

Variable Frequency Microwave Curing of Photosensitive Polyimides

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Abstract—Variable frequency microwave (VFM) curing was investigated as a means of rapid curing of two photosensitive polyimides. The properties of two polymers, PI 2734 and Ultradel 7501, cured by convective heating and VFM curing were compared. The results of this study indicate that rapid VFM curing of these polymers is feasible. Complete imidization was possible. The most significant differences in properties between VFM and thermally cured films were in the electrical properties due to the slow evolution of chemical products.

Index Terms—Photosensitive polyimide, PI 2734, rapid cure, Ultradel 7501, variable frequency microwave, VFM.

I. INTRODUCTION

THIN film polymer dielectrics are widely used in the microelectronics industry for a variety of applications [1]. In order to be used for these applications, polymers are required to have excellent dielectric, chemical, and mechanical properties in addition to thermal stability at high temperatures. Typically, these polymers are solvent cast onto the desired substrate and a cure process involving treatment at high temperatures for several hours is necessary to chemically cure the film. In a previous study, it was shown that variable frequency microwave (VFM) processing was an effective method of curing low stress polyimide [2].

In this study, a rapid cure technique involving variable frequency microwave exposure of polymer dielectrics has been investigated. The goal is to replace the long, conventional thermal cure cycle with a shorter VFM process. Two commercially available negative tone photosensitive polyimides were chosen for study. The electrical, mechanical, and optical properties of the variable frequency microwave (VFM) cured films have been characterized and compared to those of films cured using a conventional thermal cure.

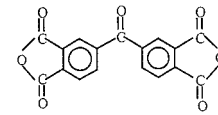
II. EXPERIMENTAL

The two polymer dielectrics examined in this work include PI 2734, manufactured by HD Microsystems, and Ultradel 7501, manufactured by Amoco Chemical Corporation. The chemistry of each system is described below.

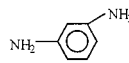
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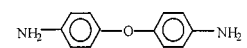
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Benzophenone dianhydride



M-Phenylenediamine (MPD)



4,4'-Diaminodiphenyl ether (ODA)

Fig. 1. Chemical structure of PI 2734 components.

PI 2734 is a negative tone, photosensitive, polyamic ester based polyimide. The polymer backbone is based on benzophenonedianhydride/m-phenylenediamine/4, 4' diaminediphenyl ether (BTDA/MPD/ODA) system (Fig. 1) [3]. The photopackage in this system (consisting of initiators and sensitizers whose chemistry has not been released by the manufacturer) is sensitive to broadband UV exposure between 350 and 465 nm. On initial exposure to UV light, the initiators form radicals which then cause a crosslinking reaction to occur between the ester crosslinking groups (*R*). This results in an insoluble crosslinked intermediate. Upon further heating during cure, the crosslinks disappear (resulting in the evolution of an alcohol), and the imidization reaction proceeds. A schematic of the crosslinking and imidization reactions is shown in Fig. 2. The *R* group for this polymer has not been disclosed by the manufacturer so the *R* group shown in this figure is representative of a typical ester crosslinking group.

PI 2734 films were spin-cast on 100 mm diameter <100> silicon wafers. Prior to the deposition of PI 2734, adhesion promoter (HD Microsystems VM 652) was spin-coated at 500 rpm for 5 s and then 3000 rpm for 30 s. PI 2734 was then spread at 500 rpm for 5 s followed by 30 s at 1200 rpm. The films were approximately 10 micrometers (μm) thick. Films prepared for FTIR analysis were spun on double side polished silicon wafers using a faster final speed which resulted in cured films of approximately 2 μm thickness. All PI 2734 films were then prebaked for 3 min on a 60 °C hotplate followed by 3 min on a 95 °C hotplate, exposed to UV radiation (365 nm) for a dose of 200 mJ/cm^2 , and then softbaked for 30 min in a 140 °C convection oven to drive off solvent and eliminate tackiness.

Ultradel 7501 is a preimidized, negative tone, photosensitive polyimide based on benzophenonetetracarboxylic acid dianhydride (BTDA) backbone. The benzophenone moiety is inherently photosensitive (autosensitive). Fig. 3 is a schematic repre-

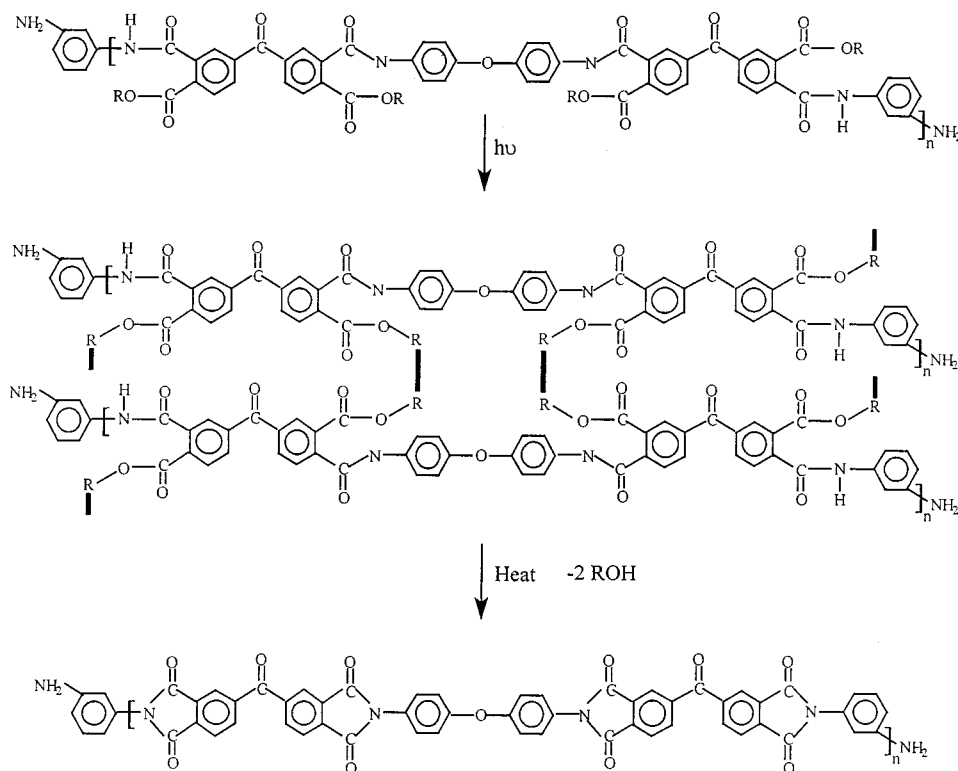


Fig. 2. Crosslinking and imidization reactions in PI 2734.

presentation of the crosslinking reaction in BTDA based autosenesitive polyimides [4], [5].

Thinfilms of Ultradel 7501 were prepared on 100 mm diameter $\langle 100 \rangle$ silicon wafers by first spin coating an adhesion promoter (Ultradel A600) for 5 s at 800 rpm and 30 s at 4000 rpm. The target thickness for the films (after curing) was 10 μm . Ultradel 7501 was spread at 500 rpm for 5 s followed by 30 s at 1000 rpm. Films prepared for FTIR analysis were spun on double side polished silicon wafers using a final speed of ~ 3000 rpm which resulted in cured films of approximately 2 μm thickness. All Ultradel 7501 films were then prebaked for 3 min on a 100 $^{\circ}\text{C}$ hotplate, exposed to UV radiation (365 nm) for a dose of 600 mJ/cm^2 , and then softbaked for 30 min in a 175 $^{\circ}\text{C}$ nitrogen purged convection oven to drive off solvent and eliminate tackiness. The cured samples were usually not immersed in the developer. It was found that developing did not effect the final properties because the cross-linked polymer was not soluble in the developer. The properties of the cured (undeveloped) polymer were the same as the published values, within experimental error.

In order to evaluate the effect of VFM cure on PI 2734 and Ultradel 7501 films, both materials were also cured according to standard thermal cure processes as recommended by the manufacturers. Preparation of films for this purpose, including spin speeds, UV exposure, and prebakes to remove solvent, was identical to that described above for films to be cured in the VFM. The standard thermal processes used for curing the two polymers are outlined in Table I.

The VFM used in this work was manufactured by Lambda Technologies, Research Triangle Park, NC. A traveling wave

tube was used as the microwave source. The unique feature of this system is the stepping through a range of frequencies: 4096 frequencies over a 1.15 GHz range every 0.1 s. This frequency stepping process provides a time-averaged uniformity in the energy distribution throughout the cavity and thereby eliminates the nonuniformities in temperature that occur in traditional single frequency systems [6], [7]. The VFM technique allows metals to be used in the microwave cavity. Charge build up and arcing due to the presence of standing fields are eliminated [8], [9]. The five most important parameters that can be controlled in the VFM system include the central frequency, frequency bandwidth, sweep rate, power, and temperature ramp rate [8].

A variety of experimental techniques were used to characterize the mechanical, electrical, optical, and chemical properties of the films cured by both variable frequency microwave and conventional thermal methods.

Residual stress levels for 10 μm thick films were determined by measuring changes in the curvature of $\langle 100 \rangle$ silicon wafers as a result of the deposition and subsequent curing of the polymer film. Measurements of wafer curvature were made at room temperature using a He-Ne laser based Flexus stress analyzer (Model F2320). The residual stress, σ , is calculated using (1) where $[E/(1-\nu)]_{sub}$ is the biaxial elastic modulus of the substrate (1.805×10^{11} Pa for $\langle 100 \rangle$ silicon), h is the substrate thickness in meters, t is the film thickness in meters, and R is the radius of curvature of the coated or uncoated wafer [10]

$$\sigma = \left(\frac{E}{1-\nu} \right)_{sub} \frac{h^2}{6t} \left(\frac{1}{R_{coated}} - \frac{1}{R_{uncoated}} \right). \quad (1)$$

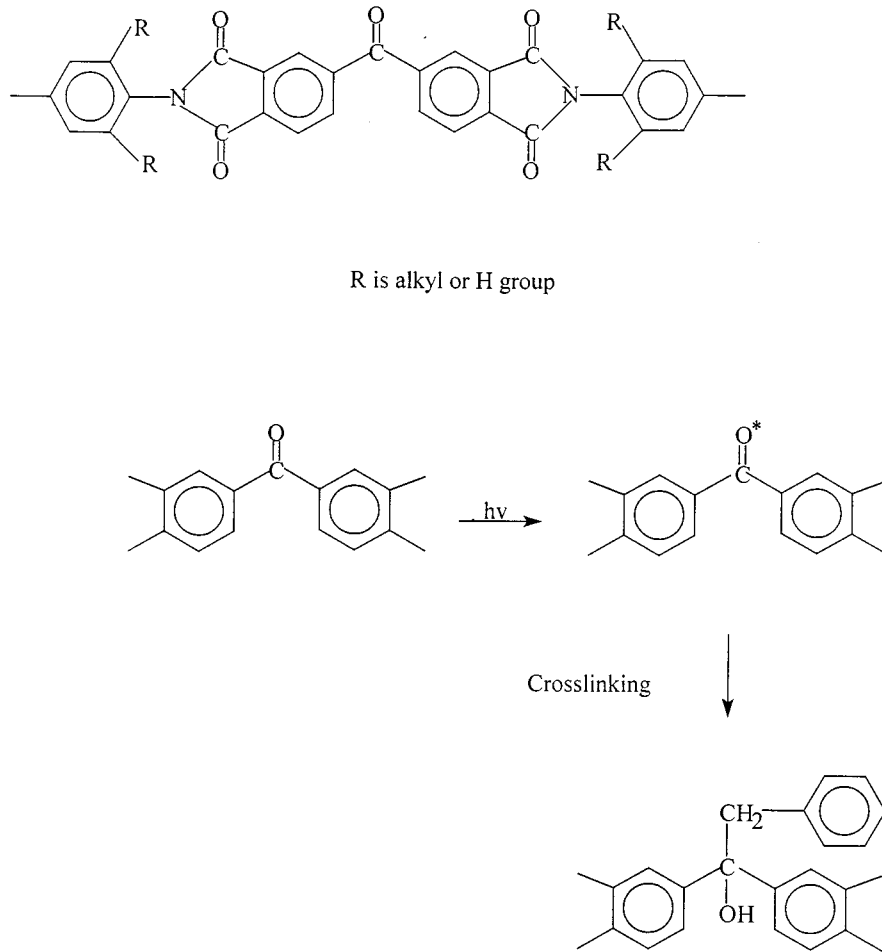


Fig. 3. Crosslinking reaction in Ultradel 7501.

TABLE I
CONVENTIONAL THERMAL CURE SCHEDULES FOR PI 2734 AND ULTRADEL 7501

PI 2734 ⁽²⁾	Ultradel 7501 ⁽¹⁵⁾
4°C/min to 200°C in furnace (in air)	10°C/min ramp to 200°C in furnace (N ₂ atmosphere)
Hold at 200°C for 30 minutes (in air)	Hold at 200°C for 1 hour (N ₂ atmosphere)
3°C/min to 350°C (N ₂ atmosphere)	10°C/min ramp to 350°C (N ₂ atmosphere)
Hold at 350°C for 1 hour (N ₂ atmosphere)	Hold at 350°C for 30 minutes (N ₂ atmosphere)
Slow but uncontrolled cooling to room temperature	Slow but uncontrolled cooling to room temperature

To experimentally determine the CTE and biaxial modulus of a polymer film, it is necessary to determine the slopes of stress versus temperature curves ($d\sigma/dT$) for identically cured films on two different substrates. The two substrates used in this work were $\langle 100 \rangle$ silicon and $\langle 100 \rangle$ gallium arsenide. The stress versus temperature curves were generated using a temperature controlled fixture in the Flexus. These curves were not linear over the entire temperature range for which data was collected (25 °C to 350 °C). Therefore, the slope is determined in the temperature range between 40 °C and 100 °C. During the first ramp up, residual moisture, which significantly affects the residual stress level, was removed from the film. Therefore, the slope was calculated from data collected during the second ramp cycle which

was reproducible. After $d\sigma/dT$ was determined on the two substrates, (2) was used to calculate the CTE and biaxial modulus of the films where $[E/(1-\nu)]_{film}$ is the biaxial modulus of the film (E is the Young's modulus and ν is Poisson's ratio), $\alpha_{substrate}$ is the CTE of the substrate (2.87 for silicon and 5.7 for gallium arsenide), and α_{film} is the CTE of the film [11]

$$\frac{d\sigma}{dT} = \left(\frac{E}{1-\nu} \right)_{film} (\alpha_{substrate} - \alpha_{film}). \quad (2)$$

Tensile properties were measured using film strips lifted off of silicon wafers. The strips were ~ 1 cm in width and ~ 4 cm in length. The strips were then lifted off the substrate by immersing

the entire sample in hydrofluoric acid (HF) for 2–3 min. HF etches the native oxide on the silicon wafer and releases the polymer strips. Each strip was pulled to failure using an Instron. The Young's modulus was calculated from the slope of the low strain region of each stress–strain curve. The elongation to break (ETB) and tensile strength are considered to be the maximum value that the test structure withstood prior to failure. It is important to note that the true ETB and tensile strength values will always be greater than or equal to the experimentally measured values. Defects or improper loading or handling of the film could produce fracture modes other than brittle, tensile fracture thereby significantly lowering the measured ETB. The values reported in this paper are the highest values obtained among all of the strips tested for a particular cure condition.

Through-plane permittivity and loss measurements were made using parallel plate capacitor structures (metal–insulator–metal) fabricated with the polymer film as the dielectric between the two parallel plates (ASTM D 150-95)[12]. Silicon wafers were thermally oxidized (~ 3000 Å) and then metallized with titanium/gold/titanium (150 Å, 1000 Å, 150 Å). Polymer films were spin-cast onto the wafers and cured according to the desired cure schedule. After cure, another layer of metal was deposited and patterned to form the top electrodes. Capacitance and conductance measurements were made using a Hewlett Packard 4236 LCR meter @ 10 kHz. The relative permittivity and loss tangent of the polymer films were determined from the capacitance, C , and conductance, G , using (3) and (4) where ϵ_0 is the permittivity of vacuum (8.85×10^{-12} F/m), ϵ_r is the relative permittivity of the film, A is the area of the top electrode (measured using a micrometer scale), t is the thickness of the film, $\omega = 2\pi f$, where f is the measurement frequency, and $\tan \delta$ is the loss tangent

$$C = \frac{\epsilon_0 \epsilon_r A}{t} \quad (3)$$

$$G = \omega C \tan \delta. \quad (4)$$

In-plane and through-plane refractive indices of the films were evaluated using a Metricon prism coupler. The difference in the in-plane and through-plane indices is known as the birefringence and is an indication of the degree of orientation in the film.

Fourier transform infrared spectroscopy (FTIR) was used to follow the chemical changes that occurred in the films during cure [13]–[15]. The imidization reaction that occurs during cure in PI 2734 causes distinct changes in the FTIR spectra which can be correlated to the degree of imidization that has occurred in the film.

The 1359 cm^{-1} peak, corresponding to the $C-N-C$ stretch of the imide ring, can be used as an indication of degree of cure [13], [15]. This peak is observed when the imide ring closes. The 1516 cm^{-1} peak, corresponding to the “ring breathing vibrations” of the 1, 4 substituted benzene, does not change during cure and can be used as an internal reference peak. The degree of imidization can be calculated using (5) where A is the absorbance and the subscript indicates the wavenumber corresponding to the peak. The reference absorbencies are determined from a film for which 100% imidization is assumed (standard thermal cure). Differences in film thickness or polymer

orientation as well as uncertainty in determining the baseline may result in slight changes in peak heights [13], [15]. These changes can significantly influence the calculation of the degree of imidization, and thus this method of evaluating the extent of reaction is considered only semiquantitative. Therefore, the percent imidization for the films is presented as a range based on the peak heights from numerous spectra

$$\text{Percent imidization} = \frac{(A_{1359}/A_{1516})}{(A_{1359}/A_{1516})_{\text{Reference}}} \times 100. \quad (5)$$

Because the Ultradel 7501 is pre-imidized, FTIR analysis does not provide any quantitative information about the degree of cure. The primary function of heating this system is to remove any solvent not removed during the softbake.

Thermal stability of select films was evaluated using thermal gravimetric analysis (TGA). All data was collected using a Seiko TG/DTA 320. Films (without substrates) were investigated using a $10^\circ\text{C}/\text{min}$ ramp to 100°C (to remove moisture), a 30 min hold at 100°C , a $10^\circ\text{C}/\text{min}$ ramp to 550°C , and a 60 min hold at 550°C . The degradation temperature is considered to be the temperature at which a polymer films begins to rapidly lose mass.

III. RESULTS

PI2734: The measured properties for PI 2734 films cured according to the manufacture's recommended thermal process are reported in Table II [2]. Also included in Table II are previously published values for the properties of this material. Minor differences exist between our observed values and those previously reported, due to measurement techniques or process variables. Our value for residual stress was obtained with the film on a $\langle 100 \rangle$ silicon wafer by use of a bending beam apparatus. Ramp rate and substrate can affect the stress. The residual stress in softbaked PI 2734 films on 100 mm diameter $\langle 100 \rangle$ silicon wafers is 17 MPa. During thermal cure, the residual stress level increases to 27 MPa. After spin casting the film on the substrate, the film and substrate are constrained at the interface. During the soft-bake process, the film shrinks primarily due to loss of solvent. This leads to a significant stress buildup in the film. During the cure process, further shrinkage occurs as a result of reaction product evolution. Reaction products include:

- 1) an alcohol resulting from the conversion of the ester in the polymer backbone to an imide;
- 2) byproducts of the photopackage.

This shrinkage in the film along with the formation of the imide ring leads to further increase in the stress to 27 MPa. Thin films of PI 2734 cured on silicon wafers were used to obtain free standing strips for tensile testing. All of the PI 2734 films were found to be very fragile and difficult to handle. Hence, it was not possible to obtain accurate measurements of Youngs' modulus, elongation to break, and tensile strength for thermally cured films.

The relative permittivity is sensitive to moisture content of the film and frequency. 50% relative humidity and 10 kHz were chosen as standard conditions throughout this work, which are different from the previously reported values. The relative permittivity in a soft-baked film is 3.9, and this decreased to 3.3 upon cure. The significantly higher value of relative permittivity in the softbaked state is due to the presence of the photoproducts and

TABLE II
SUMMARY OF PROPERTIES FOR CURED PI 2734 FILMS

→ Cure Condition → ↓ Property ↓	Thermally		VFM				
	Reported	Measured	I	II	III	IV	V
Ramp to 170°C (°C/min)	4	4	30	> 60	48	48	48
Hold at 170 °C (min)	0	0	0	5	2	2	2
Ramp to 200°C (°C/min)	4	4	30	> 60	36	36	36
Hold at 200°C (min)	30	30	0	2	2	2	2
Ramp to Final Temp (°C/min)	3	3	30	> 60	42	42	42
Final Temperature (°C)	350	350	310	300	350	350	350
Total Cure Time (min)	~ 300	~ 300	25	21.6	12	20	30
Residual Stress	18 MPa	27 MPa	36.52	21.15	25.53	28.87	34.1
Coefficient of Thermal Expansion	16 ppm/°C	-	-	-	-	-	16.8 ppm/°C
Young's Modulus	4.7 GPa	-	Too fragile	Too fragile	Too fragile	2.13 GPa	Too fragile
Elongation to Break	> 10 %	-	Too fragile	Too fragile	Too fragile	> 11.74 %	Too fragile
Tensile Strength at Break	178 MPa	-	Too fragile	Too fragile	Too fragile	86.1 MPa	Too fragile
Relative Permittivity (50% RH)	2.9 (@ 1kHz)	3.3 (@ 1kHz)	3.74	3.80	3.82	3.85	3.87
Loss Tangent (50% RH)	Not Reported	0.0053	0.013697	0.014399	0.0138	0.0126	0.0119
In-Plane Refractive Index	Not Reported	1.7756	1.6971	1.6686	1.6637	1.6687	1.6764
Through-Plane Refractive Index	Not Reported	-	1.6498	1.6101	1.6202	1.6147	1.6165
Degree of Cure (FTIR)	100%	100%	100%	99 %	100%	100%	100%
Solvent Resistance	Not Reported	> 10 days	> 10 days	> 10 days	> 10 days	> 10 days	> 10 days

the ester precursor in the softbaked film. During the cure process in PI 2734, the color of the film turns dark due to the removal of the components of the photopackage. Thus it is very difficult to use optical techniques to measure the index of refraction of the film. Hence, as noted in Table II, it was not possible to measure a through-plane index for thermally cured PI 2734.

We conclude that the thermally cured (Measured) films in Table II are a reasonable reproduction of those previously reported (Reported) within experimental error. The same measurement methods were used to evaluate the VFM cured films. Thus, the VFM results reported in Table II can be directly compared to the thermally cured (Measured) values.

Properties from films cured using 5 VFM conditions are summarized in Table II. During the VFM curing, the temperature is elevated, like a traditional, convective-oven curing, however, the method of energy transfer (microwave energy), ramp rate, intermediate hold temperature, cure time, final cure temperature, and total cure time are different. Microwave energy is absorbed throughout the film during curing, avoiding skin-effects which can occur during convective curing, and the temperature of the film can be very rapidly increased. The five VFM conditions shown in Table II explore the effect of ramp rate, hold time and temperature, and final cure time and temperature.

Spectroscopic analysis and solvent resistance show that the extent of imidization and chemical structure of these VFM cured PI 2734 films are very similar to those of thermally cured films. Fig. 4 shows a representative FTIR spectrum for a VFM cured film used to calculate the extent of imidization. Within the accuracy of FTIR, there are no detectable differences between the films.

The refractive indices, relative permittivity, and color of the VFM cured films differ from those of thermally cured films.

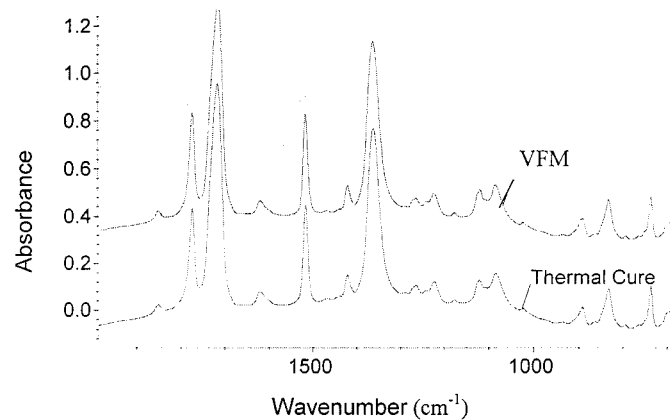


Fig. 4. FTIR spectra for VFM and thermally cured PI 2734 films.

The permittivity and loss of the VFM cured films are between those of the soft-baked and thermally cured films. This indicates that while the photo and imidization reactions have taken place, reaction products may still be present.

Thermal gravimetric analysis of VFM cured PI 2734 indicates that degradation in the VFM cured films will begin at a similar temperature as for the thermally cured films. As shown in Fig. 5, the VFM film began rapidly losing weight at ~ 328 °C (compared to the thermal at ~ 330 °C). The VFM film lost a total of 37 weight% during the entire TGA run while the thermally cured film lost only 32 weight%. This additional weight loss in the VFM film ($\sim 5\%$) may be due to the removal of reaction by-products and remnants of the photopackage which were not entirely removed during the VFM cure. It should be noted that complete removal of volatile products may occur with longer time at high temperature, or more slowly at ambient tempera-

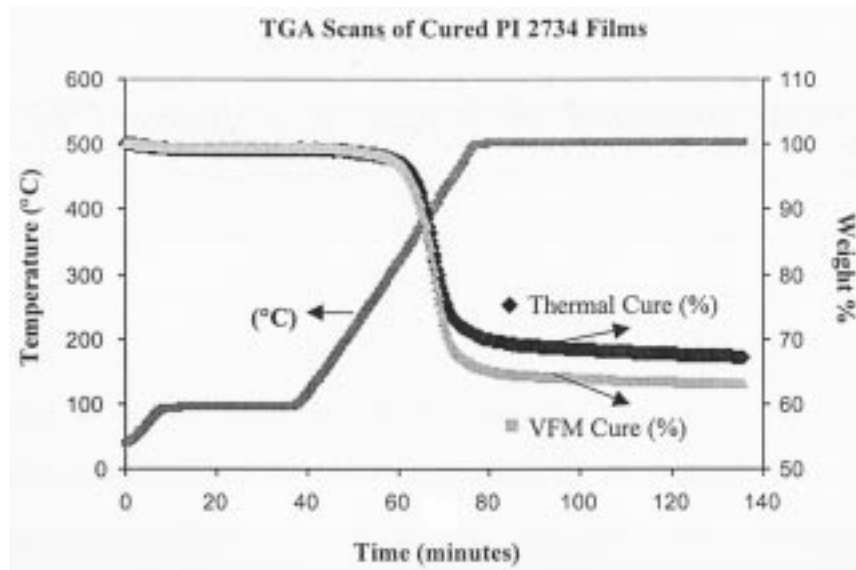


Fig. 5. TGA scans of thermal and VFM cured PI 2734.

TABLE III
SUMMARY OF PROPERTIES FOR CURED ULTRADEL 7501 FILMS

→ Cure Condition → ↓ Property ↓	Thermally		VFM	
	Reported	Measured	I	II
Ramp to 170°C (°C/min)	10	10	> 60	60
Hold at 170°C (min)	0	0	2	0
Ramp to 200°C (°C/min)	10	10	> 60	60
Hold at 200°C (min)	60	60	2	2
Ramp to Final Temp (°C/min)	10	10	> 60	45
Final Temperature (°C)	30	30	350	350
Total Cure Time (min)	~ 240	~ 240	17	20
Residual Stress	Not Reported	51 MPa	44.3	39.5
Young's Modulus	3.51 GPa	2.25GPa	-	2.22 GPa
Elongation to Break	Not Reported	7 %	-	9.08 %
Tensile Strength at Break	Not Reported	0.108 GPa	-	0.088 GPa
Relative Permittivity (50% RH)	2.8 (@ 1MHz)	3.11 (@ 10kHz)	3.26	3.24
Loss Tangent (50% RH)	0.0014 (@ 1MHz)	0.00124 (@ 10kHz)	0.007	0.004
In-Plane Refractive Index	1.59	1.5797	1.5874	1.5755
Through-Plane Refractive Index	1.59	1.5463	1.5530	1.5581
Solvent Resistance	Not Reported	> 10 days in GBL	> 10 days in GBL	> 10 days in GBL

ture. Thus, the selection of the optimum cure conditions requires knowledge of the final materials usage (which properties of importance) and the time frame for final usage.

Ultradel 7501: The measured and previously published properties for thermally cured Ultradel 7501 films are reported in Table III [15]. As with PI 2734, minor differences between the reported values and our measured values may be due to differences in measurement technique and or condition. The most significant difference between the reported and measured values are the permittivity. The frequency and ambient relative humidity were different for the two measurements.

The properties of Ultradel 7501 were significantly different in the softbaked form, as compared to the fully cured films. The residual stress increased from 35 MPa for a softbaked film to 51 MPa for a film fully cured via conventional thermal processing. The relative permittivity in the softbaked state was 4.36. During the thermal cure process, permittivity was reduced to 3.11.

As shown in Table III, the in-plane and through-plane refractive indices of Ultradel 7501 were quite close (1.5797 and 1.5463). This indicates that Ultradel 7501 has a very low degree of anisotropy (or ordering) in the films. FTIR spectra were col-

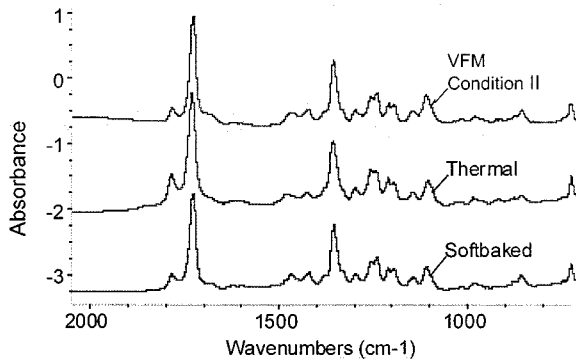


Fig. 6. FTIR spectra for softbaked, thermally cured, and VFM cured Ultradel 7501 films.

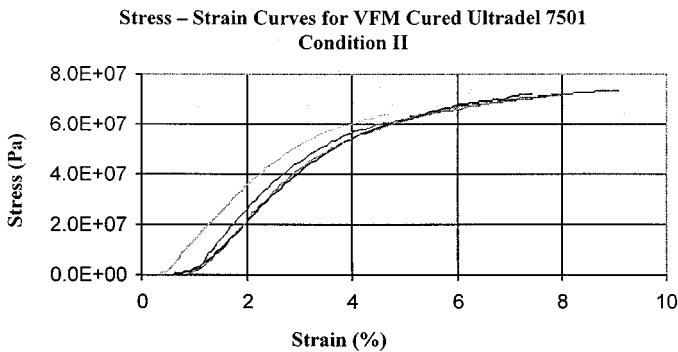


Fig. 7. Stress versus strain curves for VFM cured Ultradel 7501.

lected for softbaked and thermally cured films. As seen in Fig. 6, there is very little change which occurs in the FTIR spectra upon cure. Most of the solvent is removed during softbake and because Ultradel 7501 is preimidized, there is no imidization reaction occurring during cure. It is therefore not possible to track the degree of cure of Ultradel 7501 through FTIR spectroscopy.

Properties from Ultradel 7501 films cured using two VFM conditions are summarized in Table III. The two VFM conditions show the cure time reduced from 240 min. to 20 min. (or less). Residual stress levels for VFM cured Ultradel 7501 films are similar to those in thermally cured films. This polymer does not have a high degree of orientation after cure and therefore, residual stress levels are not particularly sensitive to ramp rates during cure. Stress-strain curves obtained for a VFM film cured using Condition II are shown in Fig. 7. The tensile properties of these films are comparable to those of thermally cured films. The solvent resistance was adequate under all curing conditions.

Spectroscopic analysis indicates that the bulk chemical structure of VFM cured Ultradel 7501 films is similar to that of thermally cured films. Other properties of the VFM cured Ultradel 7501 films including the final film thickness, refractive indices, birefringence, elongation to break, Young's modulus, and solvent resistance are also similar to those of thermally cured films.

The final permittivity and loss of the Ultradel 7501 were close to the final properties of the thermally cured films. Since reactions byproducts are not produced during the thermal curing reaction, evolution of the volatile products is not as much of an issue. In general, methods for the rapid curing of polymers must face the issue of slow diffusion and evolution of products.

IV. CONCLUSIONS

The results of this study indicate that rapid VFM curing of PI 2734 and Ultradel 7501 is feasible. The most significant differences in properties between VFM and thermally cured PI 2734 films involve a higher relative permittivity for the VFM films due to the slow evolution of volatile reaction by-products. These differences are probably a result of by-products of the photopackage and reaction products not being fully removed during VFM cure. The results for VFM curing of preimidized Ultradel 7501 indicate that properties nearly identical to thermally cured films can be obtained. Thus, curing reactions which do not rely upon transport of reactants or products through the film are more applicable to rapid curing methods.

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REFERENCES

- [1] R. R. Tummala, E. J. Rymaszewski, and A. G. Klopfenstein, *Microelectronics Packaging Handbook*. London, U.K.: Chapman & Hall, 1996, vol. 2, p. 510.
- [2] K. D. Farnsworth, R. N. Manepalli, S. B. Allen, and P. A. Kohl, "Variable frequency microwave curing of 3,3',4,4'-Biphenyltetracarboxylic Acid Dianhydride/P-Phenylenediamine (BPDA/PPD)," *Int. J. Microcirc. Electron. Packag.*, vol. 23, pp. 162-171, 2000.
- [3] HD Microsystems, "Pyralin LX PI 2734 technical data sheets," Tech. Rep., Wilmington, DE, July 1998.
- [4] J. C. Scaiano, J. C. Netto-Ferrerira, A. F. Becknell, and R. D. Small, "The mechanism of photocure of inherently photosensitive polyimides containing a benzophenone group," *Polym. Eng. Sci.*, vol. 29, no. 14, pp. 942-944, July 1988.
- [5] A. A. Lin, V. R. Shastri, G. Tesoro, and A. Reiser, "On the cross-linking mechanism of benzophenone-containing polyimides," *Macromolecules*, vol. 21, pp. 1165-1169, 1988.
- [6] M. T. Demeuse and A. C. Johnson, "Variable frequency microwave processing of thermosetting polymer matrix composites," in *Proc. Mater. Res. Soc. Symp.*, vol. 347, 1994, pp. 723-728.
- [7] R. Lauf, D. W. Bible, A. C. Johnson, and C. Everleigh, "2 to 8 GHz broadband microwave heating systems," *Microw. J.*, pp. 24-34, Nov. 1993.
- [8] B. Panchapakesan, P. Mead, Z. Fathi, and D. Tucker, "Variable frequency microwave," *Adv. Packag.*, pp. 60-63, Sept./Oct. 1997.
- [9] Z. Fathi, D. A. Tucker, W. A. Lewis, and J. B. Wei, "Industrial applications of variable frequency Microwave energy in materials processing," in *Proc. Mater. Res. Soc. Symp.*, vol. 430, 1996, pp. 21-28.
- [10] Flexus Incorporated, *Thin Films Stress Measurement System*. San Jose, CA: KLA Tencor.
- [11] T. C. Hodge, S. A. Bidstrup, and P. A. Kohl, "Stresses in thin film metalization," *IEEE Trans. Comp., Packag., Manufact. Technol.*, vol. 20, pp. 241-250, June 1997.
- [12] *Standard Test Methods for AC Loss Characteristics and Permittivity of Solid Insulating Materials*, ASTM Std. D150-95, 2001.
- [13] C. A. Pryde, "FT-IR studies of polyimides II. Factors affecting quantitative measurement," *J. Polym. Sci. Part A: Polym. Chem.*, vol. 31, pp. 1045-1052, 1993.
- [14] R. Snyder, "In situ FT-IR analysis of polyimide curing," in *Proc. 3rd Int. Conf. Polyimides—Synthesis, Characterization, Applicat.*, Ellenville, NY, Nov. 2-4, 1988, pp. 116-118.
- [15] C. A. Pryde, "IR studies of polyimides. I. Effects of chemical and physical changes during cure," *J. Polym. Sci. A: Polym. Chem.*, vol. 27, pp. 711-724, 1989.
- [16] Ultradel, "Ultradel 7501 coatings data sheets," Tech. Rep. UL-P4c, Naperville, IL, 2001.

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