Humidity Robustness Verification Test for HVIGBT Modules

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1. Introduction

Railway transportation is more energy efficient than other means of transportation, and thus reduces the environmental impact of the entire transportation sector. Accordingly, the use of railways has been encouraged around the world to help mitigate global warming. In addition, to realize a low-carbon society, various measures have been promoted such as electrification of unelectrified railway sections and introduction of battery-powered railway vehicles. As a result, electric trains are now operating in various environments around the world.

Power modules for railway vehicles need to be small, low loss and highly reliable compared to those for consumer goods and general industries. Therefore, it is important to check the durability of such modules in various environments. Since modules are not hermetically sealed, it is difficult to completely eliminate the influence of humidity in highly humid environments, and so technologies for verifying robustness to humidity are strongly needed.

Under such circumstances, Mitsubishi Electric Corporation has been developing technologies for verifying the humidity robustness of HVIGBT modules. Using these technologies, we verified the effectiveness of a surface charge control (SCC) technology, which offers excellent humidity robustness, and developed our latest-generation X series of HVIGBT modules.

This report describes the humidity robustness verification technologies for HVIGBT modules that we have developed, along with verification results for the X series.

2. Mechanisms of Failures due to Humidity

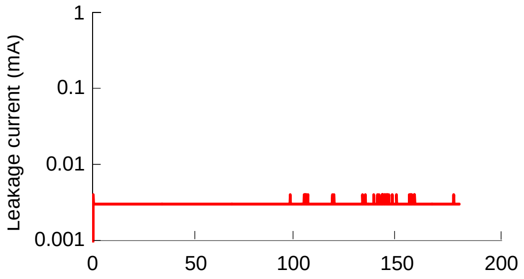
2.1 Known failure mechanisms

The blocking voltage of power semiconductor chips is retained by the terminations around their perimeter. Usually, aluminum electrodes are arranged in a ring shape at a termination and each ring bears part of the voltage. In one known failure mode, moisture ingress results in corrosion and failure of aluminum electrodes.(1) Another known failure mode is electrochemical migration (ECM) of copper, silver, and other metals.(1)

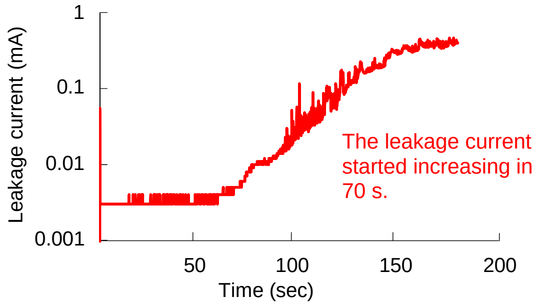
2.2 New failure mechanism

Through our studies on the humidity robustness of power semiconductors, we found a new failure mode which may cause power semiconductors to fail, besides the aforementioned aluminum corrosion and ECM. The conventional aluminum corrosion and ECM take time to cause a failure. However, for the newly found failure mode, the leakage current starts increasing in several tens to several hundred seconds after starting to apply the voltage as shown in Fig. 1. This is not enough time for aluminum corrosion or ECM to proceed, confirming that the failure mechanism is a new one.(2)

This new failure mode can be confirmed as follows: An HVIGBT module is allowed to absorb moisture, then it is rapidly cooled to form condensation, then a DC voltage is applied. As shown in Fig. 1, when the module was dry, even after a DC voltage was applied, the leakage current of the device did not increase; on the other hand, when the module was in a state with condensation, the leakage current started increasing just 70 seconds after starting to apply the DC voltage. The results showed that although the device did not break, the increase in the leakage current while applying the DC voltage may have been caused by the blocking voltage performance becoming unstable.



(a) Voltage application in a dry state



(b) Voltage application in a state with condensation

Fig. 1 Condensation test

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*Power Device Works

The mechanism by which a leakage current increases due to condensation is shown below. When a voltage is applied to a device, the gel (dielectric) polarizes along the electric field in the module; when the module absorbs moisture at the same time, the surface charge (+Qss) accumulates at the termination of the power semiconductor chip due to a combined effect with the gel polarization (Fig. 2).

Figure 3 shows the electric field distribution at the chip terminations when no surface charge (+Qss) exists and when surface charge (+Qss) has accumulated. In Fig. 3, the electric field is high in the green to red regions, and low in the blue region. The figure shows that when surface charge (+Qss) accumulates at a chip termination, the electric field at the chip termination becomes high. As a result, the blocking voltage of the device may decrease, which may increase the leakage current and the device may break in the worst case.

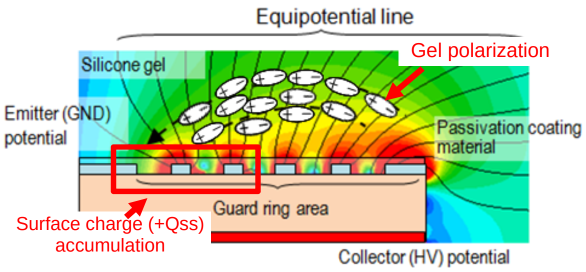

Fig. 2 Gel polarization due to condensation

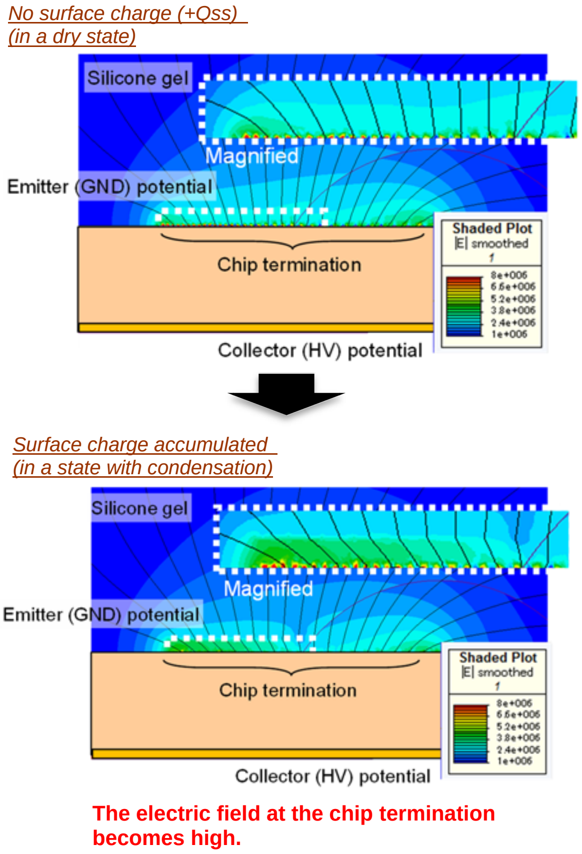

Fig. 3 Electric field inside the module in a state with condensation

3. Humidity Robustness Improvement Technology: Surface Charge Control (SCC)

For this newly found failure mode, Mitsubishi Electric developed the SCC technology(3) and released the X series of HVIGBT modules with higher humidity robustness. Figure 4 illustrates the conventional chip termination structure, and Fig. 5 illustrates the structure of the new chip termination with the SCC technology. In the conventional structure, the chip termination is covered with an insulated layer, while in the termination structure with the SCC technology, it is covered with a semi-insulated layer.

In the conventional structure, since the chip termination is covered with an insulated layer, there is no route to release the accumulated surface charge (+Qss). On the other hand, in the termination structure with the SCC technology, since the surface charge (+Qss) is released through the semi-insulated layer, the surface charge does not adversely affect the electric field at the chip termination. Therefore, the excellent blocking voltage property can be retained even when there is condensation.

Figure 6 shows the effect of the SCC technology that was verified in the aforementioned voltage application test with condensation. Figure 6 shows that even when the chip structure was the same, the leakage current increased in one cycle without the SCC technology, whereas for the structure with the SCC technology, the leakage current did not increase even in

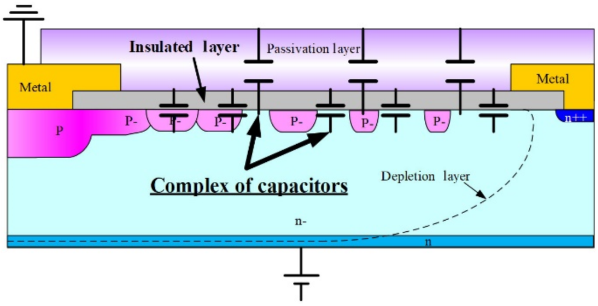

Fig. 4 The conventional chip termination: covered by an insulated layer

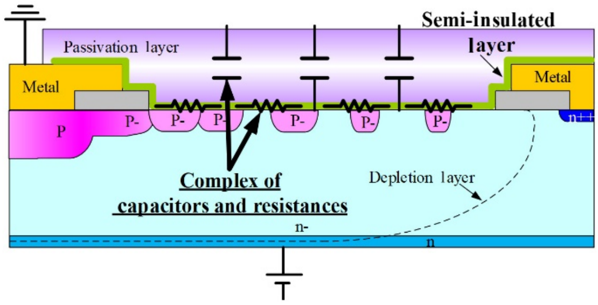

Fig. 5 The new termination with SCC technology: covered by a semi-insulated layer

seven cycles.

4. Condensation Resistance Check Tests (Condensation Cycle Tests)

Figure 7 illustrates the procedure of the condensation test mentioned above. The test piece is allowed to absorb moisture in a high-temperature high-humidity chamber in an environment of 85°C, 85%RH and then it is taken out from the chamber to cool it in a heatsink. Therefore, this procedure is not suitable for repeated tests. However, to evaluate condensation resistance, a repeated test procedure is needed. In addition, with conventional condensation tests, the severity of acceleration tests in comparison with condensation that may occur in the field was not clear. We aimed to solve these problems.

4.1 Investigation of the worst environment in the field

To find the worst environment in the field, we carried out condensation tests in which modules were allowed to absorb moisture in various environments, then they were rapidly cooled to form condensation, and a voltage was applied. As devices, 3.3-kV IGBTs (rating: 3300 V/1200 A) were used in the tests. Figure 8 shows the results.

Figure 8 shows that the higher the absolute humidity (AH) is, the worse the result is. The figure also shows that even when AH is the same, a higher relative humidity (RH) causes a worse result. That is, the worst field condition may be when both AH and RH are high. For class 5K2 specified in IEC 60721-3-5, the worst condition when the temperature changes is 30°C, 95%RH, 29 g/m^3. By adding approximately 10 g/m^3 to this value as a safety margin, we determined 36°C, 95%RH, 40 g/m^3 as the worst field environment.

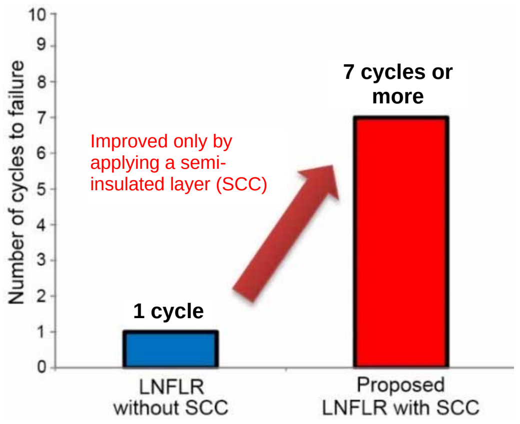

Fig. 6 Condensation test result

4.2 Investigation of acceleration factors in condensation tests for field environments

To determine the severity of condensation tests in comparison with the worst field environment determined as above, a condensation test was performed. In the test, a test piece was allowed to absorb moisture under the worst field environmental condition and was rapidly cooled; then it was compared to the result of a normal condensation test in which a test piece was allowed to absorb moisture at 85°C, 85%RH and then rapidly cooled for evaluation. Table 1 lists the results. The results show that even compared to the worst field condition, the acceleration in the established condensation test procedure is a factor of at least 80 times. The test will be evaluated by the condensation cycle test mentioned later.

4.3 Establishment of condensation cycle test procedure

As mentioned previously, in the conventional condensation test procedure, a test piece is taken out from the chamber to cool it in a heatsink, which makes the procedure unsuitable for cycle tests. To make cycle tests possible, cycle tests in which a test piece was cooled in a high-temperature high-humidity chamber were introduced to see if the effect was the same as cooling in a conventional heatsink. Figure 9 compares the changes in the amount of absorption by devices with the number of cycles. The figure shows that compared to the results of the condensation test with a heatsink, the same effect can be obtained when the number of cycles is doubled in a condensation test using a chamber, thus clarifying the cycle tests.

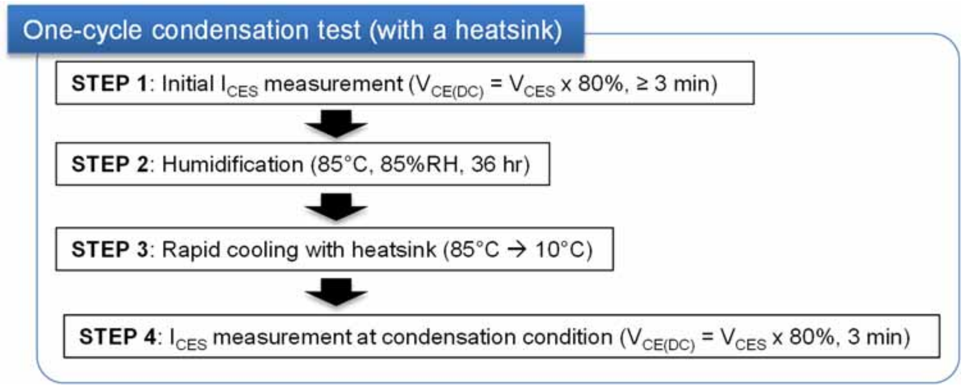

Fig. 7 One-cycle condensation test with heatsink

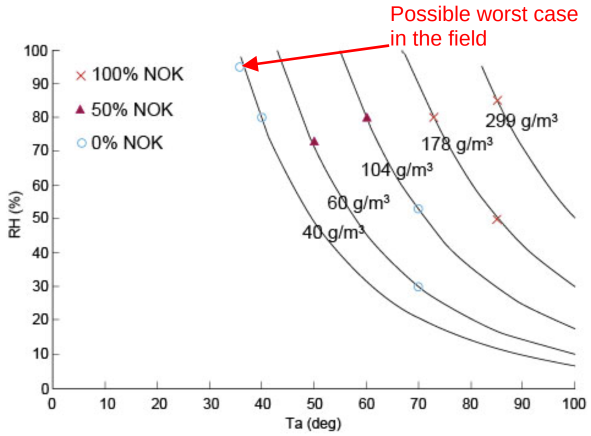

Fig. 8 Condensation test results under various humidification conditions

Table 1 Comparison of test results between field condition and accelerated test condition

Worst field environmental condition (Cooling from 36°C, 95%RH)	Failure in 80 cycles
Condensation test condition (Cooling from 85°C, 85%RH)	Failure in 1 cycle

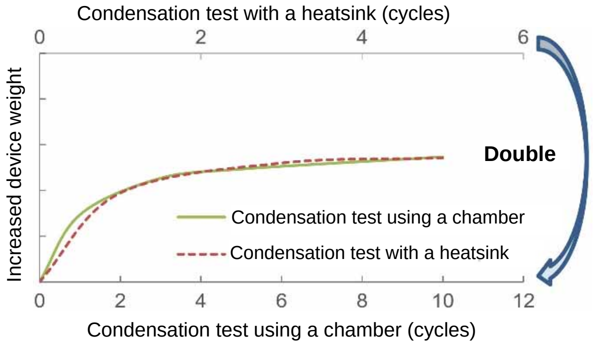

Fig. 9 Vapor absorption trend

4.4 Condensation cycle test results for the X series

As described previously, the SCC technology with excellent humidity robustness was applied to the X series. Table 2 shows the evaluation results of the X series in a condensation cycle test. The results show that the condensation resistance of the X series is at least 100 times that of the conventional device. When the aforementioned acceleration factor is considered, this result corresponds to condensation of 8,000 times in an environment equivalent to the worst field environment.

Table 2 Cycling condensation test result of X series HVIGBT module

Conventional device (3300 V/1200 A)	Failure in 1 cycle
X series device (3300 V/1800 A)	No failure after 100 cycles

5. Conclusion

We found a new mode of failure mechanism due to humidity caused by the accumulation of surface charges and confirmed the effectiveness of the SCC technology, which is used for the X series chips. In addition, we established a condensation test procedure that makes cycle tests possible and confirmed that the X series can withstand 100 cycles of condensation tests and 8,000 times of condensation in an environment equivalent to the worst field environment.

We will use the established humidity robustness evaluation and improvement technologies to enhance the reliability of power semiconductor modules, thus helping to create both a low-carbon society and affluent life.

References

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