**3.45**
**MAGNETIC MATERIALS;**
**PRINCIPLES AND APPLICATIONS**
ST 2004

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COURSE SUMMARY

This course is a graduate level course in magnetic materials. The level of treatment presumes familiarity with differential calculus as well as introductory atomic physics and quantum mechanics of solids. The course moves from observation to understanding of magnetic phenomena at increasing levels of sophistication. The characteristics of magnetic materials are treated in the context of related effects in other materials. For example, magnetic and electric polarization and susceptibility are treated in parallel; ferromagnetism is compared to ferroelectricity; the reasons for ferromagnetic spin alignment are contrasted with superconducting spin pairing; magnetic anisotropy and magnetostriction are compared with anisotropic electric polarization, electrostriction and piezoelectricity.

The text for the course is:
O'Handley, R. C. *Modern Magnetic Materials, Principles and Applications***,** New York: John Wiley and Sons, 1999.

Useful backup texts (in increasing level or treatment) include:
Jiles, D. C. *Introduction to Magnetism and Magnetic Materials.* Chapman and Hall, 1991.
Cullity, B. *Introduction to Magnetic Materials* Addison-Wesley, 1972.
Chikazumi, S. *Physics of Ferromagnetism.* Oxford University Press, 1997.

**Grades**:
There will be one one-hour exam about half way through the term. There is no written final examination. A written report and its oral presentation, on an appropriate topic chosen by the student, will be due at the end of the term. The grades will be determined as follows:

The **exam** will count for **20%** of you final grade.
**Homework** assignments will count for **20%**.
**Written assignment** will count for **40%.**
An **oral presentation** of your written assignment will count for **20%**.

I. INTRO, REVIEW, OVERVIEW.

1. Introduction. Course ground rules and overview. Approach: microscopic to macroscopic, impact of magnetism on technology (power, recording, magneto-

mechanical, transportation, security, sensors, actuators), basic scientific questions in magnetism.

2. Generating magnetic fields, Maxwell's equations. □∞ ***H*** = ***J***, and Biot-Savart law. Fields of solenoid, toroid, Helmholtz coils, electromagnet with core and gap, permanent magnets.

3. Observables of magnetism: Maxwell's equations, □∞ ***E*** = -*d**B**/dt,* define fields, *B-H* loop, M(*H,T*), susceptibility, magnetic anisotropy, magnetostriction, magnetometry.

4. Where do magnetic moments come from? CLASSICAL free electron theory of magnetism. Orbital gyromagnetic ratio. Diamagnetism, paramagnetism. Observation and models: (Langevin). Atomic spectra, orbital quantum numbers *l*, *m*l, Zeeman effect.

## II. QUANTUM MECHANICS AND MAGNETISM.

5. Spin, Anomalous Zeeman effect, and Ferromagnetism. - spin Quantum numbers: l, *s*, *j*. gyromagnetic ratios for orbital and spin moments. Quantum theory of paramagnetism. Extend Quantum paramagnet via graphical and analytic solution for Brillouin function mean field theory.

6. Exchange. Quantum origin of magnetism. Intra-atomic, Hund's rules; interatomic Heisenberg, indirect exchange, superexchange, internal pressure of magnetism and manifestations in various materials. Contrast with superconductivity.

7. Bonding and magnetism, molecular orbitals, Slater Pauling curves, ferromagnetic materials, saturation magnetization, Curie temperature, magnetic anisotropy. Spin waves. Band theories of magnetism.

8. Antiferromagnetism susceptibility, $\chi$ (*T,H*), Ferrimagnetism, mean-field theory, moments of spinel ferrites.

## III. PHENOMENOLOGY, MACRO. AND MICRO.

9. Boundary conditions, magnetic and electric dipole field. Electrostaticc, magnetostatic energy. Macroscopic expressions for exchange energy.

10, 11 Magnetic anisotropy of various materials, Free energy. Crystal symmetry. Origin: crystal field, spin-orbit interaction. Parallel with electric polarization anisotropy.

12 - 13 Magnetostriction in materials, magnetovolume effects, macroscopic expressions, microscopic origin, examples, applications, effect of magnetostriction on anisotropy. Comparison with electrostriction, piezoelectricity.

14. Domain theory, Weiss theory of domains. Macroscopic energy expressions, magnetostatic energy, exchange, anisotropy, static wall width, energy density, 180o, 90o domain walls, wall observations.

15-16. Magnetization processes. macroscopic quasistatic approach: applied field, anisotropy, magneostriction, and dipole energies. Euler equations and boundary conditions to calculate reversible rotation. Emphasize how anisotropy, magnetostriction, resistivity affect soft magnetic behavior. Microwave magnetism ferromagnetic resoanance.

**17. *Written Mid-term exam.***

18. Soft ferromagnetic materials behavior, Si-Fe, Fe-Ni, Fe-Co alloys and soft ferrites. Amorphous and nanocrystalline alloys. DC rotation permeability, irreversible rotation. AC behavior, skin depth, applications. Hysteresis loss and eddy current loss.

19. Amorphous magnetism, competing interactions. Exchange fluctuations, random anisotropy, resistivity. Models of amorphous magnetism, alloy effects vs. disorder.

20. Nanocrystalline magnetic materials. Exchange fluctuations, random anisotropy effects on properties with length scale.

21. Hard magnetic materials: *M-H, B-H*, (*B-H*)max, fine particles, nucleation, pinning. Materials: Alnico, Ba ferrite, Co-RE, Fe-RE-B.

22. Domains and Walls in thin films and particles. Bloch, Neel and cross-tie walls. Critical particle size, single-domain particles, fine particle theory, superparamagnetism.

23-24. Transport in magnetic materials. Electrical consuctivity of metals and alloys in light of electronic structure. Hall effect and magnetoresistance (MR), MR heads, mechanisms of spin scdattering, giant MR, spin tunneling.

25 - 26. Surface and thin film magnetism. Surface electronic structure and magnetism, surface moments, metastable phases, misfit strain, epitaxial growth, surface magnetic anisotropy and magnetostriction, domains, devices.

27. Magnetic Recording, Physics or recording. Basic concepts of recording media and heads, Karlkvist fields, noise.

28. Magnetic Recording Materials. Particulate: $\gamma Fe_2O_3$ $CrO_2$, Co-Ferric oxide, barium ferrite. Thin film media: longitudinal, perpendicular. Thin film heads, MR heads, spin valves, magnetic random access memories.

**Supplemental topics (selected by student interest).**

Alloy theory, Friedel virtual bound state theory, split bands. Heat of formation (Buschow), Malozemoff and Corb theories.

Magnetic annealing, Magnetic order-disorder in light of chemical order-disorder. Directional ordering, field-induced anistropy.

Magnetism and superconductivity, diamagnetism, *M-H, B-H*, fluxons, pinning, analogies with permanent magnetic materials. Antiferromagnetism and Hi $T_C$.

Special probes of magnetism: Microwaves NMR, FMR, EPR, Mossbauer effect.

**Sample homework problems:**

1. Calculate the orbital magnetic moment of an electron in a circular Bohr orbit. Use $\omega = E/h$ = 1.36 eV/h and $\omega = v/r_0 = \,!(2E/m)/r_0$ and compare the results. Which one is correct? Why?

2. Calculate the domain wall thickness and energy density for Co, $Nd_2Fe_{14}B$ and $Ni_{80}Fe_{20}$ from data in Ch. 6 assuming in each case $A = 2 \times 10^{-11}$ J/m.

3. Derive the vector field components beneath the gap of a write head by replacing the head with a current flowing in the cross-track direction in the gap at $x = 0$ and $y = 2g$. Choose the strength of the current so that $H_x(0,0) = H_g$.

4. a) Calculate for a spherical particle the critical radius below which the particle is a single domain particle, i.e. it cannot be demagnetized since it cannot support a domain wall.
(Hint: balance the wall energy against the magnetostatic energy of the particle without a wall, $(1/2)M_sH_d = (2/3)\,\pi M_s^2)$.
b) What is the critical radius for $Nd_2Fe_{14}B$ where $A = 10^{-6}$ erg/cm, $M_s$ = 1274 Gauss, and $K = 5 \infty 10^7$ erg/cm$^3$?

5. Explain what happens as Zn substitutes for Ni in nickel ferrite, $NiFe_2O_4$. Again, describe the valence electronic structure of the ions and magnetic moment variation per formula unit. Be quantitative where possible.

**Sample exam question:**

1. You want to make a magnetic actuator, that is, a magnetic material that will strain and do work when a magnetic field is applied. You decide to use a rectangular prism of polycrystalline Ni, $\lambda_\sigma$ ! -34 x $10^{-6}$. The prism measures 2 x 10 x 100 mm; assume a modulus, $E = 10^{11}$ N/m$^2$.

a) Along what direction will you apply the field to get the greatest extension?

b) What is the shape anisotropy and demagnetizing field for magnetization in that direction?

c) How does that compare with the anisotropy for single crystal Ni ($K_1$ ! -6 x $10^3$ J/m$^3$?

d) What field would you design for; how many turns, how much current to achieve this?

e) Write the expression for the free energy including external field, anisotropy magnetostriction and an external stress of 100 MPa opposing the Ni extension. Compare the magnitude of the terms.

f) Calculate and plot the field dependence of magnetization.

g) Calculate and plot the field dependence of the strain.

2. You have a process for making nanoscale magnetic particles with typical aspect ratios of 5:1. You want to make some very small but thermally stable particles.

a) Describe quantitatively your considerations in choosing between $Fe_{0.6}Co_{0.4}$ and Co assuming you could make either of these compositions with [001] crystal direction along the long particle axis. Consider the following:

i) Crystal structure, ii) magnetocrystalline anisotropy, iii) shape (magnetostatic) anisotropy, iv) single domain particle size, and v) superparamagnetic limit at lab time scales (1 sec).

b) If the particles were superparamagnetic, compare the susceptibility of particles of the two compositions having the same shape and volume.