Enhancement of Al thin wire fabrication by using electromigration in relation to the discharge resistance of the atoms

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The utilization of electromigration for enhancement of Al thin wire fabrication was investigated. The experimental sample was a passivated Al line with a square hole at the anode end, and wire fabrication was affected by both the thickness of the passivation layer and the side length of the hole. The optimum value of the passivation layer thickness was determined. Both the time to failure of the Al line and the length of formed wire increased with increasing thickness up to the optimum thickness. Wire fabrication was also enhanced by increasing the side length of the discharge hole.

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1. Introduction

Metallic micro/nanowires (MNWs) are used as functional components in micro electromechanical systems (MEMS) and small devices. In particular, aluminum (Al) MNWs are of great importance owing to their advantages in lithographic processing and their low cost [1]. Various approaches have been reported for forming Al MNWs, e.g. glancing angle deposition on a high temperature substrate [2]. However, the technique can be used only under restricted experimental conditions. Stress migration (SM) can also be used to form Al nanowhiskers by means of the compressive stress release phenomenon; however, the positions of the formed MNWs cannot be predetermined [3-5].

Al microstructures including thin wires [6, 7], micro-spheres [8, 9], and micro-belts [10], have been fabricated successfully at predetermined positions by utilizing electromigration (EM), a physical phenomenon wherein metallic atoms are transported by the electron wind. The effect of the purity of Al source material on fabricating Al MNWs has also been reported [11]. In addition, controlling accumulation and discharge of Al atoms to form microstructures has been very recently reported in relation to the position of the bottom of the hole, the thickness of Al film and the current density [12].

As an extension of the previous work on EM-enhanced fabrication of Al thin wires, in the present study, the effects on Al thin wire fabrication of the thickness of the passivation layer and the side length of the discharge hole are investigated. Larger thickness and smaller side length increase the resistance of discharging atoms through the hole. If the resistance is so high that a large number of atoms accumulating at the anode end cannot be discharged through the hole, cracking occurs at the SiO_2/substrate interface adjacent to the Al line, and leads to a line failure, owing to the pressure caused by the accumulation of atoms at the anode end. Consequently, the enhancement of wire fabrication is approached by considering the pressure and the critical value of tensile stress at the fracture interface.

2. Experimental procedure

A 300-nm-thick TiN layer deposited on an oxidized Si wafer was used as sample substrate. A 600-nm-thick Al film was deposited on the TiN layer by vacuum evaporation; the purity of the Al source material was 99%. The Al and TiN layers were then patterned, and a slit was formed. Subsequently, an SiO_2 layer was deposited as a passivation layer on the surface of the sample; the thickness of the passivation layer at the anode end was controlled by deposition time and focused ion beam (FIB) etching [6]. The SiO_2 film was wet-etched to form pads through which current could be supplied. Finally, a square hole was formed at the anode end by FIB etching, and it was confirmed by end-point detection that the hole was etched through the passivation layer and Al film. The structure of the test sample is shown in Fig. 1.

The samples were placed on a ceramic heater, and subjected to a constant direct current. The temperature of the ceramic heater was kept at 613 K, and the current density was 2.4 MA/cm^2 for all samples, which is a suitable value for wire formation by EM in 600-nm-thick Al samples [11]. During the passage of current, the potential drop along the Al line was measured between the input and output pads. After the current was increased to a specific value, the potential drop started to increase with time. At the moment when the potential drop increased rapidly, the current supply was stopped in order to prevent the sample from being destroyed as a result of Joule heating. The time at which the current supply was halted was defined as the time to failure of the line.

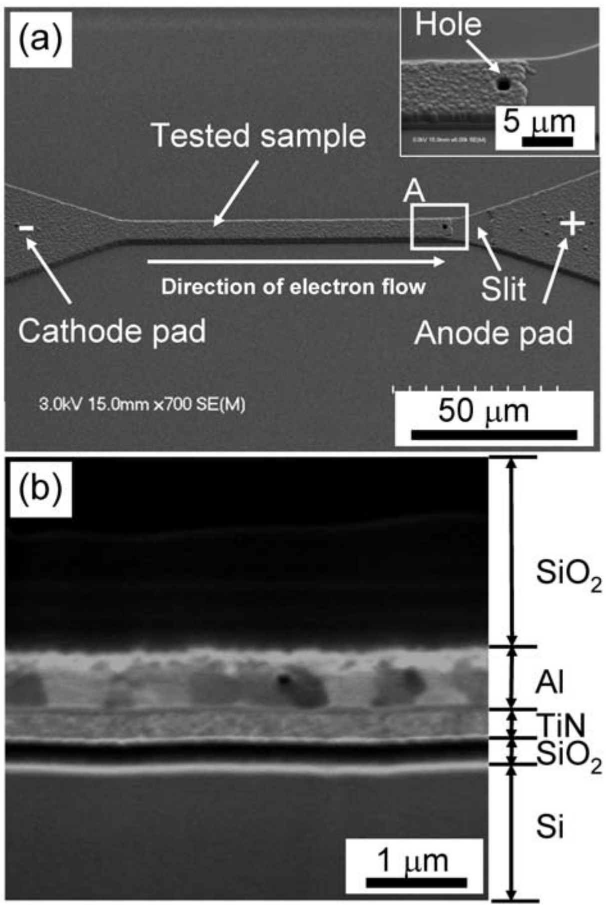

Fig. 1. Sample structure. (a) Top view with enlargement of part A, and (b) cross-sectional view.

3. Results

The experimental conditions and results are summarized in Table 1, where *T* is the thickness of the passivation layer at the anode end, *t* is the time to failure, and *l* is the side length of the square hole. F indicates that no wire was formed, S that a wire with length ≥50 μm was successfully formed, and M that a wire with length ≤10 μm was formed. Images of typical features after the passage of current, obtained by field emission scanning electron microscope (FE-SEM), are shown in Fig. 2. No wire was formed and fracture of the SiO_2/substrate interface adjacent to the Al line and the sample occurred in conditions 1, 2 and 3 (Fig. 2(a)); thin wires with length ≥50 μm were formed in conditions 4, 5, 6, 7, 10 and 11 (Figs. 2(c) and (g)); and thin wires with length ≤10 μm were formed in conditions 8 and 9 (Fig. 2(e)). The corresponding relationships between the potential drop and the current supply time for these samples are shown in Figs. 2(b), (d), (f) and (h), respectively. It is apparent that more atoms discharge from the hole when the time to failure extends.

3.1 Effect of thickness of the passivation layer

Fig. 3 shows the experimentally determined time to failure and length of the wire formed, in relation to the thickness of the passivation layer. Both *t* and the length increased with increasing *T* for *T*<3 μm, and the largest *t* and longest wires were obtained with *T*=3 μm. For *T*>3.5 μm, the time to failure reached a steady state, and no wire was formed because of fracture of the sample. The results show that the length of the wire increased as *t* increased, indicating that more atoms could be accumulated if the time to failure was extended.

Table 1. Experimental conditions and results.

Conditions	*T* (μm)	*t* (s)	*l* (μm)	Results[a]
1	5	291	0.8	F
2	4.5	311	0.8	F
3	4	223	0.8	F
4	3.5	1497	0.8	S
5	3.0	1667	0.8	S
6	2.5	1464	0.8	S
7	2.0	1290	0.8	S
8	1.5	716	0.8	M
9	1.5	714	0.8	M
10	5	1036	2.0	S
11	5	1058	2.0	S

[a]F indicates that no wire was formed, S indicates that a wire longer than 50 μm was successfully formed; and M indicates a wire shorter than 10 μm was formed.

The slopes of the curves in Fig. 2(b) and (f) are about 2.39×10^{-3} and 3.59×10^{-3} V s^{-1}, respectively, and significantly larger than the slope in Fig. 2(d), which is 0.55×10^{-3} V s^{-1}. This suggests that Al atoms discharged from the fractured area at the SiO_2/substrate interface at a higher rate. On the other hand, atoms discharged from the holes at lower rate and thin wires were formed.

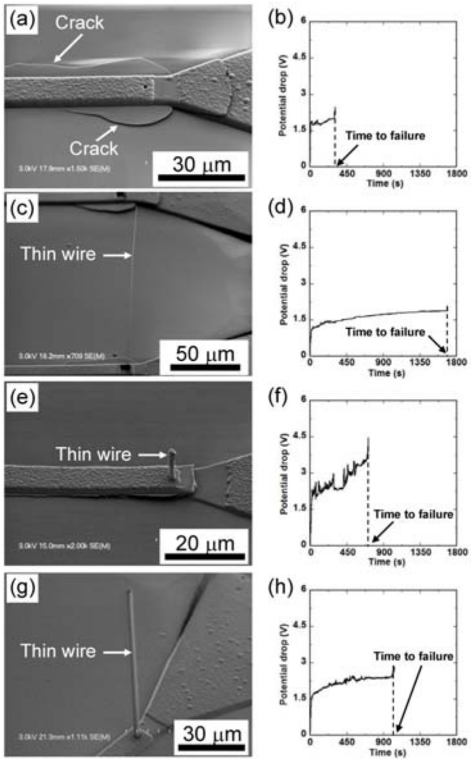

Fig. 2. FE-SEM micrographs of samples under conditions (Table 1): (a) 1, (c) 5, (e) 8, and (g) 10; after passage of current. The corresponding relationships between the potential drop and the current supply time are shown in (b), (d), (f) and (h), respectively.

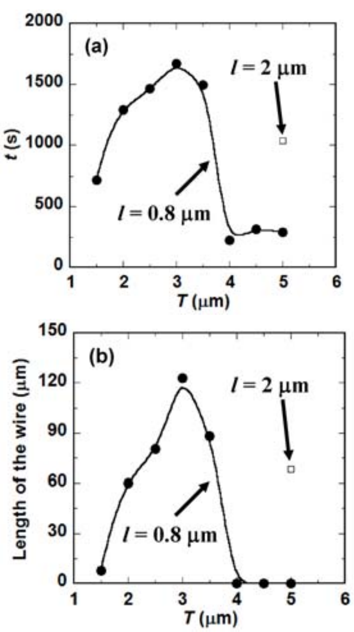

Fig. 3. Effect of the thickness of the passivation layer at the anode end on (a) the time to failure of the Al line, and (b) the length of the formed wire. The effect of the side length of the discharge hole on both the time to failure and the length of the formed wire is also shown.

3.2 Effect of side length of the hole

Line failure occurred near the anode end in the sample with a 5-μm-thick passivation layer and l =0.8 μm, and no wire was formed. However, the time to failure increased remarkably and a long wire was successfully formed when the side length was increased from 0.8 to 2 μm. The slope of the curves in Fig. 2(h) is about 1.25×10^{-3} V s^{-1}, indicating that atoms steadily discharged through the hole at a low rate.

4. Discussion

A pressure was created and increased with continuous accumulation of atoms at the anode end, and atoms were pushed out through the hole when the pressure was larger than the value corresponding to the discharge resistance, resulting in formation of wires. On the other hand, there was a critical tensile stress for fracture of the interface between the passivation layer and the substrate adjacent to the Al line. Adhesion was destroyed and cracks occurred if the pressure was so larger that the tensile stress at the interface exceeded the critical value.

There are two kinds of line failures with respect to the position at which line failure occurs. (I) Cracks initiate at the SiO_2/substrate interface adjacent to the Al line, leading to line failure near the anode end as shown in Fig. 2(a). Accumulated atoms cannot be discharged through the hole owing to high resistance, and preferentially enter the SiO_2/substrate interface, causing fracture. Atoms are then discharged from the fractured areas at a high rate. (II) Accumulated atoms at the anode end are successfully discharged through the hole at lower rate, extending the time to failure. After a large amount of atoms have migrated to the anode end, line failure occurs near the cathode end. In the latter case, wire fabrication can be significantly enhanced, and wire with substantial length can be formed. Note that to enhance wire fabrication, the discharge resistance of atoms through the hole should correspond to the tensile stress at the interface being less than the critical value for fracture of the interface.

It was shown that the discharge resistance decreased with decreasing T. In the case of l=0.8 μm, no wire was formed with T>3.5 μm, and the adhesion between the passivation layer and substrate was destroyed. On the other hand, in the case of T<2 μm, the passivation layer was so thin that the pressure caused by the accumulation of atoms was not able to be suppressed, as shown in Fig. 2(e). Therefore, the range 2≤ T≤ 3.5 μm was suitable for wire formation in the 600-nm-thick Al samples with l=0.8 μm, and the optimum value of T was 3 μm, while there was still a crack adjacent to the Al line. This crack may have been caused by further accumulation of atoms after formation of the wire. It has also been reported that 3.0-μm-thick SiO_2 can be used as a passivation layer for 750-nm-thick Al film to fabricate thin wires [10]. The pressure was effective in competition with the action of the discharge resistance, driving atoms out through the hole. We may assume that the suitable *T* will increase with increasing thickness of the Al film, because the pressure will increase with accumulation of more atoms under the same experimental conditions.

The discharge resistance also decreased with increasing *l*. For example, when the side length of the square hole in the sample with a 5.0-μm-thick passivation layer was increased from 0.8 to 2.0 μm, thin wires were successfully formed without crack formation adjacent to the Al line (Fig. 2(g)). In this case, the length of the formed wire was less than the wire formed in condition 5; however, the volume of the formed wire was larger than in condition 5.

5. Conclusions

Al wire fabrication can be enhanced by utilizing EM if the discharge resistance of the Al atoms, which increases with increasing thickness of the passivation layer and/or decrease of the side length of the hole, corresponds to the tensile stress at the SiO_2/substrate interface adjacent to the Al line being less than the critical value that causes fracture of the interface. The thickness of the passivation layer should be controlled in a suitable range, and the discharge resistance can be decreased with increasing the side length of the hole.

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