REVIEW

Polymer-Matrix Composites for Microelectronics

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SUMMARY

Polymer-matrix composite materials for microelectronics are reviewed in terms of the science and applications. They include those with continuous and discontinuous fillers in the form of particles and fibres, as designed for high thermal conductivity, low thermal expansion, low dielectric constant, high/low electrical conductivity and electromagnetic interference shielding. Applications include heat sinks, housings, printed wiring boards, substrates, lids, die attach, encapsulation, interconnections and thermal interface materials.

1. INTRODUCTION

Composite materials are traditionally designed for use as structural materials. With the rapid growth of the electronics industry, composite materials are finding more and more electronic applications. The design criteria for these two groups of composites are different because of the vast difference in property requirements between structural composites and electronic composites. While structural composites emphasize high strength and high modulus, electronic composites emphasize high thermal conductivity, low thermal expansion, low dielectric constant, high/low electrical conductivity, and/or electromagnetic interference (EMI) shielding effectiveness, depending on the particular electronic application. Low density is desirable for both aerospace structures and aerospace electronics. Structural composites emphasize processability into large parts, such as panels, whereas electronic composites emphasize processability into small parts, such as stand-alone films and coatings. Due to the small size of the parts, materials cost tends to be less of a concern for electronic composites than structural composites. For example, electronic composites can use expensive fillers, such as silver particles, which serve to provide high electrical conductivity.

2. APPLICATIONS IN MICROELECTRONICS

The applications of polymer-matrix composites in microelectronics include interconnections, printed circuit boards, substrates, encapsulations, interlayer dielectrics, die attach, electrical contacts, connectors, thermal interface materials, heat sinks, lids and housings. In general, the integrated circuit chips (dies) are attached to a substrate or a printed circuit board on which the interconnection lines have been written (usually by screen printing) on each layer of the multilayer substrate or board. In order to increase the interconnection density, another multilayer involving thinner layers of conductors and interlayer dielectrics may be applied to the substrate before attachment of the chip. By means of soldered joints, wires connect between electrical contact pads on the chip and electrical contact pads on the substrate or board. The chip may be encapsulated with a dielectric for protection. It may also be covered by a thermally conducting (metal) lid. The substrate (or board) is attached to a heat sink. A thermal interface material may be placed between the substrate (or board) and the heat sink to enhance the quality of the thermal contact. The whole assembly may be placed in a thermally conducting housing.

A printed circuit board is a sheet for the attachment of chips, whether mounted on substrates, chip carriers, or otherwise, and for the drawing of interconnections. It is a polymer-matrix composite that is electrically insulating and has four conductor lines (interconnections) on one or both sides. Multilayer boards have lines on each inside layer so that interconnections on different layers may be connected by short conductor columns called electrical vias. Printed circuit boards (or cards) for the mounting of pin-inserting-type packages need to have lead insertion holes punched through the circuit board. Printed circuit boards for the mounting of surface-mounting-type packages need no holes. Surface-mounting-type packages, whether with leads, leaded chip carriers, or without leads, leadless chip carriers (LLCCs), can be mounted on both sides of a circuit board (i.e. a card), whereas pin-inserting-type packages can only be mounted on one side of a circuit board. In surface mounting technology (SMT), the surfaces of conductor patterns are connected together electrically without employing holes. Solder is typically used to make electrical connections between a surface-mounting-type package (whether leaded or leadless) and a circuit board. A lead insertion hole for pin-inserting-type packages is a plated-through hole, a hole on whose wall a metal is deposited to form a conducting penetrating connection. After pin insertion, the space between the wall and the pin is filled by solder to form a solder joint. Another type of plated-through hole is a via hole, which serves to connect different conductor layers together without the insertion of a lead.

A substrate, also called a chip carrier, is a sheet on which one or more chips are attached and interconnections are drawn. In the case of a multilayer substrate, interconnections are also drawn on each layer inside the substrate, such that interconnections in different layers are connected, if desired, by electrical vias. A substrate is usually an electrical insulator. Substrate materials include ceramics (e.g. aluminium oxide/Al_2O_3, aluminium nitride/AlN, mullite, glass ceramics), polymers (e.g. polyimide), semiconductors (e.g. silicon), and metals (e.g. aluminium). The most common substrate material is Al_2O_3. As the sintering of Al_2O_3 requires temperatures greater than 1000°C, the metal interconnections need to be refractory, such as tungsten or molybdenum. The disadvantage of tungsten or molybdenum lies in the higher electrical resistivity compared to copper. In order to make use of more conductive metals (e.g. Cu, Au, Ag-Pd) as the interconnections, ceramics that sinter at temperatures below 1000°C ("low temperature") can be used in place of Al_2O_3. The competition between ceramics and polymers for substrates is increasingly keen. Ceramics and polymers are both electrically insulating; ceramics are advantageous in that they tend to have a higher thermal conductivity than polymers; polymers are advantageous in that they tend to have a lower dielectric constant than ceramics. A high thermal conductivity is attractive for heat dissipation; a low dielectric constant is attractive for a smaller capacitive effect, hence a smaller signal delay. Metals are attractive for their very high thermal conductivity compared to ceramics and polymers.

An interconnection is a conductor line for signal transmission, power, or ground. It is usually in the form of a thick film of thickness > 1 μm. It can be on a chip, a substrate or a printed circuit board. The thick film is made by either screen printing or plating. Thick film conductor pastes containing silver particles (conductor) and glass frit (binder which functions by the viscous flow of glass upon heating) are widely used to form thick film conductor lines (interconnections) on substrates by screen printing and subsequent firing. These films suffer from a reduction in the electrical conductivity as a result of the presence of the glass and the porosity in the film after firing. The choice of a metal in a thick film paste depends on the need to withstand air oxidation during the heating encountered in subsequent processing, which can be the firing of the green thick film together with the green ceramic substrate (a process known as cofiring). It is during cofiring that bonding and sintering take place. Copper is an excellent conductor, but it oxidizes readily when heated in air. The choice of metal also depends on the temperature encountered in subsequent processing. Refractory metals, such as tungsten and molybdenum, are suitable for interconnections heated to high temperatures (> 1000°C), for example during Al_2O_3 substrate processing.

A z-axis anisotropic electrical conductor film is a film which is electrically conducting only in the z-axis, i.e. in the direction perpendicular to the plane of the film. As one z-axis film can replace a whole array of solder joints, z-axis films are valuable for solder replacement, processing cost reduction and for improving repairability in surface mount technology.

An interlayer dielectric is a dielectric film separating the interconnection layers, such that the two kinds of layers alternate and form a thin film multilayer. The dielectric is a polymer, usually spun on or sprayed; or a ceramic, usually applied by chemical vapour deposition (CVD). The most common multilayer involves polyimide as the dielectric and copper interconnections, plated, sputtered, or electron-beam deposited.

A die attach is a material for joining a die (a chip) to a substrate. It can be a metal alloy (a solder paste), a polymeric adhesive (a thermoset or a thermoplastic), or a glass. Die attach materials are usually applied by screen printing. A solder is attractive in its high thermal conductivity, which enhances heat dissipation. However, its application requires the use of heat and a flux. The flux subsequently needs to be removed chemically. The defluxing process adds costs and is undesirable to the environment (the ozone layer) due to the chlorinated chemicals used. A polymer or glass has poor thermal conductivity, but this problem can be alleviated by the use of a thermally conductive filler, such as silver particles. A thermoplastic provides a reworkable joint, whereas a thermoset does not. Furthermore, a thermoplastic is more ductile than a thermoset. Moreover, a solder suffers from its tendency to experience thermal fatigue due to the thermal expansion mismatch between the chip and the substrate, and the resulting work hardening and cracking of the solder. In addition, the footprint left by a solder tends to be larger than the footprint left by a polymer, due to the ease with which molten solder flows.

An encapsulation is an electrically insulating conformal coating on a chip for protection against moisture and mobile ions. An encapsulation can be a polymer (e.g. epoxy, polyimide, polyimide siloxane, silicone gel, Parylene, and benzocyclobutene), which can be filled with SiO_2, BN, AlN, or other electrically insulating ceramic particles to decrease the thermal expansion and increase the thermal conductivity[1-3]. The decrease in the thermal expansion is needed because a neat polymer typically has a much higher coefficient of thermal expansion than a semiconductor chip. An encapsulation can also be a ceramic (e.g. SiO_2, Si_3Ni_4, silicon oxynitride). In the process of electronic packaging, encapsulation is a step performed after both die bonding and wire bonding, and before the packaging using a moulding material. The moulding material is typically a polymer, such as epoxy. However, it can also be a ceramic, such as Si_3N_4, cordierite (magnesium silicate), SiO_2, and so on. A ceramic is advantageous (compared to a polymer) because of its low coefficient of thermal expansion and higher thermal conductivity, but it is much less convenient to apply than a polymer.

A lid is a cover for a chip for physical protection. The chip is typically mounted in a well in a ceramic substrate, and the lid covers the well. A lid is preferably a metal because of the need to dissipate heat. It is typically joined to the ceramic substrate by soldering, using a solder preform (e.g., Au-Sn) shaped like a gasket. Due to the low coefficient of thermal expansion a material such as Kovar (54Fe-29Ni-17Co) is used for the lid. For the same reason, Kovar is often used for the can (housing or enclosure) in which a substrate is mounted. Although Kovar has a low coefficient of thermal expansion (5.3×10^{-6} °C^{-1} at 20-200°C), it suffers from a low thermal conductivity of 17 W.m^{-1} K^{-1}.

A heat sink is a thermal conductor that serves to conduct (mainly) and to radiate heat away from the circuitry. It is typically bonded to a printed circuit board. The thermal resistance of the bond and that of the heat sink itself govern the effectiveness of the heat dissipation. A heat sink is chosen that matches the coefficient of thermal expansion of the circuit board for resistance to thermal cycling.

Insufficiently fast dissipation of heat is the most critical problem that limits the reliability and performance of microelectronics[4]. The problem becomes more severe as electronics are miniaturized, so the further miniaturization of electronics is hindered by this problem. The problem also increases as the power (voltage and current) increases, so the power is restricted by the heat dissipation problem. Excessive heating from insufficient heat dissipation causes thermal stress in the electronic package. The stress may cause warpage of the semiconductor chip (die). The problem is compounded by thermal fatigue, which results from cyclic heating and thermal expansion mismatches. Since there are many solder joints in an electronic package, solder joint failure is a big reliability problem. For these various reasons, thermal management has become a key issue within the field of electronic packaging. Thermal management refers to the use of materials (heat sinks, thermal interface materials, etc.), devices (fans, heat pipes, etc.) and packaging schemes to attain efficient dissipation of heat. The use of materials is the part that is addressed in this article.

The use of materials with high thermal conductivity and low thermal expansion for heat sinks, lids, housings, substrates and die attach is an important avenue for alleviating the heat dissipation problem. For this purpose, metal-matrix composites (such as silicon carbide particle aluminium-matrix composites) and polymer-matrix composites (such as silver particle filled epoxy) have been developed. However, another avenue, which has received much less attention, is the improvement of the thermal contact between the various components in an electronic package (e.g., between substrate and heat sink). The higher thermal conductivity of the individual components cannot effectively help heat dissipation unless thermal contacts between the components is good. Without good thermal contacts, the use of expensive thermal conducting materials for the components is a waste.

The improvement of a thermal contact involves the use of a thermal interface material, such as a thermal fluid, a thermal grease (paste) or a resilient thermal conductor. A thermal fluid or grease is spread on the mating surfaces. A resilient thermal conductor is sandwiched by the mating surfaces and held in place by pressure. Thermal fluids are most commonly mineral oil. Thermal greases (pastes) are most commonly conducting particle (usually metal or metal oxide) filled silicone. Resilient thermal conductors are most commonly conducting particle filled elastomers. Out of these three types of thermal interface materials, thermal greases (based on polymers, particularly silicone) are by far the most commonly used. Resilient thermal conductors are not as well developed as thermal fluids or greases.

As the materials to be interfaced are good thermal conductors (such as copper), the effectiveness of a thermal interface material is enhanced by high thermal conductivity and low thickness of the interface material and low thermal contact resistance between the interface material and each mating surface. As the mating surfaces are not perfectly smooth, the interface material must be able to flow or deform, so as to conform to the topology of the mating surfaces. If the interface material is a fluid, grease or paste, it should have a high fluidity (workability) so as to conform and to have a small thickness after mating. On the other hand, the thermal conductivity of the grease or paste increases with increasing filler content and this is accompanied by a decrease in the workability. Without a filler, as in the case of an oil, the thermal conductivity is poor. A thermal interface material in the form of a resilient thermal conductor sheet (e.g. a collection of conducting fibres clinging together without a binder, and a resilient polymer-matrix composite containing a thermally conducting filler) usually cannot be as thin or conformable as one in the form of a fluid, grease or paste, so its effectiveness requires a very high thermal conductivity.

3. POLYMER-MATRIX COMPOSITES

Polymer-matrix composites with continuous or discontinuous fillers are used for electronic packaging and thermal management. Composites with continuous fillers (fibres, whether woven or not-woven) are used as substrates, heat sinks and enclosures. Composites with discontinuous fillers (particle or fibres) are used for die attach, electrically/thermally conducting adhesives, encapsulations, thermal interface materials and electrical interconnections (thick film conductors and z-axis conductors). Composites with discontinuous fillers can be in a paste form during processing, thus allowing application by printing (screen printing or jet printing) and injection moulding. Composites with continuous fillers cannot undergo paste processing, but the continuous fillers provide lower thermal expansion and higher conductivity than discontinuous fillers.

Composites can have thermoplastic or thermosetting matrices. Thermoplastic matrices have the advantage that a connection can be reworked by heating for the purpose of repair, whereas thermosetting matrices do not allow reworking. On the other hand, controlled-order thermosets are attractive for their thermal stability and dielectric properties[5]. Polymers exhibiting low dielectric constant, low dissipation factor, low coefficient of thermal expansion, and compliance are preferred[6].

Composites can be electrically conducting or electrically insulating; the electrical conductivity is provided by a conductive filler. The composites can be both electrically and thermally conducting, as attained by the use of metal or graphite fillers; they can be electrically insulating but thermally conducting, as attained by the use of diamond, aluminium nitride, boron nitride or alumina fillers[7,8]. An electrically conducting composite can be isotropically conducting[9,10] or anisotropically conducting[11]. A z-axis conductor is an example of an anisotropic conductor.

3.1 Polymer-matrix composites with continuous fillers

Epoxy-matrix composites with continuous glass fibres and made by lamination are most commonly used for printed wiring boards, due to the electrically insulating property of glass fibres and the good adhesive behaviour and established industrial usage of epoxy. Aramid (Kevlar) fibres can be used instead of glass fibres to provide lower dielectric constant[12]. Alumina (Al_2O_3) fibres can be used for increasing the thermal conductivity[13]. By selecting the fibre orientation and loading in the composite, the dielectric constant can be decreased and the thermal conductivity can be increased[14]. By impregnating the yarns or fabrics with a silica-based sol and subsequent firing, the thermal expansion can be reduced[15]. Matrices other than epoxy can be used. Examples are polyimide and cyanate ester[16].

For heat sinks and enclosures, conducting fibres are used, since the conducting fibres enhance the thermal conductivity and the ability to shield electromagnetic interference (EMI). EMI shielding is particularly important for enclosures[17]. Carbon fibres are most commonly used for these applications, due to their conductivity, low thermal expansion, and wide availability as a structural reinforcement. For high thermal conductivity, carbon fibres made from mesophase pitch[18-24] or copper plated carbon fibres are preferred[25-27]. For EMI shielding, both uncoated carbon fibres[28,29] and metal (e.g. nickel, copper) coated carbon fibres[30,31] have been used.

For avionic electronic enclosures, low density (lightweight) is essential for saving aircraft fuel. Aluminium is the traditional material for this application. Carbon fibre reinforced epoxy has been judged by consideration of mechanical, electrical, environmental, manufacturing/producibility, and design-to-cost criteria to be more attractive than aluminium, glass fibre reinforced epoxy, glass fibre reinforced epoxy with aluminium interlayer, beryllium, aluminium-beryllium and SiC particle reinforced aluminium[32]. A related application is the thermal management of satellites, for which the thermal management materials need to be integrated from the satellite structure down to the electronic device packaging[33]. Continuous carbon fibres are suitable for this application due to their high thermal conductivity, low density, high strength and high modulus.

3.2 Polymer-matrix composites with discontinuous fillers

Polymer-matrix composites with discontinuous fillers (particles or short fibres) are widely used in electronics[34], in spite of their poor mechanical properties compared to composites with continuous fibres. This is because materials in electronics do not need to be mechanically strong and discontinuous fillers enable processing through the paste form, which is particularly suitable for making films, whether standalone films or films on a substrate.

Screen printing is a common method for patterning a film on a substrate. In the case of an electrically conducting paste, the pattern is commonly an array of electrical interconnections and electrical contact pads on the substrate. As screen printing involves the paste going through a screen, screen printable pastes usually contain particles and no fibre and the particles must be sufficiently small, typically less than 10 μm in size. The larger the particles, the poorer is the patternability, i.e. the edge of a printed line is not sufficiently well-defined. In applications not requiring patternability, such as thermal interface materials, short fibres are advantageous in that the connectivity of the short fibres are superior to that of particles at the same volume fraction. For a conducting composite, better connectivity of the filler units means higher conductivity for the composite. Instead of using short fibres, one may use elongated particles or flakes for the sake of the connectivity. In general, the higher the aspect ratio, the better is the connectivity for the same volume fraction. The use of elongated particles or flakes can provide an aspect ratio larger than 1, while retaining patternability. Thus, it is an attractive compromise.

In the case of a conducting composite, the greater the volume fraction of the conducting filler, the higher is the conductivity of the composite, since the polymer matrix is usually insulating. However, the greater the filler volume fraction, the higher is the viscosity of the paste and the poorer is the processability of the paste. To attain a high filler volume fraction while maintaining processability, a polymer of low viscosity is preferred and good wettability of the filler by the matrix, as provided by filler surface treatments and/or the use of surfactants, is desirable.

The matrix used in making a polymer-matrix composite can be in the form of a liquid (e.g. a thermosetting resin) or a solid (e.g. a thermoplastic powder) during the mixing of the matrix and the filler. In the case of a matrix in the form of a powder, the distribution of the filler units in the resulting composite depends on the size of the matrix powder particles, as the filler units line the interface between adjacent matrix particles, and the filler volume fraction needed for percolation (i.e. the filler units touching one another to form a continuous path)[35] decreases with increasing matrix particle size. The reaching of the percolation threshold is accompanied by a large increase in the conductivity. However, a large matrix particle size is detrimental to the processability. Therefore, a compromise is needed.

In the case of a matrix in the form of a thermoplastic powder, the percolation attained after mixing the matrix powder and the filler may be degraded or destroyed after subsequent composite fabrication involving flow of the thermoplastic under heat and pressure. Hence, in this case, a thermoplastic that flows less is preferred for attaining high conductivity in the resulting composite[36].

A less common way to attain percolation in a given direction is to apply an electric or magnetic field so as to align the filler units along the direction. For this technique to be possible, the filler units (whether in the bulk or on the surface) must be polarizable electrically or magnetically. Such alignment is one of the techniques used to produce z-axis conductors.

In percolation, the filler units touch one another to form continuous paths, but there is considerable contact resistance at the interface between the touching filler units. To decrease this contact resistance, thereby increasing the conductivity of the composite, one can increase the size of the filler units, so that the amount of interface area is decreased, provided that percolation is maintained. A less common but even more effective way is to bond the filler units together at their junction by using a solid (like solder) that melts and wets the surface of the filler during the composite fabrication. The low melting point solid can be in the form of particles added to the composite mix, or in the form of a coating on the filler units. In this way, a three-dimensionally interconnected conducting network is formed after composite fabrication[37].

An intimate interface between the filler and the matrix is important to the conductivity of a composite, even though the filler is conducting and the matrix may be perfectly insulating. This is because conduction may involve a path from a filler unit to an adjacent one through a thin film of the matrix by means of tunnelling. In the case of the matrix being slightly conducting (but not as conducting as the filler), the conduction path involves both the filler and the matrix and the filler-matrix interface is even more important. This interface may be improved by filler surface treatments (by the use of chemicals, heat, plasma, etc.) prior to incorporating the filler in the composite, or by the use of a surfactant[38].

The difference in thermal expansion coefficient between filler and matrix and the fact that composite fabrication occurs at an elevated temperature cause thermal stress during cooling of the fabricated composite. The thermal expansion coefficient of a polymer is usually relatively high, so the filler units are usually under compression after cooling. The compression helps to tighten the filler-matrix interface, though the compressive stress in the filler and the tensile stress in the matrix may degrade the performance and durability of the composite.

In case of the matrix being conducting, but not as conducting as the filler, as for conducting polymer matrices[39,40], percolation is not essential for the composite to be conducting, though percolation would greatly enhance the conductivity. Below the percolation threshold (i.e. the filler volume fraction above which percolation occurs), the conductivity of the composite is enhanced by a uniform distribution of the filler units, since the chance of having a conduction path that involves more filler and less matrix increases as the filler distribution becomes more uniform. Uniformity is never perfect; it is described by the degree of dispersion of the filler. The degree of dispersion can be enhanced by rigorous agitation during mixing of the filler and matrix or by the use of a dispersant (commonly a surfactant). In the case of a matrix in the form of particles that are coarser than the filler units, the addition of fine particles to the mix also helps the dispersion of the filler[41].

Because the thermal expansion coefficient of a polymer is relatively high, the polymer matrix expands more than the filler during the heating of a polymer-matrix composite. This results in the proximity between adjacent filler units changing with temperature, thus decreasing the conductivity of the composite[42]. This is detrimental to the thermal stability of the composites.

Corrosion and surface oxidation of the filler are the most common causes of degradation which decreases the conductivity of the composite. Thus, oxidation resistant fillers are essential. Silver and gold are oxidation resistant, but copper is not. Due to the high cost of silver and gold, the coating of copper, nickel or other lower cost metal fillers by gold or silver is common for improving the oxidation resistance. By far, the most common filler is silver particles[43,44].

A z-axis anisotropic electrical conductor film is a film which is electrically conducting in the direction perpendicular to the film, but is insulating in all other directions. This film is technologically valuable for use as an interconnection material in electronic packaging (chip-to-package, package-to-board and board-to-board), as it electrically connects the electrical contact pads touching one side of the film with the corresponding contact pads touching the directly opposite side of the film. Even though the film is in one piece, it contains numerous z-axis conducting paths (not necessarily in a regular array, they can be randomly distributed), so that it can provide numerous interconnections. If each contact pad is large enough to span a few z-axis conducting paths, no alignment is needed between the contact pad array and the z-axis film, whether the conducting paths are ordered or random in their distribution[45-59]. Under this situation, in order to attain a high density of interconnections, the cross section of each z-axis conducting path must be small. However, if each contact pad is only large enough to span one z-axis conducting path, alignment is needed between the contact pad array and the z-axis film, and this means that the conducting paths in the z-axis film must be ordered in the same way as the contact pad array[60]. An example of an application of a z-axis conductor film is in the interconnections between the leads from (or contact pads on) a surface mount electronic device and the contact pads on the substrate beneath the device. In this application, one piece of z-axis film can replace a whole array of solder joints, so processing costs can be much reduced. Furthermore, the problem of thermal fatigue of the solder joints can be avoided by this replacement. Another example is in the vertical interconnections in three-dimensional electronic packaging.

A z-axis film is a polymer-matrix composite containing conducting units which form the z-axis conducting paths. The conducting units are usually particles, such as metal particles and metal coated polymer particles. The particles can be clustered so that each cluster corresponds to one conducting path[45-47,51]. Metal columns[52], metal particle columns (e.g. gold plated nickel)[50,51] and individual metal coated polymer particles[49] have been used to provide z-axis conducting paths. Particle columns were formed by magnetic alignment of the particles. Using particle columns, Fulton et al.[46] attained a conducting path width of 400 μm and a pitch (centre-to-centre distance between adjacent conducting paths) of 290 μm. Also using particle columns, Robinson[50] and Rosen[51] attained a conducting path width of ~10 μm and a pitch of ~100 μm. In general, a large conducting path width is desirable for decreasing the resistance per path, while a small pitch is desirable for high density interconnection. In contrast to the use of metal wires, metal columns or metal particle columns, Xu[61] used one metal particle per conducting path (i.e. per connection). The concept of one particle per path had been demonstrated by Li[49] by using metal coated polymer particles. However, due to the high resistivity of the metal coating compared to the bulk metal, the z-axis resistivity of the film was high (0.5 Ω.cm for a conducting path). By using metal particles in place of metal coated polymer particles, Xu[61] decreased the z-axis resistivity of a conducting path to 10^{-6} Ω.cm. Furthermore, Xu did not rely on a polymer (whether the matrix or the particles) for providing resilience, as the resilience is provided by the metal particles, which protrude from both sides of the standalone film. As a result, the problem of stress relaxation of the polymer is eliminated. In addition, the protrusion of the metal particles eliminates the problem of open circuiting the connection upon heating caused by the higher thermal expansion of the polymer compared to the conductor[58].

Most work on z-axis adhesive films[56,57] used an adhesive with randomly dispersed conductive particles (8-12 μm diameter) suspended in it. The particles were phenolic spheres that had been coated with nickel. After bonding under heat (180-190°C) and pressure (1.9 MPa), a particle became oval in shape (4 μm thick). There was one particle per conducting path. The main drawback of this technology is the requirement of heat and pressure for curing the adhesive. Heat and pressure are not desirable in practical use of the z-axis adhesive. Xu[61] removed the need for heat and pressure through appropriate choice of polymer.

A different kind of z-axis adhesive film[60] used screening or stencilling to obtain a regular two-dimensional array of silver filled epoxy conductive dots, but this technology suffers from the large pitch (1500 μm) of the dots and the consequent need for alignment between the z-axis film and contact pad array. In Xu's work, the pitch of the conducting paths in the z-axis adhesive film was as low as 64 μm.

Capacitors require materials with a high dielectric constant. Such materials in the form of thick films allow capacitors to be integrated with the electronic packaging, thereby allowing further miniaturization, in addition to performance and reliability improvements[62]. These thick film pastes involve ceramic particles with a high dielectric constant, such as barium titanate ($BaTiO_3$), and a polymer (e.g. epoxy)[63,64].

Inductors are needed for transformers, DC/DC converters and other power supply applications. They require magnetic materials. Such materials in the form of thick films allow inductors and transformers to be integrated with the electronic packaging, thereby allowing further miniaturization. These thick film pastes involve magnetic particles (e.g. ferrite) and a polymer[65,66].

The need for electromagnetic interference (EMI) shielding is increasingly rapidly due to the interference of radio frequency radiation (such as that from a cellular phone) with digital electronics, and the increasing dependence of society on digital electronics. The associated electronic pollution is an interference problem.

EMI shielding is achieved by using electrical conductors, such as metals and conductive filled polymers[67-75]. EMI shielding gaskets[76-87] are resilient conductors. They are needed to electromagnetically seal an enclosure. The resilient conductors are most commonly elastomers (e.g. rubber) that are filled with a conductive filler[88], or elastomers that are coated with a metallized layer. Metallized elastomers suffer from poor durability due to the tendency of the metal layer to debond from the elastomer. Conductive filled elastomers do not have this problem, but they require the use of a highly conductive filler, such as silver particles, in order to attain a high shielding effectiveness while maintaining resilience. The highly conductive filler tends to be expensive, making the composite expensive. The use of a less conducting filler results in the need for a large volume fraction of the filler in order to attain a high shielding effectiveness; the consequence is diminished resilience or even loss of resilience. Moreover, these composites suffer from degradation of the shielding effectiveness in the presence of moisture or solvents. In addition, the polymer matrix in the composites limits the temperature resistance, and the thermal expansion mismatch between filler and matrix limits the thermal cycling resistance.

Due to the skin effect (i.e. electromagnetic radiation at a high frequency interacting with only the near surface region of an electrical conductor), a filler for a polymer-matrix composite for EMI shielding needs to be not only electrically conducting, but also small in unit size. Although connectivity between the filler units is not required for shielding, it helps. Therefore, a filler in the form of a metal fibre of very small diameter is desirable. For this purpose, nickel filaments of diameter 0.4 μm and length >100 μm, with a carbon core of diameter 0.1 μm, were developed[89]. Their exceptionally small diameter compared to those of existing metal fibres made them outstanding for use as a filler in a polymer for EMI shielding. A shielding effectiveness of 87 dB at 1 GHz was attained in a polyethersulphone-matrix composite with only 7 vol.% nickel filaments[89-91]. The low volume fraction allows resilience in a silicone-matrix composite for EMI gaskets[92].

4. CONCLUSIONS

Polymer-matrix composite materials for microelectronics are typically designed for high thermal conductivity, low CTE, low dielectric constant, either high or low electrical conductivity, and processability (e.g. printability). Applications include heat sinks, housings, printed wiring boards, substrates, lids, die attach, encapsulation, interconnections, thermal interface materials and EMI shielding. Combinations of properties are usually required. For example, for heat sinks and substrates, the combination of high thermal conductivity and low CTE is required for the purpose of heat dissipation and thermal stress reduction. In the case of aerospace electronics, low density is also desired. Polymer-matrix composites for microelectronics include those with continuous and discontinuous fillers. They can be in the form of an adhesive film, a standalone film or a bulk material. They can be isotropic or anisotropic electrically.

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REFERENCES

1. **Sarihan V. and Fang T.**, Structural Analysis in Microelectronic and Fiber Optic Systems, American Society of Mechanical Engineers, EEP, ASME, New York, NY, 12, (1995), 1
2. **Marsh W.E., Kanakaraian K. and Osborn G.D.**, Polymer/Inorganic Interfaces, Materials Research Soc. Symp. Proc., Materials Research Soc., Pittsburgh, PA, 304, (1993), 91
3. **Nguyen L.T. and Noyan IC.**, Polymer Eng. Sci. 28, 16, (1988), 1013
4. **Yang W.-J. and Kudo K.**, Proc. Int. Symp. Heat Transfer Science and Technology, Beijing, China, Hemisphere Publ. Corp., Washington, DC, (1988), 14
5. **Korner H. , Shiota A. and Ober C.K.**, ANTEC '96: Plastics-Racing into the Future, Conf. Proc., Society of Plastics Engineers, Technical Papers Series, no. 42, Brookfield, Conn., 2, (1996), 1458
6. **Swei G.S. and Arthur D.J.**, 3rd Int. SAMPE Symp. Exhib., SAMPE, Covina, CA, (1989), 1111

7. **Li L. and Chung D.D.L.**, Composites 22, 3, (1991), 211

8. **Lu X. and Xu G.**, J. Appl. Polymer Sci., 65, 13 (1997), 2733

9. **Klosterman D. and Li L.**, J. Electronics Manufacturing 5, 4, (1995), 277

10. **Kang S.K., Rai R. and Purushothaman S.**, Proc. 46th Electronic Components & Technology, IEEE, New York, NY, (1996), 565

11. **Luten G.F.C.M., Van Noort H.M. and Beris P.J.M.**, J. Electronics Manufacturing 5, 4, (1995) 253

12. **Zussman M.P. , Kirayoglu B., Sharkey S. and Powell D.J.**, 6th Int. SAMPE Electronics Conf., (1992), 437

13. **Bolt J.D. and French R.H.**, Adv. Mater. Processes, 134, 1, (1988), 32

14. **Bolt J.D., Button D.P. and Yost B.A.**, Mater. Sci. Eng. A109, (1989), 207

15. **Mukerherjee S.P., Suryanarayana D. and Strope D.H.**, J. Non-Crystalline Solids, 147 & 148, (1992), 783

16. **Zussman M.P., Kirayoglu B., Sharkey S. and Powell D.J.**, 6th Int. SAMPE Electronics Conf., (1992), 437

17. **Glatz J.J., Morgan R. and Neiswinger D.**, Int. SAMPE Electronics Conf., 1992, 6, (1992), 131

18. **Bertram A., Beasley K. and de la Torre W.**, Naval Engineers J., 104, 3, (1992), 276

19. **Brookstein D. and Maass D.**, 7th Int. SAMPE Electronics Conf., (1994), 310

20. **Fleming T.F. and Rwey W.C.**, Proc. SPIE - The Int. Soc. for Optical Eng., Soc. Photo-Optical Instrumentation Engineers, Bellingham, WA, 1997, (1993), 136

21. **Fleming T.F., Levan C.D. and Rwey W.C.**, Proc. Technical Conf., Int. Electronics Packaging Conf., Wheaton, Ill, Int. Electronics Packaging Society, (1995), 493

22. **Ibrahim A.M.**, 6th Int. SAMPE Electronics Conf., (1992), 556

23. **Kiuchi N., Ozawa K., Komami T., Katoh O., Arai Y., Watanabe T. and Iwai S.**, Int. SAMPE Tech. Conf., SAMPE, Covina, CA, 30, (1998), 68

24. **Spicer J.W.M., Wilson D.W., Osiander R., Thomas J. and Oni B.O.**, Proc. SPIE - the International Society for Optical Engineering, 3700, (1999), 40

25. **Foster D.A.**, SAMPE Q, 21, 1, (1989), 58

26. **Foster D.A.**, 34th Int. SAMPE Symp. Exhib., Book 2 (of 2), SAMPE, Covina, CA, (1989), 1401

27. **de La Torre W.**, 6th Int. SAMPE Electronics Conf., (1992), 720

28. **Wienhold P.D., Mehoke D.S., Roberts J.C., Seylar G.R. and Kirkeride D.L.**, Int. SAMPE Tech. Conf., vol.30, 1998, SAMPE, Covina, CA, (1998), 243

29. **Luo X. and Chung D.D.L.**, Composites: Part B 30, 3, (1999), 227

30. **Morin L.G. Jr. and Duvall R.E.**, Proc. Int. SAMPE Symp. Exhib., SAMPE, Covina, CA, 43, 1, (1998), 874

31. **Lu G., Li X. and Jiang H.**, Composites Sci. Tech. 56, (1996), 193

32. **Smaldone P.L.**, 27th Int. SAMPE Technical Conf., (1995), 819

33. **Glatz J.J., Vrable D.L., Schmedake T. and Johnson C.**, 6th Int. SAMPE Electronics Conf., (1992), 334

34. **Crossman R.**, Northcon/85 - Conf. Rec., distributed by Western Periodicals Co., North Hollywood, CA, published by Electronic Conventions Management Inc., Los Angeles, CA, (1985), 21

35. **McLachlan D.S., Blaszkiewicz M. and Newnham R.E.**, J. Am. Ceram. Soc., 73, 8, (1990), 2187

36. **Li L. and Chung D.D.L.**, Polymer Composites 14, 6, (1993), 467

37. **Li L., Yih P. and Chung D.D.L.**, J. Electron. Mater., 21, 11, (1992),1065

38. **Guerrero B., Aleman C. and Garza R.**, J. Polymer Eng., 17, 2, (1997-1998), 95

39. **Omastova M., Pavlinec J., Pionteck J. and Simon F.**, Polymer Int., 43, 2, (1997), 109

40. **Chen X.B. and Issi J.-P., Cassart M., Devaux J. and Billaud D.**, Polymer, 35, 24, (1994) 5256

41. **Chen P. and Chung D.D.L.**, J. Electron. Mater. 24, 1, (1995), 47

42. **Fournier J., Boiteux G., Seytre G. and Marichy G.**, J. Mater. Sci. Lett., 16, 20, (1997), 1677

43. **Klosterman D. and Li L.**, J. Electronics Manufacturing 5, 4, (1995), 277

44. **Kang S.K., Rai R. and Purushothaman S.**, Proc. 46th Electronic Components & Technology, IEEE, New York, NY, (1996), 565

45. **Lambert W.R. and Knausenberuer W.H.**, Proceedings of the Technical Program -National Electronic Packaging and Production Conference, 3, (1991), 1512

46. **Fulton J.A., Horton D.R., Moore R.C., Lambert W.R. and Mottine J.J.**, Proc. 39th Electronic Components Conf., IEEE, (1989), 71

47. **Lambert W.R., Mitchell J.P., Suchin J.A. and Fulton J.A.**, Proc. 39th Electronic Components Conf., IEEE, (1989),99

48. **Hogerton P.B., Hall J.B., Pujol J.M. and Reylek R.S.**, Mat. Res. Soc. Symp. Proc. 154, (1989), 415

49. **Li L. and Chung D.D.L.**, J. Electronic Packaging 119, 4, (1997), 255

50. **Robinson P.T., Florescu V., Rosen G. and Singer M.T.**, Annual Connector & Interconnection Technology Symposium, 1990, International Institute of Connector and Interconnection Technology, Deerfield, IL, (1990), 507

51. **Rosen G., Robinson P.T., Florescu V. and Singer M.T.**, Proc. 6th IEEE Hoim Conf. Electrical Contacts and 15th Int. Conf. Electric Contacts, IEEE, Piscataway, NJ, (1990), 151

52. **Johnson D.D.**, Proc. 3rd Int. Symp. Advanced Packaging Materials: Processes, Properties and Interfaces, IEEE, Piscataway, NJ and IMAPS, Reston, VA, (1997), 29

53. **Kokogawa T., Morishita H., Adachi K., Otsuki H., Takasago H. and Yamazaki T.**, Conference Record of 1991 International Display Conference, San Diego, IEEE, Piscataway, NJ and Society for Information Display, Playa Del Rey, CA, (1991), 45

54. **Kreutter N.P., Grove B.K., Hogerton P.B. and Jensen C.R.**, 7th Electronic Materials and Processing Congress, Cambridge, MA, Aug.(1992)

55. **Yoshigahara H. , Sagami Y., Yamazaki T., Burkhart A. and Edwards M.**, Proc. Technical Program: National Electronic Packaging and Production Conf., NEPCON West '91, Cahners Exposition Group, Des Plaines, IL, (1991), 1, 213

56. **Bruner D.M.**, Int. J. Microcircuite and Electronic Packaging 18, 3, (1995), 311

57. **Crea J.J. and Hogerton P.B.**, Proc. Technical Program: National Electronic Packaging and Production Conf., NEPCON West '91, Cahners Exposition Group, Des Plaines, IL, 1, (1991), 251

58. **Gilleo K.**, Proc. Electricon '94, Electronics Manufacturing Productivity Facility, Indianapolis, IN, (1994), 11/1

59. **Chung K., Dreier G., Fitzgerald P., Boyle A. , Lin M. and Sager J.**, Proc. 41st Electronic Components Conf., May (1991), 345

60. **Bolger J.C. and Czarnowski J.M.**, Japan IEMT Symp. Proc. Int. Electronic Manufacturing Technology Symp., IEEE, New York, NY, (1995), 476

61. **Xu Y. and Chung D.D.L.**, J. Electron. Mater. 28, 11, (1999), 1307

62. **Chin G.Y.**, Adv. Mater. Proc. 137, 1, (1990), 47, 50, 86

63. **Liang S., Chong S.R. and Giannelis E.P.**, Proc. Electronic Components & Technology Conf., IEEE, New York, NY, 48, (1998), 171

64. **Agarwal V., Chahal P., Tummala R.R. and Allen M.G.**, Proc. Electronic Components and Technology Conf., IEEE, New York, NY, 48, (1998), 165

65. **Park J.Y. and Allen M.G.**, Conf. Proc., IEEE Applied Power Electronics Conf. and Exposition APEC, 1, (1997), 361

66. **Park J.Y., Lagorce L.K. and Allen M.G.**, IEEE Trans. Magnetics, Pt. 1, 33, 5, (1997), 3322

67. **Charbonneau R.**, Proc. Int. SAMPE Symp. Exhib., SAMPE, Covina, CA, 43, 1, (1998), 833

68. **Wang J., Varadan V.V. and Varadan V.K.**, SAMPE J. 32, 6, (1996), 18

69. **Maugdal S. and Sankaran S.**, Recent Trends in Carbon, Proc. National Conf., ed. O.P. Bahl, Shipra Publ., Delhi, India, (1997), 12

70. **Hoback J.T. and Reilly J.T.**, J. Elastomers Plastics 20, 1, (1988), 54

71. **Lu G., Li X. and Jiang H.**, Composites Sci. Tech. 56, (1996), 193

72. **Radford D.W.**, J. Adv. Mater., Oct. (1994),45

73. **Huang C. and Pai J.**, J. Appl. Polymer Sci. 63, 1, (1997), 115

74. **Radford D.W. and Cheng B.C.**, J. Testing & Evaluation 21, 5, (1993), 396

75. **Gerteisen S.R.**, Northcon/85 - Conf. Rec., distributed by Western Periodicals Co., North Hollywood, CA, Pap. 6.1, published by Electronic Conventions Management Inc., Los Angeles, CA, (1985), 9

76. **O'Shea P.**, Evaluation Engineering, 34, 8, (1995), 84

77. **O'Shea P.**, Evaluation Engineering, 35, 8, (1996), 56

78. **Rothenberg R.A. and Inman D.C.**, Int. Symp. Electromagnetic Compatibility, The Technical Group on EMC of the Institute of Electronics, Information and Communication Engineers, and The Technical Group on EMC of the Institute of Electrical Engineers of Japan, (1994), 818

79. **Child J.W.M.**, Electronic Production, Oct. (1986),41

80. **Subramanian A.K., Pande D.C. and Boaz K.**, Proc. Int. Conf. Electromagnetic Interference and Compatibility, Soc. EMC Engineers, Madras, India, (1995), 139

81. **Hoge W.**, Evaluation Engineering 34, 1, (1995), 84

82. **Walther J.F.**, IEEE Int. Symp. Electromagnetic Compatibility: Symp. Record, IEEE, New York, NY, (1989), 4045

83. **Denny H.W. and Shouse K.R.**, IEEE Int. Symp. Electromagnetic Compatibility: Symp. Record, IEEE, New York, NY, (1990), 20

84. **Bates R., Spence S., Rowan J. and Hanrahan J.**, 8th Int. Conf. Electromagnetic Compatibility, Electronics Division, Insitution of Electrical Engineers, London, (1992), 246

85. **Catrysse J.A.**, 8th Int. Conf. Electromagnetic Compatibility, Electronics Division, Institution of Electrical Engineers, London, (1992), 251

86. **Faught A.N.**, IEEE Int. Symp. Electromagnetic Compatibility, IEEE, New York, NY, (1982), 38

87. **Kunkel G.**, IEEE Int. Symp. Electromagnetic Compatibility, IEEE, New York, NY, (1980), 211

88. **Sau K.P., Chaki T.K., Chakraborty A. and Khastgir D.**, Plastics Rubber & Composites Processing & Applications 26, 7, (1997), 291

89. **Shui X. and Chung D.D.L.**, J. Electron Mater. 24, 2, (1995), 107

90. **Shui X. and Chung D.D.L.**, J. Electron. Mater. 25, 6, (1996), 930

91. **Shui X. and Chung D.D.L.**, J. Electron. Mater. 26, 8, (1997), 928

92. **Shui X. and Chung D.D.L.**, J. Electron. Packaging 119, 4, (1997), 236