Investigations on Ageing of IGBTs Under Repetitive Short-Circuit Operations

This paper received the Best Paper Award at PCIM 2008, sponsored by PEE. It describes experimental results concerning the ageing of 600V IGBTs under repetitive short circuit conditions. A critical energy, which is dependent on test conditions, has been already pointed out which separates two failure modes. The first, with a cumulative degradation effect, requires some 10,000 short circuits to reach failure, and the other leads to the failure at the first short-circuit with a thermal runaway effect. This paper is focused on the first failure mode. **M. Arab and Z. Khatir (INRETS-LTN), S. Lefebvre (SATIE), and S. Bontemps (Microsemi PPG), France**

In order to understand the ageing mechanism, 600V IGBT dies have been packaged by Microsemi. The packaging has been made in order to make possible the characterisation of some degradation by the measurement of different electrical characteristics, particularly the effects of device ageing on on-state voltage, short-circuit current and Al metallisation degradation which leads to resistance increase. The short circuit capability is one of the figures of merit which defines the robustness of the power semiconductor components, especially for IGBTs.

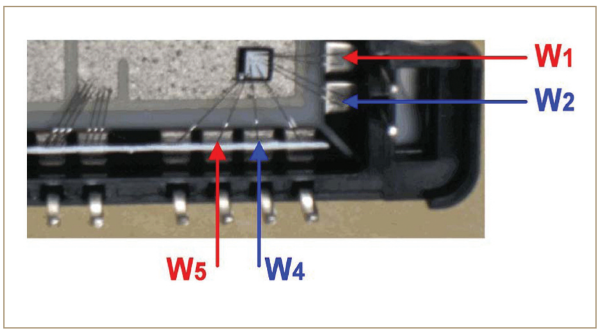

Figure 1: Dedicated IGBT power module realised by Microsemi with bond pads (W1-W4)

Development of power modules in order to highlight ageing indicators

Experimental test conditions consist of repetitive short-circuit operations applied to the device under test (DUT) with the same energy dissipated in the die until destruction. This energy is supplied by a set of capacitors and a circuit breaker (1200V/200A IGBT) that allows the DUT explosion to be avoided by an over-current detection (200A). An acquisition card controls the DUT gate drive pulses and allows the tests to stop when failure is detected. These tests are performed with a gate to emitter voltage equal to 15V in the on-state. A repetitive cycle of 0.33Hz is chosen in order to avoid the average overheating of the chip. A heating plate allows the case temperature to be controlled and the case temperature influence to b considered, especially at 25 and 125°C.

Each 1000 short circuits, several electrical parameters are regularly measured during the repetition of the short-circuit operations: on-state voltage (V_{CEON}), threshold voltage (V_{GETH}), input/output capacitors (C_{ISS}, C_{OSS}), gate leakage current (I_{GES}), collector leakage current (I_{CESS}) and short-circuit current (I_{SC}). The first three have been measured for 25°C junction temperature, leakage currents have been measured at 125°C, and short-circuit current during the short-circuit test.

Threshold voltage is measured for different values of emitter current in order to evaluate transconductance evolution (10µA, 100µA, 500µA and 1mA). Gate leakage current is estimated using a

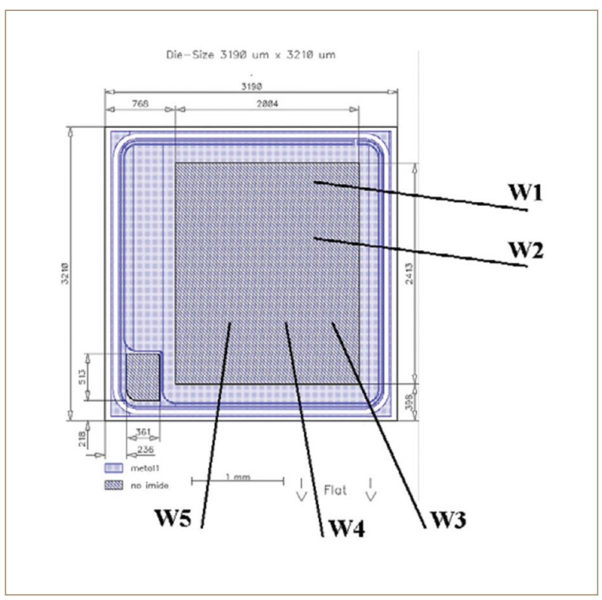

Figure 2: Bond wires locations on emitter metallisation pad of IGBT die

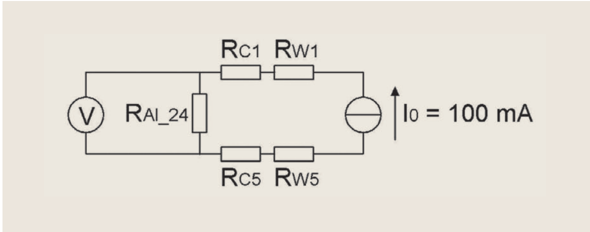

Figure 3: Part of Al layer measurement

KEITHLEY 6430 SMU. The collector leakage current is measured for a collector to emitter voltage equal to 200V (6430 SMU) at 125°C junction temperature.

In order to set up test campaigns allowing the ageing of tested devices to be followed, other electrical parameters must be evaluated. During short-circuit cycles, not only the bulk of the device is strongly thermally constrained, but also its immediate vicinity such as aluminium metallisation of emitter pad and bond wires (especially electrical contact between wires and metallisation). In order to characterise the electrical resistances of die metallisation pad, as well as contact between bond wires and metallisation, Microsemi has realised a dedicated package. Several modules with 600V IGBT dies (in Trench Field Stop technology) have been provided for this study. A four-probe contact design was chosen for the bond wire connections (with judicious location of bond contacts) in order to perform precise measurement of the Al metallisation layer (Figures 1 and 2).

Figure 3 gives an example of measurement methodology for Al layer resistance evaluation, where RAL_24 is the Al layer resistance between wires 2 and 4, R_C are the contact resistances between Al layer and bond wire and R_W are the wires' resistances.

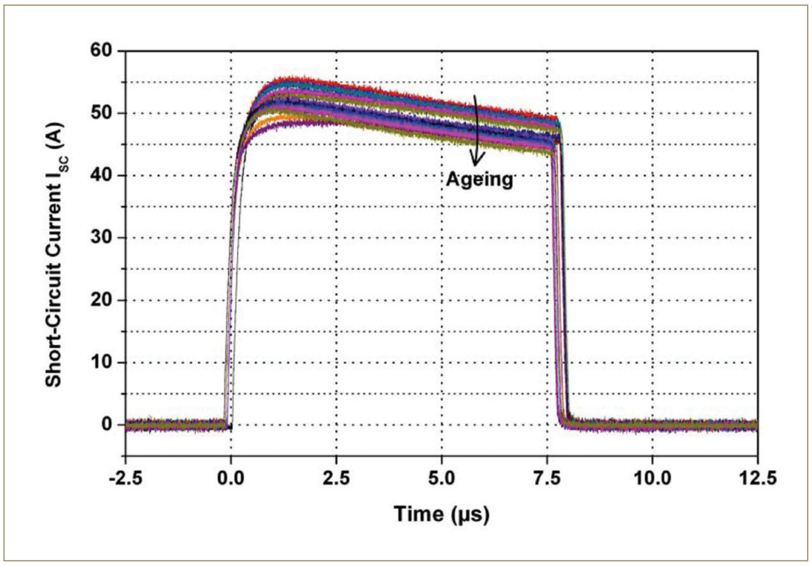

Figure 4: Decrease of short circuit current during repetition (T_{CASE} = 125°C, U = 400V)

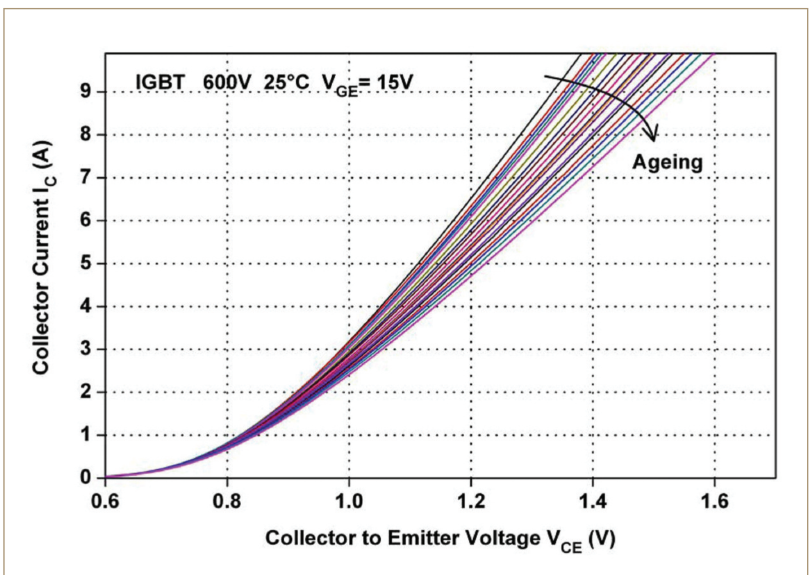

Figure 5: Increase of the on-state voltage during repetition of short circuit operations (T_{CASE} = 25°C, V_{GE} = 15V)

Characterisation results

Several 600V IGBT dies were tested in repetitive short-circuit operations and in ageing mode conditions (dissipated energy lower than the critical value). Supply voltage is equal to 400V and dissipated energy to 156mJ. Results are given for only one device which has failed after 87900 short circuits. All results obtained with other devices are similar to the one presented. On all tested devices, we can note no significant variation of the threshold voltage for different emitter currents, input/output capacitors, gate leakage current and collector leakage current. However, short circuit waveforms regularly stored during the repetitive tests show a significant decrease of short circuit current (I_{sc}), before the failure appears (Figure 4).

On-state voltage is another electrical parameter that presents a regular variation during the tests. Figure 5 shows an increase of the on-state voltage periodically measured during the repetition of the short circuit operations.

The electrical resistance of Al layer and bond contact resistance have been characterised regularly during ageing. It is well known that Al reconstruction appears in the Al layer when it is subjected to temperature cycles, especially at high temperature. Due to the large difference of coefficients of thermal expansion (CTE) between Al and Si, significant plastic deformation occurs in the aluminium layer leading to severe degradation.

After about 10,000 short circuits, the resistance of the Al layer significantly and regularly increases until failure occurs (with an increase by a factor of approximatively 2.5 for RAl_24). Contrary to on-state voltage which consistenly increases from the beginning of the tests, about 10,000 cycles are necessary to show significant evolution of Al sheet resistance. It seems that these two phenomena are not correlated.

Failure analysis

Failure analyses using SEM (Scanning Electron Microscopy) have shown that the

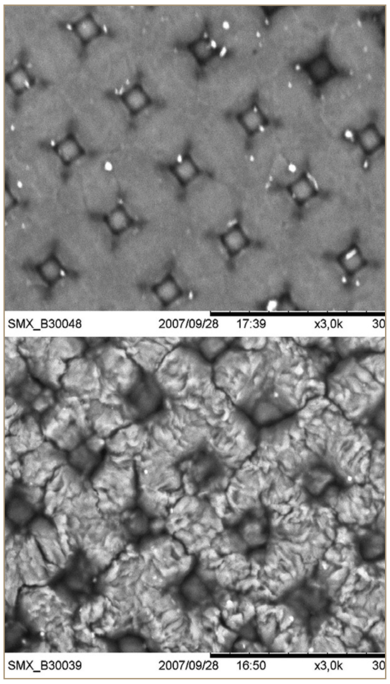

Figure 6: Al reconstruction before test (upper) and after 24,600 short-circuit cycles

failure is located to the emitter bond wire contact with significant reconstruction of the Al layer. However, the short circuit repetition generates thermal cycling in the DUT with high temperature variations. This thermal cycling introduces periodical compressive and tensile stresses in the thin emitter metallisation film due to the CTE mismatch between aluminium (23.8ppm/K) and silicon chip 2.6ppm/K). Consequently, stresses arising within the aluminium thin-film during repetitive short circuit operations of the device lead to high plastic deformation with dislocation glide.

Figure 6 shows micrographs of emitter metallisation before and after tests. A strong degradation of the metallisation after cycling is observed. This degradation causes an increase of the metallisation resistance and weakens the bond wire contacts. Cracking also take places around the bond wire contact as shown in Figure 7, leading to increase the contact resistance. In addition, the bond wire contact is probably weakened by thermo-mechanical stress induced by thermal cycling due to the repetitive short circuits. The degradation of the wire bond contact leads to an increase in the bond contact resistance. As a consequence, the local temperature rises and enhances thermal fatigue. The local temperature increase is large enough to eventually trigger the parasitic transistor of the IGBT and could explain failure at turn-off observed after repeating many short-circuits.

Failure always leads to wire bond lift-off (Figure 8) as a consequence of the high current density and of the local melting of the bond end (Figure 9).

Conclusion

Measurements allowed by Microsemi packaging have shown the effect of the repetition of short circuit operations on the increase of the resistivity of the Al layer. This is explained by Al reconstruction and cracks of the metal layer due to ageing. Strong degradation of the metallisation (Al reconstruction and cracks), as well as bond wire lift-offs, were observed on all tested devices. In these specific conditions of test (dissipated energy lower than the critical value), failure always appears at turn-off when the device begins to open the short circuit current which looks like dynamic latch-up. The local increase of temperature due to wire contact degradation and Al layer ageing when repeating short circuit could explain the failure at turn-off considering the trigger of the parasitic transistor of the IGBT which is facilitated by the temperature rise.

Literature

The full paper has been published within the PCIM 2008 Proceedings (ISBN 978-3-89838-605-0).

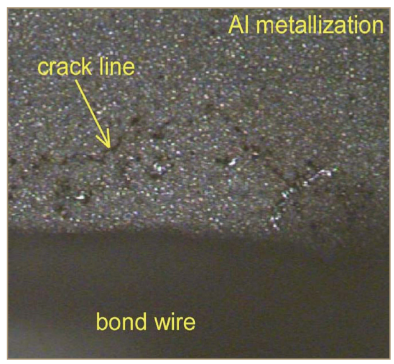

Figure 7: Cracking around the bond wire contact (optical image, 200x)

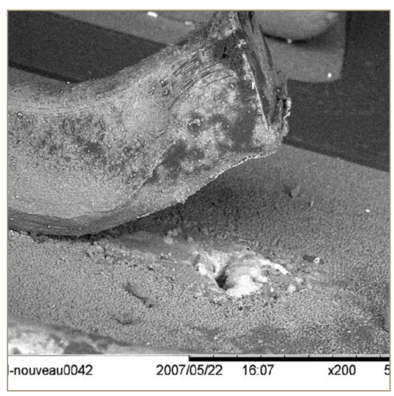

Figure 8: Bond wire lift-off after failure

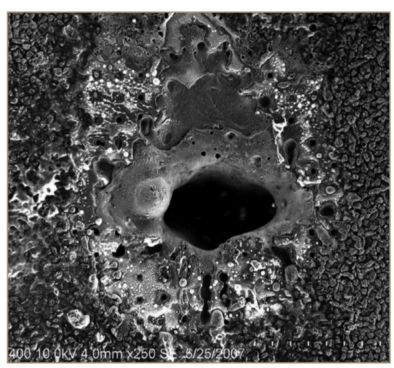

Figure 9: Melted hole on the footprint of an aluminum bond wire after lift-off