Interaction between Superconductivity and Ferromagnetism in SC/FM nanocomposites

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Supercondutor e ferromagneto
Supercondutividade

Resistência (Ω) vs. Temperatura (K)

Kammerling Onnes (em 1911)
- $B = 0 \rightarrow$ perfect diamagnetism: $\chi_M = -1$

\[ B = \mu_0 (H + M) = 0 \]
\[ M = \chi H = -H \]

- Field expulsion unexpected; not discovered for 20 years.
Critical Parameters for SC

- $T_c$
- $B_c$
- $I_c$

![Superconductor Diagram](image)
Type I and type II SC

- London Theory \rightarrow magnetic penetration depth $\lambda$

- Ginzburg-Landau Theory \rightarrow coherence length $\xi$

$\lambda + \xi \rightarrow$ two kinds of superconductors!
Conductors in a Magnetic Field

\[ \nabla \cdot \varepsilon \hat{E} = \rho \]

\[ \nabla \cdot \hat{B} = 0 \]

\[ \nabla \times \hat{E} = -\frac{\partial \hat{B}}{\partial t} \]

\[ \nabla \times \hat{B} = \mu_0 J + \frac{\partial \hat{E}}{\partial t} \]
Comportamento diferentes

Supercondutores dos tipo I e tipo II:

![Diagrama de comportamento supercondutores tipo I e II](image)

\[ B = 0 \]

**Estado misto:**  
\[ B \neq 0 \]
Estado misto de um SC do tipo II, quando \( H_1 < H < H_2 \), formam-se tubos de vórtices, a variação da densidade dos pares de Cooper \( n_s \) e a variação da densidade de fluxo.
Metallic contact between a normal metal and a superconductor

Electron-hole correlations: proximity effect

Supercurrent \rightarrow \text{Andreev bound states (ABS)}
Domain-wall superconductivity
Domain-wall supercondutividade
The phase boundaries $T_c(H_{\text{ext}})$ for an S/F hybrid, consisting of an Al film and an array of magnetic dots, in the demagnetized state, in the completely magnetized state in positive direction as well as in several intermediate magnetic states.
Campo aumenta $T_c$
Hysteresis curves of $J_c$ (a) at $T = 6\, \text{K}$ for $H \parallel I$ (CoNb1500) and (b) at $T = 5.5\, \text{K}$ for (CoNb1000).
Type II Superconductors ($\xi < \lambda$)

Normal state cores  Superconducting region

$H$

http://www.nd.edu/~vortex/research.html
Campo dos dots
Campo sempre matar SC?
• 100 nm Lead (Pb) film with varying Co particles fraction
• Here we will show results for 4% volume fraction of Co
• Co nanoparticles: ~4.5 nm diameter
Bi/Co: Sample preparation
• Narrow size distribution ~ 4.5 nm diameter
• Coercive field = 0.025 T
Resistivity measurements ($B_{ext}=0$)

\[ l = m^* v_F / n e^2 \rho_0 \]

\(~3.1\ \text{nm}\)

\[ \xi = 0.855(\xi_0 l)^{1/2} \sqrt{1 - \frac{T}{T_c}} \]

\(~10\ \text{nm at } 3K\)
Spontaneous vortices

Voltage (mV) vs. Current (mA) graph for Pure Pb:

- No vortex phase
- Vortex phase transition

Temperature from right to left (K):
5.5, 6.0, 6.5, 6.6, 6.7, 6.8, 6.9, 7.0, 7.05, 7.1, 7.2
Scaling analysis

\[ t = \frac{T - T_G}{T_G} \]

Critical exponents:
\[ \nu = 0.25 \]
\[ z = 4 \]

Not in the same universality class of the VG transition in high \( T_c \) SCs.

\[ E |t|^{-\nu(z+1)} = F_{\pm}(|t|^{-3\nu} J) \]
Magnetic field polarity

Positive field:

\[ B_+ = B_{ext} + B_{Co} \]

Negative field:

\[ \begin{vmatrix} B_- \\ \end{vmatrix} = \begin{vmatrix} B_{ext} \\ -B_{Co} \end{vmatrix} \]

\[ B_+ > B_- \]

- Particles aligned at \( T > T_B \)
- Field (<0.01 T) turned on for \( T = 2.9K (<T_G) \)
**Magnetic field polarity**

- Field (<0.01 T) turned on for $T=3.1 \text{K}$ ($\sim T_G$)
Magnetic field polarity

Field (<0.01 T) turned on for $T=3.2 \text{ K (}>T_G$)
Phase Diagram for Pb/Co 4 vol%
Magnetic properties

- $B_{\text{ext}}$
- $M_{\text{Co}} (\text{FC})$

![Graph showing magnetic properties](image-url)
Origin of PME: Interaction between Co and Pb

Y.T. Xing et al, PRB 80, 224505 (2009)
**$T_c$ as function of Co-volume fraction**

1. **Low critical Co-volume fraction** due to the formation of spontaneous vortices.
2. **Annealing leads to a decrease of critical Co-volume fraction**

**Explanation:**

\[
\xi = 0.855 (\xi_0 \ell)^{1/2}
\]

\[
d = 2\xi ; \quad \xi_0 = 83 \text{ nm}
\]

Increase of mean free path $\ell$, gives increase in $\xi$:

- $\xi_{\text{as prepared}} = 10 \text{ nm}$
- $\xi_{\text{annealed}} = 25 \text{ nm}$

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Bi: $\xi \approx 7 \text{ nm}$ Much shorter than $\xi_{\text{Pb}}$

Bulk Bi:
Rhomboedral structure, semimetal with very small $E_F \sim 27.2 \text{ meV}$ and Fermi surface (10$^{-5}$ times Brillouin zone)
**Problem:**

**Bulk Bi:** not superconducting!

**High pressure** phases of Bi: superconducting

Amorphous Bi (a-Bi): superconducting \( T_c = 6 \text{ K} \)

Bi-clusters: superconducting

Superconductivity in granular systems built from well-defined rhombohedral Bi-clusters: Evidence for Bi-surface superconductivity.

Bi films covering Co clusters

Different Co-volume (area) fractions

Co(5nm) ~ 100% A
Co(2.3nm) ~ 80% A
Co(0.7nm) ~ 24% A
Co(0.0nm) ~ 0% A
Pure Bi-films (as-prepared)
After annealing at 100 K: Metallic behavior with 2D - weak localization no indication for superconductivity

\[ \rho = \rho_0 + \Delta \rho \]

\[ \Delta \rho \propto - \ln T \]
Bi-film with Co clusters

Co(80% A)Bi(3-5.5nm)

Graph showing resistência (kΩ) vs temperatura (K) for C9-10:
- (3nm)
- (4nm)
- (5.5nm)
Thermal activated **tunneling** between islands (or grains)

Electron tunneling ($R_T$) and Cooper pair tunneling ($R_J$)

\[
R = \sum_i R_T^i + R_J^i
\]

\[
R_J = \begin{cases} 
R_T & \text{for } T > T_c \\
0 & \text{for } T < T_c 
\end{cases}
\]

\[
R = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}
\]

Tunneling resistance with Coulomb barrier
Explanation

Co(80% A)Bi(3nm); C9-10

\[ R = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2} \]

1.9<T<3.6
\[ R_0 = 3.52 \text{ k}\Omega \]
\[ T_0 = 8.6(1) \text{ K} \]

4.9<T<9
\[ R_0 = 7.4 \text{ k}\Omega \]
\[ T_0 = 8.67(4) \text{ K} \]
Co(24 A%)/Bi(5nm)
Due to annealing opening of gap in DOS of 2D crystalline Bi-layer

This is caused by (?):
(i) Magnetic impurities at surface of Bi
(ii) Stress at the interface between crystalline Bi and Co-clusters.
(iii) Disorder
SC-I transition in 2D systems

\[ R_\square = R_c \cdot F(|x - x_c|T^{-1/\nu}) \]

\[ z\nu = 1.5 \]

\[ T^{-2/3}. \text{ For } 4.3 \text{ K} < T < 10 \text{ K} \]

We have:

\[ R \square = R_C \cdot F(|x - x_c| T^{-1/2z\nu}) \]

with \( f(u) = 1 \); \( z\nu = 1.5 \)

for \( u \to 0 \); \( T \to \infty \)

\[ R \square = R_0 \cdot T^{-2/3} \]

\[ R \square \to 0 \text{ for } T \to \infty \]
Vórtices em supercondutores
Simplificação da Formação de Vórtice

A nucleação de um vórtice é possível próximo a uma região magnética com momento magnético suficientemente forte.
Corrente - entrando do plano
Corrente - entrando do plano

Força de Pinning
Corrente - entrando do plano
Corrente - entrando do plano
Corrente - entrando do plano
Sample structure
Nanodisk of NiFe
Nanodisk of NiFe
Laser ablation system

Pressure: $3 \times 10^{-7}$ torr in one hour

Laser system: 600 mJ
Ni Plasma
Sample preparation

Thin films: in vacuum

Nanoparticles: in Ar with a pressure of 1 torr
Ni nanoparticles prepared in Ar
Ni nanoparticles prepared in Ar
Ni nanoparticles prepared in Ar
Ni nanoparticles prepared in $O_2$
Ni nanoparticles prepared in $O_2$
XPS spectra of Ni nanoparticles

Laser Ablation in Ar

Si 2p

SiO₂

Ni 2p

Intensity (A.U.)

Binding Energy (eV)

110 108 106 104 102 100 98 96

880 870 860 850

Laser Ablation in O₂

Si 2p

SiO₂

Ni 2p

Intensity (A.U.)

Binding Energy (eV)

110 108 106 104 102 100 98 96

880 870 860 850
XRD of Ni nanoparticles

XRD
PLD in argon

XRD
PLD in oxygen
Magnetic susceptibility

Graph showing magnetic susceptibility versus temperature for different magnetic fields (H = 100 Oe, H = 500 Oe, H = 1K Oe).

The graphs display the magnetic susceptibility ($\chi$) in emu/Oe as a function of temperature (K). The fields H = 100 Oe, H = 500 Oe, and H = 1K Oe are represented by different markers and colors.

The x-axis represents temperature (K) ranging from 0 to 300, while the y-axis represents magnetic susceptibility (emu/Oe) ranging from 0 to 3.00E-007.
Sample prepared
Transport measurement results for two different samples:

- **NinpAr/Nb/NinpAr**
  - Measured resistances at different temperatures and magnetic fields (H 0T to H 2.5T).
  - Data shows a clear trend of resistance increasing with temperature and magnetic field strength.

- **NinpO2/Nb/NinpO2**
  - Similar measurements as above, with additional data points at B 0T to B 2T.
  - Resistance trends are consistent with the variation in temperature and magnetic field, indicating superconducting properties.

The graphs illustrate how the resistance changes under varying conditions, providing insights into the sample behavior under different environmental factors.
Transporte measurements

**NinpO$_2$/Nb/NinpO$_2$**

**NinpAr/Nb/NinpAr** T 3.5 a 4.7 K

**NinpO$_2$/Nb/NinpO$_2$**

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Magnetic measurements

SQUID

From Google Image:
Magnetic measurements

SQUID em Português:

Lula

Na google Imagem:
Obrigado!
Work at IF-UFF