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Comparative study of Al metallization degradation in power diodes under passive and active thermal cycling

Mads Brincker, Kristian B. Pedersen, Peter K. Kristensen, and Vladimir N. Popok

Abstract—Degradation of Al metallization on Si-based semiconductor chips under operation is a reliability problem known for many years but the mechanisms of this phenomenon are not fully understood. To quantify contributions of different possible effects, a passive thermal cycling setup has been developed allowing for accelerated tests by varying the device temperature on a short time scale without applying electrical power. The setup is also capable of testing devices in different atmospheres. The results obtained by the thermal tests of diode chips are compared to those from power cycled diodes with focus on degradation of the top metallization layer. The data on structural and electrical characterization of the samples show that the passive thermal cycling induces metallization degradation very similar to that found for the power cycled devices. Thus, it can be concluded that the thermal-induced stresses are the dominating mechanisms for the metallization fatigue and following failure. The role of oxidation and corrosion effects is also studied in the experiments on passive thermal cycling using different environmental conditions. It is suggested that the formation of self-passivating aluminum oxide under ordinary atmospheric conditions can play a positive role in limiting the structural, and electrical degradation of the metallization layers. The obtained results represent a considerable contribution into understanding of major failure mechanisms related to metallization fatigue and reconstruction.

Index Terms—Semiconductor device metallization, semiconductor device reliability, environmental factors, power semiconductor devices.

I. INTRODUCTION

A common stressor for semiconductor dies is oscillating temperature originated by changes in the active losses e.g. from alternating currents or pulsed conditions. The same type of semiconductor die may experience short and long load cycles with varying amplitude depending on particular operation conditions [1]–[3]. Thermal factors are especially crucial for power electronic devices where the currents can reach tens or hundreds of amperes leading to very significant thermally induced stresses [4]. An example for such case can be high power modules used in wind power generators [5]. Thermal stresses can also originate from the device location as, for example, in power electronic devices used in hybrid electric vehicles where their cooling system is shared with that of the combustion engine [3]. Additional stressors are related to environmental conditions, for instance, high relative

humidity (RH) or presence of chemically active gases, which can interplay with the thermal phenomena in a complex manner leading to change of the degradation mechanisms [6].

Consideration of the thermally-induced degradation is particularly important for interfaces and interconnects where a difference in coefficients of thermal expansion (CTE) between the components made of different materials can be large causing significant mechanical stresses under temperature variation. One of the practically important cases for power electronics is fatigue of top-side Al metallization on Si dies. These layers are typically between $1\text{ }\mu\text{m}$ – $6\text{ }\mu\text{m}$ thick and have microgranular structure. The films are needed to provide good electrical contact across the entire chip surface as well as allow for bonding of Al wires to interconnect the devices in the circuit. Due to difference in CTE between Al and Si, thermo-mechanical stresses are developed at the interface and lead to fatigue of the metallization layers causing a change of the granular structure and formation of voids and cracks. These phenomena negatively affect continuity of the film leading to increase of electric resistance and also provoking wire bond degradation and lift-off [7], [8]. Thus, a thorough understanding of the fatigue behavior of Al metallization and its interplay with wire bonds would give an important knowledge impacting the quality improvement of individual components as well as whole power devices.

The metallization fatigue has been a goal for several studies where different loading methods such as active power cycling [5], [9]–[12], passive thermal cycling [13]–[22] and cyclical bending on compliant substrates at room temperature [23], [24] were used. These investigations suggest a number of effects leading to the structural and compositional modification of Al films, among which are electromigration, grain-boundary diffusion [25], which can be enhanced by oxidation [12], hillocking [26] and dislocation slip. Hence, the failure mechanisms can be of different nature involving thermo-mechanical, electrical and environmental reasons. In order to resolve the role of every effect and its importance for overall degradation, one needs to provide conditions for accelerated test separating different origins.

The current paper presents and analyses the data obtained under passive thermal cycling of diode chips under different atmospheric conditions, thus, studying the role of pure thermal phenomena isolating them from any electric effects. Thermal tests under different environmental conditions allow to justify an importance of RH and oxidation factors as well as their interplay with the thermally-induced stressing. Comparison

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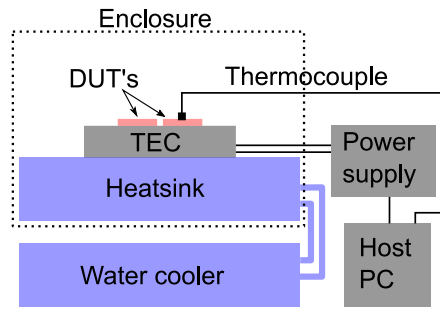


Fig. 1. Schematic picture of the passive thermal cycling setup.

of topographical, microstructural, and resistance changes of the metallization layers under the above-mentioned tests with those obtained under traditional power cycling provide clear insights into the major degradation mechanisms and related failure modes.

II. EXPERIMENTAL PROCEDURE

A. Passive thermal cycling

The passive thermal cycling setup is based on a digitally controlled thermo-electric cooler (TEC), which is connected to a water cooled Al block on the bottom side, while the top side is used to thermally cycle the samples. All active elements of the setup are put in an air-tight enclosure that provides a possibility to control the surrounding atmosphere. A schematic picture of the setup is shown in **Figure 1**. Temperature measurements are carried out by placing a thermocouple in direct contact with the topside metallization layer on one of the devices under test (DUT).

One set of data is obtained for cycling in a pure nitrogen atmosphere allowing to reach RH close to zero and exclude effect of oxidation, while another one in an ordinary atmosphere with a controlled RH=50%. This is done to examine if humidity and oxidation effects play any major role in the degradation phenomena. The temperature waveforms are triangular shaped with a period $P_{N_2} = 26$ s for the cycling in nitrogen atmosphere and a period $P_{air} = 24$ s for the cycling in ordinary atmosphere, see **Figure 2**. Other parameters, such as minimum and maximum temperature, $T_{min} = 25^\circ\text{C}$, $T_{max} = 105^\circ\text{C}$, and the mean temperature of 65°C are identical for both experiments. The DUT are high power Infineon diodes (100 A/1200 V) that are 9×9 mm squares with a measured topside metallization thickness of $3.4\mu\text{m}$. Three diodes are thermally cycled in nitrogen and in ambient atmosphere labeled as D# and A#, respectively.

B. Active power cycling

In order to compare the change in sheet resistance as well as the microstructural evolution of the passively cycled samples, a set of samples is subjected to power cycling, which is often also referred as active thermal cycling.

1) *DC pulse test*: The DC pulse test is a current load procedure, according to test standards [27], where the device is heated using only ohmic losses from a DC current. The investigated DUT is a half-bridge 300 A device with 3 parallel

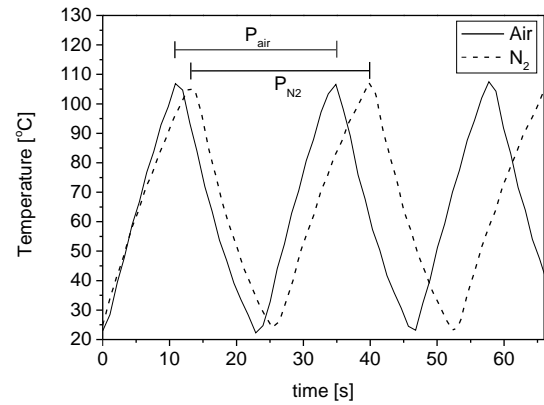


Fig. 2. Profile of thermal cycles with $P_{air} = 24$ s being the period for cycling in atmospheric air, and $P_{N_2} = 26$ s being the period for cycling in nitrogen atmosphere.

sections consisting of two IGBT chips and two diodes each. The semiconductor devices are backside soldered to a Al_2O_3 DCB and topside bonded with heavy Al wires. The chips have a standard $3.4\mu\text{m}$ thick Al metallization layer. Before the test, the silicone gel is dissolved to allow for sheet resistance measurements in between the power cycling steps. Only the low side diodes are tested in the present setup, while the top side diodes are used to measure the reference value of the sheet resistance, in order to calculate the relative change for the cycled diodes. Since the diodes are acting passively, any load variation is induced externally (water cooler, power supply, etc.), and therefore, the current amplitude, cooling temperature, and on/off time are the primary control parameters. In accordance with ordinary accelerated tests of chip level interconnects, the on time is kept at 1 s and the off time is varied to reach the desired ΔT . Chip junction temperature is monitored using calibrated small current injection. The test is run under a constant current. This means that the device loading increases when the DUT starts degrading. In general, this is considered to be a much harder test than that at constant temperature, while also closer to real operating conditions [1], [2], [4]. The accelerated test is performed with a load current per chip between 75 A – 85 A, a water cooling temperature of 80°C , and on/off times of 1 s/2.3 s. This set of parameters is chosen to obtain an initial ΔT of approximately 50°C for non-degraded devices.

2) *Sinusoidal current load*: The DUT are standard half-bridge IGBT modules consisting of six parallel IGBT chips each with a freewheeling diode. IGBTs and diodes are topside connected with heavy Al bond wires and backside soldered to a standard Al_2O_3 based DCB substrate. The modules are power cycled actively with a sinusoidal current load of 890 A at 6 Hz switched at 2.5 kHz with a DC-link voltage of 1000 V. As one of the main accelerators, the baseplate of the DUT is subjected to an elevated temperature of 80°C . Under these conditions the mean temperature of both IGBTs and diodes is online estimated and simulated to be approximately 112°C , while the ΔT of IGBTs is found to be around 29°C , and the ΔT of the diodes around 36°C , thus resulting in a maximum junction temperature of 127°C for the former and 130°C for

the latter. The reason why the modules have been tested at a workpoint far from the passive test conditions is to avoid too early failure from bond wire lift-off or solder fatigue prior to observing the metallization degradation. More details about the test procedure can be found in [5], [28].

C. Electrical characterization

For the electrical characterization, the van der Pauw method [30] is used according to the procedure described in [19].

In the case of the passive test, the resistivities of the new diodes are measured to be $28.9 \pm 0.2 \text{ n}\Omega \text{ m}$ and the exact individual values are then used to calculate the relative change of the sheet resistance for each cycled diode. For the resistivity measurements, the samples are temporarily removed from the test setups and then returned for further cycling.

In the DC pulse load case, the sheet resistance of individual low side diodes is measured after reaching a certain number of cycles. For that, the module is taken from the power cycling setup, and one diode is electrically disconnected by mechanical removal of the bond wires. After the measurement of the sheet resistance, the module is reinstalled in the setup, re-calibrated for a ΔT of 50°C , and the power cycling is continued on the remaining low side diodes. The procedure of electrical measurements is repeated on the next diode after reaching next step in the cycling. In order to collect sufficient number of cycles, two power modules are used for this accelerated test. Since resistivity values of different uncycled diodes are found to be very close to each other, $27.5 \pm 0.4 \text{ n}\Omega \text{ m}$, the average value is used as a reference for the loaded diodes, which results in an uncertainty of $\pm 1.45\%$ for the relative resistivity values given in **Figure 4**.

In the sinusoidal current load case, the power modules are taken from the setup and the silicone gel as well as bond wires of diodes are removed to provide electrical contact to the metallization of the diodes. The relative change in sheet resistance for the individual diodes at every number of cycles is calculated using the average value obtained from the uncycled module, which is found to be $27.6 \pm 0.2 \text{ n}\Omega \text{ m}$. For each power cycling step, three sections with two diodes per section are examined, thus resulting in six readings for every number of cycles.

III. RESULTS

A. Sheet resistance

The relative change in sheet resistance for the case of thermal cycling in both nitrogen and ambient atmospheres is shown in **Figure 3**. A clear increase of the sheet resistance can be seen for the diodes cycled in nitrogen atmosphere reaching up to 43% at 330 kilocycles. In this case, three phases with different degradation rates can be distinguished: phase 1 for 0-20 kilocycles that shows almost no change in the sheet resistance, phase 2 between 20-120 kilocycles that demonstrates the most severe increase of resistance, and phase 3 above 120 kilocycles that shows moderate increase. This type of curve with different phases agrees with earlier results obtained for actively thermally cycled devices [10]–[12].

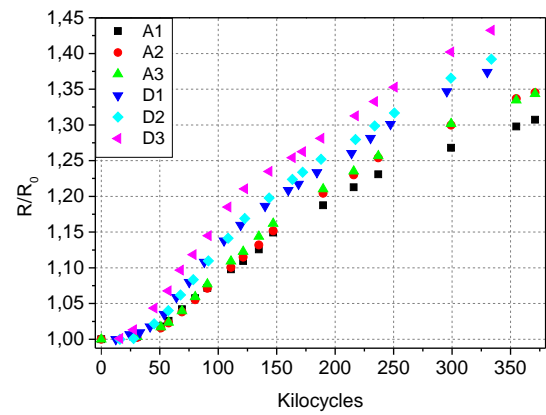


Fig. 3. Relative sheet resistance of diodes at different number of cycles. A1, A2, and A3 correspond to diodes cycled in ordinary atmosphere, and D1, D2 and D3 correspond to diodes cycled in nitrogen atmosphere.

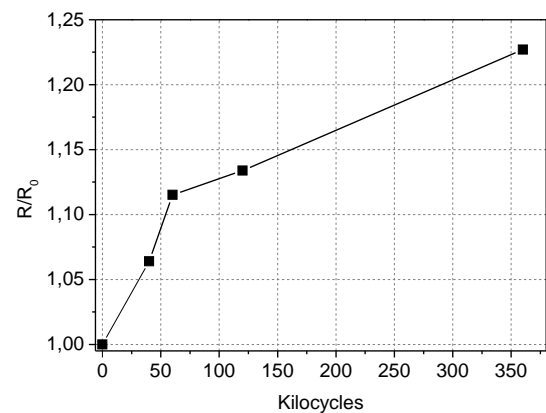


Fig. 4. Relative sheet resistance of actively cycled diodes under DC pulse load at different number of cycles.

The data for the diodes cycled in ambient atmosphere show three phases with different degradation rates similar to those found in nitrogen but with slower increase of resistance. At 300 kilocycles the average increase in sheet resistance for these diodes reaches only 28%, compared to 37% for the devices cycled in nitrogen atmosphere. Since cycling period of the devices in nitrogen atmosphere is slightly longer compared to that in air, one can expect a partial contribution of this parameter into the degradation. But influence of atmospheric oxygen is also expected to contribute into the metallization reconstruction as will be argued in the Discussion section.

The relative change of sheet resistance for the case of active power cycling under DC pulse load is shown in **Figure 4**. The evolution of the sheet resistance resembles that for the passively cycled diode chips, shown in **Figure 3**, in the way that distinct phases can be recognized. The initial interval of up to 60 kilocycles demonstrates the most severe increase of resistance, while after that the change is more moderate. The increase of resistance reaches 23% at 360 kilocycles, which is lower than the mean value of the passively cycled samples.

The change of sheet resistance for the case of active power cycling under sinusoidal current load is shown in **Figure 5**. Similar to the passively cycled diodes and those under active

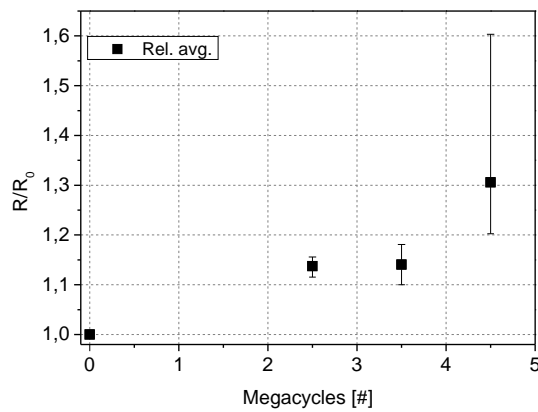


Fig. 5. Relative sheet resistance of actively cycled diodes under sinusoidal current load at different number of cycles. Each solid square represent the average of the six different measured values, while the bars represent the minimum and maximum of the measured values.

cycling with DC pulses, a clear rise of the sheet resistance can be observed. After 4.5 megacycles this value reaches a relative increase of 31%. As the number of cycles increases a wider spread of the sheet resistance values is observed, which is indicated by vertical bars.

B. Microstructural characterization

To correlate the change in sheet resistance to the microstructural evolution of the Al metallization, a scanning electron microscopy (SEM) study accompanied by focused ion beam milling (FIB) is performed according to the procedure described elsewhere [28].

In **Figure 6**, SEM images of the metallization cycled in nitrogen atmosphere are presented. **Figure 6(a)** shows the surface of the metallization after 250 kilocycles demonstrating severe restructuring. One can compare this image with **Figure 6(b)** for the uncycled device where one can see a part of the surface which is relatively flat. This figure also indicates that the film is initially crack free, while from **Figures 6(c,d)** it can be seen that the deformation occurring during cycling is not limited to the surface of the metallization. Cavities and cracks are formed in the layer bulk and propagate deep into the metallization. The total disorder of the analyzed layers increases with number of cycles. These observations correlate well with the sheet resistance measurements, which show an increase of relative resistance from 1.25 to 1.35 for diode D3 in the interval 145-250 kilocycles, see **Figure 3**.

In **Figure 7**, SEM images of the metallization cycled in ambient atmosphere are presented. **Figure 7(a)** shows the surface in the center of a cycled diode. There is a clear microstructural change similar to that seen in **Figure 6(a)**. **Figure 7(b)** shows a cross-section in the center of the metallization with severe plastic deformation of the layer. **Figures 7(c-d)** present surface and cross-section images at the edge of the diode. By comparing with **Figures 7(a-b)** it becomes obvious that the degradation is not homogeneous but most significant in the center of the diode. Lower degradation at the edges can be explained by less confinement, which leads to lower stress. Comparing the metallization degradation in

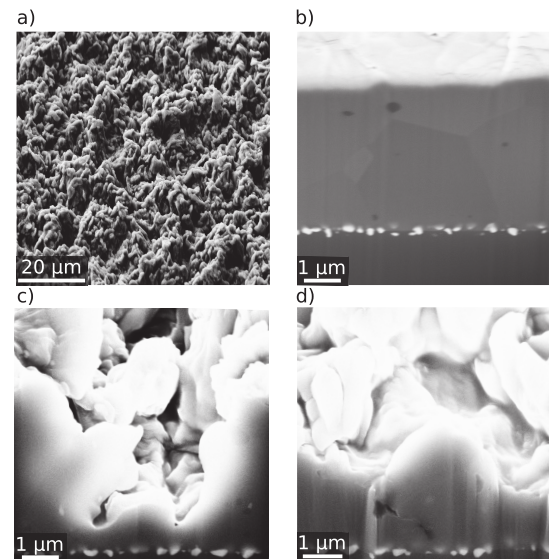


Fig. 6. SEM images of metallization for diode D3. a) Surface after 250 kilocycles, b) cross-section at 0 kilocycles, c) cross-section after 145 kilocycles, and d) cross-section after 250 kilocycles.

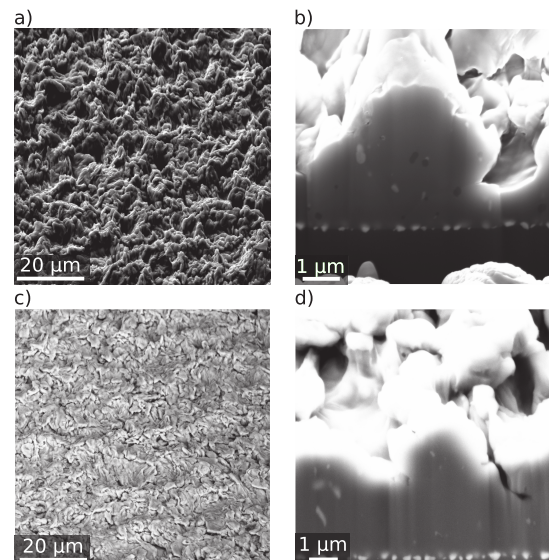


Fig. 7. SEM images of metallization for diode A2 after 110 kilocycles. a) Surface in the center, b) cross-section in the center, c) surface at the edge, and d) cross-section at the edge.

different atmospheres, one can conclude that the restructuring occurs in a similar way in nitrogen and ambient atmosphere.

In **Figure 8**, SEM images of the metallization for the power cycled diodes are presented. **Figure 8(a)** shows the surface of the metallization after 2.5 megacycles. One can see plastic deformation of the surface, but the cracks do not protrude deep into the layer (see **Figure 8(c)**). This level of structural degradation agrees well with the moderate increase in the sheet resistance that can be found in **Figure 5**. **Figure 8(b)** shows the surface of the metallization after 4.5 megacycles. In this case, the restructuring of the surface is dramatic, and as can be seen in **Figure 8(d)** the cracks and cavities penetrate almost all the way to the Si substrate, thus leading to the observed high increase in sheet resistance (see

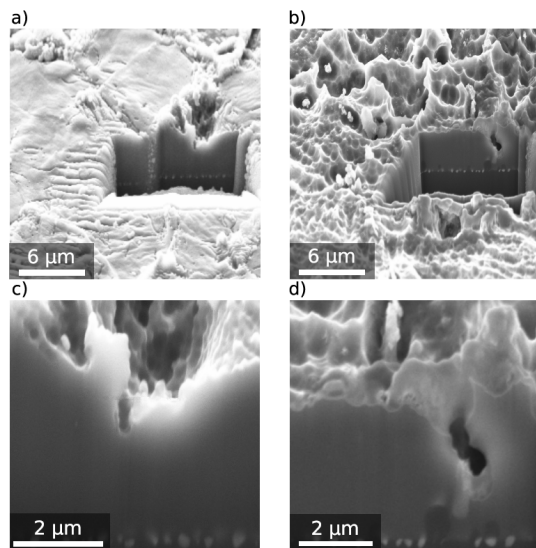


Fig. 8. SEM images of metallization for diodes that are power cycled with a sinusoidal load current. a) Surface after 2.5 megacycles, b) Surface after 4.5 megacycles, c) cross-section after 2.5 megacycles, and d) cross-section after 4.5 megacycles.

Figure 5). It is worth mentioning that under the conditions of active cycling it is primarily the diodes that are subjected to the significant power load [5]. Therefore, metallization of IGBT chips does not undergo any considerable degradation. However, if a load profile is designed to stress IGBTs one observes considerable degradation of the metallization similar to that found for the diodes [29]. Overall, it can be concluded that the microstructural evolution of the metallization on the actively cycled devices is very similar to that found for the diodes under passive thermal tests.

C. Texture analysis

To examine the texture of the metallization, X-ray diffraction (XRD) measurements are performed on the passively cycled diodes. XRD measurements can be used in thin film analysis to determine the orientation of the micro-crystals that constitute a polycrystalline film [32]. It is found that grains with crystallographic planes (111) dominate in new Al metallization layers and these data correlate well with the results published elsewhere regarding the texture of Al thin films on Si substrates [13], [17], [22], [33], [34]. As the number of thermal cycles increases, spectral peaks corresponding to (200), (220), and (311) crystal lattice planes appear for both types of cycling (in nitrogen and ambient air). The obtained tendency is in good agreement with our earlier published results [21], and therefore, we do not present the spectra here. The transformation of the grains may be explained by dislocation glide of the inclined (111) planes that are constrained by the Si substrate [17], [35].

Tendencies in the change of XRD spectra are found to be very similar for the samples cycled in nitrogen and air. However, the diode that reached 134 kilocycles in air demonstrates almost the same XRD scan as the diode having 335 kilocycles in nitrogen. This implies that the grain reorientation phenomena might only be influential until a point where no

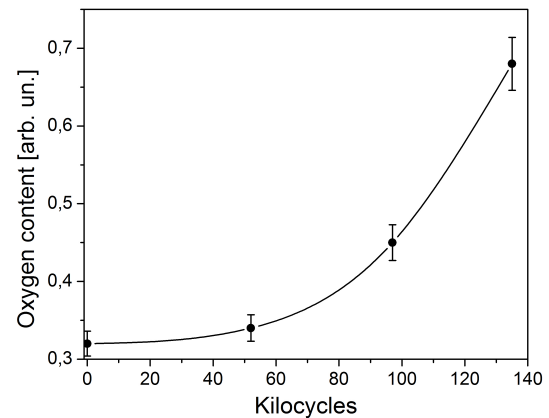


Fig. 9. Amount of oxygen in the metallization of A1, measured by EDX. The error bars represent the uncertainty of the measured values.

more relaxation can occur through this mechanism, while other mechanisms (crack and void development) continue to affect the degradation process. More studies are being carried out on this topic [22], which is not the focus of the current paper.

D. Oxide analysis

Energy-dispersive X-ray spectroscopy (EDX) measurements are performed on the passively cycled diodes to monitor the amount of oxygen present in the film, thus allowing to track the formation of aluminum oxide. The accelerating voltage of the EDX measurement was 10 kV, which according to simulations corresponds to a maximum penetration depth of 1 μm. Since oxidation occurs predominately in the relatively thin near surface layer but the data are collected from a micron thick film, quantization of oxygen content in atomic percent is hardly possible and it is given in arbitrary units. It can be seen from the data presented in **Figure 9** that the amount of oxygen in the metallization of diode A1 (ambient atmosphere) increases in a non-linear manner with the number of cycles, while the oxygen increase for diode D3 (nitrogen atmosphere) at 335 kilocycles is found to be at only 0.5 arb. un. which is lower compared to diode A1 at 135 kilocycles (see **Figure 9**). Oxidation of the metallization films cycled in nitrogen atmosphere most probably occurs during storage and when the samples are taken from the setup and exposed to ambient atmosphere while transferred to EDX. Thus, one may conclude about a considerable oxidation of the metallization under thermal cycling in ambient atmosphere.

IV. DISCUSSION

The results on sheet resistance and EDX analysis have showed two important tendencies. The electrical degradation of the metallization cycled in air is slower compared to that cycled in nitrogen atmosphere. At the same time, the EDX measurements show that the amount of oxygen in the metallization tested in ambient atmosphere is higher than in those run in nitrogen atmosphere. The increase in the amount of oxygen agrees with a qualitative diffusion model for the degradation of Al films suggested by Martineau et al [12]. They hypothesized

that sidewalls of micro-cracks, formed during the tensile phase (cooling) of a thermal cycle, self-passivate through surface oxidation in ambient atmosphere, thus leaving these cracks unable to heal in the following compressive phase (heating). In the next tensile phase, these cracks will then develop deeper into the layer causing electrical disconnections. Initially, this mechanism is expected to enhance crack formation, introduce higher disorder in the layer, and therefore increase the sheet resistance. However, this process might be counteracted by another phenomenon also arising from the oxidation.

Native oxide of Al, with a thickness of about 3 nm to 6 nm [36], could constrain the dislocation motion, thereby increasing the strength of the film and making it less prone to plastic deformation [37] in a similar way to that a compressive layer, e.g. polyimide or silicon dioxide, has been shown to suppress the degradation phenomena [7], [38], [39]. Such strengthening mechanism affecting mechanical properties and microstructure of metal thin films is suggested for Al-0.5%Cu with native oxide [13]. It is also observed for self-passivated Cu-1%Al films where dislocation glide, parallel to the surface in pure Cu layer, is converted to threading dislocation motion in the oxidized films [40]. These results indicate that the presence of a native oxide, despite its low thickness, may have an influence on the dislocation motion, and thereby on the type of degradation and degradation rate. Thus, one can suggest that the formation of native aluminum oxides can play a positive role in the evolution of metallization structure through slowing down the mechanisms leading to the loss of film continuity.

Comparing the evolution of sheet resistance for the samples under passive thermal cycling and the active power cycling with DC pulse load one can conclude about very similar character of the dependences (compare **Figure 3** and **4**). One does not clearly see the phase I for the power cycled samples, which is probably related to only very few measurements of the resistance for low number of cycles but then in both cases one can observe a very similar relatively steep resistance increase with following slowing down. The number of cycles leading to the increase of resistance is also comparable but the passively cycled devices degrade faster showing the rise of relative resistance up to 34% at 360 kilocycles while those under the DC pulse load reach only about 23% for the same number of cycles. Several factors may account for the higher degradation observed in the passively cycled diodes but the main reason is most likely the difference in ΔT , which is 80 °C for the passive test, and 50 °C for the DC pulse test.

Since the devices under the sinusoidal current load are expected to have much lower ΔT (around 36 °C on diodes) compared to the above-discussed cases, the increase in the sheet resistance undergoes much slower dynamics reaching a relative value of about 31% after 4.5 megacycles (**Figure 5**). It is quite difficult to distinguish between different phases of the degradation because with the increase of number of cycles we observe a wide spread of the sheet resistance values. These large variations are well explained by higher complexity of the systems under the sinusoidal current load conditions compared to those used in the passive and DC pulse cycling. In the two latter cases, individual elements or sections are under the load while for the former test the whole module is cycled. In this

case, the temperature increase for each diode is caused not only by the passing current but it is also affected by the state of neighboring diodes, solder layers, etc. For example, uneven current sharing between individual sections originated from the degradation of solder and wire bonds cause different stresses for each diode. This spread becomes wider with the number of cycles due to the diversity in degradation of individual devices, thus, increasing the deviation in the electrical degradation of the entire power module. Nevertheless, the observed general dynamics of resistance increase under this accelerated test is in good correlation with both the passive thermal cycling and active one with DC pulses. The microstructural changes of the device metallization under the three different types of cycling also demonstrate close similarity.

The role of the metallization restructuring in degradation of wire bond interfaces is not directly studied in this work. But one can suggest that re-orientation of grains, formation of cavities and cracks in Al films should significantly affect the bonded area, thus, accelerating wire lift-off, which is one more major failure mechanism limiting reliability of electrical interconnects.

V. CONCLUSION

To gain insights into the dominant physical mechanisms governing the degradation of Al metallizations, a passive thermal cycling setup that can operate in different atmospheres have been constructed and the results obtained on the metallization degradation under passive thermal tests have been compared with those found in actively power cycled devices. Both passive cycling in pure nitrogen and ordinary atmosphere have shown microstructural degradation of the metallization films very similar to that observed for the actively power cycled devices. The electrical characterization demonstrate a few phases of resistance increase for the passively cycled metallization and that under pulsed load of DC, which correlate well with each other. These phases are in good agreement with literature data. The metallization resistance increase of the devices subjected to the sinusoidal current load does not clearly show these phases due to a limited number of measurements for a certain number of cycles and also due to significant increase in the spreading of values for high number of cycles due to the complexity of the DUT. Since the passive thermal test excludes any contribution from electric current, the obtained results present a strong indication that thermo-mechanical stress is the dominant mechanism responsible for the restructuring and related fatigue of Al metallizations in Si based power components.

To examine the role of oxidation and corrosion effects, the degradation originated by cycling in ambient atmosphere with controlled humidity is compared to that in a nitrogen atmosphere (close to zero RH). It is found that the metallization restructuring occurs slower in the ordinary atmosphere, and it is proposed that this could be caused by a strengthening mechanism due to the formation of native oxides acting as a constraint on the dislocation movement, thus limiting the dislocation-based plasticity. Comparisons between the amount of oxygen in the metallization cycled in ordinary and nitrogen

atmospheres supports the model where self-passivation of micro-crack walls can lead to the change of the involved physical mechanisms, thus, slowing down the breakage of the film continuity. No evidences for corrosion are found for the metallization cycled in ordinary atmosphere with RH = 50%. We do not extend the role of oxidation effects on the modules that are power cycled with sinusoidal current because the test are run on the packaged modules and any significant penetration of oxygen through the silicon gel is rather unlikely.

Presently, there is a general tendency in substituting Al wires by Cu-based ones and soft solders by sintered connections in order to improve the technologies in respect to such failures as bond wire lift-off and solder fatigue [41]–[43]. Thus, one can argue that the study presented in this paper is of limited interest. However, even in this new architecture, the used Si chips are standard ones still containing Al metallization films with an additional layer of Cu on top. Moreover, Al metallization will still be a widely used industrial approach in the future due to well established technologies and lower expenses compared to Cu. This situation, therefore, leaves the Al metallization to be a bottleneck in component operation range and lifetime. Since the obtained results clarify a picture of the physical origins behind the metallization degradation, they can pave a way for further optimization on component level, and the construction of devices with improved reliability.

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