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2.5KV-30A Inductively Loaded Half-Bridge Inverter Switching Using 4H-SiC MPS Free-Wheeling Diodes

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Abstract. In this work, 4H-SiC MPS diodes were designed, fabricated and tested. The MPS diodes were fabricated based on a 30µm, n=2x10^{15}cm^{-3} doped drift layer. The diodes were designed with a multi-step junction termination extension (MJTE) to improve the blocking voltage, resulting in MPS diodes blocking over 4kV. DC I-V testing of the packaged MPS diode showed a forward voltage drop V_F=3.2V at a forward current I_F=27A. A half-bridge inverter with a bus voltage up to 2.5kV and a large load inductance of 1mH was used to characterize the MPS diode switching performance. The large inductance load was used to simulate the load of a high power AC induction motor. Switching measurements up to a current of 30A showed a substantial reduction in diode turn-off energy loss, compared to state-of-the-art ultra fast 40ns, Si diode: as high as 51% energy loss reduction at room temperature (RT). Most energy loss reduction, however, comes from the saving in the corresponding Si IGBT switch, which sees a reduction of as high as 51% at room temperature. Past reports on half-bridge inverter testing were largely done at bus voltage of a few hundred volts. This is the first half-bridge, highly inductively loaded inverter test at bus voltage of 2.5kV.

Introduction

Modern power systems favour small passive parts and active components capable of high-speed switching and high temperature operation. Unipolar Schottky Barrier Diode (SBD) can operate at higher frequency and has a lower turn-on voltage compared with bipolar PIN diode. However, SBDs tend to have substantially higher leakage currents in comparison to PIN diodes. By merging PIN and SBD (MPS) into a single diode, it combines the advantages of both SBD and PIN, resulting in a unique device which can be operated in either unipolar mode or mixed mode (with minority injection). SiC MPS diode has demonstrated excellent switching performance up to 100kW [1]. But to the best of our knowledge, SiC MPS diode testing in inductively loaded inverter system has not been done at high bus voltage and high current. In this paper, a half-bridge inverter with a bus voltage up to 2.5kV and a load inductance of 1mH was used to evaluate the high speed and low loss potential of 4H-SiC MPS diodes at the current level of 30A. The large inductance load was used to simulate the load of a high power AC induction motor.

Design and Fabrication

The cross-sectional view of SiC MPS is shown in Fig.1. The 4H-SiC epi-wafer was provided by Cree, Inc. The n-type drift-layer is 30µm doped to 2x10^{15}cm^{-3}. Multiple-energy Al implantation was done to create P+ region. Post-implantation annealing was done at 1550°C in Ar ambient for 30mins. Multi-step junction termination extension (MJTE)[2] was used to improve the blocking voltage.

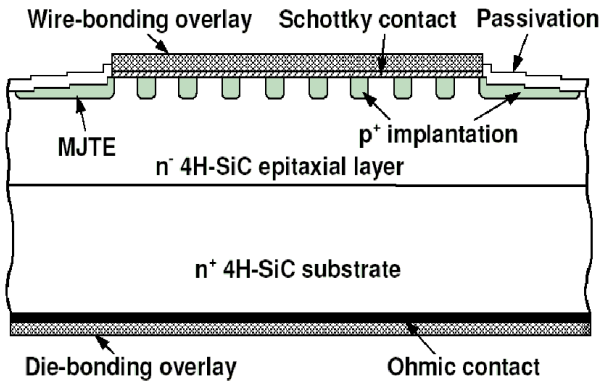

Fig.1 Cross-sectional view of SiC MPS.

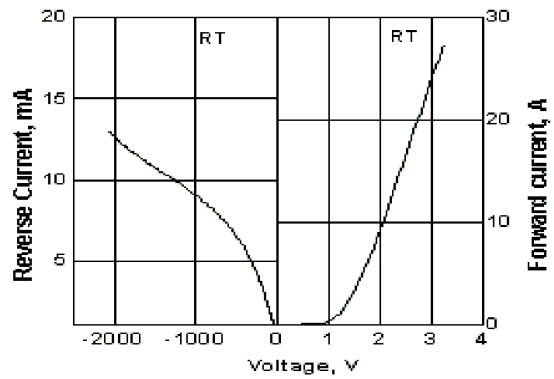

Fig.2 Room temperature DC I-V curve of packaged MPS diode with total area of 26.6mm^2.

Characterization

Wide ribbons were used to bond the MPS diode cells with a total active area of 26.6 mm^2. DC I-V testing of the packaged MPS diode has been done, showing a forward voltage drop V_F=3.2V at a forward current I_F=27A, as shown in Fig.2. The packaged MPS diode was tested in an inductively loaded (L=1mH) half-bridge inverter, using Si IGBT as the power switch and the 4H-SiC MPS diode or the best commercial ultrafast 3kV Si PIN diode (formed by stacking two 40ns, 1.6kV PIN diodes) as the free-wheeling diode. Switching measurements have been done at different bus voltages, up to the system limit at 2.5kV and at different current levels, up to 30A at room temperature. The switching test was done under two different IGBT gate resistor conditions (2Ω and 50Ω), representing two different IGBT turn-on di/dt (1A/ns and 0.2A/ns). Fig.3 shows the reverse recovery current and voltage waveforms of the Si PIN and SiC MPS diodes. The MPS diode shows a substantially reduced reverse recovery current peak. In both cases, Si PIN has a peak reverse current of 27A, which is 3 times of that of SiC MPS. Fig.4 shows the power loss spectrum of the SiC MPS diode and Si PIN diode. When IGBT gate resistor is 2Ω, the total diode turn-off energy loss is reduced from 8.3mJ for Si PIN to 4.1 mJ for SiC MPS, which represents a 51% reduction for the diode turn-off operation. When IGBT gate resistor is 50Ω, the total diode turn-off energy loss is reduced from 8.0mJ for Si PIN to 4.6mJ for SiC MPS, which represents a 42% reduction for the diode turn-off operation.

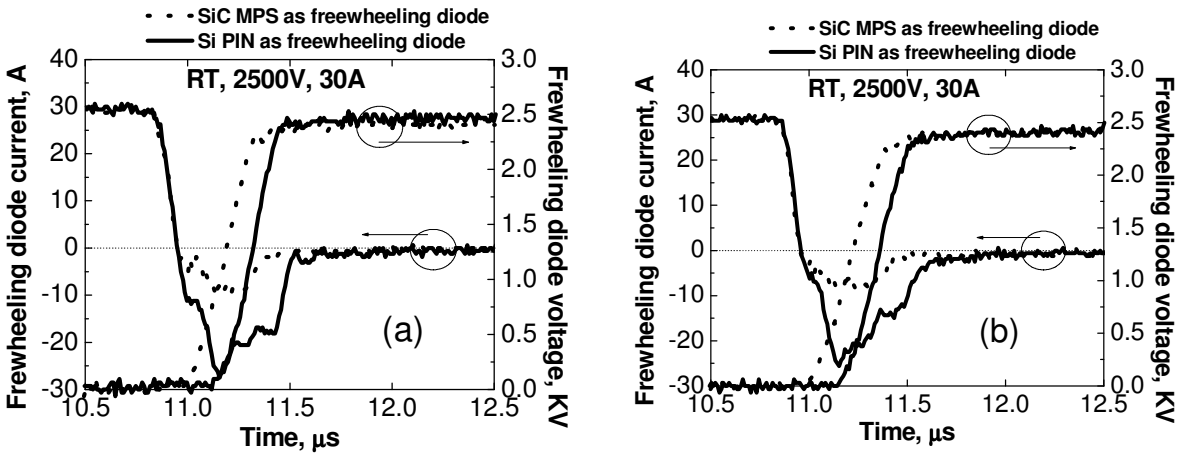

Fig.3 Reverse recovery current and voltage waveforms of SiC MPS and Si PIN diodes. (a) IGBT gate resistor is 2Ω. (b) IGBT gate resistor is 50Ω.

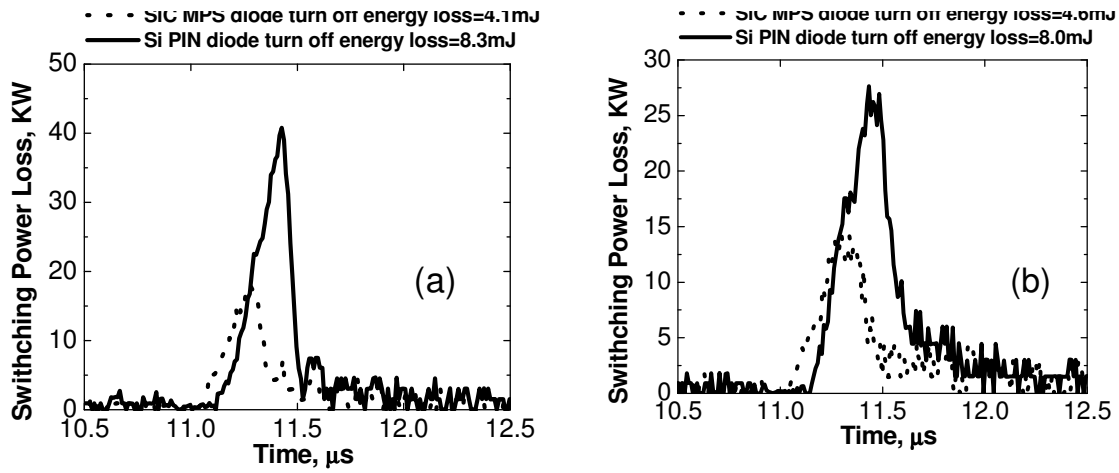

Fig.4 Reverse recovery energy loss of SiC MPS and Si PIN diodes.
(a) IGBT gate resistor is 2Ω. (b) IGBT gate resistor is 50Ω.

Most energy loss reduction, however, comes from the Si-IGBT power switch turn-on loss reduction. Fig.5 shows the turn-on current and voltage waveforms of Si IGBT with Si PIN or SiC MPS diode serving as the freewheeling diode. When IGBT gate resistor is 2Ω, the current spike of Si IGBT with a Si PIN is 42A, while the current spike of Si IGBT is only 22A with a SiC MPS, resulting in a current spike reduction of 48%. When IGBT gate resistor is 50Ω, the current spike of Si IGBT with a Si PIN is 37A, while the current spike of Si IGBT is only 11A with a SiC MPS, resulting in a current spike reduction of 70%. Fig.6 shows Si IGBT turn-on power loss spectrum with SiC MPS diode and Si PIN diode serving as the freewheeling diode. When IGBT gate resistor is 2Ω, the IGBT turn-on energy loss is reduced from 43.9mJ to 21.7mJ when SiC MPS diode replaces Si PIN diode, representing a reduction of 51% in IGBT turn-on energy loss. When IGBT gate resistor is 50Ω, the IGBT turn-on energy loss is reduced from 54mJ to 34mJ when SiC MPS diode replaces Si PIN diode, representing a reduction of 37% in IGBT turn-on energy loss. A summary of the switching test results is listed in Table.1. It can be seen that the most efficient condition is achieved by using SiC MPS diode and driving at a high di/dt rate. Also in SiC MPS case, at higher di/dt rate, Si IGBT turn off loss is 40.2 mJ, while total energy loss is only 68.7mJ: the Si IGBT turn off loss is a huge 58.5% of the whole energy loss. This is due to the bipolar nature of Si IGBT. If Si IGBT could be replaced by high voltage SiC JFET, then total energy loss reduction would be substantial.

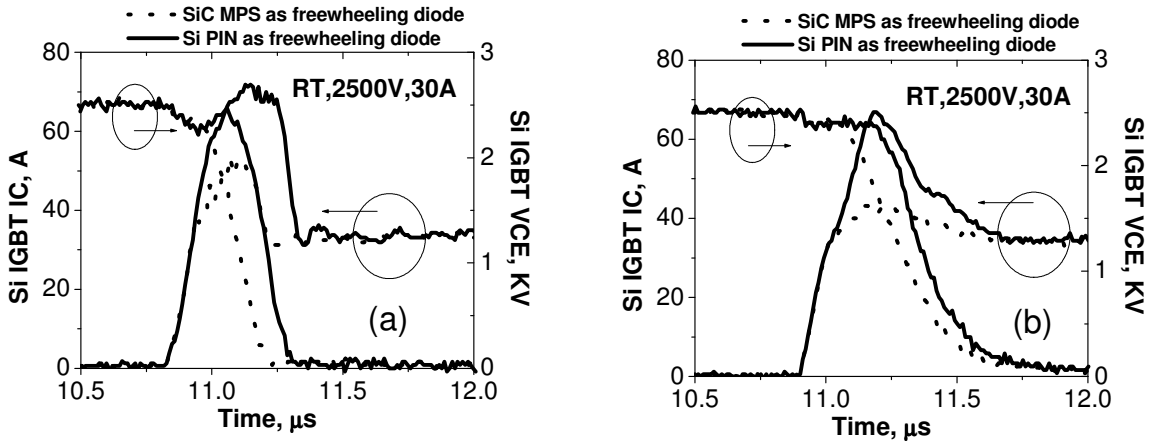

Fig.5 Si IGBT turn-on waveforms with SiC MPS or Si PIN as freewheeling diodes. (a) IGBT gate resistor is 2Ω. (b) IGBT gate resistor is 50Ω.

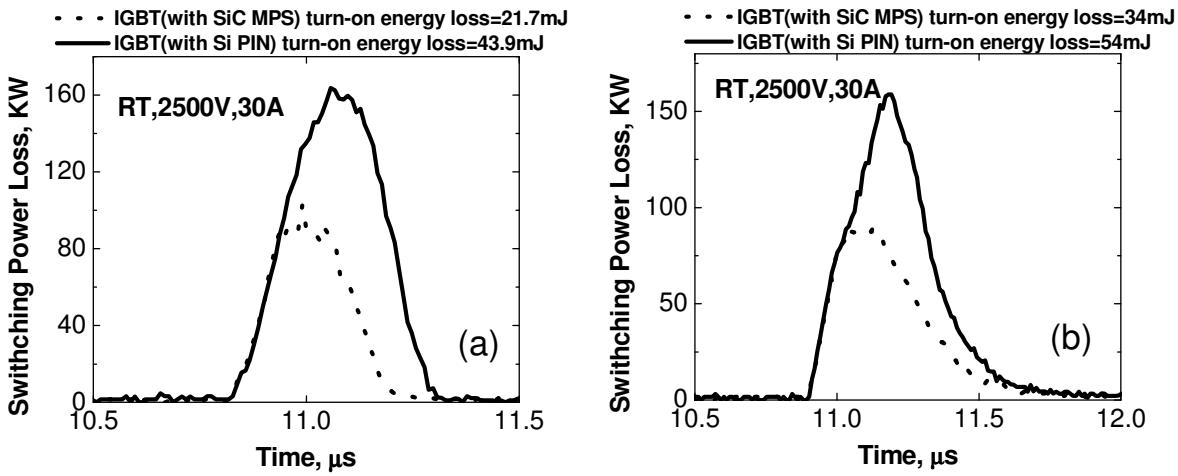

Fig.6 Si IGBT turn-on energy loss with SiC MPS or Si PIN as freewheeling diodes. (a) IGBT gate resistance is 2Ω. (b) IGBT gate resistance is 50Ω.

Si PIN/ SiC MPS	Diode off (mJ)	Diode on (mJ)	IGBT on (mJ)	IGBT off (mJ)	Total (mJ)
Rg=2Ω (di/dt=1A/ns)	8.3/4.1	2.7/2.7	43.9/21.7	40.2/40.2	95.1/68.7
Rg=50Ω (di/dt=0.2A/ns)	8.0/4.6	2.7/2.7	54/34	36/36	100.7/77.3

Table.1 Comparison of switching loss between Si PIN and SiC MPS, under two different IGBT gate resistors.

Summary

4H-SiC MPS diodes have been tested in an inductively loaded half-bridge inverter up to 2.5kV and 30A. Both SiC MPS and Si PIN were used as freewheeling diodes for Si IGBT. A large load inductance of 1mH was used. Compared with state-of-the-art ultra fast 40ns, Si PIN, the SiC MPS turn-off energy loss reduction is as high as 51% at room temperature (RT). Si IGBT benefits substantially from the use of SiC MPS diode. Si IGBT turn on energy loss is reduced by 51% at room temperature. This is the highest bus voltage tested in half-bridge, highly inductively loaded inverter using SiC MPS.

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