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M. Mansuripur



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M. Mansuripur

Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

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A method of calculating domain wall energy density from experimental observations is proposed. The technique requires measurement of the expansion and collapse fields for circular domains of arbitrary size.

Domain wall energy density σ_w is an important factor in the performance characterization of magneto-optic media. According to the classical micromagnetic theory, this energy density is given by¹

$$\sigma_w = 4\sqrt{A_x K_u}, \quad (1)$$

where A_x and K_u are the exchange stiffness coefficient and the anisotropy energy density of the material, respectively. This model is based on the following assumptions: (1) the wall is simple, i.e., it contains no Bloch lines or Bloch points; (2) the uniaxial anisotropy energy is given by $K_u \sin^2 \theta$, where θ is the angular deviation of magnetization from the local easy axis; and (3) the exchange interaction is confined to nearest-neighbor spins. Strictly speaking, none of these assumptions is valid for magneto-optic media, especially those which contain non-S state rare-earth elements such as terbium and dysprosium. Tb and Dy are believed to be responsible for the occurrence of random axis anisotropy which, in turn, causes complex domain wall structure. In the absence of good models for the wall and reliable methods for the measurement of exchange and anisotropy constants, direct methods for the measurement of σ_w have gained practical significance.

An analogy with the materials of bubble storage is useful at this point. In bubble media, domain wall energy is determined experimentally by allowing the magnetization of the sample to break into stripe domains and by observing the stripe width under equilibrium conditions. In the absence of external fields, the equilibrium state is one in which the reduction of energy due to demagnetization compensates for the increased energy caused by the creation of domain walls. The reduction of demagnetizing energy, calculated for given saturation magnetization M_s , film thickness h , and stripe width l , is set equal to the total wall energy in order to estimate the value of σ_w . Unfortunately, this approach cannot be applied to magneto-optic (MO) media; the reason being that, unlike bubble materials where coercivity is negligible, the large coercivity of amorphous rare-earth-transition metal (RE-TM) films prevents the magnetization state from reaching equilibrium. Without perfect balance between the two kinds of energy it would be impossible to estimate one energy from the other.

In this communication we describe a method for determining σ_w from measurements performed on thermomagnetically recorded domains. Consider a circular domain of radius R in a uniformly magnetized film with thickness h and perpendicular saturation magnetization M_s . Using magneto-optical techniques for domain observation, it is possible to determine the values of the externally applied

magnetic field H_1 for the onset of expansion and H_2 for the onset of collapse. Shieh and Kryder² have recently measured these fields for a particular sample and report a difference of about 200 Oe between H_1 and H_2 for a domain of radius $R = 0.5 \mu\text{m}$.

The force per unit area of the wall due to a perpendicular external field H is given by

$$F_{\text{ext}} = 2 M_s H. \quad (2)$$

This force is outward (inward) from the domain when H is parallel (antiparallel) to the magnetization of the domain.

Domain wall energy gives rise to a force density which is always inward, trying to collapse the domain. The magnitude of this force is

$$F_{\text{wall}} = \sigma_w / R. \quad (3)$$

The demagnetizing force can also be calculated provided that a structure for the wall (i.e., magnetization distribution within the wall) is postulated. Fortunately, however, in practical situations where the wall width is much less than the film thickness, exact knowledge of the wall structure is relatively insignificant for demagnetization calculations. [The wall structure is also needed in the calculation of the force of an external field but, for the same reasons, it has been ignored in deriving Eq. (2).] We shall use a simple approximation to demagnetizing energy that has been shown³ to be applicable where domain radius R is much larger and, simultaneously, the wall width is much smaller, than the film thickness h . In this approximation the demagnetizing energy per unit wall area is

$$E_{\text{dmag}} = 6 \pi h M_s^2. \quad (4)$$

Note that unlike σ_w , which is independent of film thickness, E_{dmag} is proportional to h . This is due to the fact that the relevant range of dipole-dipole interactions in the vicinity of the wall is proportional to the film thickness. The demagnetizing force per unit wall area is expansive with approximate magnitude

$$F_{\text{dmag}} = 6 \pi h M_s^2 / R. \quad (5)$$

The net outward force density is thus written

$$F_{\text{tot}} = \pm 2 H M_s - (\sigma_w - 6 \pi h M_s^2) / R. \quad (6)$$

In Eq. (6) the first term on the right-hand side has positive (negative) sign when the external field H is expansive (contractive). When H is at the threshold of expansion (i.e., $H = H_1$) the total force will be equal to the force of coercivity F_c . At the threshold of collapse (i.e., $H = H_2$) the total force will be $-F_c$. Therefore cancellation of F_c between the

two force equations corresponding to these two situations yields

$$\sigma_w = 6\pi h M_s^2 + M_s R(H_1 - H_2). \quad (7)$$

Equation (7) provides a simple formula for calculating σ_w from the experimental data. As an example, consider the aforementioned results of Shieh and Kryder. Since film thickness and saturation magnetization were not reported in their paper, let us make the reasonable assumption that $h = 100$ nm and $M_s = 50$ emu/cm³. Equation (7) gives $\sigma_w \approx 1$ erg/cm² which is within the range of acceptable values for RE-TM alloys.

In general, the technique described in this paper can be used to measure σ_w as a function of temperature. This is

done by placing the sample in a cryogenic dewar or on a hot plate and fixing the temperature at the desired level. Since the domain radius R is arbitrary, a range of measurements corresponding to different radii can be obtained at any given temperature. The results can then be fitted to a straight line for better accuracy. For small radii, the estimate of demagnetizing energy given in Eq. (4) is no longer valid, in which case exact demagnetization formulas described in Ref. 3 must be applied.

¹A. P. Malozemoff and J. C. Slonczewski, *Magnetic Domain Walls in Bubble Materials* (Academic, New York, 1979).

²H.-P. D. Shieh and M. H. Kryder, *IEEE Trans. Magn.* **24**, 2464 (1988).

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Ga vacancy-assisted diffusion of Si in GaAs

K. B. Kahen

Corporate Research Laboratories, Eastman Kodak Company, Rochester, New York 14650-2011

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A model for Si diffusion into GaAs based on the formation of $\text{Si}_{\text{Ga}}^+ - V_{\text{Ga}}^-$ pairs is developed. The model follows the formalism developed by M. E. Greiner and J. F. Gibbons [*Appl. Phys. Lett.* **44**, 750 (1984)]. Using recently derived values for the Ga vacancy diffusivity, it is shown that the pair diffusion coefficient is approximately equal to three-quarters its value. The results of the model are demonstrated to be in good agreement with the Si diffusion data.

For a number of years, the accepted model for the diffusion of Si in GaAs has been the Si-pair diffusion model of Greiner and Gibbons.¹ Their proposal is that at high Si concentrations, the dominant diffusing species are $\text{Si}_{\text{Ga}}^+ - \text{Si}_{\text{As}}^-$ nearest-neighbor pairs. These pairs diffuse substitutionally by exchanging positions with both Ga and As vacancies, V_{Ga} and V_{As} , respectively. Using two adjustable parameters, the pair diffusion coefficient, D_p , and the pair equilibrium constant, K_p , their model can predict the available Si diffusion data.^{1,2} Recently, data on the Si diffusion process has been presented by Deppe *et al.*,^{3,4} which they claim supports a model for Si diffusion in terms of $\text{Si}_{\text{Ga}}^+ - V_{\text{Ga}}^-$ pairs. In this communication, a model for Si diffusion will be presented which contains attributes of both models. The formalism of pair diffusion of Greiner and Gibbons¹ will be combined with the notion of diffusion of $\text{Si}_{\text{Ga}}^+ - V_{\text{Ga}}^-$ pairs. In addition, the pair diffusion coefficient will be shown to be a simple function of the V_{Ga} diffusivity, D_p , which recently has been determined as a function of temperature by Kahen *et al.*⁵

The basis for the Si-pair diffusion model¹ is the result that Si is highly electrically compensated in GaAs for large Si concentrations. More specifically, a Si concentration of $\sim 2 \times 10^{20}$ cm⁻³ produces a net electron concentration of $\sim 5 \times 10^{18}$ cm⁻³.¹ In spite of the complexities associated

with the high-temperature Si compensation data,⁶ Greiner and Gibbons¹ interpret the large compensation simply in terms of Si being amphoteric, i.e., Si occupies substitutionally either Ga or As sites. Therefore, during diffusion, Si can exchange sites with either Ga or As vacancies. On the basis of charge considerations, they proposed that exchange with both types of vacancies is simpler if the diffusing species are $\text{Si}_{\text{Ga}}^+ - \text{Si}_{\text{As}}^-$ pairs instead of isolated Si atoms. Consequently, Si pairs should diffuse faster than isolated Si atoms and they developed a formalism to determine the Si-pair concentration as a function of the total Si concentration. The starting point of the model is the following equilibrium relation

$$[\text{Si}_{\text{Ga}}^+] [\text{Si}_{\text{As}}^-] = K_p [\text{Si}_{\text{Ga}}^+ - \text{Si}_{\text{As}}^-], \quad (1)$$

where [] denotes concentration and K_p is given by

$$K_p = N/Z \exp(-E_B/kT). \quad (2)$$

In the above, N is the molecular density of GaAs, Z is the number of configurations of the pair ($Z = 4$), and E_B is the binding energy of the pair, which was taken to be the Coulombic interaction energy between the pair at the nearest-neighbor distance, a_D . As a first approximation, they set a_D equal to the GaAs equilibrium nearest-neighbor distance of 2.45 Å. They obtained a better fit to their data by reducing a_D by $\sim 18\%$.