SHORT COMMUNICATIONS

THERMALLY ACTIVATED FERROMAGNETIC DOMAIN WALL MOTION*

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The properties of small ferromagnetic domains are influenced strongly by thermal agitation if the energies involved in transitions between different states of magnetization (rotations and domain wall movements) are only a few times kT (k being Boltzmann's constant and T the absolute temperature). The study of such small-scale magnetic phenomena, now known as " micromagnetics " (see, for example, Brown 1959*a*), has developed rapidly in recent years in response to commercial interests in fine powder permanent magnets and thin film memory cores. The possibility of observing directly thermally induced domain wall movements is therefore a matter of some interest. It appears that Olmen and Mitchell (1959) have made such an observation, although they did not specifically claim to have done so. The purpose of this note is to present an elementary theory of thermally activated domain wall motion and to show that the results reported by Olmen and Mitchell are in agreement with it.

The delayed response of magnetic domains to changes in external field is termed " magnetic viscosity " but some ambiguity has arisen from the two different physical processes involved. Domain wall velocities have been observed in metals by Sixtus and Tonks (1931, 1932) and in ferrites by Galt (1954). In both cases the velocity v in a field H is

$$v=G(H-H_0),$$

H_0 being a critical field (static coercive force) and G is a constant of the order 10^4 cm sec^{-1} oersted^{-1}. In metals the velocity is limited principally by eddy currents. Galt explained the velocities observed in ferrites in terms of the dissipation of anisotropy energy during ionic reordering in moving walls. Galt (1954) and George (1959) have referred to this latter process as magnetic viscosity.

The expression is also used for much slower changes in magnetic domains, such as were observed by Street and Woolley (1949) in " Alnico " and subsequently recognized as important phenomena in rock magnetism (e.g. by Néel 1955). This longer period magnetic viscosity is controlled by thermal activation, which must be invoked to explain the slow domain wall motion observed by Olmen and Mitchell.

Consider a domain wall crossing a sequence of potential barriers, which will be assumed for simplicity to have equal heights E_0. In the presence of a field H in the direction of the expanding domain, the energy which must be supplied to the wall in order to impel it across a barrier is

$$E=E_0-\alpha H, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

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where energy (αH) is supplied by the field during penetration of or " climbing up " the barrier. The wall can move freely only if $E \leqslant 0$, but if $E > 0$, movement can be induced thermally. The probability P of the wall acquiring in unit time sufficient thermal energy to cross a barrier is

$$P = C \exp(-E/kT). \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Alternatively, P is the number of occasions per second on which the wall acquires thermal energy E which could impel it across the barrier. There are several calculations of the frequency factor C. Néel (1955) suggested 10^9 to 10^{10} $\sec^{-1}$; Stacey (1959*a*) obtained $C = 6 \times 10^{12}$ $\sec^{-1}$ at room temperature, but this must be regarded as an upper limit, as it expresses the probability of sufficient energy becoming instantaneously available rather than the probability that the wall will move sufficiently rapidly to make use of it (Stacey 1959*b*). A completely different formula for specific application to single domains has been given by Brown (1959*b*). In the following calculation two alternatives are assumed: (i) C is a large but arbitrary constant with negligible dependence upon parameters such as temperature. This leads to equations (**5A**) and (**6A**). (ii) C is proportional to T, as suggested by Stacey (1959*a*). This leads to the alternative equations (**5B**) and (**6B**). The difference is not very significant in the present case.

If the average separation of potential barriers in the direction of motion is d, then, assuming that the delay of the wall at each barrier is much greater than the time taken to move between barriers, the wall velocity v is given by

$$v = Pd = Cd \exp\{-(E_0 - \alpha H)/kT\}. \quad \ldots\ldots\ldots\ldots \quad (3)$$

Putting $Cd = A$, $\alpha/k = B$, and $E_0/k = BH_0$, we obtain a simpler form

$$v = A \exp\{(B/T)(H - H_0)\}. \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Equation (**4**) has the exponential dependence of wall velocity upon applied field which is required by the observations of Olmen and Mitchell. It must be noted that $H - H_0$ is necessarily negative in the range of interest as A is a large constant.

The temperature range of the observations was too limited to allow detailed comparison with (**4**) but the variation of v with T can be used to estimate the constant H_0, which is the field required to move the wall at 0 °K, or to move it very rapidly at any temperature. By differentiating equation (**4**) we obtain

$$\mathrm{d}(\ln v)/\mathrm{d}T = -B(H - H_0)/T^2 \quad \ldots\ldots\ldots\ldots \quad (5A)$$

if the frequency factor C is independent of T, or

$$\mathrm{d}(\ln v)/\mathrm{d}T = -B(H - H_0)/T^2 + 1/T \quad \ldots\ldots\ldots \quad (5B)$$

if C is proportional to T.

Examination of the data of Olmen and Mitchell shows that for their film $\mathrm{d}(\ln v)/\mathrm{d}T = 0{\cdot}09$ degC^{-1} at $T = 320$ °K and $H = 4{\cdot}0$ oersteds and that $B/T = 8{\cdot}8$ $\mathrm{oersted}^{-1}$, so that from (**5A**) $H_0 = 7{\cdot}3$ oersteds, and from (**5B**) $H_0 = 7{\cdot}1_6$ oersteds. It is not possible to distinguish experimentally between these alternatives but, as the coercive force of the film when measured at 60 c/s was 7 oersteds and would therefore be slightly higher still at even more rapid switching, this must be regarded as an excellent agreement with the theoretical estimates of H_0.

Having determined H_0, the absolute values of measured velocity may be used to estimate A. From Olmen and Mitchell's data, at 4·0 oersteds switching field and 320 °K., spike velocity is 3×10^{-2} cm/sec. Taking true wall velocity as one-seventh of this, as noted by Olmen and Mitchell, we find

$$A=Cd=1\cdot7\times10^{10}\text{ cm/sec} \quad \ldots\ldots\ldots\ldots \quad (6A)$$

if C is independent of T, or

$$A=Cd=0\cdot5\times10^{10}\text{ cm/sec} \quad \ldots\ldots\ldots\ldots \quad (6B)$$

if C is proportional to T.

At this point an inadequacy of the simple theory must be noted. It has been assumed that the wall is inflexible and that it only meets one barrier at a time, neither of which can be true. Rather we should expect the wall to encounter a more or less straight line of elementary barriers and tend to fold round each of the barriers, making individual jumps past them. In this case the wall would effectively be divided into a large but unknown number of semi-independent sections, each opposed by a single elementary barrier. This allows a physically reasonable interpretation of the constant α in equation (3), since we may put

$$\alpha=2atI_s,$$

where I_s is the saturation magnetization of the film, a is the average wall area of each effectively independent section of wall, and t is the effective half-thickness of the elementary potential barriers. However, this does not alter the foregoing equations, since we can consider the wall velocity of each section of wall separately in terms of the same equations.

If a direct microscopic observation could be made of the individual jumps of a slow-moving domain wall, so that d would be measured, the fundamental constant C could be estimated from equations (6). It may be noted as a preliminary result that a value of C as low as 10^{10} sec^{-1} does not appear to be consistent with the above figures, as it gives much too large a value of d. Taking the theoretical upper limit, $C=6\times10^{12}$ sec^{-1} (at room temperature) we would expect to find $d\sim10^{-3}$ cm. It therefore appears possible that such an observation could be made.

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