

[72] Inventor Eiichi Goto
Tokyo-To, Japan
[21] Appl. No. 872,470
[22] Filed Nov. 24, 1969
[45] Patented June 22, 1971
[73] Assignee Zaidan Hojin Parametron Kenkyusho,
Chiyoda-Ku
Tokyo-To, Japan
[32] Priority Oct. 31, 1964
[33] Japan
[31] 39/61493
Continuation of application Ser. No.
505,278, Oct. 26, 1965.

[50] Field of Search..... 307/88;
340/174

[56] References Cited
UNITED STATES PATENTS
3,193,694 7/1965 Ehresman et al. 307/88
3,193,806 7/1965 Pohm et al. 340/174
Primary Examiner—Stanley M. Urynowicz, Jr.
Attorney—Robert E. Burns

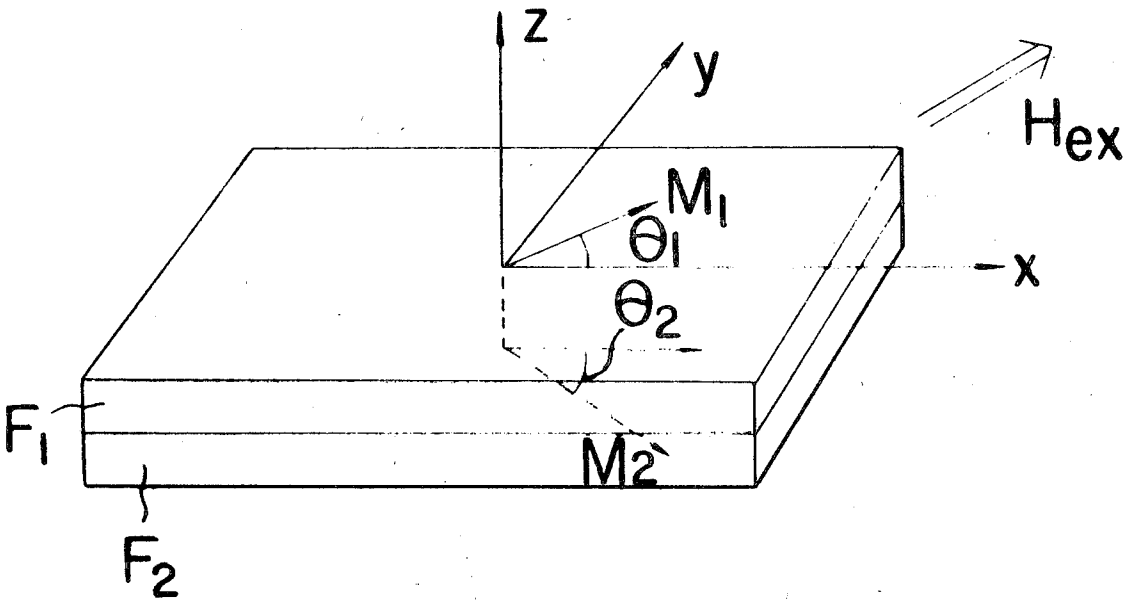
[54] FERROMAGNETIC THIN-FILM MEMORY
ELEMENT AND A METHOD OF RECORDING
INFORMATION THEREIN
2 Claims, 12 Drawing Figs.

[52] U.S. Cl. 340/174
[51] Int. Cl. G11c 11/14

ABSTRACT: A ferromagnetic thin-film memory, made of two film layers of ferromagnetic material in which the thickness d_1 and anisotropy field constant H_{k1} of the one layer and the thickness d_2 , anisotropy field constant H_{k2} and saturation magnetization M_{s2} of the second layer are selected so that the constant H_{k2} is much larger than the constant H_{k1} and satisfy the relationship:

$$d_1 \times d_2 \times M_{s2} \times H_{k2} = 1 \times 10^{-6} \text{ erg/cm.} \sim 2 \times 10^{-6}$$

and the method of recording on the film.



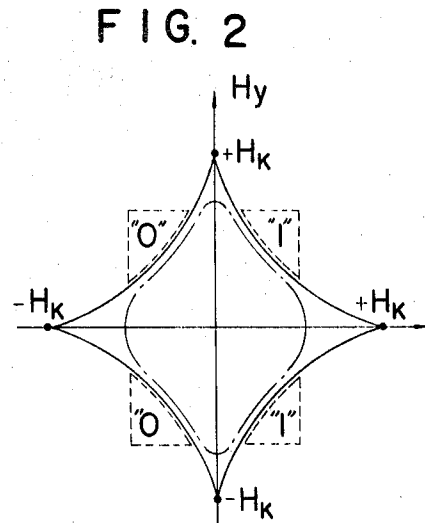
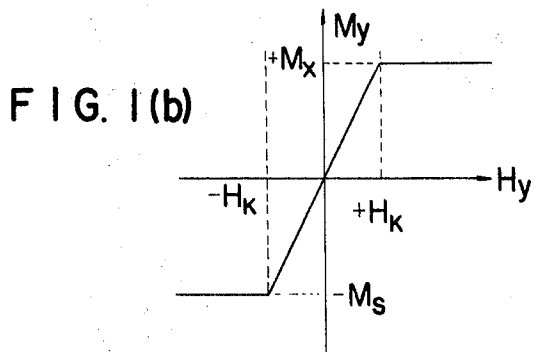
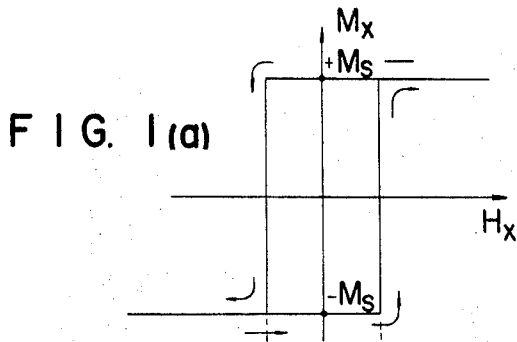


FIG. 4

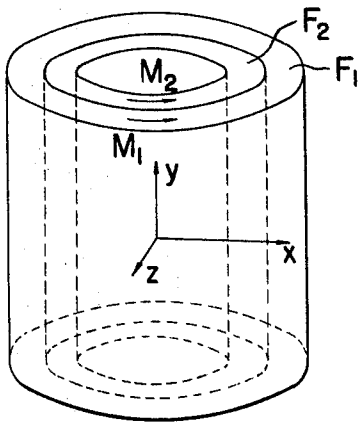


FIG. 3

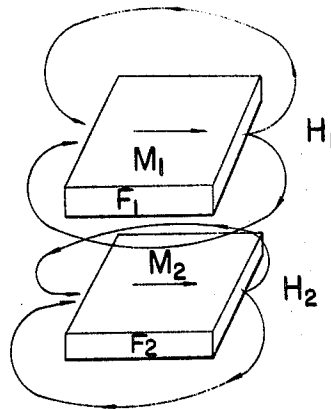


FIG. 5

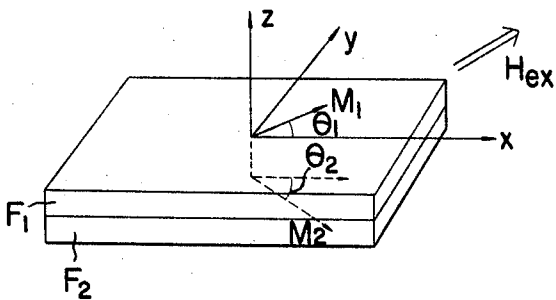


FIG. 7

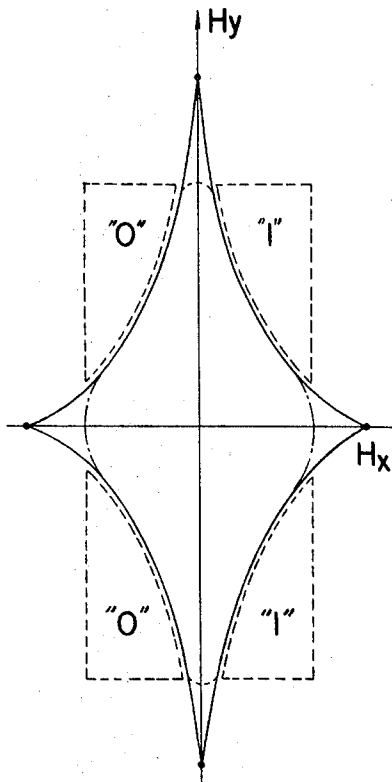


FIG. 6

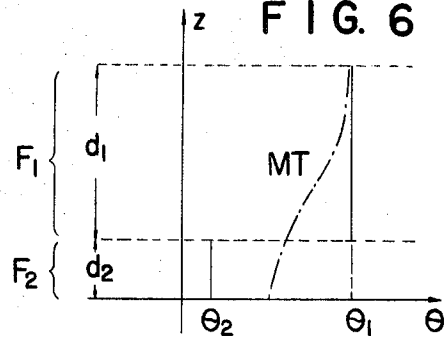


FIG. 8

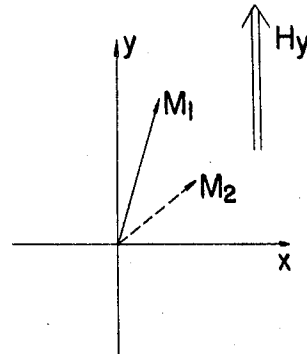


FIG. 10

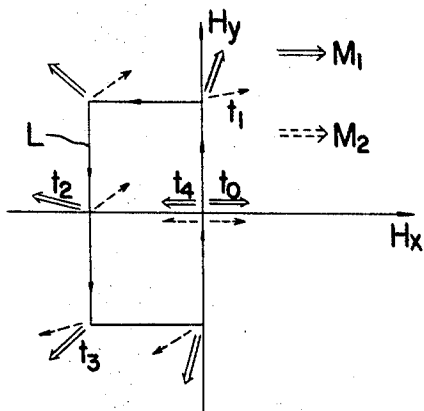


FIG. 9(a)

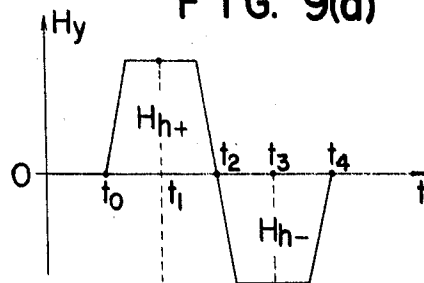
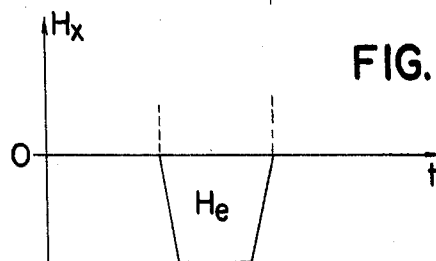


FIG. 9(b)



FERROMAGNETIC THIN-FILM MEMORY ELEMENT AND A METHOD OF RECORDING INFORMATION THEREIN

This application is a continuing application of U.S. Pat. application Ser. No. 505,278, filed on Oct. 26, 1965.

This invention relates to ferromagnetic thin-films and to memory devices wherein ferromagnetic thin-film memory elements are used. More specifically, the invention concerns a new ferromagnetic thin-film memory element of multiple layer construction and a method of recording information therein.

In general, a ferromagnetic thin-film as a memory element has unique features such as high switching speed and capability of affording nondestructive reading out. Heretofore, however, thin films made of a single magnetic material have been used in almost all cases, and this practice has led to certain difficulties as will be described more fully hereinafter.

It is a general object of the present invention to overcome these difficulties and to achieve a marked improvement in memory characteristics by the use of a multiple-layer film consisting of a plurality of ferromagnetic films of respectively different magnetic properties in molecularly intimate contact.

According to the present invention, briefly stated, there is provided a ferromagnetic thin-film memory element comprising a first thin film of a material having a soft magnetic characteristic and a second thin film of material having a magnetic characteristic which is harder than that of said first thin film, said first and second thin films being placed and maintained molecularly in intimate contact to produce ferromagnetic exchange interaction therebetween whereby the memory characteristics of said memory element are improved.

According to the present invention there is further provided a method of storing information which comprises applying a rotating magnetic field within the film planes of a ferromagnetic thin-film memory element of the above stated character thereby to write in information.

The nature, principle, and details of the invention will be more clearly apparent from the following detailed description taken in conjunction with the accompanying drawings in which like parts are designated by like reference characters, and in which:

FIGS. 1a, 1b and 2 are graphical representations indicating characteristics for an explanation of the principle of memory storage in a known memory element;

FIGS. 3 and 4 are diagrammatic perspective views for an explanation of the principle of known memory storage methods;

FIG. 5 is a diagrammatic perspective view for a description of the principle of the present invention; and

FIGS. 6 through 10, inclusive, are graphical representations to be referred to for a description of the principle of the invention.

As conducive to a full understanding and appreciation of the nature and utility of the present invention, the following brief consideration of the memory characteristics of known thin films having uniaxial anisotropy is presented.

A magnetic thin film formed by electroplating or vacuum evaporation with an inclined incidence angle of an alloy of the permalloy group (including those of approximately 20 percent of iron, approximately 80 percent of nickel, and few percent of additives such as molybdenum and cobalt) in a magnetic field is easily magnetized in the direction of the so-called "easy axis" (hereinafter taken as the x-axis direction within the film). The film is magnetized with difficulty in the so-called "hard axis" (hereinafter taken as the y-axis) direction which is perpendicular to the x-axis direction.

In the ideal case wherein the magnetization of the film surface is uniform at all parts and rotates uniformly, the magnetic energy (unit: erg) per unit area is given by the following equation.

$$E = M_s d \left(\frac{H_k}{2} \sin^2 \theta - H_x \cos \theta - H_y \sin \theta \right) \quad (1)$$

where:

M_s is the saturated magnetization (unit: gauss) of the film;

H_k is a material constant (unit: oersted) called the uniaxial anisotropy magnetic field;

H_x and H_y are respectively x and y components (unit: oersted) of an external magnetic field;

θ is the angle formed between the magnetization vector and the x axis; and

d is the film thickness.

The magnetization characteristic in the x-axis direction in the case when H_x is applied in only the x direction as an external magnetic field is as shown in FIG. 1 (a). The magnetization characteristic in the y direction in the case when H_y is applied in only the y direction as an external magnetic field is as shown in FIG. 1 (b). In FIG. 1, M_x and M_y are x and y components, respectively, of magnetization.

The magnetization in the case when an external magnetic field is not being applied assumes either of two stable states, namely that wherein it is directed in the +x direction (which is caused to correspond to digit "1") and that where it is directed in the -x direction (which is caused to correspond to digit "0"). By these two states, single digits "1" and "0" of binary number can be stored.

In order to change this stored state to write in new information, an external magnetic field H_x and H_y are simultaneously applied in the x-axis and y-axis directions and, moreover, in a manner such that they are outside of the asteroidal curve expressed by the following equation.

$$H_x^{2/3} H_y^{2/3} = H_k^{2/3} \quad (2)$$

This asteroidal curve is indicated by full line in FIG. 2.

In an actual case, however, the actual switching characteristic becomes such as that indicated by broken line in FIG. 2 because of shifting of the magnetic wall and dispersion of the anisotropic axis, and to write in "1" or "0" by the double coincidence of H_x and H_y , the values of the H_x and H_y magnetic fields must be so adjusted as to lie within the relatively confined regions enclosed by the dotted lines. In a region "1", the numeral "1" is written in the film, and in the region "0", the numeral "0" is written.

While the reading out of information from a thin film of this character can be accomplished destructively, it is preferable to accomplish nondestructive reading out. One method therefor is to apply in only the y-axis direction a magnetic field H_y of suitable magnitude (the allowable maximum limit of which is H_k in the case of an ideal asteroidal curve but must be held therebelow in an actual case to prevent erasure of information) to cause rotation of magnetization reversibly in the y direction, and to read out the variation of the x-component M_x of the magnetization from the voltage induced in a coil wound in a manner to surround M_x .

When digit "1" is written in, M_x decreases algebraically, whereas when digit "0" is written in, M_x increases algebraically. Consequently, the waveforms of the voltages induced for "1" and "0" differ, whereby the information is read out on the basis of this difference.

The above description relates to the principle of writing-in and reading out of information in a memory element of uniaxial isotropic character consisting of a single magnetic thin film. As stated above, such a memory device is disadvantageous in that the regions for writing in due to the double coincidence of H_x and H_y are relatively confined.

Recording methods wherein, by using multiple magnetic thin films in place of the above described single magnetic film, the regions of writing in by double coincidence are expanded have been considered. Heretofore, however, only methods whereby the thin films are mutually coupled in a merely magnetic manner by demagnetizing fields have been considered.

FIG. 3 indicates the state of demagnetizing fields H_1 and H_2 produced from the peripheries of two thin films F_1 and F_2 when these films are magnetized respectively as indicated by arrows M_1 and M_2 . Coupling in this manner by demagnetizing fields has the tendency to direct the magnetization of the two films in antiparallel directions. This coupling by demagnetizing fields vanishes when the films are made amply thin, their areas are made large, or the films are formed as cylinders to constitute closed magnetic circuits as shown in FIG. 4.

The use of thin films in a manner to produce large demagnetizing fields is, in general, inconvenient for achieving stability of film magnetization and also because of the possibility of erroneous operation due to stray magnetic fields, but there is a mutually contradictory condition of the coupling also vanishing when the demagnetizing fields are erased. Accordingly, even when multiple layers of magnetic thin film are used, it is difficult to produce memory elements of stable operation by merely causing magnetic coupling.

According to the present invention, by the use of a multiple-layer film formed by bonding together molecularly in intimate contact at least two magnetic thin films F_1 and F_2 as shown in FIG. 5, there is provided a memory element having a wide writing-in region due to double coincidence and having, moreover, a stable operation, and, furthermore, there is provided a new information recording method depending on sequence of the applied fields.

For the sake of simplifying the following description, it will hereinafter be assumed that each film area is amply large relative to the film thickness, or that each film forms a closed magnetic circuit as in the cylinders shown in FIG. 4, thereby to reduce the size of the demagnetizing fields to a negligible order. Referring to FIG. 5, a coordinate axis z is taken perpendicular to the film planes, and axes x and y are taken parallel to the film planes. The two films F_1 and F_2 are assumed to have mutually different magnetic characteristics (since, if they had the same magnetic characteristics, they would become a single film because they are molecularly in intimate contact).

In the case when an external magnetic field H_x is applied within the film planes, if there is absolutely no magnetic coupling between the two films F_1 and F_2 , the respective film magnetizations M_1 and M_2 will assume directions of respectively maximum stability at angles θ_1 and θ_2 from the x axis. This effect is indicated by full line in FIG. 6, in which the ordinate represents distance in the direction of the film thickness, and the abscissa represents the directional angle (from the x axis) of magnetization.

In general, the magnetization of a ferromagnetic material is imparted by the spin of electrons within the ferromagnetic material, and in a ferromagnetic material, neighboring spins tend to be parallelly directed because of the ferromagnetic exchange interaction between the spins. In this embodiment of the invention, since two films are molecularly in intimate contact, the above stated effect causes the magnetization direction θ to exhibit a continuous variation in the thickness z direction as indicated by the broken-line curve MT in FIG. 6 and a tendency to assume an average value intermediate between θ_1 and θ_2 . In FIG. 6, characters d_1 and d_2 respectively denote the thickness of thin films F_1 and F_2 .

Thus, the ferromagnetic exchange interaction has a tendency to cause the magnetization directions of the molecularly contacting thin films to be parallel. The present invention is based on the practical utilization of this tendency. In a particularly important embodiment of the invention, a hard magnetic material having an anisotropy magnetic field H_{k2} (either induced uniaxial anisotropy or crystal anisotropy), which is very much larger than the anisotropy field H_{k1} of the film F_1 is used for film F_2 . Moreover, the thickness d_2 of this film is very much less than the thickness d_1 of the magnetically soft film F_1 .

In this case, when an external magnetic field H_{ex} which, while being much smaller than the field H_{k2} , is of an order sufficient to change greatly the magnetization direction of the softer film F_1 (there would be almost no change in the magnetization direction of the film F_2 if there were no ferromagnetic exchange interaction) is applied, the magnetization direction of the hard film F_2 , being attractively influenced by the magnetization of the film F_1 , also varies greatly.

This attractive influencing effect is remarkably pronounced when magnetic energy E_2 per unit area of the hard film F_2 , said energy E_2 having the relationship $E_2 \approx d_2 H_{k2} M_{r2}$ with M_{r2} being the saturated magnetization of the film F_2 , is of approximately the same magnitude as the increase E_1 in energy for the forcible twisting within the softer film, due to the exchange interac-

tion, of the spins which have a tendency to become parallel. The energy increase E_1 is expressible by

$$E_1 \approx A \left(\frac{d\theta}{dz} \right)^2 d_1 \approx A' d_1,$$

where A is the exchange contact and has a value of approximately 10^{16} erg/cm. in the case of a metallic ferromagnetic material containing iron, nickel, or cobalt as a principal constituent.

The reason for this is that, when the energy E_2 is excessively high, it becomes difficult to move the magnetization of the film F_2 , and the aforesaid attractive influence does not occur. On the other hand, when the energy E_2 is excessively small, the total magnetism of the double film is determined almost entirely by the magnetism of the soft film F_1 . Accordingly, the following equation is obtained as the condition for effective utilization of attractive influencing effect.

$$d_1 d_2 M_{r2} H_{k2} \approx K \cdot 10^{16} \text{ erg/cm}, \quad (3)$$

where: K is a constant determined experimentally;

d_1 and d_2 are in centimeters;

M_{r2} is in gausses; and

H_{k2} is in oersteds.

A feature of the present invention is the utilization of the above described attractive influencing effect to change the shape of the asteroidal switching curve of the uniaxial anisotropic thin film indicated in FIG. 2 thereby to improve the memory characteristics of the memory element.

For a further exposition of the nature and principle of the present invention, the following description is set forth with respect to the case wherein both of the films F_1 and F_2 have uniaxial anisotropy with easy (x) axes in the x -axis direction, and the materials thereof are so selected that the anisotropy magnetic field H_{k2} of the film F_2 is markedly larger than the anisotropy magnetic field H_{k1} of the film F_1 .

If, under the condition defined by Equation (3), the value of K is suitable, it can be theoretically predicted that the switching characteristic will assume an asteroidal form which is elongated in the y -axis direction as shown in FIG. 7. The reason for this is that, in the case when, starting from the state wherein the magnetizations of films F_1 and F_2 are both directed in the $+x$ direction, an external magnetic field H_y is applied in the y -axis direction as indicated in FIG. 8, the average direction M_2 of the magnetization of the film F_2 is directed toward the y -axis direction with greater difficulty than that, M_1 , of the film F_1 , and, accordingly, even when a large external magnetic field H_y is applied, the magnetization can return reversibly to the original state without the loss of the stored information.

A double film of this character can be used by exactly the same method as that for an ordinary uniaxial anisotropic thin film, but in the case indicated in FIG. 7, in comparison with that indicated in FIG. 2, the allowable range of the magnetic field in the hard (y) axis direction in which writing in of information by double coincidence and nondestructive reading out is possible is increased. This feature was verified by the following experiment.

For the film F_1 , a permalloy (approximately 19 percent of iron and 81 percent of nickel) film was formed by electroplating in a magnetic field to a thickness d_1 of 1 micron, thereby an anisotropy magnetic field H_{k1} of approximately 3 oersteds was induced. On the films F_1 prepared according to the above process, films of approximately 40 percent nickel and 60 percent cobalt and of respectively various thicknesses d_2 were deposited as hard films F_2 by electroplating in a magnetic field. Each film F_2 had uniaxial anisotropy of H_{k2} of approximately 30 oersteds. It was confirmed that, by the addition of the films F_2 , the switching characteristics were elongated in the y -axis direction, the maximum double-coincidence, magnetic field, allowable deviation (which was approximately twice that in the case of $d_2=0$) was obtained in the case of $d_2 \approx 270$ angstroms.

When the left-hand side of Equation (3) is computed from these quantities, the following result is obtained.

$$d_1 \times d_2 \times M_{r2} \times H_{k2} = 10^{14} \text{ cm} \times 2.7 \times 10^{16} \text{ cm} \times 800 \text{ gauss} \times 30 \text{ oersted}$$

$\approx 6.5 \times 10^{16}$ erg/cm.

Accordingly, $K=6.5$ is the optimum. However, the value of this d_2 , that is, the value of k , was found to be effective also when it was in the range of from one-fifth to 2 times the optimum value.

Furthermore, by the use of multiple-layer films of this character, depending on the conditions of their formation, a new writing method, that is, an information recording method depending on the time sequence of magnetic fields applied within the plane of the films, whereby wiring in of information is accomplished for the first time when a rotating magnetic field is applied becomes possible. Whereas, reading out can be accomplished nondestructively by the same procedure described hereinbefore.

More specifically, when, in multiple-layer films F_1 and F_2 of two soft and hard layers having substantially common easy (x) axis directions, the thickness d_2 of the hard film is increased beyond the stated condition just mentioned, it becomes impossible to influence attractively the magnetization of the film F_2 to a sufficient degree unless the magnetization M_1 of the soft film F_1 is made rotate by applying external fields which form a cycle or a loop in the H_x — H_y plane.

Let a magnetic field of waveforms as indicated in FIG. 9 be applied as H_x and H_y , where H_{A+} is the positive wave height of H_y , H_{A1} is the negative wave height of H_y , and H_e is the wave height of H_x . This magnetic field has a path or locus such that, in the H_x — H_y plane, it starts from the origin at a time t_0 as indicated in FIG. 10, becomes H_{A+} in the H_y direction at time t_1 , describes 2 cycle within the H_x — H_y plane, and returns to the origin at a time t_4 , thus forming a cycle or a loop L.

When, on this path, the average directions M_1 and M_2 of the magnetization vectors respectively of the films F_1 and F_2 are both caused to start from the $+x$ direction, they become as indicated in FIG. 10, and both finally become directed toward the $-x$ direction. That is, the digit "0" is thereby written in. The digit "1" can be written in by similar method by applying magnetic field such as to form a cycle with the right-hand half plane of FIG. 10, more specifically, by reversing the polarity of the magnetic field H_x .

The existence of this new writing mode was verified by the following experiment. For the films F_1 and F_2 , films of an electrodeposited permalloy and a Ni — Co alloy permalloy under the same conditions as described above were used, and for a thickness d_1 of the soft permalloy film F_1 of 1 micron as before, a thickness d_2 of the hard film F_2 of 810 angstroms was selected. For the magnetic field, pulses H_{A+} , H_{A1} , and H_e (c.f. FIG. 9) each of 1 microsecond width were used.

Under these conditions, it was found that writing in ("0" from "1") occurs when the magnitudes of these pulses are within the following ranges:

$1.5 \text{ oersted} \leq H_{h-} = H_{h-} \leq 2.5 \text{ oersted}$ when $H_e = 5.5$ oersteds; and

$2.2 \text{ oersted} \leq H_{h+} = H_{h+} \leq 5.0 \text{ oersted}$ when $H_e = 4.1$ oersteds.

However, if any one of the pulses H_{A+} , H_{A1} , and H_e is cut off, writing in will not occur, and the magnetization will revert to the original state.

It was found further that writing in does not occur also when the time period of pulse H_e is shifted so that it coincides with either H_{A+} or H_{A1} , whereby the magnetic field does not form a

cycle. Since the thickness d_2 in this case is 3 times that in the case of the aforescribed computation (wherein $d_1=270$ angstroms), the value of K in Equation (3) is $K=20$. In general, a value of K of 5 or more was found necessary for this effect to appear.

A feature of a thin-film element of the above description is that information stored therein is not easily erased, and this element moreover, can be applied also to uses such as detection of the presence or absence specific waveforms written in by triple coincidence of the three pulses H_e , H_{A+} , and H_{A1} .

As described above in detail, the present invention affords a broadening of the region of double coincidence by providing multiple layers of magnetic thin films of magnetically different properties which films are molecularly placed in intimate contact by a method such as electrodeposition or vacuum evaporation. Moreover, it provides a memory element capable of accomplishing stable memory operation. Furthermore, the present invention provides, by the use of this memory element, a new method for writing information by using magnetic fields forming a cycle.

It should be understood, of course, that the foregoing disclosure relate to only a preferred embodiment of the invention and that it is intended to cover all changes and modifications of the example of the invention herein chosen for the purposes of the disclosure, which do not constitute departures from the spirit and scope of the invention as set forth in the appended claims.

What I claim is:

1. A method for writing information on a multiple layer memory element, said element having adjacent layers of unlike substances, disposed in intimate molecular contact with each other, comprising

Rotating a magnetic field in an X,Y plane of said memory element, said rotating magnetic field being started at an origin in said X,Y plane, and being rotated through said X,Y plane in a cyclical manner to terminate at said origin, wherein said field is rotated in a cyclical manner by applying a first pulse to direct the field in one direction along the Y-axis, applying a second pulse to direct the field in one direction along the X-axis while maintaining said first pulse, terminating said first pulse while maintaining said second pulse, applying a third pulse to direct the field in the other direction along said Y-axis while maintaining said second pulse, terminating said second pulse while maintaining said third pulse, and then terminating said third pulse to complete a cycle.

2. A method of writing on a multiple layer thin film memory element including abutting hard and soft layers disposed in intimate molecular contact and having substantially common easy-axis directions of magnetization along the X-axis of an X,Y plane, at the abutting faces of said layers, comprising

applying external fields to rotate a magnetic field of the soft layer through a cycle by starting at an origin point in said X,Y plane and rotating the direction of magnetization to finally return to said origin point, wherein said magnetic field is rotated by applying a first pulse to direct the field in one direction along the Y-axis, applying a second pulse to direct the field in one direction along the X-axis while maintaining said second pulse, applying a third pulse to direct the field in the other direction along said Y-axis while maintaining said second pulse, terminating said second pulse while maintaining said third pulse, and then terminating said third pulse to complete a cycle.