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PATENT SPECIFICATION

DRAWINGS ATTACHED

1,151,730

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on 15 Sept., 1965.

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Int. Cl.:—G 11 c 11/14

COMPLETE SPECIFICATION

Non-destructive readout of thin film memory.

We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organised according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, United States of America, do hereby declare this invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to techniques and apparatus for sensing information stored in ferromagnetic thin film memory devices.

Because it exhibits the property of uniaxial anisotropy, a magnetic thin film may be used as an information storage element in a memory device. By this is meant that the film's magnetization vector, representing the magnetization of the film, prefers to lie along a so-called "anisotropy axis" direction. This phenomena is a result of the thin film's internal anisotropy field. The anisotropy field is commonly represented by the symbol H_k and is measured in oersteds. When the film's magnetization is pointed in either direction along the anisotropy axis, the film is in its lowest energy state, which is, of course, its preferred state.

The possibility of the vector pointing in either direction along the anisotropy axis provides a convenient "I" and "O" for a memory element. One direction along the axis is designated "I" and the opposite direction is designated "O".

Further properties of magnetic thin films make it advantageous to use them as information storage elements in a memory system. The switching time of such a film is extremely small, i.e. less than 10 nanoseconds (1 nanosecond = 10^{-9} second). The preparation of extremely thin layers (either by evaporation or plating) provides low flux in the element, which reduces the voltage drive required and eliminates heating at high frequencies. A simpler planar sub-

strate-supported film makes possible extremely high bit-densities and allows the use of low-impedance strip transmission lines for high frequency pulse distribution. factors of utmost importance in determining the compatibility of high speed and large capacity systems. Film preparation permits the fabrication, handling and testing of entire arrays rather than individual components. The open flux structure eliminates the need for threading holes and permits the use of evaporated or etched wire techniques.

A conventional mode of reading magnetic film storage elements is the so-called two-dimensional orthogonal DRO mode. See J. T. Raffel, T. S. Crowther, A. H. Anderson, T. O. Hernden, "Magnetic Film Memory Design", *Proceedings of IRE*, Vol. 49, No. 1, pp 155, 1961. Using this mode, stored information is sensed by applying an external magnetic field whose magnetic vector is directed at an angle of 90° to the direction of the anisotropy axis of the magnetic film element. This direction, 90° from the anisotropy axis, is commonly called the "hard direction". Such an external magnetic field, larger than the anisotropy field (H_k) of the element, causes the magnetization of the element to rotate to the hard direction in an attempt to align itself with the externally applied magnetic field. The rotation of the magnetization causes a change in flux in a sense conductor, which induces a voltage pulse therein according to Faraday's Law of Electromagnetic Induction. The direction of the voltage pulse is then determined by the direction of the change in flux as compelled by Lenz's Law. Therefore, the direction of the voltage pulse enables one to sense the direction of the magnetization vector of the magnetic film element and thus read the stored information.

Whenever the magnetization vector is rotated 90° from its stored information position by an external magnetic field there

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is an equal probability that the vector will fall back into either position along the anisotropy axis after the removal of the external hard direction magnetic field. This, for all practical purposes, destroys the stored information as there would be only a 50% probability that the information then stored would be the original stored information. This method of sensing is thus called destructive readout (DRO).

A non-destructive readout technique (NDRO) would, of course, be desirable. Such a system would enable one to sense the direction of the magnetization of the magnetic film element without destroying the stored information. A number of NDRO systems and techniques have been proposed; however, they all require unconventional film element construction or separate circuitry for sensing and storing information in the magnetic film elements.

It is therefore an object of this invention to provide a system for non-destructive readout of ferromagnetic thin film memory devices.

It is another object to provide a random-access word-organized, multi-bit memory system utilizing ferromagnetic thin film devices and having non-destructive readout.

In accordance with one aspect of the invention apparatus for nondestructively sensing the direction of magnetization of a ferromagnetic thin film element which exhibits uniaxial anisotropy and is capable of assuming either of two stable states of magnetization, both of which lie along the anisotropy axis of the element but proceeding in opposite directions with respect to each other, said apparatus comprising: means for applying an external magnetic field to said ferromagnetic thin film element in a direction transverse to the anisotropy axis of the element as a pulse of such short duration in time that the magnetization of said element initially lying along the anisotropy axis of the element is incapable of being rotated through 90° so that the change in direction of the magnetic flux is less than 90°, and means to determine the original direction of the state of magnetisation of said ferromagnetic thin film element by sensing the direction of rotation of the magnetization signified by the change in direction of the magnetic flux resulting from the application of said external magnetic field to said element, whereby the magnetization state of said ferromagnetic thin film element returns to its original direction when the external magnetic field applied to said element is terminated.

The invention may be best understood by reference to the following detailed description of illustrative embodiments, when read in conjunction with the accompanying drawings, in which:

Figure 1 shows a magnetic film bit and word and sense conductor arrangement;

Figure 2 is a cross-sectional isometric view of the arrangement shown in Figure 1 taken along section line 2-2;

Figure 3 is a graph showing the relation between the threshold current and the word current pulse width;

Figure 4 is a graph showing the relation between the threshold current and the anisotropy axis skew;

Figure 5 shows a multi-bit system utilizing the nondestructive readout techniques of the invention; and Figure 6 is a circuit diagram showing the read and write pulse generation and gating circuits for the word lines.

Referring now to Figure 1, there is shown a single circular magnetic thin film element 1, which may be a Permalloy with a composition such as 79% Ni, 19% Fe and 2% Co, and about 1000 Å thick, supported upon a suitable conductive substrate 11. Said magnetic element 1 has a magnetization which is represented by the vector 2 and is directed along the anisotropy axis of the element 1 in the "O" direction. The magnetic element 1 is covered by a word line 3 which is aligned parallel to the anisotropy axis of the magnetic film element 1, and sense line 6 which lies at an angle of 90° with the word line 3, both of which are conductors, such as copper. All three elements 1, 3 and 6 are separated from one another by a thin layer of an insulator (not shown) to prevent shorting between said elements. Information is stored in said magnetic thin film element by a conventional method such as the two-dimensional orthogonal method.

The non-destructive readout method of the invention can best be understood with reference to FIGURE 2 which is a cross-sectional, isometric view of the element shown in FIGURE 1, taken along section line 2-2.

Of interest are the "external demagnetizing fields" of the magnetic element 1, indicated by lines 12. In the static case, these magnetic fields establish themselves in the space, ground plane and conductors surrounding the magnetic film element 1.

If the magnetization 2 of the magnetic element 1 is made to rotate to a hard direction because of a large transversely applied magnetic field, such as H_w , caused by current I_w in the word line 3, the external flux in the surrounding medium will begin diffusing in a manner that will eventually establish the same pattern, but at right angles to the initial pattern. If the applied transverse field H_w is removed before this process is completed, there will be a longitudinal magnetic field acting to restore the magnetization 2 to its original state. It is believed that this restore field is a result of two

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effects: (1) trapping of the demagnetization flux 12 in the conducting substrate 11 and lines 3 and 6; and (2) phenomenological damping caused by operating faster than the resonant frequency of the magnetic element 1. Phenomenological damping may be described as a progressive tendency on the part of the magnetization of the thin film element to return to its original state as the rotation of the magnetization approaches 90°, this being the result of the phenomenon produced by applying the external magnetic field to the ferromagnetic thin film element and terminating the external magnetic field over a period of time faster than the resonant frequency of the ferromagnetic thin film element itself. It should be understood that the two effects believed to be responsible for the restore field are merely theoretical explanations, and some other agency or effect may be partially or wholly responsible.

Figure 3 is a graph indicating the operating parameters of the technique of the invention. The graph shows the relationship between the threshold current and the word current pulse width. The threshold current is defined as the word current amplitude that produces a 20% decrease in the output signal after the bit has been interrogated 10⁵ times. This limitation has been defined to indicate non-destructive readout. The word current pulse width is the time during which a current I_w is applied in word line 3 as shown in Figure 2 to create a transverse magnetic field H_w . The film element used to obtain the data shown in the graph had an anisotropy field of about 5 oersteds and required a current of about 400-500 milliamperes (ma) interrogate (word) current to produce full rotation of said magnetization 2. Although it would seem that it would require about a 400-500 ma current to have destructive readout, the approximate asymptote for an infinite pulse width, or in other words, a constant external, transverse magnetic field, is much less than this, about 250 ma. This is due to the angular skew of the magnetic vector, as will be explained below.

As mentioned above, the NDRO technique of the invention requires that an ultra-short current pulse be applied to the word line. By this it is meant a current pulse of less than 5 nanoseconds. As can be seen with reference to FIGURE 3 a word current pulse width of less than 5 nanoseconds will allow a current pulse of from 400-700 ma. The output signal sensed is directly proportional to the square of the current applied to the word line. Thus a signal pulse may be obtained following the technique of the invention that is larger than signals obtainable previously with DRO. This large signal eliminates many of the sense and

noise problems of other NDRO techniques.

The graph of FIGURE 4 shows the effect of skew in a magnetic film element. As mentioned above, the word line 3 (in FIGURE 2) is aligned parallel to the anisotropy axis of the magnetic film element. However, when the element is not discrete but a portion of a continuous film, such as will be described below, it is likely that the word line will not be exactly parallel with the anisotropy axis of the element. The angle between the anisotropy axis and the word line is the skew. The graph in FIGURE 4 shows the effect of this skew upon the threshold current. This data was obtained for a word current pulse of 2 nanoseconds. Curves $\odot$, and $\ominus$ correspond to the two possible orientations of the bit magnetization along the anisotropy axis. In each case the bit was written counter to the background magnetization, that is, counter to the direction of the magnetization field in the large continuous magnetic thin film. It can be seen from FIGURE 4 that the optimum operating position would be where there is zero degrees skew. As the direction of the anisotropy axis moves away from the word line direction, a reduction of the allowable threshold current is effected, resulting in a lower output signal. The data recorded in FIGURE 3 was obtained using magnetic elements that exhibited a 2° skew. This accounts for the approximate asymptote being less than the current necessary to cause full rotation.

The non-destructive readout technique, NDRO, described thus far illustrates only a single bit memory. With reference now to FIGURE 5, a large number of thin film memory elements may be determined in a matrix: a three word, three bit-per-word, random access, word-organized memory device being shown. A system of this kind is capable of a very high repetition rate, i.e., 20 megacycles or more. In the arrangement shown, a continuous, thin magnetic film 40, which may be a Permalloy consisting of 79% Ni, 19% Fe, 2% Co and about 1000 Å thick, is deposited upon a conducting substrate 41 which may be aluminium. The magnetic bit elements 42 are determined by the intersection of the word lines 43 and the sense digit lines 44. This type of arrangement is known to the art, primarily for DRO systems. Conventionally, the word lines 43 and the sense digit lines 44 are of copper and are usually formed by evaporation or etching techniques. A thin layer of insulating material separates the conducting substrate 41, the magnetic film 40, the word lines 43 and the sense digit lines 44. One such suitable insulating material is Mylar (a registered Trade Mark owned by E. I. DuPont de Nemours and Company, Wilmington, Delaware, U.S.A.) polyester film,

which is a polyethylene terephthalate resin.

As mentioned above, one advantage of this system is that the same circuit logic can be used to produce the read and write line current pulses. This circuit is represented by block 45 in FIGURE 5 and will be explained more fully below. The circuit is controlled by a read control 46 and a write control 47 of conventional design. The write control also activates the digit drivers and digit gates, represented by blocks 48, also of conventional design. The write-in method conventionally calls for a timed sequence of pulses in said word lines 43 and said sense digit lines 44. That is, a first current pulse of about 40 nanoseconds is produced in the word lines 43 and then a second current pulse, also lasting about 40 nanoseconds is produced in the sense digit lines, said second pulse beginning about 20 nanoseconds after said first pulse and continuing after said first pulse terminates. The direction of the second current pulse determines whether a "1" or a "0" is stored in the element 42.

The information signals generated in the sense digit lines by the rotation of the magnetization of the elements 42 are sensed, amplified, and read out in the sense amplifier and output data register circuit 49. Because of the size of the information signal (one to two orders of magnitude larger than those obtained in DRO film memories) the gain amplification of the sense amplifier need not be as great as in conventional means, but bandwidth requirements are somewhat more severe (the amplifier having to sense a signal of less than 5 nanoseconds duration).

An essential requirement of the invention is the generation of a very fast current pulse. A suitable arrangement for creating such a pulse is described by A. F. Boff, J. L. Moll, and R. Shen, in "A New High Speed Effect in Solid State Diodes", 1960 International Solid State Circuits Conference. Such a technique is known as the step recovery diode (SRD) technique and depends upon the charge storage phenomena in a forward-biased P-N junction. This technique is utilized in the circuit shown in FIGURE 6. The effect of this circuit, comprising a shorted stub 71, variable resistor 72, capacitor 73, and step recovery diode 74, is to produce a current pulse between points 61 and 62 that has the desired characteristics, i.e., lasts less than 5 nanoseconds and is about 400 to about 700 ma. A read word command pulse received at 63 turns on transistors 75 and 76 to produce the pulse.

The current pulse so produced is gated through diode 64 and through a selected word line 43. The desired word line is selected by conventional (but fast) current mode logic from a conventional address re-

gister (not shown). The selected word line is turned on by turning on transistors 67. The latter are turned on by pulse transformers 65.

Upon receipt of a write word command (WWC) at 82, transistor 80 is turned on by transistors 78 and 79, increasing the potential on the right hand side of diode 64. This increase reverse biases diode 64 and effectively removes stub 71 from the collectors of transistors 67, allowing the word current to flow through transistors 80, diode 81 and selected word driver 67 for as long as the base current in driver transistors 67 flows. The collectors of word drivers 67 now have a low resistance path to the +12 power supply for the conduction of high word currents.

A larger system will have more than one of the circuits shown in FIGURE 6, i.e., a 256 word system might have 32 such circuits with each circuit controlling 8 word lines. If no word line in the circuit is selected, the pulse is shunted off through a non-select clamp diode 66. That is, of course, necessary to keep the pulse from breaking down transistors 67.

Various modifications of the disclosed embodiments, as well as other embodiments of the invention, will become apparent to persons skilled in the art without departing from the invention as defined by the appended claims.

WHAT WE CLAIM IS:—

1. Apparatus for nondestructively sensing the direction of magnetization of a ferromagnetic thin film element which exhibits uniaxial anisotropy and is capable of assuming either of two stable states of magnetization, both of which lie along the anisotropy axis of the element but proceeding in opposite directions with respect to each other, said apparatus comprising: means for applying an external magnetic field to said ferromagnetic thin film element in a direction transverse to the anisotropy axis of the element as a pulse of such short duration in time that the magnetization of said element initially lying along the anisotropy axis of the element is incapable of being rotated through 90° so that the change in direction of the magnetic flux is less than 90°, and means to determine the original direction of the state of magnetisation of said ferromagnetic thin film element by sensing the direction of rotation of the magnetization signified by the change in direction of the magnetic flux resulting from the application of said external magnetic field to said element, whereby the magnetization state of said ferromagnetic thin film element returns to its original direction when the external magnetic field applied to said element is terminated.



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Various modifications of the disclosed embodiments, as well as other embodiments of the invention, will become apparent to persons skilled in the art without departing from the invention as defined by the appended claims.

WHAT WE CLAIM IS:—

1. Apparatus for nondestructively sensing the direction of magnetization of a ferromagnetic thin film element which exhibits uniaxial anisotropy and is capable of assuming either of two stable states of magnetization, both of which lie along the anisotropy axis of the element but proceeding in opposite directions with respect to each other, said apparatus comprising: means for applying an external magnetic field to said ferromagnetic thin film element in a direction transverse to the anisotropy axis of the element as a pulse of such short duration in time that the magnetization of said element initially lying along the anisotropy axis of the element is incapable of being rotated through 90° so that the change in direction of the magnetic flux is less than 90°, and means to determine the original direction of the state of magnetisation of said ferromagnetic thin film element by sensing the direction of rotation of the magnetization signified by the change in direction of the magnetic flux resulting from the application of said external magnetic field to said element, whereby the magnetization state of said ferromagnetic thin film element returns to its original direction when the external magnetic field applied to said element is terminated.



2. Apparatus according to Claim 1, wherein said means for applying an external magnetic field to said ferromagnetic thin film element comprises a first spaced conductor disposed in overlying relationship to the element, and means for applying a current pulse through said first conductor; the direction of the current pulse in said first conductor being generally parallel to the anisotropy axis of said ferromagnetic thin film element.

3. Apparatus according to Claim 2, wherein said current pulse-applying means produces a current pulse in said first conductor that provides an external magnetic field greater than the anisotropy field (H_k) of said ferromagnetic thin film element.

4. Apparatus according to either of Claims 2 or 3 wherein the original direction of the magnetization state of said ferromagnetic thin film element defines a binary bit of information, said first spaced conductor overlying said ferromagnetic thin film element comprising a spaced first word line conductor, said ferromagnetic thin film element having an anisotropy field of about 5 oersteds, and said current pulse-applying means providing a current pulse from 400 milliamperes to 700 milliamperes through said first word line conductor.

5. Apparatus according to any of Claims 2-4, wherein said means for determining the original direction of the state of magnetization of said ferromagnetic thin film element comprises a second spaced conductor overlying both said ferromagnetic thin film element and said first conductor in a direction generally perpendicular to the anisotropy axis of said ferromagnetic thin film element, and means to register voltage pulses induced in said second conductor resulting from the change in direction of the magnetic flux.

6. Apparatus according to any preceding claim, wherein the external magnetic field is applied to the ferromagnetic thin film element for a period of time less than five nanoseconds.

7. Apparatus according to Claim 5, wherein a plurality of first spaced conductors are disposed in overlying relationship to said ferromagnetic thin film element and in spaced parallel relationship to each other, a plurality of second spaced conductors are disposed in overlying relationship to both said plurality of first conductors and said ferromagnetic thin film element, said plurality of second conductors being arranged in directions generally perpendicular to said plurality of first conductors and in spaced parallel relationship to each other so as to provide a plurality of intersections between said pluralities of first and second conductors overlying respective portions of said ferromagnetic thin film element, said portions of said ferromagnetic thin film element

defining a plurality of ferromagnetic thin film memories arranged with parallel anisotropy axis directions, said current pulse-applying means being selectively operable to produce a current pulse through any selected first conductor, said voltage pulse-registering means respectively sensing and registering voltage pulses produced in said second conductors by a rotation of the magnetization in any of said ferromagnetic thin film memories and the original direction of magnetization along the anisotropy axis of each of said ferromagnetic thin film memories defining a respective binary bit of information, whereby the rotation of the magnetization in any of said ferromagnetic thin film memories leaves unchanged the binary bit of information stored in said ferromagnetic thin film memory so as to provide a multi-bit memory having non-destructive readout.

8. Apparatus according to Claim 7, further including means for producing a timed sequence of current pulses in said pluralities of first and second conductors, one sequence of said current pulses being first produced in said first conductors in directions generally parallel to the anisotropy axes of said ferromagnetic thin film memories, the second sequence of said current pulses being produced in said second conductors beginning a predetermined time after said first current pulse sequence in said first conductors, and said second sequence of current pulses being directed in either direction perpendicular to the anisotropy axes of said ferromagnetic thin film memories depending upon what information is to be stored in said ferromagnetic thin film memories, whereby information is written into said ferromagnetic thin film memories.

9. Apparatus according to Claim 8, wherein each of the first and second sequences of current pulses is 40 nanoseconds in duration, with the second sequence of said current pulses beginning 20 nanoseconds after said first sequence of current pulses in said first conductors.

10. Apparatus according to any of Claims 7-9, further including a thin layer of insulation sandwiched between said ferromagnetic thin film element and said respective first conductors, and a thin layer of insulation sandwiched between said pluralities of first and second conductors and between said ferromagnetic thin film element and said respective second conductors.

11. Apparatus according to any of Claims 7-10, further including a flat conductive substrate on which said ferromagnetic thin film element is supported.

12. Apparatus according to Claim 11, wherein said substrate comprises aluminum, and said first and second pluralities of spaced conductors comprise copper

conductors.

13. Apparatus according to any of Claims 7-12, wherein the current pulse selectively applied by said current pulse-applying means is produced in a selected first conductor for a period of time less than five nanoseconds.

14. A method for nondestructively sensing the direction of magnetization of a ferromagnetic thin film element which exhibits uni-axial anisotropy and is capable of assuming either of two stable states of magnetization, both of which lie along the anisotropy axis of the element but proceeding in opposite directions with respect to each other, said method comprising the steps of applying an external magnetic field to said ferromagnetic thin film element in a direction transverse to the anisotropy axis of the element as a pulse of such short duration in time that the magnetization of said element initially lying along the anisotropy axis of the element is incapable of being rotated through 90° so that the change in direction of the magnetic flux is less than 90°, and determining the original direction of the state of magnetization of said ferromagnetic thin film element by sensing the direction of rotation of the magnetization signified by the change in direction of the magnetic flux resulting from the application of the external magnetic field to said element, whereby the magnetization state of said ferromagnetic thin film element returns to its original direction when the external magnetic field applied to said element is terminated.

15. A method according to Claim 14, wherein the pulse of the external magnetic field applied to said ferromagnetic thin film element occurs for a period of time less than five nanoseconds, the direction of the magnetization along the anisotropy axis of the ferromagnetic thin film element defining a binary bit of information, and the rotation

of the magnetization leaving the binary bit of information stored in the ferromagnetic thin film element unchanged.

16. Apparatus for nondestructively sensing the direction of magnetization of a ferromagnetic thin film element substantially as described herein with reference to and as illustrated by Figures 1, 2, 3, 4 and 6.

17. A multi-bit memory having non-destructive readout substantially as described herein with reference to and as illustrated by Figures 1 to 6.

18. A method of sensing the direction of magnetization of a ferromagnetic thin film element substantially as herein described with reference to and as illustrated by Figures 1, 2, 3, 4, and 6.

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The following corrections were allowed under Section 76 on 24th October 1969.

Page 2, lines 30, and 31, after "invention" insert "there is provided"

Page 2, line 50, Page 4, line 119, for "magnetisation" read "magnetization"

THE PATENT OFFICE,
26th November 1969

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