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An Approach Using Sudden Change in Geometrical Shape of a Sample for Fabricating Micro Materials Utilizing Electromigration

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Abstract: *The utilization of electromigration of induced micro materials in passivated aluminum films was investigated. The experimental sample was a passivated polycrystalline Al line with a hole using sudden change in geometrical shape of the specimen. However, the sudden change in the geometrical shape of the metal line is considered for effective accumulation of atoms. Therefore, the microsphere inside the hole, microsphere outside the hole and large cracks were formed at the predetermined positions of the sample using sudden change in geometrical shape. The experimental results and model are explained in the discussion.*

Keywords: *Accumulation, Electromigration, Hole, Inside microsphere, Outside microsphere*

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I. Introduction

Microelectromechanical systems (MEMS) are considered to develop potential applications in modern industry. Miniaturization of materials has become one of the driving forces in the emergence of MEMS. Recently, fabricating metallic micro and nano materials (MNMs) has become an important issue for using in MEMS. Various types of MNMs have been produced including wires, belts, tubes, and spheres using different chemical and physical techniques. These materials have possessed interesting new mechanical, electrical, optical and thermal properties, which are different from those encountered at bulk materials. As an example, bulk silicon is considered to be both a good thermal and electron conductor at room temperature, while silicon nanowires are essentially thermal insulators and at the same time good electron conductors, making them good thermoelectric materials for recovery of waste heat and power generation at a relevant temperature range. Metallic MNMs have been attracted due to their potential applications based on the physical properties as a functional element in MEMS. Various MNMs, such as nanowires [1], nanotubes [2], nanobelts [3], microspheres [4], microbelts [5], etc. have been studied and synthesized.

Top-down and bottom-up technologies have been used for producing finely structured materials. The top-down approach refers to slicing or cutting bulk materials into micro/nano sized particles. 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, in the bottom-up technology two types of growth techniques are well known, i.e., chemical and physical methods. The first type depends on chemical reactions such as the vapor-liquid-solid mechanism, the electrochemical deposition, and the template-based synthesis. Regular three-dimensional (3-D) arrays of crystalline SnO_2-In_2O_3 nanowires were produced on m-sapphire using a gold catalyst-assisted vapor-liquid-solid growth process [6]. ZnS semiconductor nanowires were produced by utilizing the electrochemical deposition method [7]. Nanotubes and nanorods of various materials can be synthesized using the template-based synthesis approach [8]. These chemical methods produce micro and nano structures with fewer defects compared with top-down approaches. However, these techniques have some limitations which include finding appropriate templates with pore channels of desired diameter, length and surface chemistry, and to remove the template completely without compromising the integrity of micro or nano structures. The other type is based on physical phenomena, such as electromigration and stress migration. Some works have already been done by applying electromigration and stress migration. Al nanowires were successfully generated in a passivated Al line buried in a W line by utilizing electromigration [9]. A mechanism for fabricating Cu nanowhiskers on the surface of evaporated polycrystalline films by the aids of stress migration technique was reported [10].

In this study, a new technique with sudden change in geometrical shape of the sample has been proposed for producing micro and nano material structures [11-12]. In this present research, a technique using sudden change in area of a sample for generating metallic MNMs and got several problems by utilizing electromigartion is investigated. Therefore, the fabrication of micro and nano materials is considered by using different current density, current stressing time and temperature. The experimental results and model are explained in the discussion.

II. Experimental procedure

Figure 1 shows the schematic illustration of the sample that has been used in the experiment. Length of the metal line was considered l=100 µm; length of the Part A and Part B was also considered $l/2$=50 µm. Width of Part A of the sample was w_1=10 µm and that of Part B was w_2=500 µm, where the thickness remained same all through the metal line.

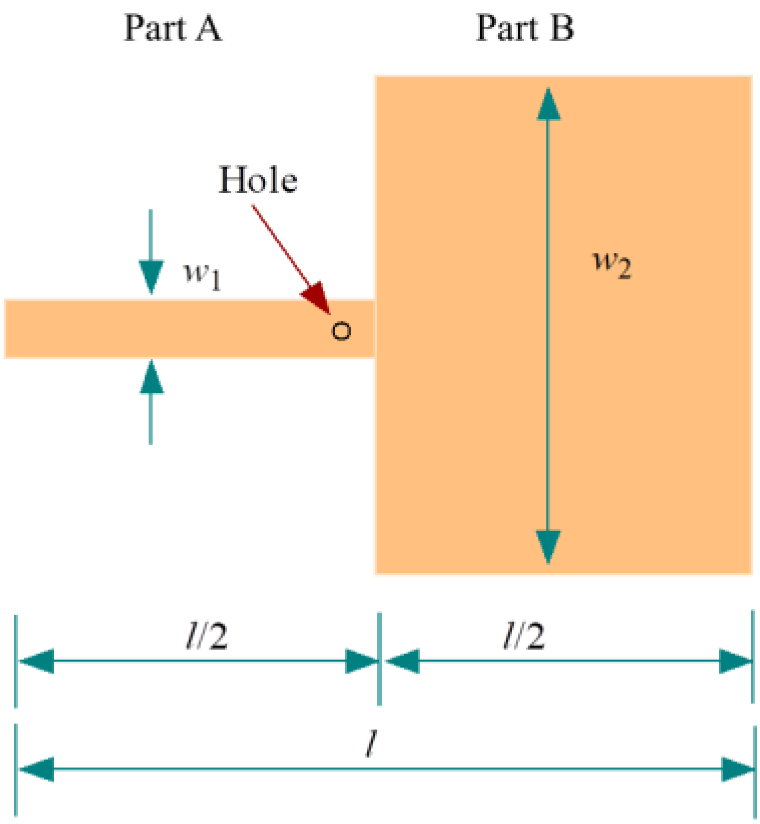

Figure 1. Schematic illustration of the sample.

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 900 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. Figure 2 shows the 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 3 shows the experimental-setup used for applying direct current to produce MNMs.

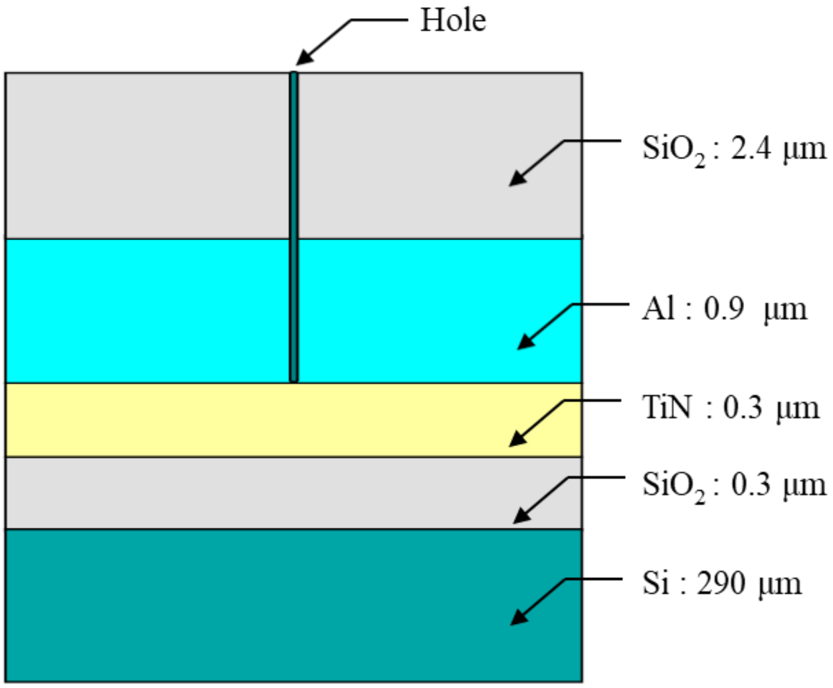

Figure 2. Cross-sectional view of the sample structure.

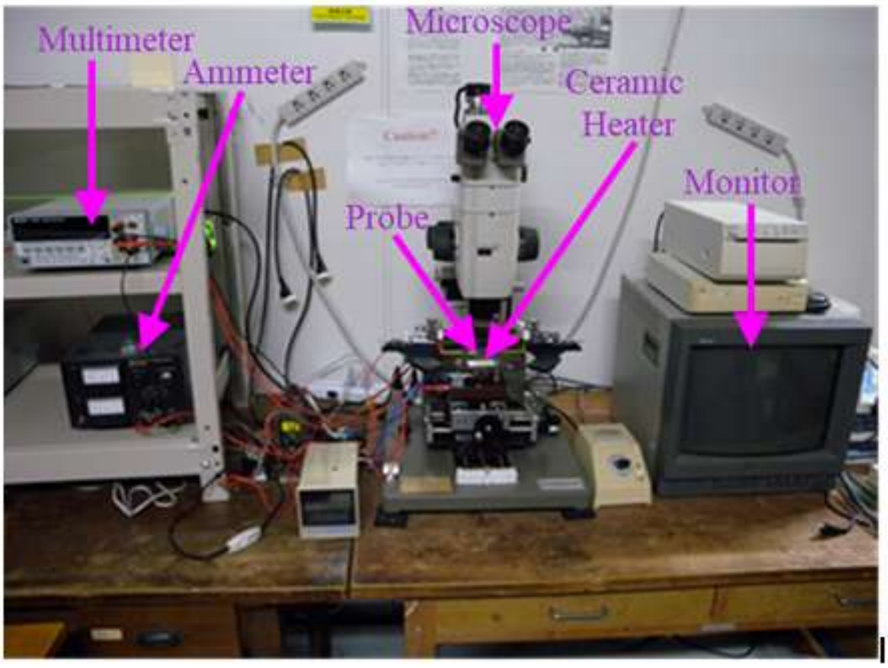

Figure 3. Experimental set-up. This set-up consists of ceramic heater, ammeter, multimeter, probes, microscope, and monitor.

III. Results and discussion

The Al metal sample of 900 nm thickness with passivation layer of 2.4 μm was used for the experiment. Microstructure of similar shape and dimensions by using the proposed new sample specimen with sudden change in geometrical shape was fabricated. The structures used in the experiment are indicated in Table I. Several values of current density, current stressing time and temperature have been used in this study are shown in Table II. Figure 4 shows the surface morphology of the sample examined by using scanning electron microscopy (SEM).

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	500	100	2

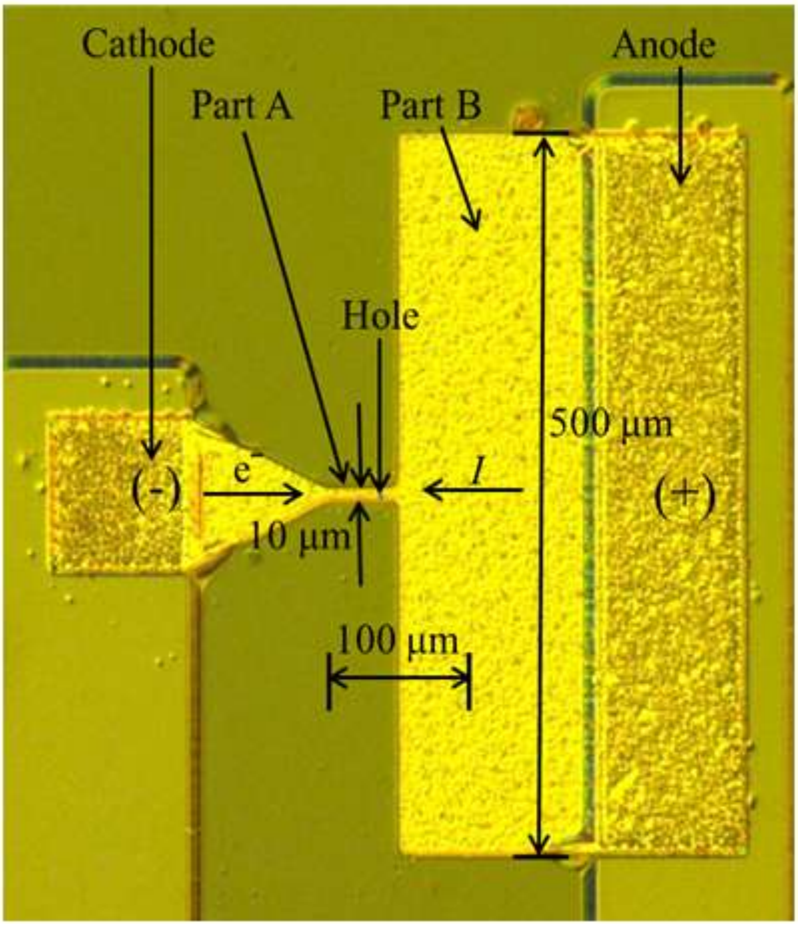

Figure 4. SEM image of a passivated Al thin film line of the sample with sudden change in geometrical shape.

Table II: Test conditions used in experiments

Sample	Substrate temperature, T_s (K)	Current density, j (MA/cm^2)	Current stressing time, t (min.)
S	333-623	1 to 12	14 to 180

After the experiment, microsphere inside the hole was obtained at the specific position, which was observed by field emission scanning electron microscopy (FE-SEM) and shown in Fig. 5. In addition, microsphere outside the hole was observed at the predefined location in the sample with a sudden change in geometrical shape. Finally, large cracks were happened in the sample. Therefore, preparation of the sample as sudden change in geometrical shape was done by considering experimental and model analysis.

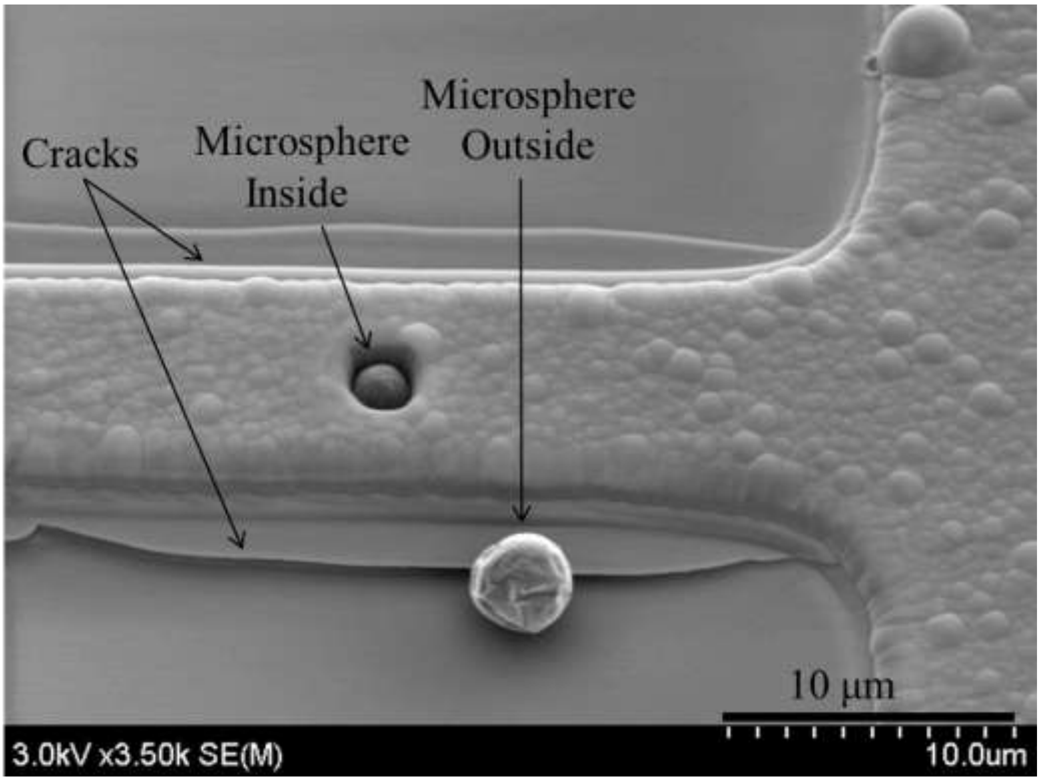

Figure 5. FE-SEM images after the experiment; microsphere inside the hole, microsphere outside the hole, and cracks were observed in the sample.

As a result of current supply, it was confirmed by FE-SEM observation that there were microsphere products from the induced hole. The formation of microsphere was seen in this place other than the closed hole of sudden change in geometrical shape. So it was confirmed that a large amount of Al atom was collected at the intended position. Finally microsphere inside the hole was obtained at the specific location in the sample with a sudden change in geometrical shape under the condition of current density, j = 3 MA/cm^2, substrate temperature T_s = 613 K and current stressing time, t = 50 min. However, microsphere outside the hole was also observed at the predefined location. In contrast, large cracks were also observed at the SiO_2/substrate interface adjacent to the Al line in the specimen. This result may be attributed to the weak adhesion between SiO_2 and substrate during the sample fabrication. However, different current density, substrate temperature and current stressing time were applied for the present sample structure.

Electromigration (EM) is a physical phenomenon wherein atoms are transported by an electron wind. The number of atoms that are transported depend on the current density, current stressing time and specific temperature of the sample metal line [13-14]. In the present study, accumulation and discharge of effective atoms in a specific location were considered using sudden change in geometrical shape of the metal line. The experimental results and the model of the sample will be discussed. The model of sample with sudden change in geometrical shape has been discussed as follows and illustrated in Fig. 6.

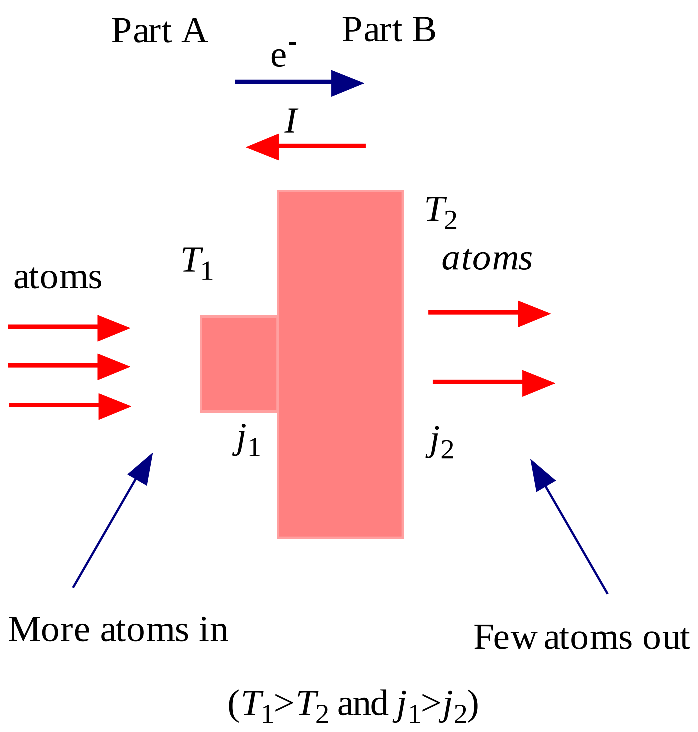

Figure 6. Sample model with sudden change in geometrical shape.

In this case, the sample material is same for both Part A and Part B. The current direction is considered from Part B to Part A direction. Therefore, the electrons and atoms are moving from Part A to Part B. Let us consider a section which is shown in Fig. 6. In this section more atoms enters due to high temperature, T_1 and high current density, j_1. In this section, the width of the sample metal line suddenly changes and the temperature and current density drastically reduces. Therefore, few atoms go out from the section due to relatively low temperature, T_2 and low current density, j_2 compared to the temperature and current density of Part A. Therefore, in this case, accumulation of atoms occurs due to the temperature difference between T_1 and T_2, and also due to the current density difference between j_1 and j_2. The accumulation is affected by temperature gradient and current density gradients. This temperature and current density gradients occur due to the sudden change in width of the metal sample line. Therefore, due to high temperature and high current density, atoms are migrated and accumulated at the specific location where the geometrical shape suddenly changed. After that compressive stress generated, atoms are solidified. Finally, atoms are discharged through the hole to release the compressive stress of atoms and microsphere inside the hole was obtained at the specific position in the sample. Therefore, microsphere outside the hole was also happened. Moreover, large cracks were also occurred in the sample. However, the contribution made by the line structure with the position and size of the hole is also important to bring together a large amount of diffused atoms at particular position to produce metallic micro and nano materials.

IV. Conclusions

Electromigration could be used intentionally to form micro and nano materials. A passivated Al line with sudden change in geometrical shape was heated by both a heater and Joule heating. More atoms are accumulated in the small region using sudden change in geometrical shape of the sample. Experiment and model analysis of Al sample shape have been done. Significant changes in the current density and temperature have been analyzed for the sample structure.

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