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The Impact of Temperature and Switching Rate on the Dynamic Characteristics of Silicon Carbide Schottky Barrier Diodes and MOSFETs

Saeed Jahdi, Student Member, IEEE, Olayiwola Alatise, Petros Alexakis, Student Member, IEEE, Li Ran, Senior Member, IEEE, and Philip Mawby, Senior Member, IEEE

Abstract—SiC Schottky Barrier Diodes (SBDs) are prone to electromagnetic oscillations in the output characteristics. The oscillation frequency, peak voltage overshoot and damping are shown to depend on the ambient temperature and the MOSFET switching rate (dI/dt). In this paper, it is shown experimentally and theoretically that dI/dt increases with temperature for a given gate resistance during MOSFET turn-ON and reduces with increasing temperature during turn-OFF. As a result of this, the oscillation frequency and peak voltage overshoot of the SiC-SBD increases with temperature during diode turn-OFF. This temperature dependency of the diode ringing reduces at higher dI/dt and increases at lower dI/dt. It is also shown that the rate of change of dI/dt with temperature (d²I/dt²/dT) is strongly dependent on the R_g and using fundamental device physics equations, this behavior is predictable. The dependence of the switching energy on dI/dt and temperature in 1.2 kV SiC-SBDs is measured over a wide temperature range (−75 °C to 200 °C). The diode switching energy analysis shows that the losses at low dI/dt are dominated by the transient duration and losses at high dI/dt are dominated by electromagnetic oscillations. The model developed and results obtained are important for predicting EMI, reliability and losses in SiC MOSFET/SBDs.

Index Terms—Power MOSFET, Schottky diode, Silicon carbide, Temperature, Oscillation

I. INTRODUCTION

Silicon carbide (SiC) unipolar devices have now become commercially available with voltage ratings of 1.2 kV and higher voltage ratings are expected in the near future [1]–[5]. These temperature rugged and power dense devices have repeatedly demonstrated improved energy conversion efficiency and reduced losses when implemented in power converters [6]–[13]. Since these devices are unipolar and are therefore not limited by minority carrier storage from conductivity modulation, they are fast switching and can thus be implemented in high frequency applications. High switching frequency can enable size reduction of passive components which is a significant advantage in applications where space or size is critical to cost. This may include aeronautical and marine applications. However, advances in packaging technologies are not catching up with devices. Parasitic inductances in power modules induce electromagnetic oscillations in output characteristics which can be detrimental through the additional losses and reduced reliability [14]–[18]. These parasitic inductances depend strongly on the architecture of the power module and its layout. However, as the switching frequency increases, even small parasitic inductances cannot be ignored because of the high dI/dt. It is well understood that SiC Schottky diodes are particularly prone to ringing as parasitic capacitances and inductances interact to cause RLC resonance [19]. The dependence of this ringing on the ambient temperature and the rate of change of current with time (dI/dt) of the switching MOSFET has not been fully characterized and understood. The deployment of these 1.2 kV SiC power devices in hard-switched high temperature modules will require more understanding in the dependence of switching energy on temperature and switching rate [20]. A solution to this ringing problem could be the use of soft-switching techniques where zero current and/or zero voltage switching can be implemented. However, this will increase the cost and complexity of converters at the power levels targeted by SiC.

In this paper, 1.2 kV SiC MOSFETs and SiC Schottky diodes have been tested in a clamped inductive switching test rig. The devices have been tested with a wide range of gate resistances (10 Ω to 1000 Ω) at ambient temperatures ranging from −75 °C to 200 °C. Using fundamental device equations, the dependence of dI/dt on the temperature and gate resistance is derived and shown to accurately replicate the experimental measurements. This temperature dependence is used to explain the performance of the Schottky diode in terms of energy losses. In Section II of this paper, the experimental measurements are presented. In Section III, the MOSFET switching and diode models are presented and compared with the experimental measurements. In Section IV, the switching performance of the silicon carbide Schottky barrier diode is analyzed while Section V concludes the paper.

II. CLAMPED INDUCTIVE SWITCHING MEASUREMENTS AND EXPERIMENTAL TEST RIG DESIGN

The clamped inductive switching test rig comprises of the devices under test (1.2 kV/30 A SiC MOSFETs and diodes),
a 7.4 mH commutation inductor, gate drive system and a power supply. A schematic of the test set-up is shown in Figure 1. Shown in Figure 2 is a picture of the test rig. The SiC MOSFET has the datasheet reference of SCH2080KE while the SiC Schottky Diode is SDP30S120.

![Fig. 1. Clamped Inductive Switching Test Rig Schematic](image1)

![Fig. 2. Quasi-Switching Test Rig Components: 1- Thermal Chamber 2- Function Generator 3- Digital Oscilloscope 4- Gate Drive Power Supplies 5-Bank Capacitors 6- Inductors 7- Gate Drive System](image2)

The switching waveforms were captured on a Tektronix TDS5054 digital phosphor oscilloscope which has a bandwidth of 500 MHz and the static characteristics were measured on a Tektronix curve tracer. The current is measured using a Tektronix TCP303 current probe connected to the oscilloscope. This circuit emulates one phase-leg of a 3 phase voltage source converter in which free-wheeling diodes (FWD) conduct current in the opposite direction to the MOSFET i.e. the diodes rectify while the MOSFETs invert. The environmental chamber shown in Figure 2 is a Tenney Environment chamber being able to vary the temperature within a range of –75 °C to 200 °C. The measurements here have been performed at a temperature range between –75 °C to 200 °C. Therefore the measurements have been performed at the above mentioned temperature range. However, for higher temperatures and harsh environments such as in aeronautical applications, bare dies should be packaged exclusively. It should be noted that emergence of SiC devices have raised the high temperature expectations considerably as they are proven to act better in such conditions compared to their silicon counterparts [21]–[24]. The power supply provides the charge voltage and the inductor is pre-charged to enable continuous current through the MOSFET/FWD arrangement. This is achieved by using the double pulse technique where the MOSFET is initially switched ON to charge the inductor to a defined current level before the main switching test is performed. The gate of the MOSFET is driven by a gate drive circuit comprised of a voltage source, a pulse generator and an optocoupler chip jointly supplying 18 V through the gate resistor for a period of 20 µs. When the MOSFET is switched OFF, majority of the supply voltage falls across it hence the FWD is forward biased and conducting. The voltage drop across the FWD during this phase will be due to its on-state resistance. As the MOSFET is switched ON and starts conducting, the current is commutated away from the FWD and the voltage across the MOSFET starts to fall to its on-state voltage drop. This causes the FWD to become reverse biased and blocking.

### III. Model Development

The dependence of the turn-ON $dI_{DS}/dt$ on temperature can be accounted for using the fundamental device equations. The MOSFET and the diode share the same total inductor current, hence, the turn-ON of the MOSFET and turn-OFF of the diode occurs within the same switching transient. Equation (1a) below is the gate charging transient characteristic during turn-ON (Equation (1b) is for turn-OFF) where $V_{GS}$ is the gate-source voltage, $V_{GG}$ is the gate driver voltage, $R_G$ is the gate resistance, $t$ is time and $C_{iss}$ is the input capacitance.

$$V_{GS} = V_{GG} \left( 1 - \exp\left( -\frac{t}{R_G C_{iss}} \right) \right) \quad (1a)$$

$$V_{GS} = V_{GG} \exp\left( -\frac{t}{R_G C_{iss}} \right) \quad (1b)$$

The rate of change of $V_{GS}$ with time $(dV_{GS}/dt)$ is evaluated simply by taking the derivative of (1a) with time for turn-ON and (1b) for turn-OFF which results in:

$$\left. \frac{dV_{GS}}{dt} \right|_{ON} = \frac{V_{GG}}{R_G C_{iss}} \exp\left( -\frac{t}{R_G C_{iss}} \right) \quad (2a)$$

$$\left. \frac{dV_{GS}}{dt} \right|_{OFF} = -\frac{V_{GG}}{R_G C_{iss}} \exp\left( -\frac{t}{R_G C_{iss}} \right) \quad (2b)$$

Equation (3) is the well-known equation for the drain current of a fully inverted long channel MOSFET in saturation.

$$I_{DS} = \frac{B}{2} (V_{GS} - V_{TH})^2 \quad (3)$$
where
\[ B = \frac{W \mu C_{OX}}{L} \]

\( V_{TH} \) is the threshold voltage, \( W \) is the width of the device, \( \mu \) is the effective mobility of the carriers, \( C_{OX} \) is the effective capacitance density of the gate insulator and \( L \) is the channel length of the device. Taking the derivative of (3) with respect to time and substituting \( dV_{GS}/dt \) yields \( dI_{DS}/dt \) as shown below in (4a) for turn-ON and (4b) for turn-OFF.

\[
\begin{align*}
\frac{dI_{DS}}{dt} \bigg|_{ON} &= B \left( V_{GS} - V_{TH} \right) \frac{V_{GG}}{R_{G}C_{iss}} \exp\left( -\frac{t}{R_{G}C_{iss}} \right) \quad (4a) \\
\frac{dI_{DS}}{dt} \bigg|_{OFF} &= B \left( V_{GS} - V_{TH} \right) \frac{-V_{GG}}{R_{G}C_{iss}} \exp\left( -\frac{t}{R_{G}C_{iss}} \right) \quad (4b)
\end{align*}
\]

The dependence of \( V_{TH} \) and its temperature dependency is given by \([25]\) as:

\[
V_{TH} = V_{FB} + \frac{2KT}{q} \ln\left( \frac{N_A}{n_i} \right) + \sqrt{4Ae_{si}KTN_A \ln\left( \frac{N_A}{n_i} \right)} \frac{C_{OX}}{R_{G}C_{iss}} \quad (5)
\]

In (5) above, \( N_A \) is the p-body doping, \( n_i \) is the intrinsic carrier concentration, \( C_{OX} \) is the oxide capacitance density of the gate dielectric and \( V_{FB} \) is the flat-band voltage (due to fixed oxide charge and the metal-semiconductor work-function difference). Equations (4a) and (4b) predict that \( dI_{DS}/dt \) will increase with temperature during turn-ON and decrease with temperature during turn-OFF. This is due to the negative temperature coefficient of the MOSFET threshold voltage as a result of thermally induced bandgap narrowing. As a result, \( V_{TH} \) will reduce at higher temperatures hence, \( dI_{DS}/dt \) will increase during turn-ON and decrease during turn-OFF according to (4). The experimental measurements of \( dI_{DS}/dt \) shown in Figure 3 for turn-ON and Figure 4 for turn-OFF agree with the trends predicted by Equations (4a) and (4b). In these figures, the temperature of the thermal chamber that houses the devices is set to 25 °C. Figure 3 shows measurements and calculations of the turn-ON \( dI_{DS}/dt \) as a function of \( R_{G} \) for the SiC MOSFETs. The calculations are based on values taken from the SCH2080KE datasheet as \( C_{iss} = 2nF \), the threshold voltage at 25 °C is 5 V and \( B \) ranges from 0.5 to 1. The values of \( t \) used in the calculations in (4a) and (4b) correspond to the switching time value at which \( dI_{DS}/dt \) is calculated and \( V_{GS} \) is calculated from the equation of the plateau voltage (\( V_{GP} \)). The plateau voltage is calculated using the standard equations from [25] and it is assumed that the current switches between the time taken for \( V_{GS} \) to rise from \( V_{TH} \) to \( V_{GP} \) during turn-ON and fall from \( V_{GP} \) to \( V_{TH} \) during turn-OFF. The measurements and calculations show good agreement over the wide range of \( R_{G} \) as can be seen in Figure 3. Figure 4 shows the measurements and calculations of \( dI_{DS}/dt \) as a function of \( R_{G} \) during turn-OFF.

There is reasonably good agreement between the measured and calculated trends however, there is some measurement noise which introduces some error especially at faster switching speeds. The rate of change of \( dI_{DS}/dt \) with respect to \( R_{G} \) can be evaluated by taking the derivative of (4) with respect to \( R_{G} \).

This derivative is shown in (6) below for turn-ON. In the case of the turn-OFF, (6) is simply multiplied by −1.

\[
\frac{d^2I_{DS}}{dt^2} = B \left( V_{TH} - V_{GS} \right) \frac{V_{GG}}{R_{G}^2C_{iss}} \exp\left( -\frac{t}{R_{G}C_{iss}} \right) \left( \frac{t}{R_{G}C_{iss}} - 1 \right) \quad (6)
\]

The dependence of \( d^2I_{DS}/dt^2 \) \( R_{G} \) on \( R_{G} \) can be observed by plotting the latter as a function of the former which is shown for the measurements and calculations in Figure 5 for turn-ON and Figure 6 for turn-OFF. Figure 5 shows good agreement between the experimental measurements and the calculations for turn-ON based on (6). Again, in Figure 6, there is some disparity at low \( R_{G} \).
due to the intrinsic carrier concentration (\(n_i\)) is invariant with respect to temperature at low temperatures. This negative temperature coefficient as a result of thermally generated carriers due to bandgap narrowing (\(dV_{TH}/dT\) is negative) and \(B\) (which depends on the on-state resistance) is invariant with respect to temperature at low temperatures. This negative temperature coefficient of the threshold voltage can be seen in (5) and is due to the intrinsic carrier concentration \((n_i)\) which increases with temperature due to increased thermal generation of carriers across the bandgap. Hence, according to (5), \(V_{TH}\) reduces as \(n_i\) increases. At higher temperatures \(dB/dT\) is negative as a result of the temperature dependence of the effective mobility i.e. phonon scattering induced mobility degradation reduces the effective mobility as the temperature is increased. Hence (7) can be re-written for low temperatures as:

\[
\frac{d^2I_{DS}}{dt\,dT} = \frac{V_{GG}}{R_G C_{iss}} \exp\left(-\frac{t}{R_G C_{iss}}\right) \left( (V_{GS} - V_{TH}) \frac{dB}{dT} - B \frac{dV_{TH}}{dT} \right)
\]  

(7)

In SiC MOSFETs, \(V_{TH}\) has a negative temperature coefficient as a result of thermally generated carriers due to bandgap narrowing (\(dV_{TH}/dT\) is negative) and \(B\) (which depends on the on-state resistance) is invariant with respect to temperature at low temperatures. This negative temperature coefficient of the threshold voltage can be seen in (5) and is due to the intrinsic carrier concentration \((n_i)\) which increases with temperature due to increased thermal generation of carriers across the bandgap. Hence, according to (5), \(V_{TH}\) reduces as \(n_i\) increases. At higher temperatures \(dB/dT\) is negative as a result of the temperature dependence of the effective mobility i.e. phonon scattering induced mobility degradation reduces the effective mobility as the temperature is increased. Hence (7) can be re-written for low temperatures as:

\[
\frac{d^2I_{DS}}{dt\,dT} = \frac{V_{GG}}{R_G C_{iss}} \exp\left(-\frac{t}{R_G C_{iss}}\right) \left( B \frac{dV_{TH}}{dT} \right)
\]  

(8)

In the case of turn-OFF, (8) is multiplied by \(-1\). It can be seen from (8) that \(dI_{DS}/dt\) increases with increasing temperature during turn-ON since the 2nd order derivative is positive and \(dI_{DS}/dt\) decreases with increasing temperature during turn-OFF since the 2nd order derivative is negative. Figure 7 shows the measured turn-ON \(dI_{DS}/dt\) as a function of \(R_G\) for different gate resistances ranging from \(-75\) °C to \(200\) °C whereas Figure 8 shows the measured turn-ON \(dI_{DS}/dt\) as a function of temperature for different gate resistances. It can be seen from Figure 7 and 8 that \(dI_{DS}/dt\) increases with temperature during turn-ON in agreement with (7) and (8); however, the rate of change of \(dI_{DS}/dt\) with temperature is not uniform for all the gate resistors. This trend can also be observed in other published reports on the performance of SiC MOSFETs at different temperatures where \(dI_{DS}/dt\) can be seen to increase with temperature during turn-ON [26], [27] or \(dV_{DS}/dt\) (meaning the absolute value, i.e. the magnitude of \(dV_{DS}/dt\)) is shown in increase with temperature at turn-ON [28].

Figure 9 shows the turn-OFF \(|dI_{DS}/dt|\) (meaning the absolute value, i.e. the magnitude of \(dI_{DS}/dt\)) as a function of \(R_G\) for different temperatures where it can be seen that \(dI_{DS}/dt\) decreases with increasing temperature as predicted by (7) and (8). Figure 9 shows the turn-OFF \(dI_{DS}/dt\) as a function of temperature for different gate resistances. The dependence of \(d^2I_{DS}/dt\,dT\) on \(R_G\) can further be considered by looking at how the former changes with respect to the latter. Figure 11 shows experimental measurements of the turn-ON \(d^2I_{DS}/dt\,dT\) as a function of \(R_G\) for the different ambient temperatures. It can be seen from the measurements in Figure 11 that the variation of \(dI_{DS}/dt\) with temperature is small at larger and smaller values of \(R_G\) (\(d^2I_{DS}/dt\,dT\) is small) and is much larger at intermediate values of \(R_G\) (\(d^2I_{DS}/dt\,dT\) is larger) i.e. \(d^2I_{DS}/dt\,dT\) as a function of \(R_G\) exhibits a bell shaped characteristic. Figure 12 shows the calculated \(d^2I_{DS}/dt\,dT\) as a function of \(R_G\) at the different temperatures using (7) and (8) where the same bell shaped characteristic can be observed at...
different temperatures. It can also be seen from Figure 11 that the maximum turn-ON $d^2I_{DS}/dt^2$ decreases as temperature increases. Equations (7) and (8) explain this behavior. It can be seen from (7) and (8) that as $R_G$ is reduced, $V_{GG}/R_GC_{iss}$ rises and $\exp(-t/R_GC_{iss})$ reduces. Hence, a plot of $d^2I_{DS}/dt^2$ as a function of $R_G$ will show a bell shaped characteristic as a result of the competing effects.

Fig. 9. Measured $dI_{DS}/dt$ as a function of $R_G$ at different temperatures during turn-OFF.

Fig. 10. Measured $dI_{DS}/dt$ as a function of temperature for different gate resistances during turn-OFF.

Fig. 11. Measured $d^2I_{DS}/dt^2$ as a function of $R_G$ at different temperatures.

Fig. 12. Calculated $d^2I_{DS}/dt^2$ as a function of $R_G$ at different temperatures.

IV. DIODE SWITCHING ANALYSIS

The response of the diode output voltage characteristics to the MOSFET switching is determined primarily by the transfer function of the diode, the gate resistance of the gate driver and the junction temperature of the device. The transfer function of the diode can be determined by the equivalent circuit of the diode which is represented by a series resistance ($R_S$), diode depletion capacitance ($C_{AK}$), diode depletion resistance ($R_{AK}$) and the stray packaging inductance ($L_{stray}$) as shown in Figure 13. The parasitic capacitance arises from the depletion capacitance of the diode, the series resistance arises from the resistance of the drift region and the stray inductance arises from the packaging.

Fig. 13. Circuit schematic of experimental test rig showing the equivalent circuit of the diode.

The diode voltage ($V_{AK}$) can then be calculated as the product of the diode transfer function and an input function that represents the switching of the MOSFET. This transfer function can be represented by the equation shown below:

$$V_{AK} = \frac{V_{DD}}{1 + sR_GC_{GD}} \times \frac{s \left( \frac{R_S}{L_{stray}} \right) + \frac{R_{AK} + R_S}{L_{stray}R_{AK}C_{AK}}}{s^2 + s \left( \frac{R_{AK}R_SC_{AK} + L_{stray}}{L_{stray}R_{AK}C_{AK}} \right) + \frac{R_{AK} + R_S}{L_{stray}R_{AK}C_{AK}}}$$

(9)
where $C_{GD}$ is the Miller capacitance of the MOSFET. As the MOSFET switches ON, the majority of the supply voltage ($V_{DD}$ in Figure 13) which initially falls across the MOSFET now falls across the diode, thereby reverse biasing the diode. Hence, the action of the MOSFET is identical to a step voltage rise across the diode with the rate of change of voltage with time dependent on the MOSFET switching time constant ($R_eC_{GD}$). The transfer function of the diode is basically that of a second order circuit which can respond as over-damped, under-damped or critically damped depending on the attenuation present. The attenuation and damping of the diode response can be derived as the equations below:

$$
\alpha = \frac{R_{SK}R_{SK}C_{AK} + L_{stray}}{2L_{stray}R_{SK}C_{AK}}
$$

$$
\zeta = \frac{R_S R_{SK} C_{AK} + L_{stray}}{2\sqrt{R_S R_{SK} L_{stray} C_{AK} + R_{SK}^2 L_{stray} C_{AK}}}
$$

The $dI_{DS}/dt$ of the MOSFET at turn-ON will determine the nature of the diode response since the same current flows through the transistor and the diode. Hence, the diode response will depend on the gate resistance and the temperature. Figure 14 and 15 show the MOSFET turn-ON current transient at different temperatures for $R_G = 150 \, \Omega$ in Figure 14 and $R_G = 15 \, \Omega$ in Figure 15.

![Fig. 14. MOSFET drain current as a function of time during turn-ON at different temperatures with $R_G = 150 \, \Omega$.](image1)

From Figure 14 and Figure 15, it can be seen that the $dI_{DS}/dt$ is more temperature invariant at $R_G = 15 \, \Omega$ than at $R_G = 150 \, \Omega$; i.e. $d^2I_{DS}/dTdI$ is larger at $R_G = 150 \, \Omega$ in agreement with Figure 11 and Equation (7). It can also be seen from Figure 15 that the turn-ON $dI_{DS}/dt$ increases with temperature according to the equations developed previously. Additionally Figure 16 and 17 show the diode voltage response at the $R_G = 150 \, \Omega$ and $R_G = 15 \, \Omega$, respectively. It should be noted that the ringing oscillation frequency of the diode at turn-OFF depends strongly on the parasitic inductances which will be unique for a certain power modules and experimental rig. However, the equivalent circuit shown in Figure 13 will be universal for power converters. The most obvious difference between Figure 16 and 17 is the higher $V_{AK}$ variation with temperature exhibited by the $R_G = 150 \, \Omega$ measurements i.e. the $R_G = 15 \, \Omega$ measurements shows less dependence of $V_{AK}$ on temperature. Previous publications have shown a temperature invariance of the SiC Schottky diode turn-OFF characteristics [14]; however, this was demonstrated at low gate resistance ($R_G = 2.5 \, \Omega$) as is the case in Figure 17. At slower switching rates (larger gate resistances); the dependence of $dI_{DS}/dt$ on temperature affects the diode temperature characteristics as shown in Figure 16. In other words, the rate at which the transistor switches will determine the response of the diode to the discharge of the free-wheeling current. If the diode is discharged very rapidly (high $dI_{DS}/dt$ from low $R_G$), then the diode will ring with less damping (circuit is excited by a larger $|dV/dt|$, resulting in larger overshoots.) and higher overshoots than if the current is discharged more slowly. The temperature dependence of the diode response also increases as the switching rate is reduced. It can also be noticed in Figure 16 that there is a time shift in the diode response with low temperature characteristics exhibiting a time delay compared to high temperature characteristics. This is due to the negative temperature coefficient of the MOSFETs threshold voltage which means that switching time is delayed at low temperatures (because of the higher MOSFET $V_{TH}$). Also, it can be seen from these figures that the damping of the oscillations for the $15 \, \Omega$ measurements is less, peak voltage overshoot is higher and the temperature dependence is smaller compared to the oscillations at $150 \, \Omega$ gate resistance.

![Fig. 15. MOSFET drain current as a function of time during turn-ON at different temperatures with $R_G = 15 \, \Omega$.](image2)

![Fig. 16. Measured diode output voltage as a function of time during MOSFET turn-ON at different temperatures with $R_G = 150 \, \Omega$.](image3)
This is a direct result of the measurements shown in Figure 14 and 15 because the diode responds to the \( \frac{dI_{DS}}{dt} \) of the MOSFET. Also, the \( \frac{dI_{DS}}{dt} \) dependence on temperature causes a time shift in the diode response with the high temperature \( V_{AK} \) occurring faster. Figures 14 to 17 can be explained by the fact that \( \frac{d^2I_{DS}}{dt^2} \) is higher at intermediate \( R_G \) values and reduces as \( R_G \) is reduced. Combining (9) and (4) yields:

\[
V_{AK} = A \times \frac{R_S}{L_{stray}} + \frac{R_{AK} + R_S}{L_{stray} R_{AK} C_{AK}} \frac{R_{AK} R_S C_{AK} + L_{stray}}{L_{stray} R_{AK} C_{AK}} + \frac{R_{AK} + R_S}{L_{stray} R_{AK} C_{AK}} + \frac{dI_{DS}}{dt} V_{DD} s \frac{BV_{GG} (V_{GS} - V_{TH})}{C_{iss}} + \frac{L_{stray} \operatorname{stray}}{C_{iss} C_{GD}} \frac{dI_{DS}}{dt} V_{DD}
\]

where

\[
A = \frac{dI_{DS}}{dt} V_{DD} s \frac{BV_{GG} (V_{GS} - V_{TH})}{C_{iss}} + \frac{L_{stray} \operatorname{stray}}{C_{iss} C_{GD}} \frac{dI_{DS}}{dt} V_{DD}
\]

In deriving (10), it is assumed that the MOSFET switching time constant \( R_G C_{GD} \) is substantially larger than \( t \), hence, \( \exp(-t/R_G C_{iss}) \) is close to 1.

Equation (10) is a very useful equation because it relates the turn-ON \( dI_{DS}/dt \) of the MOSFET to the diode output voltage. Figures 18 shows the simulated plot of (10) using \( dI_{DS}/dt \) values similar to what was measured (between 10 and 100 A/\( \mu \)s). The diode depletion capacitance is taken from an average depletion capacitance value determined from CV measurements while \( R_{AK} \) is also determined from CV measurements. \( L_{stray} \) is varied between 1 and 5 nH while \( R_S \) is assumed to be a few milliohms. The effect of \( R_S \) and \( R_{AK} \) is to dampen the oscillations, while \( C_{AK} \) and \( L_{stray} \) affect the oscillation frequency. Figures 18 is a reasonably accurate simulation of the diode’s switching behavior, however, because all of these parasitic components vary during switching and are difficult to measure, an exact replica of the experimental measurements is difficult to achieve. Figures 18 also shows that increasing turn-ON \( dI_{DS}/dt \) (which can result from either a lower gate resistance or higher ambient temperatures) causes higher \( V_{AK} \) peak overshoots and more diode ringing.

Figures 19 and 20 show 3D plots of the measured switching energy at turn-OFF and ON for the SiC Schottky diode at different \( dI_{DS}/dt \) and temperatures. The \( dI_{DS}/dt \) shown in this figure, is calculated at 25 °C. It can be seen from the figures that the diode turn-OFF energy is significantly larger than the turn-ON energy. It can also be seen from Figures 19 and 20 that for a given \( dI_{DS}/dt \) (or gate resistance), the switching energy reduces with increasing temperature during diode turn-OFF. This is due to the fact that MOSFET switching rates increases with temperature in the MOSFET as shown in Figures 7 and the response of the diode is modulated by the switching of the MOSFET as shown in (10). Figures 19 and 20 show that the dependence of the switching energy on the gate resistance exhibits a U shaped characteristic with the lowest switching energies at intermediate \( R_G \) values. At the lowest \( R_G \), the switching energy is dominated by additional losses from diode ringing, whereas at the highest \( R_G \), the switching energy is due to the prolonged transient. Hence, although using small gate resistances increases the \( dI_{DS}/dt \), the ringing that results can increase the switching energy.
The $dI/dt$ and temperature dependence of the switching performance of SiC Schottky diodes has been presented over a wide temperature and $dI/dt$ range. It is shown that the switching energy as a function of the gate resistance exhibits a U shaped characteristic with switching energy at low $R_G$ dominated by diode ringing losses and at high $R_G$ dominated by transient overlap between $V_{AK}$ and $I_{AK}$. Diode voltage turn-OFF ringing has been shown to increase with temperature for a fixed gate resistance due to the fact the $dI/dt$ increases with temperature during MOSFET turn-ON. It was also shown that the rate of increase of the turn-ON $dI/dt$ with temperature increases with the gate resistance. This resulted in greater diode $V_{AK}$ dependence on temperature for higher gate resistances. Device physics based models that explain the experimental observations were developed and were shown to account for the measurements. These results are important because they can account for electromagnetic oscillations as a function of temperature and $dI/dt$, which in turn is important for determining EMI, operating temperature and device reliability.

REFERENCES


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