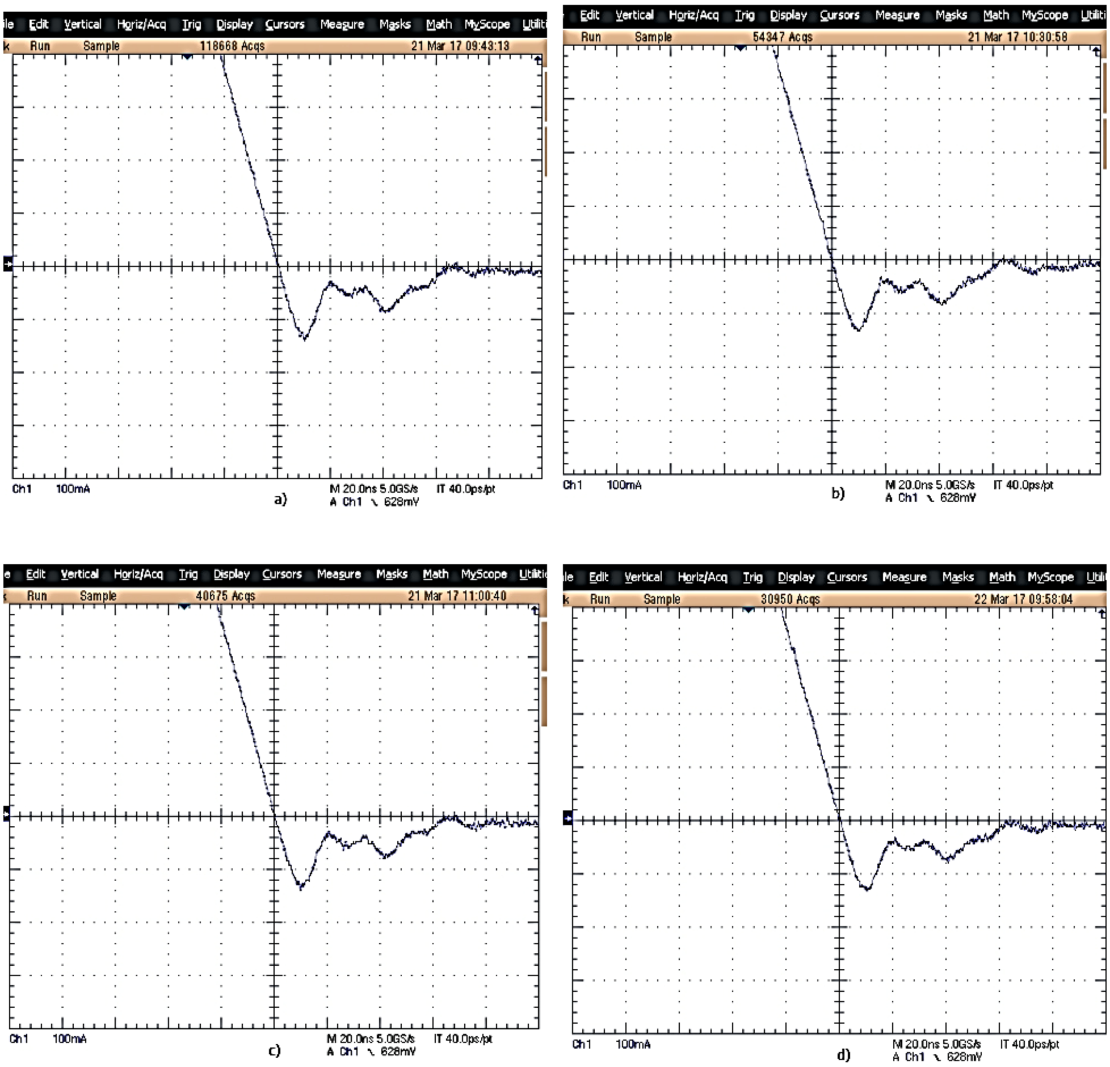

Figure 18. Reverse recovery time for the diode with.set of resistors a) 150mΩ, b) 270mΩ, c) 370mΩ, d) 560mΩ (I=100mA/div, τ=20ns/div).

Additionally, in order to show the simultaneous dependence on resistance and capacitance, some resistors were combined together with condensers and connected to the initial diode for the measurement of the reverse recovery time (Figure 19). For measurements the set of resistors and condensers was the following: 100pF+560mΩ, 330pF+330mΩ, 560pf+330mΩ.

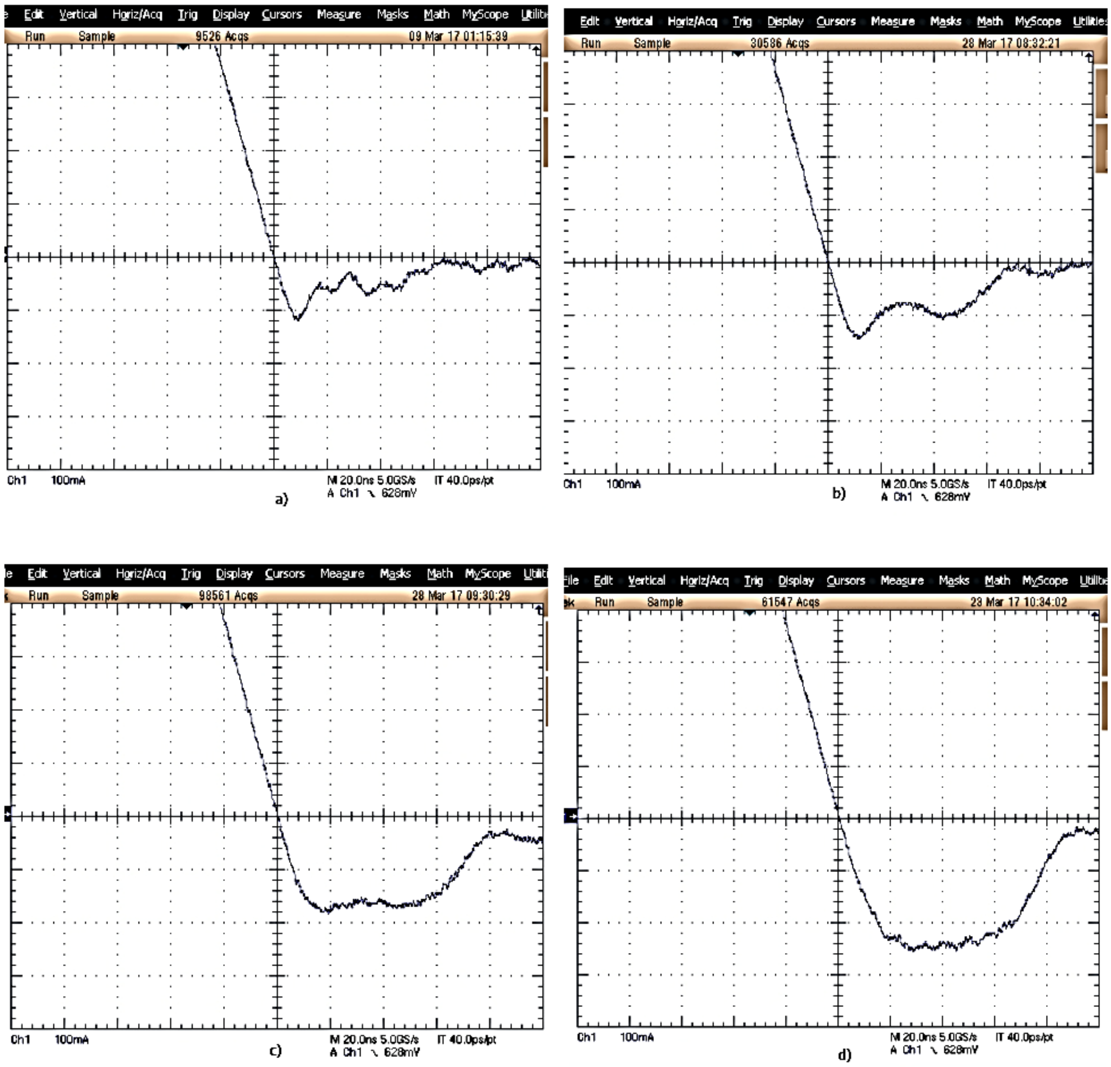

Figure 19. Reverse recovery time for the diode with condenser and resistors: a) Initial diode, b) 100pF+560mΩ, c) 330pF+330mΩ, d) 560pf+330mΩ (I=100mA/div, τ=20ns/div).

The reverse recovery time dependences with all used values of condensers and resistors shown on Figure 20 and 21.

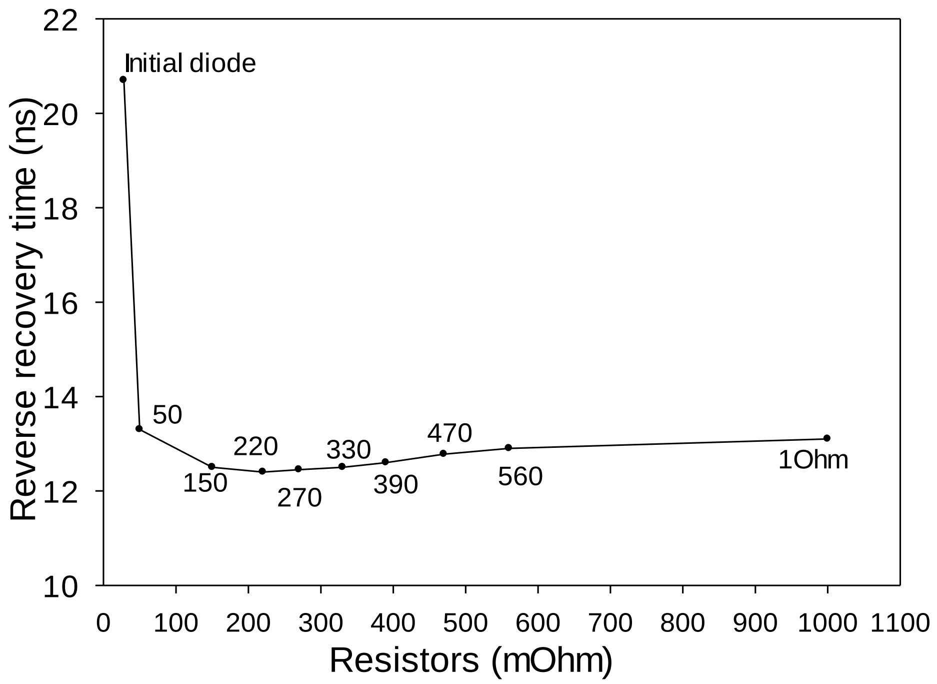

Figure 20. Reverse recovery time dependence on the diode base resistance and different values of resistors connected to the diode one by one.

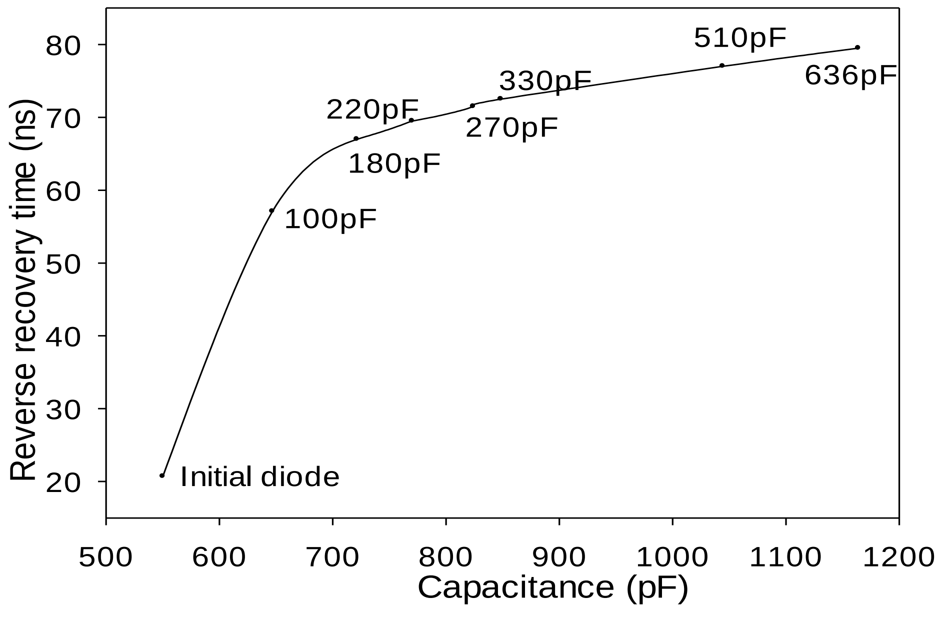

Figure 21. Reverse recovery time dependence on different values of condensers connected to the diode one by one.

As seen from the Figure 20 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 Figure 21, 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 [12]. 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 (Figure 22).

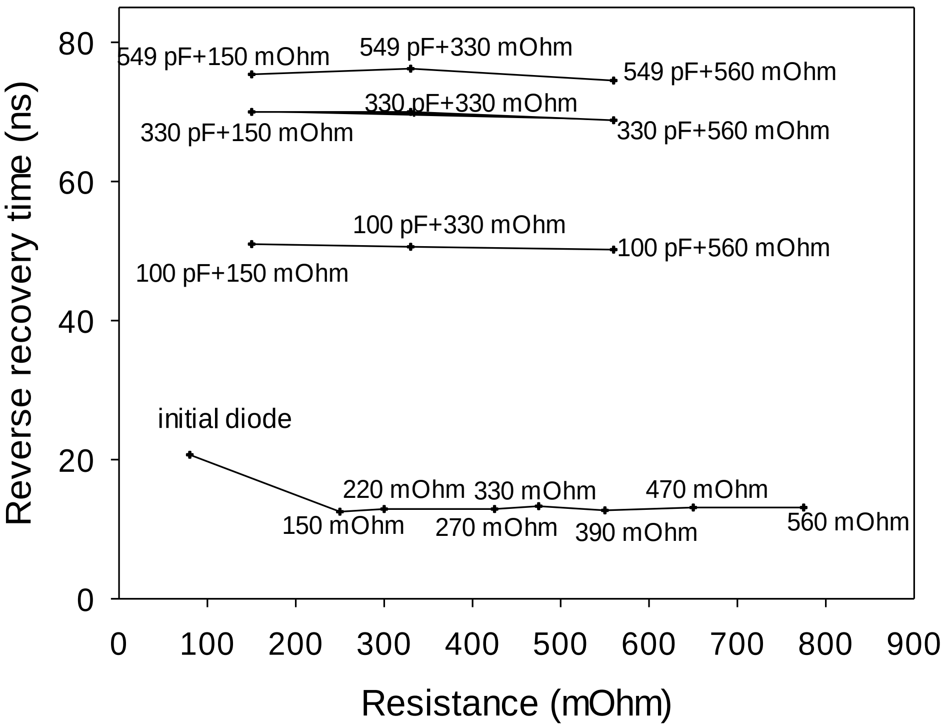

Figure 22. Reverse recovery time dependence on combined resistors and condensers.

The idea of carrying out the work presented in this publication appeared during the research of the degradation of 600 V, 4H-SiC Schottky diodes under irradiation with 0.9 MeV electrons [13]. 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 (Eq. 12):

$$\tau_M = \rho\varepsilon\varepsilon_0 \tag{12}$$

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_sC_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 > 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 τ_s branch, but this does not take into account the measurement method (see Figure 3, 17, 19).

6. 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} in 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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Appendix 1 –CREE C3D10060A Silicon Carbide Schottky Diode Z-Rec® Rectifier Data Sheet

CREE

C3D10060A

Silicon Carbide Schottky Diode

Z-REC® RECTIFIER

V_{RRM}	=	600 V
I_F (T_C=135˚C)	=	14.5 A
Q_c	=	24 nC

Features

- 600-Volt Schottky Rectifier
- Zero Reverse Recovery Current
- Zero Forward Recovery Voltage
- High-Frequency Operation
- Temperature-Independent Switching Behavior
- Extremely Fast Switching
- Positive Temperature Coefficient on V_F

Package

TO-220-2

Halogen-Free

RoHS

AEC-Q101 Qualified

Benefits

- Replace Bipolar with Unipolar Rectifiers
- Essentially No Switching Losses
- Higher Efficiency
- Reduction of Heat Sink Requirements
- Parallel Devices Without Thermal Runaway

Applications

- Switch Mode Power Supplies (SMPS)
- Boost diodes in PFC or DC/DC stages
- Free Wheeling Diodes in Inverter stages
- AC/DC converters

Part Number	Package	Marking
C3D10060A	TO-220-2	C3D10060

Maximum Ratings (T_C = 25 ˚C unless otherwise specified)

Symbol	Parameter	Value	Unit	Test Conditions	Note
V_{RRM}	Repetitive Peak Reverse Voltage	600	V		
V_{RSM}	Surge Peak Reverse Voltage	600	V		
V_{DC}	DC Blocking Voltage	600	V		
I_F	Continuous Forward Current	30 14.5 10	A	T_C=25˚C T_C=135˚C T_C=153˚C	Fig. 3
I_{FRM}	Repetitive Peak Forward Surge Current	46 31	A	T_C=25˚C, t_P = 10 ms, Half Sine Wave T_C=110˚C, t_P=10 ms, Half Sine Wave	
I_{FSM}	Non-Repetitive Peak Forward Surge Current	90 71	A	T_C=25˚C, t_P = 10 ms, Half Sine Wave T_C=110˚C, t_P = 10 ms, Half Sine Wave	Fig. 8
$I_{F,Max}$	Non-Repetitive Peak Forward Surge Current	860 680	A	T_C=25˚C, t_P = 10 µs, Pulse T_C=110˚C, t_P = 10 µs, Pulse	Fig. 8
P_{tot}	Power Dissipation	136.5 59	W	T_C=25˚C T_C=110˚C	Fig. 4
T_J , T_{stg}	Operating Junction and Storage Temperature	-55 to +175	˚C		
	TO-220 Mounting Torque	1 8.8	Nm lbf-in	M3 Screw 6-32 Screw	

1 C3D10060A Rev. E, 12-2015

Electrical Characteristics

Symbol	Parameter	Typ.	Max.	Unit	Test Conditions	Note
V_F	Forward Voltage	1.5 2.0	1.8 2.4	V	I_F = 10 A T_J=25°C I_F = 10 A T_J=175°C	Fig. 1
I_R	Reverse Current	10 20	50 200	μA	V_R = 600 V T_J=25°C V_R = 600 V T_J=175°C	Fig. 2
Q_C	Total Capacitive Charge	24		nC	V_R = 400 V, I_F = 10 A di/dt = 500 A/μs T_J = 25°C	Fig. 5
C	Total Capacitance	460.5 44 40		pF	V_R = 0 V, T_J = 25°C, f = 1 MHz V_R = 200 V, T_J = 25°C, f = 1 MHz V_R = 400 V, T_J = 25°C, f = 1 MHz	Fig. 6
E_C	Capacitance Stored Energy	3.6		μJ	V_R = 400 V	Fig. 7

Note: This is a majority carrier diode, so there is no reverse recovery charge.

Thermal Characteristics

Symbol	Parameter	Typ.	Unit	Note
$R_{\theta JC}$	Thermal Resistance from Junction to Case	1.1	°C/W	Fig. 9

Typical Performance

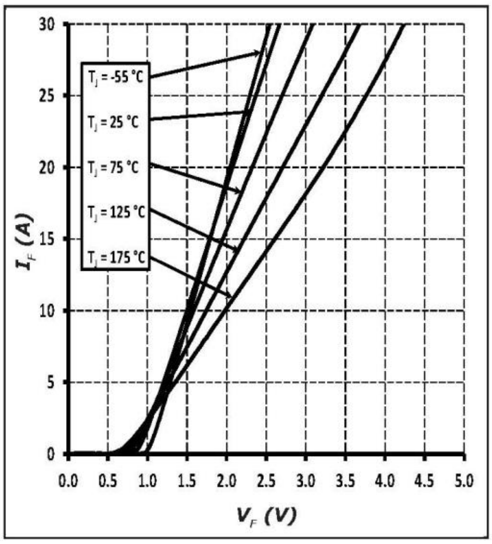


Figure 1. Forward Characteristics

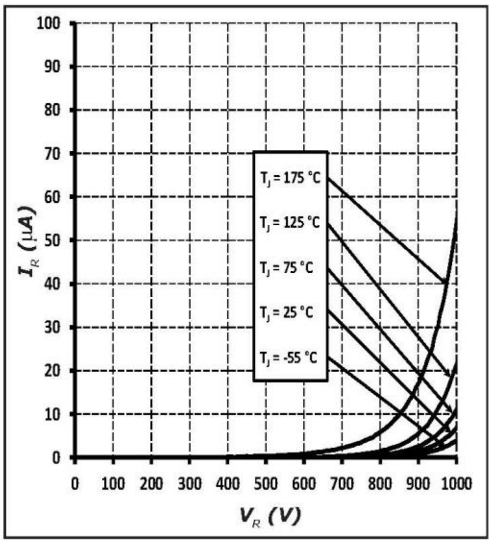


Figure 2. Reverse Characteristics

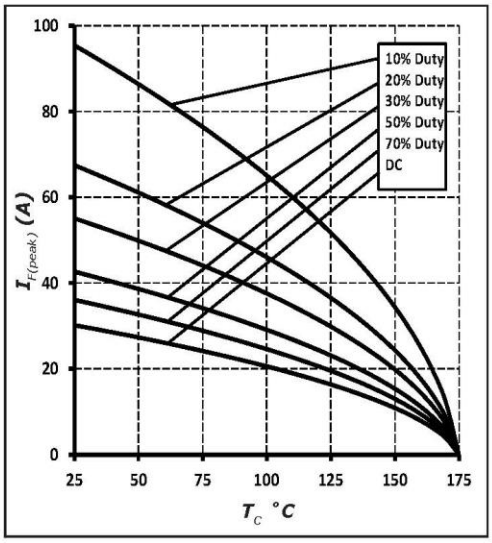


Figure 3. Current Derating

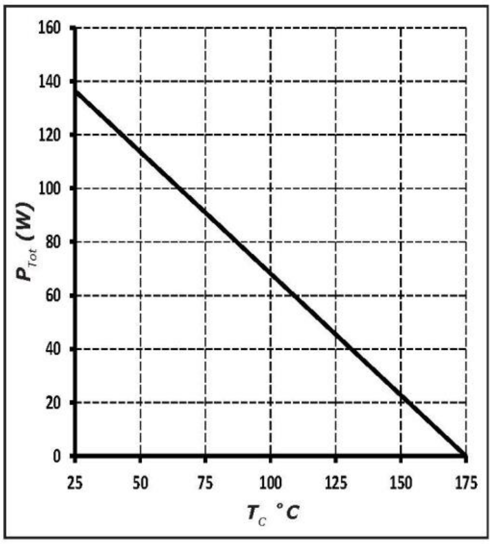


Figure 4. Power Derating

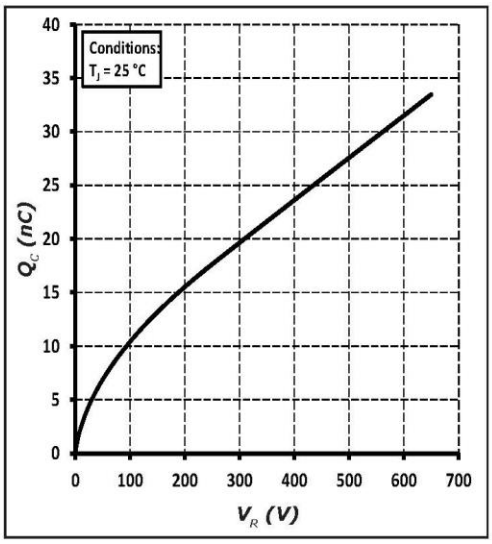


Figure 5. Total Capacitance Charge vs. Reverse Voltage

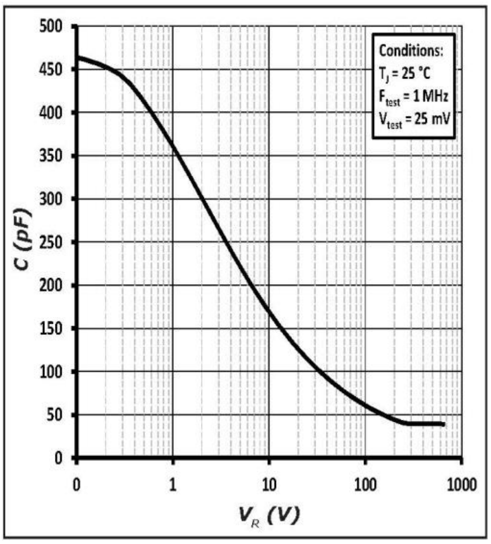


Figure 6. Capacitance vs. Reverse Voltage

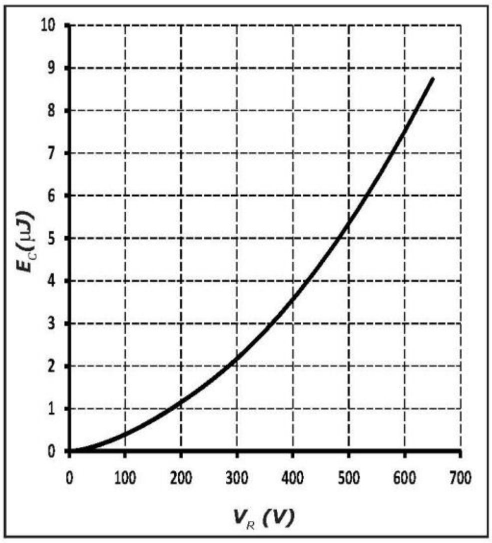


Figure 7. Capacitance Stored Energy

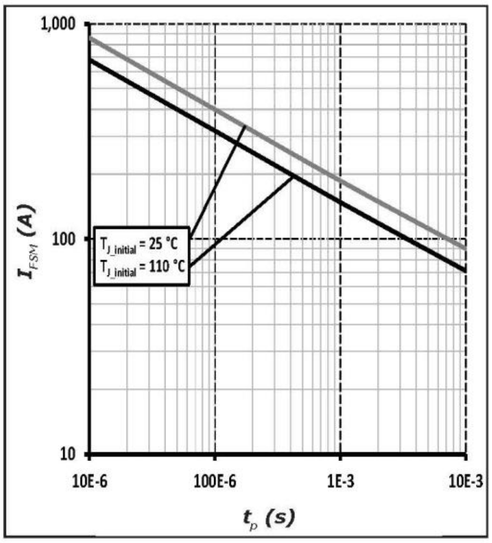


Figure 8. Non-repetitive peak forward surge current versus pulse duration (sinusoidal waveform)

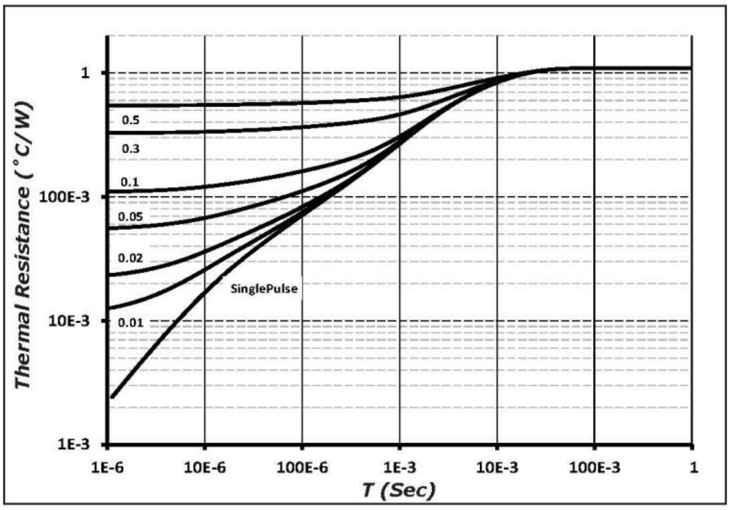
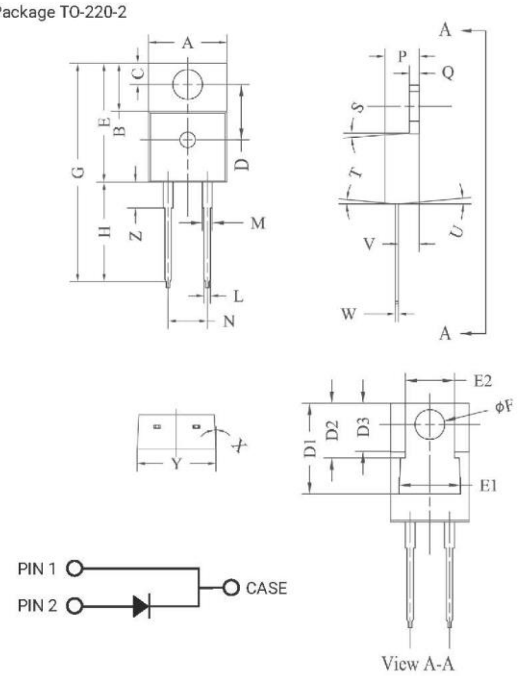


Figure 9. Transient Thermal Impedance

Package Dimensions

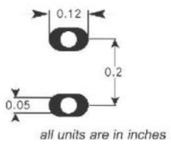
Package TO-220-2



POS	Inches		Millimeters	
	Min	Max	Min	Max
A	.381	.410	9.677	10.414
B	.235	.255	5.969	6.477
C	.100	.120	2.540	3.048
D	.223	.337	5.664	8.560
D1	.457-.490		11.60-12.45 typ	
D2	.277-.303 typ		7.04-7.70 typ	
D3	.244-.252 typ		6.22-6.4 typ	
E	.590	.615	14.986	15.621
E1	.302	.326	7.68	8.28
E2	.227	251	5.77	6.37
F	.143	.153	3.632	3.886
G	1.105	1.147	28.067	29.134
H	.500	.550	12.700	13.970
L	.025	.036	.635	.914
M	.045	.055	1.143	1.550
N	.195	.205	4.953	5.207
P	.165	.185	4.191	4.699
Q	.048	.054	1.219	1.372
S	3°	6°	3°	6°
T	3°	6°	3°	6°
U	3°	6°	3°	6°
V	.094	.110	2.388	2.794
W	.014	.025	.356	.635
X	3°	5.5°	3°	5.5°
Y	.385	.410	9.779	10.414
z	.130	.150	3.302	3.810

NOTE:
1. Dimension L, M, W apply for Solder Dip Finish

Recommended Solder Pad Layout

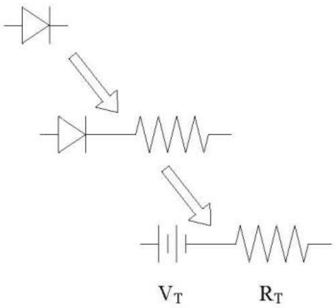


TO-220-2

Part Number	Package	Marking
C3D10060A	TO-220-2	C3D10060

Note: Recommended soldering profiles can be found in the applications note here:
http://www.wolfspeed.com/power_app_notes/soldering

Diode Model



$Vf_T = V_T + If * R_T$

$V_T = 0.94 + (T_J * -1.3*10^{-3})$
$R_T = 0.044 + (T_J * 4.4*10^{-4})$

Note: T_j = Diode Junction Temperature In Degrees Celsius, valid from 25°C to 175°C

Notes

- **RoHS Compliance**
  The levels of RoHS restricted materials in this product are below the maximum concentration values (also referred to as the threshold limits) permitted for such substances, or are used in an exempted application, in accordance with EU Directive 2011/65/EC (RoHS2), as implemented January 2, 2013. RoHS Declarations for this product can be obtained from your Wolfspeed representative or from the Product Ecology section of our website at http://www.wolfspeed.com/Power/Tools-and-Support/Product-Ecology.

- **REACh Compliance**
  REACh substances of high concern (SVHCs) information is available for this product. Since the European Chemical Agency (ECHA) has published notice of their intent to frequently revise the SVHC listing for the foreseeable future,please contact a Cree representative to insure you get the most up-to-date REACh SVHC Declaration. REACh banned substance information (REACh Article 67) is also available upon request.

- This product has not been designed or tested for use in, and is not intended for use in, applications implanted into the human body nor in applications in which failure of the product could lead to death, personal injury or property damage, including but not limited to equipment used in the operation of nuclear facilities, life-support machines, cardiac defibrillators or similar emergency medical equipment, aircraft navigation or communication or control systems, or air traffic control systems.

Related Links

- Cree SiC Schottky diode portfolio: http://www.wolfspeed.com/diodes
- Schottky diode Spice models: http://www.wolfspeed.com/Power/Tools-and-Support/DIODE-model-request2
- SiC MOSFET and diode reference designs: http://go.pardot.com/l/101562/2015-07-31/349i

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Appendix 2 – Article for the 8th International Conference on Computational Methods and Experiments in Material and Contact Characterisation

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

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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 reverse recover charge (Qrr), for a Schottky diode is normally measured in nanoseconds, ns. Some diodes exhibit τ_{rr} of 100 ps.
The experimental part consists of the measurements of reverse recovery time on a special tester LEMSYS DMS dynamic parameter system. The SiC Schottky diodes C3D10060A are used. In the present work the measuring results of reverse recovery time depending on additional resistors and condensers connected to the initial diode are presented. It has been shown that 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 drop, 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 (Eq.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.

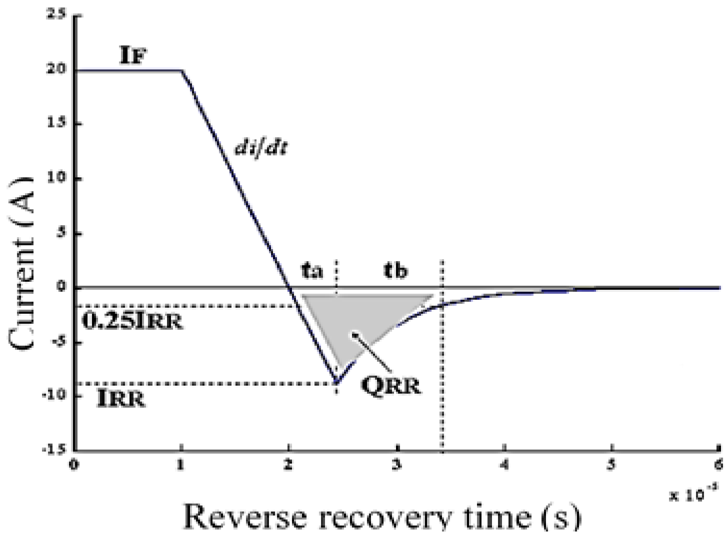

Fig. 1. Current during diode turn-off. [2].

The use of additional load of capacitance and/or resistance must lead to the change in reverse recovery time and current I_{rr}.

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 and 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 results 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.

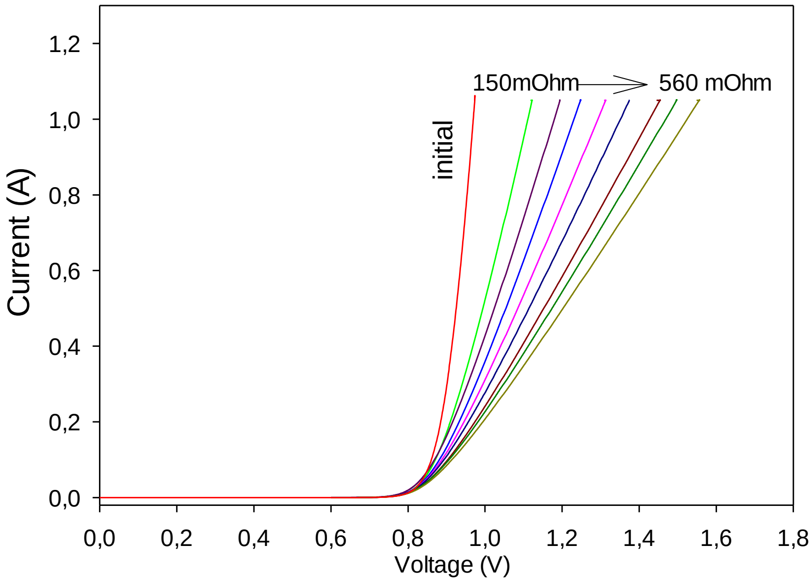

Fig. 2. Current-voltage characteristics for the initial diode and diode measured with different resistors values (from 150mΩ to 560mΩ).

As shown, 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. Next Fig. 3 shows the linear dependence of R_S on the different values of resistors.

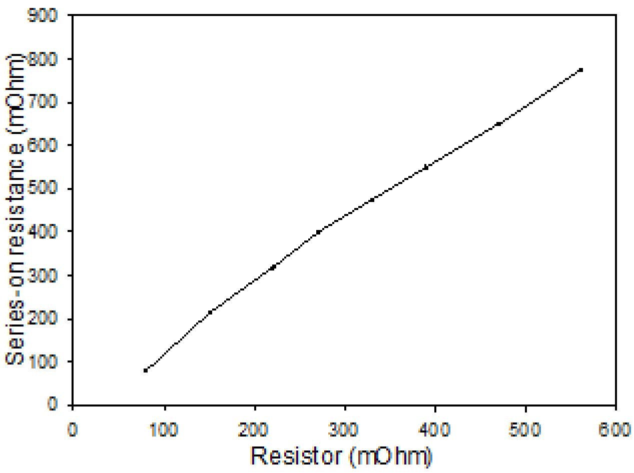

Fig. 3. Series-on resistance dependence on different resistor values.

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.

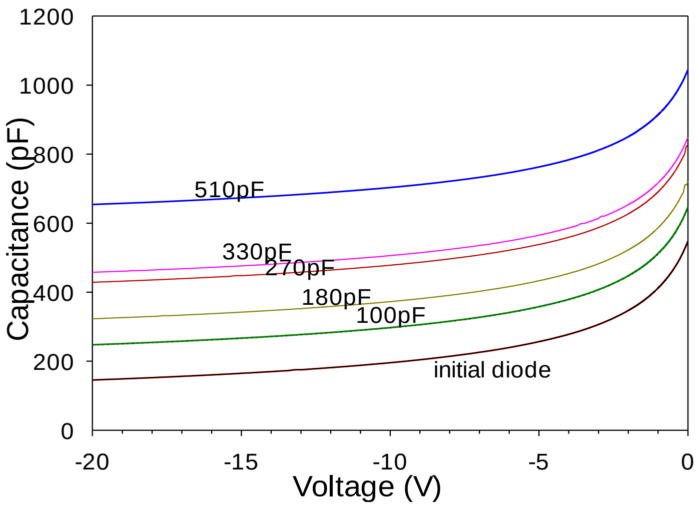

Fig. 4. Capacitance-voltage characteristics for the initial diode and diode with different condensers in parallel (from 100pF to 510pF).

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 on Fig. 5.

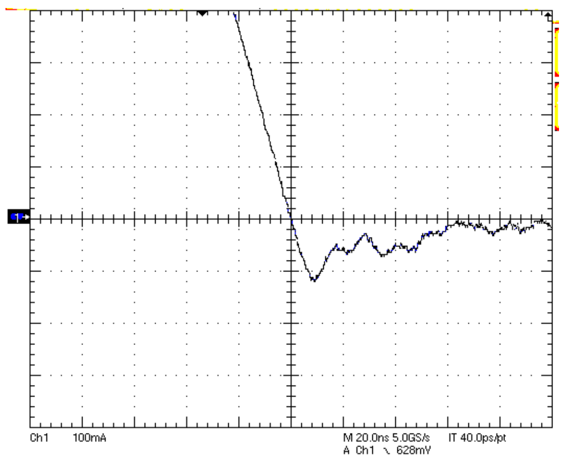

Fig. 5. Reverse recovery time characteristic for the initial Schottky diode (I=100mA/div, τ=20ns/div).

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.

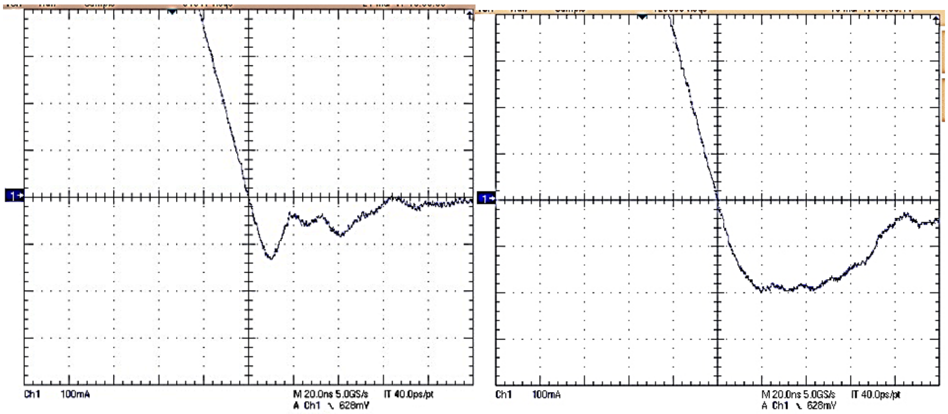

Fig. 6. Reverse recovery time for the diode with resistor (270 mΩ) on the left and for the diode with condenser (378 pF) on the right (I=100mA/div, τ=20ns/div).

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

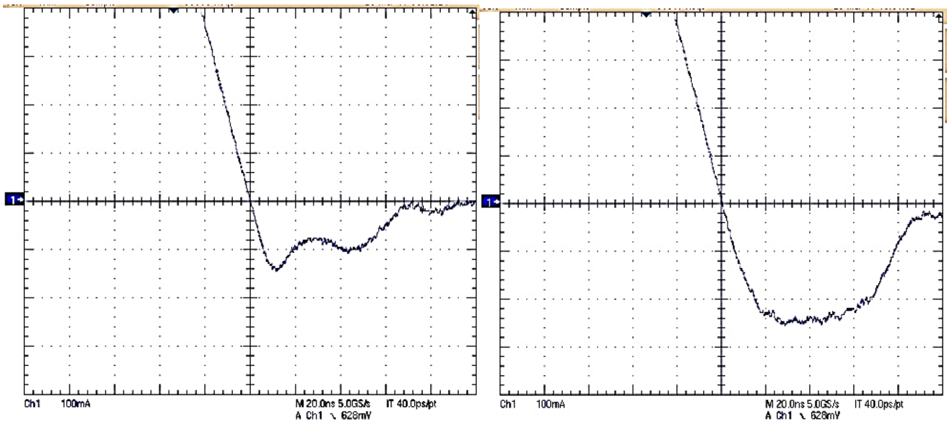

Fig. 7. Reverse recovery time for the diode with condenser and resistor (100pF+560 mΩ) on the left and for the diode with condenser and resistor (378 pF+330mΩ) on the right (I=100mA/div, τ=20ns/div).

The reverse recovery time dependences with all used values of condensers and resistors shown on Fig. 8 and 9.

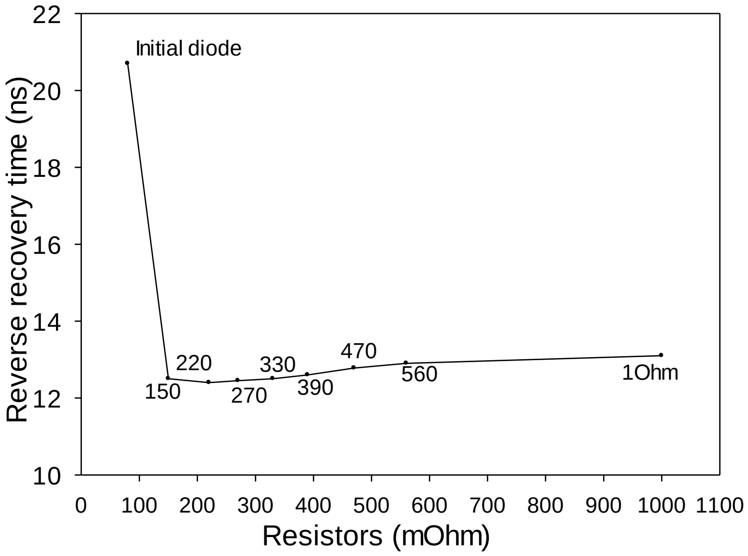

Fig. 8. Reverse recovery time dependence on the initial diode and different values of resistors connected to the diode one by one.

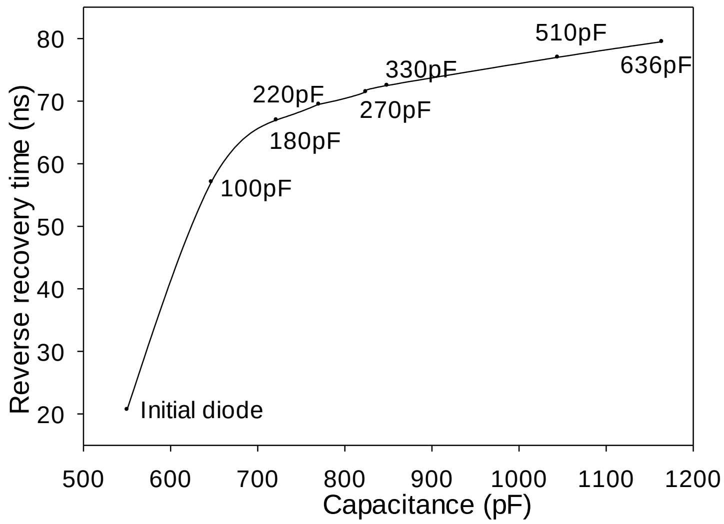

Fig. 9. Reverse recovery time dependence on different values of condensers connected to the diode one by one.

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).

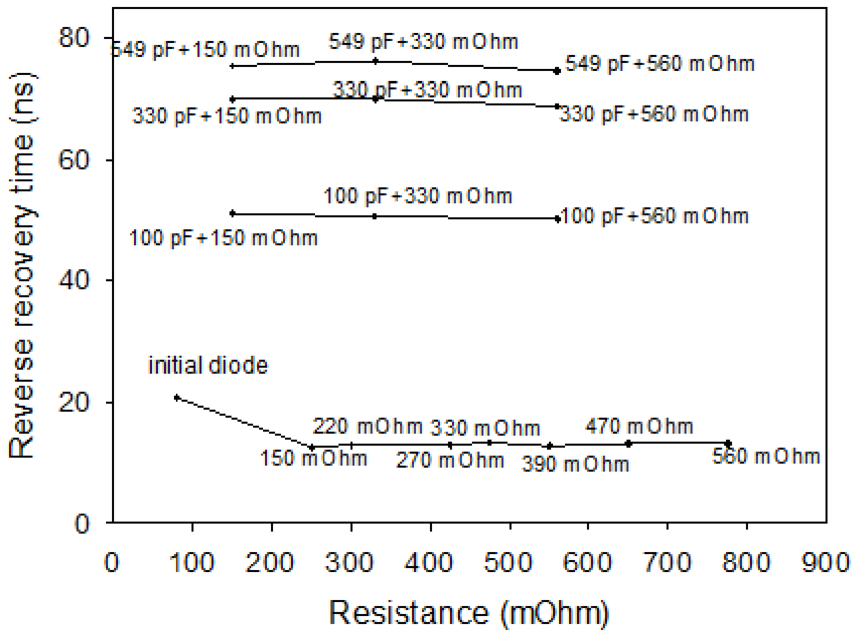

Fig. 10. Reverse recovery time dependence on combined resistors and condensers.

The idea of carrying out the work presented in this publication appeared during the research of the degradation of 600 V, 4H-SiC Schottky diodes under irradiation with 0.9 MeV 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 (Eq. 2):

$$\tau_M = \rho\varepsilon\varepsilon_0 \qquad (2)$$

where ρ is the resistivity, ε the dielectric constant, and ε_0 the electric constant. Rewriting the expression as $\tau_M = R_sC_0\ \varepsilon\ \varepsilon_0$, 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_sC_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 > 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 Fig. 1, 6, 7).

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.

ACKNOWLEDGEMENT

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