COHESIVE ZONE-BASED MODELLING OF Si/Si AND SiO_2/ SiO_2 INTERFACES IN THE PRESENCE OF A DUCTILE INTERLAYER.

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ABSTRACT
A methodology based on the insertion of a thin plastically deforming layer near the interface is proposed in order to extract the critical strength of Si/Si and SiO_2/ SiO_2 interface as well as to increase the fracture toughness. The influence of the critical strength and the ductile layer thickness on the global toughness is presented and discussed.

1 INTRODUCTION

Wafer bonding is an important microfabrication technique that allows assembling MEMS parts and packaging microsystems. Reliability of MEMS requires the development of characterization and modelling tools that allow the assessment of the integrity of bonded interfaces towards fracture and delamination. A minimum of two parameters is necessary to fully characterize the mechanical response of an interface [1,2], : i) the work of separation which represents the energy per unit area of crack advance needed to break chemical bonds and create crack tip damage, noted G_c or Γ and ii) the maximum stress, σ_c, reached in front of the crack tip in the so called fracture process zone. In order to measure G_c and evaluate various bonding techniques and rate effects, a steady-state wedge-opening test has been developed [5] following earlier works in the literature on the static wedge-opening method [3,4]. The second parameter, σ_c, could, in principle, be determined by simple uniform tensile or shear. However, such measurements heavily depend on interface defects and do not deliver the intrinsic strength of the bond [3]. An indirect method is proposed in this work in order to extract the critical stress. A thin ductile interlayer is inserted near the interface in samples presenting identical interfaces. The amount of energy dissipated by plastic deformation of the interlayer is very much dependent on the critical strength of the interface. In the meantime, plastic dissipation in the ductile interlayer also constitutes a way to increase the global toughness of the bond.

More precisely, the idea is to keep exactly the same Si/Si and SiO_2/ SiO_2 interfaces but in the presence of a thin ductile layer inserted near the interface. These tests supplement regular tests performed on samples without ductile layers. Fig. 1 schematically summarizes the principle of the method by considering two interfaces with similar fracture energy but different strengths. In the first case (see Fig 1.a), the interface is characterized by a low strength. In the second case (see Fig 1.b), plastic dissipation occurs in the ductile layer, which significantly increases the overall interface toughness, Γ, as evaluated from eqn (1). The global toughness is equal to $\Gamma_p + \Gamma_0$ where Γ_0 is the work of interface separation and Γ_p is the plastic work dissipated in the ductile layer (both terms are energy per unit area.

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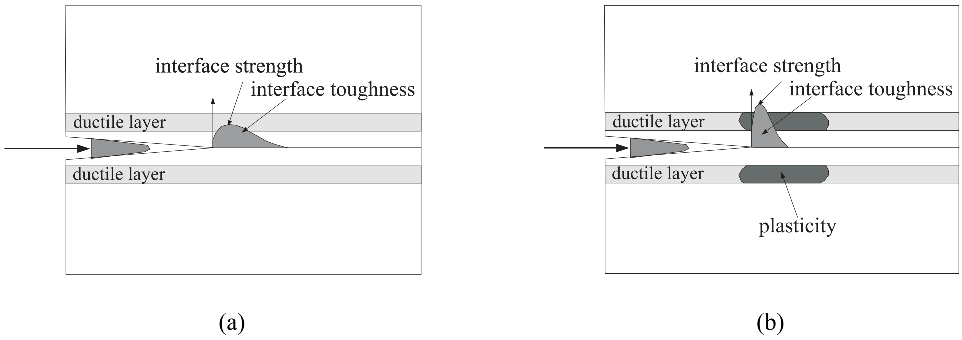

FIGURE 1: Schematic of the method used to probe the interface strength.

The steady-state wedge test provides the value of the crack length (see [3]), *a*, which is used to determine the toughness Γ of the bonding:

$$\Gamma = G_c = \frac{3\,E\,h^2\,d^3}{16\,a^4}\cdot \tag{1}$$

This relationship is only valid when the specimen remains globally elastic. The results obtained without a ductile layer directly gives $\Gamma_0 = \Gamma$.

The model used to extract the critical stress in the presence of a ductile interlayer is presented in the first section. Then, numerical results showing the influence on the global toughness of the critical stress and the ductile layer thickness are presented and discussed.

2 DESCRIPTION OF THE MODEL

Following earlier efforts by Tvergaard and Hutchinson [2], the fracture process at the interface is simulated using as an interface traction-separation law which relates the normal stress σ to the normal displacements δ and which is characterized by the fracture energy of the interface noted Γ_0 and a peak stress noted σ_c. The traction-separation law proposed by Tvergaard and Hutchinson [2] has been chosen for this investigation. The work of separation writes

$$\Gamma_0 = \sigma_c \delta_c \left(1 - \frac{\lambda_1 + \lambda_2}{2} \right) \tag{2}$$

where δ_c is the maximum separation, σ_c the peak stress and λ_1 and λ_2 are two shape parameters of the curve. The parameters λ_1 and λ_2 are taken equal to 0.15 and 0.5 in this study The different layers involved in the simulation were modelled using isotropic linear elasticity and the isotropic J_2 flow theory for the ductile layer. The main output of the model allow the determination of the ratio Γ/Γ_0 , i.e. the overall toughness divided by the toughness of the interface. Γ can be determined using (2) if the wafer thickness is large enough. From dimensional analysis,

$$\frac{\Gamma}{\Gamma_0} \equiv F\left(\frac{\sigma_c}{\sigma_0}, \frac{E_p}{\sigma_0}, n, \frac{h_{el}}{h_p}, \frac{\Gamma_0}{\sigma_0 h_p}, \frac{E_p}{E}, \nu, \nu_p \right) \tag{3}$$

where σ_0 is the yield strength of the ductile layer, E_p is the Young's modulus of the ductile layer, n is the work-hardening coefficient of the ductile layer, υ_p is the Poisson's ratio of the ductile layer, E and υ are the Young's modulus and the Poisson's ratio of the two elastic layers surrounding the ductile one, h_p is the thickness of the ductile layer and h_{el} is the thickness of the thin elastic layer. An important length controlling the energy dissipation in the ductile layer is R_0 defined as

$$R_0 = \frac{E}{3\pi\left(1-\upsilon^2\right)}\frac{\Gamma_0}{\sigma_0^2} \tag{4}$$

which represent the size of the plastic zone that would exist without the thin elastic layer if the ductile interlayer was very thick.

2.1 Numerical methods

A steady state finite element formulation for small strain-small rotation crack propagation problems was first applied by Dean and Hutchinson [7] and later implemented by several other authors [6]. The formulation consists of finding an equilibrium solution for the displacements based on a previous approximate distribution of plastic strains and then integrating the plasticity laws along streamlines to determine new approximations for stresses and plastic strains. This procedure is repeated until convergence is achieved. A small strain, large rotation formulation is used. More details about the formulation of the code can be found in [8]. Since the test is symmetrical, only half of the sandwich needs to be analysed. Plane strain conditions are assumed. The wedge is modelled with a fixed boundary condition at a normalised distance from the plane of symmetry.

3 NUMERICAL RESULTS

3.1 Influence of the critical stress

The evolution of the Γ/Γ_0 ratio with σ_c/σ_0 for various R_0/h_{el} is shown in Fig. 2. The other parameters are taken constant: $E/\sigma_0 = 4000$, $n = 0.1$, $h_p/h_{el} = 5$. These are reasonable values for typical Al interlayer deposited on Si substrate. The value of Γ/Γ_0 increases with increasing R_0/h_{el}, reaches a maximum value when it is equal to about 40 times the thickness of the thin elastic layer (see Fig. 2) and then decreases with further increase of R_0/h_{el}

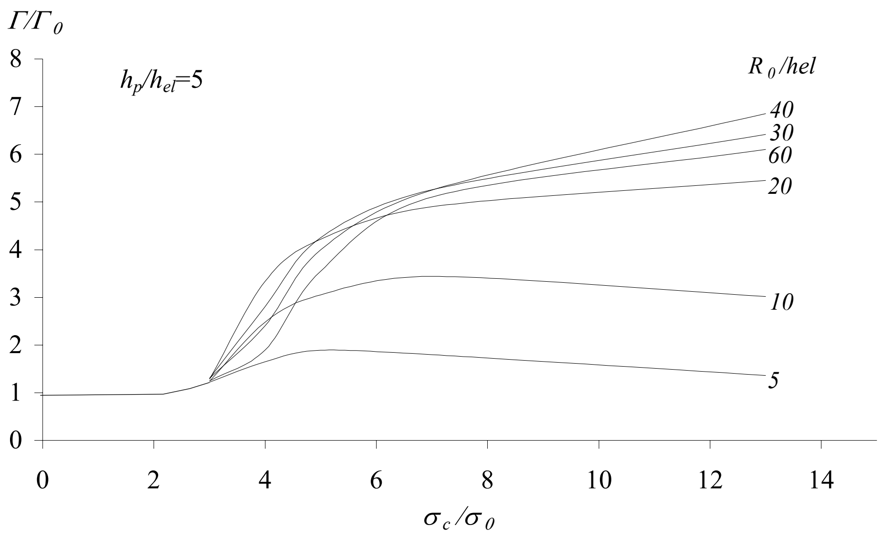

FIGURE 2: Influence of the critical stress of the interface on the global toughness for samples with a ductile layer characterized by $E/\sigma_0 = 4000$, $n = 0.1$, $h_p/h_{el} = 5$ for different values of R_0/h_{el}.

The increase of Γ/Γ_0 with increasing σ_c/σ_0 at constant R_0 results from increasing plastic dissipation in the ductile layer. Keeping R_0 constant means that Γ_0 is constant. However, when σ_c increases, the critical opening δ_c decreases proportionally and a point is attained where the decrease of δ_c becomes predominant in influencing the plastic dissipation. Increasing R_0 has the same effect as increasing σ_c. A maximum is attained because even if R_0 is increased, the increase of Γ_p is not high enough to keep the ratio $(\Gamma_p+\Gamma_0)/\Gamma_0$ increasing as Γ_0 increases proportional to R_0.

3.2 Influence of the ductile layer thickness

Increasing the ductile layer thickness increases the value of the ratio Γ/Γ_0 as shown in Fig.3. Thicker ductile layers lead to more plastic dissipation and thus to an increase of Γ.

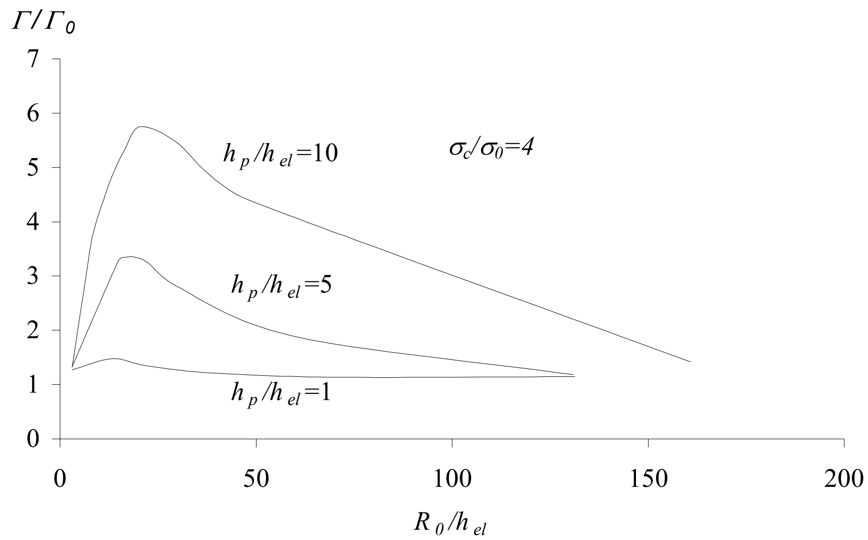

FIGURE 3: Evolution of the ratio Γ_{ss}/Γ_0 with R_0/h_{el} for three different ductile layer thickness, h_p/h_{el} = 1, 5, 10. The value of σ_c/σ_0 is equal to 4 in the three cases.

4 CONCLUSION

Fig. 2 and 3 have shown that realistic values for the layer thicknesses and material properties lead to very significant effects of the critical stress on the global toughness which is essential for identification purpose from experimental data.

The methodology presented in this paper in order to extract the critical interface strength, σ_c, (using results similar to the one shown in Fig.2) is currently applied to SiO_2/SiO_2 interfaces. Two difficulties are encountered experimentally:

1. measuring accurately the crack length requires to introduce windows in the ductile layer because the samples are not transparent anymore.
2. evaluating the flow properties of the deposited Al (σ_0, n), *e.g.* using nanoindentation.

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