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Fabrication of Al Thin Wire by Utilizing Electromigration Using a Sample with Sudden Change in Geometrical Shape

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Abstract
The fabrication of electromigration induced thin wire in passivated aluminum films was investigated. The experimental sample with sudden change in geometrical shape was a passivated polycrystalline Al line formed on a TiN layer and covered with a SiO_2 passivation layer. A hole through the oxide and Al layer at the transitional area of the line was used to control the accumulation process. The growth of the thin wire is affected by high temperature at the sudden change of geometrical shape in the metal line. Temperature distribution near the center of the specific sample was obtained which affects electromigration.

Keywords: *Electromigration, Aluminum, Thin/Micro Wire, Accumulation, Temperature*

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I. Introduction

Metallic micro and nano materials (MNMs) are used as functional elements in micro electromechanical systems (MEMS) and nano electromechanical systems (NEMS). The top-down approach uses traditional methods to guide the synthesis of nanoscale materials. The top-down approach, such as conventional deposition, photolithography and etched processes, has some limitations to synthesize the micro and nano materials. Due to limitations, imperfection of surface structures and surface defects occur. On the other hand, bottom-up approaches such as vapour–liquid–solid mechanism [1], electrochemical deposition [2] and template-based synthesis [3] based on techniques to control atoms and molecules, are now commonly used for making micro and nanostructures. In the bottom-up technology two types of growth techniques are well known, i.e., chemical and physical methods. There are some other uses physical phenomenon approaches, such as electromigration [4, 5] and stress migration [6, 7].

Elecrtromigration (EM) is very important techniques for fabricating MNMs. EM is a physical phenomenon whereby metallic atoms are transported by the electron wind. It is a serious problem in integrated circuits because of the appearance of hillocks and voids leading to short circuits and open circuits, respectively. On the other hand, it can be used intentionally to generate a compressive stress-release phenomenon due to atom accumulation to grow micro materials. Various MNMs, such as nanotubes [8], nanowires [9], micro-spheres [10], micro-belts [11], etc. have been studied and synthesized. An artificial slit was introduced into the Al layer by etching at the anode end of the sample structure. Therefore, a slit in the Al film and a hole through the oxide were used to control the accumulation of atoms. However, various MNMs such as micro-wire [12], micro-belt [13], micro-tube [14 and micro-sphere [15] have been successfully fabricated by introducing an artificial slit at the anode end of an Al line to promote atomic accumulation and discharge processes by utilizing EM. However, the introduction of a slit by wet etching is quite time-consuming and also costly. Therefore, a sample structure with sudden change in area without any slit in the fabrication process is considered for fabricating micro materials.

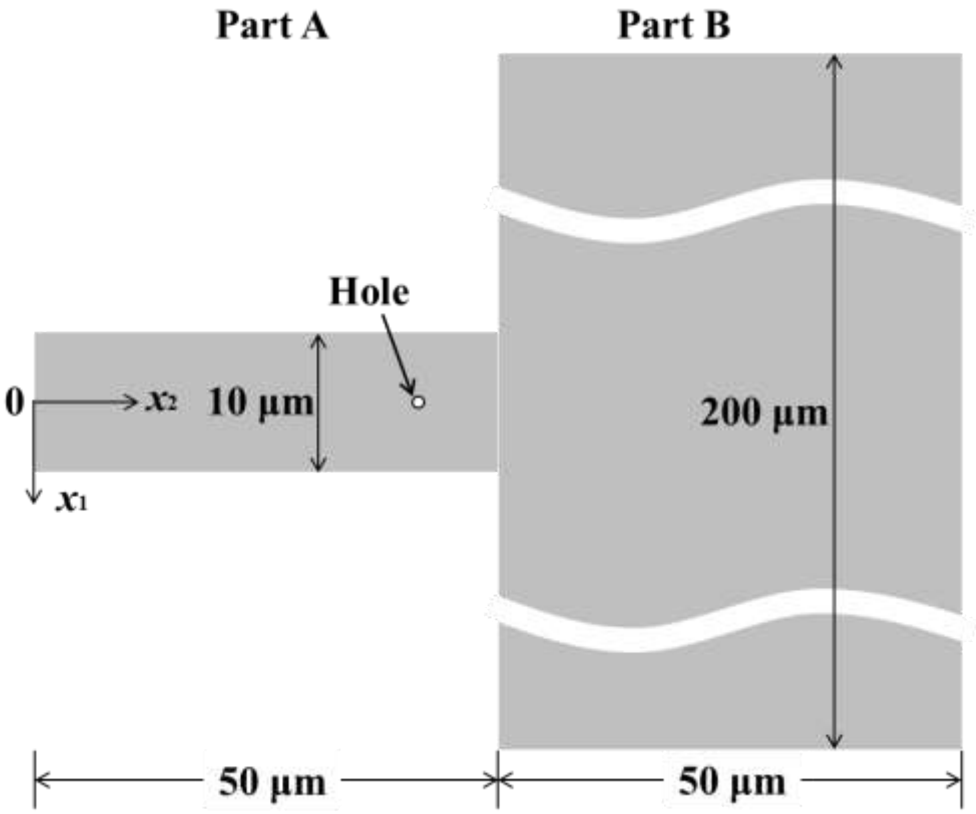
The new findings are reported on using a sudden change in geometrical shape of a sample based on the use of EM [16-18]. In the present research, a technique of generating metallic metal of thin wire has been fabricated by utilizing EM. The control of temperature distribution along the metal line is done by using the sudden change in the geometrical shape of the sample. Effect of atomic flux, temperature and current density has been discussed along the sample structure at the predefined area using finite element method (FEM).

II. Experimental procedure

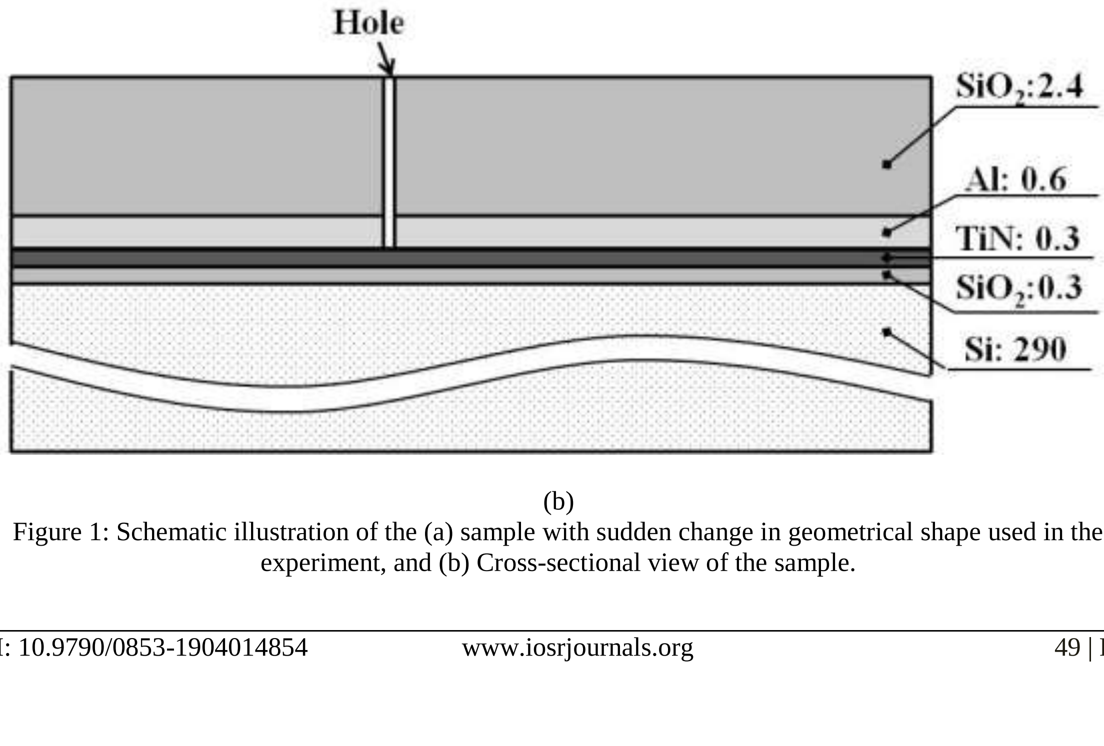
A schematic illustration of the sample with sudden change in geometrical shape used in the present work is shown in Fig. 1(a). The test sample was fabricated as follows. A 290 µm thick Si wafer was oxidized to form a 300 nm thick SiO_2 layer, and then a 300 nm thick titanium nitride (TiN) layer was deposited on the SiO_2 layer by sputtering. After that, a 600 nm Al film was deposited on the TiN layer by vacuum evaporation.

Following this, the Al and TiN layers were patterned by wet etching and fast atom beam (FAB) etching, respectively. Then a 2.4 μm thick SiO_2 film was deposited on the surface of the sample by plasma-enhanced chemical vapor deposition (PE-CVD) using tetraethyl orthosilicate (TEOS) as a source. Subsequently, the SiO_2 film was wet etched to expose the pads to current supply. Finally, a 2 μm diameter hole was etched by focused ion beam (FIB) etching. It was confirmed by the end-point detection that the hole would be etched at the Al/TiN interface. 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 10 μm and 200 μm respectively, where the thickness remained homogenous all through the metal line.



(a)



(b)

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

The sample was placed on a ceramic heater under atmospheric conditions, and a constant temperature (i.e., 613 K) was maintained during the whole experiment. The samples were then subjected to a constant direct current flow using a pair of probes in contact with the input and output pads. Figure 2 shows the experimental-setup used for applying direct current to produce MNMs. Therefore, during the experiment, current flowed from anode to cathode, and electrons, *e*-, flowed in the opposite direction of current making the mass transport of metal atoms. A constant dc current was applied via a voltmeter, a galvanometer, and the probes. The sample surface was examined by using field emission-scanning electron microscopy (FE-SEM), which is shown in Fig. 3.

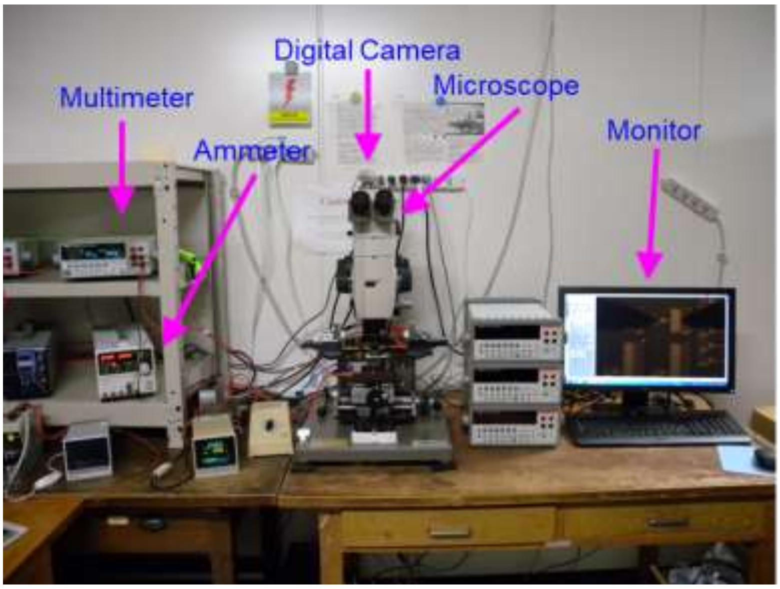


Figure 2: Experimental setup. This set-up consists of ceramic heater, voltmeter, galvanometer, probes, microscope, and monitor.

III. Results and discussion

The structural dimensions of the sample S was used in this study are shown in Table I. The experimental results obtained for each condition are shown in Table II. Field emission scanning electron microscope (FE-SEM) images of sample a are shown in Fig. 4.

Table I: Dimensions of the samples

Sample type	Structural dimensions (μm)			Hole diameter (μm)
	Width of Part A	Width of Part B	Length	
S	10	200	100	2

Table II: Experimental conditions and results

Condition	Substrate temperature T_s (K)	Current density j (MA/cm^2)	Current stressing time t (s)	Formed structure	Length of micro/thin wire (μm)
a	613	9	1380	Thin wire	10.4

Aluminum thin wire was successfully obtained under the condition of current density, j =9 MA/cm^2 and substrate temperature, T_s = 613 K, which is shown in Fig. 4. Therefore, Al thin wire with length of 10.4 µm and a diameter of 2.66 µm that grew in the sample with a sudden change in geometry by supplying a constant electrical current of I = 540 mA for a current stressing time, t of 1380 s at a constant substrate temperature of T_s = 613 K.

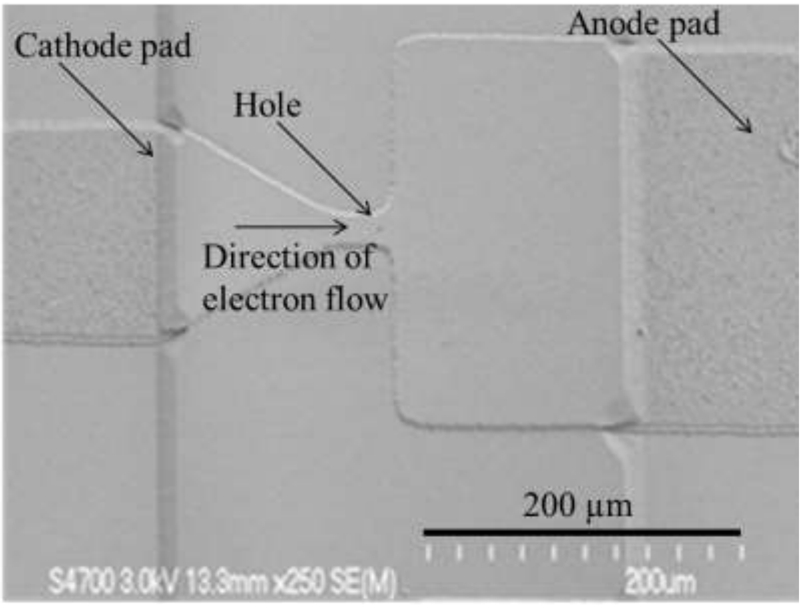


Figure 3: FE-SEM images of experimental sample with a hole at specific position.

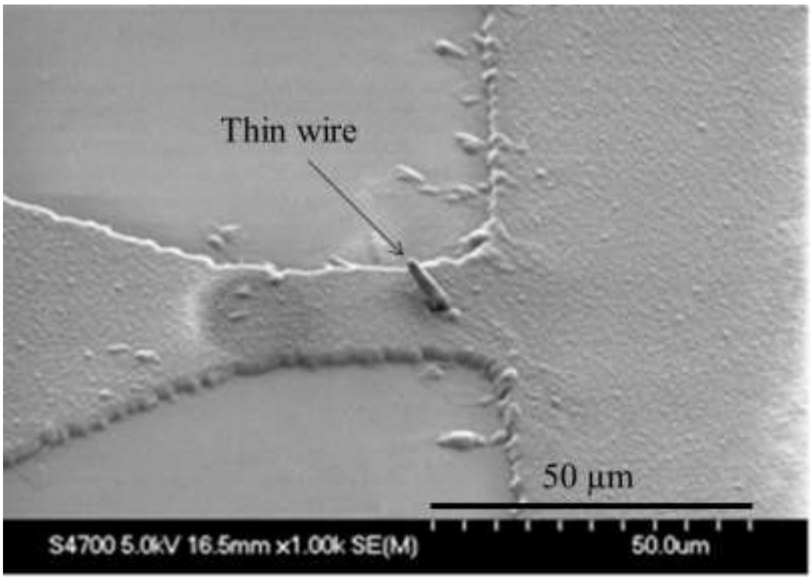


Figure 4: FE-SEM images of formation of thin wire observed after experiment at the predefined location.

In this experimental period, the potential drop of the Al line increases as time passes. Figure 5 shows an example of the potential drop and time under the condition of current density, j = 9 MA/cm^2 and constant substrate temperature, T_{sub} = 613 K. During current supply, the potential drop along the Al line was measured between the input and output pads. After the current had reached a specific value, the potential drop started to increase with time due to the continuous accumulation and discharge of atoms. At the point in time when the potential drop increased rapidly, due to geometrical changes resulting from the loss of many atoms from the Al film, the current supply was stopped in order to protect the sample from blowing as a result of Joule heating.

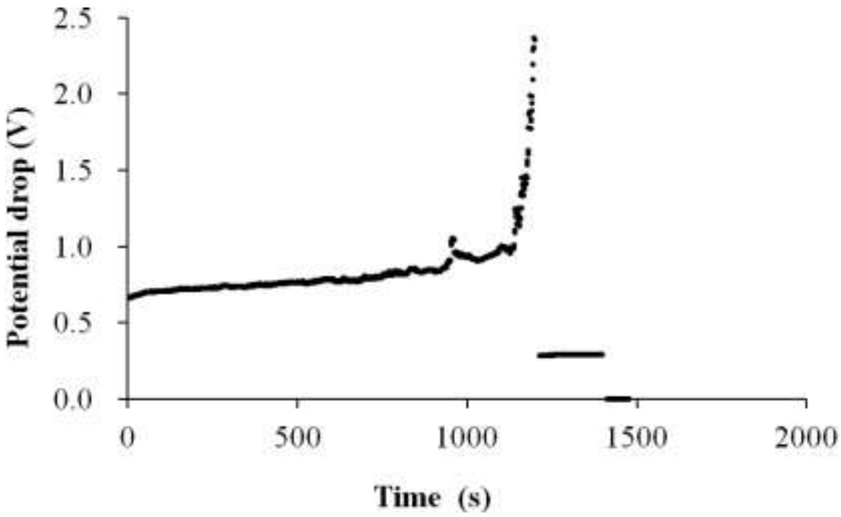


Figure 5: Voltage (V) vs. time (s) of application of current density (9 MA/cm^2) and temperature (613 K) utilization of EM and grown as thin wire.

Electromigration (EM) is a physical phenomenon wherein atoms are transported by an electron wind. The number of atoms that are transported depends on the current density, temperature and the structure of the metal line [19-20]. The electron wind due to high current density can drive metallic atoms to a specific location in a structure in a simple and efficient way. In the present study, the effective accumulation of atoms happened in a specific location of the sudden change in geometrical shape of the metal line, and therefore, fabrication of thin wire in the small region around the predefined hole on this structure was discussed.

The Huntington-Grone's equation [1] can be expressed as

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

where **J** is the atomic flux vector, *N* is the atomic density, D_0 is a prefactor, *k* is Boltzmann's constant, *T* is the absolute temperature, *Q* is activation energy, *Z** (<0 for Al) is the effective valence, *e* is the electronic charge, ρ is the electrical resistivity, and **j** is the current density vector.

Considering the upper and lower sides of the sample are electrically and thermally insulated. Electro-thermal solutions are done in respect to constant direct current and temperature. Effect of temperature due to sudden change in cross-sectional area of the metal specimen and its contribution for accumulating atoms at predefined area was discussed. The temperature distribution of the Al line was analyzed by carrying out finite element analysis (FEA) on this coupled electrical-thermal problem using the software program MSC. Marc/Mentat. After the analysis of the sample, the temperature distribution suddenly changes at 50 μm due to the change in the width of the metal line. The number of atoms are transported depends on the current density and the temperature of the metal line due to EM. The temperature distribution along the x-axis of the sample with a sudden change in geometrical shape is shown in Fig. 6. Under the temperature distribution, absolute value of temperature gradient in Part A is higher than that of Part B. After the experiment, atomic flux (**J**) and current density (**j**) becomes higher in case of part A. Therefore, higher diffusivity of atoms was happened. About part B, current density and atomic flux is lower. Finally, lower diffusivity was also done in this experiment.

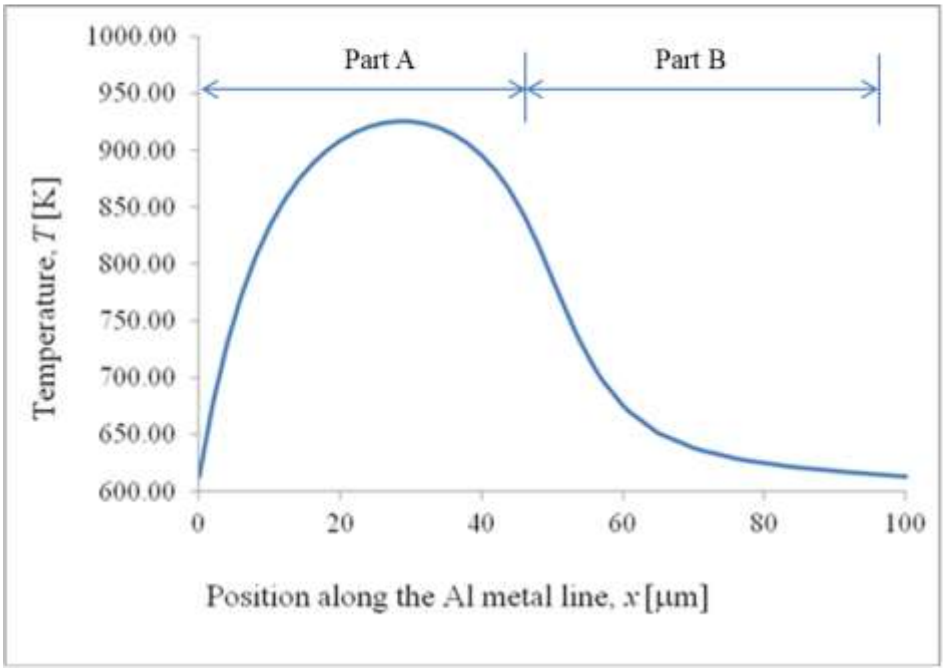


Figure 6: Temperature distribution along the sample line. The temperature distribution suddenly changes at x = 50 μm due to the change in the width of the metal line.

Temperature distribution along the sample line has an impressive effect. The temperature, T has an effective condition on atomic flux, **J** which is shown in Eq. (1). However, the relationship between atomic flux, **J** and the temperature, T is depends on several parameters, especially current density, **j** and the value of activation energy, Q according to Eq. (1). Therefore, it is observed that with any specified activation energy, Q either grain boundary diffusion or lattice diffusion, atomic flux, **J** increases initially with the increasing temperature, T and then decreases after sudden change in geometrical shape of the sample, which is shown in Fig. 6. Obviously, accumulation of atoms depends on temperature and the sample structure with sudden change in geometrical shape.

Therefore, thin wire was formed in Part A of the sample structure due to high temperature. Thereafter, due to the higher temperature and current density, more atoms were diffused in part A and fewer atoms were diffused due to lower temperature in Part B. Moreover, due to high temperature and high current density in Part A, more atoms were migrated and accumulated at the sudden change in the geometrical shape suddenly. Finally, more atoms are accumulated in the small region near the geometrical transition and compressive stresses are generated and discharge of the atoms at the predefined location happened. After the situation, the atoms are solidified and finally atoms were come out through the hole to release the compressive stress, and then thin wire was formed. Therefore, the sudden change of geometrical shape in the metal line of a sample can be used for effective accumulation of atoms to produce micro and nano wire materials. All of these things, including the lower current density and substrate temperature as well as the large hole, decrease the discharge rate of the accumulation Al atoms. Good balance between the discharge rate and cooling rate will make thin wire. Finally, it indicates that the combination of substrate temperature, lower current density, large hole diameter and longer stressing time will be the suitable to fabricate the micro and nano wires.

IV. Conclusions

Aluminum thin wires were successfully fabricated by controlling the accumulation and discharge of atoms using EM. It was revealed by experimental investigation that controlling temperature distribution along the sample line was effective for accumulation of atoms at the predefined position. The thin wire is formed at the specific range of the temperature and current density at the sudden change in geometrical shape of the sample. Potential drop increased rapidly in specific time due to geometrical changes resulting from the loss of many atoms from the Al film.

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