

[54] **ELECTRON EMISSION SYSTEM**

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[58] Field of Search. **313/336; 1/346**

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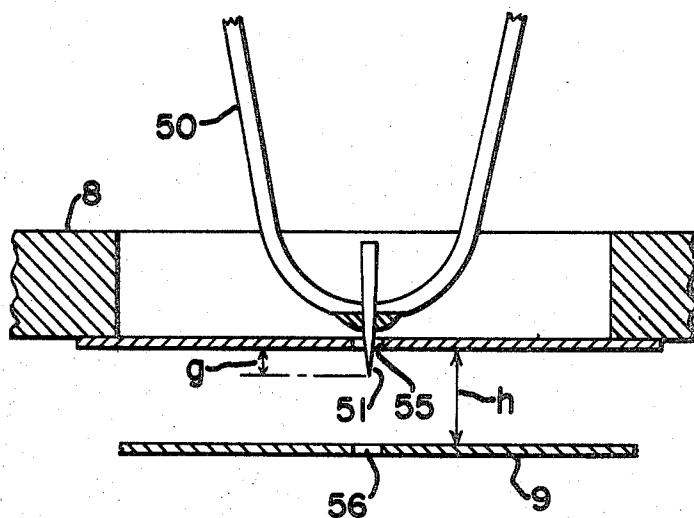
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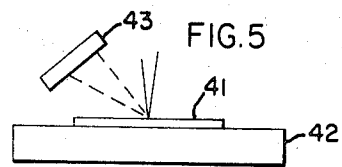
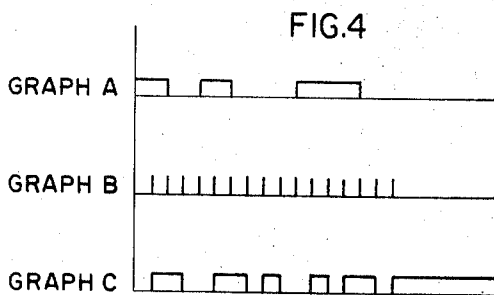
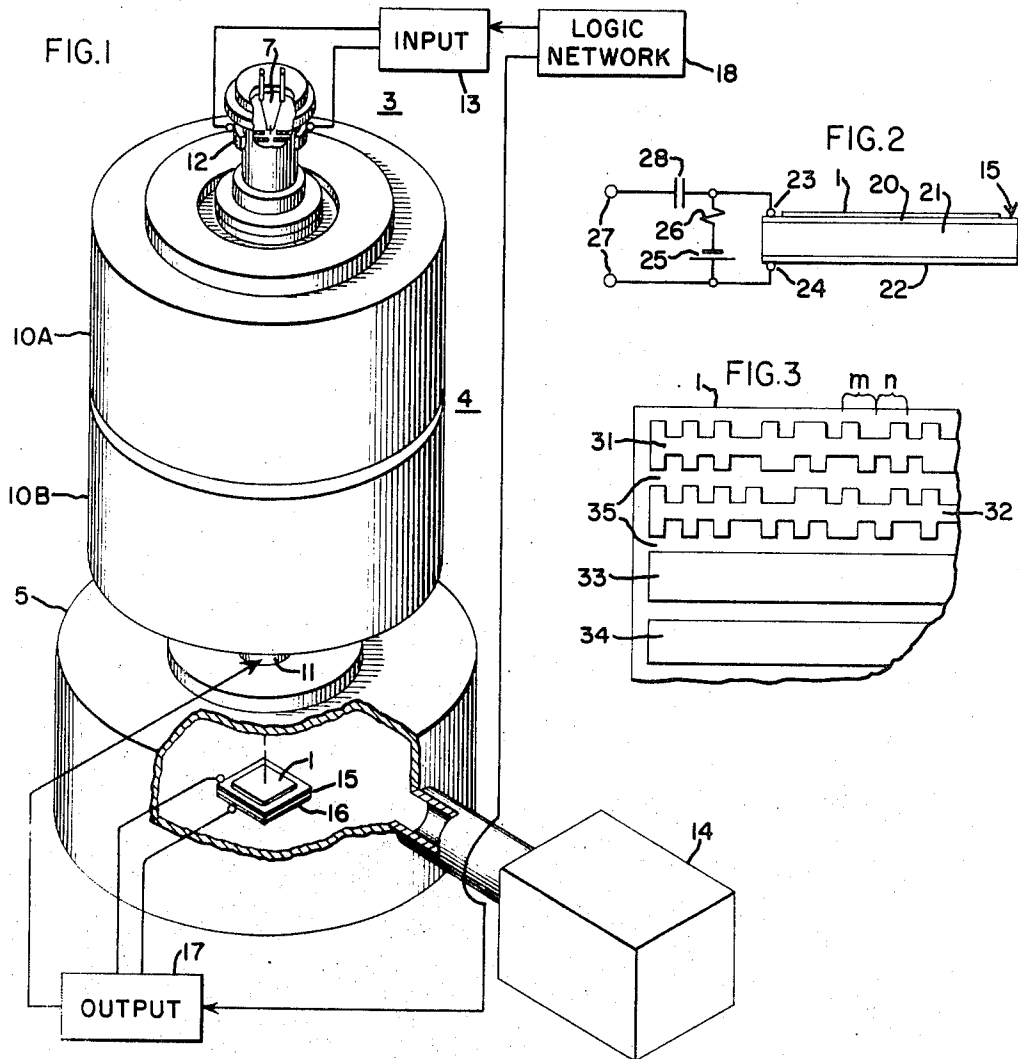
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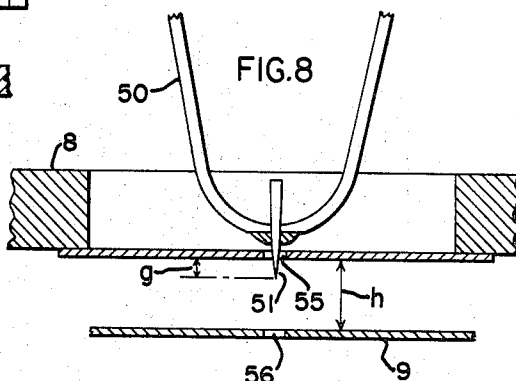
[57] **ABSTRACT**

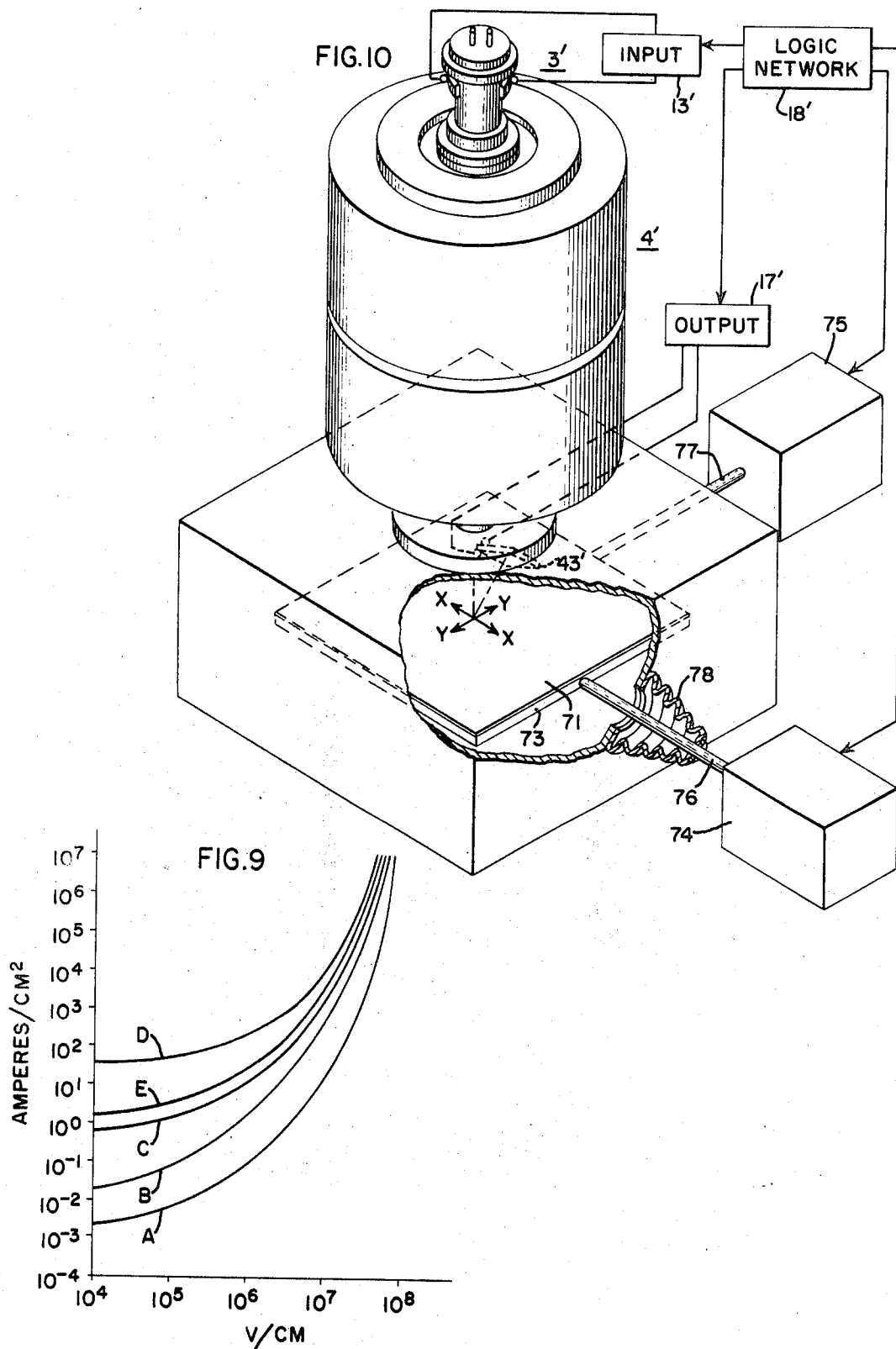
A storage system for the mass recording and readout of digital data with ultra high resolution. An electron beam structure is provided for forming a beam of extremely small focused spot diameter, on the order of 0.1 microns, and high current density capability, on the order of 1,000 amperes per sq. cm., which records data by scanning over defined areas of the storage medium surface and micromachining elemental portions of said medium as a function of beam modulation. Readout may be subsequently accomplished by similarly scanning the beam at reduced power density and detecting electrons that have been transmitted by or reflected from the storage medium.

6 Claims, 11 Drawing Figures









ELECTRON EMISSION SYSTEM

This is a division of application Ser. No. 847,972, filed Aug. 6, 1969.

BACKGROUND OF THE INVENTION**1. Field of the Invention**

The invention relates to the field of mass storage and retrieval systems for storing huge quantities of high resolution data and, in particular, to high density systems of this type employing electron beam recording and readout.

2. Description of the Prior Art

A figure of merit of 10^{12} data bits capacity has evolved for mass storage and retrieval systems. A capacity of this magnitude is considered desirable in order to satisfy present day archival storage requirements and workers in the field continue to be engaged in finding the most effective means for its accomplishment within a confined space. The principal limitation of storage systems developed to date is the resolution of the storage data. Lacking very high resolution, these systems require extensive storage space for storing large quantities of data and access times to said data are necessarily slow. In order to index elemental data bits for either storage or retrieval purposes, a relatively complex and slow mechanical accessing operation is normally required. In one system known to the art a laser beam is employed for recording and reading out data on a photosensitive storage medium which is in the form of a long continuous tape. Information is written by scanning the beam diagonally across the tape as the tape moves longitudinally, providing parallel scan lines throughout the tape's length. Because of inherent limitations in the wavelength of laser energy, on the order of 5,000 to 6,000 angstroms, data can be recorded with resolutions no greater than a few microns. Thus, for a 10^{12} bit memory, 2,400 feet of 8 mm tape must be provided. It may be appreciated that lengthy access times are required for this system.

Another existing approach is to employ an electron beam for writing on photographic film. This has been accomplished employing a beam having a 3 micron resolution and recording on 35 mm chips. For a 10^{12} bit storage capability there are required 200,000 individual chips. The mechanical accessing requirements for this system are extremely complex. Further, it is necessary to develop the photographic film before the information can be read out or checked, and data cannot be subsequently entered.

In the field of electron microscopy it has been suggested to employ a scanned electron beam of extremely small spot diameter, such as presently utilized in scanning electron microscopes, to record digital information by means of selective etching or a comparable technique. The art has been developed to where there presently exist beam forming apparatus which generate beam spot diameters on the order of several hundred angstroms and less, corresponding to a resolution orders of magnitude higher than in the above noted systems. However, these are all relatively low power density beams, not capable of providing directly permanent data storage using presently available recording materials. Accordingly, there does not exist at the present time apparatus for generating electron beams of minute dimensions for an ultra high resolution re-

cording which also have extremely high current density characteristics for a permanent data storage.

SUMMARY OF THE INVENTION

5 It is accordingly a principal object of this invention to provide a novel ultra high density storage system which permanently and directly records data at appreciably higher resolutions than presently obtainable, making possible the rapid storage of huge quantities of data within a confined space.

10 It is a further object of the invention to provide a novel storage system as above described wherein recording and readout operations are accomplished at high speed, and do not require a separate developing step.

15 A further object of the invention is to provide a novel storage system as described wherein exceedingly large quantities of data, on the order of 10^{12} bits and greater, can be stored on a single, relatively small, storage surface.

20 It is still another object of the invention to provide a novel ultra high density storage system as above described in which data is recorded by micromachining elemental portions of the storage medium by means of a scanned electron beam, the stored data being read out also by a scanned electron beam.

25 A still further object of the invention is to provide a novel electron beam forming structure for generating a beam of extremely small spot diameter, on the order of 0.1 microns, and high current density, on the order of 1,000 amperes per sq. cm.

30 A yet further object of the invention is to provide a novel electron beam forming structure for generating a beam with the above noted characteristics by means of a relatively low accelerating voltage, on the order of 5 to 10 KV.

35 It is another object of the invention to provide a novel electron emission system having a field aided thermionic cathode that emits electrons with an exceedingly high current density and is extremely stable in its operation.

40 Still another object of the invention is to provide a novel field aided thermionic cathode employing a tungsten needle coated with an atomic layer of zirconium which exhibits an extremely long lifetime, on the order of 1,000 hours and greater.

45 It is yet a further object of the invention to provide a novel electron optical system for forming a high current density, small spot diameter beam that is capable of being deflected over a relatively large number of resolvable elements.

50 Still a further object of the invention is to provide a novel electron optical system as above described in which the effective spherical aberration of the focus lenses is made low for relatively large focal lengths.

55 In accordance with these and other objects of the invention there is provided an ultra high density storage system which employs a scanned electron beam of extremely small spot size and high current density to record data on a storage medium by micromachining elemental portions of said medium. Readout of the stored data is accomplished by means of the scanned electron beam, modulated electrons from the target storage medium being collected by a detector device. The readout electron beam is at reduced current densities which will not destroy the stored data bits. For high capacity storage, data is stored as numerous discrete data blocks

over each of which the electron beams can be magnetically or electrically scanned. Mechanical drive means are provided for indexing the data blocks with respect to said beam for both write and readout operations.

With respect to one specific aspect of the invention, the electron beam is produced by a novel electron emission system through a process of field aided thermionic emission. The electron emission system is composed of a cathode including a filamentary hairpin with a welded single crystal oriented tungsten needle which is of extremely small dimension at the emissive cathode tip. Sintered zirconium is applied in a ball at the base of the needle, and upon heating of the hairpin and needle migrates as a solid up the needle to the tip. The zirconium coating acts to reduce the work function of the 100 face on the tip of the tungsten crystal to a value appreciably lower than occurring on other faces. The emission system further includes an apertured anode and grid electrode structure for generating a spherical electric field configuration about the emissive cathode tip which exhibits a very high field gradient at said tip for causing a high power density electron emission.

With respect to a second specific aspect of the invention, an electron optical system is provided which includes first and second focus lenses to provide a single stage imaging of the electrons emitted from the cathode tip onto the target. The cathode tip, which is at about the object plane, is positioned at the focal point of the first lens and the target, which is at the image plane, is positioned at the focal point of the second lens. The focused beam impinges on the target at sufficiently high power densities to vaporize away portions of the target material. Modulation of the beam is accomplished by a modulation coil which shifts the beam axis with respect to a limiting aperture provided in the vicinity of the beam source. A set of deflection coils are provided forward of the final focusing lens for deflecting the beam in both X and Y directions in the plane of the storing medium.

BRIEF DESCRIPTION OF THE DRAWING

The specification concludes with claims particularly pointing out and distinctly claiming the subject matter which is regarded as the invention. It is believed, however, that both as to its organization and method of operation, together with further objects and advantages thereof, the invention may be best understood from the description of of the preferred embodiments, taken in connection with the accompanying drawings in which:

FIG. 1 is a schematic diagram in a partially broken away perspective view of an electron beam ultra high density storage system in accordance with one embodiment of the invention employing a limited area storage medium;

FIG. 2 is an enlarged side view of the storage medium and electron detector employed in the system of FIG. 1;

FIG. 3 is a partial plan view of the storage medium employed in the system of FIG. 1, illustrating the written data format;

FIG. 4 is a series of graphs illustrating the formation of the input modulation signal;

FIG. 5 is a side view of a modified reflective readout structure;

FIG. 6 is a detailed cross sectional view of the total electron beam structure of FIG. 1;

FIG. 7 is an enlarged cross sectional view of the electron emission structure of FIG. 6;

FIG. 8 is a further enlarged cross sectional view of the cathode structure;

FIG. 9 are several curves illustrating field aided thermionic emission;

FIG. 10 is a schematic diagram in partially broken away perspective view of a further embodiment of the invention employing a large area storage medium and mechanical drive means for indexing said storage medium; and

FIG. 11 is a partial plan view of the storage medium employed in the system of FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, there is schematically illustrated in perspective view an electron beam storage system for permanently storing data at ultra high densities, exceeding 10^9 data bits per sq. cm. The data is written by a scanned electron beam of extremely small beam spot diameter, on the order of 0.1 micron, and extremely high current density. A magnetic deflection was employed in the illustrated system, although an electrostatic deflection might also be used. The writing beam, at the focused spot, exhibits a current density of 10^3 amperes per sq. cm. and greater, and therefore a power density of 10^7 watts per sq. cm. and greater within moderate anode voltages. The writing beam is modulated as a function of the input data so as to selectively micro-machine by vaporization elemental portions of the medium 1 as the beam is scanned over its surface. Scan rates as high as 10^7 data bits per second and higher are employed. A non-destructive readout of the stored data is accomplished by a scanned readout electron beam operated at reduced power levels, about one tenth that of the writing beam.

The electron beam structure for both record and readout includes an electron emission system 3 and an electron optical system 4 associated with an evacuated chamber 5 within which the beam is enclosed. The emission system 3 produces the electron beam and includes among its principal components a cathode structure 7, grid electrode 8 and anode electrode 9. The electron optical system 4 controls, focuses and deflects the beam and principally includes focusing coils 10A and 10B, deflection coils 11 and modulation coils 12. The emission system 3 and electron optical system 4 include features of novelty that make possible the extremely high resolution, high current density properties of the focused electron beam, and will be described in greater detail when considering FIGS. 6 and 7. An input means 13, shown in block form, supplies input signals for modulating the beam. Input means 13 may comprise a conventional source of digital data, e.g., the peripheral equipment of a digital computer. Although, in the disclosed embodiments of the invention the modulation signal contains digital data, the invention need not be so limited and may be useful with other data forms such as analog and alphanumeric data.

A medium vacuum, on the order of 10^{-7} mm. Hg., is provided within the chamber 5 by a vacuum pump 14, schematically illustrated in block form. A vacuum of this magnitude represents a compromise that it is relatively easy to achieve and maintain, while being compatible with the high order of performance required of the present system. Also housed within the chamber 5

is the readout structure in the form of an electron detector 15 upon which the storage medium 1 is deposited. The storage medium 1 and detector 15 are mounted on a base structure 16. An output means 17 is connected to the detector 15 for receiving the readout data. A master control logic network 18 is coupled to input means 13 and output means 17. The network 18 includes numerous logic circuits of standard design for providing the sundry logic functions which control the writing and readout operations, as well as a clock frequency generator for supplying a master timing of said operations.

The electron detector 15 may be a conventional component. In the embodiment being considered it is a single crystal silicon p-i-n junction device which in response to penetrating electrons of the readout beam generates electron-hole pairs. As shown in the side view of FIG. 2, the silicon detector includes a p region 20, an intrinsic region 21 and an n region 22, with contacts 23 and 24 made to the p and n regions, respectively. The storage medium 1 is deposited as a thin film over the p region 20. A d.c. voltage source 25 is connected through a lead resistor 26 to contacts 23 and 24 for reverse biasing the device. Output terminals 27 are coupled through a capacitor 28 to contacts 23 and 24 for sensing readout current flow through the device 15.

During the write operation the electron beam is operated at high current and power densities. As it scans across the surface of the storage medium 1, the beam selectively micromachines elemental portions thereof, corresponding to the data bits, as a function of beam modulation. A heating and rapid vaporization of said elemental portions of the material occur in response to penetration by the beam's high velocity electrons. With respect to the vaporization process, the high density electrons of the focused beam spot penetrate the storage material with relatively high kinetic energy. As the electrons are rapidly decelerated by the bulk of the material, heat is given off which in a localized area elevates the temperature to a point well above the threshold temperature of the vapor pressure versus temperature curve of the material, the threshold temperature being that temperature at which the vapor pressure commences to rise steeply as a function of temperature. At this elevated temperature, the vapor pressure of said localized area is raised orders of magnitude above the ambient pressure and rapid vaporization of the material results.

It is preferred to modulate the beam by applying the input signal to the modulation coils 12 for recurrently shifting the beam from its central axis so as to be partially intercepted during its travel, thereby maintaining a constant current emission while modulating the current density at the focused spot. The beam is rapidly scanned by the deflection coils 11 along parallel data tracks successively formed on the surface of the storage medium.

In the embodiment of FIG. 1, the storage medium 1 has a storage area about 36 mils square with about 4,500 data lines and about 4,500 resolvable elements per data line. Thus, there is provided a storage capacity in excess of 2×10^7 bits. With reference to FIG. 3, a small area of the storage medium 1 in a greatly magnified plan view is illustrated, showing four data strips 31, 32, 33 and 34, the edges of which comprise the data lines. Tracks 35, formed between the data strips, are

employed to servo the readout beam as will be further explained. Information is written along both edges of each data strip at resolvable elements on the data lines, such as shown with respect to resolvable elements m and n . In accordance with standard practice, the data lines have a string of known data bits written at the beginning of each line which are used as a reference during readout. In the present format the data strips are on centers spaced apart by 0.4 microns, and each resolvable element is 0.2 microns in length. Digital information of binary "1"s and "0"s is written as a 180° phase modulation of a square wave at one half the reference clock frequency supplied by the logic network 18, so as to correspondingly micromachine the data strips during either the first or second half of travel of the beam through each resolvable element. The writing beam may vaporize essentially the entire thickness of the storage medium or only a fraction of this thickness.

Referring to the diagram of FIG. 4, the binary bits may be fed in as a series of "1"s and "0"s at two corresponding d.c. levels, as shown by the Graph A. It will be assumed that the bits are supplied at a 10 MHz rate. The clock signal, shown in Graph B, is at twice the data rate or 20 MHz. Graph C illustrates the phase modulated square wave corresponding to the data bits in Graph A that is employed as the input signal for modulating the beam. With clock signal at a 20 MHz rate, a single data bit is written in 0.1 microseconds.

For the operation under consideration, the storage medium 1 must be a stable material capable of being selectively and rapidly vaporized at the requisite resolution of the system by the writing electron beam, and yet be totally unaffected by the lower energy readout beam. Principal properties of the medium 1 include a relatively high vapor pressure at the writing temperature, and a vapor pressure that is a steep function of temperature above threshold; a high density; and a low thermal conductivity. A high vapor pressure of the writing temperature causes the material to rapidly vaporize in response to heating by the writing beam. The steep vapor pressure versus temperature function permits a reduced power readout operation that can produce no vaporization of the material. High density and low thermal conductivity properties permit a localized heating of the material necessary for high resolution writing. The assignment of specific values for the above noted properties is dependent upon the writing and readout beam parameters as well as system requirements for resolution, speed, etc., and the interrelationship of these factors. For example, the requirements for high vapor pressure, high density and low thermal conductivity are inversely related to the writing beam current density.

In accordance with existing performance specifications for a given system, the storage medium may be selected from various classes of materials including semimetallic, semiconductor and dielectric materials. In the embodiment under consideration there is employed an alloy of selenium with 10-20% arsenic for retaining an amorphous form of the selenium. This material has a specific gravity of about 4.3, a thermal conductivity of about 10^{-3} calories per sec. per cm°C, and a vapor pressure of about 10^3 mm. Hg. at a writing temperature of 700°C, which pressure reduces to about 10^{-9} mm. Hg. at a readout temperature of 70°C. The material is deposited on one surface of the electron de-

tector 8 as a thin film, having a thickness of approximately 1,500 to 3,000 Å.

Considering the readout operation, the electron beam is operated at reduced power density. This may be accomplished by several different means, but it is preferable to reduce the current density of the focused spot through partial interception of the beam by biasing the beam off its central axis. The reduced power density causes a correspondingly reduced heating of the storage medium, and a very greatly reduced vapor pressure, as previously noted. In the embodiment of FIG. 1, as the readout beam is scanned the electrons from the beam are transmitted through the etched portions of the data elements and penetrate the electron detector 15. Electron-hole pairs are created by the penetrating electrons which generate a corresponding readout signal from output means 17. The readout signal contains the readout data in the form of phase information similar to the input signal. To maintain accuracy of the readout signal, this signal is synchronized with the clock frequency during the readout of each data bit.

In order that the readout beam precisely follow each data line, a servo system is provided for sensing and correcting any tendency for beam offset. One of several conventional servo techniques may be employed. In the storage system of FIG. 1, an edge servo system is used wherein as the beam is scanned along a data line, displacement from the edge of the data track is sensed and a correction signal generated. A servo unit, including a low pass filter and an error sensor to which the readout signal is coupled, may be embodied within the output means 17. As the beam travel may tend to deviate from a scanned data line toward or away from the adjoining servo track, a low frequency component is introduced into the readout signal the magnitude of which is a function of the beam displacement. In response to said low frequency component, the servo unit generates a correction signal which is coupled to the vertical deflection coils for compensating the beam's travel.

In FIG. 5 is illustrated an alternate embodiment of the readout structure of the reflective type. In this embodiment, a storage medium 41 is deposited upon a supporting substrate 42, e.g., of glass. An electron detector 43 is positioned above the storage surface and offset from the impinging electron beam. The electron detector 43, which may be one of several conventional types including the p-i-n junction device illustrated in FIG. 2, receives readout electrons which are reflected from the storage medium surface. The back scattered electrons can be reflected primary or secondary electrons, or both. An accelerating potential, not shown, is applied in known fashion to the detector for sensing secondary electrons. The readout operation is otherwise similar to that previously described, the detector responding to the reflected electrons for generating electron-hole pairs within its volume, which in turn provides a corresponding readout signal. Other forms of electron detectors such as channel multipliers and photon devices may also be employed.

A cross sectional view of the total electron beam structure including the electron emission system 3 and the electron optical system 4 is shown in FIG. 6, taken along the plane 6-6 in FIG. 1. An enlarged cross sectional view of the electron emission system per se is illustrated in FIG. 7, and a further enlarged view of the cathode structure is shown in FIG. 8. The electron

beam structure of FIG. 6 and 7 forms an electron beam having a theoretical current density j at the focused spot on the target that may be defined by Langmuir's equation as follows:

$$j = j_0 (1 + eV/KT) \sin^2 \alpha$$

where j_0 is the emission current density at the cathode emissive surface;

e is the electron charge;

V is the voltage at the target;

K is Boltzman's constant;

T is the absolute temperature; and

α is the half angle at the focused spot.

With reference to the above equation, it may be appreciated that the requirements of the storage system impose a number of significant constraints on the electron beam structure in providing extremely high target current densities. Thus, a prime consideration for obtaining a high target current density j is to maximize the cathode emission current density j_0 . The current density j is also proportional to the target voltage V . However, the voltage V also determines the velocity at which the electrons strike the target and an excessively high voltage will result in expanding the elemental heated portions of the storage medium and degrading resolution. Thus, the value of V must be determined with these conflicting considerations in mind. From the above equation it is also seen that the current density j is inversely proportional to the temperature T , which places a limitation on heating of the cathode.

Referring to FIG. 7, the cathode structure 7 includes a hairpin filament 50 having a cathode needle 51 joined at the vertex of said hairpin. A potentiometer, including a d.c. source 52 in shunt with a resistor 53, is coupled to the terminals of the filament 50 for heating said filament. A negative high voltage source $-V_1$ is coupled to a tap on the resistor 53. A shield 54 surrounds the cathode, grid and a part of the anode structure. The grid electrode 8 is in the form of a disk having an aperture 55 through which the cathode needle extends. A negative voltage source $-V_2$ is coupled to the grid 8, where $-V_2$ is slightly more negative than $-V_1$. The anode electrode 9 is of the re-entrant type, the re-entrant portion being provided with a central aperture 56 positioned immediately forward of the cathode lip. The anode electrode 9 is at ground potential, as is all structure forward of anode. At the opposite or forward end of the anode electrode is a limiting apertured electrode 57 in the shape of a disk having a central limiting aperture 58. A cylindrical sleeve 59 encloses the described emission structure. Several passages in the grid and anode structure, such as at 67, 68 and 69, facilitate evacuation of the electron emission region. The anode electrode, grid electrode and cathode needle structure together with the potentials applied thereto produce a hemispherical electric field configuration around the cathode tip, with the tip at the radial center of the hemisphere. The hemispherically configured electric field in combination with the extremely small dimensions of the cathode tip produce a very high electric field gradient in the vicinity of said tip. The hemispherical field also limits aberrations in the focused beam.

In one operable structure, in accordance with the invention, the cathode needle 51 is about 30 mils in length and extends forward of the grid electrode 8 by about 10 mils. This is the dimension g in FIG. 8. The grid electrode shields the hairpin and assists in limiting

emission to the tip of the cathode needle, well as in shaping the hemispherical electric field. The emissive surface at the cathode needle tip has a radius of about 1 micron. The grid electrode aperture 55 is about 10 mils in diameter. The anode electrode 9 is about 30 mils forward of the grid electrode 8, shown as the dimension h in FIG. 8. The anode electrode is about 1.125 in. wide at the forward end and has a total length in the axial direction of about 1.1 in. The anode aperture 56 is about 10 mils in diameter and the limiting aperture 58 is about 20 mils in diameter. For the indicated length, dimension and forward extension of the cathode needle 51, the grid to anode spacing and the dimensions of the grid, anode and limiting apertures, the voltage $-V_1$ was at 5.0 KV and the voltage $-V_2$ at 5.3 KV. An electric field gradient of 10^7 V/cm, was thereby provided at the cathode tip. For a voltage $-V_1$ of 10.0 KV and $-V_2$ of 10.3 KV, the grid to anode spacing is modified, computed to be about 40 mils, for retaining the 10^7 V/cm. electric field gradient at the cathode tip. The filament was heated to a temperature of approximately 1,800°K. This temperature keeps the cathode tip clean of contaminating absorbed atoms in the medium vacuum that is used. The extremely high electric field gradient in combination with heating of the filament 50 produces a high density field aided thermionic emission from the cathode tip. It is noted that the high field gradient of 10^7 V/cm. is obtained with a moderate anode voltage of less than 5 KV to about 10 KV. These values of voltage, particularly at the lower end, are found not to provide an excessively great velocity of electrons striking the present target which might cause diffuse heating of the target such as to degrade resolution. In addition, for extremely thin targets, overly high velocity electrons may penetrate completely through and not generate sufficient heat in the target material.

In accordance with the operable embodiment under consideration, the hairpin filament 50 is composed of rhenium selected for its refractory and ductile characteristics. The filament has a diameter of about 10 mils reduced to 7 mils at the vertex, as indicated in the enlarged drawing of FIG. 8. The cathode needle 51 is an oriented single crystal tungsten having the 100 crystal face at the needle tip, which is the preferential face for lowering the work function. The 100 crystal face is orthogonally related to the needle longitudinal axis within a one degree limit, preferably. The needle 51 is welded to the filament 50. A slurry of zirconium hydride is applied as a bead to the base of the needle 51 around the weld point. Upon heating of the filament, the zirconium hydride becomes sintered to form zirconium. The zirconium migrates over the surface of the needle and covers the tip, providing continuous replenishment for the effects of evaporation and ion bombardment. An atomic layer of zirconium is thereby coated over the surface of the needle 51 which, together with oxygen atoms from the residual gas in the vacuum, act to reduce the work function at the emissive tip from 4.5 ev for pure tungsten to 2.8 ev. The reduced cross sectional dimension of the filament 50 at the vertex raises the temperature of this region relative to the remaining length of the filament and assures migration of the zirconium along the needle 51 in the direction of the tip. The amount of zirconium material that need be dispersed is very little. A filament temperature of 1,800°K in a medium vacuum of about 10^{-7} mm. Hg keeps the

cathode tip clean of absorbed atoms. The described structure results in cathode lifetime that is extremely long, e.g., on the order of 1,000 hours and greater. It is noted that the optimum filament temperature is a function of pressure and for medium vacuum may exist in a range, typically, of 1,750°K to 1,850°K.

In FIG. 9 there are illustrated several field aided thermionic emission curves for both zirconium coated tungsten cathodes and plain tungsten cathodes at different filament temperatures and for a fixed vacuum. The curves are plotted as emission current density in amperes per sq. cm. vs. electric field gradient in volts per cm. Curve A represents a pure tungsten cathode heated to a temperature of 2,000°K. The curve is seen to cross the 10^7 V/cm. field gradient line at a current density of about 10 amperes per sq. cm. Curve B represents a zirconium coated tungsten cathode heated to a temperature of 1,500°K, which is seen to intersect the 10^7 V/cm. line at a current density of about 200 amperes per sq. cm. It is noted that although the filament temperature is lower than for curve A, the lowered work function of the zirconium coated tungsten element appreciably increases the current emission. Curve C represents a pure tungsten cathode heated to a temperature of 2,600°K, which crosses the 10^7 V/cm. line at a current density of about 500 amperes per sq. cm. It is seen that the elevated filament temperature raises the current emission of the pure tungsten cathode above that of curves A and B. Curve D represents a pure tungsten cathode heated to a temperature of 3,000°K, which provides an emission current density in excess of 1,000 amperes per sq. cm. at the 10^7 V/cm line. Although high emission densities are achieved, the temperature of curves C and D are found to be excessively high so as to drastically limit the lifetime of the cathode. Curve E represents a zirconium coated tungsten cathode heated to a temperature of 1,800°K, which is the type employed in the described embodiment. It is seen that this curve attains an emission current density only slightly less than that of curve D but at a very much lower temperature. Thus, at 1,800°K it is found that a high emission density and high target current density is attained, and a stable operation with long lifetime provided.

Referring again to FIG. 6, a pair of modulation coils 12 of standard design are mounted on opposing surfaces of a cylindrical sleeve 59 of the vacuum chamber 5, the sleeve being shown also in FIG. 7. The modulation coils are employed to direct the beam along a single axis in the X-Y plane, which is a plane transverse to the central axis Z of the beam. Forward of the anode electrode 9 there is mounted a first magnetic focus lens in the form of focus coil 10A which is wound about the circumference of the chamber 5 and produces a magnetic field predominantly along the central axis of the beam. The coil 10A is per se of conventional type with its conductors enclosed by a magnetic ring coil form. A gap 60 in the inner wall of the magnetic form locates the reference plane of the focus lens, which is at the middle of the gap at plane 61. The reference plane is used for spatially relating the focus coils one to the other and to the object and image planes. The reference plane is used for this purpose rather than the concept of principal plane because for these lenses the principal planes are not readily located. Forward of the first focus coil 10A is a second focus coil 10B similar to the first, having a gap 62 in the coil form that places

the reference plane of the second focus lens at plane 63. An astigmator coil 64, of standard design, is wound about the chamber 5 for generating a proper axial magnetic field in the region of the limiting aperture 58. The astigmator coil is employed to compensate any astigmatism that may be produced by the focus coils 10A and 10B. In addition, two pairs of centering coils 65, mounted on opposing surfaces of the vacuum chamber wall 66 in the vicinity of the lens plane 61 are provided for directing the beam along two orthogonally disposed axes in the X-Y plane. The centering coils adjust the beam to pass through the center of the second focus lens. Two pair of deflection coils 11 mounted on opposing surfaces of the wall 66 forward of the second focus coil 10B deflect the beam in two orthogonal directions in the X-Y plane.

Electron optics principles of the structure shown in FIGS. 6 and 7 will now be discussed. Electrons emitted from the emissive surface at the cathode emission under the hemispherical electric field configuration will generally be directed along diverging paths corresponding to radii of the hemispherical electric field, said paths appearing to emanate from a point slightly behind the cathode emissive surface which may be considered as a virtual image of the cathode. Only a fraction of the emitted electrons are passed by the anode aperture 56, the passed electrons being within about a 10° solid angle of the beam central axis. Of the electrons transmitted through the anode aperture 56 only a small fraction, within a solid angle of about 1° , are passed by the limiting aperture 58. The first focus coil 10A transposes the diverging beam into a collimated beam. The second focus coil 10B transposes the parallel beam into a converging beam which is focused on the surface of the storage medium.

Spherical aberration of a focus lens, C_s , is the most serious form of error existing in electron optical systems, in general, with respect to providing a sharply focused image. C_s is primarily a function of lens power, structural dimensions of the lens and accelerating voltage. Significantly, C_s is inversely related to the lens power, or otherwise considered, a direct function of the lens focal length. The present configuration of the electron optical system very appreciably reduces spherical aberration of the system by minimizing the effective spherical aberration C'_s of each lens. C'_s is defined as follows:

$$C'_s = C_s(a/f) \quad 4$$

where a is the distance of the object plane or image plane to the principal plane of the lens, and f is the focal length of the lens.

Through the employment of a pair of focus lenses 10A and 10B, the cathode emissive surface, corresponding approximately to the object plane, may be located at about the focal point of the first focus lens 10A. Thus, for each lens $a \approx f$ and $C'_s \approx C_s$. This may be contrasted with using a single focus lens for focusing the cathode object at the image plane where to do so the object plane and image plane must be spaced at an appreciably greater distance than the focal length, so that $a > f$ and $C'_2 >> C_s$. From the above consideration, spherical aberration of the system is reduced by increasing the power of focus coils 10A and 10B, within certain limiting factors. With respect to coil 10A, the limiting factors are principally the physical size and configuration of the anode structure. With respect to coil 10B, the

limiting factors are the placement of the deflection coils 11 and the requirement for deflecting the beam over a wide area. Where a reflective readout is employed, as in the embodiment of FIG. 5, a further limiting factor is presented in positioning of the electron detector in the region above the storage medium.

In several exemplary operable embodiments of the electron optics structure, each of the focus coils 10A and 10B were identical and had the following specifications: the bore radius $R = 13/16$ in., and the ratio $S/D = 3/13$, where S is the gap width and D the bore diameter. The spacing of the cathode needle 51 to the plane 61, which is the dimension k in FIG. 6, was 1.5 in., the exact dimension having been dictated primarily by the length of the anode electrode 9. The planes 61 and 63 were spaced apart by 3.5 in., dimension 1 in FIG. 6, which is sufficient to accommodate placement of the cores but is not considered to be a critical dimension. The coil 10A was provided with ampere turns $NI \approx 455$ at 5KV, and $NI = 640$ at 10KV. $C_s = 4.85$.

With the storage medium 1 spaced 1 in. from the plane 63, dimension o in FIG. 6, there were provided ampere turns $NI \approx 570$ at an accelerating voltage of 5KV, and $NI \approx 810$ at 10KV. $C_s = 1.85$. A spot size of 979 A diameter was achieved. Power density at the focused spot was measured at 6.64×10^6 watts per sq. cm. at 10 KV.

With the storage medium spaced 1.5 in. from the plane 63 $NI \approx 455$ at 5KV, and $NI \approx 640$ at 10KV. $C_s = 4.85$. A spot size of 1,058 A diameter was achieved. Power density at the focused spot was measured at 5.69×10^6 watts per sq. cm. at 5KV and 1.14×10^7 watts per sq. cm. at 10KV.

It may be appreciated that the angle of convergence of the beam at the storage medium surface is an inverse function of the spacing of the medium 1 and the plane 63. The beam spot size is a function of α and C_s , and may be expressed as

$\sqrt{d_o^2 + (C_s \alpha^3 / 2)^2}$, where d_o is the ideal spot size with zero error, and α is the half angle of the converging beam. In determining the spacing between the medium 1 and the plane 63, conflicting constraints are present. C_s decreases and α increases as the spacing is reduced. The selected spacing is optimized with respect to these properties, as well as the requirement for scanning over a relatively large area.

The dimensions of the coils presented above are primarily for purposes of example and not intended to be limiting. Other size coils may and have been employed, with the electrical parameters appropriately modified to provide operation in accordance with the present teachings.

During a writing operation the modulation coils 12 drive the beam along a single axis in the X-Y plane, so as to shift the central axis of the beam between a position in the center of the limiting aperture 58 and a position offset from the center where the focused beam is partially blocked by the limiting apertured electrode 57. The beam is shifted as a function of the modulation signal. With the central axis of the beam at the center of the limiting aperture 56 the focused beam spot is of maximum current density and will readily machine the storage material. At the offset position, the focused beam spot current density is reduced sufficiently so that no machining of the storage material can occur. Thus as the beam is scanned along the data lines by the

deflection coils 11, the current intensity at the focused spot is modulated and data thereby written.

During a readout operation the modulation coils 12 are employed to fixedly bias the beam in the offset position so that the beam is partially blocked by the limiting apertured electrode 57 for fixedly reducing the current density of the focused spot. The beam of the reduced current density is scanned along the data lines by the deflection coils 11 for providing readout of the stored data without effecting any physical change or destruction of said stored data. Alternatively, the anode voltage can be reduced during readout for reducing power density at the focused spot.

In FIG. 10 there is illustrated in a partially broken away perspective view a further embodiment of a storage system in accordance with the invention employing a large area storage medium 71 composed of many data blocks 72 for providing a total storage capacity several orders of magnitude greater than that of embodiment of FIG. 1. A single data block corresponds to the storage area of the medium 1 in the embodiment of FIG. 1. In the embodiment of FIG. 9, the total storage area of the storage medium 71 is a plane surface about 210×210 square mm., providing about 44,000 data blocks and a total storage capacity of 10^{12} bits. The data blocks are arranged in column and row configuration, only an exemplary number being shown in the partial plan view of FIG. 11.

The electron optics corresponds to the structure of FIGS. 6 and 7 and comparable components are similarly identified but with an added prime notation. Accordingly, the electron emission system 3' and the electron optical system 4' are identical to the previously considered embodiment. The input network 13', output network 17' and logic network 18' may be similar to that of FIG. 1. Readout is preferably by means of a reflective structure such as shown in FIG. 5 employing the electron detector 43' positioned above the storage surface. However, a transmissive readout similar to FIG. 1 may also be employed, requiring a suitable storage area electron detector structure for supporting the storage medium.

The storage medium 71 is mounted on a movable substrate 73 for positioning in both the X and Y directions. Movement Of the substrate 73 is provided by a pair of motor drive means 74 and 75 located outside of the vacuum. Drive means 74 and 75 may include motors of conventional type which position the substrate 73 with an accuracy of ± 1 mil. A variable reactance stepping motor is suitable. Means 74 through a linear drive shaft 76 drives the substrate 73 in the X direction, and means 75 through a linear drive shaft 77 drives the substrate 73 in the Y direction. The drive means 74 and 75 may each include a motion translation mechanism, such as a conventional ball screw-ball nut arrangement, for converting the motor's rotational motion to the linear motion of the drive shafts. A bellows such as shown at 78 provides a vacuum seal around the drive shafts 76 and 77 while accommodating their linear motion.

Accordingly, in the operation of the system of FIG. 10, the motor drive means 74 and 75, under control of the logic network 18', provide indexing of individual data blocks 72 with respect to the electron beam structure and the electron beam. Upon a selected data block being indexed, the electron beam may provide write and readout operations precisely as described with respect to the previous embodiment of the invention.

The invention has been described with respect to a number of specific embodiments primarily for the purpose of clear and complete disclosure. It should be recognized, however, that numerous modifications may be made to the disclosed structure by those skilled in the art which would not exceed the present teaching. For example, the present electron optical system has been employed to great advantage in combination with a novel electron emission system employing a zirconium coated oriented tungsten needle having a very low work function and capable of operating clean in a medium vacuum so as to provide an extremely high emission density and a long lifetime. The combination of the described electron optical system and the electron emission system produces at the target a focused beam spot of extremely small dimensions and high current density. Conceivably, similar operation may be achieved by the present electron optical system in combination with other electron emission systems exhibiting similar characteristics of high emission density, stability and low long lifetime in a medium vacuum. For example, a hafnium coated tungsten cathode or a lanthanum hexaboride cathode are believed to have the inherent properties for such operation, although to date are not known to have been suitably developed toward this use.

Further, within the concepts of present invention, the described storage systems may employ for storing data a material whose physical state or properties, other than or in addition to volume, are capable of being changed by a high power density beam, which change of state or properties can be detected by a readout beam. In addition, the invention is considered to embody use of a storage material capable of selective erasure by an electron beam.

It is also noted that the electron beam structure described herein may have useful application to other than information storage systems, for example to micro-machining and micro-etching operations in the field of microelectronics.

What is claimed as new and desired to be secured by Letters Patent in the United States is:

1. An electron emission system, comprising:
 - a. a hairpin filamentary heater,
 - b. a cathode needle of single-crystal tungsten having an emissive tip joined to the vertex of said filament, said needle provided with a singly oriented 100 crystal face at said tip,
 - c. a bead of zirconium coating material for reducing the work function at said supply oriented crystal face applied to the foregoing filamentary needle cathode in the vicinity of the junction between said needle and filament, said material migrating over the needle surface and coating the tip as a very thin layer in response to heating of said filament and cathode needle, and
 - d. means for operating said filamentary cathode in an atmosphere containing oxygen at a medium vacuum, said oxygen continuously combining with said migrating zirconium to facilitate continuous replenishment of said work function reducing coating.
2. An electron emission system as in claim 1 wherein said medium vacuum is on the order of 10^{-7} millimeters of mercury.
3. An electron emission system as in claim 2 in which said filament and cathode needle are heated to a tem-

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perature within the range of approximately 1,750°K to 1,850°K.

4. An electron emission system as in claim 3 in which said emissive has a radius on the order of one micron.

5. An electron emission system as in claim 1 wherein the cross sectional dimension of said hairpin filament in the region of said vertex is reduced so as to intensify heating of this region and assist in migration of the

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coating material over the needle surface.

6. An electron emissive system as in claim 1 which further includes field means for providing an electric field of generally hemispherical configuration about said emissive tip with a sufficiently high electric field gradient in the vicinity of said emissive tip to produce a high density emission.

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