United States Patent

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[72] Inventors David W. Skelly
Ballston Lake;
Robert F. Kopczewski; James F. Burgess;
Sterling P. Newberry, Schenectady, N.Y.

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[73] Assignee General Electric Company

[54] **INFORMATION STORAGE AND RETRIEVAL EMPLOYING AN ELECTRON BEAM**
14 Claims, 6 Drawing Figs.

[52] **U.S. Cl.** **340/173,** 307/238
[51] **Int. Cl.** **G11c 11/34**
[50] **Field of Search** .... 340/173 (light), (LM); 315/(Inquired); 307/238, 302

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Primary Examiner—Terrell W. Fears
Attorneys—Richard R. Brainard, Paul A. Frank, John J. Kissane, Frank L. Neuhauser, Oscar B. Waddell and Melvin Goldenberg

ABSTRACT: A storage medium is described wherein coded information is destructively written by selectively inducing breakdown in a threshold biased capacitor having an electron sensitive variable conductivity layer positioned therein. In one specific embodiment, a hexachlorobutadiene dielectric layer and a juxtaposed lead oxide semiconductive layer are sandwiched between a tin oxide electrode and an electron transparent aluminum electrode. After threshold biasing the structure in a direction opposing conductivity in the lead oxide layer, a 10 kv. electron beam is selectively penetrated into the layer of lead oxide to induce conductivity therein thereby shifting the biasing voltage division in the storage medium to effect a localized dielectric breakdown in the hexachlorobutadiene. The dielectric breakdown in the hexachlorobutadiene selectively ruptures both the dielectric layer and the aluminum electrode thereover producing 10—50 mil diameter apertures at points of electron beam irradiation. Information is readout by reverse biasing the storage medium and selectively scanning the medium with an electron beam. In a preferred embodiment, a semiconductive wafer is substituted for the tin oxide electrode to permit readout of the recorded information unimpeded by capacitive coupling between the electrodes.

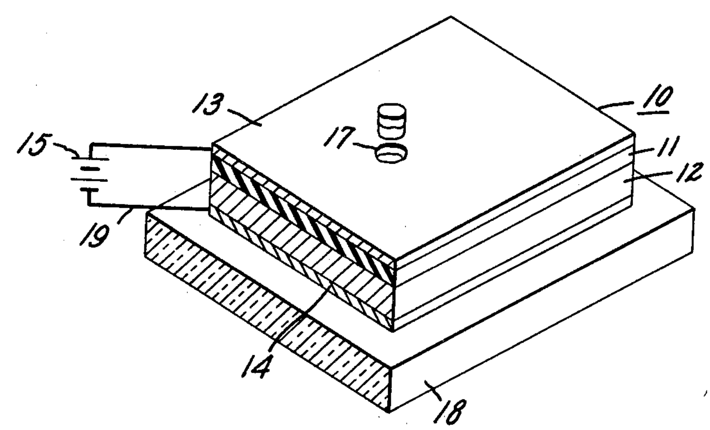

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Fig. 1.

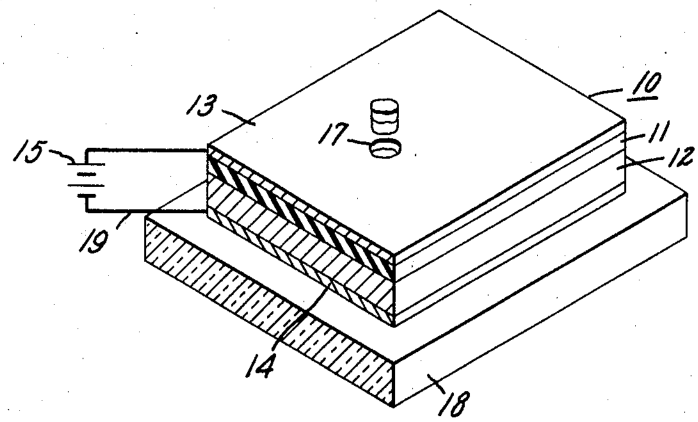


Fig. 2.

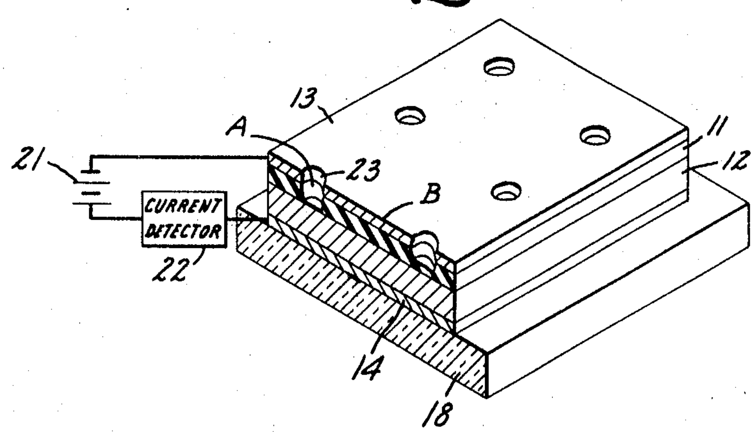


Fig. 3.

Inventors:
David W. Skelly,
Robert F. Kopczewski,
Sterling P. Newberry,
James F. Burgess,
by John J. Kissane
Their Attorney.

Fig. 4.

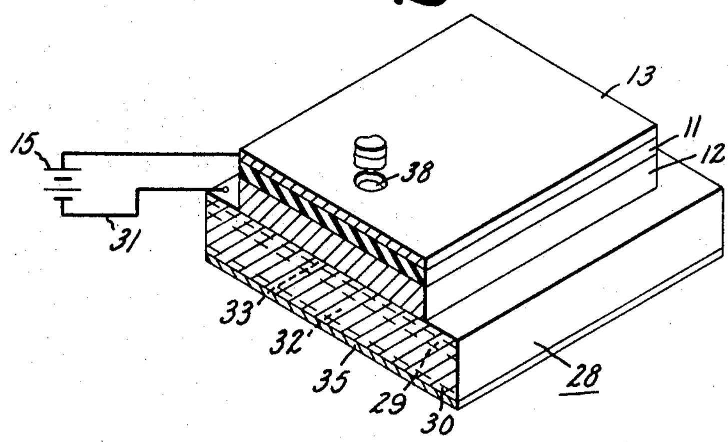


Fig. 5.

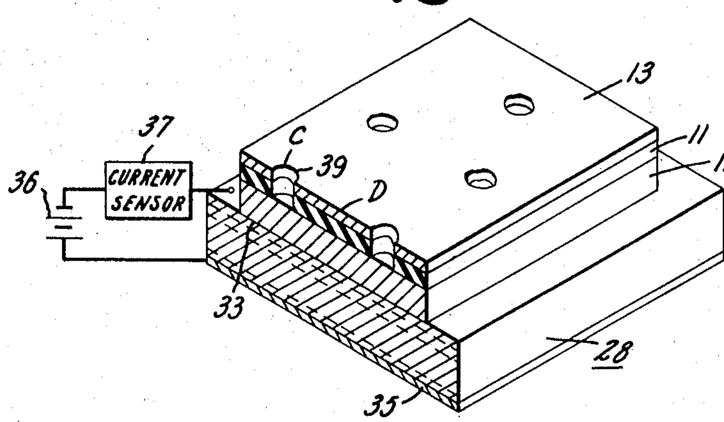
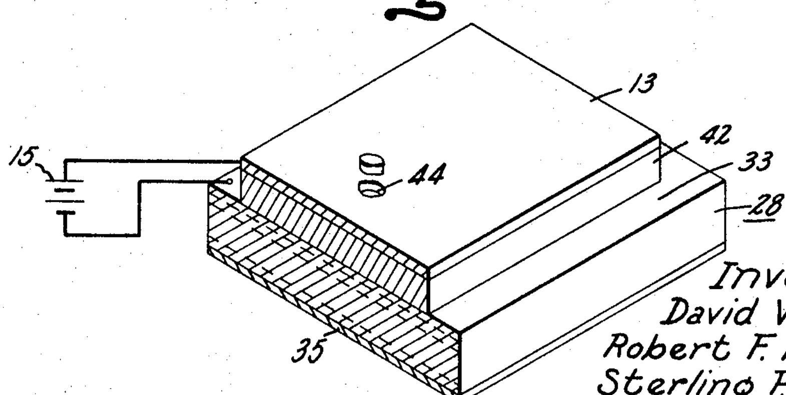


Fig. 6.



Inventors:
David W. Skelly,
Robert F. Kopczewski,
Sterling P. Newberry,
James F. Burgess,
by John J. Kissane
Their Attorney.

INFORMATION STORAGE AND RETRIEVAL EMPLOYING AN ELECTRON BEAM

This invention relates to a method of writing and reading out information from a unique storage medium and in particular to electron beam information storage by the selective breakdown of a capacitive structure having an electron controlled variable conductivity material therein. Information is readout from the storage medium by electron beam interrogation.

Electron beam storage and retrieval of digital information heretofore generally has been accomplished by electron beam bombardment of a thin film to produce a selective reduction in film thickness with readout being effected by a measurement of subsequent electron beam transmission through the film at various locations. For example, in copending application Ser. No. 717,500 filed Apr. 1, 1968 in the name of James F. Norton and assigned to the assignee of the present invention, there is described and claimed a data storage medium comprising a semiconductive wafer overlayed with an electron dense metallic or photoresist film which is selectively exposed to electron beam irradiation and subsequently chemically etched to record digital information. Subsequent electron beam impingement upon the selectively etched medium during interrogation produces a current flow in the semiconductive wafer proportional to the thickness of the overlying film through which the beam passes before striking the wafer surface. Thus, electron beam recording media heretofore generally have required a separate development step to remove portions of a film selectively exposed during information storage.

It is therefore an object of this invention to provide a development free data storage device susceptible to destructive electron beam writing and nondestructive electron beam readout.

It is also an object of this invention to provide a development free data storage device wherein only a fractional portion of the recording energy is supplied by the writing electron beam.

It is a still further object of this invention to provide a novel method of digital data storage and retrieval.

These and other objects of this invention generally are accomplished utilizing a storage medium having first and second electrodes at least one of which electrodes are transparent to an electron beam. A material characterized by an increased electrical conductivity upon electron beam irradiation is sandwiched between the electrodes and functions, either alone or in conjunction with a conventional dielectric material for increased capacitance in the storage medium, as a dielectric layer for the storage medium. Upon electron beam irradiation, the electrical conductivity increase in the variable conductivity material effects an internal localized voltage shift in the laminar storage medium to produce a physical breakdown in at least one layer of the storage medium for the permanent recordation of information. Thus in the practice of this invention, the storage medium is biased to a threshold level below the breakdown level of the dielectric and an electron beam is selectively impinged upon the transparent electrode in a predetermined coded pattern to penetrate into at least a portion of the variable conductivity layer thereby effecting a selective breakdown in at least one layer of the medium at the location of electron beam penetration.

To readout the recorded information from the physically deformed medium, the threshold bias is removed and an electron beam is selectively irradiated upon portions of the transparent electrode. At those locations whereat a portion of the electrode or dielectric has been exploded away by capacitive breakdown, the electron beam generates a signal of a different magnitude than is generated by electron beam penetration into areas of the recording medium whereat the electrode and dielectric are intact. To inhibit coupling between the electrodes during readout, the nontransparent electrode preferably is a semiconductive chip having a current flow therein proportional to the intensity of electron impingement thereon.

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, together with further objects and advantages thereof may best be understood by reference to the following description, taken in connection with the accompanying drawings, in which:

FIG. 1 is a sectionalized isometric view of a data storage medium of this invention connected in a writing mode,

FIG. 2 is a sectionalized isometric view of the data storage medium of this invention connected for interrogation,

FIG. 3 is a pictorial display of the output signal obtained during interrogation of one line of the data storage medium,

FIG. 4 is a sectionalized isometric view of a data storage medium employing a semiconductive wafer connected in a writing mode,

FIG. 5 is a sectionalized isometric view of the data storage medium of FIG. 4 during readout, and

FIG. 6 is a sectionalized isometric view of an alternate data storage medium structure in accordance with this invention connected in a writing mode.

A data storage medium **10** constructed in accordance with the principles of this invention is depicted in FIG. **1** and generally comprises a dielectric layer **11** and a juxtaposed electron bombardment induced conductive layer **12**, e.g. lead oxide, sandwiched between electrodes **13** and **14**. A voltage source **15** is impressed across electrodes **13** and **14** of the data storage medium in a direction opposing current flow in layer **12** and is divided across the bombardment induced conductive layer and dielectric **11** in a ratio tending to bias the dielectric to a threshold capacitive breakdown level. To write digital information into the storage medium, an electron beam from a suitable source (not shown), e.g. an electron gun of the type shown and described in S.P. Newberry U.S. Pat. No. 3,008,066, issued Nov. 7, 1961, and assigned to the assignee of the present invention, is selectively impinged in a coded pattern upon upper electrode **13** to penetrate through dielectric **11** into bombardment induced conductive layer **12** thereby reducing the electrical impedance of (and the voltage across) the electron bombarded areas of the layer. The reduction in the voltage across selected areas of layer **12** effects a shift in the potential applied across juxtaposed dielectric layer **11** in an amount sufficient to exceed the breakdown potential of the dielectric layer in the electron bombarded areas and the dielectric layer along with a portion of the overlying electrode is exploded away by capacitive breakdown to form apertures **17** corresponding to recorded digital information of a chosen magnitude, e.g. 1's or 0's.

Electrode **14** remote from the electron source can be any conductive material and although preferably being a metallic film less than 10,000A in thickness, can have a substantial depth. When electrode **14** is a thin film, a substrate **18** generally is employed as a mechanical support for the recording medium. Tin oxide electrodes formed by oxidation of a tin chloride film spray deposited upon a soda lime glass substrate generally are easily fabricated and provide an adequate surface to which voltage source **15** can be joined utilizing a lead-type solder and a copper external conductor **19**.

Upper electrode **13** upon which the electron beam impinges during the writing and readout of information must be sufficiently thin to permit some electron penetration therethrough, e.g. electrode **13** must be of a thickness less than the known maximum penetration of an electron beam of desired intensity into the metal forming the electrode. V.E. Cosslett et al. in an article entitled "Multiple scattering of 5—30 kev electrons in evaporated metal films II: Range-energy relations" (Brit. J. Appl. Phys., 15, 1283 (1964) describe the maximum penetration of an electron beam into a metal (and therefore the maximum thickness of electrode 13) to be expressible approximately by the formula:

$$R = kE^{1.5}$$

wherein:

R is the penetration in angstroms
E is the electron beam energy in kev. and
k is a numerical constant for the chosen metal, e.g.

274 for aluminum;
103 for copper;
82 for silver; and
45 for gold.

Thus utilizing a gold electrode and a 10 kilovolt beam, an electrode thickness less than approximately 1100A is required to assure electron passage therethrough to produce the required potential drop in layer **12** to explode away a portion of the structure by dielectric breakdown. Generally, a high percentage, e.g. 60 percent or greater, of electron beam transmission through transparent electrode **13** is desired and the transparent electrode is of a thickness less than 400A to permit ready penetration of an electron beam therethrough.

Although electrode **13** can be formed of any conductive metal, e.g. aluminum, silver and gold, soft, noncohesive metals such as indium and cadmium are preferred for the electron transparent electrode because of the low rupture strength of these metals. However, because electron beam penetration into electrode **13** generally varies as an inverse function of the density of the metal forming the electrode, low density metals, such as aluminum and magnesium, often are advantageously utilized when a low energy beam, e.g. a beam below 2 kilovolts, is employed for writing. Theoretically electron beams of any power can be employed both for information storage and readout. However because beams in excess of 30 kilovolts often generate X-rays which tend to produce distortion or noise in the readout signal, a beam power of generally less than 20 kilovolts is desired.

Dielectric layer **11** generally can be any nonbrittle, nonconductive material with dielectrics having a relatively low voltage breakdown level being preferred to minimize the threshold potential required from voltage source **15**, e.g. layer **11** preferably is of a thickness such that voltage source **15** exceeds the breakdown potential of the dielectric layer by at least 50 percent. A thin dielectric film, e.g. less than 5,000 A., deposited by photodeposition to assure a smooth pinhole free deposit is most advantageously employed in the practice of this invention. The dielectric layer however can be substantially thicker, e.g. to a thickness of approximately 5 microns, whereupon electron beam divergence in the dielectric layer tends to inhibit high resolution recording. Among the more suitable materials for dielectric layer **11** because of the low mechanical rupture strength and pinhold free characteristics of the layer are hexachlorobutadiene polymer films deposited by techniques disclosed and claimed in copending U.S. application Ser. No. 530,971, filed Nov. 19, 1966 in the name of A. N. Wright and assigned to the assignee of the present invention. Other conventional dielectric materials however, such as polystyrene, Lexan, polytetrafluorethylene, etc., also can be employed as the dielectric layer in recording medium **10**.

Bombardment induced conductive layer **12** generally is any material characterized by an ability to be switched from a relatively nonconductive state to a relative electrically conductive state upon electron irradiation and can be of the type described by Pensak in Physical Review, Vol. 75, 03, dated Feb. 1949. While any material having a variable dielectric characteristic upon electron beam impingement can be employed as bombardment induced conductive layer **12**, semiconductive lead oxide is preferred because of the complete and rapid transition to a conductive state of the electron bombarded area of the film as well as the capability of lead oxide of being induced to the conductive state by electrons which do not completely penetrate the film thickness. Thus, electron beam penetration partially into a lead oxide layer tends to switch the entire layer thickness to the conductive state at the regions of beam penetration into the lead oxide layer. The rapid switching of the bombardment induced conductor to a conductive state results in a rapid application of substantially the entire voltage from source **15** across the immediately adjacent dielectric layer to enhance the speed and the force of the dielectric breakdown produced thereby. Although only a change or a modification in the electron transmission qualities of dielectric layer **11** is required for readout purposes, preferably the capacitive discharge is of sufficient intensity to explode away both the portion of dielectric layer **11** and transparent electrode **13** directly overlying the area of layer **12** activated by the beam. The bombardment induced conductive layer preferably is deposited to a thickness at least two-fold the thickness of dielectric layer **11** to initially accept a substantial portion of voltage from source **15**.

The quantity of electron beam penetration into layer **12** required to selectively capacitively breakdown the structure generally is dependent upon such interrelated factors as the random breakdown characteristic of dielectric layer **11**, the relative capacitances of the dielectric layer and bombardment induced conductive layer **12**, the magnitude of biasing voltage **15**, the intensity of electron beam penetration into layer **12** and the electron multiplying characteristic of layer **12**. However, an electron multiplying factor of at least five fold is desirable in layer **12** to provide a convenient tolerance in the threshold bias of the storage medium while permitting information writing with a low energy electron beam. Similarly, the electron flow increase in layer **12** produced by electron beam irradiation of the layer and the multiplying effect of layer **12** upon electrons impinging thereon preferably results in a current flow at least 30 percent greater than the dark current flowing in the storage medium prior to the electron beam irradiation.

The apertures produced in electrode **13** by the selective capacitive breakdown of dielectric layer **11** is of relatively small diameter with 10 to 50 micron-diameter holes having been produced by impingement of a 10 kilovolt beam upon a 10,000A lead oxide layer underlying a 1,000A hexachlorobutadiene polymer dielectric and a 200A aluminum electrode. A tin oxide film formed the electrode remote from the writing electron beam source and a 375-volt bias was applied to the recording medium in a polarity opposing conduction in the lead oxide layer. The hole diameter generally was a function of beam dwell upon a selected area with the smallest and most precisely placed of the holes being produced with a beam dwell of less than approximately 5×10^{14} seconds. Electron beam dwell intervals less than a millisecond were found to be capable of exploding apertures **17** in recording medium **10**.

Although dielectric layer **11** and bombardment induced conductive layer **12** are shown as being juxtaposed layers in the structure of FIG. **1**, the layers also could be combined in a homogenous dispersion of fine, e.g. less than 0.2 micron, particles of a semiconductive powder in a resin binder. The resin binder could be a polymer or, alternately, a monomer which is polymerized after being mixed with the semiconductor powder. Deposition of a dispersion of this nature generally does not require vacuum techniques and inherently permits a more rapid application of the coating.

Readout of information recorded into the electron beam device of FIG. **1** can be effected utilizing the circuitry of FIG. **2** wherein a voltage source **21** is connected across electrodes **13** and **14** of digital information containing medium **10** in a polarity opposite the voltage source polarity employed in the recording of information therein. Voltage source **21** is considerably smaller than that employed during writing of information and may be a small fractional portion of the writing voltage source. A current detector **22**, e.g. a voltage amplifier and an amplitude modulated trigger device (e.g. Schmitt Trigger), is serially connected between voltage source **21** and electrode **14** to interrogate recording medium **10** by a measure of current flow through the biasing circuit during electron beam readout. For example, during a selective readout utilizing a controllable electron beam source such as is disclosed in prior-mentioned copending application Ser. No. 717,500, an initial electron interrogation of point A, e.g. the area underlying aperture **23**, results in the formation of electron-hole pairs in the electron impinged segment of semiconductive layer **12**. However because the portion of electrode **13** overlying the electron-hole pairs has been blasted away thereby effectively removing biasing source **21** from the area, there is a minimum drift of electrons and holes to their respective electrodes and a minimum current flow, e.g. exhibited by peak **24** of FIG. **3**, is produced in storage medium **10**. However, electron beam interrogation of point B of the storage medium whereat no aperture has been ruptured results in a relatively unimpeded passage of the electron beam through transparent electrode **13** and dielectric layer **11** to induce electron-hole pairs in the portion of layer **12** underlying the impingement area of the electron beam. Because voltage biasing source **21** is applied through electrodes **13** and **14** to the area of the electron-hole pairs formation, a substantial drift is effected and a current peak **25** is observed by current detector **22**. Continued interrogation of various sites of storage medium **10** results in substantial current flow between electrodes at unexploded locations, such as point B, while a minimum current flow is produced at locations, such as point A, whereat electron beam recording effected a rupturing in the dielectric and electrode layers of the medium.

An information recording medium in accordance with this invention having electron readout means incorporated therein is shown in FIG. 4 and generally comprises the employment of a nuclear particle detector **28** as the lower nontransparent electrode of the storage medium. Nuclear particle detector **28** may be a conventional lithium drift detector fabricated of a semiconductor wafer, preferably silicon. Detectors of this type typically comprise a narrow *p*-type region **29** and a narrow *n*-type region **30** which are diffused into the wafer from opposite sides so as to leave a wide intrinsic region **32**. An additional *p*-type region **33**, which is more heavily doped than *p*-type region **29** so as to be highly conductive, is uniformly diffused into the wafer surface upon which incident electron beam radiation is to impinge during readout. Because of its high conductivity, region **33** facilitates making electrical contact to the incident radiation receiving surface of detector **28**, for example, by alloying an aluminum wire **31** thereto, while contact to *n*-type region **30** may be made by alloying a gold layer **35** over the surface of the *n*-type region **30**. A more complete description of nuclear particle detectors of this type can be obtained from the Journal of Applied Physics, Vol. 31, page 291, 1960.

In writing information into the storage medium, a biasing voltage, e.g. a 375 volt source **15**, is applied between region **33** of nuclear particle detector **28** and electron transparent indium electrode **13** with the biasing direction opposing conductivity in lead oxide layer **12**. The magnitude of voltage source **15** again divides between layers **11** and **12** in a ratio directly proportional to the respective thicknesses of the films and inversely proportional to the dielectric constants of the layers to impress a threshold capacitive breakdown voltage across the dielectric layer. Upon subsequent selective electron beam penetration through electrode **13** and dielectric layer **11** into lead oxide layer **12**, an induced conductivity is produced in the irradiated portion of the lead oxide layer to shift the voltage division between the dielectric layer and the lead oxide layer. The increased voltage across dielectric layer **11** effects a capacitive breakdown in the portion of the dielectric layer overlying the point of beam impingement upon the detector and an aperture **38** is exploded in both the dielectric layer and the overlying electrode.

Readout of recorded information from the storage medium is effected by a measurement of current induced between layers **33** and **35** of the semiconductive wafer upon sequential impingement of a readout electron beam at selected areas of the recording medium. Thus, as is shown in FIG. 5, readout of information at a point C (having an aperture **39** previously exploded in transparent electrode **13** and dielectric layer **11** by dielectric breakdown) results in electron beam power loss only in lead oxide layer **12** before impingement upon the nuclear particle detector. However when interrogation is conducted at point D, (a completely intact area) electron beam power is scattered in dielectric layer **11** and the intensity of beam impingement upon surface **34** of detector **28** is diminished. Since nuclear particle detectors typically exhibit a current gain of 1,000 to 10,000 depending upon the energy of the electron when the beam strikes the detector surface, even minor variations in the intensity of electron impingement upon the detector can be observed in current sensor **37**. Thus an output signal measurable across heavily doped region **33** and gold layer **35** is produced during the interrogation of the recording medium with substantially larger output signals being produced by electron beam interrogation of the rupture locations in the recording medium. Preferably the intensity of the electron beam employed during readout is approximately equal to the intensity of the beam during recording, e.g. approximately 10 kilovolts, with dielectric breakdown in the recording medium being inhibited by a removal of the biasing voltage applied across the dielectric during the readout cycle. To enhance the drift of electrons in detector **28** during readout, a potential **36** is applied across region **33** and gold layer **35** in a polarity producing a positive voltage upon region **33** relative to layer **35**.

The storage medium of this invention also can be fabricated employing a single dielectric layer as is shown in FIG. **6** wherein a composite dielectric, variable conductivity layer **42** is situated between the electron transparent electrode **13** and a nuclear particle detector **28**. Thus while the recording medium of FIG. 4 may be fabricated of a material such as lead oxide which becomes conductive over its entire thickness upon impingement of an electron beam therein, composite layer **42** of FIG. **6** may comprise a homogeneous highly resistant material such as aluminum oxide, cadmium sulfide, silicon monoxide or zinc sulfide which materials are characterized by an ability to be switched from a nonconductive state to a conductive state only to the depth of electron beam penetration therein. When voltage source **15** again is placed across highly doped region **33** and transparent electrode **13** of the recording medium, electron impingement through the transparent electrode into layer **42** effects a diminution in the resistive thickness of the layer with capacitive breakdown occurring upon beam penetration to a desired depth, e.g. preferably between 25 percent to 75 percent of the thickness of layer **42**, and the irradiated portion of layer **42** along with the overlying electrode is exploded away to form aperture **44**. Readout of the stored information again can be accomplished in the manner disclosed in FIG. **5** by removing the threshold biasing voltage across the electrodes and biasing the nuclear particle detector in a direction to produce current flow upon electron impingement. Thus, when the beam impinges upon an aperture in the recording medium during readout a minimum scattering of the beam is effected and a substantial current flow is obtained from detector **28**. In those areas where no information was recorded, e.g. completely intact areas, the electron beam divergence produced by layer **42** diminishes the intensity of beam impingement upon the detector and a greatly reduced output current signal is obtained from the detector. Because no biasing voltage is applied across layer **42** during readout, capacitive breakdown is not induced and a nondestructive readout is obtained.

While the invention has been described with respect to certain specific embodiments, it will be appreciated that many modifications and changes may be made without departing from the spirit of the invention. For example, readout of stored information from a recording medium having two electron transparent electrodes also can be accomplished utilizing a conventional photomultiplier positioned to receive electrons passing through the selectively perforated recording medium. We intend, therefore, by the appended claims, to cover all such modifications and changes as fall within the true spirit and scope of our invention.

We claim:

1. An information storage medium comprising a laminar structure having first and second electrodes, at least one of said electrodes being transparent to an electron beam, and a semiconductor material positioned between said electrodes characterized by an increased electrical conductivity upon irradiation with an electron beam, said semiconducting material increasing in conductivity upon electron beam irradiation to produce a breakdown in said laminar structure at said points

of irradiation causing a permanent physical deformation of said laminar structure.

2. An information storage medium according to claim 1 wherein at least one electrode has exploded away apertures produced by dielectric breakdown in irradiated portions of said recording medium.

3. An information storage medium according to claim 1 including means biasing said laminar structure to a threshold level below the dielectric breakdown level of said structure.

4. An information storage medium according to claim 1 wherein said material between said electrodes include a dielectric layer less than 5 mils thick and a juxtaposed layer of lead oxide.

5. An information storage medium according to claim 1 wherein one electrode is a semiconductive radiation detecting wafer comprising a *p*-region of substantially uniform thickness extending beneath the wafer face proximate the variable conductivity material and an *n*-type region of substantially uniform thickness extending to a predetermined depth beneath the face of said wafer remote from said variable conductivity material so as to leave a depletion region between said *p*-type and *n*-type regions.

6. An information storage medium according to claim 5 wherein a layer of lead oxide is positioned atop the *p*-type region of said semiconductive wafer, a dielectric layer is situated atop the lead oxide layer and an electron transparent electrode is positioned atop the dielectric layer.

7. An information storage medium according to claim 5 wherein said transparent electrode is selected from the group consisting of indium and cadmium.

8. An information storage medium according to claim 5 including voltage biasing means connected between said transparent electrode and said *p*-type region of said semiconductor wafer, means for selectively impinging an electron beam upon the electron transparent face of said recording medium to effect dielectric breakdown in said medium corresponding to a desired coded pattern and means for locating dielectric breakdown locations in said medium by a measurement of current flow through said semiconductive wafer upon subsequent selective electron beam irradiation of said recording medium with said voltage biasing means removed.

9. An information storage medium according to claim 6 wherein said dielectric layer is less than 5 mills thick.

10. A method of information storage comprising biasing a structure characterized by a dielectric layer sandwiched between two conductive electrodes to a threshold level below the breakdown level of said dielectric layer, generating an electron beam of sufficient intensity to penetrate through one of said conductive electrodes to said dielectric layer, and selectively causing breakdowns in said dielectric layer by impinging said electron beam upon said transparent electrode in a predetermined coded pattern, said electron beam penetrating into said dielectric layer and effecting a selective breakdown in said dielectric layer at the location of said electron beam penetration.

11. A method of information storage and retrieval according to claim 10 further including removing said threshold bias upon said structure, applying a reverse bias to said structure, and detecting the locations of dielectric breakdown in said structure by selective electron beam interrogation of said structure.

12. A method of information storage and retrieval according to claim 11 wherein one of said electrodes is a doped semiconductive body and wherein said method further includes the step of detecting said dielectric breakdown by measuring current flow induced in said semiconductive electrode upon selective electron beam irradiation interrogation of said structure.

13. A method of information storage and retrieval comprising biasing a laminar structure having at least one layer characterized by an electrical conductivity variable upon electron irradiation to a threshold value below the voltage breakdown level of said structure, generating an electron beam of sufficient intensity to penetrate to said one layer, selectively impinging said electron beam upon said variable conductivity layer to selectively exceed the breakdown level of at least one layer of said structure only at the area of electron impingement upon said structure, said breakdown of said layer producing a permanent physical deformation in said layer, removing the threshold bias upon said structure and selectively detecting the locations of said physical breakdown by electron irradiation of said structure without said threshold bias.

14. An information storage medium comprising:

first and second electrodes spaced relative to one another;

a layer of dielectric material and a layer of semiconductive material sandwiched between said electrodes thereby forming a laminar structure;

said semiconductive material characterized by an increase in conductivity upon being irradiated by an electron beam causing a permanent deformation in said laminar structure.