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Submicrometer Stripes and Bubbles in Amorphous Films

Abstract: Lorentz microscopy is used to study amorphous thin films of Gd-Co-Au and Gd-Co-Mo having a range of Q values. Stripe and bubble formation are shown as a function of perpendicular bias fields and pulsed or rotating in-plane fields. In the presence of an in-plane field, stripes contain a pair of Bloch lines and break into rows of Bloch-line containing bubbles. A unichiral stripe, however, forms a unichiral bubble that is stable to higher perpendicular bias fields than are Bloch-line bubbles. Bloch-line rotation in bubble walls in the presence of external rotating fields is demonstrated, and Bloch-line motion due to sweeping in-plane walls is shown. The rare occurrence of four Bloch lines in a 0.2-μm bubble is observed, as is the pearl-like accumulation of multiple Bloch lines in walls of irregularly shaped domains.

Introduction

Magnetic bubble devices using two-micrometer bubbles in amorphous materials have been investigated extensively by Kryder et al. [1]. With the availability of electron beam and x-ray lithography it is expected that devices using even smaller bubbles will be studied. In this paper we do not report on any particular device but rather present our results, obtained by Lorentz electron microscopy, on bubbles with a diameter of 0.07 μm and larger. Bubbles of such small sizes are possibly the extreme limit of application in this technology and can, if such applications are ever realized, lead to information packing densities in excess of 10^9 bits cm^2. The small bubbles are obtained in sputtered amorphous films of Gd-Co-Au and Gd-Co-Mo alloys. The films vary in thickness between 600 and 1000 angstroms, and the quality factor of these films, defined as Q, equal to the uniaxial anisotropy energy divided by the demagnetizing energy, varies over a large range. For the purpose of this study we define a low-Q film as one that exhibits evidence of in-plane domain wall contrast and a high-Q film as one in which in-plane domain contrast is absent. The latter also gives clear images of perpendicular domain walls at remanence. We find that the image contrast from stripe domains is a function of the applied bias field as well as of the Q of the films. The range of Q that we investigate varies between 0.3 and 1. These values are determined by ferromagnetic resonance.

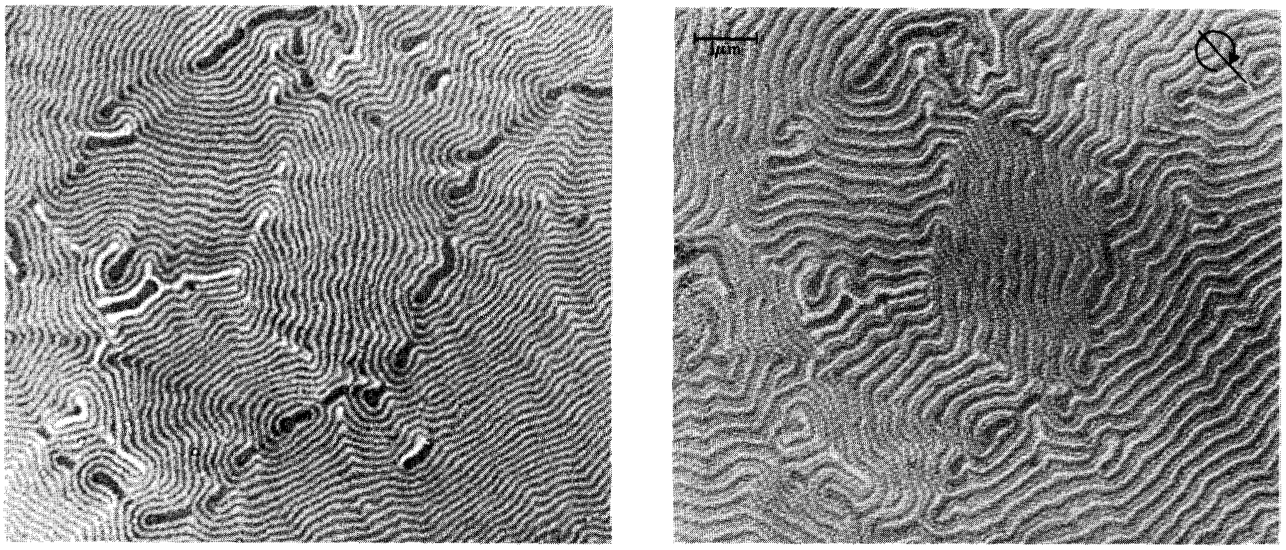
Experimental arrangement

The amorphous films were deposited on a rock salt substrate by rf sputtering. The films were then floated off the salt crystal by dissolving the latter at the film-salt interface in water and were subsequently examined by Lorentz electron microscopy in a Philips EM 301 instrument. The details of the technique have been described elsewhere [2]. The normal electron microscope heating stage was modified so that small Helmholtz coils could be fitted into the microscope to provide in-plane pulsed and rotating fields. Also a coil for a perpendicular pulse field was built into the stage. Typically all the coils were two to four millimeters in diameter and were capable of producing pulsed fields of a few hundred oersteds. The perpendicular bias field was provided by the objective lens of the microscope. In order to obtain high contrast, the moment of the film was kept high by using Gd-Co-Au films, e.g., $4\pi M_s \approx 0.4$ T (4×10^3 G). We also examined low-moment films of Gd-Co-Mo, e.g., $4\pi M_s \approx 0.2$ T, with the intent of investigating them for device applications.

Experimental results

• *Stripe domains*

Films with a low value of Q have Lorentz contrast of the type shown in Fig. 1(a). The contrast is readily understood in terms of the superposition of a perpendicular and an in-plane magnetization. The former gives rise to the stripe domains and the latter defines the directions along which the stripes lie. A second type of domain wall is formed where the in-plane component of magnetization changes direction. The contrast that delineates the stripes arises from domain walls, where the



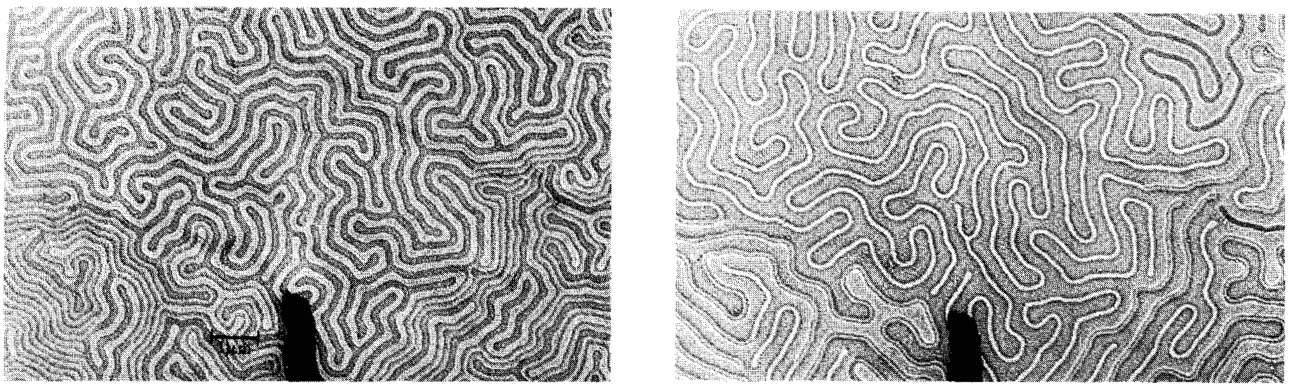
(a) (b)

Figure 1 (a) Low-Q Gd-Co-Au material showing stripes with in-plane domain walls at normal electron beam incidence. (b) Same area tilted 30° around axis indicated by bar. $H_{\perp} = 0$.

electron beam is normal to the plane of the film. The diffuse wall images associated with a change in the direction of the in-plane magnetization are outlined by the broad relatively dark and light walls. When the sample is tilted with respect to the electron beam the contrast changes and a pseudodoubling of the stripe width is noted. The stripe contrast is no longer associated with the walls but rather with the stripe itself. With an appropriate amount of tilt of the sample, the electron beam can be made collinear with the direction of the magnetization in one of the two sets of of stripes, which then gives no Lorentz deflection. The adjacent stripes, however, have increased contrast, giving rise to the "doubling" shown in Fig. 1(b). The central diamond-shaped region has a component of in-plane magnetization that is not perpendicular to the tilt axis and hence still shows residual wall contrast. However, areas where the in-plane magnetization is perpendicular to the tilt axis (indicated in the right upper corner) clearly show a doubling. Frequently the magnetization changes direction and the transition region then shows the beginning of the doubling of the period, as shown in Fig. 1(b).

The distinction been stripe and strip domains is essentially one of Q. Low-Q films have in-plane domains with perpendicular ripple. This ripple appears as stripes whose width is independent of Q and is equal to the film thick-

Figure 2 (a) Medium-Q Gd-Co-Au material showing unichiral wall strips in center and Bloch-line wall strips on edges. $H_{\perp} = 0$. (b) Same area as in (a), with $H_{\perp} = 8 \times 10^4 \mathrm{A/m}$.



(a) (b)

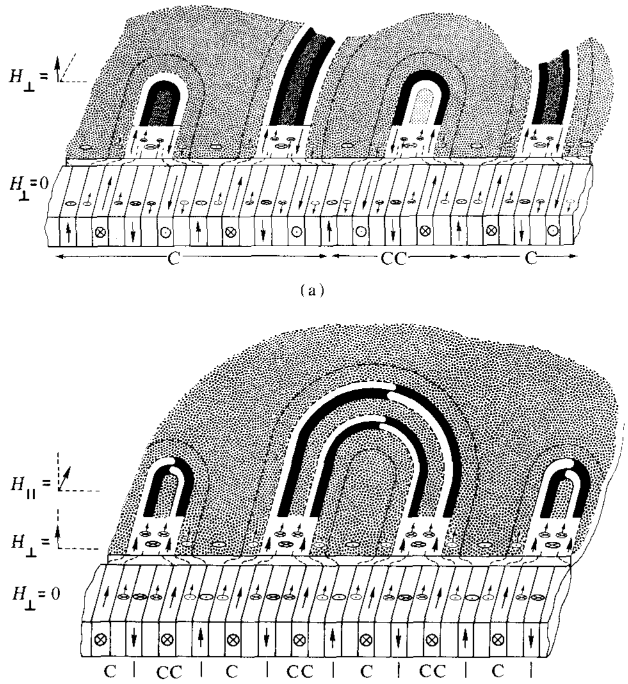


Figure 3 (a) Sketch of magnetization distribution and observed electron contrast with and without application of a perpendicular bias field. (b) Same as (a) with the addition of an applied in-plane field leading to Bloch-line wall strips and bubbles.

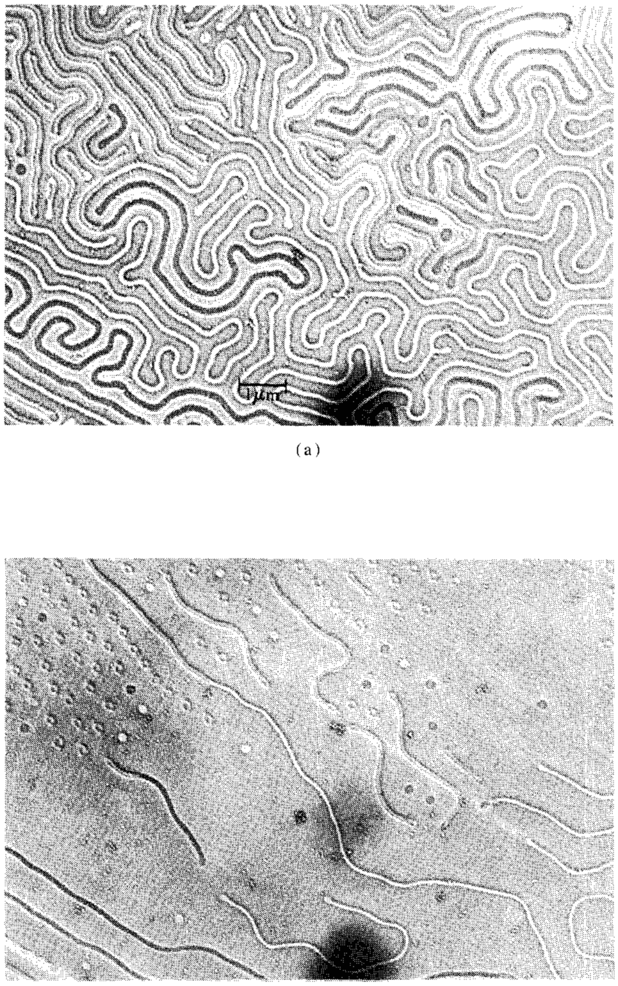
ness. High-Q films have domains of perpendicular magnetization. These are called strip domains and their width is a function of Q, the minimum width being equal to the film thickness.

With materials of successively higher Q, the in-plane component of the magnetization decreases and Lorentz contrast becomes increasingly due to the domain walls. If the walls are of unichiral nature, then electrons are either deflected into or out of a strip domain [3], effectively causing a focusing or defocusing of the intensity. This effect, combined with narrow strip width, gives rise to contrast that resembles the contrast obtained in light microscopy for Faraday or Kerr rotation, in which the volume of the domain rather than the walls produces a rotation of the polarized light. This can be seen in Figs. 2(a) and (b). The latter photograph is taken with an external bias field so that one set of the strip domains is narrower than the other. If the domain wall is not unichiral but contains Bloch lines, the focusing or defocusing effect is not present and the contrast normally associated with domain walls, for example on the lower-right and left-hand edges of Fig. 2, is much more evident. Figure 3 shows the proposed magnetization distribution in the amorphous thin films of intermediate Q and the change of that distribution after application of a perpendicular bias field. The front slab of Fig. 3(a) with $H = 0$ shows that for unichiral strips the magnetization vector across the strips continuously rotates through 360°, either clockwise (section C) or counter-clockwise (sections CC). The shaded slab shows the Lorentz contrast obtained in the image from typically winding walls and the change in the magnetization distribution in the film as a perpendicular bias field $H_\perp$ is applied. Figure 3(b) shows the same sequence when in addition a steady in-plane field along the direction of the strips is present. The illustration shows the rotation of the magnetization vector through 180° clockwise and counterclockwise, changing direction with each single strip. Application of a perpendicular bias field leads to the formation of Bloch-line strips as indicated in the shaded slab, which also shows the Lorentz contrast obtained in the image from such a magnetization distribution.

• *Bubble domains*

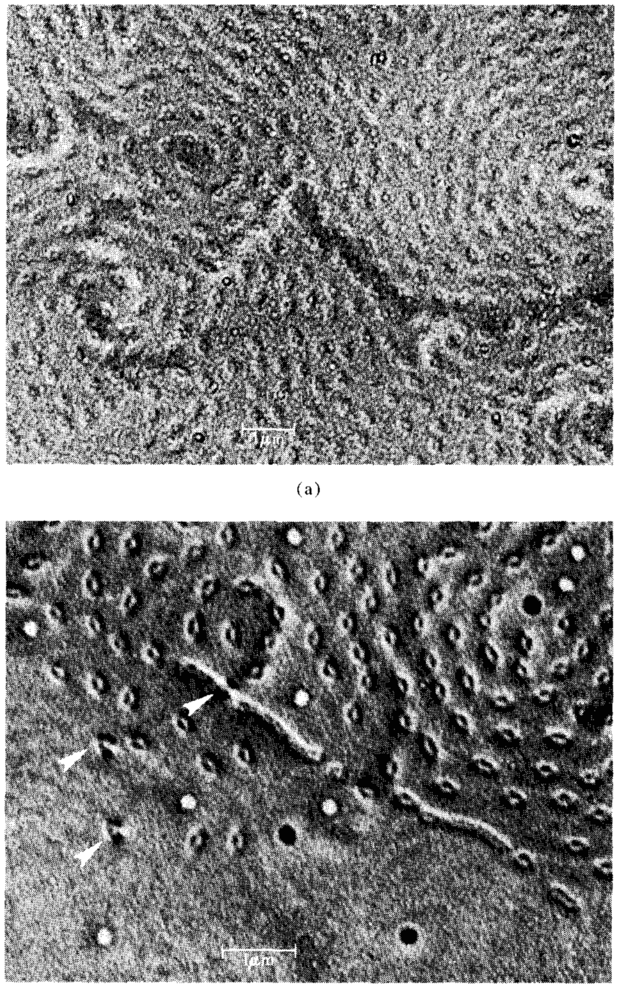
Although in low-Q materials bubbles do not form easily, and if formed, tend to saturate before the in-plane walls saturate, in intermediate-Q materials an increase in the perpendicular bias field generally leads to bubble formation. If the strip is unichiral, one bubble with a unichiral nature similar to the strip usually forms in the field of view. If, however, the strip contains a pair of Bloch lines, then increasing the perpendicular bias field leads to the formation of a string of bubbles with pairs of Bloch lines. The electron micrographs in Fig. 4 show this effect.

In Fig. 4(a) with a perpendicular bias field of 8×10^4 A/m (1000 Oe), we note the presence of strip domains containing Bloch lines in the top left-hand corner of the figure. In Fig. 4(b), when the external bias field is increased to 1.57×10^5 A/m, the unichiral strips containing no Bloch lines form few bubbles. However, the Bloch-line strips form an array of bubbles, most of which contain Bloch lines. These generally lie diametrically opposite from each other and the line joining them points to the direction of the in-plane component of magnetization. This in-plane component may be due to an external field caused by specimen buckle in the applied perpendicular field, or it may be due to the internal in-plane components of magnetization in the film. An example of the latter is seen in Fig. 5, where a large number of Bloch-line-containing bubbles map the in-plane component of magnetization at both sides of an in-plane domain wall. The difference between Figs. 5(a) and (b) is due to the Q's of the samples. The material in Fig. 5(a) is of very low Q and when the perpendicular bias is raised above 8×10^4 A/m all bubbles collapse, while the in-plane wall image still remains. Figure 5(b) shows a material of higher Q in which some unichiral bubbles are formed. When the perpendicular bias is raised they remain stable beyond the point where the



(a) (b)

Figure 4 (a) Medium-Q Gd-Co-Au material in strip stage. $H_\perp = 8 \times 10^4$A/m. (b) Same area as (a) with $H_\perp = 1.57 \times 10^5$A/m, causing formation of single unichiral bubbles and rows of Bloch-line bubbles.



(a) (b)

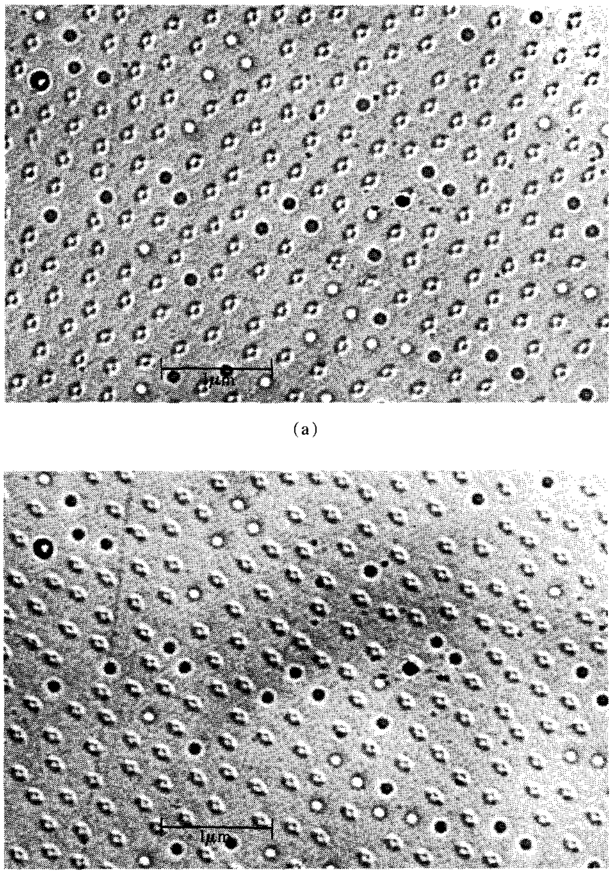
Figure 5 (a) Low-Q Gd-Co-Au material showing mapping of in-plane component to both sides of an in-plane domain wall. $H_\perp = 8 \times 10^4$A/m. (b) Gd-Co-Au, higher Q than in (a). Some unichiral (black and white) bubbles form. Arrows point to rare formation of bubbles with four Bloch lines in walls.

broad, diffuse in-plane wall image disappears. Figure 5(b) contains examples (marked by arrows) of bubbles with four Bloch lines. All previous observations on bubbles have contained only a pair of Bloch lines [2–6].

In order to verify the response of Bloch lines to an external magnetic in-plane field, we carried out dynamic experiments with rotating in-plane fields and found that the Bloch lines do indeed follow the rotating field. An example is indicated in Fig. 6, in which the external in-plane field in (a) is rotated 90° in (b). The unichiral bubbles serve as reference points. The observed Bloch-line rotation with external field is not unexpected, because the wall magnetization couples through the Zeeman term with the applied in-plane field to lower its energy. In fact the Zeeman term leads to a motion of Bloch lines along a strip domain, so that the contrast from a strip domain can be made to change continuously with a rotating in-plane field. We have not included strip domain micrographs here because the phenomenon is clearly demonstrated by the bubbles.

- *Bubble state conversion*

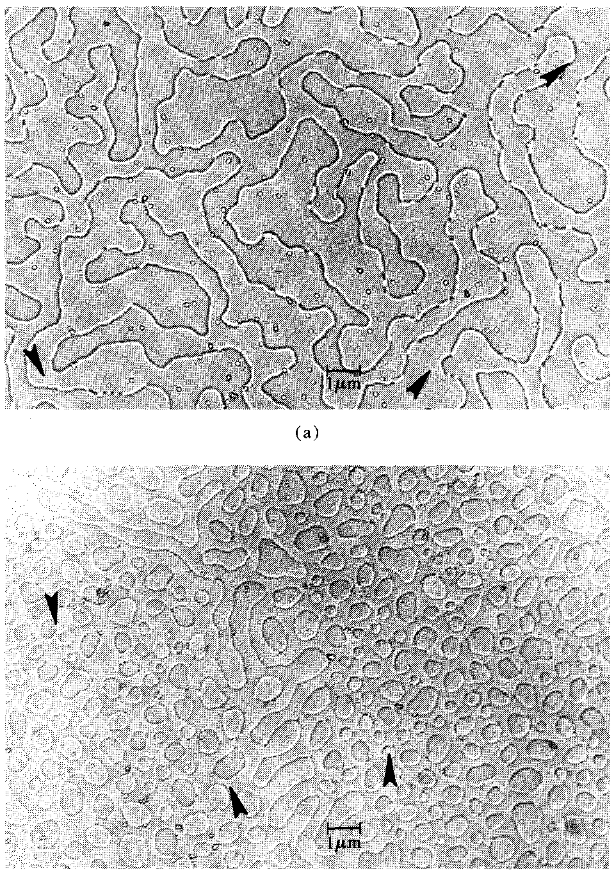
We have described the formation of Bloch-line bubbles from strips containing Bloch lines. We have also observed that in the absence of an in-plane field the Bloch-line bubbles readily convert to unichiral bubbles. An in-plane field, either an external one or a field due to low-Q material, was found necessary to stabilize them. In low-Q materials Bloch-line bubbles, once formed, collapse at lower fields than do the unichiral bubbles as the external bias field is increased.



(a)

(b)

Figure 6 (a) Bloch-line bubbles in Gd-Co-Au with in-plane field. $H_\perp = 1.6 \times 10^5$ A/m. (b) Same area as (a) after in-plane field was rotated 90°. Bloch lines follow rotation of field.



(a)

(b)

Figure 7 (a) High-Q Gd-Co-Au material showing multiple Bloch lines in walls created by pulsing. (b) Circular domains with double Bloch lines created after collapse of large (2 T) saturating in-plane field in high-Q material.

This observation is apparently in contradiction to observations on hard bubbles [7]. However, it must be kept in mind that the in-plane component of the magnetization lowers the wall energy and that this lowers the collapse field. In high-Q materials Bloch-line-containing bubbles are rare or are stable only under application of large external in-plane fields.

We were also able to convert unichiral bubbles to those containing a pair of Bloch lines by the application of an in-plane dc or pulsed field. Bubble state conversion from an $S = 1$ to $S = 0$ state was therefore possible with a combination of in-plane and perpendicular fields. Our qualitative observations support the findings of Hsu [8], who has mapped out the combination of in-plane and perpendicular bias field requirements for various bubble states. He deduced bubble states from dynamic measurements rather than by direct observation, as was done here.

Because our observation showed that most of the bubbles in low-Q films contained a pair of Bloch lines, we examined strip domains in films with low $4\pi M_s$ so that the domain size was large and corresponded to bubble materials with a diameter of 0.3 to 0.5 μm. The films are thin, and the observed domains have a rather "blotchy" appearance. This is attributed to a decrease in the wall stiffness coefficient [9]. Domain walls in such films which have low saturation fields readily respond to the drive fields and traverse relatively large distances.

There is no longer any evidence of an in-plane component of magnetization in such films. With a pulse width of the order of a microsecond and pulse amplitudes ranging from a few to a hundred oersteds, Bloch lines can readily be nucleated in the domain walls. The arrows in Fig. 7(a) show that the Bloch lines cluster and form a characteristic bead or pearl-like pattern in the wall contrast. Similar Bloch-line pairs were found after removal of a 2 T (2×10^4G) in-plane field, which resulted in the roughly circular domains shown in Fig. 7(b). We make the distinction between "circular" domains and cylindrical bubbles because the latter have a diameter-to-height

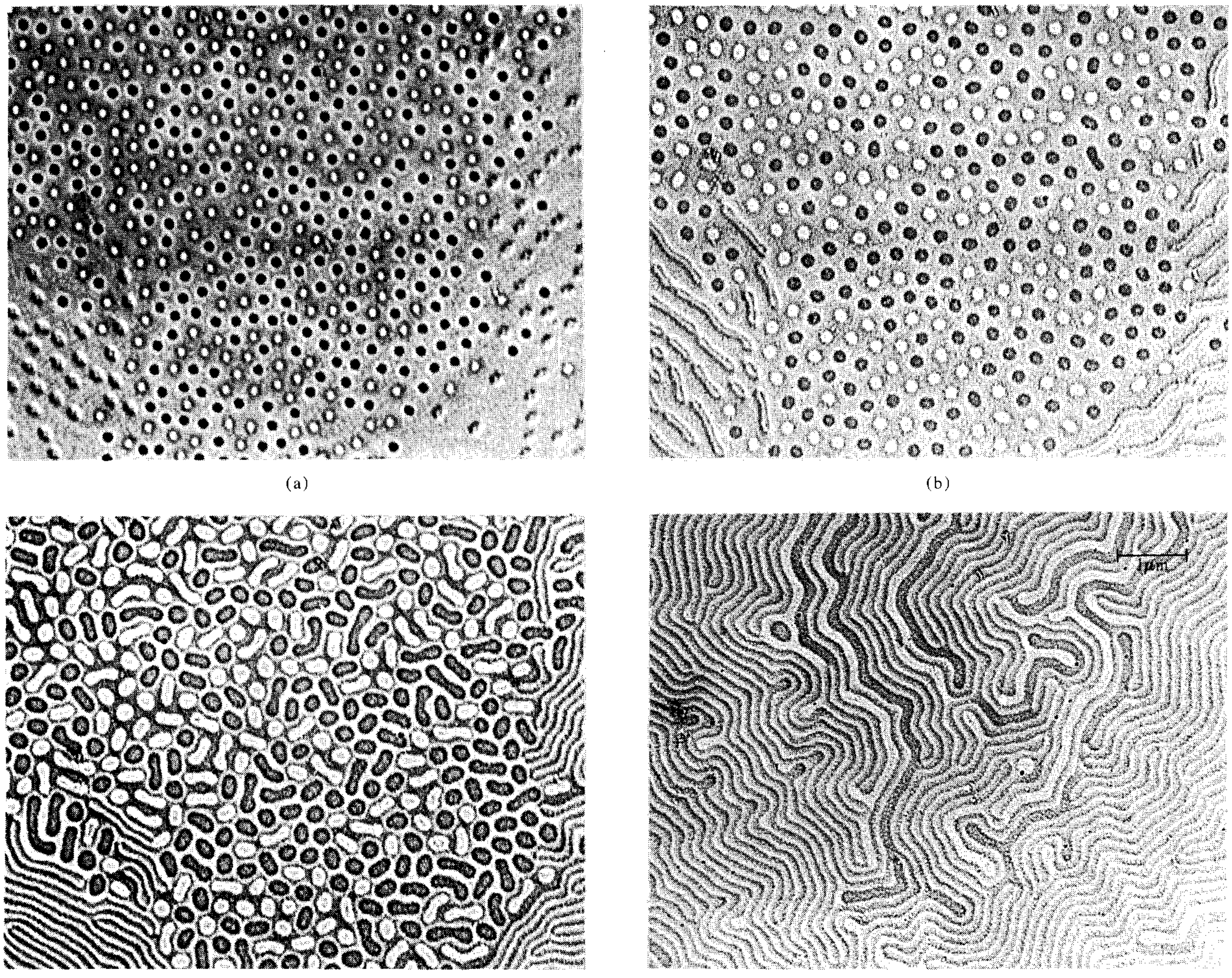


Figure 8 (a) Gd-Co-Au bubble raft created by in-plane pulsing with $H_{\perp} = 1.15 \times 10^5$ A/m. Bubble size 0.15 μm. (b) Same area with $H_{\perp} = 7.85 \times 10^4$ A/m. (c) Bubble raft at remanence. (d) Same area as (a) in strip state at remanence.

ratio of three or less. Magnetic bubble size in our films should vary between film thickness and three times that thickness, making anything above 0.3 μm a circular domain. The serpentine domain wall in Fig. 7(b) separates a region that is an upward-magnetized domain with downward-magnetization bubbles from a region that is magnetized downward and contains bubbles in which the magnetization is in the upward direction. The Bloch-line spacing in these blotchy domains was determined to be 700 to 900 Å. Only those examples were used in computing this value where a large number of Bloch lines were clustered together. This approximates the model used by Hubert [10] in computing the equilibrium Bloch-line spacing. Using estimated parameters suitable for our films [11] we find, following Hubert, the Bloch-line spacing to be 650 Å. This compares favorably with our measured value.

Bubbles are known to form a two-dimensional hexagonal (or triangular) lattice [12]. Such lattices have been observed in amorphous [13] materials and single crystal garnet [12]. They are, of course, formed in a predictable fashion in the bubble lattice file device [14]. We have attempted to form similar lattices using 1500-Å bubbles. So far we have not been successful, primarily because our starting array of bubbles is not sufficiently dense. Bubble-bubble interaction that encourages the formation of the lattice is not sufficiently strong to overcome the coercivity. We do, however, obtain irregular bubble arrays. Figure 8 shows the initial starting array, which is stabilized by using an area of the film surrounded by a buckled region. This forms the potential trough in which bubbles are formed by pulsing the sample. The part where the film begins to buckle is outlined by the bubbles containing Bloch lines [Fig. 8(a)]. When the bias field is lowered [Fig. 8(b)] the bubbles containing Bloch lines stripe out first. Unichiral bubbles are found to stripe out at lower bias fields than for Bloch-line bubbles. This is to be expected, because the unichiral bubbles are less likely to stripe out as a result of the energy from the in-plane field. Figure 8(c) shows the bubble raft at remanence, and Fig. 8(d) shows the same area in the strip state at remanence.

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