MECHANICAL BEHAVIOR OF METALLIC THIN FILM ON POLYIMIDE SUBSTRATE

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ABSTRACT

The systems composed of thin metallic film on flexible polymeric substrate are used in many technical applications, such as OLED (organic light emitting display), MEMS (micro electro-mechanical systems) especially on bio application and flex chip in semiconductor device. Knowing the mechanical behavior of film on substrate system is essential to design the system and asses the reliability. In this paper, the mechanism of crack propagation in metallic film on polymeric substrates have been studied in situ optical microscope and atomic force microscopy observation of copper submicron films on polyimide substrate under tensile stress. The observation and stress analysis show that the growth of crack in film has three stages. At first stage, the crack of film initiates and grows by tensile stress of film-Mode I loading, where the principal load is applied normal to the crack plane, tends to open the crack. The second stage is a buckle formation and the last stage of crack growth is accompanied with buckling of film. It shows that lateral mismatch strain owing to cracked film induces the delamination between film and substrate and buckling of film spontaneously. A buckle formation occurs one after the other on each side of crack line is main mechanism of crack growth in second and last stage.

Introduction

For many years, thin films have been extensively used in many technical applications. With increasing importance of thin film as a structural material, research related on measuring mechanical properties of thin film is performed extensively. According to the result of many researchers, the mechanical strength of metallic thin film is much higher than bulk material by an order of magnitude. Also elongation at fracture, however, is very small in comparison with bulk material as several percent of strain [1, 2].

Like measuring mechanical properties of thin film, understanding of mechanical behavior of film on substrate is important to design and asses to reliability of film-on-substrate structure. This structure is commonly encountered in a variety of application, such as OLED (organic light emitting display), MEMS (micro electro-mechanical systems) especially on bio application and flex chip in semiconductor device. The films on substrate are often under residual stress, originating form epitaxy, deposition process, or thermal expansion mismatch. Stress concentration at the film edge makes edges preferred sites to initiate delamination along the film/substrate interface. Although various crack patterns in thin films might develop due to crack interaction, the basic mode of thin film cracking is crack propagation perpendicular to the film/substrate interface. M. George and et al. [3] observed the crack evolution in case of a nickel thin film on polyimide substrate when an external tensile stress is applied step-by step to the substrate. H.H Yu and J. W. Hutchinson [4] analyzed the delamination of residually stressed thin film strip depending on strip width and film/substrate elastic mismatch.

Crack growth or delamination of film can be explained as a creating a new surface at an expense of elastic energy release of structure based on linear elastic fracture mechanics. There are three types of lading that a crack or delamination can experience Mode I loading, where the principal load is applied normal to the crack plane, tends to open the crack. Mode II corresponds to in-plane shear loading and tends to slide one crack face with respect to the other. Mode III refers to out-of-plane shear. A cracked or delaminated body can be loaded in any one of these modes, or a combination of two or three modes [5].

In this paper, mechanical behavior of the wide metallic submicron film on polyimide substrate under tensile stress was observed using microscope and atomic force microscopy (AFM) and then explained qualitatively based on linear elastic fracture mechanics. We used a tensile tester of our own design to apply uni-axial tensile stress to the film/substrate specimen.

Experimental Process

Polyimide foil (Kapton™ Dupont) of thickness 12.7μm was used as substrate as it has good thermal and chemical resistances. As shown in Figure 1, this material can be also deformed elastically to strains of more than 1% with 3 GPa of Young's modulus which was obtained from tensile test of bare Kapton™ specimen using the apparatus of our own design [6].

As shown in Figure 2. The copper thin film with thickness of 0.2 μm were deposited with a parallel gage section of length 10mm and width 2mm on rectangular Kapton™ substrate (7mm×20mm). The fabrication process is illustrated in Figure 3. At first, the surface of Kapton™ substrate was air blown and cleaned with acetone. Then, put Kapton™ substrate on silicon wafer and cover it with shadow metal mask. Finally copper films are deposited through the shadow mask on Kapton™ substrate with 10nm/s rate in 10^{-7} Torr environment.

To apply tensile stress of film-on-substrate system and records the image of film surface, a sophisticate apparatus was developed as in Figure 4. DC motor actuator makes linear displace of one side of specimen. Load and displacement are measured by load-cell and laser sensor respectively and image of film surface is recoded by the microscope with a built-in CCD simultaneously. Because the gage length of specimen is 10mm and the grip –to-grip distance is 15mm, the strain at 150μm displacement is somewhat larger than 1%. Tensile tests were performed with an elongation of 400 μm (about 3 % strain) and an approximate speed of around 4μm/s. During tensile test crack initiation and propagation images obtained from microscope with built-in CCD are synchronized with the sensor signal. That synchronization enables us to know under what loads and displacement conditions when the phenomenon occurs. Detail shapes of crack and buckled film were measured by atomic force microscopy (AFM) using small step-by-step tensile apparatus of our own design.

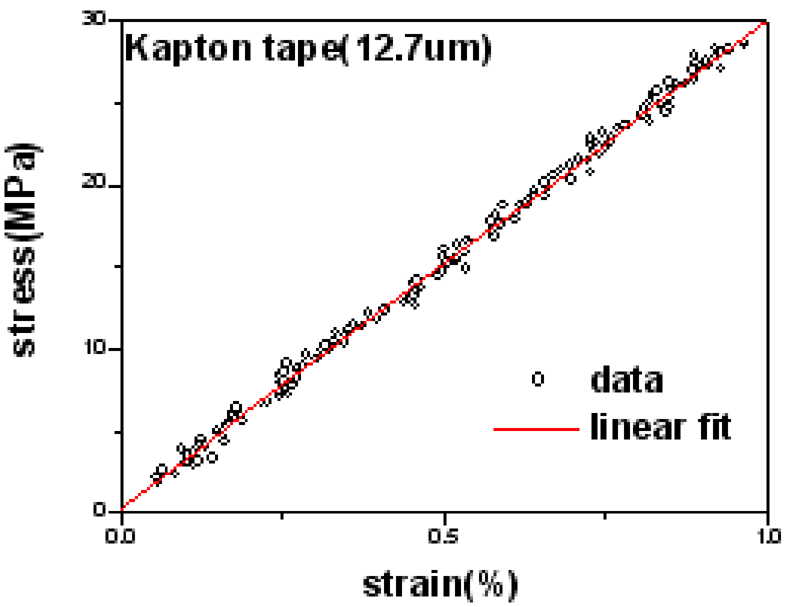

Figure 1. Stress-strain curve of Kapton™

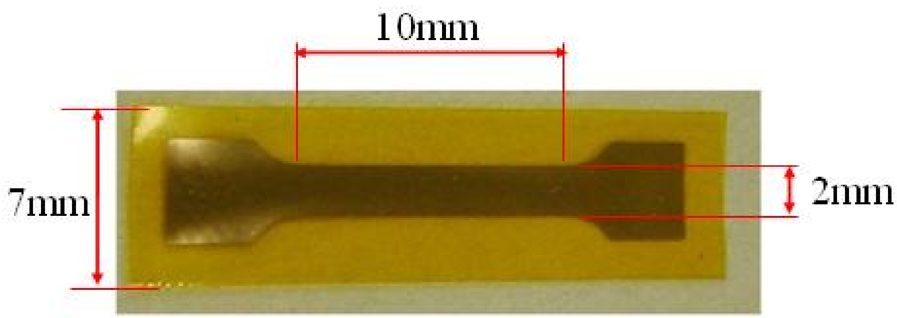

Figure 2. The copper film on Kapton™ substrate specimen for tensile test

Results and Analysis

Figure 5 shows the load-displacement curve of copper film on Kapton™ substrate. Because elastic range of substrate is more than 1%, deviation from initial linear slope within 1% strain indicates film's plastic deformation. After yielding of the film, cracks initiates in film. As shown in Figure 6(a), with the increasing of the applied stress the cracks in film propagates perpendicular to the tensile axis and then many cracks occur simultaneously. Further increasing of the applied stress as shown in Figure 5 leads to delamination between film and substrate along cracked line with spontaneous buckling of the film at an instant as shown Figure 6(b). At this point cracks of film propagate ahead of film buckling which occur in limited zone of crack line. As the number of cracks, however, increases gradually, buckling occurs and grows with crack propagation. In this specimen, copper on Kapton™, no crack of substrate was detected particularly due to relatively high toughness of Kapton™

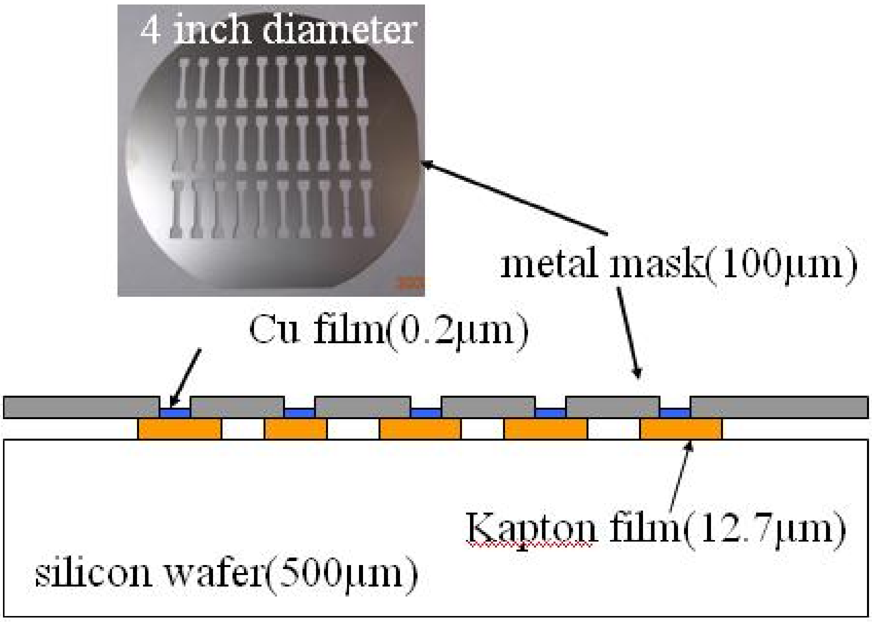

Figure 3. Fabrication process of copper film on Kapton™ substrate specimen

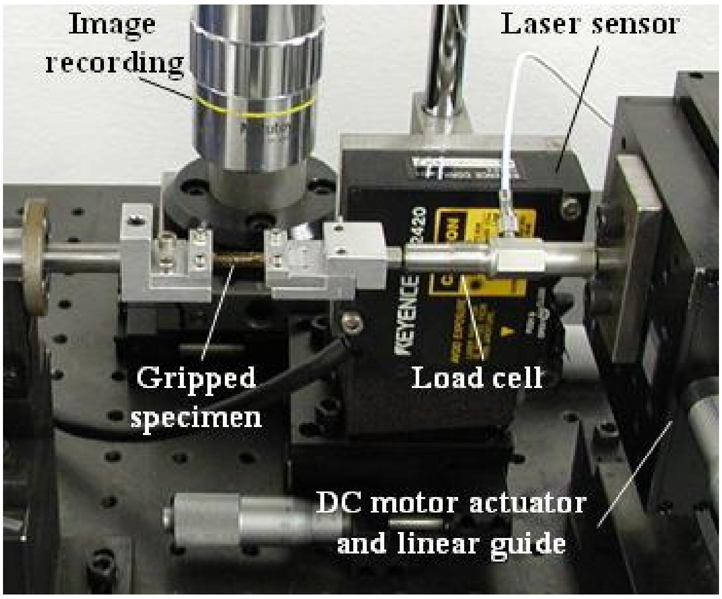

Figure 4. Apparatus for tensile testing of film-on-substrate

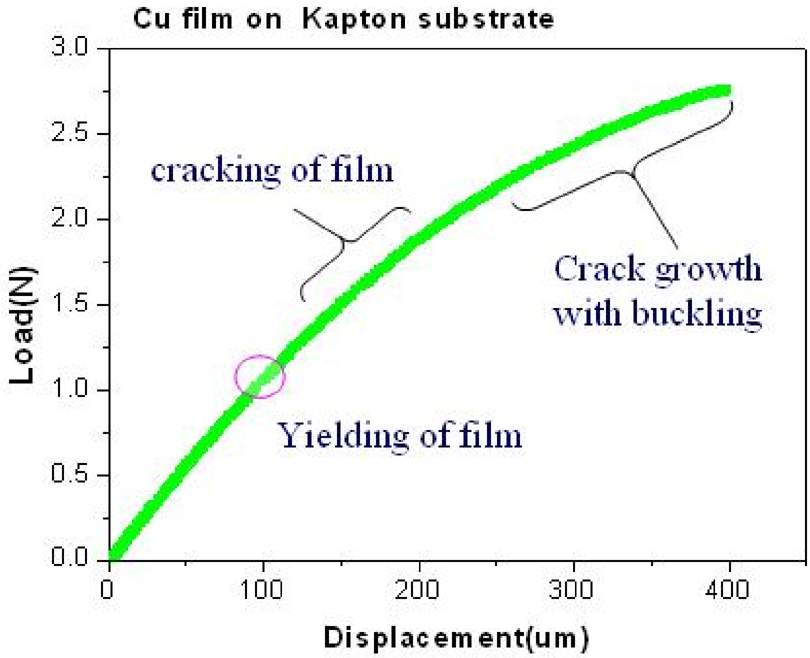

Figure 5. Load displacement curve of copper film on Kapton™ substrate

(a) (b)

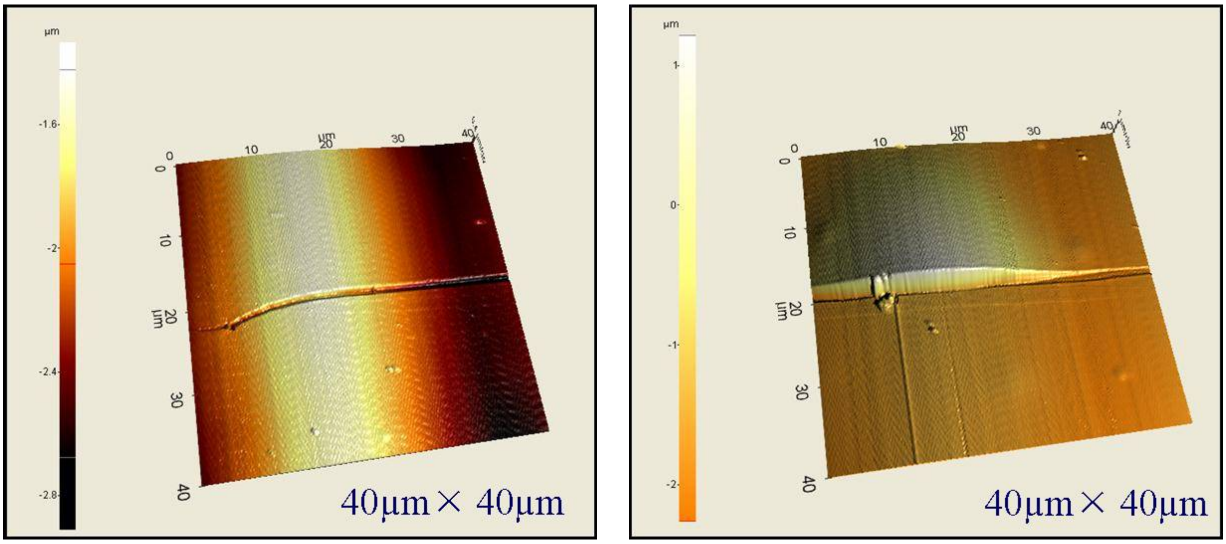

Figure 6. AFM images of (a) cracked film (b) buckled film

All the successive crack evolution mechanism of thin metallic film on polyimide substrate under uniaxial tensile stress can be divided into three stages as listed below

- Stage I : Crack initiations and propagation in film
- Stage II : Buckling of film at cracked region
- Stage III : Crack growth with a buckle formation

At first stage, crack of film initiate at many relatively weaker sites due to defects or inhomogeneity in film during fabrication as applied stress of film increases to around the tensile strength of film. And then the crack propagate along the film by opening mode, i.e., Mode I. Almost shear tractions are transferred near the edge of film so that there is no traction between film and substrate even if film stress induced by thermal mismatch instead of direct tensile loads. As soon as the crack initiates, shear tractions are generated beneath the cracked film and substrate constrains the crack from further opening as shown in Figure 7. This mechanism shows that fracture toughness in Mode I is main factor which external stress need to overcome.

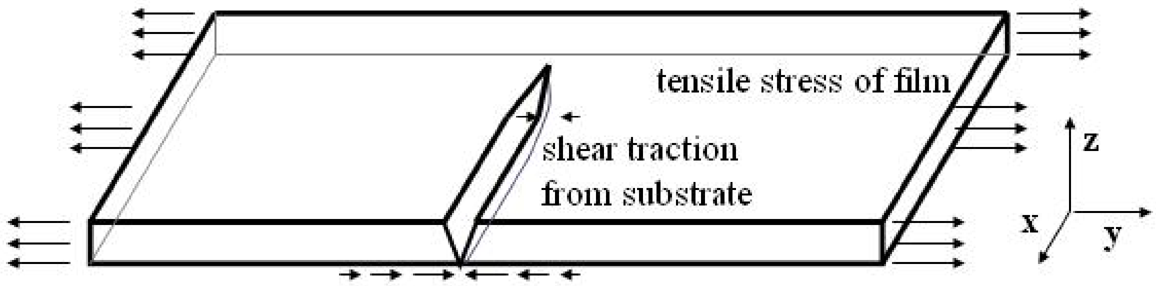

Figure 7. A schematic diagram of stress around film crack

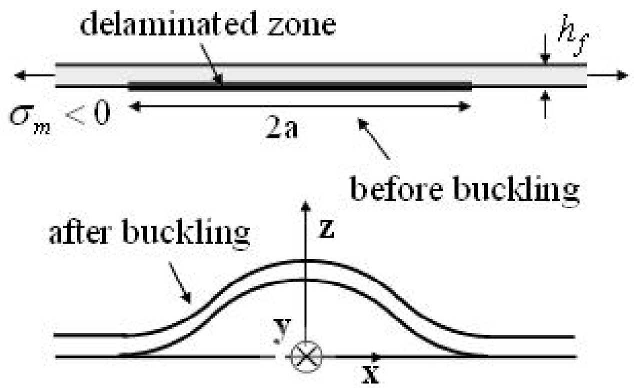

Figure 8. Schematic illustrating the two-dimensional shape of buckled film with associated nomenclature

As crack grows up to certain length, film buckles abruptly. Copper film delaminate from substrate at both side of crack line one after the other while crack is arrested. Film and substrate are contract in perpendicular direction by Poisson's ratio under tensile loading. Cracked film, however, released from tensile stress which produces mismatch strain in film/substrate in perpendicular direction. Therefore sufficient compression stress of film causes delamination with a buckle formation and release of stored energy in film/substrate structure. This phenomena can be modeled in two-dimensional beam fixed both end as shown in Figure 8. Prior to formation of a buckle, the stress in the film is the uniform mismatch stress, $\sigma_m < 0$. It is assumed that interface is not bonded over the beam $-a < x < a$. Using simple beam column theory minimum crack length that will result in buckle formation in a film with compressive stress σ_m is

$$a_m = \frac{\pi h_f}{2}\sqrt{\frac{\bar{E}_f}{3|\sigma_m|}} \tag{1}$$

Where, the symbol, a_m , h_f , $\bar{E}_f$ denote the smallest debond size, thickness of the film, and plane strain modulus, respectively. A rough estimate of the minimum debonded size can be established assuming film stress is 1GPa as an extreme case. Poisson's ratio and modulus of copper are around 0.3 and 130 GPa respectively [1]. The minimum debond size a_m is estimated about 2μm. That analysis does not include the interfacial debonding which a buckle has to overcome. Therefore more lengthy debond size will be needed for a buckle formation. The actual buckled size observed was several tens micrometers and crack length was larger than buckled size. Thus a buckle formation of film requires a minimum film's width of several tens micrometers also. At the beginning of stage II a buckle formation occurs within limited zone of cracked face as shown in Figure 9(a). And then buckles grow and merge together as shown in Figure 9(b) and finally become two buckle on each side of crack line while crack propagates with mechanism in stage I. The growth of a buckle occurs by the shear traction from mismatch strain and the bending stress by buckled shape.

As crack density increases, i.e., a number of cracks per unit length, increases gradually crack growth mechanism in stage I is not work any more. This means film stress by tensile loading sufficiently released so that cracks arrested. Two fully developed buckled films, however, on both each side of crack line grows up to crack tip of film and then break through the crack tip while substrate contracts in perpendicular direction continually as shown in Figure 9(c). Growth of two buckled film one after the other makes film be torn. So we can say that the film crack grows in Mode III with a buckle formation which was explained in stage II. Fracture toughness of film in Mode III and interfacial toughness according to phase angle are the main factors of resistance to crack growth. Also driving force for crack growth is substrate's contraction which was explained in stage II.

(a) (b) (c)

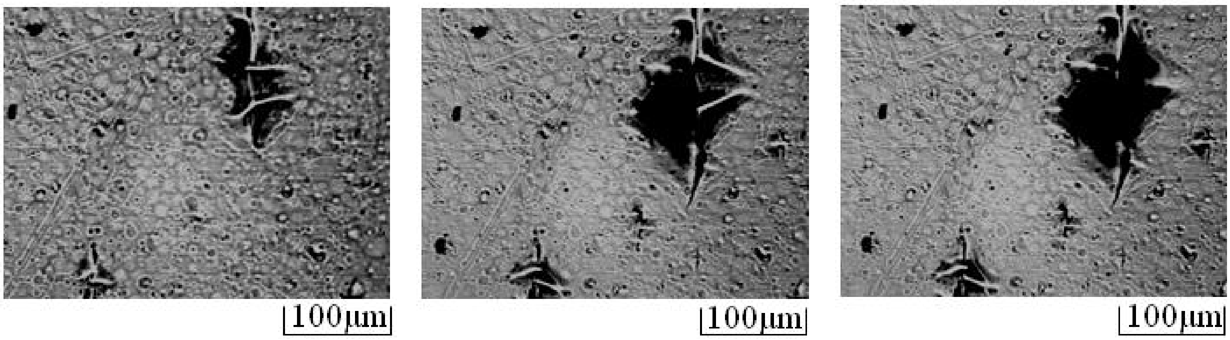

Figure 9. Microscope images of buckled films (a) buckle formations at several site of crack line (b) merged crack (c) fully developed buckles on each side of crack line

These results are limited in wide film on tough substrate. If the width of film is not wide enough to cause sufficient mismatch strain between film and substrate such as film strip (several microns) in conduction line, a crack in film will go through the width of film before a buckle formation occurs because the required the minimum crack length is above several tens micrometers. Thus stage II and III will not appear. A buckle formation can be used to measure the interfacial toughness of film/substrate provided that change of crack length and energy is given or measured delicately.

Summary

Crack growth mechanism of copper on Kapton™ substrate as an example of thin metallic film on polyimide substrate was explained from experimental results. Cracks and buckles in the copper film under tensile loading were observed using microscope and AFM. The crack growth of film can be divided into three stages, crack initiation and propagation in film, buckling of film at cracked region, crack growth with a buckle formation. The mechanisms and main driving forces growth in each stage were explained and discussed.

Acknowledgments

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