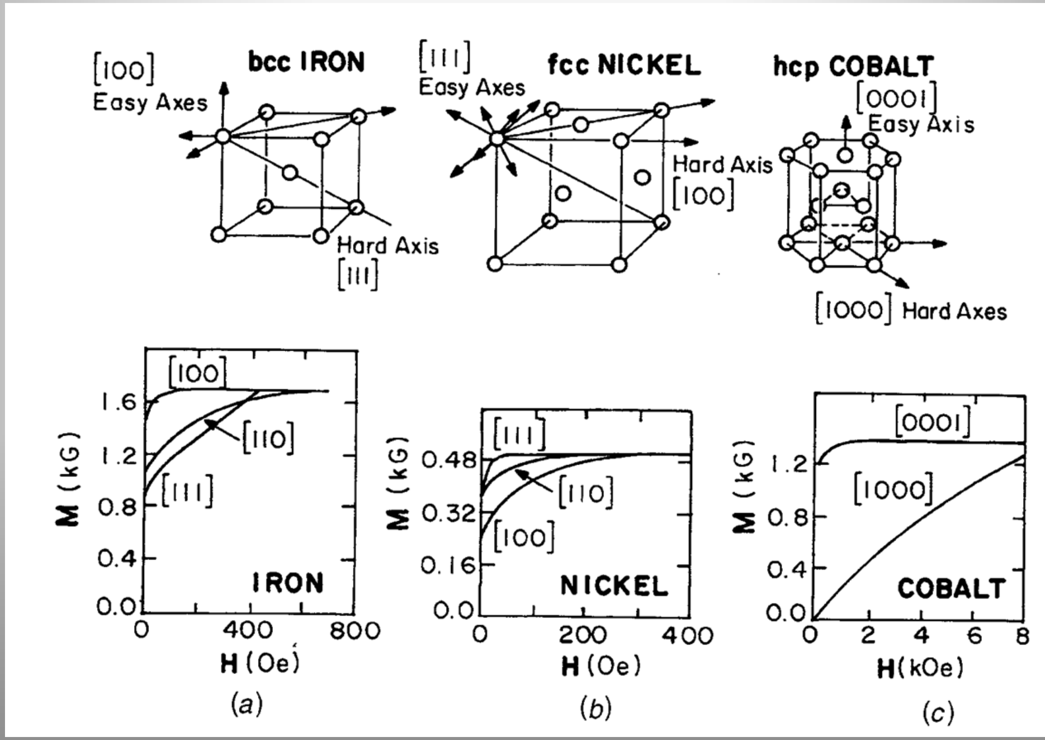
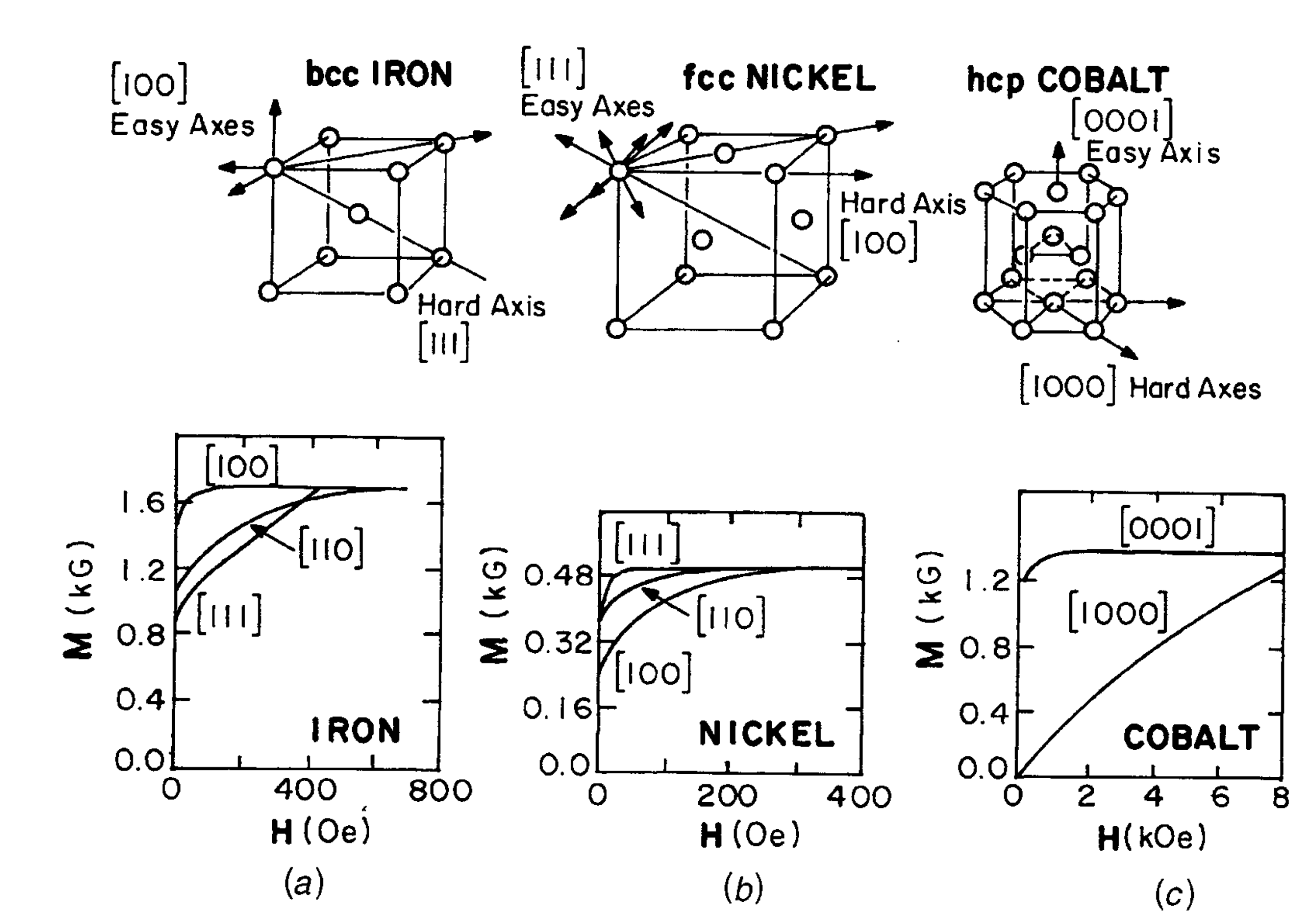
Magnetic Anisotropy and Magneto-Optic Kerr Effect

P. Poulopoulos, 25 June 2020, Patra



Η διάλεξη αυτή γίνεται διαδικτυακά στα πλαίσια των προβλημάτων του Covid-19. Είναι μόνο για διευκόλυνση των φοιτητών για το εξ αποστάσεως μάθημα και δεν έχει κανένα στόχο εμπορικής εκμετάλλευσης. Επίσης παρακαλώ τους φοιτητές να τις κρατήσουν μόνο για τους εαυτούς τους και τις εξετάσεις τους

Magnetic Anisotropy: Hard and Easy axes

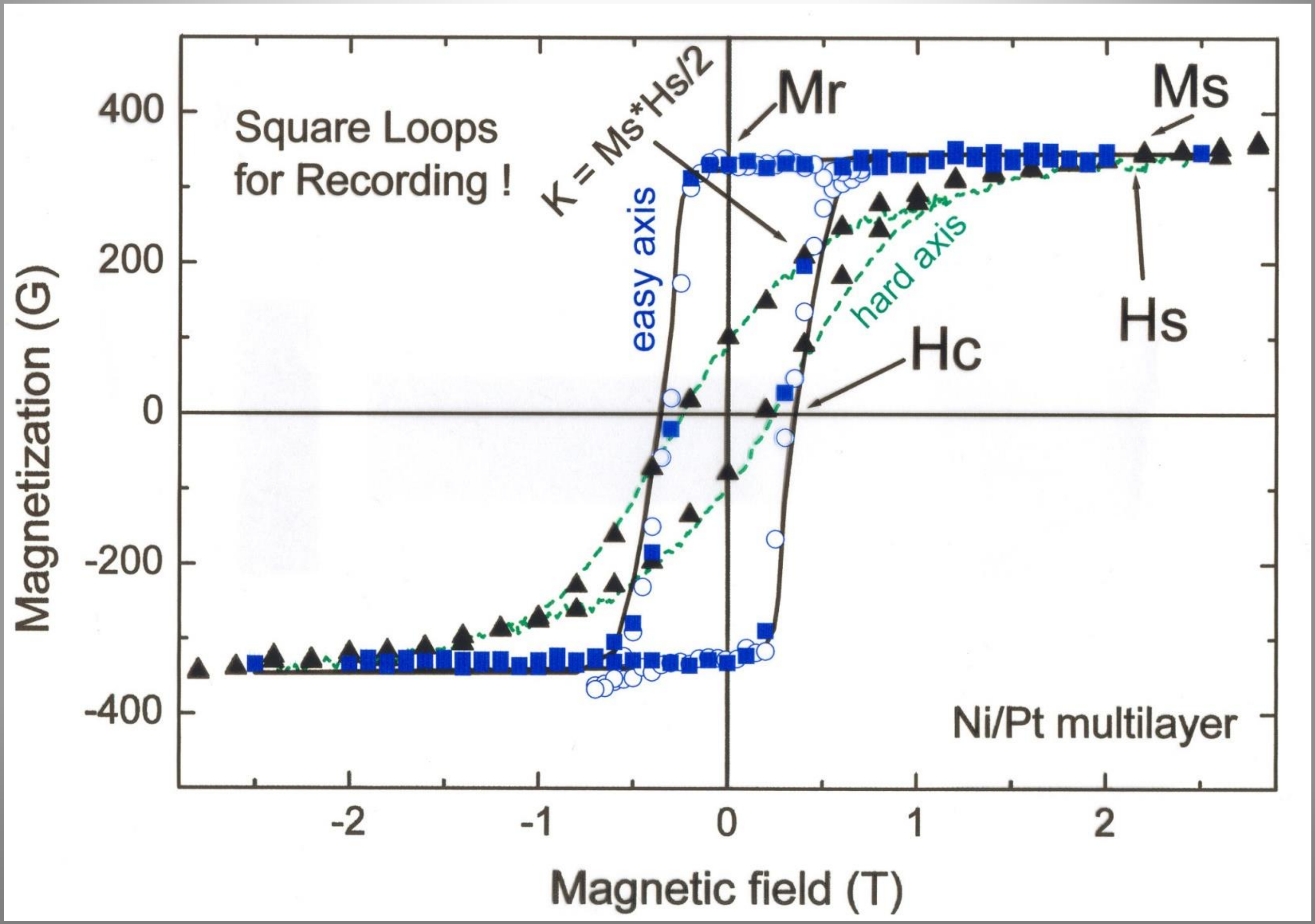


Microscopic origin: Anisotropy of orbital moment

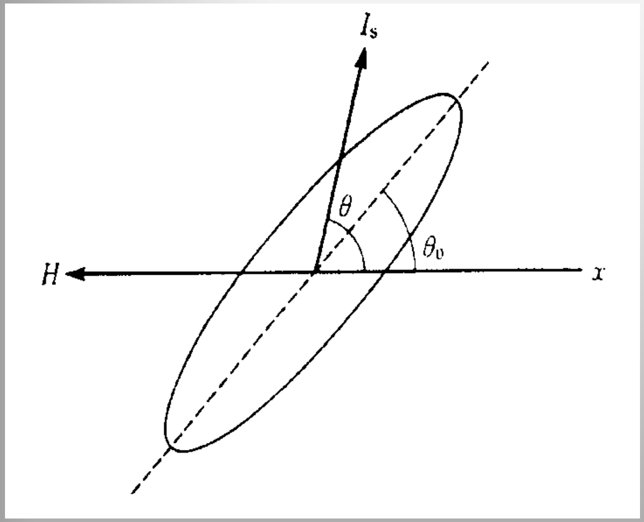
If the local crystal field seen by an atom is of *low symmetry* and if the bonding electrons of that atom have an *asymmetric charge distribution* ($L_z \neq 0$), then the atomic orbits interact anisotropically with the crystal field. In other words, certain orientation for the bonding electron charge distribution are energetically preferred.

The coupling of the spin part of the magnetic moment to the electronic orbital shape and orientation (spin-orbit coupling) on a given atom generates the magnetocrystalline anisotropy

Anisotropy in Thin Films



The Stoner – Wolfarth Model



Coordinate system for magnetization reversal process in single-domain particle.

The free energy

$$f = -K_u \cos^2(\theta - \theta_o) + HM_s \cos\theta$$

Minimizing with respect to θ, giving

$$K_u \sin 2(\theta - \theta_o) - HM_s \sin\theta = 0$$

Basic Hamiltonian for Single Layers

$$F = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta + 2\pi M_S^2\sin^2\theta - M_S H\cos(\phi - \theta)$$

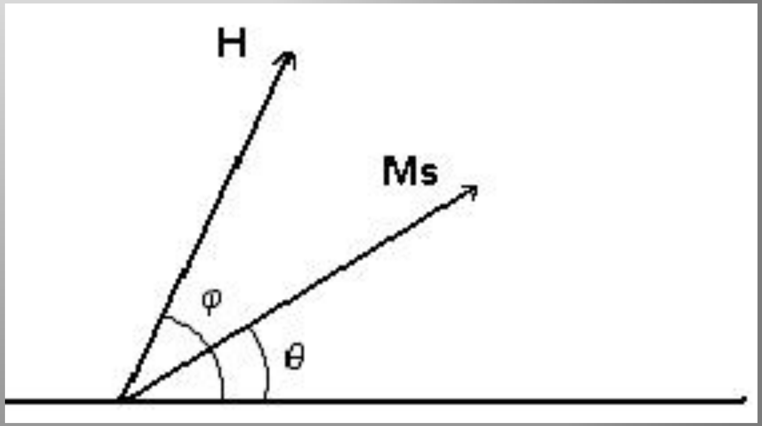
Magnetocrystalline anisotropy

Shape Anisotropy

Zeeman term

$Ku_{1,2}$ Uniaxial Anisotropy Constants

M_S Saturation Magnetization



Determination of the easy axis

$$\frac{dF}{d\theta} = 0$$

$$(K_{u1} + K_{u2} + 2\pi M_S^2)\sin 2\theta - \frac{1}{2}K_{u2}\sin 4\theta - M_S H \sin(\phi - \theta) = 0$$

$$K \equiv K_{eff} = K_{u1} + K_{u2} + 2\pi M_S^2$$

usually $K_{u2} << K_{u1}$

K>0 in-plane anisotropy

K<0 perpendicular anisotropy

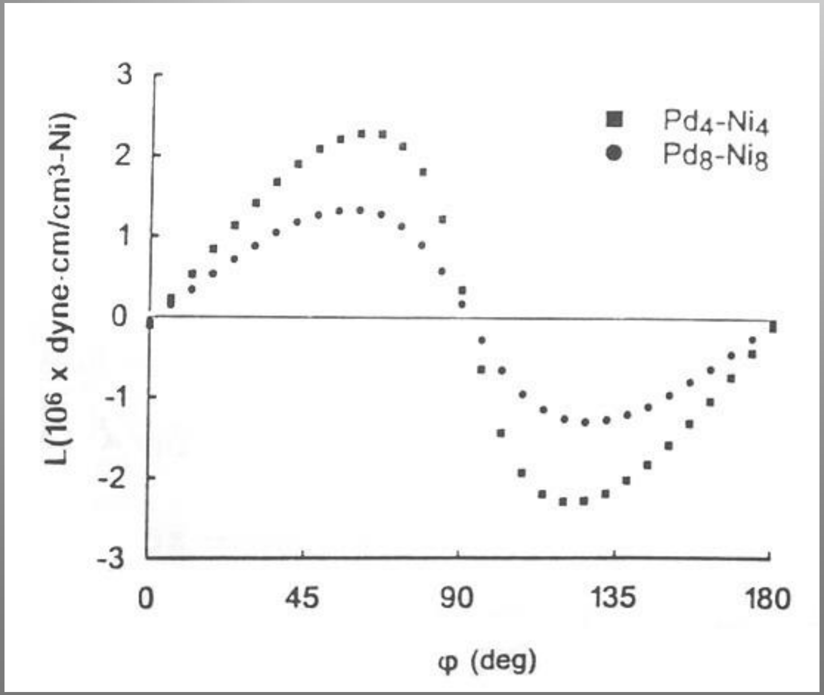
Hysteresis Curves: K = Area between Hard and Easy Axis in M=M(H) curves

Torque Magnetometry

$$L = M_S H \sin(\phi - \theta) = K \sin 2\theta - \frac{1}{2} K_{u2} \sin 4\theta$$

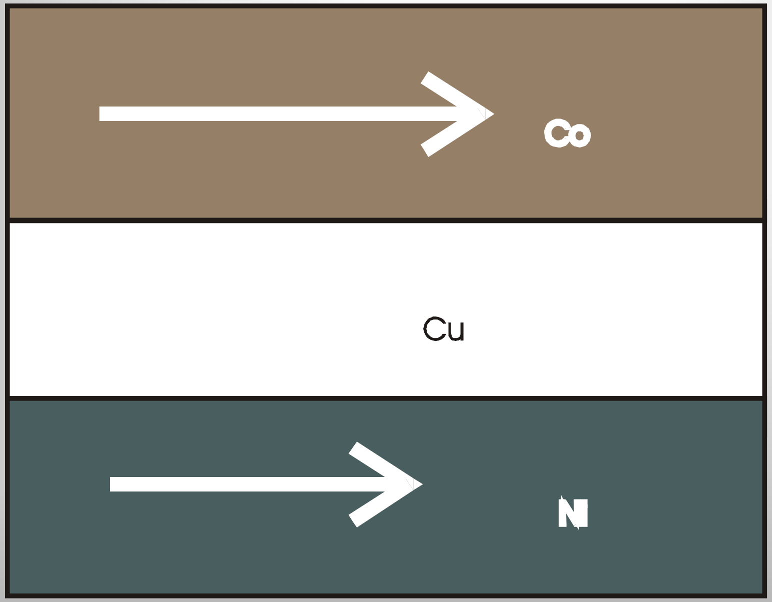
usually $K_{u2} << K_{u1}$

$$L_{\max} = K, \theta = 45^0$$



P. Poulopoulos et al., J. Appl. Phys. 75, 4109 (1994)

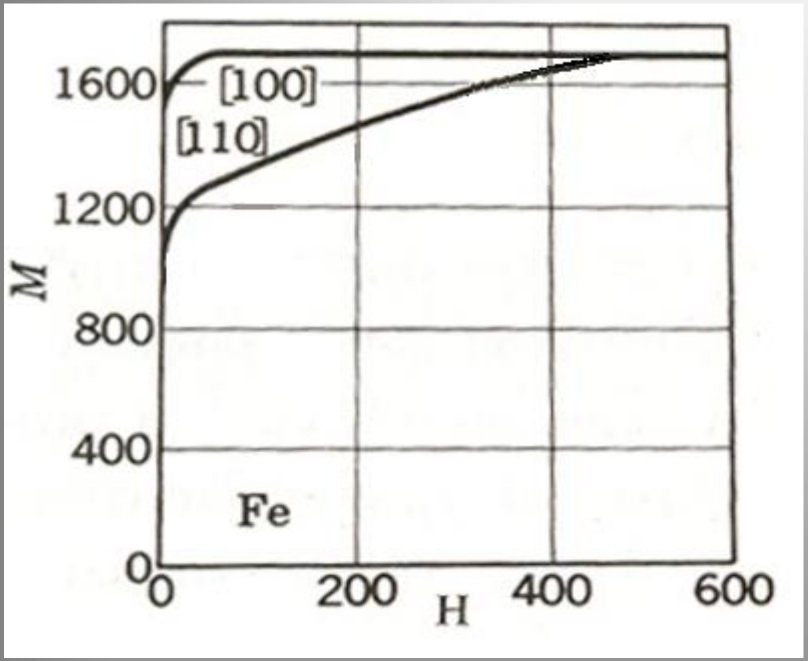
Basic Hamiltonian for Three (multi) Layers



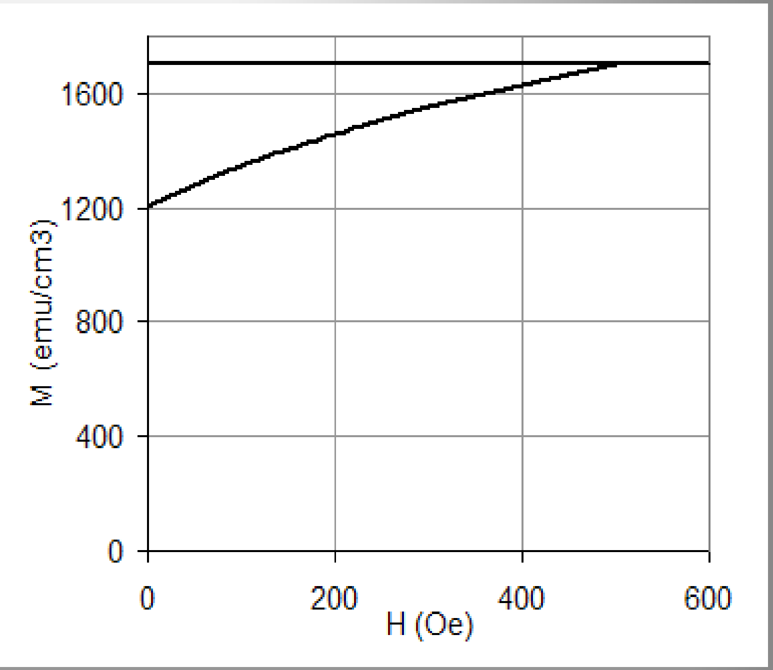
$$F = aF_1 + (1-a)F_2 - J_{12}\cos(\theta_1 - \theta_2)$$

J_{12} = Interlayer Exchange Coupling (RKKY Interactions)

Μοντελοποίηση
Results for bulk single-crystalline Fe



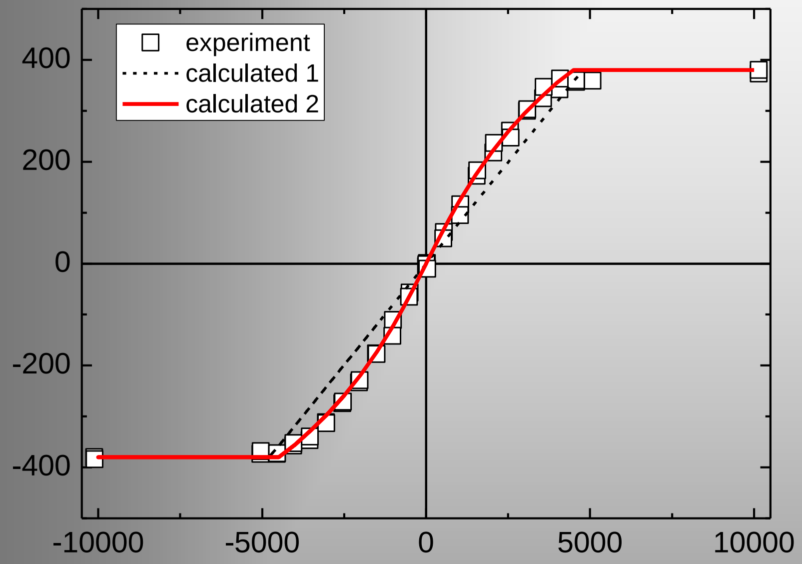
Kittel



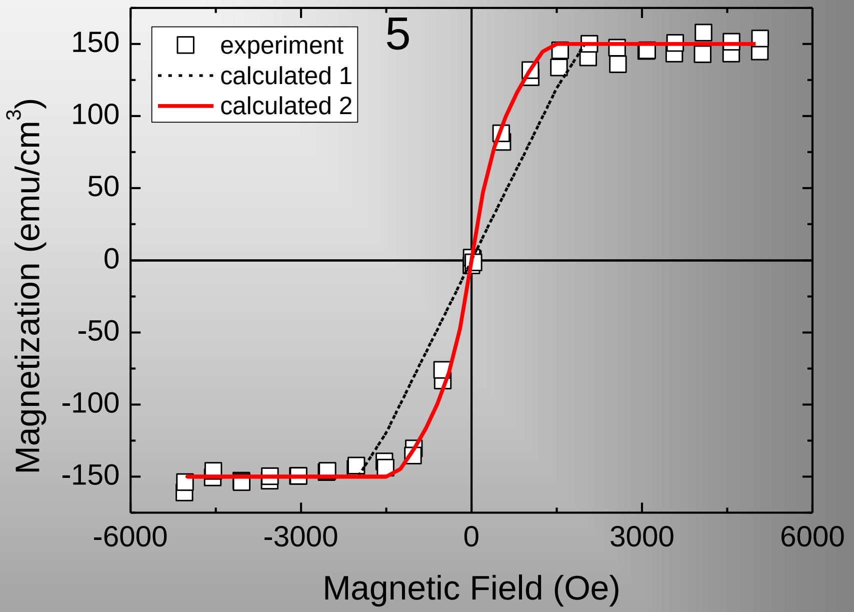
Our result

Determination of Anisotropy Constants: Valid for Hard Axis Curves

Ni_{15}/Pt_6



Ni_5/Pt_5



K_{u1} = -2x10^5 erg/cm^3 and
K_{u2} = -1.4x10^5 erg/cm^3

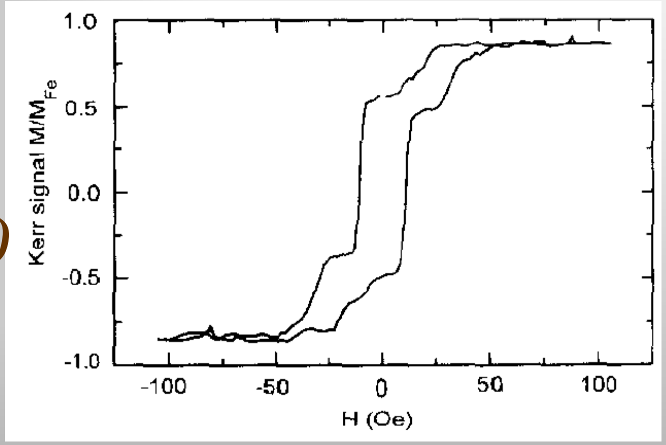
K_{u1} = -7x10^4 erg/cm^3 and
K_{u2} = -3x10^4 erg/cm^3

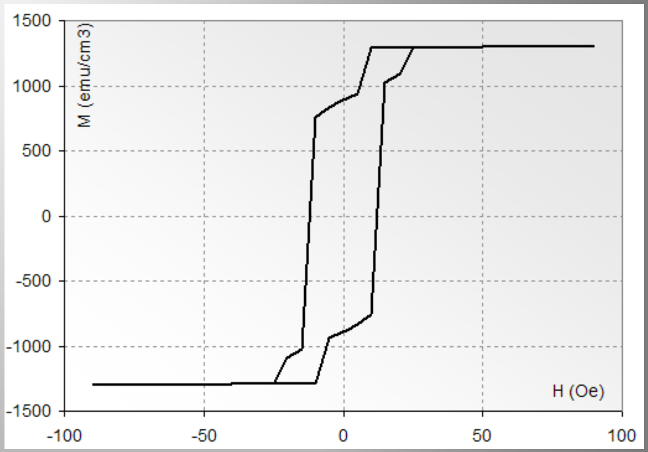
E. Th. Papaioannou et al, J. Appl. Phys. 101, 023913 (2007)
A. Troupis, Dipl. Thesis, Univ. of Patras (2006)

Another two cases (but for easy axes)

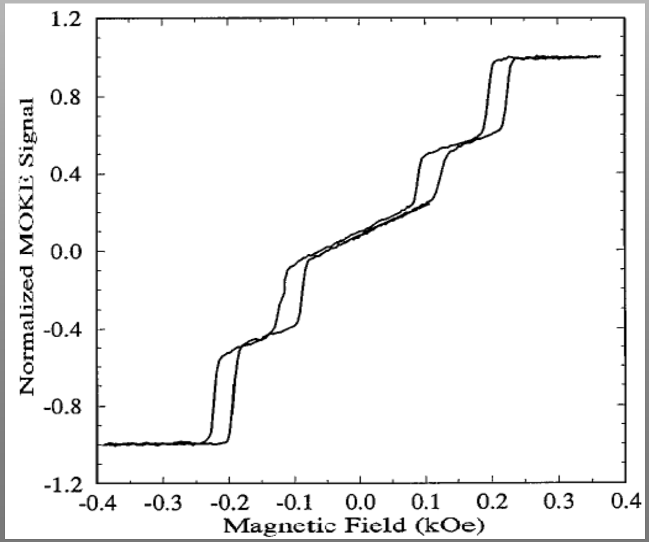
$$F = a[(K_{41}/4)\sin^2(2\theta_1) - M_1 H\cos(\phi-\theta_1)] + (1-a)[(K_{42}/4)\sin^2(2\theta_2) - M_2 H\cos(\phi-\theta_2)]$$
$$- J_{bil}\cos(\theta_2-\theta_1) - J_{biq}\cos(2(\theta_2-\theta_1))$$

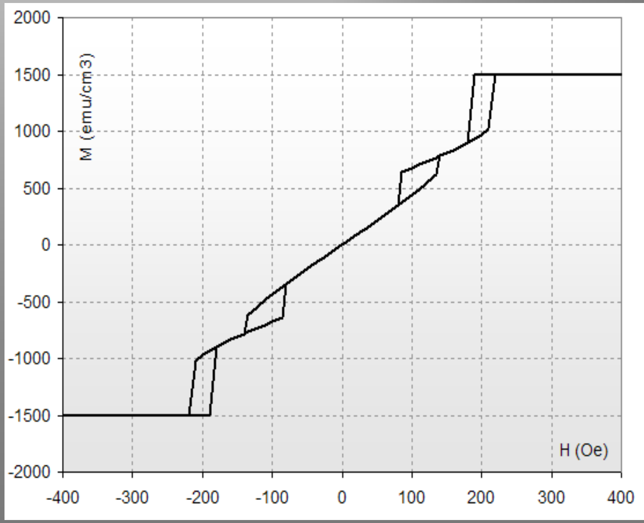
P. Poulopoulos et al., JMMM 170,57 (1997)





A. Azevedo et al., PRL 76, 4837 (1996)

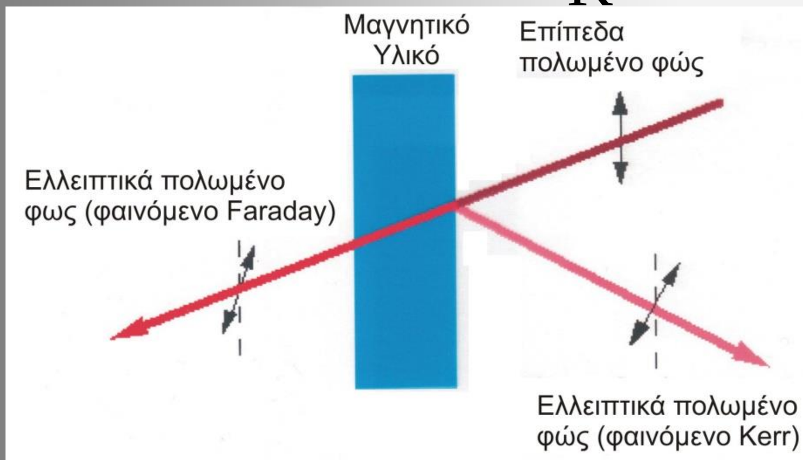




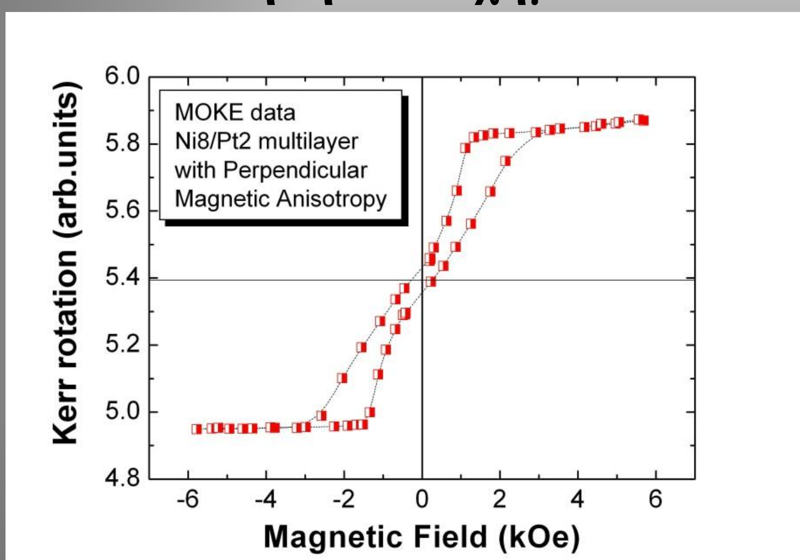
Magneto-optic Kerr Effect (MOKE)
Λόγω διπλοθλαστικότητας

Faraday Rotation : θ_K=KMd

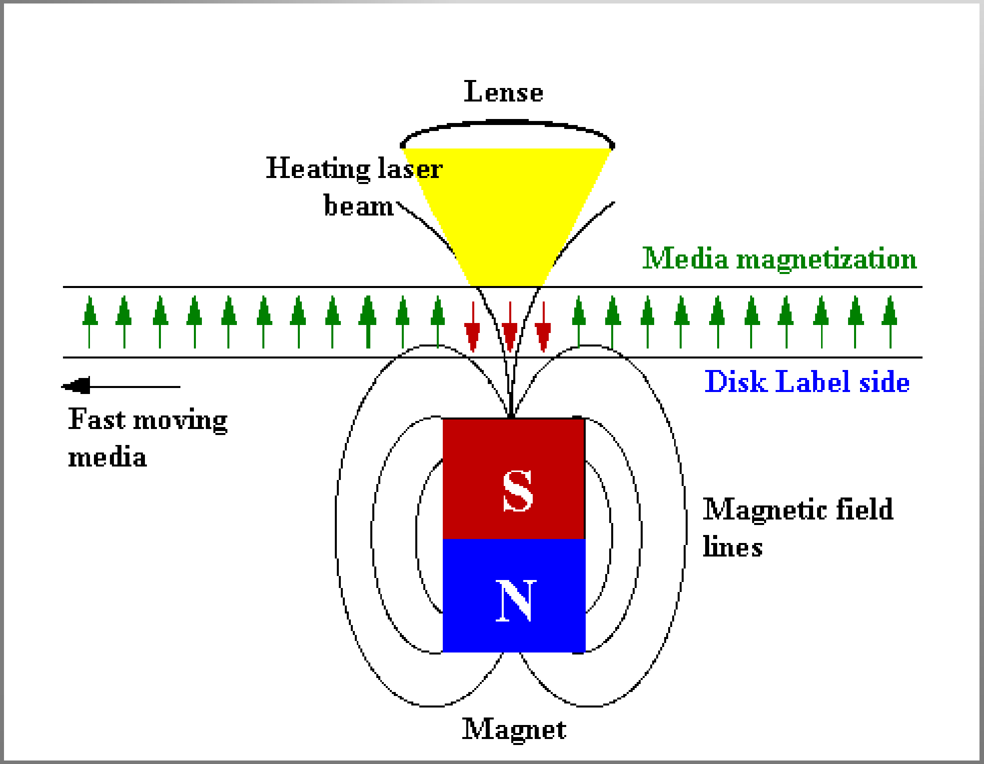
Lab in Patras



Βοηθητικό σχήμα

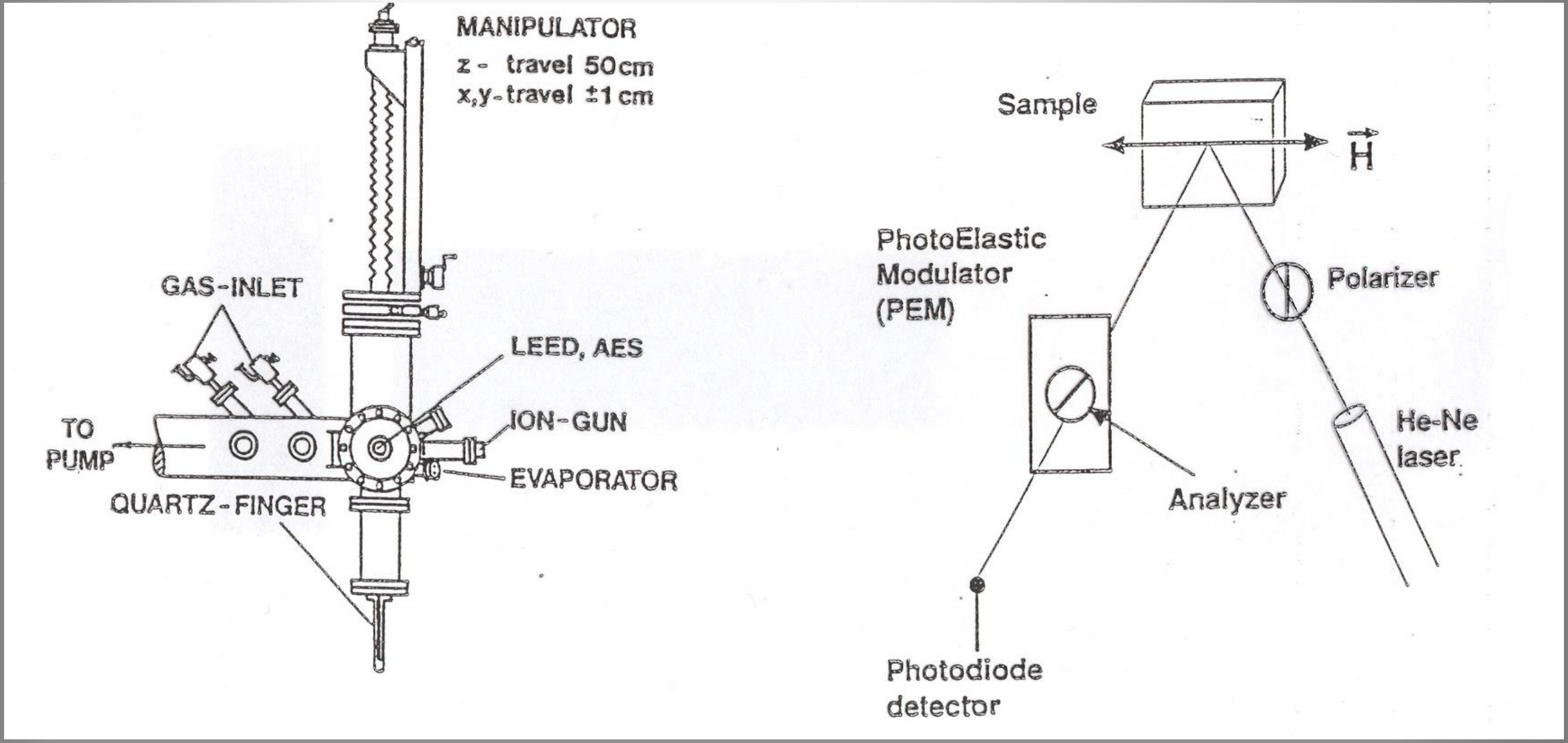


MOKE Recording Materials

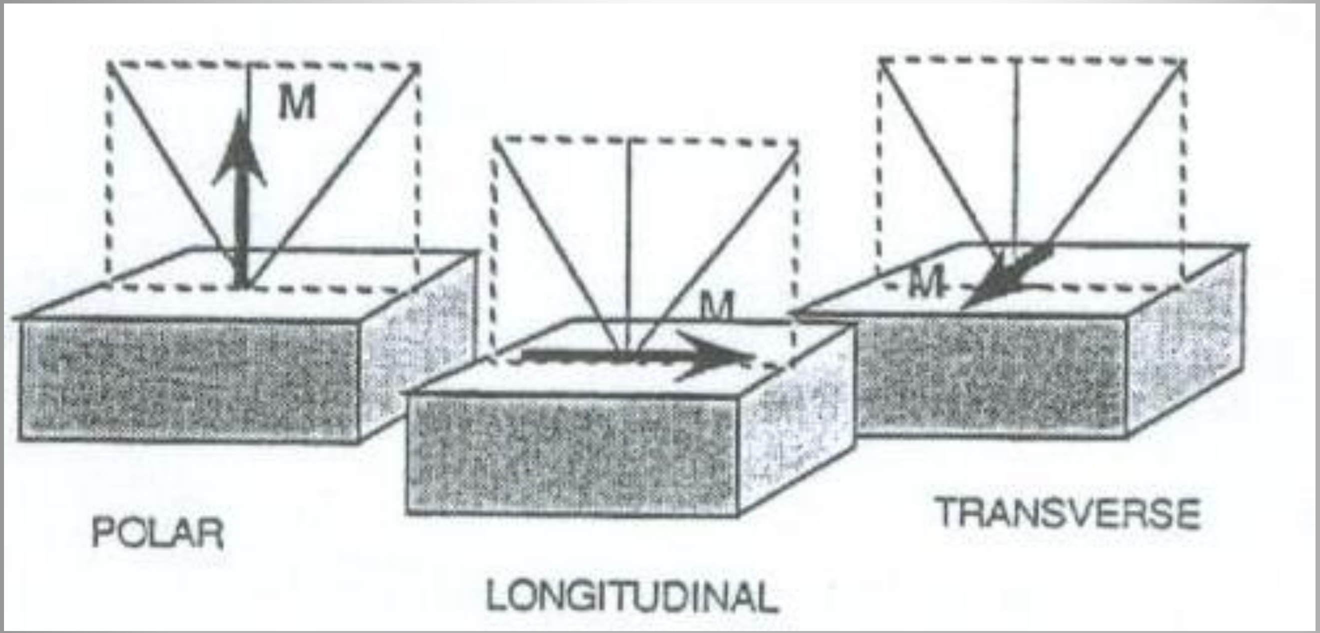


thermomagnetic writing

Typical in situ Set Up



MOKE Geometries



Polar Kerr effect about 1 order of magnitude more intense than the Longitudinal Kerr Effect

Practical Uses of MOKE

Polarimetry: For Recording of Hysteresis Loops, similar to a Magnetometer but Y-axis in arb. Units

Spectroscopy: Magneto-optic response as a function of the wavelength of light. Examination of Materials for Magnetic Recording (typical Co/Pt, CoCrPt etc.)

Magnetic Domain Imaging: With a resolution of the order of the wavelength of light

Useful Properties

High Coercivity Values
Perpendicular Magnetic Anisotropy
High MOKE response
100% Remanence
Square-like hysteresis loops
Thermal and Chemical Stability
High Reflectance
Magnetic Homogeneity
Grain Isolation
Cost-effective Production

Co/Pt-based multilayers

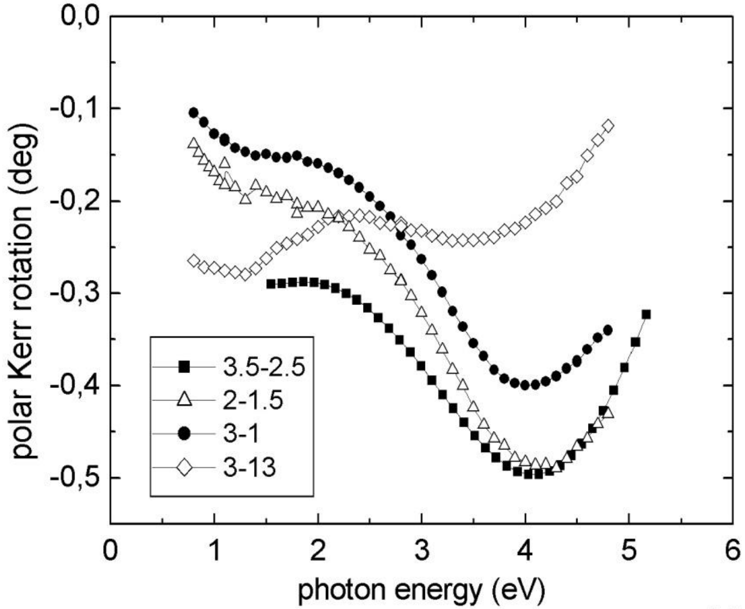


Fig. 7

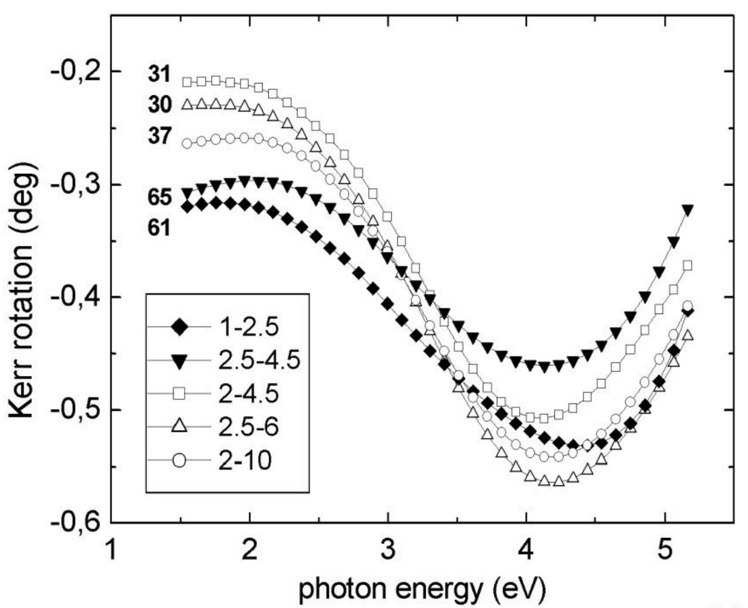


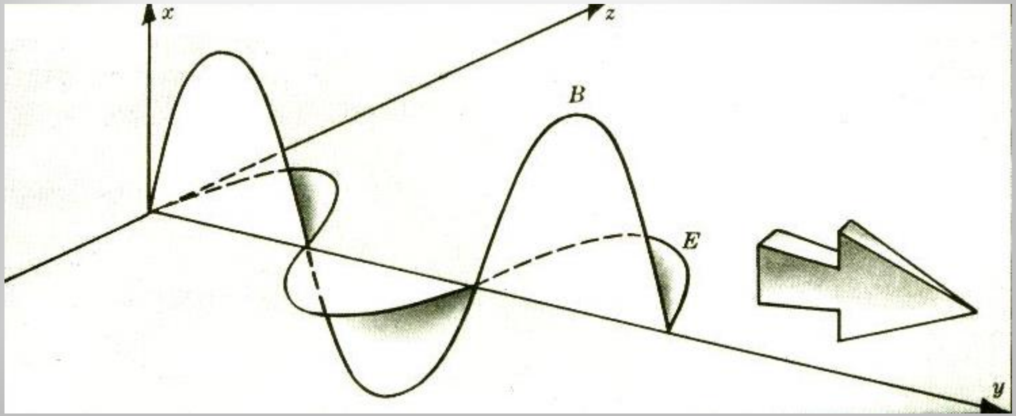
Fig. 9

P. Poulopoulos et al, J. Appl. Phys. 94, 7662 (2003)

Magneto-Optic Kerr Effect

Physics and Mathematics

Light as an Electromagnetic Wave

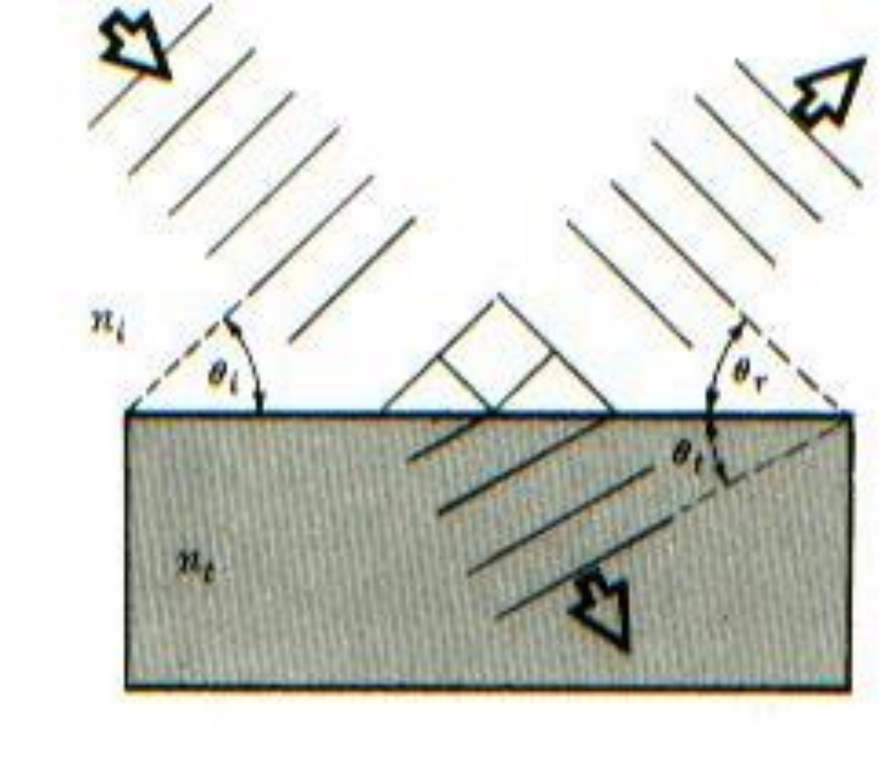


Basic Equations

$$\psi(r,t) = A\sin k(x \mp Ut) \qquad k = 2\pi/\lambda = \omega/U = \omega\sqrt{\varepsilon\mu}$$

$$\psi(r,t) = A\sin(kr \mp \omega t) \qquad \psi(r,t) = Ae^{i(kr \mp \omega t)}$$

Reflection and Refraction



Reflection

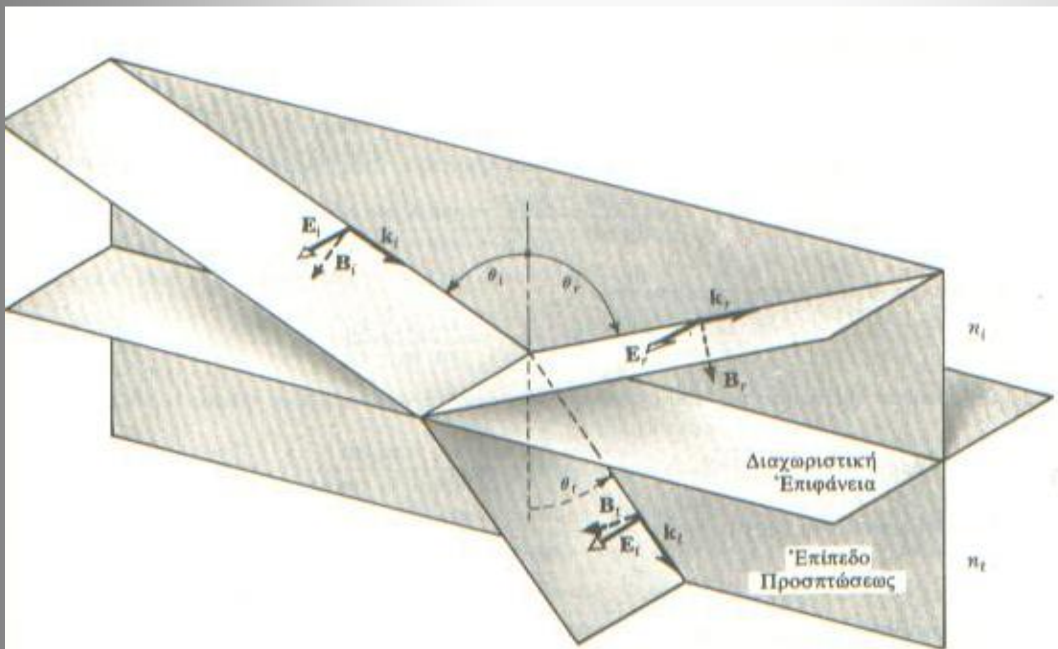
θi=θr

Refraction

Snell's Law

$$n_i \sin\theta_i = n_t \sin\theta_t$$

S-polarized light



$$\vec{E} \perp$$

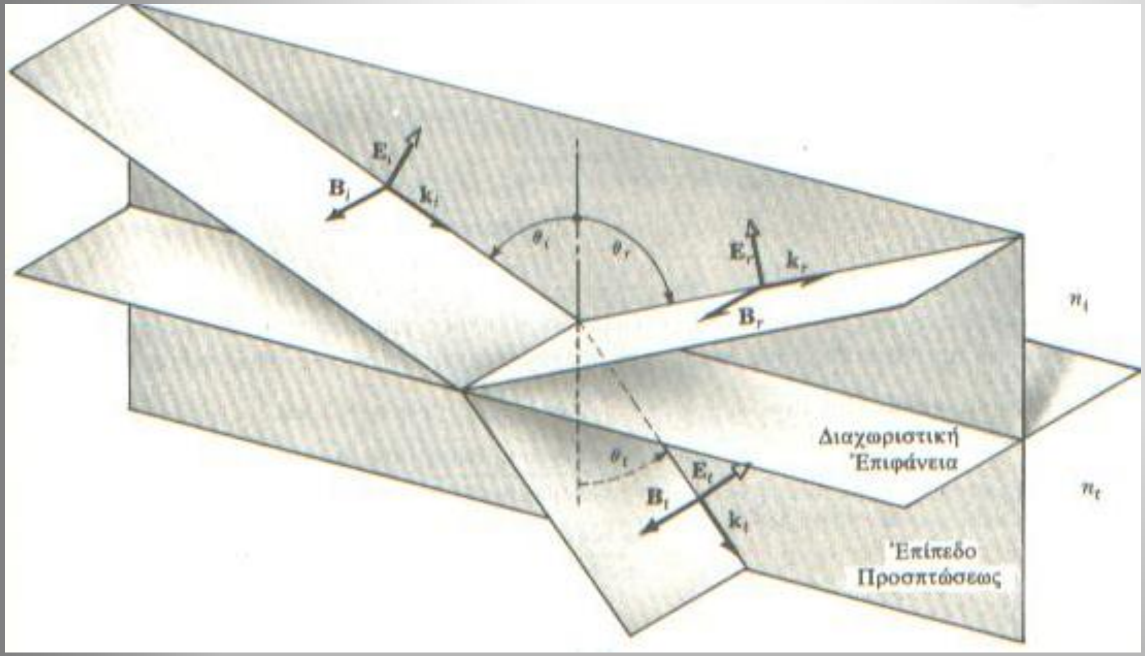
polarization plane

Fresnel coefficients

$$r_{ss} = \left(\frac{E_{or}}{E_{oi}} \right)_s = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$$

$$t_{ss} = \left(\frac{E_{ot}}{E_{oi}} \right)_t = \frac{2 n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t}$$

P-polarized light



$\vec{E}$ // polarization plane

Fresnel coefficients

$$r_{pp} = \left(\frac{E_{or}}{E_{oi}} \right)_p = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_i}$$

$$t_{pp} = \left(\frac{E_{ot}}{E_{oi}} \right)_p = \frac{2 n_i \cos\theta_i}{n_i \cos\theta_t + n_t \cos\theta_i}$$

Conducting Surfaces (Metals):

Ohm's Law: **J** = σ **E**

The dielectric constant is a complex number $\varepsilon_\omega = \varepsilon + j\sigma/\omega$

Wave number $k = \omega^2 \varepsilon \mu$

Also:

$$E(r,t) = E_o e^{-sz} e^{-i(\omega t - kz)}$$

$$B(r,t) = B_o e^{-sz} e^{-i(\omega t - kz)}$$

And the penetration depth: $\Delta = 1/s = \sqrt{2/\omega\sigma\mu}$

For normal Incidence ($r_{ss}=r_{pp}$):

$$\sigma = \frac{E_{or}}{E_{oi}} = \frac{\left(1-\frac{\mu_1 k_2}{\mu_2 k_1}\right)^2 + \left(\frac{\mu_1 s_2}{\mu_2 k_1}\right)^2}{\left(1+\frac{\mu_1 k_2}{\mu_2 k_1}\right)^2 + \left(\frac{\mu_1 s_2}{\mu_2 k_1}\right)^2}$$

Ideal Conductor: $\sigma \to \infty \quad s_2 \to \infty \quad \frac{k_2}{s_2} \to 1 \quad \frac{k_1}{s_2} \to 0$

For $\sigma \to 1$, one has an ideal mirror

Ferromagnetic Materials

The dielectric constant is a tensor

$$\tilde{\varepsilon} = \varepsilon \begin{pmatrix} 1 & iQ_y & -iQ_y \\ -iQ_z & 1 & iQ_x \\ iQ_y & -iQ_x & 1 \end{pmatrix}$$

Faraday Rotation : $\theta_K = KMd$

Q proportional to **M**, is the Voight vector,

Components of Rotation and Ellipticity that they show a linear M-dependence are usually characterized as magneto-optic Faraday or Kerr effects effects

Erratum: the (1,2) component of the tensor is Qz

Sam Bader, Review Article in JMMM 1999