# LOW WARPAGE AND IMPROVED 2.5/3DIC PROCESS CAPABILITY WITH A LOW STRESS POLYIMIDE DIELECTRIC

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# **ABSTRACT:**

The use of a polyimide dielectric layer in 2.5D and 3D stacked silicon packages with silicon through vias (TSV) normally requires cure temperatures in excess of 350°C. The choice of a silicon-CTE-matched polyimide offers the prospect of lowered stress and warpage and thus improved handling and yields. In this work, BPDA//PPD polyimide with a CTE of 3 ppm/°C is shown to be fully cured at only 200°C with the use of Variable Frequency Microwaves (VFM) in 60 minutes. The thermo-mechanical properties, including imidization, hardness, and elastic modulus match the properties of the conventionally cured material of 350-375°C. The CTE of BPDA//PPD coatings cured above the Tg (340°C) rises with the increased stress of crystallization but the films cured with VFM well below the Tg do not show this increased stress and warpage. Films with either 375°C oven cures or 200°C VFM cures had well less than 15µm of die-level (27mm x 19mm) warpage. Thinned wafers coated with two layers of BPDA//PPD and bonded temporarily to glass carriers were not delaminated from the glass after the 200°C VFM cure process. Wafer bow comparisons before and after cure were made with optical profilometry.

Key words: warpage, 3D, stacking, interposer

# **INTRODUCTION:**

Increasing stress and warpage of coated wafers continues to be an issue as the third dimension is included in packaging technologies with 2.5D and 3DIC assemblies. Dielectric polymer layers are employed in these structures for redistribution and/or passivation just as they are for other wafer level packages and in fact for most production wafers. Recently there has been additional pressure to reduce the polymer dielectric cure temperature to allow thin wafer handling, including the use of temporary bonding to a glass or silicon carrier. Lower temperature curing can also reduce the total warpage of interposers and active layers in the stacks. This is a very challenging area of development for the dielectric material suppliers. Improving processes for these structures is then three-fold: reduce overall stresses and reduce individual process temperatures while using the most robust material set.

Such low temperature processing and low stress structures are essential for producing 2.5D and 3D stacked silicon packages with through-silicon vias (TSV). For example, micro-bumped high I/O silicon dice can be connected to a silicon TSV interposer, which is assembled on a standard substrate. This enables significantly higher bandwidth and lower power consumption than conventional structures. An interposer thickness can be 100 µm or less to keep a reasonable aspect ratio of a TSV. Therefore, wafer thinning is an essential part of stacked packages. As the wafer thickness decreases, the warpage of the structure is more sensitively affected by small coefficient of thermal expansion (CTE) mismatches between the silicon, glass, and dielectric polymer. Moreover, wafer thinning is commonly achieved by attaching a wafer to a carrier wafer using a temporary bond material, which generally limits processing temperature below 250 °C. Obviously, this produces a great challenge in polyimide processing. The most common practice to address this problem is applying newly developed low-temperature materials and processes, but often have sub-optimal mechanical/electrical they performance with limited reliability data available. A poor CTE match of polyimide to silicon also causes warpage that becomes severe when the wafers are thinned to 100 microns or below. Such problems result in increased development complexity, cost, and time to market.

The thermal, chemical, and mechanical stability of thermoplastic polyimides (PI) is dependent on complete imidization typically achieved only at temperatures in excess of 350°C. With cure temperatures above the glass transition temperatures (Tg), very high elongation, and predictable processing, polyimides are still the standard production dielectric of choice for stress buffer layers and many wafer level coatings. Polybenzoxazole (PBO)

thermoplastics have recently been developed partly as a response to an interest in lower temperature cure processing. However, to achieve similar thermo-mechanical properties to PI films, it is necessary to add crosslinking which converts them to thermosets and achieves Tg values approaching 300°C. Other thermosets such as epoxies, cyclobutenes, and fluorocarbons have entered the market with cure temperatures of around 250°C for some applications but like PBOs, are often considered unacceptable due to compromised stability or process difficulties.

The use of alternative polymer curing methods including the use of microwaves have recently been shown to offer substantially reduced cure temperatures as well as the expected faster process times [1]. Microwave energy interacts with the polarizable dipoles in uncured polymer resins to cause functional group rotation especially at reaction sites. The method of heat generation is quite different in nature than the general agitation of whole molecular structures resulting from conventional conduction or convection oven heating. The dipole rotations from microwave irradiation at reaction sites create locally higher energies than the rest of the molecule, so the resultant bulk cure temperature is much lower [2]. As reactions near completion, the polymer becomes more rigid and dipoles are less mobile so the effect of the microwaves is self-limiting at end of cure. Lower temperature cure is well known to reduce material stress in both thermosets [3] and thermoplastics [4] although by different mechanisms respectively.

Lower stress in electronic assemblies can also be achieved by reducing the effective mismatch in CTE between two joined materials. Flip-chip bonding of silicon dice (3 ppm/°C) to circuit boards (18 ppm/°C) normally creates high stress and warpage on cooling from the under-fill cure temperature. Microwaves selectively heat the silicon and adhesive but not the already polymerized circuit boards so there is much less warpage created in the final packages [5].

From the CTE values in Table 1, it can be seen that high warpage should be expected from the mismatch between silicon wafers, glass, and typical dielectric coatings at all cure temperatures. Wafer warpage (in two dimensions) and bow (in three dimensions) have been reported to be significant problems in both wafer photo-lithographic patterning steps and wafer handling steps [6]. Lower temperature curing would at least reduce this warpage if that temperature reduction was significant but matching the lower CTE would be even more effective.

**Table 1**: Coefficients of Thermal Expansion

Dielectric Material	CTE (ppm/°C)
SiO <sub>2</sub>	0.5
Silicon	3
Glass	4
BT, FR4	18
Polyimide	35
BCB	42
Epoxy	60
PBO	60

The reduction of conventional cure temperature in a PBO from 350°C to 330°C was found to not significantly reduce warpage while reducing thermal and chemical stability [7]. In a 2006 study, it was found that a PBO could be custom designed to be cured by microwaves below 200°C yet have comparable thermal and chemical properties to high temperature oven cured PBOs [8].

An alternative approach to PI warpage reduction would be polyimide the use of the derived from biphenyldianhydride//p-phenylenediamine (BPDA-PPD) which has a uniquely low in-plane CTE of 6 ppm/°C when cured at the recommended 375°C for one hour (five hour cycle time including heating and cooling ramp times). The out-of-plane CTE is 25 times higher than the in-plane CTEs, which is one indicator of the high anisotropy and chain alignment of this polyimide structure (Figure 1).



Figure 1: Linear structure of BPDA//PPD

In contrast, most polyimides have some bend in their structure, like that caused by the ether linkage in PMDA//ODA (Figure 2).



Figure 2: Bent structure of PMDA//ODA

Whether there is some flexibility in the chain or not, the cure (imidization) of these thermoplastics is limited to 80-90% when the maximum cure temperature is below the ultimate glass transition temperature ( $Tg\infty$ ) [9]. With some curvature in the long polymer chains, there is a reorientation above the Tg that allows further imidization and crystallization. Curing at temperatures above the Tg, while allowing development of stable film properties, also increases CTE, birefringence, and biaxial stress. On the other hand, if the maximum cure temperature is below the Tg (340° for BPDA//PPD) there is stability in the CTE at 3 ppm/°C and minimized stress [9].

This effect is believed to be due to alignment of the imide rings with the aromatic rings of this very linear structure and the further stacking of polymers in the plane of the film (Figure 3). Increasing cure temperature allows an increase in density in the out-of-plane direction which results in a loss of alignment and some crystallization growth.



Figure 3: Stacking of aligned BPDA//PPD below its Tg

If the BPDA//PPD low stress structure could be maintained with a high imidization at a cure temperature below 250°C then a much more practical dielectric film would be produced with a CTE better matched to silicon and glass. The use of microwave curing methods to lower the cure temperature of BPDA//PPD below its Tg and even further to below 250°C will be examined. The nature of the structural alignment at these lower temperatures and the differences, if any, created by the use of microwave irradiation will be explored using measurements of CTE, Tg, modulus, hardness, and imidization. Potentially useful effects of modifications to the irradiation power duty cycle will also be examined.

# **EXPERIMENTAL:**

The microwave curing system used Variable Frequency Microwave (VFM) technology [10]. VFM digitally scans 4096 frequencies between 5.85GHz and 6.65GHz within a 0.1 sec. period repeatedly. This method insures that no standing waves are generated for longer than 25µs thus eliminating any chance of arcing and it provides a very uniform field intensity throughout the cavity containing the wafer(s). The power level (0-500W) is automatically adjusted to maintain the programmed temperature as measured directly on the dielectric film by a calibrated noncontact infrared sensor in a closed-loop system. Typical ramp rates to soak temperatures were 0.6 °C/sec and the soak temperatures were controlled to +/- 1°C during the programmed soak times. Cooling time was typically less than five minutes since the oven remains at ambient temperature. Note that recommended heating and cooling times in a convection oven combine for a much longer cycle time (typically 4-5 hours) compared to about a 1 hour cycle time in VFM. The wafers were held on quartz pins from below in the center of the chamber.

The polyimide in this study was obtained as a commercially available resin [11]. For the BPDA//PPD cure studies, 200mm wafers were spin coated and soft baked at 120°C for 180 seconds. The wafers were then cured with VFM at temperatures between 175°C to 250°C for soak times from 0 to 240 minutes. The final film thickness was about 5  $\mu$ m. Heating ramp rates were controlled at 0.2 to 1.0 °C/sec and cooling to ambient was less than five minutes. Wafer films cured for 30 minutes at 350°C in a convection oven were used as standards for this study.

There are several programming options for the VFM cure. An initial fixed ramp rate can be set or there can be an initial step of "Wait for Temperature" which applies a set constant power until the soak temperature is reached. It can also be seen in Figure 4 that during the soak period, power can applied in a constant-on, or "analog" mode. Alternatively, in Figure 5 it can be seen that power can be pulsed in an on-off or "digital" mode during the soak period. The duty cycle of power is adjusted by the setting of maximum power. The example in Figure 5 has a limit of 180W. More power would reduce the duty cycle even though the total integrated power level is the same. This is the method used to set one of the variables in one of the statistically designed experiments (DOE) discussed below.



Figure 4: "Analog" power mode (in green)



Figure 5: "Digital" power mode (expanded)

Elastic modulus and hardness of polyimide films were measured by an Agilent G200 nano-indenter, which indented each sample at 6 different locations or more with a Berkovich tip. To minimize the effect of hard silicon beneath the film, data were collected between 100 and 200 nm indentation depth where the values were nearly constant.

Glass transition temperatures (Tg) and CTE were measured by thermo-mechanical analysis (TMA) on a TA Instuments Q400 using an expansion probe. The CTE measurements were taken between 40 and 400°C using a constant force of 0.03N on a sample  $5\mu$ m thick.

To examine the effect on warpage of a thin die, polyimidecoated and cured wafers were bonded to temporary carriers, thinned down to 100  $\mu$ m Si thickness, and diced into 27 mm x 19 mm pieces. Another wafer was thermally oxidized to have a 0.5  $\mu$ m oxide layer and then thinned/diced. Sample warpage was measured by an Insidix TDM-Compact projection Moiré interferometer at 25, 100, 150, and 250 °C. Wafer-level warpage at room temperature was measured by MicroSpy optical profilometer by FRT GmbH.

Extent of imidization of the polyimide was measured by FTIR using a diamond attenuated total reflectance (ATR) probe. Quantitative analysis of the two peak heights included consistent baseline correction. The BPDA//PPD imidization was calculated by comparing the ratio of the imide C-N stretch peak height at 1360 cm<sup>-1</sup> and the internal standard of the aromatic ring "breathing" peak height at 1510 cm<sup>-1</sup>. Extent of cure (imidization) is calculated by comparison to standard oven cured sample ratios (in percent). FTIR spectra of cured and uncured samples are shown in Figure 6. Imidization extent of cure graphs display the averages of three measurements each of three to five samples.



Figure 6: Comparison of Cured and Uncured BPDA//PPD

#### **RESULTS AND DISCUSSION**

The extent of cure of BPDA//PPD at low temperatures by VFM is shown in Figure 7. It can be seen that full imidization (as measured by FTIR) is accomplished at 200°C as soon as 60 minutes. It should be pointed out again that "extent of cure" in the case of a thermoplastic like BPDA//PPD consists entirely of the imidization reaction. There are no additional cross-linking reactions and it has been shown that polyimides do not have substantial cross-chain imidization reactions [12].



Figure 7: Imidization of BPDA//PPD films on wafers with 200°C soak by VFM

The high initial imidization (64%) at "0" minutes of soak time represents significant curing while the temperature is ramped for 6 minutes (0.6 °C/sec) to the 200°C soak temperature. An alternative method would be the application of full power to reach soak temperature which only takes 60 seconds. The effects of very rapid VFM cure on wafer warpage have not been thoroughly studied yet but it has been reported that 1 °C/sec ramp rates with VFM produce much less PI wafer warpage than the rapid rates produced with hot plate cures [13].

In the comparison seen in Figure 8, with the exception of the "0" minute data, there is no significant difference in

extent of cure between the "analog" and "digital" application of power to the molecular dipoles. The initially higher cure with the "digital" method at "0" minutes can be explained by the six-fold longer ramp exposure time of the "analog" method.



Figure 8: Comparison of "digital" and "analog" mode efficiencies of cure

Two DOEs were run to compare the "analog" and "digital" methods with respect to ramp rate, soak time, and power duty cycle variables. Settings were intentionally selected to produce less than 100% cure to allow significant effects to be found. The first DOE on the "analog" process showed higher extent of cure with slower ramp rate (°C/sec) and longer soak time (min), with interaction, as would be expected (Figure 9). The much stronger ramp rate effect could be the result of such short soak times (20 minutes or less).



Figure 9: Significant effects of "analog" power variables temperature (A) and ramp rate (B)

In the case of the "digital" DOE, the ramp rate (°C/sec), power duty cycle (% -on), and soak time (min) variables were found to be in a three-way interaction. For the fastest

ramp rate of 1 °C/sec, the highest extent of cure was found at the ends of the "saddle" curve which represent either the highest duty cycle and the longest soak time, or the lowest duty cycle and the shortest soak time (Figure 10).



Figure 10: Fastest ramp rate setting of "digital" DOE

For the slowest ramp rate of  $0.2 \,^{\circ}$ C/sec, the highest extent of cure was found at the sides of the "saddle" curve which represent either the highest duty cycle and the shortest soak time or the lowest duty cycle and the longest soak time (Figure 11).



Figure 11: Slowest ramp rate setting of "digital" DOE

It is very rare to find three-way interactions in processes but more common to find them in chemical systems than engineering ones. In this case it may indicate an opportunity to adjust the morphology of the structures and to minimize stress but this has not yet been investigated. Of interest in this study was the effect of polarization of the imidized chains on their alignment with each other at temperatures well below the Tg $\infty$ . For the following data, the method used was "analog" with the center-point ramp rate of 0.6 °C/sec which would not show the interactions and not necessarily be optimized.

The hardness (Figure 12) and elastic modulus (Figure 13) values of the samples that were cured by VFM well below

the Tg are similar to the values of samples that were cured in conventional ovens well above the Tg.



Figure 12: Hardness of VFM cured BPDA//PPD



Figure 13: Elastic modulus of VFM cured BPDA//PPD

The lack of change in CTE of the BPDA//PPD during the progression of VFM cure is shown in Figure 14. The high order of chain alignment continues with increasing cure but without the crystallization that occurs with a cure above the Tg. The crystallization process decreases density, reduces order, and doubles the stress as shown in the CTE of 350°C cured samples in Figure 14 (6 ppm/°C). The VFM cure below the Tg apparently avoids crystallization and maintains the close CTE match to silicon (and glass).



# Figure 14: CTE of VFM cured BPDA//PPD over time with standard oven cure at 300 minutes

The use of BPDA//PPD cure by either standard convection oven to 350°C or by VFM to 200°C was found to result in very low stress and warpage of well less than 15µm over 27mm x 19mm x 100µm silicon dice with 5µm-thick polyimide coatings. (Table 2). These warpage measurements were made by Projection Moiré Interferometry at 25, 100, 150, and 250°C (the fringe-like pattern is an artifact; not the actual morphology). This confirms that a VFM-cured BPDA//PPD film has a very good CTE match with silicon (and glass), as does the ovencured film. For comparison, a 0.5µm thermal oxide (CTE ~ 0.5 ppm/°C) produced a warpage of ~60 µm due to very high processing temperature (~1100 °C) and a finite CTE mismatch.

Table 2: Wafer bow by Projection Moire Interferometry



Conventional polyimides (CTE ~35 ppm/°C), conventionally cured in high temperature ovens (350-375°C), produce hundreds of microns of warpage at room temperature [6]. A 200 mm diameter wafer coated with a layer of BPDA//PPD, after grinding to 100  $\mu$ m but before cure, was measured to have -110  $\mu$ m of bow as measured by optical profilometry. After a 200°C VFM cure, the wafer bow was -95  $\mu$ m (with the film side up) which compares favorably with the -86  $\mu$ m bow of an identically coated and ground wafer cured at 350°C by convection.

Additionally, assemblies of 100  $\mu$ m thick 200 mm diameter wafers with coatings of BPDA//PPD on each side and adhered to 100 $\mu$ m thick glass by temporary bonding, did not lose adhesion during VFM cure at 200°C but there was loss of adhesion when the cure temperature was 250°C as shown in the photographs of Figure 15.



Figure 15: Adhesion images after 200 °C (a) and 250 °C (b) VFM cure of BPDA//PPD film layers

Highly anisotropic polyimide films as dielectric layers can be used in 2.5D/3D stacked structures to match the film CTE to silicon and glass. This may significantly reduce the usual stress and warpage of the interposer or die stack. Variable Frequency Microwaves can reduce the film cure temperature from 350°C to 200°C and total cycle time from five hours to one hour which allows the use of lowtemperature temporary bonding materials to glass carriers. The cured film appears to be highly aligned in-plane with little evidence of crystallization based on the lack of CTE increase after a cure well below the ultimate Tg temperature.

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