Transit-time-limited wall motion in Permalloy films*

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A simple quantitative formulation of transit-time-limited wall motion is used to show that such an effect can reasonably explain the observed nonlinear wall motion in Permalloy thin films. The "critical velocity" is calculated by equating the intrinsic relaxation time T_i to the transit time T_t for the wall past an individual spin position to obtain $V_{crit} = \delta/T_i$, where δ is the wall width. The model correctly predicts (i) the magnitude and (ii) variation with film thickness of the observed knee in the velocity-field curves for wall motion in Permalloy films.

The origin of the observed nonlinear domain wall motion in thin films has been a perplexing problem for a number of years. The effect was first observed in the quasistatic mobility experiments of Middelhoek[1] and Patton and Humphrey.[2] Following these observations, more detailed studies of the nonlinear response by Telesnin and co-workers[3] and Konishi and co-workers[4] revealed a systematic correlation between the shape of the nonlinear response and film thickness. Figure 1 shows some typical curves for Permalloy films in the 300- to 800-Å thickness range, taken from the data of Konishi and co-workers.[4]

In his original paper, Middelhoek[1] proposed that, due to the rapid rotation of the spins within the domain wall moving at high velocities, the viscous flow approximation might no longer be valid and that such an effect might be the origin of the nonlinear response. A related idea, transit-time-limited wall motion, was also suggested some time ago by Hagedorn and Gyorgy to account for wall motion observations in yttrium iron garnet.[5] A quantitative if somewhat crude formulation of this model can be made by examining the conditions under which the wall transit time T_t past an individual spin position will be less than the intrinsic relaxation time T_i for that spin. Intuitively, it is clear that T_t must exceed T_i if the energy loss during wall motion is to occur through "normal" relaxation channels. If the transit time is *shorter* than T_i, the spin simply does not have time to relax to equilibrium through the "normal" relaxation channels in the time the wall moves by, a sort of "bottleneck" will occur, and the wall dynamic response to applied fields will change.

The critical velocity at which T_t just exceeds T_i is given by

$$V_{crit} = \delta/T_i, \tag{1}$$

where δ is the domain wall width. The "critical velocity" predicted from this simple equation is in close agreement with the break point in the velocity-field curves for thin films. The data in Fig. 1 show a break at 5×10^3 cm/sec for the 300-Å film, while the thicker film shows a change at a much lower velocity. This is exactly the behavior predicted from Eq. (1). As the film thickness increases, the Néel wall width δ decreases and V_{crit} decreases accordingly. In Fig. 2, the observed velocity break points from the data of Konishi and co-workers[4,6] and Patton[7] are shown versus film thickness for comparison with theory. The theoretical curve was calculated using Eq. (1) with δ values from Lorentz microscopy[8] and an intrinsic relaxation time from ferromagnetic resonance (FMR) linewidth data [$\Delta(\omega/\gamma) = 2/\gamma T_i = 30$ Oe].[9] The predicted decrease in V_{crit} with thickness is in close agreement with the data. The actual values show agreement within a factor of 2 (20% for the 300-Å film).

The actual magnitude of the theoretical V_{crit} might be somewhat higher or lower, depending on what value of T_i is really appropriate to spin relaxation during wall motion. The value from FMR is only a rough estimate.

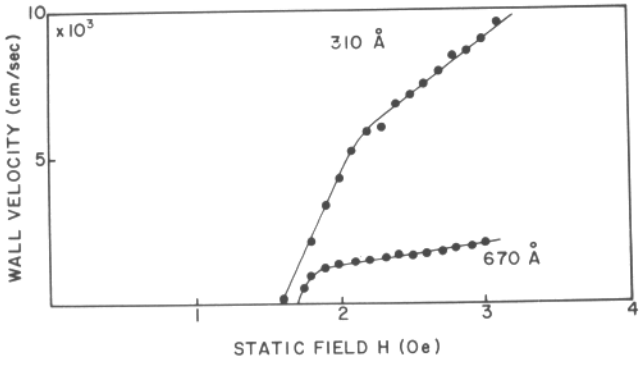

FIG. 1. Velocity-field curves for domain wall motion in thin films (after Konishi and co-workers, Ref. 4).

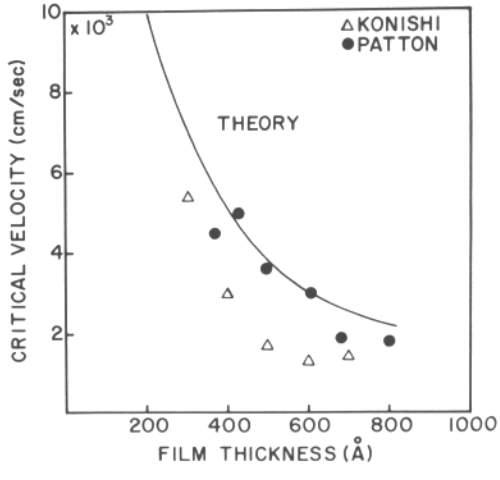

FIG. 2. Break-point velocity versus film thickness from Konishi (Ref. 6) and Patton (Ref. 7). The theoretical curve is for the transit-time-limited critical velocity.

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A small downward correction due to the slight wall contraction during motion might also be introduced, but this effect is less than 1% for the fields considered.

A more extensive analysis of this mechanism based on the analogy between wall motion and flux reversal has recently been done by Konishi, [10] which shows qualitative agreement with wall-motion data.

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