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Hughes

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[54] **METHOD AND APPARATUS FOR RETURN BEAM READOUT THROUGH A MATRIX ELECTRON LENS**

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[52] **U.S. Cl.** **313/394,** 313/432

[51] **Int. Cl.** **H01j 31/48**

[58] **Field of Search** ..... 313/68, 68 D, 92 PD, 84, 313/65 AB, 65 T, 65

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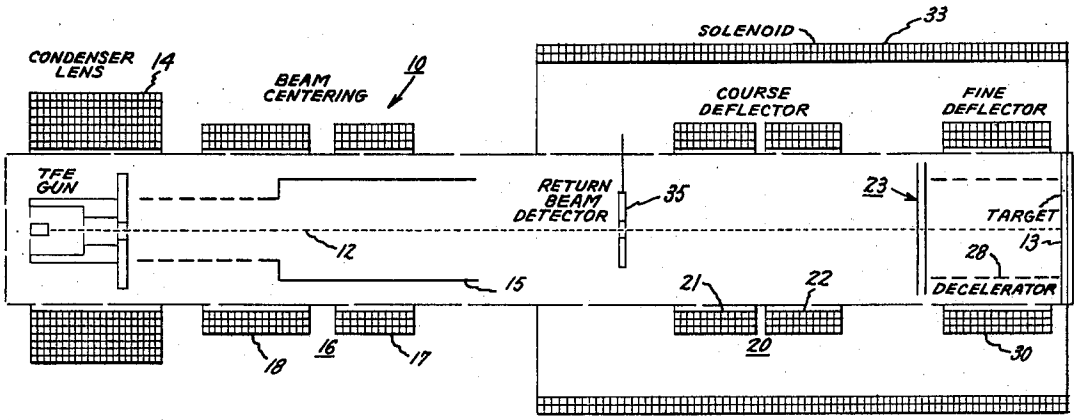
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Attorney, Agent, or Firm—Paul F. Wille; Joseph T. Cohen; Jerome C. Squillaro

[57] **ABSTRACT**

An electron beam-addressable memory apparatus and method for writing information on a memory target and reading information stored thereon are disclosed. Readout of stored information is achieved by scanning a primary electron beam across the target and detecting the secondary electrons emitted therefrom. The primary electron beam is directed first to a specific lenslet of a matrix electron lens by a coarse deflection assembly and then to a precise location on the target by a fine deflection assembly. Secondary emission electrons emanating from the surface of the target as a result of the primary electron beam are focussed back to the matrix electron lens and then are directed along a trajectory substantially similar to that of the primary electron beam to an electron detector. Since the number of detected electrons is modulated by the information stored on the target, information representative of digital data is conveniently stored and efficiently read out from the memory.

14 Claims, 4 Drawing Figures



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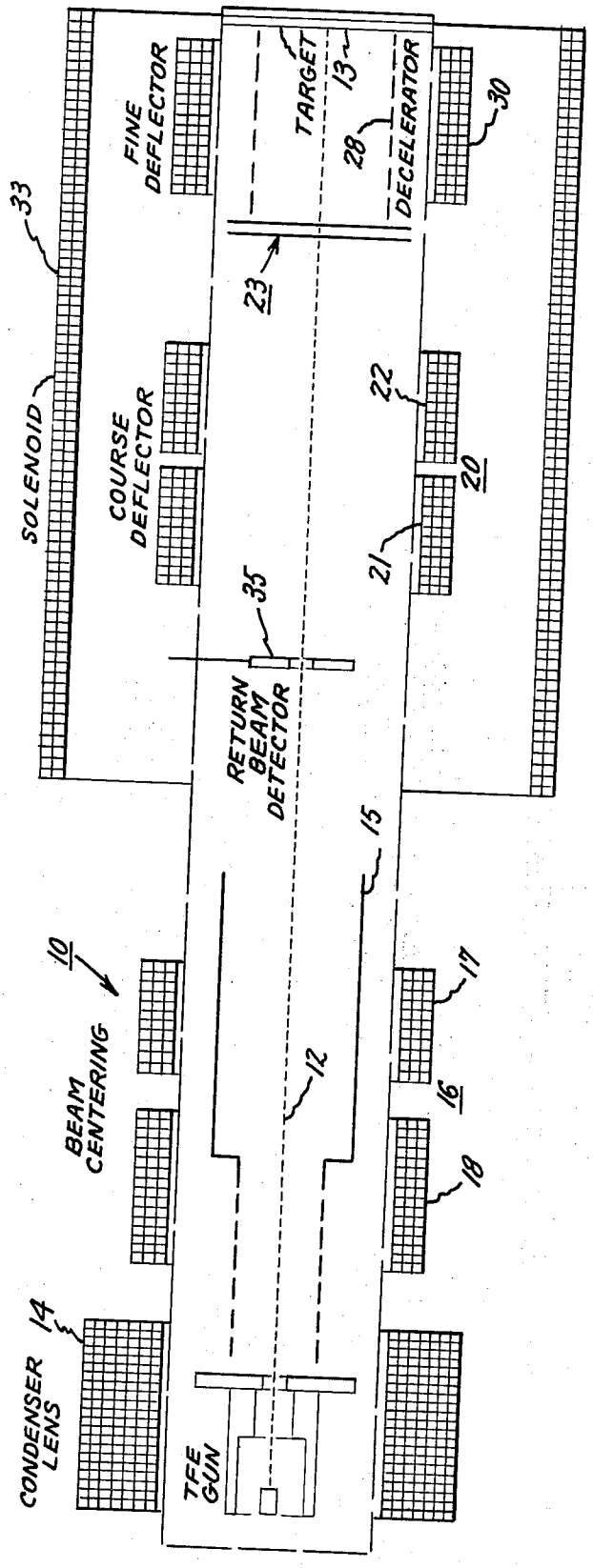


Fig. 1.

Fig. 2.

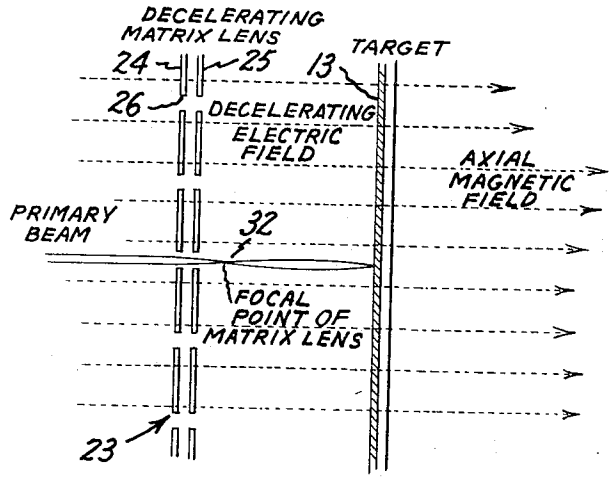


Fig. 3.

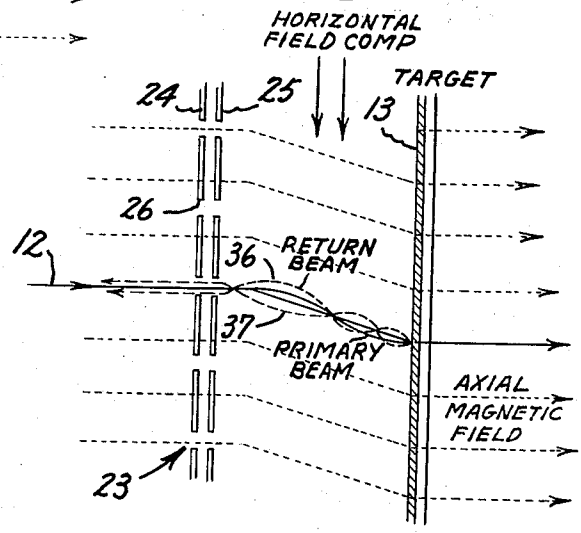
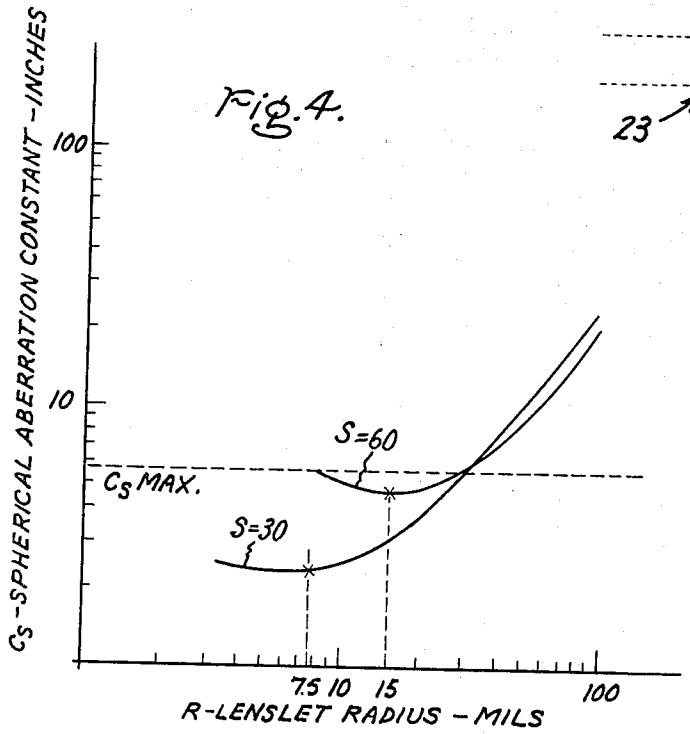


Fig. 4.



METHOD AND APPARATUS FOR RETURN BEAM READOUT THROUGH A MATRIX ELECTRON LENS

The present invention relates to electron beam apparatus and more particularly to a new and improved method and apparatus for reading out information stored on a memory target structure by collecting signal electrons from the target during readout.

In the field of data processing, high capacity random access memories of high bit storage density with rapid data storage and retrieval have become exceedingly important. Advances in computer technology and in the field of automation have placed increasing demands on data storage devices. Presently available data storage devices such as magnetic tapes and magnetic drums have a maximum storage density of the order of 1,000 bits per centimeter squared and consequently require approximately 1,000 square centimeters of storge for storing 10^6 bits of data. Such large storage areas substantially increase the access time required to read out such data. Hence, researchers have been attempting to find new storage mechanisms with higher density and shorter access times.

U.S. Pat. No. 3,170,083 to Newberry describes a high density, fast access time data storage system employing a charged particle beam-addressed memory system. It has been found that chaged particle beams, such as electron beams, can be focussed to spot diameters in the order of 100 Angstroms or less, thereby providing a means for storing data in storage sites having dimensions of a few 100 A. Such data storage systems have the potential of providing in excess of 10^{10} storage sites per square centimeter. Accordingly, charged particle beam-addressed memories offer a possible solution to the ever-increasing demands of the computer industry for higher density storage media.

Read out of information stored in the memory target depends upon the type of target employed. For example, some storage targets provide a different number of reflected electrons, depending upon the presence or absence of information stored thereon. Other storage targets detect the current flow through the target and differences therein as a result of information stored thereon. A particularly desirable method for detecting information stored on a memory target is to measure the number of secondary electrons emitted from the storage target due to the incident scanning electron beam. For example, where the memory target comprises metal removed and metal remaining portions, the number of secondary electrons emitted from the surface of the storage target differs when the electron beam is incident on a metal removed area from when the electron beam is incident on a metal remaining area. By detecting this difference in secondary electron emission, it is possible to read out information stored on the storage target.

One of the difficulties encountered in measuring or detecting this difference in secondary electron emission is the location of the detector. The detector must be located outside of the field of the primary electron beam but sufficiently close to the target to detect the secondary electron emission. Attempts to provide such detectors have not been entirely satisfactory because the presence of the electron optical system severely limits the location of such detectors. As a result, signal

detection and signal-to-noise ratios are generally unacceptable.

It is, therefore, an object of this invention to provide an electron beam-addressable memory system with an efficient secondary electron emission detection apparatus.

It is a further object of this invention to provide a method and apparatus for collecting signal electrons from a target structure with a simple and efficient electron detection apparatus.

Another object is to provide data storage and readout apparatus having high storage density employing an electron beam for both reading and writing.

Still another object is to provide a method and apparatus for accurately positioning a primary electron beam on a memory target and for collecting signal electrons from the target as a result of the primary beam scanning the target.

Briefly, in accord with my invention, a new and improved method and apparatus is provided for reading out information stored on a memory target in the form of secondary electrons emitted from the memory surface as a result of a scanning primary electron beam. The primary electron beam is directed to the memory target by a coarse deflection system positioned along the path of the electron beam for coarsely directing the electron beam to a selected lenslet of a matrix lens. The electron beam exiting from the matrix lens is then finely deflected to impinge on the target surface precisely at the desired point of impingement and normal thereto. Secondary emission electrons emanating from the surface of the memory structure as a result of the primary electron beam impinging thereon are focussed by the fine deflector back to the matrix lens along a trajectory substantially similar to that of the primary electron beam to a return beam detector where the secondary electrons are detected. Since the number of detected electons is proportional to the number emitted from the surface of the memory target, by appropriately selecting the memory target such that different numbers of electrons are emitted from a storage site representing a logic zero from a storage site representing a logic one, digital data is conveniently and efficiently read out from the memory target.

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

FIG. 1 is a simplified sectional view of apparatus embodying the electron beam memory system of the invention;

FIG. 2 schematically illustrates the details of a matrix electron lens used in accord with my invention;

FIG. 3 schematically illustrates the paths of the primary and secondary electrons between the matrix electron lens and the target; and

FIG. 4 is a plot of spherical aberration of the matrix electron lens versus lenslet radius for various lens plate spacings.

FIG. 1 schematically illustrates a data storage apparatus **10** employing a return beam matrix lens optical system for readout of the stored information in accord with the principles of the instant invention. The data storage apparatus **10** comprises an electron source or gun **11** for projecting a beam of electrons **12** to a mem-

ory target structure **13.** The electron source **11** and the memory target **13** may, for example, be conveniently located at opposite ends of an evacuated enclosure of cylindrical configuration, for example.

The electron source **11** is preferrably a thermionic field-aided emission (TFE) source providing electron beam currents of the order of 10^{-5} to 10^{-8} amperes, for example. Suitable electron sources are described in U.S. Pat. Nos. 3,008,066, 3,016,472 and 3,263,115, for example. The electron beam **12** produced by the source **11** is collimated by a magnetic condenser lens **14** which modifies the electron trajectories during their passage through the condenser lens **14** so as to provide a substantially parallel beam of electrons. The electron beam **12** is accelerated by an accelerator **15** having minimum lens characteristics. The beam of electrons is then centered along a selected axis by the use of suitable beam centering apparatus **16** comprising *x*- and *y*-centering coils, **17** and **18,** respectively.

The electron beam **12** then enters one end of a coarse deflection region comprising a horizontal and a vertical deflection assembly **20,** illustrated in FIG. **1** as magnetic deflection coils **21** and **22,** respectively. the horizontal and vertical deflection assembly **20** deflects the electron beam **12** in a predetermined manner and sequence both in the horizontal and vertical direction to scan the beam across a matrix electron lens **23.** The matrix electron lens **23** comprises two parallel lens plates **24** and **25** spaced apart from each other by approximately 20 to 80 mils, for example, and having a plurality of aligned apertures therein. By way of example and without limiting the present invention, the size of the apertures may range between approximately 5 and 50 mils, for example.

FIG. **2** illustrates more clearly the details of the matrix electron lens **23** with lens plates **24** and **25** having a plurality of aligned apertures or lenslets **26** through which the electron beam is directed. The lens plates **24** and **25** are connected to suitable voltage sources to produce a decelerating effect on the electron beam as it passes therethrough.

Returning again to FIG. **1,** the electron beam, after passing through a selected lenslet of the matrix electron lens **23,** is further decelerated by an electric field established by a decelerator **28** positioned between the matrix electron lens **23** and the storage target **13.** Surrounding the decelerator **28** is a fine deflection assembly **30** which provides fine horizontal and vertical deflection of the electron beam.

Operationally, the electron beam **12** is directed first to a specific lenslet **26** by the horizontal and vertical deflection assembly **20** and then further directed to a specific location on the storage target **13** by the fine deflection assembly **30.** Thus, once the coarse deflection assembly **20** has deflected the electron beam onto any particular lenslet **26,** the electron beam may be precisely controlled and directed to a specific location on the target structure **13** by the fine deflection assembly **30.** The extent of deflection afforded the fine deflection assembly **30** is adjusted in accord with the spacing between lenslets **26** such that the entire surface of the target structure may be scanned with an electron beam merely by selecting the desired lenslet and the appropriate deflection of the electron beam by the fine deflection assembly.

The matrix electron lens **23,** in addition to decelerating the electron beam **12,** focuses the beam immediately in front of the particular lenslet through which it passes. FIG. **2** illustrates the focal point by the numeral **32.** The focal point is then "relayed" to the target surface with a single node, under the action of an axial magnetic field produced by a solenoid **33** (illustrated in FIG. **1**) which surrounds the coarse deflector **20,** the matrix lens **23,** the fine deflector **30** and the target structure **13.**

The target structure **13** may comprise a semiconductor wafer having a pattern of radiation absorbing regions coated over its incident radiation receiving surface and which is interrogated by impingement of an electron beam on the surface thereof, such as is described in U.S. Pat. No. 3,550,094. Alternately, the storage target may comprise a dielectric layer and a juxtaposed semiconductor layer sandwiched between a tin oxide electrode and an electron transparent aluminum electrode, which exhibits localized breakdown in the dielectric layer when the semiconductor layer is struck by a writing electron beam. Readout is then achieved by detecting secondary electron emission from the storage target by impingement of an electron beam. Such a target structure is described in U.S. Pat. No. 3,573,753. Still further, the target structure may comprise an amorphous semiconductor material which is rendered crystalline in selected regions by a writing electron beam. Read-out is achieved by detecting secondary electron emission, which differs for crystalline and amorphous semiconductor material. Such a target structure is described in U.S. Pat. No. 3,750,117.

In accord with my invention, the secondary emission electrons are returned back through the matrix electron lens **23** along a path substantially similar to that taken by the primary electron beam **12** where they are detected by a detector **35.** Under the influence of the axial magnetic field of the solenoid **33** and the magnetic deflection field produced by the fine deflection assembly **30,** along with the decelerating electric field produced by the decelerator **28,** the secondary electrons are drawn back to the aperture in the electron lens **23** through which the primary beam has passed. Whereas the decelerating electric field produced by the decelerator **28** has only a minor effect on the primary electron beam, the low energy secondary electrons are accelerated substantially by this field and hence the secondary electrons are focussed back to the electron lens **23.**

FIG. **3** illustrates the return of secondary electrons from the target surface to the electron lens **23** along paths **36** and **37.** As is illustrated, the secondary electrons are guided and focussed by the magnetic field so that they return to the same lenslet (through which the primary electron beam passed) in the electron lens **23** with a multi-node focus of varying pitch. This occurs even though the primary electron beam is deflected by the fine deflection assembly **30.** By adjusting the accelerating electric field, the final focus node for the secondary electrons is made to coincide with the return focal point of the electron lens. The secondary electrons therefore are collimated and further accelerated by the electron lens and exit from the electron lens along a path similar to that followed by the primary electron beam **12.**

The return beam of secondary electrons is directed and guided by the magnetic field back to the detector **35.** The detector **35** is provided with an aperture which is just large enough to allow the primary electron beam

to pass through, but since the return beam diameter is considerably larger than the primary beam, most of the return beam electrons are collected by the detector **35.** The detector **35** is preferably a semiconductor particle detector having substantial current gain (e.g., 100 – 1,000 times the secondary electron current) so that an electrical output signal having an amplitude proportional to the magnitude of the return beam secondary electrons is provided.

Having thus described generally a data storage system employing return beam readout, a more detailed discussion of the electron optics will now be presented to enable those skilled in the art to better appreciate the numerous advantages associated with data storage systems constructed in accord with my invention.

As pointed out above, one of the primary advantages of electron beam addressed memory systems is the ability to focus an electron beam to a very small diameter, in the order of 100 A or less. As a result, it is possible to provide data storage sites of only a few hundred Angstroms, if desired. In accord with my invention and by way of example, assume that it is desired to provide an electron beam diameter of 0.1 microns (1,000 Angstroms) for accessing storage sites of less than 0.5 microns. For a given beam diameter, d, the maximum achievable beam current, I, in a 50 percent current diameter spot, d, at a given brightness, β, and spherical aberration of the matrix lens, C_s, the following relationship has been found to exist:

$$I_{max} = (2.0\ d)^{8/3}\ \beta/C_s^{2/3}$$

From this equation it can be seen that for a given spot size and beam brightness, the current is maximized by minimizing C_s. Therefore, it is desirable to minimize C_s for the matrix electron lens **23.** If V_M and $V_{L'}$ are the voltages on lens plates **24** and **25,** respectively, with respect to ground potential, and V_K is the voltage on the electron source, the accelerating voltage ratio V for the matrix electron lens is related to the lens voltages in the following manner:

$$V = (V_{L'} - V_K/V_M - V_K)$$

If the lenslets themselves are separated from each other by a distance S, have a diameter D and a radius R, the optical properties of the lens are determined by the lens dimensions and the accelerating ratio V. In general, focal length and spherical aberration both decrease as the acceleration ratio increases for given lens dimensions. However, when the acceleration ratio is increased, the field strength, E, between the lens plate also increases. Additionally, as the acceleration ratio increases, the beam energy increases in the coarse deflection region. Accordingly, coarse beam deflection becomes more and more difficult as the acceleration ratio V increases. Therefore, it is necessary to maximize E, while avoiding voltage breakdown between the lens plates **24** and **25** but not increasing V and more than necessary in order to avoid coarse deflection problems.

Assuming that it is desirable to operate the target structure at ground potential, $V_1 = 0$ volts. Further, let it be assumed that V_c, the voltage on the electron source **11** be minus 4.0 kv. Also, let it be assumed that the voltage on the lens plate **25** by 1.0 kv to provide sufficient acceleration to the secondary emission electrons. Using these values, it is then possible to select values for the acceleration ratio V, the spacing between the lens plates S, and the voltage on the lens plate **24.** Table I illustrates these values for increasing field strengths E, of 5×10^4 V/cm, 10^5 V/cm and 2×10^5 V/cm.

TABLE I

V	E=5×10⁴ V/cm		E=10⁵ V/cm		E=2×10⁵ V/cm	
	S(mils)	V_M(kV)	S(mils)	V_M(kV)	S(mils)	V_M(kV)
3	80	11	40	11	20	11
4	120	16	60	16	30	16
5	160	21	80	21	40	21

From the foregoing information contained in Table I, the spherical aberration C_s in inches for the matrix electron lens can be plotted against lenslet radius R in mils, as shown in FIG. **4.** From these curves, it is possible to select operating conditions which are below the maximum spherical aberration C_s and within the brightness capabilities of the electron source. For example, two possible operating conditions are $S = 60$ mils, $R = 15$ mils and $E = 10^5$ V/cm and $S = 30$ mils, $R = 7.5$ and $E = 2 \times 10^5$ V/cm.

From Table I above, it can be seen that V_M must be 16 kv. Therefore, with $V_c = -4.0$ kv, the electrons in the coarse deflection region have 20 kev energy. Further, it can be shown that the magnetic field required of the solenoid is approximately 200 gauss and that the coarse deflection can be achieved with 70 gauss and the fine deflection achieved with only 3 gauss. These values permit the electron beam to be deflected over the target surface with the degree of accuracy required of a storage target having storage sites less than 0.5 microns. As a result, storage targets having storage densities in excess of 10^8 storage sites per square inch are readily provided.

To recapitulate operation of the apparatus shown schmatically in FIG. **1,** the electron beam **12** is turned on whenever it is desired to read or write data, by deflecting the electron beam into the region enclosed by the coarse deflection assembly **20.** The beam is then coarsely deflected by the coarse deflection coils **21** and **22** such that the beam is directed to a specific lenslet **26** in the matrix electron lens **23.** This deflection may, for example, be controlled by voltages from a digital-to-analog converter in response to signals furnished by a computer.

The electron beam is then collimated by passage through the matrix electron lens **23** and enters the fine deflection region under the control of the fine deflection assembly **30.** Deflection of the electron beam within this region is again controlled, for example, by digital-to-analog converters in response to output signals from the computer. The electron beam is then directed to a specific storage site on the storage target **13.**

Where the target structure **13** comprises a semiconductor wafer having a radiation absorbing region coated over its incident radiation receiving surface, such as is described in U.S. Pat. No. 3,550,094, the incident electron beam is used to write information on the target structure by causing the target to absorb radiation in its radiation absorbing coating. By designating a storage site which has received sufficient radiation to produce absorption in the radiation absorbing

coating as a logic 1, and storage sites which have received no such radiation, a logic 0, digital information may be stored in the target structure.

Readout of the stored information may be achieved in substantially a similar manner by deflecting the electron beam to a specific storage site, in the manner described above, and then monitoring the secondary electron emission from that particular storage site. More specifically, and continuing with the illustration wherein the storage target is a semiconductor wafer having a pattern of radiation absorbing regions thereon, during readout, the electron beam impinging on a storage site produces secondary emission of electrons at a rate which differs in accord with whether or not a storage site was previously written on by the write electron beam. The secondary emission electrons are focussed by the fine deflection assembly **30** back to the matrix electron lens **23** along a trajectory substantially similar to that of the primary electron beam **12.** The return beams of secondary emission electrons are then detected by the detector **35.** Since the number of detected electrons is proportional to the number emitted from the surface of the memory target, it is possible to read out the information stored on the storage target without destroying the stored information.

Suitable means for operating a data storage system in accord with our invention are described in the foregoing patents and hence specific circuitry to achieve the foregoing read and write functions are not disclosed herein. It should also be apparent to those skilled in the art that whereas the invention has been described with respect to readout by means of secondary emission electrons, obviously where the information stored on a storage media is in the form of a latent electrostatic image, readout of the stored information may be achieved by reflected or turned around electrons reflected from the surface of the storage media. In this case, the return beam of electrons are not secondary emission electrons, but rather reflected or turned around primary electrons. However, the optical system in accord with out invention readily accommodates either secondary emission electrons or reflected electrons which are still detected as described above.

From the above description, it can be readily appreciated that the present invention provides a new and improved write-read electron apparatus and method making possible readout from a storage target in a non-destructive manner with an electron beam by detecting secondary emission electrons emitted from the surface of the storage target. In accord with my invention, high density, high speed storage and readout is readily achieved.

While only certain preferred features of the invention have been shown by way of illustration, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. An electron beam-addressable memory system comprising:

an electron source for producing a beam of electrons;

a data storage target disposed in the path of said beam for storing information thereon;

a matrix electron lens disposed in the path of said beam and positioned adjacent to said storage target, said lens comprising a pair of spaced parallel lens plates each having a plurality of lenslets therein for focussing said beam on said target;

coarse deflection means positioned between said electron source and said lens for directing said beam to a specific lenslet;

fine deflection means positioned between said lens and said storage target for directing said beam to a specific point of impingement on said storage target, said target emitting secondary electrons in response to said beam impinging on said target;

means for returning said secondary emission electrons along a path substantially similar to said electron beam; and

means for detecting said secondary emission electrons and providing an output signal proportional to the detected secondary emission electrons.

2. The memory system of claim **1** wherein information stored on said target is representative of digital information and said secondary emission electrons are emitted in proportional response to said stored information.

3. The memory system of claim **1** further comprising:

means establishing a magnetic field along the axis of said electron beam, said magnetic field relaying said focussed electron beam existing from said lenslet to said target with a single node.

4. The memory system of claim **3** further comprising:

means biasing said parallel lens plates to produce a decelerating electric field for decelerating and focussing said electron beam in front of said lenslet.

5. The memory system of claim **4** wherein said secondary electrons are directed to said detecting means under the influence of said magnetic field and said electric field.

6. The memory system of claim **5** wherein said secondary electrons emitted from the target surface are directed to a lenslet of said matrix electron lens with a multinode focus of varying pitch.

7. The memory system of claim **3** wherein said electron beam impinges on said target substantially normal thereto.

8. The memory system of claim **5** where said means for detecting comprises a semiconductor detector positioned along the path of said electron beam between said coarse deflection means and said electron source, said detector having an aperture therein for the passage of said electron beam therethrough.

9. The memory system of claim **4** wherein said means biasing said parallel lens plates produces an accelerating ratio in the range of 3 to 5.

10. A method of reading out information stored on a target surface with an electron beam, said method comprising the steps of

forming a beam of electrons;

focussing said beam of electrons on said target, said target emitting secondary electrons in response to said beam of electrons;

returning said secondary emission electrons along a path substantially similar to said electron beam; and

detecting said secondary electrons along said path.

11. The method of claim 10 wherein the step of focussing comprises:

coarsely deflecting said beam of electrons to a lenslet of a matrix electron lens;

decelerating said beam of electrons with said matrix electron lens; and

finely deflecting said beam of electrons to a specific point of impingement on said target surface.

12. The method of claim 11 wherein said secondary emission electrons are emitted in proportional response to information stored on said target.

13. The method of claim 12 wherein the step of returning said secondary emission electrons comprises:

establishing a magnetic field along the axis of said electron beam for directing said secondary emission electrons to said matrix electron lens with a multinode focus of varying pitch.

14. The method of claim 13 further comprising:

biasing said matrix electron lens to produce a decelerating electric field for said beam of electrons and an accelerating electric field for said secondary emission electrons.

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