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Enhancement of Al Microsphere Fabrication by Utilizing Electromigration in Sudden Change in Geometrical Shape of Sample

Faizul Mohammad Kamal*, and Sheikh Manjura Hoque
Materials Science Division, Atomic Energy Centre, Dhaka
Bangladesh Atomic Energy Commission, Bangladesh
*Corresponding author: kamal_ndt@yahoo.com

Abstract
The utilization of electromigration for enhancement of microspheres using sudden change in geometrical shape of sample was investigated. The experimental sample of Al metal line is formed on a TiN layer and covered with a SiO_2 passivation layer. The experimental results revealed that sudden change in geometrical shape of specimen significantly affects temperature, current density and current stressing time to enhance atomic accumulation for growing microspheres. The experimental results are explained in the discussion. A finite element analysis was done to investigate the effect of temperature profile due to sudden change in cross-sectional area of a sample structure.
Keywords: *Electromigration, Enhancement, Fabrication, Microsphere, Current density.*

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I. Introduction

Metallic micro and nano materials (MNMs) have been attracted due to their potential applications based on the physical properties as a functional element in micro-electromechanical systems (MEMS). Various MNMs, such as nanotubes [1], nanowires [2], micro-spheres [3], micro-belts [4], etc. have been studied. Several reports have appeared showing the passage of direct current through aluminum thin-film stripes results void formation by mass depletion and hillock formation by accumulation of atoms [5]. The electron wind due to a high current density can drive metallic atoms to a specific place in a sample structure. Based on physical phenomena, several works have already been done by applying electromigration (EM) [6, 7] and stress migration (SM) [8, 9]. Therefore, EM is the vital portion of development of MNMs.

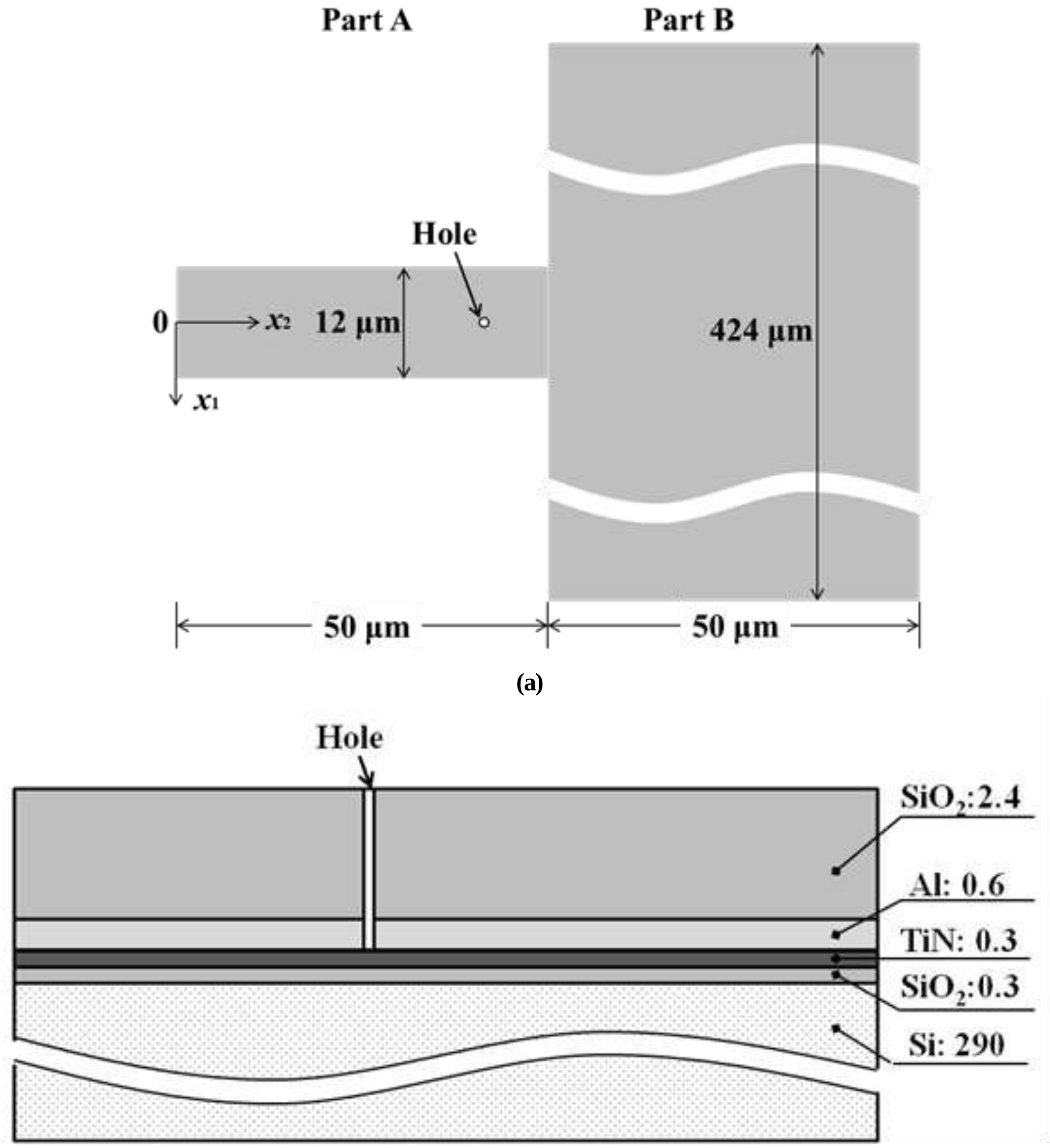
EM has been proposed for use in the fabrication of metallic micro and nano materials. Various techniques have been applied for fabricating Al micro and nano materials. A method was proposed to accumulate atoms to form Al micro and nano wires in a passivated Al line buried in a W line by utilizing EM [10]. Thereafter, another proposal was reported for accumulation of atoms to form metallic thin wires by utilizing EM [11]. The experimental sample of Al metal line was formed on a TiN layer and covered with a SiO_2 passivation layer. An artificial slit was introduced into the Al layer by etching at the anode end of the sample structure. A slit in the Al film and a hole through the oxide were used to control the accumulation of atoms and discharge processes and fabricated micro materials [12-14]. In addition, the method of fabricating Al micro materials such as wires using EM involves a sample structure with an artificial slit for accumulating atoms and a conductive passivation film made of SiO_2 to avoid unplanned atomic accumulation [15]. However, introducing artificial slit into the sample is a long process and also cost effective. Therefore, a sample structure without any slit in the fabrication process is considered for fabricating MNMs.

During this process, controlling accumulation and discharge of atoms are very important for fabricating MNMs structure. Therefore, a possible sample structure indicates an aluminum line structure with sudden change in geometrical shape can effectively promote the accumulation of atoms [16-20]. In this paper, accumulation and discharge of Al atoms are needed to effectively fabricated microspheres with EM. The rapid sudden change in the geometrical shape of the metal specimen could be expected as the Al micro materials growth. Thus optimizing the current density and current stressing time with constant temperature, the desired shape was obtained. In the present study, effect of temperature along the metal specimen with sudden change in geometrical shape at predefined area was analyzed 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). A passivated Al line had the large pads for current supply at both ends of the line. The cross section of the sample is schematically illustrated in Fig. 1(b). 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 1 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.

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.



(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 samples were placed on a ceramic heater under atmospheric conditions, and the temperature was maintained at 623 K. The samples were then subjected to a constant direct current flow using a pair of probes in contact with the input and output pads. The field emission scanning electron microscope (FE-SEM) image of experimental sample with a hole at specific position is shown in Fig. 2.

III. Results and discussion

The experimental conditions and results are summarized in Table I. FE-SEM images of typical features formed at the sudden change in geometrical shape of the samples are shown in Fig. 3.

Table I: Experimental conditions and results

Condition	Substrate temperature, T_s (K)	Current density, j (MA/cm^2)	Current stressing time, t (s)	Results
1	623	7.5	2400	Cracks
2	623	8.33	1620	Microsphere becomes outside and cracks
3	623	9.17	900	Large Microsphere

It is observed that cracks were formed, which is shown in Fig. 3(a), in case of condition 1. In contrast, microsphere discharged from the fracture area was observed at condition 2, shown in Fig. 3(b), at the SiO_2/substrate interface adjacent to the Al line, which may be attributed to the weak adhesion between SiO_2 and substrate during the sample fabrication. The diameter of the microsphere discharge from the fracture area is 8.4 µm, which is shown in Fig. 3(b). Finally, large microsphere was obtained, in condition 3, at the specific position with sudden change in geometrical shape, which is shown in Fig. 3(c). In addition, cracks were also obtained after the experiment, shown in Fig. 3(c). Microsphere was successfully observed under the condition of current density, j = 9.17 MA/cm^2, substrate temperature, T_s = 623 K, where current stressing time was at 15 s. The diameter of the microsphere is 9 µm, which is shown in Fig. 3(c).

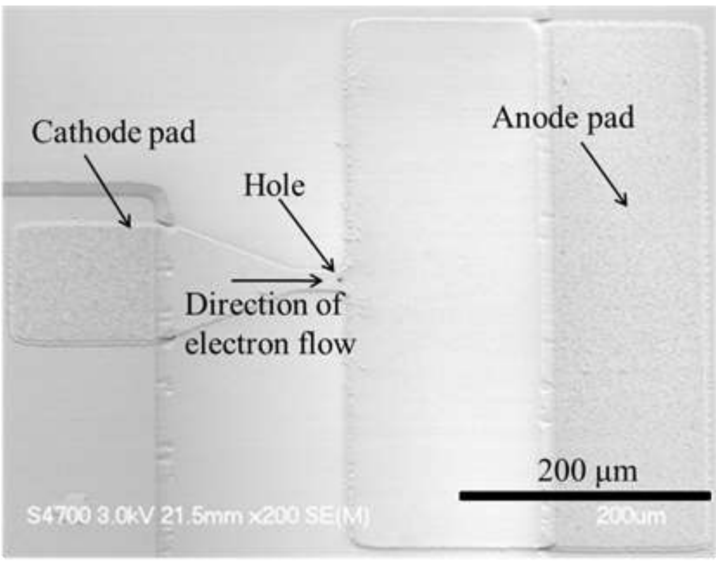
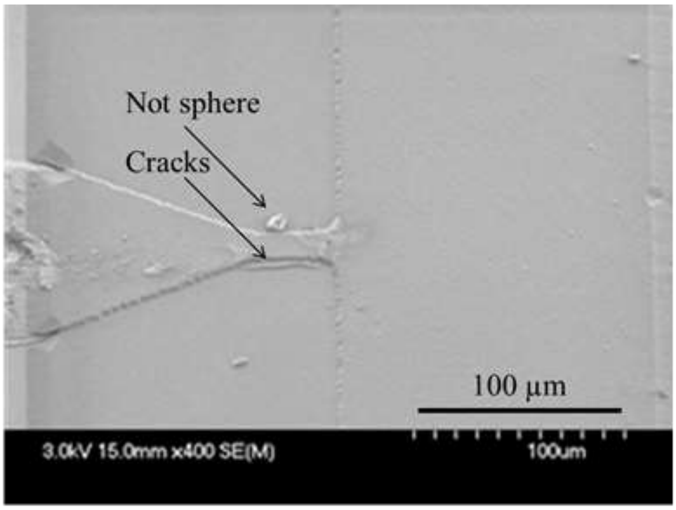
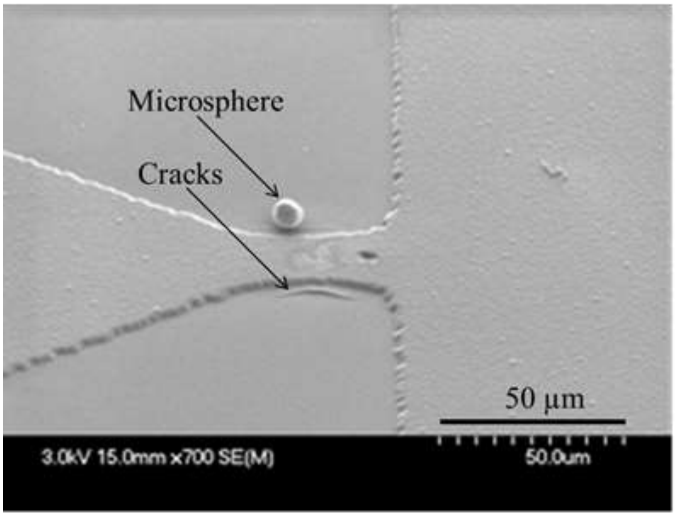


Figure 2: FE-SEM images of experimental sample with a hole at specific position.



(a)



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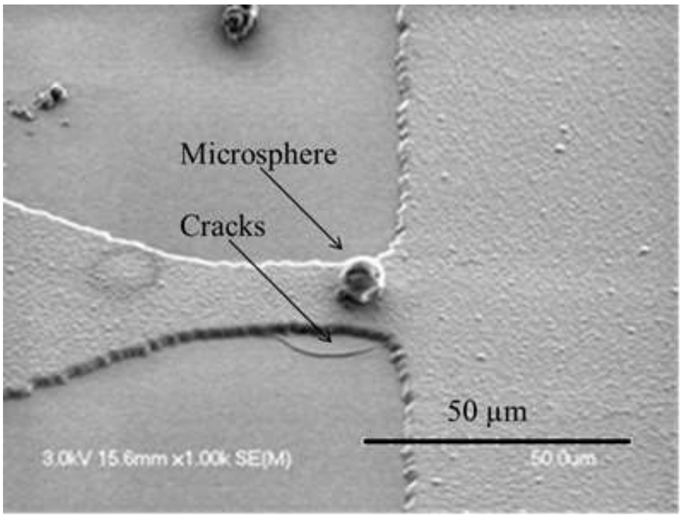


(c)

Figure 3: FE-SEM images of experimental sample with a hole at specific position showing, (a) no result but crack was observed at the predefined location, (b) cracks on one side of the sample and the microsphere discharged from the fracture area were also formed in the sample at the predefined location, and (c) large microsphere was formed observed after experiment at the predefined location.

Electromigration (EM) is a physical phenomenon whereby metallic atoms are transported by an electron wind. The atomic flux depends on the current density and temperature [21, 22]. The efficient accumulation of atoms happened in a specific location of the sudden change in geometrical shape of the metal line using EM. Therefore, from Huntington–Grone's equation [21], the atomic flux increases exponentially, enhancing the formation of Al microsphere through EM.

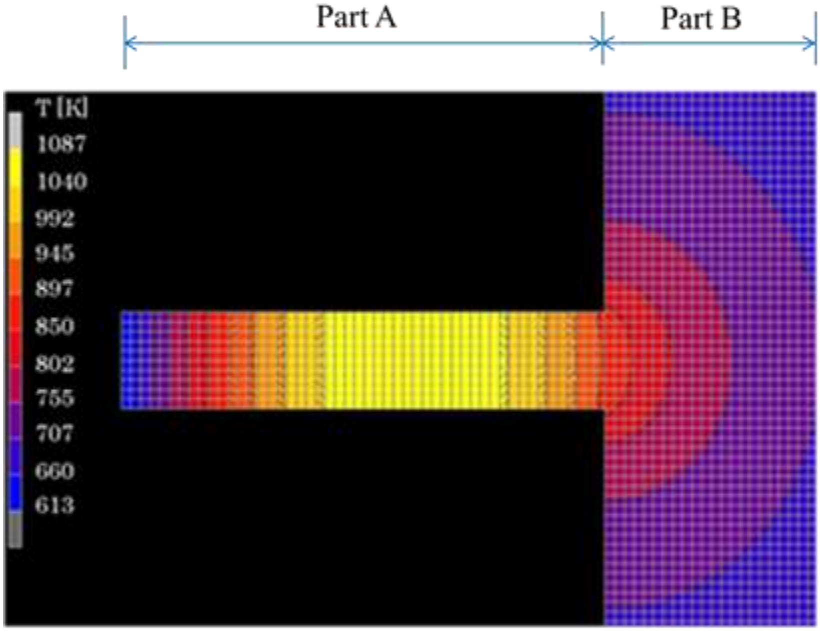
The atomic flux caused by EM can be expressed as [21],

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

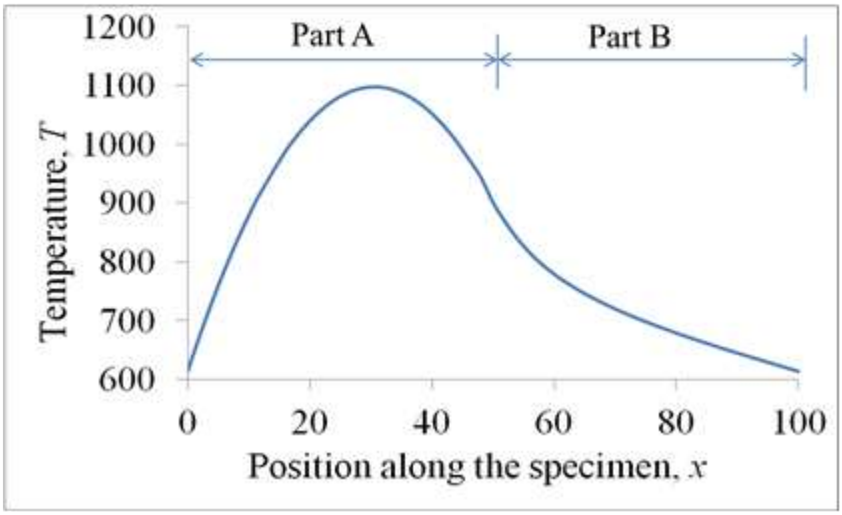
where **J** is the atomic flux vector, N is the atomic density, D_0 is a prefactor, k is Boltzmann's constant, T is the absolute temperature, Q is activation energy, Z^* (<0 for Al) is the effective valence, e is the electronic charge, ρ is the electrical resistivity, and **j** is the current density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

A theoretical model of the sample used in the experiment for evaluating and discussing the experimental results by finite element method (FEM). Finite element (FE) method was applied to analysis the temperature distribution in the sample structure and its contribution for accumulating atoms, which is shown in Fig. 4. Marc FE program was used for analysis the model. Temperature distribution was obtained by FE analysis using MSC Marc, which is shown in Fig. 4(a).

The temperature distribution of 2D-FEM analysis along the sample with sudden change in geometrical shape is shown in Fig. 4(b). FE model was constructed to simulate the temperature distribution on the metal specimen during current stressing. The effect of Joule heating was observed and have been found from the temperature distribution curve that high temperature developed in Part A compared to Part B of the metal specimen due to the resulting effect of Joule heating. In addition, absolute value of higher temperature gradient is observed in Part A and very small temperature gradient in Part B of the sample, which is shown in Fig. 4.



(a)



(b)

Figure 4: Temperature distribution obtained. (a) FE analysis using MSC Mark, and (b) 2D FE analysis of the specimen.

Consider the mechanism for the formation of Al microspheres by utilizing EM using a sample with a sudden change in geometrical shape. Al atoms migrated in the direction of electron flow. Al atoms are transported along the grain boundaries from the cathode current pad to transitional area. A pressure is created and increased with continuous accumulation of atoms at transitional area with a sudden change in geometrical shape. At the transitional area, the accumulation of Al atoms leads to the development of a compressive stress. Therefore, atoms were pushed out through the hole when the pressure was larger than the discharged resistance, resulting in the formation of microspheres.

As a result of this rapid development, Al atoms are pushed out through the hole forming the microspheres. The discharge is related to the temperature at the transitional area with sudden change in geometrical shape, which can be determined from the current density and the substrate temperature. Therefore, temperature distribution profile is obtained along x-axis of the metal line with sudden change in geometrical shape, which is shown in Fig. 4. The Al atoms are discharged out from the holes continuously to form microspheres at the current density from 8.33 to 9.17 MA/cm^2 (sample c). Obviously, the higher current density, 9.17 MA/cm^2 provides more Joule heating resulting better microsphere of a part of accumulated atoms from the transitional area. On some experiments, melted atoms are pushed out to form liquid spheres due to surface tension, then the micro materials are cooled and solidified in atmosphere conditions (sample a).

Microsphere was formed, which is shown in fig. 3 (c), after different current stress time, corresponding to 900s, respectively. Thus, the length of the microsphere depends on the current density and current stress time. Fig. 2(c) suggests that the current density is a key factor in the formation of the microsphere. It has been reported that the temperature derived by finite element analysis increases up to the transitional area. Using the present technique, Al microspheres can be formed by design by placing holes at prearranged positions through FIB etching. Therefore, the lengths of the microsphere are dependent on the temperature, current density and current-stressing time. Additionally, the widths and thickness of the Al microsphere could be readily controlled, and their lengths could be determined by the current stressing time. Therefore, the atoms of Al region have been accumulated may be partly melted. Consequently, microsphere would form in atmospheric conditions when melted Al is discharged from the hole.

IV. Conclusions

Fabrication of microspheres was achieved using sudden change in geometrical shape of the metal line. Discharge conditions of Al atoms through the holes were considered by observing the relationship between the current density and the current stressing time. Higher current density provides more Joule heating resulting better microspheres due to the transitional area of the sample. The temperature derived by finite element analysis increases up to the predefined location near the geometrical transition of the sample structure. A theoretical model of the sample structure was used for evaluating and discussing the experimental results.

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References

[1] J. Li, C. Papadopoulos, J. M. Xu and M. Moskovits, "Highly-Ordered Carbon Nanotube Arrays for Electronics Applications," Applied Physics Letters, Vol. 75, No. 3 (1999), pp. 367-369.
[2] Y. Cui, L. J. Lauhon, M. S. Gudiksen, J. Wang and C. M. Lieber, "Diameter-Controlled Synthesis of Single-Crystal Silicon Nanowires," Applied Physics Letters, Vol. 78, No. 15 (2001), pp. 2214-2216.
[3] Q. Wang, F. Y. Cao, Q. W. Chen and C. L. Chen, "Preparation of Carbon-Micro Spheres by Hydrothermal Treatment of Methylcellulose Sol," Materials Letters, Vol. 59, No. 28 (2005), pp. 3738-3741.
[4] Z. Q. Zhang, C. B. Jiang, S. X. Li and S. X. Mao, "Nucleation and Growth of Zno Micro- and Nanobelts During Thermal Evaporation," Journal Of Crystal Growth, Vol. 277, No. 1-4 (2005), pp. 321-329.
[5] J. K. Howard and R. F. Ross, "Electromigration Effects in Aluminum Film on Silicon Substrates," Applied Physics Letters, Vol. 11, Issue 3 (1967), pp. 85-87.
[6] I. A. Blech and E. Kinsbron, "Electromigtation in Thin Gold Films on Molybdenum Surfaces," Thin Solid Films, Vol. 25 No. 2 (1975), pp. 327-334.
[7] M. A. Korhonen, P. Borgesen, K. N. Tu and C. Y. Li, "Stress Evolution due to Electromigration in Confined Metal Lines," Journal of Applied Physics, Vol. 73 No. 8 (1993), pp. 3790-3799.
[8] M. Saka, M. Yamaya and H. Tohmyoh, "Rapid and Mass Growth of Stress-Induced Nanowhiskers on the Surfaces of Evaporated Polycrystalline Cu Films," Scripa Materialia, Vol. 56, No. 12 (2007), pp. 1031-1034.
[9] N. Settsu, M. Saka and F. Yamaya, "Fabrication of Cu Nanowires at Predetermined Positions by Utilizing Stress Migration," Strain, Vol. 44, Issue 2 (2008), pp. 201-208.
[10] M. Saka and R. Ueda, "Formation of Metalic Nanowires by Utilizing Electromigration,", Journal of Materials Research, Vol. 20, No. 10 (2005), pp. 2712-2718.
[11] M. Saka and R. Nakanishi, "Formation of Al Thin Wire by Utilizing Controlled Accumulation of Atoms due to Electromigration,", Materials Letters, Vol. 60, No. 17-18 (2006), pp. 2129-2131.
[12] Y. Lu and M. Saka, "Fabrication of Al Micro-Belts by Utilizing Electromigration," Materials Letters, Vol. 63, No. 26 (2009), pp. 2227-2229.
[13] Y. Lu, H. Tohmyoh and M. Saka, "Forming Microstructures by Controlling the Accumulation and Discharge of Al Atoms by Electromigration," Journal of Physics D: Applied Physics, Vol. 44, No. 4 (2011), pp. 1-7.
[14] Y. Lu, H. Tohmyoh, M. Saka and H. Pan, "Enhancement of Al Thin Wire Fabrication by Usimg Electromigration in Relation to the Discharge Resistance of the Atoms," Optoelectronics and Advanced Materials – Rapid Communications, Vol. 5, No. 11 (2011), pp. 1219-1222.
[15] Y. Kimura and M. Saka, "Simplified Processes Using Conductive Passivation Film for the Fabrication of Al Micro-Wires by Electromigation," Materials Letters, Vol. 116 (2014), pp. 278-281.
[16] F. M. Kamal and M. Saka, "An Approach Using Sudden Change in Geometrical Shape of a Sample for Fabricating Micro/Nano Metallic Materials Utilizing Electromigration", Proceedings of 13th International Conference on Electronics Materials and Packaging (EMAP 2011), Kyoto, Japan, December 12-15, 2011 (USB).
[17] F. M. Kamal, F. R. Zaki and M. Saka, "Formation of Hillock by Utilizing Electromigration," Journal of the Bangladesh Electronics Society, Vol. 13, No. 1-2 (2013), pp. 121-127.
[18] F. M. Kamal, Y. Li and M. Saka., "Fabrication of Al Microspheres by Electromigration Using a Metal Line with a Sudden Change in Geometrical Shape", Optoelectronics and Advanced Materials-Rapid Communications, Vol. 7, No. (3-4) (2013), pp. 314-318.
[19] F. M. Kamal and S. M. Hoque, "Controlling Fabrication of Aluminum Micromaterials by Electromigration Using a Thin-Film Line with a Sudden Change in Geometrical Shape", IOSR Journal of Electrical and Electronics Engineering, Vol. 19, Issue 1, Ser. 1 (2024), pp. 38-46.
[20] F. M. Kamal and S. M. Hoque, "Fabrication of Al Thin Wire by Utilizing Electromigration Using a Sample with Sudden Change in Geometrical Shape", IOSR Journal of Electrical and Electronics Engineering, Vol. 19, Issue 4, Ser. 1 (2024), pp. 48-54.
[21] H. B. Huntington and A. R. Grone, "Current Induced Marker Motion in Gold Wires," Journal of Physics and Chemistry of Solids, Vol. 20, No. 1-2 (1961), pp. 76-87.
[22] I. A. Blech, "Electromigration in Thin Aluminum Films on Titanium Nitride," Journal of Applied Physics, Vol. 47, No. 4 (1976), pp. 1203-1208.