

3.3kV High Speed IGBT Module For Bi-directional and Medium Frequency Application

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Abstract

3.3kV high speed IGBT module was developed. Optimized lifetime control realized drastically decreasing of both of turn off loss and recovery loss. This high speed characteristic is suitable for bi-directional and medium frequency application such as resonant DC/DC converter. IGBT switching and diode reverse recovery behaviour at resonant DC/DC converter modelled circuit were demonstrated. Obviously, this new designed module shows lower loss than conventional high speed module and therefore better adaptability for bi-directional and medium frequency applications. This design concept is able to apply for 6.5kV IGBT module. In addition, diode loss of new design module was compared with 3kV-SiC-JBS at resonant DC/DC converter modelled circuit.

1. Introduction

Taking place of transformers to DC/DC converters is one of a technological interest in power electronics. For example, at power generation from renewable energy sources, Back-to-Back (BTB) systems using DC/DC converters instead of transformer is considered [1]. Generally, weight of transformer is too heavy to mount electric pole and the cost is high. Also for traction application, this approach seems to provide attractive solution. A train which runs several voltage sections, for example 15kV, 16 2/3Hz and 25kV, 50Hz etc., needs a transformer. Replacing by DC/DC converter provide downsizing of transformer and expansion limited space of train [2, 3].

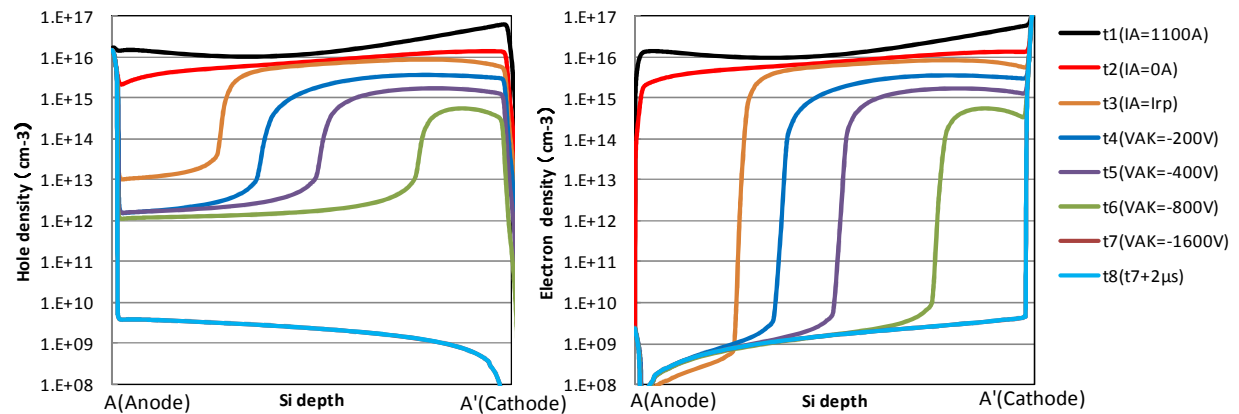
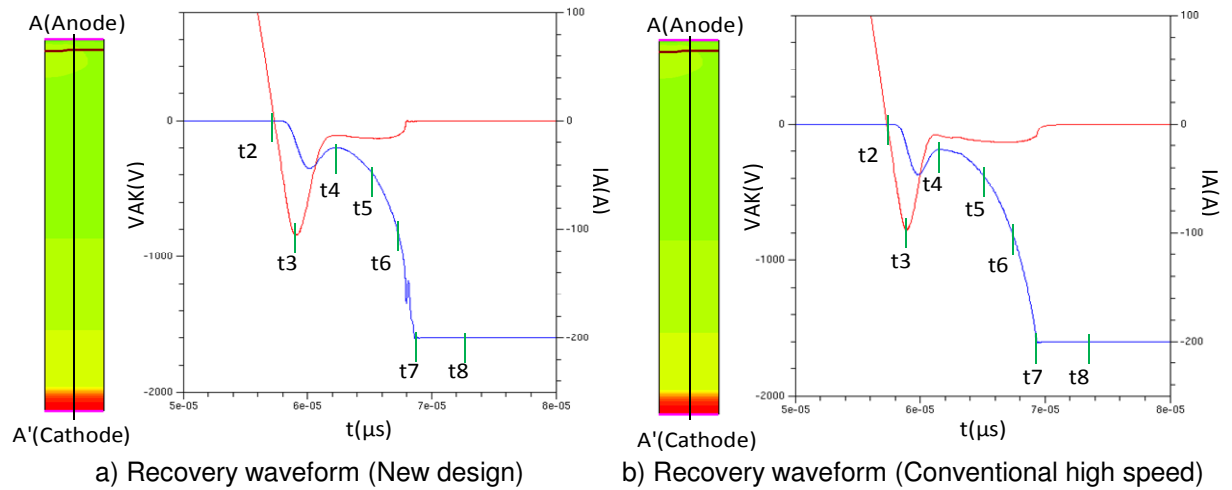
Generally, these DC/DC converters are operated at medium to high frequency range, which means several kilo hertz to several ten kilo hertz. But IGBT modules, which are considered as main components of DC/DC converter, are designed and optimized for operation at less than few kilo hertz. If conventional IGBT modules are applied to such a DC/DC converter, thermal runaway would be caused because of integration of switching or recovery loss by medium to high frequency operation. To realize replacing transformer to DC/DC converter, new design of IGBT module is needed.

Recently, a 1.2kV IGBT module was developed for 20 to 50 kHz switching frequency application. For application of more and more high power DC/DC converter, high voltage IGBT modules are necessary. And they should be suitable for medium to high frequency switching. In this paper, we report on new designed 3.3kV IGBT module for medium to high frequency switching application.

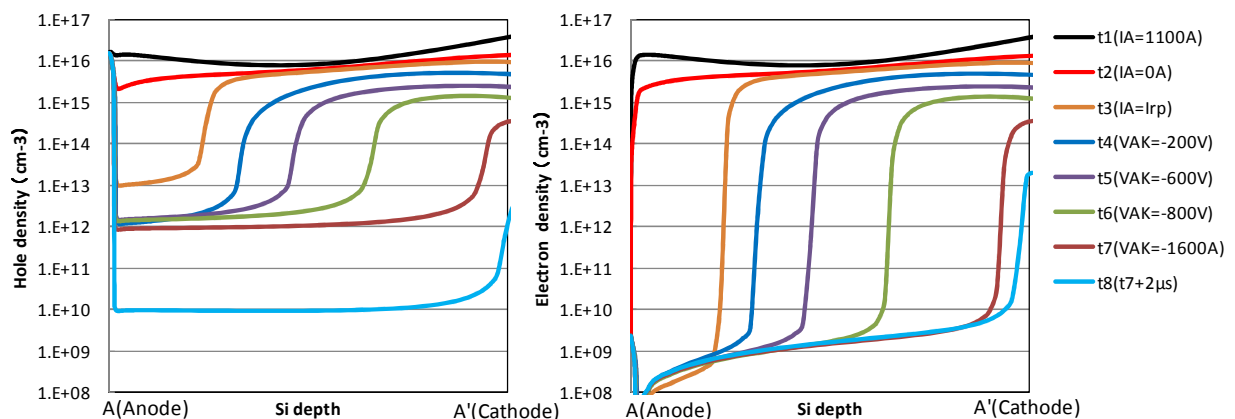
2. Device Design Concept

New design of IGBT module is strongly intended to medium frequency application. IGBT and diode chip structure designs were optimized to achieve low switching or recovery loss. Briefly,

parameter of lifetime control was considered. Lifetime killer was irradiated heavily to decrease lifetime of internal carrier.



c) Transition of hole density (New design) d) Transition of electron density (New design)
 ("A", "A'" are Anode and Cathode of diode die which shown on a cross section of Fig.1a. "t1" is time period of forward current flowing before recovery. "t2" to "t8" shows a time point during recovery operation which indicated on Fig.1a))



e) Transition of hole density (Conventional) f) Transition of electron density (Conventional)
 ("A", "A'" are Anode and Cathode of diode die which shown on a cross section of Fig.1b. "t1" is time period of forward current flowing before recovery. "t2" to "t8" shows a time point during recovery operation which indicated on Fig.1b))

Fig.1 Simulation of recovery operation at resonant DC/DC converter modeled circuit

Diode reverse recovery operation of this new design concept was simulated by ISE-TCAD. Fig.1 shows simulated diode reverse recovery waveforms and their transition of electron/hole density. New design diode shows shorter tail current than conventional high speed diode (Hitachi D-version diode die) (Fig.1a and Fig.1b). Fig.1c to Fig.1f show transitions of internal electron or hole density of diode at recovery operations, which waveforms were shown on Fig.1a and Fig.1b. At each time points on recovery waveform, electron and hole density are shown. In comparison of conventional diode and new designed one, both of electron and hole in new diode are swept out and become steady state faster. These phenomena would effect on reduction of recovery loss. This design concept was adapted to new IGBT die to achieve low turn-off loss, too.

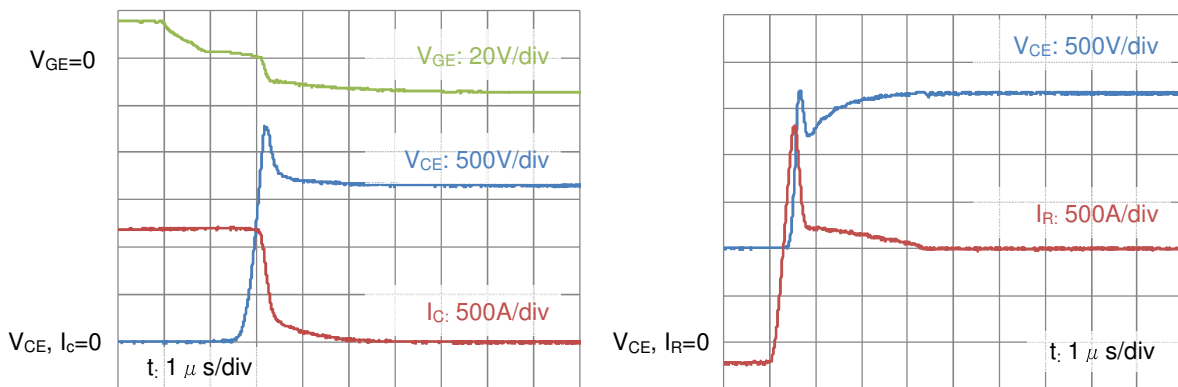
3. Electrical Characteristics

3.1 Turn-off and Recovery Characteristics

New design IGBT die and diode die are assembled in high isolation package (Fig.2). Here, 1200A 3.3kV IGBT module was evaluated. Fig.3 shows turn-off waveform and recovery waveform of new design IGBT module. New design IGBT module shows high dv/dt on turn-off waveform and short tail current on recovery waveform as shown on Fig.3. These waveforms affect low turn-off loss and recovery loss characteristics.



Fig.2 Hitachi high isolation IGBT
 $V_{ISO}=10.2kV_{RMS}$
 (Left:1200A/3.3kV, Right:800A/3.3kV)



a) Turn-off waveform

b) Recovery waveform

Fig.3 Turn-off and Recovery waveform of new design module

3.2 Trade-off and 3 level inverter simulation

Trade-off characteristics of New design IGBT module were compared with 3.3kV standard IGBT module (Hitachi's E2-version IGBT module, MBN1500E33E2) (Fig.4). Because of lifetime control, new design module's turn-off loss and recovery loss were decreased compared with standard IGBT module. On the other hand, $V_{ce(sat)}$ and V_F were increased.

By decreasing both of switching and recovery loss, new design module would be able to apply bi-directional applications.

As well as bi-directional applications, new designed IGBT module would be suitable for inverter application at more than 1 kHz. Fig.5 shows 3 level inverter loss simulations of standard IGBT module and new design one. At low carrier frequency (300Hz), standard module shows the lower loss than new design. At carrier frequency is more than 1 kHz, new design module show lower loss than standard one. Furthermore, new design module shows the distinctly low loss at 2 kHz. This tendency would become larger when carrier frequency is increased. In inverter application when the carrier frequency is high, new designed IGBT module shows better adaptability than standard IGBT modules.

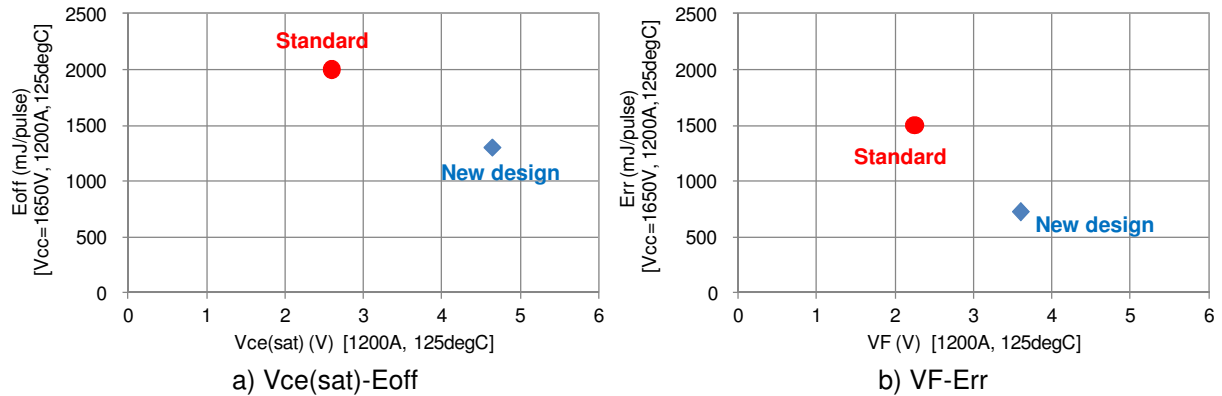


Fig.4 Trade off characteristics

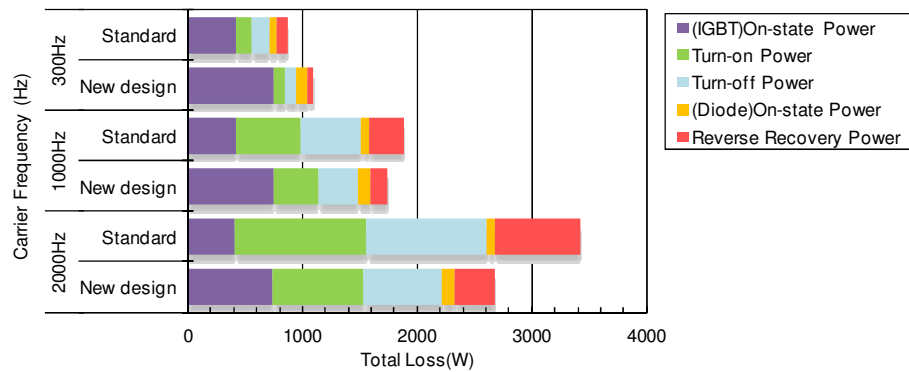


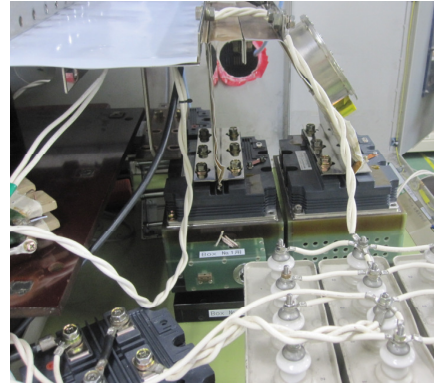
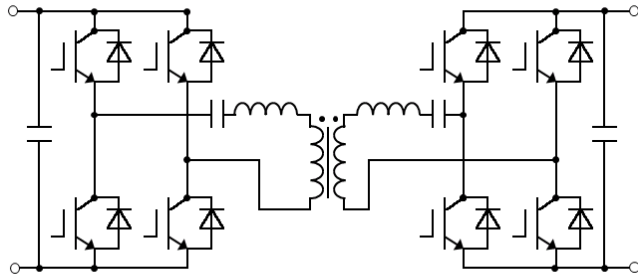
Fig.5 3level inverter simulation

4. Application for resonant DC/DC converter

4.1 Primary side IGBT

To evaluate how much this new diode is suitable for bi-directional and medium to high frequency application, we tested switching and recovery operation at resonant DC/DC converter modelled circuit. Fig.6 shows circuit topology of resonant DC/DC converter and overview of the modelled test circuit. The whole waveform of one cycle switching loss is shown on Fig.7a. This operation modelled primary side IGBT of resonant DC/DC converter. On this waveform, I_{cp} and turn-off current, which would be generated by inductance of resonant DC/DC converter, were modelled by circuit configuration. Under this switching operation, we supposed the switching frequency at 6 kHz. In generally, conventional IGBT module is operated at hard switching condition. On the other hand, in application of resonant

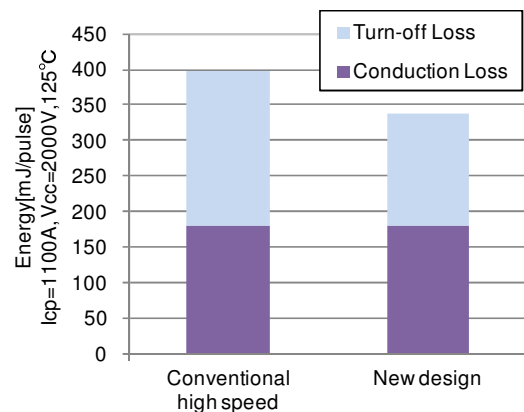
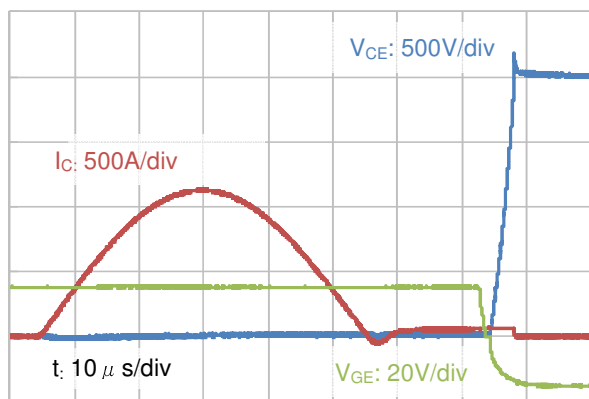
DC/DC converter which operated at medium frequency range, soft switching operation is proposed to reduce switching loss [3]. At turn-on period of Fig.7a, zero voltage switching (ZVS), which is V_{CE} being already zero before turn-on, was modelled. Therefore, turn-on loss is relatively lower than both of conduction loss and turn-off loss. The ratio of turn-on loss at total loss is about 3% by our measurement results. At turn-off period, turn-off under nearly zero current switching (ZCS) was simulated.



a) Circuit topology of resonant DC/DC converter

b) Modelled test circuit

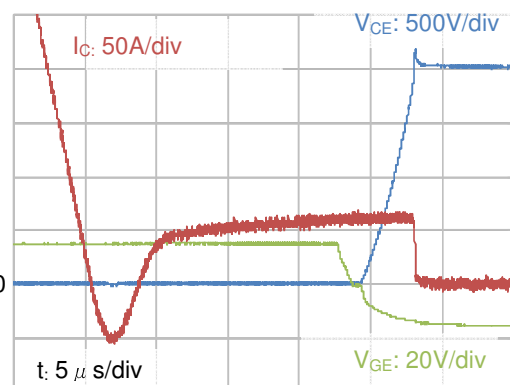
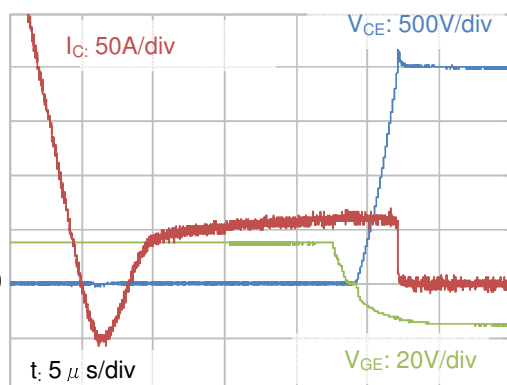
Fig.6 Circuit topology and modelled circuit of resonant DC/DC converter



a) One cycle switching waveform

b) One cycle loss comparison

Fig.7 One cycle switching waveform at resonant DC/DC converter modelled circuit ($V_{CC}=2000\text{V}$, $I_{CP}=1100\text{A}$, $T_C=125^\circ\text{C}$)



a) New design

b) Conventional high speed

Fig.8 Turn-off waveform at resonant DC/DC converter modelled circuit ($V_{CC}=2000\text{V}$, $I_{\text{turn-off}}=60\text{A}$, $T_C=125^\circ\text{C}$)

Fig.7b shows one cycle loss comparison between conventional high speed module (Hitachi's D-version IGBT, MBN1200H33D) and new design IGBT module. Turn-off loss of new design module was decreased 25% lower than conventional high speed module. As a total loss, new design module showed 15% lower loss than conventional one. Expansions of turn-off waveforms are shown on Fig.8. There is turn-off current which modelled magnetizing current and the current is nearly zero therefore ZCS was demonstrated. New design IGBT module shows higher dv/dt than conventional high speed module. This waveform results in reduction of turn-off loss at resonant DC/DC converter.

4.2 Application for 6.5kV IGBT design

To achieve electrical component smaller, it is one of a way to use higher voltage IGBT module. 6.5kV IGBT module can reduce number of a component and the size compared with 3.3kV IGBT module. In addition, by combination of 3.3kV and 6.5kV module, several configuration of DC/DC converter would be realized [2, 3]. Same as 3.3kV IGBT module, conventional 6.5kV IGBT module is optimized for low frequency and hard switching operation. To adopt medium frequency and soft switching operation, new design concept, which is same as 3.3kV IGBT, was applied to 6.5kV IGBT module, too.

Fig.9 shows turn-off waveform of 6.5kV new design IGBT and standard IGBT module (Hitachi E2-version, MBN500H65E2) at DC/DC converter modelled circuit. In waveform of new design IGBT, higher dv/dt was shown compared with standard IGBT. The loss is 25% lower than standard IGBT. Our new design concept is able to apply not only 3.3kV IGBT but also other voltage class IGBT.

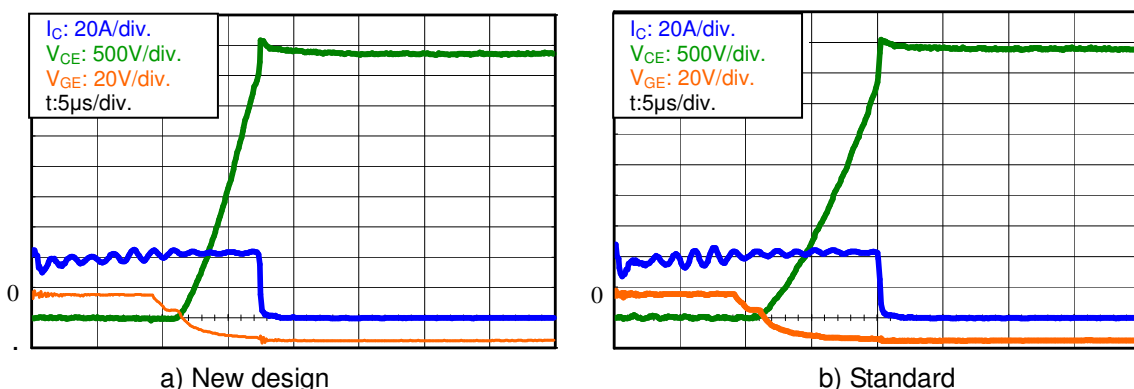


Fig.9 Turn-off waveform of 6.5kV IGBT module at resonant DC/DC converter modelled circuit ($V_{CC}=4400V$, $I_{turn-off}=40A$, $T_c=125^{\circ}C$)

4.3 Secondary side diode rectifier and comparison with SiC-JBS

Fig.10a shows the whole waveform of one cycle recovery operation. This operation modelled secondary side diode rectifier at resonant DC/DC converter. In addition to conventional high speed module and new design module, we evaluated 3.3kV 200A SiC hybrid module which is mounted SiC-Schottky barrier diodes (SiC-JBS) [5]. SiC-JBS is worth evaluation at modelled circuit because using SiC power semiconductor instead of Si one for DC/DC converter is considered as a way to achieve size reduction of converters [1, 3].

Fig.10b shows total loss comparison of one cycle operation at DC/DC converter modelled circuit. Total loss of new designed module is reduced to about 47% compared with conventional high speed module. Especially, reverse recovery loss was decreased drastically. Recovery loss of new design module was decreased more than 70% compared with conventional high speed module. SiC-JBS shows the lowest loss at our result. Reduction ratios of total loss from conventional module are 58% for SiC-JBS.

Fig.11 shows expansion waveform of reverse recovery period. New design IGBT module shows apparently faster recovery characteristics than conventional high speed module same as simulation results in Fig.1. Therefore 70% decreasing of recovery loss was achieved. For SiC-JBS, the recovery current is almost zero because of its structure. This results in lowest loss of recovery loss.

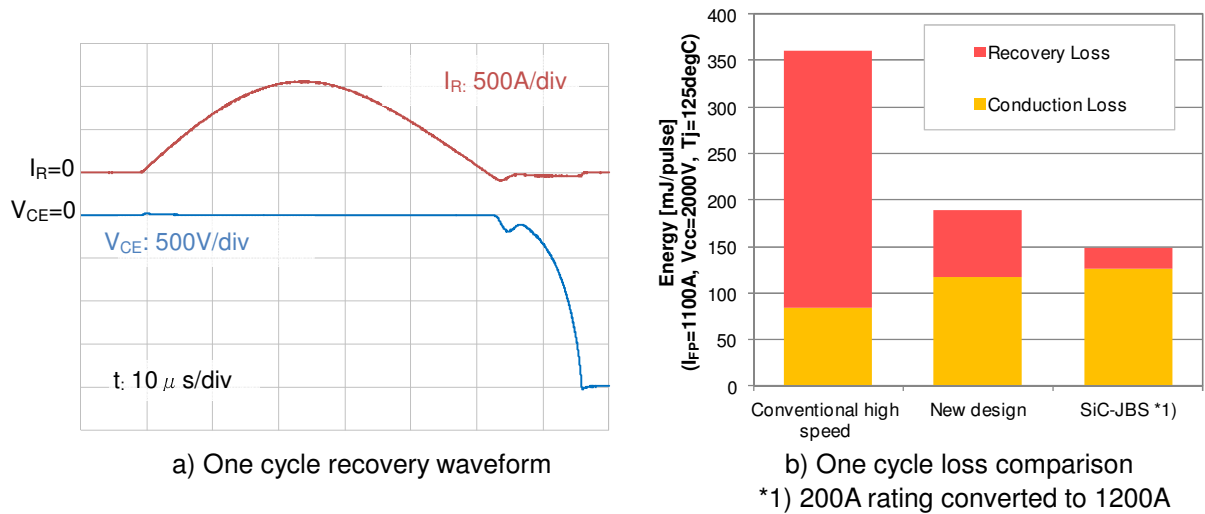


Fig.10 One cycle recovery waveform at resonant DC/DC converter modeled circuit ($V_{CC}=2000V, I_{FP}=1100A, T_c=125^\circ C$)

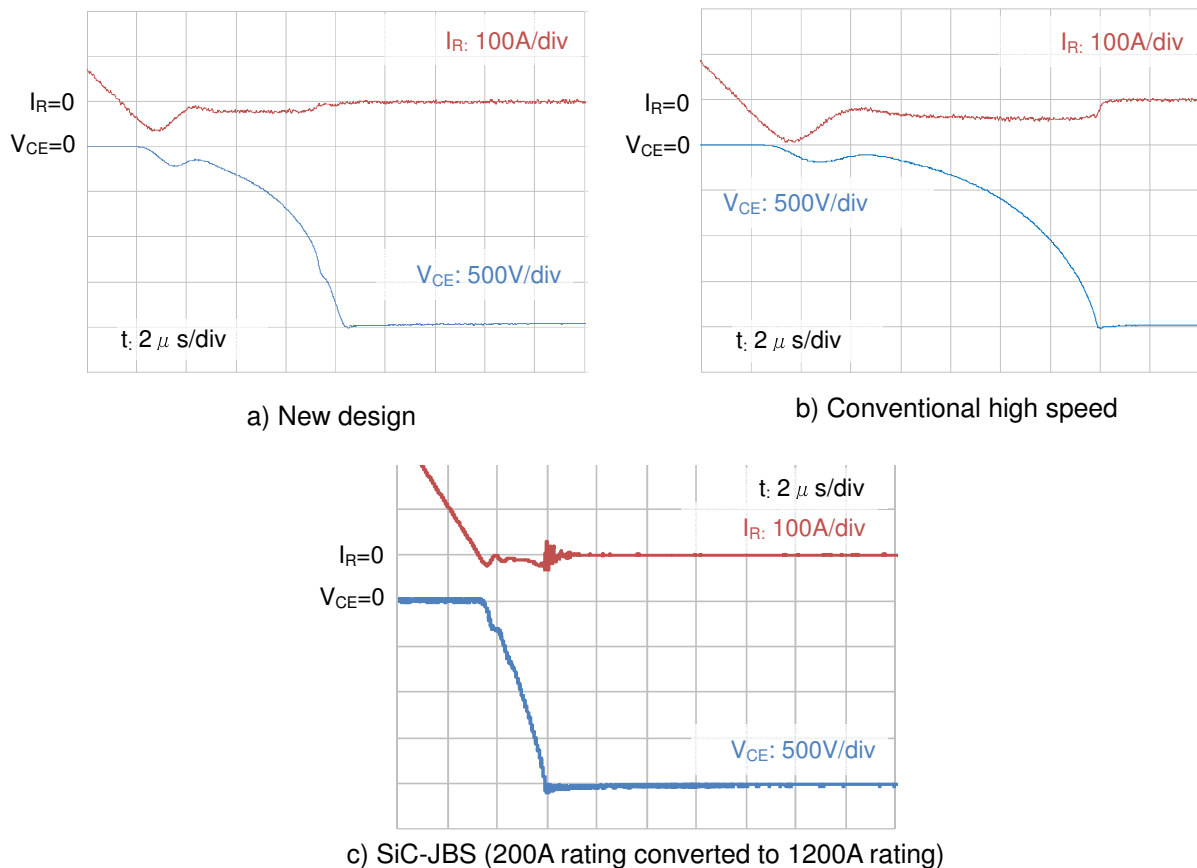


Fig.11 Recovery waveform at resonant DC/DC converter modelled circuit ($V_{CC}=2000V, I_{FP}=1100A, T_c=125^\circ C$)

5. Conclusion

Based on a concept of fast sweeping of internal carriers by lifetime control optimization, new designed 3.3kV IGBT module achieved fast switching and recovery characteristics. At resonant DC/DC converter modelled circuit, loss of primary side IGBT was decreased 15%, and loss of secondary side diode was decreased about 47% compared with conventional high speed module. By decreasing loss of both of IGBT and diode, this new design module will be suitable for bi-directional and medium frequency application such as DC/DC resonant converter. This design concept is able to apply for 6.5kV IGBT and other voltage class. Therefore several configurations of medium frequency application would be considered. In addition, we also evaluated SiC-JBS diode at the modelled circuit. SiC-JBS showed the lowest loss and it would bring big benefit for high frequency application more than 10 kHz in future. Nevertheless, we expect that this new design concept is suitable for medium frequency applications and realistic solution before appearance of SiC-JBS in power semiconductor's market.

6. Literature

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