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Performance Comparison of 6.5 kV SiC PiN Diode with 6.5 kV SiC JBS and Si Diodes

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Abstract. 6.5 kV SiC PiN diode with JTE and p+ rings termination was fabricated and characterized. The static and dynamic performance of SiC PiN diode were compared with that of SiC JBS diode and silicon diode, while switched in combination with a silicon IGBT. SiC PiN provides clear advantage while operating at higher current densities (above 100 A/cm^2) and had lower leakage current. When switched together with a silicon IGBT, they contribute to losses similar to that of a SiC JBS diode.

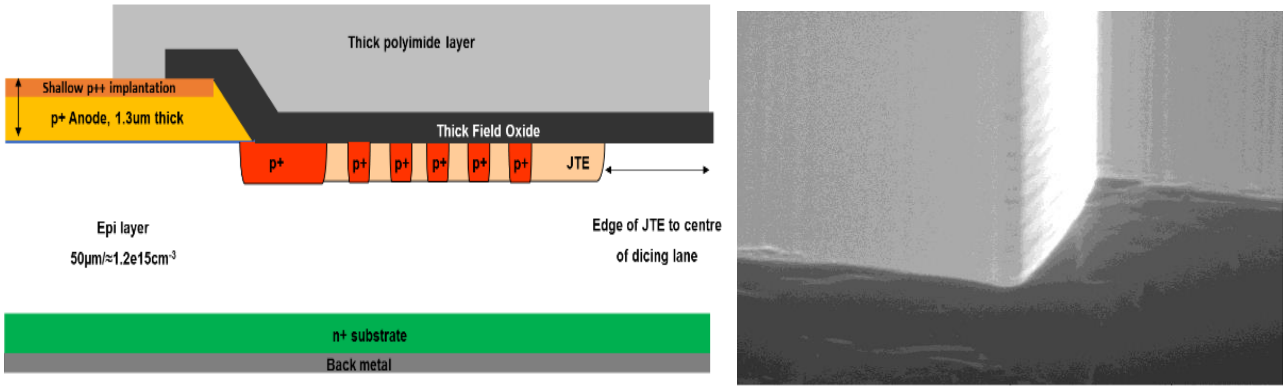
Introduction

SiC components with 6.5 kV voltage rating and above are of primary interest for power electronics applications such as distribution transformers and medium-voltage drives [1-3]. SiC diodes in particular are an essential component to SiC switches in such applications, especially when reverse-blocking components (IGBTs) are involved. In addition, MOSFETs also benefit from the implementation of antiparallel diodes. Especially in medium voltage range, bipolar diode devices (p-i-n) offer better performance compared to unipolar devices (JBS) due to conductivity modulation when high current operation is encountered [4, 5].

In this work, we have fabricated 6.5 kV PiN diode that consist of Ti/Al anode contact and an edge termination consisting of Junction Termination Extension (JTE) and p+ rings. We compare the static and dynamic performance of the 6.5 kV SiC PiN diode with that of SiC JBS and a silicon diode in terms of an application with a 6.5kV Si IGBT.

Experimental Details

6.5 kV SiC PiN diodes were fabricated using 4H-SiC wafers consisting of 50 µm epilayer with a doping concentration of 1.2e15cm^{-3} and a 1.3 µm thick anode with a doping concentration of 1e19cm^{-3}. Ti/Al metal layers were used as Ohmic contact to the anode. The periphery of the diodes was protected using a Junction Termination Extension (JTE) and 5 embedded p+ guard rings. The anode MESA angle was optimized such that the walls are also implanted with p+ (Fig 1b). No lifetime enhancing methods were used here. The average carrier lifetime values measured through µPCD were between 0.1 and 0.3µs. The fabrication of PiN diode started with the etching of anode MESA using reactive ion etching (RIE) followed by implantation of p+ rings and JTE. This was followed by activation and formation of the backside Ohmic contact. Then SiO_2/SiN passivation layers were deposited and patterned. Next, Ti/Al metal contact layers were formed on the anode and finally polyimide was deposited and patterned to complete the fabrication process.



(a) (b)

Fig. 1. (a) Pictorial cross section of SiC PiN diode, (b) SEM picture showing the sloped anode MESA.

Results

Static characterization

The normalized forward characteristics at 25°C of a 6.5 kV PiN diode is shown in fig. 1 along with the forward characteristics of 6.5 kV SiC JBS and silicon diode. It could be seen that at a current density of 100 A/cm^2 the SiC PiN diode has a forward voltage of ~ 3.8 V, whereas SiC JBS and silicon diode reach a current density of 100 A/cm^2 at a forward voltage of ~ 6.5 V and ~4.3 V, respectively. Hence, SiC PiN diode offers a clear advantage when operating at higher current densities (above 100 A/cm^2). For current densities less than 40 A/cm^2, SiC JBS and silicon diode depict a lower forward voltage drop, due to the higher knee voltage of SiC PiN diode. The reverse blocking characteristics of these diodes at room temperature are shown in fig. 2. It can be seen in the graph that SiC PiN diode has the lowest leakage current up to 6 kV. The silicon diode reveals a lower reverse leakage than SiC JBS diode throughout the whole range studied.

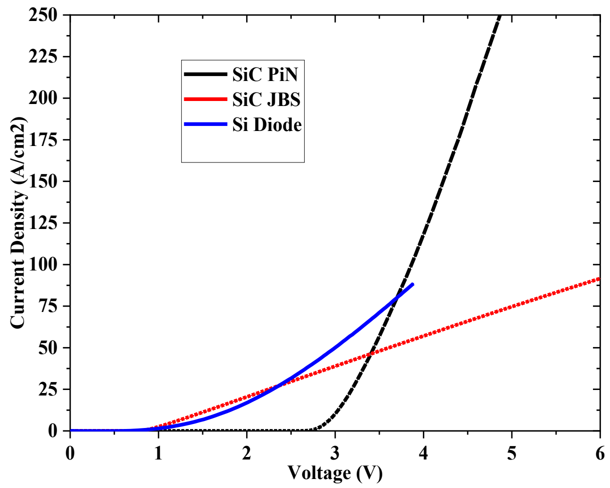


Fig. 2. Comparison of forward characteristics of 6.5 kV SiC PiN & JBS diodes with Si diode.

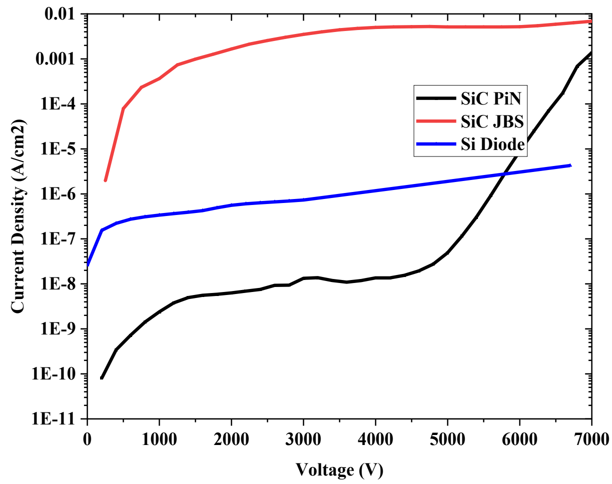


Fig. 3. Comparison of reverse characteristics of 6.5 kV SiC PiN & JBS diodes with Si diode.

Dynamic characterization

The dynamic performance of these diodes has been analysed by switching them with 6.5 kV silicon IGBT at room temperature. Fig. 3 shows the IGBT turn-on wave form using the SiC JBS, SiC PiN and the Si diode. The IGBT has been switched at a dc link voltage of 4.4 kV and a current of 20 A. As expected, the IGBT turn on current overshoot differs when switched with different diodes. IGBT current overshoot is ~90 A when switched together with silicon diode. Current overshoot is ~28 A and ~37 A when switched with SiC JBS and PiN diode, respectively. The switching losses for the diode turn-off and for the IGBT turn-on could thus be significantly reduced using SiC diodes.

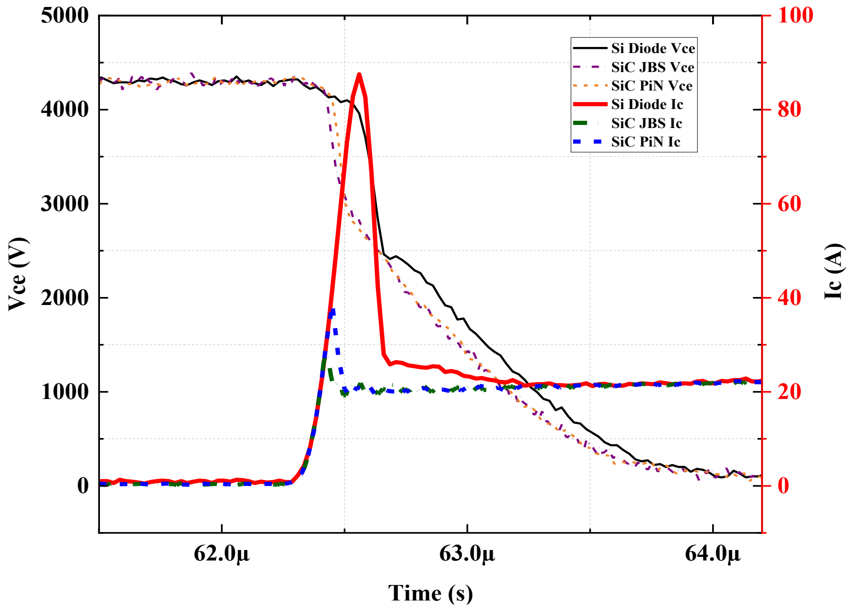


Fig. 3. 6.5kV Si IGBT turn-on characteristics when switched with SiC PiN, SiC JBS or silicon diode.

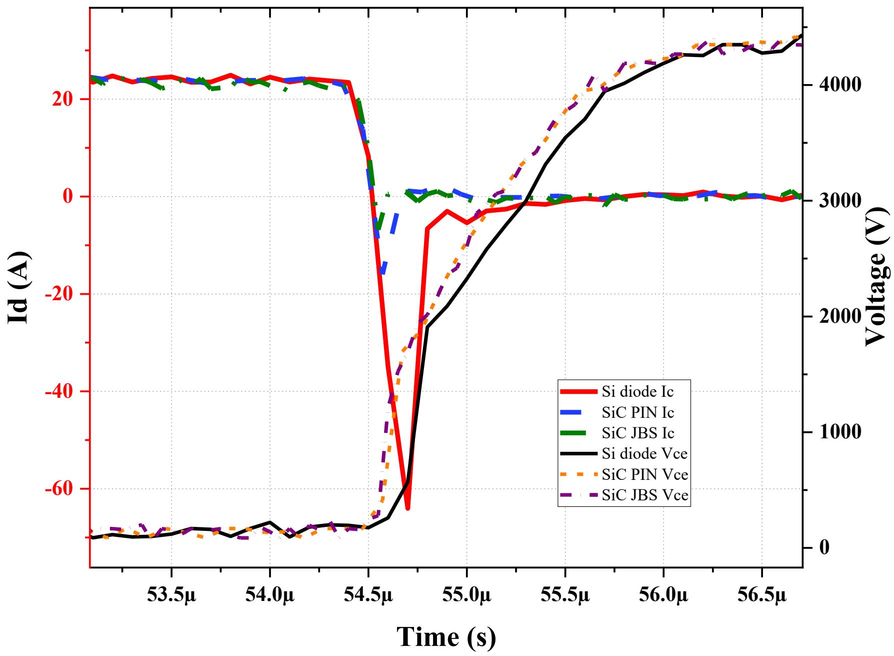


Fig. 4. Turn-off characteristics of 6.5 kV SiC PiN, JBS and silicon diode when switched together with 6.5 kV Si IGBT.

The turn-off characteristics of silicon diode, SiC PiN and SiC JBS diodes when switched together with 6.5 kV silicon IGBT at a dc link voltage of 4.4 kV and current of 20 A is shown in Fig. 4. It could be seen that current overshoot during diode turn off was very high (~65 A) for silicon diode due to reverse recovery. The current overshoot for both SiC JBS (~10 A) and PiN diode (~15 A) was low compared to the silicon diode. The overshoot was very low for SiC JBS due to the absence of minority carriers. There was not significant difference in the turn off characteristics of IGBT when switched with a silicon diode, SiC PiN or JBS diodes (not shown).

The power losses of silicon IGBT during turn on, when switched with different diodes is shown in Fig. 5. It could be seen that the power losses of the IGBT are very high when switched with silicon diode and it was more than twice than the losses of IGBT switched with SiC diodes. Again, the power losses of the IGBT switched with SiC JBS diode was the lowest. The calculated power losses of IGBT during turn on and turn off with different diodes is shown in table 1. It could be seen that the IGBT turn on losses when switched with silicon diode (~85 mJ) was more than twice when switched with SiC diodes (~41 mJ). There was not much difference in the turn-off losses of IGBT when switched with different diodes. The loss from SiC diodes (~2 mJ) was very low compared to silicon diode (~10 mJ).

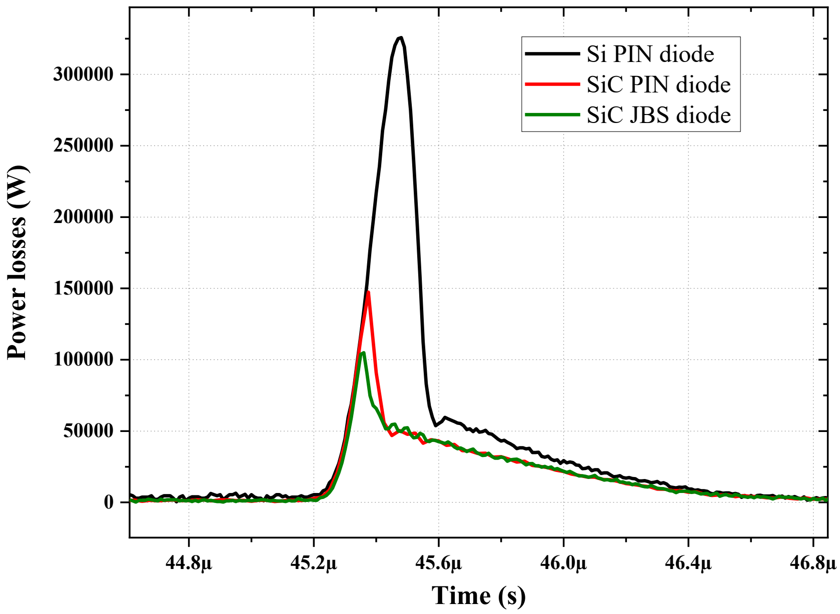


Fig. 5. Comparison of power losses of 6.5kV Si IGBT during turn-on, when switched with SiC PiN, SiC JBS or silicon diode.

Table 1. Comparison of switching losses of IGBT when switched with different diode and losses from each diode.

Switched with	IGBT turn on losses (mJ)	IGBT turn off losses (mJ)	Diode losses (mJ)
Si Diode	~85	~89	~10
SiC PiN	~41	~85	< 2
SiC JBS	~39	~85	< 2

Summary

6.5 kV SiC PiN diode with JTE and p+ rings termination was fabricated and characterized. The performance of SiC PiN diode was compared with that of SiC JBS diode and silicon diode, while switched in combination with a silicon IGBT. SiC PiN provides clear advantage while operating at higher current densities (above 100 A/cm^2) and had lower leakage current. The power loss of silicon IGBT when switched together with SiC PiN or JBS diode was similar. Considering the higher operating current density, low leakage and better dynamic characteristics, SiC PiN offers the superior solution among the diodes studied.

References

[1] F. Filsecker *et al.,* "The investigation of a 6.5-kV, 1-kA SiC diode module for medium voltage converters", *IEEE Trans. Power Electron.,* vol. 29, no.5, pp. 2272-2280, 2014.

[2] M. Rahimo, "Performance evaluation and expected challenges of silicon carbide power MOSFETs for high voltage applications", *Material Science Forum*, vol. 897, pp. 649-654, 2017.

[3] F. Filsecker *et al.,* "Comparison of 6.5 kV silicon and SiC Diodes", *IEEE Energy Convers. Cong. Expo.*, pp. 2261-2267, 2012.

[4] A. Salemi *et al.,* "Conductivity modulated on-axis 4H-SiC 10+ kV PiN diodes", *Proc. Int. Symp. Power Semicond. Devices ICs (ISPSD)*, vol. 2015, pp. 269-272, 2015.

[5] A. Salemi *et al.,* "Conductivity modulated and implantation-free 4H-SiC ultra-high-voltage PiN diodes", *Mat. Sci. Forum*, vol. 924, pp. 568-572, 2018.