Buckling behavior of metal film/substrate structure under pure bending

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Abstract

Many studies on the thin film/substrate structure and its failure mechanism were reported in recent years. The direct experimental results of thin film/substrate structure by scanning electron microscopy (SEM) presents an intriguing problem:there exists a buckling failure mechanism at the lateral edge of metal film under pure bending. The qualitative theoretical analysis has been done on such buckling failure of thin film/substrate structure. The experimental results and theoretical analysis are helpful to understand the extrinsic stresses or deformations that are induced by external physical effects.

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Thin film/substrate structure or device has recently triggered substantial research efforts focused on its structural property, damage behavior, model, as well as estimating reliability. It is mainly because the multi-layered thin film/substrate structure or device has been wieldy used in microelectronics and mechanical system (MEMS) industries. With size decreasing, many complex problems could occur and induce the thin film/substrate reliability issues, such as delamination, cracking, or morphological instability.[1] The failure mechanisms of the thin films have been reported as tunnel-delamination, wormlike delamination or wrinkling under compressive loading [2] and multi necking, debonding or rupture under a tensile loading [3-8] both in theories and in experiments. Specially, the failure mechanisms of thin films under compressive loading have been well reported. [1, 8-9]

Recently, it was found that the metal thin film often ruptured at small tensile strains (2%).[11-12] However, the large tensile strain could be sustained by the polymer-supported metal film, which even could be stretched beyond 50%.[13] In order to explain such a paradox, Li *et al*.[2-6] have made many research works on it. They found that the interfacial strength played an important role. If the metal films were well bonded to the substrates, they could subject to much larger tensile strain than the films poorly bonded to the substrates.[2-6] Such a discovery is indeed beneficial to the industry to improve the force-bearing capacity of the thin film system. However, as the metal film could sustain the large tensile strain as high as 50 %, the other failure mechanisms exist without doubt and affect the performance of thin film/substrate structure. The present work aims at the buckling failure of metal films, which is induced by the lateral shrink strain when the metal film is under pure bending with large tensile strain.

All samples used for the four-point bending tests by SEM *in-situ* observation were cut into the rectangular shape of 25 mm×4.8 mm×about 0.5 mm (length×width×thickness). The Cu film was deposited on the commercial Cu substrate by the magnetron sputter deposited technology at room temperature. The grain size of the Cu film is about 11.96 nm was measured by X-ray diffraction.[7] The thickness of Cu film, Cu substrate are about 1 μm, 500 μm, respectively. The bending test was controlled by the displacement with 10^{-3} mm/min in the vacuum chamber of the SEM using a specially designed servo-hydraulic testing system by Shimadzu, Japan (see Refs. 7, 14-16).

Fig. 1 shows the SEM *in-situ* observation cross-section for thin film/substrate structure under the four-point bending. t and d is the thickness of Cu film and thin film structure, respectively. The L, B is the length and width of the Cu substrate, respectively. $2l$ stands for the span length, where l is 5 mm here. The displacement of the loading tip is defined as δ, which can be accurately measured by displacement sensor with an error about 1μm. As the Cu substrate in the span length zone ($-l < y < l$) is under pure bending, there exists a simple geometry relationship between δ and the substrate curvature radius R, $R = (l^2 + \delta^2)/(2\delta)$. As the bending test is controlled by the displacement δ, the substrate curvature radius R is changing with the change of δ. According to the Stoney's Formula,[17] the tensile stress in the Cu film could be exactly determined by

$$\sigma_f = \frac{\overline{E}_s (d-t)^2}{6Rt(1-v_s)} \quad (1)$$

where $\overline{E}_s$ and v_s is the plane-strain modulus and Poisson's ratio of the substrate, respectively. The tensile strain of Cu film could be known as $\varepsilon = (d-t)/2R$.[18] As the thickness of the Cu film is much smaller than that of the Cu substrate, the tensile stress in Cu film is assumed as uniform tension stress in SEM *in-situ* observation region when the Cu film is under the pure bending.

In our tests, the cracks did not obviously appear until the tensile strain reached about 19.3 %, corresponding to the tensile stress of 458 MPa in the Cu film, which is in good agreement with the yield stress of 1μm Cu film.[19] Fig. 2 shows the micrograph of the Cu film subjected to the tensile strain about 21.8 %. The zigzag cracks were along the *x* direction, which is perpendicular to the direction of tensile strain (y direction). The angle between the direction of crack and tensile strain is about 52.8° and 55.6°, respectively, very close to the zigzag cracks of 60° in a nanocrystal Cu film bonded well on the Kapton substrate, as reported by Xiang *et al.*[3] Therefore, it could be analogized that the bond strength between Cu film and Cu substrate is high enough to make the Cu film sustain the large tensile strain of ~21.8 %. The bifurcation analysis has predicted that the metal thin film under uniaxial tension could be unstable to be against the perturbation of small strain amplitude when the tensile strain achieved a critical value. It is able to predict in the uniaxial tension of the metal sheet that the angle between the incipient neck and the loading direction is 54.7°.[18] Thus, the orientation of the mircocracks of the Cu film agrees well with the prediction of the bifurcation analysis by Hill.[18]

Besides the zigzag cracks in the Cu film along the transverse direction (*x* direction, as shown in Fig. 1), it is also interesting to find that there exists the buckling related delamination at the edge part of Cu film, as shown in Fig. 3. The distance of the delamination to the upper lateral of the Cu film is about 480 μm. Symmetrically, there also exists the buckling at the lower edge of the Cu film, which is about 500 μm to the lower edge. The detailed micrographs of the delamination are shown in Fig. 4. It is observed that the *debonding* of the Cu film is perpendicular rather than parallel to the direction of the tensile strain. The necking of the Cu film does not appear obviously. In addition, the cracks at the edge of Cu film almost perpendicular to the direction of the tensile strain, as shown in Fig.3. In the central part of the Cu film, the cracks have an angle titled to the direction of tensile strain (see Fig. 2). Therefore, the width of the metal film could also play an important role in the deformation of thin film, which change stress status in the film from the plane strain (edge part of the Cu film in Fig.3) to plane stress (central part of the Cu film in Fig. 2).

A schematic diagram of strain status of the Cu film is shown in Fig. 5 in order to understand the lateral buckling of the Cu film. For simplification, the y direction of the Cu film is assumed under uniaxial tensile strain. As the assumption of the volume conservation of Cu film,[13] the lateral shrink strain could be known as $\varepsilon_{sh} = \varepsilon/(\varepsilon+1)$ by ignoring the deformation of Cu film in z direction. As it given in the previous work, the critical strain for buckling of the film is [2,10]

$$\varepsilon_c = \frac{\pi^2}{12}\left(\frac{t}{b}\right)^2 \tag{2}$$

where *b* is half width of the delamination. By knowing $t = 1\mu m$ and $b = 23.38\mu m$, the critical strain for the buckling of the Cu film in present work is $\varepsilon_c = 0.15\%$.[21] It could clearly see that the lateral shrink strain could be about 18 % as the tensile strain reached 21.8%. Therefore, as the plane strain status (at the edge part of Cu film) transform to the plane stress status (at the central part of Cu film), the buckling related delamination occurred at the plane stress status zone of the Cu film (Fig.3 and Fig.4) due to the lateral shrink strain. Considering the stiffness ratio, E_s / E_f, the buckling occurs more easily at high stiffness ratio; while for small stiffness ratio, the wrinkling is easy to occur when the thin film system is under compression.[8] Therefore, it is not easy for the Cu film on Cu substrate to occur the wrinkling in present work, although it is much easy to form the lateral wrinkling of the Cu film in the previous work [3-6] as the stiffness ratio in these works is quit small (Cu film on Kapton substrate). When the Cu film sustained the large tensile strain (30 %-50 %), the lateral shrink induced wrinkles could occur in the previous works and assist the debonding and the necking of the Cu film. [3-6]

From Li et al.'s point of view,[3-6] the metal film on polymer substrate (Kapton) under tension may form *multi necks*, stretch to a much larger strain, and debond from the substrate, then rupture. Such phenomenon is mainly induced by a periodical von Mises stress distribution in the metal film under tension and the co-evolution of the interfacial *debonding* and the metal film *necking*. [3-6] Although the *debonding* (along the tensile direction) and *necking* behaviors of Cu film were not clearly found in our experimental results, one of the reasons may be the substrate (Kapton) is a strong, steeply hardening polymer in previous works [3-6] which may delocalize deformation in the metal film, carrying the metal film to strains far beyond its necking limit without rupture. However, the Cu substrate in present work is a weakly hardening metal and can not supply such function so that the rupture strain in our experiments is lower than the previous works (30-50%).[3,13]

In summary, there exists buckling related delamination of Cu film under the pure bending. Although the high interfacial strength could help the metal film sustain the tensile strain as high as 21.8 %, the buckling failure of the Cu film could be induced by the lateral shrink strain if the Cu film is on a hard substrate. Such a failure mechanism is helpful to understand the extrinsic stresses or deformations that are induced by external physical effects.

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References

[1] E. Arzt, Acta Mater. **46**, 5611(1998).

[2]J. W. Hutchinson and Z. Suo, Adv. Appl. Mech. **29** (1992).

[3]Y. Xiang, T. Li, Z. Suo and J.J. Valassak, Appl. Phys. Lett. **87**, 161910(2005).

[4] T. Li and Z. Suo, Int. J. Solids Struct. **43**, 2351(2006).

[5] T. Li and Z. Suo, Int. J. Solids Struct. **44**, 1696(2007).

[6] T. Li, Z. Y. Huang, Z.C. Xi, S.P. Lacour, S. Wagner and Z. Suo, Mech. Mater. **37**, 261(2005).

[7] J.G. Huang, X.S. Wang, X.K. Meng, Materials Transactions, **48**, 2795(2007).

[8] Z. Y. Huang, H. Wei and Z. Suo, Phys. Rev. E **94**, 6875(2003).

[9] R. Huang and Z. Suo, J. Appl. Phys. **91**, 1135(2002).

[10] H. Mei, J.Y. Chung, H.-H. Yu, C.M. Stafford, and R. Huang, Appl. Phys. Lett. **90**, 151902 (2007).

[11] H. Huang and F. Spaepen, Acta Mater. **48**, 3261 (2000).

[12] Y. Xiang and J. J. Vlassak, Scr. Mater. **53**, 177 (2005).

[13] N. Lu, X.Wang, Z Suo and J. Vlassak, Appl. Phys. Lett. **91** 221909(2007)

[14] X.S.Wang, J.H. Fan, J. Mater. Sci. **39**, 2617 (2004).

[15] X.S. Wang, J.H. Fan, Inter. J. Fatigue **28**, 79 (2006).

[16] X.S. Wang, L. Jin, Y. Li, X.W. Guo, Mater. Lett. DOI: j.matlet 2007.10.019.

[17] G.G. Stoney, Proc. R. Soc. Lond. A **82**. 172(1909).

[18] R. Hill, J. Mech. Phys. Solids **1**, 19(1952).

[19] As the Cu substrate is under the pure bending, the strain in the Cu substrate is

assumed as the linear function of the z. The strain of the neutral axial is zero. Therefore, the strain at the interface between the Cu film and Cu substrate is about $(d-t)/2R$. As the thickness of Cu film is much smaller than that of Cu substrate, the strain is the Cu film should be near to $(d-t)/2R$ for the comparability of deformation.

[20] D.Y.W. Yu and F. Spaepen, J. Appl. Phys. **95**, 2991(2004).

[21] Although Eq. 2 is derived for elastic film, it used here just for approximately evaluating the critical buckling strain ε_c for the Cu film on the Cu substrate. As the Cu film was under the plastic deformation, the Eq.(2) could may not proper for obtaining the exactly critical strain. According to the theory of elastic stability by Timoshenko & Gere (2ed Edition, McGraw-Hill 1963) and the copper characterized by the power law (Refs. 3-6), the critical strain of the Cu film could be slightly larger than the ε_c obtained by Eq. (2). However, the shrink strain in the Cu film is still larger than the critical buckling strain and also could induce the buckling of Cu film.

Figure Captions

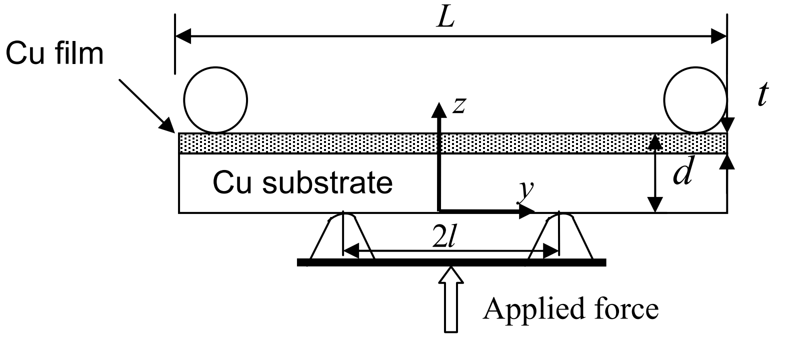
Fig. 1 Schematic depiction of four-point bending test.

Fig. 2 The top view of the central part of well bonded Cu film on Cu substrate after the tensile strain arrival to 21.8%

Fig. 3 The top view of the edge part of well bonded Cu film on Cu substrate after the tensile strain arrival to 21.8%

Fig. 4 The micrograph of the buckling related delamination at the lateral edge of the Cu film

Fig. 5 Schematic depiction of shrink strain induced buckling of the Cu film (a) top view (b) side view



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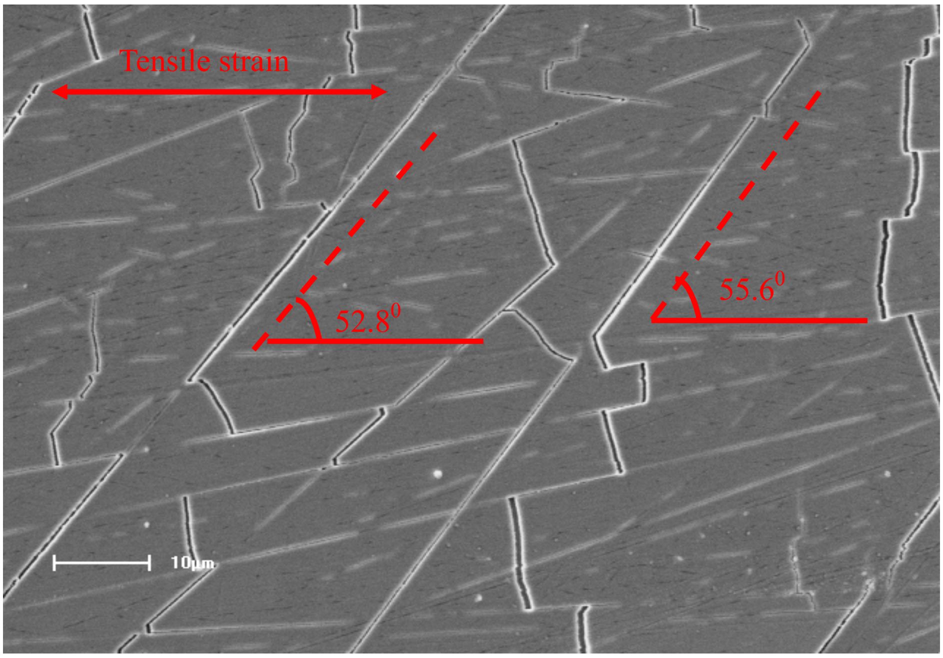

Fig. 2 The top view of the central part of well bonded Cu film on Cu substrate after the tensile strain arrival to 21.8%

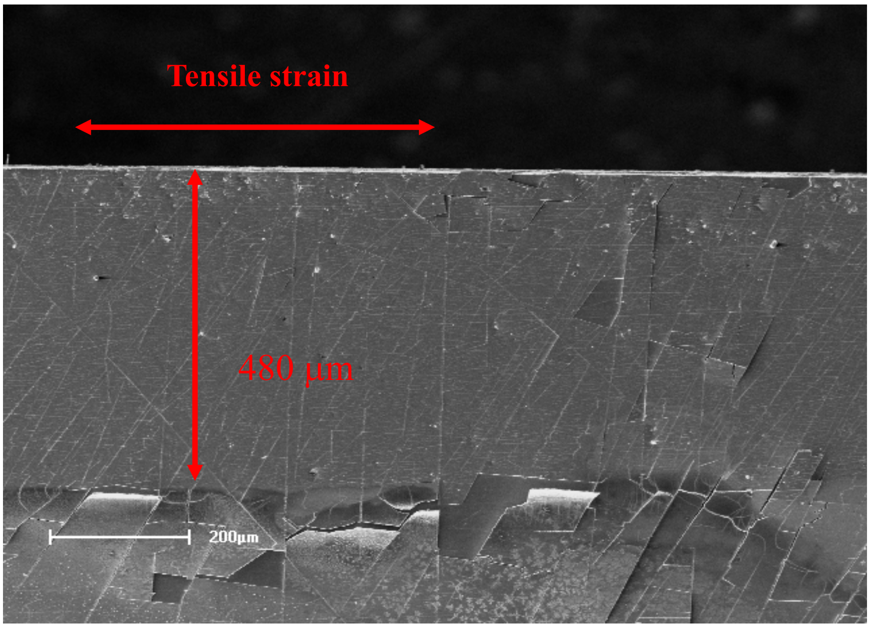

Fig. 3 The top view of the edge part of well bonded Cu film on Cu substrate after the tensile strain arrival to 21.8%

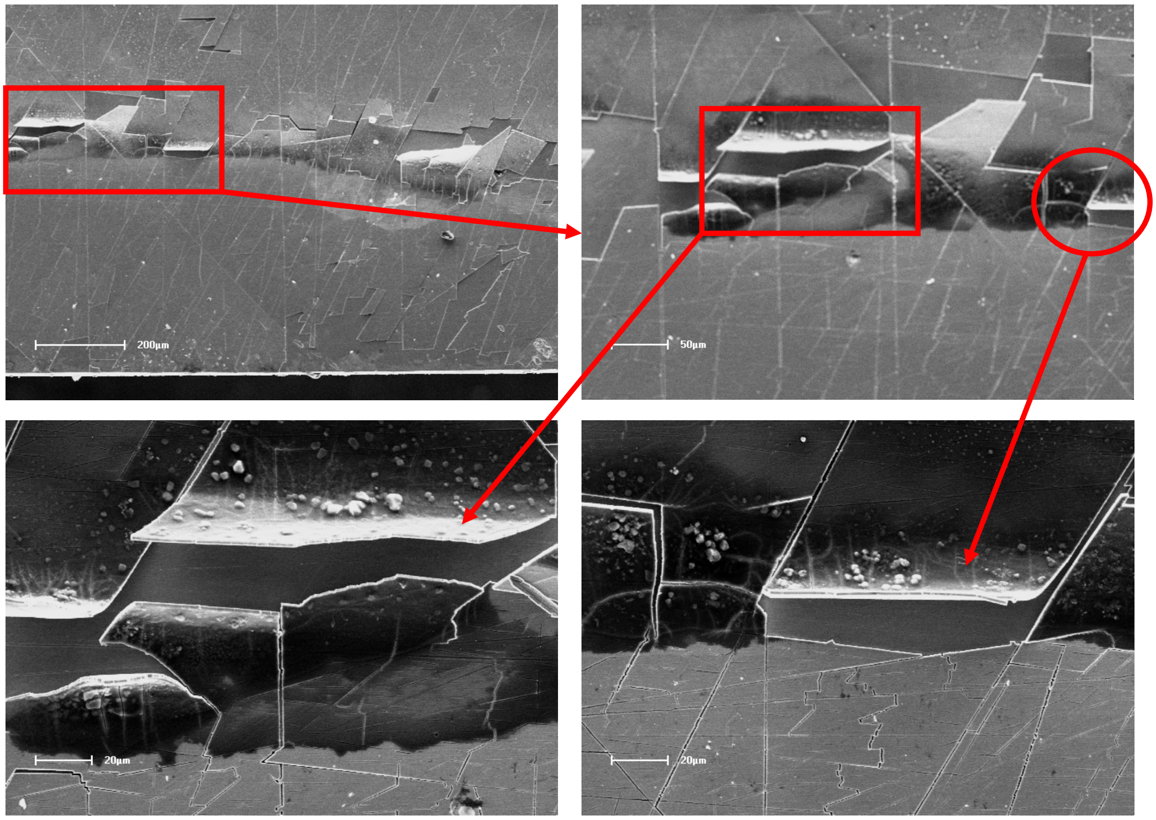

Fig. 4 The micrograph of the buckling related delamination at the lateral edge of the Cu film

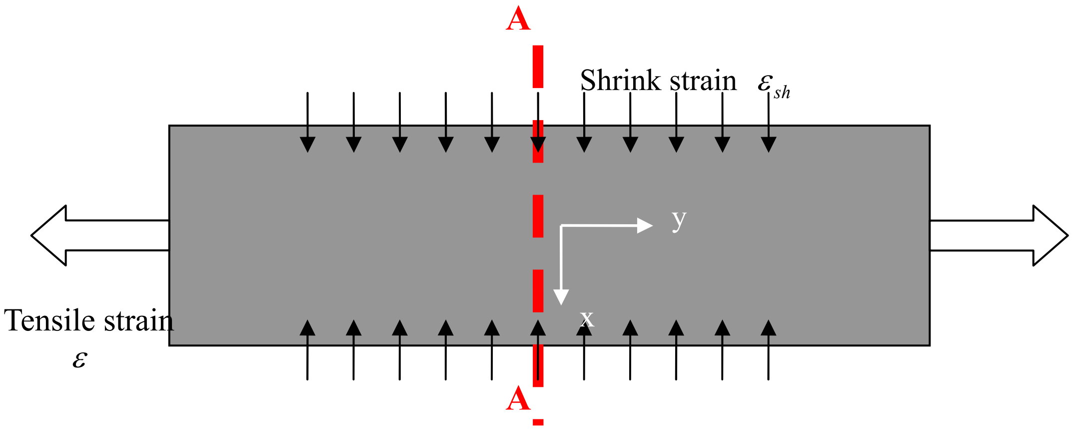

Fig 5(a)

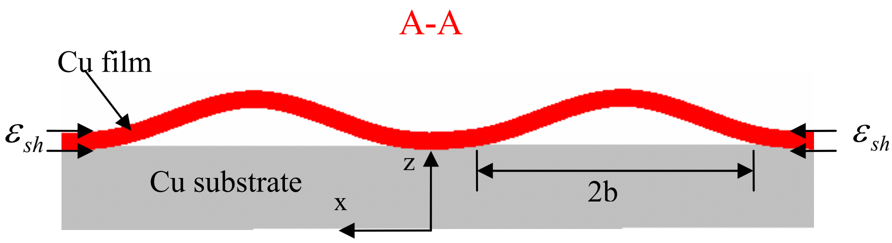

Fig 5(b)

Fig. 5 Schematic depiction of shrink strain induced buckling of the Cu film (a) top view (b) side view