A Quantitative Analysis of the Stress Relaxation Effect of Thermoplastics in Multilayer Substrates

Jin S. Kim, Kyung W. Paik, and Hyun S. Seo

Abstract—All plastics can be divided into two groups called thermoplastics and thermosets [1]. Two very different behaviors would be expected to arise from a basic difference between thermoplastics and thermosets. In addition to the normal covalent bonds which join the atoms together in the polymer chain, the thermoset plastics also have covalent bonds which join the chains one to another. These bonds between chains have been given a special name, crosslinks. Usually, thermoset materials are firm, cured, or “set” when the crosslinks are formed with thermal energy. In contrast, thermoplastic materials, which are characterized by not being crosslinked, well soften and become more “plastic” or pliable or melt with thermal energy. The temperature at which this transition occurs is called the glass transition temperature, $T_g$, where abrupt degradation of mechanical properties is generally expected. In most cases, because of not being crosslinked, thermoplastics have lower melting points and $T_g$s than thermosets, so have poor mechanical properties at high temperatures.

While many attractive properties of the materials, such as easy-to-process property, reworkability, and stress relaxation effect, have been obvious [2], because of the relatively poor mechanical properties at high temperatures, the use of the thermoplastics has for a long time been limited in microelectronics applications; where electronic polymers are typically exposed to fluctuating, and often extreme thermal histories. Recently, however, as thermoplastics having high $T_g$s and stable high temperature mechanical properties have been developed, the focus of attention has shifted to this materials system in the microelectronics industry.

In this study, we focussed on a quantitative analysis of the stress relaxation effect of thermoplastics in multilayer substrates, among many advantages of using thermoplastics. It is an important reliability and fabrication issue to realize cost-effective and high-reliability multilayer substrates. It is only empirically known that the stress generated by building subsequent layers can be significantly relieved by the viscoelastic behavior of the thermoplastic layers in a multilayer structure, when the process temperature exceeds $T_g$.

In today’s microelectronics, one important example of multilayer structures, which can take advantage of the stress relaxation effect of thermoplastic materials, is the lamination-based multichip module (MCM) substrates [3]. In the lamination process, a polymeric overlay film is overlaid on a silicon substrate using a polymeric adhesive. While thermosets have long been used as lamination adhesives partly for their high temperature stability, thermoplastic materials are drawing new attention among the industry people for their softening or stress relaxation effect when processed well above $T_g$.

In fact, the thermomechanical behavior of multilayer structures is a subject of perennial interest. A vast amount of literature exists on this topic for mechanical structures. While a few useful closed-form expressions have been developed under certain sets of assumptions and using different approximations, most of them have rarely been supported by experimental investigation. Furthermore, the viscoelastic-related thermal behavior of thermoplastics in a multilayer structure has been much less reported.

In this study, as an increasing number of polymer dielectric layers were laminated using thermoplastic adhesives, the maximum bow values ($B$) were measured layer-by-layer using a laser profilometry during thermal cycling. The result was compared with that of the multilayer structures constructed using thermoset adhesives. For the quantitative analysis, we employed the composite beam analysis (CBA) [4]. Since the lamination process uses polymer dielectric film of about 30–50 μm thickness, much thicker than aluminum thin films of less than 1 μm thickness deposited on a silicon chip, the CBA model considering the film thickness effect was appropriate.
TABLE I

<table>
<thead>
<tr>
<th>Materials</th>
<th>E (GPa)</th>
<th>ν</th>
<th>α (10^-5/C)</th>
<th>t (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>141</td>
<td>0.22</td>
<td>2.6</td>
<td>525</td>
</tr>
<tr>
<td>Ultem⁴</td>
<td>3.9</td>
<td>0.35</td>
<td>31</td>
<td>17.3</td>
</tr>
<tr>
<td>Kapton²</td>
<td>2.6</td>
<td>0.34</td>
<td>20</td>
<td>25.4</td>
</tr>
</tbody>
</table>

²Ultem is the registered trademark of GE.
⁴Kapton is the registered trademark of DuPont.

Fig. 1 shows the performance of Ultem thermoplastic on a silicon substrate. H1 = first heating cycle, C1 = first cooling cycle, etc.

II. EXPERIMENTAL PROCEDURE

Stress test structures were fabricated on 525 µm thick (001) single crystal silicon (Si) wafers with a diameter of 10 cm. The Ultem/Kapton composite, consisting of 25.4 µm Kapton film and 17.3 µm Ultem 1000 thermoplastic adhesive, was applied to the silicon substrate. The physical constants of the substrate, adhesive polymer, and dielectric film are summarized in Table I. The Ultem/Kapton composites were laminated to the silicon substrate under heating and pressure at 310 °C/61 psi/60 min. As the multilayer structures were fabricated, the maximum bow values were measured layer-by-layer using a laser profilometry during thermal cycling between room temperature and 300 °C [5].

III. RESULTS AND DISCUSSION

Fig. 1 shows the thermomechanical behavior of 17.3 µm Ultem thermoplastic on a silicon substrate. The maximum bow value at room temperature after fabrication and storage for 48 h was about 35 µm and was due to both intrinsic and thermal stresses [6]. Intrinsic stress relaxed during the first half of the heating cycle (H1), then the bow value increased by 10% on cooling (C1) as a result of the CTE mismatch. The intrinsic stress during the first heating cycle was presumably due to moisture absorption [7], because polymer dielectric materials absorb some level of moisture depending on the relative humidity of storage. Reproducible hysteresis was obtained during further cycles. The maximum bow value approaches the initial bow value of the silicon substrate at about 217 °C and changes little at temperatures above 217 °C. The Tg of Ultem thermoplastic is approximately 217 °C, so low elastic modulus and viscoelastic behavior are expected above Tg.

Fig. 2(a)–(d) show the thermal behavior of multilayer Ultem/Kapton composites on a silicon substrate during sequential build-up of the composites on a silicon substrate. Up to two layers, as the number of layers increases, the maximum bow values and the slopes increase as well, exhibiting the deflection points all at 217 °C, reflecting the presence of the Ultem layers whose viscoelastic behavior would be expected to relax the stress above Tg. No other transitions were observed since the Tg for Kapton is above 400 °C. From the three-layer structure, however, the maximum bow values at room temperature were contained at about 250 µm, and the deviation from the ideal elastic behavior was apparent as seen by the increasing nonlinearity of the slopes and size of hysteresis loops at high temperatures in Fig. 2(c) and (d).

Fig. 3 compares the experimental values of the slope (dB/dT) with the calculated values obtained from the CBA for the multilayer Ultem/Kapton composites on a silicon substrate. The slopes were measured for the temperature range well below the Tg, and the analyses assumed linear elastic behavior and used room temperature physical property values (Table I). It is generally assumed that the physical properties of polymers are constants in a low and small temperature range below Tg. Insignificant hysteresis and linear slopes indicate that the deformation is primarily elastic below Tg. The multilayer thermal behavior of the Ultem thermoplastic was highly contrasted with that of the epoxy thermoset shown in Fig. 4 [4]. While the epoxy/Kapton composites showed good agreement with the CBA up to four layers, the Ultem/Kapton composites exhibited increasingly large deviations from the calculated values as a number of layers increased.

Table II shows the amount of stress relaxation calculated from the measured and calculated bow slopes in Fig. 3 for the laminated Ultem/Kapton multilayer substrates. In Table II, the relaxed stresses were calculated from (stress relaxation) × (thermal stress) where the thermal stress, σT, was calculated from σT = E/fΔT: E/f = E/f / (1 - v/2) is the biaxial Young’s modulus of the film, where E/f and v/f are the elastic modulus and Poisson’s ratio of the film material, respectively; Δα = α(f - αs), where α(f) and α(s) are the CTE of the film and substrate, respectively; ΔT is the temperature excursion. Assuming the stress-free temperature for Ultem/Kapton laminates is the Tg of Ultem thermoplastic, 217 °C, ΔT at room temperature is 192 °C. If there is no stress relaxation as with the epoxy thermoset adhesive in Fig. 4, the internal stresses due to the CTE mismatch (hence the thermal stress) are calculated from Table I to be 33.7 and 13.2 MPa for the Ultem and Kapton films, respectively. Fig. 3 shows, however, a considerable amount of stress relaxation in each layer was obvious as summarized in Table II, where the amount of the stress relaxation reached to almost 70% for the four-layer structure, a significant amount for the reliability analysis.

While the epoxy thermoset exhibited almost an ideal elastic behavior predicted from the CBA, the bowing and stress tended to decrease from the ideal elastic behavior for the Ultem
Fig. 2. Thermal behavior of (a) single layer, (b) two layers, (c) three layers, and (d) four layers of Ultem/Kapton composites on a silicon substrate. H1 = first heating cycle, C1 = first cooling cycle, etc.

thermoplastic. It seems that the nonelastic behavior or stress relaxation effect of the Ultem thermoplastic is due to the self-relaxation nature of thermoplastic materials, whereas the ideal elastic behavior of the epoxy thermoset is due to the heavily crosslinked structure of thermoset materials.

Fig. 3. Comparison of the measured values taken from the cooling portion of the first thermal cycle with the calculated values from the CBA for Ultem/Kapton composites on a silicon substrate.

Fig. 4. Comparison of the measured values taken from the cooling portion of the first thermal cycle with the calculated values from the CBA for epoxy-based Coverlay film on a silicon substrate.

IV. CONCLUSION

In summary, by comparing the measured and calculated values from the CBA, we quantitatively analyzed the stress relaxation effect of thermoplastics as lamination adhesives during sequential build-up of polymer multilayer structures. The
thermomechanical behavior of the thermoplastic was highly contrasted with that of the thermoset. While the thermoset-based multilayer structures showed a good agreement with the calculated values, the thermoplastic-based multilayer structures exhibited a large amount of stress relaxation. This result provides an important design guideline that thermoplastics can be used as a stress relaxation layer in lamination-based multilayer MCM-D substrates.

**REFERENCES**


