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Correlation between texture and mechanical stress durability of thin aluminum films

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ABSTRACT

In this article, differently textured aluminum (Al) metallizations of surface acoustic wave (SAW) devices have been exposed to cyclic mechanical stress in order to investigate a potential correlation between their texture and their mechanical stress durability. Samples of SAW devices with differently textured Al thin film electrodes have been manufactured, and texture measurements have been carried out on all samples with electron backscatter diffraction. Subsequently, the SAW devices have been operated at heavy electrical load until a defined mechanical fatigue of its Al electrodes occurred. SAW devices with highly textured Al electrodes showed almost 20 times higher power durability than SAW devices with untextured Al electrodes. We show that this increase in electrical power durability has to be fully attributed to the strongly enhanced mechanical stress durability of highly textured Al films. Furthermore, a positive correlation between the Al films' texture and its electrical conductivity has been found.

1. Introduction

Surface acoustic wave (SAW) devices are micro-electromechanical systems and are widely used as passive high-frequency filters in radio-communication circuits [1]. Usually, SAW devices are driven at relatively low electrical load, but power durability of SAW devices become important whenever heavy load requirements are present, e.g., in the transmitting circuit path of a mobile phone. As a result of device miniaturization, the acoustic power density in SAW filters increases, which has a non-negligible, negative influence on their life time. Therefore, for ensuring the required power durability (PD), the development of high power durable metallizations becomes more important.

Although SAW devices are driven electrically, they eventually fail mechanically [2]. Surface acoustic waves introduce heavy cyclic mechanical stress in the device's Al electrodes, which finally leads to the material fatigue thereof. This phenomenon of high-frequency-related mechanical fatigue is often referred as acoustomigration [3]. In this paper, we take advantage of this phenomenon to investigate the fatigue of differently textured SAW metallizations under SAW-induced stress. This allows us finally to draw conclusions about a potential link between the texture and the mechanical stress durability of a thin Al film.

Highly textured thin aluminum films in SAW devices have attracted much interest over recent years due to their high stress durability at ultra high frequencies [4–6]. However, achieving highly textured Al films on piezoelectric single-crystalline substrates such as lithium tantalate ($LiTaO_3$) is unfortunately connected with high purity requirements of the substrate surface.

In this work, we demonstrate that using the liftoff technique for SAW device manufacture can contaminate the substrate surface with photo-resist residues and thus impedes the growth of highly textured Al films if contaminated substrates are metallized. We discover that a contaminated substrate surface can be reconditioned for epitaxial growth of Al by applying pre-cleaning processes. By using different pre-cleaning processes, we create different textures in the deposited Al films and we fabricate SAW devices from differently textured Al films. In a final electrical characterization of the SAW devices, we find a very strong dependency between the device's power durability and the texture of the Al film. Additionally, a positive correlation between the texture and the electrical conductivity has been observed.

2. Experimental details

2.1. Preliminary experiment

Using standard photolithographic technology, a monocrystalline piezoelectric substrate ($LiTaO_3$, 42° Y-X shear wave cut) has been covered all over with photo-resist by spin-on deposition. After drying the resist, the whole sample surface has been exposed to light without

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using any mask. The exposed resist has been stripped off the entire sample surface in a conventional resist developer bath.

As a reference sample, an identical monocrystalline piezoelectric substrate ($LiTaO_3$, 42° Y-X shear wave cut) has been used. The reference sample did not receive any treatment with photo-resist.

In the next step, both samples have been metallized by deposition of 10 nm thin titanium (Ti), which acts as a thin seed layer for the following main metallization comprising of 400 nm pure Al. Metal deposition has been achieved by sequential electron beam evaporation of Ti and Al in an ultra-high vacuum environment.

After sample preparation, electron backscatter diffraction (EBSD) measurements have been carried out on both samples with an EDAX/TSL, OIM Data Collection 5.2 system with a Digiview 1612 camera mounted in a field emission gun scanning electron microscope (JEOL 6700 F). The EBSD measurements have been conducted under the same conditions for all samples. The analyzed area of 20 μm × 20 μm has been scanned with a step width of 100 nm, which results in 40,000 measurement points. Texture homogeneity has been ensured by several measurements at different positions on each wafer.

2.2. Main experiment

Starting from monocrystalline piezoelectric substrates ($LiTaO_3$, 42° Y-X shear wave cut), nine samples have been prepared using standard photolithographic technology. First, photo-resist has been deposited all over the substrates by spin-coating as shown in Fig. 2a. In the second lithographic step, the resist has been exposed to light under a shadowing photo mask enclosing the device pattern. The exposed resist has been removed in a developer bath leaving a structured photo-resist pattern, as indicated in Fig. 2b. A mild pre-cleaning process has been applied to each sample in order to remove suspected photo-resist residues from the trenches, see Fig. 2c. The pre-cleaning processes included plasma cleaning with oxygen, plasma cleaning with sulfur hexafluorid, treatment in ozone atmosphere and combinations of the afore mentioned processes; furthermore, the parameters of these processes have been altered so that finally eight different pre-cleaning processes have been applied—one to each sample and no pre-cleaning process for

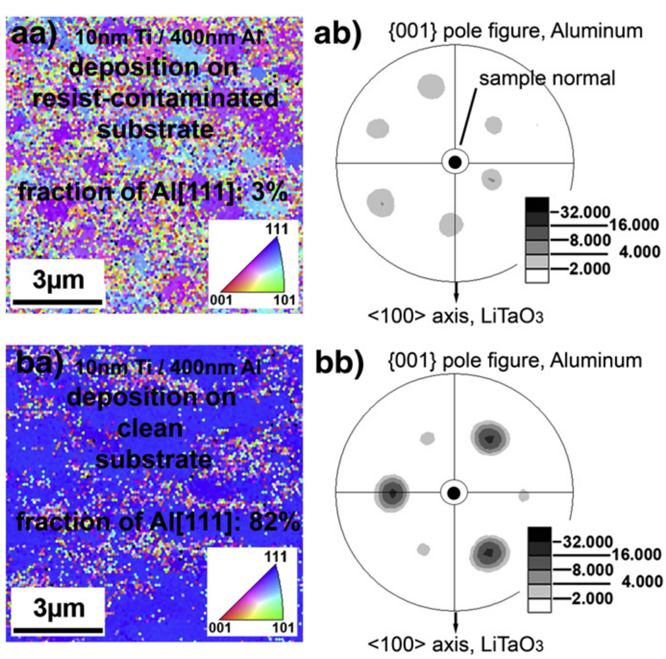

Fig. 1. Above: Grain orientation map (aa) and pole figure (ab) of a thin Al film deposited on a photo-resist contaminated substrate. Grains are mainly randomly oriented and the film's texture is very weak. Below: Grain orientation map (ba) and pole figure (bb) of a thin Al film deposited on a clean substrate. Grains are unidirectional oriented and the film's texture is very strong.

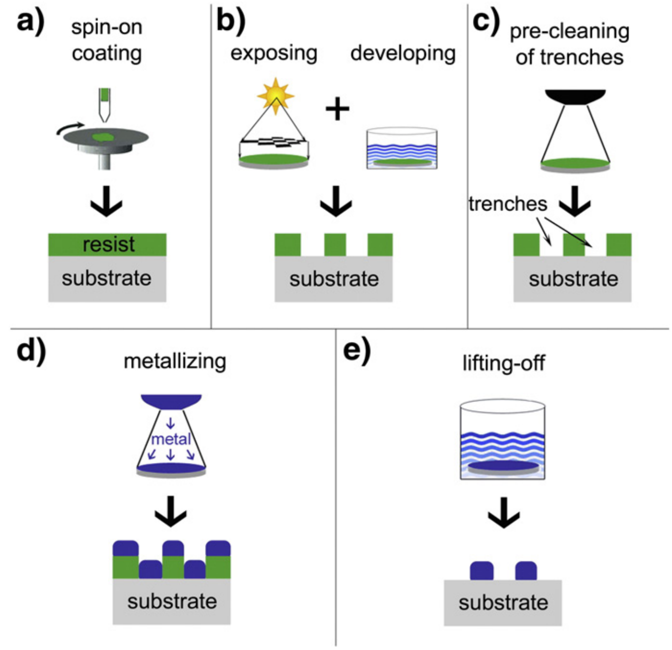

Fig. 2. Manufacture process steps of all SAW devices produced for this work.

reference sample i. In the fourth step, metal deposition has been carried out at 25 °C substrate temperature, employing electron beam evaporation in an ultra-high-vacuum chamber ($p < 10^{-7}$ Pa), see Fig. 2d. First, a seed layer of 10 nm Ti seed layer has been deposited followed by the main metallization comprising of 400 nm pure Al. A quartz microbalance was used to control film thickness during deposition. Device manufacture has been completed by the final liftoff step which removed the remaining resist in an ultrasonic bath with a solvent-based resist stripper. The Al structures remain on the substrate, as displayed in Fig. 2e.

It is noteworthy to mention that all device manufacturing process steps shown in Fig. 2 (excluding the pre-cleaning process step in Fig. 2c) have been carried out in an industrial manufacturing environment, thus guaranteeing maximum reproducibility throughout the whole series of process steps. Devices' variations only originate from different pre-cleaning processes which were conducted in a laboratory environment.

After device manufacture, the texture of the devices' Al metallization has been measured by means of EBSD with the same equipment and parameters as described in the preliminary experiment above.

The power durability of the manufactured SAW devices has been carried out on an ultra-high-frequency measurement setup devised especially for SAW device characterization. The circuit is designed in such a way that the electrical load applied to the device is maintained constant while the device's resonance frequency drops with time due a mechanical fatigue of its Al electrodes. A device has been considered as failed when the resonance frequency had dropped below 0.1 % of its original value, which was 1.0 MHz for our fabricated 1.0 GHz SAW devices. Error deviation of the PD measurement setup is specified ±0.5 dB, thus ensuring a high accuracy of the overall PD characterization [7].

Conductivity of each sample has been determined by measuring the resistance of a meander, which had been fabricated on each sample together with the SAW devices. Because of the high accuracy of the lithographic process steps, the conductivity error deviation of this method is below 0.1 % absolute.

3. Results

Fig. 1 shows the results of EBSD analysis of the preliminary experiment and are depicted in the form of grain orientation maps and pole plots. The out-of-plane texture of the Al film is displayed by grain