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Characterization of a New 6.5 kV 1000 A SiC Diode for Medium Voltage Converters

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***Abstract*—This paper presents a characterization of a new SiC PIN diode module for use in medium voltage converters. It has a rating of 6.5 kV and 1000 A, comparable to Si diodes available nowadays. The static behavior, switching waveforms and losses for the new diode are analyzed. The tests were carried out for currents between 50 and 1000 A. Different dc link voltages (2.4, 3.0 and 3.6 kV), junction temperatures (from –25 to 125°C) and di/dt values (0.9–2.2 kA/µs at 1 kA) were considered for the analysis. The effects and interactions of the different parameters in the device behavior are discussed.**

I. Introduction

Medium voltage converters (MVC) are essential for power generation and distribution systems, industrial drives and traction systems. One of the limitations of silicon devices is their trade-off between conduction and switching losses. Therefore, for a given device structure and blocking capability, it is not possible to optimize a device for minimal conduction and switching losses simultaneously. [1]

Loss reduction is not the only aim in power semiconductor development. Features like higher power density capability –e.g. higher blocking voltages, high temperature operation, wide Safe Operating Area (SOA)–, ruggedness and reliability are also demanded. The technology maturity of silicon devices makes a major breakthrough improbable. Hence, new wide band gap semiconductors, due to their superior physical properties, have become attractive for new developments in power electronics, including the field of MVC. [2]–[4]

Nowadays, SiC diodes have found a market niche with Schottky and Junction Barrier Schottky (JBS) diodes, commercially available since 2001. Devices with ratings of 1200 V, 40 A and 1700 V, 25 A are commercially available. They are applied mainly in switched-mode power supplies working at high switching frequencies or in applications with high energy efficiency needs [5].

MVCs would drastically profit from the application of SiC power devices, especially from the loss reduction in diode and IGBT, the extended SOA and the operation at higher junction temperatures. Several papers show important advances in SiC diode developments at chip level, e.g. [6]–[8].

Since the maximum chip size and its current capability are limited by the current wafer production technology, modules with high current ratings can only be achieved by a parallel connection of chips. As a consequence, a proper packaging becomes one of the crucial barriers to overcome. Problems such as heat distribution, parasitic inductances, thermal stability at high temperatures, among others, need to be solved. Reliability issues are also a decisive factor before reaching commercial status. [5], [9]–[12]

The increasing number of papers on this topic show the high interest in power semiconductors based on SiC for industrial applications [13]–[15]. This paper presents an extensive characterization of a new SiC diode module rated for 6.5 kV and 1000 A, including static characteristics and switching behavior operating with a 6.5 kV, 600 A Si IGBT. The measurements were carried out for junction temperatures between $-25°$C and 125°C. Different IGBT gate resistance values were considered. Complementary information about the SiC diode chip and module development can be found in [8], [16].

II. Test bench setup

The test circuit is a buck converter, which allows the study of the switching behavior of an active switch T and its corresponding freewheeling diode D_f through the use of a double-pulse switching pattern, see Fig. 1c.

A robust mechanical design was accomplished using 2 mm-thick planar bus bars connecting the dc link capacitor C_{dc} (composed of two 1 mF capacitors in parallel) and the modules, see Fig. 1a. It consists of layers of copper and dielectric (polycarbonate) stacked on top of each other. This design allows to keep the stray inductance as low as possible, which is necessary for hard switched devices [17]. The load L is an air core inductor of 1 mH. The stray inductance of the commutation circuit (C_{dc}, T, D_f) has a value of 235±10 nH. For simplicity, this inductance is represented by two concentrated inductors $L_{\sigma1}$, $L_{\sigma2}$ in Fig. 1c.

The junction temperature of the devices is controlled in a closed-loop by a heating/cooling device, which sets the temperature of the liquid that flows through the plate where the modules are attached to. The dc link capacitor is charged by a high-voltage power supply before the measurements are carried out. A partially automated measurement system was used. The values of V_{dc} and I_L are set using a LabVIEW program on a PC connected to the test bench. The measurements are captured by one 8 bit four-channel 200 MHz

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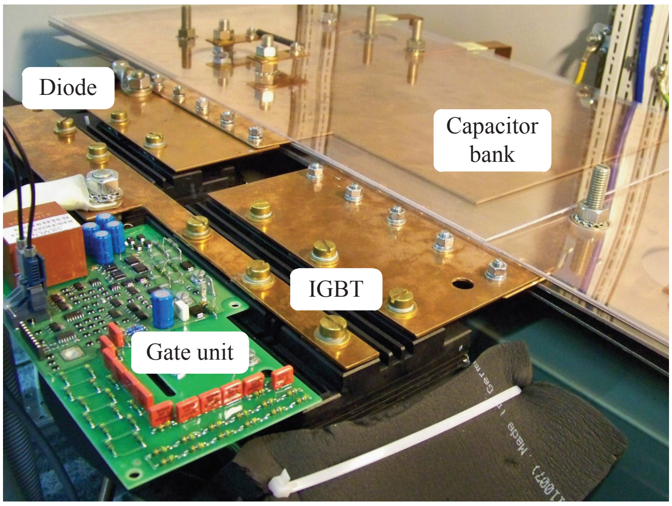
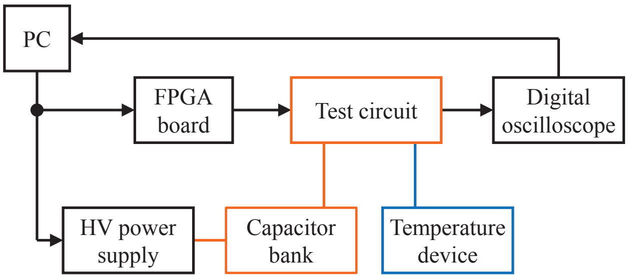


(a)



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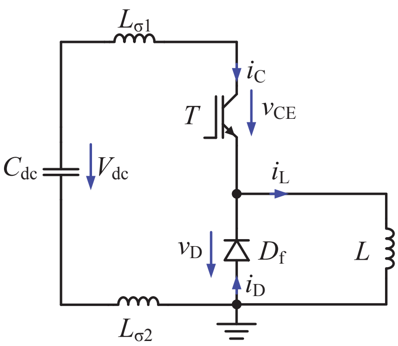


(c)

Figure 1. Test bench (a) experimental setup photo, (b) block diagram, (c) schematic diagram of test circuit (T FZ600R65KF2, C_{dc} = 2 mF, $L_{\sigma1+2}$ = 235 nH, L = 1 mH)

digital oscilloscope (LeCroy 24MXs-B), capable of working at a sample rate of 2.5 GS/s. A block diagram of this setup can be found in Fig. 1b. The instruments used for capturing voltage and current waveforms are summarized in the Table I.

Regarding the measurements for the on-state voltage, these were conducted using the same circuit presented in Fig. 1c. The voltage probe was changed to one with lower attenuation, see Tab. I, parameter v_{on}. Instead of a double-pulse, a single-pulse measurement was used. The decaying current ramp through the diode during the free-wheeling phase after the IGBT turn-off was captured together with the voltage waveform. In order to avoid self heating, the time of the free-wheeling phase was limited to 3 ms. To achieve this, the load inductance was reduced to L = 58 µH. Leakage current was measured using a 6½-digit multimeter (Keithley 2100). This allowed an accurate measurement of currents above 1 µA.

Table I
Measurement instrumentation

Variable	Type	Model	BW (MHz)	Atten.
v_D	Passive probe	PPE6KV	400	1000:1
v_{CE}	Diff. probe	TTSI9010	70	1000:1
i_D	Rogowski-coil	CWT30B	10	1000:1
i_C	Rogowski-coil	CWT15B	17	500:1
v_{on}	Diff. probe	TTSI9002	25	200:1

The switch T used in the test is a 6.5 kV IGBT from Infineon, model FZ600R65KF2, with a nominal current rating of 600 A. It is operated with an industrial gate unit that has an output power of 3.5 W and a gate voltages of -10 V and +15 V. The SiC diode module prototype uses a similar housing as the commercial Si diode module DD600S65K1, which has comparable voltage and current ratings. Inside the module there are 4 DCB, each with 20 SiC diode chips. Two DCB form a diode system rated at 500 A, which can also be paralleled, achieving 1000 A (80 chips) per module. The maximal blocking voltage is 6.5 kV. Each chip has an active area of 7.1 mm^2, totalizing an active area of 5.68 cm^2 per module. Due to the high blocking voltage needed, PIN diode technology was applied. [8], [16] The measurements for the characterization presented in this paper were carried out using the full module.

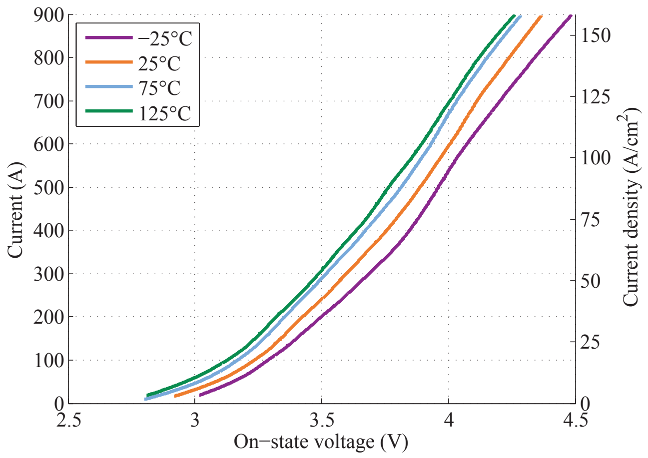
III. Experimental results

A. Static behavior

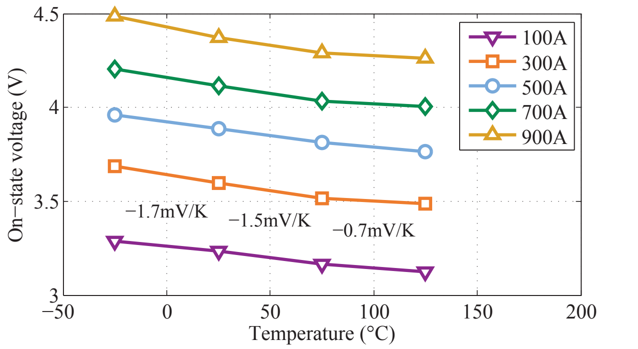
The on-state voltage curve for the SiC diode measured at four junction temperatures can be seen in Fig. 2a. The on-state voltage at 100 A/cm^2 (578 A) varies between 4.05 V at −25°C and 3.87 V at 125°C. A negative temperature coefficient (NTC) with an average of −1.3 mV/K can be observed, see Fig. 2b. The thermal coefficient decreases as the temperature increases, going from −1.7 mV/K between −25 and 25°C to −0.7 mV/K between 75 and 125°C. This behavior was also observed in previous work [18]. It was attributed out to an unsuitable ohmic contact formation, which at high temperatures does not have a major influence.

It is well known that NTC can lead to thermal runaway in parallel-connected chips [19]. In this case, the NTC is not strong enough to cause a thermal instability in the module, as preliminary measurements have shown (not included in this paper).

Fig. 3 shows the leakage current for different temperatures. The results indicate that the leakage current is kept low in the whole temperature range. The increase in current from 25 to 125°C is less than one decade, which is one of the advantages of SiC devices compared to Si devices. Excluding



(a)



(b)

Figure 2. On-state voltage (a) as a function of current and (b) as a function of junction temperature, including average temperature coefficients.

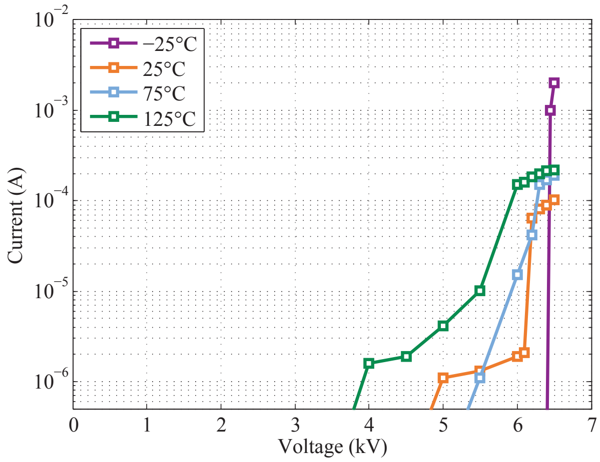


Figure 3. Leakage current for for different junction temperature values

the −25°C case, the leakage current stays under 250 µA. At −25°C the maximal current is around 2 mA, but the breakdown voltage does not diminish considerably (6.4 kV). Lower voltages exhibit no measurable leakage current.

B. Switching behavior

The switching behavior of the new SiC diode module was investigated. For this purpose, currents between 50 and 1000 A at a dc link voltage of 2.4, 3.0 and 3.6 kV were switched. The average junction temperatures T_j tested were −25, 25, 75 and 125°C.

Instant power $p(t)$ and energy $e(t)$ were calculated using the measured current $i(t)$ and voltage $v(t)$ waveforms during a commutation event starting in t_0 and ending in t_end as follows:

$$p(t) = i(t)v(t) \tag{1}$$

$$e(t) = \int_{t_0}^{t_\mathrm{end}} p(t)dt \tag{2}$$

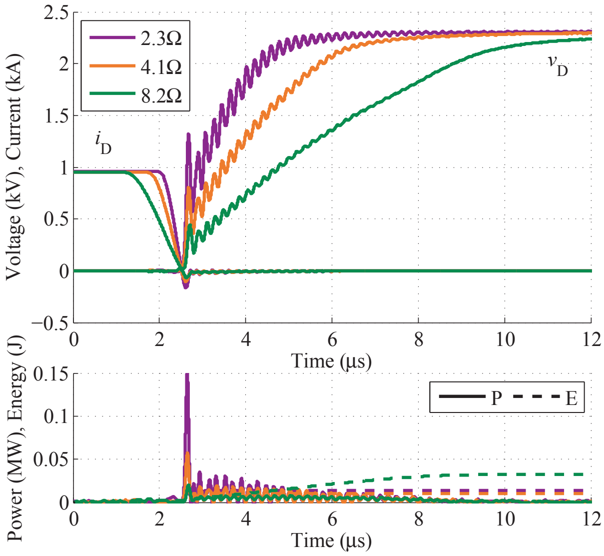
The switching energy per commutation event corresponds to $E = e(t_\mathrm{end})$. Special consideration was taken when calculating the switching energy during the diode turn-off, due to the ringing in the voltage and current waveforms. Details are explained together with the ringing phenomenon further below in this section.

For the application of SiC technology in freewheeling diodes, the diode turn-off and the IGBT turn-on transients show the advantages in loss reduction. The waveforms together with instant power and switching energy calculations for nominal current (1 kA) are shown in Figs. 4, 6 and 8, where the influence of dc link voltage, current change rate (di/dt) and junction temperature are depicted. Furthermore, switching loss calculations for the three cases through the whole current range are included in Figs. 5, 7 and 9. As a complementary information to evaluate the switching conditions, di/dt and dv/dt values for the diode turn-off transient can be found in Fig. 10.

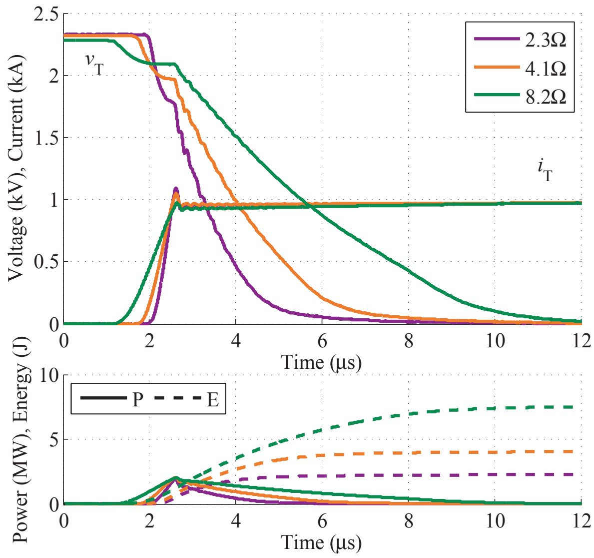
In Fig. 4, different di/dt values were accomplished by changing the IGBT's gate unit turn-on resistance between 8.2, 4.1 and 2.3 Ω, that is, a di/dt variation between 0.9, 1.5 and 2.2 kA/µs at 1000 A (for more details, see Fig. 10). In terms of current density, this corresponds to a variation from 158 to 387 A/cm^{2}µs. The SiC diode clearly shows a low tail charge by the small reverse recovery peak, 168A at 2.2 kA/µs and 66 A at 0.9 kA/µs, about 4 times smaller than for Si diodes.

The reverse recovery charge is also low, which has a direct influence in the reduction of losses during diode turn-off and IGBT turn-on. This can be further appreciated in Fig. 5. In the case of the diode, the switching losses remain under 14 mJ, even for high di/dt values. In the case of the IGBT, for a change of the di/dt from 2.1 to 0.9 kA/µs, IGBT turn-on losses increased from 2.3 J to 7.5 J (I_D = 1000 A).

In contrast to 6.5kV Si diodes, where the diode SOA basically determines the turn-on gate resistance, the drastically extended SOA of the 6.5 kV SiC diode enables a selection of the turn-on gate resistance to minimize the switching losses of the IGBT. However, there is one drawback to this approach, which can be seen in Fig. 4a. Ringing is present in the device voltage and with a very low amplitude in the device current waveforms. This is a key issue in the application of SiC



(a) Diode turn-off transient



(b) IGBT turn-on transient

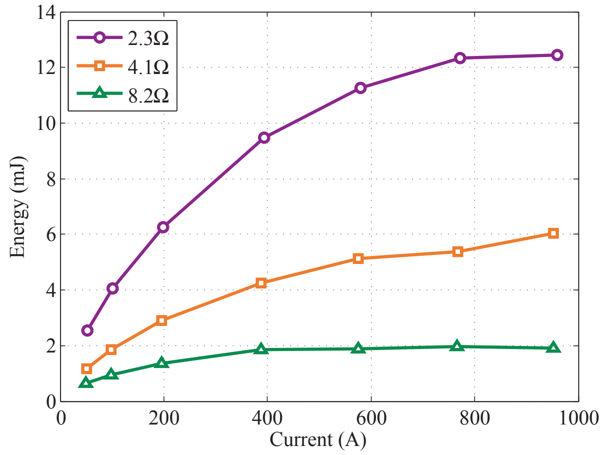
Figure 4. Commutation waveforms for different $R_{G,on}$ values (V_{dc} = 3 kV, I_D = 1000 A, T_j = 25°C, L_σ = 235 nH)

devices and has been discussed in some papers, e.g. [10], [18].

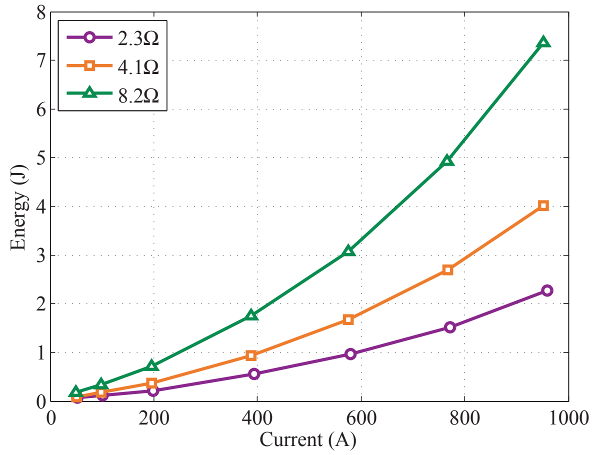
These oscillations have two possible sources [20], [21]:

- A snappy behavior of the diode due to the small reverse recovery charge causes oscillations in the commutation circuit.
- The parallel connection of the chips inside the module and their parasitic inductances.

In this particular case, probably both sources contribute to the ringing. The oscillations are of LC (reactive) nature, which means that their frequency, amplitude and damping is affected by circuit parasitics [22], [23]. The amplitude of the



(a) Diode turn-off losses



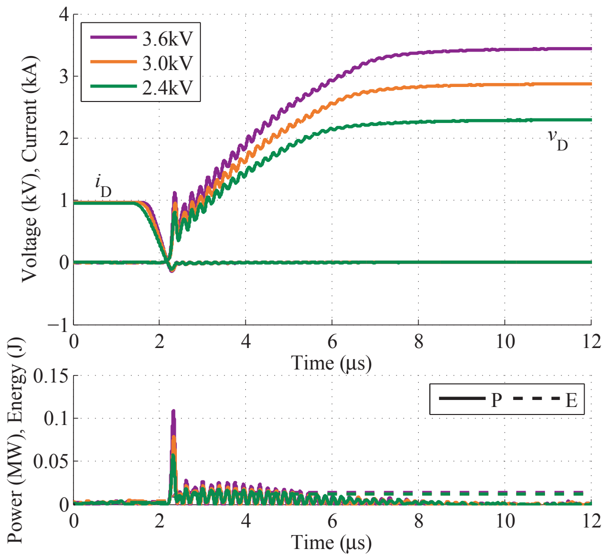
(b) IGBT turn-on losses

Figure 5. Switching losses for for different $R_{G,on}$ values (V_{dc} = 3 kV, T_j = 25°C, I_D = 50. . . 1000 A, L_σ = 235 nH)

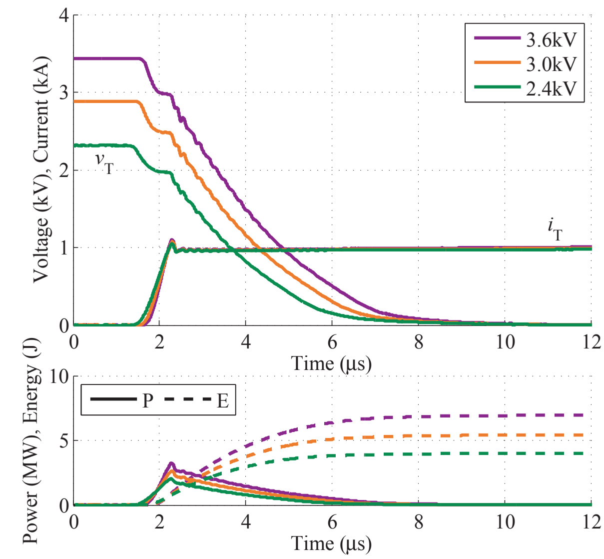
oscillations also increases with higher di/dt values, as seen in Fig. 4a. Thus, the switching loss reduction is limited by the maximally allowed ringing amplitude. Further investigations to tackle the problem include improvements in diode chip and module design and the optimization of the mechanical power circuit layout. Even though the overvoltage caused by the ringing is kept under control, EMC problems cannot be discarded, as the frequency of the oscillations is around 5 MHz.

The IGBT turn-on waveforms exhibit relatively low voltage oscillations, see Fig. 4b. This implies that the energy of the oscillations is transfered to the parasitic capacitance of the dc link bus bar connection. Evidently, circuit parasitics have a strong influence in the switching behavior and should be carefully included in the design process of future converters with SiC devices.

Special considerations were taken for the calculation of the switching losses during diode turn-off. Because of their reactive nature, they should be filtered out of the calculation.

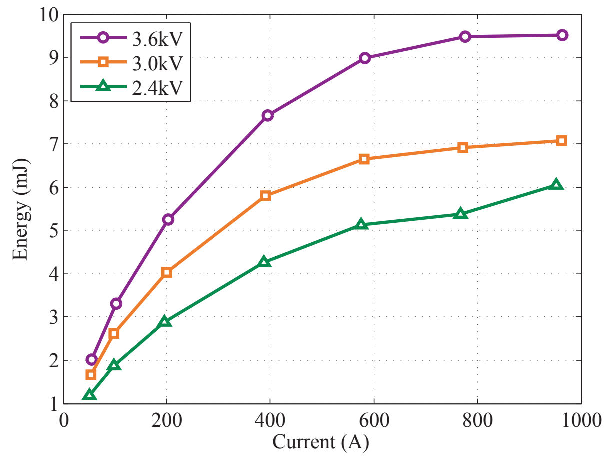


(a) Diode turn-off transient

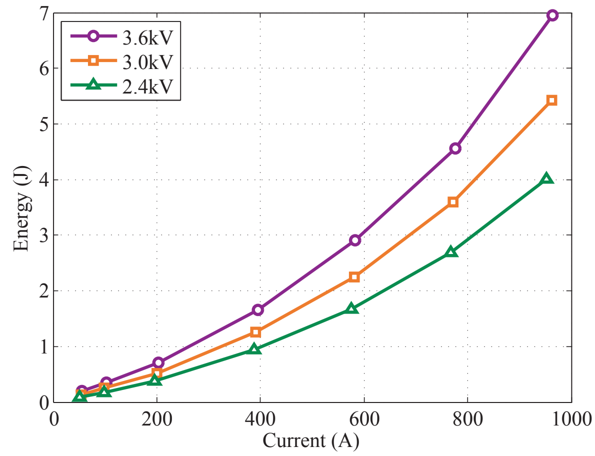


(b) IGBT turn-on transient

Figure 6. Commutation waveforms for different V_{dc} values ($R_{G,on}$ = 4.1 Ω, I_D = 1000 A, T_j = 25°C, L_σ = 235 nH)



(a) Diode turn-off losses



(b) IGBT turn-on losses

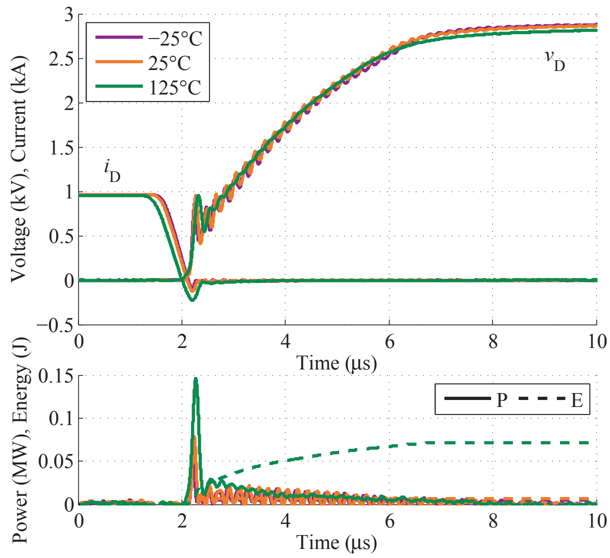
Figure 7. Switching losses for for different V_{dc} values ($R_{G,on}$ = 4.1 Ω, T_j = 25°C, I_D = 50…1000 A, L_σ = 235 nH)

This was accomplished by integrating only during the reverse recovery current waveform, see Eq. (2), if oscillations were present. This could be identified by a zero-crossing of the $p(t)$ waveform after the reverse recovery current maximum.

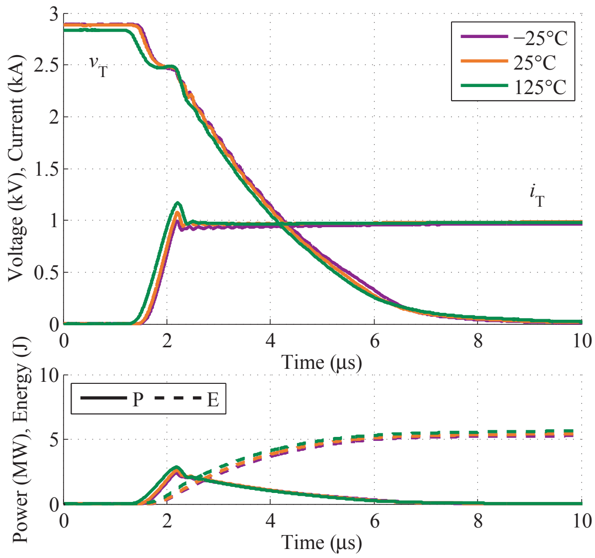
The influence of the dc link voltage V_{dc} variation in the diode turn-off and IGBT turn-on transients can be found in Fig. 6. An increase in the di/dt as the commutation voltage increases can be observed. As expected, losses increase proportionally to the applied voltage, see Fig. 7. Even though losses in the SiC diode module increase with higher voltage, they remain low in absolute terms (<10 mJ). The oscillations show no evident amplitude change as the voltage increases. This behavior is different from the results shown in [18] using similar SiC chips. In that work, ringing was present in commutations at 3.5 and 4 kV but not at 2.5 and 3 kV, even though the current density change rate dj/dt used was considerably higher than the one used in this paper. Since the tests made in [18] were at chip and not at module level, a completely different set of circuit parasitics were present. Further investigations are being conducted in order to gain more insight into this problematic.

The last parameter studied was the junction temperature T_j, see Figs. 8. For −25 and 25°C only slight differences can be observed. Losses and oscillations do not change considerably. On the other hand, switching at T_j = 125°C strongly influences the oscillations and also increases losses in the diode. For nominal current this means turn-off losses of 7 mJ at 25°C and 73 mJ at 125°C. Compared to the switching losses in the IGBT (around 5.4 J), the SiC diode turn-off losses are negligible.

Regarding the oscillations in the diode voltage waveform,



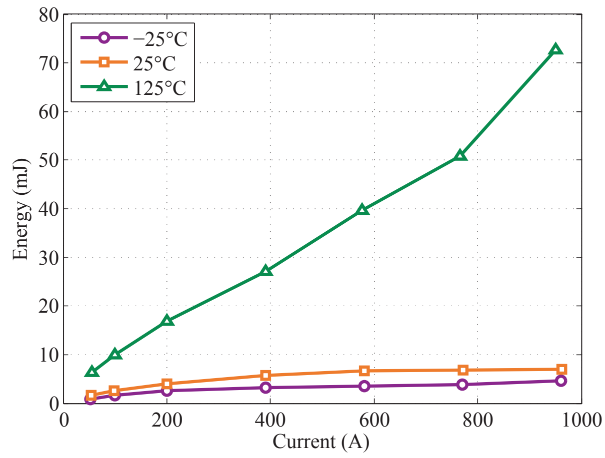
(a) Diode turn-off transient



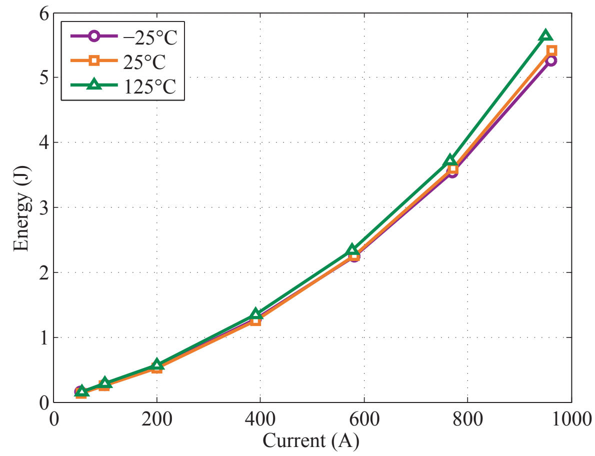
(b) IGBT turn-on transient

Figure 8. Commutation waveforms for different T_j values (V_{dc} = 3 kV, $R_{G,on}$ = 4.1 Ω, I_D = 1000 A, L_σ = 235 nH)

it can be observed that at 125°C the ringing is very low. Also the tail current after the reverse recovery maximum is longer, contributing to the higher losses. The fact that diode ringing due to snappiness is more critical at low rather than high temperatures has already been reported in the literature, e.g. [24]. These measurements support the assumption that the ringing is primarily initiated by the snappy diode behavior, i.e. the high di/dt of the reverse recovery current after the occurrence of the reverse recovery current peak. As a consequence of that, oscillations between the diode die output capacitances and the internal (module) as well as external (commutation circuit) stray inductances and capacitances appear.



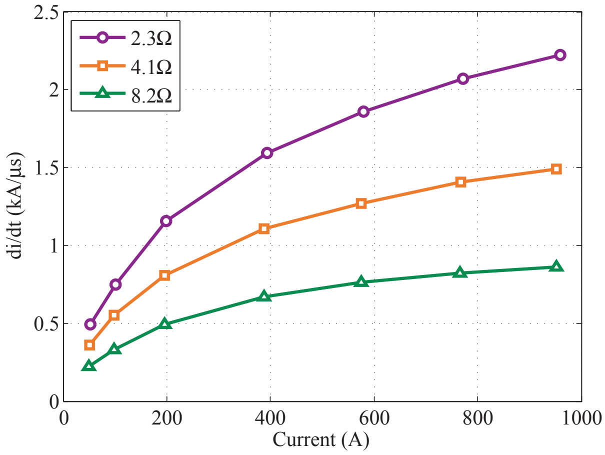
(a) Diode turn-off losses



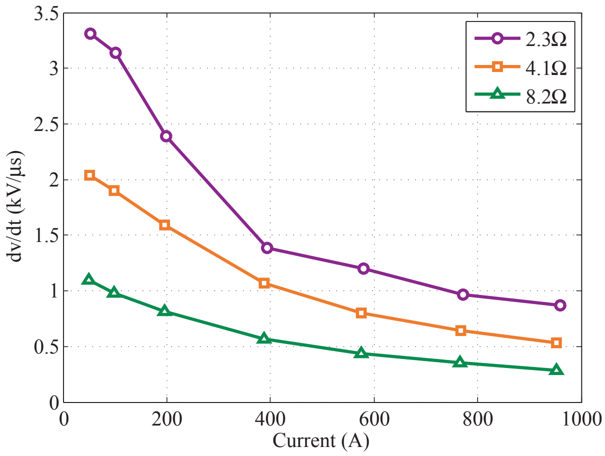
(b) IGBT turn-on losses

Figure 9. Switching losses for for different T_j values (V_{dc} = 3 kV, $R_{G,on}$ = 4.1 Ω, I_D = 50. . . 1000 A, L_σ = 235 nH)

Usually, the diode turn-on behavior is not regarded as critical, since stress and losses in the semiconductor are considerably lower than during turn-off. Switching transients for diode turn-on can be seen in Fig. 11 for different junction temperatures. The forward recovery does not vary significantly with T_j and has a maximum of 68 V at nominal current. Due to the low forward recovery, turn-on losses remain low, about 75 mJ for nominal current. It could also be observed that a variation of the dc link voltage did not influence the forward recovery behavior. The turn-on losses in the SiC diode module are in the same order of magnitude as the turn-off losses. The low value of the forward recovery has also a positive effect by diminishing the voltage stress on the IGBT during turn-off, which has to bear the overvoltage caused by the stray inductance L_σ and the forward recovery voltage simultaneously.

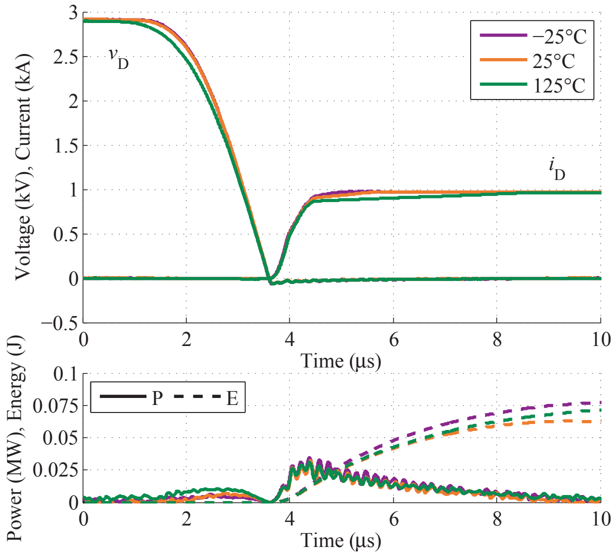


(a) Diode di/dt during turn-off



(b) Diode dv/dt during turn-off

Figure 10. Diode current change rate di/dt and voltage change rate dv/dt values for for different $R_{G,on}$ values during turn-off transient. For calculations, 90%- and 10%-values of switched quantities were taken. (V_{dc} = 3 kV, T_j = 25°C, I_D = 50. . . 1000 A, L_σ = 235 nH)



(a) Diode turn-on transient

Figure 11. Diode turn-on waveforms and losses for different T_j values (V_{dc} = 3 kV, I_D = 1000 A, L_σ = 235 nH)

IV. Conclusions

The paper has presented a new 6.5 kV, 1000 A SiC-diode module for medium voltage converters. The static as well as the switching behavior was investigated. For this purpose, a laboratory test bench that allows the characterization of the module at application-oriented conditions.

On-state as well as blocking characteristics at four different temperatures were included. For the conduction mode, the diode exhibits a negative temperature coefficient of 0.7 mV/K for temperatures between 75 and 125°C. The on-state voltage at 100 A/cm^2 (578 A) is 3.87 V at 125°C. In blocking mode, the diode has a low leakage current below 1 µA for voltages below 4 kV. Between 4 and 6.5 kV, a larger current is present, which has a maximum of 0.2 mA at 125°C .

It was demonstrated that the switching losses of the diode remain low, less than 80 mJ under all the analyzed working points. Compared to the on-state losses, the switching losses account for only a marginal contribution to total semiconductor losses. A ringing in a frequency of 5 MHz was present in the diode voltage during the turn-off transient. The ringing amplitude increases for higher di/dt values, but decreases for operation at a higher junction temperature (125°C). The study of this phenomenon will be addressed in future investigations.

Regarding the IGBT connected to the diode for switching purposes, a considerable loss reduction can be achieved by increasing the di/dt for the IGBT turn-on transients by adjusting the gate turn-on resistor. When changing the di/dt from 1.5 at 2.2 kA/µs, the losses were reduced from 7.4 to 4.0 J (46%).

This new semiconductor technology could help improving the efficiency of medium voltage converters. In a lower power scale, it has already been proven that about 10% lower semiconductor losses can be achieved in low voltage 3-level NPC converter (10 kVA) [25]. Since semiconductor losses exponentially increase with blocking voltage, the loss reductions for medium voltage converters are expected to be higher. However, the change from Si to SiC technology is not an easy path and demands a breakthrough in current technological limitations.

The work here presented helps to expand the wide band gap semiconductor technologies to the area of medium voltage converters. Reliability and long-term performance of the proposed technology needs to be assessed before a fully tested prototype can be presented. Even though a diode module was presented and characterized in this paper, defects in SiC wafers and in the epitaxial layers, as well as an optimal packaging technology, are issues that have not been completely solved yet, keeping the manufacturing cost of SiC dies and modules high. [11], [12]

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