

“Modeling and Simulation of a 5.8kV SiC PiN Diode for Inductive Pulsed Plasma Thruster Applications”

Abstract

Current ringing in an Inductive Pulsed Plasma Thruster (IPPT) can lead to reduced energy efficiency, excess heating, and wear on circuit components such as capacitors and solid state devices. Clamping off the current using a fast turn-off power diode is an effective way to reduce current ringing and increase energy efficiency. A diode with a shorter reverse recovery time will allow the least amount of current to ring back through the circuit, as well as minimize switching losses. The reverse recovery response of a new 5.8kV SiC PiN diode from Cree, Inc. in the IPPT plasma drive circuit is investigated using a physics-based Simulink model, and compared with that of a 5SDF 02D6004 5.5kV fast-switching Si diode from ABB. Parameter extraction was carried out for each diode using both datasheet specifications and experimental waveforms, in order to most accurately adapt the model to the specific device. Further experimental data will be discussed using a flat-plate IPPT developed at NASA Marshall Space Flight Center and used to verify the simulation results. A final quantitative measure of circuit efficiency will be described for both the Si and SiC diode configuration.

Introduction

Inductive Pulsed Plasma Thrusters (IPPTs) are a family of electric rocket engines that utilize electromagnetic interactions to accelerate a charged gaseous propellant out of a nozzle, thereby producing thrust [1, 2]. Energy is stored in a capacitor bank and then discharged through an inductive coil. The discharge results in the formation of a plasma current sheet and the acceleration of the plasma through interaction with the induced magnetic field. The capacitor bank, inductive coil, and stray resistance of the IPPT constitute an underdamped resistor-inductor-capacitor (RLC) circuit. Once the switch is closed, the current will ring through the circuit, even after the plasma current sheet has moved away from the coil and energy is no longer coupled into the propellant. Since current sheet decoupling occurs after the first current half cycle [3, 4], the use of a fast-switching diode in series with the switch (Fig. 1) can clamp off current ringing in the circuit, thereby reducing power loss, excess heating, and component wear.

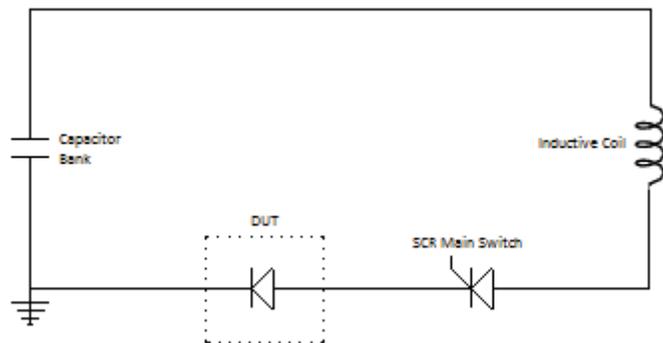


Figure 1: IPPT circuit indicating location of current clamping diode.

The amount of time needed to clamp off current ringing in the IPPT circuit depends on the reverse recovery time of the diode used. In a Silicon Carbide (SiC) PiN diode, the wider bandgap of the material results in a breakdown voltage 10 times that of Si, so that a SiC device may have a thinner drift region for a given blocking voltage [5]. This leads to smaller, lighter devices capable of blocking high voltage, as well as reduced forward conduction losses, faster reverse recovery time (faster turn-off), and lower-magnitude reverse recovery current. For this reason, SiC PiN diodes offer significant advantages to conventional fast-switching Silicon (Si) diodes for high power and fast switching applications such as switching of IPPTs. An additional advantage of SiC devices for space applications lies in the high thermal conductivity of the material, potentially allowing the former to operate at higher temperatures with a smaller, lighter heatsink (or no heatsink at all) [6].

In order to predict the efficiency of the IPPT circuit in Fig. 1 for both a conventional Si fast diode and a comparable SiC device, a previously developed physics-based Simulink model of a SiC PiN power diode [7] will be discussed and the results provided describing the switching behavior of each diode in the circuit.

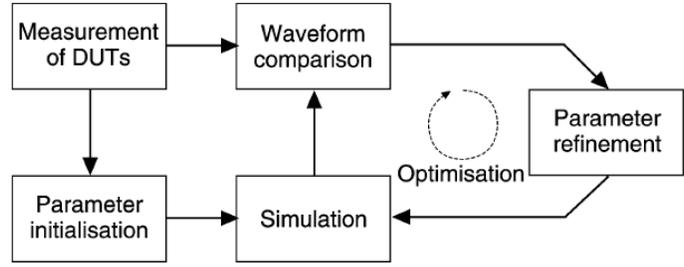


Figure 2: Parameter Extraction Procedure. [ref]

Parameter characterization was carried out for a 5SDF 02D6004 5.5kV fast-switching Si diode from ABB and a 5.8kV SiC PiN diode from Cree Inc. using the method detailed by Bryant et al. (2006) [8]. In this method, an initial estimate of the diode parameters was made using specifications given in the datasheet, and then an optimization loop was used to match the resulting simulated waveforms with experimental switching waveforms (Fig. 2). In the case of the SiC diode, no datasheet is available to allow for an initial estimate of parameters. For this reason, all parameter extraction is carried out using experimental waveforms. A discussion of the parameter extraction will be provided in the paper. A summary of the relevant parameters and the order of extraction and estimation is provided below in Table 1.

Table 1: Diode model parameters.

Symbol	Units	Description	Step
A	cm^2	Active die area	1
τ_{HL}	μs	High-level lifetime	2
N_{N^-}	cm^{-3}	Drift region doping	3
W_{N^-}	μm	Drift region width	4
h_n, h_p	cm^4s^{-1}	Emitter recombination parameters	5

Dynamic Testing

A double pulse test was conducted at ambient temperature to compare the reverse recovery of a 5SDF 02D6004 5.5kV commercial Si fast recovery diode from ABB and a prototype 5.8kV SiC diode from Cree, Inc. In this test, di/dt and forward current are both fixed. The test circuit is shown schematically in Fig. 3a, while the physical laboratory setup for the Si diode is shown in Fig. 3b. Component V_c in Fig. 3a represents a DC voltage supply that is used to charge capacitor C_1 to a voltage of 1kV. The series inductance of C_1 is approximately 90nH. The load is a series combination of a resistor, R_{load} , and an inductance, L_{load} , which represent the inductive coil of the thruster. L_{load} has a value of 166 μH , while R_{load} is 10 Ω , resulting in an average load current, I_L , of approximately 100A. Stray inductance is minimized by keeping circuit connections as short as possible.

Two pulses each of duration 10 μs and an equivalent period 20 μs (if operating in steady state) are applied to a Mitsubishi 1.7kV Si IGBT. For each set of pulses, the IGBT voltage and test diode voltage are

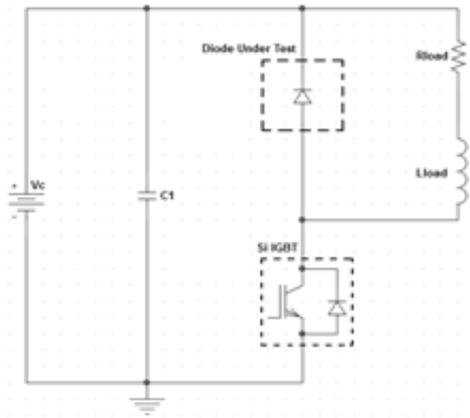


Figure 3: a) Double pulse test circuit schematic. b) Lab setup of double pulse test circuit.

measured using differential voltage probes, and current in the IGBT and test diode are measured using Pearson current transducers.

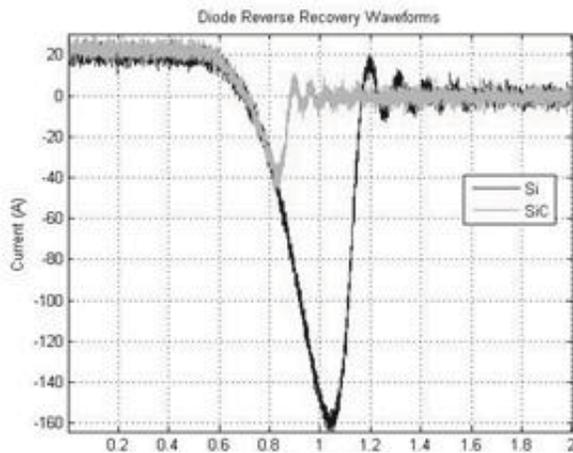


Figure 4: Comparison of Si and SiC diode reverse recovery waveforms.

The experimental results in Fig. 4 show that the 5.8 kV SiC diode has significantly lower reverse recovery losses than a comparable 5.5 kV Si diode, under fixed di/dt and forward current conditions. From this, it is reasonable to conclude that the use of SiC diodes in place of Si diodes in the IPPT drive circuit topology will lead to lower switching losses, higher efficiency, and less stress on all circuit components.

When applied to the design of pulsed electric thruster drives, this will reduce the amount of propellant that must be stored on board a spacecraft, reducing weight and freeing space for payloads and/or passengers. In addition, reduced component stress allows for longer autonomous space missions and less frequent maintenance.

Reverse recovery waveforms were collected for a prototype 5.8kV SiC PiN diode from Cree, Inc. and for a 5SDF 02D6004 5.5kV fast-switching Si diode from ABB (Fig. 5). In Fig. 5a, the temperature is held at a constant 25°C using a SunSystems thermal chamber, while the current through the diode under test is varied. In Fig 5b, the current through the diode is fixed, and data is collected at ambient temperatures of -25°C, 25°C, 75°C, and 125°C. In each case, it can be seen that the peak reverse recovery current, reverse recovery time, and total recovery energy are all significantly lower for the SiC device than for the Si device. Notably, the peak reverse recovery current for SiC at -25°C is a factor of 6 lower than for Si at the same temperature, while the reverse recovery time and total reverse recovery energy are reduced by factors of approximately 3 and 15, respectively. Measured reverse recovery parameters for both diodes are summarized in Table 2.

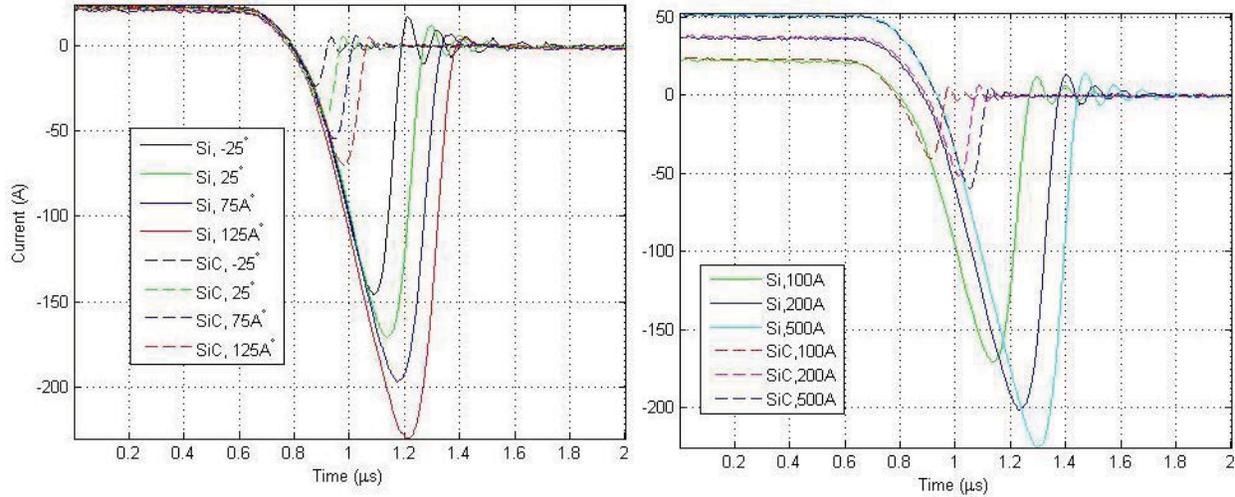


Figure 5. Measured reverse recovery waveforms for 5.8kV SiC PiN diode and 5.5kV Si fast diode. a) Fixed ambient temperature of 25°C and varying diode current. b) Fixed diode current and variable ambient temperature.

These data demonstrate the fast turn-off of the SiC device relative to a conventional fast-switching Si diode. This makes it desirable for use in high-efficiency IPPT drive applications, in which the main switch must be opened as soon as possible after the first current half-cycle in order to minimize energy loss in the drive circuit due to current ringing.

Table 2: Measured reverse recovery parameters for 5.5kV Si diode and 5.8kV SiC diode at 25°C and $I_L=100A$.

Diode Under Test	I_{DRM} (A)	t_{rr} (μs)	Q_{rr} (μC)	E_{rr} (mJ)
Si	164	.47	39	9.8
SiC	40	0.18	4	0.8

Device Simulation

Diode turn-off waveforms were obtained in an inductive circuit for various load conditions. A comparison of simulated and experimental reverse recovery waveforms for the Si diode is shown in Fig. 6. Simulation parameters will be updated to better match experimental setup parameters, and parameter optimization will aim to minimize mean squared error between the simulated and experimental waveforms.

Verification of the circuit efficiency predicted by the Simulink model and compared to the experimental results using a flat-plate IPPT developed at NASA Marshall Space Flight Center [9], will be provided in the full paper. The SiC and Si diodes were each separately integrated into the thruster assembly, and waveforms collected to compare switching efficiency and overall circuit performance. A quantitative measure of circuit efficiency will be defined and described for each configuration.

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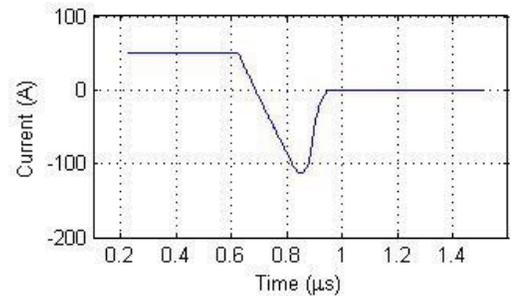
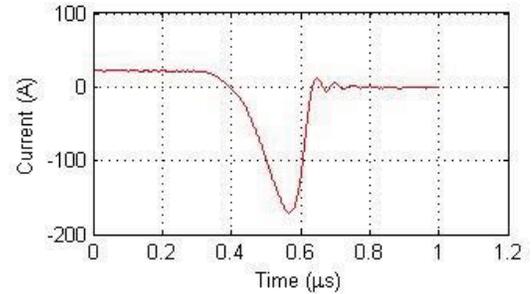


Figure 6: Comparison of experimental (top figure) and simulated (bottom figure) diode reverse recovery waveforms under an inductive load.