COMPOSITE MATERIAL SWITCHES

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A device to protect electronic circuitry from high voltage transients is constructed from a relatively thin piece of conductive composite sandwiched between two conductors so that conduction is through the thickness of the composite piece. The device is based on the discovery that conduction through conductive composite materials in this configuration switches to a high resistance mode when exposed to voltages above a threshold voltage.

8 Claims, 4 Drawing Sheets
COMPOSITE MATERIAL SWITCHES

This application is a divisional application under 37 C.F.R. §1.60 of prior patent application U.S. Ser. No. 08/530,976 filed on Sep. 20, 1995.

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the Contractor has elected not to retain title.

TECHNICAL FIELD

The present invention is in the field of materials for microelectronics, both integrated and hybrid circuits, and, more particularly, concerns a composite material that exhibits altered conductivity to provide protection for delicate electronic components.

BACKGROUND ART

Common electronic devices are constantly in danger of being exposed to damaging voltage transients. These voltage transients may be present in the electric mains due to starting or stopping of large electric motors or to lightning strikes near power lines or the like. Even static electric discharges following, for example, the shuffling of one's shoes across a carpeted surface, may cause damage to integrated circuits such as those found in personal computers.

Traditionally, fuses have been the mainstay for protecting electrical circuits from damage. A fuse might be considered an archetype of a material showing altered conductivity or nonlinear resistance. At normal power loads a fuse exhibits uniform high conductivity (low resistance), but at higher power loads, the fuse melts opening the circuit. That is, the fuse's conductivity alters (i.e., shows nonlinear resistance) and permanently changes to a high resistance mode. However, dangerous voltage transients can wreak damage in a few nanoseconds—much too short a time for any ordinary fuse to respond. Furthermore, fuses must be replaced before an electronic device can be used again; fuse-like materials that automatically reset themselves are to be much desired.

Fortunately, materials that show extremely rapid alterations in conductivity have been found and can be used to protect electronic circuitry. Materials that show altered conductivity under various conditions are well known in the art of solid state electronics. These materials are mostly semiconductors, since alteration of conductivity forms the basis for virtually all semiconductor electronics. One of the most widely-used materials that shows altered conductivity is a metal oxide “varistor” (MOV). This semiconductor device exhibits extremely high resistance when exposed to relatively low voltages like those of domestic electric supplies (i.e. 120 V). However, this same device rapidly switches to a good conductor when exposed to higher voltages. MOV materials can be custom made allowing a fairly precise choice of the potential “clamp” voltage (the voltage at which the device switches into a conducting mode).

These materials are usually employed as potential parallel pathways between a voltage supply and ground. Under normal conditions the MOV behaves as an insulator, but when a voltage transient exceeds the clamp voltage, the MOV becomes a good conductor and the transient is harmlessly conducted through the MOV to ground. The MOV then rapidly reverts to its nonconducting state until the next voltage transient arrives.

One problem with MOV materials is that they tend to have relatively high capacitance, which results in a longer than optimal switch-over time. This and related problems have been addressed through the production of altered conductivity materials produced from conducting and semiconducting materials suspended in an insulating matrix such as an epoxy plastic. These materials are reported to have superior properties over traditional MOV devices.

U.S. Pat. No. 4,977,357 to Shrier discloses another system based on a packed mixture of conducting, semiconducting and insulating particles, all embedded in a nonconducting matrix material. The materials are similar in nature to the earlier Hyatt et al. patent. In this case, however, the conducting particles are in the 100 μm range, the semiconducting particles are in the micrometer range, and the insulating particles are in the submicrometer range. The patent also discloses dimensions and packing ratios necessary to achieve particular results. A similar nonlinear resistance material is disclosed in U.S. Pat. No. 4,977,357 to Shrier, which teaches a material formed from conducting particles uniformly dispersed in an insulating binder.

All of the above-mentioned nonlinear resistors show low conductivity at low potentials and high conductivity at higher potentials. Generally, it is believed that these and similar materials operate by means of quantum electron tunneling. That is, they are all arranged with the conducting particles slightly separated so that the materials exhibit high electrical resistance. As higher potentials are imposed across the materials, electrons “tunnel” through the insulator and “jump” from conducting particle to conducting particle, thus causing the material to switch into the high conductance or low resistance mode. As soon as the potential falls, the electrons are no longer sufficiently energetic to “tunnel” so that the material regains its original high resistance.

The drawback with all of the nonlinear resistors discussed heretofore is that they all transition from high resistance at low potential to low resistance at high potential. While this behavior may be ideal for shunting a power supply to ground, it cannot solve all voltage transient problems.

There are also available a number of “repetitive fuses” (such as PolyFuse manufactured by Raychem Corporation of Menlo Park, Calif.); these devices are variable resistors whose resistance greatly increases with increases of temperature. If a circuit draws excess current through one of these devices, the device will increase in temperature. This causes the resistance to increase greatly, thereby cutting off the circuit from the power source. However, such devices are slow acting and unable to provide protection from brief, but damaging, voltage transients.

High impedance signal inputs such as the gates of field effect transistors (FET) and other similar devices remain sensitive to damage by excessive voltages. These devices can be readily damaged by high voltage pulses or even static electric discharges. Even when such inputs are connected to ground by one of the nonlinear resistors already discussed, damage may occur before the nonlinear resistor can change
state of the art, handheld instruments may lack a clear path to ground. Often, the ground planes of the printed circuits are insufficiently connected to help dissipate the high-voltage transients. Consequently, these devices are often subjected to damage due to their inability to properly reject high potentials. Such devices are often designed with a metallic shield and conductive path, creating a Faraday cage effect. However, this is an expensive solution, as it requires a dedicated ground plane and additional components to ensure proper grounding. Furthermore, the effectiveness of this approach is limited by the physical constraints of the components and the board design. The following description is provided to enable any person skilled in the art to carry out the invention. Various modifications and further applications of the invention will remain readily apparent to those skilled in the art, since the present description is intended to be an illustrative, non-limiting description of the invention. The present invention was made during a reinvestigation of the properties of conductive composite materials, which are well known in the art. The present invention is based on the discovery that conductive composite materials can be fabricated to have a unique resistance characteristic that changes state in the opposite direction to that of the silver epoxy. Further, it has been found that such materials can be used as a nonlinear resistor that changes state in response to high potentials.

The present invention is a device to protect electronic circuits from high-voltage transients. The device is constructed from a relatively high-resistance metal material and a relatively low-resistance material. The device has several advantages, including the ability to limit the transient current, the ability to limit the transient voltage, and the ability to protect the circuitry from high-voltage transients. The device is composed of two conductive composite materials, both of which are prepared from silver particles and a matrix material such as an epoxy resin. The high conductivity of the silver particles is offset by the low conductivity of the matrix material, creating a unique resistance characteristic that changes state in the opposite direction to that of the silver epoxy.

The following description is intended to enable any person skilled in the art to carry out the invention. Various modifications and further applications of the invention will remain readily apparent to those skilled in the art, since the present description is intended to be an illustrative, non-limiting description of the invention. The present invention was made during a reinvestigation of the properties of conductive composite materials, which are well known in the art. The present invention is based on the discovery that conductive composite materials can be fabricated to have a unique resistance characteristic that changes state in the opposite direction to that of the silver epoxy. Further, it has been found that such materials can be used as a nonlinear resistor that changes state in response to high potentials.
device, shown in FIG. 1, was used for some resistance measurements and consists of a single-piece silver epoxy preform 18 sandwiched between a gold ribbon 20 and a chromium/copper/gold trace (gold trace) 12 following methods explained below in relation to FIG. 2. The gold traces 12 and ribbons 20 were about 0.025-inch and 0.015-inch wide, respectively, while the pieces of preform 18 were approximately 0.05-inch by 0.05-inch and 0.003-inch thick. This means that electrical conduction was across the thickness of the preforms 18 and was oriented perpendicular to a top and bottom surface of the original preform sheet.

More precise resistance measurements used a four-probe system. As shown in FIG. 2, four gold traces 12 were deposited on an alumina substrate 14. Each of the gold traces 12 was attached at a first end to the connectors 16 which were used to connect voltmeters and other instrumentation. At a second end each gold trace 12 was connected either to a rectangular piece of the silver epoxy preform 18 or to a gold ribbon 20.

The gold ribbons 20 and preform pieces 18 were alternately fastened together to form a laminated structure 22 whose cross-section is shown in FIG. 3. The lamination was accomplished by wiggling and pressing each gold ribbon 20 into one of the preforms 18 with a wooden applicator stick using sufficient pressure to deform but not rupture the surface of the preform 18. Recall that the preform material is not fully cured so it remains tacky. The lamination was then rendered permanent by curing the laminated structure at 125°C for two hours.

The structure shown in FIGS. 2 and 3 allowed the use of a four-probe resistance measurement methods so that contact resistances would not contribute to the measured value. To make the measurements an alternating current of ±1 μA was conducted through the device from a first current connector 16a to a second current connector 16b. The direction of the current was alternated to eliminate the Seebeck effect generated between dissimilar materials in a temperature gradient. At the same time voltage was measured at a first voltage connector 16c and a second voltage connector 16d. The resistance was obtained by averaging the absolute magnitude of the positive and negative measured voltages divided by the current.

Initial tests of the current-voltage characteristics of the silver epoxy samples were made with a Tektronix 576 curve tracer and revealed intermittent behavior. As the voltage across the sample increased, switching to a high resistive state occurred with the probability of this switching increasing as the voltage level was approached.

More precise current-voltage characteristics measurements were then obtained by using a Hewlett Packard 4194A impedance/gain-phase analyzer and a Keithley 237 instrument. These results showed that a sample becomes more resistive when a threshold voltage is exceeded. Further, there is a probability of the sample temporarily returning to a lower resistance before again switching to a higher resistance. As soon as the threshold voltage is removed, the sample returns to a low resistance state. The threshold voltage for one sample varied from 0.4 to 1.9 V in subsequent voltage sweeps. Generally, measured resistance decreased with temperature (from room temperature down to 50° Kelvin), but the effect was slight.

FIG. 4 shows an example of a sample of silver epoxy preform switching to a high resistance state as a result of application of a voltage above the threshold. This sample switched form approximately 200 ohms to greater than 100 megohms. As voltage (x-axis) is increased, a trace 32 shows the current also increasing until there is a current drop 34 indicating a temporary higher resistant at about 1.4 V. After returning to a lower resistance mode, the current shows a precipitous drop 36 to a very high resistance form (>100 megohms). This switching to a high resistive state appears to be a fundamental and inherent feature of these conductive silver epoxies and of similar metal/insulator composites.

FIG. 5 shows a circuit diagram of a device 42 in a typical application. The device 42 is connected in series with a gate electrode 44 of a field effect transistor (FET) 46. The device is pictured as a resistor, but as explained above, the device's resistance is strongly dependent upon potential above a threshold voltage. The FET gate 44 can be damaged by high voltage transients such as static discharges and is normally protected by built-in clamping diodes (not shown). However, even the diodes may fail to adequately protect the gate 44. The device 42 of the present invention provides additional protection by rapid and complete cutting off of the FET 46 from damaging potentials.

The device 42 may represent a single piece of conductive composite 18 or may represent multiple pieces stacked as in FIG. 3 to alter the switching potential or the power handling capability of the device 42. Depending on the desired result the pieces of composite can be connected in series as in FIG. 3, or the intermediate gold ribbon conductors 20 can be tied to one of the device's inputs resulting in a parallel configuration.

An additional application for the present invention can be found in the fabrication of conducting cables. It should be obvious to those of ordinary skill in the art that epoxy-based and similar flexible conductive composites can be molded to construct virtually any structural feature of conductive cables.

Producing all or part of the central conductor of coaxial cables according to the structures of the present invention would be especially advantageous and well suited. Normally, the central conductor is used to deliver relatively low current, low voltage signals to sensitive electronic components. As shown in FIG. 6, a coaxial cable 42 comprises a central conductor 44, a surrounding insulating separator 46, a coaxial conductor 48 and sheathing insulation 52. By placing a "fuse link" 54 of a suitable conductive composite into the central conductor at some periodic distance one would automatically provide significant protection for vulnerable electronics. The fuse link could be placed every so many feet (say 10 or 100 ft) to ensure that any installation would have at least one fuse link 54.

Alternatively, coaxial connectors 56 (male) and 57 (female) could be fabricated with a central male connector pin 58 and a central female socket 59, respectively, fabricated from the composite conductor or containing a fuse link 54 similar to that in the coaxial cable 42.

Generally direct current conductivity of composite materials has been successfully described by Sheng's model ("Fluctuation-induced tunneling conduction in disordered materials," Phys. Rev. B 21: 2180 (1980)). Under that model conduction is dominated by electron transfer between metallic islands (charging energy). The overall conduction of the system is limited by tunnel junctions where electrons tunnel through the insulating matrix between the metallic islands. This tunneling is predicted to show a negative temperature coefficient of resistivity (TCR). TCR has long been considered an important distinguisher of conduction mechanisms on both side of the metal-insulator transition with metals having a positive TCR and insulators having a negative TCR. Since the conductive epoxy system described herein...
shows only a small variation of conductance with temperature, it behaves more like a system on the verge of the metal-insulator transition as opposed to a typical Sheng model composite conductor.

Under the conditions of a metal-insulator transition the presence of localized centers (e.g., charge and spin defects due to broken or "dangling" bonds, radicals, or lone electron pairs) in the insulating matrix (epoxy) or an insulating layer on the metal particles (oxide or sulfide) cannot be ignored. Very high electric fields may be generated between closely spaced metallic islands separated by an organic layer.

Complications in conduction are caused by the presence of weakly localized centers involved in carrier hopping and strongly localized centers leading to space-charge effects in both the epoxy matrix and the metal oxide/sulfide. Where localized centers in the insulating materials mediate conduction between the metallic islands, field distribution caused by space charge effects may be so large as to create a region in the insulator that has an electric field directed against the current leading to a complete switching off of conductivity as seen in the present case.

It must be appreciated that the described silver epoxy conductive composite is used as a model for a general class of composite conductors. Other metals and insulating matrices should give comparable results. Further, this type of device can be fabricated as an integrated circuit by depositing, by sputtering for instance, conductive particles on a thin insulating layer on a conductive substrate and then depositing an additional insulating layer over and around the conductive particles and completing the device with a conducting layer. In any case, sandwiching conductive composite material between conductors, as in the illustrated experimental devices, reveals a unique nonlinear resistance property wherein the material rapidly and repeatedly switches to a high resistance state when exposed to a threshold voltage.

Those skilled in the art will appreciate that various adaptations and modifications of the just-described preferred embodiment can be configured without departing from the scope and spirit of the invention. Therefore, it is to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described herein.

What is claimed is:

1. A device in series with an electrical circuit for protecting the electrical circuit from excessive electrical potential comprising an alternating layered structure of metallic conductors and a composite conducting material formed as a plurality of metallic particles at a concentration approaching a percolation conduction threshold in an insulating background matrix, the device comprising:
   a first metallic conductive lead with an end;
   a lamellar structure comprising a first end, a second end and at least one lamination unit conductively laminated to the end of the first metallic conductive lead wherein the lamellar structure has a first operative mode of conductivity below a predetermined threshold voltage and a second operative mode of increased resistivity at and above said predetermined threshold voltage, a lamination unit comprising:
   a first planar piece of the composite conductive material with a first surface and a second surface;
   a first piece of metallic conductor, the same planar dimensions as the first piece of composite conductive material, laminated to the first piece of composite conductive material, a first surface of the first metallic conductor in contact with the second surface of the composite conductive material;
   a second planar piece of composite conductive material, the same planar dimensions as the first piece of metallic conductor, laminated to the first piece of composite conductive material, a first surface of the composite conductive material in contact with a second surface of the insulating material, the same planar dimensions as the second piece of composite conductive material, laminated to the second piece of composite conductive material, a first surface of the second metallic conductor in contact with a second surface of the composite conductive material;
   a second metallic conductive lead with an end; and
   a planar piece of the conductive composite material forming a conductive bridge between the end of the second conductive lead and the lamellar structure at the second end of the lamellar structure.

2. The device of claim 1, wherein the conductive composite material comprises:
   a matrix of insulating epoxy resin; and
   a plurality of solid silver metal particles embedded throughout the matrix.

3. A device in series with an electrical circuit comprising:
   a first metallic conductive lead; a second metallic conductive lead and a lamellar structure forming a bridge between the first and second metallic conductive leads; wherein the lamellar structure has a first operative mode of conductivity below a predetermined threshold voltage and a second operative mode of increased resistivity at and above said predetermined threshold voltage; the lamellar structure comprising at least one composite lamellar unit comprising a first piece of a composite conductive material comprising a plurality of metallic particles of a concentration approaching a percolation conduction threshold in a background matrix of insulating material, a second piece of the composite conductive material and a metallic layer comprising a first and second surface; the first surface of the metallic layer conductively attached to the first piece of the composite conductive material and the second surface of the metallic layer conductively attached to the second piece of the composite conductive material.

4. The device of claim 3 wherein the first and second pieces of conductive composite material are oriented so that a direction of conduction is across the thickness of each piece.

5. The device of claim 3 wherein the conductive composite material comprises a matrix of insulating epoxy resin and a plurality of solid silver metal particles embedded throughout the matrix.

6. The device of claim 3 wherein the lamellar structure further comprises at least one supplemental lamellar unit comprising a supplemental metallic layer attached to a supplemental piece of the composite conductive material, and wherein the supplemental metallic layer is conductively attached to at least one composite lamellar unit at the second piece of the composite conductive material.

7. The device of claim 3 where the predetermined voltage threshold is 1.9 volts.

8. The device of claim 3 where the second operative mode of increased resistivity has a non-linear increase in resistance.

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