Electrothermal Modeling and Characterisation of SiC Schottky and Silicon PiN diodes Switching Transients

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***Abstract*— Schottky diodes are known to have lower conduction and switching losses compared to PiN diodes, however, are prone to ringing in the output characteristics. In this paper, analytical models have been developed to calculate the turn-off switching energy of SiC Schottky and silicon PiN diodes. The models account for the reverse recovery current and diode voltage overshoot in the case of the PiN diode as well as the output oscillations for the Schottky diodes. PiN diodes during turn-off exhibit significant reverse current which increases with the switching rate and temperature whereas Schottky diodes exhibit output oscillations due to RLC resonance in the circuit. By combining these models with thermal networks derived from transient thermal impedance curves of the diodes, a fast and accurate method of predicting the temperature transient for different switching frequencies and electrical time constants has been developed. These models can be used by application engineers to predict the energy dissipation when designing converters and can take account of temperature and switching rate dependencies of the diodes.**

Index Terms— Modeling, Switching Energy, Silicon Carbide, Power Devices

NOMENCLUTURE

V_D	On-state voltage drop
dI_{RR+}/dt	Slope of current before peak reverse recovery
dI_{RR-}/dt	Slope of current after peak reverse recovery
I_{RR}	peak reverse recovery
Δt	Time difference between voltage rise and I_{RR}
C_{AK}	depletion capacitance
R_{AK}	depletion resistance
L_{stray}	stray inductance parasitic
R_S	series resistance
E_{SW}	Switching energy
T	Temperature
t	Time

I. INTRODUCTION

Silicon PiN and SiC Schottky diodes are routinely used as free-wheeling diodes in voltage source converters that require bi-directional power flow [1-2]. Each technology exhibits certain characteristics in the turn-off transient. The silicon PiN diode suffers from high reverse recovery charge due to the fact that it is a bipolar device that relies on conductivity modulation via charge storage in the drift region [3-5]. Hence, when the diode is turned off, the stored charge must first be extracted via a negative current and after the diode starts blocking, the excess charge must recombine in the diode. Fig. 1(a) shows the measured switching voltage and current waveforms for a 1.2 kV PiN diode whereas 1(b) shows the switching power transient. Parasitic inductance and high *dI/dt* will contribute to higher peak diode voltage overshoot, which coupled with the peak reverse recovery current, causes high instantaneous power dissipation in the diode [6].

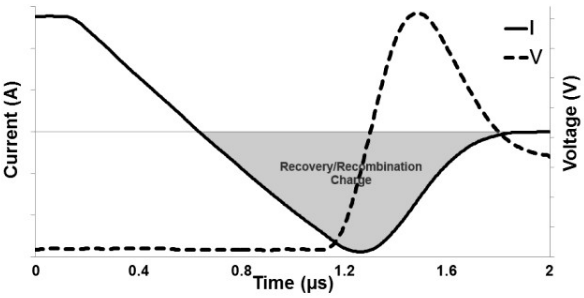


Fig. 1(a). Measured silicon PiN diode transient voltage and current

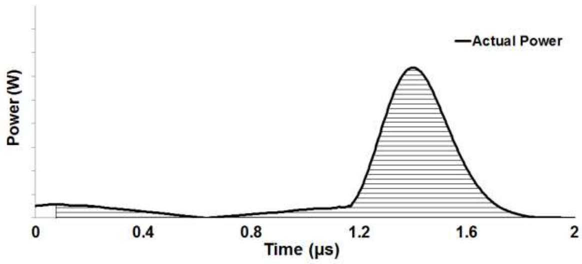


Fig. 1(b). Measured silicon PiN diode instantaneous power

On the other hand, SiC Schottky diodes are unipolar devices and hence, do not rely on charge storage thereby resulting in no reverse charge. However, the drawback of the Schottky diode is its tendency to oscillate in the presence of parasitic inductance [7-9]. This ringing characteristic contributes to the switching energy and can be minimized by reducing the switching rate. Fig. 2(a) shows the measured characteristic of a 1.2 kV Schottky diode whereas Fig. 2(b) shows the instantaneous switching power transient. The following section describes models that have been developed for each technology.

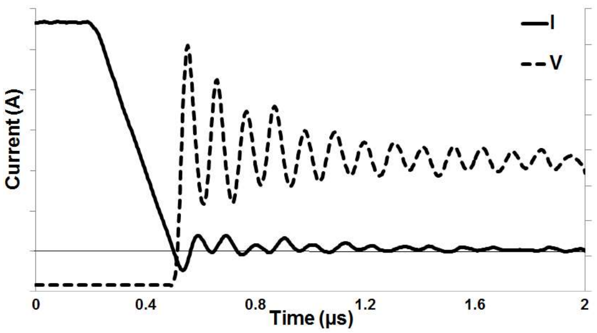


Fig. 2(a). Measured SiC Schottky diode transient voltage and current waveforms.

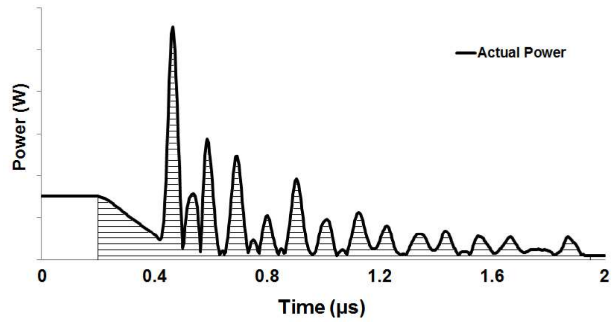


Fig. 2(b) Measured SiC Schottky diode instantaneous power

II. Model Development

The switching energy models are based on detailed linearized waveforms of the measured characteristics. In the case of the silicon PiN diode, the waveforms account for the inductive voltage overshoot and the reverse recovery current as shown in Fig. 1(a). The linearized waveforms of the PiN diode switching transients are shown in Fig. 3, where the different switching phases have been divided into different time segments. In the case of the Schottky diode model, the output oscillations are modeled by damped sinusoidal waveforms as shown in Fig. 2(a) with the maximum amplitude equal to the peak inductive voltage overshoot and the attenuation determined by the parasitic RLC components of the diode's equivalent circuit which is shown in Fig. 4. In section A below, the PiN diode model is described whereas in section B, the Schottky diode's model is described.

A. PiN Diode

The total switching energy of the PiN diode will be the integration of the switching power over time. This is shown as the lower graph in Fig. 3. The switching energy is comprised of 6 areas with algebraic functions that can easily be integrated in time. The time intervals are expressed in terms of the switching parameters of the device [10]. The equation for the switching energy of the Schottky diode is shown below:

$$E_{SW} = E_{SW1} + E_{SW2} + \sum_{n=3}^{5} E_{SWn} \qquad (1)$$

The switching energy components E_{SWn} for n=1 to 6 can be expressed mathematically as shown below

$$E_{SW1} = \frac{I_F^2 V_D}{2\left(dI_{RR+} / dt \right)} \qquad (2)$$

$$E_{SW2} = \frac{V_D}{2}\left(I_{RR} - t_1 \frac{dI_{RR-}}{dt} \right)\left(\frac{I_{RR}}{dI_{RR-}/dt} - \Delta t \right) \qquad (3)$$

$$E_{SWn} = \frac{a_n c_n}{3}(t_{n+1}^3 - t_n^3) + \left(\frac{a_n d_n + b_n c_n}{2} \right)(t_{n+1}^2 - t_n^2)$$
$$+ b_n d_n (t_{n+1} - t_n)$$

Where the coefficients in equation (3) and the temperature dependency of the PiN diodes parameters are given in [10]

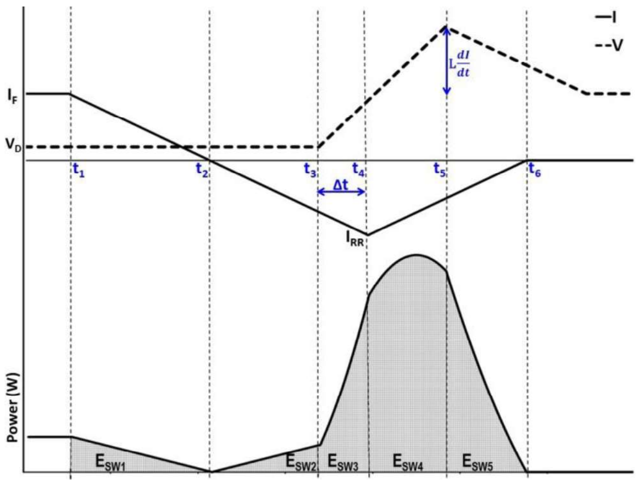


Fig. 3. Linearized power plot with the current and voltage transients divided into different segments.

B. Schottky Diode

Silicon carbide devices are previously shown to have many advantages in applications [11-13]. However, they are also known to exhibit oscillations in the output characteristics. To model the switching energy of the Schottky diode, it is important to first determine the equivalent circuit of the diode during turn-off transient. Fig. 4 shows the diode represented by a depletion capacitance (C_{AK}), a depletion resistance (R_{AK}), a stray inductance (L_{stray}) and a parasitic series resistance (R_S) [14].

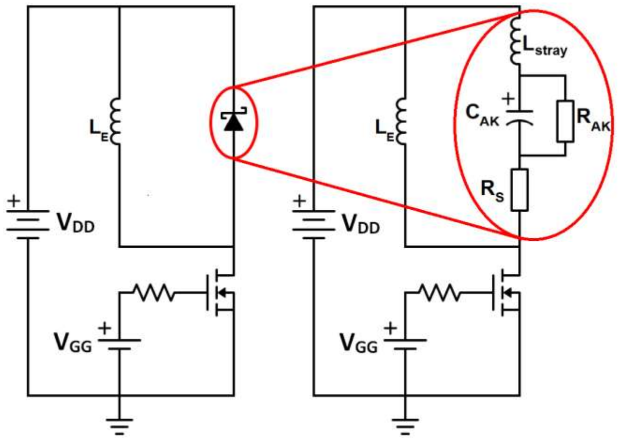


Fig. 4. Clamped inductive switching circuit showing diode equivalent circuit.

The depletion capacitance is due to the rising diode voltage which depletes the semiconductor underneath the Schottky contact, the depletion conductance is due to lossy nature of the capacitance, the stray inductance and resistance is be due to packaging and wiring of the test circuit. This circuit is a 2nd order circuit which can be solved easily in the frequency domain with expressions for the attenuation, the oscillation frequency and the damping. The diode output voltage can be expressed by the equation below:

$$V_{AK} = \frac{V_D}{1+sR_G C_{GD}} \frac{s\left(\frac{R_S}{L_{Stray}}\right) + \frac{R_{AK}+R_S}{L_{stray}R_{AK}C_{AK}}}{s^2 + s\left(\frac{R_{AK}R_S C_{AK}+L_{stray}}{L_{stray}R_{AK}C_{AK}}\right) + \frac{R_{AK}+R_S}{L_{stray}R_{AK}C_{AK}}} \quad (4)$$

Therefore the attenuation and oscillation frequency of the diodes voltage oscillations will be given by

$$\alpha_V = \frac{R_{AK}R_S C_{AK} + L_{stray}}{2L_{stray}R_{AK}C_{AK}} \quad (5)$$

$$\omega = \sqrt{\frac{R_{AK}+R_S}{L_{stray}R_{AK}C_{AK}}} \quad (6)$$

The switching energy of the Schottky diode is similarly calculated by integrating the switching power transient characteristic shown in Fig. 5. They are divided into 3 section for the ease of driving the analytical equations for the switching energy. The total switching energy is sum of E_{SW1}, E_{SW2} and E_{SW3}.

$$E_{SW1} = \int_{t_1}^{t_2} Pdt = \int_{t_1}^{t_2} V_{ON}\left(I_{ON} - \frac{dI_{DS}}{dt}t\right)dt \quad (7)$$

$$E_{SW2} = \int_{t_2}^{t_3} Pdt = \int_{t_2}^{t_3} I_{PR}e^{-\alpha_I t} \cdot \left(\frac{dV}{dt}t - \frac{I_{ON}}{dI/dt}\frac{dV}{dt}\right)dt \quad (8)$$

$$E_{SW3} = \int_{t_3}^{t_4} Pdt = \int_{t_3}^{t_4} (I_{PR}e^{-\alpha_I t}) \cdot \left(V_{DC} + L\frac{dI_{DS}}{dt}e^{-\alpha_V t}\sin(\omega t)\right)dt \quad (9)$$

Fig. 6(b) shows the switching power transient of the diode illustrating the damped nature of the ringing. The time intervals for the integration (t_1, t_2, t_3 and t_4) in Fig. 5 can be represented in terms of the diode switching parameters as shown in [15]. When performing the integration in Fig. 5, the time interval for E_{SW3} is taken as 5 times of the time constant of the decaying sinusoid. The temperature dependency of the switching characteristics of the Schottky diode has been outlined in [15].

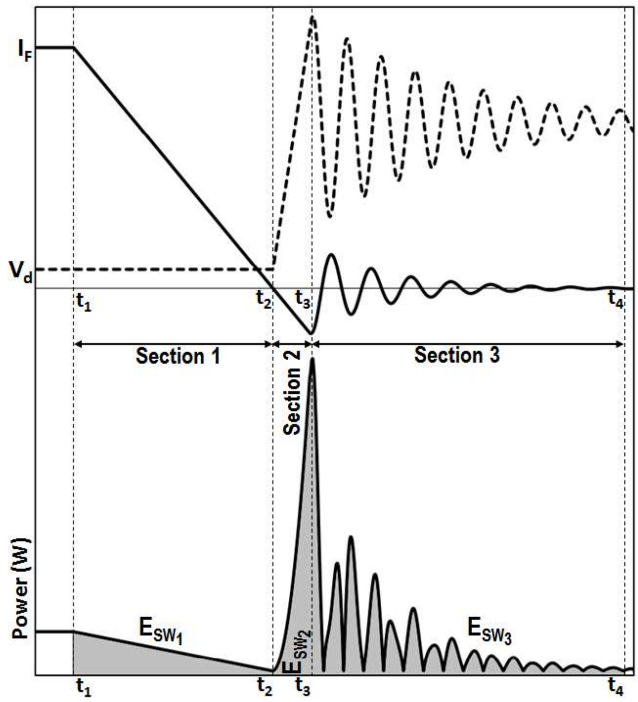


Fig. 5. Diode circuit model with the representation values of shown.

III. MODEL VALIDATION WITH EXPERIMENTAL MEASUREMENTS

The switching energy of the diodes was measured using a clamped inductive switching test set-up and the double pulse technique. The rig consists of a DC power supply, a DC link bank capacitor, a 7.5 mH inductor, a gate drive system, a thermal chamber and the devices under test. The diode is used as a high side device connected in parallel with an inductor and commutating current with a low side transistor. As the transistor is switched on, the inductor is charged to a pre-defined current determined by the duration and the inductance. The transistor is then switched off and the current is commutated to the diode. Fig. 6(a) shows the turn-off power of the 1.2 kV silicon PiN diode whereas Fig. 6(b) shows that of the SiC Schottky diode. Both are switched with a gate resistance of 10 Ω and the measurements have been performed at different ambient temperatures. It can be seen that the PiN reverse charge increases with temperature whereas the Schottky diode's output ringing characteristic is temperature invariant. Fig. 6(a) shows the switching power transient of the silicon PiN diode at different ambient temperatures where it can be seen that the switching power increases with temperature. This is due to increased carrier lifetime with temperature which causes a higher reverse charge. Also an increase in the peak power with the switching rate is seen which is due to the fact that the peak reverse recovery current and the peak voltage overshoot of the PiN diode both increase with the switching rate thereby resulting in a high peak of power.

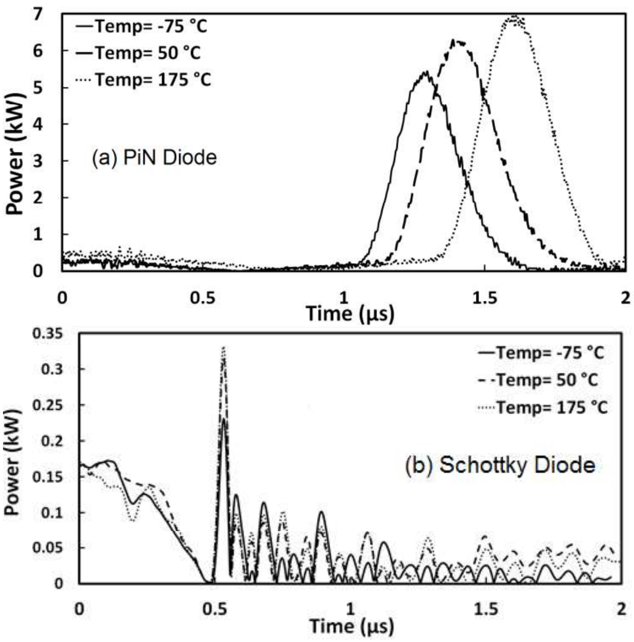


Fig. 6. Measured turn-off power as a function of temperature for a) silicon PiN diode and b) SiC Schottky diode

Fig. 6(b) shows the switching power transients at different temperatures in which due to the oscillations of current and voltage waveforms (as shown in Fig. 2(b)) of silicon carbide schottky diode, the power is also oscillating, while the total is significantley lower than that of PiN diode and is decreasing with increase in temperature unlike Silicon PiN diode. Fig. 7(a) shows the turn-off switching energy for the silicon PiN diode as a function of the gate resistance (which modulates the switching rate) and the temperature whereas Fig. 7(b) shows a similar characteristics for the SiC Schottky diode. It can be seen from Fig. 7 that under identical switching conditions, the Schottky diode has significantly smaller switching energy compared with the PiN diode. Both diodes show their lowest switching energies at intermediate switcing rates. At high switching rates, the switching energies in both diodes are dominated by high voltage overshoots resulting from parasitic inductances. In the case of the PiN diode, the high peak reverse recovery current is an additional problem whereas for the Schottky diode, oscillations in the diode voltage are the problem. As the gate resistance is increased in the case of the Schottky diode, the oscillations become better damped and the switching energy reduces as a result.

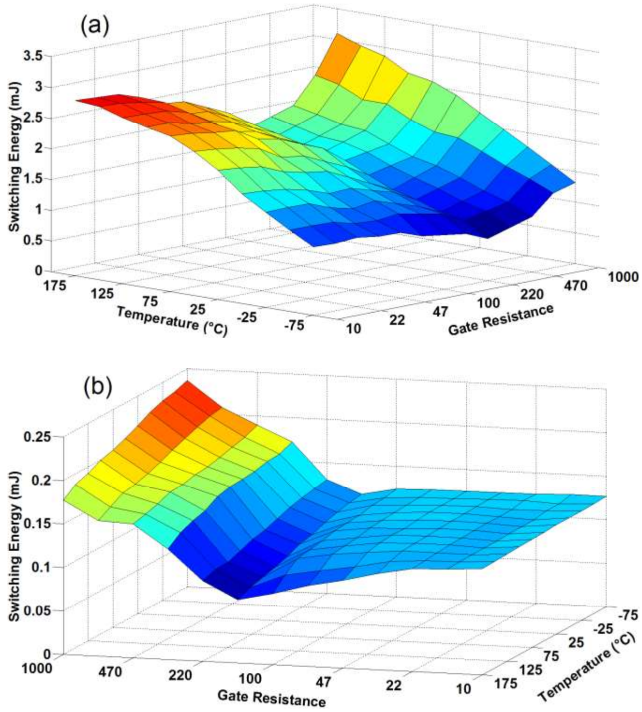


Fig. 7. Turn-off switching energy as a function of temperature and *dI/dt* for a) Silicon PiN diode and b) SiC Schottky diode

Fig. 8(a) shows the modeled and measured switching energy for the PiN diode as a function of the gate resistance of the low side switching transistor. Fig. 8(b) shows a similar plot for the SiC Schottky diode. Fig. 8(c) shows the measured and modeled switching energy as a function of temperature for the PiN diode whereas Fig. 8(d) shows a similar characteristic for the Schottky diode. It can be seen from Fig. 8 that the model is capable of yielding results that closely match the experimental measurements with some degree of margin of error. In the next section of the paper, a thermal network is combined with the model to yield temperature information as a function of technology and switching conditions. This will also shows that the expected temperature rise from the switchings of the SiC Schottky diode is lower than that of the silicon PiN diode. This is a result of lower switching energy and switching power as seen in Fig. 6 and Fig. 7.

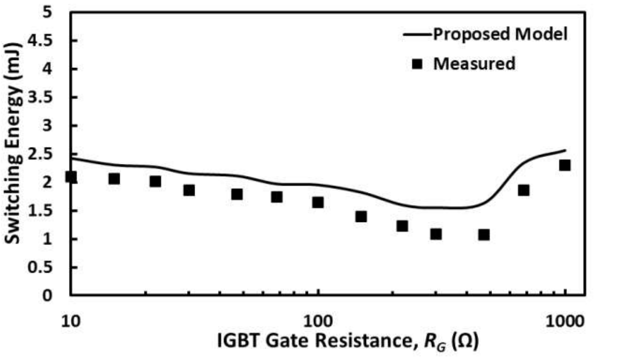


Fig. 8(a) Measured and modeled switching energy of the silicon PiN diode as a function of IGBT gate resistance

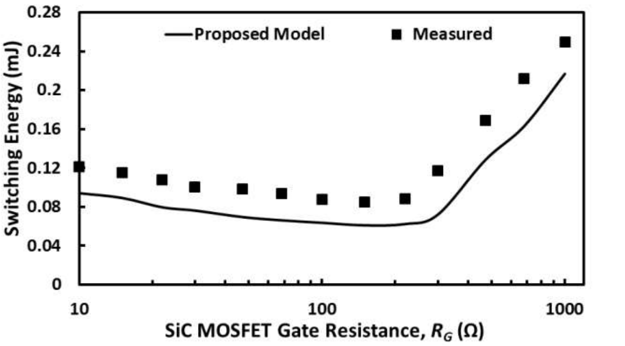


Fig. 8(b) Measured and modeled switching energy of the SiC Schottky diode as a function of SiC MOSFET gate resistance

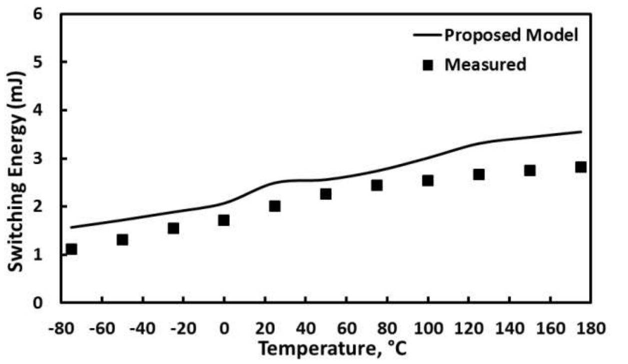


Fig. 8(c) Measured and modeled switching energy of the silicon PiN diode as a function of temperature

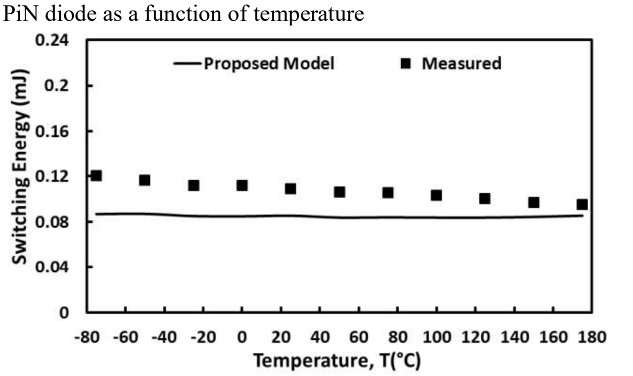


Fig. 8(d) Measured and modeled switching energy of the SiC Schottky diode as a function of temperature

IV. Impact on Temperature

The waveform derived models for the turn-off transients in the PiN and Schottky diodes will be used to estimate the device junction temperature during repetitive switching. By combining the model with a thermal network derived for the device, a fast, accurate and inexpensive method of predicting temperature profiles for different switching frequencies and gate resistances has been developed. Simply by modifying the parameters used in the model, the impact of the switching frequency and electrical time constant of the switching device on the transient thermal characteristics can be assessed. This will be done by deriving the thermal network of the device from the transient thermal impedance curve and using the results of the electrical model as an input. The transfer function of the device's thermal network is derived by curve fitting the transient thermal impedance curve. Fig. 9(a) shows the process for the silicon PiN diode whereas Fig. 9(b) shows that of the SiC Schottky diode.

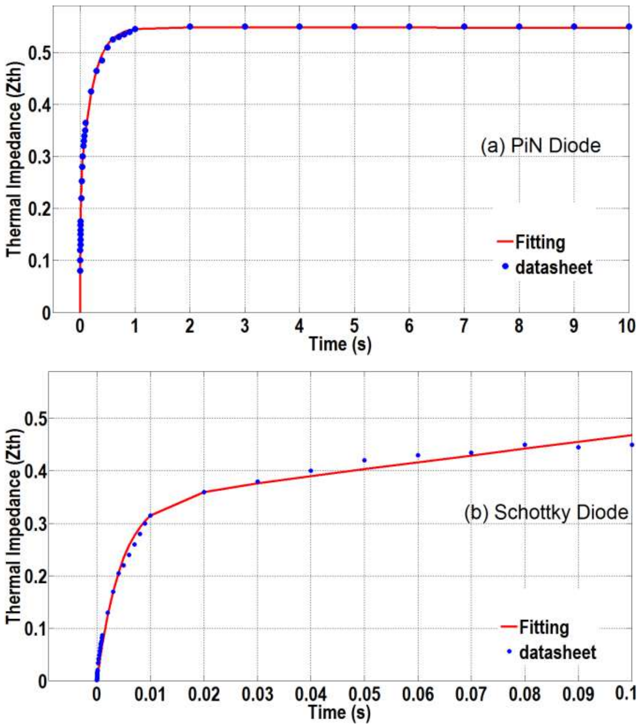


Fig. 9. Thermal impedance fitting data using MATLAB

The thermal resistances and capacitances are then extracted from the transfer function shown in equation (14) . The thermal resistances and capacitances of a Forster thermal network is generated and converted into a Cauer Network as shown in Table.1. Table.2 shows the thermal resistance and capacitance values for the SiC Schottky and PiN diodes for the equivalent Cauer Network.

$$Z_{th} = R_1 \times (1 - e^{(-t/\tau_1)}) + R_2 \times (1 - e^{(-t/\tau_2)}) + R_3 \times (1 - e^{(-t/\tau_3)}) \quad (10)$$

	1	2	3
R	0.8407 K/W	0.2929 K/W	0.1841 K/W
τ	33.43 s	0.0036 s	0.0469 s

Table. 1. Foster thermal network

	1	2	3
R	0.3208 K/W	0.1587 K/W	0.8382 K/W
C	0.01172 J/K	0.285 J/K	39.59 J/K

Table. 2. Cauer thermal network

The thermal circuit simulation is shown in Fig. 10 where a 3 layer Cauer thermal network is used. The input power pulse is comprised of the turn-on loss, the conduction loss and the turn-off loss. For both the SiC Schottky and PiN diodes, the turn-off loss is the dominant component of the total losses. In the case of the silicon PiN diode, this is due to the reverse recovery charge, whereas in the case of the SiC Schottky diode, this is due to electromagnetic oscillations in the diode voltage during turn-off. Fig. 11(a) shows the switching power pulse for the SiC Schottky diode whereas Fig. 11(b) shows that of the PiN diode. It is assumed that the duty cycle of the diode is 50% and that the leakage losses during the off-state are small enough to be neglected.

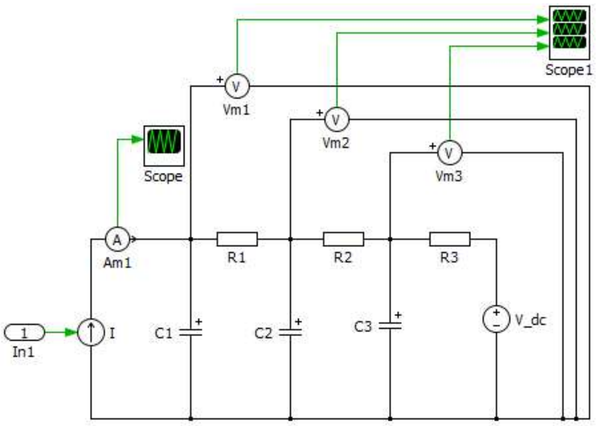
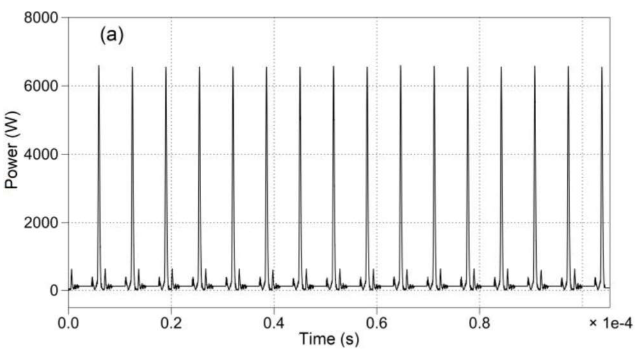


Fig. 10. The Thermal simulation circuit in PLECS



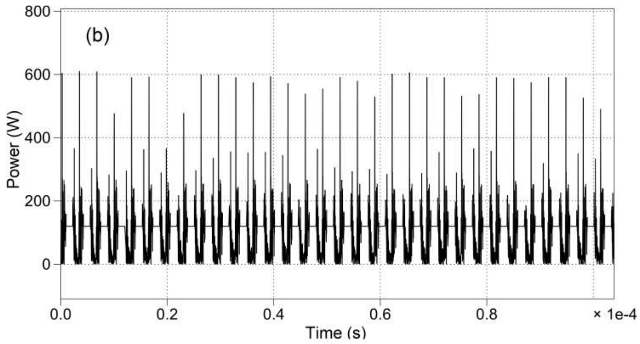


Fig. 11. Power waveforms for (a) Silicon PiN Diode and (b) SiC Schottky Diode

The results of the simulation are shown in Fig. 12 where the junction, case and heatsink temperature profile has been plotted against time for the PiN diode and Schottky diode. In Fig. 12, the switching frequency is 15 kHz and the gate resistance of the bottom side transistor used for current commutation is 10 Ω. It can be seen from Fig 12, that the Schottky diode has a significantly lower steady state temperature compared to the PiN diode. This is due to the lower instantaneous switching power losses in the SiC Schottky diode. Increasing the switching frequency in power converters is a well-known technique of increasing power density because smaller passive components can be used. However, this can be at the expense of increased operating junction temperature of the power semiconductor devices. The impact of higher switching frequencies on junction temperatures can be estimated quantitatively using the model. Fig. 13 shows the temperature profiles at a higher switching frequency of 30 kHz. It can be seen that compared to 15 kHz, the operating temperature has increased by over 50%. This is because the switching losses are a significant component of the total power losses even more so than the conduction losses. The advantage of the SiC Schottky diode, as can be seen from Fig. 13, that maximum operating temperature at higher switching frequencies is significantly lower compared to the PiN diode.

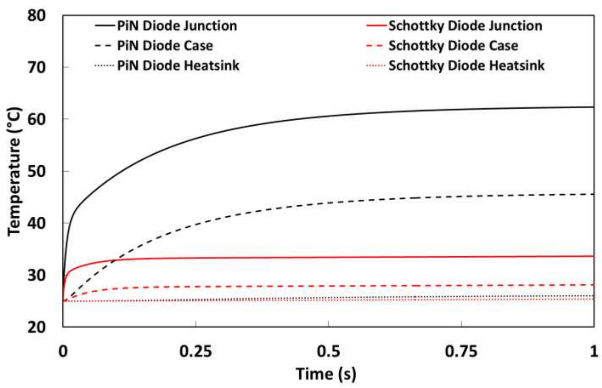


Fig. 12. PiN Diode Temperature rise at 15 kHz switching

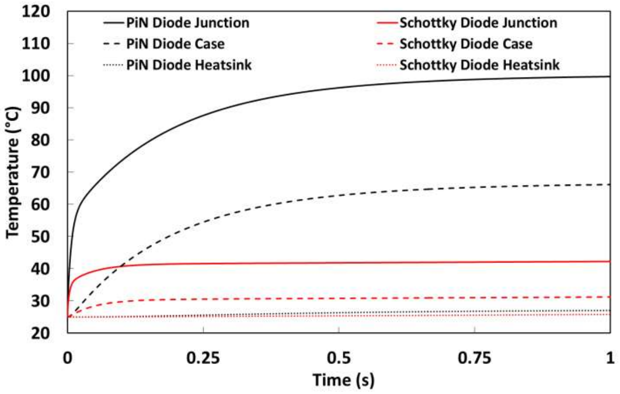


Fig. 13. Schottky Diode temperature rise at 30 kHz switching

Fig. 14 shows the steady state junction temperature as a function of the gate resistance of the low side switching transistor for the SiC Schottky diode and silicon PiN diodes. The switching frequency used is 15 kHz and the ambient temperature is 25 °C. The results show a significantly lower junction temperature for the SiC Schottky diode compared with the silicon PiN diode. Furthermore, very high switching rates can be avoided to obviate the problems of excessive ringing in the Schottky diode and excessive peak voltage overshoots and peak reverse recovery currents in the case of the PiN diode.

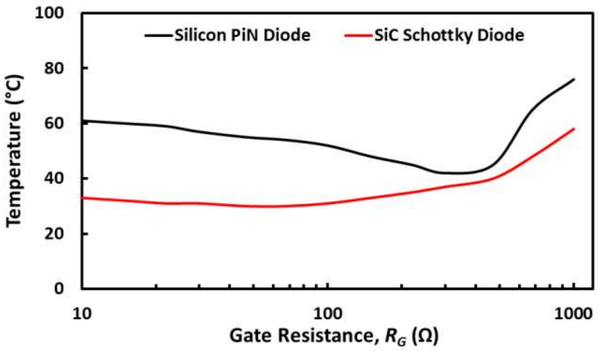


Fig. 14. Steady state junction temperature at 15 kHz switching as function of gate resistance.

V. Conclusion

Waveform based switching models and thermal simulations have been presented for silicon PiN and SiC Schottky diodes. By linearizing the voltage and current waveforms and integrating them, the switching energy can be calculated for different switching rates and temperatures. The switching behavior of PiN diodes is affected by reverse recovery while that of the Schottky diode by ringing of the diode voltage. The switching power is used as an input into a thermal network, which then generates the temperature transient profile of the diode. This can be used to estimate the operating temperatures of the devices as a function of the gate resistance and switching rate. This is important for reliability and converter design.

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