VI. Magnetism in Small Structures

(4) Surface and Thin Film Magnetism

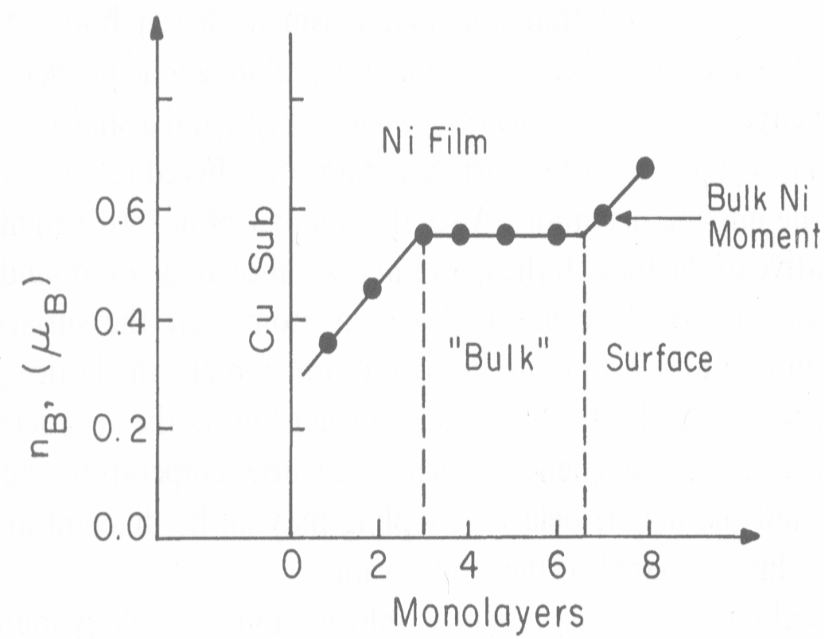
(4) Surface and Thin-Film Magnetism

- Fundamental magnetic properties at the surface(or interface) depend on the local environment:
  The symmetry, number, types and distance of an atom's nearest-neighbors at the surface are different from its bulk. Therefore, magnetic properties including the magnetic moment, T_c, anisotropy, and the magnetoelastic coupling may be different from their bulk values.

❑ Electron structure at surfaces

- Reduced coordination and reduced bonding at a surface lead to significant changes in electronic structure explainable for the unusual magnetic properties.

- Changes in magnetic moments (see Figs. 16. 1-2)
  Eight monolayers of Ni (001) on a Cu (001) substrate
  Calculated values: (cf. bulk moment = 0. 6 μ_B/Ni)
  Interior interface layer: reduced moment due to
  Bulk-like moment of central layers = 0.56 μ_B/Ni
  Surface layer moment = 0.74 μ_B/Ni
  Seven-layer Fe (001)
  Calculated values: bulk-like moment = 2.25 μ_B/Fe,
  surface layer moment = 2.98 μ_B/Fe

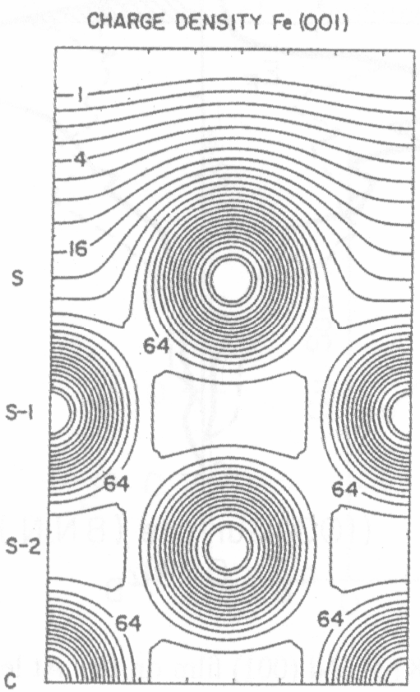


Variation of magnetic moment calculated by layer in an 8 ML Ni/Co (001) film

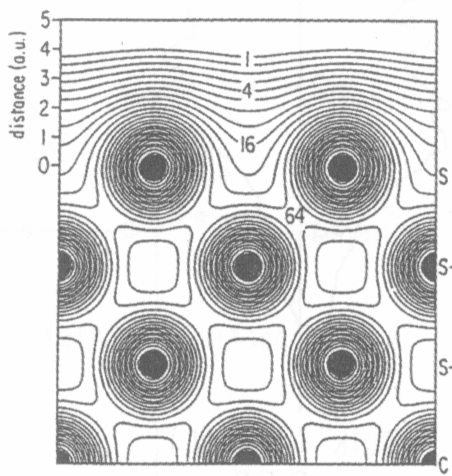
(4) Surface and Thin-Film Magnetism

❑ Electron structure at surfaces (continued)

- Changes in charge distribution(see Fig. 16.3) and spin density at a surface (see Fig. 16.4) at surface of seven-layer Fe(001) and Ni(001) films



Seven-layer Fe (001)



Seven-layer Ni (001)

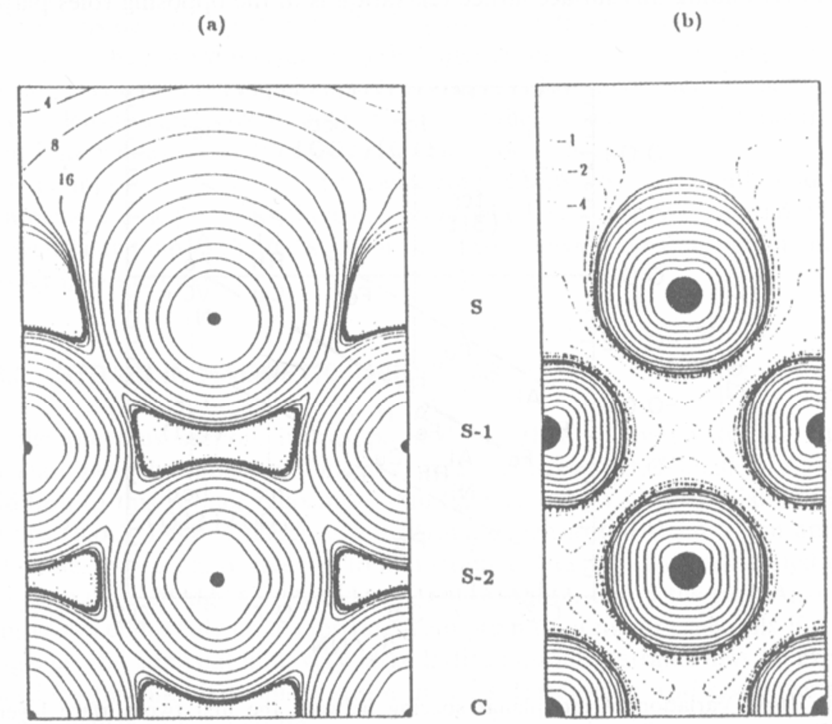
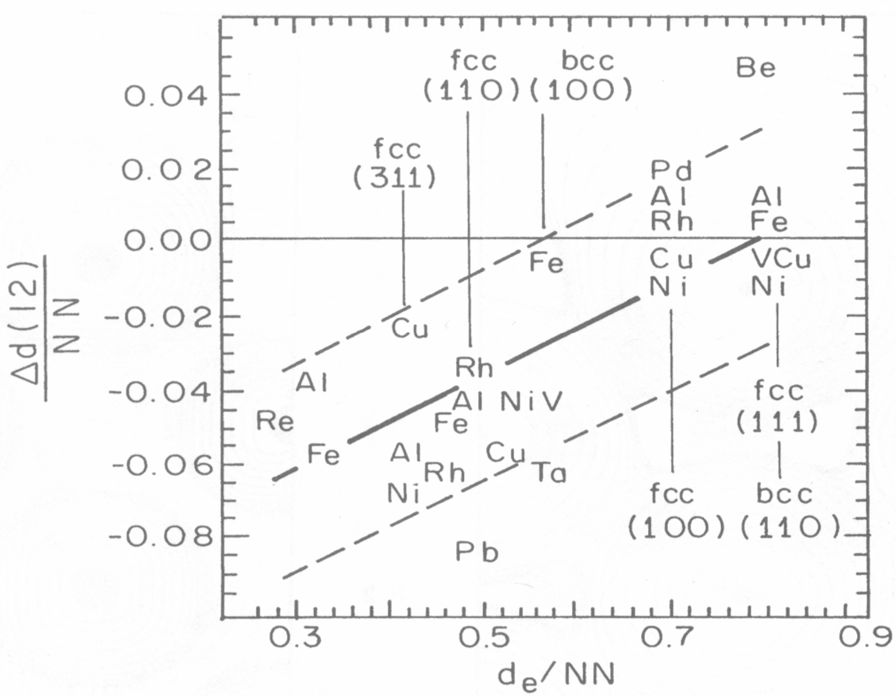


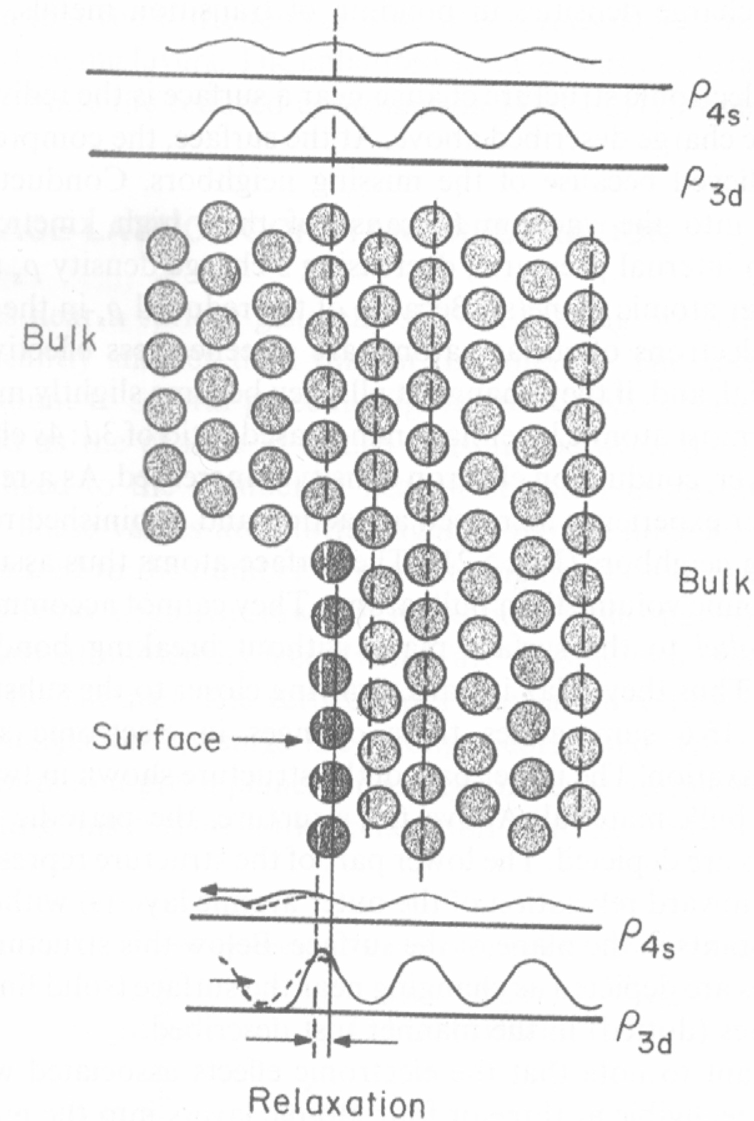
Figure 16.4 Spin density in units 10^{-4} e/(au)^3 at surface of seven layer Fe (001) and Ni (001) films; dotted lines represent negative spin densities (Freeman et al. 1991).

(4) Surface and Thin-Film Magnetism

❑ Surface Lattice Constant Relaxation

- A spacing normal to the surface is significantly smaller than in the interior.
- The surface relaxation strain amount to several percent (see Fig. 16.5)
- Most surfaces show negative (inward) relaxation.
  Relaxation is greater for lower-atom-density faces (see Fig. 16.6)
- While the electronic effects associated with a surface in metal extends only to three or four atomic layers, exchange coupling can carry magnetic surface effects much farther into the interior.

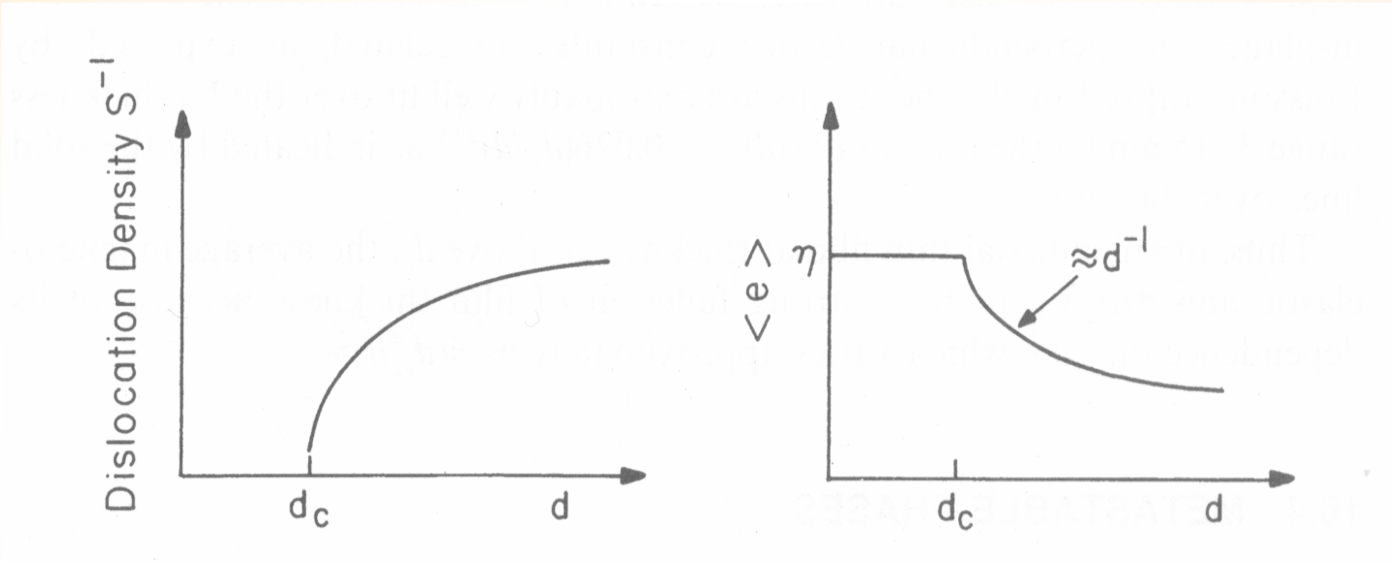




(4) Surface and Thin-Film Magnetism

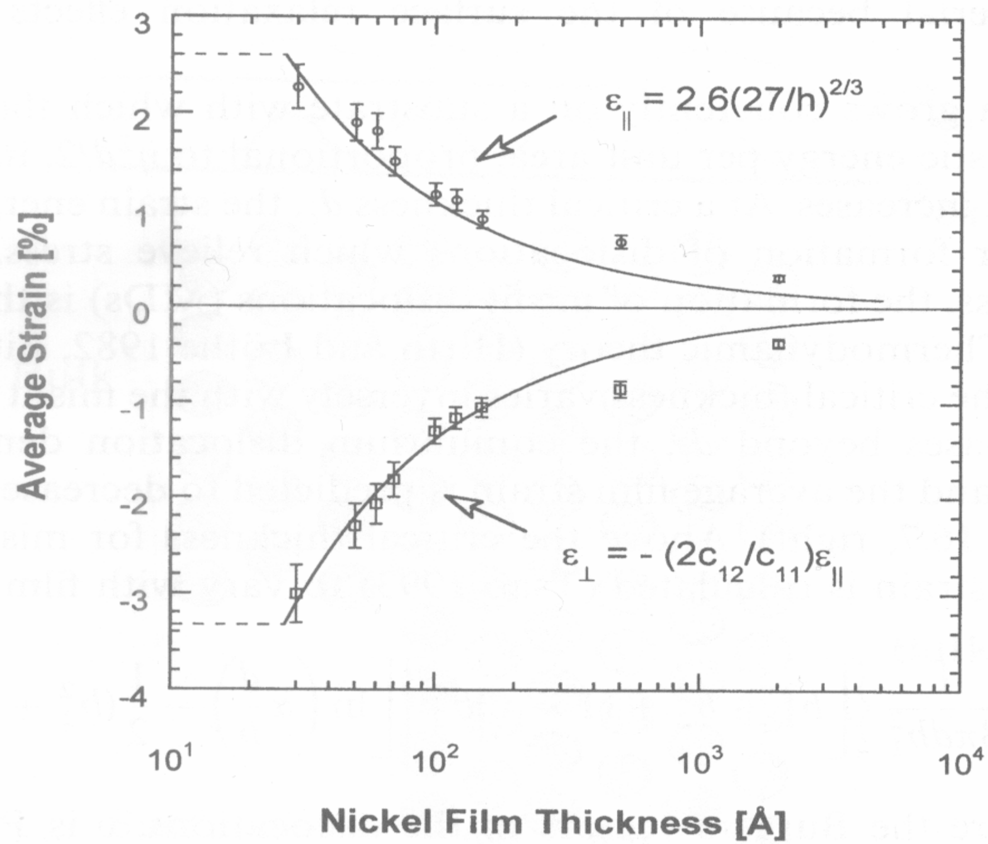
Strain in Magnetic Thin Films

- Large biaxial, in-plane strains can occur in thin films due to differences in thermal expansion between a film and its substrates.
- Very large mismatch strains for a single-crystal epitaxial film in the surface plane due to a lattice mismatch, also causing a perpendicular Poisson strain.
- Below a critical thickness, the elastic energy per unit surface area ($\propto \eta^2 d/2$, a lattice misfit $\eta = (a_s - a_f)/a_s$: a_s and a_f are the film and substrate in-plane lattice constants, respectively) increases due to a lattice mismatch as film thickness d increases.
- Above the critical thickness, the equilibrium dislocation density increases. (see Fig. 16.7)



❑ Strain in Magnetic Thin Films (continued)

- Strain vs Ni thickness in Cu/Ni/Cu sandwiches (see Fig. 16.8)



(4) Surface and Thin-Film Magnetism

❑ Metastable Phase

- Stabilization of metastable phases in thin films is possible as a result of epitaxial strains.

- Examples : FCC Fe, FCC Co/ BCC Co at room temperature (see Fig. 16.19 in O'handley)

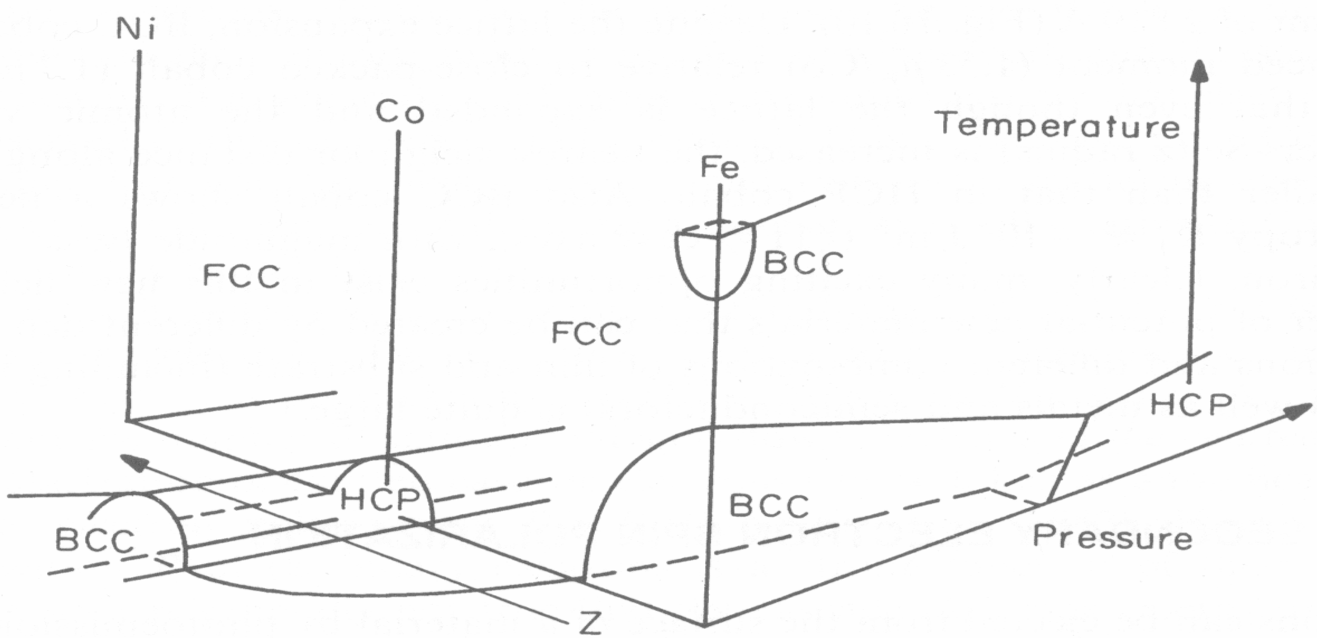


Figure 16.9 P–Z–T phase diagram (Z = atomic number) for iron, cobalt, and nickel showing fields of stability for various structures. BCC cobalt is stable at negative pressure. [After Prinz (1991b).]

(4) Surface and Thin-Film Magnetism

❑ Secondary Electron Spin Polarization

- Measurement of the spin polarization of secondary electrons is a surface sensitive probe of magnetism because secondary electrons come from the outermost layer of the material.

- Valence electrons inside materials are characterized by **a polarization *P'***

$$P' = \frac{n\uparrow - n\downarrow}{n\uparrow + n\downarrow} = \frac{n_B}{n_v}$$

- Once **the hot electrons,** created by the probe and emitted from the solid by overcoming the surface barrier, **it is called a secondary electron. The electrons emitted from a ferromagnet** may be characterized by **a polarization, *P* = (N↑ - N↓)/(N↑ + N↓),** where N↑ and N↓ represent the number of spin-up and spin-down electrons in the emitted beam.

- Since $P' \propto P$, the polarization of the emitted electrons can indicate valence electron polarization. However, usually $P > P'$ and thus measurement of the spin polarization of the secondary electrons require a scattering experiment making use of spin-dependent scattering based on exchange or spin-orbit interactions.

Examples : photoemitted electrons, Field-emitted electrons, Auger electrons

(4) Surface and Thin-Film Magnetism

❑ Surface Magnetic Anisotropy

Iron Films : Surface anisotropy constant K_s is much larger than the bulk cubic anisotropy K_1 (see Figs. 16.12-13)

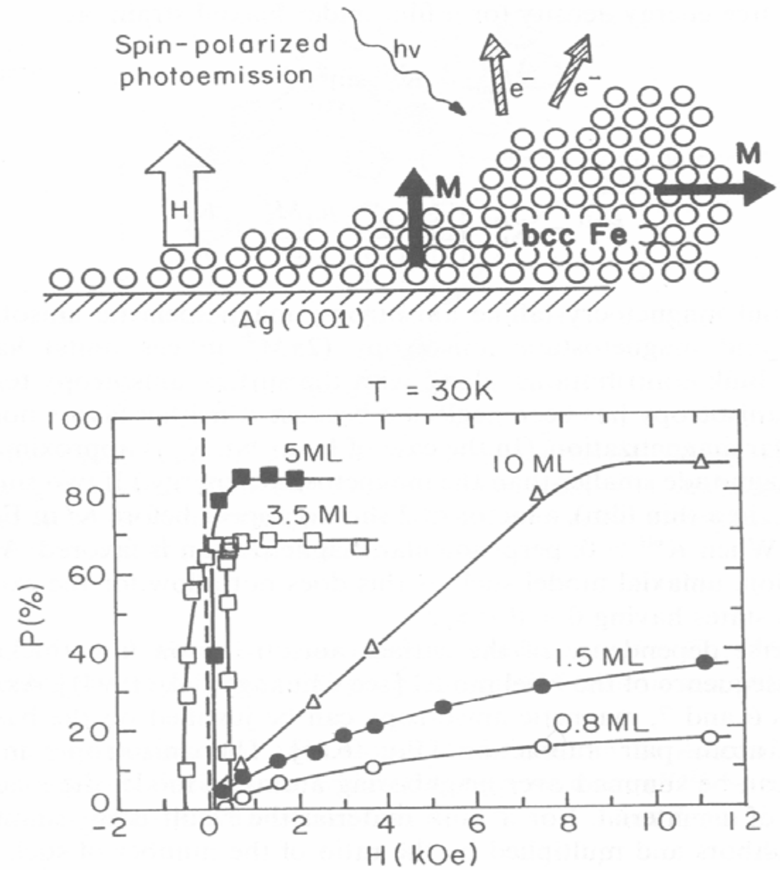


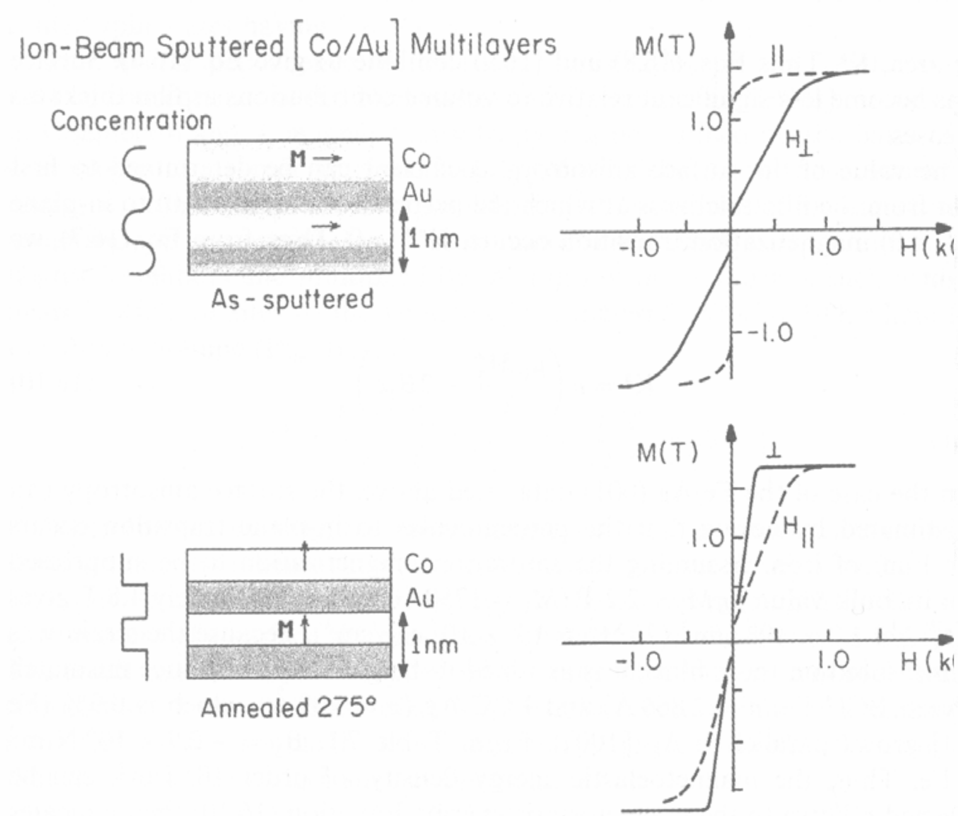
Figure 16.12 Above, schematic of experiment measuring the spin polarization of photoemitted electrons as a function of film growth. Below, results of valence electron spin polarization in BCC Fe films on Ag (001) substrates. Fe shows perpendicular magnetization over a narrow thickness range. [After Stampanoni et al. (1987).]

(4) Surface and Thin-Film Magnetism

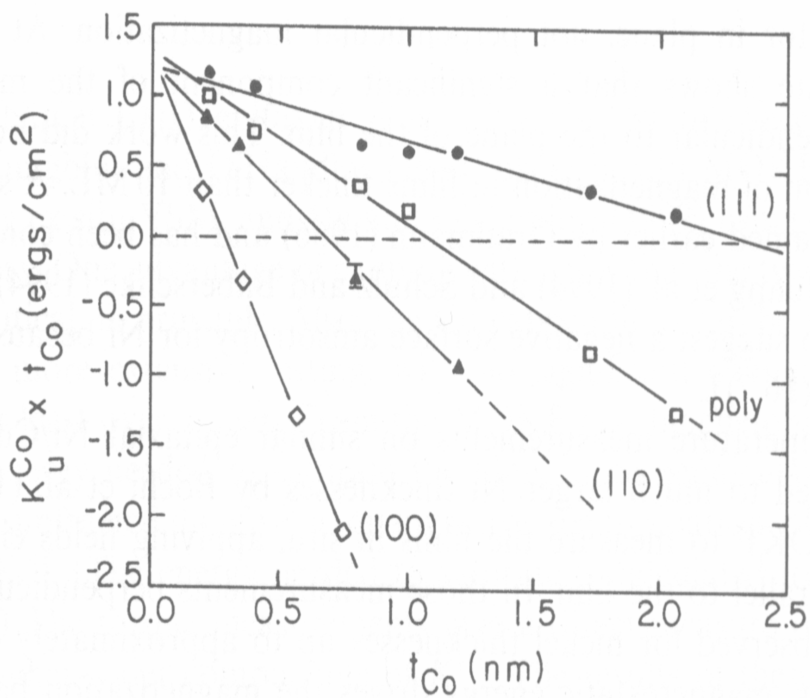
❑ Surface Magnetic Anisotropy

Cobalt Films : Experimental evidence (see Fig. 16.14-15)

Perpendicular magnetic anisotropy arising from an interface effect



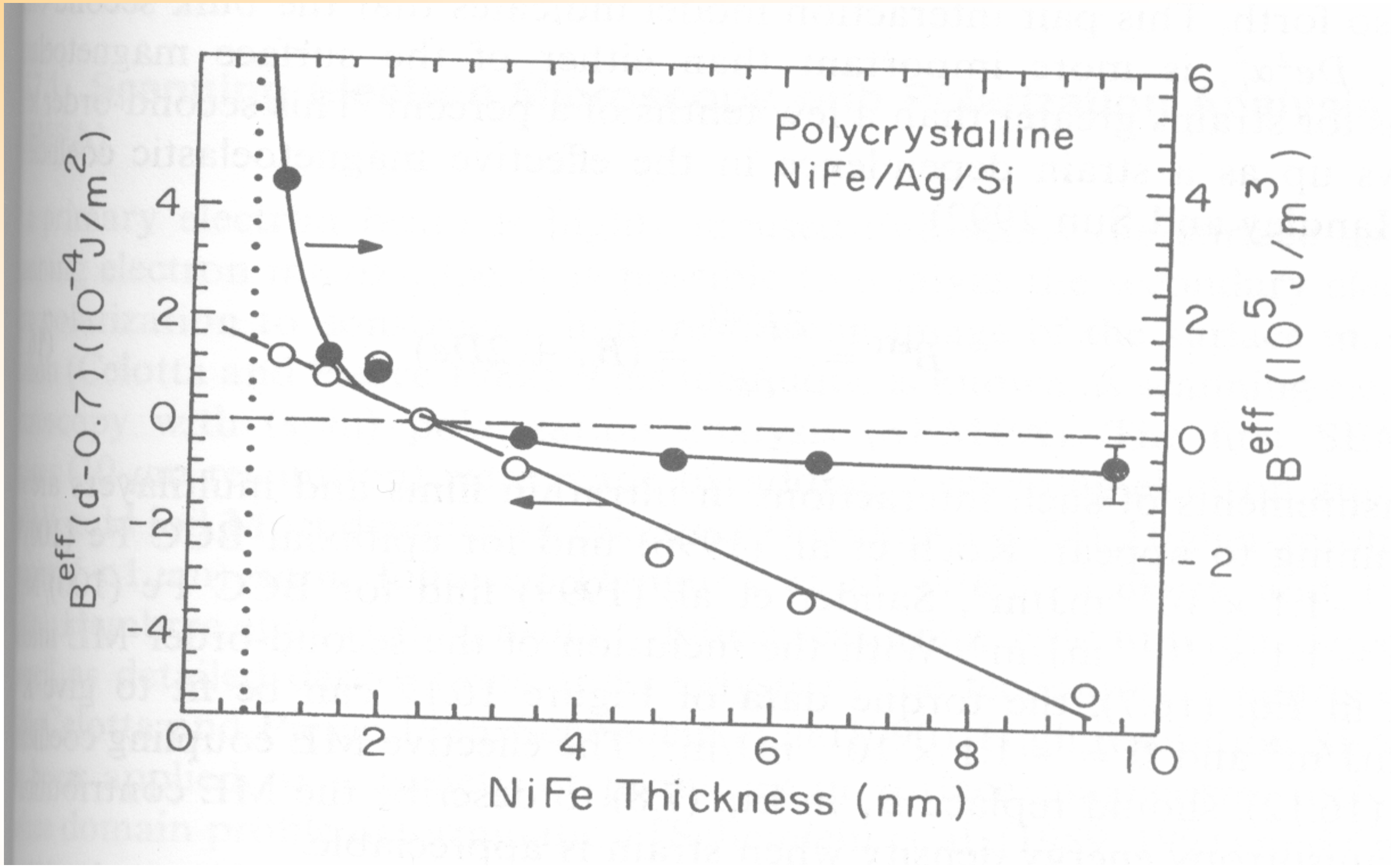
Polycrystalline multilayers of FCC [Co/Pd]n grown on GaAs substrates in an MBE chamber



(4) Surface and Thin-Film Magnetism

❑ Magnetoelastic Coupling in Thin Films

Magnetoelastic coupling constant can also deviate from bulk values. (see Fig. 16.18)



(4) Surface and Thin-Film Magnetism

❑ Magnetic Domains in Thin Films

SEMPA (Scanning electron microscopy with (spin) polarization analysis) (1982 yr)

Analysis of the secondary electron spin polarization to construct a high-resolution image of the surface magnetization,

MFM (Magnetic Force Microscopy) (see Fig. 16.19, 16.21), (1987 yr)

Comparison (see Table 16.2)

TABLE 16.2 Comparison of the Capabilities and Limitations of SEMPA and MFM

	SEMPA	MFM
Quantity measured	Spin polarization	Stray field
Atmosphere	Vacuum is essential	Vacuum not necessary but does enhance stability and sensitivity
Surface topography	Not an issue	Can be a problem without adequate tip feedback controls
Sample conductivity	Metals required[a]	Insulators as well as metals can be imaged
Vector components imaged	*x, y, z*	Mainly *z*; governed by tip orientation
Present resolution	40 nm	40 nm
Limitations on resolution	Stray fields, electron optics, spin detector efficiency, beam diameter and current	Tip size, tip height above sample, and instrumental sensitivity
Other limitations	Images cannot be collected in the presence of magnetic fields	Magnetic tip may interact with very soft magnetic materials, changing the domain pattern during imaging
Advantages	Topography and magnetism can be imaged independently Scanning at different magnifications is controlled by SEM electronics	Topography and magnetism can be separated; images can be taken in magnetic fields; vacuum not necessary

[a]Domains in insulators can be imaged if samples are coated with a thin magnetic, metallic film.

(4) Surface and Thin-Film Magnetism

Observation of magnetic domain structures in thin films
(see Figs. 16.22-23)

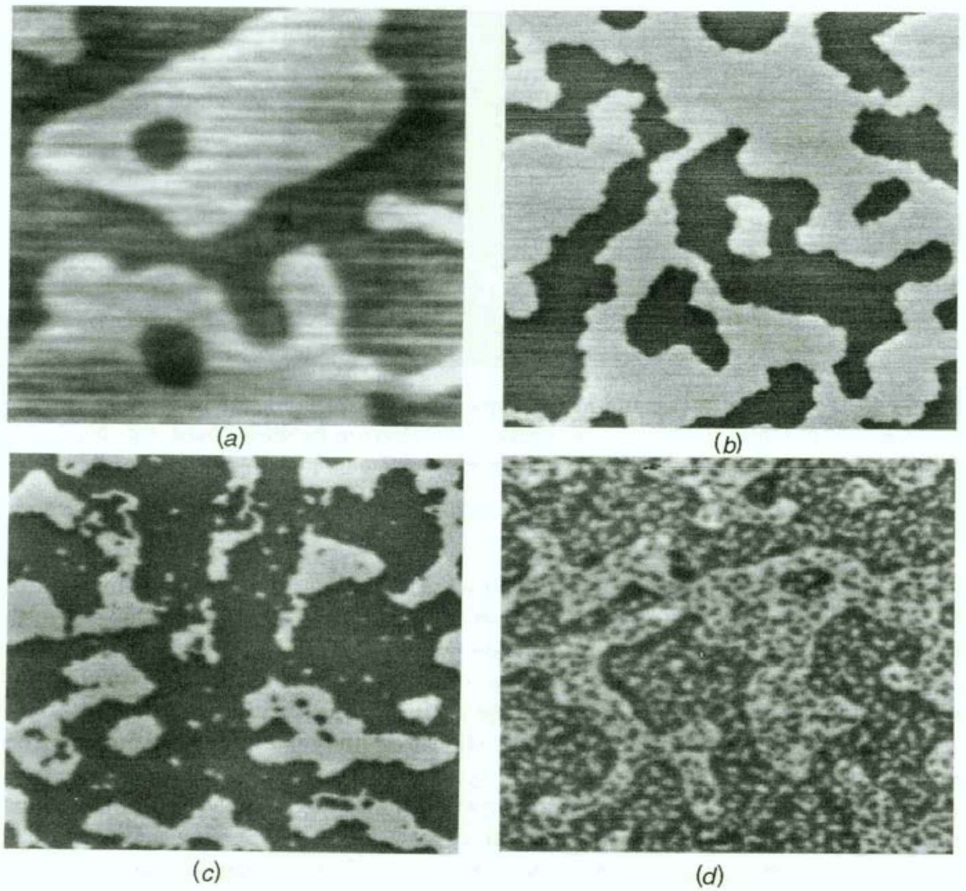


Figure 16.22 Domain structure of epitaxial Cu/t_{Ni}Ni/Cu (001) films imaged by MFM over a 12-μm square: (*a*) 2 nm Ni, (*b*) 8.5 nm Ni, (*c*) 10 nm Ni, (*d*) 12.5 nm Ni (Bochi et al. 1996).

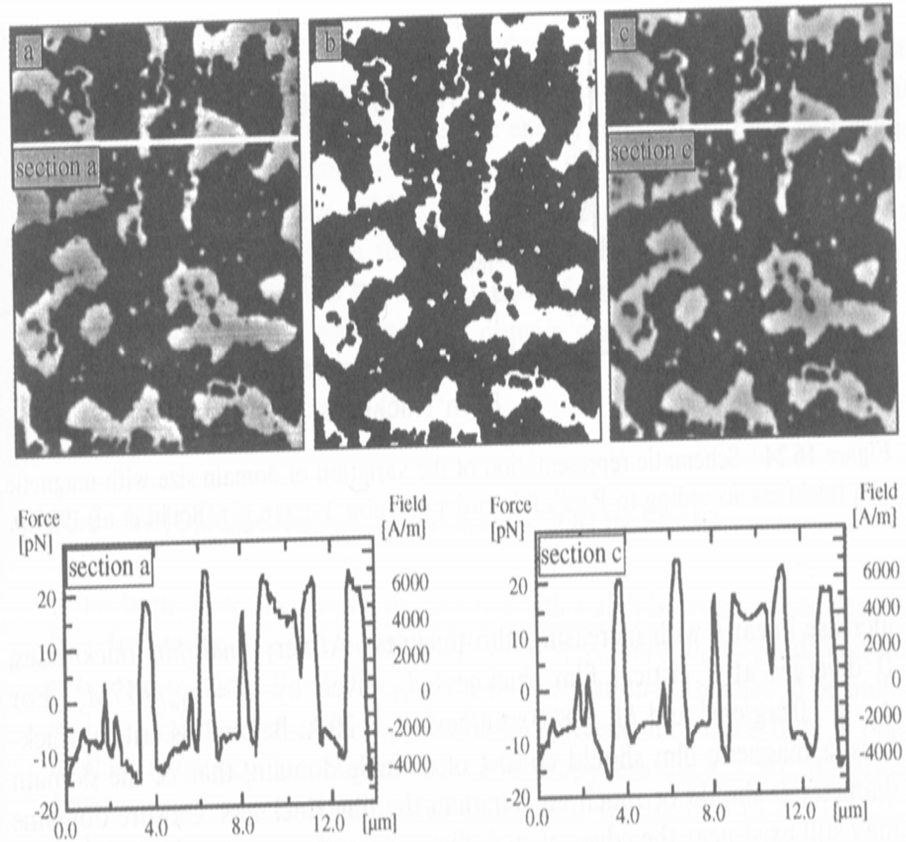


Figure 16.23 Above (*a*) MFM force-field image taken from epitaxial Cu/10 nm Ni/Cu (001) film of Figure 16.22*c*; (*b*) trial perpendicular magnetization distribution generated from (*a*) by discrimination routine; (*c*) field pattern calculated from magnetization distribution (*b*) using Eq. (16.16)); below, measured (left) and calculated (right) force and field line scans across panels (*a*) and (*c*) above (Hug et al. 1996).

(4) Surface and Thin-Film Magnetism

Domain size versus film thickness (see Fig. 16.24-25)

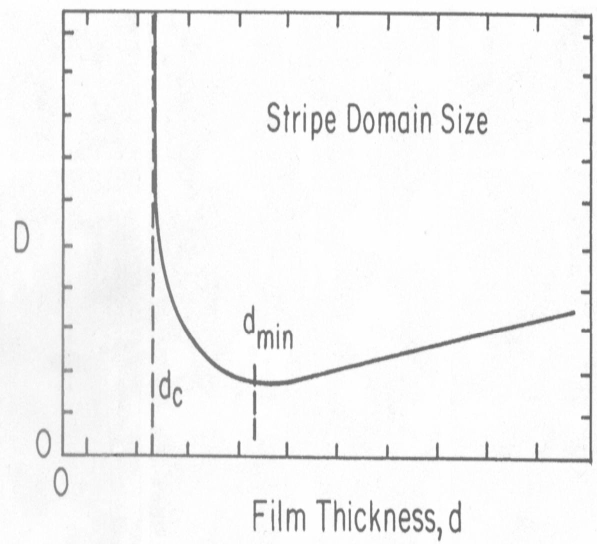
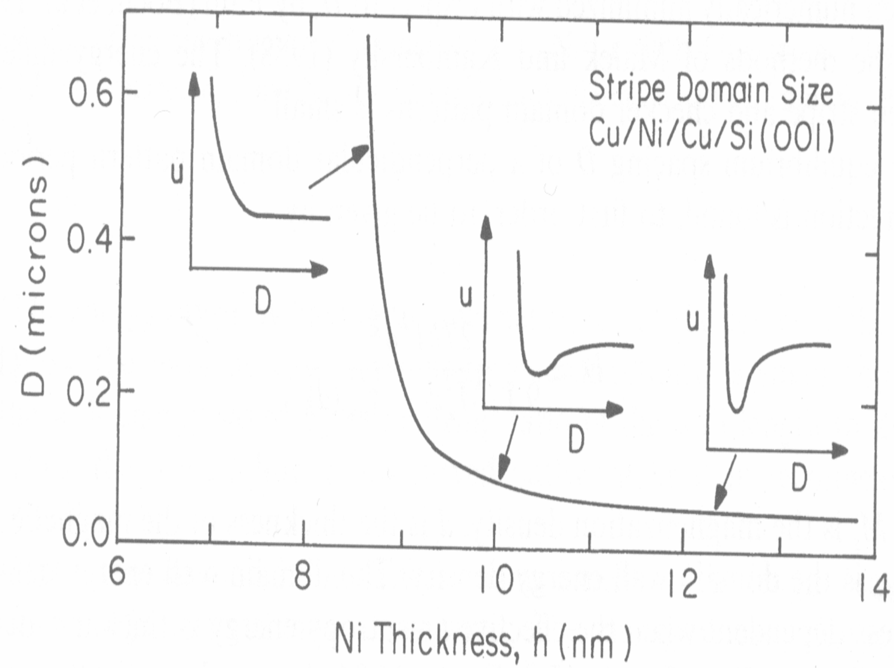


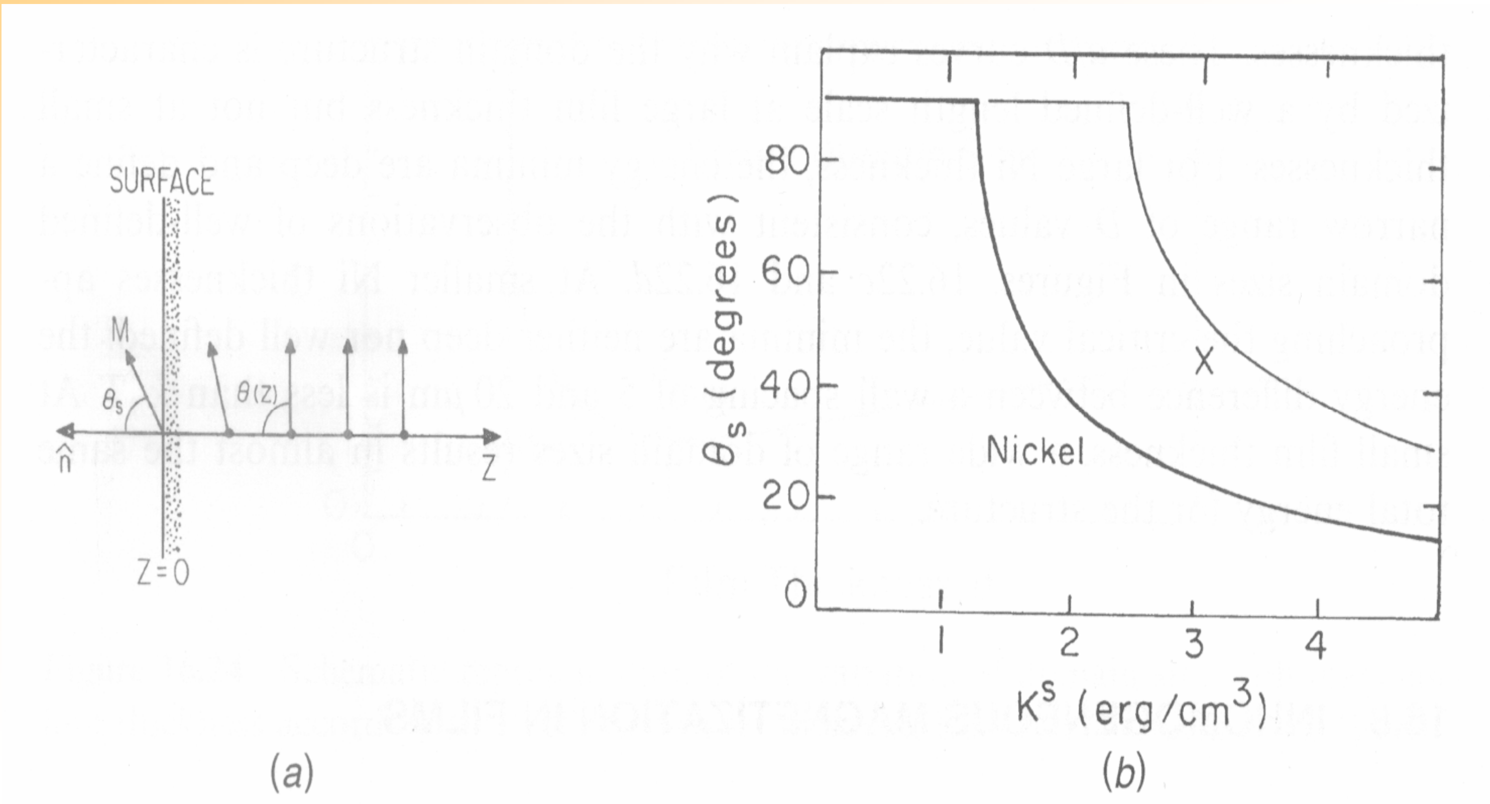
Figure 16.24 Schematic representation of the variation of domain size with magnetic film thickness according to Paul's first-order solution, Eq. (16.17) (Bochi et al. 1995b).



(4) Surface and Thin-Film Magnetism

❑ Inhomogeneous Magnetization in Films

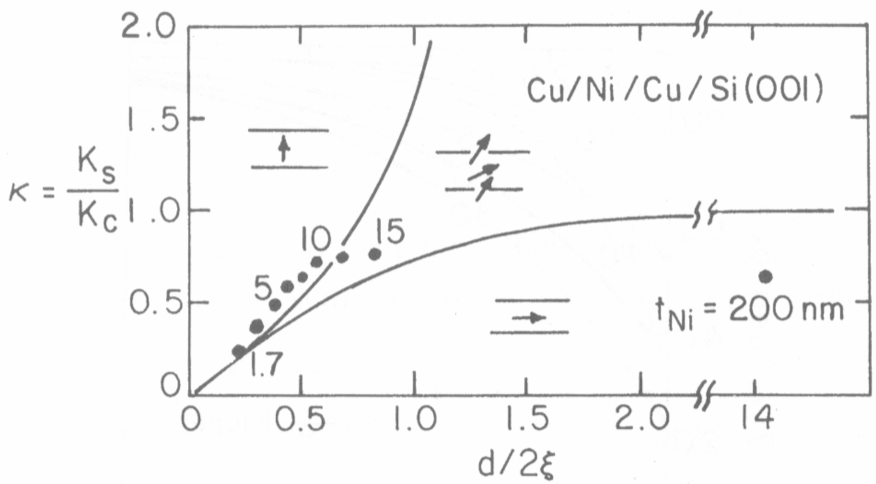
- Magnetization Variations Normal to the Film Surfaces (see Fig. 26-27)



(4) Surface and Thin-Film Magnetism

Inhomogeneous Magnetization in Films (continued)

- Magnetization Configurations with Two Perpendicular Anisotropy Surfaces (see Fig. 16.28-29)



	Stability of $M_{\perp}(\theta=0)$	Stability of $M_{\|}(\theta=\pi/2)$	
Perturbation:	$\theta_p(z) = \theta_0 \cos\frac{z}{\xi}$	$\theta_p(z) = \frac{\pi}{2} - \theta_0 \cosh\frac{z}{\xi}$	
Energy function:	$f = \Delta\theta_0^2\left[-\frac{1}{\xi}\sin\frac{d}{\xi} + \frac{2}{D}\cos^2\frac{d}{2\xi}\right]$	$f = \Delta\theta_0^2\left[\frac{1}{\xi}\sinh\frac{d}{\xi} - \frac{2}{D}\cosh^2\frac{d}{2\xi}\right]$	
Stability condition:	$\kappa = \frac{\xi}{D} > \tan\frac{d}{2\xi}$	$\kappa = \frac{\xi}{D} < \tanh\frac{d}{2\xi}$	(16.24)

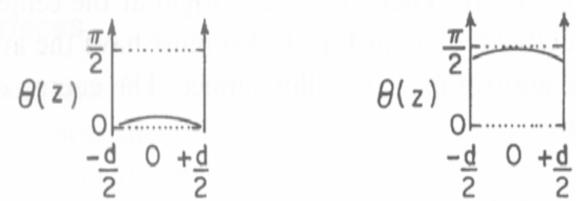


Figure 16.29 Outline of the method and results for determining thickness-dependent magnetization configuration in thin films in the presence of surface anisotropy and in-plane bulk anisotropy, but neglecting in-plane variations in magnetization. The form of the perturbation to the energy functional is sketched for the two limiting cases, and the solutions for the phase boundaries of these regions of stability are given.

(4) Surface and Thin-Film Magnetism

❑ Inhomogeneous Magnetization in Films (continued)

- Magnetization Variations in Film Plane : Ripple Domains (see Fig. 30)