Synthesis and characterization of flexible and high-temperature resistant polyimide aerogel with ultra-low dielectric constant

X. M. Zhang^{1*}, J. G. Liu², S. Y. Yang²

¹School of Electrical Engineering, Beijing Jiaotong University, 100044 Beijing, China

²Laboratory of Advanced Polymer Materials, Institute of Chemistry, Chinese Academy of Sciences, 100190 Beijing, China

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Abstract. A polyimide (PI) aerogel with excellent combined thermal and dielectric properties was successfully prepared by the polycondensation of 3,3',4,4'-biphenyltetracarboxylic dianhydride (BPDA), 5-amino-2-(4-aminophenyl)benzoxazole (APBO) and octa(amino-phenyl)silsesquioxane (OAPS) crosslinker, followed by a supercritical carbon dioxide (scCO₂) drying treatment. The developed PI aerogel exhibited an ultra-low dielectric constant (k) of 1.15 at a frequency of 2.75 GHz, a volume resistivity of $5.45 \cdot 10^{14} \Omega \cdot \text{cm}$, and a dielectric strength of 132 kV/cm. The flexible PI aerogel exhibited an open-pore microstructure consisting of three-dimensional network with tangled nanofibers morphology with a porosity of 85.6% (volume ratio), an average pore diameter of 19.2 nm, and a Brunauer-Emmet-Teller (BET) surface area of 428.6 m²/g. In addition, the PI aerogel showed excellent thermal stability with a glass transition temperature (T_g) of 358.3 °C, a 5% weight loss temperature over 500 °C, and a residual weight ratio of 66.7% at 750 °C in nitrogen.

Keywords: thermal properties, polyimide aerogel, supercritical drying, dielectric properties

1. Introduction

In the past decades, polymer dielectrics with low dielectric constant (low- k) and low dissipation factor features have been paid increasing attention in ultra-large scale integrated circuit (ULSI) fabrication due to their abilities to lower the line-to-line noise in interconnects and alleviate power dissipation issues by reducing the capacitance between the interconnect conductor lines so as to achieve faster signal transmission speed [1–3]. Among various polymer dielectrics, polyimides (PIs) have been investigated more extensively as high performance interlayer dielectrics (ILDs) than most other polymers due to their desirable high-temperature stability, excellent mechanical and dielectric properties for ULSI fabrications [4–6]. However, conventional PI dielectrics usu-

ally have k values around 3.0, which cannot meet the rapid development of ULSI assembly. For example, according to the prediction of International Technology Roadmap for Semiconductors (ITRS), by 2016, a k value below 2.0 at 1 GHz and a dielectric loss below 0.003 have to be met for the ILDs [7]. It has been proven that the common methodologies reducing the k values for conventional PIs ($k \approx 3.0$), including introduction of substituents with low molar polarizability (fluorinated groups, alicyclic groups, etc.) or with large molar volumes (phenyl, fluorene, etc.) could only achieve a lowest k value around 2.5 [8].

In recent years, it was found that incorporation of air voids ($k = 1.0$) into the polymers is efficient to achieving a k value less than 2.0. Thus, various macroporous,

*Corresponding author, e-mail: xmzhang@bjtu.edu.cn
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mesoporous or nanoporous low- k polymer films have recently been very attractive for ILD applications to reduce k to a minimum value [9]. By this methodology, various ultra low- k PIs have been reported [10–14]. However, the attempts further reducing the k values of PIs below 1.5 seem to be more challenging because the conventional methods could only achieve a very limited air loading (<60%, volume ratio).

Very recently, aerogel dielectrics have been becoming one of the most important research topics for high performance ILDs using in ULSI due to their extremely high porosity, low density, low thermal conductivity, and ultra-low dielectric constants [15]. The porosity of an aerogel material can usually reach over 80% (volume ratio). The trapped air efficiently decreases the k values of the aerogels to a low level extremely close to 1.0 for air. Among various aerogels, organic polymeric aerogels are more suitable to be used as ILDs for ULSI due to their intrinsically flexible and tough nature compared with their fragile inorganic counterparts, such as silica, alumina aerogels, etc. [16]. Various polymer aerogels, such as polyurethane, polyurea, polystyrene, and polydicyclopentadiene aerogels have been widely investigated in the literature and have been finding a variety of applications in high-tech fields [17]. However, common organic aerogels usually suffer from their low thermal and dimensional stability at elevated temperatures; thus cannot meet the severe demands of interlayer electrical insulation process for ULSI fabrications. Thus, as a representative high-temperature resistant organic aerogels, PI aerogels have been developed rapidly in recent years [18–22]. The dielectric constants and dissipation factors for PI aerogels have also been investigated in detail. For instance, Meador and coworkers studied the dielectric properties of PI aerogels and investigated their potential applications as substrates for lightweight patch antennas for aerospace applications [23, 24]. Relative k values as low as 1.16 at a frequency of X-band (~11–12 GHz) were obtained for PI aerogels made from 3,3',4,4'-biphenyl tetracarboxylic dianhydride (BPDA), 2,2'-dimethylbenzidine (DMBZ), and 1,3,5-tris(4-aminophenoxy)benzene (TAB) crosslinker. Shen and coworkers have reported intrinsically highly-hydrophobic semi-alicyclic fluorinated PI aerogel with ultra-low k values of 1.17–1.19 in the frequency range of 2–12 GHz [25].

The dielectric constants and dissipation factor of PI aerogels have been investigated in the literature; however, other dielectric behaviors for PI aerogels have been rarely addressed in the literature although they are also very important for their applications in ULSI. For example, in addition to low dielectric constants, the next generation of ILDs for submicron and nano-level electronics must also satisfy a variety of other requirements, including high dielectric strength and resistivity, high thermal and dimensional stability, low moisture adsorption, and good adhesion to semiconductor and metal substrates in order to achieve high reliability [26]. As we know, for porous low- k polymers, while increasing porosity can reduce the k values; however, the dielectric strength is often adversely affected. To the best of our knowledge, the dielectric breakdown behavior for PI aerogels or even organic aerogels has been rarely involved in the literature. In the current paper, a PI aerogel was first prepared from BPDA, APBO and OAPS via a scCO_2 drying procedure, and then the thermal and dielectric properties for the aerogel were investigated in detail. Especially the dielectric breakdown behavior for the aerogel was studied.

2. Experimental

2.1. Materials

3,3',4,4'-Biphenyltetracarboxylic dianhydride (BPDA) and 5-amino-2-(4-aminophenyl)-benzoxazole (APBO) were purchased from Tokyo Chemical Industry Co., Ltd. (TCI), Japan. BPDA was dried *in vacuo* at 180 °C overnight prior to use and APBO was used as received. Octa(aminophenyl) silsesquioxane (OAPS) was purchased from Meilian Composite Co. Ltd., Liaoning, China and used as received. *N*-methyl-2-pyrrolidinone (NMP) was purified by vacuum distillation over CaH_2 and stored over 0.4 nm molecular sieves prior to use. The other commercially available reagents were used without further purification.

2.2. Characterization

Fourier transform infrared (FT-IR) spectrum was obtained on a Bruker Tensor-27 FT-IR spectrometer. Field emission scanning electron microscopy (FE-SEM) was obtained on a Hitachi S-4800 microscope. PI aerogel surface area (σ) and pore size distribution were measured by nitrogen adsorption and desorption at 77 K using a Micromeritics ASAP 2000 surface

areas and porosity analyzer. Before testing, the PI aerogel sample was outgassed at 80 °C for 10 h *in vacuo*. The surface area was calculated by Brunauer-Emmet-Teller (BET) method and pore size distribution was calculated by Barret-Joyner-Halenda (BJH) method. The bulk density (ρ_b) and skeletal density (ρ_s) were measured by mercury intrusion porosimetry using a Micromeritics Auto Pore IV9520 porosimeter. The percent porosity was calculated as: porosity (%) = $(1 - \rho_b/\rho_s) \cdot 100$. The thermogravimetric analyses (TGA) were recorded on a TA-Q50 thermal analysis system at a heating rate of 20 °C/min in nitrogen. Thermal mechanical analyses (TMA) were performed on a TA-Q400 analyzer over 50–400 °C at a heating rate of 5 °C/min in nitrogen. The compression properties of the PI aerogels were measured on an Instron 5567 according to the ASTM Standard D 695-10. The Young's modulus was determined as the initial linear portion of the slope of the stress-strain curve. The electrical insulation properties were measured on a PC68 digital high-voltage and high-resistance Megger instrument. The surface resistivity (ρ_s) and volume resistivity (ρ_v) of PI aerogel were measured according to ASTM D-257-91. The samples were dried at 120 °C for 1 h prior to measurement. Dielectric strength of PI aerogel film ($d = 2.5$ mm) were measured according to ASTM D-149-81, which were subjected to 60 cycles AC voltage at 100 V/s rate of rise to the breakdown voltage. The broadband dielectric constant (k) and dissipation factor (δ) is measured by an Agilent vector network analyzer (Model 8510) at room temperature. The frequency was in the range of 2–12 GHz and the sample size was 50 mm × 30 mm × 2.5 mm.

2.3. Synthesis of PI aerogel

To a three-necked 250 mL flask equipped with a mechanical stirrer, a nitrogen inlet and a cold water bath was charged with APBO (1.3885 g, 6.1644 mmol) and NMP (25 g) at 10–15 °C under a nitrogen flow of 10 mL/min. After stirring for 20 min, a clear solution was obtained. Then, BPDA (1.8722 g, 6.3632 mmol) was added in one batch and an additional volume of NMP (26 g) was added to wash the residual dianhydride and adjust the solid content of the reaction solution to be 6 wt%. The cold water bath was removed after 2 h. The mixture was stirred at room temperature for 12 h to yield a viscous poly(amic acid)

(PAA) solution. To the solution, OAPS (0.0575 g, 0.0497 mmol) was added and the reaction mixture was stirred at room temperature for another 12 h to afford a pale-brown viscous solution. Acetic anhydride (3.1 mL, 31.6 mmol) and pyridine (2.6 mL, 31.6 mmol) were then added to the PAA solution. After stirring at room temperature for 30 min, the solution was poured into pre-prepared molds. The molds were pre-made into various required shapes according to the demands of different measurement standards. For example, disk-shape molds were made for dielectric properties measurements; cylinder-shape for compression measurements; and rectangular shape for TMA measurements, etc.

The PAA solution gelled within 2 h and further aged for 24 h in the molds. Then, the gels were continuously immersed into a solution of 75% NMP in ethanol for 24 h, then a 25% NMP in ethanol for 24 h, and finally a 100% ethanol for 24 h. The obtained wet gels were then dried in a 160 L supercritical CO₂ (scCO₂) autoclave (maximum temperature: 80 °C; maximum pressure: 32 MPa; and maximum flow: 400 L/h) at the condition of 45 °C under 15 MPa for three cycles, 2 h each time. Then, the PI aerogel (BPDA/APBO/OAPS) was dried *in vacuo* at 80 °C for 24 h to afford the target aerogels as yellow monolithic solids with various shapes.

3. Results and discussion

3.1. PI aerogel preparation

A PI aerogel was designed and synthesized from rigid BPDA dianhydride, benzoxazole-containing APBO diamine, and POSS-containing OAPS cross-linking agent, as shown in Figure 1. Basically rigid molecular skeleton structures would guarantee the high thermal and dimensional stability for the PI aerogel. Introduction of benzoxazole moiety into the molecular structure of the PI aerogel via diamine monomer is to endow the polymer with good dielectric properties. As we know, polybenzoxazole (PBO) has an advantage over other polar high-temperature polymers (PI, polyamide, polybenzimidazole, etc.) due to the absence of polar groups in its repeating unit. The absence of polar groups in the polymer prevents the formation of hydrogen bond between the polymer and water, therefore resulting in less water absorption in the polymer and low dielectric constant (<2.9 at 1 MHz) and dielectric loss factor [27]. Ad-

ditionally, PBO is also known for its excellent thermal and thermo-oxidative resistance, high electrical resistivity, and high dielectric strength over a long temperature period. Thus, the benzoxazole moiety in the current PI aerogel might provide various desir-

able properties for the target aerogel. At last, OAPS was chosen to be an end-capper to crosslink the PI system affording the three-dimensional network microstructure. The nanoporous cage structure for OAPS is undoubtedly beneficial to decreasing the k values

a)

b)

Figure 1. (a) Synthesis of PI (BPDA/APBO/OAPS) aerogel, (b) appearance of PI wet gel (above) and PI aerogel (below)

for the PI aerogel. Actually, OAPS has been widely used as components to develop low- k PI films. PI composite films with k values around 1.9 have been prepared by OAPS functionalized graphene oxide and PI matrix [28].

In the preparation, excessive BPDA was first reacted with APBO to give a anhydride-capped PI precursor, poly(amic acid) (PAA) solution. Then, OAPS was added into the PAA solution inducing a crosslinking reaction of the PAA. Dehydrating agent (acetic anhydride/pyridine system) was then added into the solution affording a PI wet gel. The PI wet gel exhibited excellent flexibility and toughness, which could be bent with a large radius of curvature (picture inserted in Figure 1). Then, the PI wet gel was immersed into ethanol to extract the NMP solvent. At last, the residual NMP and ethanol trapped in the gel was dried with scCO_2 at 45 °C with a pressure of 15 MPa to give the final PI aerogel (Figure 1). This drying condition is more efficient and gentle than that of other supercritical fluids, such as supercritical ethanol (critical point: 243 °C, 6.38 MPa). The prepared PI aerogel exhibited good mechanical properties. The stress-strain correlation in the compression tests indicated linear elastic regions below 10% strain and yielded in a relatively low slope for the aerogel. The compression stress of the PI aerogel at 10% strain is 0.92 MPa and the Young's modulus is 18.2 MPa. These values are comparable to those mechanically strong PI aerogels reported in ref, [21]. The good mechanical properties for the PI aerogel are mainly attributed to the flexible and tough nature for the PI resin containing rigid biphenyl and benzoxazole moieties. In our experiments, PI aerogels with various shapes and sizes, including rods, films, sheets, and bulks were prepared for further measurements.

The chemical structures of the PI aerogel were identified by FT-IR measurements, illustrated in Figure 2. The characteristic absorption bands due to the vibration of the carbonyl groups ($\text{C}=\text{O}$) in the imide segments are clearly observed at 1766 and 1722 cm^{-1} , which are assigned to the asymmetric and symmetric stretching vibrations, respectively. In addition, the stretching vibration of $\text{C}-\text{N}$ bond located at 1371 cm^{-1} and the imide ring deformation at 740 cm^{-1} further confirm the formation of PI. Meanwhile, the absence of absorbing band around 1855 cm^{-1} ($\nu_{\text{C}=\text{O}}$ in BPDA) indicated the complete reaction of the dianhydride.

Figure 2. FT-IR spectra of PI aerogel and its crude materials

Similarly, absorbing bands around 3392 cm^{-1} ($\nu_{\text{N}-\text{H}}$ in APBO) and 1640 cm^{-1} ($\nu_{\text{amide, C}=\text{O}}$ in PAA) are also absent, indicating the completion reaction of the APBO and the successful conversion from the PAA precursors to PIs by chemical imidization.

3.2. PI aerogel morphology

The microtopography and physical parameters of the PI aerogel, including density, porosity, surface area, and volume shrinkage were investigated in detail. First, the FE-SEM measurement was performed to investigate the morphology of the PI aerogel, as shown in Figure 3. For the polymer, the open-pore structure consisting of three-dimensional networks with tangled nanofibers morphology having diameters at the nanometer scale were observed. This morphology determined the properties of the PI aerogel. The open-pore structure might endow the aerogel with low density and low dielectric constants, while the three-dimensional networks tangled with nanofibers might provide good mechanical properties for the aerogel. The morphology-property correlations will be subsequently discussed in detail.

This three-dimensional network microstructures for the PI aerogel are mainly caused by the highly cross-linked structure of the molecular chains in the aerogel. The solvents in the networks were continuously extracted by the solvent exchange process and following supercritical drying procedures, leaving nano pores in the final aerogels. The volume of the PI aerogel shrinks 14.5% of its original value during the supercritical drying process. This value is comparable to the PI aerogels reported in the literature [29]. The low shrinkage and microtopography for the current

aerogel prove that supercritical drying is an efficient procedure producing polymer aerogels. It has been established that supercritical fluids obtained above the critical point in temperature-pressure diagram enable drying the wet polymer gels without capillary stress due to absence of liquid-vapor interfaces in the phase [30]. In addition, scCO_2 is a clean and versatile solvent, which has been widely used for the processing of a range of porous polymers due to the chemical, environmental, and economic advantages [31]. Using this technique, porosity higher than 85–90% and dielectric constants below 1.5 can usually be obtained. Adversely, for other porous gels, such as Xerogels prepared by common drying techniques, the gels are easily collapsed by capillary stress induced

at the liquid-vapor interfaces during drying process, resulting in apparent shrinkage for the nanoporous gels (>30%). The porosity is usually lower than 60–80% and the k values are always higher than 1.50 [32, 33].

The structural parameters for PI aerogel are tabulated in Table 1. The ρ_b and ρ_s values of PI aerogel were measured by mercury intrusion porosimetry method. The nanoporous structure for the aerogel endows them with low bulk density (ρ_b) of 0.21 g/cm^3 . Air occupies the free empty space in the aerogel with a porosity of 85.6% as calculated from the ρ_b and skeletal density (ρ_s) of the aerogel. The surface areas (σ) and pore size distribution of the PI aerogel were measured by N_2 adsorption and desorption isotherms, using the Brunauer-Emmet-Teller (BET) method. As deduced from the N_2 adsorption-desorption isotherm shown in Figure 4, the PI aerogel shows BET surface area of $428.6 \text{ m}^2/\text{g}$. The pore size distribution of PI aerogel calculated by Barret-Joyner-Halenda (BJH) method (Figure 4b) indicates that the average pore diameter in PI aerogel is 19.2 nm . In addition, it can be seen from Figure 4 that PI aerogel showed rapid increases in adsorbed volumes at relative pressure above 0.9 and the desorption plots exhibited narrow loops. All this information indicates that both mesoporous and macroporous structures exist in the PI aerogel.

Figure 3. SEM image of PI aerogel

Table 1. Structural parameters and thermal properties of the PI aerogel

Sample	ρ_b^a [g/cm ³]	ρ_s^b [g/cm ³]	Porosity ^c [%]	σ^d [m ² /g]	d^e [nm]	$T_{5\%}^f$ [°C]	R_{w750}^g [%]	T_g^h [°C]
PI aerogel	0.21	1.46	85.6	428.6	19.2	502	66.7	358.3

^aBulk density. ^bSkeletal density. ^cCalculated by $1 - (\rho_b/\rho_s)$. ^dBrunauer-Emmett-Teller (BET) surface area. ^eAverage pore diameter from the BJH desorption plot. ^fTemperature at 5% weight loss. ^gResidual weight ratio at 750 °C in nitrogen. ^hGlass transition temperature.

Figure 4. (a) N_2 adsorption-desorption isotherm data for PI aerogel. (b) pore size distribution plot (BJH plot)

3.3. Thermal properties

Thermal properties of the PI aerogel were evaluated by thermogravimetric analyses (TGA) and thermal mechanical analyses (TMA) measurements and the data were tabulated in Table 1. The TGA measurements of the PI aerogels were performed in nitrogen from 50 to 750 °C and the results are shown in Figure 5. From the plot, it can be observed that the aerogel showed good thermal stability up to 450 °C. The smooth plots around 300 °C indicated the complete remove of residual NMP solvent by the supercritical drying procedure and the complete imidization in the system. The 5% weight loss temperatures ($T_{5\%}$) are 505 °C and the residual weight ratio (char yield) of the aerogel at 750 °C is 66.7% in nitrogen, indicating good thermal stability of the aerogel.

Figure 5. TGA plot of PI aerogel

Figure 6. TMA plot of PI aerogel

The dimensional changes of aerogel at elevated temperatures were investigated by TMA measurements, as depicted in Figure 6. The aerogel showed expansion behavior after the occurrence of glass transition around 350 °C. A T_g value was recorded at 358.3 °C for the aerogel. This value is much higher than those of common polymer aerogels, which can guarantee the good reliability of the aerogel in ULSI fabrication.

3.4. Dielectric properties

The dielectric properties of the PI aerogel, including surface (ρ_s) and volume (ρ_v) resistivity, dielectric strength, dielectric constant and dissipation factor were investigated. These dielectric parameters are critical for their applications in ULSI applications. As shown in Table 2, the ρ_v and ρ_s values for the aerogel are $5.45 \cdot 10^{14} \Omega \cdot \text{cm}$ and $8.74 \cdot 10^{13} \Omega$, respectively, indicating excellent electrical insulation properties.

The dielectric breakdown strength of the aerogel is 132 kV/cm at a thickness of 2.5 mm in our measurement. This value is a bit higher than that expected for porous materials. Similar phenomenon has also been observed by Hrubesh and Pekala [34] in their research on inorganic silica aerogels. In their investigation, the dielectric strength of 128 kV/cm was recorded for silica aerogels and this value was higher than those of common ceramics, such as alumina (110 kV/cm) although lower than those of pure polymers (160–500 kV/cm). The authors ascribed this unexpected high dielectric strength for aerogels to the small pore sizes in the air-filled aerogels. The pore sizes are of the same order as the mean free path for electron collisions. Thus, electrons in aerogel pores tend to collide with the solid before gaining sufficient kinetic energy to ionize upon impact. In the current work, the dielectric strength of 132 kV/cm at a thickness of 2.5 mm was recorded, which is comparable to that of inorganic silica aerogels.

We further investigated the dielectric breakdown behavior for the PI aerogel. Figure 7 compares the surface macro- and micro-topographies of PI aerogel before and after dielectric breakdown under high

Table 2. Dielectric properties of the PI aerogel

	ρ_v^a [$\Omega \cdot \text{cm}$]	ρ_s^a [Ω]	d^b [mm]	D_s^c [kV/cm]	k^d	δ^e
PI aerogel	$5.45 \cdot 10^{14}$	$8.74 \cdot 10^{13}$	2.5	132	1.15	0.0023

^a ρ_v and ρ_s : volume and surface resistivity at 23 °C and 50% relative humidity, respectively; ^bPI aerogel thickness for k measurements; ^cdielectric breakdown strength; ^ddielectric constant at 2.75 GHz; ^edielectric loss factor at 2.75 GHz.

voltage. From the illustration, we can obviously observe that high level electrical voltage induces not only the dielectric breakdown, but apparent surface ablation phenomena in the tested area. Many pinholes were observed at the tested area, indicating dielectric breakdown of the PI solid. Basically, the dielectric properties of aerogels are dominated by the large volume fraction of trapped gas in the pores. However, during our measurement for dielectric breakdown, bright spark was observed at the moment of electrical breakdown, indicating a gaseous discharge. Meanwhile, high voltage breakdown occurred in the dense PI solid. Thus, the dielectric breakdown for PI aerogel might be ascribed to the simultaneous actions of high voltage to the trapped air and the dense PI solid. High temperature induced by the air discharge caused the surface ablation of the aerogel. At the same time, the instantaneous high temperature caused the expansion of the trapped air in the aerogel, resulting in the swelling at the surface of the

aerogel (Figure 7b). Nevertheless, the high dielectric breakdown strength makes the current PI aerogel to be effective and lightweight dielectric insulators for high-voltage insulating applications.

The broadband dielectric constant (k) and dissipation factor (δ) of PI aerogel in the frequency range of 2–12 GHz were measured at room temperature and the curve is illustrated in Figure 8. The monolithic PI

Figure 8. Dielectric constant (k) and loss tangent for PIA as a function of frequency

Figure 7. Surface macro- and micro-topographies of PI aerogel before (a) and after (b) dielectric breakdown, (c) SEM image before dielectric breakdown, (d) SEM image after dielectric breakdown

aerogel sample (50 mm×30 mm×2.5 mm) exhibited nearly a constant k value (1.15–1.13) over the entire frequency range. Thus, introduction of air within the PI reduced the k value significantly. The loss tangent (δ) value of PI aerogel also changed in a narrow range of $2.3 \cdot 10^{-3}$ – $4.0 \cdot 10^{-3}$. The frequency-independent feature of k and δ values for PI aerogel is mainly attributed to the high air loading (porosity: 85.6%) in its structure. The phenomena indicate that the dielectric constant of the PI aerogel is dominated by the trapped air rather than by the solid PI matrix.

4. Conclusions

New PI aerogel was synthesized from BPDA, APBO and OAPS via two-step chemical imidization procedure, followed by ScCO_2 drying procedure. The original purpose of molecular design aiming at developing functional PIs with potential applications as ILDs for ULSI was successfully achieved by the derived PI aerogel. Experimental results revealed that the current PI aerogel possessed various advantages compared with the other organic aerogels reported before. First, the polymer exhibited excellent thermal stability and T_g over 350 °C, which is among the most thermally stable polymers reported in the literature. Secondly, the current PI aerogel shows excellent dielectric characteristics, including ultra-low k value and dissipation factor over a broad frequency range of 2–12 GHz, high surface and volume resistivity, and high dielectric strength. The k value around 1.15 at a frequency of 2.75 GHz is one the lowest values for PI materials reported in the literature. Thus, good combined properties make the PI aerogel a good candidate as interlayer dielectric for advanced semiconductor chip interconnection.

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