

Curing Dielectric Layers for Microelectronics with Microwaves: Chemistry, Mechanisms, and Applications

R. L. Hubbard

Lambda Technologies, Inc, Morrisville, North Carolina 27560, USA

Modern electronic products are entering a new era of nanometer sized geometries, copper wiring, and specialized dielectric materials and structures. Wafer level packaging (WLP) is a rapidly growing technology which continues the build-up on the wafer with alternating polymer dielectrics and conductor layers, ultimately producing a packaged device before the wafer is diced. Recent work in curing new polyimide (PI), polybenzoxazole (PBO), and epoxy films on silicon wafers with Variable Frequency Microwave (VFM) technology has allowed faster and lower temperature processing as well as changed the nature of the polymer dielectric structures and their properties. The nature of the microwave heating mechanism will be discussed as well as the custom synthesis of polymers designed to take advantage of this unique process.

Dielectric Films for Microelectronics

Inorganic films of silicon oxide, silicon nitride and others have been the finishing layers on wafers for decades. More than ten years ago, semiconductor fabricators began adding more layers, alternating with conductive traces, as interconnect structures. It is not uncommon to have 8-10 layers of passive interconnections on top of device structures as wafers have grown from 150 mm diameter to 300 mm diameter in production. The last dielectric layer on wafers is usually a polymer dielectric film however. This layer is inherently “softer”, thicker, and less conformal than the inorganic dielectric layers. These layers provide mechanical protection; offer protection from damaging alpha particles; and “buffer” the stresses produced in the complex and brittle inorganic layers below.

These “stress buffer”, or “passivation” layers are most commonly polyimide films produced by spin coating polyamic acid resins on wafers and curing in convection ovens or furnaces to 350°C in a four to five hour cycle process. Part of this process is a slow ramping rate and an intermediate temperature hold to minimize stress and shrinkage in the final films. When used on memory devices, these films have “windows” etched or developed down to the device so that lasers can “trim” device properties that have been shifted by the additional stress added to the die surface by the thermal curing of the polyimide film. The addition of photosensitizers to the polyamic acid resins allowed the films to be photo-patterned directly without the need for extra photo-resist steps. Removal of the by products of the photosensitizers was not difficult at the elevated and sustained temperatures of the curing processes.

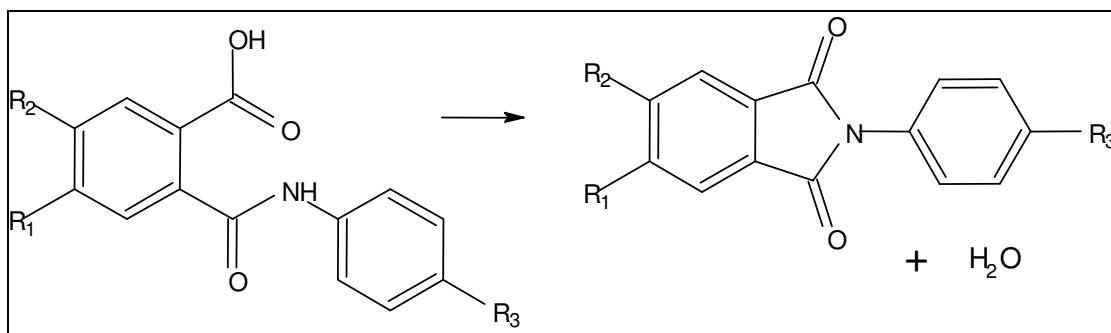


Figure 3. Imidization of polyamic acid resins to polyimide films.

Most polyimides are solvent developed however and a new class of aqueous developed polybenzoxazoles (Figure 4) was introduced that still retained the high temperature stability of the polyimides and most of the chemical resistance. In addition the PBO films could be photo-patterned and have even higher elongations (nearly 100%). One property that PBOs did not improve upon polyimides was a lower processing temperature or shorter cure. An incompletely cured polyimide is sometimes useful in applications where thermal and chemical inertness is not as critical. Incompletely cured PBO films tend to become brittle if heated at temperatures too low for substantial curing. With generally robust properties, PBO films have become increasingly popular in RDL and WLP layers.

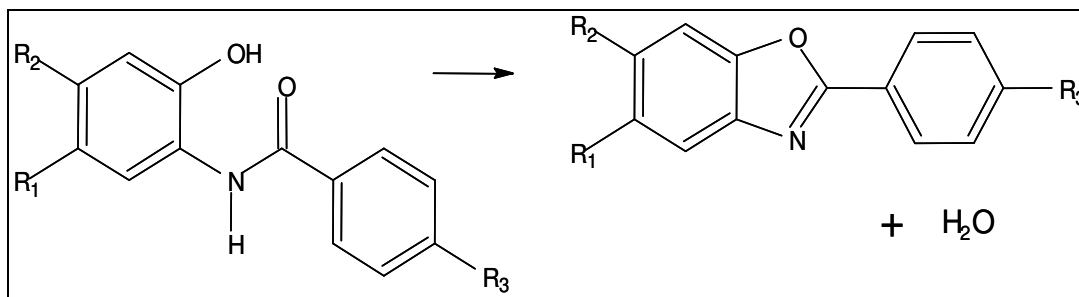


Figure 4. Curing reaction for polybenzoxazoles.

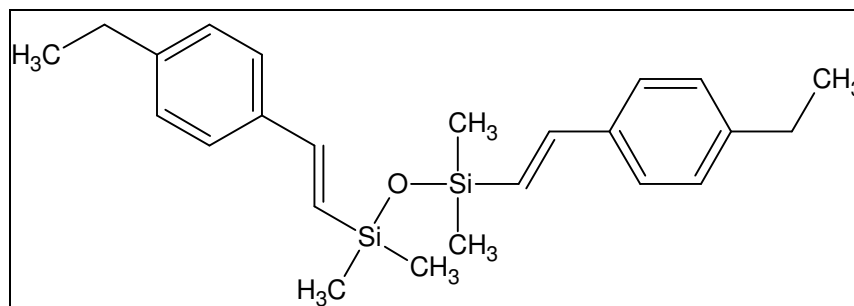


Figure 5. BCB monomer.

Epoxy co-polymers have also been developed for use as WLP dielectric layers. These tightly cross-linked materials have the advantage of the much lower processing temperatures of 150-200°C. While they allow photo-patterning they also have the

disadvantage of very low elongation (4-8% typically) and much lower glass transition temperature (T_g) values of around 200°C. Another low elongation polymer class is the bicyclobutene (BCB) shown in Figure 5. These low dielectric constant polymers have been extensively used as passivation layers but their 250°C curing temperature, brittleness, and susceptibility to oxidation have limited their use to special device applications. Table I provides a comparison of polymer dielectric film properties.

TABLE I. Polymer Dielectric Properties.

	Tg	Elongation	Photosensitive	Cure Temp	Chemical resistance
PI	350°C	40%	Y	350°C	Very high
PBO	300°C	100%	Y	380°C	High
BCB	300°C	3-5%	N	250°C	Medium
Epoxy	200°C	4-8%	Y	190°C	Medium

Microwave Heating

Microwave heating of dielectric materials is the result of the electric field interacting with labile electrons in the dipoles of the material and the inability of this polarization to follow extremely rapid reversals of the electric field (1). The resulting dielectric relaxation produces heat in the form of molecular rotations and translations.

The equation for reaction rate (k) depends on the frequency of molecular collisions (f) and the orientation factor of the reactant sites (p) as well as the activation energy (E_a) and temperature (T).

$$k = f p e^{(-E_a/RT)} \quad [1]$$

Clearly the imidization reaction of a polyimide (Figure 3), for example, would proceed at a faster rate if the excitation of the amic-acid dipoles and amine dipoles by microwave energy caused them to be in more frequent collisions and in more favorable orientations.

The well known phenomenon of rapid microwave heating is then the result of highly energetic molecular motions at exactly the dipoles involved in the chemical reactions. Other portions of polymers without dipoles are not heated by the microwave energy except by induction from the rapidly rotating portions. Consequently the energetic sites of reaction are higher in energy than the bulk of the polymer. It should be noted that this explanation provides for no change in the inherent energy of activation (E_a) for the reactants. For microwave heating, therefore, the Gibbs free energy (ΔE) of the system is increased by the unusually more energetic local motions of the reactants (entropy ΔS) as well as the enthalpy (ΔH) of the system.

$$\Delta E = \Delta H - T \Delta S \quad [2]$$

With conventional (convection or infra-red) heating, the whole bulk of the material is progressively heated by conduction from a hot environment so the entropy term is

generally very small. As heat moves through a polymer the cure progresses through the cross-section. At the initial interface with the “hot environment” the cure is completed before the heat transfers to the last portion of the polymer. This gradient is obviously larger with thicker samples. With microwave heating the entropy of the entire bulk is increased nearly instantaneously. The result is a much more uniform heating with little loss to neighboring molecules that have yet to be brought to the same temperature. Another feature of microwave heating is the lack of interaction with the surrounding air, oven walls and microwave inert materials. This “specific” heating process is able to very rapidly raise the temperature of just the targeted materials without having to heat the “environment” which consists of all fully cured polymers, metals, ceramics and glasses. It should be noted that the “environment”, having not been heated, does not have to cool back to room temperature. In reality, of course, anything in contact with a microwave heated material will warm up from conduction. This is not a very efficient loss process as can be seen in Figure 6. The silicon die and epoxy die attach are efficiently heated to 160°C by microwaves but the glass-epoxy circuit board, which is fully cured, only rises to 41°C.



Figure 6. Selective heating of die and epoxy (bottom right) but not board.

Variable Frequency Microwaves (VFM)

Fixed frequency consumer microwave ovens are well known for causing metals to arc and to provide very un-even heating. Even turntables only partially improve uniformity but the charging problem remains. The solution is to rapidly and continuously change the frequency of the microwave field. The VFM frequency sweep is from 5.85 GHz to 7.0 GHz in 4096 steps over a sweep time of only 0.1 second. With the energy bandwidth now divided into 4096 frequencies, one at a time, the resident time for each frequency is only 25 μ s. In contrast to the standing wave pattern established with fixed frequency microwaves, there is not enough time to allow charge buildup even on metals, which makes it possible to process electronic components. This Variable Frequency Microwave environment has been determined to have no effect on semiconductor device properties by several semiconductor fabricators.

The microwave heating mechanism is further enhanced by rapidly varying frequency. The direction of polarization also keeps changing with the sweeping frequencies and its reflections from the walls of the cavity. An additional effect is caused by a brief removal

of energy from the reaction site while power is pulsed. This observation may result from the reactants being able to complete the reaction while still in close proximity.

Experimental Section

Microwave cure was performed on a Lambda Technologies MicroCure 2100-700 with a central frequency of 6.425 GHz, bandwidth of 1.15 GHz and a sweep rate of 0.1 seconds. A Raytek infrared pyrometer was used to monitor and control the temperature of the surface of the polymer film. Multiple Nortech fiber-optic probes were attached to the back side of the wafer and used to calibrate the infrared emissivity which was usually in the range of 0.85 to 0.95. Temperature was automatically ramped at controlled rates typically around 1 deg/s. Cooling rates were not controlled since the ambient air, oven surfaces and fixtures remained near room temperature during the curing cycles. Typical times for cooling from 200-350°C was less than four minutes to 60°C or less. Wafers were supported on quartz pins at the edges and the wafers were suspended approximately one-third of the vertical oven height in this laboratory development tool.

For experiments at temperatures of 300°C or higher a MicroCure 3100-2000 was used with a central frequency of 8.3 GHz, a bandwidth of 0.4 GHz, and a sweep rate of 0.1 seconds. The same temperature probes were used as on the Microcure 2100-700. A vacuum chamber capable of 0.1 mtorr allows backfill and purge of inert gasses. An environment of less than 10 ppm oxygen was produced by software control before curing began on PI and PBO samples that would otherwise oxidize at temperatures above 300°C. Wafer fixtures were the same as on the MicroCure 2100-700.

PI and PBO samples were provided as wafer films that were pre-baked at 100-120°C for 60-90 seconds. Wafers were stored under nitrogen until use. Epoxy samples were provided in syringes and kept at -40°C until use. Thermal, mechanical, and chemical resistance analyses were performed at supplier or customer sites with the exception of some DSC and TMA data from Lambda Technologies analytical lab. DMA samples were prepared in non-metallic molds since standard metal molds would shield the uncured polymers from microwave energies. Imidization percentages were calculated from FTIR peak heights. Films of 10 µm thickness were required to obtain thermal and mechanical data

Microwave Curing Results

Rapid Curing

It has been well documented that polymer resins will cure to completion very rapidly with VFM. Epoxy resins are highly polar as are the curing agents (hardeners) that they cross-link with. Curing of encapsulants 10-50 times faster with VFM is common. In all comparisons it is necessary to compare cures of materials to the same level of completeness by the metric of the final Tg. The first efforts to rapidly cure dielectric films on wafers with VFM showed the potential of 20-30 minute curing times for polyimides (2, 3), BCB (4), and PBOs (5).

Very recent results with both photo-sensitive (PS) and non-photo-sensitive (NPS) polyimides compare the standard manufacturing processes at 375°C for five hours to VFM cures at 350°C for 15 minutes (Figure 7).

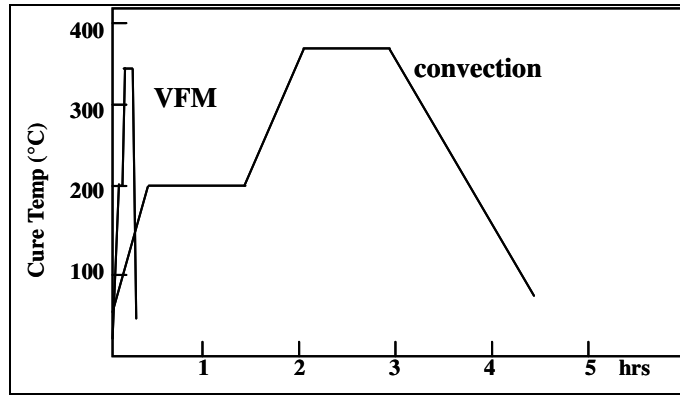


Figure 7. Process profiles of convection curing and VFM curing of polyimide films.

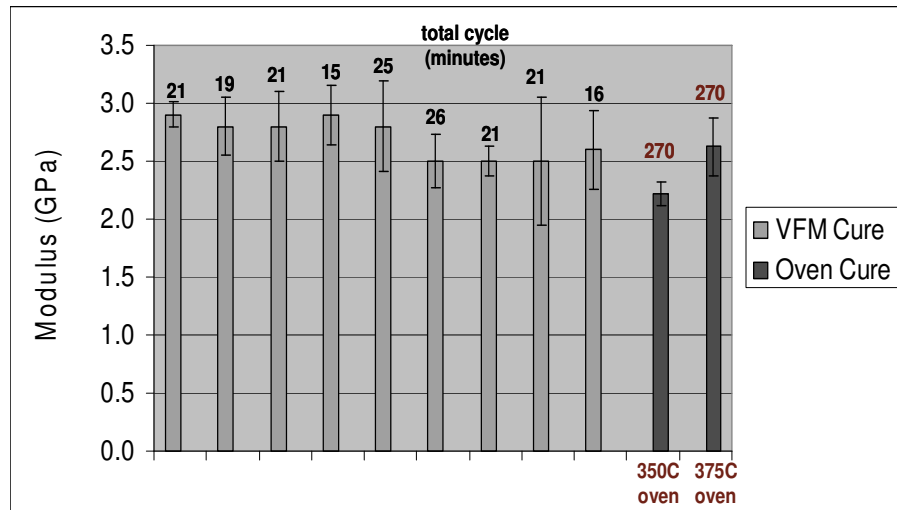


Figure 8. Modulus for NPS films.

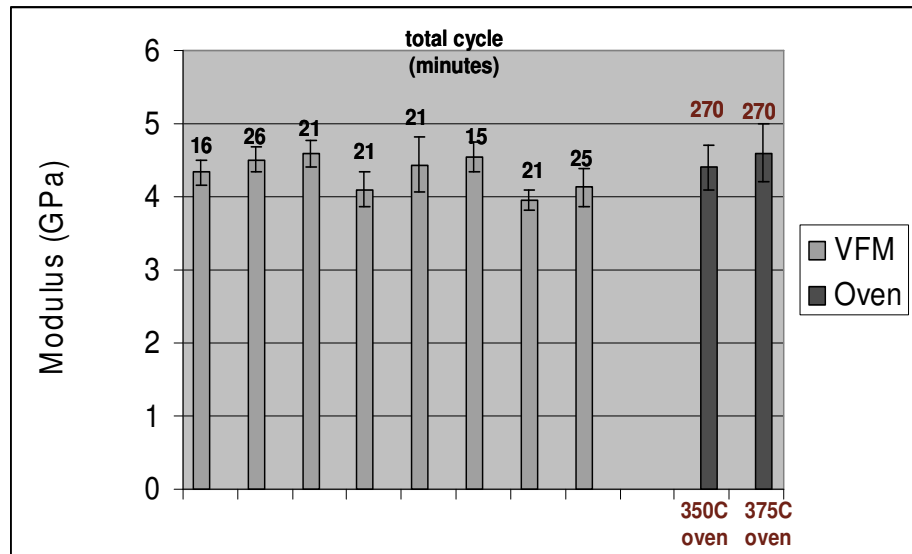


Figure 9. Modulus for PS films.

While the modulus of the two VFM cured films were unchanged (Figures 8-9); the tensile strengths were slightly better with VFM (Figures 10-11); and the elongations were significantly better with VFM (Figure 12-13). Note the low oven cure samples were before blade sharpening. Increased elongation of films (cured to the same Tg) with VFM curing was found in most of the experiments on polyimides, PBOs, and epoxies.

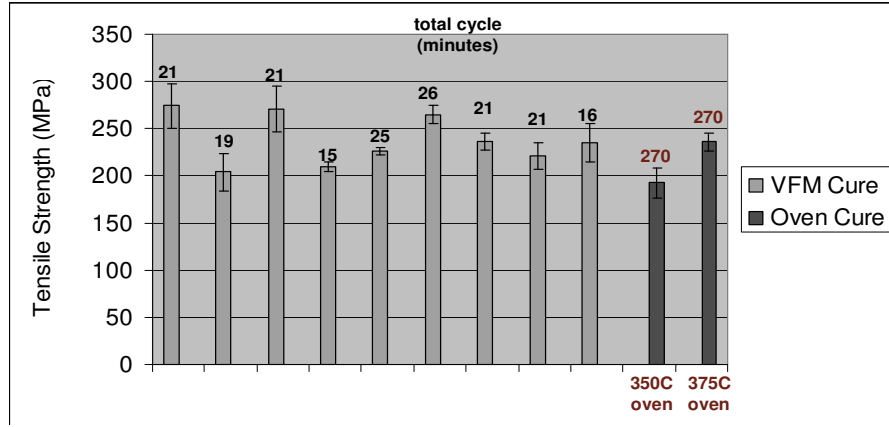


Figure 10. Tensile Strength for NPS films

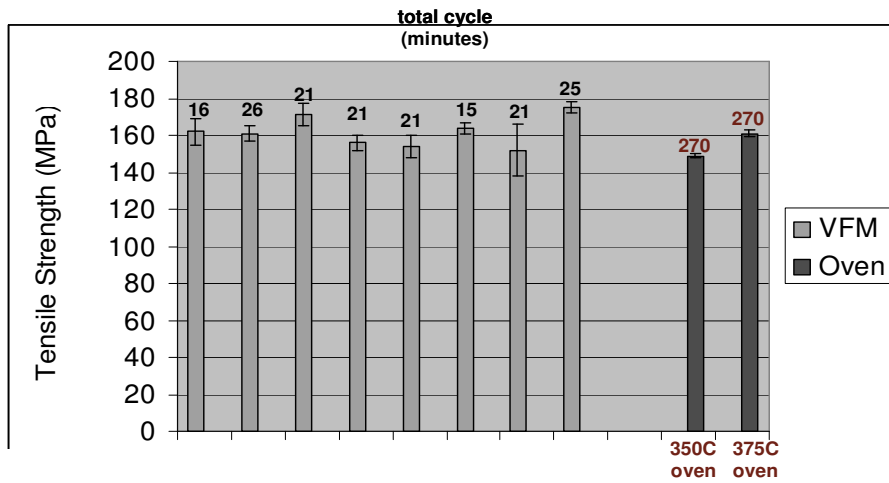


Figure 11. Tensile Strengths for PS films.

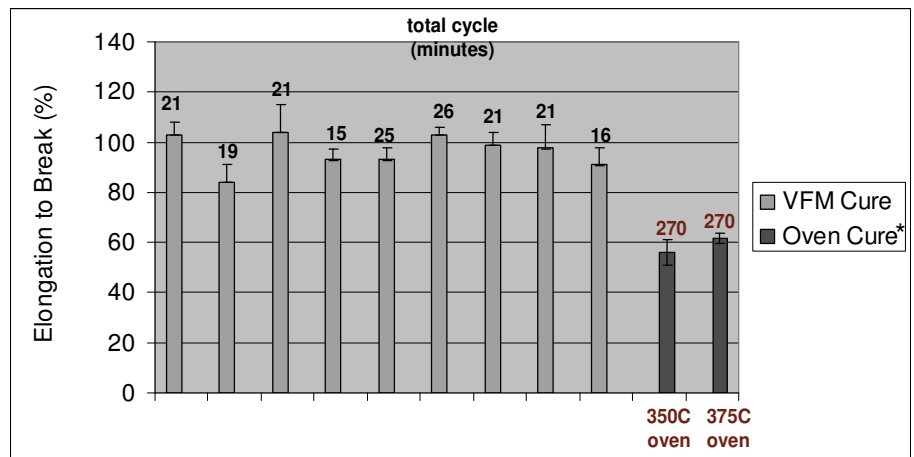


Figure 12. Elongation for NPS Films.

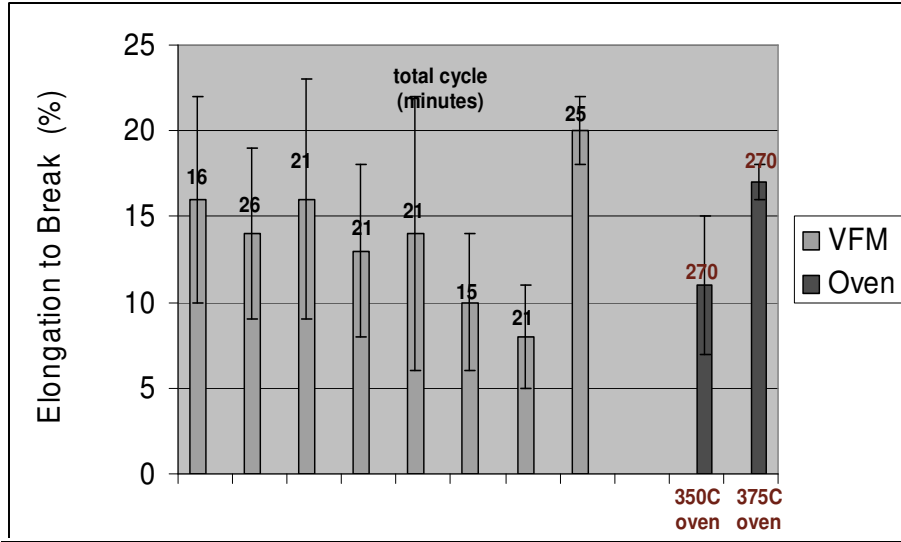


Figure 13. Elongation for PS films.

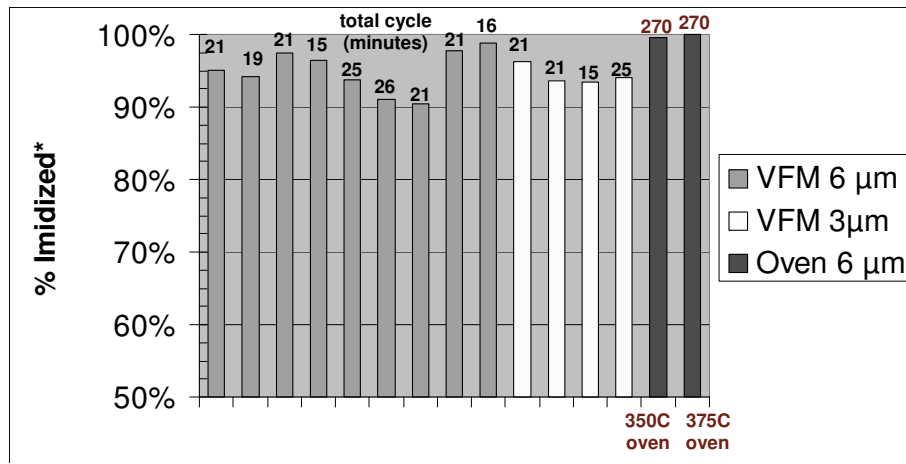


Figure 14. Imidization of NPS films (* by FTIR).

It appears that imidization is slightly lower with VFM in Figure 14 but it should be mentioned that the measurement of imidization by FTIR peak height ratios significantly decreases in accuracy above 90 %. In contrast, the equivalent residuals (Td5 – temperature at which 5 % weight is lost) measured for the NPS film and the improved residuals measured for the PS film cured by VFM suggests that the films were in fact completely cured (Figures 15-16).

As described above, the number of dielectric film layers being used for RDL and WLP is increasing so the time and thermal budget of sequentially layered wafers is becoming a bottle-neck for production at 30 wafers per hour (WPH). With a fifteen minute microwave cure the throughput for each layer increases to 200 WPH.

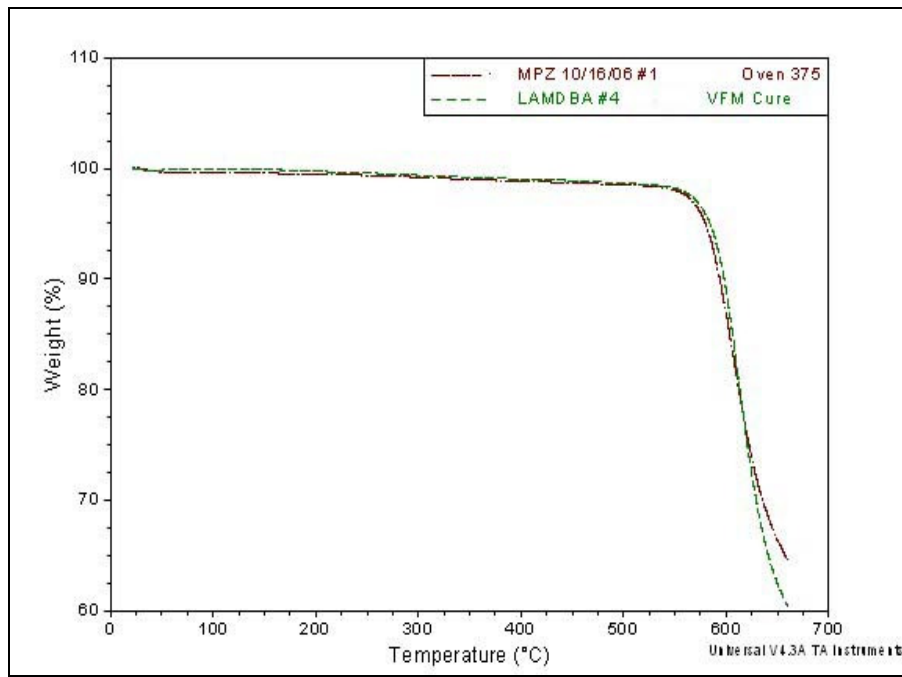


Figure 15. Residuals (Td5) for NPS Films.

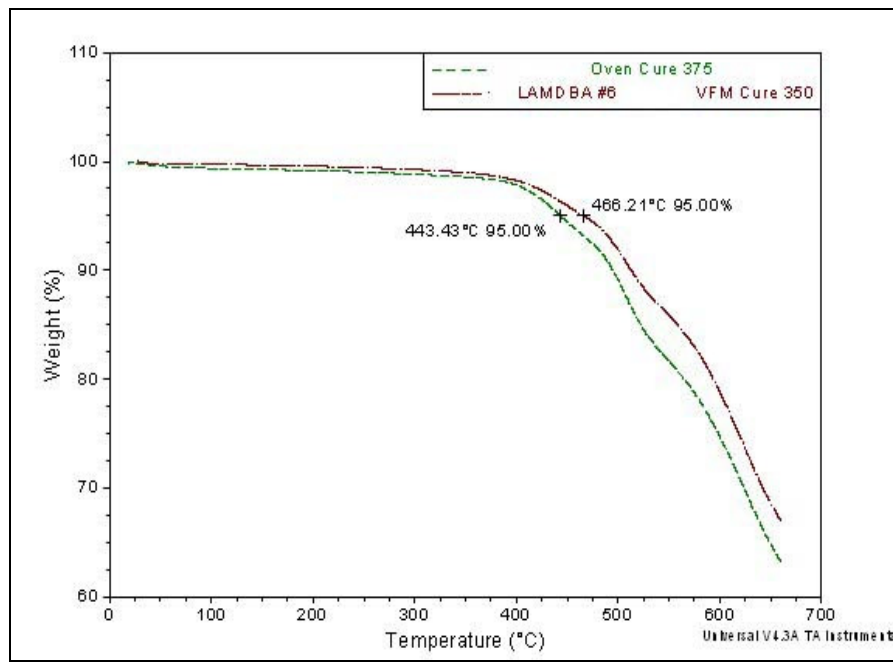


Figure 16. Residuals (Td5) for PS films

Low Temperature Curing of PI and PBO

Reducing the temperature of cure for all dielectric films has been a strong movement in the industry. Reducing the thermal budget not only saves on energy costs but also directly affects the yields of devices (particularly memories). Electrical performance characteristics will change after a polymer film is cured (and shrunk) on top of a sensitive circuit. There are also new circuit designs that will not survive being heated to 200°C for

even a short period. Materials suppliers have been formulating PI and PBO chemistries to drop the cure temperature while maintaining as many of their desirable thermal and mechanical properties as possible. The best efforts have not achieved much below 250°C however.

There were indications in the above referenced literature that a lower temperature cure might be possible with microwaves. Further results, with a variety of polyimides are shown in Figure 17. The metric for comparison of cure is the ratio of the Tg of a VFM cured film at a given lower temperature to the Tg of a film cured at standard cure (typically 350°C). It should be noted that this ratio sometimes exceeds 1.0 which indicates that a higher level of compaction is occurring after the imidization reaches 100 %. The data won't be presented here (6), but in most cases the thermal and mechanical properties of the microwave cured films are identical to the convection cured films. Two notable exceptions are the increase of elongation and decrease in residual solvents and water remaining in the film. Once again the cycle time is also affected by microwave curing as the diagram shows in Figure 18.

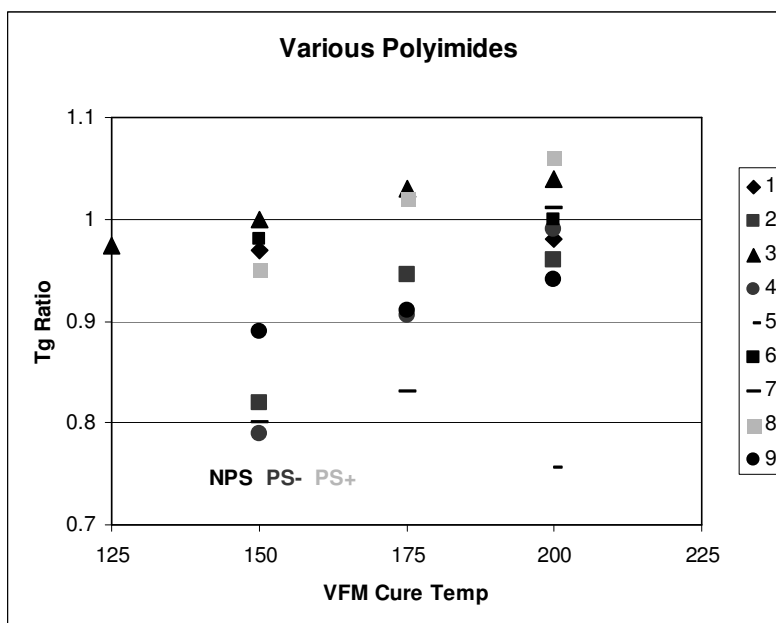


Figure 17. Tg ratios of polyimides cured at low temperatures.

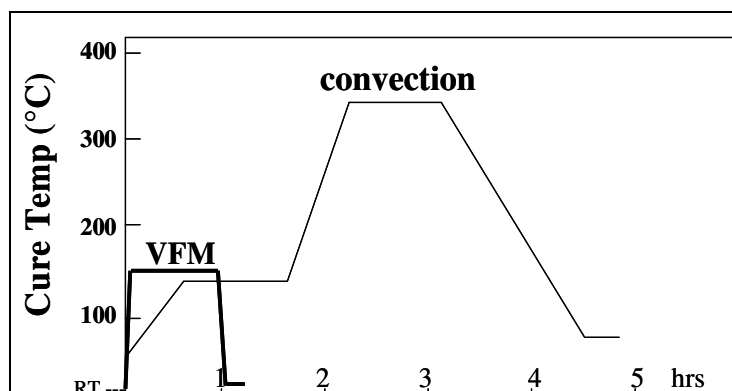


Figure 18. Cure cycle comparisons for polyimide films.

It is clear from Figure 17 that all polyimides are not “created equal” as far as microwave susceptibility is concerned. Number 3 is fully cured at 150°C while number 5 is only 75% imidized at 200°C. A three-year joint project between Lambda Technologies and HD Microsystems was able to determine what molecular features in polyimides and PBOs were most conducive to low temperature curing of wafer films with microwave energies.

All polyimides have the same cyclization (imidization) reaction which is activated by microwave absorption at the relevant dipoles. A series of polyimides was evaluated with respect to the additional dipoles in the polymers that were not at the site of the imidization reaction. Total dipole moments were calculated based on the magnitude and direction of each individual dipole (7) where b_L , b_T , and b_V represent the longitudinal, transverse, and vertical vectors respectively (Table II).

Table II. Polarizability components.

Bond	Context	b_L	b_T	b_V
C-H	Alkane	0.65	0.65	0.65
C-C	Alkane	0.97	0.26	0.26
C-C	Cyclopropane			
C-C	Cyclobutane			
C=C	Alkene	2.80	0.73	0.77
<u>C≡C</u>	Alkyne	3.79	1.26	1.26
Ar-Ar	Biphenyl			
C-F	MeF	1.2	0.4	0.4
C-Cl	Mea	3.18	2.2	2.2
C-Cl	<i>t-BuCl</i>	3.94	1.81	1.81
C-Cl	PhCl	4.2	1.9	1.5
C-Br	MeBr	4.65	3.1	3.1
C-Br	<i>t-BuBr</i>	5.98	2.6	2.6
C-Br	PhBr	6.4	2.4	2.2
C-I	MeI	6.7	4.8	4.8
C-I	<i>t-BuI</i>	9.2	3.7	3.7
C-I	PhI	9.1	5.3	3.3
c-o	Ether	0.9	0.46	0.46
c-o	Acetal			
<u>C=O</u>	Ketone	2.3	1.4	0.5
N-H	Ammonia	0.5	0.83	0.83
C-N	Amine	0.57	0.7	0.7
N-N	Hydrazine			
N=N	Azo			
<u>C=N</u>	Imine			
<u>C≡N</u>	Cyanide			
C-S	Sulphide	1.9	1.7	1.7
C-CN	<i>t-BuCN</i>	4.0	1.5	1.5
S-S	Disulfide			

All three vectors of each dipole moment were used in the matrix calculations. Any dipole moments that were cancelled out by other dipoles near the same site but in opposing directions were eliminated from the calculations.

$$\begin{aligned}
 v_1 &= c_{11}v_1^* + c_{21}v_2^* + c_{31}v_3^* + p_{11} \\
 v_2 &= c_{12}v_1^* + c_{22}v_2^* + c_{32}v_3^* + p_{12} \\
 v_3 &= c_{13}v_1^* + c_{23}v_2^* + c_{33}v_3^* + p_{13}
 \end{aligned}
 \tag{3}$$

Each dipole is represented by vectors in the longitudinal (v_1), transverse (v_2), and vertical (v_3) axes. The c_{11} represents the cosine of the angle between the first two longitudinal axes. The p_{11} represents the Cartesian coordinates of each longitudinal vector. The total molecular fraction polarizability was compared to the T_g ratio from curing experiments using VFM (Figure 19) on proprietary polyimides “A-E”.

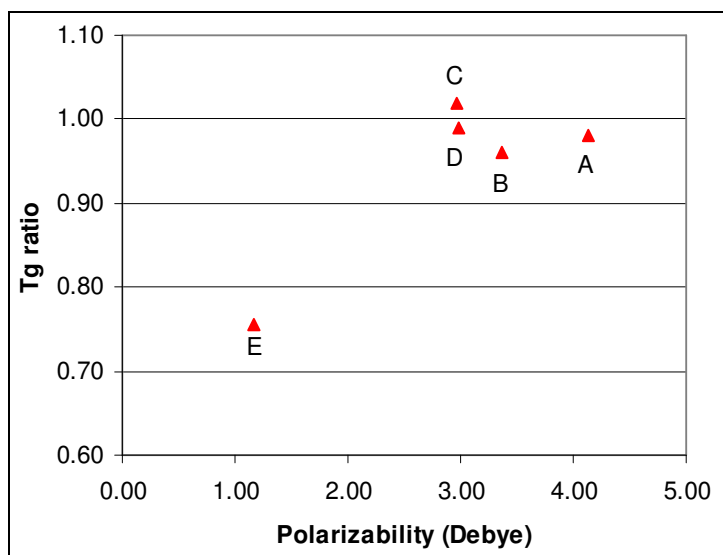


Figure 19. Molecular polarizability vs. T_g Ratio from VFM cure.

The microwave heating of a polymer is accomplished by the rotation of dipoles, so any steric hindrance to that rotation might inhibit the efficiency of the total bulk heating. Percent rigid chain length (PRCL) has long been known to correlate with the resulting physical and optical properties of polymers (8). A comparison of the same polyimides in Figure 14 with their calculated PRCL is shown in Figure 20. It can be seen that the polyimide that is an outlier in both graphs is the same material.

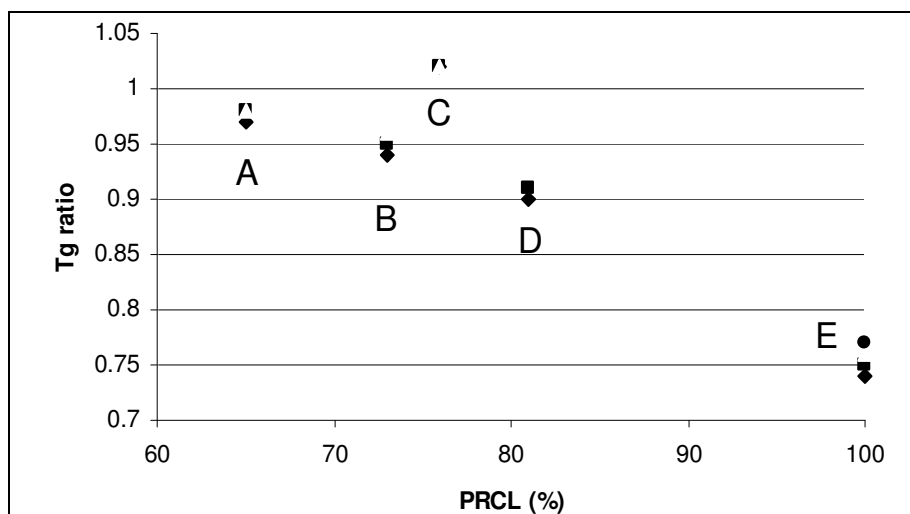


Figure 20. Polymer rigidity vs. T_g Ratio of polyimides cured with VFM.

With these two design guidelines, it should be possible to design a microwave susceptible polymer: high polarizability and high flexibility. There is increasing interest in PBO dielectric layers due to their aqueous development chemistry which is more environmentally friendly. PBOs are often cross-linked however which makes their design much more complicated.

A comprehensive design of experiments (DOE) series was planned to find a PBO that could be cured below 200°C with VFM. The variable matrix is shown in Table III. Center points were used and replicated (9).

TABLE III. DOE for low temperature curing PBO.

Variables	Low Setting	High Setting
Backbone	Aromatic	Alicyclic
Chain endcap	Low dipole	High dipole
Cyclization promoter	No	Yes
Cross-linking agent	Low dipole	High dipole
Cross-linking amount	Low	High
Soak temperature	170°C	200°C
Soak time	1 hr	2 hr
Ramp rate to soak	0.2 deg/s	1.0 deg/s
Solvent	NMP	GBL

Some of the results of this experiment were dramatic and surprising. Temperature, and especially time, were found to be relatively unimportant compared to design options. NMP solvent was far superior to GBL and the VFM cured films had smoother side-walls in photo-defined vias (Figure 21). Most importantly, design rules were generated that allowed some flexibility in designing PBOs that could be cured at 185-200°C and still have good thermal, mechanical, and chemical resistance features. Elongation was consistently higher for these designed materials when cured with microwaves.

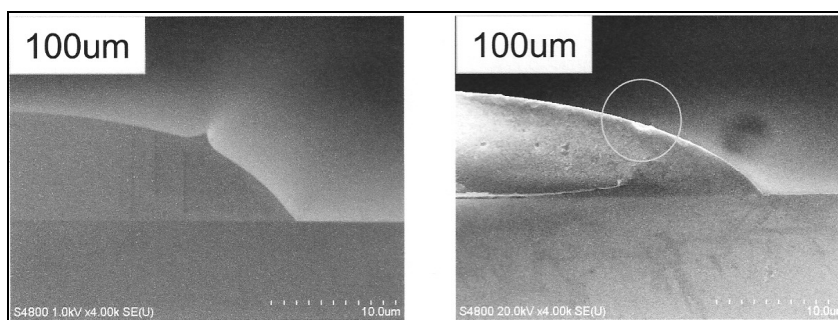


Figure 21. Via slope images of convection cured (left) and VFM cured PBO (right).

Uniformity of cure was evaluated in a prototype batch VFM system that held either 25 or 50 wafers spaced either 1" or ½ " apart vertically and coated with a PBO. Experimental variables included wafer spacing, temperature (170°C, 190°C), time (1 hr, 2 hrs), and position of the wafer in the stack. Seventeen test points, radially dispersed were measured on each of the twenty wafers interspersed with blank wafers. There was no statistical significance to any of the variables as measured by film thickness variability.

The standard deviation from 5.10 μm was less than 0.24% for wafer-to-wafer, position of wafer, spacing of wafers, temperature, time, and position on the wafer.

Low Temperature Curing of Epoxies

The successes with low temperature curing of PI and PBO dielectrics led to the closer examination of another popular cross-linked dielectric polymer: epoxies. There was an indication from the PBO work that VFM might have a selective effect between the cyclization reaction and the cross-linking reaction during cure. Lower shrinkage and lower stress have been found to be side benefits of VFM curing of epoxy encapsulants and under-fills (10). Lowering the curing temperature of epoxies has been found to increase elongation, toughness, and resistance to crack propagation, while decreasing modulus, brittleness, and shrinkage (11).

One of the keys to this less brittle epoxy formation has been found to be a larger network “mesh” formed at lower temperatures (12). If the initial cure can be performed at lower temperatures without inducing the gel state, shrinkage and modulus are reduced (13). A more leisurely cure time above the gel point would also lead to lower stress (14). A lower temperature cure would require a longer process time with convection curing however, as would longer times at higher temperatures. Microwaves could be used to start the cure at the reaction sites at lower temperatures than normal while maintaining reasonable total cure processing times.

A selection of epoxy encapsulants and under-fills were cured with both standard convection ovens and VFM systems. Once again, the metric of T_g was used to obtain cured films with comparable completeness and satisfactory adhesion. Initial experiments (15) used VFM cure temperatures close to the “onset temperatures” as measured by the DSC curves of the epoxies. Later experiments used even lower temperatures since it was found those temperatures significantly affected modulus and CTE (Table IV). Note the unusual combination of lower modulus and lower CTE. Both the liquid-state cure process (before gelation) and the solid-state cure process (after gelation) need to be studied since the solid-state cure is necessary for achieving adequate adhesion properties. This work is just beginning and more mechanical data needs to be compiled.

TABLE IV. Low temperature epoxy curing with VFM.

Epoxy	Modulus (conv)	Modulus (VFM)	CTE α_1/α_2 (conv)	CTE α_1/α_2 (VFM)
Encapsulant	18.7 GPa	6.3 GPa		
Underfill	1.94 GPa	0.14 GPa	26ppm / 102ppm	41ppm / 1551 ppm

Material suppliers of epoxies have produced wide ranges of mechanical parameter sets to assist in providing low stress and low shrinkage materials. The T_g and modulus are keys to assuring that stress levels at the solder ball joints are as low as possible. Unfortunately, the addition of low-k dielectric layers on wafers using 90 nm geometries and below have created a challenge to avoid cracking of these layers from high T_g and high modulus under-fills. By lowering the T_g and modulus a compromise can be achieved with low stress at the low-k dielectric layer interface and tolerable stresses at the

solder ball interfaces (16). As geometries move to 45 nm there is expected to be more work needed to provide epoxy properties to satisfy all these conflicting requirements.

Since epoxy mixtures (or copolymers) are beginning to be used as RDL and WLP layers, there are experiments underway to evaluate wafer film properties after curing with the new multi-step VFM profiles. An interesting result was discovered in the evaluation of epoxy-polyamic acid co-polymerizations with VFM (17). For low temperature VFM cured samples only, there was a change in reaction chemistries that produced exceptional elongation-to-break values. Improving the elongation of epoxy films would allow them to be used in portable applications where drop test data is important.

Another concern with epoxy processing is void entrapment during cure. A vacuum step is often used to pull any remaining voids out of the epoxy before the actual cure steps. It has been found that voids migrate out of epoxies very effectively during the first stages of standard VFM curing (18). This is most likely due to the uniform heating of the bulk material and the instantaneous microwave heating of the void surfaces while the epoxy viscosity is decreasing in the first stages of the process. This is supported by the fact that voids will be retained if the initial ramp rate is too rapid.

Conclusions

Material suppliers have developed specialized polymer dielectric films to meet the increasingly difficult requirements of packaging microelectronic devices. Curing these materials with microwave energy, and specifically the Variable Frequency Microwave technology, has allowed these same materials to be cured faster and/or at lower temperatures. This now allows highly thermally stable polymer dielectrics to be cured at less than 200°C with even some improvement in properties. Some cross-linked polymers and co-polymers have been cured with substantially different mechanical characteristics than would be the case with conventional oven curing. Empirical design rules have been found that allow material suppliers to synthesize dielectric materials specifically for microwave curing to enhance specifically desired thermal or mechanical properties. There are also some indications that cross-linked polymers may be cured with differing chemical structures when VFM is used at lower temperatures. More development is needed to widen the scope of the data derived so far and to investigate the mechanisms responsible for the improvements in thermal and mechanical properties of existing dielectric polymers when cured with microwaves. Additional cooperative design studies with material suppliers may provide even more substantial improvements in the manufacturability and reliability of microelectronic products.

Acknowledgments

The author would like to acknowledge the efforts of Mel Zussman, Tomoko Kawamura, and Masayuki Ohe of HD Microsystems and Keith Hicks and Iftikhar Ahmad of Lambda Technologies in the planning and execution of the curing experiments and measurements of the thermal and mechanical properties of the many, many wafer films and assorted samples described in this paper.

References

1. A.C. Metaxix, R.J. Meredith, *Industrial Microwave Heating*, 1983, Peter Peregrinus Ltd., Lo(1) M. Ahmad, S. Teng, J. Xue, *39th International Symposium on Microelectronics*, San Diego, California, 2006.
 2. K. Tanaka, S.A. Bidstrup Allen, P.A. Kohl, *IEEE Transactions for Components and Packaging*, in review.
 3. R.L. Hubbard, J. Schake, *56th Proceedings of the Electronic Components and Technology Conference*, San, Jose, California, 2006.
 4. R.V.Tanikella, S.A. Bidstrup Allen, and P.A. Kohl, *Journal of Applied Polymer Science*, **83**, 3055 (2002).
 5. R.V.Tanikella, T. Sung, S.A. Bidstrup Allen, and P.A. Kohl, *IEEE Packaging and Components Manufacturing Technology*, September 2003.
 6. R.L. Hubbard, Z. Fathi, J. Wander, T. Hattori, H. Matsutani, T. Ueno, C.E. Shuckert, *Symposium on Polymers for Microelectronics*, Winterthur, Delaware, May 3-5, 2003.
 7. J. Applequist, J.R. Carl, K.K. Fung, *J. Am. Chem. So.*, **94(9)**, 1972.
 8. V. Carlier, J. Devaux, R. Degras, *Macromolecules*, **25**, 6646, 1992.
 9. R.L. Hubbard, I. Ahmad, K. Hicks, M. Ohe, T. Kawamura, *Symposium on Polymers for Microelectronics*, Winterthur, Delaware, May 3-5, 2006..
 10. Z. Fathi, D. Tucker, I. Ahmad, E. Yeager, M. Konarski, L. Crane, J. Heaton, *Proceedings of Electronic Packaging Materials Science IX*, pp 125, Boston, Massachusetts, 1997.
 11. H. Lee, K. Neville, *Handbook of Epoxy Resins*, pg. 6-7, 1967, McGraw-Hill, New York.
 12. Weiss, *Epoxy Resin Symposium of the SPE*, Minneapolis, Minnesota, 1958
 13. R.L. Hubbard, I. Ahmad, B. Toleno, R. Zhao, *International Microelectronics Device Packaging Conference*, Scottsdale, Arizona, 2006.
 14. Burhans, *RIP Division of SPI*, Chicago, 1965.
 15. R.L. Hubbard, I. Ahmad, R. Zhao, Q. Ji, *39th International Symposium on Microelectronics*, San Diego, California, 2006.
 16. M. Ahmad, S. Teng, J. Xue, *39th International Symposium on Microelectronics*, San Diego, California, 2006.
 17. K. Tanaka, S.A. Bidstrup Allen, P.A. Kohl, *IEEE Transactions for Components and Packaging*, in review.
 18. R.L. Hubbard, J. Schake, *56th Proceedings of the Electronic Components and Technology Conference*, San, Jose, California, 2006.
-

