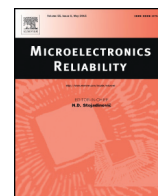




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## Mechanisms of metallization degradation in high power diodes

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## ARTICLE INFO

## Article history:

Received 21 June 2016

Accepted 6 July 2016

Available online xxx

## Keywords:

Metallization degradation

Thermo-mechanical fatigue

Aluminum

Thin film

Plastic deformation

## ABSTRACT

Under operation the topside metallization of power electronic chips is commonly observed to degrade and thereby affect device's electrical characteristics. However, the mechanisms of the degradation process and the role of environmental factors are not yet fully understood. In this work, we investigate the metallization degradation by passive thermal cycling of unpackaged high-power diode chips in different controlled atmospheres. The electrical degradation of the metallization is characterized by sheet resistance measurements, while the microstructural damage is investigated by scanning electron microscopy (SEM) and X-ray diffraction (XRD). To study the evolution of the chemical composition of the metallization, energy dispersive X-ray spectroscopy (EDX) is also applied. Since the degradation depends on the initial microstructure of the metallization, the film texture and grain size distribution is determined using electron backscatter diffraction (EBSD). The obtained data show that the type of atmosphere plays a minor role in the degradation process, with a slight tendency that cycling in dry nitrogen atmosphere accelerates the degradation compared to the experiments in ambient atmosphere with a controlled relative humidity of 50 and 95%.

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## 1. Introduction

Silicon based electronic chips with thin aluminum metallization layers are widely used for power converters. The conventional assembly method of power modules requires this Al metallization to allow the bonding of heavy Al wires and to provide good electrical contact across the entire chip surface. However, due to the difference in the thermal expansion coefficient between Al and Si, the metallization experiences mechanical stress when subjected to temperature cycling, which leads to structural degradation and loss of functional properties [1,2]. The degradation of chip metallizations has been investigated in a number of studies, see for example [3–12], however a systematic approach to the influence of varying atmospheric conditions has not yet been applied. To investigate this and the thermo-mechanical degradation mechanism, a series of passive thermal cycling experiments is performed on unpackaged high-power diodes under different atmospheric conditions.

## 2. Experimental procedure

The passive thermal cycling of the high-power Infineon diodes (100 A/1200 V) is carried out in a setup based on a thermo-electric cooler that can be placed under different atmospheric conditions. Further details about the thermal cycling setup can be found in [3,4]. The thermal cycling is performed at  $T_{\min} = 25$  °C,  $T_{\max} = 105$  °C and a period of approximately 25 s. Three sets of data are compared, namely cycling

performed in pure nitrogen atmosphere, cycling in ambient atmosphere with a controlled relative humidity (RH) of 50%, and cycling in a climatic chamber in ambient atmosphere with RH = 95%. For each atmospheric condition three diodes are thermally cycled and studied. During cycling, the diodes are temporarily removed from the setup to apply various characterization techniques such as sheet resistance measurements, SEM and XRD analysis. The initial microstructure of uncycled diodes has been examined by EBSD to reveal the grain texture and grain size distribution.

The sheet resistance measurements are performed using a four point probing technique in a Van der Pauw configuration [13]. This approach removes the influence of contact resistances and ensures a very high repeatability with relative measurement uncertainties of approx. 0.1%.

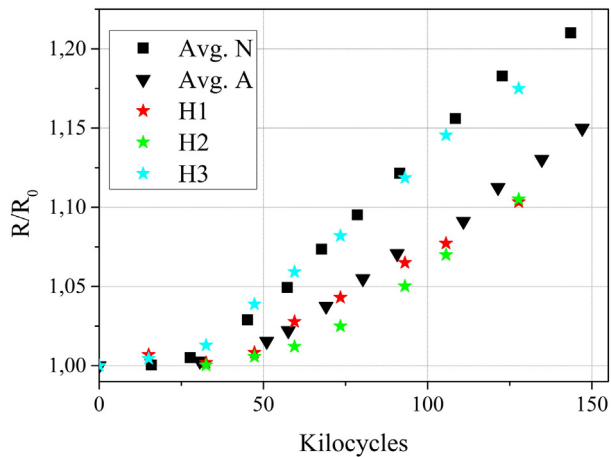
## 3. Results

## 3.1. Sheet resistance evolution

The evolution of the sheet resistance is shown in Fig. 1. It can be seen that the sheet resistance increases with the number of cycles and follows a nonlinear dependence. The cycling performed in nitrogen atmosphere on average yields a faster electrical degradation compared to the cycling in ambient atmosphere. The results for the cycling in ambient atmosphere at high humidity (H1–3) show a relatively large spread in the measured values. Though all the diodes are taken from a single wafer, this spread of the data might stem from different manufacturing qualities of the metallization across the wafer. For example, the metallization structure can be slightly different in the middle of the wafer compared to the edges. However, there is a general tendency that the

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**Fig. 1.** Relative change in sheet resistance during thermal cycling. Avg. N and A refer to the average values for diodes cycled in nitrogen atmosphere (RH = 0%), and ambient atmosphere (RH = 50%), respectively. H1–3 refers to diodes cycled in ambient atmosphere under RH = 95%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cycling in nitrogen accelerates the degradation compared to the cycling in ambient atmospheres. Increasing RH up to 95% does not seem to affect the degradation mechanism. But more cycles need to be performed to substantiate this.

### 3.2. Microstructural analysis

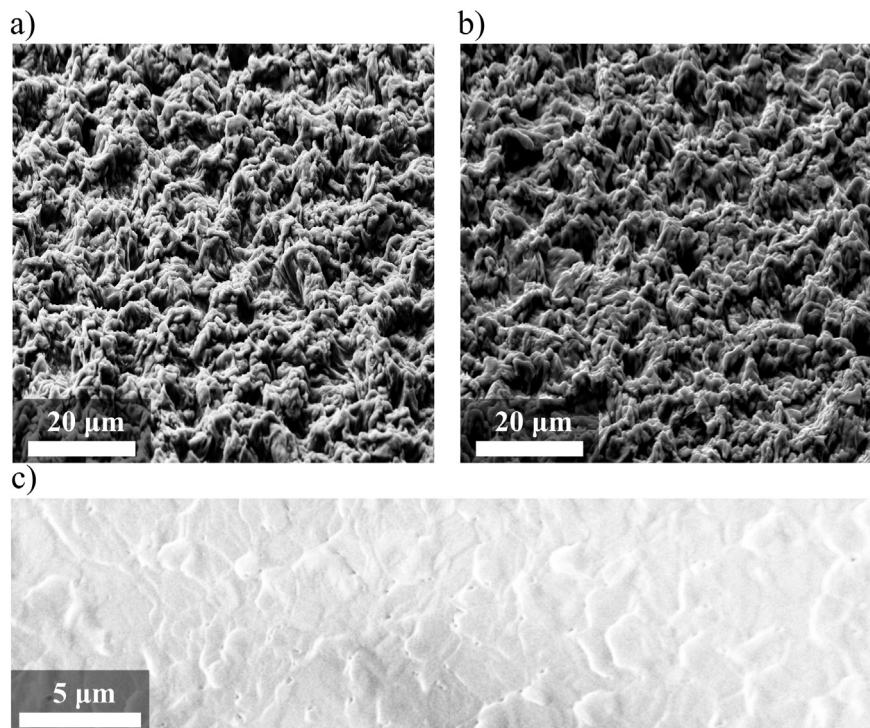
To correlate the evolution of the sheet resistance with the change of the microstructure of Al metallization, a SEM study is performed. The surface of the metallization after thermal cycling can be seen in Fig. 2(a–b). Compared to the initial surface of the metallization, shown in Fig. 2(c), it is clear that the metallization undergoes significant plastic deformation during thermal cycling. To get more detailed information

about the reconstruction, cross-sectional SEM images are obtained and shown in Fig. 3(a–b). For comparison, a typical image for the metallization of an uncycled diode is shown in Fig. 3(c). It can be seen that the metallization degrades dramatically: cracks and cavities protrude into the metallization layer towards the silicon substrate. This decreases the effective cross-section of the film, thus leading to the observed increase in sheet resistance (see Fig. 1). The microstructural evolution for diodes cycled in pure nitrogen shows very similar features and more details can be found in [3,4]. No distinguishable difference in the microstructural evolution between the diodes cycled in ambient atmosphere at RH = 50% and RH = 95% is found.

### 3.3. Texture analysis

An EBSD map displaying the initial microstructure of the surface of Al metallization can be seen in Fig. 4, demonstrating a dominant (111) texture. The grain size distribution of the metallization is presented in Fig. 5. It shows a maximum occurring at approximately  $15 \mu\text{m}^2$ . This corresponds to a mean diameter of  $4.2 \mu\text{m}$  for a circular grain which is slightly larger than the metallization thickness of  $3.4 \mu\text{m}$ . Both the observed grain texture and grain size distribution corresponds well to the typical texture of Al films on Si [9,10,14–16]. EBSD is a highly surface sensitive technique. Therefore, it is not possible to obtain EBSD data of cycled diodes due to the severe surface roughening occurring during cycling. In this regard, XRD can be used as a complementary method for acquiring information about the texture of the metallization as the number of cycles increases.

In Fig. 6 XRD measurements of the metallization before and after cycling are presented. It can be seen that during cycling, the texture changes from a strong (111) orientation towards a more randomly oriented polycrystalline film. The intensity of the (111) peak decreases significantly during cycling in a similar manner both for RH = 50% and RH = 95%, while peaks corresponding to the (200) and (311) crystallographic planes appear and increase in intensity with the number of cycles. When comparing to earlier XRD results for the cycling in nitrogen (see ref. [4]) it can be concluded that the overall tendency of the texture



**Fig. 2.** SEM images of the metallization surface of diodes cycled in ambient atmosphere a) after 93 kilocycles at RH = 95%, b) after 110 kilocycles at RH = 50%, and c) the metallization surface of an uncycled diode.

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