Lateral indirect exchange coupling in a two-dimensional nanostripe array

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We observe a lateral indirect exchange coupling in a multistripe system of parallel Fe nanostripes grown by self-organized growth on a vicinal single-crystal W(110) surface. The width and the distance between the stripes of monolayer height were modified via the total amount of deposited Fe. The easy axis of the magnetization lies perpendicular to the stripe edges and in the surface plane, thus resulting in a ferromagnetic dipolar coupling. In addition to the dipolar coupling we observe an antiferromagnetic indirect exchange coupling for the nanostripe system covered by Au. The coupling causes a superferromagnetic phase transition in the nanostripe array.

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Ferromagnetic films separated by a nonmagnetic interlayer are magnetically coupled by indirect exchange coupling.[1] Much research effort has been devoted to this indirect exchange coupling since the first leading experiments.[1–3] For most metallic interlayer materials the coupling oscillates with increasing interlayer thickness.[3] The origin of the indirect coupling is strongly related to the occurence of quantum-well states in the interlayer close to the Fermi energy, depending on the interlayer thickness and on the relative orientation of the magnetization.[4,5] The coupling mechanism provides a direct access to the Fermi surface of the interlayer.

A similar coupling mechanism can also be expected for lateral magnetic nanostructures. A simple geometry for an experimental test is provided by a system of parallel and separated stripes. The preparation of parallel stripes at step edges of vicinal single crystal surfaces is a well-established technique,[6] and has found much experimental[7–10] and theoretical[11,12] interest. A theoretically predicted quasi-one-dimensional behavior of narrow stripes[13] was confirmed experimentally for Fe stripes grown on vicinal Cu(111) (Ref. 8) and vicinal W(110).[14] A two-dimensional system of parallel ferromagnetic stripes separated from each other forms an analogon to a multilayer system of alternately magnetic and nonmagnetic layers. The substrate material takes the role of the nonmagnetic interlayer in multilayer systems. The properties of the nonmagnetic intersections are varied by additional coatings of the ferromagnetic nanostripe system. Despite the reduced dimensionality an indirect exchange coupling varying with the separation width between the stripes can be expected.

In this paper we report on pseudomorphically grown Fe/W(110) stripes with step edges parallel to the [001] orientation, coated by Au. For uncoated stripes the magnetic easy axis lies along [110], i.e. perpendicular to the long stripe axis (see, i.e., Ref. 10). The same holds for Au-coated Fe stripes.[15] Thus the magnetization in the stripes imposes a ferromagnetic dipolar coupling. As pointed out in Ref. 10 the ferromagnetic dipolar coupling causes magnetic long-range order in the stripe system. Because the coupling is ferromagnetic it is impossible to measure coupling values from easy axis magnetization loops below the Curie temperature. Instead, we take advantage from the fact that the lateral coupling between the stripes is crucial for the magnetic long-range order, and obtain coupling values from an analysis of the magnetic susceptibility at the magnetic phase transition. In the first part of the paper we discuss a mean-field model adapted to Fe nanostripes, considering both the short-range interaction of moments within the stripe and the long-range interaction between the stripes. The Curie-Weiss behavior of the susceptibility reveals the long-range coupling. In the second part of the paper we present experimental results for Fe/W(110) nanostripes coated by Au. For stripe separations of about 1 nm we find a lateral coupling which is smaller than expected from the dipolar coupling, thus indicating an additional lateral indirect exchange coupling of antiferromagnetic sign.

For a single stripe without any coupling to adjacent stripes the internal spin dynamics are governed by exchange fields of the order of 10–100 T. In this case superimposed coupling fields, i.e., internal dipolar coupling fields, below 0.1 T can be neglected. Due to the strong uniaxial in-plane anisotropy the spin dynamics of a single stripe consisting of W parallel rows of spins can be described by the one dimensional Ising model where the exchange coupling constant J is replaced by WJ. Let $T_C(\infty)$ be the temperature of a stripe of infinite width. If the stripe width W is finite no spontaneous order will occur according to the one-dimensional Ising model. For $T<T_C(\infty)$ the magnetization decomposes into fluctuating spinblocks of full stripe width and a length L increasing with decreasing temperature.[11] These full width spin blocks act similar as the moments of an Ising chain. The magnetization decays exponentially at any finite temperature and no remanent order is left. The one-dimensional behavior shows up in the exponential decrease of the magnetic susceptibility with increasing temperature T,[13]

$$\chi_0 = \frac{C}{T}\exp\left(\frac{T_A}{T}\right), \tag{1}$$

where T_A denotes the energy one needs to create a spin block (which is $2J$ for the Ising chain). C depends weakly on the temperature because single fluctuating spins decrease the average magnetic moment per atom within a spin block.

In the following step we consider an additional lateral coupling between adjacent stripes. Because the magnetic

easy axis is perpendicular to the long stripe axis the main contribution to the coupling is the dipolar coupling. In addition an indirect exchange coupling might be superimposed. The long-range nature of the coupling (reduction of $1/r^2$ instead of exponential decrease with distance r) justifies the mean-field ansatz for the magnetization M,

$$M=\chi_0(H+\lambda M), \tag{2}$$

with the mean-field constant λ. The magnetic susceptibility results in

$$\chi=\frac{\chi_0}{1-\chi_0\lambda}. \tag{3}$$

The lateral coupling thus provokes a diverging susceptibility for $\chi_0(T_C)=1/\lambda$, indicating the onset of spontaneous order at a finite temperature T_C. We approximate Eq. (3) in two different temperature regimes. For $T\gg T_C$ the coupling can be neglected since χ_0 decreases rapidly with increasing temperature, i.e. $\chi=\chi_0$. For T close to T_C, however, we write Eq. (3) in the form

$$\frac{1}{\chi}=\lambda\left(\frac{\chi_0(T_C)}{\chi_0(T)}-1\right)=\lambda\frac{T}{T_C}(e^{(T_A/T_C)-(T_A/T)}-1). \tag{4}$$

When T is close to T_C [i.e., $T-T_C\ll T_C^2/(T_A-T_C)$], the exponential term can be linearized and we obtain

$$1/\chi=\lambda\frac{T_A}{T_C}\frac{T-T_C}{T_C}, \tag{5}$$

with a temperature dependence similar to the Curie-Weiss behavior. We replace $1/\chi$ by a saturation field defined by $H_s=M_s/\chi$,

$$H_s=H_\lambda\frac{T_A}{T_C}\frac{T-T_C}{T_C}, \tag{6}$$

with the coupling field defined by $H_\lambda=\lambda M_s$. Without further electronical coupling, H_λ is identical to the dipolar coupling field. Note that this analysis is valid in the temperature interval $T_C<T<T_C(\infty)$, only. In the case of an Fe/W(110) monolayer coated by Au this interval is particularly large: $T_C\approx 200$ K and $T_C(\infty)=290$ K.[15]

Experiments have been performed in ultra high vacuum, films prepared by molecular-beam epitaxy at pressures $p<5\times10^{-10}$ Torr, and characterized structurally and chemically using low energy electron diffraction, Auger spectroscopy, and scanning tunneling microscopy (STM).[14,17] We prepared an array of parallel Fe stripes of monolayer height by depositing Fe on a vicinal W(110) surface with step edges parallel to the [001] direction following previously described procedures[17] (see Fig. 1). The surface normal deviates from [110] by $1.4^0\pm0.1^0$, resulting in atomic steps with a mean step separation of 9.1 ± 0.6 nm. The terrace width corresponds to $W_0=41$ atomic rows. The mean width W of the Fe stripes is given by the terrace width multiplied by the coverage. STM reveals a considerable distribution of widths with a full width at half maximum of $\Delta W/W=0.3$.[10,17] Finally, the stripe array was covered by 6 monolayers (ML) of Au at room temperature. Previous Mössbauer studies showed that interdiffusion does not occur at room temperature or below.[15]

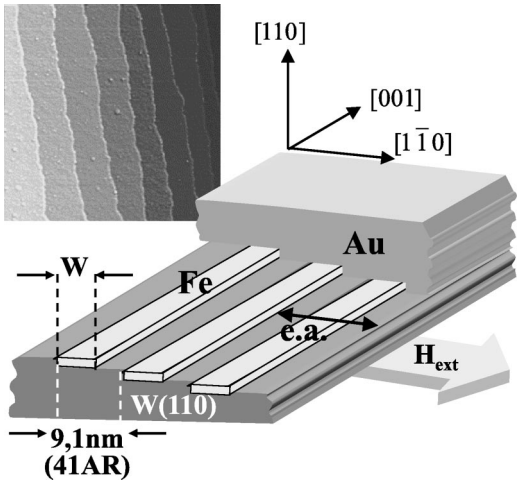

FIG. 1. Schematic model of the Fe nanostripe system on stepped W(110) surface covered by Au. Crystallographical and magnetical directions are indicated. Topographical STM image (100×100 nm^2) of 0.5 ML Fe on W(110) after annealing at 700 K and before Au coverage. Whereas the atomic step edge of the Fe nanostripe is visible and indicates the step flow growth mode, the stripe edge at the tungsten step edge could not be resolved.

The Kerr rotation θ_K of the longitudinal Kerr effect was measured in longitudinal fields applied along [110] (magnetic easy axis of the monolayer). Using a compensation technique, θ_K could be measured in absolute units. Temperatures were measured with a relative accuracy of 0.1 K and an absolute accuracy of about 1 K using a thermocouple spring attached to the sample crystal. Measurements presented in this study were done during slowly warming up with a rate of about 1 K/min. We measured samples of homogeneous Fe coverage, and scanned 4-mm-long wedges of 0–1.1 ML Fe thickness (prepared using a shadow mask) with a focused probe beam of 0.1 mm diameter.

Values for M_s and H_s are determined by a fit of $M=M_s\tanh(H/H_s)$ to the experimental magnetization loops. The susceptibility is calculated from $\chi=M_s/H_s$. The Arrhenius plot shown in Fig. 2 confirms Eq. (1) for Fe coverages below the full monolayer. From the slope we obtain values for the activation energy T_A. The strong coupling for overlapping stripes ($\Theta>1$) causes deviations from the one dimensional behavior [Eq. (1)].

The linear increase of H_s with T as shown in Fig. 3 confirms the temperature dependence predicted by the model [Eq. (6)] for separated stripes ($\Theta<1$), whereas H_s increases nonlinearly for overlapping stripes ($\Theta>1$). In contrast to the model H_s does not vanish at $T=T_C$. With decreasing stripe width we observe an increasing offset. This can be explained by considering the fluctuating stripe widths. Morphological interruptions of the nanostripes cause an effective limitation of the correlation length of fluctuations.[12] For such stripes of finite length, the divergence of the susceptibility is suppressed, thus providing a weakly temperature-dependent

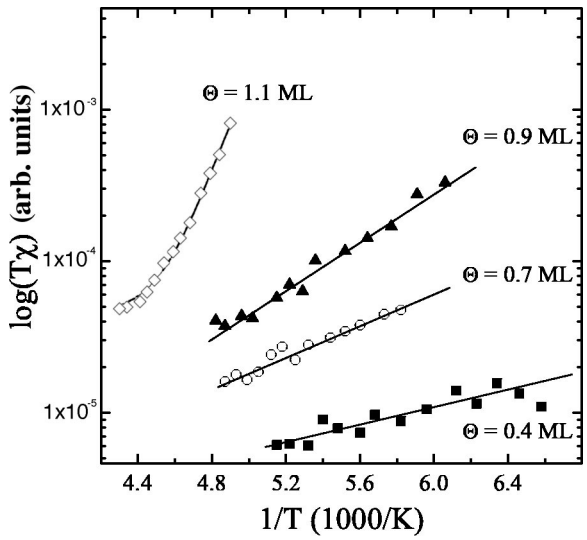

FIG. 2. Temperature dependence of the normalized magnetic susceptibility $T\chi/C$ as defined in the text for averaged stripe widths W as indicated in the figure. The Arrhenius plot reveals the exponential temperature dependence of χ for coverages $\Theta<1$.

background signal for $1/\chi$. The number of interruptions and hence the offset will increase if the mean stripe width decreases.

From the slope of $H_s(T)$ (see Fig. 3) we obtain values for H_λ. Data for varying Fe coverages Θ taken from wedge samples are collected in Fig. 4(a). H_λ is plotted versus the separation $W_a = W_0(1-\Theta)$ between adjacent stripes. We observe a sharp decrease of H_λ with decreasing coverage close to $\Theta=1$ indicating the transition from overlapping, i.e. $W_a<0$, to separated stripes, i.e. $W_a>0$.

We compare H_λ with the dipolar coupling field estimated from a model of local moments μ_{Fe} localized at the Fe atoms. We assume that μ_{Fe} lies perpendicularly to the stripe

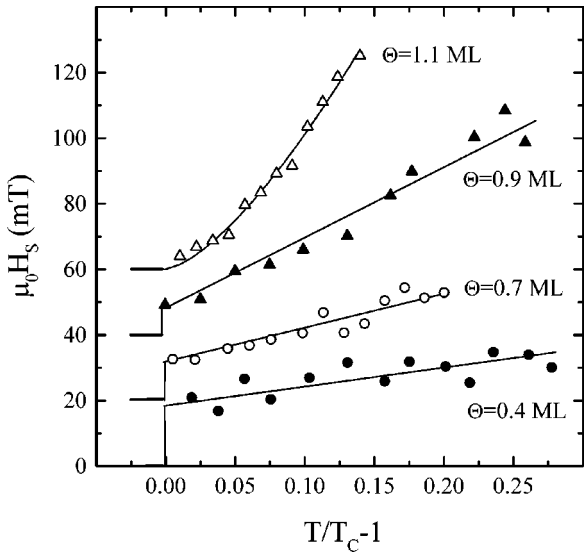

FIG. 3. Temperature dependence of the saturation field H_s in the vicinity of T_c. T_c increases from 160 to 200 K with increasing Fe coverage.

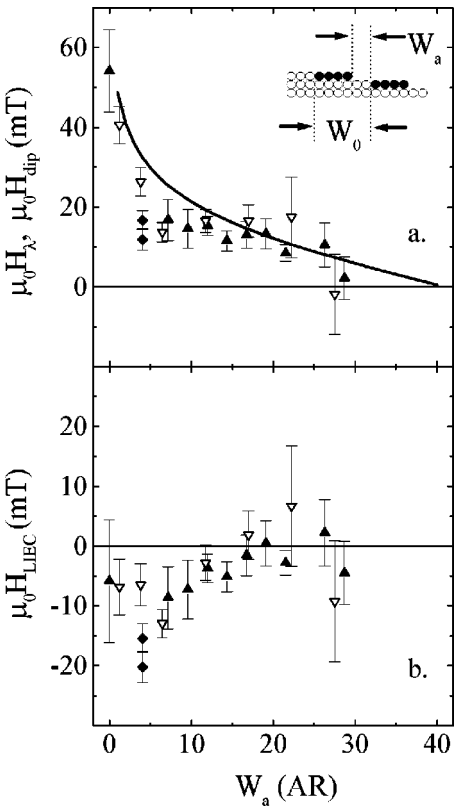

FIG. 4. Lateral magnetic coupling between the stripes. (a) Total coupling field H_λ as a function of the distance W_a (in atomic rows AR) between adjacent stripes [wedge samples (triangles) and samples with homogeneous Fe coverage (diamonds)]. The solid line indicates the dipolar coupling field H_{dip} calculated by a model of local moments. (b) Lateral indirect exchange coupling $H_J = H_\lambda - H_{\mathrm{dip}}$ vs stripe separation W_a.

axis and in the surface plane. The dipolar field produced by an infinitely long row of atoms at a distance r is given by $\mu/(2\pi a_{\mathrm{W}} r^2)$ (the tungsten lattice constant $a_W = 0.316$ nm). We add up the field of W atomic rows in an adjacent stripe (index i) and average the resulting field for the stripe under consideration (index j). Finally we obtain the dipolar coupling field produced by all homogeneously magnetized stripes on both sides of the stripe under consideration (index n):

$$\mu_0 H_{\mathrm{dip}}(W) = \frac{1}{\pi}\frac{\mu}{a_{\mathrm{W}}^3}\frac{1}{W}\sum_{n=1}^{\infty}\sum_{i=1}^{W}\sum_{j=1}^{W}\frac{1}{(nW_0+j-i)^2}. \quad (7)$$

Using $\mu = \mu_{\mathrm{Fe}} = 2.2\mu_{\mathrm{B}}$ as the saturation moment per Fe atom [as measured for Fe/W(110) monolayers covered by Ag (Ref. 18) we find numerical values as plotted in Fig. 4(a). Note that the dipolar field increases nonlinearly with decreasing separation W_a and increasing width W. In the limit of small coverages ($W \ll W_0$), Eq. (7) can be linearized to $\mu_0 H_{\mathrm{dip}}(W) = 21.6\ \mathrm{mT} \times W/W_0$, as stated in Ref. 10. For separations $W_a = 4-10$ atomic rows, H_λ is smaller in comparison to the dipolar coupling field thus indicating an additional coupling component favoring an antiparallel magnetization alignment. The most likely reason for this observation

is a lateral indirect exchange coupling (LIEC) similar to the indirect exchange coupling observed in multilayers. The corresponding coupling field $H_{\mathrm{LIEC}}=H_{\lambda}-H_{\mathrm{dip}}$ is plotted in Fig. 4(b). We observe an antiferromagnetic maximum $H_{\mathrm{LIEC}}=-15$ mT of the LIEC at a stripe separation $W_a=5$ atomic rows. For increasing stripe distance H_{LIEC} rapidly decreases toward zero. We do not observe an oscillation of the exchange coupling. However, as observed in film experiments[16] the oscillations are rapidly damped for inhomogeneous film thicknesses of the intermediate layer, which corresponds in our system to inhomogeneous stripe distances. In our case the distance variation is given by the terrace width distribution (30%) which was estimated from STM images. Thickness variations of the same order of magnitude for the Cr interlayer in a Fe/Cr/Fe(110)-trilayer system[19] also supressed oscillations of the coupling. The maximum value of the antiferromagnetic coupling corresponds to an interstripe coupling energy of $J_1=(\mu_0/2)H_{\mathrm{LIEC}}MWa_{\mathrm{W}}/\sqrt{2}=-1.4\times10^{-3}$ mJ/m^2, which is small in comparison to values obtained from multilayer systems. From the understanding of the conventional indirect exchange coupling we expect that the oscillation period and amplitude of the LIEC depend on the Fermi surface of the nonmagnetic interstripe sections. Both substrate (W) and coating material (Au) contribute to the coupling. A compensation of ferromagnetic and antiferromagnetic contributions might at least partly be the reason for the small value for J_1. If the coating material is exchanged, i.e. by the easy polarizable Pd, one might expect a smaller antiferromagnetic or even ferromagnetic LIEC.

In conclusion we have shown a lateral magnetic coupling between adjacent monolayer stripes. The lateral coupling is the sum of a lateral indirect exchange coupling and a dipolar coupling. The LIEC shows an antiferromagnetic maximum of $H_{\mathrm{LIEC}}=-15$ mT at a stripe distance of five atomic rows. The effect is similar to the well known indirect exchange coupling between magnetic films separated by a nonmagnetic interlayer.

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[1] P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, and H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).
[2] M. N. Baibich, J. M. Broto, A. Fert, and F. Nguyen Van Dau, Phys. Rev. Lett. **61**, 2472 (1988).
[3] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).
[4] P. Bruno, Phys. Rev. B **52**, 411 (1995).
[5] M. D. Stiles, Phys. Rev. B **48**, 7238 (1993).
[6] F. J. Himpsel, J. E. Ortega, G. K. Mankey, and R. F. Willis, Adv. Phys. **47**, 511 (1998).
[7] A. Dallmeyer, C. Carbone, W. Eberhardt, C. Pampuch, O. Rader, W. Gudat, P. Gambardella, and K. Kern, Phys. Rev. B **61**, R5133 (2000).
[8] J. Shen, R. Skomski, M. Klaua, H. Jenniches, S. S. Manoharan, and J. Kirschner, Phys. Rev. B **56**, 2340 (1997).
[9] J. -S. Suen and J. L. Erskine, Phys. Rev. Lett. **78**, 3567 (1997).
[10] J. Hauschild, H. J. Elmers, and U. Gradmann, Phys. Rev. B **57**, R677 (1998).
[11] P. Sen, D. Stauffer, and U. Gradmann, Physica A **245**, 361 (1997).
[12] M. Müller and W. Paul, J. Stat. Phys. **73**, 209 (1993).
[13] E. V. Albano, K. Binder, D. W. Heermann, and W. Paul, Z. Phys. B **77**, 445 (1989).
[14] M. Pratzer, H. J. Elmers, M. Bode, O. Pietzsch, A. Kubetzka, and R. Wiesendanger, Phys. Rev. Lett. **87**, 127201 (2001).
[15] U. Gradmann, G. Liu, H. J. Elmers, and M. Przybylski, Hyperfine Interact. **57**, 1845 (1990).
[16] J. A. Wolf, Q. Leng, R. Schreiber, P. A. Grünberg, and W. Zinn, J. Magn. Magn. Mater. **121**, 253 (1993).
[17] H. J. Elmers, J. Hauschild, and U. Gradmann, J. Magn. Magn. Mater. **221**, 219 (2000).
[18] H.J. Elmers, G. Liu, and U. Gradmann, Phys. Rev. Lett. **63**, 566 (1989).
[19] H. J. Elmers, J. Schwabenhausen, and T. Dürkop, in *Magnetic Ultrathin Films, Multilayers, and Surfaces*, edited by J. Tobin, D. Chambliss, D. Kubinski, K. Barmak, P. Dederichs, W. de Jonge, T. Katayama, and A. Schuhl, MRS Symposia Proceedings No. 475 (Materials Research Society, Pittsburgh, 1997), p. 605.