Multilayer Planarization of Polymer Dielectrics

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Abstract—Polymers are widely used in the microelectronics industry as thin-film interlevel dielectrics layers between metal lines, as passivation layers on semiconductor devices and in various packaging applications. As multiple layers of polymer and patterned metal are constructed, the ability of these polymers to planarize topographical features becomes increasingly important. In this study, the degree of planarization (DOP) for five commercially available polymers has been examined for three different structural configurations with the intent of simulating practical applications. Specifically, this study investigates single layer planarization, multiple coat planarization, and planarization of metal lines patterned on a polymer base. This study also examines the effects of orientation of the metal structure to polymer flow during spin casting and location on the wafer. The polymers were selected to investigate different polymer chemistries frequently used in the microelectronics industry. The underlying structures were fabricated using standard photolithography and electroplating techniques. Feature dimensions include 25–200 μm line spacings and widths with the polymer overcoat thickness being twice the height of the underlying structures.

Index Terms—BCB, DOP, epoxy, multilayering, planarization, polyimide, polymer dielectrics, solvent induced swelling.

I. INTRODUCTION

IN order to meet the demand for smaller and faster devices in the semiconductor industry, multilevel interconnection schemes are being considered as an alternative to traditional packaging techniques [1]. This includes interconnection structures with several layers of metals lines and dielectric materials deposited in alternating layers. As the number of layers increases, planarization of underlying topography is of increasing importance. The photolithographic resolution and quality of the subsequent layers is strongly dependent on surface planarity. As patterned feature sizes continue to decrease, the level of planarization becomes increasingly critical and more difficult to achieve.

When dielectric films are initially spin cast on a substrate, they partially planarize the underlying topography. Contraction of the polymer due to solvent removal and cure acts to decrease the planarizing ability of a polymer, resulting in a lower final degree of planarization (DOP) [1]. Many variable factors including molecular weight, backbone rigidity, cure mechanisms, solvent volatility, solution viscosity, solids content, feature dimensions, processing and cure conditions affect the final topography

of each layer. The DOP is therefore determined by both the polymer-solution properties and by the dynamics of processing.

In order to compare planarizability, it is necessary that each of the materials be evaluated under similar conditions. There have been numerous planarization studies that involve a limited number of materials under specific conditions [2], [3]. However, few of these studies have compared a broad range of materials under identical conditions. There are numerous techniques to artificially planarize nonplanar surfaces [4]. Chemical mechanical polishing (CMP), for example, is commonly used to solve planarization problems by polishing back non level surfaces. There is, however, a lack of published literature on inherent planarization of multilevel structures without artificial leveling. In this work, five polymer dielectrics have been evaluated for planarizing ability in single and multilayer structures with a variety of line spacings and widths.

The polymers in this study were selected to directly compare the structural differences inherent in each system. The three polyimides were selected to have either rigid rod (PI 2611), photosensitive (PI 2734), or pre-imidized photocrosslinkable (Ultradel 7501) backbone nature. Two low molecular weight thermoset polymers were selected to compare filled (LMB 7081) to nonfilled (DVS-BCB 3022-57) systems.

II. MATERIALS

Three different kinds of polyimides are included in this study, specifically PI 2611 (HD Microsystems), PI 2734 (HD Microsystems) and Ultradel 7501 (Amoco). Two different thermosets have been studied, specifically DVS-BCB 3022-57 (Dow Chemicals) and LMB 7081 (Ciba-Geigy).

PI 2611 is a polyamic acid based rigid rod polymer, whereas PI 2734 is a negative tone photosensitive polyamic ester based polymer. In both of these polymers, the imide ring is formed upon exposure to high temperature completing the "cure" reaction [5]. Ultradel 7501 is a pre-imidized, negative tone, photosensitive polyimide where the UV exposure combined with high temperature treatment leads to cross-linking in the film [6]. DVS-BCB 3022-57 is a partially polymerized, thermosetting resin dissolved in solvent. During its cure cycle, the benzocyclobutene ring opens and reacts, resulting in an increase in the molecular weight and a highly crosslinked network [7]. LMB 7081 is a negative tone photosensitive epoxy system in which UV exposure followed by heating similarly results in an increase of molecular weight and a highly crosslinked film [8].

III. FABRICATION PROCEDURE

Thermally oxidized silicon wafers (oxide thickness ca. 2000 Å) with a sputtered seed layer of Ti/Cu/Ti (thickness 100

TABLE I
STANDARD CURE CONDITIONS FOR POLYMER DIELECTRICS

| Polymer	Adhesion Promoter	Soft Bake	Exposure	Post Exposure Bake	Cure
PI 2611	Yes	30 min @ 120°C (oven)	--	--	3°C/min to 350°C, hold @ 350°C for 1 hr (N$_2$ purged furnace)
PI 2734	Yes	3 min @ 60°C (hotplate), 3 min @ 95°C (hotplate)	200 mJ/cm^2 @365nm	30 min @120°C (oven)	4°C/min to 200°C, hold @ 200°C for 30 min (in air), 3°C/min to 350°C, hold @ 350°C for 1 hr (N$_2$ purged furnace)
Ultradel 7501	Yes	3 min @ 100°C (hotplate)	600 mJ/cm^2 @365nm	30 min @ 175°C (N$_2$ purged oven)	10°C/min to 200°C, hold @ 200°C for 1 hr, 10°C/min to 350°C, hold @ 350°C for 30 min (N$_2$ purged furnace)
BCB 3022-57	Yes	30 min @ 120°C (oven)	--	--	10°C/min to 250°C, hold @ 250°C for 1 hr (N$_2$ purged furnace)
LBM 7081	No	15 min @ 75°C (hotplate)	2000 mJ/cm^2 @365nm	30 min @ 110°C (oven)	5°C/min to 165°C, hold @ 165°C for 1 hr (N$_2$ purged furnace)
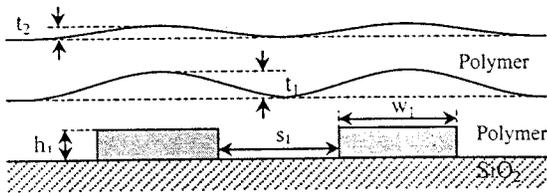
Fig. 1.   DOP on a feature with two layers of polymer on top (DOP1, DOP2).

Fig. 2.   DOP on a feature with a metal layer built on polymer base (MP).

Å/1000 Å/100 Å) were used as the base to build the requisite structures. Using photolithographic techniques, each sample was patterned with metal lines having different line widths and spacings. After patterning, the exposed areas were electroplated with copper to approximately 2 μm in height. An acidic copper electroplating bath comprising of 200 g/L of $CuSO_4 \cdot 5H_2O$ in 1 M H_2SO_4, a copper foil anode, and a current density of 20 mA/cm^2 was used in the experiments. The structures on each sample wafer were then fully characterized by using an Alphastep profilometer to measure the height (h_1), width (w_1), and spacing (s_1) of lines as shown in Fig. 1. A film of polymer was spun on to each wafer and thermally cured according to the manufacturers recommended conditions (Table I). After cure, the planarization achieved with the each of the polymers was evaluated by measuring the relief height (t_1) over the previously characterized underlying structures. The DOP is evaluated using (1) [9]

$$DOP\% = \left(1 - \frac{t_1}{h_1}\right) * 100. \qquad (1)$$

After completing the measurements on the first layer of polymer, copper structures were fabricated on top of the polymer on an adjacent area of the wafer using the same mask pattern. This process involved sputtering a seed layer of Ti/Cu/Ti (thickness 100 Å/1000 Å/100 Å), patterning and electroplating the copper structures. After patterning, an etch-back step was used to remove the Ti/Cu/Ti seed layer, leaving only
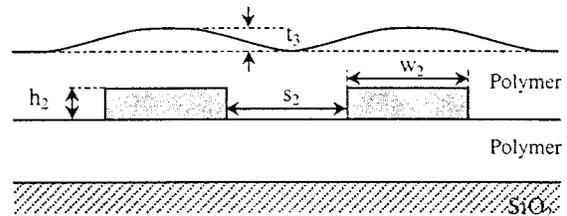
the metal lines. The structures were again characterized by measuring the height (h_2), width (w_2), and spacing (s_2) of the lines (Fig. 2). A second coat of polymer was then spun on to each of the samples and cured using the manufacturer's standard thermal cure schedule. The relief heights over both sets of structures, (t_2) and (t_3), were measured in order to calculate the degree of planarization for the multilayer structure (MP). The DOP for each sample (i.e., DOP1 corresponding to planarization over the first layer, DOP2, corresponding to planarization due to addition of second polymer layer and MP, corresponding to the planarization of metal lines built on a polymer base) were calculated. The latter structure (MP) is representative of an actual application for multilayer interconnects.

The degree of planarization for each configuration (DOP1, DOP2, MP) was studied as a function of feature size, line spacing, the location on the wafer, and orientation to flow. This procedure was repeated for each polymer system on three independent wafers. These parameters are defined in Table II. A schematic of the test structure and wafer layout is shown in Fig. 3.

IV. RESULTS

The degree of planarization has been determined for each of the five polymer systems. The DOP is evaluated for four different feature sizes (25, 50, 75 and 100 μm) varying the width to spacing ratio, location on the wafer, and orientation to polymer

TABLE II
STUDY PARAMETERS FOR DOP1, DOP2, MP

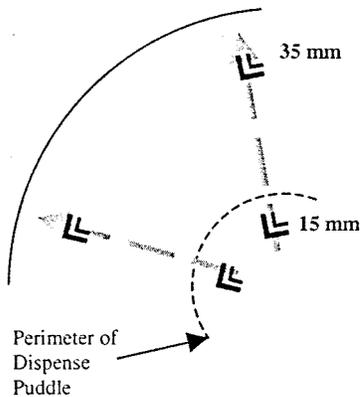| Variables	
Feature Size	25, 50, 75, 100 μm
Spacing	1:1 and 1:2
	line width:line spacing
Location on Wafer	15 and 35 mm from center
Polymer Flow Direction	Parallel and Perpendicular Flow

Fig. 3.   Location and polymer flow parameters.

flow as described earlier in Table II and Fig. 3. In each case, the DOP value calculated is the statistical average of six data points measured over three independent wafers fabricated in series. The standard deviation is also calculated for each value. Three different degree of planarization values are determined: (1) after one layer of polymer is applied (DOP1), (2) after application of a second coat (DOP2), and (3) planarization of metal lines on a cured polymer base (MP).

Table III displays the data for single layer planarization (DOP1). It can be clearly seen that polyimides (PI 2611, PI2734, and Ultradel 7501), in general, planarize features to a lesser extent ($< 40\%$) than the oligomeric epoxy (LMB 7081) and benzocyclobutenes (DVS-BCB 3022-57). Another striking result is that for PI 2611 and Ultradel 7501, the DOP calculated is sometimes negative. These issues are explored later in this paper.

Table IV lists the data for second layer planarization (DOP2). There is an appreciable increase in DOP for all dielectric systems due to the application of a second planarizing coat. No negative values of DOP are observed.

Finally, the results for planarization of metal lines over a cured polymer base (MP) are given in Table V. The DOP measured in this configuration for PI 2734, DVS-BCB 3022-57, and LMB 7081 are statistically similar to their respective values for single layer planarization. The results for PI 2611, on the other hand, resemble the results observed for second layer planarization (DOP2). Ultradel 7501 is excluded from this table as it exhibited unique surface profiles that precluded usual degree of planarization calculation. Fig. 4 shows an example of the surface profiles observed. These issues are discussed in greater detail later.

V. DISCUSSION

A. Single Layer Planarization (DOP1)

The degree of planarization is measured for a single polymer layer over a metal line patterned over a metal base (DOP1). This configuration is shown in Fig. 1. This is the most common procedure for determining the DOP. In general, manufacturers extrapolate the results from a single layer structure to predict the planarizing performance of the dielectric in a multilayer structure.

Each polymer exhibited a wide range of planarization values depending on the specific configuration of underlying structures. In order to compare materials with different chemistries, it is therefore important to compare the property of interest over identical features. The DOP value presented then is specific to a particular line spacing, location on a wafer, and orientation to polymer flow. The results for a 1:1 line spacing, 15 mm from the center of the wafer, parallel to the flow of polymer are shown in Fig. 5. This cross-section of data shall be used as a representative set by which to compare the five polymers studied. Table VI lists the maximum and minimum values of DOP measured over all features.

The most striking result is that for PI 2611 and Ultradel 7501, negative DOP values are observed. One must be cautious when considering either zero or negative DOPs because it is often confused with conformal coating. A negative DOP indicates that the relief height is undesirably greater than the underlying feature and does not give any additional information of the profile of the feature. For this study, single coat samples for all polymers possessed smooth nonconformal coatings.

Polymers, in general, are selected for various packaging applications because of their planarizing ability. The solution dynamics are such that a polymer, on application, will flow in between metal lines and hide underlying feature proportions. A negative DOP indicates that this process does not occur as expected.

After a polymer is spin coated over structures, the fluid nature of the coating allows the spaces between metal lines to be filled by flowing from the top of metal lines in to the spaces in between. The polymer will flow further when the film is heated for solvent removal. The film shrinks as the solvent evaporates. At this point in the process, the film has an initial degree of planarization. During the subsequent cure progress, the film undergoes a chemical change specific to each system that may result in evolution of volatile products. Film shrinkage manifests itself directly as a change in thickness as the lateral dimensions are fixed on the wafer. Polyimides (specifically nonpreimidized polyimides) shrink as much as 50% upon solvent loss and cure [5]. Shrinkage acts to exaggerate nonplanar features and lower the planarizing ability [10]. Neglecting polymer flow before imidization during cure, a polyimide that shrinks by 50% on cure can, at best, have a DOP of 50%. Both PI 2611 and PI 2734 are therefore limited by this constraint.

The poor planarization observed for PI 2611 (-12% to 7%) can be partially attributed to the rigid rod nature of the backbone. This polymer is engineered with a biphenyl ring directly in the polyimide backbone [5]. The direct bond between these two phenyl rings provides additional rigidity and drives the polymer chains to lie parallel to the wafer. Although, this feature desirably produces a low residual stress wafer, the backbone rigidity also inhibits flow over metal lines. Assuming a shrinkage of

TABLE III
SINGLE LAYER PLANARIZATION (DOP1) RESULTS

Location	Polymer Flow	Spacing	Feature Size	PI2611 DOP	PI2611 s.d.	PI2734 DOP	PI2734 s.d.	Ultradel 7501 DOP	Ultradel 7501 s.d.	DVS-BCB 3022-57 DOP	DVS-BCB 3022-57 s.d.	LMB 7081 DOP	LMB 7081 s.d.
15 mm	Parallel	1:1	25	-3.49	2.65	37.00	3.07	7.78	2.87	84.33	0.64	84.33	0.64
			50	-3.27	4.21	37.68	1.90	3.27	1.52	85.37	1.09	85.37	1.09
			75	2.04	1.96	37.36	1.92	27.30	1.26	89.33	1.35	89.33	1.35
			100	-8.33	3.61	33.97	2.27	13.81	1.09	89.34	2.04	89.34	2.04
		1:2	25	-2.40	2.14	38.29	2.81	5.27	2.14	75.33	1.49	68.59	6.62
			50	-3.10	3.14	38.51	1.87	0.21	1.76	73.15	0.81	71.46	2.77
			75	-11.60	3.72	40.20	1.57	18.52	3.75	89.44	0.91	89.03	3.18
			100	-6.58	2.84	40.59	2.01	10.23	1.97	89.72	0.97	84.92	8.54
	Perpendicular	1:1	25	-3.73	3.27	39.94	3.77	6.91	2.00	86.21	1.74	80.46	4.35
			50	-2.54	2.32	36.04	2.55	3.05	1.96	82.47	0.93	71.27	7.80
			75	3.25	1.65	40.61	1.24	21.15	0.84	89.03	1.25	92.00	6.51
			100	-7.37	2.74	37.44	2.28	12.09	1.47	88.50	1.17	87.11	3.63
		1:2	25	-6.80	1.55	42.60	2.02	1.35	0.65	80.37	1.84	73.15	5.33
			50	-0.43	2.02	38.31	2.34	1.43	2.88	71.35	1.58	62.77	8.62
			75	-6.20	2.45	41.78	1.35	20.64	1.78	87.30	0.40	88.52	4.10
			100	-5.07	3.56	36.31	2.08	7.19	1.19	86.56	2.19	84.60	4.49
35 mm	Parallel	1:1	25	3.75	2.07	38.64	3.39	2.65	2.26	88.07	2.49	75.91	1.86
			50	-5.62	1.53	37.38	1.92	-3.17	1.70	84.55	1.34	80.02	5.70
			75	6.85	2.28	38.08	2.46	24.25	1.54	88.48	2.42	88.07	6.79
			100	-6.40	1.53	39.02	1.28	5.24	2.86	87.69	3.36	87.71	6.53
		1:2	25	4.08	2.52	41.73	0.89	-2.33	2.18	84.65	3.01	66.80	4.17
			50	-4.09	2.62	36.31	1.93	-6.37	1.75	77.33	2.87	72.50	7.09
			75	-5.16	1.76	40.25	1.39	12.33	3.55	89.60	0.93	86.19	7.49
			100	-3.71	1.44	38.37	1.24	4.28	1.49	87.59	2.49	84.47	6.77
	Perpendicular	1:1	25	0.81	1.49	40.60	1.84	1.09	2.67	88.68	2.14	83.63	4.25
			50	-3.50	1.79	34.31	3.25	-3.94	2.08	81.21	2.77	73.36	4.97
			75	4.37	1.93	42.63	1.65	28.85	1.76	90.12	1.52	92.20	2.66
			100	-7.53	2.13	36.08	1.24	8.07	1.55	86.12	3.19	85.66	3.62
		1:2	25	-0.35	4.72	43.17	1.00	-4.19	1.36	82.73	3.40	77.74	6.62
			50	-2.20	2.38	35.89	1.80	-8.62	1.59	69.65	5.92	69.81	7.12
			75	-0.54	3.16	43.47	1.56	16.01	1.90	91.85	0.52	89.43	4.36
			100	-5.02	2.26	37.31	1.75	1.73	1.87	84.23	6.38	81.86	4.81

	PI2611 DOP	PI2734 DOP	Ultradel 7501 DOP	DVS-BCB 3022-57 DOP	LMB 7081 DOP
Maximum	6.85	43.47	28.85	91.85	92.20
Minimum	-11.60	34.31	-8.62	69.65	62.77
Average	-2.81	38.93	7.38	84.85	81.18

TABLE IV
SECOND LAYER PLANARIZATION (DOP2)

Location	Polymer Flow	Spacing	Feature Size	PI2611 DOP	PI2611 s.d.	PI2734 DOP	PI2734 s.d.	Ultradel 7501 DOP	Ultradel 7501 s.d.	DVS-BCB 3022-57 DOP	DVS-BCB 3022-57 s.d.	LMB 7081 DOP	LMB 7081 s.d.
15 mm	Parallel	1:1	25	8.69	3.49	61.93	3.85	7.87	1.47	97.65	1.74	79.35	3.12
			50	9.92	2.68	61.79	4.53	8.51	1.54	97.79	0.93	76.38	3.35
			75	38.64	4.76	63.26	3.20	68.72	0.67	94.98	0.69	84.42	5.18
			100	8.23	2.18	62.81	2.90	26.09	1.13	95.83	2.46	82.44	4.53
		1:2	25	10.69	2.71	65.92	3.33	15.03	1.34	97.69	1.20	80.87	4.11
			50	11.92	2.48	61.98	1.74	10.04	1.13	97.25	1.09	66.68	8.27
			75	12.40	4.76	64.35	1.88	47.49	1.15	95.98	0.49	67.32	8.53
			100	6.70	2.28	64.81	1.16	20.15	0.86	98.80	0.81	64.00	6.87
	Perpendicular	1:1	25	8.77	2.65	63.01	4.30	9.17	1.17	96.97	2.44	92.81	3.45
			50	11.54	1.64	61.41	1.62	9.25	1.72	96.76	1.37	90.38	2.47
			75	41.15	1.64	66.95	2.46	64.83	0.56	97.10	0.61	88.99	3.80
			100	8.18	1.97	62.48	2.42	25.47	1.04	95.68	1.69	81.51	2.56
		1:2	25	12.77	1.17	65.06	1.59	14.28	1.67	97.34	0.99	92.01	4.14
			50	13.16	1.68	60.37	1.83	11.07	1.43	94.00	1.34	85.11	3.44
			75	13.11	1.90	67.27	1.37	47.76	1.29	97.33	0.43	83.18	3.21
			100	5.22	1.47	63.35	1.10	20.93	0.92	95.89	1.07	79.21	5.24
35 mm	Parallel	1:1	25	2.33	4.23	62.38	2.47	3.96	0.96	97.16	1.77	93.41	2.37
			50	10.61	1.07	61.68	1.16	2.38	1.32	96.71	1.98	90.58	2.51
			75	45.43	4.22	66.24	2.97	67.87	0.58	96.05	0.63	85.65	2.13
			100	12.20	2.23	63.59	1.43	24.51	2.56	86.84	1.71	84.11	4.15
		1:2	25	14.76	4.76	64.16	2.12	3.53	2.40	97.30	0.99	91.63	2.05
			50	12.70	2.14	60.56	2.57	5.23	1.26	97.01	1.06	86.88	5.24
			75	23.95	3.36	65.87	1.60	44.09	0.74	97.66	0.44	83.95	3.21
			100	12.39	2.07	64.68	1.01	16.28	1.10	97.95	0.93	82.43	5.30
	Perpendicular	1:1	25	4.78	2.80	63.70	2.49	4.40	1.30	97.71	1.61	93.83	2.27
			50	12.70	2.09	60.45	1.73	5.73	1.13	97.59	1.22	88.24	5.48
			75	49.39	2.13	68.56	2.63	68.22	1.18	96.44	0.75	87.94	3.41
			100	11.04	1.25	61.10	2.38	22.92	1.72	96.56	2.19	82.12	2.64
		1:2	25	14.81	4.26	64.97	1.62	2.60	1.50	97.19	1.08	90.27	3.61
			50	13.01	1.91	59.61	1.99	6.32	1.03	94.85	1.60	84.15	4.18
			75	24.60	4.76	67.60	2.00	43.68	1.76	97.59	0.41	87.10	5.76
			100	10.62	1.95	62.88	1.47	16.10	0.93	96.19	1.22	78.16	4.35

	PI2611 DOP	PI2734 DOP	Ultradel 7501 DOP	DVS-BCB 3022-57 DOP	LMB 7081 DOP
Maximum	49.39	68.56	68.72	98.80	93.83
Minimum	2.33	59.61	2.38	86.84	64.00
Average	15.51	63.59	23.26	96.49	83.91

~50%, the polymer after solvent removal is estimated to have a initial DOP near zero (−25% to 14%). This low (sometimes negative) value is consistent with polymer chains that are unlikely to flow from the top of metal lines. Shrinkage on cure also plays a major role in PI 2611 low final DOP.

PI 2734 has a similar backbone structure to that of PI 2611, however, two key structural differences give PI 2734 an inherently more flexible backbone compared to PI 2611: the absence of the biphenyl ring and the presence of functional groups for crosslinks. PI 2734 has a very consistent planarizing ability with DOP values from 34% to 44%. Assuming PI 2734 shrinks 50% on cure, the shrinkage model discussed above predicts the initial DOP before cure is near 80%. The high DOP estimated for the polymer film before cure suggests that although the film is

TABLE V
PLANARIZATION RESULTS OF METAL LINES ON A CURED POLYMER BASE (MP)

Location	Polymer Flow	Spacing	Feature Size	PI2611 DOP	PI2611 s.d.	PI2734 DOP	PI2734 s.d.	Ultradel 7501 DOP	Ultradel 7501 s.d.	DVS-BCB 3022-57 DOP	DVS-BCB 3022-57 s.d.	LMB 7081 DOP	LMB 7081 s.d.
15 mm	Parallel	1:1	25	5.61	3.35	42.97	2.02	N/A See Solvent Effects		85.93	1.23	84.80	2.65
			50	7.06	4.34	43.24	1.87			85.68	7.69	81.24	3.00
			75	31.50	5.49	39.38	2.25			89.82	1.00	87.37	1.98
			100	8.07	2.73	42.31	1.90			88.35	5.55	86.28	2.93
		1:2	25	10.31	1.92	44.04	1.47	N/A See Solvent Effects		81.38	2.20	75.54	6.15
			50	5.84	5.83	44.61	1.80			82.39	2.09	76.72	4.87
			75	17.17	5.04	40.14	1.85			89.79	0.63	86.01	1.57
			100	9.86	4.14	45.32	1.57			90.78	2.23	82.09	4.07
	Perpendicular	1:1	25	-1.37	3.98	42.18	2.46	N/A See Solvent Effects		87.96	3.13	89.61	4.29
			50	8.81	2.22	43.64	3.15			86.21	4.55	82.92	9.15
			75	34.36	1.27	36.82	2.89			88.82	1.28	85.89	2.67
			100	7.17	1.56	42.57	2.63			90.06	1.08	90.17	1.93
		1:2	25	7.23	3.75	42.12	1.75	N/A See Solvent Effects		84.05	3.08	83.79	6.94
			50	4.79	4.07	44.43	3.20			77.92	1.23	68.34	7.41
			75	15.49	2.22	40.65	2.39			91.16	0.29	78.51	3.46
			100	4.98	3.03	43.63	4.18			87.54	3.36	85.84	3.90
35 mm	Parallel	1:1	25	0.25	1.77	40.59	3.90	N/A See Solvent Effects		87.24	1.59	85.51	1.73
			50	7.98	3.76	43.50	2.42			89.31	1.25	81.11	2.68
			75	29.72	2.35	37.97	2.59			90.13	1.11	87.45	5.18
			100	8.79	2.08	41.28	1.67			89.22	2.32	85.91	2.93
		1:2	25	3.24	4.55	41.84	2.10	N/A See Solvent Effects		84.33	2.92	79.00	1.47
			50	4.03	5.68	42.04	2.63			83.82	2.90	78.38	13.23
			75	9.88	2.26	40.52	3.63			90.91	0.81	88.33	0.42
			100	3.09	4.33	44.00	2.08			92.56	2.13	83.88	6.32
	Perpendicular	1:1	25	4.06	4.22	41.32	3.53	N/A See Solvent Effects		88.43	2.71	88.70	2.13
			50	8.84	3.57	41.22	4.67			92.19	0.82	71.02	8.65
			75	33.19	2.61	38.62	2.43			88.41	0.99	91.03	3.49
			100	6.76	1.55	40.57	1.74			91.54	2.44	83.63	5.10
		1:2	25	4.83	4.15	42.57	2.98	N/A See Solvent Effects		84.78	3.54	73.86	7.35
			50	8.88	2.26	42.73	1.89			80.84	3.55	69.92	6.58
			75	11.13	5.73	39.80	2.43			90.86	0.51	88.54	3.34
			100	5.82	2.74	42.81	1.54			87.99	4.14	86.84	3.96

	PI2611 DOP	PI2734 DOP	Ultradel 7501 DOP	DVS-BCB 3022-57 DOP	LMB 7081 DOP
Maximum	34.36	45.32	N/A See Solvent Effects	92.56	91.03
Minimum	-1.37	36.62		77.92	68.34
Average	10.23	41.79		87.51	82.76

flexible it cannot fully planarize the underlying features before cure. This is most likely due to the slow flow dynamics from the top of metal lines to spaces in between metal lines.

The poor planarization of Ultradel 7501 (−9% to 30%) is unexpected. Ultradel 7501 is a pre-imidized polymer that undergoes UV initiated crosslinking. The final film is insoluble due to the formation of a crosslinked network. The polymer solution as deposited possesses polymer chains with closed imide rings. These imide rings make the backbone inherently more rigid than PI 2734. The polymer solutions as received from the manufacturer have higher percent solids than PI 2611 or PI 2734. A solution of Ultradel 7501 has a higher viscosity than PI 2734 or PI 2611. Higher viscosity solutions have been shown to exhibit flow characteristics that produce lower DOP [11]. Ultradel 7501 contracts only 10% during cure. This corresponds to a maximum DOP before cure of 90%, where as the results of this study indicate the DOP before cure is estimated to be only 30%. This further suggests that flow limitations play a large role in the final surface profile.

Another striking feature of these results is the high levels of DOP observed for DVS-BCB 3022-57 and LMB 7081. These polymer systems possess similar planarizing ability with DOP values from 63% to 92%. Both of these materials are deposited as low molecular weight polymers and are easily able to flow and fill the spaces between metal lines. The raised temperature cure links the short chain molecules into a tight network. This inherently improves their planarizing capability because they are more able to flow into cavities between lines before cure [10]. The DOP values match well for these polymers with those from literature [7], [8]. Shrinkage appears to not play a role with either of these two systems.

Degree of planarization appears to be strong function of feature width for all polymers except PI 2734, where the range in DOP values is only ±5% in normalized DOP units. Because of the dynamics that occur during spin coating, it is expected that smaller feature widths would be easier to planarize. This is postulated because as the feature widths decrease (holding the spacing as equivalent or twice the width), the group of lines acts as one feature rather than independent lines. Larger feature widths are accompanied by larger spaces since our test structures are either spaced as 1:1 or 1:2 (width: spacing). This larger space provides a greater region into which polymer solution can flow. This study found, however, that small features were not planarized better than larger features. As shown in Fig. 5, 25 μm features were in fact planarized to a lesser extent (lower DOP) than the larger 75 or 100 μm features. Although this observation is counterintuitive, the features sizes chosen for this study may not be small enough to isolate the dependence on feature width from dependence on spacing and other contributing factors. The thickness of the polymer is much less than the width of the metal line. This factor may allow the metal lines to be treated as independent lines rather than as a set with neighboring lines.

One unique result observed is that the DOP measured for all polymers is consistently the greatest for 75 μm lines. Although this trend is most pronounced in PI 2611 and Ultradel 7501, it is evident in all other polymer systems to a lesser, sometimes insignificant level. For all permutations of the line spacing or feature orientation this effect consistently reoccurs. No clear reason for the maximum planarization over these lines has been identified and may simply be a byproduct of experimental conditions. Both PI 2611 and Ultradel 7501, however, have rigid backbones that hinder the flow from on top of metal lines. This suggests that polymers ability to flow after spin coating may be a contributing factor to this phenomenon.
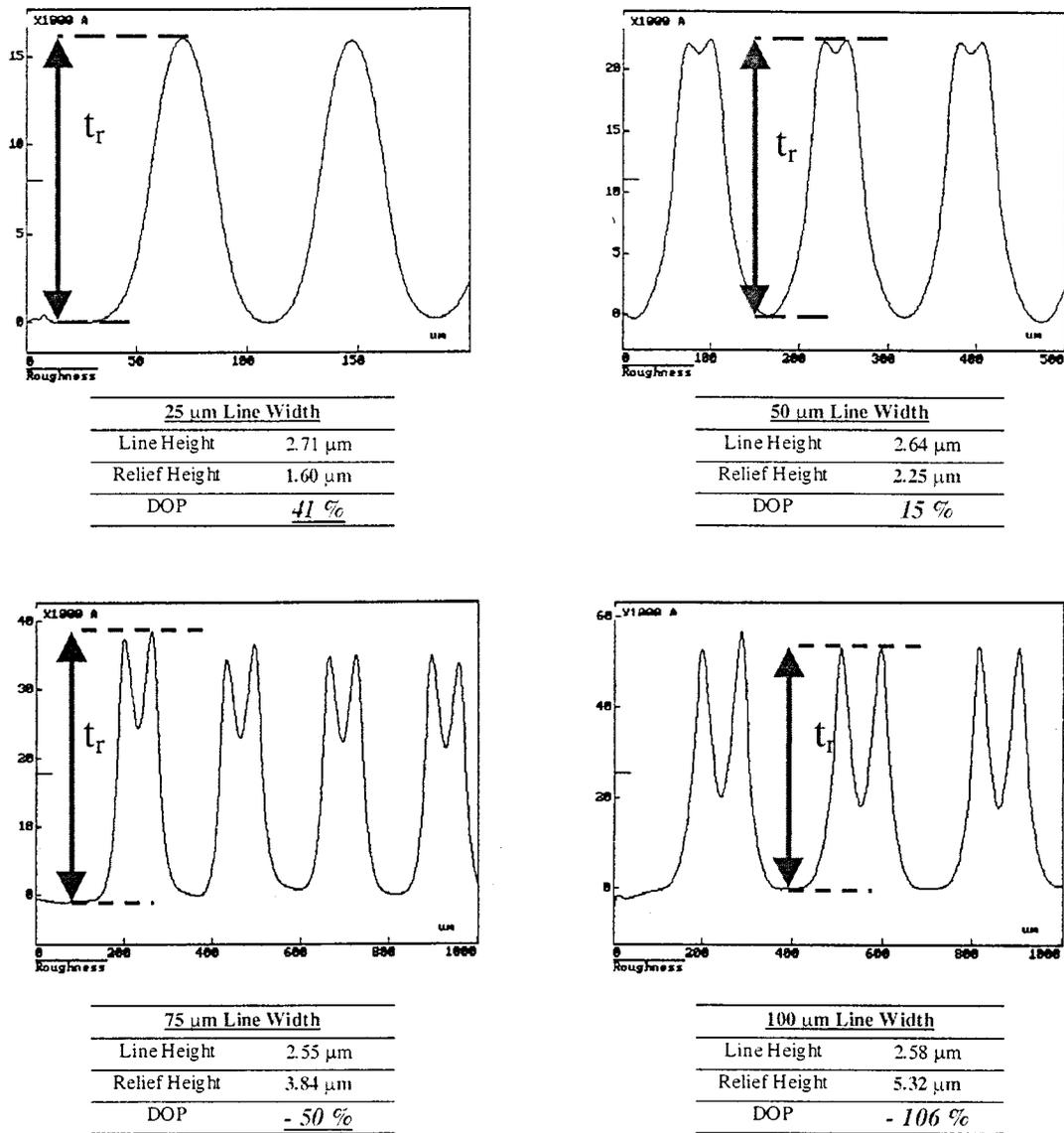
25 μm Line Width	
Line Height	2.71 μm
Relief Height	1.60 μm
DOP	41 %

50 μm Line Width	
Line Height	2.64 μm
Relief Height	2.25 μm
DOP	15 %

75 μm Line Width	
Line Height	2.55 μm
Relief Height	3.84 μm
DOP	- 50 %

100 μm Line Width	
Line Height	2.58 μm
Relief Height	5.32 μm
DOP	- 106 %

Fig. 4. Surface profilometry results for Ultradel 7501 in polymer-metal-polymer configuration (MP) for 1:2 line spacing, 15 mm from the center, oriented parallel to polymer flow.

First Layer Planarization (DOP1)
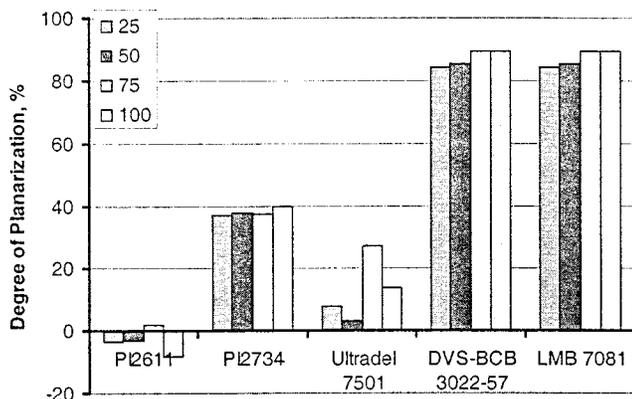
Fig. 5. Single layer planarization (DOP) for features with 1:1 line: width spacing, 15 mm from the center of the wafer, oriented parallel to polymer flow.

TABLE VI
DEGREE OF PLANARIZATION 1) AFTER ONE LAYER OF POLYMER (DOP1), 2) AFTER TWO LAYERS (DOP2), AND 3) OF POLYMER OVER METAL LINES OVER POLYMER (MP)

Polymer Dielectric	DOP1	DOP2	MP
PI 2611	-12 % to 7 %	2 % to 49 %	-1 % to 34 %
PI2734	34 % to 44 %	60 % to 69%	37 % to 45 %
Ultradel 7501	-9 % to 29 %	2 % to 69 %	N/A
DVS-BCB 3022-57	70 % to 92 %	87 % to 99%	78 % to 93 %
LMB 7081	63 % to 92 %	64 % to 94%	68 % to 91 %

uated. Fig. 6 shows a comparison of the degree of planarization of 1:1 versus 1:2 line width to spacing for structures near the center of the wafer perpendicular to polymer flow. An increase in line spacing further isolates the line from neighboring lines and would be expected to reduce the contribution from these neighboring features producing a lower degree of planarization.

The effects of orientation and location on the wafer were also studied. The underlying assumption of spin coating is that a uniform, spatially consistent film can be deposited regardless of underlying features. For a single layer of polymer, our results
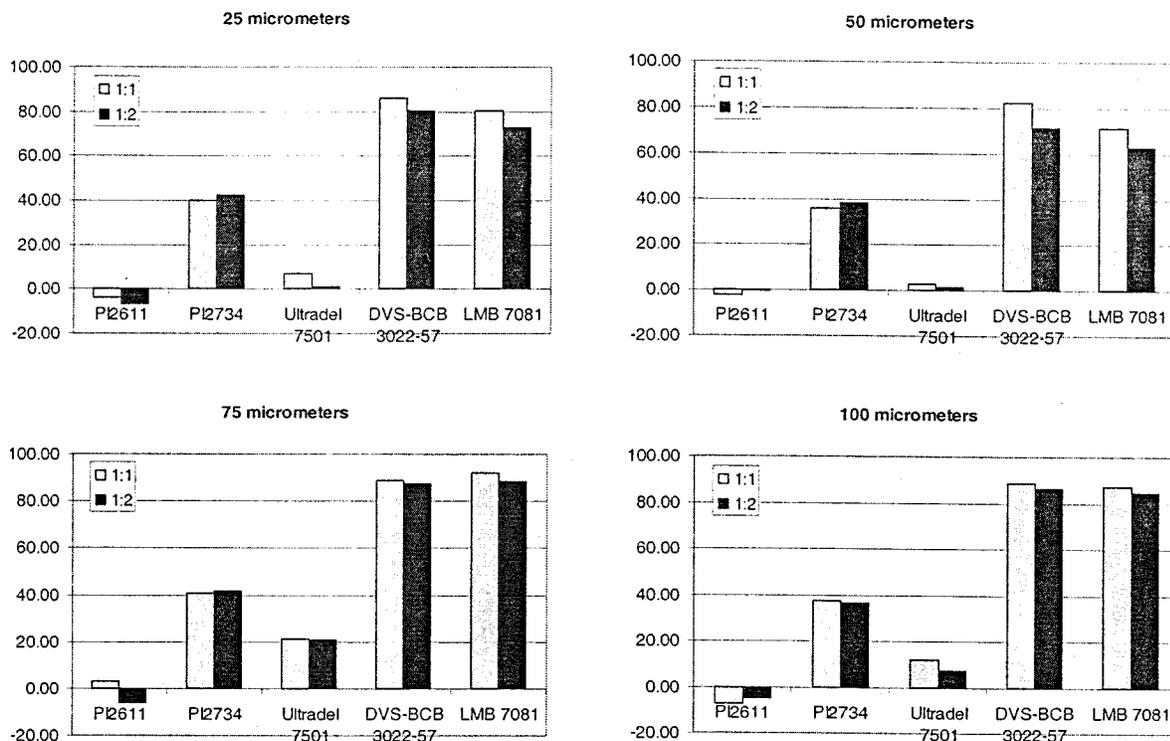
In general, as the line spacing is increased from 1:1 to 1:2 (line width: spacing), the DOP decreases for all polymers eval-

Fig. 6. Effect of line spacing on DOP1:1:1 versus 1:2 (width: space) for 25, 50, 75, 100 μm features, 15 mm from the center, perpendicular to polymer flow.
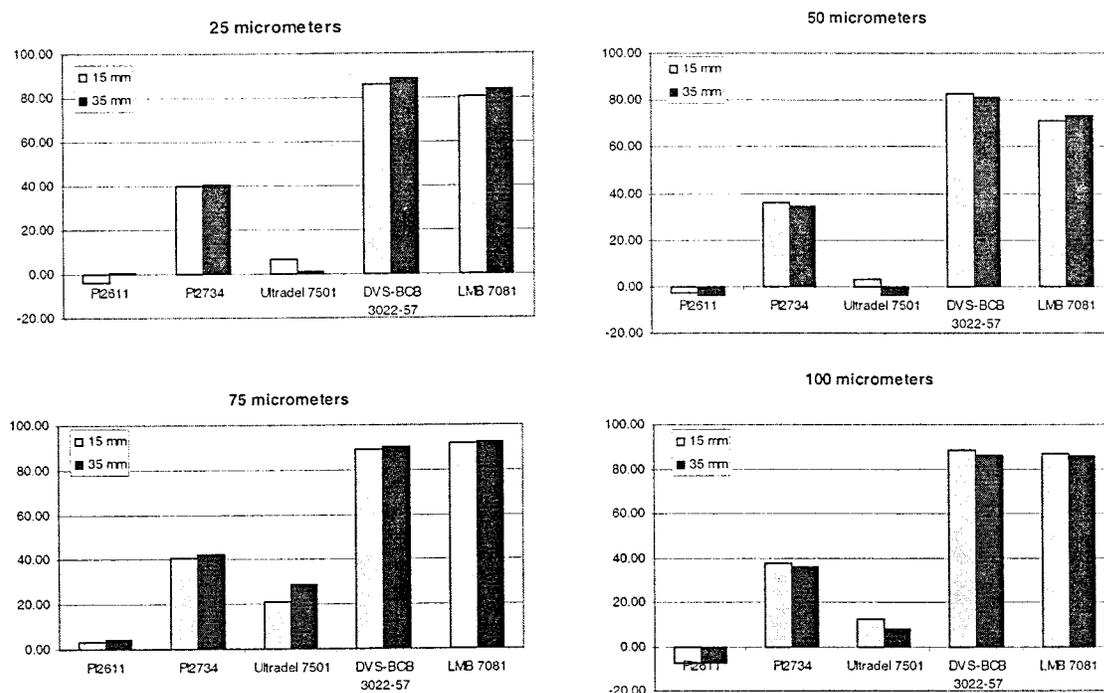

Fig. 7. Effect of location on the wafer on DOP1: 15 mm versus 35 mm from the center of the wafer for 25, 50, 75, 100 μm features, 1:1 spacing, perpendicular to polymer flow.

confirm this hypothesis. Fig. 7 shows DOP measured for features comparing the planarizing differences of structures 15 and 35 millimeters from the center of the wafer. A feature near the center of the wafer is planarized to a similar as a feature near the edge of the wafer. A puddle dispense would initially cover the center features and flow over the edge features. Centrifugal effects on planarization can therefore be ignored. Lines oriented either parallel or perpendicular to the flow of the polymer so-

lution as it spreads appear to have very similar degrees of planarization as well. These results are shown in Fig. 8. These results are consistent over all polymer systems tested.

B. Second Coat Planarization (DOP2)

The degree of planarization was measured after a second coat of polymer is deposited over the initial first coat (DOP2). When the initial coat of a polymer fails to planarize the underlying fea-
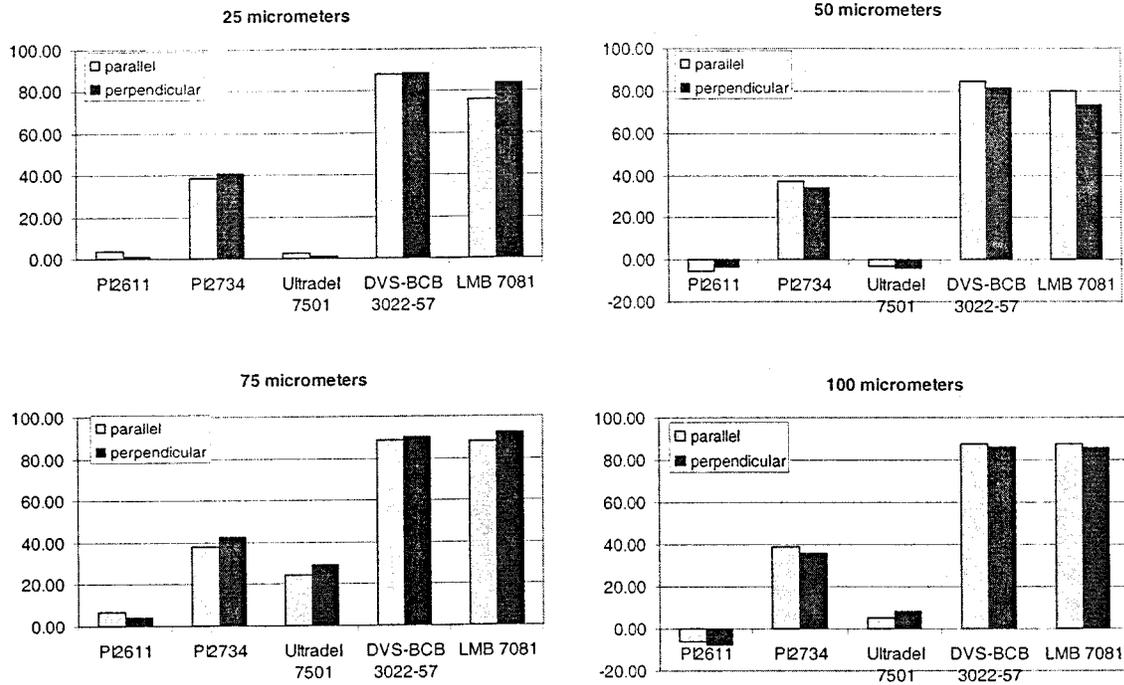
Fig. 8.   Effect of orientation to polymer flow on DOP1: parallel versus perpendicular for 25, 50, 75,100 μm features, 1:1 line spacing, 35 mm from the center.
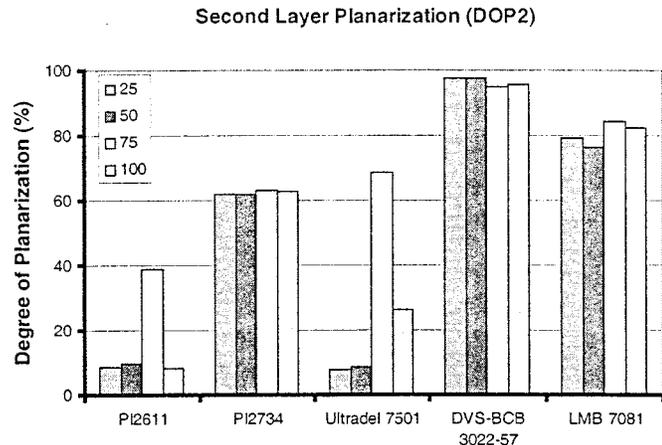

Fig. 9.   Second layer planarization (DOP2) for features with 1:1 line: width spacing, 15 mm from the center of the wafer, oriented parallel to polymer flow.

ture sufficiently, the addition of a second layer of polymer to further planarize the first layer is a common practice [1]. If the first polymer layer can be treated as an inert layer (with independent planarizing ability), the resulting DOP due to additional layers can be extrapolated from the initial DOP value by (2) where 'n' is the number of polymer layers [12]

$$DOP(n) = (1 - (1 - DOP1)^n) * 100. \qquad (2)$$

For this study, only two layers of polymer are deposited ($n = 2$). Significant deviations from this approximation occur if there exists interaction between layers. Table IV lists the maximum and minimum values for the degree of planarization measured after a second polymer layer is deposited over all features. The results for 1:1 line spacing, 15 mm from the center, oriented parallel to polymer flow are shown in Fig. 9. For all polymers, the results from this study confirm that the degree of planarization improves with the addition of a second coat of polymer. Fig. 10

shows a comparison of first layer to second layer planarization for this same configuration. The DOP values of predicted from single layer planarization for 25, 50, 75, and 100 μm features are shown in Table VII.

The addition of a second layer of polymer improved the planarization for all polymer systems. Two polymer systems, PI 2734 and DVS-BCB 3022-57, closely follow (2). The DOP for DVS-BCB 3022-57 increases to an average of 96% from a single coat average of 87%, where as the DOP for PI 2734 increases to an average of 63% from a single coat average of 38%. The first layer is polymer is chemically different from the second deposited layer, minimizing solvent induction into the underlying layer. Solvent effects are discussed later in this paper for Ultradel 7501 and PI 2611 systems.

LMB 7081, a photodefinable epoxy, is expected to perform similarly to DVS-BCB 3022-57. Both systems are deposited as an oligimers and crosslink significantly on cure. The results of this study, however, showed no significant difference between planarization after a single coat and planarization after two coats for LMB 7081. This is most likely due to the filled nature of this polymer system. The filler in this epoxy system has dimensions similar to that of the relief height of test structures. The filler therefore acts to obscure the planarization advantages of additional layers.

The degree of planarization for PI 2611 improved to values ranging from 2% to 49%. These values are a significant improvement from the first layer planarization values, where some negative values were observed. This increase may be attributed to the addition of a second layer of polymer that would further planarize the underlying features. Predictions based on single layer results of DOP for PI 2611 indicate that this is unlikely. There is negligible planarization after one layer of polymer, suggesting DOP2 will be similarly low. Instead, these results suggest there is an interaction that occurs between the second and
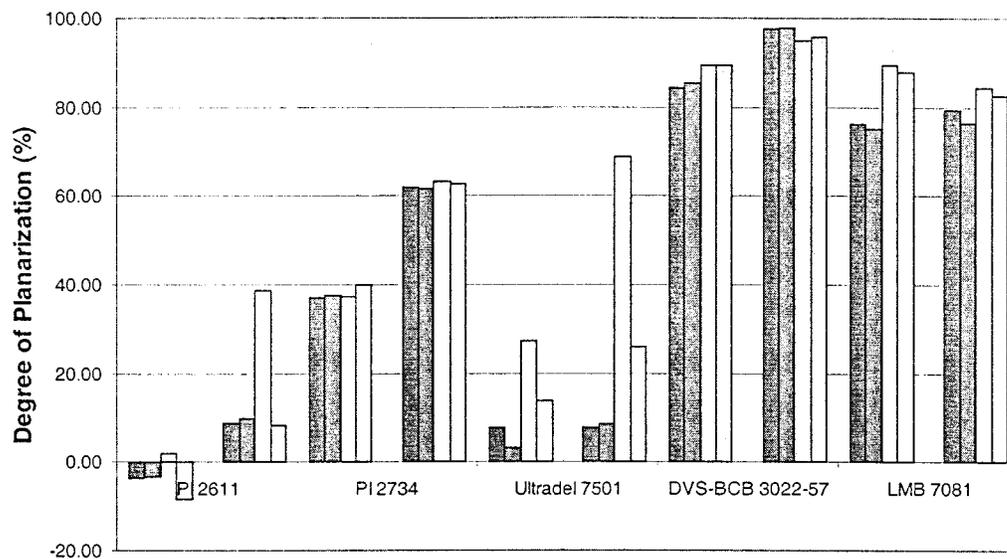
DOP1 vs. DOP2

Fig. 10. DOP1 versus DOP2 for 1:1 line spacing, 15 mm from the center, oriented parallel to polymer flow.

TABLE VII
PREDICTION OF DOP USING (2), FOR FEATURES WITH 1:1 LINE SPACING 15 mm FROM THE CENTER, ORIENTED PARALLEL TO POLYMER FLOW

Polymer	Feature Size	DOP1	DOP2	DOP2 (predicted)
PI 2611	25	-3.49%	8.69%	-7.09%
	50	-3.27%	9.92%	-6.64%
	75	2.04%	38.64%	4.03%
	100	-8.33%	8.23%	-17.35%
PI 2734	25	37.00%	61.93%	60.31%
	50	37.68%	61.79%	61.16%
	75	37.36%	63.26%	60.76%
	100	39.97%	62.81%	63.96%
Ultradel 7501	25	7.78%	7.87%	14.96%
	50	3.27%	8.51%	6.44%
	75	27.30%	68.72%	47.15%
	100	13.81%	26.09%	25.71%
DVS-BCB 3022-57	25	84.33%	97.65%	97.54%
	50	85.37%	97.79%	97.86%
	75	89.33%	94.98%	98.86%
	100	89.34%	95.83%	98.86%
LMB 7081	25	76.25%	79.35%	94.36%
	50	75.17%	76.38%	93.83%
	75	89.51%	84.42%	98.90%
	100	87.84%	82.44%	98.52%

first coat of polymer that results in an improvement in planarization. The difference in behavior between PI 2611 and PI 2734 maybe partially attributed to the rigid rod nature of PI 2611.

It is important to recall that the second layer was not simply spun on existing structures. While fabricating the test samples, the cured first layer is metallized via sputtering and etched back. The abrasive sputtering environment may have roughened the surface of the PI 2611 allowing this interaction to occur. In fact, the manufacturers commonly use a plasma treatment to allow such interaction to occur and assist interlayer adhesion. Further study of the interaction between multiple polyimide layers is necessary to understand this phenomenon.

The DOP of Ultradel 7501 similarly increased from low (sometimes negative) DOP's to values ranging from 2% to 69%. This increase can be partially attributed to planarizing effects of the

second layer, however, a larger contributor to this effect is most likely the physical nature of the system. As a lightly crosslinked polymer film, Ultradel 7501 will swell but not dissolve in its own solvent. Significant interaction is likely to occur, between the solvent from the second layer and the first layer of polymer resulting in swelling of the cured first layer. Further detailed analysis of these solvent effects is presented later in this section.

The data for second layer planarization displays similar trends as those observed from single layer planarization. The dependence of DOP on feature size is less pronounced after the second layer is deposited for all cases except PI 2611 and Ultradel 7501. Although the degree of planarization increased for these two polymers, they demonstrated similar dependence on feature size as observed with single layer planarization. Additionally, all polymers except PI 2611 and Ultradel 7501 show decreased dependence on line spacing. These two polymers show a significant decrease in DOP with an increase in line spacing, especially for 75 μm feature widths. Specifically, the DOP for PI 2611 decreases on average by 58% by doubling the line spacing. Ultradel 7501 decreases on average by 32% with increased spacing. This compares to a very subtle change in DOP ($\sim$10%) when increasing the spacing for a single coat.

The DOP after a second coat is not a strong function of orientation and position for all polymers except PI 2611 and Ultradel 7501. The dependance on feature location is illustrated Fig. 11. For PI 2611 and Ultradel 7501, features near the center of the wafer (15 mm) are planarized to a greater degree than those near the edge of the wafer (35 mm). The structures near the center are within the dispense puddle for spin casting. Structures near of the edge of the wafer are coated by centrifugal spreading of the dispense puddle. This suggest that prolonged solvent exposure (between puddle dispense and initiation of spin) is a factor that may improve planarization. A metal line's orientation to polymer flow (parallel or perpendicular) does not appear to affect the DOP (Fig. 12).
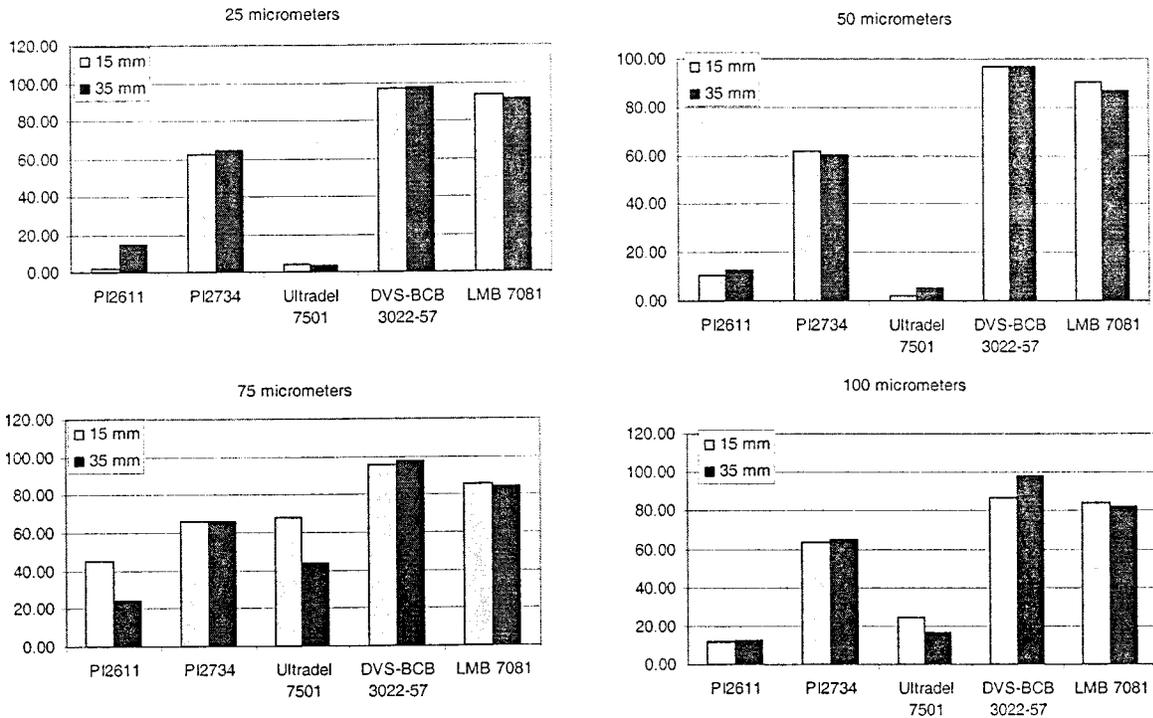
Fig. 11.   Effect of location on the wafer on DOP2: 15 mm versus 35 mm from the center of the wafer for 25, 50, 75,100 μm features, 1:1 spacing, perpendicular to polymer flow.
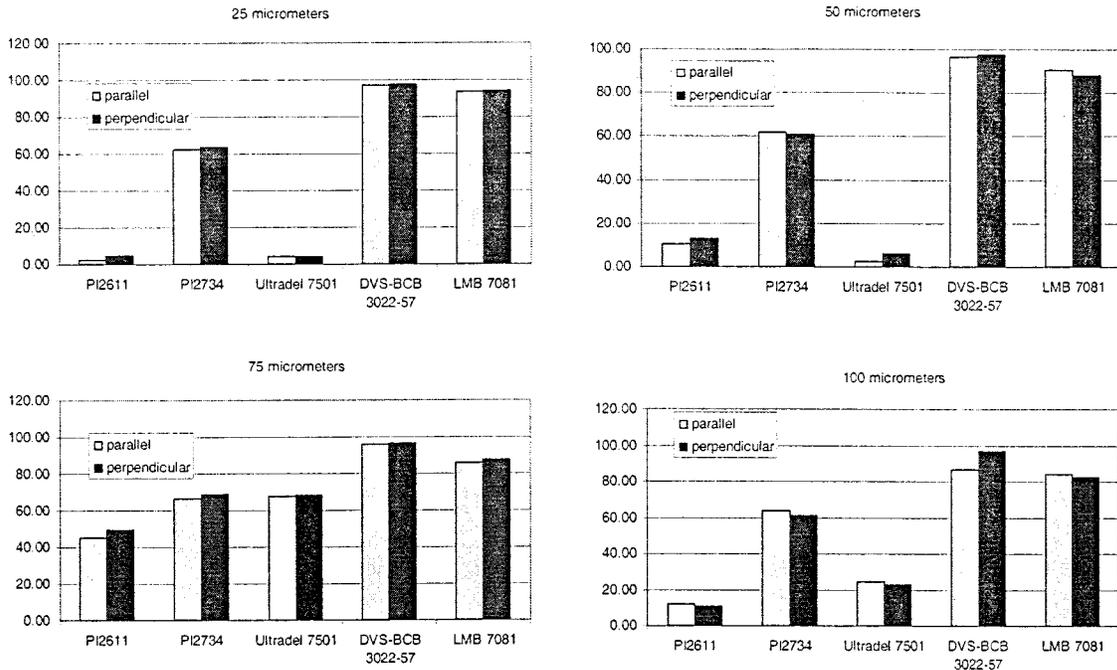

Fig. 12.   Effect of orientation to polymer flow on DOP2: Parallel versus perpendicular for 25, 50, 75,100 μm features, 1:1 line spacing, 35 mm from the center.

C. Planarization of Metal Lines Patterned over a Cured Polymer Base

The planarization of metal lines on top of a polymer base by an addition layer of dielectric as shown in Fig. 2 is studied. This measurement is a unique characteristic of this study as planarization of a multilayer structure is rarely studied. In most cases, the degree of planarization for a multilayer structure is assumed to be equivalent to the degree of planarization measured

on a single polymer coat (DOP1). Extension of single layer degree of planarization results to multilayer structures is valid if each polymer layer can be assumed to be completely independent. This basic premise can be incorrect, especially if the solvent solubility of the underlying polymer film has not significantly changed by cure.

The maximum and minimum values measured for the polymer-metal-polymer configuration (MP) are listed in Table VI. Specific results for 1:1 line spacing, parallel orien-
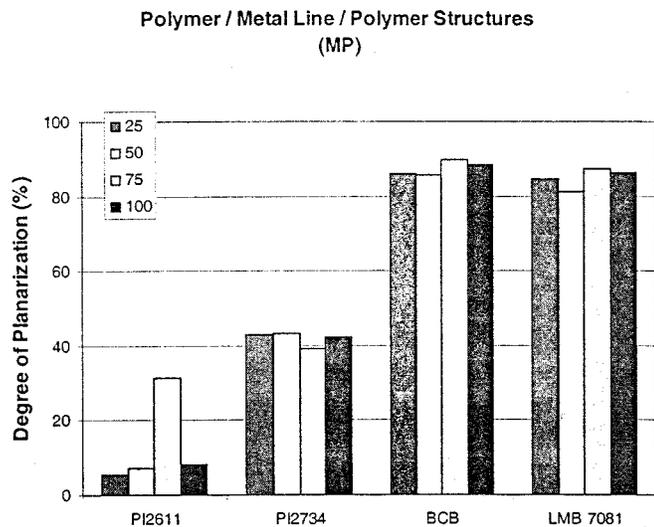
Fig. 13. Polymer-metal-polymer planarization (MP) for features with 1:1 line spacing, 15 mm from the center of the wafer, oriented parallel to polymer flow.

tation to flow, 15 mm from the center of the wafer are shown in Fig. 13. Ultradel 7501 exhibited unique surface topography that will be discussed separately and is therefore excluded from the results discussed in this section.

Three polymer systems showed statistically similar planarizing ability in single layer (DOP1) and polymer-metal-polymer (MP) configurations. These polymers are DVS-BCB 3022-57, LMB 7081, and PI 2734. A comparison of DOP1 to MP is shown in Fig. 14. This behavior indicates that it is likely there is little interaction between layers. DVS-BCB 3022-57 and LMB 7081 both form tightly crosslinked networks on cure. Deposition of additional layers of polymer exposes the underlying layers to solvent that can swell the polymer matrix. For these two systems, the level of crosslinking is high enough so that solvent effects are minimal. PI 2734 undergoes a chemical change in its backbone on cure that changes its solubility in its original solvent (NMP). These results follow the results of second coat planarization (DOP2) presented above, where DVS-BCB 3022-57 and PI 2734 both show additive planarization, following (2). These results support the theory that each layer only minimally interacts with each other for these polymers.

The DOP for PI 2611 was greater for the multilayer structure (MP) than for single coat structure (DOP1). In fact, DOP2 results and MP results for PI2611 are very similar further suggesting interaction between layers. Interaction between layers, as postulated for DOP2 measurements of PI 2611, may support these results.

The degree of planarization results for polymer-metal polymer structures (MP) exhibits very similar trends as those reported for single (DOP1) and double layer planarization (DOP2). Specifically, DVS-BCB 3022-57, LMB 7081 and PI 2734 showed little, if any, dependence on feature size, feature spacing, feature orientation and location on a wafer. PI 2611 showed a dramatically larger DOP for 75 μm features. As the feature spacing increases from 1:1 to 1:2 the DOP for PI 2611 significantly decreases especially for 75 μm features. The difference due to spacing may be attributed either to interaction

between polymer layers or to increased orientation of the rigid rod polyimide chains along the surfaces of the features and substrate.

D. Solvent Effects: Ultradel 7501 and PI 2611

Surface profilometry of polymer-metal-polymer test features constructed with Ultradel 7501 exhibited unusual profiles. Fig. 4, shown previously, displays the surface profile for 25, 50, 75, 100 μm feature widths with a width to line spacing ratio of 1:2. Each test feature shown is 15 mm from the center of the wafer and is oriented parallel to the centrifugal flow as the polymer spreads over the wafer. For 25 μm features, the DOP is 41% and the profile is smooth and bell shaped. For features 50 μm or greater, the surfaces near the edge of the lines are raised. The height of the raised surfaces greatly increases as the line width (and line spacing) increases. The degree of planarization is poorest for 100 μm features. In this case, a 2.58 μm thick feature is coated with a 6 μm polymer layer. The final surface profile possesses a raised surface of 5.32 μm. Taking this value as the final relief height, the DOP is calculated to be -106%. Similar trends in surface profiles were observed for all feature configurations in this study. The appearance of these unique surface profiles have been further confirmed by scanning electron microscopy (SEM).

The unexpected appearance of these unusual structures indicates solvent effects play a large role in the dynamics of processing a multilayer structure. Results from second layer planarization (DOP2) with Ultradel 7501 also support the theory that solvent penetration and swelling are key mechanisms to consider when evaluating planarization.

The key dynamic step in processing is the period immediately after spinning and before soft bake. When a solvent cast polymer film is deposited on top of a fully cured polymer layer, the solvent from the top layer is likely to be partially extracted into the bottom layer. Although curing of Ultradel 7501 lightly crosslinks the layer, the cured layer is not significantly different from an uncured film. Solvent from the second coat will still have affinity for the initial layer and will attempt to incorporate itself into the cured polymer matrix. DVS-BCB 3022-57 and LMB 7081 do not display such solvent effects because they are both highly crosslinked films. The resultant polymer matrix for these two polymers has only a limited solvent affinity.

The results of polymer-metal-polymer structures for Ultradel 7501 are attributed to solvent swelling effects. Patterned copper lines over a cured polymer base partially mask the underlying layer from exposure to solvent in subsequent layer. Solvent will redistribute to the underlying layer in an attempt to equilibrate concentration gradients through the double film layer as shown in Fig. 15. The physical blocking of regions will produce viscosity variations that may change the dynamics of polymer flowing over metal lines. Higher viscosity polymer regions can form over lines making it difficult for polymer to flow from the top of metal lines to values between metal lines. This process produces raised surfaces near the edges of the metal lines. As line spacing increases, more area is available between metal lines for solvent diffusion and therefore the unique surface profiles are greater in magnitude. Features near the center of the wafer are within the initial puddle of static
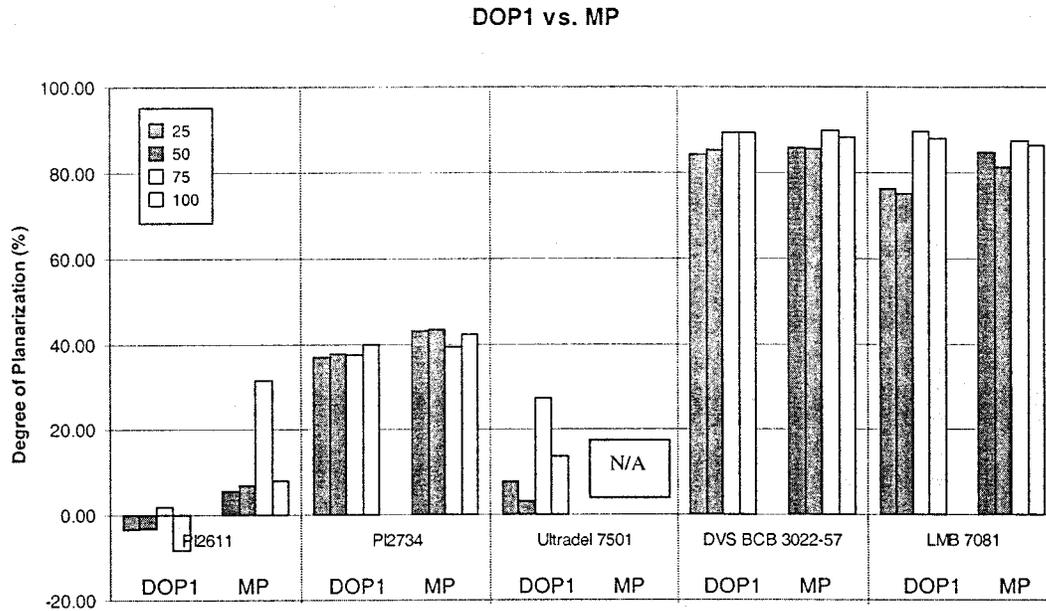
DOP1 vs. MP

Fig. 14.   DOP1 versus MP for 1:1 line spacing, 15 mm from the center, oriented parallel to polymer flow.
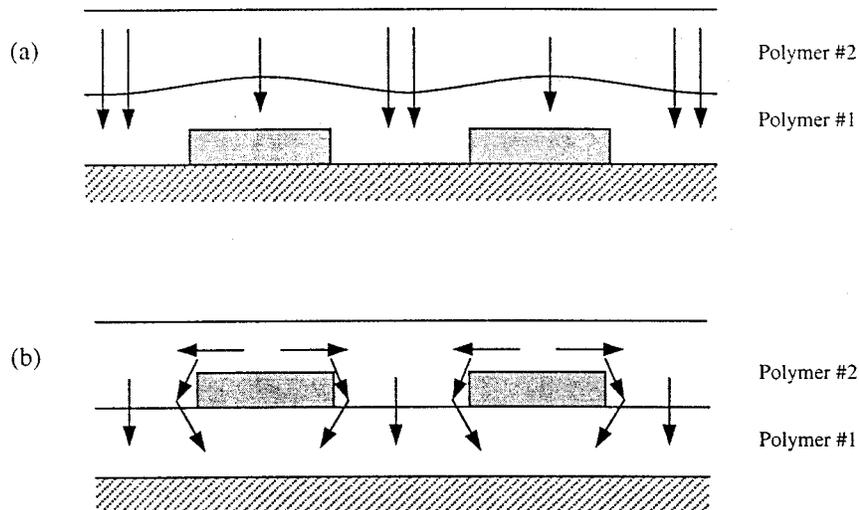

Fig. 15.   Solvent redistribution in (a) DOP2 and (b) MP.

dispense and have longer contact time between puddle dispense and spin. These features also exhibit a greater exaggeration of surface profiles.

Incorporation of solvent in regions below metals can be detrimental to the performance and reliability of the device. Swelling forces and induced stresses can cause adhesive failures creating interconnection discontinuities that will cause the device to fail or have a shortened lifetime. Metal lines, for example, may become geometrically distorted and strained due to the forces produced by incorporating solvent into the nearby polymer matrix.

The theory of solvent redistribution can be extended to explain second layer planarization results as well. Referring to the previous section on second layer planarization (DOP2), the degree of planarization for Ultradel 7501 is greatly improved with an additional coat. This great improvement is most likely attributed to solvent effects. In this case, the cured polymer base is completely exposed to solvent from additional layers.

Viscosity differences can not be attributed to masking of this layer as hypothesized for the polymer-metal-polymer (MP) structures. Although all areas are susceptible to solvent redistribution, the regions between metal lines have a greater thickness to which solvent can be extracted as shown in Fig. 15. Higher viscosity regions may be created between metal lines, where as lower viscosity regions may be formed on top of metal line. This difference in viscosity may be created by greater solvent redistribution from regions between metal lines. Lower viscosity polymer solution over metal lines will readily flow off of polymer lines, directly improving the degree of planarization. Test features near the center of the wafer (in the puddle of static dispense) showed the greatest improvement in DOP. Increasing the spacing is expected to also increase these solvent effects, however does not improve the DOP because an increased spacing inherently more difficult to planarize, neglecting solvent effects.

Second layer (DOP2) and polymer-metal-polymer (MP) planarization results for PI 2611 suggest that interaction between layers plays a large role in determining the final surface profile of the structures. Assuming solvent effects can be attributed for these results, the mechanisms proposed above for films of Ultradel 7501 also apply to similar films of PI 2611.

VI. Summary and Conclusions

The planarization of metal lines by five different polymer dielectrics has been characterized. The inherent properties of the polymer appear to be much more important than the size and orientation of underlying features. As expected DVS-BCB 3022-57 was determined to have the best planarizing ability, where as PI 2611 and Ultradel 7501 perform the worst, sometime exhibiting negative degrees of planarization. Solvent interaction between layers plays a large role for Ultradel 7501 and a lesser role for PI 2611. Unique surface profiles are observed for Ultradel 7501 in polymer-metal-polymer structures (MP), confirming these solvent interactions.

Effective application of polymer layers as dielectrics for packaging or microelectronics markets require that their coating characteristics be fully defined. Planarization of underlying features is a key property that must be defined. Propagation of nonplanar features through a device could severely limit the overall yield in a process.

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