Fracture behavior of thin aluminum films on soft substrate

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Abstract
Thin metal films on soft substrate are conventional in flexible electronics and flexible devices. Thermal stress often exists in the thin metal films due to thermal mismatch during the physical vapor deposition (PVD) process, which leads to the fracture failure of metal films. Theoretical analysis and numerical simulations have predicted that the cracking of a thin stiff layer on a soft substrate depend on the relative stiffness and thickness of the film and the substrate. However, few experimental results reported support the hypothesis.
In this paper, An experimental investigation is conducted to study the fracture behavior of the aluminum films on soft Polydimethylsiloxane(PDMS) substrate during physical vapor deposition. It has been found that when the thickness of the aluminum film is relatively smaller, surface wrinkling is induced to accommodate the mismatched strain between the substrate and the film. When the thickness of the aluminum film is relatively larger, cracking of the film occurs.
Keywords Aluminum film, PDMS substrate, PVD process, Fracture behavior

1. Introduction

Films/substrate structures have been widely researched for the extensive application of this structure. Thin stiff film including metal film and non-metal film on soft substrate are exploited for the use of flexible electronics and devices [3,8-10,13,14]. Several ways have been applied to fabricate the relatively thin solid film on the flexible substrate forming flexible structures. Transferring the thin silicon film onto the pre-stretched soft PDMS substrate leading to the waving surface structures is a frequently used process [4]. Casting the viscous PDMS on the metal foils, and then conducting a photolithography process to obtain the structure is another means[16]. Evaporation and sputtering are two deposition means forming several nanometers to micrometers thick film on the substrate [6,11,15]. During the deposition process, the temperature on the surface of the substrate will rise and leads to thermal expansion of the substrate. The PDMS substrate is heated when the gold film is deposited onto the substrate [1]. Because the thermal expansion coefficient is several times larger than the gold film. When the surface temperature cools down, a thermal mismatch will be produced. From former observation [1], this thermal mismatch will lead to wrinkling of the film on the soft substrate, which is generally produced in other experiments [7].
In this paper it is found wrinkles will be formed on the film when the thickness of the film is the range of several hundred nanometers. When the thickness of the film exceeds this confine, approximate orthogonal cracks occur on the film. The detailed illustration of this difference is given out from the experimental results.

2. Experimental details

In our experiment, aluminum films with different thickness have been fabricated on the PDMS substrate. The PDMS is formed by mixing Sylgard 184 silicone elastomer with the curing agent at ratio 10:1 (by weight) and then the uncured mixture is spread on the glass substrate, which is placed in a vacuum drying oven at temperature 70℃ for an hour later. The cured PDMS have the same smooth surface with the glass substrate. The thickness of the PDMS substrate is in the range of 1-2mm. Pure aluminum is deposited on the PDMS substrate by E-beam evaporation at pressure of 5 ×10-5 torr. The elastic modulus of the PDMS substrate is 2.2 Mpa [7]. The elastic modulus and

Possion's ratio of the aluminum film are 72Gpa and 0.33 respectively. During the deposition process, the surface temperature of the substrate will rise and this leads to a thermal expansion of the substrate. When the deposition finished, the surface temperature cools down. Because the thermal expansion coefficient of the PDMS substrate is several times larger than that of the aluminum film, a thermal mismatch will be produced between the substrate and the film. This strain mismatch will lead to the surface wrinkles of the specimen when the thickness of the deposited aluminum film is in the range of several hundred nanometers. But when the thickness exceeds that confine, cracks will occur generally on the aluminum film. Aluminum film with thickness 40nm, 150nm, 200nm, 260nm and 700nm are fabricated on the PDMS substrate. Different experimental phenomena reflecting different mechanical behavior are observed after the deposition of the film under the microscopy.

3. Experimental results and discussions

During the deposition of the aluminum, the cooling of the aluminum steam on the surface of the PDMS substrate leads to the temperature elevating. After deposition, the temperature cools down. And this change leads to a deformation mismatch due to the distinct difference of the thermal coefficient of these two materials. The induced compressive stress in the film can be expressed as [1]:

$$\sigma = \frac{E_f(\alpha_f - \alpha_s)(T_D - T)}{(1-\upsilon_f)} \tag{1}$$

In the expression, the subscripts *f* and *s* represent the film and substrate respectively. T_D represents the deposition temperature and T corresponds to the cooled down temperature. α represents thermal coefficient of the film and the substrate respectively. υ is the Possion's ratio of the film. The thermal coefficient of the PDMS substrate and the aluminum film is about 300×10^{-6} and 20×10^{-6}. For the aluminum film with thickness of several hundred nanometers, wrinkles occur to accommodate the deformation mismatch.

For the film with thickness of 40nm, no surface wrinkles are found under the microscopy. This can be understood that the surface temperature during the deposition of the 40nm thick film is below the critical buckling temperature. For the film with thickness of 150nm, disordered wrinkles (Fig.1) can be observed under the microscopy. The measured wavelength for the wrinkles is about 10 μm. The overall estimation of the wavelength of the buckled wrinkles is [5]:

$$\lambda_c = 2\pi h\left[\frac{E_f(1-\upsilon_s^2)}{3E_s(1-\upsilon_f^2)}\right]^{1/3} \tag{2}$$

According to the theoretical solution, the wavelength of the film with thickness 150nm is about 20 μm, two times of the experimental result. This discrepancy comes mainly from two aspects: the simplification of the theoretical model and the neglecting of the change of the surface elastic modulus of the PDMS substrate [1].

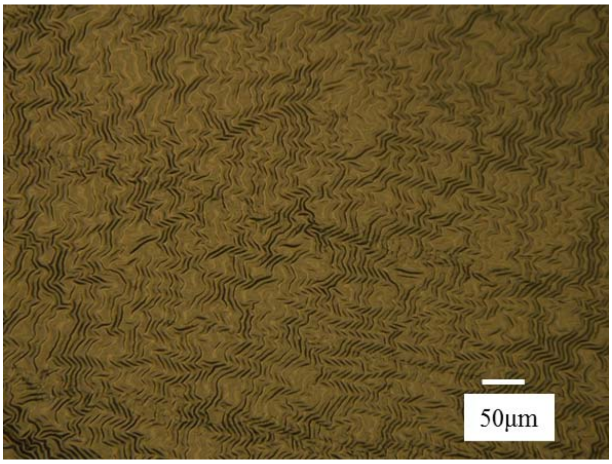

Figure 1. Wrinkling surface of the aluminum film with thickness 150nm on the PDMS substrate

The wavelength of the wrinkles of the film with thickness 200nm and 260nm are about 12 μm and 17.5 μm respectively (Fig.2). From Eq.2, it can be seen that the buckling wavelength only rely on the thickness of the film for the aluminum film on PDMS substrate. But this is not the real case. The deposition temperature varies with the thickness of the film. So the elastic modulus of the PDMS substrate changes to a certain extent. The wavelength does not simply rely on the thickness of the film, but also the surface temperature which may alter the surface elastic modulus of the PDMS substrate.

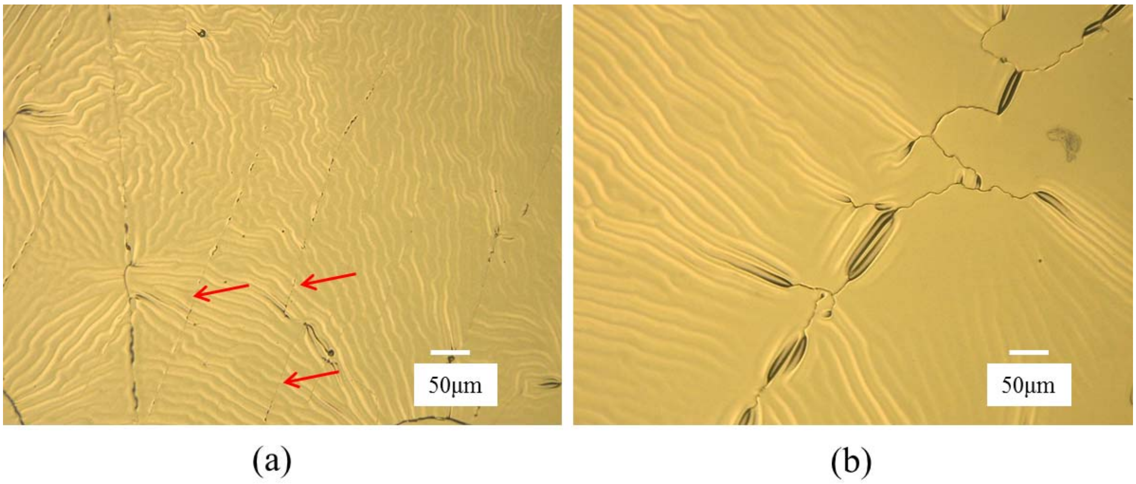

Figure 2. Wrinkled surface of the aluminum film with thickness 200nm and 260nm on soft PDMS substrate

From the observation, the wrinkles are mostly initiated from a flaw, which may induce stress concentration. There are some cracks occurring in the aluminum film (marked by red arrow in Fig.2 (a)). This can be understood that the wrinkles occurring vertical to the maximum compressive stress and. In the direction vertical to the maximum compressive stress, the tensile stress may be induced, which leads to cracking of the film in the direction vertical to the wrinkles.

For the aluminum film with thickness of 700nm, there are definitely no wrinkles formed on the film. Instead of this, approximate vertical cracks appear in the aluminum film (Fig.3). In former report, wrinkles formed on the PDMS substrate have been researched from experiments and finite element modeling. But few reports concern the cracking behavior of the stiff film on the PDMS substrate. This is mainly because the film thickness in former research work is relatively small. For film with relatively large thickness, cracking may be induced for mismatched strain. In this experiment, aluminum film is found cracking on the PDMS substrate with thickness of 700nm.

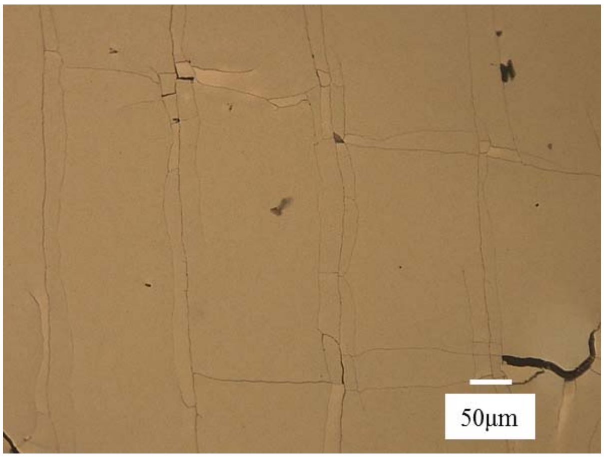

Figure 3. Cracking of the aluminum film on the PDMS substrate

Cracking substitutes wrinkling for the aluminum film with relatively larger thickness. In theoretical analysis, the bending equilibrium equation of the wrinkles formed on the thin stiff film is [12]:

$$\frac{E_f I}{1-\upsilon_f^2}\frac{d^4 w}{dy^4}+F\frac{d^2 w}{dy^2}+Kw=0 \tag{3}$$

Where w is the displacement of the film in z direction (Fig.4), the expression of w has been obtained from both theory and experiment, which can be expressed by [2]:

$$w(y)=A(1+\cos\frac{2\pi y}{\lambda}) \tag{4}$$

Where λ is the buckling wavelength and A is buckling amplitude of the wrinkles.
$I=h^3/12$ is the second bending moment of the film around the x axis per unit width. F is the compressive force provided by the substrate in the film. K reflects the influence of the underlying substrate expressed by [2]:

$$K=\frac{E}{1-\upsilon^2}\frac{\pi}{\lambda} \tag{5}$$

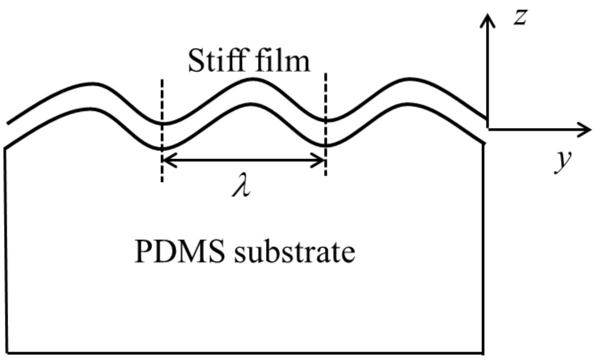

Figure 4. A schematic of the surface wrinkling on stiff film/soft substrate

F is derived from Eq.3-5 and expressed by [12]:

$$F=E_f I\left[\frac{4\pi^2}{(1-\upsilon_f^2)\lambda^2}+\frac{E}{4\pi(1-\upsilon_f^2)E_f I}\lambda\right] \tag{6}$$

In Eq.6, it can be seen that the compressive force in the film is in proportion to the thickness of the film. For the overall mechanical behavior of the film/substrate, the compressive stress is in linear with the thickness of the film. In local, the tensile stress at the crest induced by bending of the film is in the same increasing rate with the compressive stress in the film. When the tensile stress at the crest exceeds the tensile strength of the aluminum film, the film will crack instead of wrinkle to accommodate the mismatched strain. Fractured ribbons are induced during the cracking of the film (marked by red arrows). The fractured ribbons released the compressive force of the film. And the stress in the isolated fractured fragment is insufficient to lead to wrinkling of the film. The buckling and wrinkling behavior of the film transfer into the fracture behavior of the film when the thickness of the film is relatively larger.

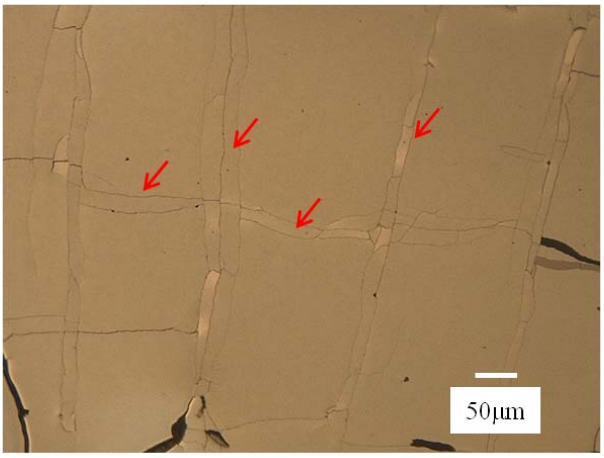

Figure 5. Approximately vertical cracking of the film and fractured ribbons (marked by red arrows)

4. Conclusions

In this paper, wrinkling and cracking behavior of the aluminum film on the PDMS substrate have been studied from experimental results. For aluminum film with smaller thickness (less than several hundred nanometers), wrinkling is mostly likely to happen due to the mismatched strain. When the thickness of the aluminum film is relatively larger, cracking substitutes the wrinkling to accommodate the mismatched deformation between the film and the substrate. The reason of this transformation lies in the increasing of the tensile stress with the thickness of the film. When the tensile stress in the film exceeds the tensile strength of the aluminum film, cracking behavior of the film predominates.

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