An Improved Methodology for Determining Temperature Dependent Moduli of Underfill Encapsulants

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Abstract—Finite element analyses (FEAs) have been widely used to preventively predict the reliability issues of flip-chip (FC) packages. The validity of the simulation results strongly depends on the inputs of the involved material properties. For FC packages Young’s modulus-temperature relationship is a critical material property in predicting the package reliability during -55°C to 125°C thermal cycling. Traditional tensile tests can obtain the modulus at selected temperatures, but it is tedious, expensive, and unable to accurately predict the Young’s modulus-temperature relationship within a wide temperature range. Thus, this paper is targeted to provide a simple but relatively accurate methodology to obtain the Young’s modulus-temperature relationship. In this paper, three commercial silica filled underfill materials were studied. A simple specimen (based on ASTM D638M) preparation method was established using a Teflon mold. A dynamic-mechanical analyzer (DMA) was used to obtain the stress-strain relationship under controlled force mode, storage and loss modulus under multi-frequency mode, and stress relaxation under stress relaxation mode. A simple viscoelastic model was used and an empirical methodology for obtaining Young’s modulus-temperature relationship was established.

Index Terms—Loss modulus, modulus-temperature relationship, storage modulus, stress-strain relationship, underfill encapsulant, viscoelastic model, Young’s modulus.

I. INTRODUCTION

The rapid development of integrated circuit (IC) fabrication technology and the accelerated growth of the market for faster, smaller, yet less expensive products continue to challenge IC packaging technology [1], [2]. As an ultimate solution for this trend, flip-chip technology on organic substrate has been invented, developed, and practiced for more than ten years [3], [4]. Current FC technology needs underfill material to extend the fatigue life of C4 (controlled collapse chip connection) interconnects. Evaluation of the underfill encapsulant has become an indispensable step in implementing the FC technology since most of the commercially available encapsulants are not specifically designed for a certain flip-chip application. Generally speaking, the sequential underfill evaluation steps include the material property characterization, selection of underfill materials with the aid of computer simulation, and in-situ reliability testing using assembled functional flip-chip packages as test vehicles. Always, there are numerous new underfills emerging in the market place every year and in-situ reliability testing is time- and cost-intensive. FEA computer simulation has become one of the crucial screening processes for the selection of new underfills. But it needs reliable characterized material property data as inputs. The characterization of underfill materials has become one of the major factors in determining a new FC product development cycle and cost. One of the challenges in the development of a flip-chip package is the package cracking, especially the die cracking. Stress-strain relationship and Young’s modulus-temperature relationship of underfill encapsulants are two of the main factors for the package cracking [5], [6]. Therefore, the development of a simple and reliable approach to obtain these two critical material properties of the underfills is of practical importance. This work thus explored a simple methodology to obtain the stress-strain relationship and Young’s modulus-temperature relationship by only using DMA instrument. The established methodology was mainly based on the storage modulus-temperature relationship of the materials. Because currently widely used underfill materials all have the similar storage modulus-temperature relationship; the established methodology should be applicable to all these underfill materials within the temperature range up to glass transition temperature (Tg).

II. THEORETICAL BACKGROUND

There are three categories of materials: elastic, viscous and viscoelastic materials. Underfill materials are typical viscoelastic polymeric materials. Fig. 1 shows the stress responses under constant strain loading of pure elastic and viscoelastic materials, respectively [7]. Generally, the stress response for viscoelastic polymeric material is a function of time while that for elastic material is a constant, i.e. time-independent.

One important property used to describe the viscoelastic polymeric materials is relaxation modulus $E(t)$. The relaxation modulus $E(t)$ is defined as the ratio of stress and strain [7], i.e.,

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)},$$

(1)

If an underfill is assumed to be linear viscoelastic, the linear superposition law can be applied to the underfill materials. The superposition law states that the entire history of the stress can be reconstructed by adding the stress histories that correspond
to individual bits of a strain history, i.e., the stress response is the convolution integrals of strain history, as shown in (2) \[7\].

\[
\sigma(t) = \int_{-\infty}^{t} E(t-\tau) \frac{d\varepsilon}{d\tau} d\tau \tag{2}
\]

where \(E(t-\tau)\) is the relaxation modulus at time \(\tau\). When strain is chosen to be in the form of \(\varepsilon(t) = \varepsilon_0 \sin(\omega t)\), where \(\omega\) is the circular frequency in radians per second. The static stress can be obtained from the (2). The ratio of stress over strain is defined as complex modulus \(E^*(\omega)\). From (2), it can be found that \(E^*(\omega)\) is the Fourier transform of relaxation modulus \(E(t)\) \[7\]:

\[
E^*(\omega) = i\omega \int_{0}^{\infty} E(t)e^{-i\omega t} dt \tag{3}
\]

Therefore, as long as either relaxation modulus or complex modulus is known, other mechanical properties can be calculated through (3). Storage modulus and loss modulus is defined as the real and imaginary part of complex modulus, respectively.

Another consideration is that the mechanical properties of underfill materials are highly temperature dependent. Theoretically, if Young’s modulus or complex dynamic modulus of a glassy polymeric material is known at one temperature, these moduli at any temperature can be estimated using time-temperature superposition shift factor, which can be calculated from the Williams–Landel–Ferry (WLF) equation with the measured glass transition temperature (\(T_g\)) value \[8\]. However, the accuracy of such kind of estimation is a real concern since some basic assumptions may be invalid when the time-temperature superposition principle is applied to the complicated silica filled cross-linked thermosetting underfill materials. Therefore, an alternative solution is needed for real-life application. Our idea is to establish a relationship between Young’s modulus and complex dynamic modulus within the temperature range up to \(T_g\) based on a modified Maxwell model \[see (4)\]. Since the complex modulus in a wide temperature range can be conveniently obtained by simply running a specimen on a DMA instrument, the Young’s modulus in the same temperature range can be easily obtained by just converting the complex modulus from the established relationship.

III. SIMULATION MODEL

Maxwell model gives a reasonable prediction of relaxation behavior of polymers in molten state \[7\]:

\[
E(t) = ke^{-nt}. \tag{4}
\]

Combining (4) and (3), we can get complex modulus as \[7\]:

\[
E^*(\omega) = \frac{k\omega^2}{\eta^2+\omega^2} + i\frac{k\eta\omega}{\eta^2+\omega^2}. \tag{5}
\]

From (5), we can calculate strength of relaxation \(k\) and characteristic time \(\eta\) from the storage modulus and loss modulus at different temperatures. If Maxwell model is valid for underfill material, we can use parameter \(k\) to represent the Young’s modulus of underfill material. However, Maxwell model is too simple to satisfactorily describe the physical feature of an underfill material. Thus, for underfill materials, \(k\) can not be simply considered as the Young’s modulus. On another hand, \(k\) represents elastic property of material because it is the initial relaxation modulus. It is reasonable to introduce a fitting factor \(f(T)\) that correlate Young’s modulus \(E\) and \(k\). In another word, we are trying to find a function of temperature for underfill materials that can connect \(k\) and Young’s modulus

\[
E = f(T) \cdot k \tag{6}
\]

\(f(T)\) was chosen in the form of

\[
f(T) = f_0 + f_1 \cdot (1 - e^{f_2\cdot T}) \tag{7}
\]

where \(f_0, f_1,\) and \(f_2\) are constants. Now, if \(f_0, f_1,\) and \(f_2\) can be identified, the Young’s modulus at any temperature can be quickly calculated using (6). The reason that we chose such a fitting factor lies in the fact that (7) can universally describe the storage modulus-temperature relationship with very good accuracy. The three constants \(f_0, f_1,\) and \(f_2\) are then derived from Young’s modulus at three different temperatures using fitting theory. From above assumption, we think this method can be used to predict temperature dependent Young’s Moduli of other linear viscoelastic materials, no only underfill materials. This point needs to be proved through more research.

IV. EXPERIMENTS

A. Materials

Three commercial underfill materials A, B, and C were supplied by Dexter Hysol Co. of California. These materials were stored in a freezer at -40 °C. Before these materials were used to prepare the specimens, they were taken out of the freezer and warmed at room temperature for 1 h.

B. Specimens Preparation

Different specimens were prepared to fit different tests. For dynamic tests, the specimen preparation procedures are as follows: About 4 g of warmed underfill material was placed into an aluminum pan (37.5 mm diameter), then the pan was transferred to an 80 °C preheated connective oven, and then the material was cured using the curing recipe given by Dexter. After curing, the material was removed from the oven and cooled down to
Fig. 2. Shape and dimensions of the prepared specimens in this study.

Fig. 3. Relaxation moduli of underfill material A, B, and C at 30°C.

room temperature. The aluminum pan was then peeled off and the cured sample was polished into a disk with two parallel surfaces. Finally, a diamond saw was used to cut the cured sample into strips with dimensions of about 32 × 11 × 3 mm.

For tensile tests and stress-relaxation tests, the specimens were prepared by dispensing the warmed underfill material into the cavity of a Teflon mold that had been pre-heated to 70°C for better underfill flow. The Teflon mold was then transferred to a convective oven and the underfill material was cured following the curing condition given by Dexter Company. The specimens, which comply with ASTM D638M standard, were then removed from the Teflon mold. The shape and dimensions of the prepared specimens are shown in Fig. 2. The thickness of the specimens is 0.5 mm.

C. Mechanical Testing

Tensile tests, dynamic tests, and stress relaxation tests were performed on a Dynamic Mechanical Analyzer (DMA model 2980 of TA Instruments) instrument, which is equipped with an environmental chamber to precisely control temperature changes (−145°C–600°C, 0–50 °C/min). Fig. 4 shows the film tension clamp of DMA. Using the film tension clamp, we can conduct tensile and stress relaxation tests. Dynamic tests were performed under single cantilever mode using 1 Hz sinusoidal strain loading (strain amplitude = 0.2%), which gives the storage modulus and loss modulus of the material in the temperature range from −60°C to 250°C. Tensile tests were performed under DMA control force mode that gives the stress-strain relationship at a particular loading rate and temperature. Stress relaxation tests were performed under stress relaxation mode that gives the stress response versus time under a constant strain as shown in Fig. 3. Prior to the testing, all specimens were annealed at the temperature near their Tg’s for 1 h to release residual stresses introduced during the specimen preparation. Dog-bone specimens have the advantage of reducing grip effect that may cause specimen early failure due to the stress concentration. In the tensile testing, only a few specimens failed at the location close to the grips. The failure of most specimens occurred at locations far away from the grips, indicating that it was reasonable to use this type of specimen. DMA can record the deformation between two grips and calculation strain. The actual length between two grips is in the range of 10–15 mm. The loading rate of tensile tests is 0.1 N/min. The tensile tests were performed at seven different temperatures: −30°C, 30°C, 40°C, 60°C, 70°C, 90°C, 120°C.

V. RESULTS AND DISCUSSION

Figs. 5 and 6 show the storage moduli and loss moduli of the three underfill material A, B, and C. From the figures, we can know that the glass transition temperature (Tg) of these three materials are around 150°C.

As shown in (5), the parameter k for the three underfill materials can be calculated using tested storage moduli and loss moduli. Fig. 7 shows the calculated k for these materials in the temperature range between −30°C to 120°C. At 30°C,
$k$ is equal to 5.96 GPa, 6.2 GPa, and 4.72 GPa for the underfill materials A, B, and C, respectively. The stress relaxation result (Fig. 2) shows that the initial relaxation moduli of underfill materials A, B, and C are 6.11 GPa, 6.35 GPa, and 4.83 GPa, respectively. The comparison between the calculated $k$ and measured initial relaxation modulus finds that the two values comply with each other very well for all the three underfill materials. This finding gives a strong support to the verification of our simulation model [see (4)]. In order to obtain the function $f(T)$ that correlates $k$ and Young’s modulus, static tensile tests were conducted at three different temperatures: $-30^\circ C$, $60^\circ C$, and $120^\circ C$. Figs. 8–10 show the stress-strain curves at three different temperatures for underfill materials A, B, and C, respectively. The Young’s moduli are obtained as the average slope of stress-strain curves in low strain range (strain $< 0.1\%$). DMA can only conduct force control tensile testing and loading rate is 0.1 N/min. Table I lists the Young’s moduli at different temperatures for the three underfill materials. From the measured modulus and calculated $k$ values of each material, the parameter $f_0$, $f_1$, and $f_2$ for this material can then be calculated using (6) and (7). The calculated $f_0$, $f_1$, and $f_2$ of each material were tabulated in Table II and the $F(T)$ function was shown in Fig. 11. Thus, $f_0$, $f_1$, and $f_2$ can be used to estimate Young’s modulus at any temperatures by multiplying $f(T)$ and $k$ values using (6) and (7). This actually is the ultimate purpose of this work.

Figs. 12–14 compare the simulated Young’s moduli and tested Young’s modulus of underfill material A, B, and C (at temperature $30^\circ C$, $40^\circ C$, $70^\circ C$ and $90^\circ C$), respectively. From those curves, we can see the tested Young’s moduli comply with simulation curves very well. Table III presents the error $R$ of simulated values compared to tested data using (8)

$$R = \frac{E_s - E_t}{E_t} \times 100\%$$

where $E_s$ is the simulation value of Young’s modulus, while $E_t$ is the tested value.

Table III shows that the errors of simulated Young’s moduli of all three underfill materials are less than 10%, which satisfies the requirement of the industry. Thus, we find a practical approach
that can estimate Young’s modulus of underfill materials in certain temperature range (below Tg). The entire methodology includes the following steps.

1) Use DMA to measure storage modulus and loss modulus of a material in desired temperature range.
2) Use (7) to calculate parameter $k$.
3) Conduct static tensile testing at three different temperatures, which can properly cover the interested temperature range.
4) Use the data we get in 2) and 3) to obtain the parameter of fitting function.
5) Use (6) to calculate simulation value of Young’s modulus.

VI. CONCLUSION

The mechanical properties of underfill materials are always the key concern of FC technology. Obviously, we need to study the detailed relationship between the molecular structure and the properties if we want to predict materials properties properly. The work shown here is just a valuable attempt to predict materials’ static mechanical properties through dynamic properties. It does provide a relative simple and valuable approach that forecasts Young’s modulus within the interested temperature range with error less than 10%.

REFERENCES


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