Thermal Shock Resistance of Plastic IC Package

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Synopsis

Dual-in-line packages (DIPs) were formed from epoxy molding compounds with various physical properties using a transfer molding machine. The compounds were prepared by changing kinds and amounts of additives and addition methods. The thermal shock test was carried out by the following procedures. The plastic package was soaked alternately in liquid nitrogen (−196°C) and in liquid solder (250°C) in the cycle of 140 s. The packages were intermittently subjected to optical microscopic inspection for crack initiation. The median life to crack initiation is defined to be the number of the cycles when half of the specimens exhibited crack initiation. Glass transition temperature, coefficient of linear expansion, and flexural modulus were measured to calculate thermal stress in plastic packages. According to the linear fracture mechanics, the following expression was obtained among the median life N, thermal stress σ_t, and strength σ_b: $N = C/\sigma_b^2 \cdot (\sigma_b/\sigma_t)^m$. We found the linear relation between logarithm of $N\sigma_b^2$ and logarithm of σ_b/σ_t for various packages, and obtained that the value of C and m are estimated as 3×10^4 MPa^2 and 5.5, respectively. Therefore, the median life can be predicted from the glass transition temperature, coefficient of linear expansion, flexural modulus, and strength of plastic materials for packages.

INTRODUCTION

The silicon integrated circuits are usually placed in packages to improve electric insulation and thermodiffusion and to protect the devices from any deleterious environments, i.e. dusts, water, impacts, and vibration.[1] The packages are further classified as (a) molded plastic packages and (b) hermetically sealed packages whose material is glass, ceramics, or metal. The plastic packages are widely used and the market is further increasing because of their low cost and improved reliability.[2]

In recent plastic-encapsulated IC and LSI, thermal stress due to enlarging devices and thinner packages is likely to induce failures, such as package cracks, passivation layer cracks, aluminum pattern deformation, and fracture of bonding wires.[3,4] It is necessary to reduce the thermal stress in plastic packages to prevent those failures. The thermal stress can be evaluated by the thermal shock resistance of plastic packages.[5]

We have made a thermal shock testing machine which estimates their thermal shock resistance. In this paper, we report a method to predict the thermal shock resistance from the thermal stress and the strength of plastic packages.

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EXPERIMENTAL

Materials

Epoxy molding compounds used for this experiment were composed of base resin, curing agent, flame retardants, filler, and additives. Base resin that was used for package was novolac epoxy resin because of its high heat resistance.

The addition of suitable curing agent causes the resins to polymerize into highly crosslinked solid. A phenolic curing agent was used to reduce the residual ionic contamination in the molding compounds. Brominated novolac epoxy resin and antimony trioxide were used as flame retardants. Fused silica was added to the polymers in the range of 68–74 parts per hundred parts of resin. This not only reduces cost but also improves the physical properties of the package polymers, increasing its strength and reducing the coefficient of thermal expansion. In addition, additives such as small amounts of silane coupling agent, accelerator, pigment, mold release agent, and elastomer were added to improve processing and to reduce the elastic moduli of the package polymers. The compounds which had various physical properties were prepared by changing the kind and amount of additives and their addition methods. The material of the lead frame was nickel iron alloy (Alloy 42) and a 2 × 4 × 0.5 mm rectangular silicon chip was bonded to the island of the frame with epoxy adhesive. Dual-in-line packages (DIP) and testing specimens were formed from epoxy molding compounds using a transfer molding machine.

Thermal Shock Test

The thermal shock resistance of DIP was estimated with the testing machine shown in Figure 1, and the test was carried out by the following procedures. The plastic packages were soaked alternately in liquid nitrogen (−196°C) and in liquid solder (250°C) in the cycle of 140 s (soaking time is 60 s), and they were intermittently subjected to optical microscopic inspection for cracks. The temperature in DIP was measured by a thermocouple embedded in the packages. Figure 2 shows the change in temperature during a soaking cycle in the liquid

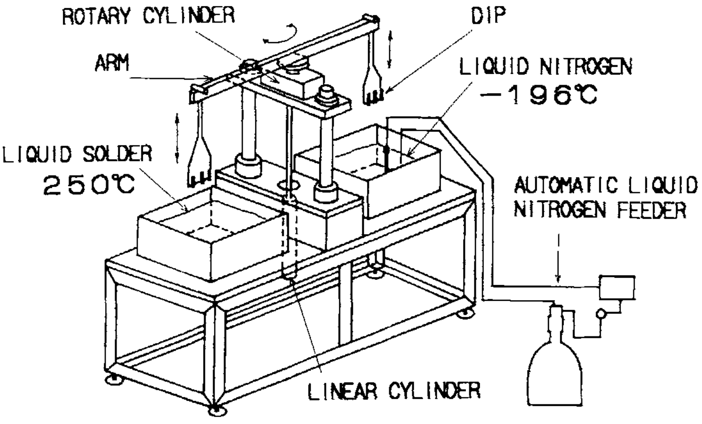

Fig. 1. Schematic diagram of thermal shock testing machine.

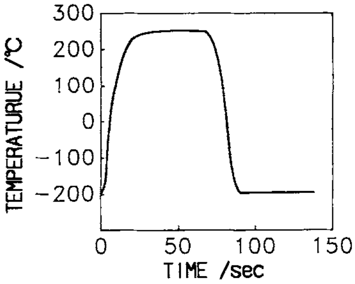

Fig. 2. Change in temperature of package during soaking cycle in liquid nitrogen and in liquid solder.

solder and liquid nitrogen. When DIPs were soaked in liquid solder from liquid nitrogen, the temperature increased with time and approached 250°C within 30 s. Soaking in liquid nitrogen from liquid solder, the temperature decreased and approached −196°C within 30 s. Therefore, the temperature in the package has reached the equilibrium state in soaking of 60 s. The package crack occurred at the edge of the model chip or island of lead frame. We tested 16 compositions which have different physical properties (each composition has more than five specimens the same).

Physical Properties of Package Polymers

Glass Transition Temperature

Dynamic viscoelastic properties were measured with a dynamic viscoelastometer from the Iwamoto Seisakusho Co. The storage modulus E' and the loss modulus E'' was determined at 10 Hz in the temperature range between −150 and +300°C. The specimens were heated at a rate of 2°C/min. The peak of E'' was identified as glass transition temperature T_g because a large decrease in E' occurred at this point.

Coefficient of Linear Expansion

The thermal expansion was measured with a differential thermal analyzer DT1500 from the Sinku Riko Co. The specimens were heated at a rate of 5°C/min. The thermal expansion was proportional to the temperature up to the T_g and the coefficients of linear expansion were calculated from the slope.

Flexural Modulus and Strength

Flexural test was carried out with an Autograph DSS-5000 from the Shimadzu Corp. Flexural modulus and flexural strength were calculated from the stress strain curve.

RESULTS AND DISCUSSION

Thermal shock test of DIP was carried out with a testing machine shown in Figure 1. Figure 3 shows some examples of the relation between the test cycles

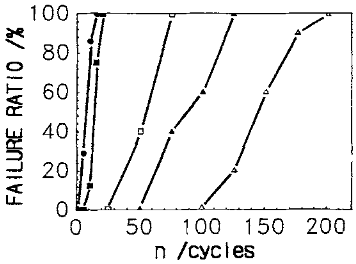

Fig. 3. Relation between test cycles n and failure ratio: (●) $T_g = 197°\text{C}$, $\alpha_p = 1.99 \times 10^{-5}\,°\text{C}^{-1}$, $E_p = 14.5$ GPa, $\sigma_b = 95.3$ MPa; (■) $T_g = 197°\text{C}$, $\alpha_p = 1.99 \times 10^{-5}\,°\text{C}^{-1}$, $E_p = 13.0$ GPa, $\sigma_b = 60.8$ MPa; (□) $T_g = 210°\text{C}$, $\alpha_p = 2.02 \times 10^{-5}\,°\text{C}^{-1}$, $E_p = 12.2$ GPa, $\sigma_b = 71.5$ MPa; (▲) $T_g = 210°\text{C}$, $\alpha_p = 1.75 \times 10^{-5}\,°\text{C}^{-1}$, $E_p = 13.1$ GPa, $\sigma_b = 113$ MPa; (△) $T_g = 220°\text{C}$, $\alpha_p = 1.60 \times 10^{-5}\,°\text{C}^{-1}$, $E_p = 14.8$ GPa, $\sigma_b = 115$ MPa.

n and the failure ratio (% of failed specimen). One crack in a specimen is counted as one failure. The failure ratio caused by the cracks increased with the cycles. Each package with different physical properties, such as glass transition temperature T_g, coefficient of linear expansion α_p, flexural modulus E_p, and flexural strength σ_b has a different life. This means that the thermal shock resistance of DIP can be estimated by the specially designed testing machine. The median life to crack initiation, N, an index of thermal shock resistance, is defined to be the number of the cycles when crack is observed in half of the specimens.

It was reported that the median life was well described by the contribution of the thermal stress in DIP.[5] The thermal stress in the plastic package can be obtained using a strain gauge embedded in the packages[6] or calculated on the basis of the classical approach to stress analysis.[7] In our experiments, the stress was calculated in the following manner.[8,9] We made a parallel model for shape of package polymer and lead frame. If it is assumed that there is no slippage between the polymer and frame, and that the stress strain relationship is linear, then the force in the polymer f_p is just equal to that in the frame f_l as expressed in

$$f_p = f_l \tag{1}$$

The total change in the length of the polymer at any temperature T, which is higher than that of the liquid nitrogen (−196°C), is equal to that of the frame. This is shown in

$$I_0(T + 196)\alpha_p - \frac{f_p I_0}{A_p E_p} = I_0(T + 196)\alpha_l + \frac{f_l I_0}{A_l E_l} \tag{2}$$

where I_0 is the length of DIP and α_p and α_l are coefficients of linear expansion, E_p and E_l are flexural moduli, and A_p and A_l are cross-sectional areas of package polymer and lead frame, respectively. Substituting eq. (1) into eq. (2), the thermal stress σ_t in package polymer is given by

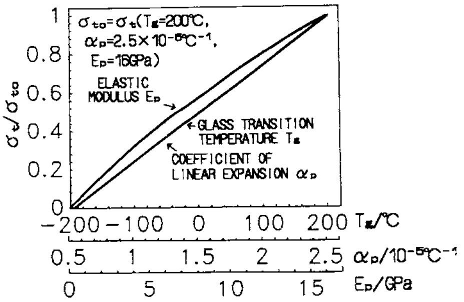

Fig. 4. Reduced thermal stress σ_t/σ_{t0} as a function of physical properties.

$$\sigma_t = \frac{E_p(T + 196)(\alpha_p - \alpha_l)}{1 + (A_pE_p/A_lE_l)} \tag{3}$$

The thermal stress σ_t above glass transition temperature T_g is much less than that below T_g, because a large decrease in the elastic modulus occurs above T_g.[10] Under this assumption, σ_t in plastic package is given by

$$\sigma_t = \frac{E_p(T_g + 196)(\alpha_p - \alpha_l)}{1 + (A_pE_p/A_lE_l)} \tag{4}$$

where α_l and E_l are 5.2×10^{-6}°C^{-1} [11] and 451 GPa,[11] respectively and the term A_f/A_p is estimated from the shape of the DIP to have a value of 9. In eq. (4), thermal stress can be estimated from T_g, α_p, and E_p. Figure 4 shows reduced thermal stress, σ_t/σ_{t0}, as a function of physical properties T_g, α_p, and E_p. The stress decreases with decrease in T_g, α_p, and E_p. It seems that the reduction of T_g below 200°C, α_p below 10^{-5}°C^{-1}, and E_p below 8 GPa exerts a similar influence to lowering the thermal stress. The actual ranges of T_g from 165 to 220°C, α_p from 1.60×10^{-5} to 2.51×10^{-5}°C^{-1}, and E_p from 12.2 to 14.9 GPa were explored. The median life N is plotted against the thermal stress calculated by eq. (4) as shown in Figure 5. It should be noted that in this case median life is not only a function of σ_t. The life N is replotted for the package with flexural strength σ_b = 120–140 MPa in Figure 6. N increases inversely with the decrease of σ_t Figure 7 shows the relation between N and σ_b for the package

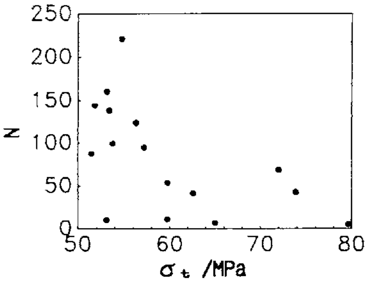

Fig. 5. Relation between median life N and thermal stress σ_t estimated by eq. (4).

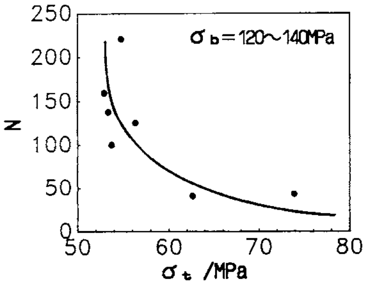

Fig. 6. Relation between median life N and thermal stress σ_t with flexural strength σ_b = 120–140 MPa.

with σ_t = 53–55 MPa. N increases with increasing σ_b. These results indicate that N is a function of σ_t and σ_b. We may study the relation between N and σ_t, σ_b, theoretically.

According to the linear fracture mechanics,[12] the relationship between cyclic crack growth rate da/dn and stress intensity factor ΔK is assumed as the form

$$da/dn = C_0 \Delta K^m \tag{5}$$

where C_0 and m are constants, $2a$ is crack length, and n is the number of the test cycles. For a wide plate containing the crack length $2a$ subjected to the thermal stress σ_t, the stress intensity factor is given by

$$\Delta K = \sigma_t (\pi a)^{1/2} \tag{6}$$

Substituting this into eq. (5) gives

$$da/dn = C_0 [\sigma_t (\pi a)^{1/2}]^m \tag{7}$$

This can be integrated to give

$$N = \frac{1}{C_0 (\sigma_t)^m \pi^{m/2}} (a_N^{1-m/2} - a_0^{1-m/2}) \tag{8}$$

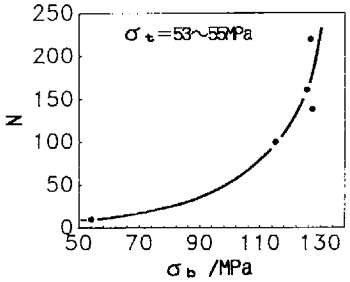

Fig. 7. Relation between median life N and flexural strength σ_b with thermal stress σ_t = 53–55 MPa.

where $2a_0$ is the intrinsic crack length and $2a_N$ is the crack length at the number of the crack initiating cycles. We can assume that $2a_N$ is much larger than $2a_0$ and N is much larger than 2. Under this assumption,

$$N = \frac{-a_0^{1-m/2}}{C_0(\sigma_t)^m \pi^{m/2}} \tag{9}$$

The critical stress intensity factor Kl_c [see eq. (6)] is

$$Kl_c = \sigma_b(\pi a_0)^{1/2} \tag{10}$$

where σ_b is the strength of the polymer. Substituting eq. (10) in eq. (9), the following equation is obtained:

$$N = \frac{C}{\sigma_b^2}\left(\frac{\sigma_b}{\sigma_t}\right)^m \tag{11}$$

where

$$C = \frac{-1}{C_0 \pi^{m/2}(1 - m/2)}\left(\frac{Kl_c}{\pi}\right)^{2-m}$$

Equation (11) shows that the relation between $\log(N\sigma_b^2)$ and $\log(\sigma_b/\sigma_t)$ should be linear, in which the thermal stress is calculated using eq. (1). This relation is demonstrated in Figure 8. We found a linear relation between logarithm of $N\sigma_b^2$ and logarithm of σ_b/σ_t for various packages. The values of C and m are estimated as 3×10^4 MPa^2 and 5.5, respectively. The coefficient of correlation is 0.95 and the standard deviation of $\log(N\sigma_b^2)$ is 0.24. Therefore, the median life can be predicted from the glass transition temperature, coefficient of linear expansion, flexural modulus, and strength of plastic materials for packages.

CONCLUSION

We have developed a specially designed thermal shock testing machine which estimates the thermal shock resistance of plastic package. The median life to crack initiation, N, can be predicted from the following equation:

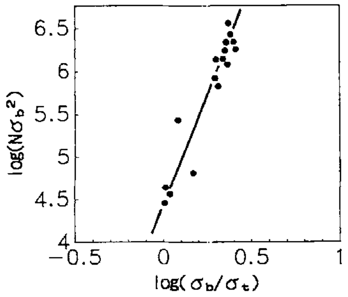

Fig. 8. Relation between $\log(N\sigma_b^2)$ and $\log(\sigma_b/\sigma_t)$.

$$N = \frac{3 \times 10^4}{\sigma_b^2} \left(\frac{\sigma_b}{\sigma_t} \right)^{5.5} \tag{12}$$

where σ_b is the flexural strength and σ_t is the thermal stress calculated from the glass transition temperature, coefficient of linear expansion, and flexural modulus of plastic materials for packages.

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