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A New Type of Cylindrical Magnetic Domain (Bubble Isomers)

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I. INTRODUCTION

Cylindrical magnetic domains (bubbles) are, by now, well known. Their device applications[1] and theoretical description[2] have been adequately described. We shall call these bubbles "normal" (NB). In this B.S.T.J. Brief we wish to describe a new type of cylindrical domain that can coexist in many of the materials that support NB's. They were first observed by R. F. Fischer and R. H. Morrow of Bell Laboratories while testing a Y-Bar shift register using a platelet cut from bulk GdTbIG. These domains, which we shall call "hard" bubbles (HB), have properties that can be substantially different from NB's.

II. STATIC PROPERTIES

A NB has a diameter range[2] from run-out to collapse of about 3:1 and a bias field change[2] of about 0.10 ($4\pi M$). Some HB's, on the other hand, have a diameter variation of 10:1 and exist over a bias range of 0.23 ($4\pi M$). In one material (thickness = 5.2 μm, characteristic length = 0.67 μm, $4\pi M$ = 190 gauss), NB's collapse at a diameter of 3 μm and bias of 92 Oe whereas the HB's collapse at a diameter of 0.7 μm and bias of 135 Oe.

The diameter and field bias at run-out are similar for both NB's and HB's. Any material that shows HB's also exhibits a range of bubbles that collapse at diameters and bias fields between those of NB's and HB's. These we shall call intermediate bubbles (IB). In materials thus far studied, there appears to be a continuum of IB's, i.e., the bias field at collapse forms a continuous range of values between that of the NB and HB. Thus a NB and a HB are the limiting cases of the IB continuum. All types of bubbles are classed together as bubble isomers.

HB's have been formed in both bulk and epi films. All of the experiments with HB's have thus far been restricted to garnet materials. In a given material, all bubble isomers have the same Faraday rotation, and the domain walls appear identical, with no apparent structure, under optical microscopic observation. The walls also appear identical using Bitter pattern techniques.

There are many ways that HB's can be formed, but the technique with the most success consists of pulsing the bias field by means of a small circular coil (diameter of about 100 μm) just above a NB in the material. With a bias pulse of about 200 Oe in a direction that causes the NB to expand, a NB will grow to the size of the coil. When the pulse is terminated, the domain configuration of the material within the coil changes rapidly and at the correct bias a multifingered domain will result. When the bias is increased, the resulting bubble is frequently an IB or HB. A common factor to all HB formation appears, at this time, to be a rapid demagnetization of the material into a domain pattern with many complex fingers attached to a central stripe domain.

An experiment that leads to some insight towards the nature of a HB is illustrated in Fig. 1. In this experiment a hard bubble (1) is

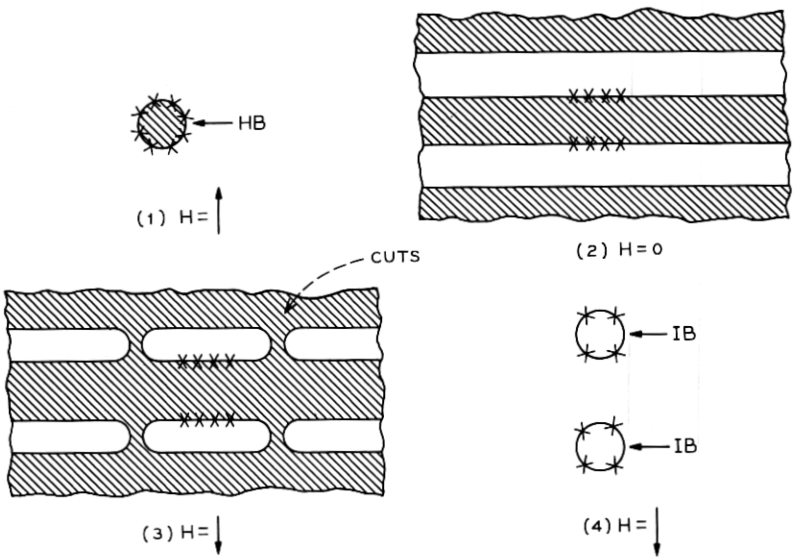

Fig. 1—HB cutting experiment demonstrating the conversion of one HB to two IB's.

allowed to run out by decreasing the field to zero (2). The bias field is now increased in magnitude in a sense that is opposite to that in (1) and the cuts are made in domains adjacent to the parent HB strip (3). When the bias field is increased further [also in a direction opposite to that in (1)], two IB's result. This procedure can be repeated on one of the IB's and the result is that it tends to become more like a NB.

III. TRANSPORT PROPERTIES

HB's behave differently from NB's in a magnetic field gradient. Whereas a NB moves parallel to the gradient with a velocity that in most cases can be described by a mobility, a HB moves at an angle to the gradient. Table I contains the results of experiments on an epi layer of $YGdTmGa_{0.8}Fe_{4.2}O_{12}$ grown on a (111)-oriented substrate of GdGaG. $V_{\parallel}$ and $V_{\perp}$ are the velocities parallel and perpendicular to the gradient and ΔH is the field difference across the bubble diameter. The value of the angle, θ, that the motion of the HB defines with respect to the field gradient is equal to $\tan^{-1}(V_{\perp}/V_{\parallel})$. Several points can be established from Table I: (*i*) the forward velocity, $V_{\parallel}$, is more or less a constant, independent of drive; (*ii*) θ increases as the drive increases, reaching a value of 80 degrees at the highest drive; (*iii*) for the same drive a NB moves much more rapidly than a HB. A NB in this material can be characterized by a mobility of about 500. Other aspects of HB transport are that there are both left-going and right-going HB's, i.e., $V_{\perp}$ can be either to the left or right. It has also been established that the motion is entirely defined by the field gradient and is independent of the orientation of this gradient in the plane of the material. IB's move in a similar way to HB's, but for a given value of drive θ is less for an IB. The value of θ is correlated with the value of the collapse field, i.e., IB's that collapse at lower bias fields have smaller values of θ.

TABLE I—TRANSPORT PROPERTIES OF HARD BUBBLES IN $YGdTmGa_{0.8}Fe_{4.2}O_{12}$

Bubble Dia (μm)	$V_{\parallel}$ cm/s	$V_{\perp}$ cm/s	ΔH Oe
6.2	12	26	0.8
	12.5	72.8	2.5
	16.3	144	5.9
3.9	8.3	13.5	0.3
	11.8	34.8	1.4
	10.5	75.5	3.5
3.3	12.5	44	3.0

It has been found that HB's in this material will irreversibly transform to an IB or NB at drives of around 2 Oe/μm. A HB will also revert to a NB if the bubble is rapidly expanded in a rapidly decreasing bias field.

IV. HB MODEL

All of the experiments thus far performed, with the exception of the optical observation of the walls, indicate that the properties of the IB and HB are due to characteristics of the wall. The transport mechanism for the transverse motion can only be explained by a wall motion mechanism, as the moment within the bubble, no matter how it is oriented, cannot produce a transverse drive in a field gradient. The bubble cutting experiments are also readily explained by wall properties. We can explain the number of different IB's by stating that the wall can possess a number of elements and that a HB has the largest number. The left- and right-going transport properties require that this element exist in two forms. We propose for this element the wall structure shown in Fig. 2. It can exist in both a clockwise (cw) and counterclockwise (ccw) orientation. The right-going bubble has one of these orientations and the left the other. An IB or HB can only exist with one type of element, as a cw element can easily be annihilated with a ccw element. Optical observation of the domain walls, as stated earlier, does not reveal these elements. We postulate that they are too small for observation.

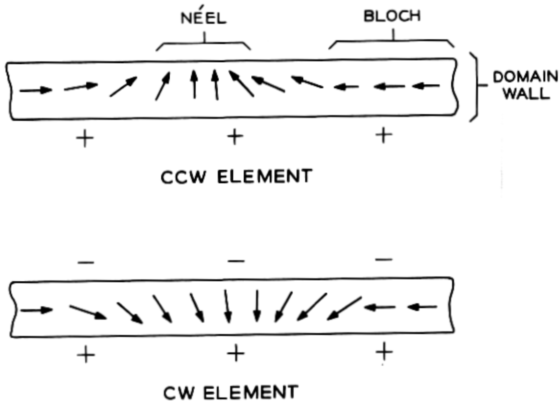

Fig. 2—Elements of a domain wall that show Bloch to Néel transitions with counterclockwise and clockwise rotation of the spins. The arrows represent the magnetic spins in the center of the domain wall. The material below the wall is magnetized up (+), while that above the wall is magnetized down (−).

V. ACKNOWLEDGMENT

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Multilayer Epitaxial Garnet Films for Magnetic Bubble Devices–Hard Bubble Suppression

By A. H. BOBECK, S. L. BLANK, and H. J. LEVINSTEIN

(Manuscript received May 26, 1972)

A conventional magnetic bubble material consists of a magnetic garnet film deposited on a nonmagnetic substrate. Garnet films with stress- and/or growth-induced uniaxial anisotropy are deposited by chemical vapor deposition (CVD) or liquid phase epitaxy (LPE) usually on $Gd_3Ga_5O_{12}$ substrates. In this B.S.T.J. Brief we report on the properties of multilayer garnet films deposited by LPE.

An extremely important property of the multilayer epitaxial films that we will describe is the complete absence of hard bubbles.[1] Hard bubbles differ from normal bubbles in both their static[2] and dynamic[3] behavior. It is quite unlikely that garnet films which support hard bubbles will find use in devices. Hard bubbles generally have much lower wall mobilities than normal bubbles and their presence severely limits the data rates.

The work on multilayered magnetic films was originated after the study of a series of single-layer epitaxial films of nominal composition $Gd_{2.34}Tb_{0.66}Fe_5O_{12}$ grown on (111)-oriented $Nd_3Ga_5O_{12}$ substrates.[4] Strip domains differing in both width and Faraday contrast were often observed in these films. It was determined that the wide, high-contrast

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A variation in composition through the height of the epitaxial layer producing a magnetization and/or wall energy gradient can account for many of the effects observed in these films. W. J. DeBonte[5] has determined stability criteria for surface bubbles.

The classic magnetic bubble is a reversed volume of magnetization in the shape of a right cylinder the stability of which has been reported by A. A. Thiele.[6] However, as already noted above, some epitaxial films exhibit behavior not predicted by Thiele's theory. In an attempt to produce in a more controllable manner the equivalent of some of these films, several two-layer and three-layer epitaxial garnet films were prepared. We searched, for example, for multilayer combinations that would support bubbles over a wider range of bias field than single-layer films.

The cross section of the standard bubble domain is illustrated in Fig. 1a. This bubble is bounded by a domain wall which W. J. Tabor, et al.,[1] report can contain a large number of Bloch-Néel transitions. In Fig. 1b, a magnetic layer intermediate to the bubble supporting layer and the substrate has been added. If the intermediate layer ① is assumed saturated by an external bias field, as it would be if the bubble collapse field in layer ① is much less than the strip-to-bubble transition in the upper layer ②, then an additional domain wall at the base of the cylinder will be present. By providing a "cap" to the

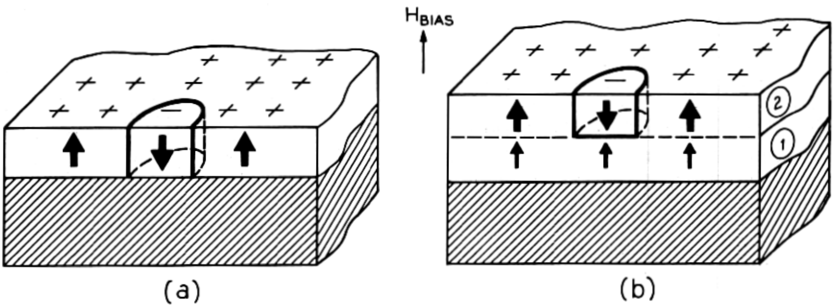

Fig. 1—(a) Sectional view of a conventional bubble domain found in a uniform single-layer garnet film deposited on a nonmagnetic substrate. (b) Addition of an inner low-moment magnetic layer, saturated upward by the bais field, provides a domain wall "cap" to the base of the bubble. This is defined as a Type I bubble.

bubble, the degrees of freedom available to the wall geometry are apparently reduced to those that allow normal bubbles and not hard bubbles.[7] When viewed in a polarizing microscope, surface bubbles have subtle shadings which convey the impression that they are more hemispherical than cylindrical.

Evidence that the adjacent garnet layers exchange couple is found in the presence of an effective bias field very similar in nature to that reported by T. W. Liu, et al.,[8] for $Co_{3.2}Cu_{1.3}Fe_{0.5}Ce_{0.25}Sm_{0.75}$ films deposited on $Sm_{0.55}Tb_{0.45}FeO_3$ platelets. The effective bias field H_{ex} derived there becomes, for our configuration, $H_{ex} = \sigma_{w12}/2h_2M_{s2}$ where σ_{w12} , h_2 , and M_{s2} are the wall energy of the interface, thickness, and magnetization of layer ②, respectively. It has been determined experimentally that adjacent garnet films do exchange couple at their interface and that the exchange energy is at a minimum when their respective Fe sublattices align parallel. For the bubble geometry of Fig. 1b, the effective bias field H_{ex} adds to the external bias field. Examples are found, however, where the polarity of H_{ex} is such that H_{ex} subtracts from the bias field.

Refer to Fig. 2a. In this two-layer configuration, garnets are chosen with compensation temperatures on opposite sides of room temperature. In actual two-layer specimens the demagnetized strip domains assume a variety of configurations with that illustrated in Fig. 2b being typical of most. Solid arrows define net magnetization directions and dotted arrows tetrahedral Fe sublattice directions. The latter is included so that we may establish the location of the interfacial domain wall energy. With a suitable external bias field, strip domains in the layer ① disappear and surface bubbles are stable in layer ②. Note that the interfacial domain wall lies *outside* the bubble and the bias field needed to collapse the bubble is therefore increased over that needed to collapse a bubble in an identical but isolated upper layer. Hard bubbles are eliminated in this bubble geometry which we designate Type II just as they were in the geometry of Fig. 1b which we designate Type I. Type II bubbles should attract one another at close spacings.

The direction of magnetization of the lower layer of Fig. 2c depends critically upon the thickness h_1 of the lower film. By comparing the applied field energy of the bottom layer to the interfacial domain wall energy, it can be shown that $h_1 > \sigma_{w12}/H_A \rightarrow M_{s1}$ is a necessary inequality for Type II bubbles. For typical garnet film parameters of $\sigma_w = 0.2$ erg/cm^2, $H_{bias} = 100$ Oe, and $M_{s1} = 4$ gauss, the calculated minimum for h_1 is 5 μm.

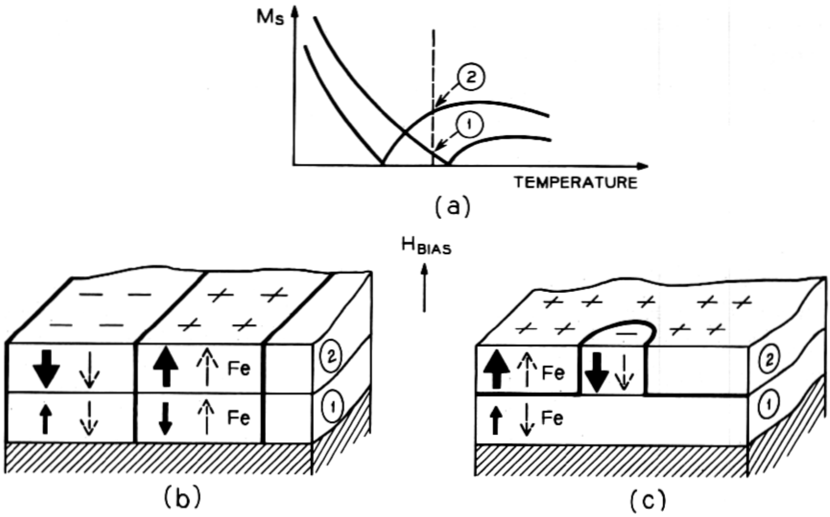

Fig. 2—(a) Garnet layers with compensation temperatures on opposite sides of the operating temperature are used in this two-layer film. (b) Domain pattern at zero bias. Solid arrows indicate net magnetization, dotted arrows the tetrahedral Fe sublattice orientation. (c) At operating bias a Type II bubble is observed since interfacial domain walls are present wherever the Fe is aligned antiparallel.

Multilayer films prepared for this study include both Type I and Type II double-layer films and a Type I triple-layer film. In the latter example, completely enclosed bubble domains reside in the middle layer of the three-layer sandwich. The films were grown on (111)-oriented $Gd_3Ga_5O_{12}$ substrates by the "dipping" technique utilizing supercooled melts.[9,10] The apparatus and experimental details have been discussed in detail elsewhere.[9,10] Melts were contained in cylindrical platinum crucibles 3.8 cm diameter by 5 cm height. A platinum partition was welded into the crucible allowing two melts of different compositions to be contained in the same furnace. Melts used for upper and lower layers were adjusted to saturate at the same temperature within ±5°C.

One such film consisted of an 8-μm, high-moment upper layer of $Er_{1.8}Eu_{1.2}Fe_{4.34}Ga_{0.66}O_{12}$ garnet grown epitaxially on a 6-μm, low-moment lower layer of $Er_{1.8}Eu_{1.2}Fe_{3.79}Ga_{1.21}O_{12}$. At zero bias the strip domain pattern for this two-layer film is indistinguishable from that of a single-layer film. There is maximum Faraday rotation and strips are equal in width. It is only with an applied bias that the undulating surface domains are seen. Surface and composite bubbles can coexist in this film. Surface bubbles range from 20–4 μm in diameter over a bias range of 38–63 Oe. Composite bubbles range from 20–10 μm for a 48–63 Oe bias range.

A second example is a two-layer film composed of a 5-μm, high-moment upper film ② of $Tm_{0.35}Y_{1.59}Gd_{1.06}Ga_{0.62}Al_{0.43}Fe_{3.95}O_{12}$ garnet grown epitaxially on a 5-μm, low-moment lower film ① of $Tm_{0.24}Y_{1.50}Gd_{1.26}Ga_{0.76}Al_{0.36}Fe_{3.88}O_{12}$. Film ① has a compensation temperature at +27°C; film ② at −18°C. Either Type I or Type II surface bubbles can be established with this combination. Above 23°C Type I bubbles are supported, below 20°C either Type I or Type II bubbles can be established, there being a hysteresis in the magnetized state of layer ①. At a temperature such as 10°C the operating bias fields for Type I and Type II bubbles are displaced by 12 Oe indicating the $H_{ex} = 6$ Oe. Using $H_{ex} = \sigma_{w12}/2h_2M_{s2}$ we calculate $\sigma_{w12} \sim 0.1$ erg/cm^2.

This film, which has a domain wall mobility of 500 cm/s-Oe, has been used successfully in devices at 100-kHz data rates.

The fabrication of multilayer films adds a further complication to the process of manufacturing bubbles supporting magnetic films. The eventual utilization of films made by this approach will depend upon the outcome of other solutions being considered for the hard bubble problem. An alternate approach is ion implantation[11] into a single-layer film.

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