MAGNETIC BUBBLES

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Preface

In September 1969 I spent a day at the Bell Telephone Laboratories at Murray Hill. Having always been interested in magnetism and magnetic crystals, my first request was to see the work there on magnetic bubbles. It was really good luck to meet Andrew H. Bobeck himself and spend some time with him seeing the fascinating work that he and his colleagues were doing at that time. I came back to London determined to try out some of these experiments myself and my colleague Dr E. A. D. White, Director of the Crystal Growth Laboratory at Imperial College, was just as enthusiastic. Our first experiments were done on some small bulk crystals of gallium substituted Y.I.G. but at least it was a beginning.

Since then, experimental work has led to the theoretical work which I have attempted to explain here. The book is not intended to say very much about magnetic bubble domain devices but I have tried to collect together some of the fundamental theory which is needed by anyone who takes up this interesting new field. The majority of young engineers learn very little about magnetism in their degree courses today so that the book has been written with them in mind.

I should like to thank my colleagues, Dr E. A. D. White and Dr G. E. Lane for letting me use some of their crystals. The work was helped considerably by the contact Dr White established with Dr E. A. Giess at the IBM Research Laboratories, Yorktown Heights, and this contact led to me being able to discuss a number of problems with Dr B. E. Argyle, Dr H. Chang, Dr A. P. Malozemoff and Dr J. C. Sloncewski there. They have also been kind enough to let us have copies of their many papers in advance of publication. In this country we have had the same invaluable contact with Dr R. D. Enoch and Dr M. E. Jones at the Post Office Research Laboratory. I should also like to thank Mr B. A. Boxall and Mr K. R. Papworth for their contribution to the work at Imperial College which is supported by Research Grants from the Science Research Council and the National Research and Development Corporation.

Finally, I should like to thank Dr M. E. Jones and Dr G. E. Lane for reading and commenting on the manuscript which was typed so well by Miss E. Farmer and Mrs J. Jeffery.

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List of Principal Symbols with Their Units

M = magnetisation, amps/metre, A/m
μ_0 = $4\pi \times 10^{-7}$ henries/metre, H/m: permeability of free space
B = magnetic field, Tesla, T (10^{-4} T = 1 Gauss)
W = strip domain width, m
h = thickness of a layer of bubble domain material, m
B_0 = the externally applied bias field, T
D = the bubble domain diameter, m
E = energy, joules, J
L = inductance, henries, H
σ_w = domain wall energy density, J/m^2
F = force, newtons, N
λ = the characteristic length, m
q = a numerical constant, value 0·726
K_μ = uniaxial anisotropy energy density, J/m^3
Q = quality factor for a bubble domain material
k = Boltzmann's constant, $1{\cdot}38 \times 10^{-23}$ J/°K
H = the magnetic excitation, A/m
M_p = the saturation magnetisation in an overlay bar, A/m
$\hat{M}$ = the magnetisation at the centre of an overlay bar, A/m

Contents

1 Magnetic Bubble Domains and Bubble Domain Devices

This book is about a new and very interesting entity which has been named the 'magnetic bubble domain' and how it may be used to build devices which are of great interest in electronics. In this introductory chapter, we shall begin by saying what the magnetic bubble domain is and describing some of its properties. This will immediately suggest possible applications of the magnetic bubble and the remainder of this chapter will be spent in describing some of these and showing how the bubble domain device may prove to be of great importance in the electronics of the future, particularly in the field of data processing.

The remaining chapters of the book deal with specific problems which arise when we are working with magnetic bubble domains. Chapter 2 considers the magnetostatic theory which is needed to understand how the magnetic bubble behaves in an applied field, its stability and the importance of the various physical properties of the materials which must be provided for bubble domain work. This leads to Chapter 3, where the preparation and characterisation of these materials are discussed. Chapter 4 considers dynamic problems, because we shall see in this first chapter that it is the motion of magnetic bubble domains which makes them useful in device work. In Chapter 5 we look at the problem of making bubble domains move in the controlled manner needed for device applications. The book concludes with a brief summary and some other fields of application which may be of interest.

1.1 Magnetic Domains

What is a magnetic domain? The answer to this question will be seen to explain the very important part which magnetism, or more precisely ferromagnetism, plays in electrical technology. Without the magnetic steels and alloys we should have no electric power or transport. The ceramic magnetic materials play an equally important part and are found in every radio and television receiver, in the magnetic core stores of computers and on the surface of magnetic recording tapes and discs.

The explanation for this technical importance of magnetism was perhaps best given by Kittel (1949) in the introduction to his well known review paper 'The physical theory of ferromagnetic domains'. Kittel pointed out that the essential features of ferromagnetism are characterised by the following remarkable experimental fact:

It is possible to change the overall magnetisation of a suitably prepared ferromagnetic specimen from an initial state of zero (in the absence of an applied magnetic field) to a saturation value of the order of 1000 gauss, by the application of a field whose strength may be of the order of 0·01 Oersted.

Units are traditionally confused in magnetism and the above quotation would be more immediately dramatic if we said that the magnetic field inside the ferromagnet changed from zero to 10^3 when the externally applied field changed from zero to 0·01. The material, it would appear, has amplified the magnetic effect by a factor of 10^5. This would be the situation in a long thin sample of material, or a sample in the form of a closed ring.

How does this remarkable behaviour come about? The answer is illustrated by figure 1.1 which shows a rectangular bar of magnetic material inside a coil through which current may be passed. When there is no current flowing in the coil, the magnetic material is in the demagnetised state. This really means that small volumes inside the bar, called ferromagnetic domains, will be found fully magnetised in certain directions but, taken overall, just as much of the bar will be found magnetised in any one direction as another so that the net magnetisation adds up to zero.

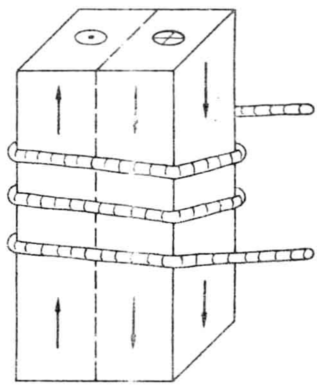

Figure 1.1. The demagnetised state; equal volumes of material are magnetised both up and down.

Things have been made particularly simple in figure 1.1 by looking at what we would call a uniaxial ferromagnet, that is, one which can only be magnetised along one particular direction. A further simplification has then been made by supposing that one half of the bar shown in figure 1.1 is one single magnetic domain which is magnetised upwards while the other half is a single domain magnetised downwards. The net result is zero overall magnetisation.

Now consider what happens when a small current is passed through the coil, as shown in figure 1.2. Experimentally, we find that the very small magnetic field produced by this current may be sufficient to move the boundary between the two domains a considerable distance and so produce

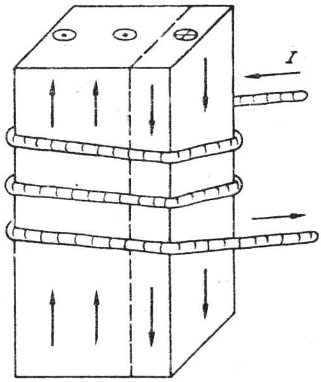

Figure 1.2. A small magnetising current may produce a large change in the net magnetisation.

a large net magnetisation. The magnetic effects which we used in technology rely upon behaviour of this kind—the existence of ferromagnetic domains and the movement of the domain walls which separate them. The early development of magnetic materials might be summarised by saying that there were two main lines of effort—one group of people were concentrating on making the domain walls move more easily (high permeability, low loss materials) while the other group were trying to stop them moving completely (materials for permanent magnets).

1.2 Single Crystals of Magnetic Material

The familiar magnetic alloys and ceramics are polycrystalline; a mass of microcrystals, usually a few microns in diameter, usually orientated randomly. The true situation inside a rectangular bar of magnetic steel, for example, which finds itself in the situations shown in figures 1.1 and 1.2, would be that the bar would be divided up into a very large number of magnetic domains. It might be found that every microcrystal in the bar contained several magnetic domains, all magnetised along different, but corresponding, crystallographic directions, or it could be that each ferromagnetic domain contained several microcrystals, and then the easy directions of magnetisation would be decided by the internal stresses of the material. In either case, it is immediately obvious that these polycrystalline materials are going to show very complex magnetic behaviour because the movement of a very large number of domain walls will be involved whenever the state of magnetisation is changed by applying external magnetic fields.

If it is possible to prepare a single crystal specimen of magnetic material, the whole problem of the magnetic domains becomes far more straightforward. A single crystal is completely homogeneous on an atomic scale and the magnetic domains will be found magnetised along particular crystallographic directions. In the three most well-known magnetic elements, iron, nickel and cobalt, for example, we find that the direction of magnetisation is normally along the cube edge, the cube diagonal and the hexagonal axis, respectively. The early experiments on single crystals of magnetic material were done on these metal crystals quite early in the twentieth century and are reviewed by Bozorth (1961). Later work on single crystals of metal alloys is reviewed by Kittel (1949). The metal crystals are, as a rule, very difficult to grow because the crystal structure just below the melting point is usually quite different to the one which is found when the metal is cooled to room temperature. For this reason, and because they are very easily destroyed by the slightest mechanical stress, the metal single crystals have not found any great application technically. In addition, metals are electrical conductors which is not conducive to good high frequency performance in a magnetic material.

A very different situation applies when we look at the magnetic oxide materials which began to make a serious impact upon technology around 1947 when the work done by Snoek during the second world war on the ferrites was published (Snoek, 1947). Single crystals of the ferrite materials were soon grown (Galt *et al.*, 1950) and this was followed by the growth of single crystals of the other oxide materials—the orthoferrites (Remeika, 1956) and then the magnetoplumbites and garnets (Nielson and Dearborn, 1958).

The growth technique for single crystals of the magnetic oxides usually involves making a solution of the magnetic material at very high temperature in a flux, such as lead oxide, and allowing this solution to cool very slowly. If conditions are right, a few crystals will nucleate when the solution becomes supersaturated and these will grow as cooling proceeds. The resulting crystals are very different from the single crystals of the metals and alloys in that the oxides are very hard refractory materials which, once grown as single crystals, can be cut and polished to any desired shape. In addition, the oxide materials are nearly all excellent insulators so that they are useful as magnetic materials at very high frequencies. Single crystals of the garnets, for example, were soon used in a multitude of microwave devices.

1.3 Magnetic Domains in Single Crystals

1.3.1 *Observing domains*

A remarkable property of the oxide magnetic materials is that they can be made reasonably transparent. This follows because of their insulating properties and because the optically excitable atoms in their structure may be quite dilute. When a magnetic material is transparent it is possible to

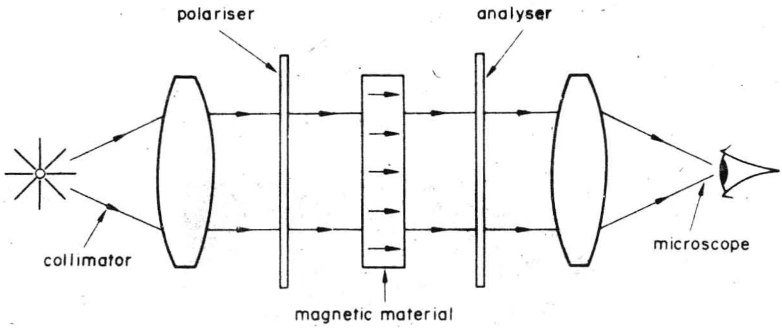

Figure 1.3. The Faraday effect. Polarised light has its plane of polarisation rotated when it passes through a magnetic material—clockwise or anticlockwise depending upon whether the direction of propagation is the same as the direction of magnetisation or in the opposite direction.

actually see the magnetic domains inside it by means of the Faraday effect, which is illustrated in figure 1.3.

Let us again consider a uniaxial ferromagnetic material, as we did in figures 1.1 and 1.2, but, this time, let us suppose that it is in the form of a thin single crystal sheet, as shown in figure 1.4, cut so that the easy direction of magnetisation is normal to the surface of the sheet. If the material is strongly anisotropic, which means that it is very difficult for the magnetisation to deviate from the easy direction, we shall find that the sheet is split up into magnetic domains, as shown in figure 1.4(a), with their directions of magnetisation alternately up and down, producing zero net magnetisation overall.

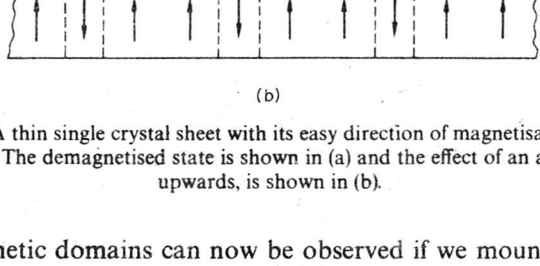

Figure 1.4. A thin single crystal sheet with its easy direction of magnetisation normal to its plane. The demagnetised state is shown in (a) and the effect of an applied field, upwards, is shown in (b).

These magnetic domains can now be observed if we mount the sheet, as shown in figure 1.3, in a beam of polarised light. Because of the Faraday effect, the plane of polarisation of the light will be rotated in different directions for the two different directions of magnetisation which are found in the sheet. The angle of the analyser shown in figure 1.3 can be adjusted to extinguish the light which has passed through one kind of domain, the ones magnetised away from the observer, for example, so that these domains appear dark. Domains magnetised towards the observer will then appear light.

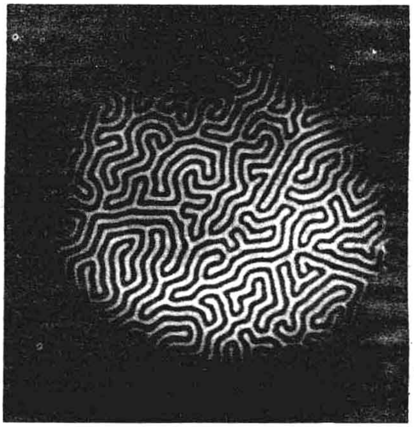

Figure 1.5. Faraday rotation micrograph showing the magnetic domains in a 10 μ thick epitaxial garnet layer.

Figure 1.5 shows such a picture, or Faraday rotation micrograph, taken of a thin sheet of magnetic garnet. Here we see equal areas of light and dark serpentine magnetic domains, showing that a section through the sheet would, in fact, show the state of magnetisation shown in figure 1.4(a). Because this particular garnet is very isotropic in its in-plane properties, the magnetic domains wind around one another in an entirely random manner. This pattern is the one which we normally observe in such single crystal layers when there is no applied field. It is the demagnetised state, which was idealised in figure 1.1. Equal volumes of the sample are magnetised towards us and away from us.

1.3.2 *The effect of an applied field*

We now consider the effect of an externally applied magnetic field on the thin sheet shown in figure 1.4(a). This field, B_0, will be continuous right through the sheet, because of the fundamental relationship $\text{div}\,\mathbf{B} = 0$, and will increase the energy density of the domains which are opposed to B_0, that is, the domains magnetised downwards. Similarly, the energy density of the domains which are magnetised in the same direction as B_0, upwards, will be decreased. It follows that there will now be a force upon the domain walls which will cause these to move in such a way that the high energy domains contract and the low energy domains expand. This will produce a net magnetisation upwards, as shown in figure 1.4(b).

The effect upon the Faraday rotation micrograph is shown in figure 1.6. The domains which appeared dark in figure 1.5 have become thinner as a result of the field applied in a direction towards the observer.

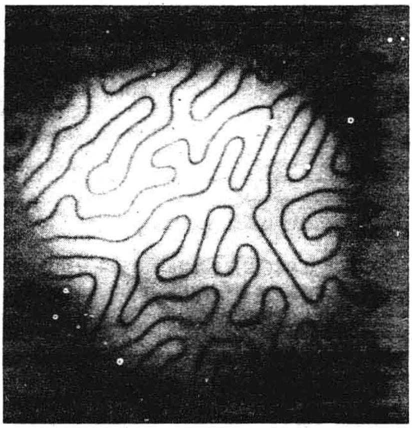

Figure 1.6. The effect of a bias field upon the domains shown in Figure 1.5. The field of view is 0·5 mm in diameter.

1.3.3 *The magnetic bubble domain*

It is from figure 1.6 that we may introduce the entity which is the subjec of this book—the magnetic bubble domain. Figure 1.6 shows the situation which comes about when a constant field, B_0, is applied in a direction normal to the surface of the thin sheet. This field squeezes the dark domains, shown in figure 1.5, into the narrow strip domains of figure 1.6. Suppose we now add a pulsed magnetic field to B_0. At the instant the pulsed field is applied, the strips shown in figure 1.6 begin to contract still further and, if the pulse were sufficiently intense and were to last a sufficient length of time, these strips would collapse completely and leave the thin sheet of magnetic material uniformly magnetised, or saturated, in the direction of the applied field.

It turns out that this contraction cannot occur absolutely uniformly but happens in the wave-like manner shown in figure 1.7. Before collapsing completely, the thin strip domains of figure 1.6 actually break up into small parts which then contract symmetrically, figure 1.7(e). If, at this point, the pulsed field is switched off, we find ourselves left with these small isolated domains, which expand slightly and turn out to be stable entities in the constant bias field, B_0. The domains shown in figure 1.7(e) are small cylindrical domains. They are the magnetic bubble domains which we are going to study here.

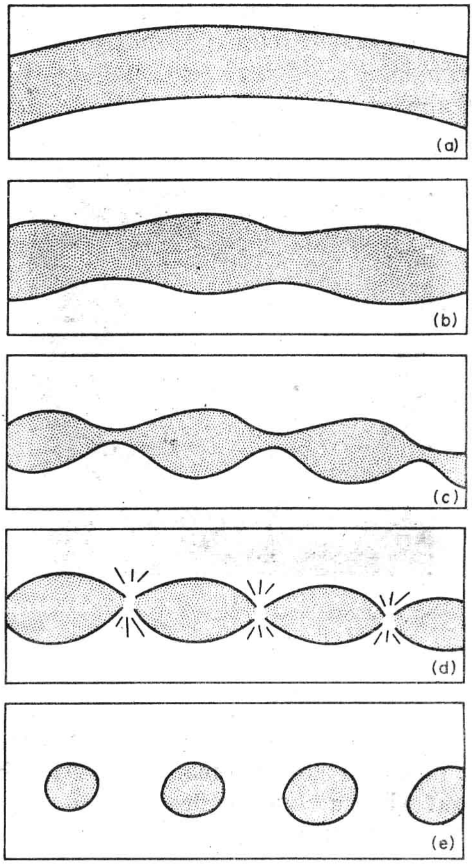

Figure 1.7. Showing the contraction of a thin strip domain, (a), occurring in a wave-like manner, (b) to (c), and finally breaking up, (d), to form bubble domains, (e).

Figure 1.8 shows this effect actually happening. The narrow strips of figure 1.6 have been subjected to just one field pulse and we can see that some of them have broken up into magnetic bubble domains. Some correlation between the original strips of figure 1.6 and the strings of bubble domains in figure 1.8 can be seen, although this is not necessarily to be expected because the bubbles, once created, can move quite freely around and will do so because of the weak dipole interactions they have with one another and with the remaining strip domains. This is further illustrated in figure 1.9 which shows the result of applying several more pulses, after the photograph for figure 1.8 had been taken. It can be seen that all the strips have now been broken up into bubble domains, in figure 1.9, and that these have arranged themselves into a fair hexagonal lattice because of their mutual repulsion.

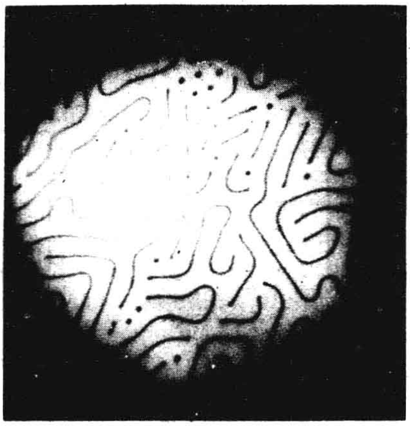

Figure 1.8. A pulsed magnetic field is applied to the domains shown in Figure 1.6. Magnetic bubble domains are generated.

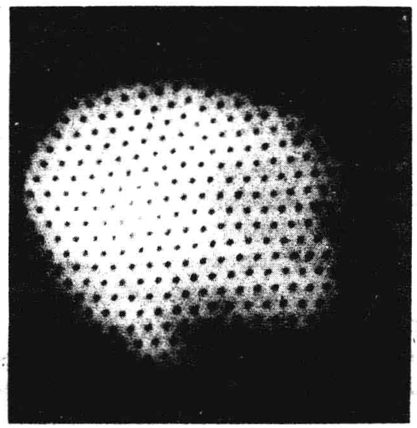

Figure 1.9. Repeated pulses generate an array of magnetic bubbles. In this particular garnet, these bubbles are $\approx 6\ \mu m$ in diameter.

1.3.4 *Bubble stability*

The magnetic bubble domain shown in figures 1.8 and 1.9 is a small cylindrical magnetic domain passing right through a single crystal layer of uniaxial magnetic material. In Chapter 2 we shall see how it is that the bubble domain is held in stable equilibrium by the squeezing force of the applied field being opposed by the internal magnetic pressure which is produced by the magnetisation within the bubble itself. This is illustrated in figure 1.10. The circular shape of the bubble domain is maintained because of a third force; the magnetic surface tension of the wall which surrounds the bubble domain.