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FERRITE INDUCTOR

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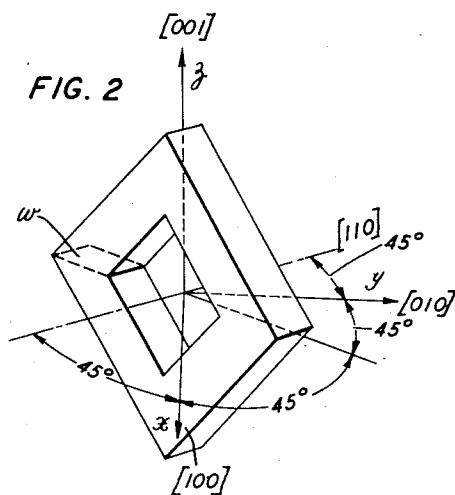
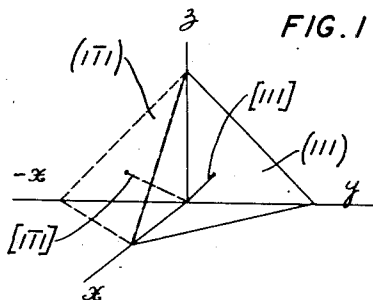


FIG. 3A

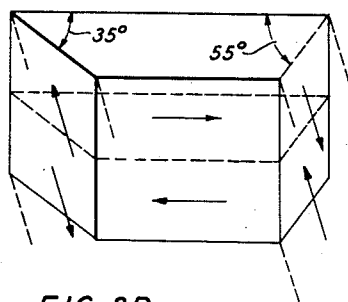


FIG. 3B

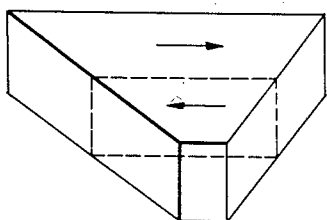


FIG. 4

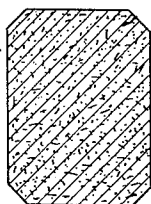


FIG. 5

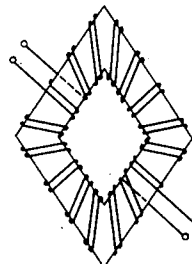


FIG. 6

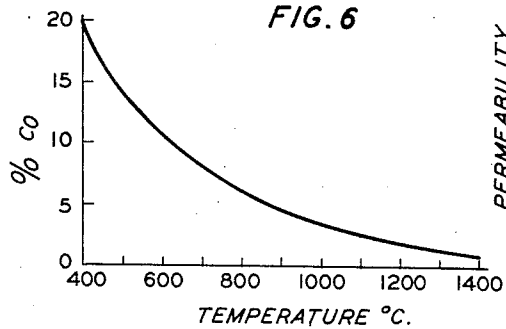
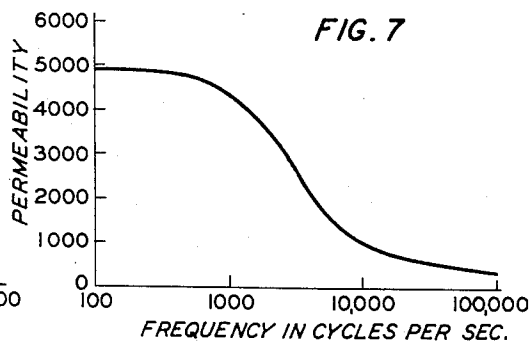


FIG. 7



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FERRITE INDUCTOR

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9 Claims. (Cl. 336-233)

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This invention relates to magnetic-cored electrical inductance elements and it is concerned more specifically with such an element in which the magnetic core is composed of a ferrite or the like.

Principal objects of the present invention include a reduction in flux leakage from the magnetic core of a ferrite-cored inductance element, and an increase in the permeability of the core and therefore also in the inductance of the element. Related objects are to reduce substantially the size of element needed to yield a prescribed inductance and to provide a practical miniature inductance element.

In another aspect of the invention it is an object to achieve in a core of ferrite or the like the maximum permeability and minimum flux leakage of which the core material is capable.

The magnetic ferrites are distinguished by electrical resistivity that may be several orders of magnitude greater than that of other magnetic materials commonly employed, and by correspondingly low eddy current losses. These properties and others have led to the use of ferrites in magnetic cores and in various other magnetic structures. The material as so used heretofore has been in the form of a polycrystalline aggregate that is powdered, compressed into the form desired, and sintered.

The objectives of the present invention are achieved in an inductance element that has a magnetic core fabricated from a single, large, pure, mechanically sound crystal of ferrite, the core taking the form of an integral closed polygonal ring the members of which are oriented with reference to certain axes of the crystalline material in a manner to be described.

The magnetic ferrites have the chemical formula $MO.Fe_2O_3$, where M is a divalent metal such as cobalt, copper, iron, magnesium, manganese, nickel or a mixture of such metals among themselves and/or with zinc. Their crystalline structure is cubic or, more specifically, that of either normal or inverse spinel. In respect of certain of their magnetic properties, they are anisotropic; thus, for the purposes of the present invention, it is significant that their intrinsic induction is much more easily directed along certain axes or directions through the crystalline material than others. Such reference directions are commonly designated the "directions of easy magnetization" and they are related to the crystallographic axes in a definite manner that is known or determinable for any magnetic material.

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In $FeO.Fe_2O_3$, for simple example, one of the directions of easy magnetization is the [111] direction and, since the structure is cubic, there are three other equivalent directions each likewise inclined equally to the three mutually perpendicular crystallographic axes.

One feature of a monocrystalline ferrite core embodying the invention is that each of the legs of the core lies along one of the directions of easy magnetization of the crystalline material. In this connection it is noted that one may trace out in any crystal of cubic structure, while following only directions of easy magnetization, a number of multisided closed figures, among which are four-sided planar figures that are parallelograms. One such figure in a material in which [111] is a direction of easy magnetization for example, is a rhombic or diamond-shaped one that lies in a (110) crystal plane and of which one pair of opposite sides extends in the [111] direction and the other pair of opposite sides extends in say the $\bar{1}\bar{1}1$ direction.

Another feature of an inductance device in accordance with the invention is that each leg of the integral core structure essentially constitutes in itself no more than two magnetic domains. That is, in each of these major parts of the core the magnetization is substantially confined to a single direction, or to two antiparallel directions, aligned with the longitudinal dimension of the leg. Further, each of these domains is joined at its end with domains that are like-directed around the core: there is no significant aggregation of magnetic poles (ideally, none) and the flux is completely confined.

The nature of the present invention and its various features, objects and advantages will appear more fully on consideration of the specific embodiments hereinafter described with reference to the accompanying drawings.

In the drawings:

Fig. 1 is a diagram illustrating the relation of certain significant planes and directions to the crystallographic axes;

Fig. 2 illustrates a rhombic core and its relation to the crystallographic axes;

Figs. 3A and 3B illustrate diagrammatically the magnetic domain structures that are obtained in certain cores embodying the invention;

Fig. 4 is a cross-sectional view of a modified core leg;

Fig. 5 is a diagrammatic showing of a transformer embodying the invention; and Figs. 6 and 7 comprise curve diagrams.

Pursuing further the example of a cubic crys-

talline material in which the $[111]$ direction is a direction of easy magnetization, Fig. 1 shows the three mutually perpendicular crystallographic axes x, y, z , of the material and, in solid lines, the $[111]$ direction and a (111) plane. The corresponding direction $[\bar{1}\bar{1}\bar{1}]$ and a $(\bar{1}\bar{1}\bar{1})$ plane in another octant are also shown in dotted lines, and it will be evident that there are corresponding directions and planes in each of the other octants also. Each of six pairs of these directions defines a plane that is parallel to one of the axes x, y, z , and inclined at 45 degrees to the other two axes. One plane so defined is the (110) plane and, because of the prevailing cubic symmetry, the other planes so defined are equivalent and may be given the same designation for present purposes. Similarly the $[111]$ direction and its equivalents may all be designated $[111]$ directions.

Fig. 2 shows diagrammatically a rhombic core of the kind described and its relation to the crystallographic axes. The forward diamond-shaped face of the core lies in a (110) plane and so also does the parallel rear face. The four legs of the core are of uniform rectangular cross section and extend in $[111]$ directions. The angles that the $[111]$ directions make with each other can be determined readily by geometric calculation. The acute angle of the rhombic turns out to be $2 \sin^{-1} 1/\sqrt{3}$ or about 70 degrees and the obtuse angle is its supplement or about 110 degrees.

Fig. 3A shows diagrammatically one of the legs of the Fig. 2 core and two magnetic domains. In the absence of an applied magnetic field the material is spontaneously magnetized in a manner suggested by the arrows, that is, the magnetization is oppositely directed in the two parts of the cross section that are separated by a plane parallel to the diamond-shaped faces, and throughout each such part the magnetization is uniform in strength and direction. The magnetization in each leg links up with the magnetization in adjacent legs so that the magnetization is continuous around the core and completely closed on itself, being clockwise on one side of the mentioned plane and counterclockwise on the other. If a sufficient longitudinal magnetic field be applied to the several legs, as by means of a coil on the core, it in effect shifts the position of the plane, and changes the net flow of flux around the core.

Fig. 3B shows another form that the magnetic domains may take in each of the legs of the core. Here the plane that separates the oppositely directed magnetization in each leg is perpendicular to the last-mentioned plane and its movement under the influence of an applied field is toward and away from the center of the rhombus. Whether the magnetic domains assume the form shown in Fig. 3A or that in Fig. 3B depends on such factors as cross-sectional shape of the core and the relative areas of the two domain-separating planes. In Fig. 3A the cross section is elongated in the $[110]$ or thickness direction; in Fig. 3B the elongation is in the other direction.

The end walls of the domains in Figs. 3A and 3B lie in diagonal planes through the rhombus, and one of them is shown at w in dotted lines in Fig. 2. Each is inclined at an angle of either 35 degrees and 16 minutes or 54 degrees and 44 minutes to the length of the leg. The separate showing of core legs in Figs. 3A and 3B is not intended to suggest that these portions

be separately fabricated and assembled, for the desired registry of the crystalline lattice structures on opposite sides of these walls precludes any such technique. This registry, or more accurately the integral monocrystalline character of the core, avoids unwanted local domains of reverse magnetization at the corners and elsewhere. Similar considerations dictate the selection of pure, sound crystalline material that is free of inclusions, cracks or the like and care should be exercised also in fabricating the core to avoid cracking or chipping the material.

In a core of perfectly rectangular cross section it is believed that the movable domain wall tends to favor a position adjacent an external surface of the core and to move toward such a position when the applied field is removed. The initial magnetic condition of the core on successive applications of field thus tends to vary and thereby to introduce a kind of instability that may be undesirable in some applications of the inductance element. This tendency was not observed in a core substantially as described with reference to Fig. 3A in which the cross section was modified by chamfering the four edges of each leg alike, somewhat as illustrated in cross section in Fig. 4.

Fig. 5 shows diagrammatically a complete inductance device with windings of insulated wire applied to the core and brought out to two pairs of terminals to constitute a transformer. Each winding should extend completely around the core with a view to providing uniformly distributed excitation and thereby to preserve to the fullest the relative freedom of the structure from magnetic flux leakage. One winding only will be needed if the element is to serve as an auto-transformer or choke coil or the like.

In one instance of practice a core conforming with Figs. 2 and 5 was fabricated from a synthetic crystal of $\text{FeO} \cdot \text{Fe}_2\text{O}_3$. The length of each leg, on the inner side, was 0.104 centimeter, the cross-sectional dimension in the (110) plane was 0.051 centimeter and the other cross-sectional dimension was 0.102 centimeter. Fig. 7 shows how the measured permeability varied as a function of frequency. The indicated permeability of nearly 5000 at low frequencies is to be contrasted with permeability figures of about 40 for cores cut with random orientation from single crystals of the same material, and 3 to 10 for powdered, compressed cores of that material. Further, it is to be seen from Fig. 7 that high values of permeability are maintained over a frequency range (of several thousand cycles per second) that is wide enough to be of practical significance, as for example in telephone transmission circuits. This high relaxation frequency is associated with the high electrical resistivity of the core material.

The methods that are available for use in growing pure, sound crystals of sufficient size for present purposes are elaborate but well known, and they will be described only briefly.

The Verneuil method involves feeding finely powdered material through an oxyhydrogen flame along with the oxygen stream. The powder melts in the flame and as it flows, or falls, further it strikes the surface of a crystal where it again freezes as part of the crystal. The crystal is grown in this way. By varying the proportions of oxygen and hydrogen in the flame the oxidation potential of the atmosphere can be varied.

Another method involves pulling a seed slowly out of a melt of the ferrite in such a way that

the solid-liquid interface remains near the surface of the melt, and crystal growth occurs at that point.

The Bridgman method consists in lowering a sintered bar of the material through a furnace in such a way that a temperature gradient occurs along the sample. The sample melts and recrystallizes as a single crystal at an interface which occurs in the thermal gradient at the point at which the temperature is the melting temperature of the ferrite.

As J. Smiltens and D. H. Fryklund report their application of the Bridgman method to the growth of $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ crystals, for specific example, the details of procedure were as follows.

A long tubular furnace was used to bring the temperature up to the neighborhood of the melting point of Fe_3O_4 . A small platinum-wound inner furnace of about 0.6 inch diameter was placed inside the larger tube and used to adjust the temperature gradient.

An atmosphere of CO_2 was established inside the furnaces by allowing the gas to flow through at 1 centimeter per second. A sintered bar of magnetite was brought to a temperature of 1605 degrees to 1610 degrees centigrade and then lowered through the temperature gradient. Crystallization started at 1575 degrees centigrade where the temperature gradient was adjusted to be 25 degrees centigrade per centimeter. The sample was contained in a crucible made of 0.009 inch platinum sheet, and it was lowered at 5 millimeters per hour. Care was taken to eliminate back-lash in the lowering mechanism. The temperature of the inner furnace was held constant to ± 0.4 degree centigrade.

The sintered bars used at the start were prepared by heating "Baker's Analyzed" ferric oxide at 1550 degrees centigrade in a CO_2 atmosphere for seven hours.

Once the crystals were grown they were cooled slowly in a controlled atmosphere. The annealing rate down to 400 degrees centigrade was 1 degree centigrade per minute. Below 400 degrees centigrade the cooling was slower—about 0.4 degree centigrade per minute. The growth process took 26 hours, the annealing about 36 hours. The atmosphere was controlled by adding various amounts of CO at various temperatures from 1400 degrees centigrade down as the crystal cooled. The amount of CO by volume is shown at various temperatures in Fig. 6.

Although the present invention has been described largely with reference to certain specific embodiments, other embodiments within the spirit and scope of the invention will be evident to those skilled in the art. For example there are a few materials in addition to those mentioned, such as certain lanthanum and strontium

manganites, that are magnetic, of electrical resistivity high enough that their eddy-current losses are a small fraction of their total magnetic losses, of cubic crystalline structure, and otherwise adapted to the purposes of the invention.

What is claimed is:

1. An electrical inductance device comprising a monocrystalline core of magnetic material of high electrical resistivity in the form of an integral polygonal ring each of the legs of which lies along a direction of easy magnetization, and at least one winding on said core.

2. An electrical inductance device comprising a core formed from a single crystal of magnetic oxide as a multi-leg ring, each of the legs of which lies along a direction of easy magnetization, and at least one winding on said core.

3. An electrical inductance device comprising a monocrystalline core of magnetic ferrite having integral legs that form a polygonal ring and that lie along respective directions of easy magnetization, and at least one winding on said core.

4. An electrical inductance device in accordance with claim 3 in which said polygonal ring is diamond-shaped and said legs meet at angles of substantially 70 and 110 degrees.

5. An electrical inductance device comprising an integral monocrystalline core of magnetic ferrite in the form of a hollow parallelogram each of the four legs of which extends in a [111] direction through the crystalline material, and at least one winding on said core.

6. As an article of manufacture, a core formed from a single crystal of non-metallic magnetic material and comprising a plurality of integral legs together forming a closed ring, each of said legs lying along a direction of easy magnetization, and at least one electrical winding on said core.

7. An article in accordance with claim 6 in which said legs are substantially rectangular in cross section and have chamfered edges.

8. An article in accordance with claim 6 in which said winding comprises a plurality of complete turns and is distributed substantially uniformly over said legs.

9. A miniature, low-leakage electrical transformer comprising an integral core in the form of a polygonal ring formed from a single, pure crystal of magnetic ferrite with each of the legs of the ring conforming in direction with one of the directions of easy magnetization of the crystalline material, said legs having a substantially rectangular cross section, and a pair of windings on said core.

No references cited.