Korean J. Chem. Eng., **17**(1), 41-46 (2000)

Thermal Fatigue-Resistant EMCs (Epoxy Molding Compounds) for Microelectronic Encapsulation

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(*Received 24 May 1999 • accepted 27 November 1999*)

Abstract–Highly thermal conductive EMCs (Epoxy Molding Compounds) should be considered for the alleviation of thermal stress-related problems caused by low thermal conductivity, and high elastic modulus of EMCs and by a mismatch of CTE (Coefficient of Thermal Expansion) between EMCs and the Si-wafer. Compared to crystalline silica-filled EMCs, alumina filled EMC improved the value of thermal conductivity by 100% and lowered the value of CTE by 50%. As a result, compared to typical crystalline silica-filled EMCs, the thermal fatigue resistance of alumina-filled EMC was improved by sixfold.

Key words: Thermal Fatigue, Thermal Conductivity, CTE, Alumina and EMCs

INTRODUCTION

Molding compounds are used to protect semi-conductor devices from environmental hazards such as moisture, chemical agents, dust, light, and external impact [Lupinski, 1989]. Over the last several decades, the microelectronics industry has grown dramatically, and this rapid growth has required equally rapid development of computers and communication devices that can manage a large volume of data. Thus, ICs (Integrated Circuits) having high performance are in high demand and such demand has been increasing markedly [McClean, 1986].

At present, thermal management is an important consideration in IC performance, due to the damage that may occur at high temperature [Tummala, 1989]. As semi-conductor devices increase in transistor density, the heat dissipation requirement increases, resulting in the need for improved thermally conductive packaging materials [Manzione, 1990]. The heat produced from a semi-conductor chip should be removed from the die surface (See Fig. 1).

However, typical EMCs (Epoxy Molding Compounds), which have low thermal conductivity, cannot effectively dissipate the heat of a silicon die. Therefore, highly thermal conductive EMCs should be considered for alleviation of thermal stress-related problems caused by low thermal conductivity and high elastic modulus of EMCs, and by the mismatch of CTE (Coefficient of Thermal Expansion) between EMC and the Si-wafer. However, a highly thermal conductive molding compound has often led to CTE problems. For example, highly thermal conductive epoxy molding compounds filled with crystalline silica have higher CTE values than that of compounds filled with standard fused silica. To solve such problems more effectively, other types of filler (List on Table 1) have been considered [Manzione, 1990]. If the thermal conductivity of EMCs is increased and the CTE values of EMCs approaches that of a silicon die or a metal leadframe, the reliability of semi-conductor devices related to thermal fatigue will be greatly enhanced. Therefore, in this study, the performance of alumina-filled EMCs was compared with that of crystalline silica-filled EMC, focusing on the values of thermal conductivity and the CTE.

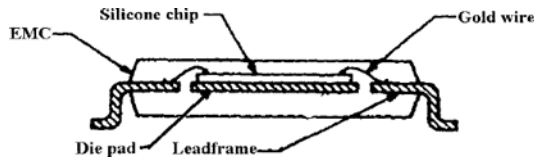

Fig. 1. Schematic diagram of a SOP (Small Outline Package).

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EXPERIMENTS

1. Raw Materials

1-1. Matrix

Metal and ceramic were the traditional materials for electronic encapsulation, but plastic (especially, thermosetting epoxy resin) has become more widely used since 1975. For thermosetting epoxy, massive and cheap production is rendered possible by the process of transfer molding. In addition, because of its high reliability, it is being widely used as a packaging material for semi-conductors [Thomson, 1994]. Epoxy resin can be divided into two types, bisphenol-A and novolac. Solid novolac epoxy has been used more

Table 1. The physical properties of ceramic fillers and epoxy resin

Materials	Dielectric constant	Coefficient of thermal expansion (10^{-6}/K)	Thermal conductivity (W/m-K)	Volume resistivity (Ohm-cm)
Cry. silica	4-5.5	9	2-10	10^{16}
Al_2O_3	9.5	5.5	30	10^{14}
Epoxy	6-7	50-90	0.2-0.4	10^{14}

widely than bisphenol-A epoxy as a packaging material for semiconductors. Also, compared to bisphenol-A epoxy, novolac epoxy has an excellent resistance to heat. For these reasons, in this study, the novolac epoxy was selected as the base resin, and phenol novolac was elected as the hardener. Although phenol-cured epoxy is not widely used commercially, it is high in quality and has excellent properties, compared with other types of cured epoxy used in the packaging of microelectronic products [Biernath, 1992].

1-2. Filler

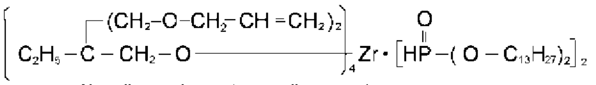
Even though filler can improve an EMC's thermal conductivity, the thermal expansion, as well as its mechanical properties, filler can also cause a decline in the moldability and fluidity of EMCs. The intent of this study is to show the proper filler by comparing thermal conductivity, thermal expansion, and dielectric characteristics of EMCs. The mean particle size of alumina (Al_2O_3, granule type) filler was 13 μm (Sumitomo Co., Japan), and that of the crystalline silica was also 13 μm (Morimura Co., Japan).

1-3. Coupling Agent

The role of a coupling agent is to increase the mechanical properties and the water resistance of EMCs by the enhancing adhesion between the filler and the matrix through a chemical bonding. The purpose of this study is to select the proper coupling agent for improving the adhesion between the alumina filler and the epoxy resin by the evaluating water resistance and the flexural strength of EMC. Amino-silane and neoalkoxy-zirconate were used as coupling agents because amino silane showed excellent adhesion for the crystalline silica/epoxy system, and neoalkoxy-zirconate showed excellent adhesion for the aluminum nitride/epoxy system [Kim, 1999]. The chemical structures of the coupling agents (Ken-react Co., USA) are as follows:

$H_2NC_2H_4NHC_3H_6Si(OCH_3)_3$

Amino-silane coupling agent



Neoalkoxy-zirconate coupling agent

2. The Basic Composition of Epoxy Molding Compounds (EMC)

Novolac epoxy, phenol novolac, and alumina were used as the matrix, the hardener, and the filler, respectively. The basic composition of the epoxy molding compounds was determined as shown in Table 2 [Kim, 1997].

3. 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 filled EMC (with over 50 vol% of filler). The rotating speed of the two rolls used for high-viscosity mixing was arranged to be Left : Right=14.5 : 21 RPM. To provide a lower degree of curing for EMC, an alumina-filled master batch was mixed at the roll surface temperature of about 90 °C for a proper dispersion time of 10 minutes. A disc-shaped EMC was molded at 175 °C for $2\frac{1}{2}$ minutes, then post-cured for four hours. Conventional extrusion or injection molding methods were not appropriate for thermosetting epoxy compounds, so a low-pressure transfer molding method was generally used. The advantages of this process are the possibility of mass production (compared to compression molding) and, by preheating, the elimination of void formation, in the manufacture of high viscosity composite materials. Therefore, the preheating process and transfer molding have been used in this study. The overall manufacturing process of alumina-filled EMC is shown in Fig. 2.

Table 2. Basic composition 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. ratio of epoxy/phenol=1.0
Inorganic filler (alumina, silica)	50-85	
Mold release agent (wax)	0.5	Density of alumina; 3.96
Coupling agent	0.5	Density of cry. sillica; 2.65
Stress-relief agent (BYK-130)	0.4	

4. Test Methods

4-1. Thermal Conductivity

Thermal diffusivity (δ) was measured by the laser flash method (Sinku-Riko Co, model TC-7000, Japan) at room temperature. Specific heat (c) was measured by DSC (Differential Scanning Calorimetry, Perkin-Elmer Co., model Pyris 1, USA). Also, the density (ρ) of the specimen was measured by water displacement. By using the previous measured values, thermal conductivity (κ) was calculated by Eq. (1) [Incropera, 1996].

$$\kappa=(c\cdot\delta\cdot\rho) \quad (1)$$

4-2. Coefficient of Thermal Expansion

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

$$\alpha=\Delta L/(L_0\cdot\Delta T) \quad (2)$$

where α is the coefficient of thermal expansion of the specimen, L/L_0 is the strain of the specimen, and ΔT is the temperature difference.

4-3. Water Resistance

A disk-shaped specimen (40ø×4 mm) was polished with sandpaper before being immersed in water at 85 °C. To measure the water absorption ratio of the specimens, the surface of the immersed specimen was fully dried by wiping off any moisture with dri-

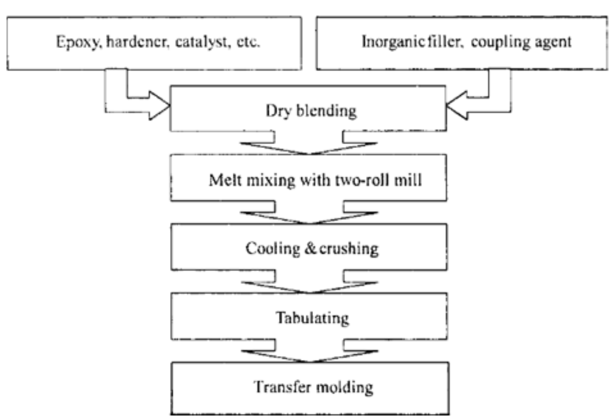


Fig. 2. Manufacturing process of EMCs.

ed cloth, and then the weight change of the specimen was measured daily.

4-4. Dielectric Properties

The dielectric property of the composite material was measured by using a disk-shaped specimen (10ø×2 mm) in the LF Impedance Analyzer (Hewlett Packard, model HP 4192A, testing frequency: 1 MHz) at the room temperature. The values of the dielectric constant were calculated by the following equation [Kingery, 1975]:

$$D=C/[(A/d)\cdot E_0] \quad (3)$$

where D is the dielectric constant of the specimen, C is the dielectric capacitance of the specimen, A is the area of the specimen, d is the thickness of the specimen and E_0 is the dielectric capacitance in a vacuum.

4-4. Mechanical Properties

The mechanical properties of the encapsulating compounds were evaluated by using a UTM (Universal Testing Machine, Instron Co., Model 4301, USA). Flexural strength and 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 150 seconds, and then cured on hot plates at 175 °C for 4 hours.

RESULTS AND DISCUSSION

1. Adhesion between Filler and Epoxy Matrix

Figs. 3 and 4 show the results of measured flexural strength and water resistance for alumina-filled EMC (60 vol%), which contains 0.0 wt% and 0.5 wt% of coupling agents such as amino-silane and neoalkoxy-zirconate respectively. According to the evaluation of flexural strength and water resistance, excellent chemical adhesion between alumina and the epoxy matrix was observed for the case of the amino-silane coupling agent. The excellent adhesion may be due to the effectiveness of the methoxy group of amino-silane for the covalent bonding between alumina and the coupling agent, compared to a long-chain alkoxy group of neoalkoxy zirconate. Also, the alkyl group of neoalkoxy zirconate is very bulky, and this may be detrimental to the reaction between

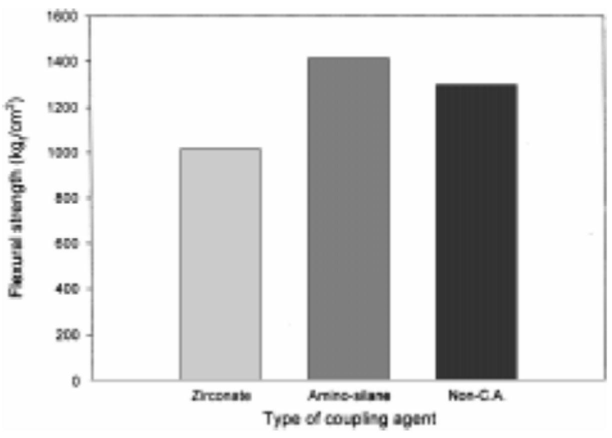


Fig. 3. The effects of coupling agents on flexural strength at room temp. for an alumina filled epoxy (60 vol%).

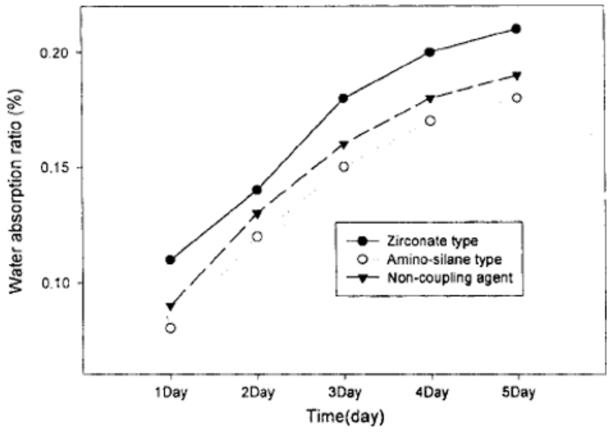


Fig. 4. The effects of coupling agents on the water-absorption ratio as a function of time (day) for an alumina-filled epoxy (60 vol%).

the epoxy resin and the hardener, or be reactive to each other. Therefore, the amino-silane coupling agent was used in the following study.

2. Thermal Conductivity

The low thermal conductivity of a polymer causes it to have great difficulty in maintaining proper temperature in a thermal dissipation device. The thermal conductivity of a polymer can be improved by mixing it with filler that has high thermal conductivity. When the effect of polymer component is dominant, the thermal conductivity of composite materials can be calculated by Eq. (4) [Manzione, 1990]. For EMC, Eq. (4) cannot represent the experimental data. To fit the experimental data, a new model [modified from Hadley's model (Verma's model)], represented by Eq. (5), was considered [Verma, 1991].

$$\text{Series;} \quad 1/k_T=(\phi_1/k_1)+(\phi_2/k_2) \quad (4)$$

$$\text{Verma's model;} \quad k_T=\frac{k_2\phi_2F+k_1(1-\phi_2F)}{1-\phi_2(1-F)+\phi_2(1-F)\left(\frac{k_1}{k_2}\right)} \quad (5)$$

$$F=\exp[-(k_2/k_1)^{1/3}]$$

where k_T is the thermal conductivity of a composite, k_1 is the thermal conductivity of the filler, k_2 is the thermal conductivity of the epoxy matrix, ϕ_1 is the volume fraction of the filler and ϕ_2 is the volume fraction of the epoxy matrix.

Fig. 5 shows the results of thermal conductivity for EMC with various proportional volumes of crystalline silica and alumina as filler. Also, the results of the application of theoretical models are shown in Fig. 5.

It can be seen that, due to the thermal barrier of the epoxy matrix, the thermal conductivity of EMC with 40 vol% crystalline silica and alumina is low, compared to the filler itself. Also, the thermal conductivity of EMC with 50 vol% crystalline silica is slightly increased. However, there is a sharp increase in the thermal conductivity of EMC with over 60 vol% alumina, and the data follows Eq. (5) quite well. The thermal conductivity of EMC with 65-70 vol% alumina filler approximately doubled, compared to that of an EMC with 70 vol% crystalline silica filler.

3. Coefficient of Thermal Expansion

Internal thermal stress is produced by the difference of the CTE

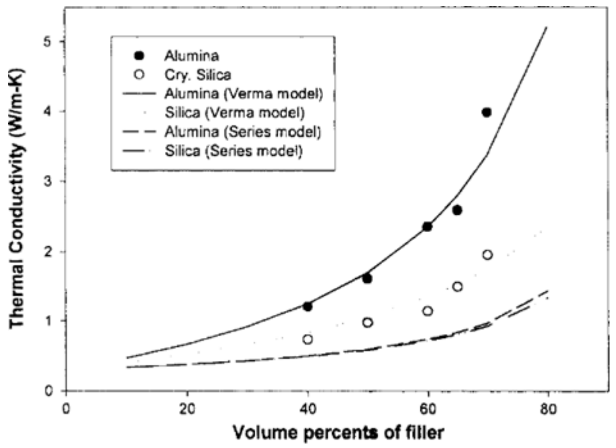


Fig. 5. Thermal conductivity as a function of filler contents at 293 K for EMC filled with various fillers.

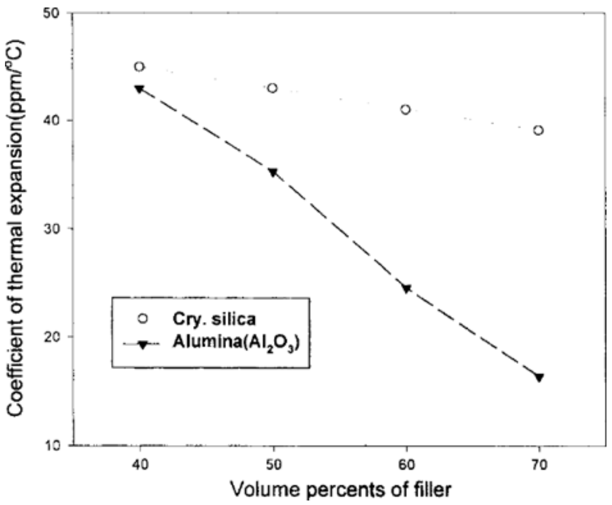


Fig. 6. C.T.E. (Coefficient of Thermal Expansion; α_1, T<Tg) as a function of filler contents for EMC filled with various fillers.

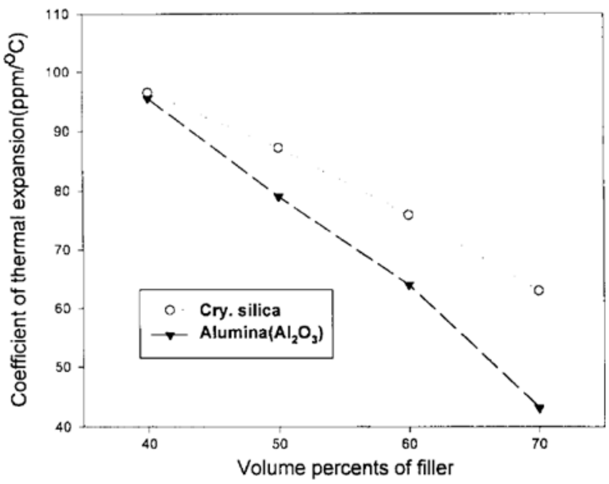


Fig. 7. C.T.E. (α_2, T>Tg) as a function of filler contents for EMC filled with various fillers.

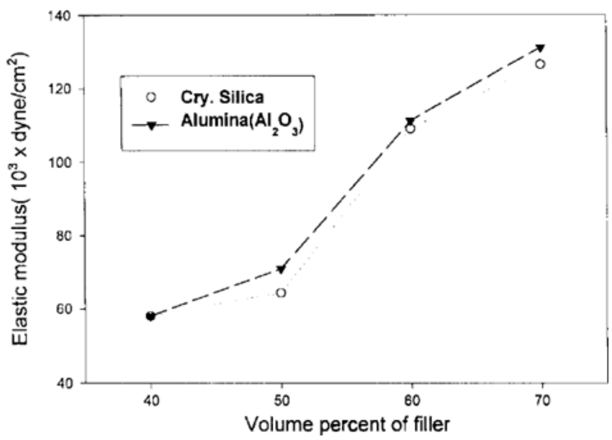


Fig. 8. Elastic modulus as a function of filler contents at room temp. for EMC filled with various fillers.

between the encapsulating material and the Si-chip or leadframe. As shown in Table 1, compared to alumina or crystalline silica, epoxy shows high values of CTE, so the CTE of EMC can be lowered by increasing filler contents. Figs. 6 and 7 show that the value of CTE, α_1 (when T<Tg) and α_2 (when T>Tg), was decreased as the vol% of filler increased.

The value of the CTE of alumina-filled EMC is lower than that of crystalline silica-filled EMC when added in equal volumes because the value of the CTE of alumina is lower than that of crystalline silica. When the temperature is higher than the glass transition temperature (about 150 °C) of the epoxy resin, the value of CTE at the same filler content approximately doubles, compared to the case of T<Tg. Also, the elastic modulus of EMC with filler content is shown in Fig. 8. Fig. 8 shows that the elastic modulus of EMC was increased with filler content, but the difference in elastic modulus between alumina-and crystalline silica-filled EMC was very small, because the shape of alumina is granular which is very similar to that of crystalline silica.

3. Dielectric Properties

High signal accumulation of the device itself and a higher clock rate can be obtained by using a material that has low values of the dielectric constant. Fig. 9 shows the measured values of the dielectric constant of EMC filled with crystalline silica and alumina, respectively.

Fig. 9 demonstrates that crystalline silica, which has lower values of the dielectric constant than that of the epoxy matrix, decreased the value of EMC little by little as the amount of silica was increased. In the case of alumina, its dielectric constant value was higher than that of the epoxy matrix, so the value of the dielectric constant of EMC increased according to the amount of alumina. As a result, alumina-filled EMC showed worse dielectric properties than cry. silica-filled EMC.

4. Mechanical Property

Molded plastic encapsulants should have sufficient mechanical strength to protect a chip from physical impact. To evaluate the mechanical strength of EMC, the flexural strength of EMC with various filler contents was measured by UTM (Universal Testing Machine). Fig. 10 shows the results of the flexural strength of EMC with various volume percents of crystalline silica and alumina. It can be seen that the flexural strength of EMC is increased depending on the filler contents. In the case of alumina, the

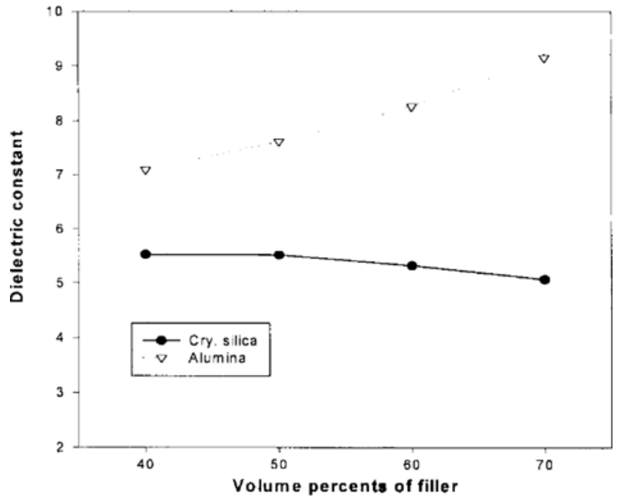


Fig. 9. Dielectric constant as a function of filler contents at room temp. for EMC filled with various fillers.

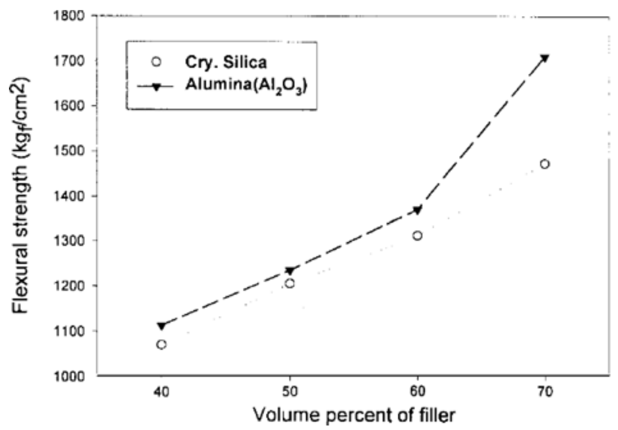


Fig. 10. Flexural strength as a function of filler contents at room temp. for EMC filled with various fillers.

flexural strength of EMC is higher than that of crystalline silica-filled EMC, and this trend was more significant above 60 vol% of filler.

5. Thermal Fatigue Resistance

To summarize the above results and represent thermal fatigue resistance, the thermal shock parameter was considered. For engineering materials, Bobrowsky et al. [Manson, 1981] used the thermal shock parameter which is shown by Eq. (6). Generally, materials that have high values of the thermal shock parameter can withstand thermal fatigue without early cracking.

$$\text{Thermal shock parameter} = (k \cdot \varphi)/(\alpha \cdot Ec) \quad (6)$$

where k is the thermal conductivity of EMC, φ is the tensile or flexural strength, α is the CTE of EMC, and Ec is the elastic modulus of EMC.

Fig. 11 shows the results of the thermal shock parameter for EMC with various volume percents of cry. silica and alumina as filler. It was found that a sharp increase occurred in the thermal shock parameter of EMC with over 60 vol% alumina. This is mainly due to the high values of thermal conductivity and low values of CTE of alumina-filled EMC, compared with crystalline

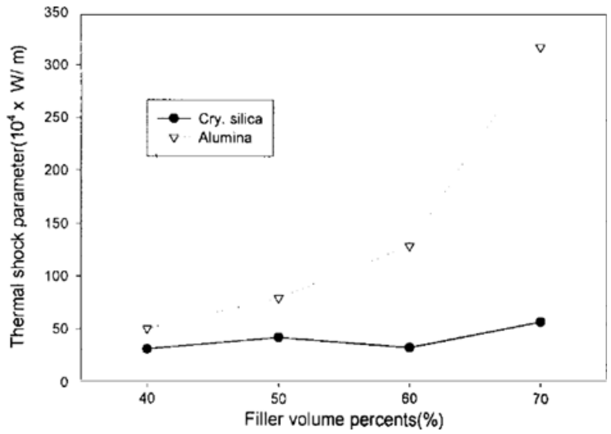


Fig. 11. Thermal shock parameter as a function of filler contents for EMC filled with various fillers.

silica-filled EMC. As a result, the thermal fatigue resistance of alumina-filled EMC improved sixfold, compared to the typical thermal conductive EMC filled with 70 vol% of crystalline silica.

CONCLUSIONS

An amino-silane coupling agent showed good adhesion between the filler and the epoxy matrix regardless of filler type. Alumina-filled EMC showed a sharp increase in thermal conductivity above 60 vol% of alumina, but that of crystalline silica-filled EMC was slowly increased by increasing the contents of the filler volume. Compared to crystalline silica-filled EMC, alumina-filled EMC improved the value of thermal conductivity by approximately 100 % and lowered the value of CTE by approximately 50%. As a result, the thermal fatigue resistance of alumina-filled EMC was improved by about sixfold, compared to typical crystalline silica-filled EMC. Consequently, alumina-filled EMC can be considered as an advanced packaging material that provides high reliability against thermal fatigue for semiconductor devices.

ACKNOWLEDGMENTS

This work was supported by Pusan National University Research Grant 1995 and Korea Science and Engineering Foundation (Grant No.: 95-0300-16-01-3). And also the authors wish to thank Korea Chemical Co., LTD for supplying the raw materials.

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