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Magnetic hysteresis of cobalt ultrathin films with perpendicular anisotropy

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We have investigated the coercivity mechanism in cobalt ultrathin films with perpendicular anisotropy. Important time-dependent effects suggest that thermally activated phenomena play a dominant role in these materials. A simple model based on thermally activated wall motions accounts fairly well for the experimentally observed shape and time dependence of the hysteresis loops. Conversely, it provides useful information on the activation energy distribution.

Recently, cobalt-based multilayers have been shown to be very promising candidates for magneto-optic storage applications and therefore have attracted very much interest [1]. These new materials possess over the traditional rare-earth–transition-metal alloys the advantage of a larger magneto-optic Kerr rotation at short wavelength (thus allowing a larger storage density), together with a much higher chemical stability; the perpendicular magnetization can be achieved for low Co-layer thicknesses thanks to a strong interface anisotropy [2]. For the thermomagnetic writing process, the dependence of the coercivity on temperature is of greatest importance. The long time stability of the written bits is essential for data storage applications. Recently, it has been shown that important time dependent effects happen at room temperature in ferromagnetic ultrathin films [3]; they are displayed: (i) by a dependence of the hysteresis loop and coercive force with respect to the field variation rate; (ii) by a strong relaxation of the magnetization in constant field. These phenomena have been interpreted as resulting from thermal activation of wall displacements. Since these thermally activated processes depend exponentially on temperature, it is clear that they will strongly influence the temperature dependence of the coercivity. The present paper is devoted to the detailed study of the time-dependence of hysteresis and coercivity in a Co-ultrathin film of thickness 8.1 Å with a perpendicular easy axis. We will show, in particular, that a quantitative analysis of the hysteresis curves allows us to obtain some detailed information on the activation energy distribution.

The Co film has been grown by thermal evaporation under ultra-high-vacuum conditions onto a 250 Å thick polycrystalline Au substrate (average lateral size of the crystallites: 2000 Å) with (111) surface orientation and atomically flat over distances of several hundreds of Å. The Co grows epitaxially on Au with the hcp (0001) structure and is subsequently covered by a 250 Å thick protective Au layer. For magnetic investigations,

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the Au/Co/Au sandwich has been removed from its glass substrate using amylacetate varnish. Further details on the preparation and structural characterization have been reported in previous publications [4, 5]. Due to a large interface anisotropy, this film presents a perpendicular easy magnetization axis.

The magnetic studies have been performed at room temperature by using the recently developed alternating-gradient magnetometer, which combines the advantages of being fast and highly sensitive [6]. It has been shown that the logarithm of the relaxation time in constant field varies linearly with respect to the applied field [3]; assuming that the relaxation time τ follows an Arrhenius law

$$\tau = \tau_0 \exp(E_A/k_B T), \tag{1}$$

this observation implies that the activation energy varies linearly with respect to the applied field, i.e. it can be written (for $-H_p \le H \le 0$):

$$E_A(H) = V^* M_S (H + H_p), \tag{2}$$

where M_S is the saturation magnetization, the field H_p is the field needed for a magnetization reversal in absence of any activation processes (i.e. it is actually an "intrinsic" coercive field), and the characteristic volume V^* is related to the Barkhausen volume – whose magnetization is reversed within a single activation event. It is thus easily shown [7] that the equation of this hysteresis loop as a function of the field variation rate $\dot{H}$ is (for $-H_p \le H \le 0$):

$$M(H) = M_s\{2\exp[(1/\tau(H=0) - 1/\tau(H))k_B T/(V^* M_s \dot{H})] - 1\}, \tag{3}$$

and that the coercive field is given by

$$H_c = [\ln(\dot{H}) + \ln(\ln(2) \times \tau(H=0) V^* M_s/k_B T)]\, k_B T/V^* M_s; \tag{4}$$

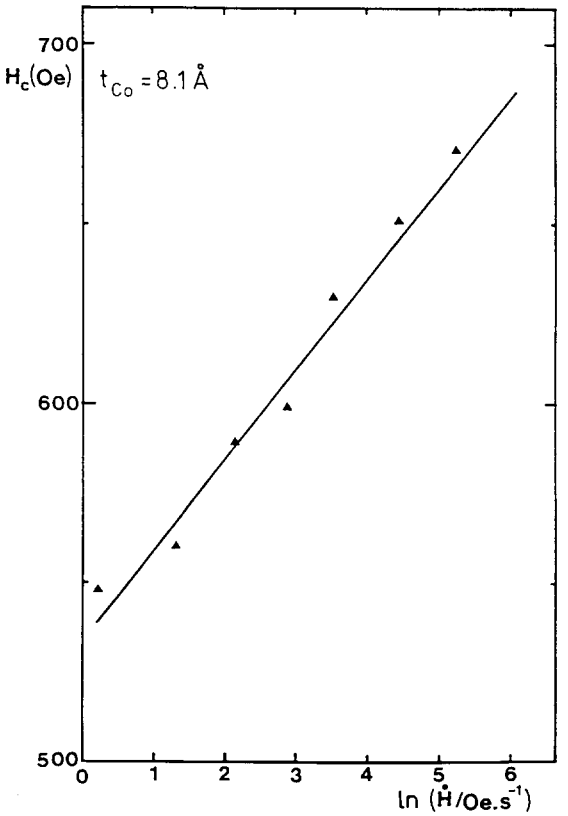

Fig. 1. Plot of the coercive field H_C, measured perpendicularly to the film plane at $T = 294$ K, as a function of the logarithm of the field variation rate $\ln(\dot{H})$.

H_c must therefore vary linearly with respect to the field variation rate $\ln(\dot{H})$. This is confirmed by the experimental observations as shown in fig. 1. From this plot, we can evaluate V^* and $\ln(\tau(H=0))$; in particular, we obtain $\ln(\tau(H=0) \approx 25$, and $V^* \approx 1.2 \times 10^{-6}\,\mu\text{m}^3$. By using eq. (3), together with the above values for V^* and $\ln(\tau(H=0))$, we have calculated the hysteresis loop for two different values of the field variation rate (respectively $\dot{H} = 1.22\,\text{Oe s}^{-1}$ and $\dot{H} = 82.0\,\text{Oe s}^{-1}$) and compared them with the experimental data. The result is shown in fig. 2; one observes a strong discrepancy between the experimental (solid points) and calculated (dot–dashed line) loops: the latter show a much steeper magnetization reversal than the former. As we will see, this discrepancy is due to a

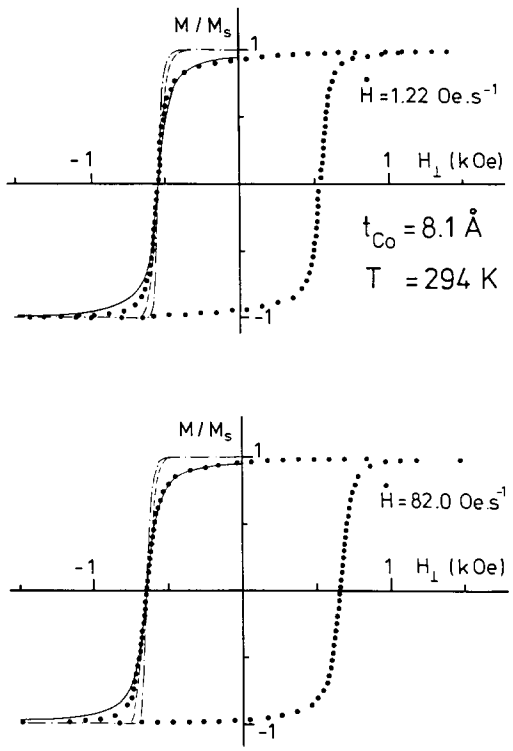

Fig. 2. Perpendicular hysteresis loop, at $T = 294\,\mathrm{K}$, for two different values of the field variation rate: $\dot{H} = 1.22\,\mathrm{Oe\,s^{-1}}$ (upper panel), and $\dot{H} = 82.0\,\mathrm{Oe\,s^{-1}}$ (lower panel); experimental data (solid points), and theoretical curves calculated using eq. (3), with $V^* = 1.2 \times 10^{-6}\,\mu\mathrm{m}^3$ and $\ln(\tau_0/s) = 25$, and assuming (i) a single activation energy (dot–dashed lines), (ii) a square-shaped distribution of activation energies of width $\Delta E_A/k_B T = 6$ (dashed lines), (iii) a Lorentzian distribution of activation energies of width $E_A/k_B T = 4$ (solid lines).

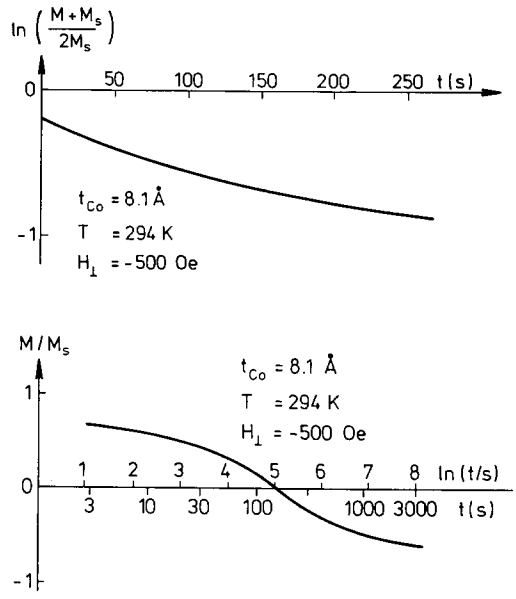

Fig. 3. Upper panel: plot of $\ln((M + M_s)/2M_s)$ as a function of time, at $T = 294\,\mathrm{K}$, in a field $H = -500\,\mathrm{Oe}$ after prior saturation in the positive direction; lower panel: same data as above, but in a $M(t)/M_s$ vs. $\ln(t)$ plot.

distribution of the activation energy which was neglected in the above discussion. In fig. 3 (upper panel), we show the logarithm of $(M + M_s)/2M_s$ as a function of the time t, measured in a field of $-500\,\mathrm{Oe}$, after prior saturation in a positive field. If there would be no distribution of the activation energy we should obtain a straight line with the slope giving the relaxation time. Actually, the experimental curve is not a straight line, which proves that there must be some distribution of the activation energy, with a typical width ΔE_A not negligible as compared to $k_B T$. A plot of M/M_s as a function of $\ln(t)$ allows us to estimate ΔE_A; one can easily show [7] that the maximum slope of this curve is of the order of magnitude of $k_B T/\Delta E_A$. The corresponding curve is displayed in fig. 3 (lower panel) and yields $\Delta E_A/k_B T \approx 6$.

In fig. 2, we show the calculated hysteresis loops (dashed lines) for a square distribution of width $\Delta E_A/k_B T = 6$, compared to the experimental results (solid points), for two different values of $\dot{H}$; the agreement between the experimental and theoretical curves is improved in the neighborhood of the coercive field, but otherwise remains rather poor. We have therefore tried other shapes for the activation energy distribution:

(i) by using a Gaussian distribution, there is little improvement as compared to the square distribution;

(ii) on the contrary, with a Lorentzian distribution of the activation energy, we obtain a very satisfactory agreement between the experimental (solid points) and theoretical (solid lines) hysteresis loops, as demonstrated in fig. 2.

This proves that the distribution of activation energy is not a very compact one (like the square

and Gaussian distributions), but rather presents quite long tails in the low and high energy regions (as a Lorentzian does); these tails are, in turn, responsible for the rounding of the hysteresis loop.

In conclusion, we have demonstrated that a simple activation energy model allows to interpret the time dependence as well the shape of the hysteresis loops. Conversely, this method provides useful information about the mechanism driving the coercivity in ferromagnetic ultrathin films.

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