CRACK AND DELAMINATION RISK EVALUATION OF THIN SILICON BASED MICROELECTRONICS DEVICES

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ABSTRACT

Enhancing miniaturization and system integration of microelectronics components demands growingly for novel solutions toward embedding active and passive components into substrates, clothes, protective sleeves of consumer goods – smart, thin applications in general. As a result, the embedding of very thin silicon dies and metallic structures into highly flexible polymeric, paper like or textile materials causes several mechanical problems preventing those applications from being utilized. Various kinds of inhomogeneity, residual stresses from several steps of the manufacturing process contribute to interface delaminations, chip cracking and fatigue of solder interconnects.

This paper intends to demonstrate and discuss advantages and needs of using fully parameterized modeling techniques for design optimizations of thin devices on the basis of nonlinear finite element simulations. These numerical investigations take into account the nonlinear, temperature and rate dependent behavior of the different materials used and the application of advanced fracture mechanics concepts (energy release rate, integral fracture approaches, mode-mixity examinations) with regards to the specific area of surface-near and interface-near micro scaled regions. For improving the utilized methodology, the evaluation of mixed mode interface delamination phenomena and fracture were combined with experimental investigations by means of SEM and AFM.

1 INTRODUCTION

Microelectronic packages like Flip-Chip, CSP assemblies and smart, thin electronics devices are typically compounds of materials with quite different Young's moduli and thermal expansion coefficients. Furthermore, various kinds of inhomogeneity, residual stresses from several steps of the manufacturing process and extreme thermal environmental conditions are factors for interface delamination, chip cracking and fatigue of solder interconnects. Consequently, numerical investigations by means of nonlinear FEA, fracture mechanics concepts are frequently used for design optimizations and sensitivity analyses – see Auersperg et al.[1] and Ostmann et al. [2].

In particular, enhancing miniaturization and system integration of microelectronics components demands growingly for novel solutions toward embedding active and passive components into substrates, clothes, protective sleeves of consumer goods – smart, thin applications in general. As a result, the embedding of very thin silicon dies and metallic structures into highly flexible polymeric, paper like or textile materials causes several mechanical problems possibly preventing those applications from being utilized.

As chip cracking and/or delamination are the well-known major risks downgrading the mechanical reliability of thin silicon applications fracture mechanics concepts are used here to investigate the influence of several design parameters using parameterized finite element modeling. They take also into account the nonlinear, temperature and rate dependent behavior of the different materials used and the application of advanced fracture mechanics concepts (energy release rate, integral fracture approaches, mode-mixity examinations) with regards to the specific area of surface-near and interface-near micro scaled regions. The utilized methodology is always a combined approach of numerical and experimental investigations. SEM and AFM based image correlation techniques support the evaluation of mixed mode interface delamination and fracture phenomena.

2 MIXED MODE FRACTURE EVALUATION

It is common knowledge in mechanical engineering that cracks starting at sharp edges have to be taken into account in order to come to a conservative evaluation of the fracture toughness of the several materials interfaces present in advanced electronic packages. The application of fracture mechanics concepts is the recommended procedure, but has not been examined just as well for mixed mode conditions at materials interfaces as it has for mode I situations in homogeneous media. However, coming from K-concept usage, a lot of work was done recently in order to explore mode mixity effects (e.g. Liu [3] and Wang [4]). Although, in contrast to investigations into bulk material fracture phenomena integral fracture concepts like the J- or the ΔT*-integral from Brust, Atluri et al. [5,6], which have the potential to take into consideration the inelastic behavior of the related materials, remain almost unconsidered for use. One reason for this seems to be the subdivision of the region of interest into two or more parts and the mechanical behavior of the interface itself. But, as integral fracture approaches base on energy release considerations, this methodology should be moved more into the center of interest, taking into account that some work has to be done in order to make it utilizable.

Therefore, the numerical investigations performed and discussed here are trying the energy release rate and the phase angle between its components as parameters - see also Sun [7].

Hutchinson et al. [13] introduced a complex stress intensity factor (SIF) $K=K_I+iK_{II}$ characterizing the near tip stress field at an interfacial crack with

$$(\sigma_{xx}^{\infty} + i\sigma_{yy}^{\infty})_{\Theta=0} = Kr^{i\varepsilon} / \sqrt{2\pi r} \tag{1}$$

where the oscillatory exponent is

$$\varepsilon = \frac{1}{2\pi}\ln\left[\frac{\left(\frac{\kappa_1}{\mu_1}+\frac{1}{\mu_2}\right)}{\left(\frac{\kappa_2}{\mu_2}+\frac{1}{\mu_1}\right)}\right] \; and \; \kappa_j = \begin{Bmatrix} 3-4\nu_j & plane\,strain \\ (3-\nu_j)/(1+\nu_j) & plane\,stress \end{Bmatrix} \tag{2}$$

Here, μ_j is a shear modulus, ν_j Poisson's ratio and subscripts j denote upper and lower materials, respectively. The most important obstacle for utilizing the well known conceptions from bulk material fracture mechanics is the oscillatory nature of the stress fields under LEFM conditions. Sun et al. [7] characterize the oscillation zone size as

$$r_0 = 2a\exp\left(-\frac{\pi}{2\varepsilon}\right) \quad for\; \sigma_{yy} \; and \; r_0^* = 2a\exp\left(-\frac{\pi}{\varepsilon}\right) \quad for\; \sigma_{xy} \tag{3}$$

Both, r_0 and r_0^* turn out to be the size of that (possibly overlapping) zone. Because of the oscillatory singularity in the near tip stress field, K_I and K_{II} for interfacial cracks cannot be associated with Mode I and Mode II fracture as defined in homogeneous media. Hutchinson [8] suggested for the case ε = 0

$$G(\psi_G) = G_c(\psi_G) \; with \; \psi_G = \tan^{-1}\left(\frac{G_{II}}{G_I}\right) \; and \; G = G_I + G_{II} \tag{4}$$

However, the energy release rate G (ERR) equals the change in strain energy with crack area extension (building new surface area at the crack flanks). G can be calculated by a virtual crack closure technique (VCCT) originally proposed by Rybicki and Kanninen [9]. For bimaterial interfacial cracks, however, the energy release rates for Mode I and Mode II (obtained by separating shear and tension of the Rybicki and Kanninen's formula) do not converge because of their oscillatory nature.

Therefore, Sun and Qian [7] derived accurate (for plane strain or stress linear elastic conditions) stress intensity factors $\mathbf{K_I}$ and $\mathbf{K_{II}}$ as well as non-oscillatory energy release rates $\mathbf{G_I}$ and $\mathbf{G_{II}}$ to be used as a fracture criterion for interfacial cracks.

3 THIN SILICON ON/IN THIN SUBSTRATE

Very interesting for further thin silicon devices is the embedding of thin dies into substrates – see cross section and a related FE-model in Fig. 1.

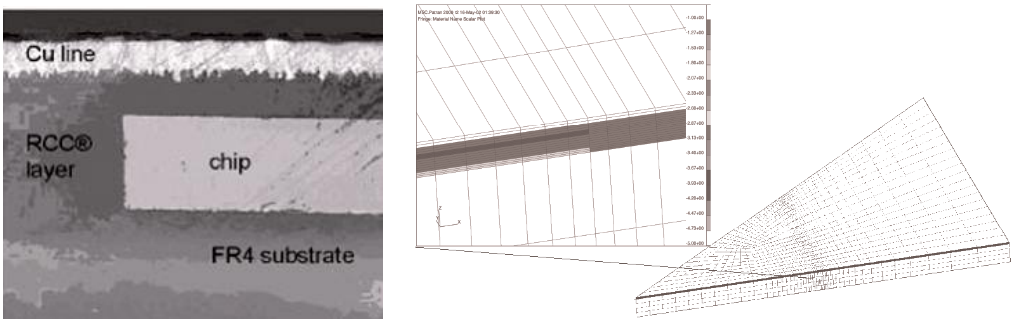


Figure 1: Cross section of a substrate embedded thin silicon die

3D parameterized FE-Models have been created which allowed the variation of several geometric and materials parameters in order to investigate the criticality of micro-cracks present on the die surface or starting from the die edge as shown in Fig 2 and interface cracks to study the delamination risk at several materials interface edges.

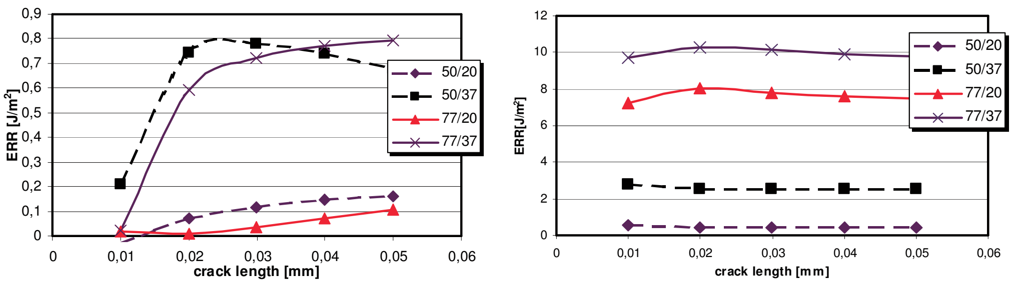
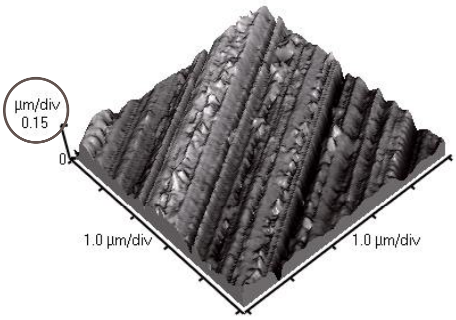


Figure 2: Energy-release-rate at an adhesive-substrate interface (left) and a die-adhesive interface (right) of a thin-chip on substrate application for varying crack lengths

4 SILICON FRACTURE EXPERIMENTS

Numerous experiments have been carried out to evaluate the possible influence of CMP backside treatment on fracture behavior of silicon dies. AFM topography scans of Fig. 3 illustrate the effect of CMP. Scratches after grinding are clearly recognized on the left topography scan. Surface roughness is significantly reduced by additional CMP.



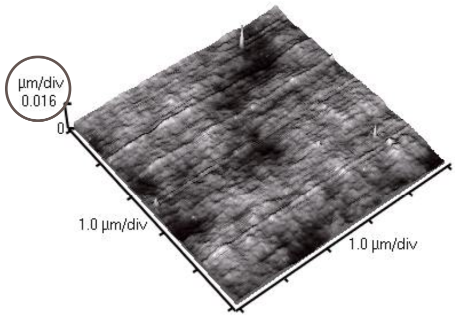


Figure 3: Backside topography of silicon dies before (left) and after (right) CMP, RMS roughness values Rq = 17,5 nm after grinding and Rq = 1.6 nm after subsequent CMP

Fig. 4 demonstrates the testing for two different specimen by recorded curves of load vs. bending path. As can be seen from the figure the ultimate achievable specimen load or bending is nearly independent on additional backside CMP.

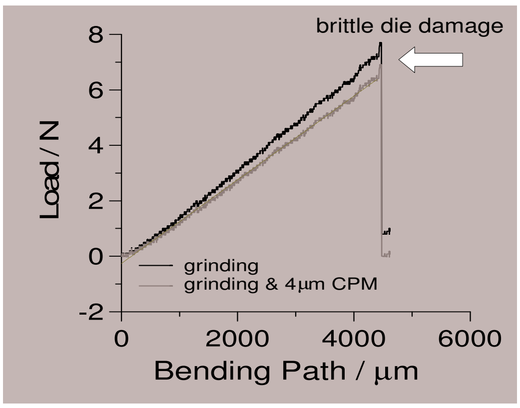


Figure 4: Three-point bending tests for Si slices with & without CMP treatment, bending stiffness: 1510 N/m after grinding and 1570 N/m after additional CMP

These 1st results indicate, for conventional waver dicing cracks introduced to the die edges by the dicing process seem to be more important for die damage than cracks initiated from the remaining backside roughness after grinding. However, special processing approaches like e.g. dicing-by-

thinning can alter the damage scenario. This indication confirms exactly with the simulation results.
AFM measurements also assist to identify crack tip locations by the help of grayscale image correlation methods. Assuming LEFM conditions this method allows the use of adapted fitting techniques in the very vicinity of a crack tip as an improved basis for strain and crack opening measurements in micro- and nanoscaled regions. That way, finite element models can be improved due to the appropriate description of the material behavior, of loading and boundary conditions and an enhanced modeling of the processes in the crack tip near region.

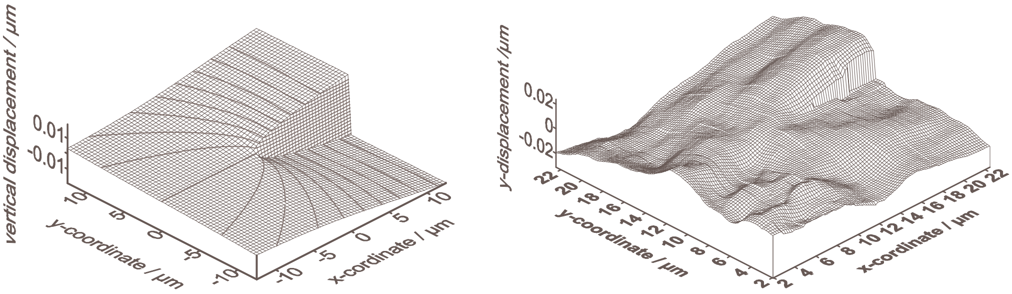


Figure 5: Mode I crack opening out of plane displacement – theory (left) and measured (right)

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