ANL/MSD/CP--86639
[Invited: Brazil Mtg., June 1995]

Conf-9506224--1

Magnetic Phase Transitions in Epitaxial Fe/Cr Superlattices*

Eric E. Fullerton

Materials Science Division
Argonne National Laboratory, Argonne, IL 60439

RECEIVED
JUN 19 1995
OSTI

INVITED PAPER: **8th Brazilian Meeting of Condensed Matter Physics [XVIII Encontro Nacional de Fisica da Materia Condensada], Sao Paulo, Brazil, June 6-10, 1995**

*Work supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under contract #W-31-109-ENG-38.

Magnetic Phase Transitions in Epitaxial Fe/Cr Superlattices

Eric E. Fullerton
Materials Science Division
Argonne National Laboratory, Argonne, IL 60439, USA

Introduction

Fe/Cr superlattices exhibit a variety of intriguing magnetic properties not observed in bulk materials. Examples include oscillatory interlayer coupling[1,2] and giant magnetoresistance.[3] Growth of epitaxial superlattices allows the interlayer coupling and magnetic anisotropy to be tailored to probe rather subtle magnetic ordering transitions of thin-film antiferromagnets. I discuss two such transitions, the surface spin-flop transition in Fe/Cr(211) superlattices[4] and the Néel transition of thin Cr layers in proximity with Fe in Fe/Cr(001) superlattices. The surface spin-flop transition is a first-order, field-induced phase transition in antiferromagnets with uniaxial magnetic anisotropy and the field applied along the easy direction. It was first predicted over 25 years ago,[5] but not realized experimentally until the appearance of Ref. 4. In Fe/Cr(100) superlattices, the antiferromagnetic ordering of the Cr spacers results in anomalies in a variety of physical properties. The transition temperature is strongly Cr thickness dependent. A 'transition-temperature shift exponent' is extracted from the data in the thick Cr regime (<160Å) and discussed in terms of a combination of finite-size and spin-frustration effects.

Surface spin-flop transition

In a MnF_2-type antiferromagnet (AF), a magnetic field parallel to the easy axis induces a first-order phase transition from the spin being antiparallel along the easy axis direction to the spin-flop phase in which the spins of each sublattice are canted with respect to the field direction. For a thin antiferromagnetic film, surface effects strongly influence the magnetic response of the system. The lower coordination of the surface spins allow them to respond more easily to external fields. If the surface spin is pointed antiparallel to the external field, the surface undergoes a surface spin-flop transition at a lower field than the bulk spin flop. For higher fields, the surface spin-flop transition evolves in a quasicontunuous manner into the bulk spin-flop transition as described in Ref. 4.

Experimental searches of the MnF_2 system for the surface spin-flop transition at the time of the original theoretical prediction were unsuccessful. In the work of Ref. 4. Fe/Cr(211) superlattices were utilized.[6] In these structure, the spin configuration is governed by:(i) the Zeeman interaction of the Fe with the external field, (ii) the antiferromagnetic interlayer coupling across the Cr layers, and (iii) a uniaxial in-plane anisotropy for each Fe layers. Therefore, these superlattices are isomorphic to the MnF_2-class antiferromagnets with a (100) surface.

Consider a superlattice which contains N layers of Fe. If N is even, then the two terminal Fe layers will point antiparallel to each other. Therefore, in an applied field, one of the surface layers will be antiparallel to the external field and will undergo the surface spin-flop transition. If N is odd, then the two terminal Fe layers will be parallel and align with the field and only a bulk spin-flop transition is observed. Shown in Fig. 1 is the static susceptibility measured for a (211)-oriented Fe(40 Å)/Cr(11) superlattice with N=22 measured by a SQUID magnetometer. The susceptibility plot shows two peaks identified as the surface and bulk spin-flop transitions. To confirm that the transition at the lower field results from the surface, we compare the SQUID results with surface magneto-optic Kerr effect measurements. The Kerr-effect measurement is surface sensitive, by virtue of the optical skin depth, which reflects itself in a stronger intensity of the surface transition. Similar measurements on superlattices with an odd number of layers show only the bulk transition as expected. This study provided the first experimental observation of the surface spin-flop transition and highlights the rich magnetic phases possible in coupled magnetic superlattices.

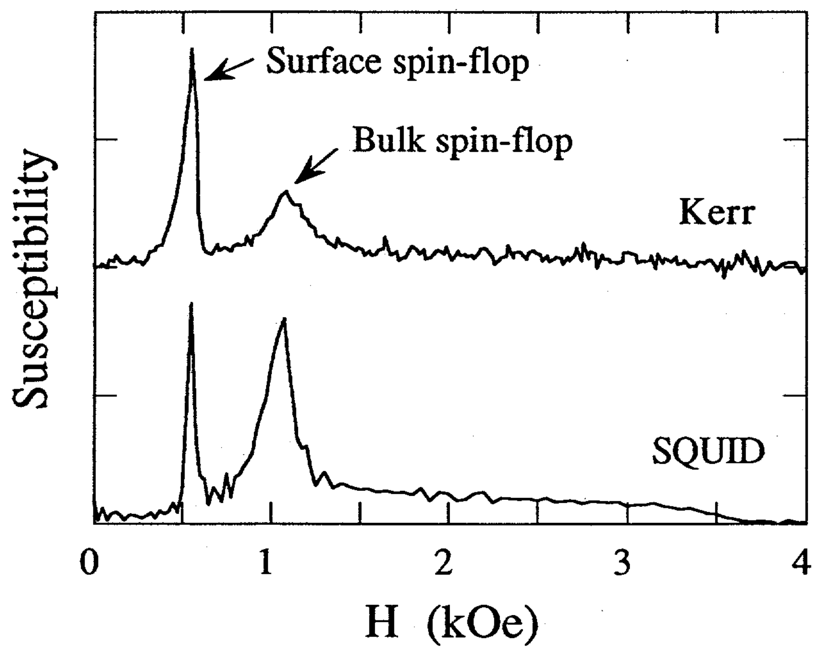

Figure 1: Static susceptibility curves of a [Fe(40 Å)/Cr(11 Å)]$_{22}$ superlattice with the applied field parallel to the easy axis. The upper curve is measured by the magneto-optic Kerr and the lower curve by a SQUID magnetometer.

Cr Néel transition

An outstanding problem in understanding the interlayer coupling in Fe/Cr superlattices is the role of the magnetic ordering within the Cr spacers. Bulk Cr is an itinerant antiferromagnet (AF) with a Néel temperature (T_N) of 311 K. An incommensurate spin density wave (SDW) is formed which is characterized by a wave vector **Q** determined by the Fermi surface nesting. At high temperature, the Cr spin sublattices S are transverse to **Q** (**S**$\perp$**Q**), while below the spin-flip transition at 123K **S** rotates 90° to form a longitudinal SDW with S$\parallel$**Q**.[7]

In the present work, the AF ordering of Cr spacer layers in sputtered, epitaxial Fe/Cr(001) superlattices is considered. Epitaxial Fe/Cr(001) superlattices were grown by d.c. magnetron sputtering onto MgO(001) single-crystal substrates. Transport measurements are often used as a probe of the AF ordering in Cr and Cr alloys, where ρ is enhanced above its extrapolated value as the temperature T decreases through T_N. Utilizing this anomaly in ρ to identify T_N, T_N vs. t_{Cr} is plotted in Fig. 2. For t_{Cr}<42Å there is no evidence of the Cr ordering. For t_{Cr}>42Å T_N increases rapidly and reaches a value of 265K for a 165-Å Cr thickness. Neutron diffraction confirms that the Cr spacer exhibits a transverse AF SDW with a wavelength comparable to that of bulk Cr. Fitting the T_N data in Fig. 1 to scaling theory for finite thickness films is shown by the dashed line which exhibits a transition-temperature shift exponent λ=1.4±0.3 characteristic of three-dimensional (3D) Heisenberg (1.42) or Ising (1.59) models.

The sharp drop in the value of T_N near t_{Cr}~50Å indicates the presence of an additional effect for the thinnest Cr spacers that is attributed to spin frustration in the vicinity of the rough Fe-Cr interfaces. Such interfaces contain atomic steps as shown in the inset of Fig. 2. The interfacial exchange energy can be minimized only locally, and frustration of the interfacial spins will occur if the Fe and Cr magnetically order long-range. In the Fig. 2 inset, excess magnetic energy is schematically located at the Fe-Cr interface to the right of the step where the Fe and Cr moments are forced to align ferromagnetically. For thin Cr layers, the frustration energy is sufficiently high to suppress long-range ordering of the Cr. As t_{Cr} increases, the system overcomes the frustration energy and begins to order long-range. The crossover thickness for the present samples is 42Å of Cr.

Finally, the AF ordering of the Cr spacers results in anomalies in a variety of physical properties, including the interlayer coupling, remanent magnetization , coercivity, resistivity and magnetoresistance. Most strikingly, the biquadratic coupling of the Fe layers (90° orientation of adjacent Fe layers) observed for T>T_N vanishes below T_N.

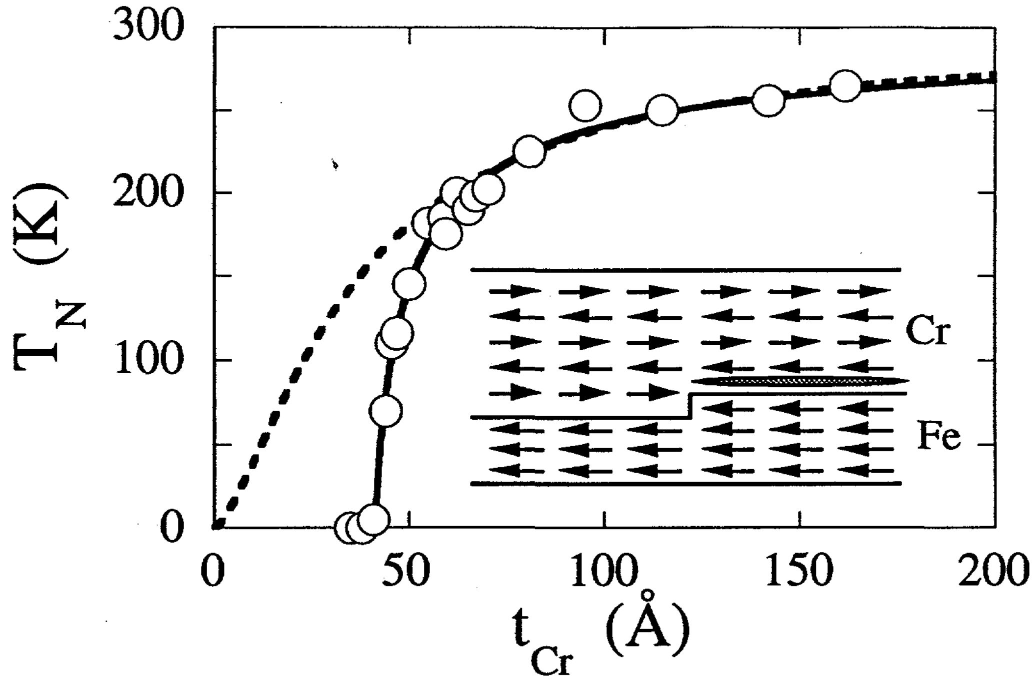

Figure 2: T_N for a series of $[Fe(14Å)/Cr(t_{Cr})]_N$ superlattices *vs.* Cr thickness. The inset shows a possible spin configuration of Cr on a stepped Fe surface in which the region of spin frustration at the Fe-Cr interface is shown schematically by the shaded ellipse to the right of the atomic step.

* Work supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under contract No. W-31-109-ENG-38.

1. P. Grunberg, R. Schreiber, Y. Pang, M. B. Brodsky, and C. H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).
2. S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).
3. M. N. Baibich, J. M. Broto, A. Fert, F. N. VanDau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).
4. R. W. Wang, D. L. Mills, E. E. Fullerton, J. E. Mattson, and S. D. Bader, Phys. Rev. Lett. **72**, 920 (1994).
5. D. L. Mills, Phys. Rev. Lett. **20**, 18 (1968).
6. E. E. Fullerton, M. J. Conover, J. E. Mattson, C. H. Sowers, and S. D. Bader, Phys. Rev. B **48**, 15755 (1993).
7. E. Fawcett, Reviews of Modern Physics **60**, 209 (1988).