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Electromigration-formed Al micromaterials regulated by discharge hole shape

YEBO LU*
Mechanical and Electrical Engineering College, Jiaxing University, 118 Jiahang Road, Jiaxing 314001,
Zhejiang Province, PR China

A technique for forming differently shaped Al micromaterials, based on electromigration through discharge holes has been developed. A passivated polycrystalline Al line with a discharge hole at the anode end provides the means to fabricate Al micromaterials fabrication with well-determined shape profiles. The cross-sectional profile corresponds to that of the discharge hole, and its area on the size of the hole needs to be confined to a suitable range because of temperature requirements and limitations from etching technique.

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1. Introduction

Metallic micro/nanomaterials (MNMs) have attracted much attention because of their unusual electrical, optical, mechanical, and thermal properties compared with conventional metals [1]. Metallic MNMs are widely used as functional components in microelectromechanical systems and micromachines. In particular, aluminium (Al) MNMs are of great importance because of their advantages in lithographic processing and low cost [2]. Thus far, various approaches have been reported for forming Al MNMs. Suzuki et al. [3] have reported the growth of Al whiskers by glancing angle deposition at high temperatures; however, this technique can only be used under restricted experimental conditions. Blech et al. [4] reported nanowire growth from Al films covered with a TiN film. Lee et al. [5] reported that Al nanowires were formed through stress migration. These techniques are somewhat inefficient when used to fabricate Al micromaterials comprising a large number of atoms. On the other hand, some specific techniques such as focused-ion-beam (FIB) and fast-atom-beam (FAB) etching can fulfil requirements for fabricating fine structures but these techniques are extremely time-consuming and costly. In our research, Al micromaterials are fabricated using electromigration (EM) based on discharging atoms through discharge holes of controlled shape and size.

EM is a physical phenomenon in which metallic atoms are transported as a result of electron wind. This phenomenon is on the one hand a significant problem in integrated circuits affecting contacts, but on the other hand, can be used to generate compressive stress release exploited in growing whiskers. Al MNMs, including thin wires and micro-spheres, have been fabricated successfully at predetermined positions by using EM [6-–8].

In this paper, we describe an EM technique based on discharging atoms through controlled holes for forming differently shaped Al micromaterials, including Al thin wires, micro-belts, and split micro-tubes. Both shape and area of the discharge hole influence Al MNM fabrication. The growth mechanism was characterised and we found that the size of the hole needs to be controlled to avoid line failure and to fulfil etching technique requirements.

2. Experimental procedure

The test structure used to fabricate the Al micromaterials is similar to that described in our previous papers [9, 10]. The sample was a passivated polycrystalline Al line with a slit and a discharge hole at the anode end of the line. Three sample types labelled Samples I, II, and III were used. Sample I (see field emission scanning electron microscopy (FE-SEM) image in Fig. 1) was prepared from a 290 μm thick Si wafer that was oxidized to form a 300 nm thick SiO_2 layer, on which a 300 nm thick TiN layer was then deposited by vacuum sputtering. Following this, a 600 nm thick Al film was deposited on the TiN layer by vacuum evaporation. The Al and TiN layers were patterned by wet etching and FAB etching, and the Al at the anode end of the line was etched to form a slit. Subsequently, a 3 μm thick film of SiO_2 was deposited on the surface of the sample by plasma-enhanced chemical vapour deposition (PE-CVD) using tetraethyl orthosilicate (TEOS) as a source. The SiO_2 film was then wet etched to expose pads for supplying the current. Finally, a U-shaped discharge hole was created in the passivation film by FIB etching. Samples II and III were prepared with rectangular and circular holes, respectively, etched at the anode end.

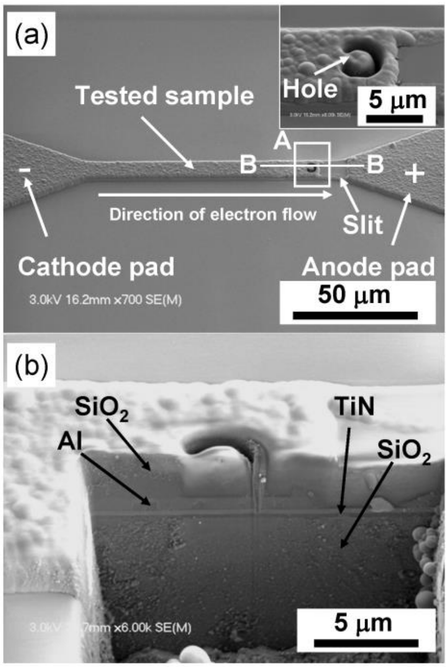

Fig. 1. (a) FE-SEM micrograph of Sample I with a hole and a slit at the anode end. The inset shows a magnified view of part A. (b) Cross section at line B-B showing the structure of Sample I.

All samples were placed on a ceramic heater, set at 613 K under atmospheric pressure, and supplied with a constant direct current using a pair of probes in contact with the input and output pads. During the experiment, the current density was set at 2.4 MA/cm^2. While current was supplied, the potential drop along the Al line was measured between the input and output pads. After reaching a specific current threshold, the potential drop increased with time because of the continuous accumulation and discharge of atoms. The rate of increase become rapid because of geometrical changes resulting from the loss of many atoms from the Al film, at which time the current supply was cut to protect the sample from Joule-heated breakdown. The time interval determined from when the current supply was cut was deemed to be the time to failure of the line.

3. Results and discussion

The experimental results were confirmed to show repeatability. The FE-SEM image of Sample I after current supply (Fig. 2(a)) shows that a split micro-tube of length 13.75 µm and diameter of about 3 µm had formed. The potential drop (Fig. 2(b)) increased slowly indicating Al atoms were steadily discharged from the hole. In contrast, a micro-belt and a thin wire were formed in Samples II and III, respectively (see FE-SEM images in Fig. 3; the insets show the holes before testing).

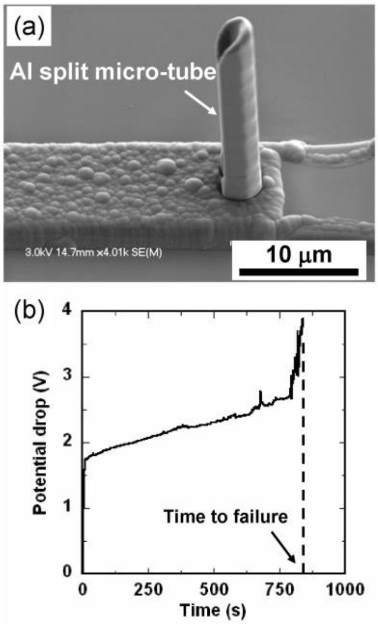

Fig. 2. (a) FE-SEM micrograph of Sample I after current supply. (b) The rise in potential drop against the current supply time.

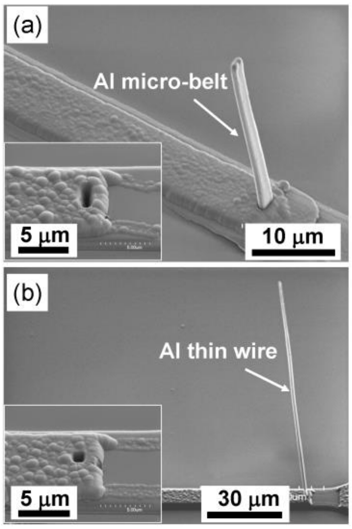

Fig. 3. FE-SEM micrographs of a micro-belt (a) and a thin wire (b) formed in Samples II and III after current supply. The insets show the rectangular and circular holes before current supply.

4. Discussions

Let us consider the mechanism for the formation of Al micromaterials by utilizing EM. While under current stress, Al atoms are transported along the grain boundaries from cathode to anode as a result of the electron wind. At the anode end, the accumulation of Al atoms leads to the development of a compressive stress. The presence of the slit caused the compressive stress, which was developed rapidly beneath the discharge hole. As a result of this rapid development, Al atoms are pushed out through the hole to form the Al micromaterials.

Under similar experimental conditions, the shape of the Al micromaterials formed corresponded to the shape of the discharge hole. By measuring its diameter and length, the volume of the split micro-tube in Sample I was calculated to be 43.2 μm^3. In the same way, the volumes of the micro-belt and the thin wire were 35.6 μm^3 and 42.5 μm^3, respectively. The three volumes correlate well indicating that we can reliably control the shape attributes of the discharge hole to form differently shaped micromaterials.

The discharge resistance decreased when the area of the discharge hole was increased, leading to a higher discharge rate of Al atoms. Accordingly, the atom-discharge time decreased. Moreover, the formation of Al micromaterials was affected by Joule heating and thermal energy losses at the anode end (see Ref. [11] for details of atom discharge). Thermal energy losses decreases as atom-discharge times decrease; therefore, the temperature at the anode end increased, resulting in line failure. Thus, the area of the discharge hole needs to be below a critical value. The FIB etching technique is an enabling technology in micro/nano-milling application, however, it is extremely difficult and high costly to create a nano-sized discharge hole. Consequently, the size of the discharge hole is confined within a restricted range.

The present technique forms different shaped Al micromaterials at predetermined positions through shape-regulated discharge holes. Widths of the Al micromaterials can be readily controlled, and the length depends on the current supply time. Other shaped micromaterials are envisaged for potential applications in micro electromechanical systems.

5. Conclusions

Based on controlling discharge hole shape, differently shaped Al micromaterials, such as Al thin wires, micro-belts, and split micro-tubes have been successfully fabricated by EM. The technique is expected to be an effective approach for forming Al micromaterials of simple shapes that are well determined by the shape and area of the discharge hole. For the present, etching of the different discharge holes restricts the size to a limited range.

Acknowledgments

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*Corresponding author: luyebo@mail.zjxu.edu.cn