Electron Beam Enhanced Multilayering and Planarization in Preimidized Polyimides

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***Abstract*—High-density packaging and interconnection applications frequently involve the use of polyimide-based materials as interlevel dielectrics for multilevel interconnection schemes. Surface planarity after each polymer layer is very important to the fabrication of multilayer structures. Highly nonplanar surfaces were observed in a multilayer test structure, fabricated using a thermally cured polyimide (Ultradel 7501). In this study, the effect of a novel cure technique involving electron beam (e-beam) exposure on multilayering and planarization behavior in Ultradel 7501 is investigated. Planarization measurements were conducted on different feature sizes and at various locations on the wafer in order to investigate the effect of solvent exposure, time and area of contact between multiple layers. The degree of planarization was found to improve from −206% for a thermally cured case to +15% for an e-beam cured sample. Analysis of the solvent induced polymer swelling and its effect on multilayer planarization of Ultradel 7501 is presented.**

***Index Terms*—Crosslinking, degree of planarization, electron beam curing, multilayering, planarization, preimidized polyimide, solvent induced swelling, Ultradel 7501.**

I. Introduction

POLYIMIDE based dielectrics have been extensively used in electronic packaging for a variety of applications including stress relief buffers, alpha particle barriers, and as passivation layers in integrated circuits (ICs) [1]. Polyimides are also commonly used as interlevel dielectrics in high-density packages, providing means for interconnection between active ICs. One of the key concerns in these applications, especially in the fabrication of multilayer polymer based packages, is the ability to form planar surfaces at each layer, in order that high-density packaging can be achieved. As the number of layers in a package increases, planarization of the underlying topography is of increasing importance in order to achieve acceptable photolithographic resolution. Several studies have been conducted in the past to evaluate the factors, which influence the planarization ability of polyimides [2], [3].

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In a previous study [4], it was found that the planarization of a preimidized polyimide (Ultradel 7501) is significantly compromised by solvent diffusion from one layer of the polyimide to the other. The degree of planarization (DOP), defined by equation (1) and Fig. 1, was used as a figure of merit, to characterize the planarization behavior in multilayer test structures

$$\mathrm{DOP}\% = \left(1 - \frac{t_r}{h}\right) \times 100. \tag{1}$$

Highly nonplanar surfaces were observed in test structures with thermally cured Ultradel 7501 [4] primarily due to insufficient solvent resistance in the thermally cured films. Similar solvent swelling effects have also observed by others in another preimidized polyimide [5] based on a similar backbone chemistry.

During spin coating of pre-imidized Ultradel 7501 polyimide in multilayer applications, it was found that deposited thickness was not only a function of the standard parameters (time, spin speed, amount deposited, fluid viscosity), but was also a function of the thickness of previously deposited polyimide. The reason behind this is that thermally cured Ultradel polyimide retains an affinity for solvent, and the rate at which the under-layer absorbs solvent from the as-deposited (i.e., top) layer is a function of the under-layer thickness. Because the viscosity of the as-deposited fluid depends on its solvent content, it was found that for a fixed set of spin parameters, as the underlayer thickness increased, the thickness of the as-deposited layer also increased. This behavior complicates coating thickness control because variance in under-layer dielectric thickness leads to changes in the spin-curve.

In this study, e-beam radiation of the base layer of Ultradel 7501 is investigated. Electron beam radiation can lead to crosslinking in the polyimide matrix; the effect of enhanced crosslinking on planarization and thickness control in multilayer structures is studied.

II. Experimental Procedure

Ultradel 7501, manufactured by Amoco Chemical Corp (Naperville, IL), is a preimidized, negative tone, photosensitive polyimide based on the BTDA (benzophenonetetracarboxycilic acid dianhydride) backbone. The polymer is dissolved in γ-butyrolactone (solvent), and the polymer solution is used for solvent casting thin polymer films. Multilayer spin coating experiments were performed using a SVG Model 8628 track coating/developing system. The standard cure process involves ultraviolet (UV) exposure followed by a high temperature bake

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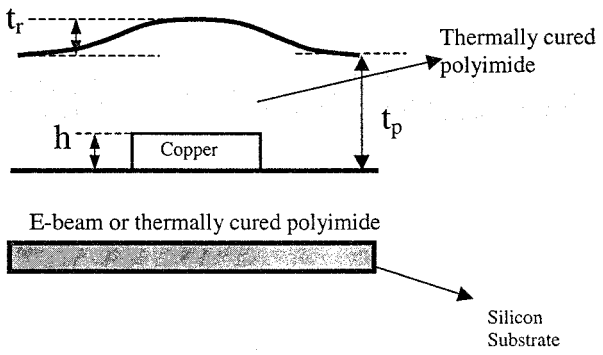


Fig. 1. Definition of degree of planarization (DOP) in a multilayer structure h = height of copper metal line, t_p = thickness of polymer, t_r = relief height of polymer over metal line.

TABLE I
SUMMARY OF CURE CONDITIONS USED FOR BASE POLYIMIDE LAYER (MULTILAYER SPIN CURVE EXPERIMENTS)

Condition	Dose (μC/cm^2)	Accelerating Voltage (keV)	Total UV Exposure (mJ/cm^2)	Max Temperature	Total Cure Time
Cure A	NA	NA	2000	250 °C	~4 hours***
Cure B	NA	NA	2000	350 °C	~6 hours*
Cure C	1000	20	400	180 °C	~5 minutes **
Cure D	1000	20	400	350 °C	~5 minutes **
Cure E	2000	20	400	180 °C	~7 minutes **

in nitrogen or vacuum [6]. Exposure to UV radiation leads to activation of the benzophenone group in the backbone of the polymer chain and leads to crosslinking in the film [7], [8]. This mode of crosslink formation is proposed to create solvent resistance in the cured film.

E-beam curing of the samples was carried out using Allied Signal's Electron Cure 30-200A-T electron beam exposure system. This e-beam system facilitates flood exposure of large area substrates to electron beam radiation. The physics behind the operation of the electron beam system is explained in detail elsewhere [9]. The total dose (or flux) of electrons (measured in μC/cm^2) was obtained by integrating the beam current (mA/cm^2) over time. During e-beam exposure, some samples were heated from the underside using an array of quartz lamps.

A. Test Structure Fabrication

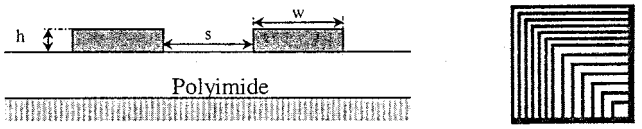
Two sets of experiments were conducted in this study: multilayer spin speed curve characterization and degree of planarization (DOP) characterization. In the first set of experiments, multilayer structures were fabricated to characterize the spin curve behavior of polyimide deposited over e-beam or thermally cured polyimide. Oxidized silicon wafers were coated with adhesion promoter, then spin coated with Ultradel 7501 for 1500 rpm for 30 s (expected thickness after descum and cure $\sim$5 μm). These wafers were softbaked on a 100 °C hotplate for 3 min followed by a 160 °C oven softbake (in N2) for 60 min, followed by a patterning exposure to UV radiation for a dose of 400 mJ/cm^2 (calibrated at 365 nm). The polyimide-coated wafers were then subjected to one of the cure conditions outlined in Table I. The thermally cured wafers were given an additional 1600 mJ/cm^2 flood-exposure prior to cure. This extra dose is as recommended by the manufacturer to assist in improving the solvent resistance. Cured thicknesses were measured using a surface profilometer in patterned areas (isolated 200 μm lines), then the wafers were spin coated with a second layer of Ultradel 7501 polyimide (for 40 s at either 2000, 4000, or 6000 rpm spin speed). These wafers were then processed in the same fashion as for the first layer application, and all wafers were cured according to cycle A. The wafers were then re-measured for second layer thicknesses.

In the second set of experiments, multilayer structures were fabricated to characterize the degree of planarization (DOP) [4], [10] with e-beam or thermally cured polyimides. Thermally oxidized 4 in silicon wafers with an oxide thickness ca. 2000 Å were used as substrates to build the requisite test structures. A thin seed layer of titanium, copper, and titanium (Ti/Cu/Ti; thickness: 100 Å/1000 Å/100 Å) was sputtered on to the oxidized wafer. Adhesion promoter, Ultradel AP 600 (containing γ-aminopropyltriethoxysilane) was applied to the surface prior to the polyimide deposition. Ultradel 7501 was then spun coat at 1000 rpm for 30 s (expected thickness after cure $\sim$10 μm), softbaked in an oven at 100 °C for 10 min, exposed to UV radiation for a dose of 600 mJ/cm^2 (calibrated at 365 nm) and hard baked in an oven at 140 °C for 30 min. The polyimide-coated wafers were then subjected to one of the five cure conditions outlined in Table II. The accelerating voltage on the cathode in the DOP experiments was fixed at -28 kV. This sets the kinetic energy of the electrons impinging onto the polymer film to 28 keV and is sufficient for the electrons to penetrate through at least 10 μm of the polymer film [11]. A thin seed layer of Ti/Cu/Ti (40 Å/800 Å/40 Å) was then sputtered on to the cured layer of polyimide. Using standard photolithography techniques, lines of specified width and spacing were patterned on each sample. The seed layer of titanium was then etched and the exposed areas were electroplated up with copper. A plating bath consisting of 200 g/L of $CuSO_4$.5 H_2O in 1 M H_2SO_4 was used in our experiments with a 99.9% pure copper foil as the anode and at a current density of 20 mA/cm^2. The seed layer of the Ti/Cu/Ti was then etched from the rest of surface, resulting in isolated metal lines on the cured polyimide layer as shown in Fig. 2. The resulting electroplated copper lines were designed to be 2.5 μm high.

The test structures on each sample were fully characterized using a surface profilometer to measure the height (h), width (w) and the spacing (s) between the metal lines. Test structures of four different sizes (widths), 25 μm, 50 μm, 75 μm, and 100 μm, were evaluated in this study. The spacing between the lines was varied such that the w/s ratio was either 1 : 1 or 1 : 2. A set of these test structures were fabricated close to the center of the wafer and another set toward the edge of the wafer as shown in Fig. 2. A second layer of the Ultradel 7501 polymer solution was then dispensed onto the center of the wafer, held for 15 s prior to spinning, and spun at 1500 rpm for 30 s (expected thickness of second film $\sim$6 μm). The test structures at the center of the

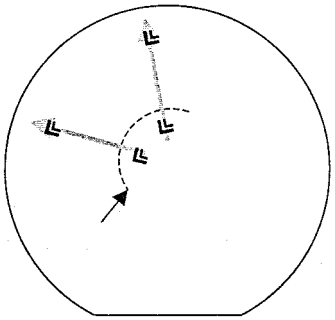
TABLE II
SUMMARY OF CURE CONDITIONS USED FOR BASE POLYIMIDE LAYER (DOP EXPERIMENTS)

Condition	Dose ($\mu C/cm^2$)	Temperature	Total Cure Time
Cure 1	NA	350 °C	~5 hours*
Cure 2	500	350 °C	~8 minutes **
Cure 3	1000	350 °C	~9 minutes **
Cure 4	1500	350 °C	~10 minutes **
Cure 5	2000	350 °C	~12 minutes **



(a)

(b)



(c)

Fig. 2. Test structure for characterization of degree of planarization: (a) schematic side view, (b) top view of a single structure, and (c) schematic view of the wafer.

wafer were exposed to the puddle of polymer solution dispensed prior to the spin cycle. The test structures at the edge of the wafer however, were exposed to the polymer solution only during and after the spread cycle in the spin coating process. This was done to study the effect of the spin coating process on solvent absorption into the cured layer and planarization in multiple polyimide layers. The second layer of the polymer was then cured in each of the five different cases using the manufacturers recommended thermal cure cycle as outlined in Table I. The final test structure had one of the two different scenarios, either a thermally cured base layer of polymer with a thermally cured second layer or an e-beam cured base layer of polymer with a thermally cured polymer layer on the top as shown in Fig. 1. Relief heights (t_r), as shown in Fig. 1, were measured over the metal lines of height "h," using a profilometer for all the line widths and spacings for the five different cure conditions. DOP [4], [10] was then evaluated for all the different cases using (1).

III. RESULTS

A. Multilayer Spin Curve Characterization

The thickness data for the second layer of polyimide (over the various cured initial layers) is shown in Fig. 3. In this figure, cycles A and B refer to wafers with a thermally cured base layer of polymer, and cycles C through E refer to wafers with an e-beam cured base layer of polymer. The spin speed curve for a polyimide layer deposited and thermally cured on an inert base is also presented as a reference. The actual cure conditions corresponding to these cycles are listed in Table I. As seen from Fig. 3, the spin speed curve for the second layer of the polyimide is strong function of the cure condition used for curing the base layer. The spin speed curve for the second layer of polyimide on a thermally cured base is significantly different from the reference curve. For cycle A, where the base layer of the polyimide is cured at 250 °C, the thickness of the second layer of the polyimide is 7 μm at a spin speed of 2000 rpm. The expected thickness from the reference curve, at this spin speed is 4.5 μm. As the spin speed used for the second coat is increased, the thickness of the second layer of the polyimide decreases, but still is higher than thickness expected from the reference curve. For cycle B, where the base layer of the polyimide is cured at 350 °C, the spin speed curve is even worse. The spin speed curves on all the e-beam cured wafers, in contrast, are very similar to the reference curve, indicating that depositing polyimide on an e-beam cured polyimide base is equivalent to deposition on inert surfaces. The difference between the measured thickness and expected thickness is less than 3%. This is found to be true for all the e-beam cured films irrespective of the back heating temperature used for curing the film.

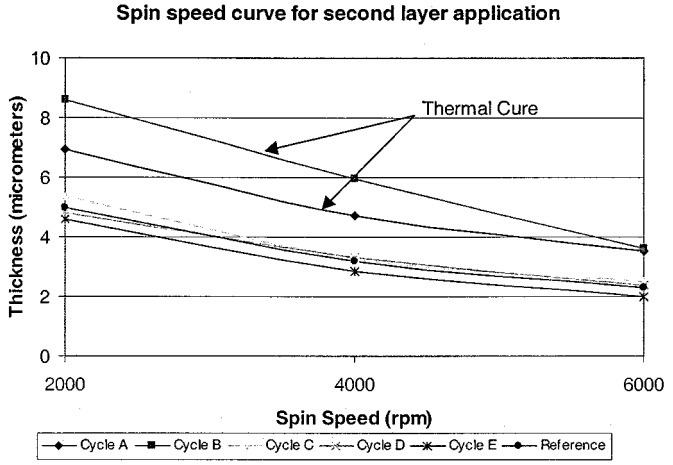


Fig. 3. Spin speed curve for second layer of polyimde spun over polyimde base cured under various conditions.

In this study another set of e-beam cure conditions involving lower accelerating voltages (5 keV in comparison to the standard 20 keV for 5 μm films) were also examined. These conditions were chosen to investigate the effect of e-beam curing the top 1 μm (calculations show that 5 keV electrons only penetrate through 1 μm of the film) of the polyimide film on multilayering behavior. However, these films showed severe swelling related failures when subjected to multilayering indicating that e-beam curing of the entire thickness of the material is necessary in order to completely realize the benefit of e-beam enhanced multilayering. Specifically these films exhibited gross surface nonuniformities and in some cases even dissolution and lift off of the polyimide film from the wafer surface.

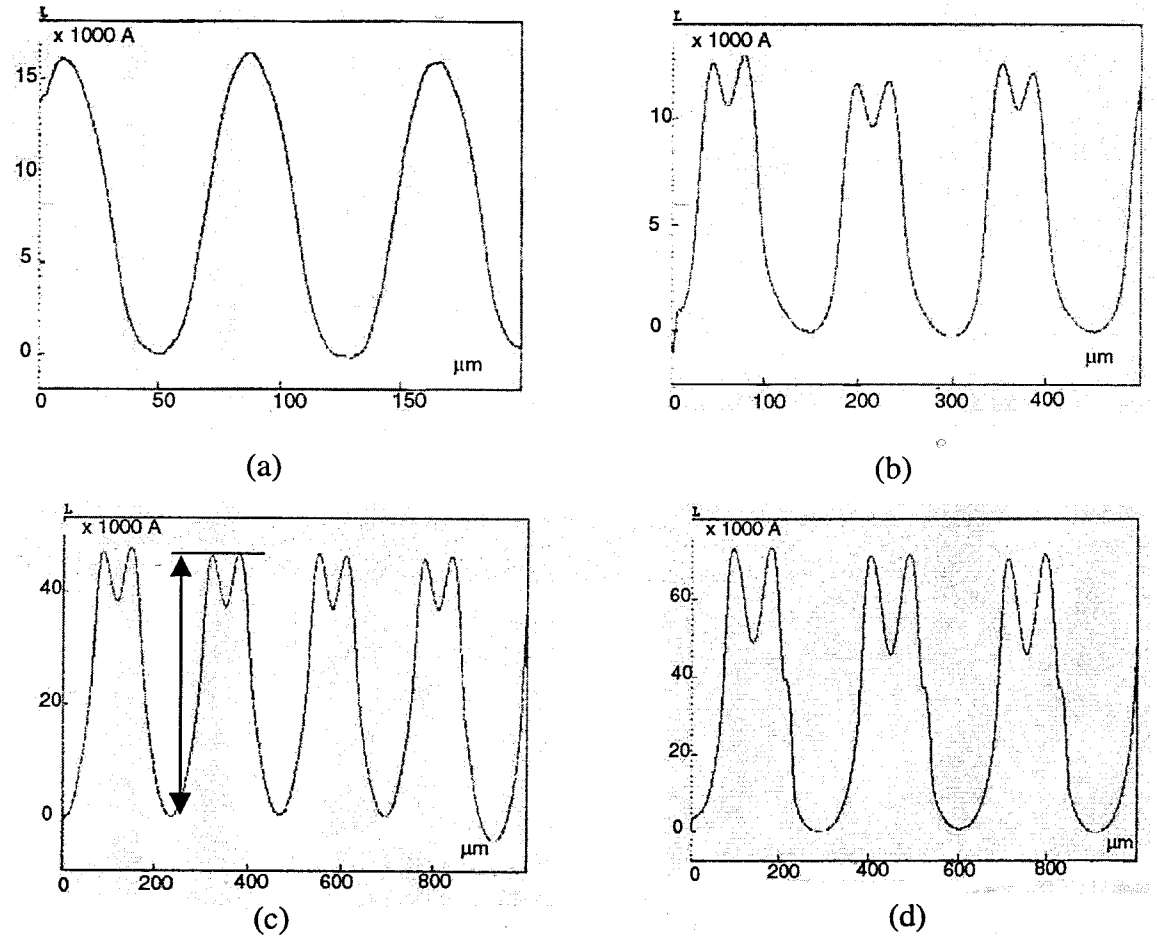


Fig. 4. Surface topography scan of polymer on top a metal line, with a thermally cured base with a width/spacing ratio of (a) 25 μm/50 μm, (b) 50 μm/100 μm (c) 75 μm/150 μm and (d) 100 μm/200 μm feature size (average height of metal line 2.5 μm).

B. Degree of Planarization (DOP) Characterization

DOP values for each set of cure condition were evaluated for a total of 16 different cases. These values correspond to measurements on 25 μm, 50 μm, 75 μm, and 100 μm wide features for both 1 : 1 and 1 : 2 width : spacing ratio. Measurements were also made on the set of structures near the center of the wafer (inside the puddle) and at the edge of the wafer (outside the puddle). The DOP value for each feature size is an average of at least six measurements and the standard deviation among each set of numbers is less than 8%.

The surface topography scans of the polymer over the metal lines for four different feature sizes (25, 50, 75, and 100 μm, 1 : 2 spacing) fabricated on top of a thermally cured polyimide base is shown in Fig. 4. Fig. 4(a) contains the surface profile of the polymer on top of a 25 μm wide line (of height 2.71 μm). As seen from the scan, the polymer planarizes the metal line, with a final relief height of 1.6 μm. As the width (and hence spacing) of the line increases to 50 μm and beyond, the surface profile of the polymer over the metal line becomes very uneven. For the 75 μm and 100 μm feature sizes (to some extent in 50 μm feature as well), a dip in the polymer surface directly above the metal line is observed as shown in Fig. 4(c) and (d). The magnitude of this dip increases as the width of the line increases. This trend is observed for all the 75 μm and 100 μm test structures when a thermally cured base is used (including 1 : 1, 1 : 2 features, inside and outside the puddle).

Fig. 5 contains surface topography scans of the polymer over the metal lines for four different feature sizes (25, 50, 75, and 100 μm, 1 : 2 spacing) fabricated on top of an e-beam cured polyimide base. The e-beam dose used in this case to cure the base layer of polyimide was 2000 μC/cm^2 (cure cycle 5, Table II). As seen from these surface profile scans, e-beam curing the base layer of polyimide dramatically improves the surface topography in multilayer structures. No uneven surface profile is observed in any of the features, including features inside and outside the puddle.

DOP values were calculated for all the five different cure conditions using (1). Fig. 6 contains the DOP results for five different cure conditions (conditions in Table II) for features outside the puddle with a 1 : 1 width : spacing ratio. From this figure, it is clear that DOP is a function of cure condition of the base layer. In a thermally cured sample, the DOP decreases dramatically as the feature size increases. The DOP value for a 25 μm feature is 44% and drops to -125% as the feature size increases to 100 μm. This is a change in the DOP value of 169% on the same wafer from small features to large features. As the e-beam dose in the base layer of polyimide is increased, the DOP values in general, improve considerably. At a dose of 500 μC/cm^2, the DOP value for the 75 and 100 μm features are still

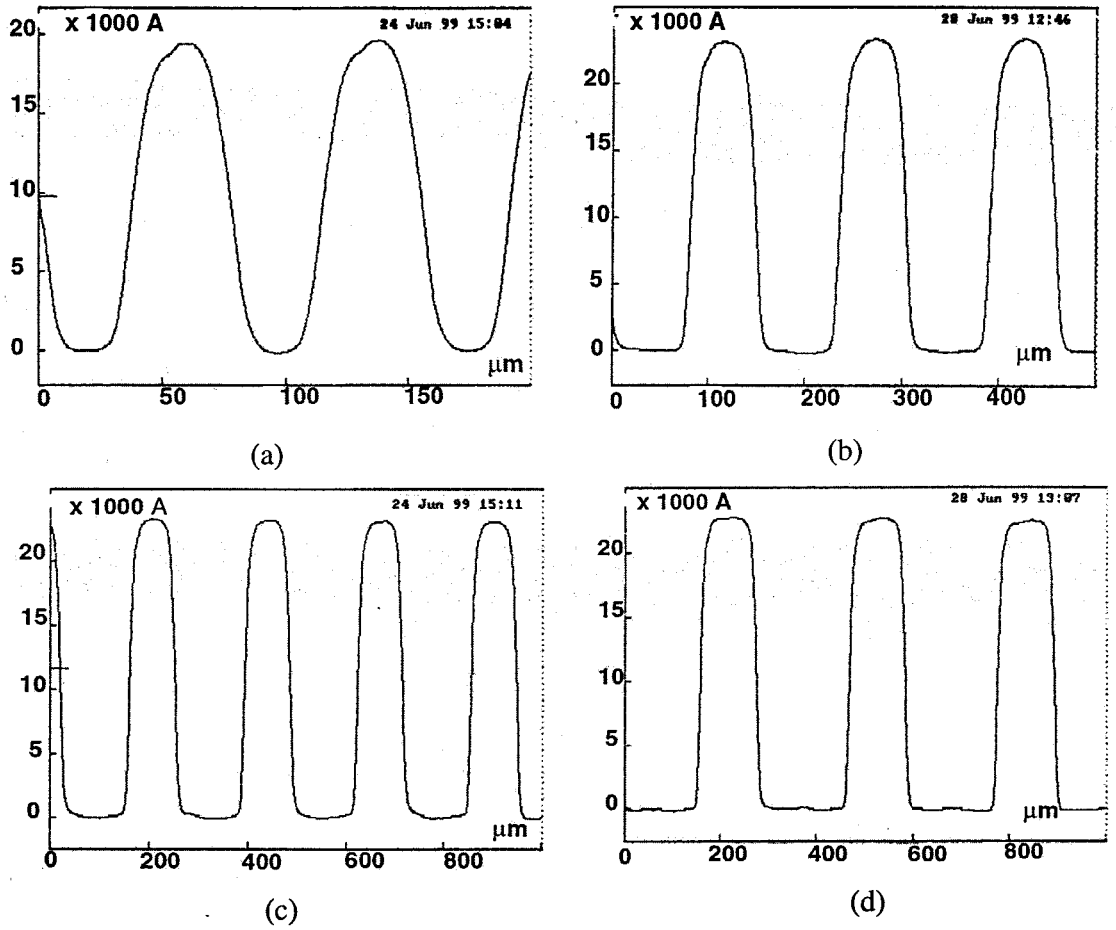


Fig. 5. Surface topography scan of polymer on top a metal line, with an e-beam cured base with a width/spacing ratio of (a) 25 μm/50 μm, (b) 50 μm/100 μm, (c) 75 μm/150 μm, and (d) 100 μm/200 μm feature size (average height of metal line 2.5 μm).

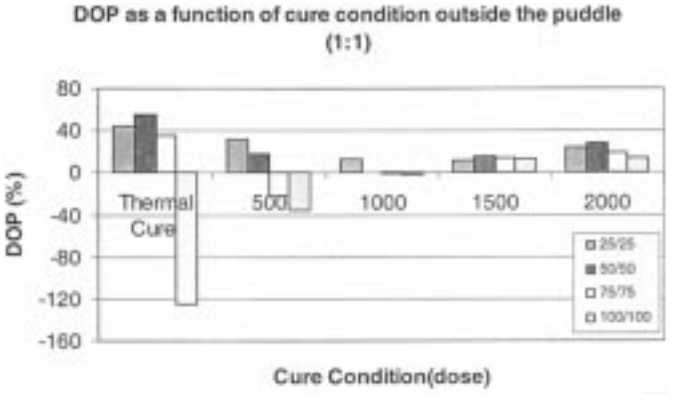


Fig. 6. Degree of planarization as a function of cure condition for features (1 : 1) outside the puddle (average height of metal line 2.5 μm).

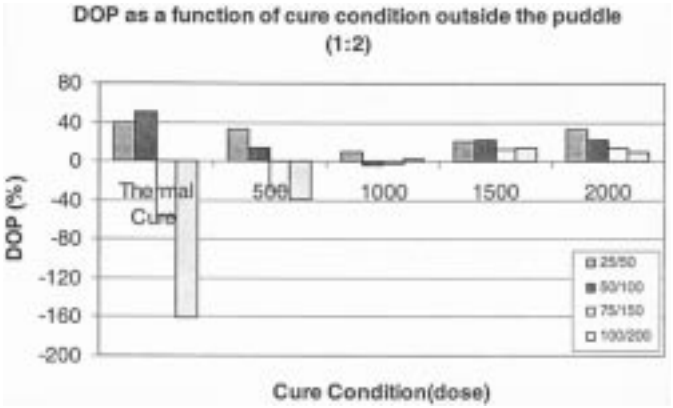


Fig. 7. Degree of planarization as a function of cure condition for features (1 : 2) outside the puddle (average height of metal line 2.5 μm).

negative, but the magnitude of the DOP value is relatively small. As the dose in the base layer of the polyimide is increased, the DOP value improves. At a dose of 1500 μC/cm^2, the DOP for all feature sizes is positive. As the dose is further is increased to 2000 μC/cm^2, the DOP value improves for all feature sizes.

Fig. 7 contains the DOP results for features inside the puddle but with a width : spacing ratio of 1 : 2. In this case, the spacing between lines is twice the width of the metal line. In the thermally cured sample, the increased available area between lines does not the change the planarization behavior in 25 μm and 50 μm features. However, for 75 and 100 μm lines a large drop in the DOP value is observed. The DOP value for the 75 μm feature changes from $+14\%$ (for 1 : 1 thermally cured base) to -51% (for 1 : 2 thermally cured base). A drop of 40% was observed in the 100 μm feature. As the dose used for curing the base layer of the polymer was increased, the DOP values improve for all feature sizes.

Figs. 8 and 9 show DOP values as a function of cure condition for features inside the puddle. The trend from these figures is

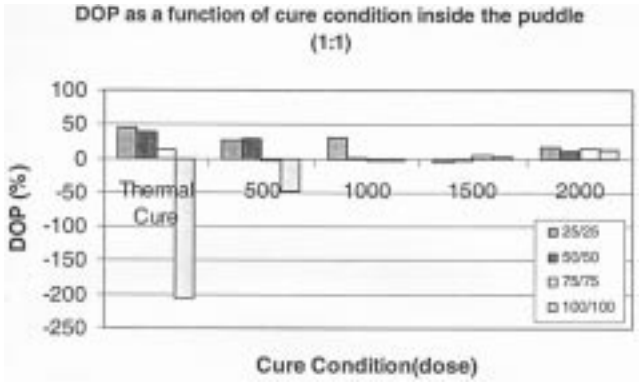


Fig. 8. Degree of planarization as a function of cure condition for features (1 : 1) inside the puddle (average height of metal line 2.5 μm).

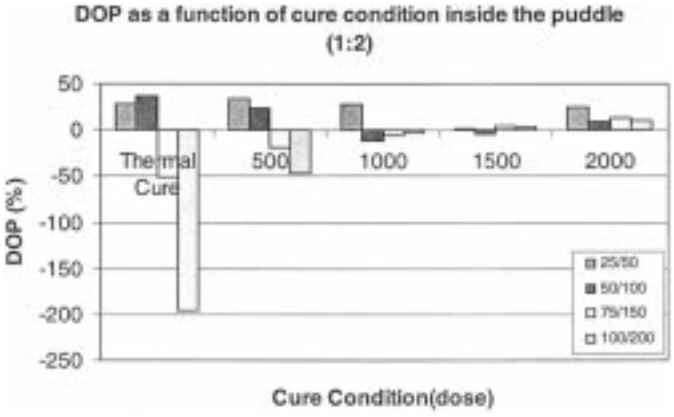


Fig. 9. Degree of planarization as a function of cure condition for features (1 : 2) inside the puddle (average height of metal line 2.5 μm).

TABLE III
DOP AS A FUNCTION OF CURE CONDITION FOR FEATURES INSIDE THE PUDDLE

Feature size/spacing	Thermal Cure	500 μC/cm^2	1000 μC/cm^2	1500 μC/cm^2	2000 μC/cm^2
25/25	44	26	31	-4	16
50/50	39	29	0	-3	10
75/75	14	-2	-2	5	15
100/100	-206	-47	-4	2	13
25/50	29	34	28	2	25
50/100	36	24	-12	-4	9
75/150	-51	-19	-5	5	13
100/200	-196	-46	-2	3	11

TABLE IV
DOP AS A FUNCTION OF CURE CONDITIONS FOR FEATURES OUTSIDE THE PUDDLE

Feature size/spacing	Thermal Cure	500 μC/cm^2	1000 μC/cm^2	1500 μC/cm^2	2000 μC/cm^2
25/25	44	31	13	12	24
50/50	55	17	0	15	28
75/75	35	-22	-1	14	19
100/100	-125	-35	-2	12	14
25/50	39	32	9	21	33
50/100	51	14	-4	22	22
75/150	-56	-30	-3	13	13
100/200	-161	-39	3	14	10

similar to the trend observed in Figs. 6 and 7; however, the DOP values for features outside the puddle are in general better than the DOP values for features inside the puddle. A summary of all the results from Figs. 6–9 is presented in Tables III and IV.

IV. DISCUSSION

Multilayer spin speed thickness measurements in Fig. 3 show that the second layer spin speed curve for the polyimide is a strong function of the cure state of the underlying polyimide. As shown in Table II, the thermally cured samples cured according cycles A and B, received a photo-exposure dose of 2000 mJ/cm^2. The recommended dose for curing Ultradel 7501 is 600 mJ/cm^2 [6]. The excess dose for Ultradel 7501 is known to improve the multilayering behavior of this polymer system [6]. However, even at this high level of photo-exposure of the underlying polyimide, the spin speed curve for the second layer of the polyimide is significantly different from the reference curve. The thickness of the second layer of the polyimide is greater than the thickness predicted from the reference curve. This is primarily because thermally cured films have an affinity for solvent due to insufficient crosslinking of the polyimide matrix. This results in a redistribution of solvent from the dispensed polyimide solution to the cured polyimide base that occurs during the spin coating process. Because the time for the solvent diffusion and redistribution to occur is relatively fast, it is difficult, if not impossible, to minimize these effects by simply altering process times. Therefore the viscosity of the second layer of the dispensed polyimide solution is higher and hence resulting in a thicker second layer coat. It can be seen from Fig. 3 that the results between wafers cured with cycle A (max temperature 250 °C) and those cured with cycle B (max temperature 350 °C) are significantly different. Although these wafers have nearly identical first layer thickness ($t = 5.27$ μm for cycle A, $t = 5.28$ μm for cycle B) the slight increase in solvent loss due to the higher cure temperature translates into an appreciable change in spin coating behavior. In contrast, the e-beam cured wafers exhibit remarkably similar spin-speed curves, despite change in dose and back heating temperatures (cycles C through E).

Solvent diffusion and swelling between layers can be effectively characterized using the DOP measurements. Since our DOP test structures involve interaction between three heterogeneous surfaces namely, uncured solvent-rich-polymer, cured polymer, and electroplated copper, any solvent-based interactions are likely to be amplified. In the absence of heterogeneous interfaces, especially the electroplated copper, the solvent diffusion process would be uniform and can lead to uniform swelling of the first layer. This behavior was observed in the multilayer spin speed curve characterization experiments. However, in order to quantify the effect of solvent swelling it

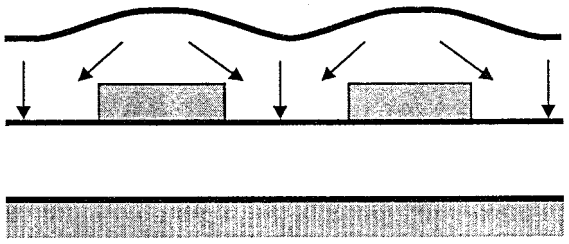


Fig. 10. Solvent redistribution from second layer of polymer leading to solvent swelling effects.

TABLE V
AREA UNDER SURFACE PROFILE SCANS FOR MULTILAYER STRUCTURES (1 : 2 WIDTH/SPACING, OUTSIDE THE PUDDLE)

Feature Height(μm)	Feature Width(μm)	Area (μm^2)	Area/ Width
2.71	25	49.87	1.995
2.64	50	160.5	3.21
2.55	75	358.25	4.77
2.58	100	600.11	6.01

is necessary to investigate the planarization in multilayer structures. Further, the interconnect line widths and polyimide thickness chosen in the DOP study conform to the design criteria commonly employed in the fabrication of multilayer packages. Thus, any effect of solvent induced swelling is a true representation of problems encountered in the fabrication of multilayer structures.

The uneven surface profile scans observed in Fig. 4 for the sample with the thermally cured base can be attributed to solvent redistribution and swelling effects in the multilayer structure. After spin coating and prior to cure, the second layer of the polymer is solvent rich compared to the cured base layer. Solvent from the second layer can thus diffuse into the cured base layer, leading to solvent redistribution in the multilayer structure. Due to presence of the copper lines in certain regions on the base cured layer, this diffusion process is not uniform over the entire area at the interface between the second layer and the cured base layer. Further, the affinity of the solvent (and the polymer solution) toward the heterogeneous surfaces like electroplated copper and the cured polymer layer, can be widely different. As a result, a preferential redistribution of the solvent from the second layer to the base layer of the polymer is set up. This can lead to local variations in the viscosity of the polymer, as certain regions of the solvent rich polymer layer are more likely to lose solvent rapidly than other regions. Also, associated with the solvent absorption is the swelling of the base layer the polymer adjacent to the metal lines. The swelling is amplified in wider feature sizes due to greater available area for solvent redistribution. A schematic diagram showing possible solvent redistribution in the multilayer structure is shown in Fig. 10. In multilayer structures with a thermally cured base, the area under the surface profile scan of the polymer layer, on top of a metal line was estimated. These values are presented in Table V for four different features. The scans chosen correspond to the features outside the puddle, with 1 : 2 width spacing ratio. As seen

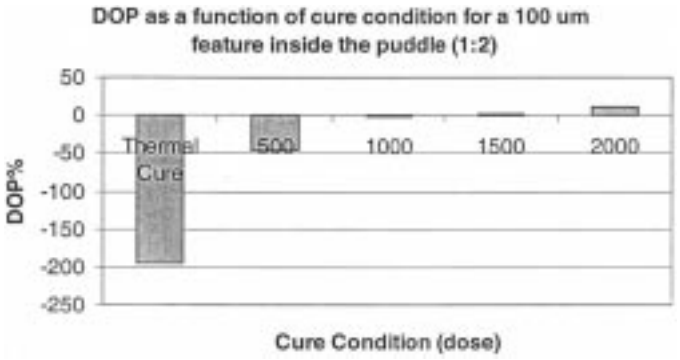


Fig. 11. DOP as a function of cure condition for a 100 μm feature inside the puddle with 200 μm spacing between lines.

from the table, the area under the surface profile scan per unit width, for a 25 μm feature is 1.995 μm. As the feature size increases to 100 μm, this value increase to 6 μm. Since the area under the surface profile scan can be directly correlated to the mass of polymer on top of the metal line, it can be concluded that more polymer is accumulated per unit width on wider lines than on narrower lines. This shows that a net redistribution of polymer occurs as a result of the solvent interaction between the multiple polymer layers. The solvent redistribution effect is also seen in the negative planarization values. However when the base layer of the polyimide is e-beam cured the surface profile of the polymer on top of the metal lines becomes remarkably uniform as shown in Fig. 5, indicating that the interaction between multiple layers is greatly minimized. This minimized interaction is also visible in the improved DOP values with the e-beam cured samples. This is illustrated in the planarization values for a 100 μm feature with 1 : 2 spacing, inside the puddle, shown in Fig. 11.

It is to be noted that the DOP values for the 25 μm and 50 μm features are positive in the thermally cured case indicating that the solvent swelling is not a significant factor at these feature sizes. Further, the DOP values for some of the e-beam cured samples at these feature sizes are negative. It is to be noted that apart from the solvent swelling effects, planarization is significantly affected by polymer solution properties like molecular weight of the polymer, the solution viscosity, surface tension of the polymer solution on heterogeneous surfaces such as electroplated metal and cured polymer. These factors seem to have a major influence over the planarization behavior in 25 and 50 μm features, until the underlying base layer of the polymer is turned completely inert, which occurs at 2000 $\mu C/cm^2$. As the e-beam dose in the base layer is increased to 2000 $\mu C/cm^2$, the DOP improves and reaches a value close to 15%. At the highest dose investigated in this study (2000 $\mu C/cm^2$), the DOP value for any feature size, spacing and location is positive indicating that the solvent interaction between layers is minimized. A comparison of DOP values inside and outside the puddle for thermally cured and e-beam cured samples is presented in Fig. 12. As seen from the figure, the variation in DOP based on the location of the structure on the wafer can be minimized to a great extent with e-beam cure. This result is significant as it provides a means to achieve acceptable planarization values, independent of the method of deposition of the second polyimide layer and

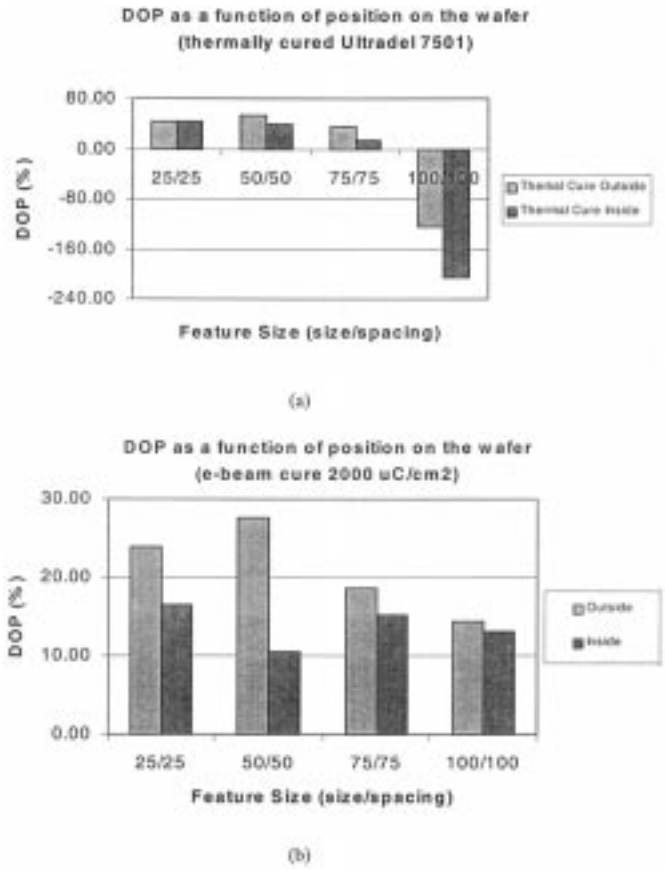


Fig. 12. Degree of planarization as a function of feature location on the wafer (a) thermally cured base (b) e-beam cured base cured with a dose of 2000 μC/cm^2.

the time of exposure of underlying polyimide layer to solvent. This improvement in planarization can be attributed to reduced solvent swelling of the polyimide base layer. Crosslinking of the polyimide matrix as a result of e-beam exposure [12] significantly reduces the amount of solvent interaction between layers, minimizing the swelling in the base polymer film. A complete investigation of other properties (including dielectric, mechanical and chemical) is in progress and preliminary results indicate that [12] properties comparable to thermal cure are achievable through e-beam cure.

V. Conclusions

Multilayer processing of Ultradel 7501, a photosensitive preimidized polyimide was investigated in this study. Thermally cured Ultradel 7501 films were found to suffer from insufficient solvent resistance even after cure. Solvent from the second layer of the polyimide diffuses into the cured layer, swells the polyimide film, and leads to uneven surface topography in multilayer test structures. In this study, a novel technique involving electron beam curing was investigated. E-beam cure of Ultradel 7501 was found to decrease the interaction between the solvent and cured layer of the polyimide film. This reduced interaction (and hence the solvent induced swelling in the film) leads to improved multilayering and planarization for all feature sizes and across all locations on the wafer. Improvements in coating behavior were also demonstrated as a result of e-beam cure. The application of electron beam curing to other polyimide as well as other polymer chemistries is an interesting extension of this work and has been looked in more detail [12].

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