Al alloying effect in functionalization of mechanical resistance to foldable display interconnections

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ABSTRACT

For the metal interconnection in foldable displays, bending resistance is essential in addition to heat resistance and low electrical resistivity. The bending resistance of Al-Nd alloy interconnections can be controlled by precipitation of intermetallic compounds. Then, the Al alloy interconnections capable of dry-etching patterning have also been developed.

1 INTRODUCTION

Flexible displays have been attracting attention because they are thin and light, and have various functions, such as foldable, rollable and stretchable, which are not found in conventional rigid displays. Especially, foldable displays (bending radius: 1~5 mm) have already on sale in the market, and the demand for such displays is expected to increase considerably in the future [1-2].

The development of high resolution displays has been promoted, and required high-speed operation of the TFT (Thin Film Transistor). Therefore, Low Temperature Poly Silicon (LTPS), which has a higher carrier mobility, is essential. Although a high temperature up to about 600°C is usually applied in the manufacturing process of the LTPS TFT, recently, the process temperature has been lowered, to enable production at ~450°C. Therefore, the gate electrodes of foldable displays are required to have three properties, heat resistance (~450°C), low electrical resistivity and bending resistance [3].

For the gate electrodes of rigid displays, Mo or Mo alloys are used because of their excellent heat resistance. Unfortunately, the electrical resistivity of these metals is high, and these metal interconnections are disconnected when they are bent at a radius of 1 mm.

In contrast, we reported the bending resistance of Al-Nd alloys, which was used as a gate electrode for amorphous silicon (a-Si) TFTs. Al-2.0 at% and 4.0 at% Nd alloys interconnections were not disconnected after the bending test, and the increasing rate of electrical resistance was lower than that of pure aluminum (p-Al). [4] Several reasons why the bending resistance of Al-Nd allloy improved were assumed, such as precipitation of the intermetallic compound (Al_4Nd, precipitated after 450°C annealing process), hillock suppression, and its hardness. Among them, we focused on the precipitation of intermetallic compounds, and evaluated the influence of intermetallic compounds on bending resistance. However, since the Al-Nd alloys are difficult to dry-etch, it is required to search for Al alloy materials that can be dry-etched easily. Therefore, Al-Ta-based alloy, which contains other elements and can be dry-etched easily, was prepared. Al-Ta-based alloy also shows good heat resistance and low electrical resistance. Moreover, the bending resistance of Al-Ta-based alloy is also evaluated since intermetallic compounds is produced in it similar to Al-Nd alloys.

2 EXPERIMENT

Al-Nd and Al-Ta-based alloy thin films (thickness: 250 nm) were deposited by DC magnetron sputtering on 38-μm polyimide (PI) substrates at room temperature. In order to control the amount of Al_4Nd intermetallic compounds, the amount of Nd additions was set to 0.2~15 at%.

To investigate the bending resistance, straight-shape metal interconnections (width: 1.0 mm, length: 70 mm) were produced through a photolithography process. After patterning, the metal interconnections were annealed at 450°C for 1 hour in a N_2 atmosphere (Fig. 1(a)).

The bending test was conducted up to 100,000 times at a speed of 90 times per minute by in-bending flexion with a radius of 1 mm (Fig. 1(b)).

The bending resistance was evaluated by the electrical resistance change rate (R/R_0), where R is electrical resistance after bending test and R_0 is electrical resistance before bending test.

The hardness of the interconnections was measured by nanoindentation to confirm the difference in hardness depending on the Nd addition.

The dry etching of Al alloys was performed by using $Ar/Cl_2/BCl_3$ mixed gas. The etching rate of each alloy was compared with that of p-Al.

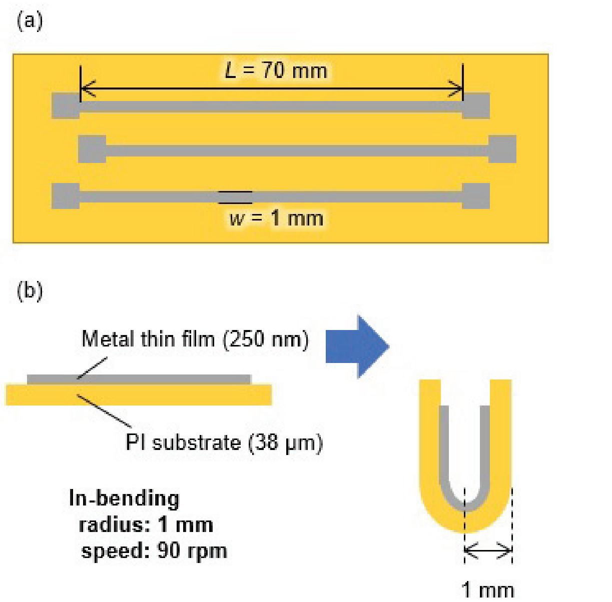

Figure 1. (a) Schematic diagram of metal wirings on PI substrate (b) Schematic image of the bending test

3 RESULTS

Table. 1 shows the hardness of Al-Nd alloy films after 450°C annealing. It was observed that the hardness increased as the Nd addition increased. This correlates with an increase in the precipitation amount of the intermetallic compound Al_4Nd.

Table. 1 Hardness of Al-Nd films

sample	Hardness (450°C-annealed)
p-Al	71
Al-0.6 at% Nd	105
Al-2.0 at% Nd	144
Al-4.0 at% Nd	174
Al-7.5 at% Nd	329
Al-15 at% Nd	427

Figure. 2 shows the photomicrographs of Al-Nd alloys films surface after the 10,000 bending. Cracks were observed in all samples after bending test. The cracks on some Al-Nd alloys samples (Nd: 0.2~4.0 at%) are mesh-like shape. On the other hand, in the other samples with Nd addition of 7.5 and 15 at%, linear cracks along the bending direction were observed.

In Figure. 3, the transition of R/R_0 is plotted for each bending cycle. Unfortunately, Al-15 at% Nd sample was disconnected up to 100,000 bending cycles. On the other hand, p-Al sample and Al-Nd (Nd: 0.2~4.0 at%) alloys samples could be bent up to 100,000 times without disconnection. The R/R_0 after 100,000 bending cycles of p-Al sample increased to 180%, while the Al-2.0 at% and 4.0 at% Nd alloys samples only increased by about 140%.

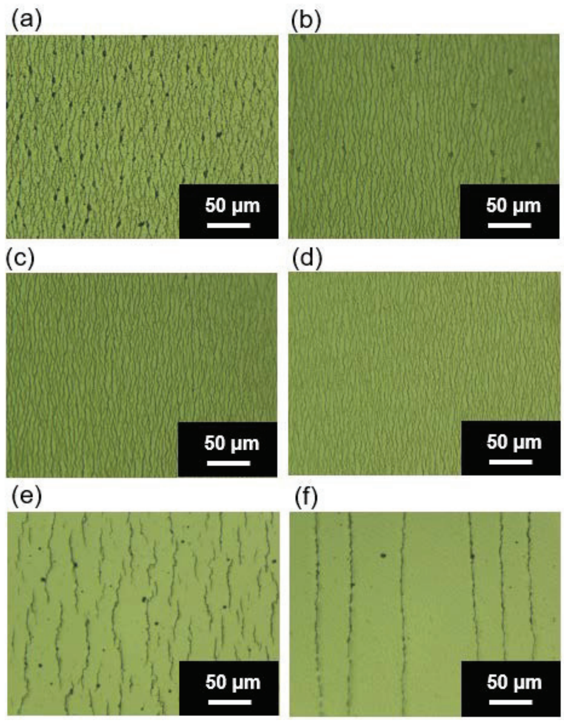

Figure 2. Surface optical micrographs of (a) p-Al, (b) Al-0.6 at% Nd, (c) Al-2.0 at% Nd, (d) Al-4.0 at% Nd, (e) Al-7.5 at% Nd, (d) Al-15 at% Nd after 10,000 bending

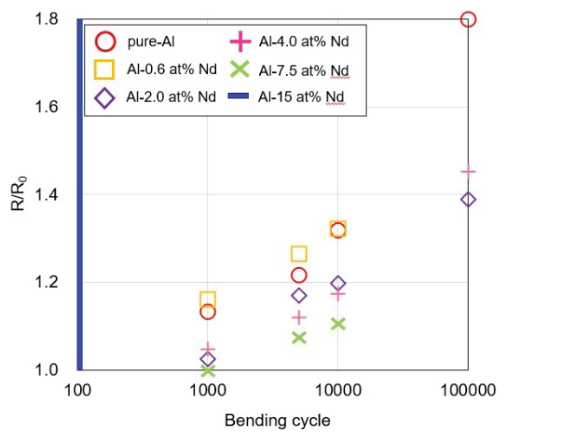

Figure 3. Resistance change rate (R/R_0) of 450°C-annealed p-Al, Cu and Al-Nd after bending test

4 DISCUSSION

The increase in R/R_0 after bending cycles is related to the cracks progression. Figure 4 shows the crack density and its maximum length with various Nd addition. Note that this graph shows after 10,000 bending. The Maximum crack length and crack density decrease with increasing Nd addition.

Figure 5 shows cracks progression in the Al-2.0 at% and 4.0 at% Nd alloys, which show good bending resistance after 100,000 bending with plane-view TEM.

Compared to p-Al, the grain size of Al-Nd alloy decreases with increasing Nd addition. Al_4Nd is at the triple point of the grain boundary, and it prevents the diffusion of Al along grain boundary, and therefore, makes it possible to miniaturize in order to inhibit the grain growth [5-6]. After further observation of the crack area of Al-Nd alloys, the cracks were seen to be selectively propagated in the aluminum matrix part avoiding the harder Al_4Nd intermetallic compounds.

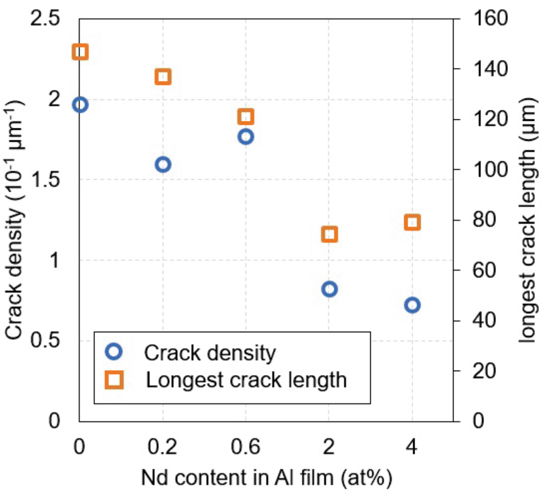

Figure. 4 Correlation graph of crack density, longest crack length and Nd addition

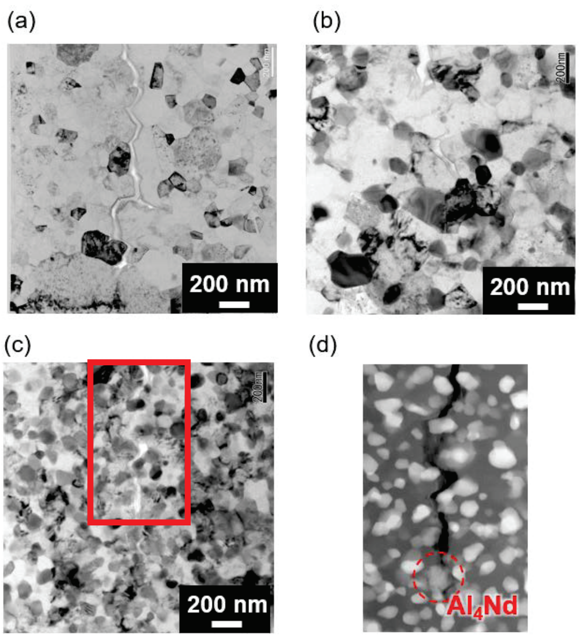

Figure 5. Plane-view TEM of (a) p-Al, (b) Al-2.0 at% Nd and (c) Al-4.0 at% Nd after bending test. (d) shows a Z-contrast image of enclosed area by a red rectangle in (c)

Moreover, it was observed that Al_4Nd inhibits the crack progression (Fig. 5(d)). These results show that the precipitation of Al_4Nd intermetallic compound strengthens the grain boundaries and suppresses the cracks progression. However, if a large amount of Al_4Nd intermetallic compounds is precipitated (ex. Al-7.5 at% and 15 at% Nd), the Al-Nd interconnections become harder, and disconnect after bending test. Therefore, the amount of Al_4Nd intermetallic compound precipitation and bending resistance can be controlled by Nd addition, and there is the optimal Nd addition (2.0~4.0 at%) that can suppress the increasing rate of electrical resistance.

5 Bending resistance of Al-Ta-based alloy

Based on the idea that precipitation of intermetallic compounds improved bending resistance of metal interconnection, we extracted Al-Ta-based alloy that generate intermetallic compounds similar to Nd element. The Al-Ta based alloy shows good heat resistance and low electrical resistance. Therefore, its bending resistance is also investigated.

A bending test was performed under the same conditions, and R/R_0 value of the Al-Ta based alloy was same as that of Al-Nd alloy (Fig.6). According to planar TEM observation, intermetallic compounds were precipitated and dispersed in the Al-Ta based alloy sample. Therefore, it is implied that the Al-Ta based alloy with the bending resistance is strengthened by the precipitation of intermetallic compounds, similar to Al-Nd alloy (Fig.7).

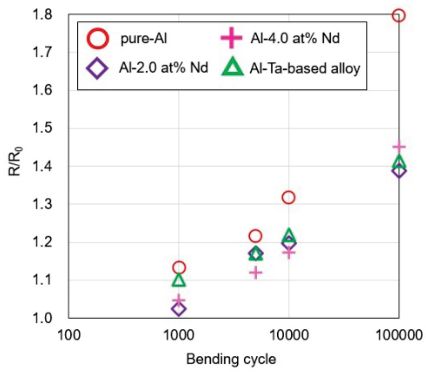

Figure 6. R/R_0 after bending test

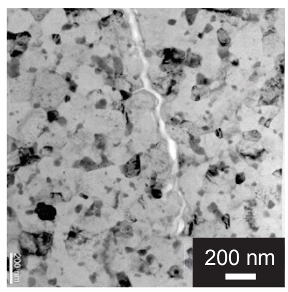

Figure 7. Plane-view TEM image of Al-Ta-based alloy

Furthermore, the results of examining the dry etching rate of Al-2.0 at% Nd and Al-Ta-based alloy is shown in Figure.8. Compared to the etching rate of p-Al, Al-2.0 at% Nd shows low etching rate (about 10% of p-Al). On the other hand, the etching rate of Al-Ta-based alloy is about 80% compared to p-Al. This result means that our Al-Ta-based alloy satisfied three elements which is needed for foldable displays, and its ease of dry etching can be applied to a gate electrode of foldable display.

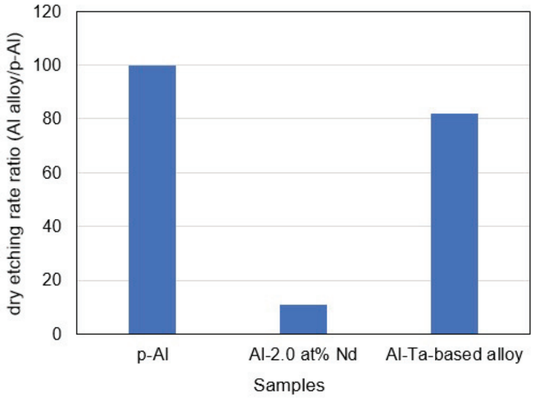

Figure 8. Dry etching rate ratio of Al alloy samples

6 CONCLUSIONS

The bending resistance of Al-Nd alloys is related to the precipitation of Al_4Nd intermetallic compounds. This leads to strengthen the grain boundary and suppress the crack propagation. It is essential to control the amount of Nd added to satisfy good bending resistance.

It was also found that the Al-Ta-based alloy shows bending resistance by the same mechanism as Al-Nd. It exhibits heat resistance and low electrical resistance in addition to the ease of dry-etching processing. Therefore, it is expected to be used as the gate electrode of next-generation foldable display.

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