# Development of fast short-circuit protection system for advanced IGBT

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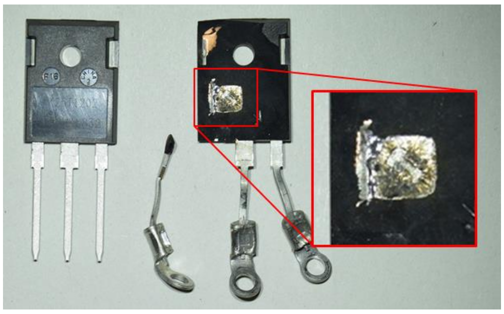
**Abstract**

The higher current density of IGBTs has made it difficult to achieve high short-circuit withstand capability as well as good conduction characteristics. Therefore, a fast and reliable protection system is required for the safe operation of IGBT. This paper determines the short-circuit safe protection area (SCSPA) for advanced IGBT that has no short-circuit withstand capability and proposes the protection system satisfied this SCSPA. The fast protection is brought by PCB Rogowski coil and digital gate driver using digital circuit (FPGA). Experimental results verify that short-circuit detection time is 70ns, shut-down time is reduced by controlling the gate resistance at turn-off.

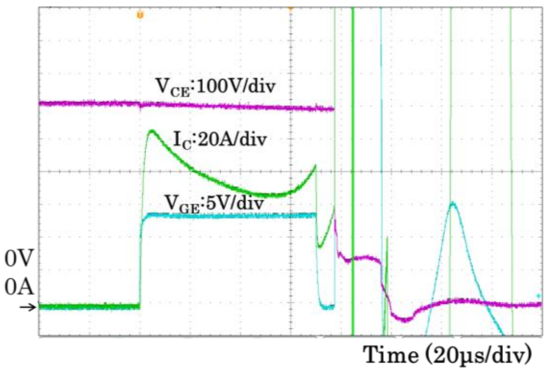
## 1. Introduction

Power electronics equipment trends high power density. IGBTs, one of the representative power devices, have been increased current density by improving the structure [1]. Even now, new structures have been proposed [2, 3]. It indicates that the current density of IGBTs will continue to increase. The higher current density needs to improve conduction characteristics, however, the short-circuit withstand capability decreases due to a trade-off relationship [4, 5]. Lower short-circuit withstand capability is easier to cause short-circuit destruction. Fig.1 shows the catastrophic destruction of an IGBT as an example. Future IGBTs is difficult to achieve both of conduction characteristics and short-circuit withstand capability. Therefore, to improve further conduction characteristics, it is necessary to install a new system to prevent the IGBT from destruction even with low short-circuit withstand capability [6-9].

Conventional detection method employs non-isolated current detection such as sense IGBT and shunt resistor [10-12]. This method detects short-circuit condition after 2μs or more because the low-pass filter is embedded to remove noise components [13, 14]. In addition, short-circuit current must be cut off with suppressed surge voltage under rated voltage. The conventional shut-down method, soft shut-down uses higher resistance than normal condition one. It causes increasing high-power dissipation at turn-off [15].



(a) Broken IGBT by short-circuit.




(b) Short-circuit waveforms.

Fig.1. IGBT destruction in short-circuit.

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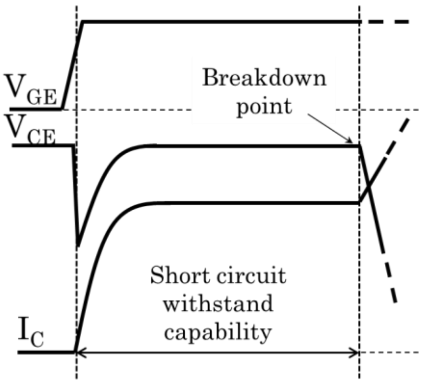
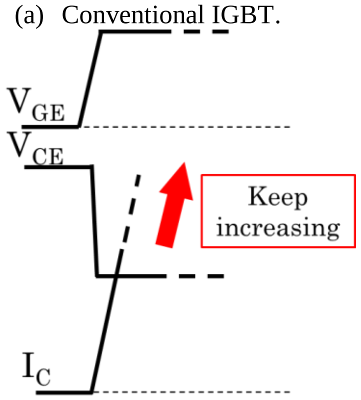



(a) Conventional IGBT.




(b)

(c) (b) Advanced IGBT.

(d) Fig.2. Short-circuit operation waveforms.

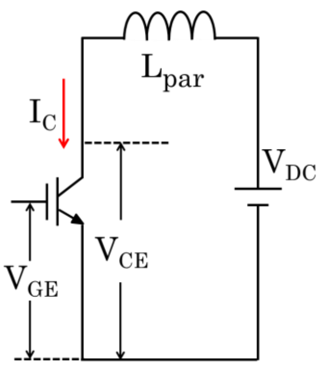



Fig.3. Test circuit in short-circuit.

This paper determines the short-circuit safe protection area (SCSPA) for advanced IGBT that has no short-circuit withstand capability and proposes a fast protection system satisfied this SCSPA. Unlike the previous papers, the system has the special capability of not only fast detection of short-circuit but also fast current shut-down after the detection. The faster protection is effective to protect both of energy and electrical failure mode [16].

*2.1. Short-circuit operation of advanced IGBT*

The short-circuit waveforms of advanced IGBT tends to differ from the conventional one. Fig.2 shows the operation waveforms of these IGBTs in short-circuit. The current of conventional IGBT goes through a sharp transition from linear region to saturation region in short-circuit. Consequently, the current and hence power dissipation get self-limited. On the other hand, advanced IGBT has higher current density. This characteristic cause increasing the maximum current of the saturation region. Therefore, advanced IGBT eventually has linear and non-saturation region.

Table1. Parameters.

| Symbol | Description |
|---|---|
| $V_{DC}$ | Supply voltage |
| $V_{CES}$ | Collector-emitter breakdown voltage |
| $V_{CE(SC)}$ | Collector-emitter voltage in short-circuit |
| $I_C$ | Collector current |
| $J_C$ | Collector current density |
| $L_{par}$ | Parasitic inductance |
| $E_{max}$ | Maximum joule heat per $1cm^2$ |
| S | Chip area |
| $T_1$ | On state time in short circuit |
| $T_2$ | Turn off time in short circuit |

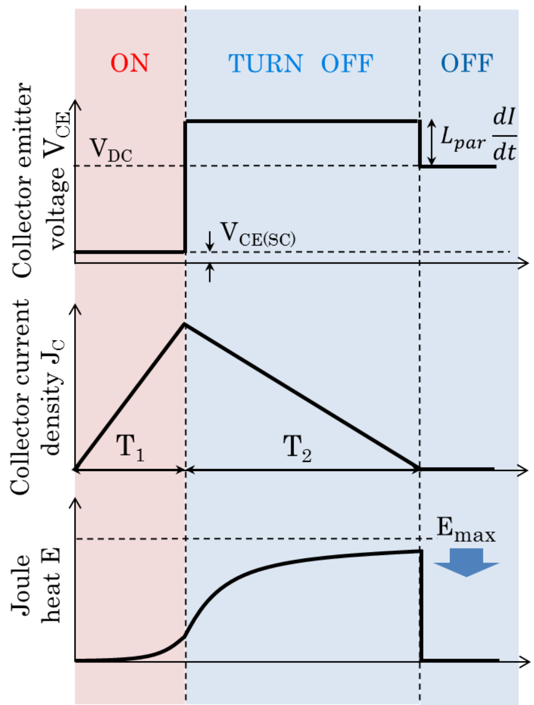



Fig.4. Waveforms with short-circuit protection

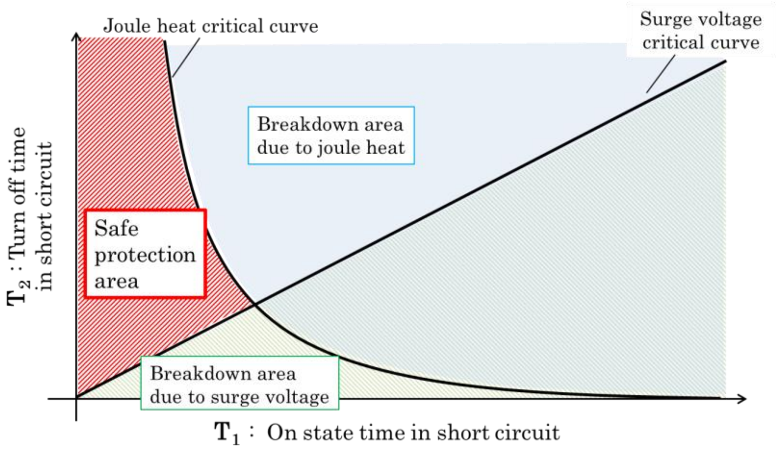



Fig.5. SCSPA for advanced IGBT.

*2.2. How to determine the short-circuit protection area (SCSPA)*

In order to determine SCSPA from short-circuit destruction mechanisms, Fig. 3 and 4 show the test circuit diagram in short-circuit and the operation waveforms with protection. Table 1 also shows the definitions of symbols. The causes of the short-circuit failure are an exceeding critical temperature and an exceeding rated voltage [5]. While short-circuit current increases, a supply voltage is divided by an IGBT and a parasitic inductance. In contrast, the IGBT has applied the voltage over the supply voltage at turn-off. These mean that most of the heat due to power dissipation generates at the turn-off. Shorting the turn-off time suppresses the generated heat. However, it increases surge voltage because di/dt becomes large. This surge voltage also induces the IGBT to short-circuit destruction. Furthermore, the larger maximum value of short-circuit current makes difficult to suppress both the heat and the surge voltage within the allowable value. Therefore, short-circuit protection system for advanced IGBT needs fast short-circuit detection and current shut-down with surge voltage suppression.

The proposed SCSPA is represented by $T_1$ and $T_2$ to evaluate the performance of the short-circuit protection system. $T_1$ is the ON state time in short-circuit. $T_2$ is the turn-off time in short-circuit. The generated heat is limited by Joule heat $E_{max}$ [J/cm$^2$]. $E_{max}$ rise to the critical temperature that the device and peripheral metals such as bonding wire and solder can keep performing its function. Also, the surge voltage at turn-off is limited by the rated voltage $V_{CES}$[V] of the device. From these, the following inequalities are obtained.

$$\int_0^{T_1+T_2} J_C \times V_{CE}\, dt \le E_{max} \quad (\mathrm{J/cm^2}) \qquad (1)$$

$$V_{DC} + L_{par}\frac{dI}{dt} \le V_{CES} \quad (\mathrm{V}) \qquad (2)$$

From equation (1) and equation (2),

$$T_2 \le \frac{2E_{max}L_{par}S}{(V_{DC} - V_{CE(SC)})V_{DC}T_1} - T_1 \qquad (3)$$

$$T_2 \ge \frac{V_{DC} - V_{CE(SC)}}{V_{CES} - V_{DC}}T_1 \qquad (4)$$

The area obtained from equation (3) and equation (4) is SCSPA for advanced IGBT. Fig. 5 shows SCSPA for advanced IGBT.

**3. Proposed short-circuit protection system**

*3.1 Overview of the proposed system*

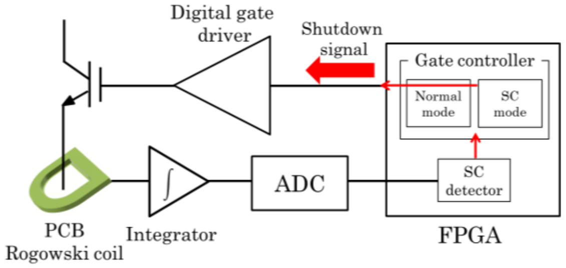



Fig.6. Overview of the proposed system.

The proposed system consists of a small PCB Rogowski coil, integrator, AD converter, digital circuit (FPGA) and digital gate driver. Fig.6 shows an overview of the proposed system. Table 2

Table2. Devices used in this system.

| | | |
|---|---|---|
| FPGA | Devise | Xilinx SpartanR-6 FPGA (XC6LX16-CS324) |
| | Clock | 100MHz |
| AD converter | Devise | Texas instruments ADC08100 |
| | Clock | 100MHz |
| | Bit | 8bit |

summarizes the devices used in this system. PCB Rogowski coil detects short-circuit current. The measured current is fed to FPGA through ADC. When the digital signal exceeds a threshold considered short-circuit, FPGA outputs shut-down signals to a digital gate driver. Therefore, IGBTs are protected even if overcurrent other than short-circuit mode. Details of current sensing and gate driver are described below. By the way, a specific IC can be also used to change gate resistance instead of FPGA.

### *3.2 Current sensing with PCB Rogowski coil*

PCB Rogowski coil realizes fast short-circuit detection by removing the low-pass filter which is the cause of detection delay [17]. PCB Rogowski coil is an isolated current detector. The main pattern is very close to the ideal Rogowski coil by using printed circuit board technology. Furthermore, PCB Rogowski coil used in this system has high accuracy and noise immunity because of employing a fishbone coil pattern, noise-shield layer and coaxial connector [18-20]. In addition, the PCB Rogowski coil is small and thin as shown in Fig.7. Therefore, the PCB Rogowski coil is suitable for short-circuit protection system of the power module.

Rogowski coil outputs a proportional value to the differential value of the measured current. In order to acquire the waveform of the measured current, the proposed system uses an analog integrator based on an operational amplifier.

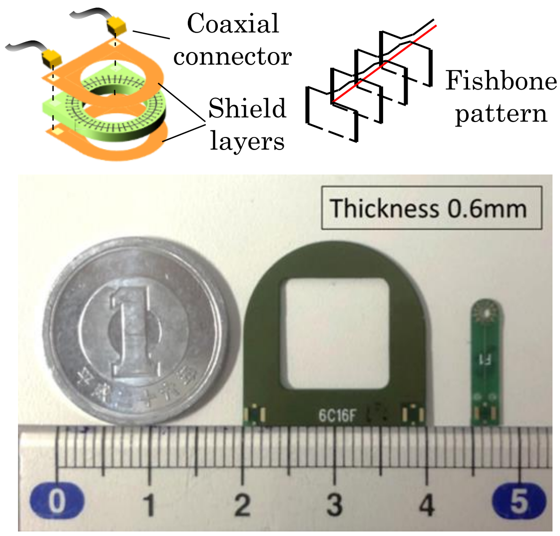


Fig.7. PCB Rogowski coil.

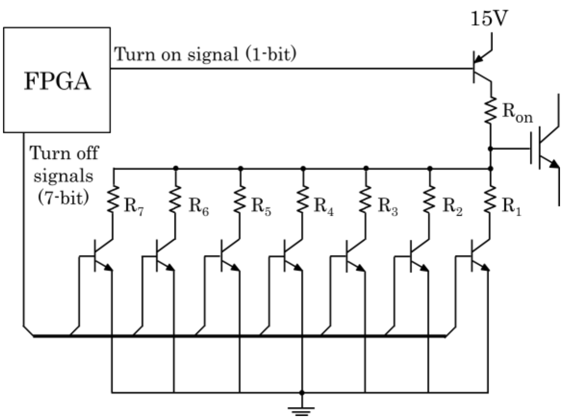
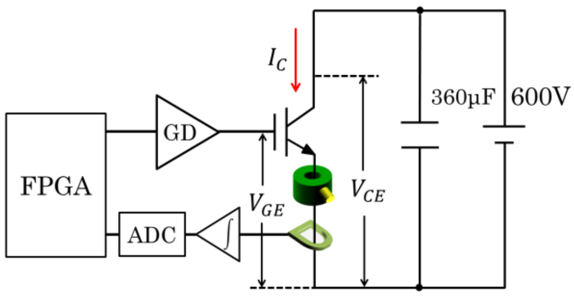


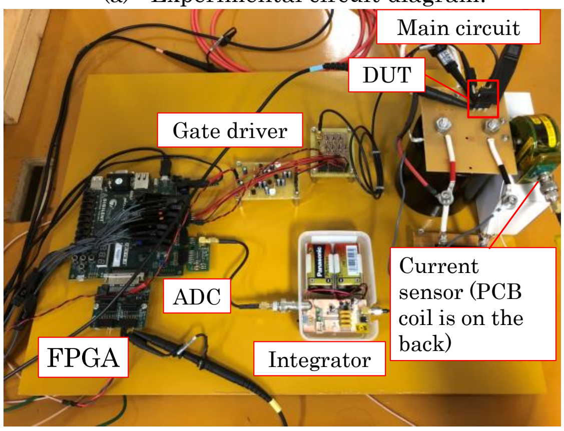
Fig.8. Diagram of digital gate driver.

### *3.3 Digital gate driver*

The proposed system employs a digital gate driver for fast current shut-down time and suppression surge voltage at turn-off. Fig.8 shows a circuit diagram of the digital gate driver. The digital gate driver changes the gate resistance at turn-off by the signals from FPGA. FPGA controls the gate resistance with a binary code of 7-bit. This means that the gate resistance can be changed 127 steps except all the 7-bit signals are '0'. The gate resistance can be switched every 100 ns at turn-off by the signals from FPGA. The range of the gate resistance is from 29Ω to 5.1kΩ. In order to turn on short-circuit current sharp, $R_{on}$ uses 10Ω.



(a) Experimental circuit diagram.



(b) Picture of setup.

Fig. 9. Experimental setup.

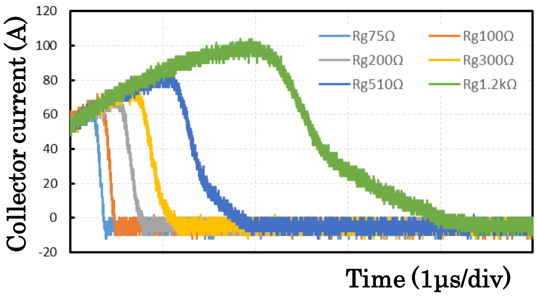



Fig. 10. Current waveform of short-circuit by constant $R_{off}$.

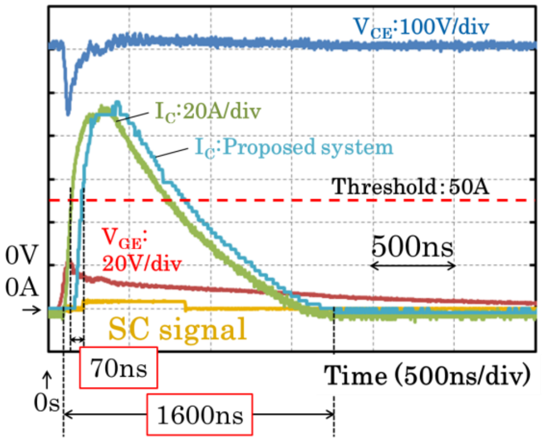



Fig.11. Short-circuit waveform with the proposed system ($R_{off}$=200Ω).

## 4. Experiment

*4.1 Circuit configuration*

Fig.9 shows the experimental circuit diagram and the picture of the experiment. We use a representative commercial current sensor (Pearson) to compare with the current waveform obtained from the proposed system. The IGBT (1200V/50A rated, IKW 25 N 120 T 2, Infineon) is directly connected to a dc voltage source of 600 V. The current waveform of short-circuit is changed by $R_{off}$ as shown in Fig. 10.

*4.2 Results*

Fig.11 shows short-circuit protection performance without controlling the gate resistance. SC signal is output at the time that FPGA judges short-circuit. The proposed system detects short-circuit at

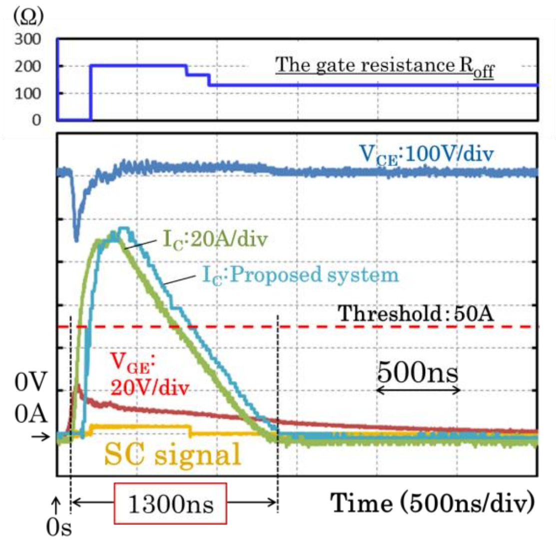



Fig.12. Short-circuit waveform with proposed system

70ns from exceeding the threshold. The time of flowing short-circuit current is 1600 ns. Fig.12 shows short-circuit protection performance by controlling the gate resistance. The shut-down time is shortened by gate resistance control with the same surge voltage condition as constant gete resistance. The time of flowing short-circuit current is 1300 ns. It's reduced by 20% compared with Fig.11. By the relationship of equation (2), optimum shut-down di/dt is constant. Therefore, gate resistance is lowered gradually to realize constant di/dt. From equation (3) and equation (4), time limit of T1 for advanced IGBT is 0.65 μs as shown in Fig. 13. The T1 of conventional system is 2 μs even the fastest, therefore the system does not satisfy the detection

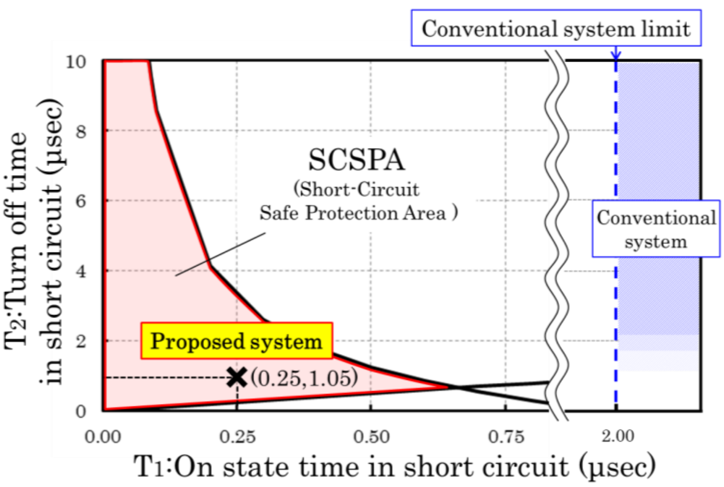



Fig.13. Evaluation of proposed system.
($V_{DC}$=600V, $L_{par}$=100nH, $E_{max}$=5.73J/cm$^2$)

speed. On the other hand, T1 and T2 are 0.25 μs and 1.05 μs respectively by the proposed system and satisfied the time limit and the SCSPA.

## 5. Conclusion

This paper determines the safe protection area for advanced IGBT and proposes fast short-circuit protection system. The proposed system consists of mainly PCB Rogowski coil and a digital gate driver to shorten the protection time. In short-circuit test with the IGBT rated 1200V/50A connected to a dc voltage source of 600 V, the short-circuit detection time is 70ns. The shut-down time is reduced by controlling the gate resistance at turn-off. This result verifies that this system is satisfied with the short-circuit safe protection area (SCSPA).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