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Analysis of Chemically and Thermally Induced Residual Stresses in Polymeric Thin Film

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Abstract

This paper deals with the residual stresses developed in an epoxy film deposited on Si wafer. First, chemically induced residual stresses due to the volumetric shrinkage in cross-linking resins during polymerization are treated. The curvature measurement method is employed to investigate the residual stresses. Then, thermally induced stresses are investigated along the interface between the epoxy film and Si wafer. The boundary element method is employed to investigate the whole stresses in the film. The singular stress is observed near the interface corner. Such residual stresses are large enough to initiate interface delamination to relieve the residual stresses.

Key Words : epoxy layer, polymeric thin film, chemically induced stress, curvature measurement method, thermally induced stress

1. Introduction

Polymeric films such as an epoxy are widely used in electronic industry as adhesive layers [1]. These layers may be damaged through a thermal process and residual stresses can reach significant levels near the free edges, possibly leading to interface debonding or delamination. Fig. 1 shows epoxy layers separated from wafer substrates. When the temperature change occurs, adhesion of epoxy layer to substrates such as wafer tends to fall off.

Polymeric films deposited on a substrate can be subjected to residual stresses due to the volumetric shrinkage in cross-linking resins during polymerization and the differences between the thermal expansion coefficients of the components. The deformation of the film is constrained by the substrate, and hence residual stresses are built up in the film. Such residual stresses can play a very important role during subsequent loading of the film/substrate system. Such residual stresses may cause premature failure upon external loading.

Fig. 1. Epoxy layers separated from wafer substrates.

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Residual stresses in bi-material systems have received much attention. Stoney [2] observed that a metal film deposited on a thick substrate was in a state of tension or compression when no external loads were applied to the system and that it would consequently deform the substrate so as to bend it. He suggested a simple analysis to relate the stress in the film to the amount of bending in the substrate. Timoshenko [3] derived thermoelastic solutions for curvature and stress development in a bimetallic strip as a function of temperature change, for arbitrary variation in the relative thickness and elastic properties of the two films in the strip. Freund [4] presented certain conditions governing the onset of plastic deformation with arbitrary combinations.

The change in substrate curvature induced during curing processes provides valuable insight into the development of residual stress in the thin film. Methods to measure changes in substrate curvature during stress development in a thin film can be broadly classified into the following groups: mechanical methods, capacitance methods, x-ray diffraction methods, and optical methods. All these techniques, with the exception of x-ray diffraction, have the common feature that they provide a measure of the out-of-plane deflection of the curved film-substrate system. The optical method for measuring substrate curvature is generally convenient for in-situ measurement of film deposition stress, provided that optical access is provided to the substrate and that the specimen is mounted in a manner that facilitates unconstrained curvature evolution in one direction. One of the most common optical methods of estimating thin film stress, particularly for films deposited on Si wafer used in microelectronics, involves the reflection of a laser beam from substrate; this technique is simply referred to as the wafer curvature measurement method. Details of methods for curvature measurement can be found in Freund and Suresh [1].

In this study, the chemically induced residual stress in an epoxy film deposited on Si wafer due to the volumetric shrinkage in cross-linking resins during polymerization is investigated using the curvature measurement method first. Then, the analysis of thermal stress induced along the interface between the polymeric layer and the wafer substrate due to uniform temperature change is performed. The polymeric layer is assumed to be a linear viscoelastic material and to be theromorheologically simple. The boundary element method is employed to investigate the behavior of interface stresses.

2. Chemically Induced Residual Stress

Epoxy resin is coated on p-type silicon wafer with 3 inch diameter and 380 μm thickness. The coated epoxy is soft cured at the room temperature. Residual stresses originate during the film formation and curing processes as a result of solvent evaporation and the cross-linking of thermosetting films. The change in substrate curvature induced during curing processes provides valuable insight into the development of residual stress in the epoxy film.

Details of the fundamentals of curvature measurement method can be found in Pan and Blech [5], Volkert [6], and Shull and Spaepen [7]: however, a brief review of such process is in order. The curvature measurement method is based on the principle that a laser beam reflected on a curved surface depends on the orientation of the surface. The substrate is fixed at one point such that its position and orientation there are known. Then, a laser beam incident on the substrate surface is scanned along a straight line, and the angular deflection of the reflected beam from the incident is measured as a function of distance from a reference point. The scanning mirror arrangement, shown in Fig. 2, utilizes mirrors and laser to scan a single laser beam along the specimen surface. The deflection of the scanned beam is monitored through a position-sensitive detector. Referring to the geometric relations shown in Fig. 3, the law of deflection yields

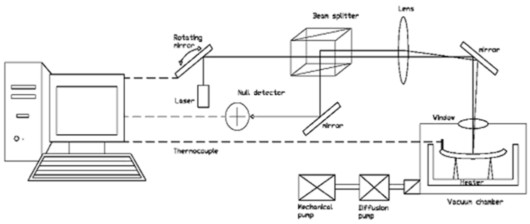

Fig. 2. Schematic illustration of the experimental setup.

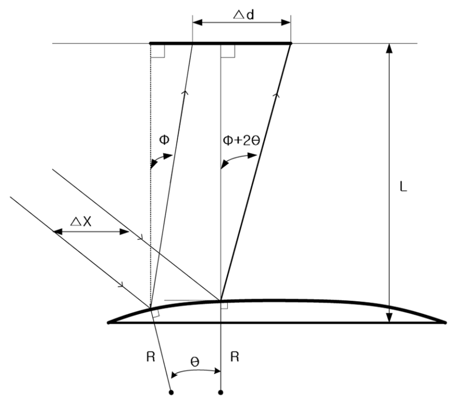

Fig. 3. Schematic illustration of laser beams reflected on a specimen surface.

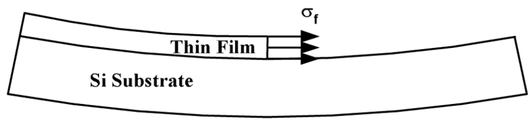

Fig. 4. The mean stress in the film.

the radius of curvature in terms of Δx, Δd, and L as follows:

$$R = \frac{2\Delta x L}{\Delta d - \Delta x} \tag{1}$$

in which the translation of laser beam in x–direction, Δx, is assumed to be very small enough to have $\Delta x = R\theta$.

Residual stress in thin film deposited on a substrate can be obtained by Stoney's formula as follows:

$$\sigma_f = \frac{E_s h_s^2}{6(1-v_s)Rh_f} \tag{2}$$

where subscripts s and f represent the substrate and the film, respectively, E_s and v_s are Young's modulus and Poisson's ratio of the substrate, respectively. h_s and h_f represent the substrate thickness and film thickness, respectively.

Stress distribution across thickness of the film is shown in Fig. 4. The residual normal stress σ_f across thickness of the film is less than 1 *MPa*, which is relatively small. These stresses may not cause distortion of finished components and premature failure.

3. Thermally Induced Residual Stress

The thermal stress induced along the interface between the polymeric film and the wafer substrate due to uniform temperature change is analyed. The polymeric film is assumed to be a linear viscoelastic material and to be theromorheologically simple. The boundary element method is employed to investigate the behavior of interface stresses.

A viscoelastic thin layer bonded to a thick substrate is shown in Fig. 5. The polymeric layer has thickness h_f and length 2 W. Due to symmetry, only one half of the layer needs to be modeled. Fig. 5 represents the two-dimensional plane strain model for analysis of the interface stresses between the layer and the substrate. Calculations are performed for $W/h_f = 20$.

A uniform temperature change $\Delta TH(t)$ in the film is equivalent to increasing the tractions by $\gamma(t)n_j$ [8] where

$$\gamma(t) = 3K\alpha\Delta TH \tag{3}$$

Here, K is the bulk modulus; n_j are the components of the unit outward normal to the boundary surface; and α is the coefficient of thermal expansion of the viscoelastic layer.

With a uniform thermal change in the layer, it is convenient to write the boundary integral equations with respect to *reduced time* ξ, instead of *real time t*. Then, the boundary integral equations without any other body forces are written as follows [8]:

For viscoelastic layer,

$$c_{ij}(y)u_j(y,\xi)$$

$$+\int_s \left[u(\mathbf{y}',\xi)T_{ij}(\mathbf{y},\mathbf{y}';0+) + \int_{0+}^{\zeta} u_j(\mathbf{y}',\xi-\xi')\frac{\partial T_{ij}(\mathbf{y},\mathbf{y}';\xi')}{\partial \xi'}d\xi' \right] dS(\mathbf{y}')$$

$$= \int_s \left[t_j(\mathbf{y}',\xi)U_{ij}(\mathbf{y},\mathbf{y}';0+) + \int_{0+}^{\zeta} t_j(\mathbf{y}',\xi-\xi')\frac{\partial U_{ij}(\mathbf{y},\mathbf{y}';\xi')}{\partial \xi'}d\xi' \right] dS(\mathbf{y}')$$

$$+\int_s \left[\gamma(\xi)n_i U_{ij}^m(\mathbf{y},\mathbf{y}';0+) + \int_{0+}^{\zeta} \gamma(\xi-\xi')n_j\frac{\partial U_{ij}(\mathbf{y},\mathbf{y}';\xi')}{\partial \xi'}d\xi' \right] dS(\mathbf{y}') \tag{4}$$

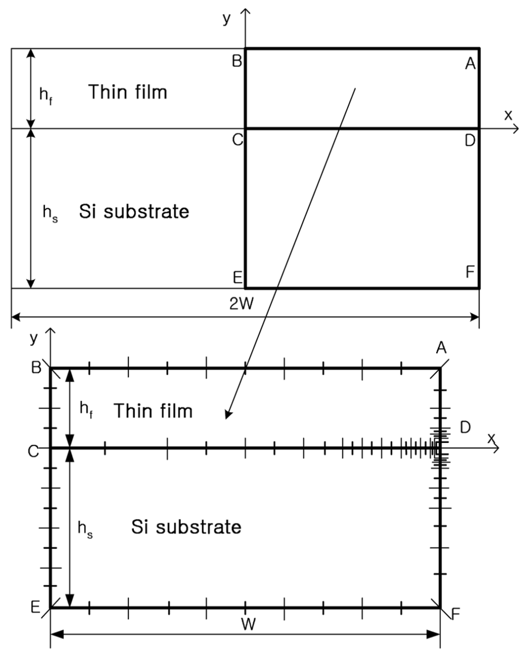

Fig. 5. Boundary element analysis model.

For wafer substrate

$$c_{ij}(\mathbf{y})u_j(\mathbf{y},\xi)T_{ij}(\mathbf{y},\mathbf{y}')dS(\mathbf{y}') = \int_s t_j(\mathbf{y}',\xi)U_{ij}(\mathbf{y},\mathbf{y}')dS(\mathbf{y}') + \int_s \gamma(\xi)n_j U_{ij}(\mathbf{y},\mathbf{y}')dS(\mathbf{y}') \quad (5)$$

where u_j and t_j represent displacement and traction, and S is the boundary of the given domain. $c_{ij}(\mathbf{y})$ is dependent only upon the local geometry of the boundary. For $\mathbf{y}$ on a smooth surface, the free term $c_{ij}(\mathbf{y})$ is simply a diagonal matrix $0.5\delta_{ij}$. The viscoelastic fundamental solutions, $U_{ij}(\mathbf{y},\mathbf{y}';\xi)$ and $T_{ij}(\mathbf{y},\mathbf{y}';\xi)$, can be obtained by applying the elastic-viscoelastic correspondence principle to Kelvin's fundamental solutions of linear elasticity.

Eqs. 4 and 5 can be solved in a step by step fashion in time by using the modified Simpson's rule for the time integrals and employing the standard BEM for the surface integrals [8]. Solving Eqs.4 and 5 under boundary conditions leads to determination of all boundary displacements and tractions.

The polymeric layer considered here is characterized by a tensile relaxation modulus and an elastic bulk modulus as follows:

$$E(\xi) = E_0 + \sum_{i=1}^{14} E_i \exp\left[-\frac{\xi}{\beta_i}\right] \; MPa\,(\xi:\text{min.}) \quad (6)$$

$$K(\xi) = k_o = 3.556 \times 10^3 \quad MPa \quad (7)$$

where $E(\xi)$ is a tensile relaxation modulus and $K(\xi)$ is a bulk modulus. The values of E_i and β_i are listed in Table 1.

The numerical values used in this example are as follows:

$$\Delta T = 57^{\circ}C,\ \alpha = 6 \times 10^{-5}/^{\circ}C \quad (8)$$

The numerical values used for the elastic substrate are as follows:

$k = 220$ GPa, $\nu = 0.29$

Figure 6 shows the distribution of normal stress σ_{yy} and shear stress τ_{xy} on the interface at times $t = 0$ and $t = 75$ min. The numerical results exhibit the relaxation of interface stresses and large gradients are observed in the vicinity of the free surface. Such stress singularity dominates a very small region relative to layer thickness. Since exceedingly large stresses at the interface corner, however, cannot be borne by the coating layer, delamination or interfacial edge cracks can occur in the vicinity of a free surface.

Table 1. The constants of Eq. (6).

β_i (min)	E_i (MPa)
0.5×10^{14}	0.10817 E + 03
0.5×10^{13}	0.12935 E + 03
0.5×10^{12}	0.18168 E + 03
0.5×10^{11}	0.23739 E + 03
0.5×10^{10}	0.28994 E + 03
0.5×10^{9}	0.32514 E + 03
0.5×10^{8}	0.33116E + 03
0.5×10^{7}	0.30568 E + 03
0.5×10^{6}	0.25760 E + 03
0.5×10^{5}	0.20145 E + 03
0.5×10^{4}	0.14720 E + 03
0.5×10^{3}	0.10934 E + 03
0.5×10^{2}	0.48615 E + 02
0.5×10	0.15854 E + 03
-	E_o = 0.16876 E+03

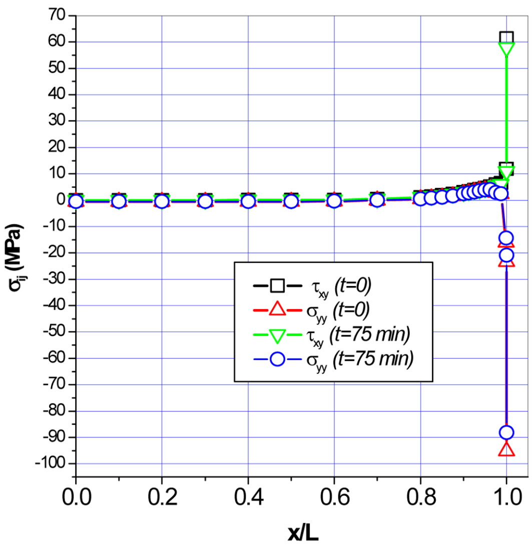

Fig. 6. Distribution of interface normal stresses and shear stresses.

4. Conclusions

First, the chemically induced residual stresses in an epoxy film deposited on Si wafer have been investigated. Such residual stresses originate during the film formation and curing processes as a result of solvent evaporation and the cross-linking of thermosetting films. The curvature measurement method has been employed to investigate the residual stresses. Epoxy resin has been coated on p-type silicon wafer with 3 inch diameter and 380 μm thickness. The coated epoxy has been soft cured at the room temperature. The normal stress across thickness of the thin film has been estimated from wafer curvature measurements to be less than 1 *MPa*, which is relatively small. These stresses may not cause distortion of finished components and premature failure. The boundary element method has been employed to investigate the whole stresses in the film due to a uniform temperature change. The singular stress has been observed near the interface corner. The residual thermal stresses are large enough to initiate interface delamination to relieve the residual stresses. Such residual thermal stresses near the interface corner may cause epoxy layers separated from wafer substrates. In this study, an epoxy material has been selected as being a technical interest. This method, however, can be extended to other types of polymeric materials.

Acknowledgements

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