United States Patent

Bhola

[15] **3,691,631**

[45] **Sept. 19, 1972**

[54] **METHOD OF MAKING A VOLTAGE ACTUATABLE SWITCH**

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[73] Assignee: **Conductron Corporation,** St. Charles, Mo.

[22] Filed: **Jan. 29, 1970**

[21] Appl. No.: **12,535**

Related U.S. Application Data

[62] Division of Ser. No. 794,283, Jan. 27, 1969, Pat. No. 3,546,540.

[52] **U.S. Cl.** .....**29/622,** 29/580, 29/588, 29/625, 117/212, 200/61.08, 340/173 SP, 317/101 A

[51] **Int. Cl.**.....**H01h 11/00**

[58] **Field of Search** .....200/61.08, 61.09; 317/258; 307/93–95, 108, 109, 101 A; 29/622, 625, 580, 588; 340/173; 117/212

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Assistant Examiner—Robert W. Church
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[57] **ABSTRACT**

A voltage actuated switch comprises a conductor, an essentially defect-free layer of insulating material which has a portion thereof that overlies and engages at least a part of a surface of that conductor and that has a predetermined thickness and resistivity to enable it to have a relatively high breakdown voltage, a tiny area of that layer of insulating material which has a thickness and resistivity that enable it to have a predetermined lower breakdown voltage, and an electrode which overlies and engages said tiny area of said layer of insulating material. The tiny area of the layer of insulating material will normally insulate the electrode from the conductor; but it will respond to a voltage, which is higher than the predetermined breakdown voltage of that tiny area but which is lower than said relatively high breakdown voltage, and which is applied across that electrode and that conductor, to break down and permit an irreversible, low-resistance connection to form between that electrode and that conductor.

7 Claims, 11 Drawing Figures

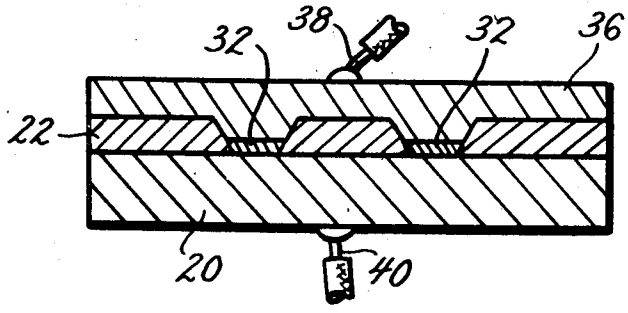


FIG. 1.

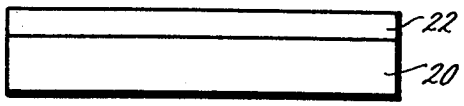


FIG. 2.

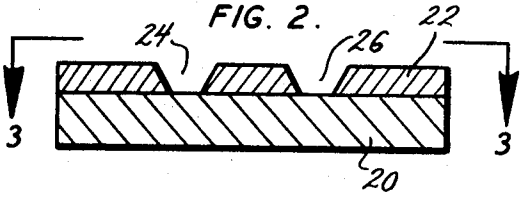


FIG. 3.

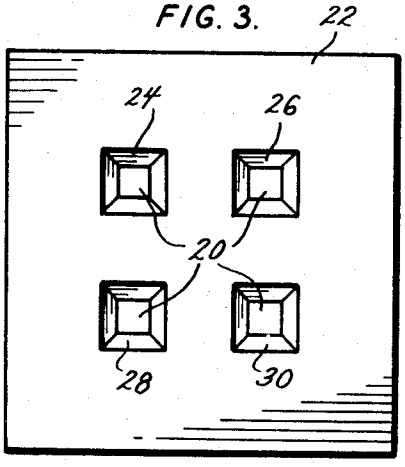


FIG. 4.

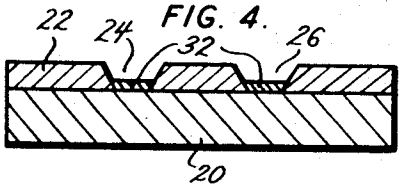


FIG. 5.

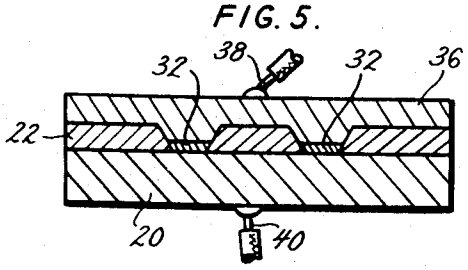


FIG. 6.

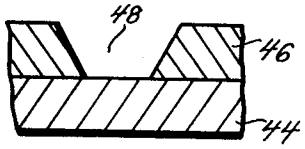


FIG. 7.

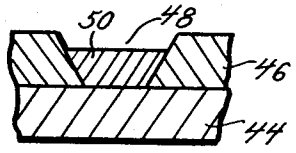


FIG. 8.

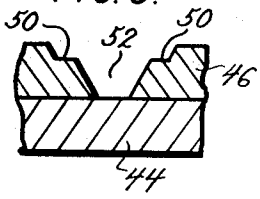


FIG. 9.

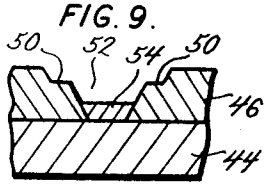


FIG. 10.

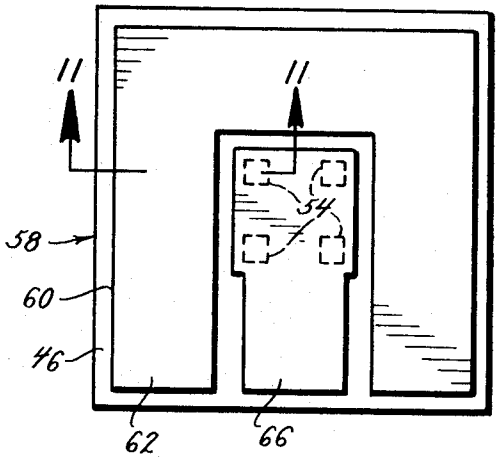
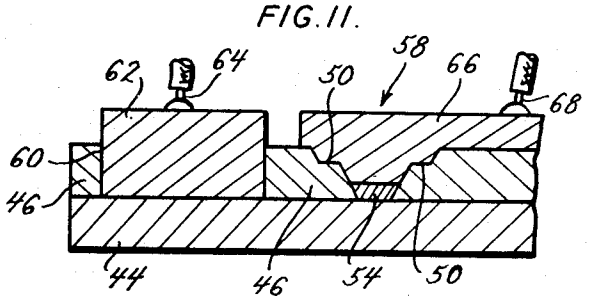


FIG. 11.



METHOD OF MAKING A VOLTAGE ACTUATABLE SWITCH

This is a division of application Ser. No. 794,283 filed Jan. 27, 1969, now U.S. Pat. No. 3,546,540.

This invention relates to improvements in Control Systems. More particularly, this invention relates to improvements in voltage actuated switches for control systems.

It is, therefore, an object of the present invention to provide an improved voltage actuated switch for control systems.

Some control systems, such as the Control System For Sequentially Actuating A Plurality of Loads disclosed in co-pending patent application, Ser. No. 589,560 now U.S. Pat. No. 3,417,259 of Nozawa and Nasser which was filed Oct. 26, 1966, utilize voltage actuated switches; and one commonly-used type of voltage actuated switch is generally similar to an electrolytic capacitor. Specifically, that type of voltage actuated switch usually consists of a foil of aluminum which has an anodized insulating film on one surface thereof, of a metal screen which is formed on that anodized insulating film, and of an electrode which is bonded to that metal screen. While voltage actuated switches of that type are usable, the voltages at which those voltage actuated switches change from their initial high-resistance states to their low-resistance states cannot be predicted with a sufficiently close degree of accuracy. Moreover, voltage actuated switches of that type can sometimes respond to current or voltage surges to change back from their low-resistance states to their initial high-resistance states. It would be desirable to provide a voltage actuated switch which would change from its initial high-resistance state to a low-resistance state whenever a closely-predictable breakdown voltage was applied to it, and which would thereafter remain in its low-resistance state even though it was subjected to voltage or current surges. The present invention provides such a voltage actuated switch; and it is, therefore, an object of the present invention to provide a voltage actuated switch which will change from its initial high-resistance state to a low-resistance state whenever a closely predictable breakdown voltage is applied to it, and which will thereafter remain in its low-resistance state even though it is subjected to current or voltage surges.

The voltage actuated switch provided by the present invention comprises a conductor, an essentially defect-free layer of insulating material which has a portion that overlies and engages at least a part of a surface of that conductor and that has a predetermined thickness and resistivity to enable it to have a relatively high breakdown voltage, a tiny area of that layer of insulating material which has a thickness and resistivity that enable it to have a predetermined lower breakdown voltage, and an electrode which overlies and engages said tiny area of said layer of insulating material. The tiny area of the layer of insulating material will normally insulate the electrode from the conductor; but it will respond to a voltage, which is higher than said predetermined breakdown voltage of that tiny area but which is lower than said relatively high breakdown voltage, and which is applied across that electrode and that conductor, to break down and permit an irreversible, low-resistance connection to form between the electrode and that conductor. The essentially defect-free

nature of the layer of insulating material will obviate any premature breakdowns of the voltage actuated switch; and hence that voltage actuated switch can have a closely-predictable breakdown voltage. The thickness and resistivity of the tiny area will make the predetermined breakdown voltage for that tiny area high enough so a sufficiently large portion of that tiny area will be broken down to enable an irreversible, low-resistance connection to form between the conductor and the electrode. It is, therefore, an object of the present invention to provide an improved voltage actuated switch which comprises a conductor, an essentially defect-free layer of insulating material which has a portion that overlies and engages at least a part of a surface of that conductor and that has a predetermined thickness and resistivity to enable it to have a relatively high breakdown voltage, a tiny area of that layer of insulating material which has a thickness and resistivity that enable it to have a predetermined lower breakdown voltage, and an electrode which overlies and engages said tiny area of said layer of insulating material.

One preferred embodiment of the voltage actuated switch provided by the present invention comprises a wafer of silicon, a layer of silicon dioxide on one surface of that wafer, a tiny opening in that layer of silicon dioxide, a reduced thickness layer of silicon dioxide within that tiny opening, and an electrode in engagement with that reduced-thickness layer of silicon dioxide. That reduced thickness layer of silicon dioxide normally isolates the electrode from the silicon wafer, but it will respond to a predetermined breakdown voltage to break down and permit a low-resistance connection to form between that electrode and that silicon wafer. The voltage which is required to convert the voltage actuated switch from its initial high-resistance state to its low-resistance state can be closely controlled by closely controlling the thickness of the reduced thickness layer of silicon dioxide; and that voltage will be high enough so a sufficiently large portion of that reduced thickness layer will be broken down to enable an irreversible, low-resistance connection to form between the conductor and the electrode. If a current or voltage surge were to be applied to the said preferred embodiment of the voltage actuated switch, after that voltage actuated switch had changed from its initial high-resistance state to its low-resistance state, that voltage or current surge could not cause that voltage actuated switch to revert to its initial high-resistance state. If such a voltage or current surge were to have any effect upon the voltage actuated switch, it would merely cause more of the reduced-thickness, silicon dioxide layer to breakdown —thereby making even more certain that the voltage actuated switch would not revert to its initial high-resistance state. It is, therefore, an object of the present invention to provide an improved voltage actuated switch which comprises a wafer of silicon, a layer of silicon dioxide on one surface of that wafer, a tiny opening in that layer of silicon dioxide, a reduced-thickness layer of silicon dioxide within that tiny opening, and an electrode in engagement with that reduced thickness layer of silicon dioxide.

Other and further objects and advantages of the present invention should become apparent from an examination of the drawing and accompanying description.

In the drawing and accompanying description two preferred embodiments of the present invention are shown and described but it is to be understood that the drawing and accompanying description are for the purpose of illustration only and do not limit the invention and that the invention will be defined by the appended claims.

In the drawing,

FIG. 1 is a side elevational view of a conductor and of a layer of insulating material on the upper surface of that conductor,

FIG. 2 is a vertical section through the conductor and layer of insulating material shown in FIG. 1 after tiny openings have been formed in that layer of insulating material,

FIG. 3 is a plan view of the conductor and layer of insulating material shown in FIG. 2, and it is taken along the plane indicated by the line 3—3 in FIG. 2,

FIG. 4 is a vertical section through the conductor and layer of insulating material shown in FIG. 2 after further layers of insulating material have been formed within the tiny openings in the layer of insulating material of FIG. 2,

FIG. 5 is a sectional view through a voltage actuated switch which is made from the conductor and the layers of insulating material of FIG. 4,

FIG. 6 is a sectional view through a second conductor and a layer of insulating material thereon,

FIG. 7 is a sectional view through the conductor and layer of insulating material of FIG. 6 after a second insulating layer has been formed within a small opening in the layer of insulating material shown in FIG. 6,

FIG. 8 is a sectional view through the conductor and the layers of insulating material shown in FIG. 7 after a tiny opening has been formed in the second layer of insulating material,

FIG. 9 is a sectional view through the conductor and layers of insulating material of FIG. 8 after a third layer of insulating material has been formed within the tiny opening in the second layer of insulating material,

FIG. 10 is a plan view, on a smaller scale, of the conductor and layers of insulating material shown in FIG. 9 after two spaced electrodes are formed on that conductor and on those layers of insulating material, and

FIG. 11 is a sectional view, on the scale of FIG. 6, through the conductor and layers of insulating material shown in FIG. 10 after leads have been attached to the spaced electrodes formed on that conductor and on those layers of insulating material.

Referring to the drawing in detail, the numeral 20 denotes a conductor which has a smooth upper surface, and which will be incorporated into one preferred embodiment of voltage actuated switch that is made in accordance with the principles and teachings of the present invention. A layer 22 of insulating material overlies the upper surface of the conductor 20, and that layer is an essentially defect-free layer of insulating material; and that layer will have a thickness and a resistivity which will enable that layer to have a relatively high breakdown voltage. In the said one preferred embodiment of voltage actuated switch provided by the present invention, the conductor 20 is a single crystal wafer of silicon, and the layer 22 of insulating material is a layer of silicon dioxide which is "thermally grown" on the upper surface of that silicon wafer. The wafer of silicon is square in plan, each side is 18 thousandths of an inch long, and it is 1 and ½ thousandths of an inch thick. The layer 22 of silicon dioxide is about 7500 Angstroms thick. Tiny openings 24, 26, 28 and 30 are formed in the layer 22 of insulating material; and those tiny openings will preferably be formed in that insulating layer by an etching process. For example, a layer which is resistant to an etching agent can be formed on the upper surface of the layer 22 of insulating material by a photolithographic process, and that resistant layer will have four openings therein in the positions occupied by the tiny openings 24, 26, 28 and 30 in FIG. 3. Thereafter, a suitable etching agent will be applied to the resistant layer; and that etching agent will flow through the four openings in that resistant layer and form the tiny openings 24, 26, 28 and 30 in the layer 22 of insulating material. In the said one preferred embodiment of voltage actuated switch provided by the present invention, the bottom of each of the openings 24, 26, 28 and 30 is square, and it is one thousandth of an inch on each side.

Once the tiny openings 24, 26, 28 and 30 have been formed, the etching agent and the resistant layer atop the layer 22 of insulating material will be removed; and then reduced thickness layers 32 of insulating material will be "thermally grown" within those tiny openings. The thicknesses of all of the reduced thickness layers 32 of insulating material within the tiny openings 24, 26, 28 and 30 will be as close to being the same as it is possible to make them; and those reduced thickness layers of insulating material will be essentially defect-free — having essentially the same breakdown voltage that a theoretically perfect layer of the same insulating material of the same thickness would have. The thickness of each of the reduced thickness layers 32 of insulating material within the tiny openings 24, 26, 28 and 30 will be very much smaller than the thickness of the layer 22 of insulating material and hence the breakdown voltage of each of the reduced-thickness layers 32 of insulating material will be substantially smaller than the breakdown voltage of the layer 22 of insulating material.

The numeral 36 denotes an electrode which overlies the reduced thickness layers 32 of insulating material within the openings 24, 26, 28 and 30; and that electrode also overlies the layer 22 of insulating material. That electrode will preferably be made of aluminum; and it will preferably be applied by an evaporation process. A lead 38 is secured to the upper surface of the electrode 36, and a lead 40 is secured to the bottom of the conductor 20; and those leads will permit the voltage actuated switch of FIG. 5 to be incorporated into an appropriate control system.

In the said one preferred embodiment of voltage actuated switch provided by the present invention, each of the reduced thickness insulating layers 32 is about 600 Angstroms thick, and the electrode 36 is about 20,000 Angstroms thick. Each of the reduced thickness layers 32 of insulating material within the openings 24, 26, 28 and 30 will have a breakdown voltage of 22 volts plus or minus 2 volts. To make sure that all of the reduced thickness layers 32 of insulating material within the openings 24, 26, 28 and 30 have breakdown voltages close to or above the lower limit of 20 volts, the voltage actuated switch will be tested by applying a

D.C. voltage of 19 and ½ volts to the leads **38** and **40**. If any of the reduced-thickness layers **32** of insulating material within the openings **24**, **26**, **28** and **30** is not essentially defect-free or does not have the prescribed thickness, and thus break downs when the 19 and ½ volts are applied to the leads **38** and **30**, the voltage actuated switch will be considered a reject and will be discarded. Only those voltage actuated switches which do not experience a breakdown when 19 and ½ volts are applied to the leads **38** and **40** will be accepted; and hence full assurance can be given that those voltage actuated switches will not break down under D.C. voltages less than 19 and ½ volts.

When the voltage actuated switch of FIG. **5** is incorporated into a control system which utilizes one or more voltage actuated switches, the reduced thickness layers **32** of insulating material within the openings **24**, **26**, **28** and **30** will insulate the electrode **36** from the conductor **20**, as long as the voltage applied to the leads **38** and **40** does not exceed 19 and ½ volts. However, when a voltage in the range of 22 volts, plus or minus 2 volts, is applied to the leads **38** and **40**, that voltage will exceed the breakdown voltage of one of the reduced thickness layers **32** of insulating material within the openings **24**, **26**, **28** and **30**; and an appreciable portion of that reduced thickness layer will be converted from its initial high-resistance state to a low-resistance state. The conversion of the appreciable portion of the reduced thickness layer from its initial high-resistance state to a low-resistance state will be very rapid — occuring in less than 25 microseconds; and the ohmic resistance of that reduced-thickness layer, after an appreciable portion thereof has been changed to a low-resistance state will be quite low — being no greater than 1 and ½ ohms.

Where the reduced-thickness layer **32** that breaks down is square and is 1 thousandth of an inch on each side, from 50 percent to 80 percent of the area of that reduced thickness layer of insulating material will be converted from its initial high-resistance state to its low-resistance state as that reduced thickness layer breaks down. The conversion of such a substantial area of the reduced thickness layer from its initial high-resistance state to its low-resistance state is desirable; because it will keep a voltage or current surge from causing that area, of that reduced thickness layer, to revert back to its initial high-resistance state. Consequently, once a voltage actuated switch provided by the present invention changes from its initial high-resistance state to its low-resistance state, that voltage actuated switch will not revert back to its initial high-resistance state.

The present invention makes certain that an appreciable percentage of the area of the reduced thickness layer of insulating material will be converted to its low-resistance state, by making the upper surface of the conductor **20** as smooth as possible, by making the reduced thickness layer essentially defect-free, and by giving the reduced thickness layer a uniform thickness. A smooth upper surface on the conductor **20** will coact with an essentially defect-free, uniform thickness layer **32** of insulating material to require a breakdown voltage which is high enough to cause sufficient energy to be released, as the reduced thickness layer **32** breaks down, to effect the conversion of an appreciable portion of the area of that reduced thickness layer from its initial high-resistance state to its low-resistance state. If the upper surface of the conductor **20** was not smooth, or if the reduced thickness layers **32** were not essentially defect-free or were not of uniform thickness, it would be possible for a voltage, appreciably lower than the desired breakdown voltage, to cause that reduced thickness layer to break down; and the amount of energy which was released when that lower voltage caused that reduced thickness layer to breakdown could be insufficient to convert an appreciable portion of the area of that reduced thickness layer from its initial high-resistance state to its low-resistance state. In that event, a voltage or current surge might be able to cause that reduced thickness layer to revert back to its initial high-resistance state. For example, the type of voltage actuated switch that consists of a foil of aluminum which has an anodized insulating film on one surface thereof, of a metal screen which is formed on that anodized insulating film, and of an electrode which is bonded to that metal screen has been known to revert from its low-resistance state to its high-resistance state when subjected to a current surge of 8 amperes for 20 milliseconds or to a voltage surge in the range of 12 and ½ volts to 42 volts; and any such reversion is very objectionable. Any such reversion is obviated by the present invention; and hence any voltage actuated switch provided by the present invention, that has been converted to its low-resistance state, will remain in that low-resistance state — despite the application of anticipatable voltage or current pulses to that voltage actuated switch.

The numeral **44** in FIGS. **6–11** denotes a conductor; and that conductor has a layer **46** of insulating material on the upper surface thereof. The layer **46** of insulating material is appreciably thicker than the layer **22** of insulating material on the upper surface of the conductor **20** in FIGS. **1–5**. A very small opening **48** is formed in the layer **46** of insulating material, and that opening extends to the upper surface of the conductor **44**. The numeral **50** denotes a second layer of insulating material which is thinner than the layer **46** of insulating material; and that second layer fills the lower part of the very small opening **48** in the layer **46** of insulating material. The numeral **52** denotes a tiny opening which is formed in the second layer **50** of insulating material; and the numeral **54** denotes a third layer of insulating material — appreciably thinner than the layer **50** of insulating material — which is located in the bottom of the tiny opening **52** in the layer **50** of insulating material. The bottom of the tiny opening **52** can have the same configuration and dimensions as the bottom of any of the tiny openings **24**, **26**, **28** and **30** in the layer **22** of insulating material shown in FIG. **3**; and the layer **54** of insulating material will directly engage the upper surface of the conductor **44**. Where the conductor **44** is a silicon wafer and the layer **46** of insulating material is silicon dioxide, the very small opening **48** can be formed by an etching operation; the second layer **50** of insulating material can be "thermally grown" on the upper surface of the conductor **44**, the tiny opening **52** can be etched in the second layer **50** of insulating material, and the layer **54** can be "thermally grown" on the upper surface of the conductor **44**. As indicated particularly by FIG. **10**, the layer **46** of insulating material

has four openings **48** therein, each of the four layers **50** has a tiny opening **52** therein, and each of the openings **52** has a reduced thickness layer **54** therein.

The layer **46** of insulating material has a generally U-shaped recess **60** therein; and an electrode **62** is formed in that recess and extends upwardly above the upper surface of the layer **46**. A lead **64** is suitably connected to that electrode; and that lead will serve as one lead of a voltage actuated switch **58** which includes the conductor **44**, the layers **46**, **50**, and **54** of insulating material, the electrode **62**, and an electrode **66**. The electrode **66** overlies the four reduced thickness layers **54**, and a lead **68** is connected to that electrode. The fact that the layer **46** of insulating material is thicker than the layer **22** of insulating material in FIGS. **1–5** makes it possible for very heavy pressures to be applied to the conductor **44** and to the electrode **66** when the lead **68** is affixed to that electrode. Heavy pressures are required with some electrodes and with some leads, and injury to the layer **46** of insulating material can be avoided by making that layer thick, in the manner shown by FIGS. **6–11**.

The conductor **20** and the conductor **44** are preferably made from a material, such as silicon, which can have an insulating layer readily formed thereon. However, those conductors can be made from different materials such as aluminum, germanium and gallium. Aluminum oxide, germanium oxide, gallium arsenide, glass, silicon carbide, zirconium oxide, and many other insulating materials could be used as the layers **22**, **32**, **46**, **50** and **54**. The electrodes **36**, **62** and **66** can be made from many different metals, and they can be made of any desired thickness.

The forming of tiny openings **24**, **26**, **28**, **30** and **52** in the layers **22** and **50** of insulating material, and the forming of reduced thickness layers **32** and **54** in those tiny holes, limit the areas where voltage-induced breakdowns can occur to specific areas, and thus do not permit breakdowns to occur in randomly located areas. By restricting voltage-induced breakdowns to a small number of tiny areas, the present invention avoids the highly objectionable premature breakdowns which have been experienced with the voltage actuated switches that generally resemble electrolytic capacitors. A voltage actuated switch of that type can break down prematurely at any point on the overall surface thereof where the aluminum oxide coating contains a defect or is not of full thickness; and each of those voltage actuated switches inherently contains a considerable number of points where the aluminum oxide coating contains a defect or is not of full thickness. As a result, it has been exceedingly difficult to obtain commercial quantities of voltage actuated switches, that generally resemble electrolytic capacitors, with closely predictable breakdown voltages. Moreover, because such voltage actuated switches can frequently be broken down by voltages smaller than the desired breakdown voltages, the energy released during the breaking down of those voltage actuated switches can be too small to form an irreversible, low-resistance connection between the conductor and the electrode; and hence subsequently applied voltage or current surges have been known to cause those voltage actuated switches to revert from their low-resistance states to their initial high-resistance states.

In the two preferred embodiments of the present invention shown by the drawing, the conductors **20** and **44** are single crystal silicon wafers, and the upper surfaces of those conductors are substantially perfectly smooth. Where such conductors are used, the thicknesses of the layers **22** and **46**, and the thicknesses of the layers **32**, **50** and **54** can be controlled with a high degree of precision. Furthermore, those layers can be made so they are essentially defect-free; and hence the voltage actuated switches made by the present invention can have closely predictable breakdown voltages. Where the layers **32** and **54** are made of silicon dioxide and are about 600 Angstroms thick, those layers have initial ohmic resistances in excess of 1 megohm; and they have low-resistance ohmic values of about three tenths of an ohm after they have broken down and permitted the voltage actuated switches to become actuated.

In the preferred embodiment of voltage actuated switch shown by FIG. **10**, the conductor **44** is square, is 3 hundredths of an inch on each side; and is 2 thousandths of an inch thick. That conductor will initially be formed as part of a larger conductor, and then will be suitably separated from the rest of that larger conductor by scoring and cutting or breaking that larger conductor into small pieces.

The layers **22**, **32**, **46**, **50** and **54** of insulating material can be formed in different ways. Where the conductors **20** and **44** are made from materials which can have oxides or other salts with dielectric properties formed on the surfaces thereof, those layers of insulating material can be formed in the manner in which oxides or other salts with dielectric properties are formed on conductors. Where the conductors **20** and **44** are not made from materials which can have oxides or other salts with dielectric properties formed on the surfaces thereof, the layers **22**, **32**, **46**, **50** and **54** of insulating material can be formed by a depositing or coating process. The primary requirements of the layers **32** and **54** of insulating material are that they are essentially defect-free and are of uniform thickness,

As indicated by FIG. **5**, the leads for a voltage actuated switch can be attached to the opposite faces of that voltage actuated switch; and, as indicated by FIG. **11**, the leads for a voltage actuated switch can be attached to the same face of that voltage actuated switch. As a result, voltage actuated switches which are made in accordance with the principles and teachings of the present invention can be made to have almost any configuration and geometry that is desired.

In the drawing, the various layers of insulating material which are intended to break down are shown as being thinner than the surrounding layers of insulating material; and such an arrangement is very useful and desirable. However, if desired, the layers of insulating material wherein the breakdowns are to occur could be made so the thicknesses thereof are the same as the thicknesses of the surrounding layers of insulation but could be made so the dielectric values thereof are lower than the dielectric values of the surrounding layers of insulation. In either event, the layers of insulating material which are intended to break down will have breakdown voltages lower than the breakdown voltages of the surrounding layers of insulation.

Voltage actuated switches that are made in accordance with the principles and teachings of the present invention can be made to respond to breakdown voltages of different values. For example, those voltage actuated switches could be made to respond to breakdown voltages as low as five volts, and they could be made to respond to almost any desired voltage above 5 volts. The particular voltage at which a voltage actuated switch of the present invention will break down will be a function of the thickness and of the dielectric strength of the layers **32** and **54** of insulating material. Almost any desired dielectric strength can be attained, by selecting an appropriate material for the layers **32** and **54**; and, if desired, suitable dopants can be used to modify the inherent dielectric characteristics of a material to give that material the desired dielectric strength. As a result, the voltage actuated switches of the present invention can be made to respond to almost any desired breakdown voltage; and those voltage actuated switches will promptly and irreversibly change from their high-resistance states to their low-resistance states when subjected to those breakdown voltages.

The shapes and sizes of the openings in which the breakdowns are to occur can vary; but those openings should be tiny. Openings wherein the longest dimensions are less than 3 thousandths of an inch are preferred; and the longest dimension of any opening in which a breakdown is to occur should not exceed 1 hundredth of an inch.

Only one tiny opening is actually needed in a voltage actuated switch; because only one breakdown ordinarily occurs when a voltage actuated switch changes from its initial high-resistance state to its low-resistance state. However, two, three or four tiny openings will usually be provided to make certain that the breakdown voltage is not higher than desired, as would be the case if just one tiny opening was provided and the layer of insulating material within that opening was inadvertently made thicker than desired. While the provision of two, three, or four tiny openings increases the possibility that the voltage actuated switch might have a reduced thickness layer of insulating material which was undesirably thin, the testing of the voltage actuated switches at voltage values just a fraction of a volt below the lower limit of the desired range of breakdown voltages makes it possible to reject any voltage actuated switch which might tend to breakdown prematurely because one of its reduced thickness layers of insulating material was too thin. In actual practice, where the conductors are silicon wafers and the layers of insulating material are silicon dioxide, the provision of four tiny openings in each voltage actuated switch has not significantly increased the likelihood of premature voltage-induced breakdowns. Also, where the conductors are silicon wafers and the layers of insulating material are of silicon dioxide, the voltage actuated switches can be made at less cost than can voltage actuated switches which are similar to electrolytic capacitors.

It thus should be apparent that the present invention makes it possible to provide voltage actuated switches which become actuated at closely predictable voltages. Further, it should be apparent that once those voltage actuated switches have been actuated, they will not revert to their initial high-resistance states even if they are exposed to predictable voltage or current surges. In addition, it should be apparent that those voltage actuated switches can be made at moderate cost.

Whereas the drawing and accompanying description have shown and described two preferred embodiments of the present invention, it should be apparent to those skilled in the art that various changes may be made in the form of the invention without affecting the scope thereof.

What I claim is:

1. The method of making a voltage actuated switch on a selected portion of the area of a substrate of conductive material that comprises:

selecting a substrate of conductive material which has a smooth upper surface,

forming an insulating layer which overlies and engages all of said selected portion of said substrate,

forming said insulating layer so it has a predetermined constant thickness and predetermined resistivity to enable said insulating layer to have a predetermined breakdown voltage and also to have a substantially flat upper surface,

forming a tiny hole of predetermined area in said insulating layer that extends to said substrate of conductive material and that has the sides thereof defined solely by said insulating layer,

forming a further but thinner layer of insulating material that is located wholly within said tiny hole, that directly engages said substrate of conductive material, that overlies the entire bottom of said tiny hole, and that extends to and directly engages those portions of said insulating layer which define the sides of said tiny hole,

forming an electrode that overlies and engages said further but thinner layer,

forming said further but thinner layer of insulating material so it has an essentially uniform thickness, and so it has a substantially flat upper surface,

forming said further but thinner layer of insulating material so it has a thickness and a resistivity which enable said further but thinner layer of insulating material to have a breakdown voltage substantially lower than said predetermined breakdown voltage and so said further but thinner layer of insulating material will respond to the application of a voltage across said substrate and said electrode, which is greater than said breakdown voltage of said further but thinner layer of insulating material but which is less than said predetermined breakdown voltage, to break down and thereby permit an irreversible, low-resistance connection to form between said electrode and said substrate.

2. The method of making a voltage actuated switch on a selected portion of the area of a substrate of conductive material that comprises:

selecting a substrate of conductive material which has a smooth upper surface,

forming an insulating layer which overlies and engages all of said selected portion of said substrate,

forming said insulating layer so it has a predetermined constant thickness and predetermined resistivity to enable said insulating layer to have a predetermined breakdown voltage and also to have a substantially flat upper surface,

removing a predetermined area of said insulating layer to expose all of said selected portion of said substrate of conductive material and to form a hole which has the sides thereof defined solely by said insulating layer,

forming a further layer of insulating material that is located wholly within said hole, that directly engages said selected portion of said substrate, that overlies the entire bottom of said hole and that extends to and directly engages those portions of said insulating layer which define the sides of said hole,

forming said further layer of insulating material so it has an essentially uniform thickness and a substantially flat upper surface,

forming said further layer of insulating material so it has a portion of predetermined thickness and predetermined resistivity to enable said portion of said further layer of insulating material to have a second and different predetermined breakdown voltage,

forming an electrode that overlies and engages one of said layers of insulating material,

forming said one of said layers of insulating material so it has a thickness which is less than the thickness of the other layer of insulating material,

whereby said one layer of insulating material has a breakdown voltage which is substantially lower than the breakdown voltage of said other layer of insulating material,

forming said one layer of insulating material so it responds to the application of a voltage across said substrate and said electrode, which is greater than said breakdown voltage of said one layer of insulating material but which is less than the breakdown voltage of said other layer of insulating material, to break down and thereby permit an irreversible, low resistance connection to form between said electrode and said substrate,

said substrate being formed from silicon,

forming said layer of insulating material from silicon dioxide, and

forming said further layer of insulating material from silicon dioxide.

3. The method of making a voltage actuated switch as claimed in claim 1 wherein the thickness of said further but thinner insulating layer is substantially smaller than the thickness of said portion of the first said insulating layer but wherein the ohmic resistance of said further but thinner insulating layer is in excess of one megohm.

4. The method making a voltage actuated switch as claimed in claim 1 wherein the longest dimension of said further but thinner layer of insulating material is less than 1 hundredth of an inch.

5. The method of making a voltage actuated switch as claimed in claim 1 wherein each of said substrate and said electrode is formed so it is many times thicker than said further but thinner layer of insulating material.

6. The method of making a voltage actuated switch as claimed in claim 1 wherein said further but thinner layer of insulating material is dimensioned so the major portion thereof will be converted from an initial high-resistance state to a low-resistance state as said further but thinner layer of insulating material responds to said voltage across said substrate and said electrode to break down.

7. The method of making a voltage actuated switch on a selected portion of the area of a substrate of conductive material that comprises:

selecting a substrate of conductive material which has a smooth upper surface,

forming an insulating layer which overlies and engages all of said selected portion of said substrate,

forming said insulating layer so it has a predetermined constant thickness and predetermined resistivity to enable said insulating layer to have a predetermined breakdown voltage and also to have a substantially flat upper surface,

removing a predetermined area of said insulating layer to expose all of said selected portion of said substrate of conductive material and to form a hole which has the sides thereof defined solely by said insulating layer,

forming a further layer of insulating material that is located wholly within said hole, that directly engages said selected portion of said substrate, that overlies the entire bottom of said hole, and that extends to and directly engages those portions of said insulating layer which define the sides of said hole,

forming said further layer of insulating material so it has an essentially uniform thickness and a substantially flat upper surface,

forming said further layer of insulating material so it has a portion of predetermined thickness and predetermined resistivity to enable said portion of said further layer of insulating material to have a second and different predetermined breakdown voltage,

forming an electrode that overlies and engages one of said layers of insulating material,

forming said one of said layers of insulating material so it has a thickness which is less than the thickness of the other layer of insulating material,

whereby said one layer of insulating material has a breakdown voltage which is substantially lower than the breakdown voltage of said other layer of insulating material,

forming said one layer of insulating material so it responds to the application of a voltage across said substrate and said electrode, which is greater than said breakdown voltage of said one layer of insulating material but which is less than the breakdown voltage of said other layer of insulating material, to break down and thereby permit an irreversible, low resistance connection to form between said electrode and said substrate,

forming said one layer of insulating material so it has a thickness which is substantially smaller than the thickness of said other layer of insulating material,

dimensioning said one layer of insulating material so the major portion thereof will be converted from an initial high-resistance state to a low-resistance state as said one layer of insulating material responds to said voltage across said substrate and said electrode to break down.

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