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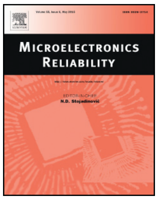

Mechanisms of power module source metal degradation during electro-thermal aging

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ABSTRACT

The long-term reliability of power devices for applications in the automotive industry is limited by the electro-thermal and/or thermo-mechanical aging of the metallic parts. In the present work, we characterize the bonding wire and source metallization degradation of power MOSFETs-based devices under accelerated aging conditions, through electron and ion microscopy. The metal degradation is driven by an enhanced self-diffusion of aluminium (Al) atoms along the grain boundaries and a generalized fatigue crack propagation from the surface down to the silicon (Si) bulk. The metallization under the wire bonds is a critical location because it is initially plastically deformed during the bonding process. In addition, the wire-metal interface presents several imperfections, such as small cavities and Al oxide residues. During the electro-thermal cycles, they could be the starting point for harmful cracks that run along the interface (and eventually cause the wire lift-off or the cracking of the substrate). Whichever the propagation direction, the generation of these cracks locally increases the device resistance and temperature, and accelerates the aging process until failure.

1. Introduction

In the reliability chain of power modules, the metallization and wire bondings constitute a key link as they are more prone to plastic deformation [1–3]. The main sources of mechanical stress arise from the differential between the coefficient of thermal expansion (CTE) between the metal and the oxide/semiconducting parts. As aging progresses, the degradation of the metal may increase its resistance, which in turn will increase the temperature of the device in the on-state and therefore augment the mechanical stress. This feedback causes a degradation of the top metal through specific processes [4,5]. The wire bondings, that are ultrasonic cold welded on top of this metallization, complexify significantly the initial device structure [6]. In the present work, we report how we can access the structure of both the metallization and the bonded wire but also their interface even in its damaged state. New observations indicate that catastrophic failure of the device initiate in this aged interfacial region before propagating into the substrate. This mode of degradation of Al and Al bonding wires is widely encountered in power MOSFETs aging and may be of interest for manufacturers and users.

2. Experimental procedure

2.1. Device under test and accelerated aging tests

The device under test is a 12 V SmartMOS module from NXP Semiconductors designed for car applications. The power die (Fig. 1) consists in five MOS sectors, connected by eight Al wedge bond wires having a diameter of 380 μm (15 mils). Here we focus on the interface between the wires and the Al (0.5 wt% Cu and W) source metallization, which is 3.6 μm thick.

We performed specific aging tests (AECQ100-12 [7]) at 70 °C, putting the device under repetitive short-circuit conditions until failure [5,8]. During the tests, only one sector undergoes the electrical pulses (by using an external gate driver and suppressing the control die functionalities), so the others can serve as reference for the microstructural characterization of the metallic part. The life time of DUT spans between 300k and 5M cycles depending on the test temperature [6].

2.2. Thermal cycles – curvature experiment

In parallel, thermal-only cycles (from −190 °C to +350 °C) were performed under vacuum in a home-made test bench (Fig. 2a) based on a KSA MOS laser reflectometer and an ARS cryo-holder. The tested samples are reference power dies (without the bonding wire connections). During the tests, the curvature imposed by the Al film to the Si

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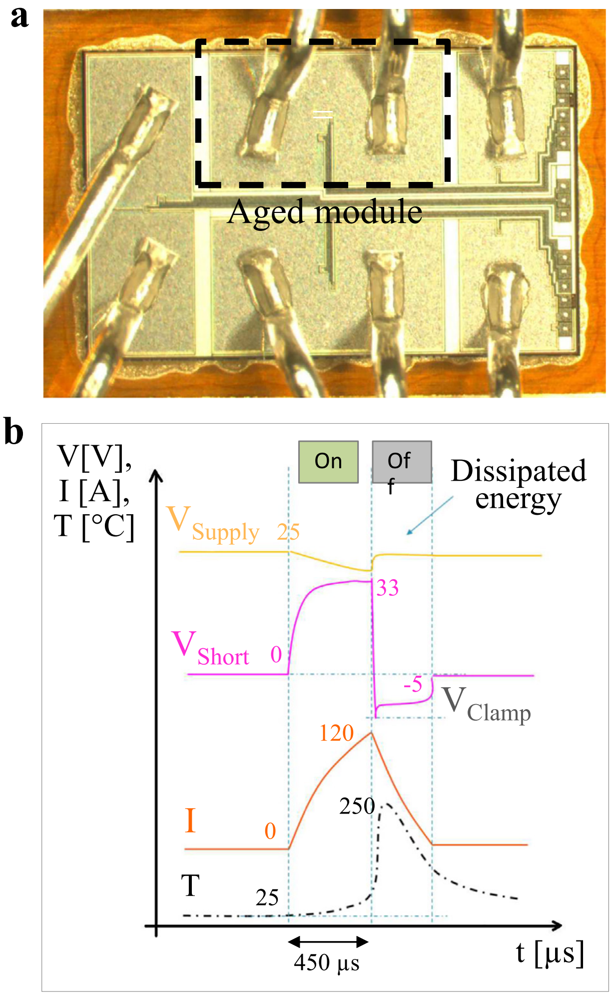

Fig. 1. (a) Power die of a 12 V SmartMOS from NXP Semiconductors showing 5 sectors. Only the central-lower one is electro-thermally aged. (b) Typical signals during a short-circuit event in the power device by activation of overload protection. Temperature has been simulated using a FEM software for an environment set at 85 °C.

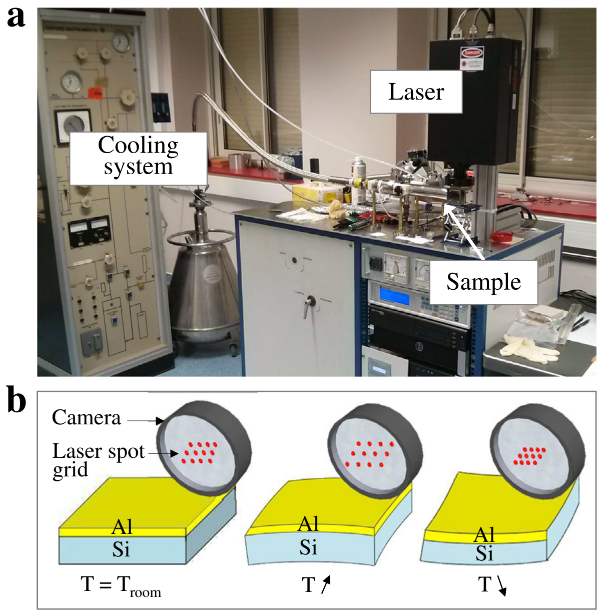

Fig. 2. (a) Thermal aging test bench. (b) Schematic illustration of the laser spot behavior depending on the Si-Al wafer curvature during the thermal cycles.

substrate (due to the difference in CTE) is measured by laser profilometry (Fig. 2b). The Stoney equation [9,10] is used to obtain directly the stress variations in the Al film. These thermal tests were not performed in sufficient numbers to induce significant aging of the device. In the following, aged devices only refer to those that have endured repetitive short-circuits, corresponding to electro-thermal cycles.

2.3. Microstructural characterization

Preliminary surface (Fig. 3a, b) and cross-sectional (Fig. 3c, d) observations of the source metallization were performed in a Helios 600 FIB/SEM (Focused Ion Beam/Scanning Electron Microscope) from FEI before and after electro-thermal cycles, confirming a heavy surface reconstruction upon aging.

To increase the observation areas and to disclose the whole wire-metallization interface without damaging their microstructure, the device was then prepared using an ion beam Cross-Polisher (CP) from JEOL. In the CP, a 6 kV argon ion (Ar^+) beam irradiates the region of interest and creates a mirrored face for FIB/SEM inspection (Fig. 4d). The whole process, explained through Fig. 4, consists in covering the power die with conductive epoxy (G-1, Gatan Inc. mixed with Carbon Paint from Agar Scientific) (Fig. 4a), curing it overnight at ~80 °C, mechanically polishing it parallel to the metallization (Fig. 4b) before applying a mask across the selected area and milling it at 90° from the top surface (Fig. 4c).

As-processed and aged devices were observed in the FIB/SEM using electron and ion channelling contrast, the latter being strictly dependent on the grain orientation [11]. Fig. 5a shows a low magnification SEM image of the bonding wire from a non-aged module.

At higher magnification (Fig. 5b), the ion image of the wire-metal interface reveals a strong plastic and uneven deformation imposed by the bonding process to the Al metallization prior to aging As will be explained later, his plastic deformation locally induces a smaller grain size and wavy interfaces.

Finally, Energy Dispersive X-ray (EDX) analysis in the FIB/SEM has been used to analyze the severe cracking occurring at failure in the region beneath the bonding wire.

3. Results

3.1. Al metallization outside of the bonding area

Away from the bonding contacts, the initial metallization structure (Fig. 3a, c) is characterized by a grain size on the same order of the metallization thickness, with most of the grain boundaries (GBs) perpendicular to the surface (bamboo structure).

We know that the repetitive electro-thermal cycles induce plastic deformation and surface reconstruction in the Al metal (Fig. 3b, d). Typically, successive short-circuits of several tens of microseconds induce temperature gradients on the order of 200 °C [12].

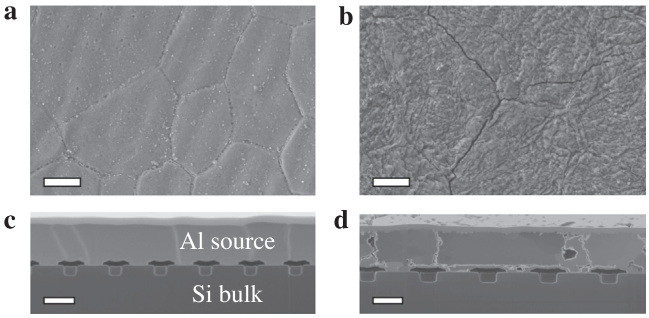

Fig. 3. SEM images of the source metal surface of a (a) non-aged module and an (b) aged one and relative cross-sections of a (c) non-aged module and an (d) aged one. Scale bar 2.5 µm.

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