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Fabrication of insulated metal substrates with organic ceramic composite films for high thermal conductivity

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ABSTRACT

Insulated metal substrates (IMSs) were fabricated and characterized using an organic ceramic composite as a coating mixture. Organic-inorganic sol solutions were prepared by a sol-gel process using TEOS (tetraethylorthosilicate), MTMS (methyltrimethoxysilane) and PhTMS (phenyltrimethoxysilane). Ceramic fillers were composed of aluminum oxide (1 and 4 μm) and silicon nitride. The optimal ratio of ceramic filler in the coating mixture was found to be 70 wt%. A thermal conductivity of 3.16 W/mK and a breakdown voltage of 4 kV with a leakage current of 0.17 mA/cm^2 were obtained for the 122 μm-thick film. A well-networked microstructure between the sol resin and filler in the organic ceramic composite films enhanced the properties of the IMS, such as thermal conductivity and electric insulation.

1. Introduction

Insulated metal substrates (IMSs) have attracted attention as a promising substrate for high-density packaging because they have good thermal dissipation and high thermal conductivity and can act as a heat sink or heat substrate [1,2]. Especially in the field of power modules, IMSs have many applications, such as metal-oxide semiconductor field-effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), intelligent power modules (IPMs) and backlight units in the automotive and semiconductor industries [3]. In ultra-large-scale integration (ULSI) circuits, such as systems on a chip (SOC) and wafer-scale integrations (WSIs), the rapid radiation of generated heat is important because of the numerous integrated chips, resulting in a decrease in device lifetime of the power module. For this reason, the plastic circuit board for power modules has been changed to an IMS for its high thermal conductivity, radiant heat and withstanding voltage. However, most IMSs are made of epoxy resin with some ceramic fillers, such as alumina (Al_2O_3) and aluminum nitride (AlN), which are known to have a thermal endurance below 200 °C due to the limited tolerance of the epoxy [4], which results in weight loss of the epoxy resin beginning at 150 °C and reaching a loss of 5% at 346 °C [5]. Therefore, hybrid coatings, so-called organic-inorganic mixtures, have been considered as good candidates for the fabrication of IMSs, and many studies have reported the successful avoidance of cracks on the metal substrates from different thermal expansions and thermal shock [3,6,7], as well as improved thermal properties by adding filler [8–12]. In this paper, we fabricated a mixture of organic-inorganic sol and ceramic filler as a coating material for IMS application. Via a sol-gel process, the organic-inorganic sol solution is synthesized from tetraethylorthosilicate (TEOS) as an inorganic network former, methyltrimethoxysilane (MTMS) and phenyltrimethoxysilane (PhTMS). The fillers Al_2O_3 and silicon nitride (Si_3N_4) were added into the organic-inorganic sol solutions for the coating mixture. The sol-gel based coating mixture was deposited on an aluminum alloy substrate. To obtain improved thermal conductivities and withstanding voltages, various ratios of ceramic filler were investigated.

2. Experimental details

Fig. 1 shows a flow chart of the synthesis of the organic-inorganic sol solution. As a starting solution, silica sol and organosilanol sol were prepared with a mole ratio of 0.6 ~ 0.9:1. The silica sol was prepared in ambient atmosphere for 12 h by stirring tetraethylorthosilicate (TEOS, Dow Corning) with ethanol, HCl, and distilled water in a molar ratio of TEOS:ethanol:HCl:H_2O =1:4:0.0001:4. The organosilanol sol was obtained from MTMS (methyltrimethoxysilane, Dow Corning), which

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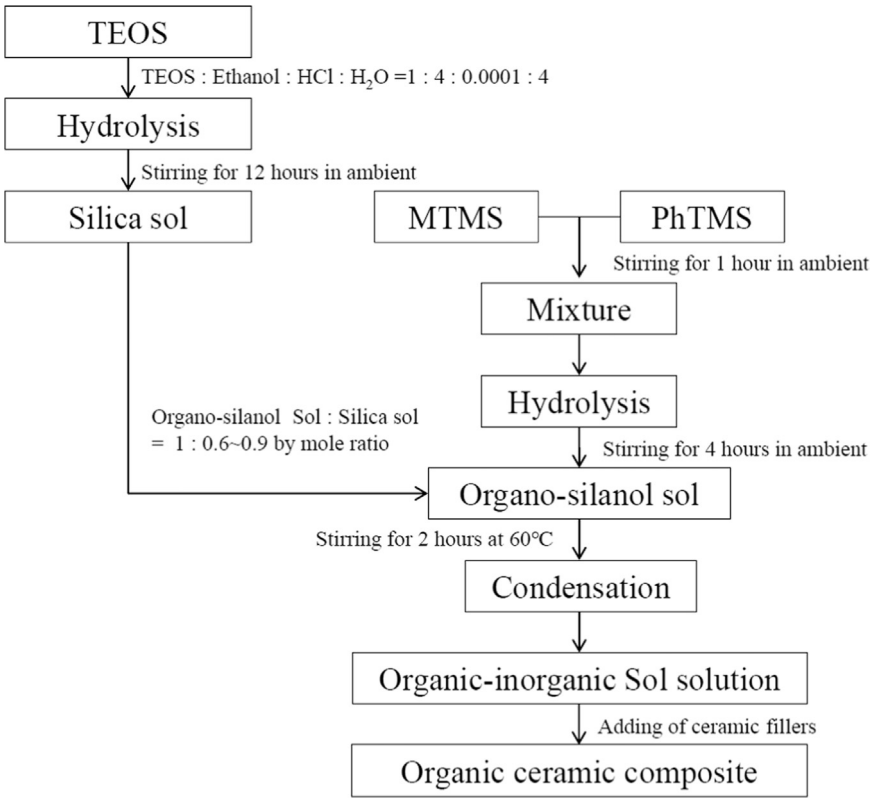

Fig. 1. Flow chart for organic-inorganic sol solution synthesis.

Table 1
Material properties of ceramic fillers and their mixing ratios.

Filler	Al_2O_3 (1)	Al_2O_3 (2)	Si_3N_4
Median diameter (μm)	1	4	0.4
Morphology	Spherical	Spherical	Polygonal
Specific surface area (m^2/g)	4.9	0.5	5.4
Mixing ratio (wt%)	16	74	10

acts as heat resistant resin former when it combines with TEOS, and PhTMS (phenyltrimethoxysilane, Dow Corning) as a resin modifier for high temperature endurance. The molar ratio of organosilanol sol was MTMS:PhTMS:IPA:H_2O:acetic acid =1:0.2:4:4:0.04. Then, the organic-inorganic sol solution was prepared from the silica sol and organosilanol sol mixture by stirring at 60 °C for 2 h. The filler consisted of 90 wt% Al_2O_3 and 10 wt% Si_3N_4 of tiny particle size for high thermal conductivity performance. The alumina filler had spherical shapes of 1 μm and 4 μm, respectively. The material and mixing ratio of the filler are given in Table 1. For film formation by the spraying method, the final mixture was composed of the organic-inorganic sol solution and the ceramic fillers. To disperse the filler mixture, ball milling was carried out for 12 h. The as-prepared mixtures with various filler concentrations of 40–75 wt% were air-sprayed on aluminum alloy substrates (Al 6061, T6) and treated by an 80-mesh emery sand blast for 30 s. The thickness of the as-prepared film was approximately 120 μm with an area of 150 mm×70 mm. Post-heat treatment was performed at 60 °C for 6 h and 300 °C for 2 h with a temperature ramping rate of 5 °C/min. A long-time low-temperature curing process (60 °C) is necessary to avoid the formation of stress due to capillary forces. A final curing by heat treatment at up to 600 °C is required for complete drying of the pores in order to strengthen the silica skeleton structure [13]. However, the final curing temperature in this study was 300 °C because of the aluminum substrate elongation. The chemical bonding configuration of the samples was investigated by Fourier transform infrared spectroscopy (FT-IR, Perkin Elmer Clarus 500). Thermal properties, such as weight loss and exo- and endothermal reaction, were investigated by differential scanning calorimeter-thermogravimetric analysis (DSC-TGA, SDT Q600). Field emission scanning electron microscopy (FE-SEM, JEOL 840) was used to investigate the cross-sectional view and the microstructure. The withstanding voltage and breakdown strength were measured by an I-V tracer (KIKUSUI TOS 5051 tester). A cylindrical-shaped pellet was prepared for thermal conductivity (TC) measurements by the laser flash method. The pellets were fabricated by compression molding with an axial pressure of 80 MPa for 5 min and then heated to 300 °C for 4 h. The pellets had a diameter of 12.3 mm and a thickness of approximately 2.25 mm. Flake, obtained from the final mixture dried at 60 °C for 12 h, was used for fabrication of the pellets.

3. Results and discussion

3.1. Chemical bonding analysis (FT-IR)

Fig. 2 shows the chemical bonding configuration in the mixture with various concentrations of silica sol in the organic-inorganic sol solution. The synthesized sol solution had major absorbance peaks around 910 cm^{-1}, 1020 cm^{-1}, 1106 cm^{-1}, and 1268 cm^{-1}. These peaks are attributed to stretching vibrations of Si-OH, C-O, Si-O-C and Si-O-Si, respectively. Absorption bands at 1270 and 1040–1090 cm^{-1} are assigned to Si-O-Si asymmetric modes [13,14]. The absorption band at 790 cm^{-1} is associated with symmetric Si-O-Si stretching or vibrational modes of a ring structure [15]. As more silica sol was added to the organic-inorganic sol solution, the Si-O-Si absorption peaks were slightly shifted to higher wavenumbers, and the C-O absorption peaks were slightly shifted to lower wavenumbers.

3.2. Thermal behavior of the coating material (DSC-TGA)

Fig. 3 shows the thermodynamic reactions in the mixtures with