

Thin film cracking and ratcheting caused by temperature cycling

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Layered materials are susceptible to failure upon temperature cycling. This paper describes an intriguing mechanism: cracking in a brittle layer caused by ratcheting in an adjacent ductile layer. For example, on a silicon die directly attached to an organic substrate, cracking often occurs in the silicon nitride film over aluminum pads. The silicon die and the organic substrate have different thermal expansion coefficients, inducing shear stresses at the die corners. Aided by cycling temperature, the shear stresses cause ratcheting in the aluminum pads. Incrementally, the stress relaxes in the aluminum pads and builds up in the overlying silicon nitride film, leading to cracks.

Temperature cycling is a main test for the reliability of layered materials, such as electronic packages, composites, and thermal-environmental barrier coatings. Failure modes observed in such a test, however, are often poorly understood. The lack of mechanistic understanding prolongs the process of material selection and geometric design. This paper describes a failure mechanism that has broad implications, namely, cracking in a brittle layer caused by ratcheting in an adjacent ductile layer.

Figure 1(a) illustrates a flip-chip electronic package. A silicon die is bonded to a packaging substrate, with the interconnect structure facing the packaging substrate. Between the die and the substrate are epoxy-glass underfill and solder bumps. Figure 1(b) details the left corner of the die. Illustrated is an aluminum pad of the top level interconnects. Silicon nitride (SiN) is a commonly used passivation film, which conformally covers the top level aluminum pads and silica. Failure modes caused by temperature cycling include die-underfill or underfill-substrate debonding,^{1,2} solder bump detachment,³ and SiN film cracking.^{4–8} This paper focuses on SiN film cracking.

Figure 2 is a plan view of the die surface near a corner of a test structure. After temperature cycling, the packaging substrate and the underfill were removed to expose the die surface. The structure had many aluminum pads. Cracks developed in the SiN film over some of the aluminum pads. The main experimental observations include (i) cracking occurred in the SiN film at the die corners; (ii) cracking occurred after some temperature cycles; (iii) cracking occurred in the SiN film over alu-

minum pads, but not in the SiN film over silica; and (iv) cracking was more likely when the aluminum pad is wide and the SiN film is thin.

As a persistent failure mode, such SiN film cracking has been investigated by several teams.^{4–8} However, its mechanism has so far been obscure. The packaging substrate has a larger thermal expansion coefficient than the silicon die. Upon cooling from the bonding temperature (~160 °C), the substrate would like to contract more than the die, but the bonding resists sliding between the substrate and the die. Consequently, shear stresses develop on the die surface, concentrated at the die corners, pointing to the die center.^{7–9} Indicated in Fig. 1(b) is the shear stress direction at the left corner of the die. The shear stresses by themselves, however, do not account for the observed cracking. The magnitude of the shear stresses is limited by the yield strength of the underfill, which is in the range 50–100 MPa.¹⁰ The yield strength of the aluminum pads exceeds 100 MPa,¹¹ and the fracture strength of the SiN film is on the order of GPa.¹² How can such a low shear stress level crack the high strength SiN film? Why does cracking occur after *cyclic* temperature change?

This paper describes a mechanism that explains the main experimental observations. The underfill has a lower yield strength than the aluminum pad, so that the shear stresses due to packaging by themselves do not cause plastic deformation in the aluminum pad. Before temperature cycling, the shear stresses on the top SiN surface are transferred to the aluminum pad, and the magnitude of the stress in the SiN film is small, much

below its fracture strength. Consequently, the SiN film does not crack upon first cooling from the bonding temperature. In a cycling test, the temperature is kept below the bonding temperature, so that the shear stresses on the die surface always direct to the die center, and do not reverse direction. Because aluminum has a larger thermal expansion coefficient than silica, during temperature cycling the aluminum pad deforms plastically. As illustrated in Fig. 1(c), the shear stresses due to the packaging direct the aluminum pad to deform incrementally in the same direction. After many temperature cycles, the accumulated plastic deformation is very large. Such large deformation of aluminum pads at die corners has been observed experimentally.^{13,14} The phenomenon is similar to *ratcheting* observed in pressure vessels and composites, where a small unidirectional load, aided by cycling temperature, incrementally causes large plastic deformation.^{15,16} As the aluminum pad ratchets, the overlaying SiN film distorts toward the right. It is this incremental elastic distortion that builds up the stress in the SiN film overlaying the aluminum pad. By contrast, the SiN film overlaying silica does not crack, because silica is elastic.

The magnitude of the shear stresses on the die surface varies with time and position, as affected by the temperature-dependent viscoplastic property of the underfill. A complete model should predict the shear stress distribution. In this paper, to focus on the main concept, we represent the underfill-die interaction with a constant shear stress, τ_0 . Figure 3(a) illustrates the idealized model. Because silicon and silica have comparable thermal expansion coefficients, the silica and low level interconnects are not included in the model, and the aluminum pad is placed directly on silicon. The structure

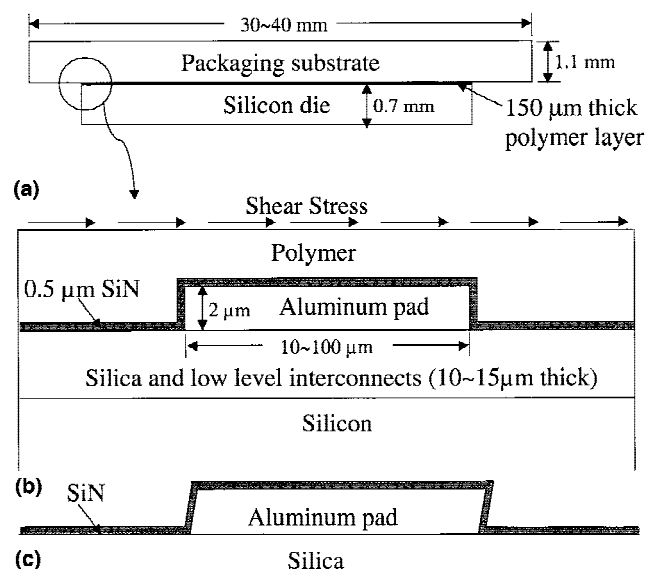


FIG. 1. (a) Flip-chip structure, (b) magnified view of the left corner of the silicon die, showing a conformal SiN film over an aluminum pad and silica, and (c) deformed structure after temperature cycles.

is in a state of plane strain deformation. These simplifications will affect numerical values, but not the qualitative picture.

After some temperature cycles, the aluminum pad no longer supports shear stress, and τ_0 is fully sustained by the SiN film itself. The structure reaches a steady state. Figure 3(b) shows the free body diagram of the SiN film. Denote σ_0 as the magnitude of the normal stress in the plane of the SiN film at the two ends, tensile on the left, and compressive on the right. Force balance requires that

$$\sigma_0 = \frac{\tau_0 L}{2t}, \quad (1)$$

where t is the thickness of the SiN film, and L the length of the aluminum pad. Although the shear stress τ_0 is small, the ratio L/t can be large. Consequently, the stress in the SiN film can build to a high level to cause cracking. The magnitude of the stress in the SiN film increases with the die corner shear stress and the width of the aluminum pad, but is inversely proportional to the SiN

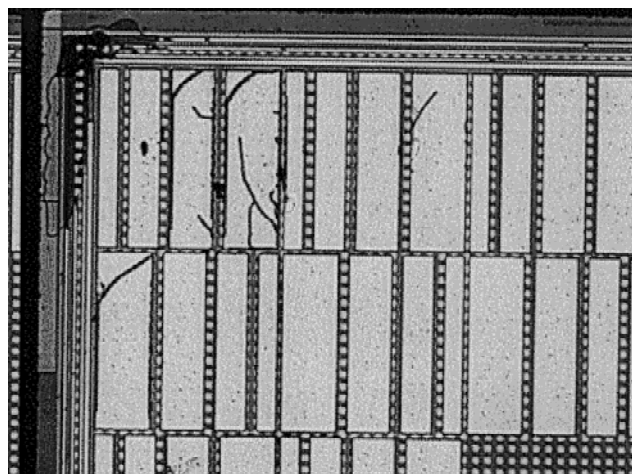


FIG. 2. An optical micrographs of a die surface near a corner of a test structure. Cracks develop in the SiN film over some of the aluminum pads.

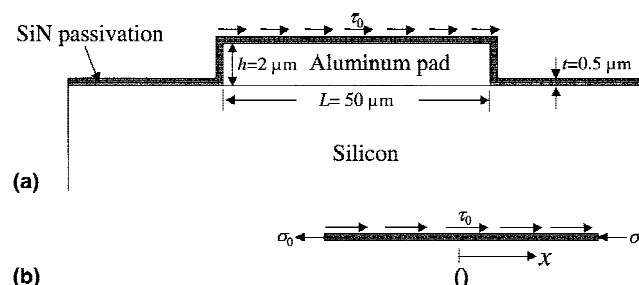


FIG. 3. (a) Idealized model and (b) force balance of the SiN film in the steady state. The aluminum pad no longer supplies shear stress.

film thickness. These are consistent with the experimental observations. The normal stress in the SiN film varies linearly with the position, given by

$$\sigma(x) = -2\sigma_0 x/L, \quad (2)$$

where x is the distance from the center of the aluminum pad.

To ascertain the main features of the mechanism, we analyzed the idealized model in Fig. 3(a) using the finite element software ABAQUS, (version 5.7, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, 1997). Aluminum was taken to be elastic and perfectly plastic, with the uniaxial yield strength 100 MPa. We took $\tau_0 = 50$ MPa, and the temperature cycle range 140 °C. Elastic constants and thermal expansion coefficients of silicon, aluminum, and SiN took the usual values. Figure 4 shows the deformed meshes after 1, 10, 50, and 100 temperature cycles. As expected, the structure distorts incrementally toward the right. Between 50 and 100 cycles, the additional distortion is negligible. The structure is close to the steady state after about 50 cycles.

Figure 5 shows the shear stress distribution in the aluminum pad. For the first cycle, the shear stress on the top SiN surface is mostly transferred to the aluminum pad. After 100 cycles, except at the two ends, the aluminum pad no longer carries shear stress; it acts like a liquid. Figure 6 shows the normal stress distribution in the SiN film. (Except at the two ends, this stress component is nearly constant across the film thickness. Plotted in Fig. 6 is the stress in the top SiN surface.) As the temperature cycles, the stress magnitude increases. Again, between 50 and 100 cycles, the stress changes negligibly; the structure has approached a steady state. In Fig. 6, Eq. (2) is the straight line, which agrees well with the finite element result for 100 cycles, except at the two ends of the SiN film. We also did finite element calculation assuming that aluminum acts like a liquid, i.e.,

having a vanishing yield strength. The stress distribution (zero aluminum yield strength, no temperature cycling) is the dotted line in Fig. 6, which closely traces the curve for 100 cycles.

A mechanistic understanding has emerged from this study. The die corner shear stress, aided by cycling temperature, causes the aluminum pad to ratchet. As temperature cycles, stress relaxes in the aluminum pad and builds up in the overlaying SiN film. After some cycles, a steady state is reached, in which aluminum acts like a liquid, and the overlaying SiN film becomes a compliant elastic structure supporting the die corner shear stress. The mechanistic understanding has immediate implications for design rules and qualification tests. If the SiN film can sustain the steady state without cracking, the structure is immortal. Eq. (1) gives the gross stress level in the steady-state for the idealized structure. This stress level depends on the die corner shear stress (taken to be the yield strength of the underfill), the width of the aluminum pad, and the thickness of the SiN layer. For an immortal structure, the transient stress evolution is unimportant. If the SiN film cannot sustain the steady state, the structure is mortal; it will crack in finite cycles. The transient stress development becomes important. In ad-

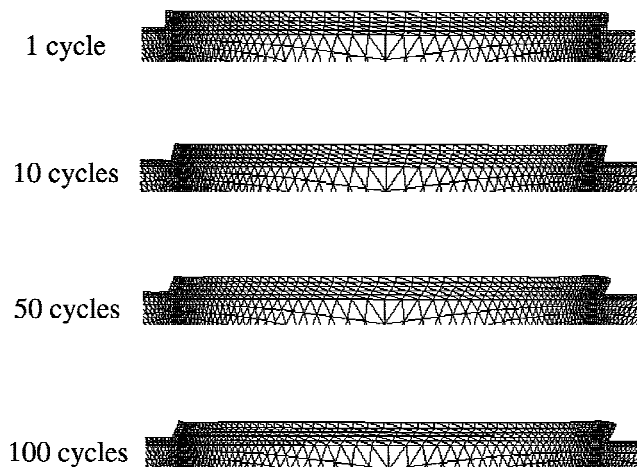


FIG. 4. Deformed meshes. Displacements are amplified by factor 5 for visual clarity.

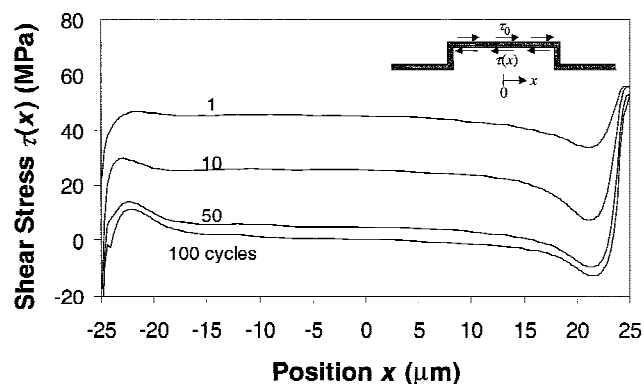


FIG. 5. The shear stress distribution along the SiN-aluminum interface.

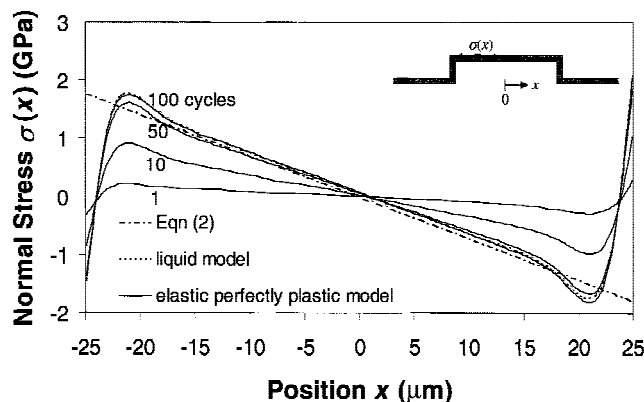


FIG. 6. The distribution of the normal stress in the plane of the SiN film.

dition to various geometric lengths and the yield strength of the underfill, the yield strength of aluminum and the temperature range play roles. All these effects can now be quantified within this understanding. This paper demonstrates the mechanism by analyzing an idealized structure. The qualitative conclusions are broadly applicable. To be quantitatively predictive, calculations are needed for realistic structures of 3D geometry, with time and cycle dependent deformation laws.¹⁷ Furthermore, the evolving stress field must be combined with fracture criteria suitable for complex structures of small feature sizes.¹⁸ The mechanistic understanding provides a roadmap for subsequent studies.

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