

The properties of AlN-filled epoxy molding compounds by the effects of filler size distribution

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AlN filler was compared with crystalline silica as a filler for advanced epoxy molding compounds. Properties such as the thermal conductivity, dielectric constant, CTE, flexural strength, elastic modulus and water absorption ratio of water-resistant grade AlN-filled molding compounds according to the contents or size of AlN and the filler size distribution were evaluated. A spiral flow test was also carried out to measure the change in viscosity according to the AlN size distribution for improved fluidity. The properties of EMC that is filled with a 70 vol.% of 12 micron AlN was compared with a crystalline silica-filled EMC. Thermal conductivity was improved by 2.2 times, the dielectric constant was reduced to less than one-half, the flexural strength was improved, and the CTE was also reduced. A binary mixture of an AlN-filled (65 vol.%) EMC showed improved fluidity, thermal conductivity, dielectric constant, flexural strength and water resistance compared to a single-size AlN-filled EMC. The maximum improvement was obtained when the fraction of small particles in the binary mixture of the AlN is 0.2–0.3. The CTE of EMC was decreased by increasing the volume fraction of small particles in the binary mixture of the AlN.

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1. Introduction

Molded plastic packages are used to protect semiconductor devices from exposure to environmental hazards such as moisture, chemical agents, dust, and light, and to provide them excellent mechanical strength. Over the last few decades, the micro-electronic industry, which demands rapid development in computer and communication devices for rapid treatment of huge amounts of data has grown rapidly in size. Thus, integrated circuits having high performance are in demand and the demand has been increasing steeply [1–3]. The major functions of packaging are protecting devices from mechanical and chemical hazards, distributing signal and power, and dissipating heat. The ability of a package to adequately perform these functions depends on the properties of the device as well as the properties of the package material. Polymer is the most popular material in use for electronic packaging because it is cheap, its processing ability is excellent, and the circuit signal delay is minimal, according to a low dielectric constant. However, because of its low thermal conductivity, the use of a polymer is restricted to parts requiring high thermal dissipation [4].

Recently, package density is increasing for performance improvement and cost reduction. But, as pack-

age density increases, the electrical energy consumed in a device ultimately appears as heat, elevating the temperature of the active junction and other parts of the package housing of a device. Increased temperature adversely affects the reliability of a device [5, 6]. So, package material should have high thermal diffusion, i.e., high thermal conductivity. And, there are several other physical properties of polymeric materials that are important to micro-electronics packaging, some of which are a low dielectric constant, a low coefficient of thermal expansion (CTE), and a high flexural strength [7, 8].

Generally, epoxy molding compounds (EMC) consists of components such as epoxy resin, a hardener, and an inorganic filler, etc. Thermal conductivity of a plastic package strongly depends on the property of the filler used. Thermal conductivity of filler is very high when compared to that of an epoxy resin that has low atomic density. But, the thermal conductivity of a compound filled with a filler is not as high as the filler itself.

To more effectively solve the thermal dissipation problem, the use of highly thermal conductive ceramic fillers (listed in Table I) can be considered.

A crystalline silica-filled EMC, which has a thermal conductivity of about 1.7 W/m-K has already appeared on the market. Alumina seems good as a filler

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TABLE I The physical properties of inorganic fillers and epoxy resin [7]

Materials	Dielectric constant	Coefficient of thermal expansion (ppm/K)	Thermal conductivity (W/m-K)	Volume resistivity (Ohm-cm)
Crystalline silica	3.8–5.4	15	14	10^{14}
Alumina	8.9	6.7–7.1	20–25	10^{13}
AlN	8.8	4.5	130–260	5×10^{13}
Epoxy	6–8	50–90	0.02–0.04	10^{14}

but their main problem is the high abrasion of the molding equipment used to encapsulate the devices by an alumina-filled EMC. Though aluminum nitride (AlN) has higher possibility than the previous two materials, its usage was restricted to ignition modules and power transistors that require high thermal dissipation. High price (five to ten times higher than alumina), abrasion and hydrolysis by moisture were the main disadvantages of AlN. Nowadays, however, studies using AlN as a filler for the next generation EMC are being conducted because the price has decreased due to mass production and the introduction of the Si-O layer coated AlN has reduced the hydrolysis and the abrasion [9].

The dielectric constant of plastic packaging also plays an important role in device performance. The leads of devices and the wire bonds are completely embedded in the molding compound. Hence, the propagation characteristics of signals moving off a chip are directly dependent on the dielectric properties of the molding compound [10]. The signal speed is inversely proportional to the square root of the dielectric constant of the medium [11].

Fillers are often used in electronic package materials to decrease the coefficient of thermal expansion of EMC and are combined to modify the material fluidity. For higher filler loading by filler-size distribution to improve fluidity of EMC, the two-parameter Mooney equation (Equation 1) can be applied to predict the viscosity of the filled system [7].

$$\ln \frac{\eta}{\eta_0} = \frac{K_e \Phi}{1 - \Phi/\Phi_m} \quad (1)$$

where Φ_m is the maximum packing fraction that can be achieved by the ideal filler-size distribution, and K_e is the Einstein coefficient. Spherical filler particles have a maximum loading of approximately 60 vol.%. The highest loading are achieved with a combination of filler shapes or sizes so that the interstitial spaces are filled. Ultimate filler loading of over 90 vol.% can ideally be achieved in this way, but the physical properties of these low-resin systems are degraded to the point where they are no longer suitable for package applications. The Mooney equation describes the nonlinear behavior of the viscosity increase as the filler loading approaches the maximum packing fraction. It can be expected that the viscosity of compounds will be lower as the maximum packing fraction of the Mooney equation is increased. Fig. 1 shows idealized packing of binary mixture of spheres as a function of composition with diameter ratios as a parameter [12].

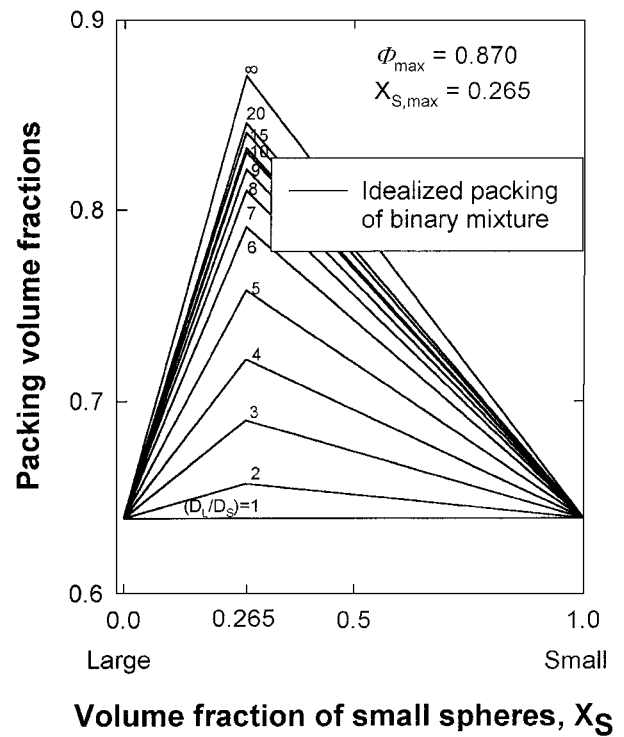


Figure 1 Idealized maximum packing of binary mixtures of spheres as a function of composition with diameter ratios as a parameter [12].

If the thermal conductivity of EMC is increased and the value of CTE of EMC is approached with the values of CTE of silicone die or a metal lead frame, the reliability of semiconductor device to the thermal fatigue will be greatly enhanced.

Understanding the changes in EMC's various properties according to the type, size, and contents of a filler is necessary for the development of excellent packaging materials. In this study, an AlN filler was compared with a crystalline silica filler for advanced epoxy molding compounds. Properties such as the thermal conductivity, CTE, flexural strength, and water resistance of AlN-filled molding compounds were evaluated according to the contents or size of AlN and the filler-size distribution. A spiral flow test was also carried out to measure the change of viscosity according to the AlN filler-size distribution for improved fluidity.

2. Experiment

2.1. Raw materials

The epoxy resin can be divided into two types; bisphenol-A and novolac. Solid novolac epoxy is the most widely used as a package material for semiconductors because novolac epoxy has excellent thermal stability. For this reason, in this study the novolac epoxy was selected as a base resin, and phenol-novolac as the hardener. Although phenol-cured epoxy is not widely used commercially, it provides high quality and excellent properties when compared with other cured epoxy used in microelectronic packaging. The average epoxy equivalent weight of novolac epoxy is $200 \text{ g}\cdot\text{mol}^{-1}\text{eq}$, and the average hydroxyl equivalent weight of phenol novolac is $106 \text{ g}\cdot\text{mol}^{-1}\text{eq}$. A coupling agent, an accelerator, and natural wax were used as additives. The basic recipe is shown in Table II [13].

TABLE II Basic recipe of epoxy molding compounds

Materials	wt%	Remark
Novolac epoxy resin	7–30	Equiv. wt of epoxy; 200
Phenol novolac hardner	3.5–15	Equiv. wt of phenol; 106
Catalyst (TPP)	0.75 phr	Equiv. wt ratio of epoxy/ phenol = 1.0
Inorganic filler (AlN, Cry. silica)	50–85	
Mold release agent (wax)	0.5	Density of AlN; 3.26
Coupling agent	0.5	Density of cry. silica; 2.65
Stress-relief agent	0.4	

Crystalline silica (supplied by Morimura Co., Japan, having the average particle size of 12 micron) and Si-O layer coated aluminum nitride (supplied by ART Co. U.S.A., having the average particle sizes of 2, 12, and 30 microns) were used as the filler.

2.2. The manufacturing process for EMC

A two-roll mill, which can support high torque, was chosen as a mixer in consideration of the high viscosity of a filled EMC (with over 50 vol.% of filler). According to the recipe shown in Table II, a aluminum nitride-filled master batch was mixed at the roll surface temperature of about 90°C for a proper dispersion time of 10 minutes to lower the degree of curing to the minimum. After that, the melt mixed EMC was cooled and crashed into granules. A disc-shaped EMC (which was made from preheated granules) was forced to flow into a heated cavity by a transfer molding machine with the pressure of 75 kg_f/cm², and after that, it was molded at 175°C for 2.5 minutes. The molded EMC was post-cured at 175°C for four hours. Conventional extrusion or injection molding methods are not appropriate for thermosetting epoxy compounds, so a low-pressure transfer molding method is generally used. The advantages of this process are the possibility of mass production (compared to compression molding) and the elimination of void formation by preheating in the manufacturing of composite materials from highly viscous materials. Therefore, for this study, the preheating process was included, and transfer molding was used. Overall, the manufacturing process of an AlN-filled EMC is shown in Fig. 2.

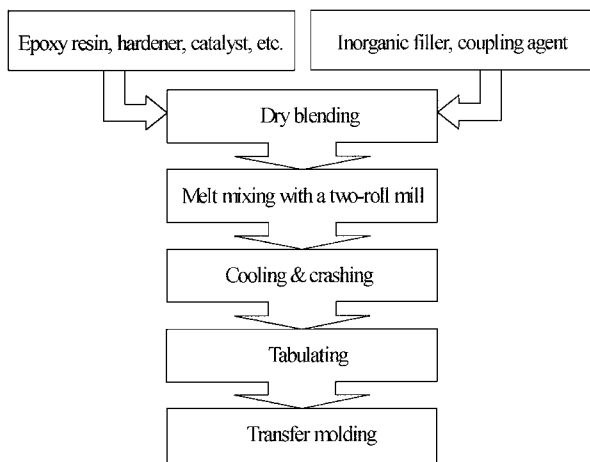


Figure 2 Manufacturing process of epoxy molding compounds.

2.3. Thermal conductivity

There are various equations including volume fraction, to estimate the thermal conductivity of composite materials. But, no equation can actually predict the thermal conductivity of complicated composite materials because predicting thermal conductivity depends on many factors, not just volume fraction. These equations are only useful in estimating thermal conductivity; accurate thermal conductivity should be measured by experimental measurements.

The measurement of thermal diffusivity (δ) was carried out by a laser flash method (Sinku-Riko Co. Model TC-7000) at room temperature. Specific heat (C) was measured by a DSC (Perkin-Elmer Co, Pyris D). Also, density of specimen was measured by water displacement. After that, thermal conductivity (k) was calculated by Equation 2 [14]:

$$k = C \times \rho \times \delta \quad (2)$$

2.4. Mechanical properties

Evaluation of mechanical properties of encapsulating compounds was carried out by using a universal testing machine (UTM). Flexural strength and elastic modulus were measured at room temperature by a three-point bending test with a cross-head speed of 2 mm/min, according to ASTM D790. The test specimens (2 × 10 × 60 mm) were prepared by transfer molding at 175°C for 2.5 minutes and cured in hot plates at 175°C for over 4 hours.

2.5. Dielectric properties

The dielectric properties of the composites material was measured by using a disc-shaped specimen (10φ × 2 mm) with a LF Impedance Analyzer (Hewlett Packard, model HP 4192A, testing frequency: 1 MHz) at room temperature. The dielectric constant can be calculated by Equation 3 by measuring the dielectric capacitance (c) [15]:

$$E = \frac{c}{(A/d)E_0} \quad (3)$$

where E is the dielectric constant of the specimen, c is the dielectric capacitance of the specimen, A is the area of cross-sectional surface, d is the thickness of the specimens, and E_0 is the dielectric constant in a vacuum. The sample was coated on both sides of the cross-sectional surface with a silver paste to let the electricity flow well on the surface.

2.6. Coefficient of thermal expansion

The coefficient of thermal expansion (CTE) of the composite was measured by using a bar-shaped specimen in a linear dilatometer (ANTER Co.) with a heating rate of 5°C/min. from room temperature up to 250°C. Equation 4 was used to calculate of CTE:

$$\alpha = \frac{\Delta L}{L_0 \Delta T} \quad (4)$$

where α is the coefficient of thermal expansion, $\Delta L/L_0$ is the thermal expansion ratio of a sample, and ΔT is the difference of temperature.

2.7. Spiral flow

A spiral flow test is extensively used by IC manufacturers to check the fluidity of thermosetting molding compounds, and all material vendors report the data [7]. This test consists of loading the molding compound into the heated transfer pot of the press and transferring it through a spiral coil with a semicircular cross section until the flow ceases. According to the test procedure (ASTM D3123), the recommended pressure and temperature are $110 \text{ kg}_f/\text{cm}^2$ on the material and 150°C for the mold. But, in this study, the test was carried out at $75 \text{ kg}_f/\text{cm}^2$ and 175°C .

2.8. Water resistance

The surface of the sample ($40\phi \times 4 \text{ mm}$) was polished with sandpaper before immersing it in water at 85°C for 7 days. To measure the degree of water resistance, the surface of the immersed sample was fully dried by wiping the moisture with dried cloth, and after that, the weight change of the sample was measured every 24 hours.

3. Results and discussion

3.1. Properties according to filler volume contents

3.1.1. The effects of filler volume contents on thermal conductivity

Thermal conductivity of AlN ($130\text{--}260 \text{ W/m-K}$) is higher than that of crystalline silica (14 W/m-K), but, in the compounds, the epoxy matrix ($0.02\text{--}0.04 \text{ W/m-K}$) in the space between fillers acts as a thermal barrier. Thus, the thermal conductivity of a compound is very low, compared to the filler itself. In Fig. 3, increased thermal conductivity of a compound caused by increasing filler loading contents is shown. For the case of an AlN-filled EMC, the slope of thermal conductivity as a function of filler volume fraction was steep. This is due to the large difference in the value of thermal conductivity between AlN and the epoxy matrix. But, the difference between the thermal conductivity of EMC filled with the aluminum nitride and that filled with crystalline silica was not large, even though the difference

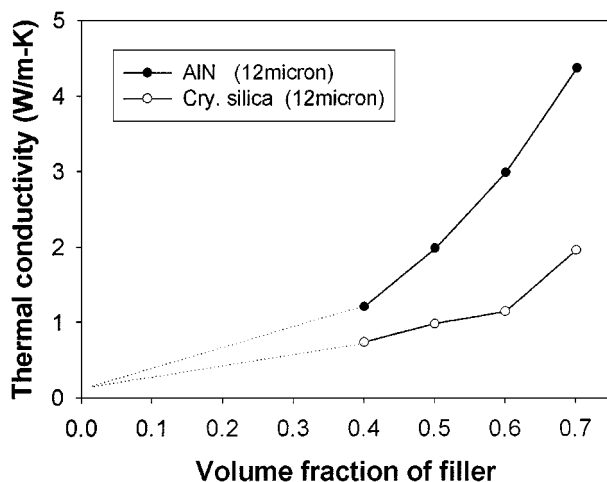


Figure 3 Thermal conductivity as a function of filler contents at 293 K for EMC filled with AlN and crystalline silica.

in the thermal conductivity of the filler itself is large. This is due to the huge effect of the thermal barrier of the epoxy matrix that is positioned between fillers. The thermal conductivity of an AlN-filled EMC was about 2.2 times greater than that of crystalline silica-filled EMC at room temperature for 70 vol.%. The increased thermal conductivity of EMC can reduce thermal gradients in the EMC surrounding the chip, and this can lead to improve resistance to thermal cycle fatigue.

3.1.2. The effects of filler volume contents on the dielectric constant

The dielectric constant was calculated from Equation 3 by measuring the dielectric capacitance of the sample with a LF Impedance Analyzer (Hewlett Packard co., U.S.A.) at 1 MHz. The effects of filler volume contents on the dielectric constant are shown in Fig. 4. By increasing filler volume contents, the value of the dielectric constant of EMC filled with crystalline silica was slightly decreased because the value of the epoxy matrix is higher than that of the filler. For the case of AlN-filled EMC, the value was increased because the value of AlN is higher than that of the epoxy matrix. But, at above 60 vol.% of filler content, the dielectric constant of AlN-filled EMC rapidly decreased. This is an opposite phenomenon compared to general cases and may be due to the electrical bridging of the particles above this volume fraction.

3.1.3. The effect of filler volume contents on flexural strength

Generally, when the amounts of contents of a filler in composite materials is increased, the flexural strength is also increased. The change of flexural strength according to the increase of filler volume fraction is shown in Fig. 5. Flexural strength of crystalline silica-filled epoxy molding compound was linearly proportional to the filler volume contents. When the matrix effect on

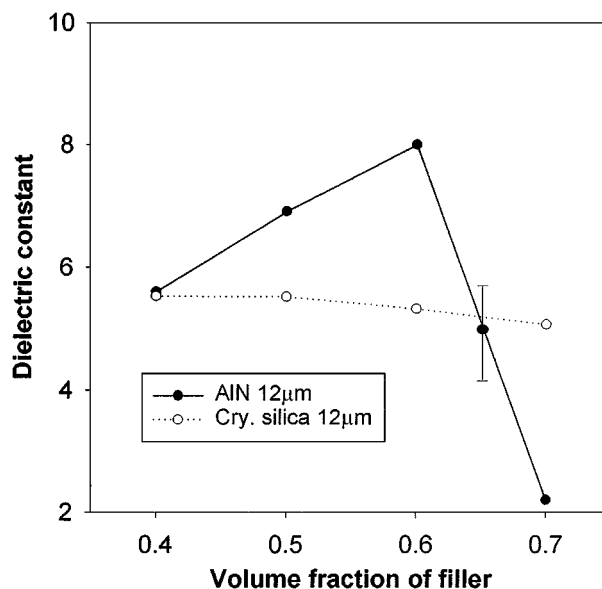


Figure 4 Dielectric constant as a function of filler contents at 293 K for EMC filled with AlN and crystalline silica.

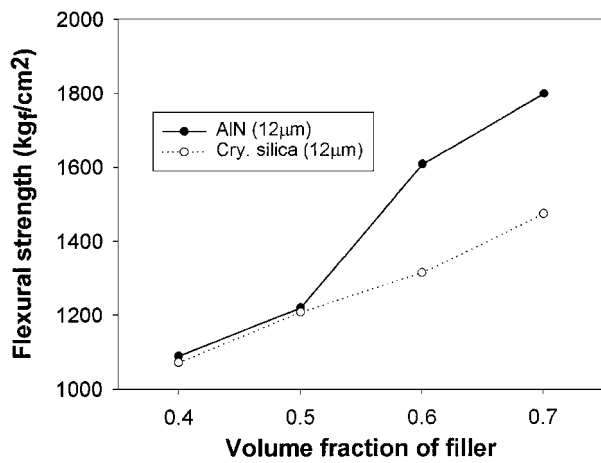


Figure 5 Flexural strength as a function of filler contents at 293 K for EMC filled with AlN and crystalline silica.

flexural strength is dominant, there is almost no difference in the value of flexural strength according to the filler type. But, filler effect on flexural strength becomes dominant by increasing filler volume contents. Si-O layer coated AlN-filled EMC shows higher values of flexural strength than crystalline silica-filled EMC when the contents of the filler is over 50 vol.%.

3.1.4. The effects of filler volume contents on the coefficient of thermal expansion (CTE)

If the value of the CTE of contacting materials shows a large difference, high thermal stress will build up. Thermal stress between two contacting materials can be calculated by the following relationship: $E_c \times \Delta\alpha \times \Delta T$, where E_c is the elastic modulus of EMC, $\Delta\alpha$ is the difference in CTE, and ΔT is the difference in temperature [11]. The value of the CTE of EMC can be lowered by increasing the filler loading content. The glass transition temperature of the EMC used in this study was about 150°C. In Fig. 6, CTE (α_1) below T_g and elastic modulus are shown. The CTE of the EMC decrease as the filler volume contents increased. The decreasing ratio of the EMC filled with AlN is somewhat higher than that of EMC filled with crystalline silica. But, the

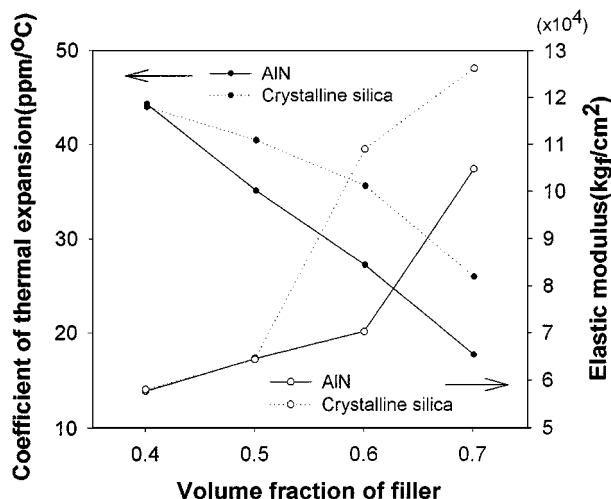


Figure 6 CTE and elastic modulus as a function of filler contents at 293 K for EMC filled with AlN and crystalline silica.

elastic modulus was increased along with filler volume contents. As a result, the thermal stress should be quite low for the case of an AlN-filled EMC because of the low values of the elastic modulus, CTE difference and the temperature difference (due to high thermal conductivity).

3.2. Properties according to filler size distribution

For a binary mixture of AlN fillers, filler volume content of the EMC was fixed as 65 vol.% because the processability on the two-roll mill, which involve such factors as mixing and dispersion of fillers in the epoxy matrix, was very poor when more than 65 vol.% of a binary mixture of AlN was used.

3.2.1. The effects of filler size distribution on spiral flow length

The reason for conducting filler size distribution in the EMC is to improve fluidity. In this study, for the binary mixture of AlN fillers, a 2-micron AlN filler was mixed with a 12-micron or a 30-micron AlN filler. After mixing AlN fillers and epoxy resin with a two-roll mill, a press tabulated the EMC, then a spiral flow test was carried out by a transfer molding machine with the pressure of 75 kgf/cm². In Fig. 7, best fluidity was obtained around the maximum packing fraction in both cases of $D_L/D_S = 6$ and 15. Here, D_L and D_S are the respective average diameters of large and small particles of AlN. Thus, it can be confirmed that fluidity can be improved by filler size distribution even if the shape of a filler is not sphere, i.e., the shape of an AlN filler is granular. Improvement of fluidity by filler size distribution was pronounced for the case of $D_L/D_S = 6$, which showed low fluidity at $X_S = 0.0$ here, X_S is the volume fraction of 2-micron AlN in a binary mixture of fillers. Fluidity of EMC, which is filled with 30-micron/2-micron AlN, is better than that in the case of 12-micron/2-micron AlN. This is due to the large total surface area of small-size fillers, which lead to a high viscosity of the EMC. As a result, fluidity can be improved by filler size distribution, but the effects of filler particle's size overrides the fluidity of the EMC.

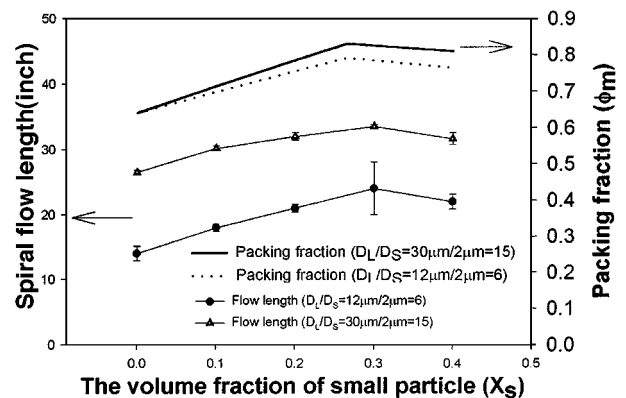


Figure 7 Spiral flow length of EMC filled with 65 vol.% of binary mixture of AlN as a function of 2 µm AlN composition at 175°C; with diameter ratio ($D_L/D_S = 15$ and 6) as a parameter Flexural strength as a function of filler contents at 293 K for EMC filled with AlN and crystalline silica.

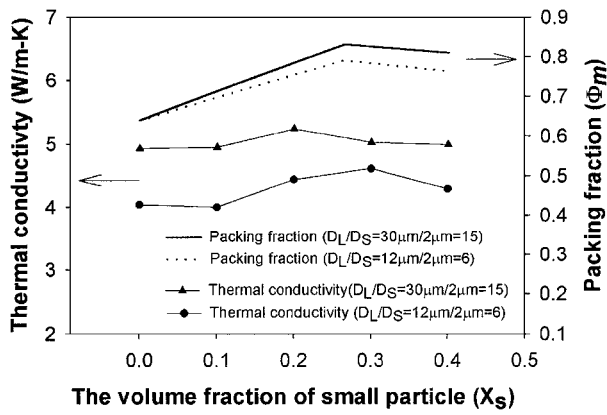


Figure 8 Thermal conductivity as a function of the content of 2 μm AlN in the binary mixture of AlN, at 293 K for EMC filled with 65 vol.% of AlN.

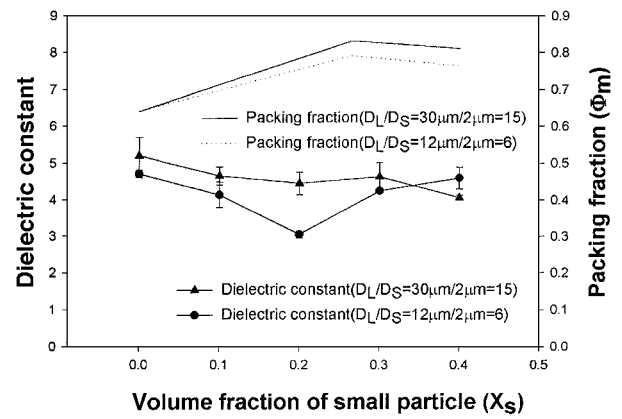


Figure 9 Dielectric constant as a function of the content of 2 μm AlN in the binary mixture of AlN, at 293 K for EMC filled with 65 vol.% of AlN.

3.2.2. The effects of filler size distribution on thermal conductivity

Thermal conductivity of EMC (65 vol.% of AlN) as a function of the volume fraction of 2-micron AlN in a binary mixture of fillers is shown in Fig. 8. For the case of a $D_L/D_S = 6$ binary mixture of fillers, the highest thermal conductivity, i.e., 4.6 W/m-K, was obtained at $X_S = 0.3$. This value is 1.15 times higher than that of a 12-micron AlN-filled EMC ($k = 4.0$ W/m-K). For the case of a $D_L/D_S = 15$ binary mixture of fillers, the highest thermal conductivity ($k = 5.2$ W/m-K) was obtained at $X_S = 0.2$. This value is 1.06 times higher than that of a 30-micron AlN-filled EMC ($k = 4.9$ W/m-K). 30-micron AlN fillers used in this study have a little broad distribution of filler size, so the highest thermal conductivity appeared at $X_S = 0.2$. But, 0.2 of X_S is not far from the value at which ideal maximum packing occurs ($X_S = 0.265$). The improvement of thermal conductivity by filler size distribution was pronounced for the case of $D_L/D_S = 6$ binary mixture of fillers. When the thermal conductivity was compared at $X_S = 0.0$, large size of AlN-filled EMC showed higher values of thermal conductivity. As a result, filler size distribution can improve the thermal conductivity of EMC, but the effects of a filler particle size overrides filler size distribution in the thermal conductivity of EMC.

3.2.3. The effects of filler size distribution on dielectric constant

The value of the dielectric constant of EMC as a function of the volume fraction of 2-micron AlN in a binary mixture of fillers is shown in Fig. 9. For the case of $D_L/D_S = 6$, dielectric constant of EMC (65 vol.%) showed a low values at $X_S = 0.2$. However, for the case of $D_L/D_S = 15$, the value of dielectric constant slightly decreased as the value of X_S increased. When $X_S = 0.0$, the value of the dielectric constant for EMC filled with small particles was lower than that of one filled with large particles. These results depend on the effects of filler distribution which may have micro-voids between small particles. Such micro-voids could decrease the value of the dielectric constant of the material because the value of the dielectric constant of voids is approximately one.

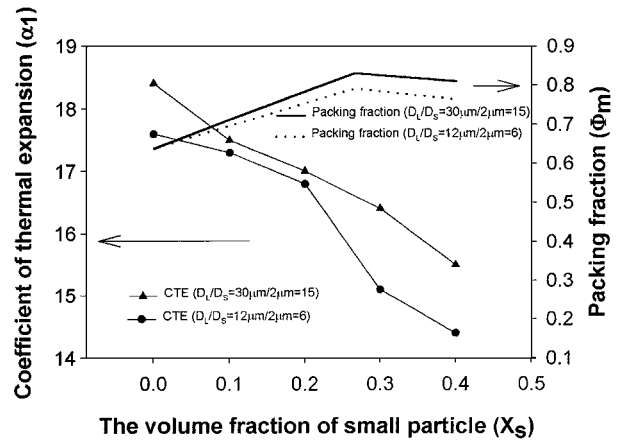


Figure 10 CTE ($T < T_g$) as a function of the content of 2 μm in the binary mixture of AlN for EMC filled with 65 vol.% of AlN.

3.2.4. The effects of filler size distribution on the coefficient of thermal expansion

The CTE of EMC (65 vol.%) as a function of the volume fraction of 2-micron AlN in a binary mixture of AlNs, i.e., X_S , is shown in Fig. 10. The value of the CTE decreased as the value of X_S increased, i.e., when $X_S = 0.4$, the value of the CTE was 82–84% of that of EMC filled with large-size particles AlN. EMC filled with large-size particles showed slightly higher values of the CTE than EMC filled with small-size particles. When $X_S = 0.0$ –0.4, the value of α_1 of 65 vol.% AlN-filled EMC is 14.5–18.5 ppm/ $^{\circ}\text{C}$. This value is less than one-half of crystalline silica-filled EMC ($\alpha_1 = 40$ ppm/ $^{\circ}\text{C}$), and similar to that of copper lead frame ($\alpha_1 = 17$ ppm/ $^{\circ}\text{C}$). As a result, matching the values of α_1 can reduce thermal stress.

3.2.5. The effects of filler size distribution on flexural strength

Flexural strength of EMC (65 vol.%) as a function of the volume fraction of 2-micron AlN in a binary mixture of AlN, i.e., X_S , is shown in Fig. 11. In both cases of $D_L/D_S = 6$ and 15, the flexural strength of EMC (65 vol.%) as a function of X_S showed maximum values at $X_S = 0.2$. When $X_S = 0.0$, flexural strength of

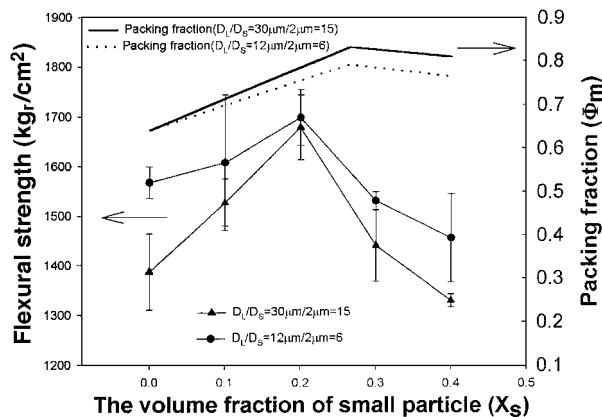


Figure 11 Flexural strength as a function of the content of 2 μm AlN in the binary mixture of AlN at room temp., for EMC filled with 65 vol.% of AlN.

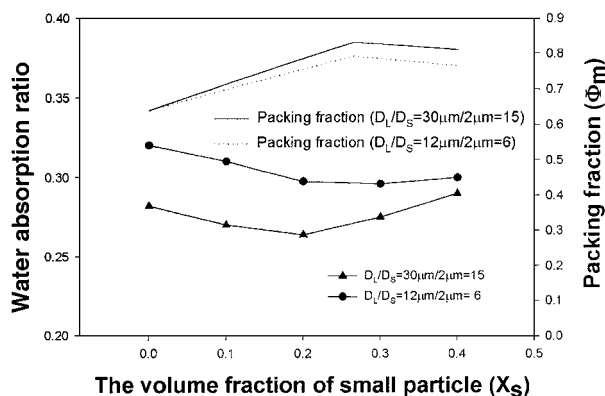


Figure 12 Water absorption ratio as a function of the content of 2 μm AlN in the binary mixture of AlN for EMC filled with 65 vol.% of AlN.

EMC that is filled with 12-micron AlN is higher than that of a 30-micron AlN-filled EMC. But, for the case of $D_L/D_S = 15$ binary mixture of AlN, the improvement of flexural strength of EMC by filler size distribution was higher than that of the $D_L/D_S = 6$ binary filler system, i.e., 20% vs. 8% of flexural strength improvement, respectively.

3.2.6. The effects of filler size distribution on flexural strength

Water resistance of EMC (65 vol.% of filler) as a function of the volume fraction of 2-micron AlN in a binary mixture of AlN, i.e., X_S , was evaluated. Disk-shaped EMC samples ($40\phi \times 4$ mm) filled with AlN (65 vol.%) were prepared and an immersion test was carried out at 85°C for 7 days (168 hours) in distilled water. The results are shown in Fig. 12. After immersion for 7 days, the respective water absorption ratios of EMC as a function of X_S showed minimum value at $X_S = 0.2$ – 0.3 . When $X_S = 0$, EMC filled with 30-micron AlN showed a slightly low value of water absorption ratio. This may be due to the small interfacial area between the matrix and the fillers.

4. Conclusions

When the properties of EMC that is filled with 70 vol.% of 12-micron AlN were compared with crystalline silica-filled EMC, thermal conductivity was improved by 2.2 times, dielectric constant was reduced to less than one-half, the flexural strength was improved, and the CTE was also reduced. As a result, EMC filled with 70 vol.% of AlN showed excellent thermal conduction and physical properties for advanced encapsulation of microelectronics.

EMC filled with large-size AlN particles (65 vol.%) showed superior properties in fluidity, thermal conductivity, and water resistance. But, EMC filled with small-size AlN showed good properties in dielectric constant, CTE and flexural strength. A binary mixture of an AlN-filled (65 vol.%) EMC showed improved fluidity, thermal conductivity, dielectric constant, flexural strength, and water resistance (compared to EMC filled with single size particles AlN). Maximum improvement was obtained when the fraction of small particles in the binary mixture of AlN is 0.2–0.3. The CTE of EMC was decreased by increasing the volume fraction of small particles in the binary mixture of AlNs.

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