Micro-transfer-printing of Au thin-film with Atomic diffusion bonding: effects of air-exposure time and stamp modulus

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KEYWORDS: Transfer printing, Atomic diffusion, Au thin-film, Air-exposure, Modulus

This present study describes micro-transfer-printing of Au thin-film with the assistance of atomic diffusion bonding. The Au thin-film, coated on micro-ridges of h-PDMS stamp, is contacted to another Au thin-film previously coated on the substrate. These two Au thin-films are strongly bonded by inter-diffusion of Au atoms, and then the Au thin-film is transfer-printed from the stamp to be formed in a micro-pattern onto the substrate in atmospheric condition. This study is intended to show effects of air-exposure time and stamp (indentation) modulus on the transfer printing of line-patterned Au thin-film assisted with atomic diffusion bonding. The longer time of air-exposure make more contamination, adsorbing water molecules, to decrease transfer rate. It is found that both the Au-coated h-PDMS stamp and the substrate need to be kept in dry and low humidity environment before transfer-printing. The modulus of h-PDMS stamp is controlled with the ratio of prepolymer/curing agent. The lower modulus of h-PDMS stamp enables higher transfer rates due to large contact area. It is demonstrated that 150-nm-wide line pattern of Au thin-film can be transfer-printed.

1. Introduction

Transfer printing is a technology to transfer a thin-film coated on a stamp to a substrate. The technology requires strong adhesiveness between the thin-film and the substrate, so the authors have proposed and demonstrated micro-transfer printing assisted with atomic diffusion bonding (ADA-TP) as shown in Figure 1.[1] By using inter-diffusion of metal atoms between contacted two thin-films, strong adhesive force is generated to improve its transferability with low contact pressure and low substrate temperature.[2] The inter-diffusion is generated in contacted clean thin-films. Previous studies showed bond strength significantly decreased with long air-exposure time after thin-film formation in the case of wafer-bonding.[3] It is also considered that both air-exposure time and stamp modulus affect thin-film transferability in ADA-TP because of cleanliness and true contact area. In our previous study, nano-scale patterns of Au thin-film also had not been fabricated by ADA-TP, because it utilized the micro-meter scale of h-PDMS stamp.

This present study is intended to show effects of air-exposure time and stamp (indentation) modulus on the transferability of ADA-TP, and also to demonstrate a fabrication of a nano-scale pattern.

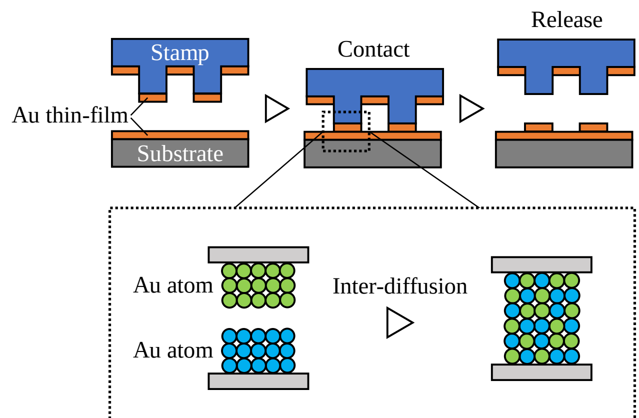


Fig. 1 Schematic diagram for ADA-TP

Table 1 Preparation of h-PDMS stamp

Prepolymer	3.4 g	
Curing agent	0.5 g	1.0 g
Curing temperature	343 K	
Geometry of master mold	150-μm-wide grooves	150-nm-wide grooves

2. Materials and methods

A h-PDMS stamp was prepared as follows. As shown in Table 1, two different moduli of h-PDMS stamps were fabricated with the ratio of prepolymer/curing agent. The mixture of the prepolymer (VDT-131, Gelest Inc.) and curing agent was polymerized in a master mold, which was previously made by photo- or e-beam lithography.[4] The indentation modulus of fabricated h-PDMS stamps were 7.7 and 34 MPa. The h-PDMS stamps have 150-μm or 150-nm-wide micro-ridges, and they were coated with 50-nm-thick Au thin-films by vacuum vapor deposition and ECR sputtering. Meanwhile, the substrates were also previously coated with 30-nm-thick Au thin-film. Both the h-PDMS stamp and the substrate was kept in a storage box, where humidity and temperature were kept being 15, 30, and 50% and room temperature (298 K), respectively. The air-exposure time were changed with the range of 30 minutes and 7 days. These water contact angles (wettability) of Au thin-films surfaces were measured to investigate their cleanliness.

Figure 2 shows an experimental set-up for ADA-TP. The stamp was contacted to the Au-coated substrate with contact pressure 500 kPa, substrate temperature 383 K or 423 K, and contact time 10 - 600 s.

3. Results and discussion

3.1. Effect of air-exposure time

Figure 3 shows the water contact angles of the Au thin-films at each humidity after air-exposure. The contact angle increased with air-exposure time, but there were major differences in increasing rate of contact angle between humidity conditions. In another analysis of FT-IR, C-O peaks indicating organic molecules also increased with humidity and air-exposure time. It was reasonable that the Au surfaces were contaminated with adsorption of organic molecules. Meanwhile, it was also confirmed that surface roughness was almost same to be less than 0.8 nm *Sa* regardless of air-exposure time and humidity.

Figure 4 shows microscope images of the substrate after ADA-TP of Au thin-film at 383 K. The Au thin-films were transfer-printed to the Au-coated substrate, but their transfer rates changed with both air-exposure time and humidity. Transfer rate is calculated by area of transferred Au thin-film divided by contacted micro-ridge area of stamp. Figure 5 shows the relationship between air-exposure time and the transfer rate. In the case of 15% humidity, the transfer rate was kept being more than 90% for 7 days of air-exposure time. Meanwhile, the Au thin-film exposed in 50% humidity had not been transfer-printed after 2 days.[5]

It is found that lower humidity allows the Au thin-film to be successfully transfer-printed, as it generates inter-diffusion of Au atoms between contacted thin-films to provide adhesive strength for ADA-TP. The allowable air-exposure time for ADA-TP was longer than that case of wafer bonding using inter-diffusion of atoms.[2]

3.2. Effect of stamp modulus

The modulus of h-PDMS stamp also affected transfer rate of Au thin-film as well as air-exposure time. Figure 6 shows the relationship

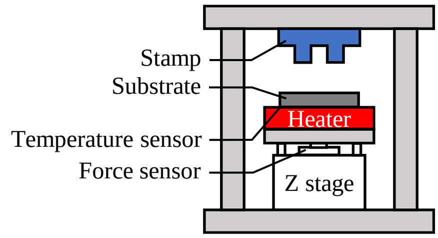


Fig. 2 Experimental set-up for transfer printing

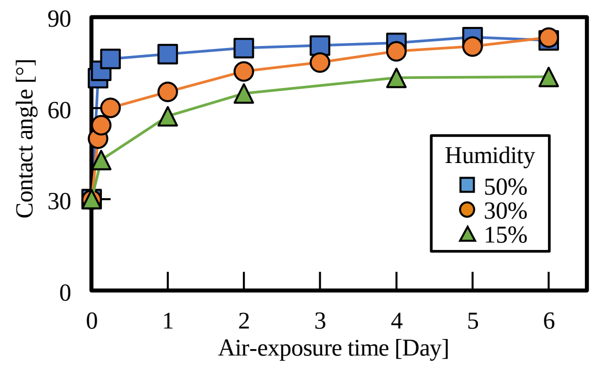
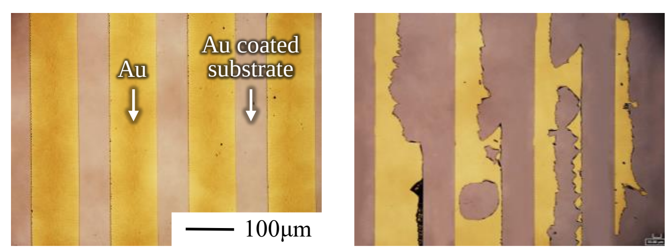


Fig. 3 Relationship between air-exposure time and contact angle



(a) 15% humidity (7 days) (b) 50% humidity (1 day)

Fig. 4 Substrate surfaces after ADA-TP of Au thin-film

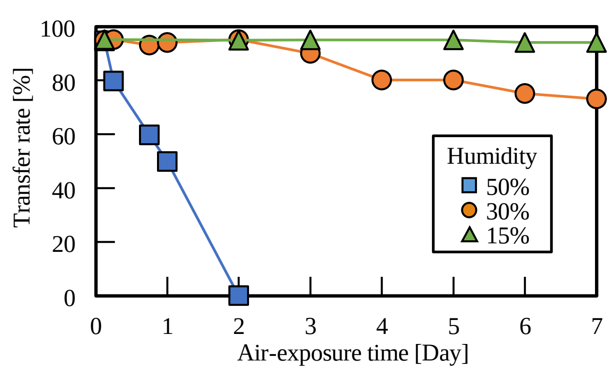


Fig. 5 Relationship between air-exposure time and transfer rate

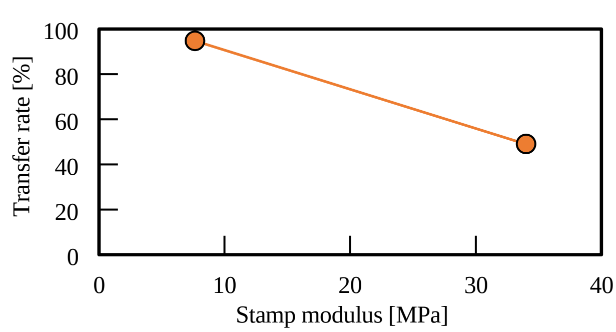


Fig. 6 Relationship between stamp modulus and transfer rate

between stamp (indentation) modulus and transfer rate. The Au thin-film was transfer-printed at 423 K. The lower modulus of the stamp makes transfer rate increased, as it expanded true contact area of Au thin-films. It enabled much shorter processing time for ADA-TP as compared to that of wafer bonding, although there should be appropriate range of stamp modulus.

3.3 ADA-TP of Au nano-pattern

Figure 7 shows SEM images of the substrate after ADA-TP of Au thin-film at 423 K using the 150-nm-wide micro-ridge stamp. The 150-nm-wide line pattern of Au thin-film was accurately transfer-printed on the Au-coated substrate as well as that of the micro-pattern. In the nano-scale interfaces between the contacted Au thin-films, the Au atoms successfully inter-diffused to provide enough adhesiveness for transfer-printing. It was demonstrated that ADA-TP of Au thin-film could be used for nano-pattern fabrication.

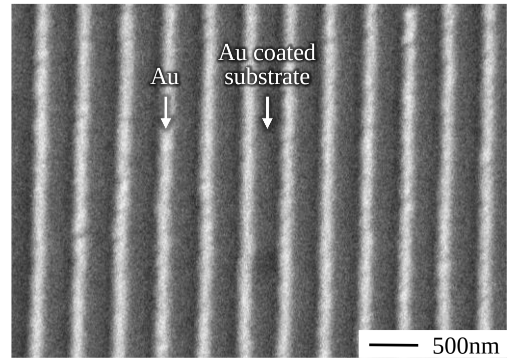


Fig. 7 SEM image of the substrate after ADA-TP of Au thin-film

4. Conclusions

This present study is summarized as follows.

(1) The Au thin-film could be transfer-printed even after 7 days of air-exposure, as it was kept in low humidity less than 15%.
(2) The lower modulus of stamp makes transfer rate of Au thin-film higher.
(3) Nano-pattern was fabricated by ADA-TP of Au thin film.

Acknowledgement

The authors wish to thank Ms. Ito of ELIONIX INC. for nano-indentation tests. This research was supported by Grant-in-Aid for Scientific Research (JP22H01377) and the Foundation for Promotion of Machine Tool Technology.

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