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Comments on measuring thin-film stresses using bi-layer micromachined beams

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Abstract. Bi-layer structures are formed by depositing a thin pre-stressed film onto an existing micromachined beam which is made of a base-layer material. The resulting static deformation of the built-up beam is measured through optical profilometry, and the mean residual strain in the thin film is determined by calibrating a strain-deflection model to the measurements. The method is demonstrated with AlCu and diamond-like carbon films that are deposited onto SiO_2 cantilevers produced through bulk machining. Critical to the technique is the inclusion of initial and non-ideal deflections of the base-layer cantilever, which have not been reported in previous investigations of the bi-layer method and which can play a significant role in determining the film's stresses.

1. Introduction

Thin-film materials with particular electrical, magnetic and optical properties are used extensively in microfabrication. In data storage systems for instance, thin films are used in recording heads, magnetic layers on rigid disks, protective overcoats, and more recently, miniaturized actuators and suspensions. Such films can range from 100–1500 Å in thickness, with tribological overcoats being some of the thinnest layers.

Residual stresses, typically undesirable in these films, arise naturally from their deposition or growth processes. Diamond-like carbon, for instance, is sputtered on rigid disks having an aluminum or glass substrate, and is intended to protect the underlying magnetic layer from head/disk collisions [1]. These films are known to be in a state of high residual compression, potentially damaging the film itself or the magnetic layer beneath it. Residual stress can also couple with a film's magnetic properties through magnetostriction [2]; this phenomenon becomes of concern when high-performance magnetic media or recording heads are developed. The ability to measure stresses in thin films thus becomes relevant to the design of both fabrication processes and actual devices. In short, methods for measuring residual stress, and models for interpreting those measurements, frame a generic problem in the use of thin-film materials. Such considerations can contribute to improved device reliability and functionality.

One technique used to determine residual stress is the so-called bi-layer method [3, 4]. In it, a cantilever beam made of a base material is micromachined, and a (different) material of interest, termed the film layer, is deposited onto the cantilever so as to form a bi-layer sandwich-like structure. The stress level in the film layer is then deduced by measuring the deflection of the bi-layer cantilever. Bi-layer structures are especially useful for making measurements on very thin films since competing diagnostic structures [5, 6] are not readily fabricated of such thin materials. This approach offers several advantages over such techniques as measurement of the global curvature of the wafer on which the film is deposited [7–9]—particularly improved sensitivity, and the ability to gauge uniformity (or lack thereof) of stress over the entire substrate.

In previous developments of the bi-layer method, the cantilever's radius of curvature R, which is related to the strain level in the film, was obtained by measuring only the deflection δ of the free end, and by inferring R from the model relation $R = L^2/2\delta$, where L is the cantilever's length. Implicit in this approach is the assumption that the base-layer cantilever was ideally straight and undeformed prior to the film layer having been deposited. In what follows, that assumption is shown to be not always valid. In fact, initial deflection of the base-layer cantilever can have significant implications for stress estimates obtained through the bi-layer method. In one case study discussed below, when initial deflection is not considered, residual compression is predicted; when the method is subsequently corrected to account for initial deflections, as is the case here, the actual stress value is shown to be tensile.

Several improvements to the bi-layer technique are discussed: first, the initial deformation of the base layer is taken into account in both measurement and analysis; second, the full deflection profiles of the test beams are

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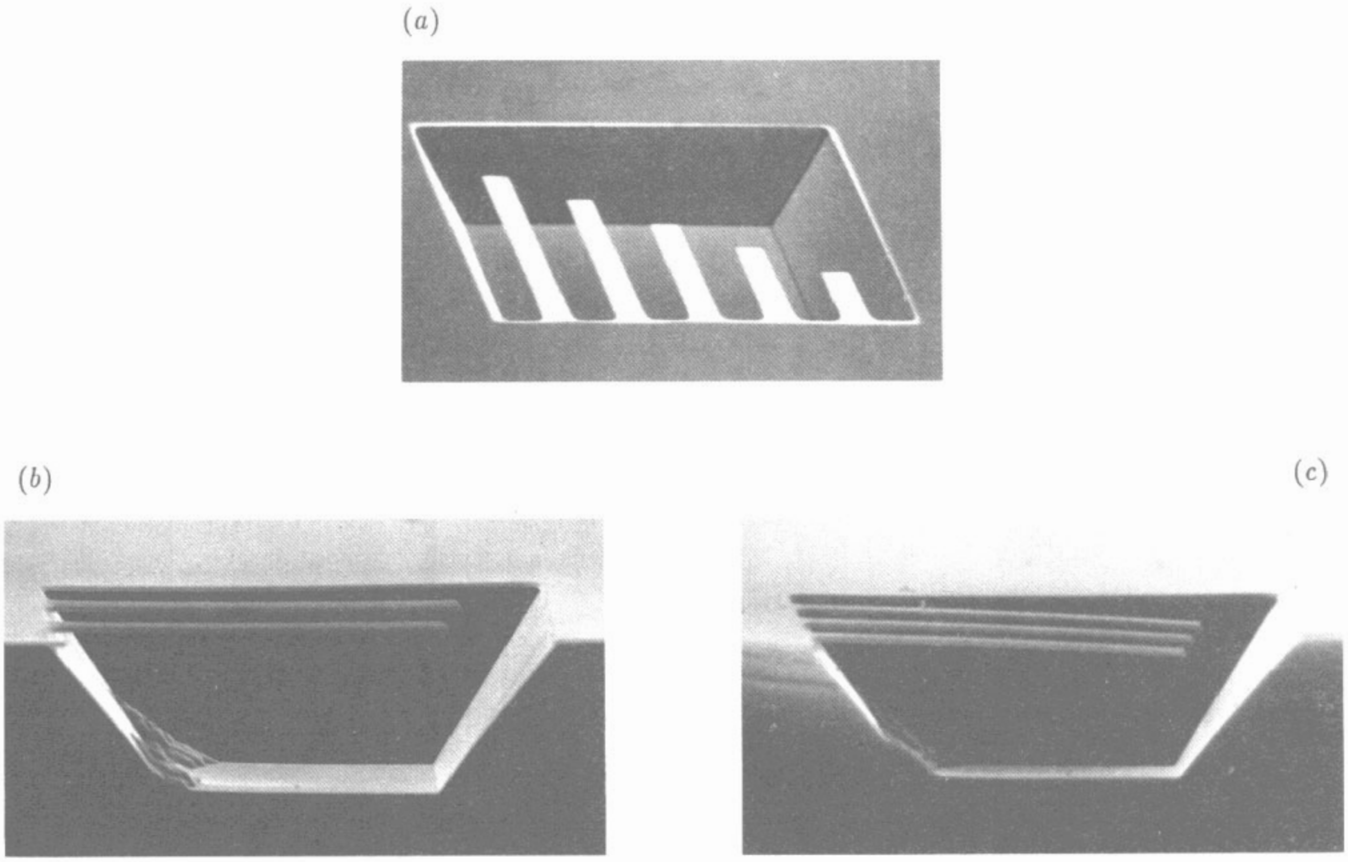

Figure 1. SEM photographs of micromachined beams (*a*) in an isometric view, (*b*) in their initial state, and (*c*) after deposition of 150 Å DLC.

measured. With regard to the latter, the radius of curvature is determined by fitting the entire measured deflection profile to the model, rather than by using a single tip deflection value. This is a useful point to the degree that the measurements so obtained support the modeling approximation of the beam having a constant radius of curvature.

2. Actual and apparent deflections

The micrograph of figure 1(*a*) shows cantilever silicon dioxide beams with lengths 50–150 μm and thickness 2.0 μm which are fabricated on a ⟨100⟩ silicon substrate. The SiO_2 'base layer' was thermally grown at 1100 °C on a polished single-crystal substrate, and it was patterned by ion milling. The substrate was then etched anisotropically with 35–38% (by weight) KOH at 85 °C. When relieved from the substrate, the completed beams were suspended above a pyramidal cavity with {111} sidewalls, as indicated by the side view shown in figure 1(*b*). Beams of different thickness were fabricated subsequently in order to adjust the sensitivity of the deflection measurements for various combinations of materials. A different film, termed the 'film layer', was then deposited onto the SiO_2 beams so as to form bi-layer cantilevers. The deflection of such bi-layer structures can be significant, even being visible in figure 1(*c*) with only 150 Å of diamond-like carbon (DLC) forming the film layer.

The geometry of the base B and film F layers is sketched in figure 2(*a*). To model the cantilever's deformation with fidelity, three regions of these films are explicitly identified

(i) B_c, the cantilever made of the base material,
(ii) B_b, the portion of B that remains bonded to the substrate and is contiguous with the cantilevers, and
(iii) F_c, the portion of the film layer that is attached to B_c.

The bi-layer cantilever thus comprises B_c and F_c, and, in general, both of these layers experience residual stress. In fact, the presence of such stresses in the base layer alone can cause B_c to deform, relative to the surface of the substrate, prior to the film layer having been deposited. As demonstration, figure 3 shows profiles of a cantilever that were measured by using non-contact interferometric profilometry; deflections before and after deposition of an AlCu film are shown. Before the film was deposited, the SiO_2 base layer had a downward tip deflection of 0.39 μm, and positive curvature. After the 0.25 μm AlCu film was deposited, the deflection increased to 1.28 μm, but with negative curvature. The additional deformation that was afforded by the release of residual stress in the AlCu film was therefore superposed on the initial, non-negligible deflection of B_c. It is the change in deflection, termed the

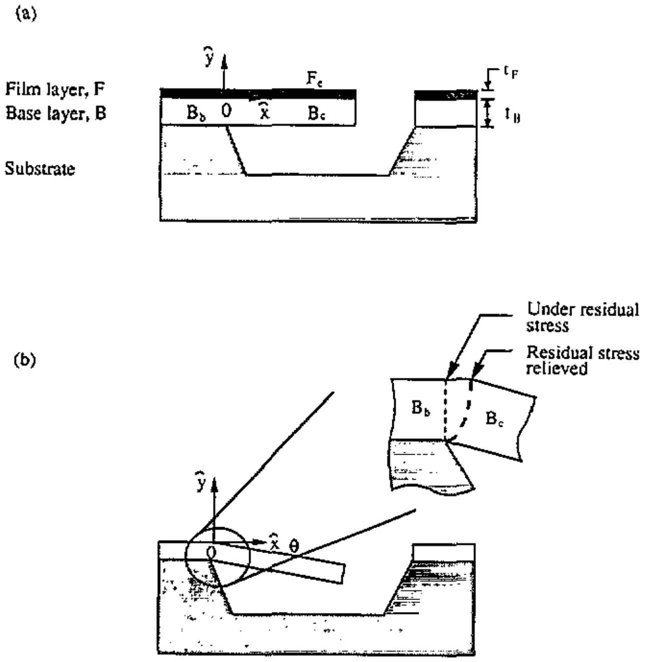

Figure 2. (*a*) Bi-layer beam model, and (*b*) boundary rotation of B_c that results from residual stress in the base layer.

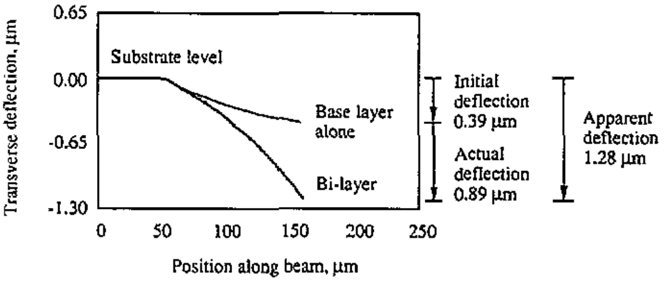

Figure 3. Deflection profiles of an SiO_2 cantilever measured through interferometry before ('base layer alone') and after ('bi-layer') the AlCu film was deposited. The 'actual deflection' of 0.89 μm at the tip is attributed to stresses in the film layer. $L = 100$ μm, $t_F = 0.25$ μm and $t_B = 2$ μm.

'actual deflection' in figure 3, from the initial state to the final one that is associated with residual stress in the AlCu film.

The treatment of bi-layer structures should therefore be formulated by first considering the deflection of B_c prior to the deposition of the film layer. In general, the cumulative (uniaxial) residual stress σ_B in B can be represented by the polynomial

$$\sigma_B = \sum_{k=0}^{\infty} \sigma_k \left(\frac{\hat{y} + t_B/2}{t_B/2} \right)^k \tag{1}$$

with $\hat{y} \in (0, -t_B)$ in figure 2(*a*). In the first approximation, only the mean σ_0 and the gradient σ_1 components of stress are retained, as in

$$\sigma_B \approx \sigma_0 + \sigma_1 \left(\frac{\hat{y} + t_B/2}{t_B/2} \right). \tag{2}$$

Using thermally grown SiO_2 as an example, the mean stress σ_0 is caused primarily by the mismatch of thermal expansion coefficients between the substrate and oxide film, and the stress gradient σ_1 can be attributed to oxygen diffusion while the film is forming.

When the cantilever B_c is machined from the base layer, the mean stress in it is relieved by in-plane expansion or contraction at the cantilever's free end. However, since B_c is contiguous with B_b, and since B_b remains bonded to the substrate so as to prevent complete relief of its stresses, the state of stress in B_b also influences the cantilever's deflection. As shown in figure 2(*b*), at the interface of B_b and B_c, the top surface is free to move, whereas the base layer is constrained at its lower surface by the substrate. When compressive stress in B_b is relieved, the junction of B_b and B_c, which is initially straight and vertical, deforms as shown in the figure's inset. Therefore, B_c becomes supported in effect by a deformed and rotated boundary, and the cantilever 'tilts' in the far field at angle θ. This base rotation in nominally 'clamped' micromachined structures is generic, and is discussed in more detail in [10].

In addition, if gradient stress is present in the base layer, beams made of it will 'curl' out of the plane of the substrate as a result of the bending moment induced by relief of σ_1 [11, 12]. By superposing these two effects, the net out-of-plane deformation of a cantilever formed of the base layer alone can be represented by

$$\hat{y} = \theta \hat{x} + \frac{1}{2r} \hat{x}^2 \tag{3}$$

where r is its radius of curvature. Here θ derives primarily from relief of the mean stress, and r is associated with the gradient stress only.

Following [10], the radius of curvature and the initial angular deflection of B_c can be determined through a fit of its measured deflection to equation (3); for instance, these parameters for the SiO_2 beam shown in figure 3 are $\theta = -6.1$ mrad and $r = 23.8$ mm. For that 100 μm long beam, approximately -0.61 μm of initial B_c tip deflection is attributed to tilt deformation, and $+0.22$ μm to curl. In this case at least, most of the tip deflection is, in fact, caused by boundary rotation.

In [3, 4], the aforementioned simple relation between r and δ is given, but it is clear that tip deflection of a bi-layer structure is not caused by stress in F alone. As described below, the micromachined bi-layer beam model can be improved by accounting for the initial deflection of B_c.

3. Bi-layer deflection model

The bi-layer structure is modeled as comprising a micromachined beam on which a film has been deposited. This composite structure is subject to no external force or bending moment, but in the light of the motivating measurements of figure 3, the beam is treated as being initially deformed. To account for this initial shape, the angular deflection $\theta \hat{x}$ of B_c in equation (3) is nulled by rotating the substrate coordinates $\hat{x} - \hat{y}$ into $x - y$ as shown in figure 4(*a*). In these new coordinates, the cantilever deflects in figure 4(*b*) with curvature only, and the gradient residual strain ε_1 in the base layer is determined through

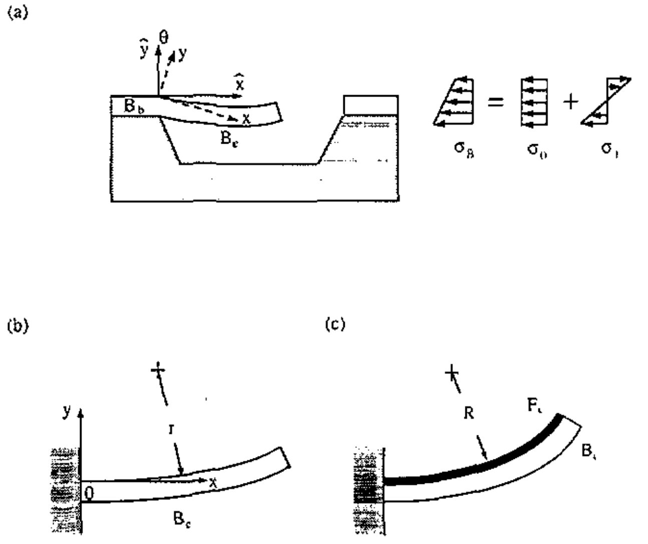

Figure 4. A sequence of deflections used in modeling a bi-layer micromachined beam. (*a*) The initial shape of the base layer alone attributed to residual stress σ_B in it, (*b*) the initial shape when base rotation of the cantilever θ is suppressed, and (*c*) the final deflected state of the bi-layer.

the relation $\varepsilon_1 = t_B/2r$, where t_B denotes the thickness of B. When the bi-layer structure is formed, it deflects to the new configuration of figure 4(*c*). However, although the residual stress ε_F will also cause an angular deflection of the bi-layer beam, its magnitude is less than 10% of θ according to finite-element analysis. Thus the contribution of the angular deflection by the ε_F is negligible.

The differential deformation of the bi-layer is then examined to find the residual strain in F. Through standard stress and deflection analyses, the relation between the residual strain ε_F in the film layer and the radius of curvature R of the bi-layer beam becomes

$$\frac{t_B}{R} = \frac{2c_1}{(1+c_2)} \tag{4}$$

where

$$c_1 = \frac{Et\varepsilon_F - c_2(Et+1)}{Et^2-1} \tag{5}$$

$$c_2 = \frac{E^2t^4\varepsilon_F + 3Et^2\varepsilon_F + 4Et\varepsilon_F + \varepsilon_1(Et^2-1)}{3(Et^2-1)^2 - 4(Et+1)(Et^3+1)}. \tag{6}$$

Here $E = E_F/E_B$ and $t = t_F/t_B$ are two nondimensional parameters for the ratios of elastic moduli and thicknesses between the film and base layers. Since stress and strain are proportional in the uniaxial model, ε_F is used henceforth.

4. Applications

In applying this revision to the bi-layer technique, two thin films—an aluminum copper alloy and a diamond like carbon film—have been used in case studies. AlCu is a common interconnecting conductive material, and DLC is used as a tribological coating. In the experiments discussed, AlCu was deposited by sputtering, and DLC was deposited by plasma-assisted chemical vapor deposition (CVD). In the latter, negligible material is deposited on the lower surface of B_c because the underlying cavity is substantially shallower than the 1 mm or so depth necessary to establish the plasma; this is not the case with other CVD methods. The primary parameter studied was the variation of residual strain with the film thickness.

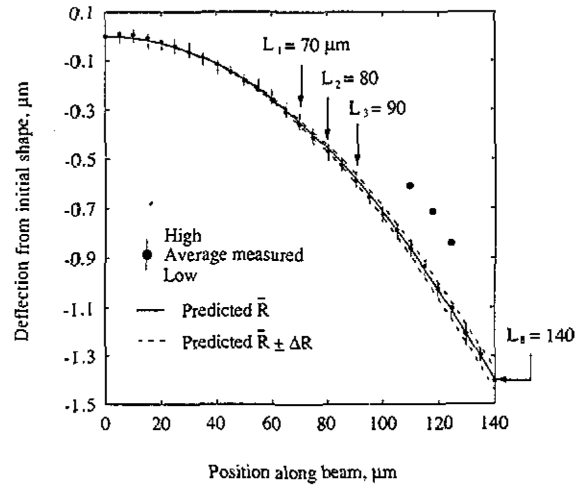

Figure 5. Compilation of measured profiles of eight beams in two different beam arrays with lengths between 70 and 140 μm in 10 μm length increments. All data collapse onto the master deflection profile (solid line). The base layer is 2 μm thick SiO_2, and the film layer is 0.25 μm AlCu.

The parameters ε_1 and θ for the base layer are found through measurement of its initial deformation. In what follows, all data presented are in terms of $x - y$ following suppression of the initial tilt $\theta\hat{x}$ in equation (3). Film thicknesses were measured by profilometry for $t_F > 0.1$ μm, and were estimated by calibration of the deposition process for smaller values. With E and t in equation (6) being determined from measured elastic constants and thicknesses, ε_F is found in turn through equation (4) when the radius of curvature of the bi-layer cantilever is measured.

Figure 5 shows a compilation of measured profiles for eight beams with lengths between 70 and 140 μm. Since the model predicts that the deformed bi-layer beams have constant and identical radii of curvature, there exists a 'master profile' on which experimental profiles for beams of any length must lie. This curve is shown in figure 5, where the average radius of curvature is $\bar{R} = 7000$ μm with variation $\Delta R/\bar{R} \approx \pm 3\%$. Since measurements are taken on beams with different lengths, from different arrays on the same wafer, and also at different positions along the beam's length, errors associated with the deviation of any single measurement are minimized. Through equation (4), the residual strain of the sputtered AlCu film becomes $\varepsilon_F = 5.53 \times 10^{-4}$, using the values $E_B = 66$ GPa and $E_F = 70$ GPa. Figure 5 is useful to the degree that repeatibility of the measurements is demonstrated, as well as, a verification of the model's approximation that the beams have constant and identical curvature.

The deflection profiles of bi-layer beams with different t_F are shown in figure 6, where actual deformations from the initially deflected profile of B_c are given. The radius of curvature clearly changes sign, from positive to negative,

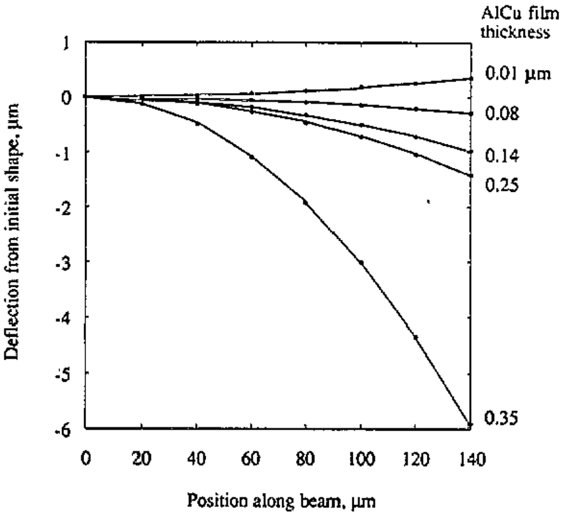

Figure 6. Measured deflection profiles from the initial B_c configuration of bi-layer beams with different AlCu thickness; $L = 140$ μm.

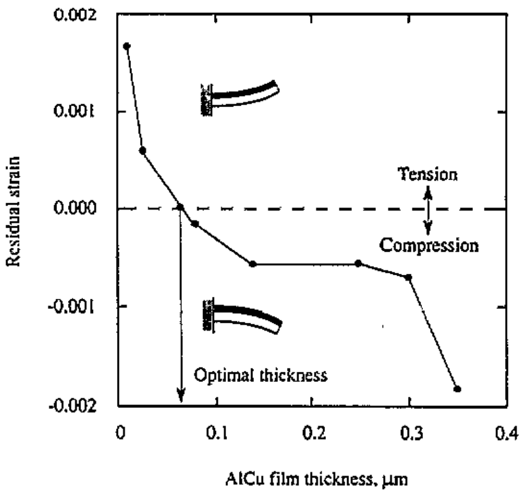

Figure 7. Variation of residual strain with AlCu film thickness. The data points are averaged over five samples.

as t_F is increased from 0.01 μm to 0.08 μm; further variation of stress with $0.01 < t_F < 0.35$ μm is shown in figure 7. Stress in the AlCu film changes from tension to compression when the thickness is near 0.06 μm, so that with no other restrictions on the thickness, this would be the optimal value. For slightly thicker films, the strain is nearly constant at $\varepsilon_F \approx 5.5 \times 10^{-4}$ (compression). For a substantially thicker film, the AlCu layer is evidently placed into higher compression. A potential mechanism that gives rise to this behavior is the existence of voids or defects in the structure that accumulate during sputtering. The tensile stress decreases as the voids fill, but the process is continued, the residual stress becomes dominated by 'atomic peening' [13], and the film becomes further compressed. Analogous results are shown in figure 8 for DLC ($E_F = 150$ GPa), with variations in stress shown over thickness between 50 and 150 Å. High stress in the DLC film is undesirable, in part because of effects on the underlying magnetic layer.

5. Discussion and summary

Thin-film stresses depend on film thickness and on the fabrication processes used, since several mechanisms during deposition can change the stress state. It is therefore not reliable to extrapolate stress values obtained at one thickness to those at others. The bi-layer approach provides a candidate method to characterize very thin films without significant loss of measurement sensitivity. The technique can monitor the variation of stress or strain in the film with not only thickness, but also with different deposition, growth, or working conditions. With this capability, such optimal deposition parameters as pressure, power, substrate bias, and so on can be determined.

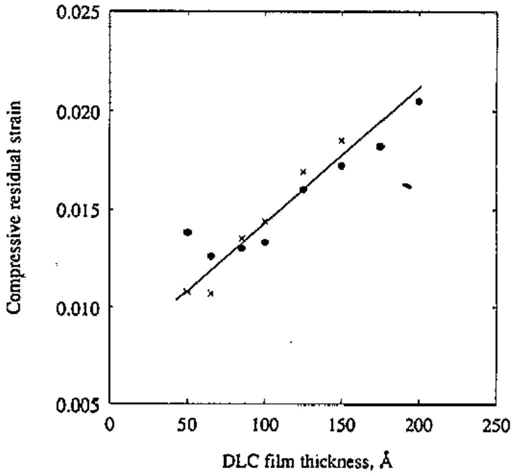

Figure 8. Variation of residual strain with DLC film thickness; sample 1 (•), sample 2 (×).

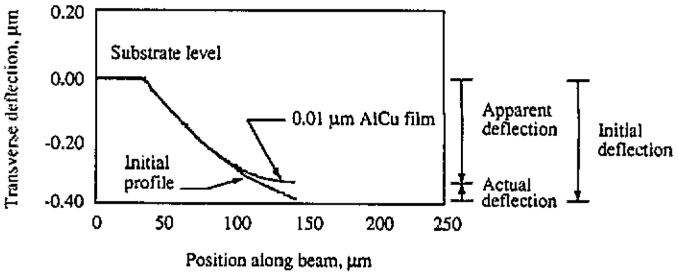

Figure 9. Deflection profiles of a cantilever measured before (base layer alone, 'initial profile') and after (bi-layer, '0.01 μm AlCu film') the thin film was deposited. The actual upward deflection is attributed to relief stresses in the film layer. $L = 100$ μm, $t_F = 0.01$ μm and $t_B = 2$ μm.

Several mechanisms contribute to errors in techniques that are based on measuring only the tip deflection of the cantilever beams, as in [3,4]. Table 1 provides a summary comparison of the results obtained from the present technique, and from one in which the initial shape of B_c is ignored. With the example of the sputtered AlCu film, if the initial deflection is ignored, the residual strain would be taken as 9.0×10^{-4} for a 0.25 μm film, which is some 60% larger than that value obtained when it is corrected for initial imperfections in B_c. If the thickness

Table 1. Comparison of results obtained when residual strain is determined from models in which the initial deflection of the base layer is included ('actual'), or neglected ('apparent').

Strain	0.35 μm AlCu	0.25 μm AlCu	0.08 μm AlCu	0.01 μm AlCu
Actual	-1.8×10^{-3}	-5.5×10^{-4}	-1.1×10^{-4}	1.7×10^{-3}
Apparent	-2.1×10^{-3}	-9.0×10^{-4}	-3.3×10^{-4}	-4.0×10^{-3}
Error	17%	63%	190%	tension versus compression

of the AlCu film decreases to 0.08 μm, the difference in the results obtained using these two techniques increases to 190%. The error can be as great as to falsely indicate compression when the film is actually in tension, as for 0.01 μm AlCu. Deflections for this latter case are shown in figure 9. If the measurement relies on tip deflection alone, one might conclude that the bi-layer beam has deflected downward, and that F is in compression. However, if the initial deflection of the test beam is considered, it becomes clear that the bi-layer beam deflects upward relative to its initial shape, and F is correspondingly subject to residual tension.

Acknowledgments

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