Cluster dynamics of the Bloch lines at the domain wall of a garnet ferrite film with a perpendicular anisotropy

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The dynamics of vertical Bloch line clusters in garnet ferrite films with a perpendicular anisotropy is studied experimentally and theoretically.

The vertical Bloch lines (VBL) which divide the regions of the domain walls (DW) of ferromagnets with oppositely directed magnetic moments are important elements of the domain-wall structure.[1] The dynamics of the VBL in epitaxial garnet ferrite films with a perpendicular anisotropy has so far not been studied experimentally. These studies are important for the understanding of nonlinear DW dynamics in view of Konishi's proposal to use VBL to develop superdense magnetic-memory systems.[2] The dynamic DW profile with a single VBL was calculated in Ref. 3. The

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resonant oscillations of the VBL and the effect of a VBL on the DW dynamics of yttrium garnet ferrite plates were studied by Nikitenko and Dedukh *et al.*[4] In this letter we present the results of the first experimental study of cluster dynamics of VBL in garnet ferrite films with a perpendicular anisotropy and we predict theoretically the dynamic profile of the domain wall which contains a VBL cluster. Slonczewski has shown theoretically that the mobility of the regions of a DW with VBL is much slower than that of the regions of a DW without VBL.[1] An rf-field-induced oscillation of the DW was used to find the position of the static VBL in the DW.[5] The regions of the DW moving at different velocities were detected by means of a single high-speed photography of the dynamic DW,[6] but the results of an experimental study of the dynamics of VBL by this method have not yet been published. We used a double high-speed photography[7] to detect the dynamics of a VBL in a DW of a garnet ferrite film with a perpendicular anisotropy. This method makes it possible to detect two positions of the dynamic DW which were obtained by means of two light pulses. The periods of the domain structure in films 11.4- and 7-μm thick were 85 and 47 μm. By applying a 1500-Oe/cm gradient magnetic field perpendicularly to the sample surface we formed a single straight domain wall in a garnet ferrite film. The samples with such a DW were placed in a pulsed magnetic field H applied along the direction perpendicular to

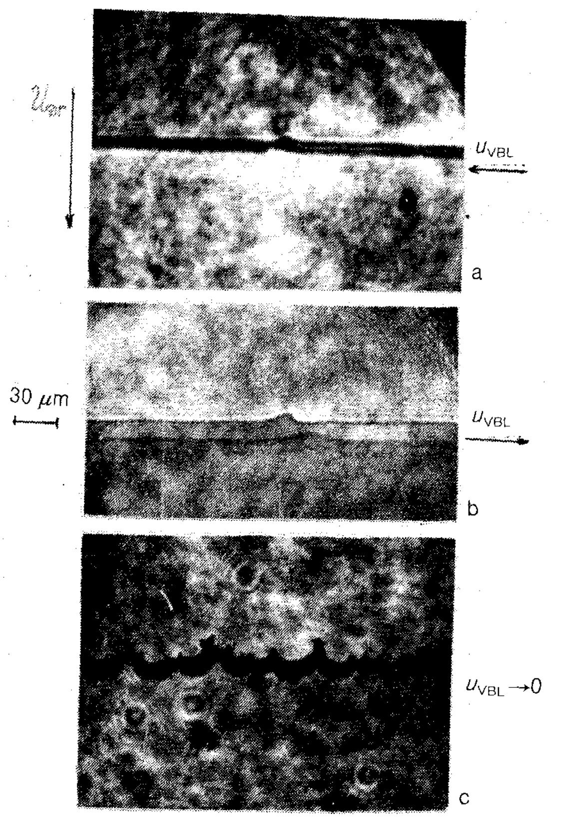

FIG. 1. Double high-speed photographs of the dynamic domain wall with a VBL cluster in a garnet ferrite film. a—Domain contrast, $H_z = 15$ Oe; b—domain-wall contrast, $H_z = 15$ Oe; c—domain contrast, $H_z = 40$ Oe.

the film plane, which set the domain wall in motion. Because of the Faraday effect, which is unusually strong in bismuth-containing garnet ferrites,[8,9] we were able to photograph a moving DW in two positions. Figure 1a is a photograph of sample 2. In this photograph the dark band is the region traversed by a DW in a time between two light pulses. The time of the light pulses is 8 ns and the delay time is 0.4 μs. The DW moves downward. Figure 1 clearly shows that the domain wall has a formation which lags behind the entire DW and which moves along it. At this location on the domain wall there is a VBL cluster. The amplitude of the multidimensional characteristic of the DW is 5 μm and its shape is asymmetrical. The multidimensional characteristic relaxes in several microseconds in sample 1 and in several tenths of a microsecond in sample 2. Figure 1b shows a similar result obtained for sample 2 as a result of photographing the DW twice in a contrast regime. The velocity at which the VBL cluster moves along the DW is related nonlinearly to the strength of the field (Fig. 2). The velocity of the cluster increases with increasing H, and the number of clusters at the DW remains constant in a certain magnetic-field interval. In fields higher than 70 Oe the number of clusters in sample 1 increases, complicating the determination of their velocity along the DW. Under our experimental conditions the maximum VBL cluster velocity is 15 m/s for sample 1 and 57 m/s for sample 2 and is approximately twice as high as the DW velocity. In fields higher than 20 Oe the velocity of a VBL cluster in sample 2 decreases because of the formation of VBL clusters along the entire DW (Fig. 1c). The $u(H)$ curve for the DW velocity in this case has a peak, beyond which the velocity decreases sharply. No such peak was observed for sample 1. A change in the direction of the DW velocity causes the direction of the velocity of the VBL cluster to change, indicating that the gyrotropic force affects the motion of the VBL cluster.[1] The velocity of the VBL in sample 1 reaches the apparent saturation evidently because of the saturation of the DW velocity. The VBL velocity determined above is much lower than the cutoff velocity of a single VBL.[1]

The dynamics of the spins which are localized in the domain wall of the ferromagnet with a large Q factor, $Q = K/2\pi M^2 \gg 1$, is described by the Slonczewski equation.[1] If the velocity at which the VBL moves along the DW is low far from the cutoff velocity, $u_c \sim \gamma\sqrt{8\pi A}$, the self-similar motion $\psi = \psi(x - ut)$ of the spins in the DW is described by the equations

$$\begin{cases} \dfrac{-uq_x}{4\pi M\gamma\Delta} = \dfrac{1}{2}\sin 2\psi - \Delta_L^2 \dfrac{\partial^2 \psi}{\partial x^2} & (1) \\[2ex] \dfrac{-u\psi_x\Delta}{4\pi M\gamma} = \alpha u q_x + (\Delta_L^2 q_{xx} - b^2 q) \\ \qquad + \dfrac{\Delta}{\pi h}\displaystyle\int_{-\infty}^{\infty} [q(x) - q(x+y)]\left[\dfrac{1}{|y|} - \dfrac{1}{\sqrt{y^2 + h^2}}\right] dy\,, & (2) \end{cases}$$

where q is the position of the DW center along the y axis, x is the coordinate directed along the DW, ψ is the angle of departure of the magnetization from the DW plane, M is the magnetization, γ is the gyromagnetic ratio, Δ is the wall thickness, $b^2 = H_z'\Delta/$

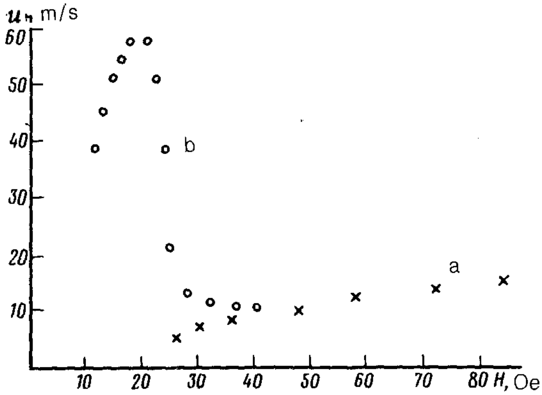

FIG. 2. The velocity of a VBL cluster along the domain wall versus the magnetic field in (a) sample 1 and (b) sample 2.

$4\pi M$, H_z' is the magnetic field gradient, h is the film thickness, and Δ_L is the thickness of the VBL. The term associated with the dissipation is dropped in the first equation, which is valid if $\alpha u \ll 4\pi M\gamma\Delta_L$. The term which takes into account the scattering fields produced as a result of bending of the DW because of the magnetic poles at the film surface is introduced in Eq. (2).[10] In the linear approximation with respect to the velocity u, the left side of (1) can be set to zero. The structure of the cluster comprised of N lines can then be represented in the form $\psi = \Sigma_{-N/2}^{N/2} \times \varphi_0(x + nx_0 - ut)$, where x_0 is the distance between the VBL in the cluster, and $\varphi_0(\xi)$ is the structure of the VBL described by Eq. (1). To derive some estimates, we assume that $x_0 = \pi\Delta_L$, $\varphi_0(\xi) = 2\arctan \exp(\xi/\Delta_L)$, and $\xi = (x - ut)$. The flexure of the DW caused by the gyroscopic pressure during the motion of the cluster in this case can be found from Eq. (2) by the Fourier-transform method:

$$q(\xi) = 4\pi\gamma M\Delta u \int_0^\infty \frac{\cos(k\xi + \varphi_k)\sin\left(\frac{N}{2}k\pi\Delta_L\right)}{\sqrt{\omega_k^4 + \alpha^2 u^2 k^2}\,\sin(k\pi\Delta_L)\cosh\frac{\pi k\Delta_L}{2}}\,dk, \quad (3)$$

where

$$\frac{\omega_k^2}{(4\pi M\gamma)^2} = b^2 + (k\Delta_L)^2 - \frac{\Delta}{\pi h}[c + \ln(kh/2) + k_0(kh)]$$

here c is Euler's constant, $k_0(x)$ is the elliptic function of the imaginary argument, $\tan\varphi_k = \alpha uk\, 4\pi\gamma M/\omega_k^2$, and $N \ll 2/b$.

Under the conditions $N \ll b^{-1}$ and $b_c \ll b \ll 1$, where b_c is the critical "rigidity" of the domain wall at which the stability of its planar state is disrupted (flexural instability[11]), we find the following relation from (3):

$$q(\xi) = \frac{uN}{8M\gamma Q^{1/2}b}\left[1 - \frac{\alpha\xi u}{\Delta_L^2\, 8\pi M\gamma}\right]\exp(-b|\xi|/\Delta_L). \quad (4)$$

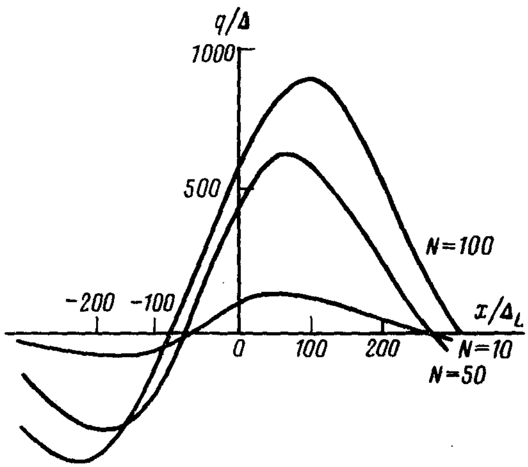

FIG. 3. Theoretical shape of the profile of the domain wall with a cluster of 10, 30, and 50 VBL moving at a velocity $u = 15$ m/s, $\alpha = 0.2$, $h = 10$ μm, $4\pi M = 60$ G, $A = 2\times 10^{-7}$ erg/cm, and $K/2\pi M^2 = 140$.

Accordingly, in the presence of dissipation ($\alpha \neq 0$) the flexure of the DW is, in contrast with that in Ref. 12, unsymmetric with respect to the center of the cluster ($\xi = 0$) (Fig. 3). The amplitude of the flexure at the center $q(0)$ depends on the number N of the VBL in the cluster and on the "rigidity" of the grid which is characterized by the parameter b. The bending deflection, which occurs when $N \sim 2/b$, is $q_{\max}(0) = u/\gamma H_2^1 \Delta_L$.

As a result of reduction of the gradient H_g', the bending deflection of the DW and its inertia increase particularly strongly near the point at which the stability of the DW planar state is lost ($b \to b_c$). The shape of the DW flexure in Fig. 1 corresponds to the results of the theory shown in Fig. 3. Figure 1 clearly shows a change in the sign of the DW deviation in front of a moving VBL cluster. A slight difference in the velocities of the VBL cluster stems from an increase in the viscous retardation of the cluster as a result of a strong bending deflection of the DW due to a large number of VBL. Our experiment showed that a cluster with a small number of VBL can be visualized.

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