Study of the Thermomechanical Strain Induced by Current Pulses in SiC-Based Power MOSFET

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***Abstract*—Power SiC MOSFETs are going to substitute Si devices by to their significantly better performances that make them much suitable in power switching applications such as electric/hybrid vehicles. The increasingly use of these devices in critical mission profiles requires an ever-higher reliability, whereas the increase of the dissipated power during high-speed working cycling due to short current pulses leads to unavoidable thermal and mechanical stress. Here, we propose a direct method to evaluate the mechanical stress due to current pulses. This method highlights that high Power SiC-based MOSFET undergoes to almost two different thermomechanical processes with completely different time scale. The results allow a link between the thermo-mechanical stress and the device failure conditions, with special focus on the current pulses effects on metal surface, as this is a main power devices weakness.**

***Index Terms*—Power MOSFET, reliability, silicon carbide, strain wide band gap semiconductors, Coffin Manson.**

I. INTRODUCTION

WIDE Band Gap (WBG) semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), push the research to improve the devices that are already commercially available since the begun of the century. The SiC-based devices largely outperform the silicon-based ones and find applications in many fields of power electronics. [1]–[4]. These devices are increasingly used in mission critical application; hence a deeper comprehension of their failure mechanisms is needed. Due to its higher stiffness compared to silicon, the power cycling capability of SiC devices is particularly crucial [5], [6]. The repetitive quick increasing of temperature during high current pulses cycling leads to both thermal and mechanical stress, that wears out the gate oxide layer, the metal and the bonding [7]–[9].

In this frame, the reliability becomes more challenging to evaluate, specially taking into account that the modern devices technology has shifted towards ultra-thin body transistors and high thermal conductivity materials. In these devices, the crowding of carriers along a confined dimension [10] not only reates local hotspots but also gives rise to mechanical stress among the layers. Hence, the study of deformation mechanisms and the relationship between temperature and failure mechanisms could provide key information to improve reliability modeling and prediction. In the last years, many experimental techniques and theoretical simulations have been proposed in order to measure micrometric mechanical deformations and cracks, such as: Digital Image Correlation (DIC) method [11], Finite Element Analysis [12], Shearography [13]. The industry qualification of the devices is based on the reliability prediction that relies on the well know statistical methods based on the Coffin Manson model that defines the number of actual failures occurring as a fraction of the total number of units subjected to an accelerated test [14], [15]. The temperature cycles are one of the considered critical parameters for the premature aging of the electronic devices, as well as the gate threshold voltage, avalanche events, body diode degradation and so on [7]. Usually, this statistical approach is based on information about the difference induced by the accelerating parameters in the DUT after and before the aging treatment.

In Si-based devices, it has been observed that high current pulses may lead to a quick temperature increasing (beyond 100 °C) during their operation. The overheating can irreversibly damage the DUT surface [6]. Therefore, detecting the presence of hot spots is a powerful method for improving design and increasing reliability. A direct consequence of the thermomechanical cycles is an alternance of compressive and expansive displacements that involve the entire DUT. The out-of-plane mechanical displacement can be evaluated without decapsulating the DUT, hence observing it in its real working conditions [16]. The above phenomena become very important in automotive applications where the frequencies involved are of the order of a few hundreds of Hz, for example in applications such as gasoline or diesel injection, or power management in electric engine. In these cases, the strain mechanisms and the thermal behavior are fast enough to follow the current pulses and give rise to cumulative effects of mechanical stress.

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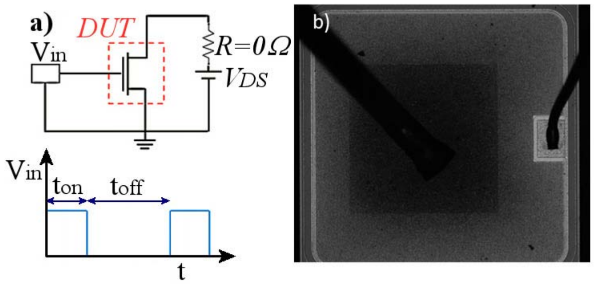

Fig. 1. (a) Electric configuration for TSC (Terminal Short Circuit) overload test; (b) Optical image of the entire device after its failure.

In this letter, we focus on the strain mechanisms involved during the power cycling at frequencies of a few hundreds of Hz, and demonstrate that the DUT undergoes almost two different thermomechanical processes. Even if the temperature reaches relatively low values, both mechanisms are able to damage the metal and should be taken into account for a more precise lifetime estimation. The described experimental approach can be applied to many different kinds of electronic devices. However, some simple conditions must be satisfied: (*i*) the analyzed surface is reflective, indeed the out-of-plane mechanical displacement measurements are based on the optical interferometry principle; (*ii*) the package is removed to detect the temperature achieved by the metal layer. The thermo-mechanical results are correlated to the morphological variations of the metal induced by the stress. This allowed individuating a precise mechanism of the metal degradation.

II. EXPERIMENTAL SECTION

The analyzed DUT is a Power MOSFET based on silicon carbide technology provided by ST Microelectronics. The DUT has been decapsulated to allow the detecting of the thermal behaviour and the mechanical strain of the DUT during the test. The latter was performed using a Terminal Short Circuit (TSC) configuration (see Fig. 1) [17]. Through the V_{in}voltage, DUT is activated for a fixed t_{on} time interval ($t_{on} = 5$ ms) and it is switched off for $t_{off} = 1.5$ s. For each V_{in} pulse, the peak current value is 80 A with $V_{DS} = 10$ V and $V_{GS} = 15$ V. Thermal measurements have been performed by a high-speed emission microscope working in the infrared range [18]. The sub micrometric out-of-plane mechanical displacements have been measured by a microscope-based vibrometer (Polytec, MSA-500).

Synchronizing the current pulses with the acquisition, it is possible to record point by point the time resolved displacement of the surface. Designing a suitable grid of points, the system will produce a movie of the deformation during the pulses. AFM measurements have been performed in semi-contact mode using an NT-MDT mod. SMENA microscope.

III. RESULTS AND DISCUSSION

Figure 2a shows the thermal map of the DUT acquired at 5 ms after the current pulse started, also corresponding to the instant when the temperature reaches its maximum. The thermal map shows that the temperature reaches its maximum near to the bonding wire area. Figure 2b describes the temporal behavior of the temperature acquired at the hottest point on the metal surface. The temperature does not exceed 80 °C in the above defined working conditions. Figure 2c shows the surface displacement frozen at the end of the current pulse.

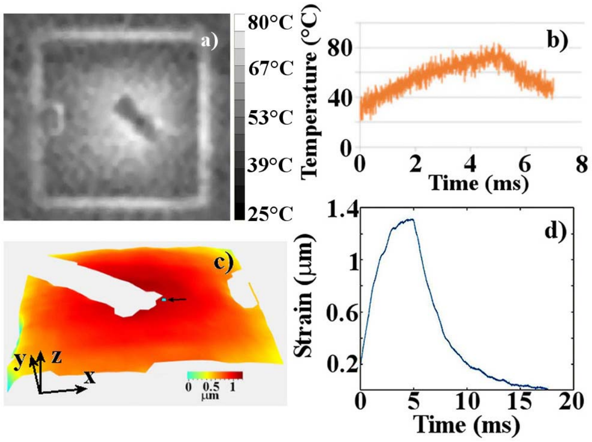

Fig. 2. (a) Thermal map acquired at 5ms after the start of the current pulse. (b) temperature behaviour versus time acquired at the hottest point of the metal surface. Mechanical deformations of DUT during its operation in TSC configuration: (c) maximum displacement acquired at 5ms; (d) displacement vs time at the center of the DUT (considered point is marked in Figure 3a) acquired for 20ms.

The displacement map is characterized by a maximum displacement located at the hottest point of the surface. Figure 2d reports the displacement trend vs time, acquired in the point marked in Figure 2c. Interestingly, the displacement shows a narrow peak when the current pulse occurs, after the end of the current pulse, the metal comes back near to the zero position and a slow displacement starts (not shown for a single pulse). For a better understanding of the stress undergoes the DUT, we repeated the experiment exciting the DUT with a burst consisting of three current pulses at a frequency of 100Hz. Each pulse was 5ms wide with a duty cycle of 50%. The three pulses have been obtained by a 0.16 F capacitor; hence they have a decreasing peak current, and precisely of 85A, 80A and 75 A.

The DUT surface displacement *vs* time during the current train collected at the position, where the temperature reaches its maximum, is showed in Figure 3. The surface displacement follows the current pulses amplitude, and ranges between $1{,}6 \cdot 10^{-6}$m to $1 \cdot 10^{-6}$m as the current peaks decrease from 85A to 75A. After each pulse, the displacement goes back, but never reaching the starting point (Figure 3a). After the current train end, a slow displacement of the entire surface is observed (Figure 3b). These findings suggest that, during the pulse current cycling, the DUT undergoes two rather different processes: at the beginning, a quick strain that mainly involves the metal and presumably the first layers of semiconductor affecting the solder joint too. Subsequently, a displacement that involves the whole device is observed. This displacement is related to the slow heat diffusion related to the power dissipation inside the semiconductor that produces an increasing of the temperature of the entire chip and a thermal expansion.

The above observation let us conclude that during the normal operation, the DUT temperature will increases its baseline reaching a mean value. At operational frequencies of the order of hundreds of Hz, the temperature quickly increases following the current pulses and reaching a value far beyond the one measured with standard systems such as thermal cameras. Moreover, despite the relative low value

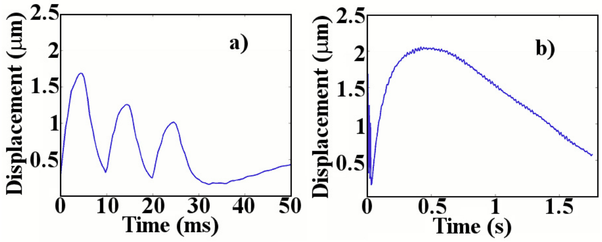

Fig. 3. Displacement of the DUT surface during the current train, collected near to the solder joint where the temperature reaches its maximum, for (a) 50ms and (b) 1.7s.

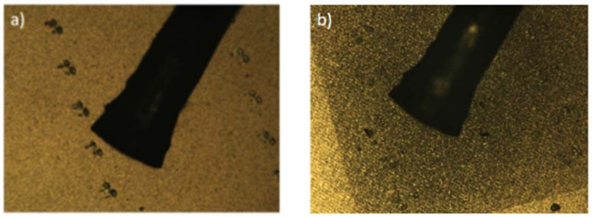

Fig. 4. Optical images of the DUT surface close to the bonding area acquired with a magnification of 10X: (a) before the stress (b) after the stress.

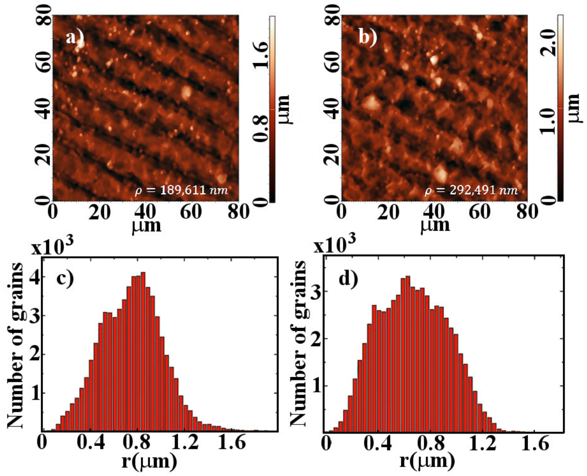

Fig. 5. (a) AFM image (scan size 80 μm × μm) of the good area (close to the gate contact) and measured average roughness; (b) AFM image (scan size 80 μm × 80 μm) of the stressed area (close to the drain contact) and measured average roughness. Histogram of the grains radius distribution calculated (c) in the good area and (d) in the stressed area of the DUT metallization.

reached by the temperature, the quick displacement due to the current pulses induces a cumulative stress on the metal that, together with the slow surface movement, must be taken into account for a more complete estimation of the lifetime. During the above reported test, the investigated DUT fails after approximately 21500 current pulses.

Figure 4 shows the optical image of the DUT surface, after the failure. Noticeably, the optical image acquired with a magnification of 10X clearly shows a stressed area at the center of the DUT, while close to the gate contact it is still intact (Figure 1b), with a smooth surface. We can foresee that the metal layer suffers a considerable compressive stress during the heating cycles.

Literature distinguishes two temperature regimes [22]: above 175 °C when diffusional creep and plastic deformation involving conservative motion of dislocations occurred and below 175 °C when the main mechanism of mass transport is the plastic deformation caused by the compressional fatigue [19]. The plastic deformation can lead to the extrusion of single grains the surface roughness of the metallization with the macroscopic observable effect of a dull non-reflective surface appearance. In the cooling phase of the temperature cycle, if the elastic regime is exceeded, tensile stress can lead to cavitation effects at the grain boundaries. In the chosen operating conditions, the repetitive thermo-mechanical cycles activate the reconstruction of metallization. Since the maximum achieved temperature (about 80 °C, see Figure 2b) is well below of the threshold 175 °C, we attribute the cause of the reconstruction of metallization to the mechanical fatigue of the metal layer. The relatively low number of operating cycles of the DUT (before its failure) highlights that the strain/strain rate ratio acts as a very high efficiency acceleration factor.

Figure 5 a-b shows the AFM images (scan size 80 μm × 80 μm) and the distribution of the radius of the metal grains measured in the good and in the stressed region respectively. The average roughness of the metal surfaces is reported inside the AFM images. AFM analysis and calculated roughness agree with the previous analyses: the average roughness increases from about 190 nm, in the good region, to 292 nm in the stressed region. This variation, of about 100 nm, of the surface average roughness is linked to the variation of the metal grains size.

Figure 5 c-d shows the histograms of the grain radius distribution calculated in both analyzed regions. The roughness related to the good metal surface is characterized by a narrow band centered at 0.8 μm, with a shoulder at lower values. The histogram of the stressed region is characterized by a flat and large band, slightly shifted towards higher values of the radius size highlighting an increasing of the grains size that confirms the grains reconstruction process of metallization, which leads to a progressive damage of the metal contact, until the DUT failure.

IV. CONCLUSION

In conclusion, the high-speed thermal maps confirm that the SiC-based DUT operates at low temperatures (maximum temperature detected is 80 °C on the metal layer in the selected operating conditions). However, the failure of the device occurs after approximately 21500 current pulses. This rapid irreversible damage has been studied, considering the thermo-mechanical behaviour of the DUT. The time resolved mechanical displacement maps allow to identify two different processes that affect the device during its cycle of operation: a fast process engaging the metallization and the DUT first layers and a slow process due to the to heat diffusion involving the whole device [21].

The heat capacity and the thermal conductivity play a key role in the dynamics of the strain. In this frame, from the thermal point of view, the system works as a low pass filter, therefore, if the frequency increase too, the phenomenon will be cut off, and, presumably, other damage mechanisms may be activated. Under the test conditions considered, the fast process is individuated as the main responsible of the metal damage. For long operation time, the repetitive fast current pulses generate a cumulative stress in the metallization that act as input for the grain reconstruction process. Hence the displacement and strain-rate must be taken into account as a key factor in a predictive Coffin Manson model to obtain a more realistic evaluation of the lifetime.

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