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Magnetoelastic coupling and epitaxial misfit stress in ultrathin Fe(1 0 0)-films on W(1 0 0)

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Abstract

Measurements of the magnetostrictive stress in epitaxial Fe films on W(1 0 0) reveal a sharp deviation of the magnetoelastic coupling in nm films from bulk magnetostriction. Fe films thinner than 20 nm contract upon magnetization in [1 0 0], whereas thicker films expand upon magnetization in [1 0 0]. In situ stress measurements are analyzed to correlate the film thickness dependent magnetoelastic coupling with the thickness dependence of film strain. A strain dependent contribution to the magnetoelastic coupling is found to describe the experimental data for films thicker than 15 nm. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetoelastic coupling; Magnetostriction; Film stress; Epitaxial strain

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The magnetoelastic coupling in epitaxial films is of fundamental interest in the phenomenological description of the dependence of the magnetic anisotropy on misfit-induced film stress [1,8]. However, the application of bulk magnetoelastic coupling constants to ultrathin, epitaxially strained films might be problematic as both experimental [2–4,9,10] and theoretical [5,11] investigations indicate that bulk magnetoelastic coupling constants do not apply to ultrathin epitaxial films in general.

The goal of this work is to present experimental evidence for the influence of epitaxial misfit stress on the magnetoelastic coupling. We measure *positive* magnetostrictive stress for Fe films thicker than 20 nm, that are only slightly stressed by ~ 1 GPa, whereas thinner Fe films are under larger misfit stress of several GPa and show *negative* magnetostrictive stress. This thickness dependent magnetoelastic coupling in epitaxial Fe(1 0 0) films is ascribed to a strain dependent correction of the magnetoelastic coupling, that gives a good description of the experimental data for film thicknesses above 15 nm.

We employ an optical deflection technique to detect the change of the radius of curvature of the W substrate due to film stress or due to magnetostrictive stress, as discussed in detail previously [4,6]. We calculate the magnetostriction constant $\lambda_{1\,0\,0}$ from the experimentally determined magnetoelastic coupling constant B_1, that is given by the change of curvature $1/R$:

$$\tfrac{3}{2}\lambda_{1\,0\,0}(c_{11}^{\mathrm{Fe}} - c_{12}^{\mathrm{Fe}}) = -B_1 = \frac{Y_{\mathrm{S}} t_{\mathrm{s}}^2}{(1+\nu_{\mathrm{S}})6t_{\mathrm{F}}}\left[\frac{1}{R^{\mathrm{L}}} - \frac{1}{R^{\mathrm{W}}}\right]. \quad (1)$$

The subscripts F and S refer to film and substrate properties, respectively. The superscripts L and W refer to magnetization along the substrate length –Fe[1 0 0]– and width –Fe[0 1 0]–, respectively. The substrate thickness is $t_{\mathrm{S}} = 100$ μm, the film thickness is given by t_{F}, the Young moduli and Poisson ratios are: $Y_{\mathrm{F}} = 131$ GPa, $\nu_{\mathrm{F}} = 0.37$, $Y_{\mathrm{S}} = 402$ GPa, $\nu_{\mathrm{S}} = 0.28$ [4]. The intrinsic films stress τ is given by the curvature R, $\tau = Y_{\mathrm{S}} t_{\mathrm{s}}^2/(6(1-\nu_{\mathrm{S}})t_{\mathrm{F}}R)$. Low energy electron diffraction indicates a Fe(1 0 0)-film orientation and we expect isotropic epitaxial film stress τ, from which the corresponding

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isotropic strain ε is calculated by $\varepsilon = \tau(1 - \nu_F)/Y_F$ (Fig. 1(b)).

The magnetizing field can be oriented along any direction by a suitable superposition of the fields of independent electromagnets [6], the sample magnetization is monitored by the magneto-optical Kerr effect, and magnetic domains are imaged with a Kerr-microscope.

The in situ combination of stress measurements during film growth with measurements of the magnetostrictive stress reveals the Fe film thickness dependence of both the magnetoelastic behavior and of the film stress, as evidenced in Fig. 1. Fig. 1(a) shows a plot of the magnetostriction constant λ, left axis, and of the magnetoelastic coupling B_{eff} on the right axis as a function of the Fe film thickness. Fig. 1(b) shows the film stress, left axis, and the calculated film strain, right axis, as a function of Fe film thickness.

The most interesting result of our investigation is that the so-called magnetostriction *constant* $\lambda_{1\,0\,0}$ of Fe is thickness dependent and changes its sign for a film thickness below 20 nm. The gradual decrease of $\lambda_{1\,0\,0}$ from positive values in region II of Fig. 1(a) to negative value in region I for thinner films is correlated with the increase of the film stress with decreasing thickness, as presented in Fig. 1(b). The magnetostriction constant and the magnetoelastic coupling for the thickest films of 70 nm Fe are approximately a factor of six smaller than the respective bulk values, that are indicated by the dashed line in Fig. 1(a). For films thinner than 5 nm the situation is even more complicated: the magnetostriction rises from -12×10^{-6} at $t_{\mathrm{Fe}} = 5$ nm to -4×10^{-6} at 1 nm, whereas the film stress continues to increase from 2 to 8 GPa in the same thickness range. The solid curve in Fig. 1(a) is derived from a simple model of the strain dependence of the magnetoelastic coupling, derived below, and gives a reasonable description of the thickness dependence of λ for $t_{\mathrm{Fe}} > 15$ nm.

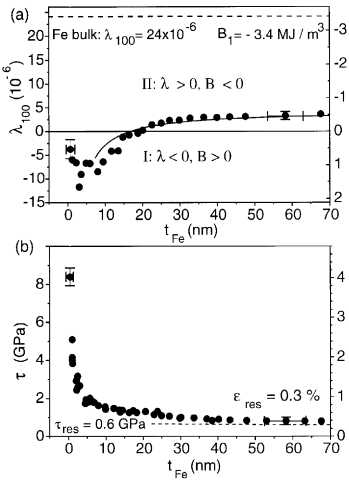

Fig. 1. (a) Magnetostrictive strain $\lambda_{1\,0\,0}$, left axis, and magnetoelastic coupling B_{eff}, right axis, vs. Fe film thickness on W(1 0 0). Note that the magnetostrictive strains and the magnetoelastic coupling change their sign for increasing film thickness from region I to region II at $t_{\mathrm{Fe}} = 20$ nm. The broken line indicates the respective bulk values, the solid curve describes the thickness dependence of B in a model of a strain dependent correction to B_{eff}, as discussed in the text. (b) Film stress vs. Fe film thickness. The broken line indicates a residual stress of 0.6 GPa ($\varepsilon_{\mathrm{res}} = 0.3\%$).

The correlation magnetoelastic coupling and strain can be described by [3]: $B_{\mathrm{eff}} = B_1 + D\varepsilon$. This mimics a strain dependence of B, and consequently of λ (Eq. (1)). The strain dependence of B may express itself in a thickness dependence of B, as it is commonly observed [1,7], that the epitaxial misfit strain relaxes with increasing film thickness. We derive the thickness dependence of the misfit strain from our measurements of film stress. The correlation between the magnetoelastic coupling and the film strain is investigated by plotting B_{eff}, as derived from Fig. 1(a), vs. ε, as derived from Fig. 1(b). This strain dependence of the magnetoelastic coupling is presented in Fig. 2(a).

Only in region II of negative B_{eff} in Fig. 2(a), is a linear strain dependence observed. In the following, we limit the discussion of the strain dependence of B_{eff} to region II, which translates to thicknesses above 20 nm. The analysis of the y-intercept and the slope of the solid line in region II gives: $B_1 = -1.2 \pm 0.2$ MJ/m^3, $D = 200 \pm 30$ MJ/m^3. Note, that D is more than factor of 100 larger

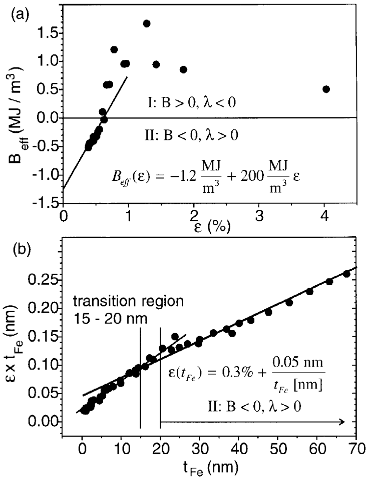

Fig. 2. (a) Effective magnetoelastic coupling vs. film strain. In region II, $B_{\mathrm{eff}} < 0$, the data are described by a linear strain dependence, as indicated by the solid curve. Y-intercept and slope give B_1 and D. (b) Plot of the product strain times film thickness vs. film thickness to check the validity of $\varepsilon(t) = \varepsilon_{\mathrm{res}} + \eta/t_{\mathrm{Fe}}$. Two linear sections are separated around $t_{\mathrm{Fe}} = 15$–20 nm. Slope and y-intercept of the curve in region II give $\varepsilon_{\mathrm{res}}$ and η.

than B_1, and already small strains are capable of changing B_{eff} dramatically. The value of B_1 is less than half of the respective Fe bulk value and points towards the issue if choosing the appropriate reference state. Measurements on epitaxial Fe films on MgO(1 0 0) for film stresses between 0.1 and 0.8 GPa revealed a factor of five larger value for D [3]. However, in contrast to our results, the Fe bulk value for B_1 was found to apply for Fe on MgO. In conclusion, we suggest that, due to its magnitude, D constitutes an important contribution to the magnetoelastic energy of epitaxially strained films. The nature of the film–substrate composite seems to influence D considerably.

To derive an analytical expression for the thickness dependence of the film strain $\varepsilon(t)$, we include the residual strain $\varepsilon_{\mathrm{res}}$ to the usually suggested [1] $1/t$ – dependence of the strain by $\varepsilon(t) = \varepsilon_{\mathrm{res}} + \eta/t$ [7]. To test the validity of this model we plot in Fig. 2(b) the product $\varepsilon(t)$, as obtained from Fig. 1(b), times film thickness t_{Fe} vs. t_{Fe}. This analysis distributes the data of Fig. 1(b) on two linear curves, one extending in region I: $0 < t < 20$ nm, the other curve covers in region II $t > 20$ nm. Quite remarkably, the kink in the curves between the two regions appears around the Fe film thickness of $t = 15$–20 nm, close to the thickness of 20 nm where the transition from positive to negative magnetostrictive strain is observed. Further investigations are clearly called for to test whether the kink in the slopes of Fig. 2(b) is due to some structural transition in the film that might account for the different strain and magnetoelastic behavior in regions I and II. In region II we find from the slope and the y-intercept of the curve $\varepsilon_{\mathrm{res}} = 0.3\%$, and $\eta = 0.05$ nm, respectively. This residual strain and the initial misfit agree with the data of Fig. 1(b) for high and low thicknesses, respectively.

Finally, inserting these values into the expression for $\varepsilon(t)$ we can model the thickness dependence of B for $t > 20$ nm by $B_{\mathrm{eff}} = -1.2\ \mathrm{MJ/m^3} + 200\ \mathrm{MJ/m^3}\ (0.003 + (0.05/t_{\mathrm{Fe}}\ [\mathrm{nm}]))$. The solid curve in Fig. 1(a) is a plot of this relation. It agrees with our experimental data for $t > 20$ nm, but the complicated magnetoelastic behavior for $t < 15$ nm cannot be described by the simple model, as clearly demonstrated by the deviation between experimental data and the solid curve in Fig. 1(a). It remains to be investigated whether a structural transition is indicated by the kink in the curves of Fig. 2(b), and how this might influence the magnetoelastic coupling.

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