

Characterization of ageing failures on power MOSFET devices by electron and ion microscopies

D. Martineau^{a,*}, T. Mazeaud^b, M. Legros^a, Ph. Dupuy^b, C. Levade^{a,c}, G. Vanderschaeve^{a,c}

^a CEMES-CNRS, 29 rue Jeanne Marvig, 31055 Toulouse Cedex 4, France

^b Freescale Semiconductor, Inc., Avenue du Général Eisenhower, 31023 Toulouse, France

^c Université de Toulouse, INSA, 31077 Toulouse Cedex, France

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ABSTRACT

Extreme electro-thermal fatigue tests have been performed to failure on power MOSFET devices that were later observed using electron and ion microscopy. At variance with devices from the former technology generation, fatigue-induced ageing of these components is observed only in the source metallization zone. An increase in drain–source resistance may originate from both a loss of contact between the wire bondings and the Al layer and/or an extensive decohesion between the metal grains. Failure modes include local melting of the Al and creation of eutectic alloys.

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1. Introduction

The integration effort on power devices in automobiles requires a good knowledge of their reliability, which, on the R&D side, implies to have deeper insight in their mode of ageing [1]. The components investigated here were developed by Freescale Semiconductor to support increasingly high electrical loads [2]. There is no current standard test procedure for power device ageing because these devices are of many different types, and have to comply with various specifications [3,4]. The procedure adopted in this study is an association of extreme cyclic electrical fatigue and multi-scale structural analysis. The tests have been performed beyond the operating limits to assess the limit of device's robustness in extreme conditions.

The devices under study gathers on a single frame a MOSFET power device and a control chip which is able to monitor the electric fluctuations and to detect errors. Their purpose is to command the on/off states of light bulbs for cars. The first device under study contains four areas with 15 mΩ drain–source resistance (R_{dson}) at 25 °C [5] while the second one contains two 10 mΩ R_{dson} areas and two 35 mΩ R_{dson} areas at 25 °C [6]. The device operates under a tension of 12 V and a nominal current of 20 A (5 A per area).

In the former generation devices, it appeared that the most important failure mode was the delamination at the die attach solder between the silicon substrate and the copper heatsink [7]. The origin of the delamination lies in the large mismatch between the thermal expansion coefficients of copper and silicon [8]. Here, after an optimization of the component structure in this new generation, it is shown that this failure process is no longer operative

and that the fatigue-induced ageing mainly affects the active region of the MOS, that is the source metal and the wire bondings [9]. Detailed evidences of the ageing modes of this region are given and are discussed in terms of possible physical processes leading to structural changes in the metal layer and bondings.

2. Experimental procedure

Prior to electrical ageing, a set of 10 devices was inspected by transmitted (SAT) and regular (SAM) acoustic microscopy to evaluate potential defects and initial delamination on top and beneath the power die. X-ray analysis was also done to rule out potential voids inside the devices. After these initial tests, batches of coupons carrying these power devices were electrically tested in two similar and thermally regulated electrical benches. Among all the different tests, the most harmful one consisted in trains of 90 A, 6 ms square electrical pulses followed by a nine times longer pause at 90 °C. The pulse intensity is high enough to activate an overload protection that turns off the MOS. Stressed devices were re-examined by X-ray, SAM and SAT for comparison with initial component structures. Improved analyses were made on failed devices. The mold compound was removed by chemical etching, making possible the Scanning Electron Microscopy (SEM) observation of the metallization and Al wires. Energy Dispersive X-ray (EDX) analyses were carried out to reveal a potential evolution of the composition of the different Al alloys. We focused mainly on the active MOS area: Al wires and metallization, silicon substrate and polysilicon spacers. Transmission Electron Microscopy (TEM) cross-sections were prepared using a tripod and diamond lapping films while final electron transparency was attained with Ar ion bombardment. In regions hardly accessible with tripod preparation such as Al bonding and Al metallization, TEM cross-sections were made using

* Corresponding author. Tel.: +33 562257831; fax: +33 562257999.
E-mail address: donatien.martineau@cemes.fr (D. Martineau).

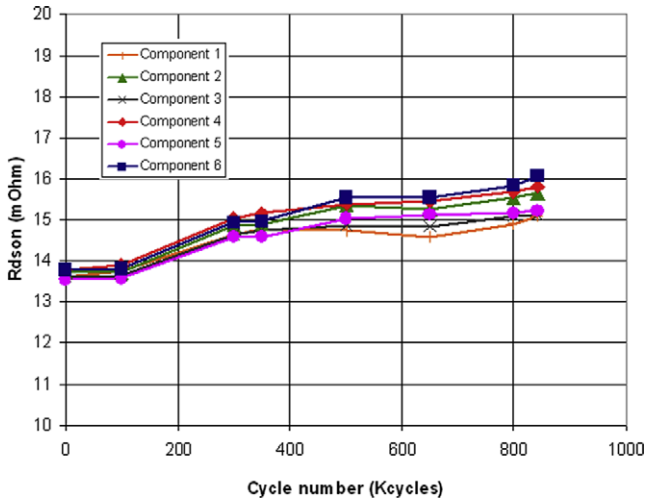


Fig. 1. Distribution of R_{dson} evolution for six different stressed devices which have undergone a 100 mΩ short circuit after 842,000 cycles at 40 °C. These components were still operative but their R_{dson} increased from 11% to 16%.

a Focused Ion Beam (FIB) apparatus equipped with a micromanipulator.

3. Results

Investigations were first carried out on functional components. The first step was to measure the evolution of the R_{dson} . This parameter always increased after electrical ageing, but the rise was different between components of a same batch (Fig. 1). In our tests, the larger augmentation reached 30% in functional components. The second step was to compare SAM and SAT results before and after electrical tests. We investigated both the mold compound/die and leadframe delamination by SAM and the die attach delamination by SAT. These analyses did not show any delamination at the die attach nor under the mold (Fig. 2). This result demonstrates the better ability of this new generation of devices to maintain a constant evacuation of heat between the silicon and the copper heat sink (delamination was identified as the main failure mode in devices from the former generation [7]). We also compared X-ray observations before and after electrical tests. As in the preceding generation of switches, we did not notice any growth of the initial voids in the solder between the leadframe and the power die.

As illustrated by Fig. 2, delamination was not observed in these components. In fact, we found that most of the degradation occurred in the active transistor region that is either in the Al metallization of the source or in the wire bondings that carry the current to this metallization. This hypothesis was supported by lo-

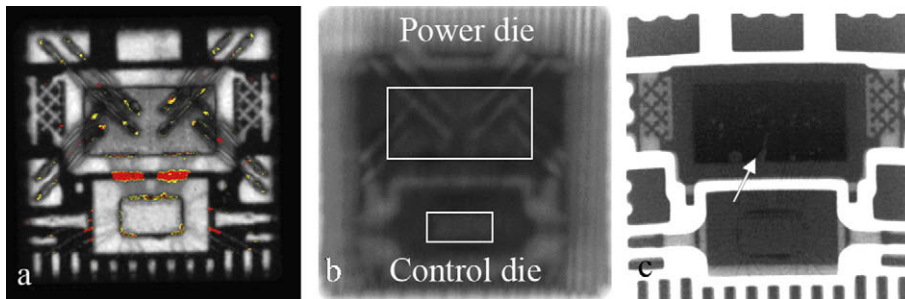


Fig. 2. Acoustic microscopy images of an aged device. Delaminations are observed by SAM at the mold (a) and by SAT at the die attach (b). The control and power die are indicated by white lines. Red zones in (a) correspond to delaminated area between the mold and the power die and black zones in (b) correspond to delaminated area between the power die and the leadframe. In (c) the white arrow points to a void in solder between the power die and the leadframe. (For interpretation of the references in colour to this figure legend, the reader is referred to the web version of this article.)

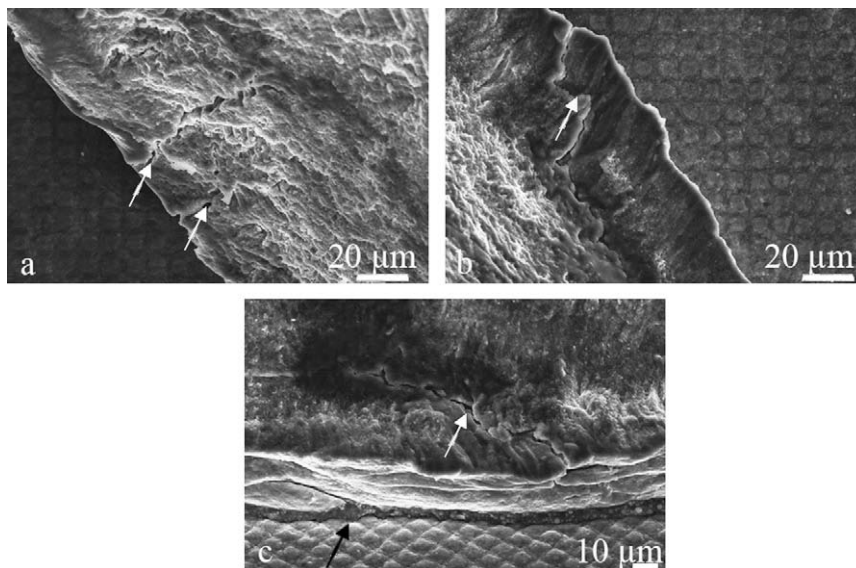


Fig. 3. SEM images of Al metallization and Al wire bonding. White arrows indicate cracks in and under Al wire bonding. In (c) black arrow indicates mold debris present in cracks (those can be the result of a local heating or to the post mortem chemical etching of the mold).

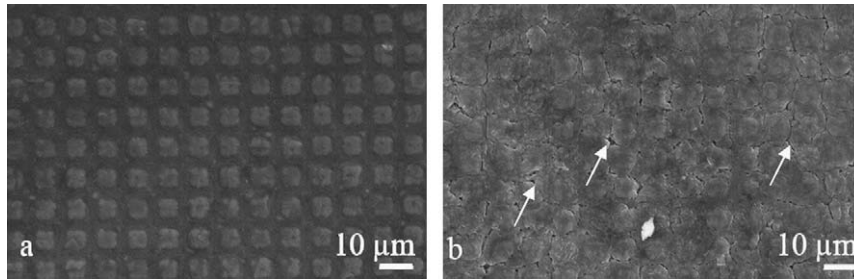


Fig. 4. SEM images of the Al metallization of devices under study. Before tests (a), the Al surface is smooth and individual grains cannot be detected. The destructured metallization in (b) corresponds to a stressed device which has undergone an 85 A square electrical pulse during 250,000 cycles at 85 °C. This component was still operative but its R_{dson} increased about 30%. White arrows show some inter-granular cracks in the metallization layer.

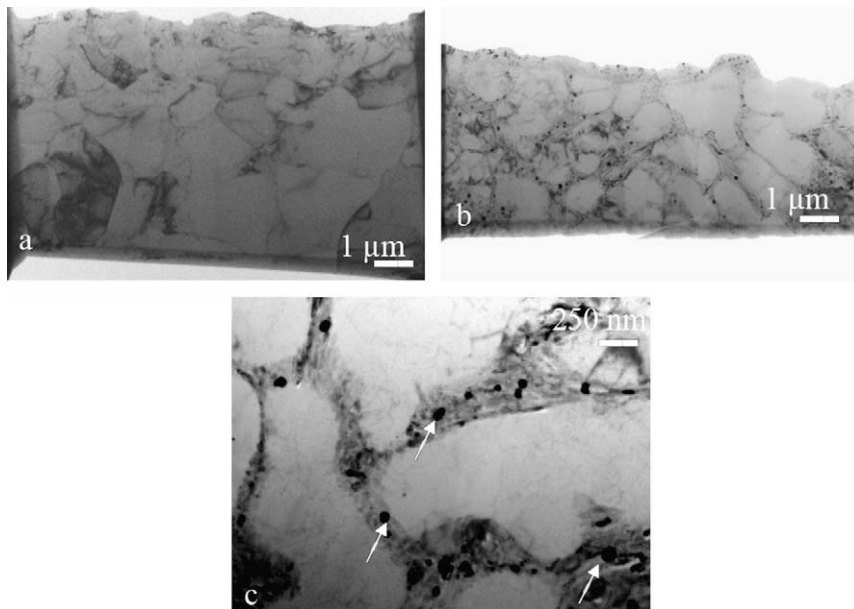


Fig. 5. TEM images of Al wires. Al grains with various crystalline orientations are observed in an untested Al wire (a). In a burned out Al wire a single crystallographic orientation is found for all Al grains and sub-grains (b). White arrows in (c) indicate Si grains between Al sub-grains. This microstructure is typical of a high temperature eutectic alloy formation between Si and Al.

cal electrical measurements carried out on one device that showed an increase of R_{dson} of 30% between wire bonds and Al metallization. SEM observations of the wire bondings revealed that cracks were present across the wire section (Fig. 3). Most of these cracks span over a small section of the wire and are unlikely to cause such an increase of resistance in the wire. Some cracks were however observed below the wire, at the interface with the Al layer (Fig. 3b). Plane view SEM observations cannot reveal how far these cracks go. If they crawl underneath the wire from one side to the other, they could lead to a complete detachment of the wire from the metallization. Even incomplete, such a delamination could result in a substantial increase of the resistance between the wire and the active cells. Especially if some mold debris are absorbed in these cracks during the electrical tests (Fig. 3c).

Other SEM observations clearly point to the degradation undergone by the metallization. Fig. 4 represents the surface of the device before testing (a) and after 250,000 cycles at 85 °C with an 85 A square electrical pulse (b). Square structures in (a) correspond to transistor cells. The metallization underwent a complete degradation in (b) characterized by many inter-granular cracks in the stressed metallization.

These cracks are probably formed by stress and temperature-induced accelerated diffusion at the grain boundaries [10–12]: a severe loss of contact between Al grains, which is not complete here, could again induce an increase of the total source resistance.

Investigations were also performed on components that were no longer operative after electrical tests. Some of them burned, probably because the resistance drastically increased, thus leading to an abrupt temperature upsurge. Regular TEM preparation was not possible in case of burned out Al wire so FIB lamellae had to be extracted from the damaged region and then analyzed by means of EDX and TEM. We observed both a migration of Si from the active area of the MOS to the Al wire and a complete reorganization of Al grains of the wire (Fig. 5). In Fig. 5b, a crystallographic analysis showed that the whole TEM section consisted in one unique Al grain divided by Si grains, Al–Si eutectic alloy bands and sub-grains, which is a proof that a local melting of the Al metallization occurred in this region.

Further analysis is currently carried out to pinpoint the local micro-structural changes that could lead to a severe resistance and then temperature increase that could explain such major transformations in the Al layer.

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