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Experimental electro-mechanical static characterization of IGBT bare die under controlled temperature

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Abstract

Silicon dice soldered in power assemblies have to withstand simultaneously electrical, thermal and mechanical stress. Mechanical stress is an important issue because it will directly impact on both the device behaviour and power modules reliability. This paper focuses on the electro-mechanical static characterization of a planar gate IGBT by the help of experiments at controlled temperatures. A specific test bench is proposed to make the experiments on silicone bare dice. It can be highlighted that mechanical stresses have a strong influence on the electrical characteristics of IGBT and this effect is independent from the die temperature. These properties might be a key point to point out an early failure indicator to improve design of the power module.

1. Introduction

Over the past few years, reliability considerations in power electronics became an important issue for the design of power assemblies. Indeed, a power assembly is based on the association of several materials: at first, power semiconductor devices are soldered on a metal-ceramic substrate like Direct Bonded Copper (DBC) or Insulated Metal Substrate (IMS) as in Figure 1.

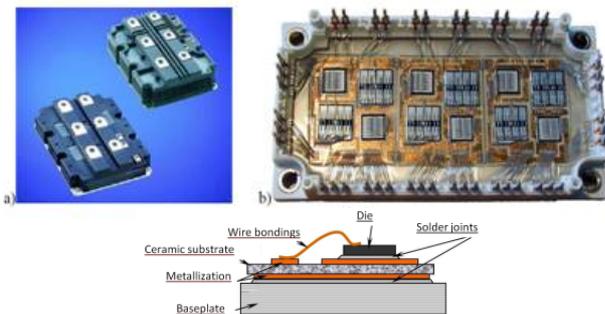


Figure 1 - Power modules assembly using wire bonding

Then, this substrate is soldered onto a base-plate using a second solder joint to enhance the conduction heat transfer. Due to the mismatch of the coefficient of thermal Expansion (CTE) of the various materials during active power cycling (power device under switching configurations) and passive thermal cycling (device switched-off and mainly due to the temperature environment), the solder joints have to withstand repetitive and accumulative mechanical fatigue. Depending on the mission profile hardness, the solder joints may crack more or less quick leading to an increase of the thermal resistance of the assembly and then to a device failure linked to a drastic junction temperature rise.

Furthermore, for higher integration, the tendency is to reduce the chip size as well as to increase the current density in the power dice. Then, conventional power modules may not be suitable to evacuate the heat generated with a high efficiency. For a better thermal evacuation, novel power module structures in which power devices are directly soldered on the base-plate or in between two copper plates are proposed (Figure 2).

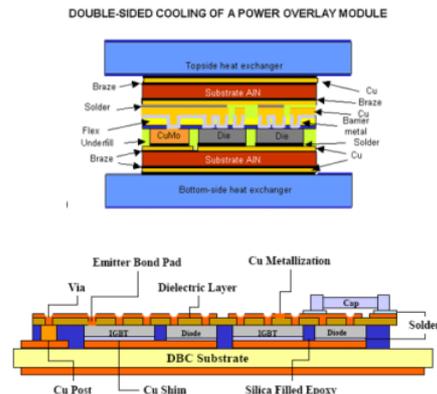


Figure 2 - Power Overlay technology proposed by General Electric in 2001 [1]

In this latter case, the thermomechanical stress induced in power devices is larger than that on the conventional module. It is well known that temperature is an important parameter and modifies considerably the silicon device behavior.

The literature shows that the mechanical stress also has an impact on the silicone device behavior [2 - 5]. However, in [2, 3] IGBT silicone dice used were soldered on a substrate, which means that the dice are already stressed by the solder process. In the present study, we propose to work on IGBT silicone dice strip or “flying dice” in order to investigate the impact of

mechanical stress on the electrical characterization of the device. Indeed, since a soldered die in a power package is already stressed, in case of a crack occurs in the solder joint just under the die, the mechanical stress in the silicon die will be reduced and affect electrical waveforms. Then such approach might be used to monitor the mechanical state of the power assembly and to highlight an early failure indicator.

2. Mechanical stress at power assembly level

As a first approach, in this study, we would like to point out the effect of uni-axial mechanical stress on the electrical IGBT behavior without any thermal influence to dissociate both effects and by considering only a half-cell structure.

Using ANSYS finite elements software, a 3D mechanical simulation of power assembly has been carried out. For convergence purposes only a quarter of the power assembly is simulated (Figure 3).

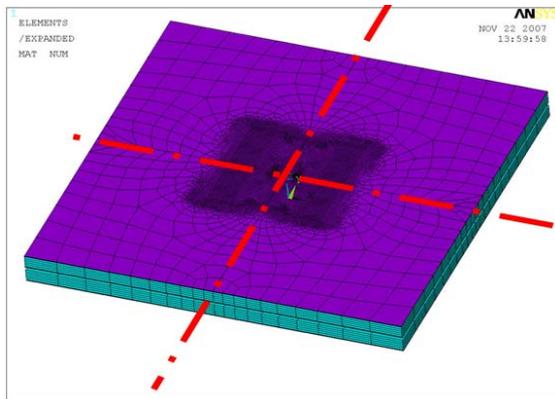


Figure 3 – 3D model used in the ANSYS simulations

The first thermomechanical simulation focuses on the single side cooling power assembly: a DBC (Direct Bonded Copper) power assembly as shown in Figure 4.

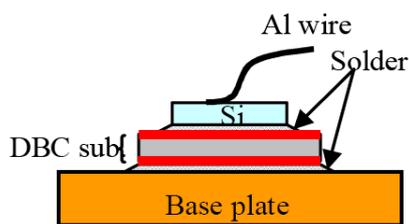


Figure 4 – Single side DBC power assembly

The figure below illustrates the simulation result of a quarter of the assembly after soldering the chip onto the substrate and after a storage of the assembly power for three months. As a consequence, Figure 5 highlights that the peak mechanical stress is about 233MPa at the center of the power chip.

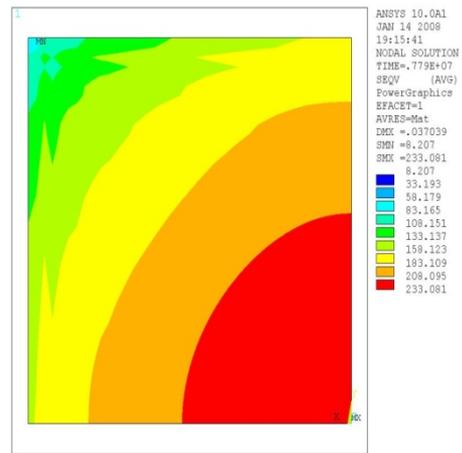


Figure 5 – Von Mises stress distribution on silicon die for a single side DBC power assembly (ANSYS simulation)

The second simulation points out the case of a double sided cooling power assembly using high heat dissipation materials as shown in figure 6.

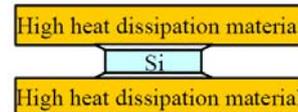


Figure 6 – Double side cooling power assembly

The results of simulation point out that the thermomechanical stress (585MPa), at the chip level, is higher than thermomechanical stress of DBC power assembly as shown by the ANSYS simulation in figure 7.

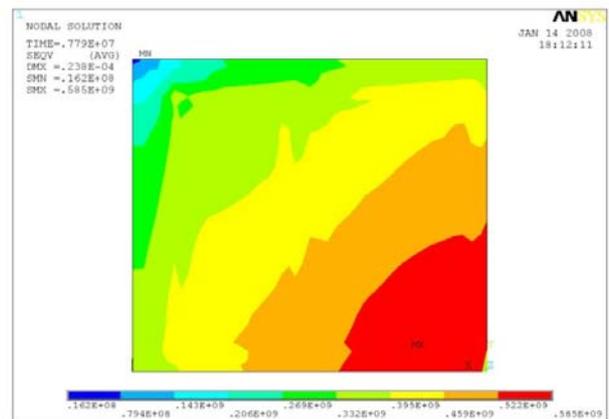


Figure 7 – Von Mises stress distribution on silicon die for a double side DBC power assembly (ANSYS simulation)

From both these simulation, it can be highlighted that the mechanical stress saw by a power silicone chip may vary from 233MPa up to 585MPa.

3. Four point bending technique

For the experimental approach, the four-point bending method is used to study the effect of mechanical stress on the electrical behavior of a semiconductor device. Figure 8(a) and 7(b) illustrate the four-point bending configuration applied to a

silicone dice strip. Silicon dice strip is supported on two outer points, and deformed by driving two concentrated loads. The maximum stress is located at the loads. The produced mechanical stress is uni-axial along the x-axis and is not uniformly distributed over the thickness of the device.

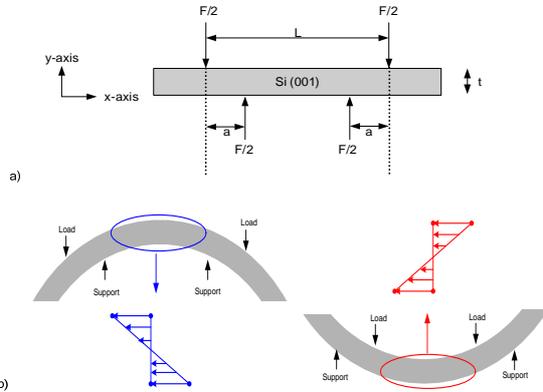


Figure 8 - (a) Four-point bending technique and (b) investigated configurations

The analytical expression of the maximum mechanical stress depends on the Young's modulus of silicone and the geometric characteristics of the silicone lame. This expression along the x-axis is given by:

$$\sigma_{xx} = \frac{Eyt}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)} \quad (1)$$

where E is Young's modulus of silicon, y is the displacement of the lame along y-axis, t is the thickness of the lame, a and L correspond to the lengths shown in figure 7(a).

Depending on the location of sustaining points and loading points, it is possible to realize two configurations as shown in Figure 8(b). The first one is the application of a tensile stress on the upper part of the component and a symmetric compression on the lower part of the component and vice versa.

4. Experimental electromechanical results

4.1. Four point bending test bench description

Figure 9 shows the four point bending test bench. The mechanical stress is applied by a tensile-compressive machine "Instron 5565". This equipment has a maximum load capacity up to 5000N. For a mechanical characterization in bending of silicon dice strip, the mechanical test bench has been associated with a force sensor equal to 50N.

This test bench will allow to apply a calibrated mechanical stress on the device based on its direction, level and nature (compressive or tensile). A specific electrical set up has been designed to apply an electrical configuration on the device under test on the dice strip.

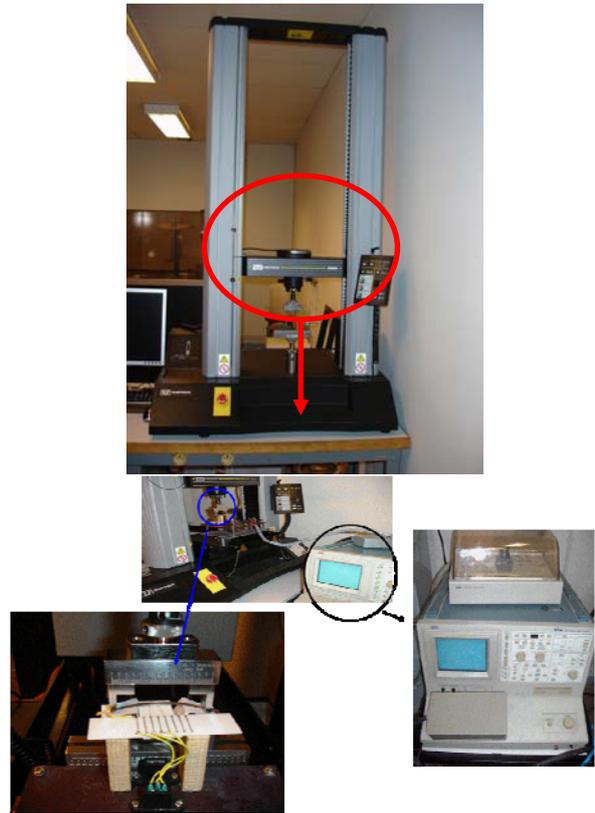


Figure 9 – Four point bending test bench with power curve tracer TEK371A

At first step, it is necessary to determine the maximum stress values that can be reached on the tested IGBT die without braking the silicone strip. For the two configurations shown previously, we have experimentally obtained the results shown in Figure 10.

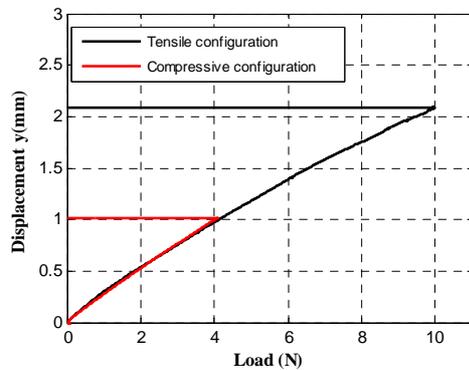


Figure 10 – Experimentally displacement versus load at ambient temperature 300K for an IGBT silicone dice strip.

By setting up $L = 6\text{cm}$ and $a = 1\text{cm}$, it is possible to obtain a maximum displacement along y-axis of 1.1mm in compressive configuration while in tensile configuration it is 2mm. These values correspond to a maximum stress at the chip under mechanical stress equal to 150MPa in compressive configuration and 250MPa in tensile configuration.

Thanks to the climatic chamber shown in figure 11 associated to the four-point bending test bench, it is possible to perform electromechanical characterizations under various temperature conditions (from 175K up to 575K). Negative temperatures are obtained through liquid nitrogen associated with the mechanical characterization machine. High

temperatures are obtained through thermal resistances of the thermal enclosure.



Figure 11 – Climatic chamber allowing ambient temperature from 175K up to 575K

The investigated IGBT is a 3rd International Rectifier generation of planar IGBT controlled by a planar gate. This device is a punch through type and has been designed for a rated current of 40A and a rated voltage of 600V. The thickness of the device is 380 μ m. It is necessary to point out that this device is relatively thick compared to recent 70 μ m wafer technology from IXYS but this choice is made according to the wafer availability and also for an easier finite elements device model validation for further investigations.

After cutting silicon dice strip on the wafer according to two crystal orientation [110] and [$\bar{1}10$] as depicted in figure 12, test vehicles have been designed.

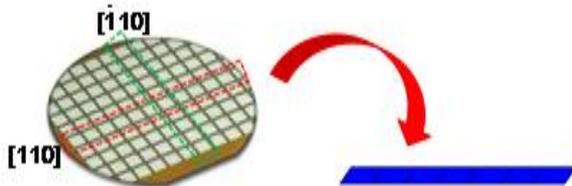


Figure 12 – IGBT dice strip obtained by wafer cutting

The central chip for the silicon dice strip is connected to a metal-ceramic substrate with aluminum wire-bonding. Through these wires, it is possible to connect the single chip to a static electrical characteristic curve tracer TEK371A (Figure 13).

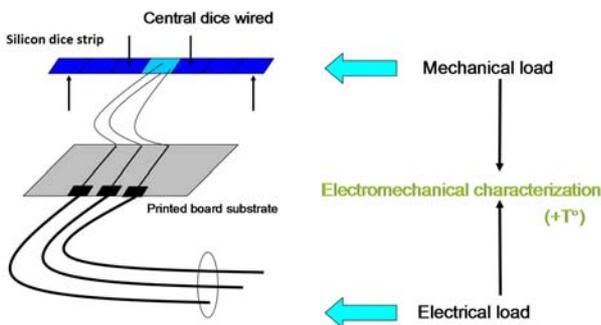


Figure 13 – Electromechanical characterization

4.2. Test at 300K

In this section, all measurements are made at controlled room temperature equal to 300K.

First it is important to note that silicone die strip is not able to dissipate heat in opposite to soldered silicone die due to the lack of substrate and heat

spreader. The, it should be verified that the self-heating effects are negligible in static mode based on 300 μ s pulse mode and low power of the curve tracer. An infrared mapping, done by FLIR-Infracam (9Hz sampling rate) has been done to consolidate this result. Indeed, the temperature variation is less than 3 $^{\circ}$ C for a 8V@3A static pulsed electrical bias as shown in figure 14(b).

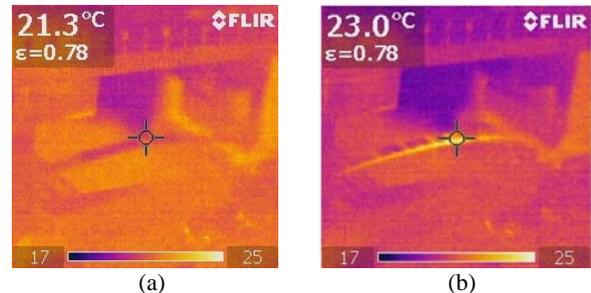


Figure 14 – Temperature mapping on the silicone dice strip under (a) no electrical bias and (b) under 8V@3A pulse electrical bias

Figure 15 shows the transfer characteristic $I_a(V_{gk})$ at $V_{ak} = 5V$.

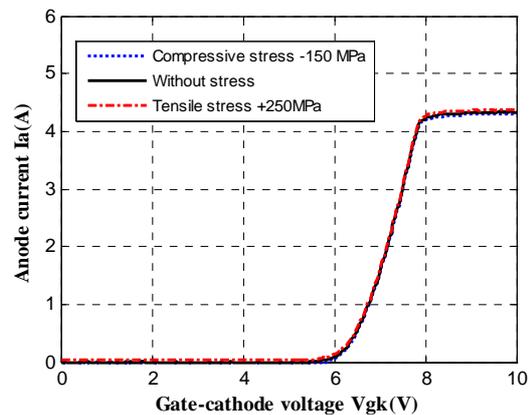


Figure 15 – $I_a(V_{gk})$ following cases of applied uni-axial mechanical stress

Whatever the stress value and its type (compressive or tensile), the value of the threshold voltage (about 6V) is not changed. It is also possible to note that the transconductance g_m is not influenced by the applied stress (case for low anode current).

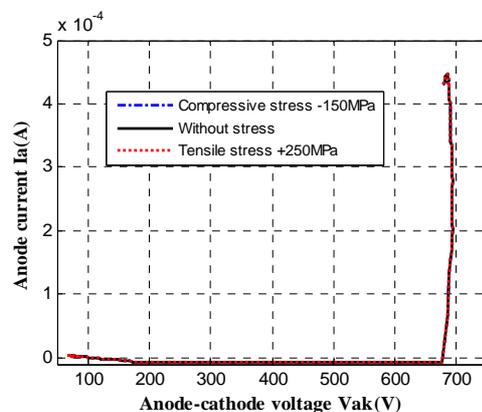


Figure 16 – $I_a(V_{ak})$ at $V_{gk} = 0V$ following cases of applied uni-axial mechanical stress

Regarding the breakdown voltage of the device shown in figure 16, the breakdown voltage of the IGBT is about 680V and is not sensitive to the application of uni-axial mechanical stress.

Only output characteristics are influenced by the application of mechanical stress. In figure 17, which represents $I_a(V_{ak})$ at $V_{gk} = 7V$, it is possible to note that the saturation current level is changed when the chip is stressed. Moreover, its variation depends on the type of applied stress: its level increases with tensile stress while it decreases with compressive stress. The gate voltage V_{gk} is kept low to avoid any significant self-heating within the chip under test.

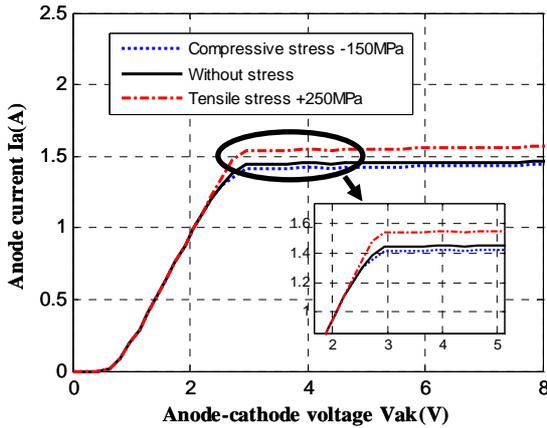


Figure 17 – $I_a(V_{ak})$ at $V_{gk} = 7V$ following cases of applied uni-axial mechanical stress

4.3 Test at 235K and 400K

The objective here is to see if the temperature increases the effect of mechanical stress on the static characteristics of the IGBT. The ambient temperature has been set to 235K and 400K, and the mechanical stress has been applied within the thermal enclosure. Note at the same time the static electrical characteristics of the IGBT under test.

Whatever the stress value and its type (compressive or tensile), the value of the threshold voltage is not changed with mechanical stress but it is changed with temperature. The transconductance g_m is not influenced by the applied stress (Figure 18).

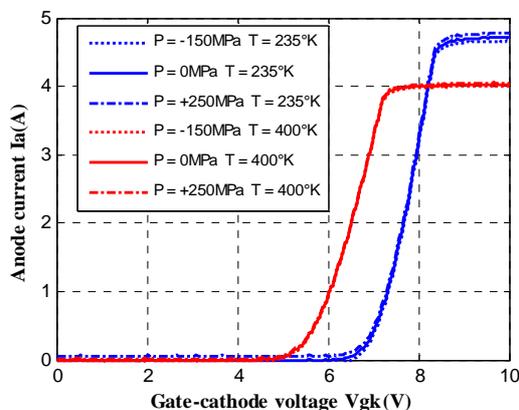


Figure 18 – $I_a(V_{gk})$ following cases of applied uni-axial mechanical stress

For a given temperature breakdown voltage is not influenced by the mechanical stress applied on the tested IGBT, with high temperatures, the blocking voltage increases as shown in figure 19.

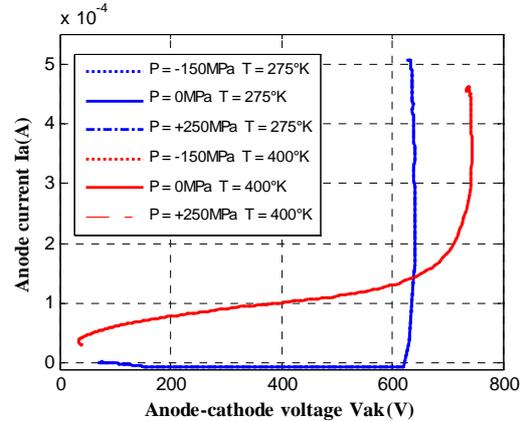


Figure 19 – $I_a(V_{ak})$ at $V_{gk} = 0V$ following cases of applied uni-axial mechanical stress

While output characteristics (figure 20) are very sensitive to temperature, these characteristics are less influenced by mechanical stress at a fixed temperature.

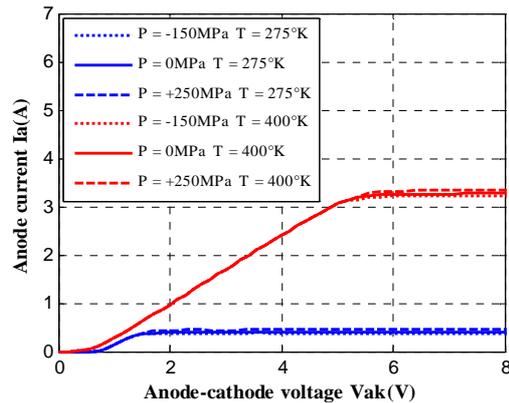


Figure 20 – $I_a(V_{ak})$ at $V_{gk} = 7V$ following cases of applied uni-axial mechanical stress

5. Conclusion

In this paper, we have proposed an electro-mechanical characterization for a planar gate punch through IGBT operating under three static operating configurations (output characteristics, forward transfer and breakdown voltage) under controlled temperature. The effect of temperature and mechanical effects could be investigated separately to analyze thanks to a specific test bench. Experimental results show that whereas the mechanical stress has low effect on breakdown voltage, the forward current is strongly affected by external mechanical stress depending on its level, direction and nature (compressive or tensile). Furthermore it has been shown that the temperature has more influence on the static characteristic than mechanical stress.

Work is in progress to focus on the influence of other types of mechanical stress such as shear and multi-axial stress on the electrical parameters of IGBTs.

Making IGBT very sensitive to mechanical stress, the influence of mechanical stress on the static and dynamic electrical characteristics of IGBT can be used as early failure indicator of the power assembly.

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