ANALYSIS OF STRESS SINGULARITIES IN BI-MATERIAL INTERFACES WITH APPLICATIONS TO IC PACKAGING

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During temperature cycling of plastic-packaged semiconductors, stress concentrations arise at interface corners. This may lead to delamination (loss of adhesion between the different materials) and other failures such as cracks inside the plastic encapsulation. The order of the stress singularity at the edges of the silicon chip does not depend on the coefficients of thermal expansion, but only on the Dundurs parameters which are related to the shear moduli and Poisson ratios. Situations with complete adhesion and with delamination are compared.

INTRODUCTION

Semiconductors are encapsulated by a plastic mould compound. Because of the demand for integrated circuits with higher memory capacities the silicon chips have increased in size, while the plastic-package dimensions have become smaller and thinner. This has resulted in an increase in the failure rates of the devices during temperature cycling tests between +150°C and −65°C. Observations by van Doorselaer and de Zeeuw [1] using scanning acoustic tomography showed a correlation between crack initiation inside the plastic and delamination, i.e. total loss of adhesion between the silicon chip or the metal leadframe and the plastic encapsulation. An example is given in Fig. 1. In order to understand this simultaneity of failures and fracture, the effects of adhesion and delamination in bi-material interfaces are analysed.

PROBLEM FORMULATION

For an investigation of the stress components near the edges of the silicon, the model of a bi-material wedge corner is employed. We distinguish between (a)

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geometries where both interfaces of the wedge are perfectly bonded, and (b) geometries where one interface has delaminated, see Fig. 2. Both materials are assumed isotropic and linearly elastic, having shear modulus μ_k, Poisson's ratio ν_k and coefficient of thermal expansion C_k. We define $\kappa_k = 3 - 4\nu_k$ for plane strain and $\kappa_k = (3 - \nu_k)/(1 + \nu_k)$ for plane stress $(k = 1, 2)$.

We introduce the complex coordinate $z = x + iy = r\,e^{i\theta}$, where $0 \leq \theta \leq \omega$ for material 1 and $\omega - 2\pi \leq \theta \leq 0$ for material 2, with wedge angle ω, and use the complex function formulation for linear elasticity, see Muskhelishvili [2]. The normal and shear stresses $\sigma_{N,S}$ along any curve AB, the displacements u, v and the temperature T in material k $(k = 1, 2)$ are given by

$$\int_A^B (\sigma_N + i\,\sigma_S)\,\mathrm{d}z = \left[\phi_k(z) + z\,\overline{\phi_k'(z)} + \overline{\psi_k(z)}\right]_A^B, \tag{1}$$

$$2\mu_k(u + i\,v) = \kappa_k\,\phi_k(z) - z\,\overline{\phi_k'(z)} - \overline{\psi_k(z)} + 2\mu_k C_k \eta_k(z), \tag{2}$$

$$2T = \eta_k'(z) + \overline{\eta_k'(z)}, \tag{3}$$

where $\phi_k(z)$ and $\psi_k(z)$ are holomorphic stress functions and $\eta_k(z)$ are holomorphic temperature functions in the respective sectors of the wedge. These functions are determined by the boundary conditions. Across interfaces with perfect adhesion the stresses $(\sigma_N + i\,\sigma_S)$ and the displacements $(u + i\,v)$ are continuous. Delaminated interfaces are assumed to be stress-free.

THERMAL EFFECTS

During the temperature cycling tests for semiconductors, the temperature varies at a very low rate and can therefore be regarded as quasi-static and uniform, $T \equiv \Delta T$. Consequently, the complex temperature functions in the equation (3) are given by $\eta_k(z) = \Delta T \cdot z$ for both materials.

The complex stress functions show a limiting behaviour z^λ for $z \to 0$. Therefore, the stress and temperature functions in the equation (2) are only of comparable order when $\lambda = 1$, i.e. when the stresses remain finite near the vertex of the wedge [3]. From this we conclude that the order of stress singularities is not influenced by uniform temperature distributions or by the coefficients of thermal expansion. Of course, the temperature variation of the environment introduces thermal stresses inside the materials, but it only influences the intensity of the stress field. The singular behaviour of the stresses is typically caused by the mismatch of elasticity constants.

ANALYSIS OF STRESS SINGULARITY

The singular behaviour of the stress components in the vicinity of the wedge is characterized by a scalar parameter λ, the order of the singularity. The complex stress functions behave like

$$\phi_k(z) = A_k\,z^\lambda, \qquad \psi_k(z) = B_k\,z^\lambda, \qquad (z \to 0). \tag{4}$$

It has been shown by Theocaris [4] that the complex conjugate expressions with $\overline{\lambda}$ can be omitted. Since the energy density at the vertex $z = 0$ must be integrable, we have the restriction $0 < \text{Re}\,\lambda \leq 1$.

Substitution of (4) into the boundary conditions with the use of the expressions (1)–(2) and elimination of the constants A_k and B_k yields characteristic equations for the parameter λ, which are subsequently solved for λ in the complex plane. The order of the singularity is now determined by the root λ with the smallest real part under the restriction imposed above. Smaller values of the real part of λ imply more severe stress concentrations.

The parameter λ depends on the wedge angle ω and the four elasticity constants μ_1, κ_1 and μ_2, κ_2. It is possible to reduce this dependence by using the so-called Dundurs parameters [5] which are defined by

$$\alpha = \frac{\mu_2(\kappa_1+1)-\mu_1(\kappa_2+1)}{\mu_2(\kappa_1+1)+\mu_1(\kappa_2+1)}\,, \qquad \beta = \frac{\mu_2(\kappa_1-1)-\mu_1(\kappa_2-1)}{\mu_2(\kappa_1+1)+\mu_1(\kappa_2+1)}\,. \tag{5}$$

The parameters coincide, i.e. $\alpha = \beta$, when the materials have equal shear moduli, $\mu_1 = \mu_2$. In the case of two identical materials we find $\alpha = \beta = 0$.

The elasticity constants are in the range $0 < \mu_k < \infty$ and $1 \leq \kappa_k \leq 3$ for plane strain ($k = 1,\ 2$). Consequently, it is found that $-1 \leq \alpha \leq +1$ and $(\alpha - 1) \leq 4\beta \leq (\alpha + 1)$. Thus, it is convenient to introduce $\gamma = \beta - \alpha/4$ which is between $-1/4$ and $+1/4$. For plane-stress situations, however, we have $5/3 \leq \kappa_k \leq 3$ and therefore $(\alpha - 1) \leq 8\gamma \leq (\alpha + 1)$.

The characteristic equation for λ in the case of two adhering interfaces is determined in [6]. It is expressed in the parameters α and β and the wedge angle ω by the formula

$$\begin{aligned} \Delta_A \;=\; & \lambda^4(\alpha-\beta)^4\sin^4\omega - \lambda^2(\alpha-\beta)^2\sin^2\omega\left\{(1+\beta)^2\sin^2(\lambda\omega)\right. \\ & \left. + (1-\beta)^2\sin^2(\lambda(\omega-2\pi)) + 2(\alpha^2-1)\sin^2(\lambda(\omega-\pi))\right\} \\ & + \left\{(1-\beta^2)\sin(\lambda\omega)\sin(\lambda(\omega-2\pi))\right. \\ & \qquad \left. -(1-\alpha^2)\sin^2(\lambda(\omega-\pi))\right\}^2 = 0\,. \end{aligned} \tag{6}$$

The characteristic equation for situations where delamination is present is derived in [6, 7]. With the use of the Dundurs parameters we obtain

$$\begin{aligned} \Delta_D \;=\; & 4\lambda^4(\alpha-\beta)^2\sin^4\omega - 4\alpha^2\lambda^2\sin^2\omega + 4(\alpha-\beta)\lambda^2\sin^2\omega \,\times \\ & \qquad \times\left\{(\beta+1)\sin^2(\lambda\omega) + (\beta-1)\sin^2(\lambda(\omega-2\pi))\right\} \\ & +2(1-\alpha)\sin^2(\lambda\omega) + 2(1+\alpha)\sin^2(\lambda(\omega-2\pi)) \\ & +(\alpha^2-1)\sin^2(2\lambda(\omega-\pi)) \\ & +4(\beta^2-1)\sin^2(\lambda\omega)\sin^2(\lambda(\omega-2\pi)) = 0\,. \end{aligned} \tag{7}$$

RESULTS AND APPLICATIONS TO IC PACKAGING

In Figs. 3 and 4 the solutions to the characteristic equations (6) and (7) are shown as functions of α and γ. The wedge angle was chosen $\omega = \pi/2 = 90°$. Other wedge angles are studied in [6, 7]. The results for the wedge with one delaminated interface agree well with Fig. $6^{(b)}$ of Bogy [8]. Because of the larger real part of λ, the severity of the stress singularity in the case of complete adhesion is considerably lower than for delaminated geometries. Furthermore, it is observed that no stress singularity occurs ($\lambda = 1$) for perfectly bonded wedges of materials with equal shear moduli ($\alpha = \beta$).

In relation to integrated-circuit packaging these results imply that

1. delamination leads to higher stress concentrations at edges of the silicon;
2. the order of singularity only depends on two combinations of elasticity parameters and is not influenced by coefficients of thermal expansion;
3. stress singularities are avoided when silicon and plastic encapsulation have equal shear moduli.

In accordance with the reliability research in [1, 3], it is concluded that failures in plastic-packaged integrated circuits during the temperature cycling tests start with loss of adhesion. As a result, the stresses inside the packaging material are intensified and, eventually, fracture may occur. Consequently, the reliability of encapsulated semiconductors is improved when adhesion of all interfaces can be preserved. The present research has indicated which parameters are important in preventing the occurence of delamination.

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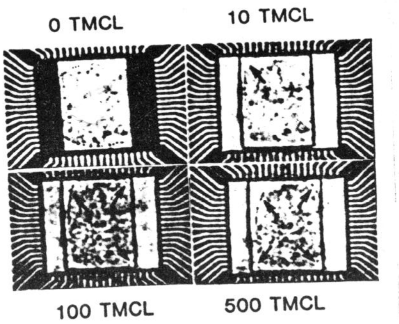

Fig. 1. Progress of delamination during temperature cycling (TMCL). Loss of adhesion is indicated by arrows.

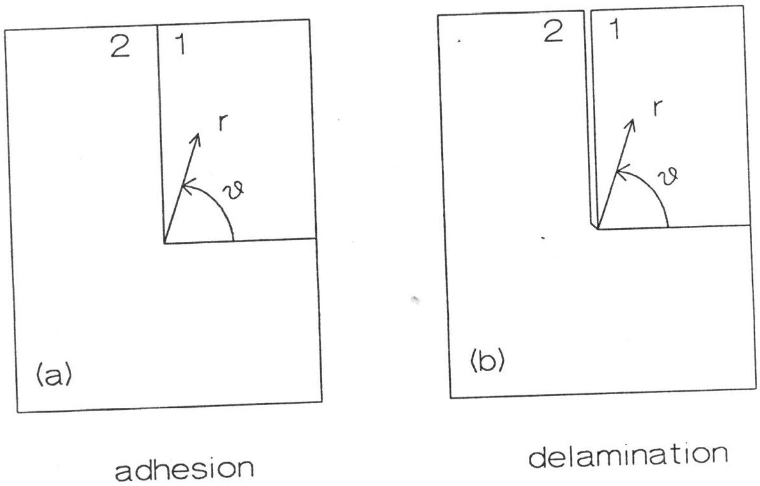

Fig. 2. Geometry of bi-material wedges with adhesion and delamination.

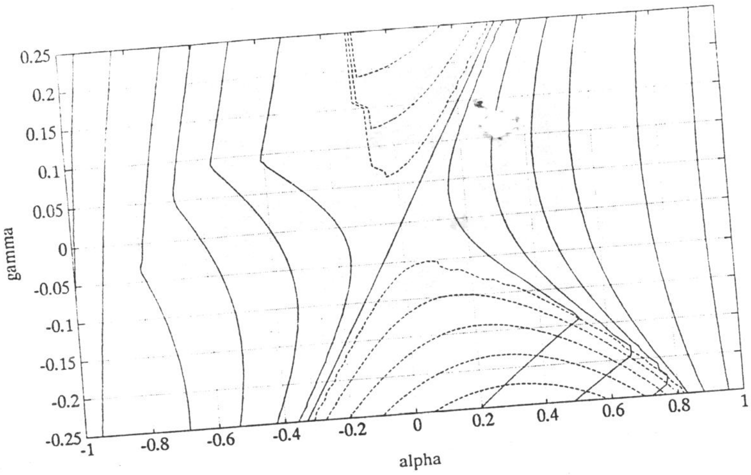

Fig. 3. Adhesion. Re λ (—) is 1.00, 0.95, 0.90, 0.85, 0.80, 0.70, 0.60 and Im λ (- - -) is 0.04, 0.08, 0.12, 0.16, 0.20 (both from middle to the sides).

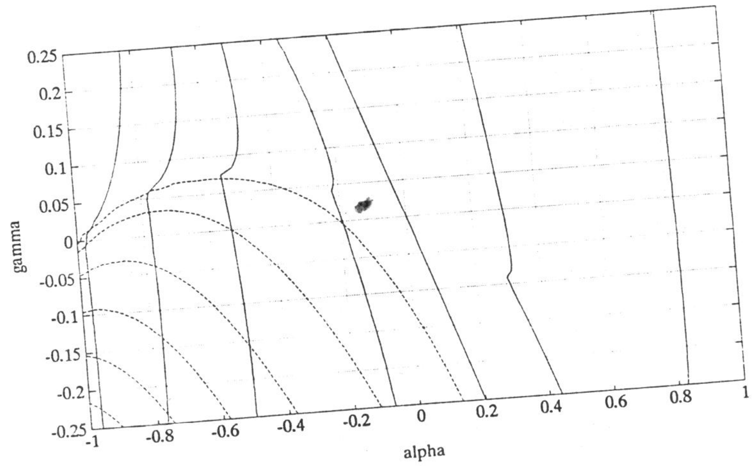

Fig. 4. Delamination. Re λ (—) is 0.35, 0.40, 0.44, 0.48, 0.50, 0.52, 0.54 (left to right) and Im λ (- - -) is 0.005, 0.02, 0.04, 0.06, 0.08, 0.10 (from centre).