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Myer

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[54] **METHOD OF GENERATING CYLINDRICAL MAGNETIC DOMAINS**

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[73] Assignee: **Hughes Aircraft Company,** Culver City, Calif.

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[52] **U.S. Cl.** .... **340/174 TF**

[51] **Int. Cl.** **G11c 11/14**

[58] **Field of Search** .... 340/174 TF, 174 SR

[56] **References Cited**

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3,662,359 5/1972 Genovese .... 340/174 TF

3,727,197 4/1973 Chang .... 340/174 TF

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[57] **ABSTRACT**

There is disclosed a method and apparatus for the formation of cylindrical uniaxial domains or magnetic bubbles in a sheet of magnetic material characterized by a preferred direction of magnetization out of the plane of the sheet. The method uses a magnetically soft amorphous ferrite flux concentrator with a semi-toroidal configuration having one end of the toroid pointed to a 90° included angle in order to apply perpendicularly to the plane of the sheet of magnetic material or along the easy axis thereof, a pulsed field which rises intermittently to a high intensity with fast rise and fall time, which is an extremely localized field surrounded by steep field gradients confined to one portion of the area of the magnetic material, and which has field gradients which are curved in the plane of the material at the localized portion to provide a pinching off action for bubbles formed by excess domain wall area. The method is particularly suitable for use with such materials having high magnetic anisotropy values and high domain wall energy such as is possessed by orthoferrite crystal platelets.

5 Claims, 4 Drawing Figures

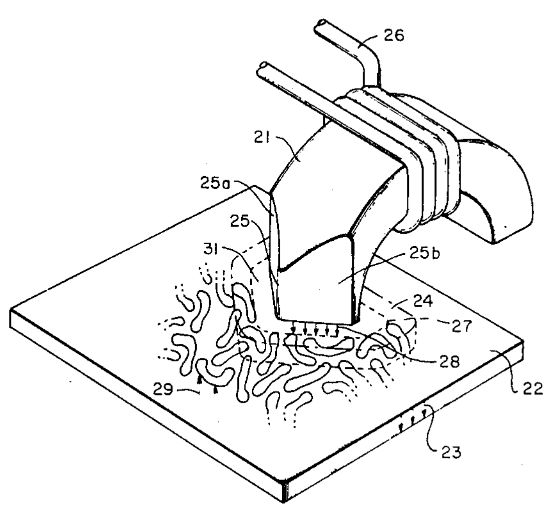


Fig. 1.

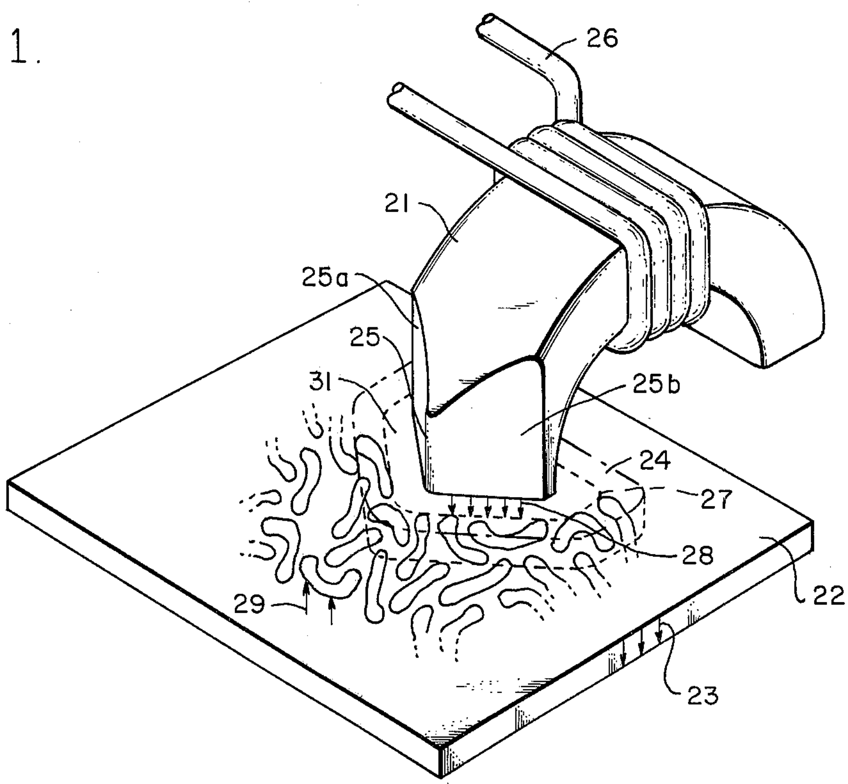


Fig. 2.

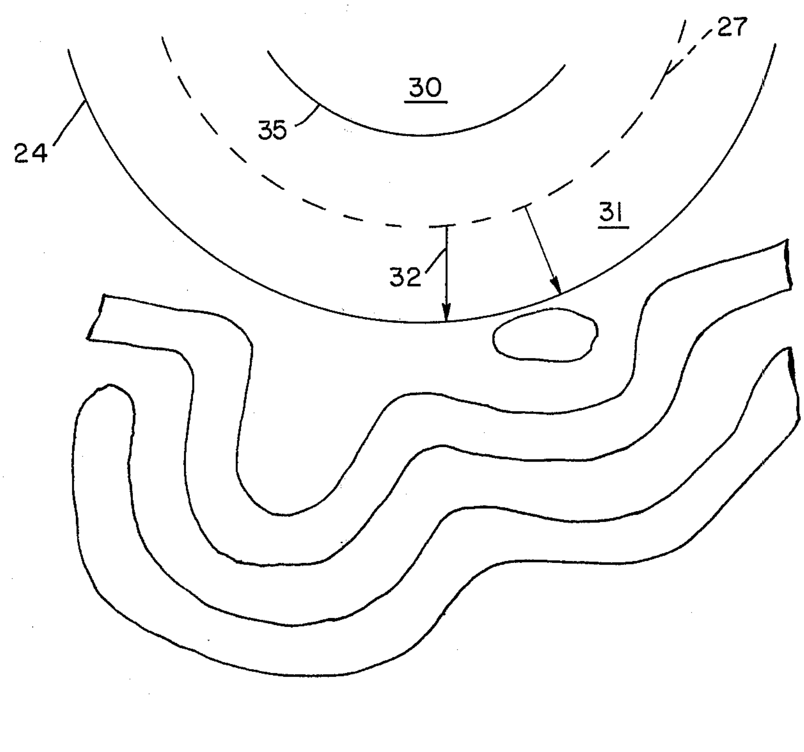


Fig. 3.

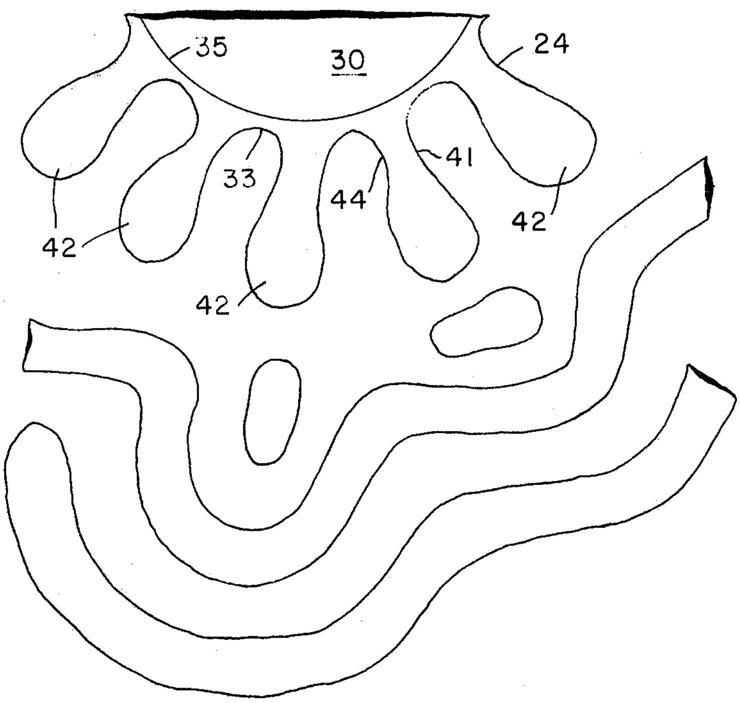
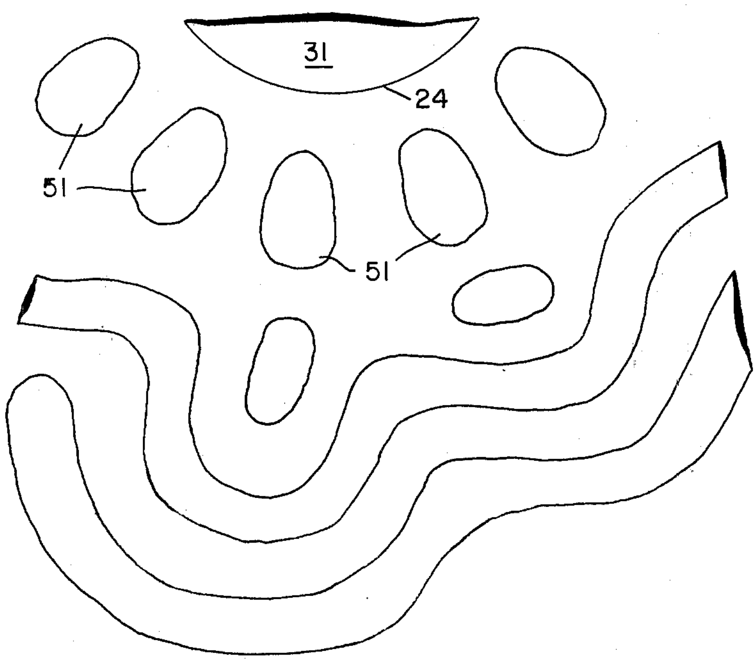


Fig. 4.



METHOD OF GENERATING CYLINDRICAL MAGNETIC DOMAINS

CROSS REFERENCE TO RELATED APPLICATIONS

The method and apparatus disclosed herein is an improvement over the known prior art manufacturing techniques which were disclosed in my eariler filed applications, Ser. No. 242,474, filed Apr. 10, 1972, and Ser. No. 205,095, filed Dec. 6, 1971, now U.S. Pat. Nos. 3,806,903 and 3,806,899, respectively both of which relate to devices utilizing mobile cylindrical magnetic domains in crystal platelets and both of which are assigned to the Hughes Aircraft Company as is this application.

BACKGROUND OF THE INVENTION

The utilization of mobile or movable cylindrical magnetic domains in certain single crystal ferromagnetic materials which are characterized by a preferred direction of magnetization out of the plane of the sheet of crystal has been disucssed in detail in my above referenced applicaton, Ser. No. 205,095 and in the prior art cited therein and applied thereto. The formation of the cylindrical domains in orthoferrite or garnet crystals was also described in an article in the June, 1971 issue of "Scientific American" entitled "Magnetic Bubbles" by A. H. Bobeck and E. D. Scovil, beinning at page 78. At page 81 therein they point out that as the crystal wafer naturally containing meandering strip domains is immersed in an external magnetic field perpendicular to the wafer and as the filed strength is rasied, the wavy strips whose magnetization is opposed by the filed begin to get narrower and shorter and continue to do so until at a certain field strength all of the island domains or strips not pinned to the edge of the wafer suddenly contract into small cylindrical domains which are called bubbles.

However, this technique of creating bubbles permits one to establish only as many cylindrical domains as there were original island meandering domains naturally occurring in the crystal platelet. If one wishes to create a very large number or foam bubbles, some other technique must be used. The Bobeck article at page 86 shows one bubble generator using a rotating "in plane" field in combination with a bubble nucleating generator spot. Another method for creating a predetermined number of magnetic bubbles in a crystal platelet by means of applying a laser beam to locally heat a predetermined portion of the crystal is described in U.S. Pat. No. 3,786,452, issued to J. E. Geusic on Jan. 15, 1974, and entitled "Single Wall Domain Generator". This technique is particularly suited for generation of an arbitrary number of bubbles in garnets rather than orthoferrites since the Curie temperature for orthoferrites is very much higher than it is for garnets. For example. Geusic at line 57 of column 3 of his patent gives a typical Curie temperature of 127°C for garnet. The corresponding Curie temperature for terbium orthoferrite is 379°C and for yttrium orthoferrite it is 370°C.

Other studies in the past have suggested the possibility of applying a magnetic field parallel to the plane of the crystal rather than perpendicularly to it as discussed above in order to physically break up the meandering domains into smaller domains by forcing them into alignment with one of the hard axes to churn the domains and thereby increase the number of bubbles. However, this technique is also more readily feasible with garnets than with orthoferrites since the garnet materials have a considerably lower anisotropy field and domain wall energy than do the orthoferrites and thus require a smaller churning field than do the orthoferrites.

These conclusions ae born out by the following studies reported in the scientific literature as noted below.

1. E. Della Torre, "Pressures On Cylindrical Magnetic Domain Walls," TEEE Trans. Mag MAG-**6**, 822–827 (1970).
2. A. J. Perneski, "Propagation of Cylindrical Magnetic Domains in Orthoferrites," IEEE Trans. Mag. MAG-**5**, 554–557 (1969).
3. F. A. De Jonge and W. F. Druyvesteyn, Proceedings of AIP Conference on Magnetism and Magnetic Materials, No. 5, 130–134 (1971).
4. J. A. Cape and G. W. Lehman, "Magnetic Domain Structures in Thin Uniaxial Plates With Perpendicular Easy Axis," J. Appl. Phys. **42**, 5732–5736 (1971).
5. J. M. Nemchik and S. H. Charap, "Measurement of Domain Wall Mobility in GdIG," Met. Trans. **2**, 635–639 (1971).
6. D. J. Craig and D. A. McIntyre, "Critical Fields For Magnetization Reversal in Yttrium Orthoferrite," Phys. Letters **21**, 288–289 (1966).
7. F. B. Hagedorn, J. Appl. Phys. **41**, 1161–1162 (1970).
8. Arjeh Kurtzig and Fred B. Hagedorn "Noncubic Magnetic Anisotropies in Bulk and Thin Film Garnets", IEEE Transactions on Magnetics, MAG. **7** No. 3, pp. 473–476. (Sept. 1971)

A careful review of this literature will indicate that the early orthoferrite investigators only formed singular bubbles with magnetic probes and used complex bubble replicating circuits to do so. They were never able in practice to generate a bubble foam comprising a large number of bubbles with a simple churner in an orthoferrite crystal, although it is possible to generate a bubble foam in a garnet crystal by applying a pulsed magentic field in a direction parallel to the major plane of the crystal in order to churn the domains therein (See Reference 8). In fact, all succesful prior bubble churning studies were applied to garnets which have low anisotropy and wall energies, and form small domains. It is thus quite easy to churn domains in garnets and break them up into cylindrical bubbles.

Cutting of a single elongated domain in orthoferrite was theoretically analyzed by Della Torre (Reference 1 above) and reduced to practice by Perneski (Ref. 2) using special bubble generator circuits. No prior art on the generation of a large number or foam of bubbles in orthoferrites by churning has been found in the literature. The technique of applying a pulsed magnetic filed to the cyrstal can, as noted above, accomplish this churning or domain breakup in garnets with a field of reasonable magnitude applied parallel to the major plane of the crystal or orthogonal to the easy axis of magnetization thereof. Since the domain wall energies in garnets are relatively low, the rotational force on the domains is sufficient to split them with a field of reasonable size. In orthoferrites the anisotropy and domain wall energies are substantially higher and although the same technique can theoretically be used, it requires an inconveniently large magnetic field and has not been achieved in practice.

De Jonge and Druyvesteyn (Ref. 3) have successfully churned imperfect garnet crystals with low anisotropy by using a very small air coil carrying large current pulses and applying the churning field parallel to the easy axis of the crystal or orthogonal to its major plane surface. Similarly, Cape and Lehman (Ref. 4) have formed bubble foam in stressed garnet layers. As a matter of fact, Nemchik and Charap (Ref. 5) attribute the ease of bubble formation in garnets to large mobility inhomogenieties. To quote them: "Garnets have regions where the local mobility is ten times the average value, (while) orthoferrite having very uniform properites, fails to produce bubble domains."

Thus, it appears that homogeneous crystal platelets with large magentic anisotropy fields and large domain wall energies, such as orthoferrites, require an unrealistically large churning field if it is applied in the plane of the crystal and are impossible to churn by an air coil carrying a pulsed current with the magnetic field applied along or parallel to the easy axis of the crystal. Any uniform field applied along the easy axis which is strong enough to break up the elongated domains will exceed platelet saturation and will polarize the whole platelet freezing out all domains (Ref. 6).

SUMMARY OF THE INVENTION

The present invention achieves the creation of more magnetic domains than occur naturally in the crystal, that is, it achieves the creation of a bubble foam or large number of bubbles by providing the apparently contradictory requirements of a bubble churner useful for orthoferrites. These requirements are:

1. a high intensity pulsed field applied along the easy axis with fast rise and fall time;
2. an extremely localized field surrounded by steep field gradients confined to one portion of the platelet area; and,
3. field gradients which are curved in the platelet plane at said localized portion to provide the required pinch-off and wall forming forces.

These requirements are provided in the present invention by using a magnetically soft amorphous ferrite flux concentrator with a semitoroidal configuration having one end of the toroid pointed to a 90° included angle, so as to apply perendicularly to the plane of the crystal or along the easy axis thereof a pulsed field which provides the above requirements.

BRIEF DESCRIPTION OF THE DRAWINGS

The manner in which this is achieved together with other objects and advantages of the invention will be more clearly seen from the attached drawings in which like reference characters refer to like parts throughout and wherein:

FIG. **1** is a perspective view showing the manner in which a magnetic field generating element is shaped and positioned to apply a magentic field to an orthoferrite crystal;

FIG. **2** is a plan view of the magnetic domains in the crystal showing a stage of the process at which an increasing current in the exciting coil forms an expanding domain in the platelet;

FIG. **3** is a view similar to FIG. **2** showing the magnetic domains at a later stage in the process when the current pulse stops and the fields in the pole piece and in the platelet collapse; and,

FIG. **4** is a view similar to FIGS. **2** and **3** showing the later effect of zero field from the pole piece and the resulting pinch-off of the new domains.

DETAILED DESCRIPTION OF THE INVENTION

As was noted above, the requirements of a bubble churner useful for breaking up domain walls in sheets of magnetic material characterized by a preferred direction of magnetization out of the plane of the sheet and by high anisotropy and high domain wall energy such as the orthoferrites possess, are apparently contradictory in that the churner must form a high intensity magnetic field, the maximum magnitude of which exceeds the greatest bias field magnitude at which stable domains can be maintained in the material and the direction of which is perpendicular to the plane of the sheet of material, while at the same time the field must be localized in the sheet of material and have steep field gradients which are curved in the plane of the sheet of material at at the point of localization therein. This requirement permits a field to be applied at one point in the crystal which is large enough to break up domain which while still permitting already existing bubbles to continue to exist in other portions of the crystal. Additionally, the field intensity must be rapidly pulsed to form a single large rapidly expanding and contracting domain in the sheet of material at the localized point of application of the field. The pulse must fall rapidly enough to provide reduced magnetic gradients and shrinking domain circumference to thus form excess wall area surrounding a domain wherein the excess wall area is necessarily absorbed by the formation of a plurality of pinched projections extending from the original domain. If now the rapid reduction of the field by the fast fall time of the pulse is carried through to zero field at the end of each pulse these projections can be pinched off to form single domains and these domains in turn separate from each other and from the large domain by mutual repulsion.

In order to carry out this process a magnetically soft amorphous ferrite flux concentrator with a special pole profile is used as shown in FIG. **1** to obtain the desired churning action. As can be seen therein, the shaped end **25** of pole piece **21** forms a magnetic field perpendicular to the plane of the crystal platelet **22** which is magnetically unbiased or which may be weakly biased in the same direction **23** as the pole field. A magnetic domain **30** surrounded by a wall **35** (FIG. **2**) will form in the platelet opposite the end **25** of pole piece **21** and its wall **35** will follow the contour of the cross-section of the pole piece projection **25** which is parallel to the plane of the major top surface of the crystal **22**. A plan view of that portion of domain **30** which lies under the point of the angle included between tapered faces **25***a* at **25***b* of end **25** of piece **21** is shown in FIG. **2**. A rising pulse producing an increase in current through the excitation winding **26** on the pole piece **21** will move the initially formed domain wall **35** in direction **32** away from the pole piece to such contours as **27** and **24** (FIG. **1**).

In one experimental example of the invention the crystal platelet **22** was a crystal of terbium orthoferrite and the pulse generator connected to winding **26** formed 2 microsecond pulses spaced 16.6 milliseconds apart with an adjustable peak current of 0 to 120 amperes. This pulse generator (not shown) was connected to feed four turns of wire forming the excitation coil **26** on pole piece **21**. This wire was wrapped around the pole piece which was a bisected ferroxcube toroidal ferrite core (type 768T188-3E2A) which had dimensions of 0.285 inches inner diameter, 0.500 inches outer diameter, and 0.190 inches wide. One pole piece projection **25** of this half-toroid was ground to a point having a 90° angle included between two flat surfaces **25***a* and **25***b* respectively. By virtue of the toroid being symmetrically bisected, the pointed pole piece projection **25** also made a 90° angle with the flat surface of the toroid positioned parallel to the major plane surface of the crystal platelet **22** so that the field generated was substantially perpendicular to the plane of the crystal and had the required characteristics set forth above.

The flux concentrator when slowly passed over the crystal platelet effectively breaks up the long meandering domains naturally occurring in unbiased orthoferrite and provides a simple effective domain injector which is capable of rapidly generating multiple domains for the purpose of manufacturing devices of the type discussed above.

During a current pulse through the coil **26** of the flux concentrator, a single large, rapidly expanding and contracting magnetic domain **30–31** is formed in the crystal platelet area opposite the surface of the pole piece which is parallel to the top of the crystal platelet and at the specially shaped end **25** of the pole piece wherein the magnetic field **28** from the pole piece is directed in opposition or antiparallel direction to the magnetic field **29** of the meandering domains to be broken up or in the normal bias direction **23** of a field applied to the platelet in operation. It has been experimentally found that the wall surrounding this domain must be curved in order to form bubbles. It is believed that they are formed by pinching them off from the expanding and contracting larger domain as it contracts from its maximum size **31** to its minimum size **30**. This curvature is provided by grinding down pole piece **25** to the shape shown in FIG. **1** wherein the flat surface **25***a* and **25***b* have a 90° angle included between them and provide the localized curved field having steep gradients around it which is pulsed with a fast rise and fall time as noted above. It was found that a pole piece with a sharper contour, i.e., a smaller angle between the flat surfaces **25***a* and **25***b* causes magnetic saturation of the pole piece due to the reduced cross section of the magnetic medium. Conversely a pole piece with a larger included angle does not provide sufficient curvature for the bubble forming mechanism of this invention to take place. A reasonable range of angular tolerance from the preferred 90° is plus minus 10° for the amorphous ferrite core presently used, or for materials with similar permeability and saturation. Cores with higher permeability and saturation magnetization can be formed into bubble churners with more acute angles.

The detailed bubble formation phenomenon occurs so rapidly that high speed cinematography is required for a complete analysis. Such cinematography is complicated by the optical density of the crystal platelet which imposes the difficult requirement of extremely high optical flux densities in the monitoring Faraday microscope. Consequently, the exact mechanism of bubble formation is not fully understood at this time. It is believed, however, that the sequence of events illustrated in FIGS. **2**, **3** and **4** is responsible for the formation of the large number or foam of bubbles which has been observed.

As shown in FIG. **2**, increasing current in the exciting coil **26** will form the expanding domain **31** from original domain **30** in the uniaxial platelet opposite the under surface of the pole piece end **25**. This domain **31** expands with time in the direction **32** obliterating all domains of opposite polarity encountered during the expansion and forming wall **24**.

FIG. **3** shows the events taking place when the current pulse stops and the fields in the pole piece and in the domain **31** in the platelet collapse. The curved wall **24** surrounding domain **31** contracts and the field gradient which forms the domain all decreases. Two mechanisms are now at work forming "superfluous wall area." First, the reduced gradient generates meandering walls, and secondly, the shrinking domain circumference can accommodate less wall length. Consequently, these two mechanisms form excess wall area surrounding a domain with many projections **42** which are pinched as at **41** at the point of connection to the residue of the collapsing wall **24**.

FIG. **4** shows the final state of affairs effected by zero field from the pole piece. The new domains **51** have been pinched off by cutting the pinched portions **41** of projections **42** and are now entirely separated from the original wall **24**. The new domains **51** are then separated from each other and from the original domain by mutual repulsion.

The foregoing description represents an idealized sequence in accordance with the best understanding presently available from experimental results. In reality, a few new domains have been observed to be formed with each pulse. The effects or residual coercivity in the crystal platelet in aiding or hindering this mechanism are not presently known. It is however believed that this description approximates the bubble forming sequence reasonably well since a "positive" domain expanding around the pole piece leaves "positive" miniature domains behind while a "negative" pole piece domain forms "negative" small domains. These resulting domains in static state can be readily observed with a Faraday microscope after they have been generated and the pole piece or churner has been removed.

What is claimed is:

1. The method of forming a plurality of cylindrical uniaxial domains in a sheet of magnetic material characterized by a preferred direction of magnetization out of the plane of the sheet, each of said domains having its axis of symmetry extending in said preferred direction, said method comprising the steps of:

a. maintaining a bias field in said preferred direction at all points throughout said sheet of magnetic material, said bias field having a value less than the saturation value for said sheet in order to sustain domains which are formed in said sheet at any point thereof;

b. forming a localized high intensity magnetic field at a preselected point in said sheet in the direction of and within the confines of said bias field, the maximum magnitude of said localized field exceeding the greatest bias field magnitude at which stable domains can be maintained in said material and the direction of said localized field being perpendicular to the plane of said sheet of material and parallel to said preferred direction of magnetization, said field having a localized maximum net intensity in said sheet of material and having steep field gradients which are curved in the plane of the sheet of material at said point of localization;

c. rapidly increasing and decreasing said field intensity in pulses to form a single large rapidly expanding and contracting domain in the sheet of material at said localized point of application of said field, said pulses having a fast fall time to provide rapidly shrinking magnetic gradients and a shrinking domain circumference in said sheet of material; and,

d. reducing said field at the end of each pulse to form a plurality of separate cylindrical domains and to separate them by mutual repulsion thereby forcing them out of the area subject to said high intensity localized field so that they are sustained in an area of said sheet of magnetic material subject only to said bias field.

2. The method as in claim **1** wherein said sheet of magnetic material is further characterized by high anisotropy field and high domain wall energy.

3. The method as in claim **2** wherein said sheet of magnetic material is a uniaxially anisotropic orthoferrite crystal platelet.

4. The method as in claim **1** wherein said localized magnetic field having steep field gradients which are curved in the plane of the sheet of material at the point of localization is the field pattern produced from the tip of a bisected toroidal core which has been brought to a point having substantially a 90° included angle and which is supplied with field generating energy by a coil wrapped around said core.

5. The method as in claim **4** wherein said pulses have a duration of the order of magnitude of two microseconds and are spaced apart by a time interval of the order of magnitude of 16 milliseconds.

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