Fabrication of Al microspheres by electromigration using a metal line with a sudden change in geometrical shape

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A technique using the sudden change in the geometrical shape of an Al line is introduced for the effective accumulation of atoms and, therefore, the fabrication of micro materials by electromigration. The effectiveness of the present technique is verified by the formation of an Al microsphere from a predefined hole. According to a finite element analysis of this electrical-thermal problem, the physical mechanism governing the observed behavior can be attributed to a decrease in atomic flux along the electron flow direction, resulting from a sudden change in geometry, in the small region surrounding the predefined hole.

(Received December 5, 2012; accepted April 11, 2013)

Keywords: Al microsphere, Atomic accumulation, Atomic flux, Electromigration, Finite element analysis

1. Introduction

Electromigration (EM) is an atomic migration phenomenon wherein metallic atoms are transported by electron wind due to high current density in a metal line. This phenomenon is well known as a threat to the reliability of integrated circuits in the form of short circuits due to whisker formation or open circuits due to void formation [1-4]. However, our research group has utilized EM to fabricate micro materials (MMs) at specified locations by designing various sample structures [5-7]. Several interesting studies have been reported in this respect; for example, various MMs (e.g., Al microsphere, Al thin wire) have been successfully fabricated by introducing an artificial slit at the anode end of an Al line to promote atomic accumulation [6,7]. However, the introduction of a slit by wet etching is quite time-consuming (usually taking 3~5 hours) and also makes this fabrication method costly. Fortunately, a hint at a possible breakthrough is provided by our latest findings [8], which indicate that an Al line structure that undergoes a sudden change in geometrical shape can effectively promote the accumulation of atoms during EM. However, the implementation of such a technique to form Al MMs has not been reported. Moreover, the corresponding physical mechanism has only been roughly discussed using one-dimensional theoretical analysis.

Therefore, as a continuing study in this line of research, a sudden change in geometry was introduced into an Al line sample to enhance the effective accumulation of atoms and therefore fabricate microspheres by EM. The effectiveness of this technique was verified by the formation of an Al microsphere from a predefined hole. To clarify the physical mechanism governing this technique, a finite element analysis (FEA) on this coupled electrical-thermal problem was carried out.

2. Experimental details

According to the findings of our exploratory work [8], a sudden change in geometrical shape can be introduced in an Al line to fabricate MMs by EM. A schematic illustration of the sample structure used in the present work is shown in Fig. 1a. The sample fabrication process is summarized as follows: (1) First, a Si [100] substrate with a thickness of 290 μm was thermally oxidized to form a 0.3-μm-thick SiO_2 layer on the surface. (2) 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, promoting adhesion between Al and the Si wafer, and providing a bypass for current in case an electrical shortcut is induced by the growth of voids due to EM. (3) 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). Note that the present Al source with such low purity of 2N is chosen because the impurity can result in the increase of vacancy concentration and the decrease in the activation energy for grain boundary diffusion, which finally effectively promotes atomic migration and therefore increases the atomic flux [9, 10]. (4) 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. 1a. Note that the narrow part of the Al line has a width of 12 μm, and the width ratio between the wide part and the narrow part is approximately 35. (5)

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 should be subsequently wet etched to expose the Al layer and thereby provide electrical pads for current stressing. (6) Finally, a circular hole with a diameter of 1 μm, denoted as H in Fig. 1a, was etched by focused ion beam (FIB) to control the discharge of accumulated Al atoms. Note that this hole was located 7 μm away from the geometrical transition, as shown in Fig. 1a, which should be deepened down to the interface between Al and TiN to promote surface diffusion. This sample fabrication process is similar to procedures reported in previous studies [6, 7] but without complicated slit processing steps. The omission of these steps makes the present technique time-saving and cost-effective. An example of a prepared sample is shown in Fig. 2a.

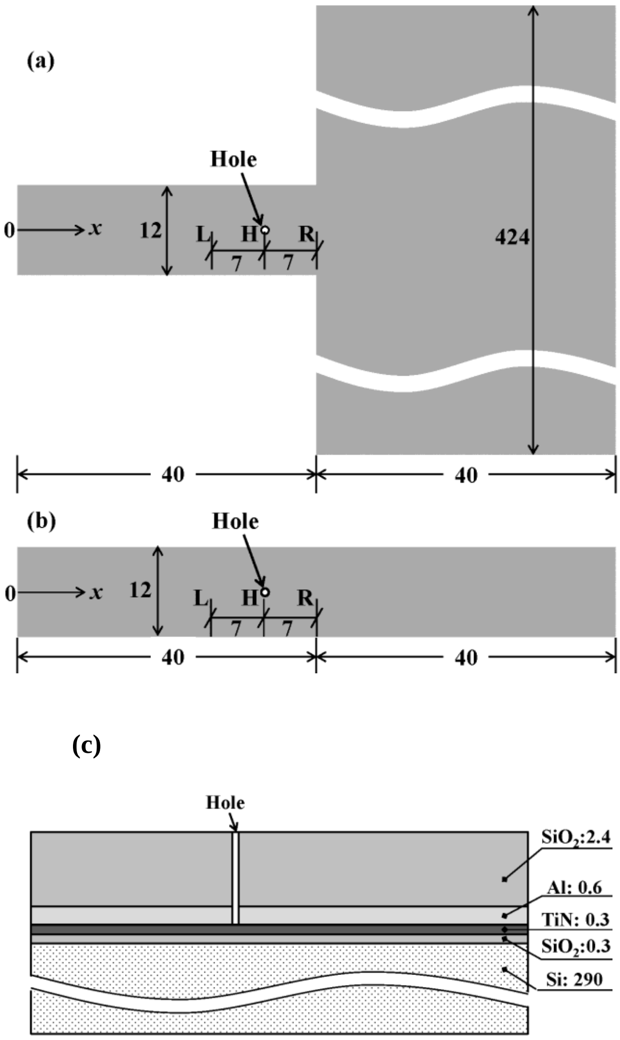

Fig. 1. Schematic illustration of samples [unit: μm]. (a) Planar view of sample with sudden change in geometrical shape. (b) Planar view of sample without geometrical change. (c) Cross-sectional view of samples.

As a reference, a sample without a geometrical change was also fabricated by simply changing the pattern mentioned in step 4 above to a straight Al line. The two types of Al samples (i.e., Fig. 1a and Fig. 1b) had the same line length of 80 μm, and a hole was created at the same position of each sample. The *x*-axis runs along the center of the samples, with the origin located at the left end, as shown in Fig. 1a and Fig. 1b. Fig. 1c shows that the schematic cross-sectional views of the samples were also the same.

Electrical heating experiments were conducted on the two samples under ambient conditions. The substrate temperature, T_S, and current, I, varied over ranges of 300 ~633 K and 420 ~ 660 mA, respectively. This caused the current density, $|\mathbf{j}|$, of the part with width of 12 μm of the samples to vary from 5.83 to 9.17 MA/cm^2. During the EM experiment, current flowed from anode to cathode, and electrons, e^-, flowed in the opposite direction of current making the mass transport of metal atoms. The experiment was stopped once the voltage increased suddenly or when the sample started to melt due to Joule heating at ultrahigh temperature.

3. Results and discussion

For samples without any geometrical change, no microstructure was observed at the predefined location. However, microspheres were fabricated at the predefined location in the sample with a sudden change in geometrical shape, which demonstrates the effectiveness of the present technique in fabricating MMs. Figure 2b shows an example of an Al microsphere with a diameter of 7.4 μm that grew in the sample with a sudden change in geometry by supplying a constant electrical current of I=600 mA for a current stressing time of 1320 s at a constant substrate temperature of T_S = 623 K. Here, four specimens were used under the same electrical stressing conditions. Successful formation of Al microspheres was observed at the hole location in two specimens, which indicates to some extent the experimental repeatability. In contrast, large crack was observed at the SiO_2/substrate interface adjacent to the Al line in the other two specimens, which may be attributed to the weak adhesion between SiO_2 and substrate during the sample fabrication. Note that the current density of the narrow part (width: 12 μm) of the sample with a sudden change in geometry was approximately 8.33 MA/cm^2. The diameter of this microsphere is comparable in size to that of the microsphere obtained by Sun *et al.* [7] using the conventional sample with a slit at the anode end, which also indicates the effectiveness of the present technique. However, it should be noted that the current stressing conditions are quite different between these two types of samples, in which higher current density and substrate temperature, longer current stressing time were observed for the present sample structure when compared to those for the conventional sample with slit [7]. Such distinctive difference can be attributed to their different mechanism to realize atomic accumulation as discussed later.

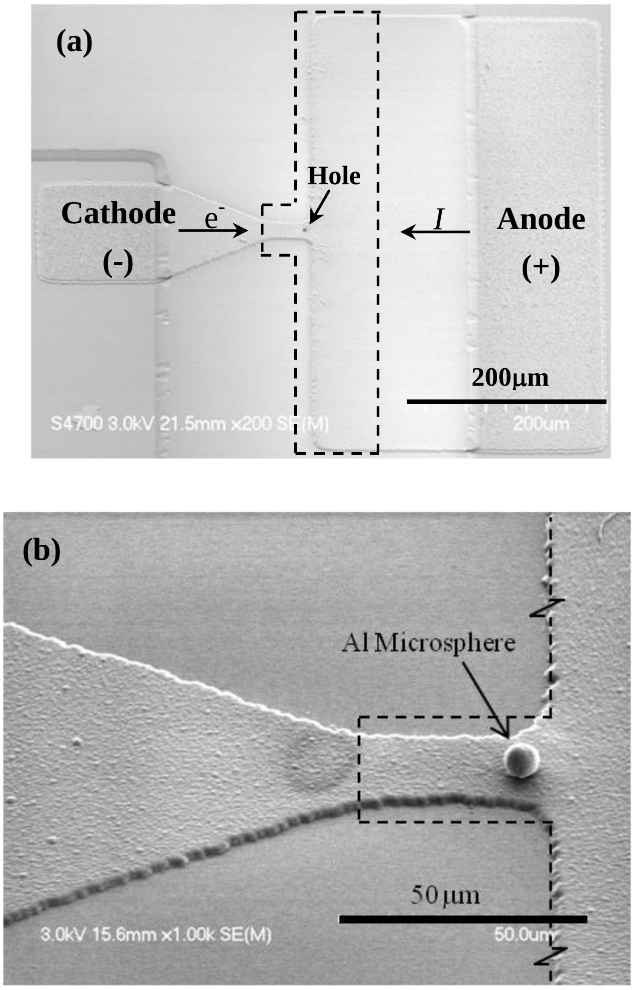

Fig. 2. FE-SEM images of the sample with a sudden change in geometrical shape, where the dashed lines enclose the sample shown in Fig. 1a. (a) Experimental sample. (b) Formation of Al microsphere at the predefined location.

To clarify the physical mechanism underlying the enhancement in the effective accumulation of atoms in the Al line with a sudden change in geometrical shape (Fig. 1a), the EM-induced atomic flux along the electron flow direction in the small region around the predefined hole was studied.

It has been reported [11, 12] that the atomic flux caused by EM can be expressed as

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

where $\mathbf{J}$ 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 $\mathbf{j}$ is the current density vector.

The current density and temperature distributions of the Al line were analyzed by carrying out two-dimensional FEA on this coupled electrical-thermal problem using the software program MSC. Marc/Mentat. Four-node quadrilateral elements (Type 39) were used. Considering the symmetry of the sample, only one half of the structure was modeled. It should be noted that the effect of the predefined hole on the current density and temperature distributions was neglected because of the hole's rather small diameter of 1 μm. The following material constants at room temperature were used for simplicity: $31.5\times10^{-3}\Omega\cdot\mu$m for electrical resistivity [13] and 94×10^{-6} W/(μm·K) for thermal conductivity [14]. The following boundary conditions were applied: T_S = 623 K at x = 0 and 80 μm; $|\mathbf{j}|$ =8.33 MA/cm^2 at x = 0; the electrical potential at x = 80 μm is approximated to be constant. Note that all other sides of the model were electrically and thermally insulated.

The current density and temperature distributions along the x-axis of the sample with a sudden change in geometry are shown in Fig. 3, where the temperature is normalized by the substrate temperature. Obviously, there is a sudden decrease in current density near the geometrical transition of the sample along the electron flow direction as shown in Fig. 3 (a). It should be noted that the simulated maximum temperature for each type of sample is much higher than the melting point as given in Fig. 3 (b), which is impossible in reality. The reason can be attributed to the neglect of the effects of several important factors, such as the pads for input and output of electric current, heat transfer, and temperature dependency of material properties. Although the consideration of such factors will change the value of temperature at any specified place in the sample, our focus, i.e., the trend of temperature distribution along the electron flow direction, keeps the same. Therefore, the present temperature analysis is reliable to some extent by neglecting the above factors for simplicity. Taking a small region L-H-R with H (i.e., hole location in Fig. 1) as the center, the atomic flux at L and R are discussed. Fig. 3 clearly shows that both the current density and temperature at L (on the left side of hole H) are much higher than those at R (on the right side of H). As given in Eq. (1), it is obvious that the atomic flux $|\mathbf{J}|$ increases with the increasing current density $|\mathbf{j}|$ monolithically. However, the relationship between $|\mathbf{J}|$ and the temperature T is more complicated, and it depends on several parameters, especially the value of Q. It is found that with any specified Q for either grain boundary diffusion or lattice diffusion, $|\mathbf{J}|$ increases initially with the increasing T and then decreases. Here, the temperature where $|\mathbf{J}|$ altering from increase to decrease is several thousands of kelvins, which is much higher than Al's melting point of 999K. Therefore, $|\mathbf{J}|$ in the present case within the corresponding limited temperature range, which is lower than Al's melting point, also increases with increasing temperature *T* monolithically. Therefore, the atomic flux at L is higher than that at R according to Eq. (1). This indicates that more atoms enter the small region than flow out. Thus, more atoms are accumulated in this small region near the geometrical transition, allowing for the formation of MMs.

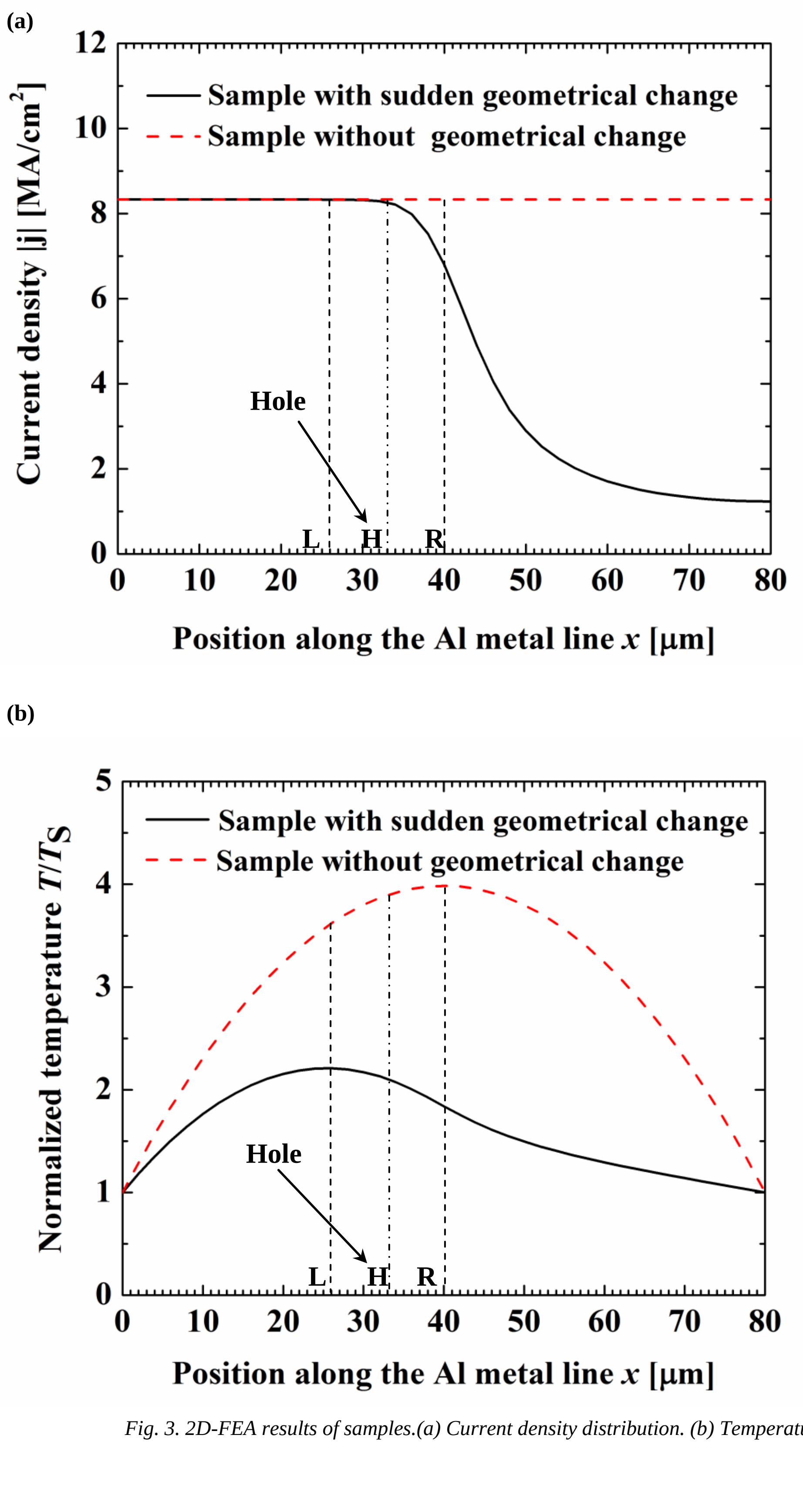

Fig. 3. 2D-FEA results of samples.(a) Current density distribution. (b) Temperature distribution.

Moreover, it is found that the trend of temperature distribution along the electron flow direction of the present sample with sudden geometrical change is quite different from that of the previous conventional one with slit located near the anode. For the former, the maximum temperature occurred near the geometrical transitional area. On the other hand, for the latter, the temperature increases gradually from the cathode to the anode, in which the maximum temperature takes place near the anode [7]. Although both sample structures can realize the fabrication of Al microspheres by electromigration, the ways to make atomic accumulation are quite different, which therefore makes the different current stressing condition to fabricate Al microsphere with the comparable size as stated before. Compared to that based on the previous sample structure with slit near anode [7], the present sample structure using geometrical transition to realize atomic accumulation provides another alternative to the introduction of slit for fabricating micro/nano materials with successful formation of Al microsphere and economic sample preparation.

For comparison, a similar FEA was also carried out on the sample without any geometrical change (Fig. 1b). The obtained current density and temperature distributions along the *x*-axis are also shown in Fig. 3. Taking a corresponding small region L-H-R centered at hole H, it is found that the temperature at L (on the left of H) is lower than that at R (on the right of H), and there is no change in current density. Therefore, the atomic flux at L is lower than that at R according to Eq. (1), contrary to what was observed for the sample with a sudden change in geometrical shape. This will lead to the possible depletion of atoms instead of accumulation because there are more atoms flowing out of the small region than there are flowing in.

4. Conclusions

In this work, an Al microsphere was fabricated at a predefined location by introducing a sudden change in the geometrical shape of an Al line sample, which led to a significant change in the current density and temperature at the predefined location near the geometrical transition. The induced decrease in the atomic flux along the electron flow direction in the small region, centered at a hole created in the predefined location near the geometrical transition, enhances the accumulation of atoms for fabricating MMs. The present technique, characterized by cost-effective sample preparation, is expected to be utilized to fabricate various MMs by optimizing the sample dimensions and current stressing conditions.

Acknowledgements

This work was supported by the Grant-in-Aid for Scientific Research (B) 23360050. Part of the experimental work was carried out at the Micro/Nano-Machining Research and Education Centre of Tohoku University. The simulations were performed using supercomputing resources at the Cyberscience Center of Tohoku University.

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