Superconductor-insulator transition in disordered FeSe thin films

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Thin Films and Interfaces
Outline

- overview of iron-based superconductors
- FeSe thin films: preparation and properties
- ordered FeSe thin films: excess conductivity and BKT transition
- disordered FeSe thin films: superconducting and insulating phases, superconductor-insulator transition
- disordered FeSe thin films in a magnetic field
- summary
Material classes of superconducting FePn / Ch

- **11** FeTe$_{1-x}$Se$_x$  
  $T_c = 15$K for $x = 0.5$ and $T_c = 8$K for $x = 1$

- **122** A$_{1-x}$Fe$_{2-y}$Se$_2$  
  $T_c \approx 32$K  
  ($A = K, Rb, Cs, (Tl,K), (Tl,Rb)$)

- **122** BaFe$_2$As$_2$  
  $T_c = 38$K in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$

- **111** LiFeAs  
  $T_c = 18$K

- **1111** ReFeAsO$_{1-x}$F$_x$  
  $T_c = 25 - 56$K

- **21311** Sr$_2$VO$_3$FeAs  
  $T_c = 37$K  
  "$(n+1)n(3n-1)22$"
Unit cells and structural motif

FeSe, LiFeAs, SrFe$_2$As$_2$, LaFeAsO/SrFeAsF, Sr$_3$Sc$_2$O$_5$Fe$_2$As$_2$


β - FeSe


- concentration range of the β-phase very small
- tetragonal phase turns to orthorhombic below 90 K
- structural transition not accompanied by magnetic ordering
- superconductivity sensitive to composition

Pressure effect

- largest among Fe Pn/Ch
- $T_c$ increase to 37 K at 4 GPa
- connected with decreasing Se height
- superconductivity sensitive to structure

FeSe thin films: deposition and optimization

Surface and orientation

SEM
- 500 nm thick film
- smooth
- free of precipitates
- aligned grains
- rectangular shape
- sizes 100 to 400 nm
- lattice mismatch minimized to 5%

XRD
- (00l) Bragg reflections
- [001] FeSe || [001] MgO
- $a_{\text{film}} > a_{\text{bulk}}$
- small value of FWHM
- good growth quality
- fourfold rotational symmetry
- [100] FeSe || [110] MgO

Excess conductivity

- linear at low T
- parabolic with negative curvature at high T
- rounding of the transition

Excess sheet conductance per Fe-Se layer:

\[ \Delta G_s = G_s - G_s^n \]
\[ G_s = \frac{1}{R_s} \]
\[ G_s^n = (a + bT)^{-1} \]

2D Aslamazov-Larkin theory:

\[ \Delta G_s = \frac{e^2}{16\hbar} \frac{1}{\varepsilon} \]
\[ \frac{e^2}{16\hbar} = 1.52 \times 10^{-5} \ \Omega^{-1} \]
\[ \varepsilon = \ln \frac{T}{T_{MF}} \approx \frac{T - T_{MF}}{T_{MF}} \]

- 2D character of the superconducting fluctuations


L.G. Aslamazov, A.I. Larkin
Phys. Lett. A 26, 238 (1968)
BKT transition and $Gi$

2D Ginzburg - Levanyuk number $Gi$:

$$T_{BKT} = 5.5 \text{ K} \quad T_{MF} = 8.8 \text{ K} \rightarrow Gi = 5 \times 10^{-2}$$

A. Larkin, A. Varlamov
*Theory of Fluctuations in Superconductors*
N.Y.: Oxford University Press (2005)

- comparable to $YBa_2Cu_3O_{7-x}$
- large $m$ and low $n_s$ favor large $Gi$

- 2D superconducting fluctuations important in the layered FeSe compound


$$\ln \frac{R_s(T)}{R_s^0(T)} = a - bt^{-1/2}$$

$$t = \frac{T}{T_{BKT}} - 1$$

jump in $\alpha$ to 3 at $T_{BKT} \approx 4.7 \text{ K}$

V.L. Berezinskii, Sov. Phys. JETP **34**, 610 (1972)
High sensitivity to disorder

Thickness threshold at 300 nm

- bulklike features for \( t > 300 \) nm
- increase of \( \rho_0 \)
- decrease of RRR
- decrease of \( T_c \) with decreasing \( t < 300 \) nm

Fanlike set of curves

20 nm < \( t < 300 \) nm
- \( R_s(1.2K) \neq 0 \)
- \( R_s(0) \neq 0 \)

19 nm < \( t < 20 \) nm
- horizontal separatrix indicating SIT

\( t < 19 \) nm
- \( \frac{\partial R_s(T,t)}{\partial T} < 0 \)

Disorder driven SIT

\[ R_s = R_c \cdot f \left( \frac{|t - t_c|}{T^{1/z}} \right) \]

\[ z = 2.33 \pm 0.03 \]

- Boson localization
  - finite-size scaling of \( R_s \)
  - linear log-log plot provides \( z \)
  - \( z=1: \nu=7/3 \) consistent with universality class of quantum percolation

- Isotherms \( R_s(t,T=\text{const.}) \)
  - crossing point \((t_c,R_c)\)
  - strong exponential decrease of \( R_s \) with increasing \( t \)
  - crossover to weak \( 1/t \) decrease

Quantum percolation


plateau transitions in quantum Hall liquids

Ultrathin YBa$_2$Cu$_3$O$_{7-x}$ films

$z_\nu = 2.2$
Scaling of $R_s(B,T)$

- collapse of the branches $B<B_c$ and $B>B_c$ onto a single curve
- scaling prediction of the Bose-glass model independently confirmed

Isotherms $R_s(B,T=constant)$

- crossing point ($B_c, R_c$)
- no magnetoresistance peak below 14 T

Different tuning parameters


- thickness $d$ tuned SIT
  - $vz \approx 1.2$
  - universality class of classical percolation in 2D
  - describes SIT in a 2D disordered system

- magnetic field $B$ tuned SIT
  - $vz \approx 0.7$
  - universality class of 3D XY model
  - describes SIT in a 2D ordered system
Summary

- reproducible synthesis of superconducting $\beta$-FeSe thin films by sputtering
- excess conductivity, BKT transition, large $Gi$
  - 2D character of superconductivity
  - importance of thermal fluctuations
- high sensitivity to disorder results in a thickness-driven SIT
- SIT also driven with magnetic field
- finite-size scaling according to the Bose-glass model
- universality class of quantum percolation
Temperature-doping phase diagrams

Magnetism and superconductivity

Fe-based superconductors

Cuprate superconductors

Cho (2010)
$T_C$ and structural details

Huang (2010)

Bellingeri (2010)
Resistance tails

- Evolution of resistance tails
- Described by "Inverse Arrhenius law"

\[ R_s(T) = R_s(0) \exp \left( \frac{T}{T_0} \right) \]

Typical for granularity


Granularity and weak links

- 20-nm-thick film at the edge of the superconducting phase
- individual crystallites
- structureless homogeneous matrix

- nonlinearities in the V(I) characteristics
- current-dependent resistance $R=V/I$
- weak links with a broad distribution of low critical currents
The theory of boson localization predicts a continuous SIT at $T=0$ as a result of the interplay of the attractive electron-electron interaction and the long-range Coulomb repulsion.

SIT is a Quantum Phase Transition (QPT): Transition at $T=0$ between competing ground states of a quantum system when a parameter $x$ in the Hamiltonian crosses a critical value.

- **Bose Metal** with $R_c = R_q = h / (2e)^2$
- **Superconductor**
- **Insulator**

Value of the critical sheet resistance $R_c$ is *universal* (independent of the material system and the microscopic details) and is equal to the quantum resistance $R_q$ of electron pairs.
**Insulating phase**

![Graph showing the relationship between $R_s$ and $T$](image)

- **strong localization**

- **sequence of exponential $G_s(T)$ dependencies**

(a) $T < 4K$  Efros-Shklovskii VRH  

(b) $4K < T < 50K$  Mott VRH  

(c) $50K < T < 160K$  Arrhenius  

$$G_s = A_0 \exp \left(- \left( \frac{T_0}{T} \right)^{1/2} \right)$$  
**soft Coulomb gap**

$$G_s = A_1 \exp \left(- \left( \frac{T_1}{T} \right)^{1/3} \right)$$  
**constant DOS**

$$G_s = A_2 \exp \left(- \frac{\Delta E_A}{k_B T} \right)$$  
**hard gap**

- **T-G-A dependencies**
Superconducting phase in a magnetic field

\[ R_s = R_0 e^{-\frac{U(B)}{T}} \]

\[ U(B) \approx B^{-2} \]

\[ U(B) = U_0 \ln(B_0/B) \]

- logarithmic field dependence \((U_0 = 0.098 K, B_0 = 8.85 T)\)
- possible creep-type dissipation mechanism
- small values of \(U\), low pinning barriers
- power-law fit definitely fails


Insulating phase in a magnetic field

- weak localization
- $R_s = R_0 \ln \left( \frac{T_0}{T} \right) + R_b$
- $R_s = R_0 \ln \left( \frac{T_0}{T} \right) + R_b$
- weakly localized Cooper pairs (Bose glass)
- vortices in a quantum liquid phase
- crossover from ln to exp T - dependence
- in line with bosonic description of SIT