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The evaluation of Young's modulus and residual stress of copper films by microbridge testing

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Abstract

This paper investigates the variation of the deflection and maximum stress of copper film microbridge in a wide range of length, thickness, elastic modulus and residual stress by both large and small deflection theories of microbridge testing. The limits of deflection and load for the microbridge samples to be deformed elastically are determined by the assumption that the maximum stress could not be larger than the yield strength. Furthermore, the deflection and load limits of small deflection theory are decided by setting a threshold preset for the normalized deflection and maximum stress difference between large and small deflection theories. Based on the results above, the microbridge dimensions are chosen and the deflection range suitable for the small deflection theory is calculated. The copper film microbridge samples electroplated on silicon substrate are fabricated by MEMS and the microbridge testing is conducted with nanoindenter XP system. From the small deflection theory, the Young's modulus and residual stress for the electroplated copper films is calculated, and it is 115.2 GPa and 19.3 MPa, respectively.

Keywords: Mechanical properties; Metal thin film; Microbridge testing; Nanoindentation

1. Introduction

Microelectromechanical systems (MEMS) are a new technology to manufacture microsystems, microdevices and microstructures whose dimensions are only a few hundred microns. The materials used in MEMS are always in thin film from, based on certain substrates or composite with other thin films, which have an important role on the performance of MEMS devices and microstructures. The deposition processes of thin film and different thermal expansion coefficient between thin film and substrate always lead to the residual stresses in thin films, which may change the performance of the devices. Characterizing, understanding and controlling the mechanical properties of MEMS materials have been an active research area during the recent years, and many different methods have been developed such as nanoindentation [1], tensile testing [2], beam bending [3] and bulge testing [4]. Review papers on the measurements of the mechanical properties of MEMS materials are also available [5]. Recently, Zhang et al. proposed a novel microbridge testing method [6–8], which can simultaneously determine the residual stress, elastic modulus and even the bending strength of thin films. This method uses MEMS to fabricate samples and the sample holding problem and substrate effect can be avoided. In the meanwhile, many samples having different sizes can be fabricated on the same wafer. Nanoindenter is used to measure the load–deflection curves of thin film microbridges, and by combining the theoretical analysis model, the Young's modulus and residual stress can be obtained. Furthermore, according to the deformation of the microbridges, the formulas could be divided into two groups, namely the large deflection theory and the small deflection theory for microbridge testing [6]. By using these formulas, one can simultaneously evaluate the Young's modulus, the residual stress and even the bending strength of thin films from the experimental load–deflection curves. As a result, Zhang et al. have successfully measured the Young's modulus, residual stress and the bending strength of ceramic films such as Si_3N_4 and SiO_2 films [6–8]. However, for the metal thin films, they display rather a different mechanical behaviors than the ceramic films, such as lower yield strength, creeping easily and lower

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hardness, this makes it difficulty to measure the load–deflection curves correctly for metal thin film microbridges. Consequently, in order to measure the mechanical properties of metal thin film microbridges accurately, careful design of the dimensions of the microbridges must be done in order to get the deformation in the elastic ranges of the load–deflection curves. Furthermore, according to Zhang et al., the small deflection theory was preferred than the large deflection theory in fitting the experimental data when the deflection was small enough and the load–deflection relationship was in a linear characteristic in ceramic films, which may also be suitable for the case of metal films. Whereas Zhang et al. did not clarify the limits of the load and deflection of the small deflection theory for a microbridge sample with unknown mechanical properties [6]. In this paper, considering the effect of elastic modulus and residual stress, we investigate the deformation behavior of the copper film microbridges over a wide range of dimensions, and the range of the deflection and load for the small deflection theory is defined. In addition, an experiment is carried out to demonstrate the mechanical properties of copper films electroplated on silicon wafer.

2. The calculation principle of the microbridge testing

Since the width is included in the line load, the crucial geometric parameters are the length and thickness of the microbridge sample. As a result, the deformation behavior of the microbridge samples is intensively studied over a wide range of length from 80 to 2500 μm and the thickness from 0.8 to 9 μm. In addition, the influence of Young's modulus and residual stress is also included. The Young's modulus is 100–130 GPa, which covers the possible value of Young's modulus of copper films, and the residual stress is set in the range of 5–100 MPa.

To simplify the calculations, we assumed that the substrate did not deform, and the built-in boundary condition was chosen. The following Eqs. (1)–(8) were used to calculate the load–deflection relationships based on the large deflection and small deflection theories, respectively; together with Eq. (9) for the load-maximum-stress relationship [6].

For large deflection, the bridge deflection at the bridge center with the lateral load applied is given by

$$w = -\frac{Q\tanh(kl/2)}{2N_x k} + \frac{Ql}{4N_x} - \frac{M_0}{N_x}\left[\frac{1}{\cosh(kl/2)} - 1\right] \tag{1}$$

where w is the deflection at the bridge center, Q the lateral load per unit width, l the bridge length, N_r the residual force per unit width in the film along the length direction, N_x is the force per unit width in the middle plane of the film along the length direction, $k=\sqrt{(N_x/D)}$, $D=E_f t^3/12$, where t being the film thickness and E_f the Young's modulus of the film, and M_0 is a generalized force connecting the film and the substrate. M_0 and N_x is expressed respectively as follows:

$$M_0 = \frac{Q[1-\cosh(kl/2)]}{2k\sinh(kl/2)} \tag{2}$$

$$I - \frac{l(N_x - N_r)}{2E_f t} = 0 \tag{3}$$

where I is given by

$$\begin{aligned} I = \frac{1}{8k}[&(a^2+b^2+2c^2)kl + 8(a-b)c\sinh(kl/2) \\ &+ 2abkl\cosh(kl) + (a^2+2ab-b^2+8bc)\sinh(kl) \\ &+ b^2\sinh(2kl)] \end{aligned} \tag{4}$$

In Eq. (4), a, b and c are given by

$$a = -\frac{Q\sinh(kl/2)}{N_x\sinh(kl)} - \frac{M_0 k}{N_x\sinh(kl)} \tag{5}$$

$$b = \frac{M_0 k}{N_x\sinh(kl)} \tag{6}$$

$$c = \frac{Q}{2N_x} \tag{7}$$

For small deflection, the axial deformation of the bridge beam induced by the lateral load is neglected and hence $N_x = N_r$. Thus, the center deflection w is reduced to

$$w = \left[\frac{kl}{4} - \tanh\left(\frac{kl}{4}\right)\right]\frac{Q}{N_r k} \tag{8}$$

The Young's modulus and residual stress are determined from fitting the experimental load–deflection curve with the theoretical solution by the least square technique, i.e. minimizing the positive function

$$S = \sum_{i=1}^{n}[w_i^e(Q_i) - w_i^t(Q_i, N_r, E_f)]^2 \tag{9}$$

where n is the number of data, w_i^e the experimentally observed deflection, and $w_i^t(Q_i, N_r, E_f)$ is the theoretical deflection obtained by the (8). The iteration technique is used to regress the Young's modulus E_f and residual force N_r, which gives the residual stress as $\sigma_r = N_r/t$.

The stress in the bridge beam, which is composed of two parts, one due to the middle plane tension and the other due to bending, is given by

$$\sigma = \frac{N_x}{t} - \frac{d^2 w}{dx^2}\frac{t}{2}E_f \tag{10}$$

Although the yield strength may be dependent on the film thickness and preparation methods, a certain value would be necessary for the determination of the dimensions of the film microbridges. In fact, in our experiments, the maximum stress is much smaller than the yield strength. For the copper film, the yield strength of 260 MPa [9] is used to define the limit of the maximum stress to confine deformation in the elastic ranges of the load–deflection curves, and then the load limit could be determined from the load-maximum-stress curves. In order to determine the range of load and deflection for small deflection theory, the load-maximum-stress and deflection relationships is calculated by the large deflection and small deflection theories, respectively, from which the load-normalized deflection difference and load-maximum-stress difference functions are created.