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Controlling Fabrication of Aluminum Micromaterials by Electromigration Using a Thin-film Line with a Sudden Change in Geometrical Shape

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ABSTRACT:

Aluminum microspheres were fabricated by electromigration using a sample with sudden change in geometrical shape, where a hole in the transitional area was used to guide the formation of micromaterials. By performing electrical heating experiments, effects of several controlling factors including current density, current stressing time, temperature, and the size of guiding hole were explored. It was found that there is an optimal range of current density and temperature for fabricating Al micromaterials. Furthermore, good balance between the discharging rate of atoms through the hole and cooling rate was identified by changing the size of the hole can make the growth of Al microsphere.

***Keywords**: Electromigration, Fabrication, Discharge, Adhesion, Thin film.*

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I. Introduction

Micro/nanomaterials (MNMs) are essential functional elements in micro-electromechanical systems (MEMS), nano-electromechanical systems (NEMS), and other devices. The MNMs, such as micro-belts [1], microspheres [2], nanorods [3], nanotubes [4], nanobelts [5], nanowires [6] possess interesting mechanical, electrical, optical and thermal properties, which are different from those encountered in bulk materials. The mechanical, electrical, optical and thermal properties of MNMs are attractive properties with wide applications. Among these MNMs, microspheres, microwires, etc. are of both scientific and technological interests. For example, microspheres have extensive applications in catalysis [7], electron-detector [8], leather technology [9], luminescence technology [10], to name a few. Also, microwires have important potential applications [11-12] of communications, solar cell, sensing, lasers, biology, and chemistry.

To date, several bottom-up approaches [13-15] have been developed for fabricating micro-materials. Among them, electromigration (EM) based on physical phenomenon of atomic diffusion have gained special interests from researchers [16, 17]. EM is known as phenomenon where metallic atoms can be transported by electron wind due to high current density and high temperature in the metal line sample**.** Several Aluminum (Al) micromaterials including microsphere [18, 19], micro-belt [20], microwires [21-23] have been successfully fabricated by introducing an artificial slit into an Al thin-film line to promote the effective atomic accumulation. Also a way of simplifying the processes for preparing the sample has recently been reported [24]; where conductive passivation helps to omit processes such as creating the slit to accumulate the atoms and etching pad to apply the current [24]. Another approach for simplifying the processes is the use of sudden geometrical change has also been previously examined [25].

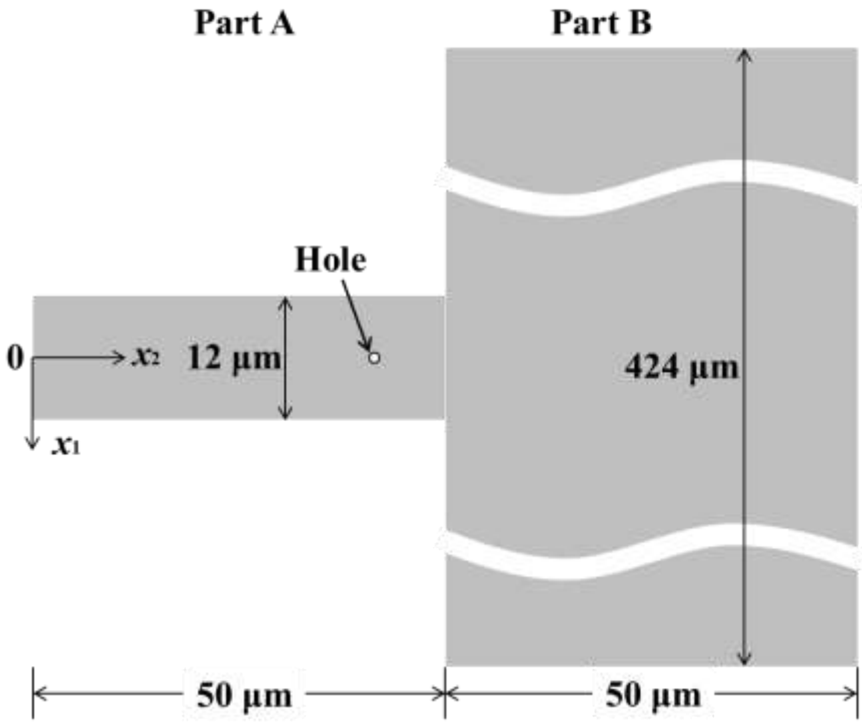
This study involved electrical heating experiments performed using a passivated Al thin-film line with sudden geometrical change to investigate the fabrication of Al micromaterials by EM. An artificial slit was introduced into the Al layer by etching at the anode end of the experimental sample that was used for forming metallic MNMs utilizing EM [19-23]. However, introducing the artificial slit into the metal sample is a long process which consumes more chemicals, time and it is not cost effective. Therefore, a sample structure with fewer steps in the fabrication process without an artificial slit was used.

A sample structure with sudden change in geometrical shape was proposed for forming micro/nano metallic materials [25, 26]. In the present paper, a technique using the sudden change in the geometrical shape of an Al line was introduced for the effective accumulation of atoms and, therefore, fabrication of microsphere by EM. This paper proposes an improved approach by adding several additional controlling factors including current density, temperature, current stressing time, and sample size were investigated. The experimental results are explained in the discussion.

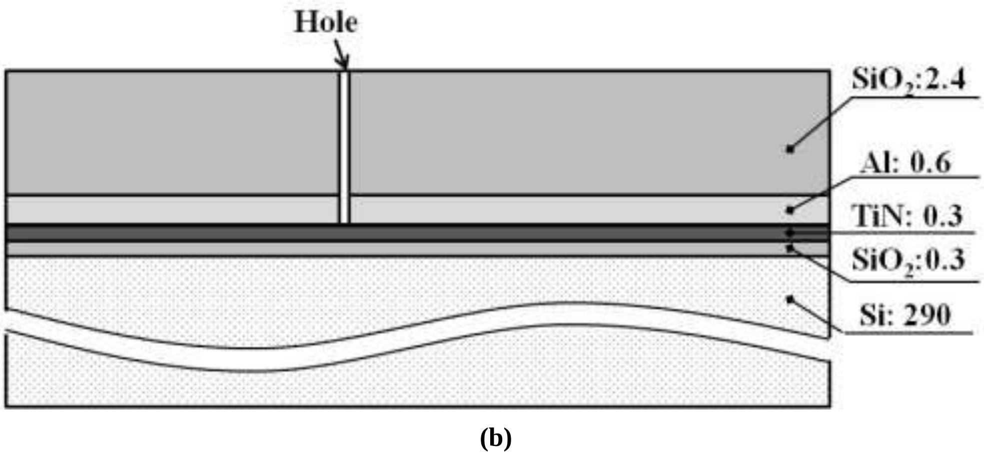
II. Experimental Methods

A schematic illustration of the sample structure used in the present work is shown in Fig. 1(a). The test sample fabrication process is summarized as follows. First, a Si substrate with a thickness of 290 μm was thermally oxidized to form a 0.3 μm thick SiO_2 layer on the surface. Then, a 0.3 μm thick titanium nitride (TiN) layer was sputtered onto the SiO_2 layer; this TiN plays several important roles, including preventing the atomic migration of Al toward the Si wafer and providing a bypass for current in case an electrical shortcut is induced by the growth of voids due to EM. Subsequently, a 0.6-μm-thick Al film was deposited on the TiN layer by vacuum evaporation using an Al source of 99% purity (2N). The Al and TiN layers were then patterned by wet etching and fast atom beam (FAB) etching, respectively, to obtain an ideal sample structure with a sudden change in geometrical shape as shown in Fig. 1. Then, a 2.4 μm SiO_2 film was deposited over the Al surface by plasma-enhanced chemical vapor deposition (PE-CVD); this film acted as a passivation layer to provide sufficient compressive stress. It is noted that both ends of the SiO_2 film were subsequently wet etched to expose the Al layer and thereby provide electrical pads for current stressing. Finally, a circular hole was etched by focused ion beam (FIB) to control the discharge of accumulated Al atoms. The omission of these steps makes the present technique time-saving and cost-effective. The cross section of the sample is schematically illustrated in Fig. 1(b).

Length of the metal line was 100 μm. Width of Part A and B of the sample were 12 μm and 424 μm respectively, where the thickness remained homogenous all through the metal line.



(a)



(b)

Figure 1: Schematic illustration of (a) sample structure with sudden change in geometrical shape, and (b) cross-sectional view of the sample.

The sample was placed on a ceramic heater under atmospheric conditions, and a constant temperature was maintained during the whole experiment. The samples were then subjected to a direct current flow using a pair of probes in contact with the input and output pads. Figure 2 shows the experimental set-up for applying current to produce MMNs. A constant DC current was applied via a voltmeter, a galvanometer, and the probes. The temperature, T_s of the ceramic heater was kept at 613 K, and the current density was ranging from 7.5 MA/cm^2 to 10 MA/cm^2 for all samples. The current stressing time was varied from 240 s to 3000 s. The field emission scanning electron microscope (FE-SEM) image of experimental sample with a hole at specific position is shown in Fig. 3.

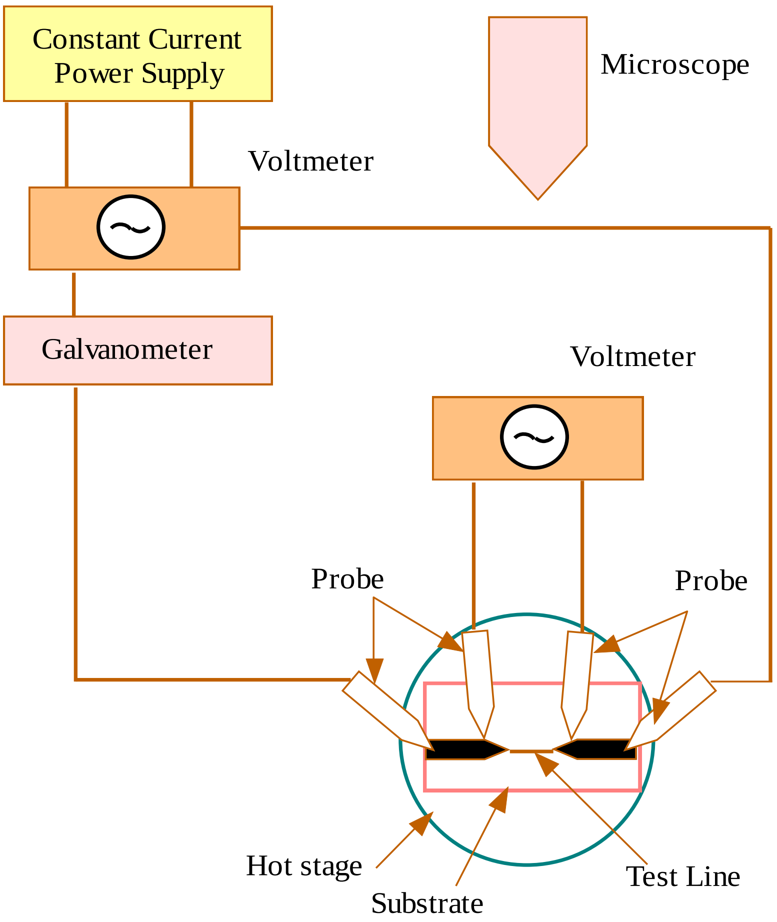


Figure 2: Experimental set-up. The set-up consisted of ceramic heater, voltmeter, galvanometer, probes, microscope, and monitor.

III. Results and discussion

The experimental conditions and obtained results are shown in Tables I. Several images of the typical features after the passage of current, obtained by field emission scanning electron microscope (FE-SEM), are shown in Fig. 4.

Table I: Experimental conditions and summary of results (substrate temperature 613 K)

Sample	Substrate temperature, T_s (K)	Current density, j (MA/cm^2)	Current stressing time (s)	Formed structure	Diameter of microspheres (μm)
a	613	7.5	840	Small micro sphere/sphere goes outside of the sample	4.37
b	613	7.5	3000	Crack/spheres were formed outside of the sample	6.89
c	613	9.17	1200	Large microsphere	8.33
d	613	10	240	Melting	-

A small microsphere formed and a microsphere discharged from the fracture area and went outside which is shown in the sample a (Fig. 4(a)). Cracks and several microspheres/hillocks discharged from the fracture area were observed in sample b (Fig. 4(b)). On the other hand, a large microsphere was formed with a diameter of 8.33 μm which is shown in sample c (Fig. 4(c)). It was observed that the narrow part of the sample was completely melted when the current density was increased to 10.00 MA/cm^2 shown in sample d (Fig. 4(d)).

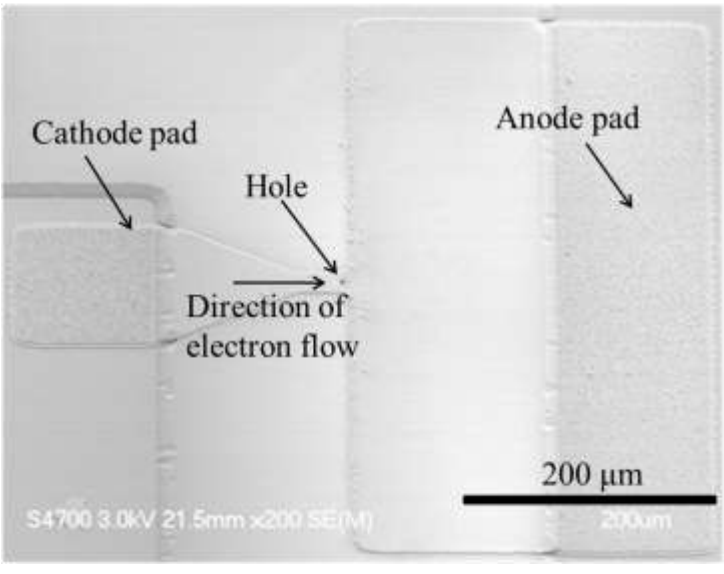
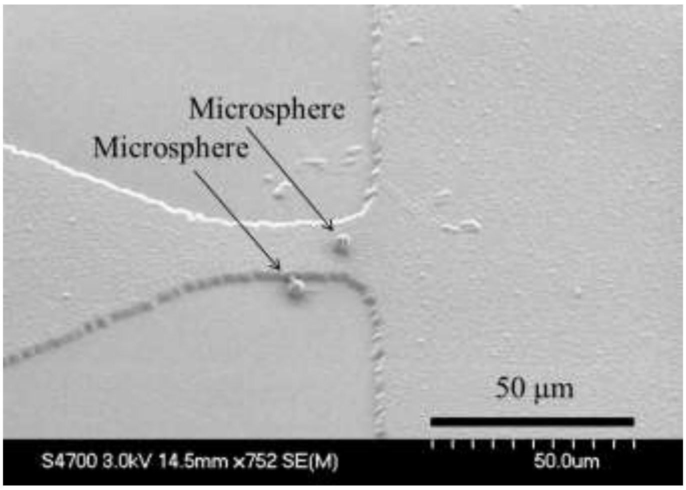
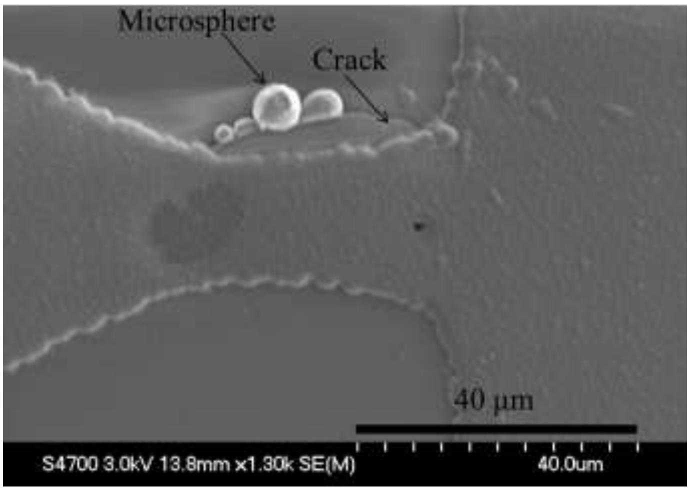


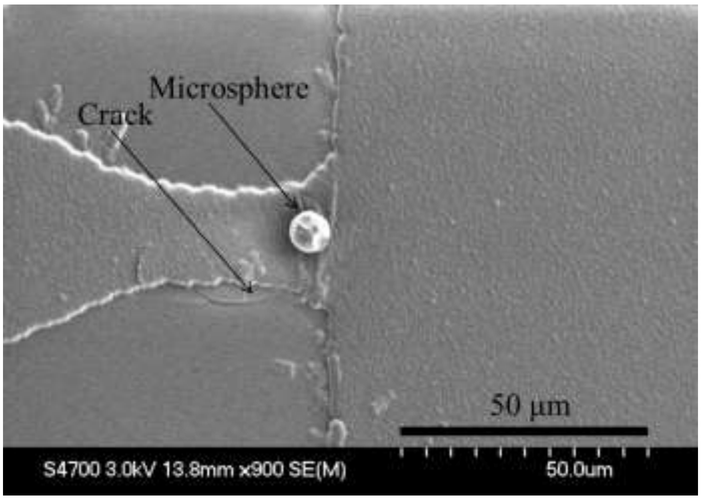
Figure 3: FE-SEM images of experimental sample with a hole at specific position.


Microsphere
Microsphere
50 μm
S4700 3.0kV 14.5mm x752 SE(M)
50.0um

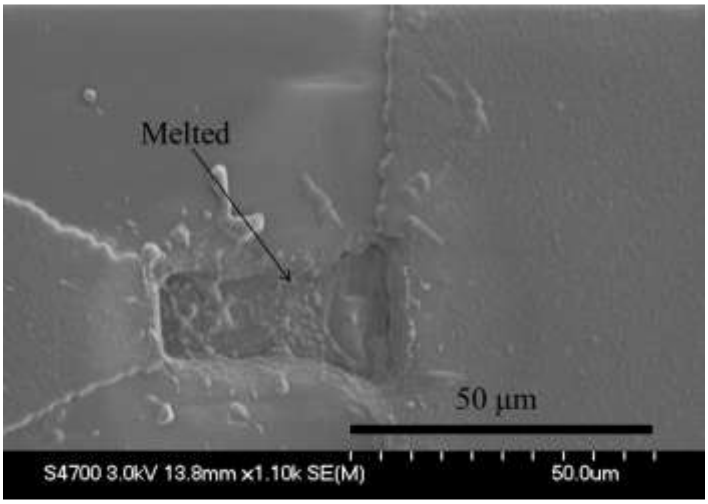
(a)


Microsphere
Crack
40 μm
S4700 3.0kV 13.8mm x1.30k SE(M)
40.0um

(b)


Microsphere
Crack
50 μm
S4700 3.0kV 13.8mm x900 SE(M)
50.0um

(c)



(d)

Figure 4: FE-SEM images of the samples a-d after current stressing in thin film with sudden change in geometrical shape of specimen. (a) A small microsphere was formed and a microsphere discharged from the fracture area and goes outside in sample a. (b) Cracks and several microspheres/hillocks discharged from the fracture area was observed in sample b. (c) A large microsphere and cracks were formed in sample c. (d) The narrow part of the sample was completely melted when the current density was increased to 10.00 MA/cm^2 in sample d.

Electromigration (EM) is a physical phenomenon wherein atoms are transported by an electron wind. The number of atoms is transported depends on the current density, temperature and the structure of the metal line [27-28]. Actually, atomic flux along the electron flow direction in the small region around the predefined hole could be very important to enhance the accumulation of atoms in the Al line with the sudden change in geometrical shape. The atomic flux due to EM, **J**, can be described from Huntington and Grone equation [1]:

$$\mathbf{J} = \frac{ND_0}{kT}\exp\left(-\frac{Q}{kT}\right)Z^* e\rho\mathbf{j} \quad (1)$$

where, N is the atomic density, D_0 is the pre factor, k the Boltzmann constant, T stands for the absolute temperature, Q represents the activation energy, Z^* is the effective valence, e is the electronic charge, ρ is the electrical resistivity and the symbol **j** represents the current density.

The significant increase in the atomic flux, **J** of the Al material due to EM is evidence that a sample with sudden change in geometrical shape has a significant effect on the experiments. In addition, the temperature, T also has an impressive effect on atomic flux, **J**, which will increase following an exponential function based on − (1/T) according to Eq. (1). However, as given in Eq. (1), the atomic flux, **J** increases with the increasing current density, **j** and also increasing the temperature, T monolithically along the electron flow direction in the small region, which is in Part A on the sample with sudden change in geometrical shape. Obviously, current density is higher in Part A than that at Part B according to the sample structure. Therefore, more atoms are accumulated and discharged in the narrow part of the geometrical transition and finally, microspheres were formed.

As shown in Table I, at a substrate temperature of 613 K, when the current density increased from 7.5 MA/cm^2 to 9.17 MA/cm^2, the diameter of the fabricated microsphere changed from 4.37 μm (Fig. 4(a)) to 8.33 μm (Fig. 4(c)). It can be explained as follow. A pressure is created and increased with continuous accumulation of atoms at the transitional area. When the pressure is larger than the discharged resistance, accumulated atoms will be pushed out through the hole, resulting in the formation of microspheres.

However, it should be noted that not all samples generated microspheres at the predefined hole. Instead of microspheres being generated at the predefined hole, cracks or cracks and the microspheres/hillocks discharged from the fracture area were also observed near the transitional area around some samples (Fig. 4(b)). It is believed that the poor adhesion between the passivation layer (SiO_2) and the substrate adjacent to the Al line during sample preparation played the key role in this deviation [27]. It is hypothesized that there was a critical tensile stress fracture of the interface between the passivation SiO_2 layer and the substrate adjacent to Al line. Poor adhesion will decrease the critical value. Once the critical stress decreased, the pressure induced by the accumulated atoms destroyed the adhesion, and cracks happened. Therefore, good adhesion between the passivation layer and the substrate is also one important factor to fabricate the micro materials using the present sample structure.

When the current density was increased up to 10 MA/cm^2 and higher, the narrow part of the sample was completely melted (Fig. 4(d)). It is believed that the corresponding temperature of the Al should be higher than its melting point (934 K) because of the combination of substrate temperature and Joule heating. Therefore, the combination of higher current density, temperature, smaller hole and current stressing time enable microsphere fabrication.

IV. Conclusions

In this work, Al microspheres were fabricated by introducing a sudden change of geometrical shape at the predefined location near the geometrical transition of Al line sample. Instead of microsphere at the predefined hole, cracks, or cracks and microspheres discharged from the fracture area were observed near the transitional area. In addition, microspheres were completely fabricated by controlling the specific temperature at the effect of the hole diameter of the Al line sample. However, when the current density started to increase higher level, the narrow part of the sample was completely melted. The combination of current density, temperature, current stressing time and sample size has to be suitable conditions for fabricating largest microspheres.

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