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CHARACTERIZATION OF SIC POWER SCHOTTKY BARRIER DIODE AND MERGED PIN SCHOTTKY DIODE IN SPICE MODEL

Master's thesis

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SIC VÕIMSUSE SCHOTTKY TÕKKE DIOODI JA ÜHENDATUD PIN SCHOTTKY DIOODI ISELOOMUSTUS SPICE MUDELIS

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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 cited. This thesis has not been presented for examination anywhere else.

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Abstract

Power diodes plays an important role in the power electronics applications. An efficient power diode should have better performance with high power density, large power handling capability, and a wide range of operating temperatures. The compact model in the circuit simulator can fulfill the improvement of power diodes functional capabilities. In this thesis, commercial simulation software (LTSpice) is utilized on two power diodes made by Silicon carbide (SiC) material. Simulated diode models of Schottky barrier diode (SBD) and Merged PiN Schottky diode (MPSD), and their Current-Voltage (I-V), reverse breakdown, reverse recovery, and first reverse recovery characteristics are discussed for dependent temperature, voltage, current, switching frequency, and time delay. These SBD and MPSD results are compared and discussed briefly in their static and transient characteristics. This circuit level study can be implemented for a real SiC based experimental SBD and MPSD development.

This thesis is written in English and is 43 pages long, including 7 chapters, 35 figures and 7 tables.

Annotatsioon

SiC võimsuse Schottky tõkke dioodi ja ühendatud PiN Schottky dioodi iseloomustus Spice mudelis

Lõputöö on kirjutatud Inglise keeles ning sisaldab teksti 43 leheküljel, 7 peatükki, 35 joonist, 7 tabelit.

List of abbreviations and terms

SiC	Silicon Carbide
SBD	Schottky Barrier Diode
MPSD	Merged PiN Schottky Diode
JBS	Junction Barrier Schottky
t_{rr}/trr	Reverse Recovery Time
SPICE	Simulation Program with Integrated Circuit Emphasis
HV	High Voltage
MS	Metal-Semiconductor
IC	Integrated Circuit
V_F	Forward Voltage
FOM	Figure of Merit
I-V	Current-Voltage
JFET	Junction Field Effect Transistor
MOSFET	Metal Oxid Semiconductor Field Effect Transistor

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1 Introduction

1.1 General Overview

Designing a power diode is very important for high power and high voltage electronic circuit. Two most efficient types of power diodes are Schottky barrier diode (SBD) and Merged PiN Schottky diode (MPSD) diode [1]. Silicon Carbide (SiC) power devices are the most promising semiconductor devices mainly for high power applications, with high heat resistance, excellent thermal properties and effective performance at high switching frequencies and power levels [2]. So, developing SiC based Schottky barrier diode (SBD) and Merged PiN Schottky diode (MPSD) are usual demand that can withstand several thousand volts and high temperature with reasonably low turn-on resistance. This type of diodes based on Silicon Carbide (SiC) are available in the market, but their simulation models in Spice are not commercially available in user level [3]. In order to appropriate development of both devices based on SiC, it is necessary to characterize the device for better understanding about their behavior. Care must be taken to analyze their characteristics in easy and convenient way.

1.2 Background

The needs of an electronic power diode, which can operate in harsh environments is increased specially for applies as drilling, electrical vehicle, electrical aircraft, space prob etc. For answering of this problematic, we have considered the development of an integrated circuit technology in Silicon Carbide (SiC). The property of this material (SiC) allows surpassing the physical limits of the current solutions (working in high temperature, improving of the electrical yield thanks to the decrease of the electrical losses, increasing of the working frequency, weight reduction etc.) [4]. To serve high power applications, SBD and MPSD are shows better performance and efficiency compare to other types of power diodes. Nowadays, the SBD and MPS diodes are the most widely used and provide a better adjustment between the forward voltage drops and reverse bias leakage current, following a voltage drop at the junction level [5].

1.3 Problem Statement

Efficient device simulation models are required to evaluate the performance of SiC SBD and MPS diodes in different applications and guide system design. Although several models have been developed for these diodes, most of them are based on device physics or based on experiments [4]. For the former, usually several 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 reliable models of SiC Schottky power diodes specialized for system modeling [6].

1.4 Motivation

SiC power devices show better performance compared to devices made with other semiconductors such as Silicon, Germanium, Gallium arsenide, gallium nitride etc. This is primarily because SiC has an order of magnitude higher breakdown electric field (V/cm) to (V/cm) and higher temperature capability than conventional Si materials. The higher breakdown electric field allows the design of SiC power devices with thinner (0.1 times that of silicon devices) and more highly doped (more than 10 times higher) voltage-blocking layers [7].

Almost all circuit simulators contain library parts for various commercially available silicon (Si) devices, but there has yet to be a commercially available silicon carbide (SiC) device library component [8]. This is largely because SiC devices are just beginning to emerge. The first generation of these new SiC devices includes Schottky, PiN, Merged PiN Schottky (MPS) power diodes. These devices have been compared to similarly rated silicon devices and proved to provide significant performance advantages for on-state characteristics, reverse recovery characteristics, temperature dependence, power converter efficiency etc. [9]. Although several macro-models of these diodes have been proposed in Spice, they are rather complex, unlike the proposed model which is quite simple, flexible and very much practical [10].

1.5 Objective of The Study

- Electrical properties of SBD and MPS diode for SiC material
- Device microcircuit model implemented by using these electrical properties in LTspice simulation software
- Circuit model for detecting the static and transient behavior of both diodes
- Observation and comparison of their characteristics

1.6 Thesis Outline

In the next chapter, the physical properties, crystal structure, and few applications of silicon carbide will be discussed briefly. Third chapter will illustrate the cross-section construction of SBD, PiN, and MPSD with their I-V and transient characteristics. Furthermore, it also discusses several pros and cons between SBD and MPSD and few possible applications where they may use. Chapter four based on spice modeling of both diodes includes familiarization with simulation software, diode model specification, syntax of diode in LTSpice, and parameter extraction. Simulation model and results of static characteristics of SBD and MPSD was discussed in the following chapter. Observing I-V characteristic, forward conduction, reverse conduction, reverse breakdown for different condition was the main content of that chapter. Transient characteristics and the circuit model for simulation of each behavior was discussed in chapter 6. The transient behavior was measured for two different categories such that, high speed switching transient and fast reverse recovery. The most important characteristics of diode which is reverse recovery time also contain in this section. Finally, the last chapter cover the summary of the thesis following with references.

1.7 Scope of Work

This simulation profile in SPICE will provide an open platform for an anonymous user who interested to work with related study. LTSpice is a freeware open source analog simulation software which gives the user access with more freedom.

1.8 Challenges

Table 1. Encountered challenges in according to different phases of thesis.

Task Name	Challenges
State of Art and Literature survey	• Less research for this field • Hard to find similar kind of work
Physical model & macro model	• Less common platform with the literature • Unclear models in the previous works
Characterization of the device	• Identifying parameters is a complex mathematical term • Unknown behavior of the material

2 Silicon Carbide Material Properties

2.1 Introduction

The technology of producing Si power devices has practically reached its physical limits [11]. There is very little room for new developments in this field. SiC has many advantages over Si. SiC properties make it suitable to use the material in high temperature, high power, high frequency, and radiant resistant applications, where Si starts to fail. There are semiconductor materials like GaAs, AlN, GaN, BN, diamond, ZnSn with good properties for above applications. Still, SiC has the widest use in named applications because of several advantages. Most important of them is the fact that the technology of producing SiC semiconductor devices is close to well-known Si technology [12]. About 30 years ago, the GaAs were thought of as universal future semiconductor material. Nowadays it has found only a small part of a wide semiconductor materials market. Compared to GaAs, SiC has higher thermal conductivity than GaAs and wide band gap then it, which makes SiC more promising in high power applications, but also in high packaging density integrated circuits and other applications.

However, there are still many technological problems in taking SiC technology into wider use. The quality of the crystal is not good enough, the quality of native oxide SiO is poor, etching is difficult because of the inertness of SiC to chemical reactions, the diffusion process is unusable because of high temperatures needed, high-temperature contacts are to be developed to use the ability of SiC to work on high temperatures. Because of high electric field strength in SiC Schottky diode, the junction termination and passivation issues are very important [13]. There are many problems to solve like it mostly is with new technologies. The knowledge that SiC can be used as a semiconductor material for electronics purpose is not new. In fact, SiC crystals were grown already in 1893 by Acheson and a light emitting diode in SiC was produced in 1907 by Round [14].

2.2 Properties

Silicon carbide is a semiconductor with a wide, indirect bandgap. With the chemical composition of SiC, it is the only stable compound in the binary phase diagram of the two group IV elements, silicon, and carbon. The thermal stability of SiC is about 2000°C even with in oxidizing and aggressive environments [15].

As seen from formula (1) of Johnson's Figure of Merit which is for high frequency and high-power applications, it depends on break down electric field strength and electron saturation velocity, and therefore can be described as: how fast and how high electrical fields strength can a device from this semiconductor material possibly drive [18].

$$\mathrm{JMF} = \frac{E_B^2 v_s^2}{4\pi^2} \tag{1}$$

E_B - break down electric field strength,

V_s - electron saturation velocity.

If we compare the JMF of SiC and Si, then SiC looks about 281 times better than Si. Of course, this is the case only if technologies of both materials could be able to make devices near the edge of physical limits. This is almost true for Si, but long away for SiC. Still, there are already many SiC devices with better characteristics than physical limits allow producing from Si. The Keyes' Figure of Merit is mostly for integrated circuit application, where high-density packaging and working frequencies are important [17]. As seen from formula (2), this figure of merit depends on thermal conductivity and electron saturation velocity. The thermal conductivity of material takes into account how dense can packaging be without overheating and electron saturation velocity takes into account how fast can circuit be.

$$\mathrm{KMF} = \kappa\sqrt{\frac{c v_s}{4\pi\varepsilon_0\varepsilon_r}} \tag{2}$$

κ - thermal conductivity

c - velocity of light

ε_0 - dielectric constant of vacuum

ε_r - relative dielectric permittivity of semiconductor

According to Keye's FOM, SiC is 6.5 times better than Si.

Electron and hole mobility are parameters, which affect the high frequency performance, transconductance, and other important device parameters. The low and anisotropic electron mobility of 6H-SiC is one of the primary reasons for the growing popularity of 4H-SiC. The mobility of electrons in perpendicular to the c axis is about 1.25 times lower than in parallel to the c axis in 4H-SiC and 4.8 times higher in 6H-SiC at 300K. Also, other parameters vary widely on different polytypes.

Table 2. Physical parameters of common semiconductors at room temperature in comparison to silicon carbide [17].

Property	**Ge**	**Si**	**GaAs**	**3C-Sic**	**6H-SiC**	**4H-SiC**	**GaN**
Band gap E_g (eV)	0.66	1.12	1.43	2.4	3.0	3.2	3.4
Crit. Field Ec (MV/cm)	0.1	0.25	0.3	2.0	2.5	2.2	3.3
Mobility μ_n (cm^2/Vs)	3900	1350	8500	1000	500	1000	1000
μ_p (cm^2/Vs)	1900	480	400	40	80	120	30
Intrinsic conc. N_i (cm^{-3})	10^{13}	10^{10}	10^{6}	10^{1}	10^{-6}	10^{-8}	10^{-9}
Permittivity ε_r	16.0	11.9	13.1	9.7	10.0	10.0	~10
therm.conduct. κ (W/cm K)	1.6	1.5	0.46	≳ 3.5	≳ 3.5	≳ 3.5	≳ 1.6
Density ρ (g/cm^3)	5.3	2.3	5.3	3.2	3.2	3.2	6.1
lattice	cubic	cubic	cubic	cubic	hexag.	hexag.	hexag.
lattice const. α (Å)	5.65	5.43	5.65	4.36	3.08	3.08	3.19
c (Å)	–	–	–	–	15.12	10.08	5.19

All the above properties discussed before and in the table 2 make SiC a very good solution for outer space conditions. Out of all the wide bandgap semiconductors, silicon carbide is presently the most intensively studied one and the one with the highest potential to reach market maturity in a wide field of device applications.

2.3 Crystal Structure of SiC

3C - is the cubic structure with the stacking sequence ABC as shown in figure 1 (a).

4H - is a hexagonal symmetry and the stacking sequence ABAC, this is the currently most intensively studied polytype for power electronic devices. On a microscopic scale it shows 50% cubic and 50% hexagonal lattice sites as shown in figure 1 (b).

6H - ABCACB is the stacking sequence of the first silicon carbide polytype, which was available in the form of single-crystalline wafers. Compared to the 4H polytype, 6H silicon carbide shows a more pronounced anisotropy of its material parameters. The crystal lattice contains 2/3 cubic and 1/3 hexagonal sites as shown in figure 1 (c).

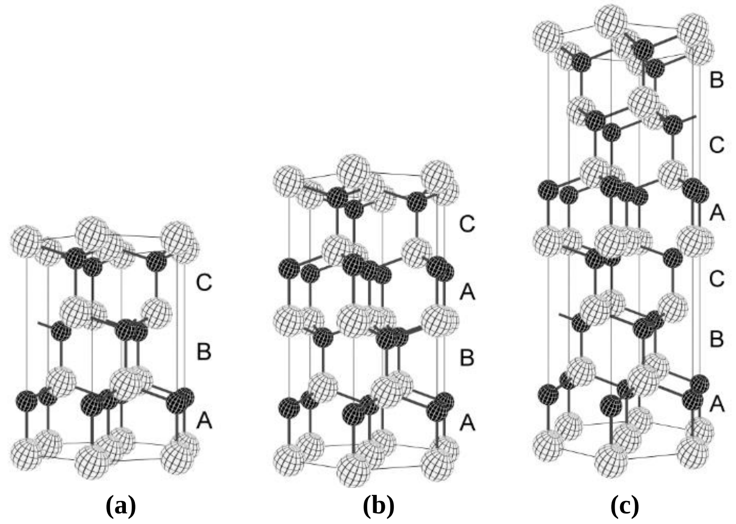


Figure 1. Stereogram pairs showing the crystal lattice of (a) 3C silicon carbide, (b) 4H silicon carbide, (c) 6H silicon carbide [17].

2.4 Applications of SiC

Nowadays SiC is mostly used for many applications. Some common device where SiC may use as a material semiconductor as shown below-

- Powerful microwave electronics for radar and communications [18]
- The sensors and controls for jet aircraft and automobile engines [19]
- Ultraviolet sensitive photodiodes and high temperature JFET's [20]
- SiC power MOSFET's and diode rectifiers

Due to the good thermal properties of SiC devices, some day it may be cheaper to use it even on everyday high-speed logic chips like microprocessors. Higher working temperatures and better thermal conduction make cooling easier. Cooling can be sometimes extremely expensive. One breakthrough in computer technology could be the dynamic memories of SiC. The bandgap of SiC is so wide, that charges put into microscopic SiC device at room temperature, can be read after 100 years. In computer technology, this means ultra-fast and very reliable hard disks without mechanical parts [21].

2.5 SiC Material Processing

Unlike many other semiconductor materials of technological interest, silicon carbide does not show a liquid phase. There is only one way is to synthesize, purify and grow silicon carbide raw material for device processing is by means of gaseous phases. Under firm growth conditions, larger single crystalline platelets of silicon carbide can be found in cavities and at the outer surface of the synthesized material. The raw material of silicon carbide can also be produced by pyrolysis of silica-rich plants and agricultural waste products [22]. From raw to fabrication ready material there are two steps of processing require which is creating substrate and doping.

For subtracting, the monocrystals of SiC are typically grow using technologies based on the adapted Lely process. In this process SiC vapors sublimate from higher temperature (2400 K) polycrystalline source and condense on lower temperature (2200 K) crystal seed. As a result, a single polytype monocrystal were created. Growth rates of this technology are about few millimeters per hour [19].

For doping there are mostly two methods are used in SiC device: epitaxially controlled doping and hot ion implantation. The Diffusion method is not possible because of extreme temperatures (over 1800 ˚C) needed to overcome high bond strength in SiC. In epitaxially controlled doping, the depth of doping is controlled from 10^{19} cm^{-3} to 10^{14} cm^{-3} with varying Si and C source gases: silane and propane correspondingly. On the other hand, Ion implantation is broadly used because of the absence of a usable diffusion procedure. The implantation is conducted on high temperatures (over 700 ˚C) to avoid the amorphization of SiC. Annealing at 1100 ˚C to 1650 ˚C is also essential after implantation for activating dopants. Ion implantation is used to do selective doping [17].

2.6 Device Fabrication

Different from silicon technology, where the cut and the polished wafer surface is the starting point for device processing, silicon carbide components are often fabricated on the as-grown surface after epitaxial growth [23]. SiC fabrication also have to follow the same steps as Si fabrication which includes etching, Oxidation, Ohmic contract, and Schottky contract.

2.7 Conclusion

There are some possibilities for the rapid development of SiC technology for semiconductor devices:

- Si technology tend to its physical limits
- New technologies are desirable for several applications
- SiC technology is close enough to Si for starting

There are some drawbacks, which are holding down the speed of migration from Si to SiC. Resolving those problems seems to be a matter of time:

- Quality of bulk SiC
- Technology for managing with chemically inert SiC
- Forward degradation

3 SBD and MPSD Structural Difference and Characteristics

As a two-terminal switching device, the power diode is considered to have a simple device structure compared with MOSFET and IGBT. Generally speaking, there are three classes of power diodes: firstly Schottky diodes, which offer extremely high switching speed but suffer from high leakage current and high drift region resistance; secondly PiN diodes, which offer low leakage current but suffer from low switching speed; and finally Merged PiN Schottky (MPS) diodes / Junction Barrier Schottky (JBS), which offer Schottky-like on-state while working in the JBS mode and PiN-like on-state while working in the MPS mode and fast switching characteristics, and PiN-like off-state characteristics [24].

3.1 Schottky Barrier Diode

Power Schottky diode is also interpreted as metal-semiconductor (MS) diode as seen from Figure 2. An ideal MS contact has the properties of: (1) The metal and semiconductor are assumed to be in intimate contact on an atomic scale; (2) No inter-diffusion or intermixing between metal and semiconductor; and (3) No impurities or extra surface charges at the MS interface [25]. In this sub-section, the detailed description will be presented for both static and transient characteristics including the forward conduction characteristic, the reverse blocking characteristic, the capacitance-voltage characteristic, and the reverse recovery characteristic.

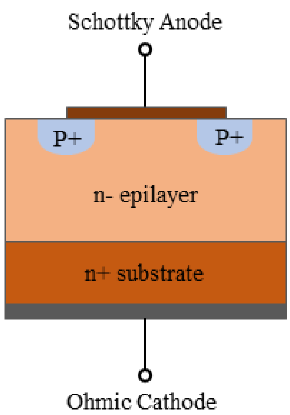


Figure 2. Structure of Schottky Barrier Diode [29].

3.1.1 I-V Characteristics

In the case of moderately or low doped semiconductors the current transport through the Schottky junction is dominated by emission of majority carriers over the potential barrier from the semiconductor into the metal contact [18]. If the Schottky barrier is significantly higher than the thermal energy $q\Phi B \gg k_B T$, the thermionic emission-diffusion theory describes the current-voltage characteristic of the Schottky junction as

$$I = I_0\left(e^{qV/nk_BT} - 1\right) \quad (3)$$

Where I_0 – the saturation current, [A]; T – the absolute temperature, [K]; V – the voltage, [V]; q – the elementary charge, [C]; k_B – Boltzmann constant, [J/K]; n – the Schottky diode ideality factor [14].

The thermionic emission-diffusion theory predicts a constant leakage current density for a reverse biased Schottky diode of the same size as the saturation current density [18].

$$I = -I_0 = -A^* T^2 e^{-qV/nk_BT} \quad (4)$$

Where A* – the effective Richardson constant.

Figure 3 shows a typical current and voltage characteristic for both forward and reverse operation of Schottky Barrier Diode.

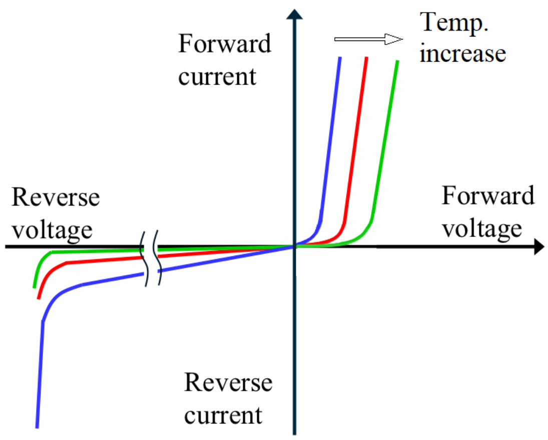


Figure 3. Current voltage characteristics of Schottky Barrier Diode [28].

3.1.2 Transient Characteristics

Because Schottky diodes are majority carrier devices, these devices exhibit extremely fast reverse recovery speed. However, the fast turn-off with high di/dt and dv/dt will cause severe ringing's in the current and voltage waveforms due to the parasitic inductance and capacitance [17].

3.2 PiN Diode

The power PiN diode was one of the earliest power devices developed for power circuit application. Differ from a p-n junction diode; there is an intrinsic layer (usually lightly doped N-type semiconductor) in between, which offers the capability of high voltage blocking. As a minority carrier device, under forward conduction, holes will be injected into the n- epilayer as illustrated in Figure 4 which is called conduction modulation. Due to this, the resistance of the i-region becomes very small allowing these devices to carry a high current density during the forward conduction. However, there are two major drawbacks of PiN diodes that need to be stated out. First, when device is turned on with a high di/dt, there is a voltage overshoot which is called forward recovery. This overshoot comes from the initial high resistance in i-region before the conduction modulation. The second drawback is its poor reverse recovery characteristics during turn-off caused by the minority carriers that injected into the i-region. Two major mechanisms employed to get rid of the minority carriers in the i-region are electric field sweep-out and recombination.

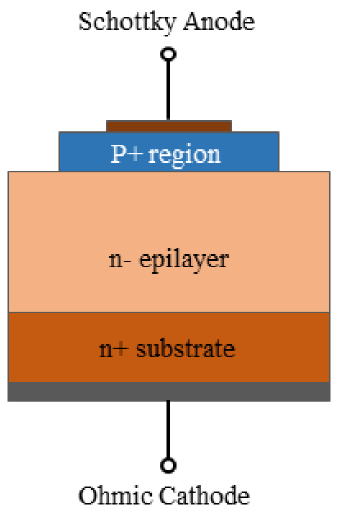


Figure 4. Structure of PiN Diode [29].

3.2.1 I-V Characteristics

The physics of the forward conduction of PiN diode is more complicated than the one used for Schottky diode. The nature of the current-voltage (I-V) characteristic depends strongly upon the current level, which are Recombination current, Low-Level Injection current, High level Injection current, Emitter recombination current and Series resistance region [25]. At very low current levels, the current flow in the PiN diode is mostly generation and recombination in the depletion region about the P-I junction due to the presence of recombination centers. The forward current density due to recombination in the depletion region is

$$I_{DR} = \frac{qn_iW_D}{2\tau_{SC}}\left(e^{qV/2k_BT} - 1\right) \quad (5)$$

Where, W_D is the depletion layer width.

In equation (5) the quantity $\frac{qn_iW_D}{2\tau_{SC}}$ is defined as the saturation current density, and when multiplied by the device area becomes the saturation current.

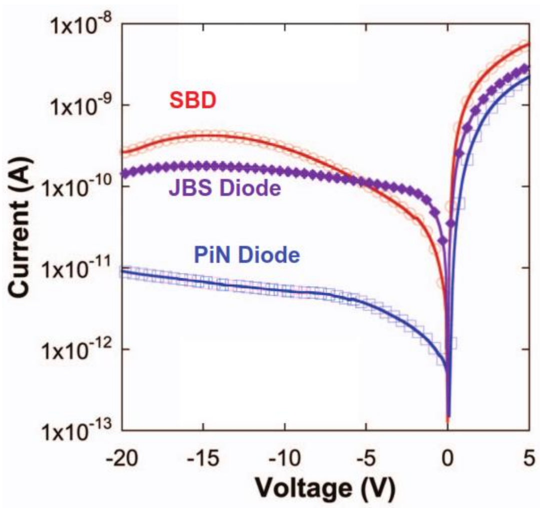


Figure 5. Forward and reverse I-V characteristics of a SBD, PiN diode, and MPS diode [19].

The power PiN diode is designed to be used in high voltage rating application. The capability of voltage blocking depends on the doping profile and the thickness of the drift region. Differ from the Schottky diodes, power PiN diodes offer much lower reverse leakage current. In Figure 5 a comparison between SBD, PiN diode, and MPS diode for forward I-V characteristics is shown [29].

3.2.2 Transient Characteristics

When the diode is forward biased, the excess carrier concentration builds up. Hence, when the device is turned off, the excess carrier must be removed before the junction goes to the blocking mode. The process of removing excess charge from the base and the resulting ability of the diode to block voltage is known as the reverse recovery phenomenon. The process consists of the sweeping out of stored charge due to the electric field, the diffusion of stored charge out of the base, and the recombination of stored charge. Once the junction can block voltage, the voltage begins to rise across the diode as the remaining stored charge decays [29].

3.3 Merged PiN Schottky (MPS) Diode

The structure of MPS diodes combines Schottky and PiN diodes as illustrated in Figure 6 with p-well embedded in the n- epilayer. An MPS diode consists of inter-digitated Schottky and p+ implanted areas. For on-state voltage drops less than 3V, only the Schottky regions of the diode conduct and thus the device is also referred to as a Junction Barrier Schottky (JBS) diode [29].

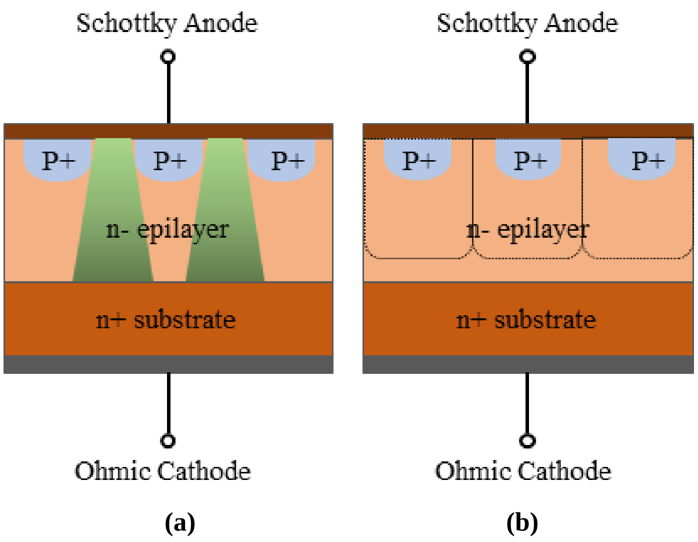


Figure 6. Structure of MPS Diode under (a) forward bias; (b) reverse bias [29].

3.3.1 I-V Characteristics

Under forward bias, there are two operation modes JBS and MPS which is determined by the forward bias voltage level. When the bias voltage is not high enough to turn on the inherent PiN diode, only the Schottky-part is conducting as shown in Figure 6 (a). As the bias increases, minority carriers start to be injected into n-layer from p-well to modulate the conductance in the epilayer. This type of operation is referred to as the MPS mode.

Under reverse bias, the depletion region starts to expand in order to support the blocking voltage as shown in Figure 6 (b). As seen from Figure 6 (b), the depletion layers will intersect under the Schottky barrier when the reverse bias exceeds a certain level, which is called pinch-off. After depletion layer pinch-off, further increase in applied voltage is supported by it with the depletion layer extending toward the n+ substrate, and the potential barrier shields the Schottky barrier from the applied voltage. This shielding prevents the Schottky barrier lowering phenomenon and eliminates the large increase in leakage current observed for conventional Schottky diodes. Ideally, once the pinch-off condition is established, the leakage current remains constant. Due to the suppressed leakage current, the Schottky barrier height used in the MPS diode can be significantly less than for the conventional Schottky diodes [29].

3.3.2 Transient Characteristics

As current flows through Schottky area, there is no significant minority carrier charge store and no need to discharge it. The switching speed may be slower on high forward currents because of the same minority carrier charge, which builds up also in MPS devices in case of high forward currents [29].

3.4 Pros and Cons of the SiC SBD and MPS Diode

Although SiC semiconductor-based diodes have many advantages over other type of semiconductor devices, but they also have several drawbacks. Table 3 will comprise the pros and cons of SiC SBD and MPSD with others.

Table 3. Advantages and disadvantages of SBD and MPSD [1][2][3][4].

Si		**SiC**		**GaN**	
(SBD)	**(MPSD)**	**(SBD)**	**(MPSD)**	**(SBD)**	**(MPSD)**
Advantage 1. Fast Switching speed 2. Low FB voltage drop 3. Efficient for particular applications 4. Low cost	**Advantage** -*	**Advantage** 1. Low trr 2. Low peak reverse current 3. High frequency enable 4. Low junction capacitance	**Advantage** 1. High thermal stability 2. Very small trr 3. Low static loss 4. Less space on wafer	**Advantage** 1. High blocking voltage 2. Low switching loss 3. Long minority carrier lifetime	**Advantage** -*
Disadvantage 1. High reverse leakage current 2. Less thermal stability.	**Disadvantage** -*	**Disadvantage** 1. Increase of static forward voltage drop over time	**Disadvantage** 1. Relatively smaller life span because of stacking faults	**Disadvantage** 1. Nonoptimal material quality 2. Low theoretical performance	**Disadvantage** -*

Note: '-*' no MPSD data are available for that corresponding material.

3.5 Applications of the SiC SBD and MPS Diode

Power SBD and MPS diode has many applications, these applications involve mostly power converters [31], i.e., power electronics devices whose function is to change the magnitude and/or shape of an input signal. Some of them could be -

- Power converter (HV applications)
- Feedback diode for power inverter
- Clamp of a power/ground rail voltage [32]

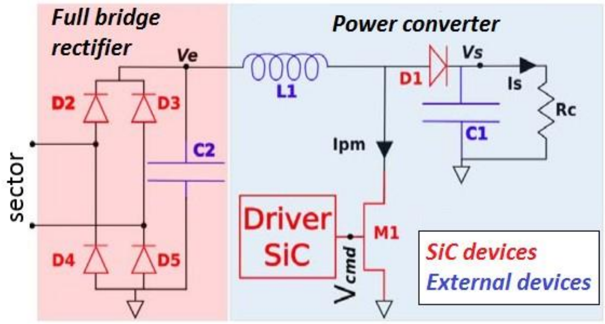


Figure 7. Electrical schematic of the considered AC/DC demonstrator with a full bridge rectifier and a boost converter [30].

The considered demonstrator of implementation of SiC SBD or MPSD is presented in Figure 7. It is an AC/DC converter with a full-bridge rectifier for the first stage and a boost topology for the stage of the power converter. The driver would be integrated on the same SiC cheap than the power devices M1 (power MOSFET) and D1 (power diode). The diodes of the full bridge rectifier (D2, D3, D4 and D5) will be integrated too on the same substrate than the previous devices [30].

4. Spice Modelling of the Diodes and Parameters Selection

4.1 Introduction

Accurate simulation of all devices in a complete design is an important step in understanding the final product. One of the most common software tools used for analog circuit simulation is SPICE (Simulation Program with Integrated Circuit Emphasis). Many software companies including Cadence, Ansoft, Mentor, and Synopsys specialize in creating such software. There is some manufacturer company like Infineon Technologies, Analog Devices, and Texas Instruments also have SPICE software for their users as proprietary licenses (freeware) basis. LTspice from Analog Devices one of the well-known and user-friendly platforms for users.

4.2 Familiarization with LTspice

LTspice is freeware computer software implementing a SPICE electronic circuit simulator, produced by semiconductor manufacturer Linear Technology, now part of Analog Devices. It is used in-house at Linear Technology for IC design, and the most widely distributed and used SPICE program in the industry. LTspice is not artificially crippled to limit its capabilities (no node limits, no component limits, no subcircuit limits) [34].

LTspice provides schematic capture to enter an electronic schematic for an electronic circuit, an enhanced SPICE type analog electronic circuit simulator, and a waveform viewer to show the results of the simulation. Circuit simulation analysis based on transient, noise, AC, DC, DC transfer function, DC operating point can be performed and plotted as well as Fourier analysis. Heat dissipation of components can be calculated, and efficiency reports can also be generated [34].

4.3 Diode Model Specification

A diode requires a `.model` card to specify its characteristics. There are two types of diodes available. One is a conduction region-wise linear model that yields a computationally light weight representation of an idealized diode. The other model available is the standard Berkeley SPICE semiconductor diode but extended to handle more detailed breakdown behavior and recombination current. The area factor determines the number of equivalent parallel devices of a specified model. Table 4 shows the diode model parameters [35].

Table 4. Diode model specifications [35].

Name	Description	Units	Default	Example
Is	saturation current	A	1e-14	1e-7
Rs	Ohmic resistance	Ω	0	10
N	Emission coefficient	-	1	1
Tt	Transit-time	sec	0	2n
Cjo	Zero-bias junction cap.	F	0	2p
Vj	Junction potential	V	1	0.6
M	Grading coefficient	-	0.5	0.5
Eg	Activation energy	eV	1.11	1.11-Si, 0.69-Sbd, 0.67-Ge
Xti	Sat.-current temp. exp	-	3	3-jn, 2-Sbd
Kf	Flicker noise coeff.	-	0	
Af	Flicker noise exponent	1	1	
Fc	Coeff. for forward-bias depletion capacitance formula	-	0.5	
BV	Reverse breakdown voltage	V	Infin.	40
Ibv	Current at breakdown voltage	A	1e-10	
Tnom	Parameter measurement temp.	ºC	27	50
Isr	Recombination current parameter	A	0	
Nr	Isr emission coeff.	-	2	
Ikf	High-injection knee current	A	Infin.	
Tikf	Linear Ikf temp coeff.	/ºC	0	
Trs1	linear Rs temp coeff.	/ºC	0	
Trs2	Quadratic Rs temp coeff.	/ºC/ºC	0	

4.4 Parameter Extractions

The maintained parameters collected from the different sources articles as well as from different datasheets. Table 5 shows values for all necessary parameters for both the diode models.

Table 5. Diode perimeter values for each model [2] [12] [18] [38] [39].

Name	Description	Units	SBD	MPSD
Is	saturation current	A	2e-8	4.6e-11
Rs	Ohmic resistance	Ω	1	1.85
N	Emission coefficient	-	2	1
Tt	Transit-time	sec	3e-9	2e-9
Cjo	Zero-bias junction cap.	F	35e-12	30e-12
Vj	Junction potential	V	1.2	1.2
M	Grading coefficient	-	0.333	0.5
Eg	Activation energy	eV	0.2	1.6
Xti	Sat.-current temp. exp	-	2	11.1
Kf	Flicker noise coeff.	-	N/A	N/A
Af	Flicker noise exponent	1	N/A	N/A
Fc	Coeff. for forward-bias depletion capacitance formula	-	0.6	0.5
BV	Reverse breakdown voltage	V	47	65
Ibv	Current at breakdown voltage	A	5u	6u
Tnom	Parameter measurement temp.	ºC	27-327	27-327
Isr	Recombination current parameter	A	4e-18	2.26e-13
Nr	Isr emission coeff.	-	2	1
Ikf	High-injection knee current	A	N/A	N/A
Tikf	Linear Ikf temp coeff.	/ºC	N/A	N/A
Trs1	linear Rs temp coeff.	/ºC	-3mV	1.45e-3
Trs2	Quadratic Rs temp coeff.	/ºC/ºC	N/A	46.7e-6

4.5 Diode Models

A diode requires a `.model` card to specify its characteristics for simulation in LTSpice. The syntax of the diode as follow [35] –

```
Symbol Names: DIODE, ZENER, SCHOTTKY, VARACTOR.

Syntax: Dnnn anode cathode <model> [area]
+ [off] [m=<val>] [n=<val>] [temp=<value>]

Examples:

D1 SW OUT MyIdealDiode
.model MyIdealDiode D(Ron=.1 Roff=1Meg Vfwd=.4)

D2 SW OUT dio2
.model dio2 D(Is=1e-10)
```

Now, values from the table 5, need to put according to specific syntax for diode.

Model for the SBD:

```
.MODEL SIC1R234A D(is=2e-8 rs=1 cjo=35e-12 vj=1.2 eg=0.2 fc=0.6 bv=47
ibv=5u isr=4e-18 nr=2
+ n=2 tt=3e-9 m=0.5 xti=2 tnom=27 trs1=-3mV)
```

Model for the MPSD:

```
.MODEL SIC1R234A D(is=4.6e-11 rs=1.85 cjo=30e-12 vj=1.2 eg=1.6 fc=0.5
bv=65 ibv=6u isr=4.26e-13 nr=1
+ n=1 m=0.5  tt=2e-9  xti=11.1 tnom=27 trs1=1.45e-3 trs2=46.7e-6)
```

4.6 Diode Full Micromodel's

A macromodel is a simplified circuit model that typically includes just a handful of "real" elements, but mainly consists of dependent and independent voltage and current sources. Macromodels are not full transistor level models. For many applications, SPICE simulations using macromodels will provide a good (not exact) first-order approximation to real circuit performance. This is especially true when dealing with high-speed applications. The micromodels for simulating diode's behavior were placed with their appropriate simulation results in the following two chapters.

5 Simulation of Static Characteristics

5.1 Introduction

Characterization is very important for a device before using it in any application. It gives a fundamental concept of how it behaves in practice. The static characteristics mainly show the current flowing conditions and directions with respect to applied voltage across it. This chapter will discuss the static characteristics of both SBD and MPSD in different dependent variables.

5.2 I-V Characteristics

One of the most significant characteristics of a diode is the current-voltage (I-V) relationship. From that relationship curve, we know how the current flowing through the device and what potential difference is responsible behind this. As a simple example, the current through the resistors is linear to the voltage across it according to Ohm's Law. On the other hand, a diode has a completely non-linear I-V relationship.

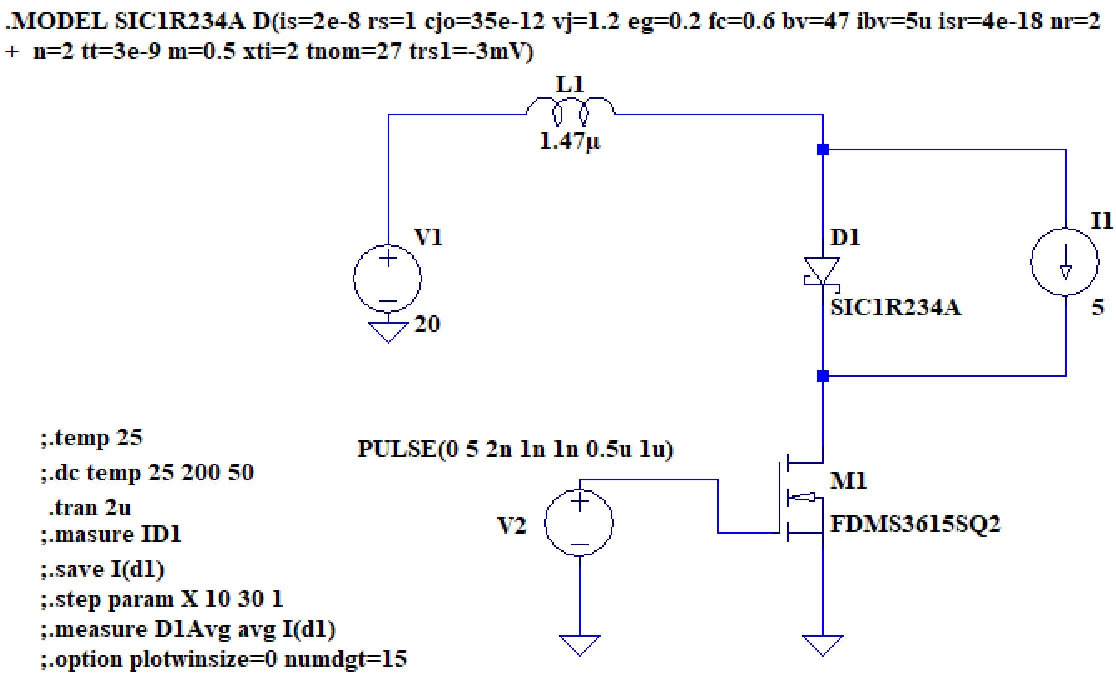


Figure 8. Circuit model for V-I characteristics determination [5].

The circuit configuration in figure 8 is for extracting the current-voltage characteristics of the diodes for both forward and reverse bias operations. In this circuit, there is one independent voltage source connected with the diode through an inductor in series. An independent current source is used parallel with diode to provide boost configuration to reach the peak point of the applied voltage. The pulse generator also called time-dependent pulsed voltage source is driving the NMOS which is acting as a switch. It is configurable with any desired values. The syntax of the pulse generator is-

```
Syntax: PULSE(Voff Von Tdelay Tr Tf Ton Tperiod Ncycles )
```

The elaboration of each variable is shown in table 6. In the circuit, the value of V2 is PULSE(0 5 2n 1n 1n 0.5u 1u) which means it is a square wave with 5V amplitude, 2nS delay, 1ns rise and fall time, 1MHz frequency, and it is a free-running pulse. Another directive called `.tran 2u` means, it is a transient time simulation and carried out for 2 microseconds. Before semicolon (;) of any directive means it is disabled for the simulation.

Table 6. Elaboration of each variables for time-dependent pulsed voltage source.

Name	**Description**	**Units**
Voff	Initial value	V
Von	Pulsed value	V
Tdelay	Delay	sec
Tr	Rise time	sec
Tf	Fall time	sec
Ton	On time	sec
Tperiod	Period	sec
Ncycles	Number of cycles(undeclared for infinite cycle)	cycles

Figure 9 shows the I-V characteristics curve of SBD and MPSD at different temperatures. From this following comparison in figure 9, is shown that MPSD has more temperature dependency then SBD. The sensitive points will be shown later in the forward bias and reverse bias section.

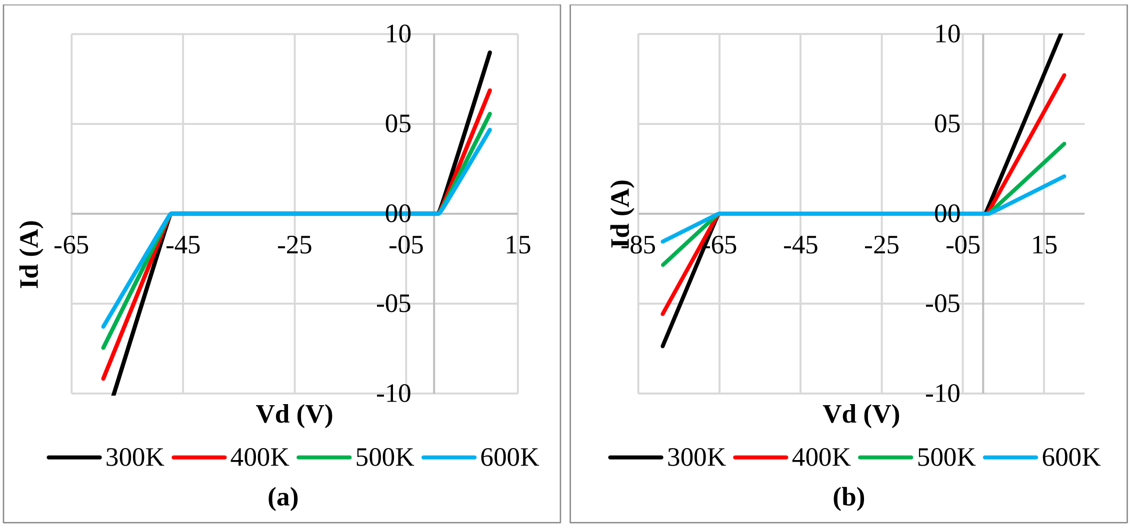


Figure 9. I-V characteristics curve of (a) SBD and (b) MPSD at different temperature for 20V supply voltage.

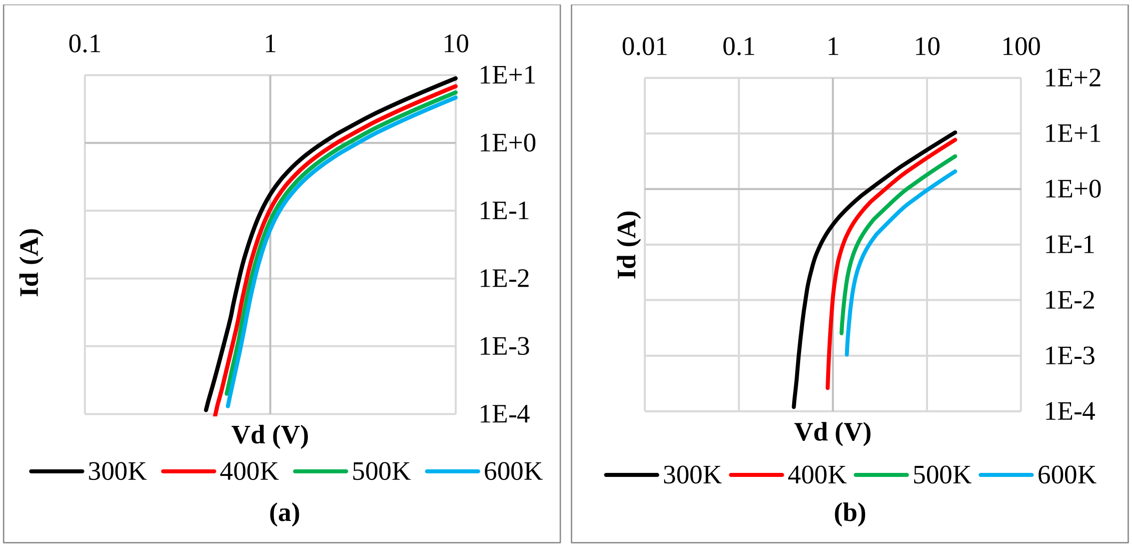


Figure 10. Characteristics curve of (a) SBD and (b) MPSD (full log).

For better conception to find more details about I-V characteristics of SBD and MPSD an illustration is shown in figure 10 which represents the same characteristics but in logarithmic scale.

5.3 Forward Conduction

In order to "turn on" and conduct current in the forward direction, a device requires a certain level of a positive voltage to be applied across the terminals. The typical voltage required to turn the diode on is called the forward voltage (V_F) or threshold voltage (V_{th}).

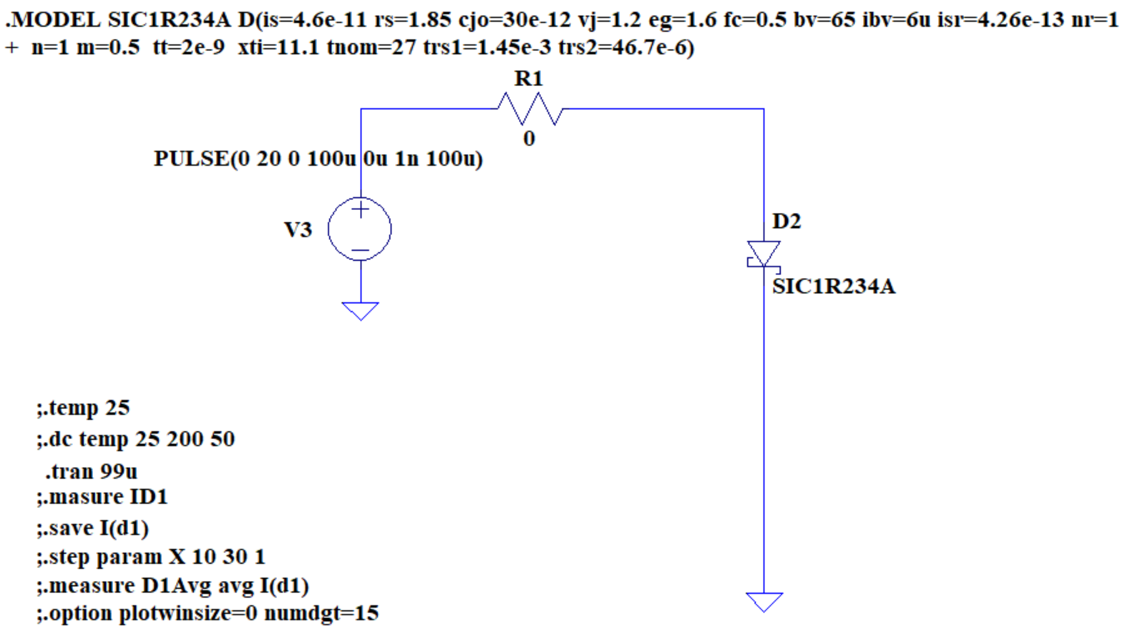


Figure 11. Circuit model for forward and reverse conduction.

Figure 11 shows the simple series circuit to determine the forward and reverse characteristics of the diodes. For forward characteristics, the value of voltage source is PULSE (0 20 0 100u 0u 1n 100u) which means the voltage is increase from 0V to 20V for 100μs. For reverse characteristics, it should be PULSE (0 -60 0 100u 0u 1n 100u) before breakdown and PULSE (0 -100 0 100u 0u 1n 100u) with breakdown.

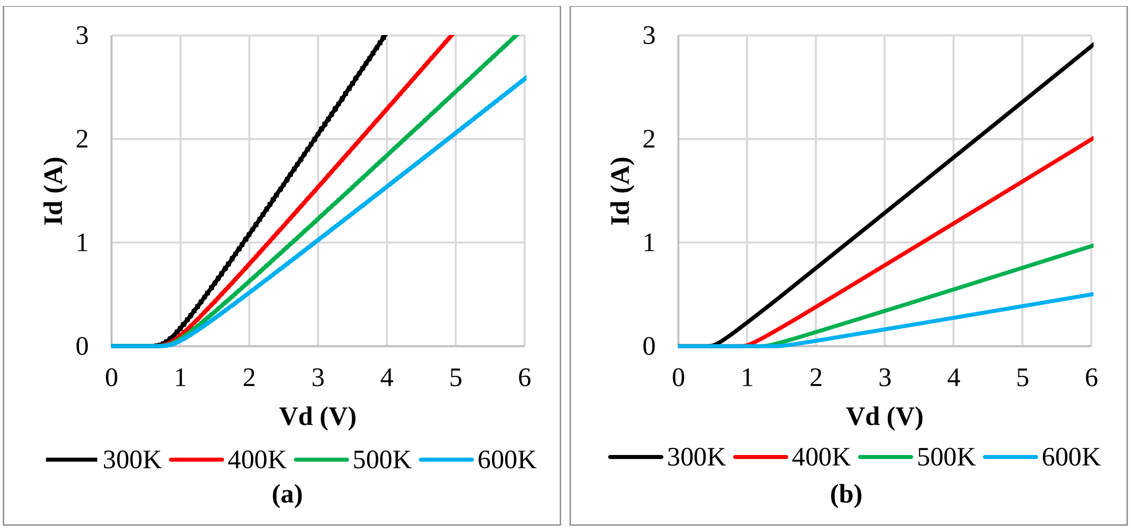


Figure 12. Forward characteristics curve of (a) SBD and (b) MPSD.

Forward characteristics of SBD and MPSD is shown in figure 12 in different temperature. The forward voltage of the diode is depending upon a few factors, such as semiconductor material of that device, temperature, etc. As it is known from the I-V relationship of the diode, voltage across the diode and the current through it are totally interdependent. When the voltage reaches up to the forward voltage rating, a large amount of current starts flowing, and a big increase happen for a very small rise in voltage. For SBD the turn-on voltage is about 0.8V to 1.2V correspondingly for the temperature 300K to 600K. But for MPSD that variation is significant, i.e. 0.7V to 2.2V for temperature 300K to 600K.

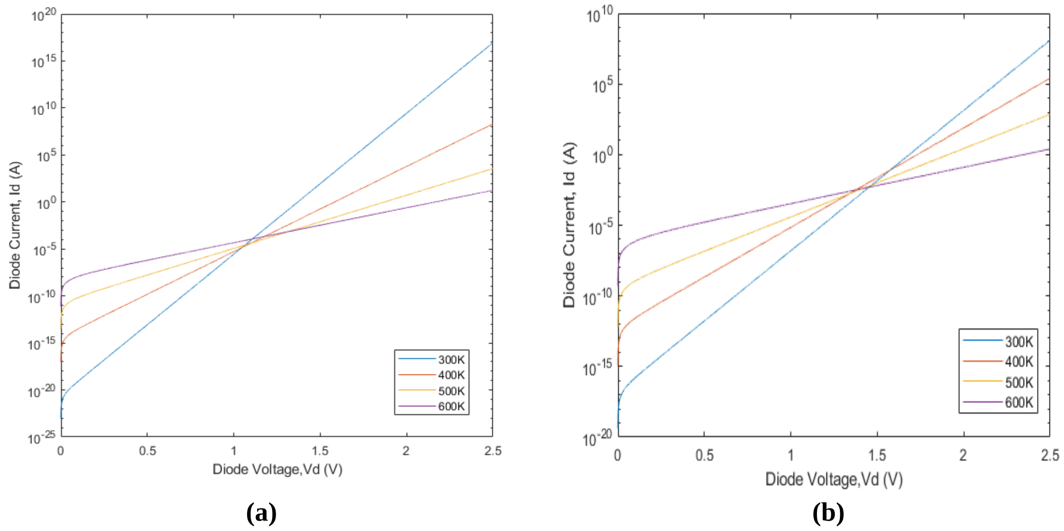


Figure 13. Forward characteristics curve from equation solution in MATLab of (a) SBD and (b) MPSD.

To compare these simulated forward conduction characteristics theoretically, it is needed to calculate values from the equation of forward characteristics which has been shown in equation (4). Figure 13 shows the forward characteristics curve for both SBD and MPSD from the equation (4) by using MATLab simulation. In that figure, we can easily notice the low-level injection current which also called saturation current for each temperature. The actual input variants are shown in table 7.

Table 7. Diode perimeter values for each model [2] [12] [18].

	Ideality Coefficient, n		**Saturation current. I0 (A)**	
Temp. (K)	**SBD**	**MPSD**	**SBD**	**MPSD**
300	1.12	1.69	2.8×10^{-21}	1.8×10^{-17}
400	1.39	1.78	4.5×10^{-15}	6.5×10^{-13}
500	1.78	2.08	2.5×10^{-11}	5.5×10^{-10}
600	2.26	3.26	9.9×10^{-9}	8.9×10^{-7}

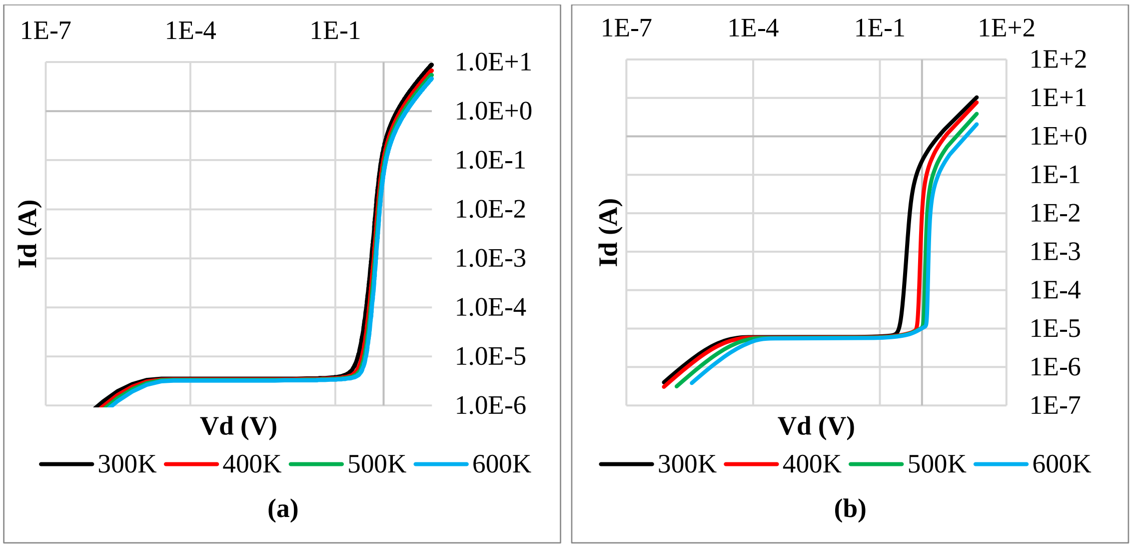


Figure 14. Forward characteristics curve for (a) SBD, (b) MPSD (full log).

Figure 14 shows the forward characteristics curve of SBD and MPSD in the logarithmic scale for indicating ups and downs more visually which has not been seen in the normal decimal scale in the previous pictures.

5.4 Reverse Conduction

A diode is called reversely biased when the cathode (n-type material) is connected to a positive potential, and the anode (p-type material) is connected to the negative potential. If the diode considered an ideal component, it would not conduct any current in that region, however, no diode is ideal practically, and it does conduct a negligible amount of current, it is called the leakage current.

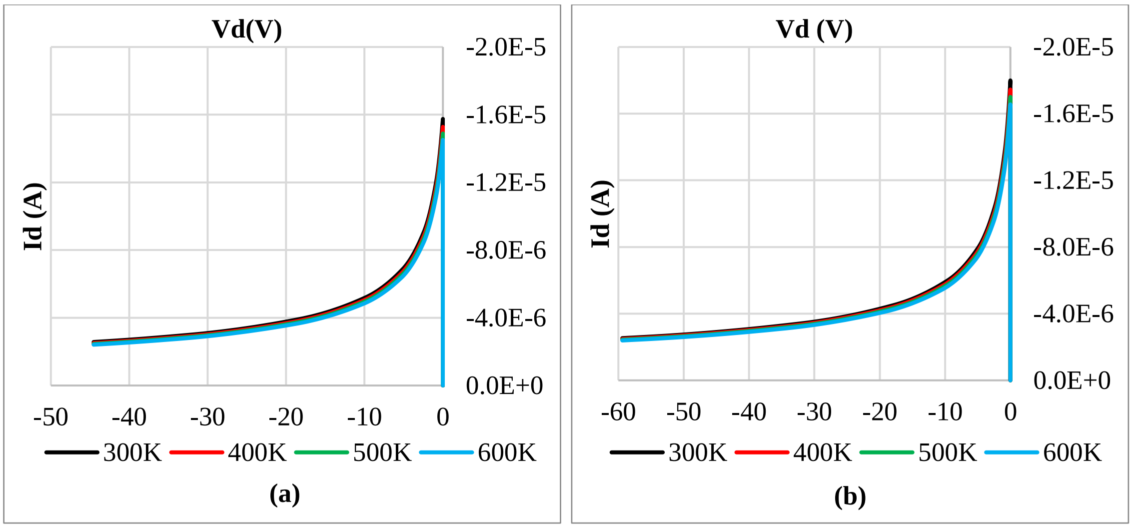


Figure 15. Reverse characteristics curve of (a) SBD and (b) MPSD before breakdown.

Figure 15 shows the leakage current flowing through SBD and MPSD before entering the breakdown region. There is no significant fluctuation of leakage current depends on the temperature for both diodes. If a large negative voltage is applied across the diode, suddenly a large amount of current starts flowing in the reverse direction. That voltage cause behind this reason is called the breakdown voltage. After breakdown no matter how much reverse voltage is applied, the voltage across the diode will remain the same.

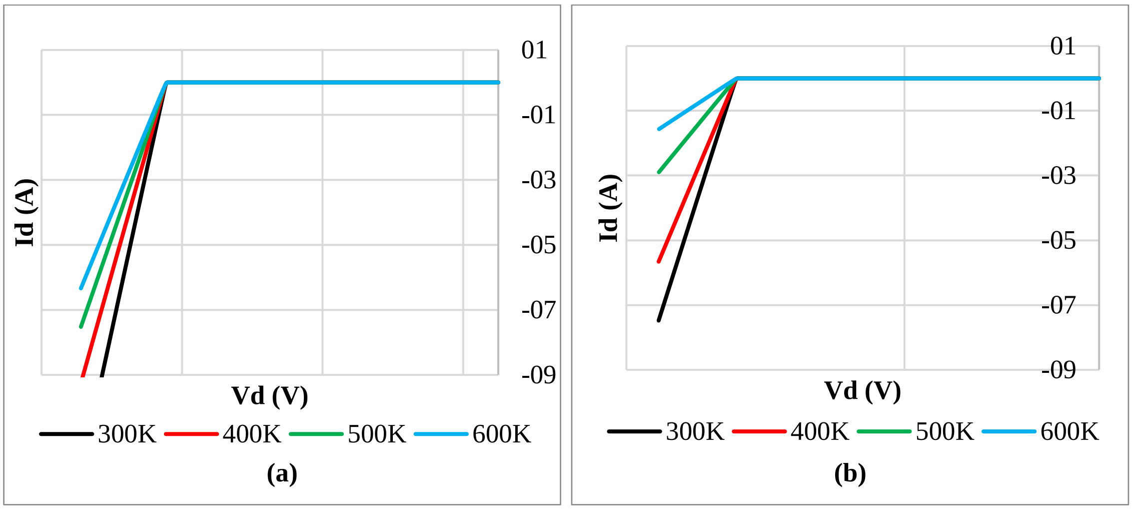


Figure 16. Reverse characteristics curve for (a) SBD and (b) MPSD after breakdown.

Figure 16 shows the reverse characteristics after breakdown happens for both diodes. As we can see in the figure, the voltage scale did not mention in the horizontal axis, its simply because the breakdown voltage heavily depends on the temperature. It means for each temperature they have different breakdown voltage as shown in figure 17. In this figure, the temperature dependency is not measurable, for this reason, a random value was considered as breakdown voltage in figure 16 to show the comparison of temperature effect on breakdown voltage more visually.

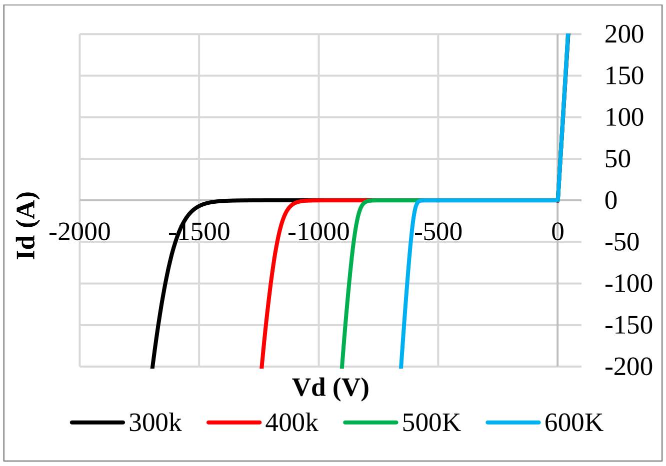


Figure 17. I-V characteristics curve for SBD.

6 Simulation of Transient Characteristics

6.1 Introduction

Transient characteristics of a diode are also called switching characteristic which is the dynamic characteristic for showing the variation of the diode current or voltage concerning the time. A power diode takes a finite time to change its state from ON (conduction-state) to OFF (blocking-state) and vice-versa. This is a very important parameter for the characterizing of a diode. Transient characteristics give the following information about the diode:

- It shows the time taken by the diode to change its state
- It shows the variation in the magnitude of voltage and current during the switching period and
- Switching losses of power dissipation caused by transient behavior

The switching time of a diode and the waveforms of the voltage and current of the diode both are affected by the intrinsic properties of the diode and by the circuits in which they are used.

6.2 On-time Transient

When the diode conduction enters from reverse bias to forward bias it called on time transient. Figure 18 shows the turn-on transient characteristics of the diode. Turn-on transient spans over periods t_1 and t_2 and two processes occur during these periods -

1. During t_1: space-charge stored in the depletion region due to the reverse biasing is removed because the diode is now forward biased.
2. During t_2: the forward-biased diode causes the injection of the excess carriers into the drift region double injection takes place.

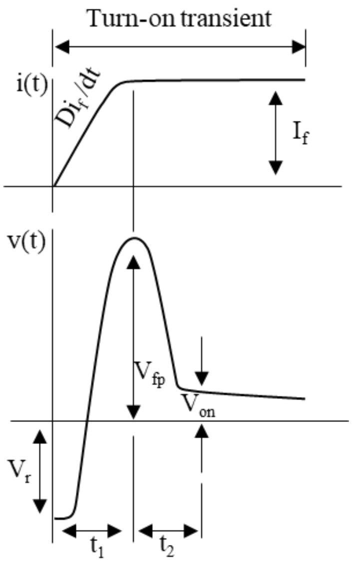


Figure 18. Turn ON Characteristics of power Diode [36].

During the Reversed Biased condition, the stored charge exists in the depletion region hence the region acts as a capacitor. Therefore, even if the diode is shortly forward biased, the voltage across the diode increases smoothly because the capacitance of the Space-charge region and current starts to increase as shown in figure 18.

Current also increases smoothly due to the inductance of the material and similarly the voltage across the depletion region increases smoothly due to the capacitance of the Depletion Region [36].

$$v(t) = v_{\Omega} + v_L = Ri_f + L\frac{di_f}{dt}$$

Where, v(t) = voltage across the diode,

v_{Ω} = voltage due to the resistance R of the Drift Region,

v_L = voltage due to the inductance L of the material

v(t) becomes maximum when current increases to the maximum value I_f at t= t_1. After t_1, the Conductivity Modulation starts hence the resistance of the drift region decreases so V_{Ω} (= Ri_F) also decreases and V_L = 0 since i_F attains a constant value I_F. Therefore, V_{diode} decreases from peak value to steady-state value Von and at t = t_2, conductivity modulation is completed. Now the forward turn ON time i.e. ton = t_1 + t_2 [36].

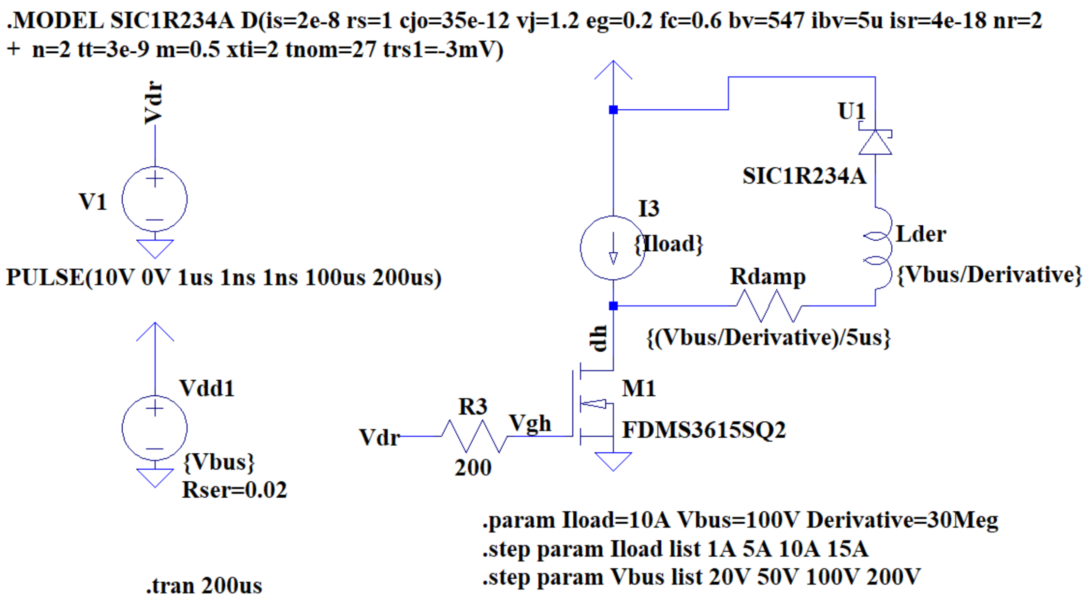


Figure 19. Circuit model for reverse recovery characteristics observation [9].

The reverse recovery circuit model is shown in figure 18. In this circuit, the value of the driver is PULSE (10 0 1u 1n 1n 100u 200u) which means 5 kHz switching frequency. By default, the current load value is 10A and the voltage supply set to 100V, but it can be changeable as a `.step param` function to any desired values. For example, if we ignore `.step param Iload list 1A 5A 10A 15A` function by putting an asterisk (*) before them, the simulation has been carried out for voltages (20V, 50V, 100V, 200V) for the default value of Iload (10A). But if we ignore `*.step param Vbus list 20V 50V 100V 200V` the simulation now counts only for different current load with default supply voltage (100V). For ignoring both current load and voltage supply variable the simulation now stetted with a default value which is 10A and 100V correspondingly. Simulation time 20µs with directive comment `.tran 20u` will give on-time transient. On the other hand, directive comment `.tran 0 113u 100u` will show reverse recovery time. The current prob should be placed on the entering path of the current.

Figure 20 shows the changing effect of the current load while voltage source remains constant. The turn-on transient for SBD and MPSD is about 12 ns and 23 ns for 10A current load and 100V supply voltage. The recovery type is not soft but abrupt. The oscillation magnitude is very small and its damping over time gradually. The peak of the recovery for both diodes is almost the same which is around 1.1A. The higher the load current the bigger the reverse peak value.

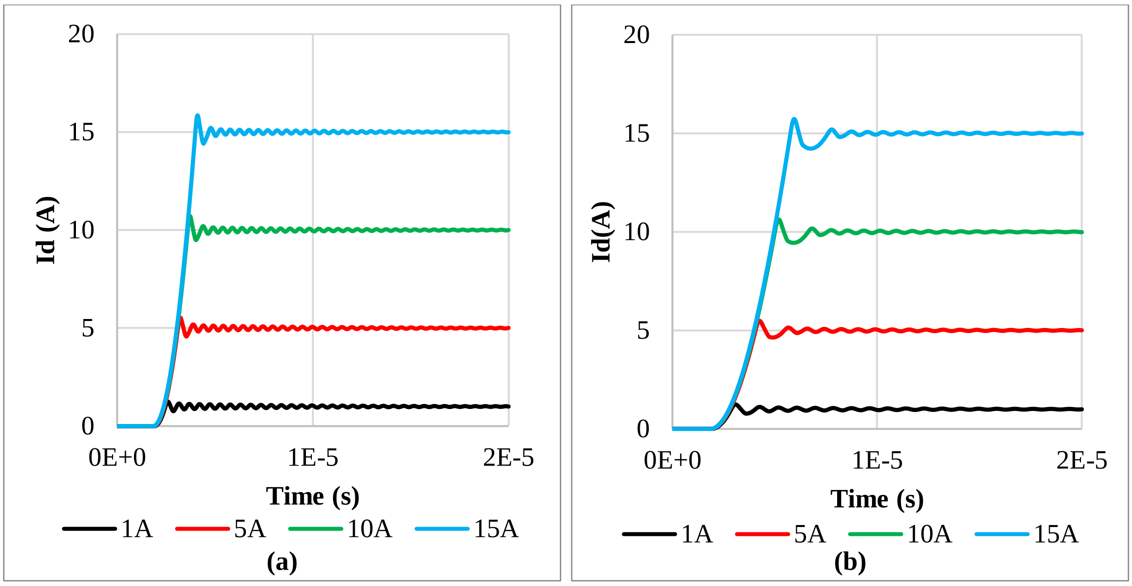


Figure 20. Turn ON Characteristics of Diode for the different current load of (a) SBD (b) MPSD when voltage supply remains 100V. The simulation was carried out at 5 kHz switching frequency and 300K temperature.

In figure 21 the turn-on transient for different voltage supply is shown when the load current set to 10a and the switching frequency was 5kHz. The transient gradually increases with the higher supply voltage for both diodes but the change in MPSD is greater than in SBD. Also, the higher voltages cause a larger di/dt slope which is significantly high for MPSD.

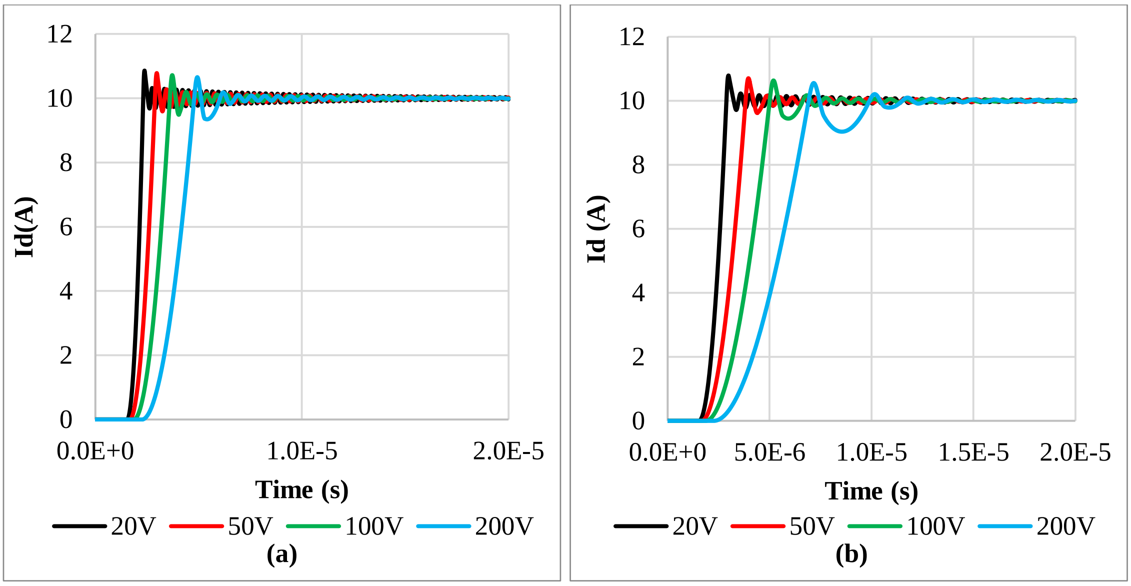


Figure 21. Turn-on Characteristics of Diode for different supply voltage of (a) SBD (b) MPSD when current load fixed at 10A. The simulation was carried out at 5 kHz switching frequency and 300K temperature.

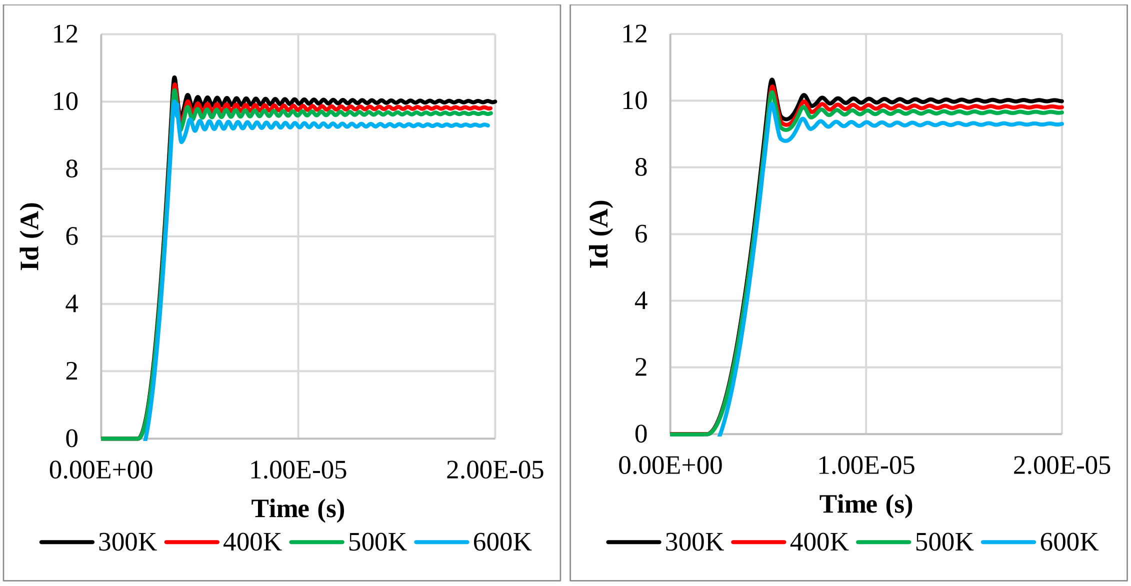


Figure 22. Turn ON Characteristics of Diode for different temperatures when the supply voltage is 100V and load current 10A of (a) SBD (b) MPSD. The simulation was made at 5 kHz switching frequency.

Figure 22 shows the temperature effect in turn-on transient characteristics of both diodes for default voltage supply and current load. The figure shows that the temperature has a very slight impact on turn-on transient time but change only reflected for the peak current level. Because of the higher temperature the ohmic resistance is increasing so the resultant current output is slightly decreasing.

6.3 Reverse Recovery Time (trr)

When the forward conduction falls to zero, the diode tries to continue the conduction in the opposite direction. The reason behind this is the depletion layer and p/n-layer stored some charge. The reverses conduction flows until reverse recovery time (t_{rr}). The t_{rr} starts counting when the forward current becomes zero till 25% of the maximum reverse recovery current. In figure 23 time t_a represent the charges stored in the depletion layer removed where time t_b means charges from the semiconductor layer are removed. The shaded area in figure 23 (a) represents stored charges QR which must be removed during reverse-recovery time t_{rr}.

Power loss across diode = $v_f \times i_f$ as shown in figure 23 (c), also the majority of power losses occurs in the diode during the period t_b.

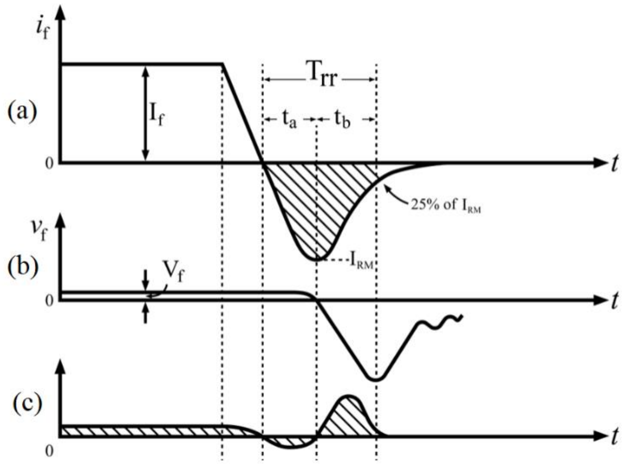


Figure 23. Turn-Off Characteristics of Power Diode: a) Variation of forward current i_f ; b) Variation of forward voltage Drop v_f ; c) Variation of power loss [37].

Recovery can be abrupt or smooth as shown in figure 24. To know it quantitatively, we can use the Softness factor or S-factor which is the ration of T_b and T_a. It can measure the voltage transient that occurs during the time the diode recovers. When the s-factor is equaled to 1, the low oscillatory reverse-recovery process of soft recovery diode, but if the value is less than 1, large oscillatory over-voltage or fast-recovery diode [37].

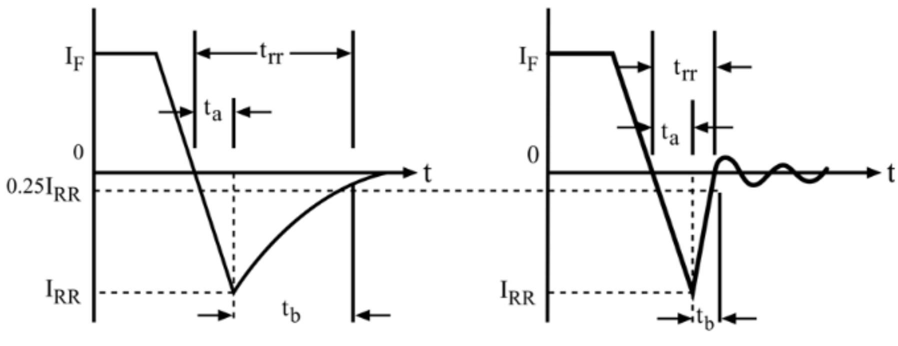


Figure 24. Reverse-Recovery Characteristics of Power Diode: (a) soft Recovery, (b) abrupt recovery [37].

The waveforms in figure 25 show the relationship between time and different current during the reverse recovery of SBD, and MPSD at room temperature while the switching frequency was 5 kHz. The dI_f/dt slope for SBD is about 300A/µs and for MPSD 350A/µs. The peak recovery current is -2.5A on average for SBD where -1.2 for MPSD. The reverse recovery time (t_{rr}) for SiC SBD is about 24ns but for MPSD the t_{rr} time is shorter near 15ns. The reverse recovery current peak is very small compared to other semiconductor base diode. Only the displacement current from the junction capacitance is visible. This leads to significantly lower turn-off losses for both SiC diodes, particularly in MPSD.

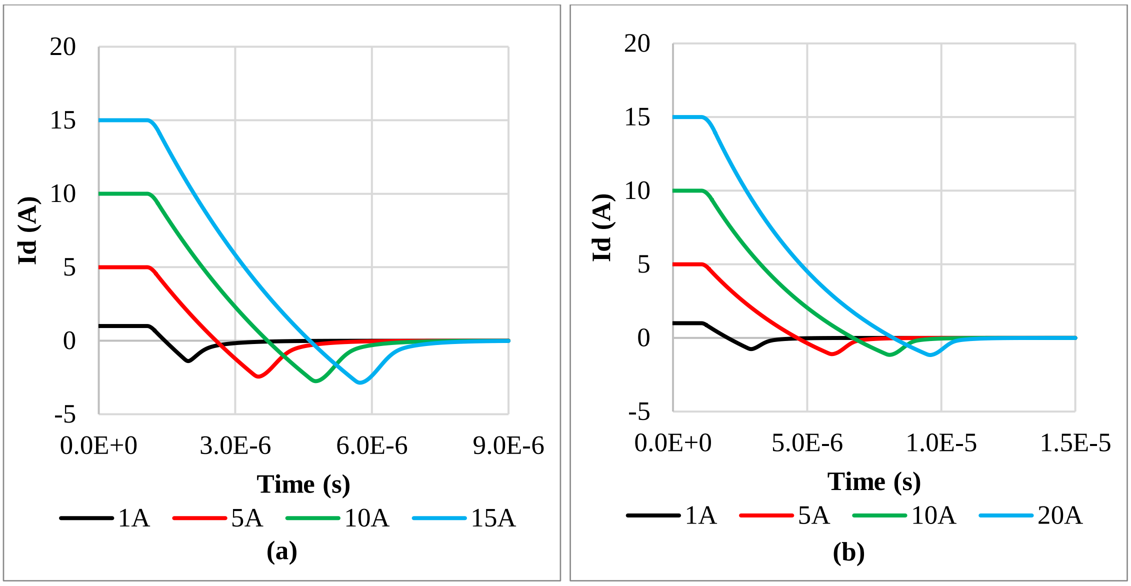


Figure 25. Reverse-Recovery time for different current load when supply voltage set to 100V of (a) SBD, (b) MPSD at room temperature and 5 kHz switching frequency.

Figure 26 shows the reverse recovery characteristics for SBD and MPSD for different supply voltages when the load current is a constant value of 10A. As shown in the waveform for both diodes, we can see there is almost no change in dI_f/dt slope only a little change occurs in t_b. It means the values remain average as previously mentioned for different load waveforms.

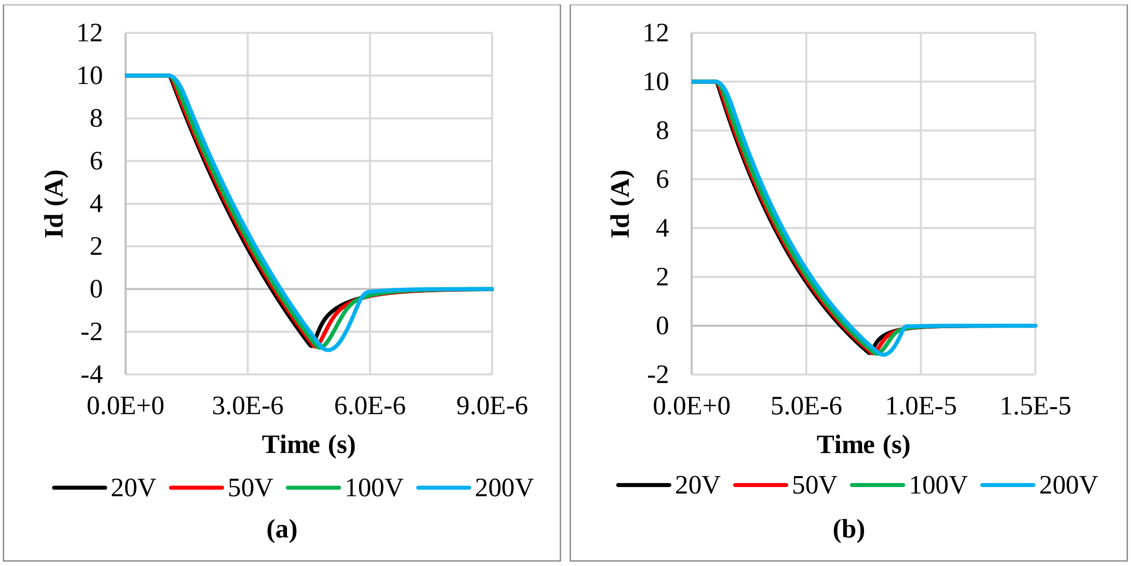


Figure 26. Reverse-Recovery time for different voltage supply when current load fixed at 10A of (a) SBD, (b) MPSD at room temperature and 5 kHz switching frequency.

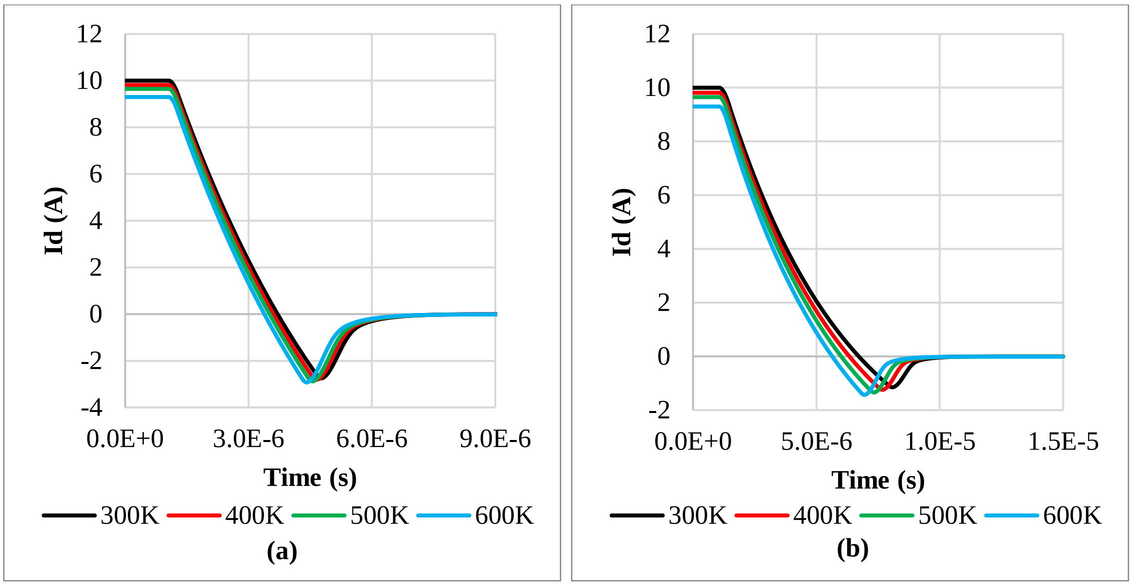


Figure 27. Reverse-Recovery time for different temperature level when source voltage was 100V and current load was 10A of (a) SBD, (b) MPSD at 5 kHz switching speed.

Temperature dependency is very small for both SBD and MPSD as shown in figure 27. Only change happens because of the thermal resistivity of the device and the circuitry.

In summary for trr, since the dynamic characteristic of a Schottky diode is capacitive, the reverse recovery characteristic of a SiC Schottky diode is independent of forward current, di/dt and device junction temperature.

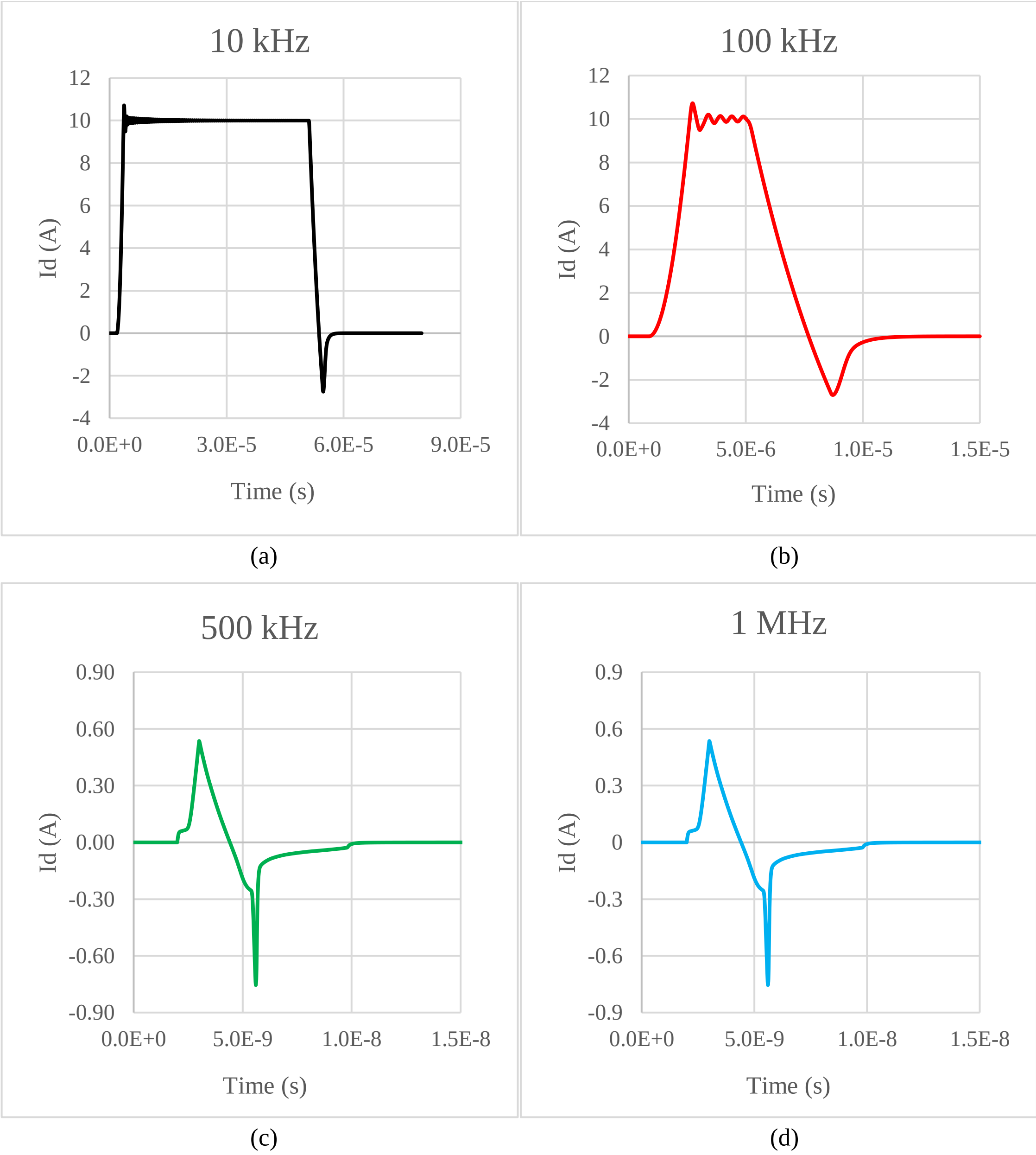


Figure 28. Turn-on and Reverse-Recovery characteristics for different switching frequency (a) 10 kHz, (b) 100 kHz, (c) 500 kHz, (d) 1 MHz at room temperature for 100V supply voltage of SBD.

Figure 28 shows the revaluation of switching characteristics depends on switching speed from lower to higher. The ideal output should be a square wave on 1 MHz speed but the output current almost negligible and the shape of the wave is no longer square wave. However, it has the turn-on transient and reverse recovery characteristics left noticeably. The next part of this chapter will be discussed high speed switching at 1 MHz frequency since everything discussed previously was at 5 kHz switching frequency.

6.4 High Speed Switching Transient

The simulation for high-speed switching transient had been carried out from the circuits in figure 29.

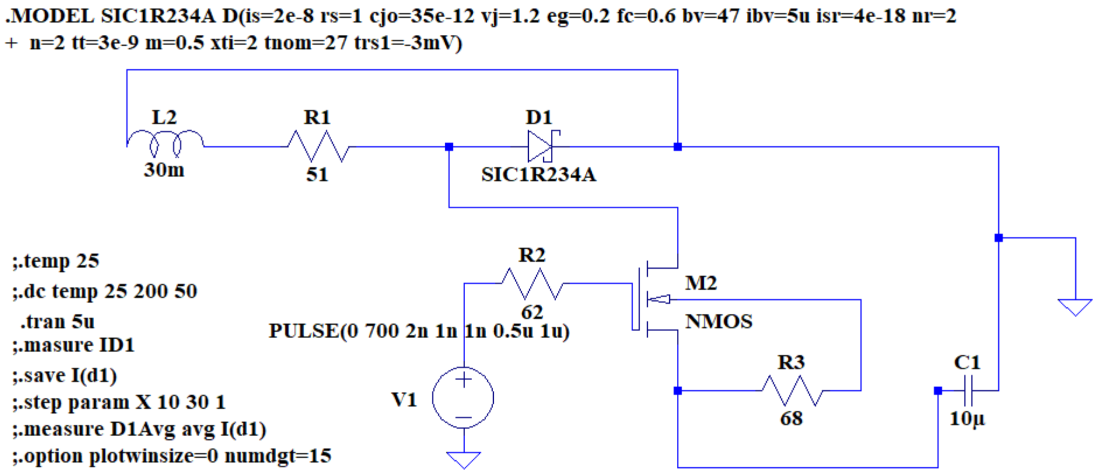
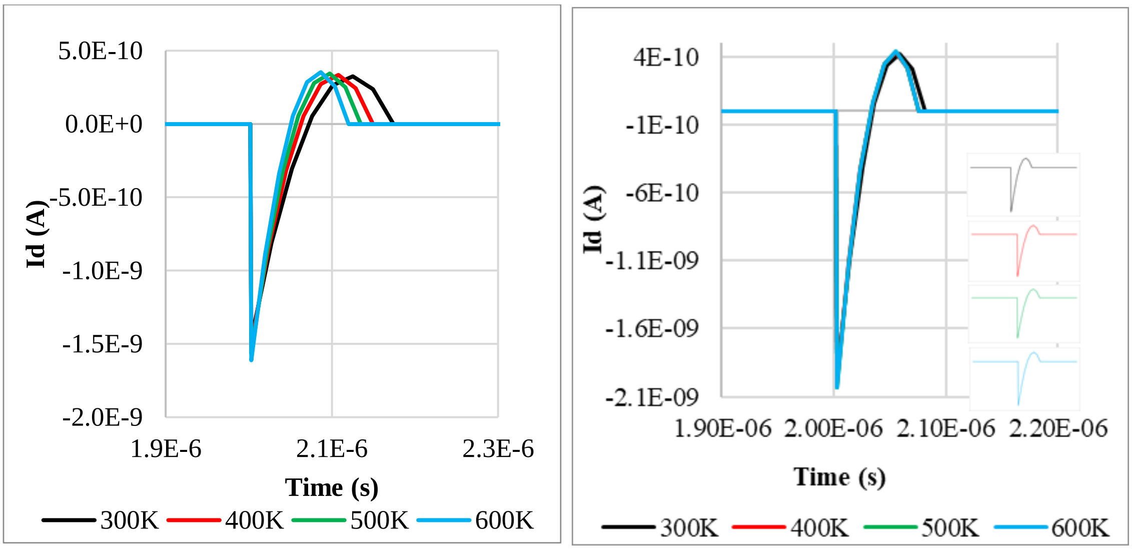


Figure 29. Circuit model to observe burst switching transient analysis [2].

The fast recovery circuit model which shown in figure 29 is used a 700 V burst as supply to determine the time of recovery. The driver value is PULSE (0 700 2n 1n 1n 0.5u 1u) which means 1 MHz switching frequency. There is no secondary voltage supply present in this model. The diode only turns on when the peak value of the burst reaches. From this principle, we can find the recovery time of the diode at a very high frequency.



(a) (b)

Figure 30. High speed switching transient at burst configuration (500V-burst) of (a) SBD and (b) MPSD at different temperature levels. The switching frequency was 1 MHz.

Figure 30 shows the turn off switching transient for 500V burst at 1 MHz frequency at different temperature levels for SBD and MPSD. The t_{rr} of SBD is about 12ns on average and 8ns for MPSD. But the change in MPSD for higher temperatures is almost nothing.

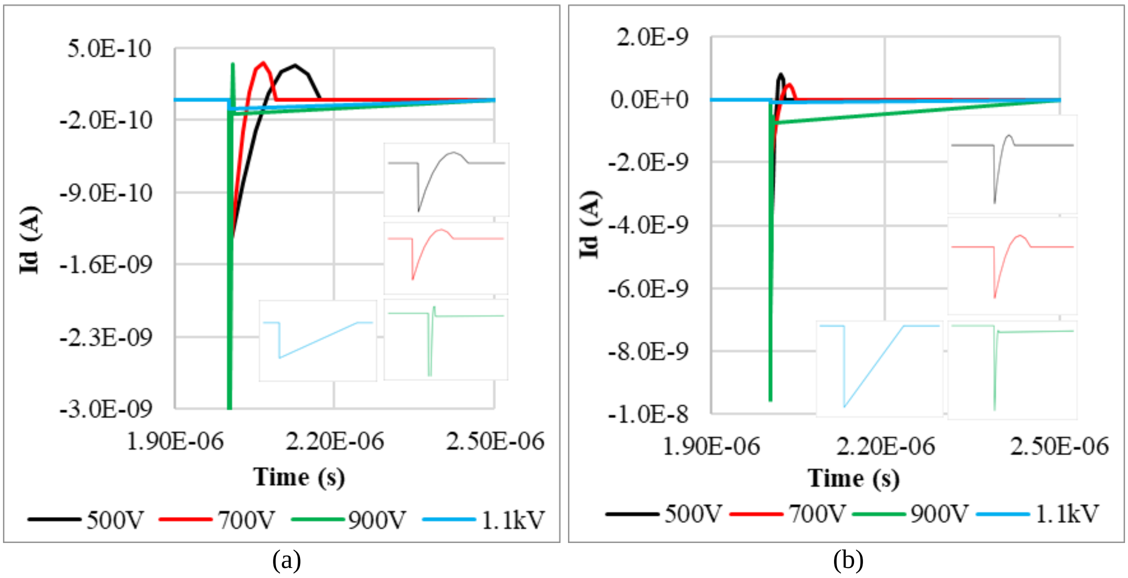


Figure 31. High speed switching transient at burst configuration of (a) SBD and (b) MPSD at different burst voltage. The switching frequency was 1 MHz.

Figure 31 is showing the effect of changing burst voltage even higher compere to the previous figure. Here the recovery type is changing from abrupt to soft when higher voltages are applied. However, the peak recovery current of soft recovery for 1.1kV is very small compare to abrupt recovery for 500V.

6.5 Fast Reverse Recovery

At very high speed the amount of current flowing through the diode is significant decreases although the input voltage is high enough. Figure 32 shows a conventional circuit configuration for observing reverse recovery time. In this circuit, an alternating pulse was needed to drive the switch. Also, a fixed voltage source applied in series with the testing diode.

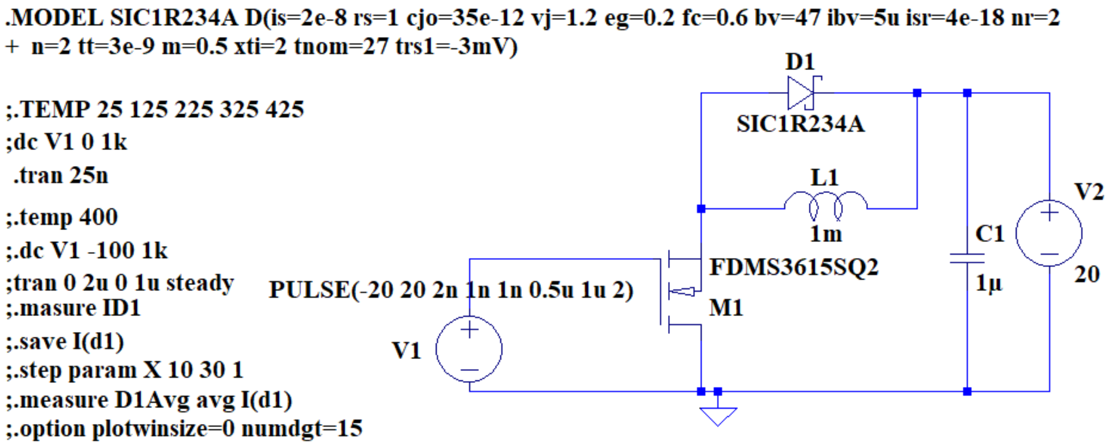


Figure 32. Circuit model to observe fast switching transient in reverse recovery configuration [6].

Figure 33 shows the temperature effect on switching transient for SBD and MPSD at 20 V supply and 1 MHz switching frequency. The average peak recovery current for SBD is about -350 mA and for MPSD its -120 mA. The recovery time form SBD and MPSD are about 7 ns and 5 ns respectively. The temperature has very less effect on MPSD also for this case compare to SBD.

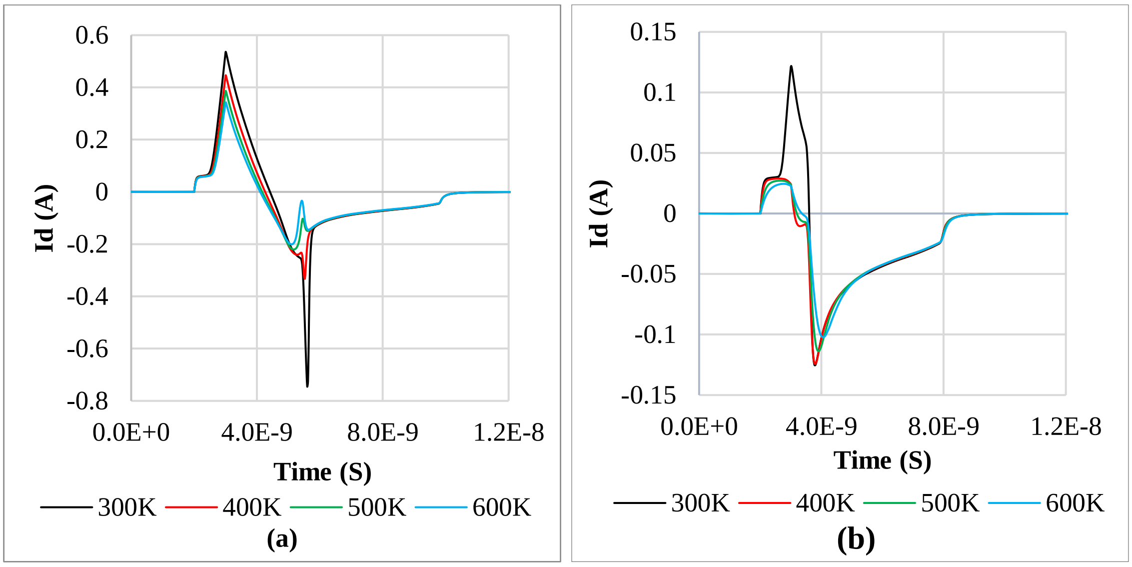


Figure 33. High speed switching transient at reverse recovery configuration of (a) SBD and (b) MPSD at different temperatures. The supply voltage was 20 V and the switching frequency was 1 MHz.

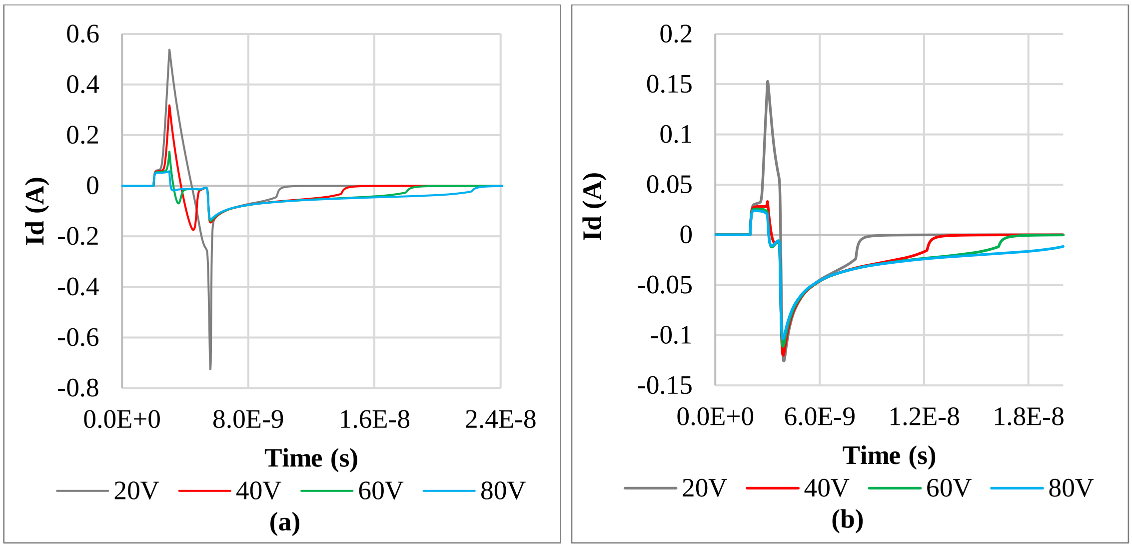


Figure 34. High speed switching transient at reverse recovery configuration of (a) SBD and (b) MPSD at different supply voltages.

Figure 34 demonstrates the switching transient in case of changing supply voltage for reverse recovery formation of SBD and MPSD at room temperature and 1 MHz switching frequency. For SBD, increasing the supply voltage can be lowering the peak recovery current but increasing the recovery time. On the other hand, for MPSD peak current remain the same but recovery time is also increasing like SBD.

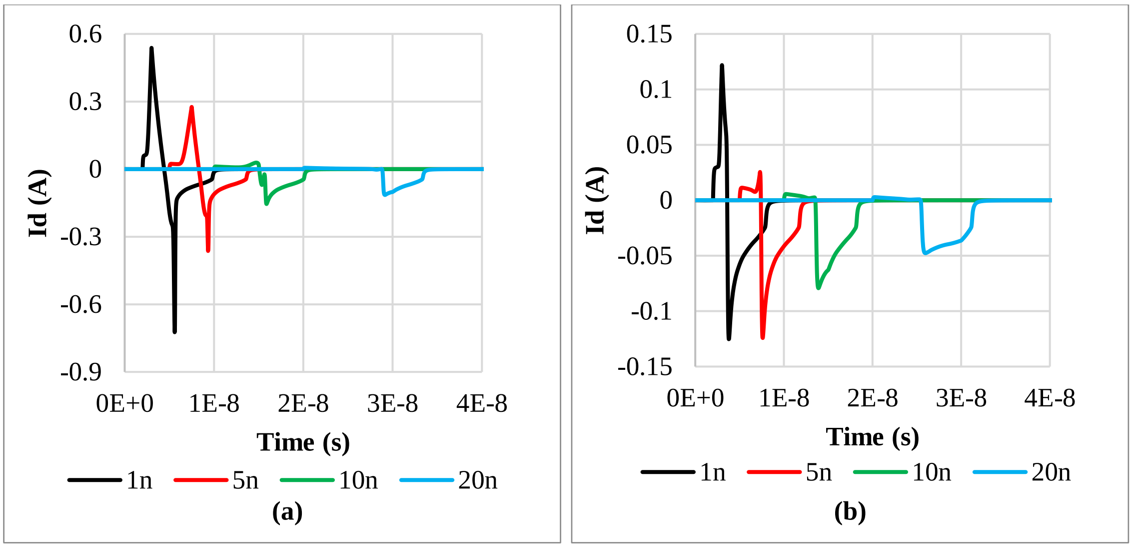


Figure 35. High speed switching transient at reverse recovery configuration of (a) SBD and (b) MPSD at different switching delay.

In chase of adding higher switching delay, both of the diodes show the same characteristics as shown in figure 35 which is decreasing the peak reverse recovery current as well as turn-on transient.

7 Summary

This work presents spice models and analysis of the two most efficient types of power diodes (SBD and MPSD) required for a most promising semiconductor with wide bandgap, excellent thermal properties, and quick recovery time. This works also represents vital characteristics of those diodes with a comparison between them. The best advantage of the proposed model lies in its immanent simplicity and flexibility as to be implemented in modern simulators, adopting Spice programming. The parameters were carefully extracted and verified from dependable sources to ensure the accuracy of the simulation.

The diodes were simulated for both static (current-voltage) and dynamic (transient) characteristics. Under forward conduction, they displayed increased resistivity and reduced junction potential with increasing temperature. At room temperature (300K) the forward current of SBD is about 38% higher than MPSD and for high temperature (600K) it is 66%. The threshold or forward voltage of SBD is 0.8V to 1.2V for room to high temperature where 0.7V to 2.2V for MPSD. Almost similar temperature dependency was reflected to reverse bias for both diodes. Mathematically and Spice model results are verified in forward conduction and they show very good agreements. The diodes were also tested under several transient conditions using a typical method for low-speed switching as well as two different techniques for the high-frequency environment. Both diodes have very good reverse recovery capabilities and switching properties in various high temperature and load conditions. The reverse recovery time (trr) of MPSD is 60% and peak recovery current 48% smaller than SBD. At 5kHz switching frequency, the I_D was almost same as rated current but for 1MHz the current was less than 1A for both diodes.

Although, MPS has a better performance than SBD both are very fast, efficient, dependable because of its constructing material (SiC) which makes them immune from other types and materials base diode.

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