Planarization and Dielectric Properties of Thin Photosensitive and Nonphotosensitive BCB

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Abstract

Thin films (0.2 μm to 1.8 μm) of photosensitive and nonphotosensitive BCB were fabricated and the degree of planarization (DOP) and dielectric properties were investigated. It was found that a high DOP for wide spaces (>20 μm spaces with 1 μm of BCB) was possible with nonphotosensitive BCB but not photosensitive BCB because of the cross-linking reaction during the photo-process. Thin films (as thin as 0.2 μm) exhibited dielectric properties similar to thick films. The dielectric properties of the photosensitive BCB were slightly higher than nonphotosensitive BCB. Low loss properties were observed at all thickness.

Introduction

Low dielectric constant insulators are essential to the performance of high-speed electronic devices. [1] Thin films of dielectric materials, deposited by spin casting are often used as insulators for semiconductor devices and printed circuit boards. Insulation is needed between layers of metallization and as a final dielectric layer protecting the component.[1] The degree of planarization (DOP), or ability of the spin-cast dielectric to planarize nonuniform surfaces can be critical to the device fabrication. Polymers of benzocyclobutene (BCB) are known to have low permittivity and loss, and exhibit excellent planarization of underlying topography. [2] There have been several planarization studies, however, much of the planarization data refers to nonphotosensitive BCB. [2, 3, 4] Negative tone, photosensitive BCB uses an azide cross linking group to lower the solubility of the irradiated polymer so that patterns can be developed. The cross linking of the polymer may effect the planarization because of the higher molecular weight of the in-process polymer. Further, specific applications of BCB can be targeted toward very thin layers of the polymer. Thus, the possible deviations from bulk properties for very thin films are of interest with respect to its electrical and planarization properties.

In this work, the planarization and dielectric properties (permittivity and loss) of photosensitive and nonphotosensitive BCB were investigated as a function of film thickness. The effect of cross-linking (photosensitive BCB) on the properties is of particular interest.

Experimental

Two versions of BCB polymers were studied: 3022 nonphotosensitive and 4022 photosensitive polymers. The BCB was obtained from Dow Chemical (Midland, MI) under the trade name Cyclotene. [5] The viscosity of the polymer solutions was dependent on the weight percent solids of the initial solutions. The starting material was 35 wt% solids for the photosensitive BCB (identified as 4022-35) and 57 wt% solids for the nonphotosensitive BCB (3022-57). The viscosity of the polymer solutions used in this study was adjusted by dilution with mesitylene, the casting solvent. The effect of different viscosities on planarization was investigated. Films of similar thickness were prepared by adjusting the viscosity of the BCB solution and changing the spin speeds. The BCB was cured according to the manufacturer's recommended processes. The final cure occurred at 250°C for 1 hour in a nitrogen-purged furnace. In each case, FTIR measurements were performed to ensure that the BCB was fully cured.

Test structures with different line spacing were prepared to determine the DOP. Thermally

oxidized (oxide thickness ca. 2000Å) silicon wafers with a sputtered layer of aluminum metal were used to form the step to be planarized. Each aluminum-coated wafer was lithographically patterned with different line widths and spacings. The exposed metal was etched producing a step whose height was that of the aluminum thickness. An Alphastep profilometer was used to measure the height (h_1), and spacing of the lines. The DOP (as a percentage) was calculated from Equation 1.

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

Where t_1 is the height of the step after polymer processing, and h_1 is the height of the original metal step. Thus, if no planarization of the aluminum step is provided by the polymer, then $t_1=h_1$ and DOP=0%. If the polymer fully compensates for the aluminum step and produces a flat or planar surface, then $t_1=0$ and DOP=100%.

The relative 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. The process sequence for the fabrication of the sample is as follows.

1) Oxidize silicon wafers in tube furnace approximately 2000 Å.
2) Deposit approximately 2500 Å of aluminum by DC sputtering.
3) Spin coat the polymer and cure using standard DOW procedures.
4) Deposit top metal layer of 2500 Å aluminum by DC sputtering.
5) Pattern top layer of metal with photolithography.
6) Etch aluminum in exposed areas.

All measurements were made using a HP 4236 LCR meter @10 kHz on a Karl Suss Probe station. The relative permittivity, ε_r, and loss tangent, $\tan\delta$, were calculated using Equations 2 and 3, respectively.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{t} \qquad (2)$$

$$G = \omega C \tan\delta \qquad (3)$$

Where ε_o is the permittivity of vacuum (8.85 x 10^{-12} F/m), ε_r is the relative permittivity of the medium, A is the area of the top electrode, t is the thickness of the polymer film, $\omega = 2\pi f$, where f is the measurement frequency, C is the capacitance, $\tan\delta$ is the loss tangent and G is the conductance. All measurements were performed at 40 % relative humidity and room temperature. The effect of fringing fields was neglected because the area of the electrode was significantly greater than the thickness of the dielectric. The low temperature loss measurements were measured as previously described. [6] The free film samples were fabricated on 13 mm thick potassium bromide plates as the substrate for the polymer. After curing, the KBr plates were dissolved in distilled water producing free films.

Results and Discussion

BCB is known for providing a high degree of planarization. [2] Thin layers of nonphotosensitive BCB (1.2 μm of 3022) and photosensitive BCB (1.4 μm of 4022) were coated over patterned aluminum wafers where the aluminum thickness was 0.7 μm. The higher percent solids solution (e.g. 3022-35) was spun at a lower spin speed to produce the same polymer thickness, as compared to the less viscous, lower percent solids solution (3022-25). The line spacing varied from 17.5 μm to 70 μm. The DOP results are shown in **Table 1** for both polymers. The nonphotosensitive BCB (3022) shows excellent planarization even for the very wide spaces (wide with respect to the height of the polymer). The results are similar to previously published results for thicker BCB films. [2] The DOP drops below 90% only for the widest spacing of 70 μm. There is a slight trend for the less viscous, higher spin speed samples to be more planarizing, as can be seen from the 70 μm spacing. However, in the narrower spaces, the error in the DOP measurements was greater than then the differences in DOP with viscosity.

A duplicate set of experiments was performed with 1.4 μm of the photosensitive BCB (4022). The DOP was significantly less at each value of line spacing, even though the 4022 was slightly thicker than the 3022. The lower degree of planarization for the 4022 photosensitive polymers is a result of several factors. The primary factor is the presence of the

photosensitive, azide cross-linking agent. During exposure and processing, the photo package acts to increase the molecular weight of the polymer and lower its solubility. This higher molecular weight lowers the mobility and flow of the polymer during curing, thus decreasing its ability to planarize the surface (lower DOP). Thus, the cross linking action of the photo package effectively sets the spatial position of the BCB and lowers its ability to flow. Also, the 4022 had a higher starting molecular weight than 3022. This is reflected in the need to start with a lower percent solids solution to obtain similar thickness.

Table 2 shows DOP data for both polymers at a thickness of 1.0 um. The results show that the 3022 had essentially the same DOP as the 1.2 μm films (Table 1). The results are within experimental error of each other. However, the DOP for the 4022 films are lower than those in Table 1. This can most easily be seen at the wider line spacing. No plararization was observed for the 70 μm wide structures.

The dielectric constant (relative permittivity and loss tangent) was measured for the two polymers (3022 and 4022) as a function of polymer thickness in the range from 0.2 μm to 1.8 um. There is concern that as the thickness is reduced, deviations from bulk properties may occur. The permittivity results for 3022 and 4022 BCB are shown in **Figures 1 and 2**, respectively. Each data point represents the average of 20 individual capacitors and the error bars are the one standard deviation values. The thickest film permittivity of 3022 BCB was about 2.65, in reasonable agreement with vendor reports. [5] The relatively humidity and measurement frequency can cause minor differences between reported values. Also, the relative error in measuring the thickness of the polymer contributes to the overall error for thin films. The permittivity values observed were essentially the constant with thickness down to 0.25 μm, within experimental error. The permittivity of the 4022 BCB was slightly higher than 3022, primarily due to the presence of the photo-package and its secondary effects, such as moisture absorption. The permittivity values were relatively constant with thickness.

The loss tangent measurements are shown in **Figures 3 and 4** for the 3022 and 4022 BCB, respectively. The loss tangent values are slightly less than previous reports (0.0008 at 1 KHz-1 MHz). [5] In addition to the thickness being considerably less in this study, the relative humidity may have also been different.

The conductance-based loss values shown in Figures 3 and 4 are low and at the limit of accuracy for the test method. More accurate values of loss were of interest for comparison purposes. Thick films (5 to 10 μm thick) of 3022 and 4022 were prepared on KBr crystals and the loss was evaluated at 77K by using use of a superconducting resonator structure. [6] The loss value for 3022 was 0.00035 (average of four measurement) and loss tangent was 0.00013. The loss for the 4022 was 0.00041 (average of six measurements) and loss tangent was 0.00015. These values are consistent with previous reports. [5]

Table 1. Weight Percent Solids versus Degree of Planarization

Polymer - Percent Solids	DOP (as %) for Four Line Spacings			
	70 um	35 um	20 um	17.5 um
3022-35	69.0	92.6	93.6	93.3
3022-30	67.1	93.2	93.8	93.6
3022-25	78.6	93.0	93.1	92.7
4022-25	2.9	37.4	56.6	66.7
4022-20	5.5	21.7	43.7	54.2
4022-15	15.3	37.3	56.2	65.6

(Polymer Overcoat Thickness 3022 ~ 1.2 um: 4022 ~ 1.4 um)

Table 2. Weight Percent Solids versus Degree of Planarization

Polymer - Percent Solids	DOP (as %) for Four Line Spacing			
	70 um	35 um	20 um	17.5 um
3022-35	70.2	92.1	93.2	92.9
3022-30	75.6	90.0	92.7	93.5
3022-25	68.3	91.9	92.0	92.1
4022-25	0.2	18.0	43.3	58.9
4022-20	-6.6	19.8	42.5	58.2
4022-15	-2.7	24.1	47.4	65.0

(Polymer Overcoat Thickness 3022 and 4022 ~ 1.0 um)

Figure 1. Dielectric Constant vs. Polymer Thickness for 3022 BCB

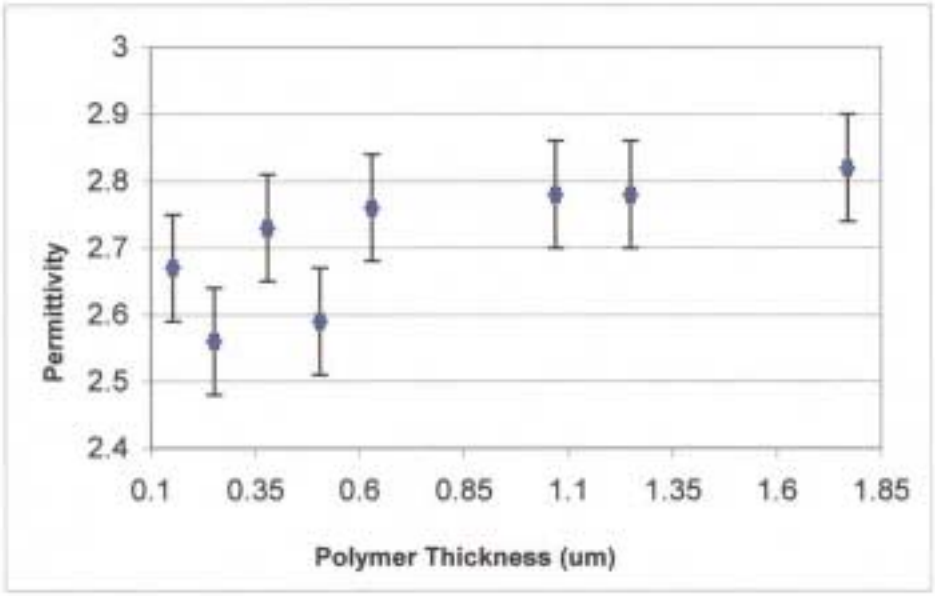

Figure 2. Dielectric Constant vs. Polymer Thickness for 4022 BCB

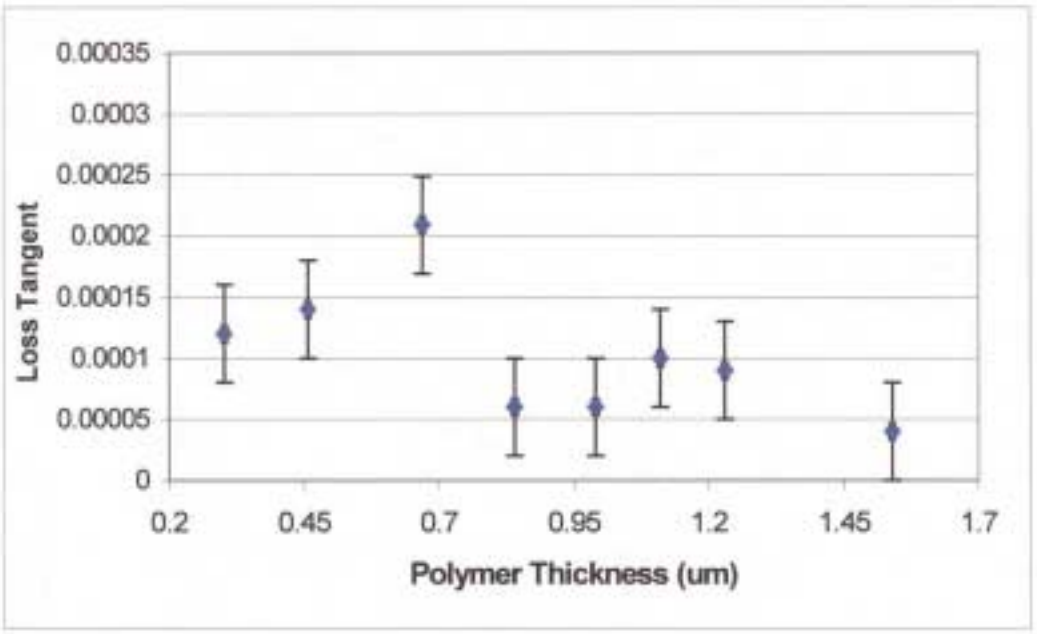

Figure 3. Loss Tangent vs. Polymer Thickness for 3022 BCB

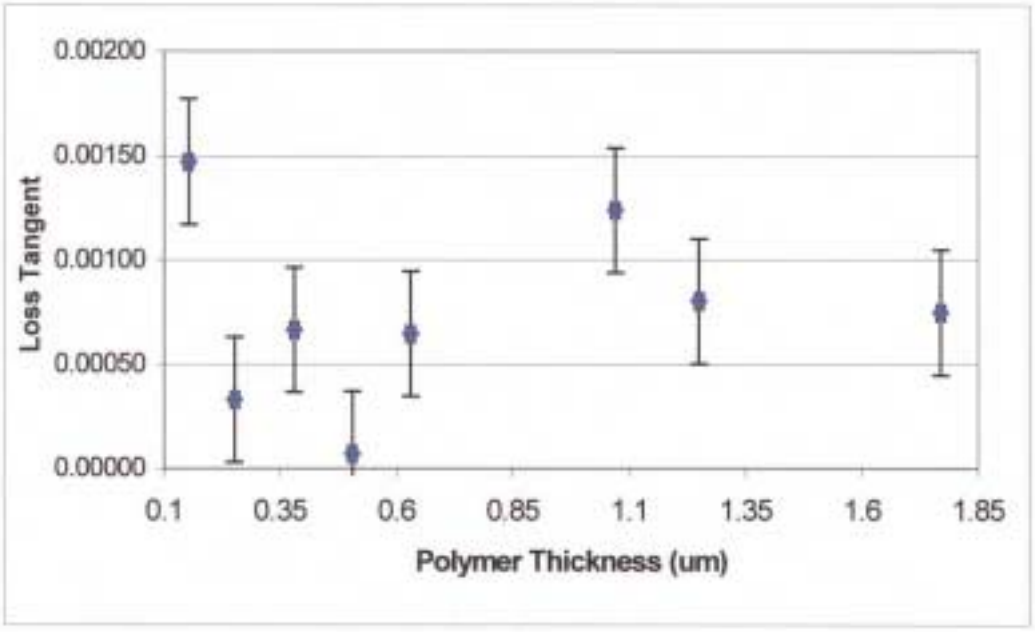

Figure 4. Loss Tangent vs. Polymer Thickness for 4022 BCB

Conclusions

Thin films of photosensitive and nonphotosensitive BCB were fabricated and the DOP and dielectric properties were investigated. It was found that the no significant thin-film effects were observed. That is, films as thin as 0.2 μm exhibited dielectric properties similar to thick films. The dielectric properties of the photosensitive BCB were slightly higher than nonphotosensitive BCB. The degree of planarization of the thin 3022 BCB was substantial, even when the polymer thickness was much less than the width of the structure to be planarized. The photosensitive BCB (4022) did provide some planarization, it was significantly less than the nonphotosensitive BCB because of the photo-induced cross-linking.

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