Thermal spin excitations in epitaxial Fe nanostructures on GaAs(001)

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Thermal spin excitations in confined ferromagnetic structures become increasingly important, e.g., because they reduce tunnel magnetoresistance in highly integrated magnetic memories and the stability of stored information. Here, the effect of lateral confinement on the temperature dependence of magnetization in ultrathin films was studied. Epitaxial Fe films were grown on GaAs(001) by molecular beam epitaxy. Patterning into dot arrays with several million dots of well defined circular shape was accomplished by electron beam lithography, lift-off, and ion beam etching. The magnetic properties of the samples were investigated by superconducting quantum interference device magnetometry between 10 and 350 K. All films—in addition to the fourfold magnetocrystalline anisotropy—have an in-plane uniaxial magnetic anisotropy with the easy axis along [110], which is fully conserved during patterning. The temperature dependence of the spontaneous magnetization for \( T < 0.5T_C \) can be well described by Bloch’s law, \( M_s(T) = M_s(0)(1 - BT^{3/2}) \), for all samples. For a dot diameter of 500 nm the spin wave parameter \( B \) is significantly increased compared to the extended 14 ML film, which in turn shows about twice the bulk value of \( B_{FE} = 5 \times 10^{-6} \text{K}^{-3/2} \). The enhancement of spin wave excitations with decreasing film thickness and lateral dimension is discussed in comparison to existing theories and model simulations. © 2003 American Institute of Physics. [DOI: 10.1063/1.1555314]

The temperature stability of magnetic memory cells, e.g., in magnetic random access memories (MRAMs) or magnetic tunnel junctions is essential for their functionality. These applications require ferromagnetic elements with sub-\( \mu \)m dimensions and uniaxial anisotropy for storing information in two stable states. Thermal spin excitations significantly reduce the tunnel magnetoresistance, \(^1\) and hence, the signal-to-noise ratio of the read-back signal. It can be expected that spin excitations increase with decreasing layer thickness and lateral dimensions of the memory cell. Therefore, we studied the temperature dependence of magnetization in ultrathin epitaxial Fe films and the effect of nanopatterning.

High quality bcc Fe films were grown at room temperature by molecular beam epitaxy (MBE) at a base pressure below \( 10^{-10} \) mbar on GaAs(001) substrates. (4 \( \times \) 2) reconstructed singular GaAs(001) surfaces were prepared by UHV-annealing at 600 °C and subsequent Ar-ion sputtering at the same temperature. \(^2\) After the substrate preparation Fe films with thicknesses between 4 and 18 ML were deposited at room temperature. Good epitaxial growth was achieved according to reflective high-energy electron diffraction. Because of the low temperature during Fe deposition no magnetically dead layers are formed. \(^3\) The Fe films were finally covered with a 4 nm thick Au layer to prevent oxidation.

Before patterning, the samples were examined by using an alternating gradient magnetometer (AGM) at room temperature and a superconducting quantum interference device (SQUID) in a wide temperature range (2 K \( \leq T \leq 350 \) K, \( H \approx 7 \) T). They show a superposition of a fourfold and a uniaxial in-plane magnetic anisotropy. The corresponding anisotropy constants \( K_1 \) and \( K_U \) vary linearly with the inverse film thickness. \(^4\)

Subsequently, patterning of the films was accomplished in two steps. First, an etch mask was fabricated with electron beam lithography (EBL), thermal evaporation of 30 nm Al and subsequent lift-off. In the second step, the resulting etch mask was transferred into the Fe film by ion beam etching using 500 eV Ar\(^+\) ions. The advantage of EBL is to produce dots with a well-defined circular shape. In order to get a signal large enough for an integral measurement like SQUID or AGM large arrays of several million dots with a dot diameter of 500 nm and a period of 1 \( \mu \)m were fabricated.

Figure 1(a) shows in-plane magnetization loops for a continuous 14 ML Fe film, i.e., 2 nm thick, along the easy axis (ea) (ea [110]) and the hard axis (ha) (ha [1−10]). The behavior is dominated by the uniaxial in-plane magnetic anisotropy. The ea magnetization loop is nearly rectangular with a coercivity of about 5 Oe, which indicates an excellent quality of the epitaxial film. Fitting an analytic expression to the ha loop as described in Ref. 2 the anisotropy constants are determined as \( K_1 = 2.6 \times 10^5 \text{erg/cm}^3 \), \( K_U = 5.9 \times 10^5 \text{erg/cm}^3 \) at room temperature.

Magnetization loops for the patterned 14 ML film are shown in Fig. 1(b). The ha loop is nearly the same as for the continuous film, i.e., the anisotropy is fully conserved, while in the easy axis the coercivity has increased to 250 Oe at room temperature and even 440 Oe at 10 K. Dipolar coupling among the dots can be neglected. \(^5\)

As a well known fact, the Curie temperature \( T_C \) of ultrathin films decreases with decreasing film thickness due to reduced coordination. In general, for temperatures well below the Curie temperature the temperature dependence of the spontaneous magnetization \( M_s(T) \) is given by Bloch’s relation. \(^6\)

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\[ M_s(T) = M_0(1 - BT^b) \]

\( B \) is the Bloch constant or spin-wave parameter with \( B_{\text{bulk-Fe}} = 5 \times 10^{-6} \text{ K}^{-3/2} \) for bulk \( \alpha \)-Fe, \( b \) the Bloch exponent, which is given by \( b = 3/2 \) for a three-dimensional system.

We measured the temperature dependence of the spontaneous magnetization of continuous Fe films with a thickness range from 4 to 18 ML, grown in the way described above. All films were measured along the easy axis \([110]\), where the remanence was verified to be equal to the spontaneous magnetization for all temperatures. First the sample was saturated in an applied field of 2 kOe, then the field was switched off. The remanent magnetization was measured with increasing temperature ranging from 10 to 350 K. Figure 2(a) shows the magnetic moments for different samples plotted versus \( T^{3/2} \). All moments are normalized to their values at \( T = 10 \text{ K} \). The data can be fitted very well by Bloch’s equation [Eq. (1)] with a Bloch exponent \( b = 3/2 \) (solid lines). The spin wave parameter \( B \) is determined for all samples with an error of \( <10^{-6} \text{ K}^{-3/2} \).

Finally, the same measurements were carried out for a 14 ML Fe(001) film patterned into an array of circular dots with a diameter of 500 nm. The data [Fig. 2(b)] clearly show that again a \( T^{3/2} \) law is fulfilled with a spin wave parameter \( B \) enhanced by about 40%.

Qualitatively, the increase of the spin wave parameter \( B \) in low-dimensional systems compared to the respective bulk material can be understood as a consequence of the reduced coordination of surface spins. Reduced exchange energy per spin will lower the energy of a spin wave with a given wave vector \( k \) leading to enhanced spin wave excitations at a specific temperature which are equivalent to an increase of the spin wave parameter \( B \). For a quantitative theory, however, spin wave dispersion as well as density of states for all spin wave modes and energies must be calculated for each individual system. This becomes even more complex by the necessity to include the correct anisotropies and boundary conditions (“pinning” or “antipinning”).

Numerous calculations have been reported in the literature for ultrathin films to explain experimental data; some of
them are reviewed in Ref. 7. For some time it had been proposed that the spontaneous magnetization varies as a linear function of temperature in two-dimensional systems. This has been disproved by many investigations including the present one where \( M(T) \) is well described by a \( T^{3/2} \) dependence (see Fig. 2). Indeed, a \( T^{3/2} \) behavior has been observed in high quality continuous films down to the monolayer range.\(^{8,9}\) Even if a \( T^{3/2} \) law is not theoretically founded for two-dimensional systems it has been shown by Mathon and Ahmad\(^{10}\) that an “effective \( T^{3/2} \) law” is expected to be valid in a certain temperature range.

Concerning surface spin excitations, it was first pointed out by Rado\(^{11}\) that spin wave amplitudes at surfaces and hence the spin wave parameter \( B \) should have twice the bulk value in the case of unpinned surface spins which correspond to an antinode of the spin waves at the surface. This argument was confirmed later in a detailed calculation by Mills and Maradudin.\(^{12}\) However, surface relaxation and roughness will reduce the exchange coupling strength at surfaces and interfaces in real films and lead to a further enhancement of the spin wave parameter \( B \) in agreement with experimental findings.\(^{13}\)

The increase of the parameter \( B \) with decreasing thickness has been discussed in a number of papers (e.g., Refs. 7–9, 14). In particular, it should be pointed out that \( B(t)/B_{\text{bulk}} \) was found to increase linearly with the inverse thickness in some cases, but in many other systems a non-linear variation was observed.\(^{7}\) Theoretically, Swirkowicz \textit{et al.}\(^{14}\) have argued that the Bloch coefficient, \( B \), will have a linear dependence on the inverse film thickness if the energy of the lowest spin wave mode is independent of film thickness. This is expected to be true in the absence of very strong anisotropies. The presence of a strong anisotropy will cause a thickness dependence of low spin wave energies and, hence, a non-linear variation of \( B \) with \( 1/t \).\(^{14}\)

To check the prediction of Swirkowicz \textit{et al.},\(^{14}\) the spin wave parameter determined from Fig. 2 is plotted as a function of the inverse thickness in Fig. 3. It is clearly seen that \( B \) does not scale as a linear function of \( 1/t \). This can be understood from the arguments of Swirkowicz \textit{et al.}, considering the very strong in-plane uniaxial anisotropy of the films thinner than 20 ML, which shows up in Fig. 1. The fact that the data can be fitted quite well with a \( (1/t)^{3/2} \) dependence cannot be explained at present, but should receive further consideration in theoretical studies of the problem.

In order to further check the reasoning of Swirkowicz \textit{et al.}, \( \text{Fe}_{70}\text{Co}_{30} \) films epitaxially grown on \( \text{Au}(001) \) will be studied in the future. For this system we expect vanishing anisotropies of second and fourth order\(^{15}\) and, therefore, it should allow for a critical check of the theoretical prediction.\(^{14}\)

Finally, the enhancement of the spin wave parameter \( B \) in the dots by about 40% in comparison to the extended film [Fig. 2(b)] can be qualitatively understood from the reduced coordination at the edge of the dots. However, if we assume a similar mechanism for spin wave amplitude enhancement as for surfaces of bulk or thick films,\(^{11–13}\) i.e., an enhance-ment of the parameter \( B \) for the edge spins by a factor of 2 (Ref. 11) or 3 (Ref. 13) for the outermost 2–3 atomic rows, we would expect an increase of the average value of \( B \) for a dot with 500 nm diameter by less than 1.5%. This means that a different mechanism must account for the observed increase of spin excitations. One possibility is that in the dots additional spin wave modes with relatively low energy and a high density of states are excited. Such modes have been observed in permalloy circular dots (diameter 1 \( \mu\)m) by means of Brillouin light scattering (BLS).\(^{16}\) For a quantitative answer to the question about the nature of these excitations investigations of smaller dots and magnetic microscopy with picosecond time resolution in combination with spin wave calculations and numerical simulations will be required in the future.

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\(^{6}\) F. Bloch, Z. Phys. 61, 206 (1930).