local probes

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types of local probes

✓ microscopic (site-specific)
  – NMR
  – neutrons
  – Mossbauer

✓ stationary
  – Bitter decoration
  – magneto-optics (Kerr and Faraday effects)

✓ stationary and scanning
  – Hall probes, micro-SQUID
  – Magnetic force microscope

✓ electron microscopy
  – Lorentz microscopy
  – electron holography

X-Ray Magnetic Circular Dichroism (XMCD)  
Spin Polarized Low Energy Electron Microscopy (SPLEEM)
Nuclear Magnetic Resonance (NMR)

NMR spectroscopy is one of the principal techniques used to obtain physical, chemical, electronic and structural information about molecules due to either the chemical shift Zeeman effect, or the Knight shift effect, or a combination of both, on the resonant frequencies of the nuclei present in the sample. It is a powerful technique that can provide detailed information on the topology, dynamics and three-dimensional structure of molecules in solution and the solid state.
Mössbauer spectroscopy (German: Mößbauer) is a spectroscopic technique based on the resonant emission and absorption of gamma rays in solids. This resonant emission and absorption was first observed by Rudolf Mössbauer in 1957 and is called the Mössbauer effect in his honor. Mössbauer spectroscopy is similar to NMR spectroscopy in that it probes nuclear transitions and is thus sensitive to similar electron-nucleus interactions as cause the NMR chemical shift. Furthermore, due to the high energy and extremely narrow line widths of gamma rays, it is one of the most sensitive techniques in terms of energy resolution having the capability of detecting changes of just a few parts per 10^{11}.

In its most common form, Mössbauer Absorption Spectroscopy, a solid sample is exposed to a beam of gamma radiation, and a detector measures the intensity of the beam transmitted through the sample. The atoms in the source emitting the gamma rays must be of the same isotope as the atoms in the sample absorbing them. In accordance with the Mössbauer effect, a significant fraction (given by the Lamb-Mössbauer factor) of the emitted gamma rays will not lose energy to recoil and thus will have approximately the right energy to be absorbed by the target atoms, the only differences being attributable to the chemical environment of the target, which is what we wish to observe. The gamma-ray energy of the source is varied through the Doppler effect by accelerating it through a range of velocities with a linear motor. A typical range of velocities for 57Fe may be +/-11 mm/s (1 mm/s = 48.075 neV).
"magnetic" peaks will reflect doubling of the lattice constant.
Figure 1. Diagram comparing the magnetic field sensitivity and spatial resolution of electron microscopy, MFM, Bitter decoration, SHPM, MO imaging and scanning SQUID microscopy.
Figure 2. Diagram comparing the image acquisition time and spatial resolution for five of the techniques described in figure 1.
Figure 37. Layer structure of a GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure (top). Sketch of the corresponding conduction-band edge perpendicular to the layers showing the location of the two-dimensional electron gas (2DEG) (bottom).
Figure 38. Sketch of an idealized 2D Hall probe.
Figure 39. Response function for a 2D Hall probe with leads 1 \( \mu \text{m} \) wide as a function of the position of a highly localized vortex within it.
scanning Hall probe
Figure 41. Electron micrograph of a scanner Hall probe with 0.8 μm spatial resolution.
Schematic diagram illustrating (a) the STM tracking and (b) the flying modes of SHPM.
magnetic fields in superconductors

(a)

(b)
Figure 7. Magnetic field profile at various heights $z$ above an Abrikosov lattice of vortices in an applied field of 10 mT.
Scanning Hall probe images of Vortices, 1997

Scanning Hall probes
YBaCuO film, 1000G

A. Oral et al.
University of Bath
Figure 45. SHPM image of flux vortices in a niobium strip 100µm wide after cooling to 6.3 K in a field of 0.034 mT (Field 1997).
Figure 46. SHPM image showing finger-like penetration of flux into the niobium strip of figure 45 after ramping the field from zero to 33 mT at 4.5 K (Field 1997).
Figure 48. Real-time SHPM images of vortices in a BSCCO single crystal (a) about 45 s, (b) about 180 s and (c) about 315 s after the field was suddenly increased from 0 to 0.8 mT at 77 K (image sizes, about 7 μm × 5.6 μm, greyscale spans about 0.255 mT).
scanning SQUID
Figure 59. Image of vortices in a YBCO thin-film edge-junction washer SQUID with a scratch running from top left to centre right. Images were recorded after (a) field cooling at a very low field and cycling to (b) 0.06 mT and (c) 0.22 mT at 4.2 K. (d) Image at 4.2 K after cycling to 0.24 mT at 77 K (Kirtley et al. 1995b). [Copyright 1995 International Business Machines Corporation. Reprinted with permission of IBM Journal of Research and Development, Vol. 39, No. 6.]
Figure 62. Schematic diagram of the tricrystal YBCO ring samples used to observe half-integer flux quanta: GB, grain boundary.
Figure 63. (a) Scanning SQUID image of the sample sketched in figure 62 after cooling in a field of less than 0.5 μT (top). (b) Line scans (---) through the central three-junction ring along with fits to the data assuming it contains half of a flux quantum (-----) (bottom) (Kirtley et al. 1995b). [Copyright 1995 International Business Machines Corporation. Reprinted with permission of IBM Journal of Research and Development, Vol. 39, No. 6.]
Scanning SQUID Microscopy of half-integer vortex, 1996

Scanning SQUID Microscopy YBaCuO grown on tricrystal substrate

J. R. Kirtley et al.
IBM Thomas J. Watson Research Center
Magnetic Force Microscopy

General Presentation

Functioning Principle

Advantages

Types

Applications

The principle of MFM is to measure the change in the interaction force between a magnetized probe and the local magnetic field from the sample.

To achieve this, a ferromagnetic probe attached to a cantilever is scanned across the surface of the sample. The image obtained with the MFM is a space distribution of a particular parameter characterizing the magnetic probe-sample interaction, i.e., interaction force, force gradient.

The most important problem in MFM is to distinguish the topography from the magnetic image. This is achieved using a two-pass method. In the first step, the topography is determined by situating the tip close to the surface (under 100 nm) e.g. in contact mode or non-contact mode. In the second step, the cantilever is raised to a selected height and the surface is scanned using the stored topography (without feedback). The constant tip-sample separation must be large enough to eliminate Van der Waals forces. This way, the cantilever is influenced only by the long-range magnetic forces.

There are two main approaches to MFM imaging: force mode (or DC mode) and force gradient mode (or AC mode).

For small tip-sample distances, atomic forces (e.g., Van der Waals) are stronger than magnetic forces so MFM delivers a predominantly topographic image. For large distances (in the order of 100 nm), the long-range magnetic forces are much more significant and the image will reflect the magnetic properties of the analyzed surface.
Magnetic-force microscopy of Vortex Lattice

Figure 4  Top: A schematic diagram showing an inductive recording head writing domains of in-plane magnetization on a magnetic recording tape. Bottom: An interference micrograph, obtained using electron holography, illustrating the flux distribution both outside (top 25% of image) and inside (bottom
Figure 9. (a) Sketch of an electron trajectory passing by a horizontal flux string containing a single flux quantum. (b) Total change $\Delta \phi$ in phase accumulated by electrons on different trajectories.
Figure 12. Classical response of a beam of electrons incident on a horizontal flux line.

Figure 13. Diagram of an electron microscope designed for investigating vortices in superconductors.
Figure 14. Schematic diagram of the experimental set-up for performing Lorentz microscopy.

Figure 16. Lorentz micrograph of a niobium film at 4.5 K in a field of 10 mT. [Reprinted with permission from Nature (Harada et al. 1992) Copyright 1992 Macmillan Magazines Limited.]
Figure 19. Video frames of regions of vortex lattice in a niobium film at various times after the field was suddenly reduced from 18 to 8.5 mT at 6 K: (a) $t = 0$s, (b) $t = 0.27$s, (c) $t = 0.43$s, (d) $t = 0.80$s. Implanted defects are located at the black discs and domain boundaries for the vortex lattice are indicated by dotted lines. [Reprinted with permission from T. Hasegawa, K. Harada, H. Kasai, O. Kanazawa and A. Tanigawa, 1996, Science, 271, 1393. Copyright 1996 American Association for the Advancement of Science.]
Lorentz microscopy

Fe-Pd alloys
Figure 20. Schematic diagram of the experimental set-up for performing electron holography.
Figure 24. Schematic diagram of a real-time electron holography system: YAG, yttrium aluminium garnet; VCR, video cassette recorder.
Figure 22. Interference micrograph of the vortex lattice in a niobium film (phase amplified 16 times) at 4.5 K in an applied field of 10 mT. [Reprinted from Bonevich et al. (1993). Copyright 1993 by the American Physical Society.]

Figure 23. Interference micrograph of a single vortex in niobium at (a) 4.5 K, (b) 7 K and (c) 8 K (phase amplified 12 times). [Reprinted from Bonevich et al. (1994b). Copyright 1994 by the American Physical Society.]
stationary probes

Figure 31. Schematic diagram of a typical Bitter decoration system.
First image of Vortex lattice, 1967

Bitter Decoration
Pb-4at%In rod, 1.1K, 195G

U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
Vortex lattice in high-Tc superconductor, 1987

Bitter Decoration
YBa2Cu3O7 crystal, 4.2K, 52G

P. L. Gammel et al.
Bell Labs
Figure 32. (a) Twin layers (dark lines) in a partly detwinned YBCO single crystal as viewed in the optical microscope with polarized light. (b) Bitter decoration image of the same region of the sample. [Reproduced from Grigorieva (1994) by permission of IOP Publishing Limited.]
Figure 35. Bitter decoration image of vortex chains in an untwinned YBCO single crystal in a field of 2.48 mT applied at 70° away from the crystal c axis. [Reprinted from Gammel et al. (1992). Copyright 1992 by the American Physical Society.]
Figure 36. Bitter decoration image of the vortex pattern in a BSCCO single crystal in a field of 3.5 mT applied at 70° away from the crystal c axis. [Reprinted from Bolle et al. (1991). Copyright 1991 by the American Physical Society.]
Magneto-optical imaging: Kerr effect

Kerr

Polar

Longitudinal

Transverse
CeAgSb$_2$
magneto-optical imaging: Faraday effect

Figure 49. Sketch of the position of the magneto-optically active layer (MOL) and superconducting sample for (a) high-resolution imaging with europium chalcogenide films and (b) imaging with garnets.
Magneto-optics (Faraday effect)
Figure 50. Diagram of a typical experimental set-up for performing MO imaging on superconductors.
Existing magneto-optical setup

~ 2.5 K base temperature
~ 2-10 \(\mu\)m spatial resolution
~ 0.5 G field sensitivity
credit card
Figure 52. MO image of a Tl-Ba-Ca-Cu-O single crystal in the Meissner state at 76 K with an applied field of 7.2 mT. The sample is about 600 μm wide at its largest point. [Reprinted from Indenbom et al. (1990) with permission from Elsevier Science.]
type-II superconductors

Meissner State  Partial Penetration  Trapped Flux
influence of grain boundaries
Magneto-optical studies of a c-oriented epitaxial MgB2 film show that below 10 K the global penetration of vortices is dominated by complex dendritic structures abruptly entering the film. Figure shows magneto-optical images of flux penetration (image brightness represents flux density) into the virgin state at 5 K. The respective images were taken at applied fields (perpendicular to the film) of 3.4, 8.5, 17, 60, 21, and 0 mT.
Pattern formation in type-I superconductors

Irreversible (dendrite) flux in cold-worked samples
Reversible flux tubes upon flux penetration

flux exit

tube formation

SC rings and worms
Topological hysteresis in stress-free lead

Tubes suggested by L. D. Landau, J. Phys. USSR 7, 99 (1943)
Topologies of reversible and irreversible regimes
Induction profiles in a tubular phase

- Graph showing intensity (a.u.) vs. distance (mm) for different sections.

Each graph displays a series of peaks and troughs, indicating variations in intensity as a function of distance.
Structure of a smallest bubble

Distance ($\mu$m)

$H_c \sim 400$ Oe

Gaussian distribution

$B(G)$

Distance ($\mu$m)

15 $\mu$m
Smearing of the magnetic field?

- \(L = 0.5 \text{ mm} \)
- \(a = 10 \mu \text{m}\)
- \(a = 50 \mu \text{m}\)

Graphs showing magnetic field distribution with different parameters.
High-resolution setup

~ 2 (0.5 $^{3}$He) K base temperature
< 1 µm spatial resolution (NF)
< 0.01 G sensitivity

IMAGES: Superconductivity Lab.
University of Oslo, Norway
Figure 1: An illustration of several magnetic imaging techniques using a pattern written on magnetic storage media. The test pattern is composed of horizontal tracks, each about 10 μm wide and containing a series of magnetization reversals, or "bits". The bit length ranges from 10.0 to 0.2 10 μm. The bit length and spacing of the large bits in the XMCD electron yield image is 10 μm (Tommer et al, 1994). Note: The Bitter and XMCD images are from a different, but similar, test sample.
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Specimen Modification

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Problems

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