March 3, 1964 U. E. ENZ ETAL 3,123,807

MULTISTABLE MAGNETIC ELEMENT

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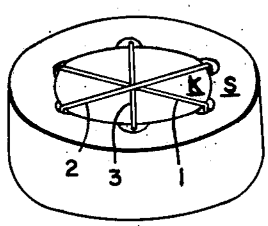

FIG. 1a

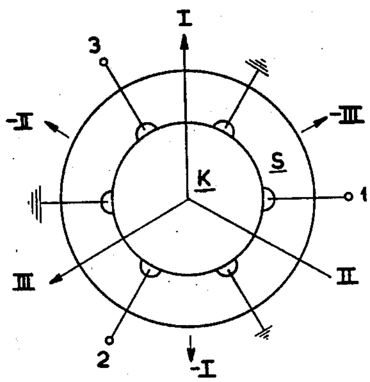

FIG. 1

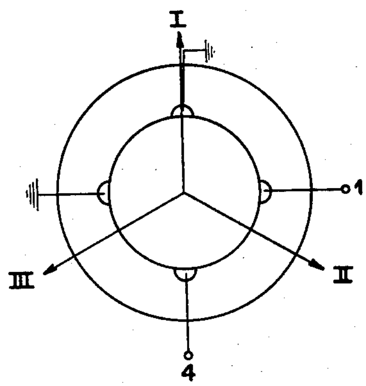

FIG. 3

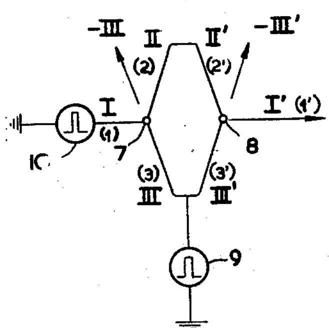

FIG. 4

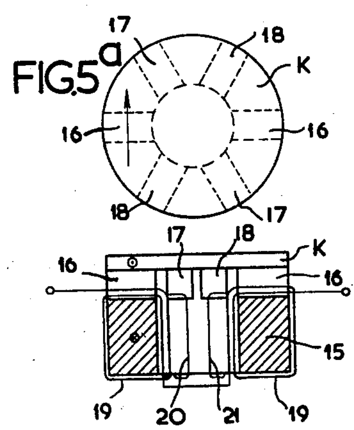

FIG. 5

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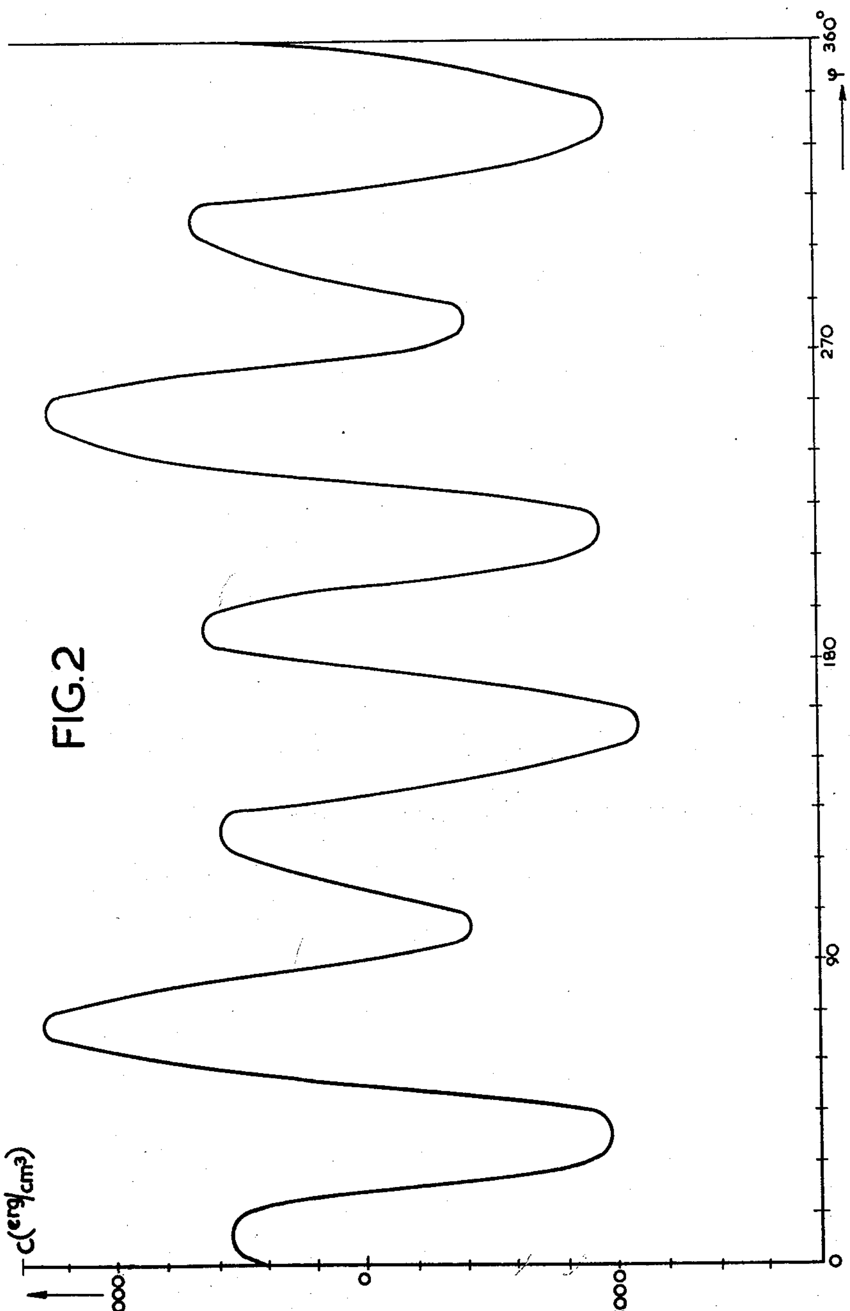
FIG.2



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MULTISTABLE MAGNETIC ELEMENT

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9 Claims. (Cl. 340—174)

The present invention relates to devices comprising a magnetic element, the remanent magnetization state of which is determinative of the production of an output pulse by the action of a control pulse. Such devices are used, for example, as a storage element in electric computers. The production of an output pulse is based on the fact that the remanent magnetization reverses its direction under the influence of the control pulse. Hence, such an element has only two remanent magnetization states.

The present invention utilizes a phenomenon occurring in particular magnetic materials, in which a plurality of remanent magnetization states are possible, thus permitting a greater diversity of information per element. It has the feature that the magnetic material of the element has remanence states subtending angles different from 180° with respect to each other, so as to produce an output pulse by change of direction of the remanent magnetization.

In order that the invention may be readily carried into effect, an example will now be described in detail with reference to the accompanying drawing, in which

FIG. 1 is a plan view of one embodiment of the invention,

FIG. 1*a* is a perspective view of the embodiment of FIG. 1.

FIG. 2 shows characteristics for explaining FIG. 1.

FIG. 3 is a variant of FIG. 1.

FIG. 4 represents a circuit arrangement comprising devices as shown in FIG. 1.

FIG. 5 shows an elevational, partly cross-sectional view of another modification of FIG. 1.

FIG. 5*a* is a top plan view of the FIG. 5 embodiment.

In FIG. 1, the reference K represents a crystal of a material, the remanent magnetization states I, II, III of which are at angles different from 180° with each other, in the illustrated example 120°. The member K is preferably a single crystal. Materials having such a behaviour are found among the "Ferroxplana" materials known in the art. Compositions of suitable materials are described in copending applications, Serial Nos. 603,134; 603,135; 603,136; 635,614; 659,516 and 728,849, filed respectively, on August 9, 1956; August 9, 1956; August 9, 1956; January 23, 1957; May 16, 1957; and April 16, 1958; now U.S. Patents 2,955,085; 2,946,752; 2,946,753; 2,960,471; 2,977,312; and 3,043,776, respectively, issuing on October 4, 1960; July 26, 1960; July 26, 1960; November 15, 1960; March 28, 1961; and July 10, 1962, respectively. The formation of the material in single crystal form is described in the copending application, Serial No. 739,694, filed June 4, 1958, and in Philips Technical Review, vol. 19 (1957), page 209 et seq. They may, for example, have a composition according to the chemical formula $Ba_2Me_2Fe_{12}O_{22}$ or $Ba_3Me_2Fe_{24}O_{41}$, where Me preferably contains at least cobalt. They have a crystal energy c as a function of the angle φ, measured in the plane at right angles to the hexagonal axis of the single crystal, as shown in FIG. 2. In directions, in which the crystal energy c has its minima, the magnetization vector will have preferential positions. If, for example, the magnetization vector coincides with the direction I (see FIG. 1), a given minimum field, for example in the direction II, corresponding to variations of the crystal energy c is required to make the magnetization vector follow this direction. In fact, FIG. 2 shows six minima of the crystal energy c which, however, pairwise subtend angles of 180° with each other. The plane of the drawing in FIG. 1 is the preferred plane at right angles to the hexagonal axis. Thus, the crystal K exhibits three preferred directions of magnetization in its preferred plane of magnetization. The three preferred directions being at 120° relative to one another are thus non-parallel.

The crystal K is enclosed by a ring S consisting of soft-magnetic material, for example ferrite, furnished with recesses accommodating windings 1, 2 and 3. The windings encircle the crystal K and lie in planes perpendicular to the preferred crystal directions I, II and III. The soft ring S encloses the whole system of crystal K and windings 1, 2 and 3 to provide a magnetic closed circuit for each of said windings. Upon supplying a suitable current to the winding 1, the magnetization vector will assume the direction I thus establishing a first remanent magnetization state. Upon supplying a current pulse to the winding 2, the magnetization vector will take the direction II thus establishing a second remanent magnetization state and, moreover, pulses will be produced in the windings 1 and 3. If, conversely current pulses of such polarity are supplied to the windings 1 and 3, the magnetization vector will assume the direction II, and a corresponding current pulse will be produced in the winding 2. The device of FIG. 1, having three preferred directions, will thus possess a total of six remanent magnetization states. The device according to the invention is based on these phenomena.

When used as a storage element, for example, simultaneous read-in current pulses are supplied to two windings, with the result that the magnetization vector assumes the direction at right angles to the plane of the third winding. However, the pulses chosen are weak so that a pulse supplied to only one winding is unable to produce a permanent change of direction of magnetization.

For reading-out the information stored by the remanent magnetization state of the crystal K, a weak pulse may be supplied to one of the windings, as a result of which the magnetization slightly fluctuates about the inscribed preferential direction, but the information state is retained. From the pulses produced in the other windings, the preferential direction of the magnetization vector can then be derived. If, for example, this were the direction I and a small current pulse were supplied to the winding 1, then low, equal and opposite voltages are produced in the windings 2 and 3. If, contrary thereto, the direction of magnetization were II, a pulse considerably exceeding that produced in the winding 2 is produced in the winding 3, and the revese holds if the magnetization initially had the direction III.

Similarly, the information can alternatively be read out with a strong current pulse so that the magnetization moreover assumes the direction corresponding to the winding or windings to which the read-out pulse is supplied. The read-out may be simplified by combining, for example, the windings 2 and 3 to form a single winding 4, the plane of which extends at right angles to that of the winding 1, as shown in FIG. 3. As shown in the following table, the read-in may be effected by supplying a combination of positive and negative pulses to the windings 1 and 4, and for read-out a pulse is supplied to the winding 1 and the output pulse then produced in the winding 4 is measured. The numbers appearing in the table represent the relative magnitude of the input and output pulses, and the plus and minus signs their polarity.

Reading-in		Resultant magnetization direction in crystal	Reading-out
Pulses supplied simultaneously to—			Output pulse in winding 4 after reading pulse of −2 is applied to winding 1
winding 1	and to winding 4		
+2	0	I	0
−1	$+\sqrt{3}$	II	$+\sqrt{3}$
−1	$-\sqrt{3}$	III	$-\sqrt{3}$

In practice, it is alternatively possible to use equal, adequate positive and negative read-in pulses in the windings 1 and 4. The magnetization thus produced automatically tends to assume the desired preferential state after termination of the pulses. The same possibilities as referred to above are naturally obtained when using the device shown in FIG. 1. Moreover, when supplying the opposite combination of positive and negative read-in pulses to the windings 1 and 4, the opposite remanent magnetization states —I, —II, and —III are obtainable. For reading-out it is possible to use the value and polarity of the voltages in one of the windings 2 and 3, respectively, and their difference as well.

Alternatively, the device according to the invention may be used as an adding element in computer circuit arrangements. For example, if the magnetization vector initially occupies the position —I and the windings 2 and 3 are supplied with pulses, each of which is unable to cause the magnetization to leave the position —I but which jointly make it assume the position +I, a sufficient output pulse will be produced only in the last-mentioned case in the winding 1 to serve as a measure for the adding operation.

An element as shown in FIG. 1 further permits a coincidence circuit to be built. Assuming the initial magnetization to occupy a position —II, when sufficiently strong non-coincident pulses are supplied to the windings 2 and 3 respectively causing the magnetization to pass over from the position —II to the position —III and conversely, such passing over produces, however, only a negligible pulse in the winding 1, since the component of the magnetic flux flowing through this winding remains unchanged. If, contrary thereto, the pulses in the windings 2 and 3 coincide so that the magnetization will assume the position I, a considerable output pulse is produced in the winding 1. By integration of the pulse in the winding 1, the criterion of coincidence can be made still more acute.

FIG. 4 shows a pulse-differentiating circuit comprising two elements 7 and 8 as shown in FIG. 1. The windings 1, 2, 3 and 1′, 2′, 3′ respectively of these elements are characterized by the directions I, II, III, and the directions I′, II′, III′ respectively, at right angles to the plane of these windings, which directions moreover correspond to the preferential directions of magnetization. A clock-pulse generator 9 is connected to the windings 3 and 3′, and a source 10 of the pulses to be tested is connected to the winding 1 of the element 7. The windings 2 and 2′ are connected together and the winding 1′ of the element 8 serves as an output.

As long as coincidence subsists between the pulse sources 9 and 10, the magnetization in the element 7 will retain the direction II, while the magnetization in the element 8 will retain the direction —III′, so that no pulse is produced in the output winding 1′. In the absence of a pulse from the source 10, the magnetization of the element 7 assumes the position —III and the next coincidence of the pulses from the sources results in 9 and 10 producing a pulse in the winding 2 so that the magnetization of the element 8 assumes the direction I′, and a pulse is produced in the output winding 1′. On subsequent coincidence of the two pulses the magnetization of the element 8 reassumes the position —III′ and an opposite pulse is produced in the output winding 1′.

In order to simplify the device shown in FIG. 1, the disc-shaped crystal K may be provided on a ring 15 of soft magnetic material (FIG. 5) furnished with slots 16, 17, 18 for the passage of windings 19, 20, 21. The arrow in FIG. 5*a* shows the resultant magnetic field when introducing a current from the left-hand terminal of the winding 19.

What is claimed is:

1. A magnetic memory device comprising a magnetic storage element composed of hexagonal-crystal-structure ferrite material and having a preferred plane of magnetization and at least three non-parallel preferred directions of magnetization in said plane and at least three non-parallel stable states of remanent magnetization, and at least two windings coupled to said element for selectively magnetizing said element in any one of said three preferred directions.

2. A device as set forth in claim 1 wherein the element is a single crystal of said ferrite material.

3. A device as set forth in claim 1 wherein the element is composed of a barium-cobalt ferrite.

4. A magnetic memory device comprising a magnetic storage element possessing at least three non-parallel preferred directions of magnetization and at least three non-parallel stable states of remanent magnetization in a preferred plane, and winding means coupled to said storage element for selectively magnetizing said element in any one of said three preferred directions.

5. A magnetic memory device comprising a disc-like ferromagnetic storage element possessing at least two non-parallel preferred directions of magnetization in the plane of said disc and said disc-like element thus being capable of assuming four stable remanent magnetization states, at least two windings coupled to the disc so that their winding planes are at right angles to the plane of the disc, means for passing current pulses through said windings selectively to establish said four magnetization states, which are retained even after the pulses terminate, and means coupled to at least one of the windings to derive an output signal indicative of the state established.

6. A magnetic memory device comprising a disc-like ferromagnetic storage element possessing three non-parallel preferred directions of magnetization in the plane of said disc and said disc-like element thus being capable of assuming six stable remanent magnetization states, at least two windings encircling the disc so that their winding planes are at right angles to the plane of the disc, means for passing current pulses through said windings selectively to establish said six magnetization states, which are retained even after the pulses terminate, and means coupled to at least one of the windings to derive an output signal indicative of the state established.

7. A device as set forth in claim 6 wherein the two windings have winding planes at right angles to one another.

8. A magnetic memory device comprising a monocrystalline disc-like hexagonal-cobalt-containing-ferrite storage element possessing a preferred plane of magnetization in the plane of the disc and three non-parallel preferred directions of magnetization in said plane and three non-parallel stable states of remanent magnetization, three windings magnetically coupled to the disc to establish magnetic fields in the disc causing it to be magnetized in any one of the three directions, input means for passing current pulses through said windings selectively to establish any one of the three preferred directions of magnetization, sensing means for applying a sensing pulse to one of the windings, and output means coupled to another of the windings to derive an output voltage indicative of the established direction of magnetization when the sensing means are activated.

9. A device as set forth in claim 8 wherein current pulses are simultaneously applied to two of the windings.

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