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Embedded benzocyclobutene in silicon: An integrated fabrication process for electrical and thermal isolation in MEMS

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Abstract

This paper reports a novel fabrication process to develop planarized isolated islands of benzocyclobutene (BCB) polymer embedded in a silicon substrate. Embedded BCB in silicon (EBiS) can be used as an alternative to silicon dioxide in fabrication of electrostatic micromotors, microgenerators, and other microelectromechanical devices. EBiS takes advantage of the low dielectric constant and thermal conductivity of BCB polymers to develop electrical and thermal isolation integrated in silicon. The process involves conventional microfabrication techniques such as photolithography, deep reactive ion etching, and chemical mechanical planarization (CMP). We have characterized CMP of BCB polymers in detail since CMP is a key step in EBiS process. Atomic force microscopy (AFM) and elipsometry of blanket BCB films before and after CMP show that higher polishing down force pressure and speed lead to higher removal rate at the expense of higher surface roughness, non-uniformity, and scratch density. This is expected since BCB is a softer material compared to inorganic films such as silicon dioxide. We have observed that as the cure temperature of BCB increases beyond 200 °C, the CMP removal rate decreases drastically. The results from optical microscopy, scanning electron microscopy, and optical profilometry show excellent planarized surfaces on the EBiS islands. An average step height reduction of more than 95% was achieved after two BCB deposition and three CMP steps.

Keywords: Benzocyclobutene; BCB; MEMS; Electrical isolation

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1. Introduction

Electrical and thermal isolation, as well as physical properties of dielectric materials, play an increasingly important role in the performance, efficiency, and reliability of microelectromechanical systems (MEMS). The range of dielectric materials and isolation techniques in MEMS has grown, especially in recent years. Traditionally, silicon dioxide has been and still is used for insulation in microelectronics and MEMS. Recent advances in the area of power MEMS [1,2] include a significant number of research activities on development of crack-free, low-stress, and thick silicon dioxide films [3–5]. In addition to electrical insulation, thick silicon dioxide has been used for high-frequency [6] and thermal [7,8] isolation. The drawbacks of silicon dioxide as an insulating film for MEMS applications include high dielectric constant, limited thickness due to high residual stress, and high-temperature process, which affects the performance, efficiency, and reliability [9].

Low-dielectric-constant (low-k) polymers based on benzocyclobutene (BCB) [10,11] have several advantages over silicon dioxide for variety of applications, including electrical and thermal isolation in MEMS. BCB polymers ere primarily used as an interlayer dielectric (ILD) for microelectronic applications [12], and more recently for low-temperature adhesive wafer bonding [13] and as a structural material [14] in MEMS. BCB polymers are commercially available in the form of partially cured BCB monomers in mesitylene solvent under a trademark name (Cyclotene) from Dow Chemical (Midland, MI).

Table 1 compares common physical properties of silicon dioxide and those of BCB polymers. The lower dielectric constant of BCB polymers ($k = 2.65$) in combination with employing a thicker film leads to lower parasitic capacitances, and as a result, to lower electrical energy loss in electrostatically driven MEMS. The higher volume resistivity of BCB polymers ($\rho = 10^{19}\ \Omega\,\text{cm}$) reduces the leakage current through the insulating layers.

Table 1
Physical properties of BCB polymers and silicon dioxide (at 25 °C unless otherwise noted) [BCB properties from manufacturer's data sheets]

Physical properties	SiO_2	BCB polymer
Dielectric constant	3.9	2.65 (hard-cured)
Dissipation factor	0.0002	0.0008–0.002 (at 1 MHz to 10 GHz)
Dielectric strength (V/cm)	$6–9 \times 10^6$	3×10^6
Volume resistivity (Ω cm)	1×10^{14}	1×10^{19}
Tensile strength (MPa)	69–276	85 ± 9 (dry-etch) 87 ± 9 (photo)
Tensile modulus (GPa)	73	2.0 ± 0.2 (dry-etch) 2.9 ± 0.2 (photo)
Tensile elongation (%)	N/A	8 ± 2.5 (at break)
Poisson ratio	0.17	0.34
Residual stress on Si (MPa)	100–300 (comp.)	28 ± 2 (tensile)
Thermal conductivity (W/m K)	1.4	0.29
Specific heat (J/kg K)	1400	2180
CTE (ppm/°C)	0.5	52 (at 25–300 °C)
Transition temperature	1710 °C (melting)	350 °C (glass transition)
Thermal stability (% weight loss/h)	N/A	1.6 (at 350 °C)
Index of refraction	1.46	1.54 (hard-cured) (at 1300–1550 nm)
Density (g/cm^3)	2.19	1.05 (hard-cured)
Moisture uptake (%)	N/A	0.13 (dry-etch, at 81%RH) 0.14 (photo, at 84%RH)
Shrinkage (%)	N/A	<5 (hard-cured)
Planarization (%)	N/A	>90