Vortex Matter in Magnet – Superconductor Hybrids

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Overview

Motivation

Nanoscale magnetic field sources

Superconductor with embedded nanorods

Array of magnetic and superconducting nanowires

Conclusion
Characteristic Scales

Coherence length $\xi$

Penetration depth $\lambda$

Vortex Energy

$$\varepsilon = \varepsilon_0 \ln \frac{R}{\xi} + \varepsilon_1$$

$$\varepsilon_0 = \frac{\phi_0^2 d}{16\pi^2 \lambda^2}$$

$$\phi_0 = \frac{hc}{2e}$$
Superconductor Film on Magnetic Substrate
Homogeneous Superconductor in Inhomogeneous Magnetic Field

Magnetic Field from Magnetic Domains and Domain Walls

Theory: Bulaevskii et al, (1999), E. Sonin

Experiment:


From: W. Gillijns et al,

MFM pictures 5X 5micron $^2$ at 300 K
The dark /bright color represents domains with positive /negative magnetization
Magnetic dots
Magnetic rods
Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods

- Magnetic field inside array

Template: 

\[-4\pi M \left( \frac{\pi R^2}{A} \right)\]

Nanowire: 

\[\vec{B} = 4\pi \vec{M} + \vec{H} = 4\pi \vec{M} \left( 1 - \left( \frac{\pi R^2}{A} \right) \right)\]
Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods in External Field
\[ H_{\text{eff}} = H - H_{\text{return}}(H_{\text{eff}}) \]

\[ H_{\text{return}}(H_{\text{eff}}) = 4 \pi \left( \frac{A_{\text{rod}}}{A_{\text{cell}}} \right) M(H_{\text{eff}}) \]
Hysteresis, Resistance and Phase Diagram
Array of Magnetic Rods with and Without a Magnetic Field

Array of magnetic rods with aligned magnetic moments create vortices bound with dots (o) which induces antivortices (x) in interstitia sites. Regular lattice of vortices and anti-vortices is strongly pinned.

Magnetic rods magnetization direction is random. Induced vortices and antivortices are placed randomly. Weak pinning of vortices.
Homogeneous Superconductor in Inhomogeneous Magnetic Field

Magnetic Field from Magnetic Nanorods in Alumina Template

TAMU group (2008)
MFM image of the nickel nanowire array with a pitch of 150nm embedded in an alumina matrix. The magnetic polarization of the pillars alternately "up" (white) and "down" (black).
Magnetic Field from Nanorod Array

MFM image of Ni nanorod arrays at 300 K

AFM image of Ni nanorod arrays at 300 K

Profile across two nanorods
Magnetic Field from Nanorod Array
Scanning Hall Probe Microscope

SHPM image of Ni nanorod arrays at 100K

AFM image of Ni nanorod arrays at 300 K

MFM image of Ni nanorod arrays at 300 K

Profile across two nanorods
Magnetic Nanorod and Vortex

\[ \varepsilon_{fl} = \frac{\phi_0^2}{16\pi^2\lambda^2} \ln \frac{\lambda}{\xi} = \varepsilon_0 \ln \frac{\lambda}{\xi} \]

\[ \varepsilon_M = 2\pi \int H(\rho) M \rho d\rho \]

\[ H(\rho) = \frac{\phi_0}{2\pi^2\lambda^2} K_0\left(\frac{\rho}{\lambda}\right) \]

\[ \varepsilon_M / \varepsilon_{fl} = \left(\pi / 4\right) \left(\varphi_M / \varphi_0\right) \]

Flux from the rod \( \varphi_M \)

Lyuksyutov, Naugle 1999
Nickel nanorods embedded into a film of conventional superconductor (left part). Right part shows uncovered substrate (dark) with nickel nanorods (white).

AFM picture of Ni nanocolumn array with period 2 microns, column diameter 50nm and height 350nm;
Comparison of Magnetic Dots and Rods

Nickel dots 120 nm diameter by 110 nm height, niobium film 95 nm thick

Nickel rods 70 nm diameter 350 nm height, PbBi film 90 nm thick

Critical current of Nb film as a function of field for the high density triangular dot array at $T = 8.00, 8.40, 8.46,$ and $8.52$ K (top to bottom) $T_c = 8.56$ K

Critical current as a function of field at $T = 7.0$ K, 7.4 K, 7.6 K and 7.7 K (top to bottom) $T_c = 7.9$ K for PbBi film with MNC array

$H_{\text{Matching}} = \frac{\Phi_0}{D^2}$

$H_{\text{Matching}} = n \cdot 329$ Oe
Phase Diagram and Hc2 for Magnetic Nanorods Array
Iron-Brass laminate structure.
Ni stripes embedded in Pb$_{82}$Bi$_{12}$ film

Ni stripes: Width ~90nm (from SEM)
Spacing ~250nm (from SEM)

Pb$_{82}$Bi$_{12}$ 110 nm

Phase diagram
RABiTS / MOD 2G Strip Architecture

- Substrate: Ni-5%W alloy
  - Deformation texturing
- Buffer stack: Y₂O₃/YSZ/CaO₂
  - High rate reactive sputtering
- YBCO
  - Metal Organic Deposition of TFA-based precursors
- Ag
  - DC sputtering

Width Evolution
+cm → 4 cm → 10 cm

Scale-up of Second Generation HTS Wire

Presenters: Steven Fleshler, Alex Malozemoff and Martin Rupich
Self-assembled single-crystal ferromagnetic iron nanowires
(α-Fe nanocolumns embedded in a LaSrFeO4 matrix)

Dark-field cross-section image of a film showing α-Fe nanocolumns embedded in a LaSrFeO4 matrix

Plan-view TEM image of self-assembled nanostructures in LaSrFeO4 thin films. Film deposited in vacuum at $T = 760 \, ^\circ\text{C}$, showing the decomposition of the perovskite target into a second phase embedded in the matrix

Room-temperature magnetic properties of α-Fe nanocolumns embedded in a LaSrFeO4 matrix. Out-of-plane (wide loop) and in-plane (narrow loop) magnetic hysteresis loops correspond to α-Fe nanocolumns and indicate strong anisotropy

Vertically Aligned Nanocomposite (VAN) structure

Cross-section TEM image of YBCO/CoOx VAN structure (insert is the corresponding selected area diffraction pattern from the view area) produced by Wang at TAMU;

Cross-section TEM image of a BFO/SmO nanocomposite produced by Wang at TAMU showing an ordered pattern of BFO and SmO domains.
Conclusions

Interesting physics with magnetic nanorods

Size is matter

Shape is matter

YBCO films with magnetic nanorods are feasible