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A study for an aluminum electro-thermally actuated U-shaped microtweezer

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Abstract. In this paper we present the investigations of two aluminium layers with different thicknesses in order to be used for manufacturing of MEMS and the design, simulation, fabrication and characterizations of a microtweezer designated for micromanipulation applications. Electro-thermo-mechanical finite-element simulations were performed in order to describe the behaviour of MEMS devices. The microtweezers have been fabricated in aluminium, as structural material, by surface micromachining processes. Different characterizations of the structural material by Atomic Force Microscope (AFM), X-ray Diffraction System (XRD) and Scanning Electron Microscopy (SEM) characterization tools were presented.

1. Introduction

In the last decades the micro-electro-mechanical systems (MEMS) production increased a lot. Silicon, its derivatives and metals have been extensively used as structural materials with high mechanical properties [1-3]. High thermal conductive metals with low costs such as aluminium and copper have been used widely to manufacture micro heaters or MEMS devices [3-4]. Aluminum films and Al alloys are widely used for electronic device applications and include the majority of the interconnections used in the semiconductor chips [5].

Microtweezers, as MEMS devices, provide advantages in terms of compact size and low cost having an extensive role in microassembly and micromanipulation fields for manipulating micromechanical or bio components [6-8]. Different actuation principles, such as shape memory alloys, electrostatic, electro-thermal, electro-magnetic, piezoelectric, pneumatic, were proposed to drive MEMS microtweezers. Electro-thermal microactuators are usual components in microsystems and can be power-driven electrically through Joule heating or optically with a laser.

MEMS devices offer great prospective for vibrational or micromanipulation applications due to their remarkable features like small size, low power consumption, large frequency-quality factor product, low cost production, etc [9]. Investigations and controlling of different uncertainties, occurring in the fabrication process, the geometric and environmental/processing parameters effects on MEMS devices is of significant importance for increasing the production yields and reducing the fabrication costs of different micromachined sensors and actuators [10-12].

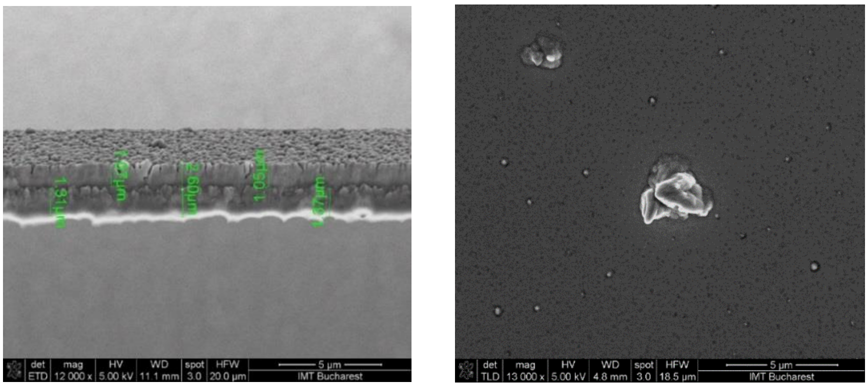
In this work we investigated two aluminium layer with different thicknesses in order to be used as structural materials for the fabrication of a microtweezer based on electro-thermal actuators. A design, simulation and the fabrication process of the microtweezer were presented. Different characterizations of the structural materials and of the fabricated microtweezer were realized.

2. Materials and Characterizations

In this paper two single layers of aluminium were deposited on (100) oriented 4" silicon wafers using E-beam high vacuum thin film deposition system. The layers were deposited with a thickness of 1 µm and with 2 µm, respectively. The physical and tribological properties of the Al films usually depend intensely on their microstructure, which can be characterized using different techniques.

Aluminium layers obtained with different thickness on silicon substrates were analysed by SEM, atomic force microscopy and the X-ray techniques.

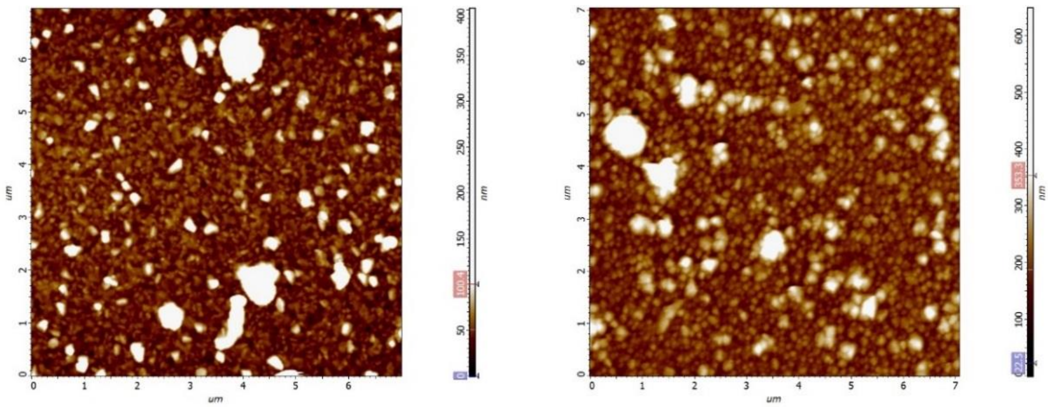
The deposited layers were characterized using SEM by measuring the thickness for each layer and analysing the top surface of the aluminium (Figure 1). The top surface view show some defects of the aluminium layer surface (Figure 1b) due to the deposition process or after processing the structures.



(a) (b)

Figure 1. SEM images of the Al layers after processing: (a) measurements of the thickness for the 2 µm layer; (b) top view of the Al surface with1 µm thickness.

Corresponding characterization of the surface topography were performed using AFM. The surface morphology of the aluminum layers was characterized by an Ntegra Aura Scanning Probe Microscope (NT_MDT Spectrum Instruments) operated in intermittent-contact mode. AFM probes with 9 N/m spring constant and 10 nm nominal radius were used in the measurements. The scanned areas were 7 µm x 7 µm for different location of the samples (Figure 2).



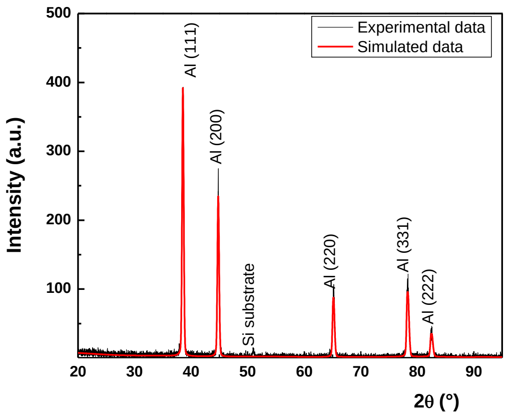
(a) (b)

Figure 2. AFM 2D images for aluminum layers with a thickness of: (a) 1 µm; (b) 2 µm (scanned size 7 µm x 7 µm).

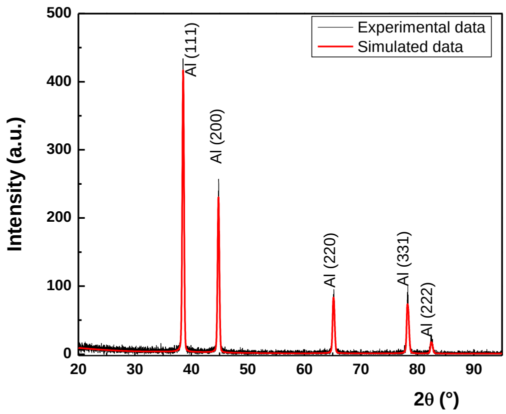
We analized the root mean square (Sq) for each sample. The root mean square increase while the thickness of the layer increase. The root mean square for the aluminum layer with 1 μm thickness is Sq = 25.6 nm, while for the aluminum layer with 2 μm thickness Sq = 57.9 nm.

X-ray diffraction measurements were carried out using 9kW Rigaku SmartLab diffractometer, equipped with CuKα1 source, that provides monochromatic X-rays with wavelength 0.1506 nm. In order to obtain information from layer, it was employed GI-XRD (Grazing Incidence X-ray diffraction) measurements. In this configuration, the source was kept at 0.5°, while the detector position moves from 20 to 95°. The obtained pattern indicates multiple diffraction peaks, such as (111), (200), (220), (331) and (222). According to ICDD database, card number 230-0250, the obtained peaks correspond to aluminium. To gain a deeper understanding of the aluminium microstructure, the experimental X-ray patterns (black curve) were refined using Rietveld procedure (red curves). After fitting, we conclude, on the one hand, that the lattice strain is very small in both cases (e.g. 0.06% for 1 μm and 0.09% for 2 μm, respectively) and on the other hand, the mean crystallite size decreases from 26.1 to 24.7 nm. A decreasing of the mean crystallite size is ascribed with a higher dislocation density and a worse crystallinity. In this context, a different layer thickness is related to different both lattice strain and mean crystallite size.

As the film thickness increases, the (111) peak intensity increases in comparison with the (200) and (220) peaks (Figure 3).



(a)



(b)

Figure 3. (a) Difraction spectra XRD measurements for 1 μm aluminium layer; (b) Difraction spectra XRD measurements for 2 μm aluminium layer.

3. Design and Simulation

As a test structure, a microtweezer was designed based on the U-shape electro-thermal actuators in order to be fabricated using aluminium as structural material with a 2 μm thickness and to study his behaviour in air after actuation. The U-shaped actuator is formed by a traditional pair of a hot arm and a cold arm. The cold arm were designed with holes in order to be easily release over the silicon substrate (Figure 4). The hot arms have a width of 5 μm and the total length of the structure is 580 μm. The initial opening of the free arms is 5 μm. During the actuation the tips of the microtweezer will open in order to grip a micro-object.

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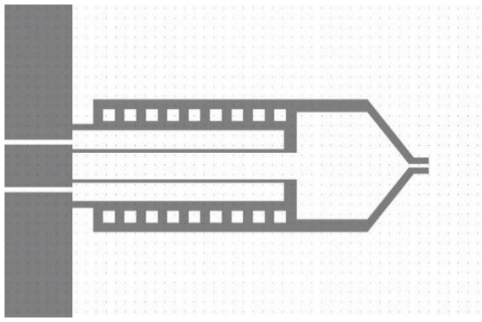
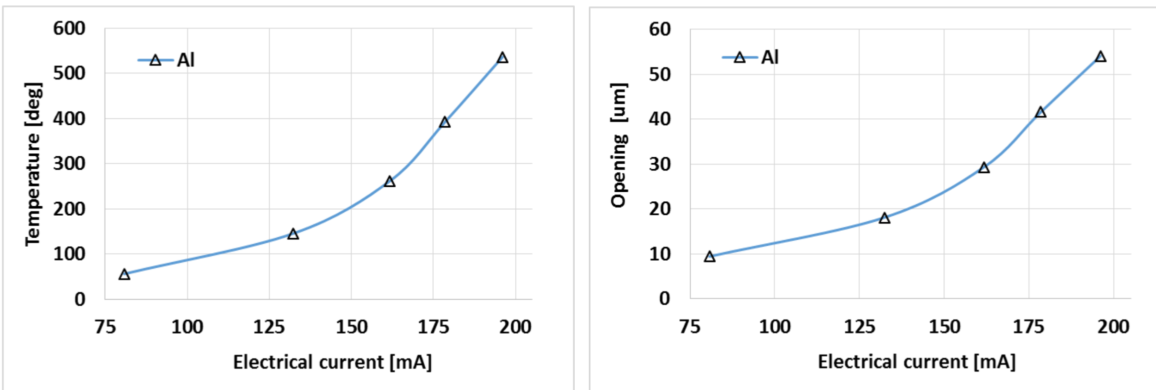


Figure 4. The Al microtweezer design (Coventorware modelling).

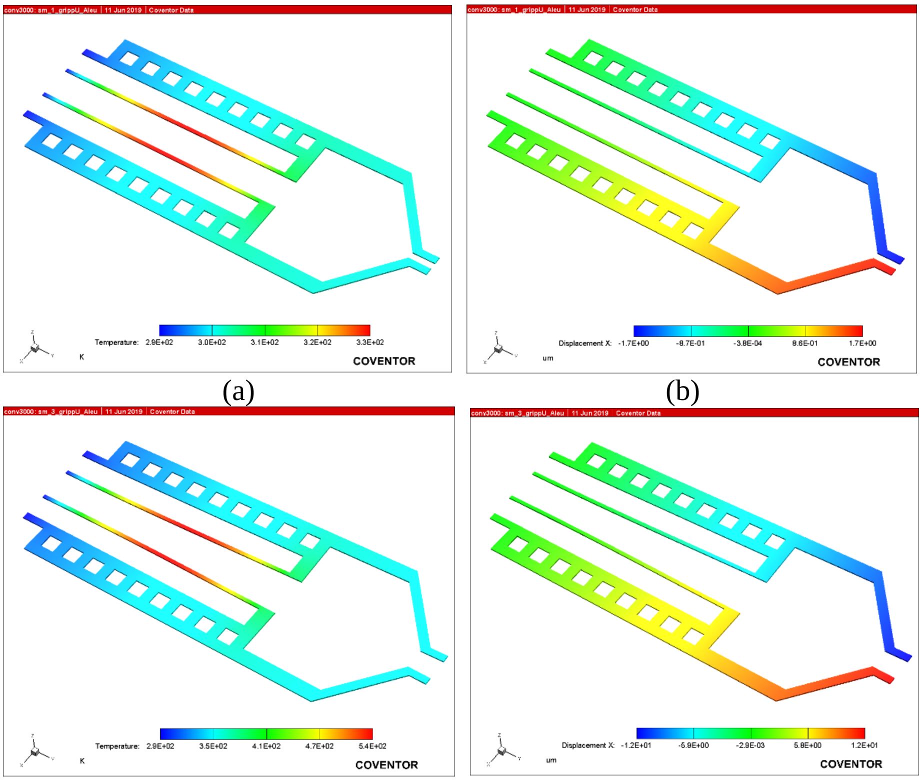
The electro-thermo-mechanical behaviors of the microtweezer in air have been 4hermos4 using the FEM simulations of the software tool CoventorWare. Electro-thermomechanical coupled simulations were performed in order to analyse the temperature and displacement values during the actuation. The boundary conditions of the simulations used for experimental thermal actuator were the following: the initial temperature of the whole structure and the temperature of the environment were considered to be T_0=20°C; the air convection coefficient was set to 3000 W/m^{2}K. For the material properties settings of the Aluminum a Young's modulus of 77 Gpa, a Poisson's ratio of 0.3, a thermal coefficient of expansion of 2.3×10-5 K^{-1} and a thermal conductivity depends on the temperature values were set [13]. The MemMech solver which is dedicated for mechanical and 4hermos-mechanical analyses was used for simulations. The simulated 3D microtweezer model has been meshed using hexahedral elements (Extruded bricks), with 27 nodes/element, which generate accurate results for all solvers of Coventorware program.

Due to the Joule effect the hot less wide arms will be heated and the material will expand then an in plane displacement occurred for free tips. The simulations results show that the structure can operate for an electrical current up to 250 mA and the temperatures vary from 20 to 550°C (Figures 5-6). Considering that the melting point of aluminum is 660°C, the microtweezer can operate with success for a higher electrical current in order to obtain the desired opening. The simulation results show that an opening of 55 μm can be obtained for 197 mA and a maximum temperature in the hot arm of 525 °C.



(a) (b)

Figure 5. Simulation results: (a) The maximum temperatures in the hot arms; (b) The opening of the microtweezer tips (Coventorware simulation).



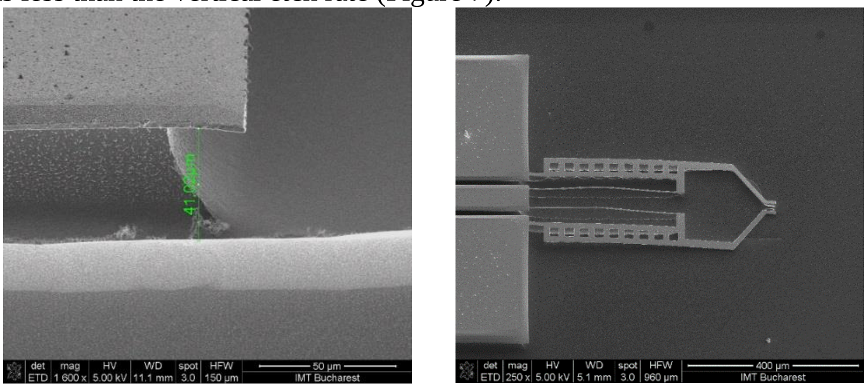
(a) (b)

(c) (d)

Figure 6. Simulation results: (a) Temperature distribution for 80 mA; (b) In-plane displacement for 80 mA; (c) Temperature distribution for 161 mA; (d) In-plane displacement for 161 mA (Coventorware simulation).

4. Fabrication and characterization

Aluminum was chosen for manufacturing also due to its high electric conductivity and mechanical properties. The 2 µm aluminum layer has been deposited directly on the silicon substrate. The microtweezer configuration was obtained using a photolithographic mask. A wet isotropic etching of the aluminum was realized in order to obtain the chosen layout. The release of the arms has been done using dry etching (RIE) of the silicone substrate. Isotropic etching of silicon was performed on a RIE system (Sentech Instruments GmbH, Germany), using SF6 gas. A SEM characterization shows that the lateral etch rate was less than the vertical etch rate (Figure 7).



(a) (b)

Figure 7. SEM images of the released microtweezer: (a) detail with the Al pad; (b) the Al released structure.

The gap obtained after releasing was around 41 μm (Figure 7a) and a stress in the whole structure were observed (Figure 7b).

5. Conclusions

Atomic Force Microscope (AFM), X-ray Diffraction System (XRD) and Scanning Electron Microscopy (SEM) characterizations of the aluminium structural materials with 1 μm and 2 μm thicknesses were presented.

A microtweezer design based U-shaped actuators was proposed as test structure. The simulations, fabrication and characterization of the structure were realised, using 2 μm aluminum thickness. The simulation results show an opening of the microtweezer tips of 55 μm for 197 mA and a maximum temperature in the hot arm of 525 ^{o}C.

In order to improve the device performance, a further thermal treatment will be performed for the aluminum structural layer in order to reduce the stress and a careful settings of the material deposition parameters will be analysed and improved to reduce the defects of the Al surface and to reduce the stress also.

Acknowledgments

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