COMPOSITE MATERIAL SWITCHES

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Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

Application No.: 09/606,111
Filed: Jun. 20, 2000

Related U.S. Application Data

Division of application No. 08/530,976, filed on Sep. 20, 1995.

Assignee: The United States of America as represented by the Administrator of the National Aeronautics and Space Administration, Washington, DC (US)

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Abstract

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.
COMPOSITE MATERIAL SWITCHES

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. 4,726,991 to Hyatt et al. discloses a mixture of conductive particles (carbonyl nickel, nickel, tantalum carbide, gold, silver, etc.) in the size range of 100 μm coated with an insulator such as silicon dioxide and mixed with similarly-sized semiconductor particles (doped silicon, selenium, germanium, etc.) and suspended in an insulating binder such as organic polymers like epoxy. This material is reported to have a more rapid response time than MOV devices and can be made with clamping voltages as low as 5 V.

In U.S. Pat. No. 4,992,333 to Hyatt 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 and shunt the voltage pulse to ground. Further, many
hand-held instruments may lack a clear path to ground
rendering these protective devices ineffectual. Furthermore,
the need for ground shunts may result in excess fabrication
cost or may even alter the operation of some circuits. Having
the input shunted to ground by each voltage transient may
do also tend to introduce noise into the circuit. What is needed
is a nonlinear resistor that changes state in the opposite
direction; that is, one that conducts at low potentials and
rapidly develops high resistance at higher potentials. Such a
resistor could be placed in series with the input and effecti-
cut off the input whenever the signal contained
excessively high voltage.

STATEMENT OF THE INVENTION

The present invention is a device to protect electronic
components from high voltage transients. The device is con-
structed from a relatively thin piece of conductive silver
epoxy sandwiched between two conductors. The device is
based on the discovery that conductive composite materials
in this configuration switch to a high resistance mode when
exposed to voltages above a threshold voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the present invention, which
are believed to be novel, are set forth with particularity in the
 appended claims. The present invention, both as to its
organization and manner of operation, together with further
objects and advantages, may best be understood by reference
to the following description, taken in connection with the
accompanying drawings.

FIG. 1 shows a cross-section of a device constructed with
a single silver epoxy preform;

FIG. 2 shows a top view of an experimental device
constructed with multiple silver epoxy preforms and used to
make precision current-voltage measurements;

FIG. 3 shows a cross section of the device of FIG. 2;

FIG. 4 is a diagram showing current in the silver epoxy
device of FIG. 2 at different voltages;

FIG. 5 shows an example of a circuit diagram with the
device of the present invention in actual use; and

FIG. 6 shows the present invention used as a “fuse link”
in a central lead of a coaxial cable, in a central connector pin
in a male coaxial connector, and in a central connector
socket in a female coaxial connector.

DETAILED DESCRIPTION OF THE INVENTION

The following description is provided to enable any
person skilled in the art to make and use the invention and
sets forth the best modes contemplated by the inventor of
carrying out his invention. Various modifications, however,
will remain readily apparent to those skilled in the art, since
the generic principles of the present invention have been
defined herein specifically to provide a device consisting
essentially of alternating layers of metallic conductors and
conductive composite which can protect electronic devices
by becoming temporarily nonconductive in the face of
increased electrical potential.

Conductive composite materials are well known in the art
of integrated circuits and microelectronics. These materials
consist of metal particles embedded in a background of
insulating material. The present inventor has discovered
hitherto unknown properties of conductive composite mate-
rials in which the concentration of the metal particles is close
to percolation threshold. Above the percolation threshold
the concentration of the particles is high enough and/or the
shape of the particles is such that there is significant particle
to particle contact so that conduction will occur directly
from particle to particle. Below the threshold the particle
concentration is lower and/or the particle shapes preclude
significant particle to particle contact and most conduction
occurs through the insulating background matrix.

A well-known example is the so-called “silver paint”
which is a conductive mixture of silver particles in a liquid
vehicle. Such a material can be used to paint or print
conductive paths onto circuit boards or other substrates.
Silver-filled epoxy is another similar material consisting of
an epoxy resin matrix into which a relatively large quantity
(generally 50% by weight or greater) of silver particles
(flakes, “popcorn,” “cigars,” or other shapes, depending on
design parameters) has been mixed. This material is used as
an electrical and/or heat conductive adhesive for affixing
components and silicon dies to circuit boards. Besides a
liquid paste, silver-filled epoxies are also available as parti-
cularly cured sheets (preforms) which can be used to lay out
conductive traces as well as to attach components to circuit
boards.

Although silver-filled epoxies are usually thought of as
conductors, they are quite similar in structure to some of the
particulate semiconductors discussed above. The epoxy
matrix material is an insulating material. While the indi-
vidual silver particles are metallic conductors, they may be
coated by insulating silver compounds such as silver oxide
or silver sulfide formed by a reaction of silver metal with the'
exoxy resin or oxidation by air. Further, depending on the
size, shape, and spacing of silver particles, some of the
current conduction may occur by means of quantum electron
tunneling from silver island to silver island through a sea of
epoxy.

There have been a number of reports of conductivity
problems or anomalies with silver epoxy composites. A
report entitled “Electrical Reliability of Silver Filled
Epoxies for Die Attach,” Opila, R. and J. D. Sinclair, IEEE
International Reliability Physics Symposium Proceedings,
164–72 (1985) is typical of these reports. This report
addresses the conditions that result in intermittent high
resistance, as opposed to desired high conductivity, silver
epoxy contacts. The study concludes that conduction in the
silver epoxy takes place through a percolative network of
silver particles with a combination of contact conduction
through the silver particles and quantum tunneling through
the epoxy. Further, high resistivity seemed to be mediated by
an insulating layer formed around the silver as well as by the
orientation of the silver particles at epoxy interfaces.

The present invention was made during a reinvestigation
of intermittent silver epoxy conductivity. To limit the vari-
ability caused by mixing silver particles with epoxy resin
and catalysts a premixed, partially hardened silver epoxy
material was used (ECF-563 Ablestik). This material is avail-
able as partially hardened preform sheets of precise thickness
(0.003-inch) fabricated by rolling a premixed epoxy. The material is not fully cured and retains
considerable stickiness. To attach components to a board,
pads and traces are cut from the ECF-563 sheet and pressed
onto the board, where they stick firmly. The components are
then pressed onto the material and the cure is completed by
oven baking. The manufacturer recommends maintaining
pressure on the components during the curing process. In the
present experiments, the components were too small to
readily apply pressure during curing.

For test purposes silver epoxy composite structures shown
in FIG. 1 and FIGS. 2 and 3 were constructed. The simplest
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 575 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 some threshold voltage 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 dependant 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 capacity 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 sides 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 effective 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 the insulating materials to create a thin insulating layer on a conductive substrate and by 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 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 piece of planar composite conductive material, the same planar dimensions as the first piece of metallic conductor, laminated to the first piece of metallic conductor, a first surface of the composite conductive material in contact with a second surface of the metallic conductor; and
   a second piece of metallic conductor, 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;
   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,
   the planar pieces of conductive composite oriented so that a direction of conduction is across the thickness of each planar piece.

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 threshold in a background matrix comprising a 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 a 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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