Cohesive Strength Characterization of Brittle Low-k Films

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Abstract

The cohesive strength of low k dielectric films is an important property in predicting thermo-mechanical integrity of the Cu/low k interconnect structure. An approach to measure the cohesive strength of brittle low k films is presented, in which residual stress, elastic modulus and film thickness, are considered. The importance of residual film stress in cohesive failures is demonstrated.

Introduction

The drastic deterioration in mechanical properties with the introduction of "low-k" dielectric films has led to serious process challenges in both integration and assembly. As a result, the thermo-mechanical stability of the Cu-low k interconnect structure has emerged as a major reliability concern, with interfacial delamination and ILD cohesive fracture being the leading failure modes. Failures can occur during fab processing when mechanical or thermal stresses are introduced (e.g., chemical mechanical polishing (CMP) or high-temperature process steps), during packaging due to the large difference in thermal expansion coefficients between the die and package substrates, or during reliability testing (temperature cycling or highly accelerated stress testing).

Figure 1 shows the drop in mechanical strength as k is reduced. The low k films typically have dielectric constant less than 3 such that modulus E is generally less than 10 GPa(vs. ~75GPa for silica). The reduction in k is achieved through the introduction of C-C bonding or the incorporation of porosity. A fundamental change of the low-k ILD films is their tensile intrinsic stress, compared with the compressive stresses in conventional SiO_2-based films, shown in Figure 2. Consequently, cohesive failure in ILD films becomes one of the dominant failure modes for interconnect system.

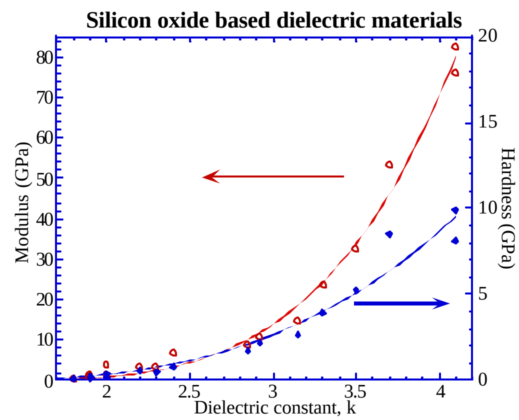

Figure 1. Mechanical properties of low K films as function of dielectric constant.

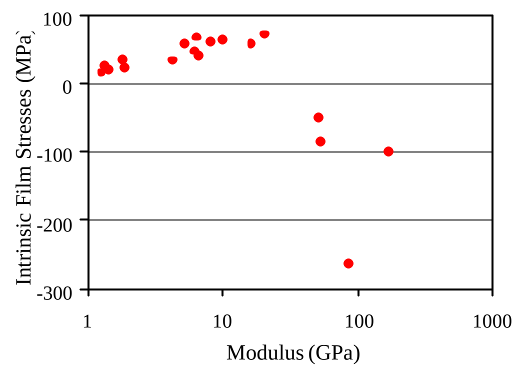

Figure 2. Intrinsic film stress vs. modulus.

Thin film adhesion is measured using the technique of four-point bending [1] which provides a reproducible, quantitative measure of interfacial adhesion energy. It has been shown [2] that the adhesion of Cu/low k interfaces can be modulated with changes to the low k film surface before Cu barrier films are deposited. Interfacial chemistry can thus be engineered to increase mechanical strength. Thin film cohesion, however, is an inherent film property. The film itself must be optimized to minimize or eliminate thin film cracking upon application of thermo-mechanical stresses. It is thus critical to be able to accurately measure thin film cohesion. In this paper a method for the measurement of cohesive strength is presented. Further the relationship between cohesive strength, other mechanical properties and reliability results are presented.

Experiments

The channel cracking technique, used for fracture toughness measurements, is illustrated in Figure 3. Samples are cleaved from wafers consisting of blanket ILD films deposited on a silicon substrate. The samples are loaded as shown in the figure.

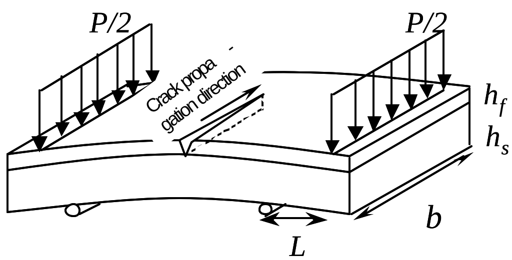

Figure 3. Channel cracking configuration.

The channel cracking technique has been described previously [3]. The difference here is the lack of a metal underlayer beneath the brittle ILD film. Therefore, the calculation must be modified accordingly. Here the total stress on the film is calculated as

$$\sigma_f = \sigma_0 + \frac{3PL}{h_s^2 b}\frac{1-\nu_s^2}{1-\nu_f^2}\frac{E_f}{E_s} \qquad (1)$$

The first term σ_0 is film residual stress and the second term represents the external stress applied to the film through bending. The fracture cohesive energy release rate is [4]

$$G = \Gamma_{el}\frac{\sigma_f^{\,2} h_f (1-\nu_f^2)}{E_f} \qquad (2)$$

In equations (1) & (2), E_f, E_s and ν_f, ν_s are Young's modulus and Poisson's ratio for the film and Si, respectively. And Γ_{el} is a constant, which depends on the elastic mismatch of the film and substrate; it is calculated using finite element modeling. During testing, crack growth was observed through an optical microscope and velocities were recorded at corresponding loads. Upon completion of testing, a curve of crack growth velocity as a function of G was generated. G_c is defined as the value at v=0.1µm/s in order to compare different ILD materials.

Results

Figure 4 is a plot of crack propagation velocity as a function of applied energy release rate for two different low k ILD films. The results show that ILD2 is stronger than ILD1. However, this is not consistent with other mechanical tests, such as bump shear, in which shear and tensile forces are applied on the base of the bump to simulate stresses induced during packaging. In the bump shear test, ILD1 required higher loads to cause failure than ILD2.

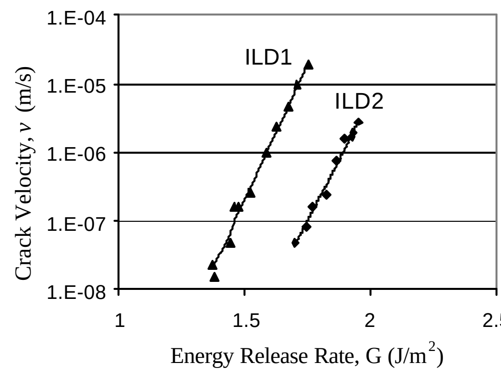

Figure 4. Crack growth velocity as function of energy release rate for 2 ILD films.

It should be pointed out here in that in mechanical tests such as bump shear, or the real assembly situation, the applied external stress will determine which ILD film is stronger. The contribution of intrinsic stress to film fracture strength makes the fracture energy somewhat misleading, especially when comparing ILD films of different intrinsic stress. To take this into account, we have proposed a new parameter, cohesive strength, σ_s, which is the applied external stress to cause film crack propagation at a fixed crack velocity. Furthermore, to take the thickness effect into account, the cohesive strength is normalized to a fixed film thickness of 1.5µm:

$$\sigma_s = \sqrt{\frac{GE_f}{\Gamma_{el}(1-\nu_f^2)*1.5\mu m}} - \sigma_0 \qquad (3)$$

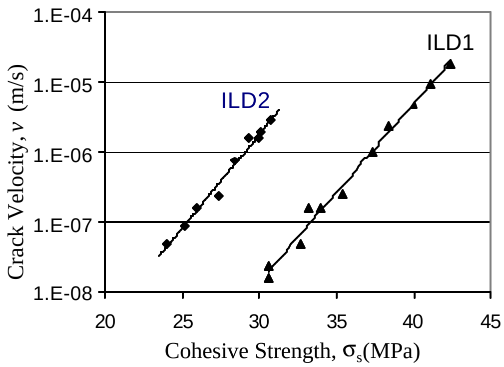

Figure 5. Crack velocity as function of cohesive strength, normalized to 1.5mm film thickness.

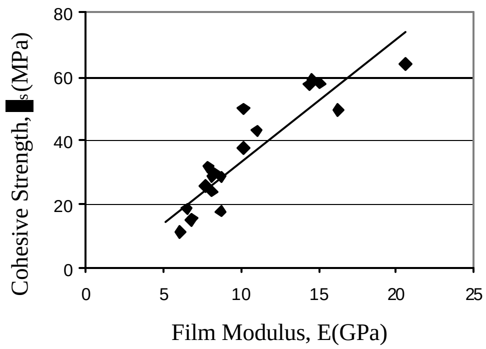

Figure 6. Cohesive strength as function of film modulus. Cohesive strength is normalized to 1.5mm film thickness and at 0.1mm/s.

The residual stress for ILD1 and ILD2 are 60MPa and 70MPa, respectively. Figure 5 shows the cohesive strength normalized to 1.5um film thickness at different crack velocities. The results show that ILD1 is stronger than ILD2, consistent with other mechanical tests.

One more important application of the channel cracking measurement is to predict critical thickness, h_c, the threshold thickness at which the film will crack in the absence of external stress; h_c can be calculated as follows:

$$h_c = h_f \frac{s_0^2}{s_f^2} \quad (4)$$

Figure 6 is a plot of measured cohesive strength as a function of film elastic modulus, showing a linear increase of cohesive strength with film modulus. As modulus increases, the k value is expected to increase too. In low k film development there is a tradeoff between optimization of mechanical properties such as modulus and cohesive strength and reduction in k value to meet requirements in both performance and reliability.

Conclusions

Introduction of low k materials presents serious reliability challenges due to their drastic deteriorating mechanical properties. Cohesive/adhesive strength and intrinsic film stress identified as critical mechanical properties for brittle low-k ILD. A new metric "cohesive strength at fixed film thickness" for thin film cohesion has been proposed and validated. It was also found that the film cohesive strength linearly increases while film modulus increases.

Reference

[1] Q. Ma, "A Four-Point Bending Technique for Studying Subcritical Crack Growth in Thin Films and at Interfaces," *J. Materials Research,* 12, p.840-845, 1997.
[2] E. Andideh, and T. Scherban *et al*, "Interfacial Adhesion of Copper-Low k Interconnects", Proceedings of the IEEE 2001 IITC, p.257-259, 2001.
[3] Q. Ma *et al*, "Channel Cracking Technique for Toughness Measurement of Brittle Dielectric Thin Films on Silicon Substrates", Materials Reliability in Microelectronics VIII, *Mater. Res. Soc Symposium*; vol. 365 p.331-336, 1998.
[4] J. W. Hutchinson and Z. Suo, "Mixed Mode Cracking in Layered Materials," *Advances in Applied Mechanics,* 29, p.63-191, 1992.