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Magnetism of nanowires of Fe(1 1 0) on W(1 1 0)

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Abstract

Ferromagnetic nanowires of Fe have been fabricated by molecular-beam epitaxy on a vicinal W(1 1 0) single-crystal surface with steps along the [0 0 1] direction. The magnetic properties were investigated by Kerr magnetometry. The magnetic easy axis is in the substrate plane and perpendicular to the steps. The remanent magnetization disappears near T_c in a temperature range much narrower than predicted by standard theory of finite-sized systems. Above T_c, the magnetization can be saturated in saturation fields H_s which are small compared to two-dimensional systems.

Keywords: One-dimensional system; Critical phenomena – onset of ferromagnetism; Ferromagnets; Nanoscale materials

Nanostructured magnetic materials allow the investigation of fundamental aspects of magnetic-ordering phenomena and also provide new potential applications [1]. Magnetic nanostructures with a long extent in only one dimension (named nanowires) can be prepared by depositing magnetic materials on vicinal single-crystal surfaces of a nonmagnetic substrate, using the tendency of metal atoms to stick at step edges because of the higher coordination number at the edge sites [2–4]. In the ideal case this step-flow growth mode results in stripes of monoatomic height, virtually infinite length and finite width. The width of the stripes can be reduced simply by reducing the coverage. The direction and distance of the steps can be controlled by the orientation of the substrate surface prior to polishing.

We have prepared ferromagnetic nanowires of Fe by molecular-beam epitaxy on a vicinal W(1 1 0) single-crystal surface with steps along the [0 0 1] direction. The mean distance of the steps was $s = 8$ nm with a normal distribution of width $\Delta s/s = 0.3$. For coverages below the complete monolayer, Fe grows pseudomorphically despite the epitaxial misfit $f = 10.4\%$, due to the large surface energy of W. The growth of the wires was optimized using the structural information of scanning tunneling microscopy (STM). Fe was deposited at room temperature at 0.3 ML/min (1 pseudomorphic monolayer (ML) = 1.42×10^{15} atoms/cm^2) and subsequently annealed for 3 min at 800 K. STM confirmes that at this growth conditions continuous wires of monoatomic height are formed with nearly no interceptions, as shown in Fig. 1. The width $w = \Theta s$ of the stripes is proportional to the coverage Θ. It is of interest to note that the smooth wires shown here cannot be prepared at step edges along the [1 $\bar{1}$ 0] direction, because only closed packed step edges are stable [2].

The magnetic properties were analyzed from Kerr magnetization loops, as shown in Fig. 2, with the field applied along the [1 $\bar{1}$ 0] direction. At low temperatures we measure ferromagnetic hysteresis loops. In contrast to nanowires of Fe on stepped Cu(1 1 1) surfaces [4] no time-dependent relaxation of the magnetization was observed. The magnetic easy axis is in the substrate plane and perpendicular to the steps. At the coercive field H_c the magnetization rapidly flips to the opposite direction indicating a single-domain state. H_c is small compared to the anisotropy field of roughly 5 T, as estimated from the in-plane anisotropy of W(1 1 0)/Fe monolayers [3]. Therefore, the magnetization reversal is presumably not a result of homogeneous rotation but rather of domain-wall movement. Small values of H_c indicate the smoothness of the wires. The remanent magnetization M_r rapidly vanishes near the Curie temperature T_c. The T_c decreases with decreasing w following the finite-size law $T_c(w) = T_c(\infty)(1 - w_0/w)$ with $T_c(\infty) = 230$ K

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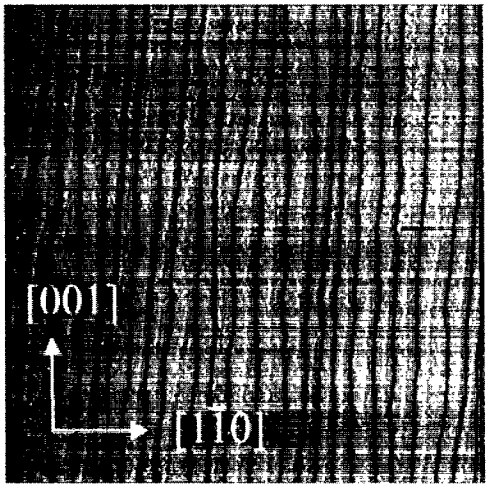

Fig. 1. STM image (200 × 200 nm) of a vicinal W(1 1 0) surface with steps along [0 0 1], covered by 0.5 pseudomorphic monolayers of Fe. Growth conditions as given in the text. In order to enhance the contrast the image has been differentiated. The lighter colored stripes adjacent to the step edges are the Fe nanowires.

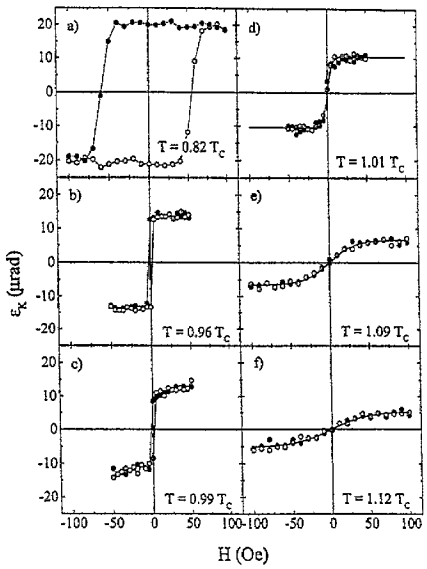

Fig. 2. Kerr ellipticity ε_K as a function of external field H applied along [1 $\bar{1}$ 0] for Fe coverage $\Theta = 0.8$ ML corresponding to a width $w = 6.4$ nm on a stepped W(1 1 0) surface with steps of distance 8 nm along [0 0 1]. Relative temperatures are given in units of the Curie temperature $T_c = 178$ K. Full circles for decreasing and open circles for increasing fields.

being the Curie temperature of the two-dimensional monolayer of infinite area and w_0 the minimum width for ferromagnetic order (Fig. 3). The dependence on w is in agreement with previous experimental results of nonordered wires [3, 5]. Above T_c, the magnetization has

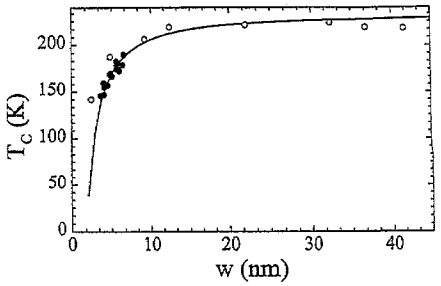

Fig. 3. Curie temperature T_c as a function of stripe width w (full circles) for ordered Fe-stripes, prepared on stepped W(1 1 0) as in Fig. 1. Data for nonordered Fe-stripes, prepared on nominally smooth W(1 1 0) with steps of arbitrary orientations, are given for comparison (open circles, data from Ref. [3]).

a field dependence similar to that of an Ising superparamagnet, $M(H) = M_s \tanh(H/H_s)$ with a surprisingly small saturation field $H_s < 50$ Oe even at the relative temperature $T/T_c = 1.1$. This is in contrast to two-dimensional films, where saturation fields at $T/T_c = 1.1$ are much larger [6].

Because the distance between the parallel wires is in the nanometer range, too, a magnetic coupling of adjacent wires has to be considered. A magnetic coupling could result from a RKKY-type coupling through the substrate as well as from a dipolar coupling [7]. The RKKY-type exchange coupling oscillates as a function of distance. Therefore, the varying terrace width of our samples possibly averages out this type of exchange coupling. The dipolar coupling energy between adjacent wires is found from integrating the field due to the magnetization within the plane of wires. For $w = 7$ nm we result in $\Delta E_c \approx 10^{-13}$ J/m, which is two orders of magnitude smaller than the bulk value of the exchange constant A. However, the dipolar coupling is of long-range nature in contrast to the direct exchange coupling. Deviations of our experimental results from the Ising model [8] may result from the neglect of this additional long-range coupling.

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