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Magnetic susceptibility determination of the relaxation time for domain-wall motion in perpendicularly magnetized, ultrathin films

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Abstract

The temperature dependence of the magnetic relaxation time $\tau(T)$ is investigated in perpendicularly magnetized, ultrathin Fe/2 monolayer Ni/W(1 1 0) films by magnetic susceptibility measurements. Complex magnetic susceptibilities $\chi(T) = \chi'(T) + i\chi''(T)$ were measured by the polar Kerr effect as a function of temperature T. In all cases, $\chi'(T)$ and $\chi''(T)$ have broad peaks that are not obviously related to the Curie temperature T_C. An experimental relaxation time $\tau(T)$ is determined from the ratio $\chi''(T)/\chi'(T)$. The results support previous arguments that the susceptibility arises from domain-wall motion.

Keywords: Ultrathin films; Polar Kerr effect; Domain-wall motion

Until recently, no distinction was made between the high-temperature behaviors of ultrathin films with perpendicular versus in-plane magnetization. New experiments indicate perpendicular magnets may collapse into a multidomain state at high temperature, complicating the loss of ferromagnetic order and obscuring the measurement of the Curie temperature T_C [1–3]. Specifically the temperature T_{REM} where remanence is lost as measured by macroscopic, averaging techniques, may be considerably less than T_C. These issues are addressed here using a relaxation time analysis of magnetic susceptibility measurements of perpendicularly magnetized, ultrathin Fe films grown on a 2 monolayer (ML) Ni buffer. Although T_C is not determined, the analysis confirms that domain-wall motion dominates the magneto-optic signal as remanence is lost at high temperature and shows that the susceptibility remains domain-like to temperatures well above T_{REM}.

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The preparation methods, structure, and magnetic properties of Fe on a 2 ML Ni buffer on W (1 1 0) have been extensively studied and published in previous articles [2–4,14]. The Fe structure is slightly strained FCC for thicknesses less than 3 ML, and ferromagnetism is observed at low temperatures. Films 2 ML or thinner have an out-of-plane moment, whereas a reorientation phase transition (RPT) occurs for films thicker than 2 ML. Complex magnetic susceptibilities $\chi = \chi' + i\chi''$ were measured as a function of temperature with the AC magneto-optic Kerr effect technique (MOKE) technique [5,6,13] using a modulation field of 1.3 kA m^{-1} (16 Oe) at a frequency of 210 Hz.

Fig. 1 shows a previously published [3] complex $\chi(T)$ data set for a 1.5 ML thick Fe film on 2 ML Ni(1 1 1)/W(1 1 0), plotted on a semilogarthmic scale. An estimate of 250 K < T_{REM} < 260 K is obtained by extrapolating to $\chi'' = 0$ on the linear scale, since χ'' is proportional to the remanent magnetization [13]. T_{REM} is only an approximate marker, as χ'' is small but nonzero for $T > T_{REM}$. The approximately exponential decay of $\chi'(T)$ was previously identified as the signature

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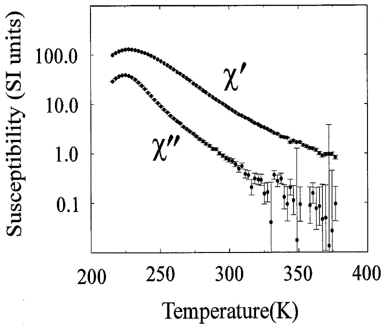

Fig. 1. Real χ' and imaginary χ'' parts of the complex susceptibility are plotted for a perpendicularly magnetized, 1.50 ML Fe film grown on a 2 ML Ni buffer. The approximately simple exponential dependence of χ' is a signature of a domain phase that condenses with increasing temperature.

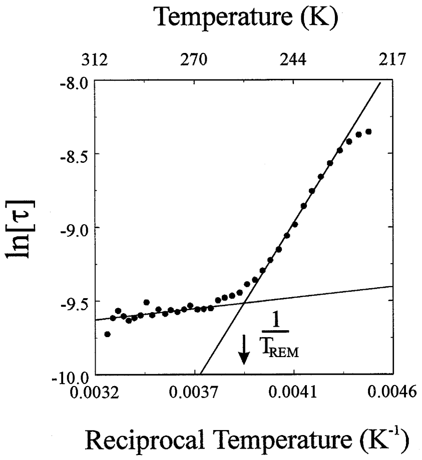

Fig. 2. An Arrhenius plot of $\ln[\tau]$ vs. T^{-1} shows two regions as indicated by the lines. The region at high T^{-1} gives a slope T_A and intercept τ_0 that are consistent with domain-wall motion in an ultrathin film. A second region may indicate a change in domain structure.

of a perpendicular domain phase that condenses spatially with increasing temperature [2,3]. Similar domain effects have been observed in other systems near the RPT by spin-polarized electron microscopy [7,8]. In the domain-wall-motion mechanism proposed by Kashuba and Pokrovsky [9], magnetic response arises from domain-wall motion: domains oriented parallel to the applied field grow at the expense of those antiparallel to the applied field. The domain walls stiffen with respect to an applied field during condensation and the susceptibility decreases with increasing temperature. Domain-wall motion through perturbations such as sample defects is thermally activated and therefore χ has an associated relaxation time. In the limit that the applied field amplitude is small and the magnetization responds linearly to the applied field, the complex susceptibility is given by

$$\chi = \frac{(1 + \mathrm{i}\omega\tau)\chi_{\mathrm{eq}}}{1 + (\omega\tau)^2}, \tag{1}$$

where χ_{eq} is the static susceptibility, ω is the experimental angular frequency, and τ is the relaxation time. An experimental relaxation time is therefore defined as

$$\tau(T) \equiv \chi''/\omega\chi', \tag{2}$$

a form that is independent of χ_{eq}. The form of $\chi'(T)$ differs from the equilibrium susceptibility because of the temperature dependence of $\tau(T)$. A simple Arrhenius model for the temperature dependence of τ using a single temperature-dependent activation barrier E_A gives

$$\tau(T) \approx \tau_0 \exp[E_A(T)/k_B T]. \tag{3}$$

For a single activation event in the limit of a small applied field [10],

$$E_A(T) \approx V_B \mu_0 M(T) H_0, \tag{4}$$

where V_B is the Barkhausen volume associated with a domain-wall displacement and H_0 is the field required to move domains at $T = 0$. An Arrhenius plot, $\ln[\tau]$ vs. $1/T$, should therefore track the magnetization within the domain structure, giving a slope of $E_A(T)/k_B$ and intercept $\ln[\tau_0]$.

This simple model is investigated in Fig. 2 for the data of Fig. 1. The plot excludes the nonlinear region above $0.0044\ \mathrm{K}^{-1}$ (below 230 K) where the growing coercive field produces nonlinearity in χ'' and invalidates the relaxation model, as well as the noisy region below $0.0032\ \mathrm{K}^{-1}$ (above 310 K). Two tangent lines are drawn to estimate E_A and $\ln[\tau_0]$. At large T^{-1} (low T), the first tangent line gives $T_A = E_A/k_B = 2400 \pm 300$ K and $\ln[\tau_0] = -19 \pm 2$, where τ_0 is in seconds. For the second tangent at lower T^{-1}, $E_A = 0$ within the experimental error, but gives $\ln[\tau_0] = -10.0 \pm 0.3$.

The relaxation-time analysis is consistent with domain-wall-motion as the magnetic contrast mechanism in the susceptibility measurements. The Arrhenius plot for $T < T_{\mathrm{REM}}$ confirms the existence of a thermally activated process that is quantitatively comparable to domain-wall motion in other perpendicularly magnetized, ultrathin films [10–12]. This consistency and theory [9] support the identification of the exponential decay of χ' as a signature of a condensing domain phase [2,3].

For $T > T_{\mathrm{REM}}$, the magnetic response is more complicated. Exponential decay persists to at least 100 K above T_{REM}, suggesting that spatial condensation of the domain structure occurs to at least these temperatures. Also, the magnitude of χ' is greater than 1 (SI units) throughout this range of temperature [2]. These two points are consistent with the presence of domains at high temperature and suggest that T_{REM} *is many tens of degrees below* T_{C}. The high temperature relaxation time is ambiguous, however. A possibility that must be considered is that this second regime is an artifact and does not correspond to a physical crossover. For the given data, the most probable candidates for artifacts are the difficulty in determining the phase ϕ between χ' and χ'', or an offset in χ''. If it is indeed physical, the dramatic decrease of E_{A} near T_{REM}, could indicate a vanishing local moment within the domains. Contradicting this interpretation, however, is the fact that the two temperature regimes have dramatically different τ_0. One possibility is that a subtle transition in the domain topology and dynamics occurs near T_{REM}, as in liquid crystals. Such topological transitions are predicted by theory [9,15]. Another possibility is that elastic wall displacement needs to be included in the quantitative analysis of the susceptibility.

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