Superconductor-to-Insulator Transition: an Introduction

Motivations and basic concepts
Basic questions

Question #1: What happens to the superconductivity at smaller thicknesses?

Question #2: What does 2D mean in experiments?
Superconductivity

1. Zero resistance for $T<T_c$

2. Exclusion of magnetic field

3. Strong decrease of specific heat

Quantum phenomenon + Collective phenomenon
Superconductivity

ii. Cooper pairs

2e particles condensed in a single wave function

http://supraconductivity.fr
Superconductivity

iii. Lengthscales

1. Superconducting coherence length : $\xi$

2. Penetration length : $\lambda$

Tixador & Brunet, *Tech. Ing.*, D2 701
Superconductivity

iv. Energy Scale

\[ \Delta = \text{strength of the superconductivity} \]

\[ \Delta \propto k_B T_c \]

\[ \xi = \frac{\hbar v_F}{k_B T_c} \]
SC in granular materials

i. What are granular materials?

Barrier:
Metal or Insulator or Void

Question:
At what condition(s) is the material superconducting?
SC in granular materials

ii. What grain size?

Condition on grain size

$L > \xi$
iii. Energy scales

1. Josephson coupling energy: $E_J$

2. Thermal energy: $k_B T$

3. Charging energy: $E_c$

Dimensionality effects

What happens when $L \sim 0.1 \text{nm}$?
Disordered materials

i. What are disordered materials?

Limit: grain size = atomic scale

Amorphous

NbSi samples

X-Ray Diffraction
i. Localization

Disorder potential (random)

Localization of the e- on a lengthscale $\xi$

Dimensionnality effects

Lee et al., RMP, 57 287 1985
Disordered materials

i. Localization (2)

Explanation:
Quantum interferences

Scattering on lengthscales l (mean free path)

Bergmann, PRB, 28 4914 1983
Disordered materials

i. Localization (3)

Energy Scales:
1. Disorder potential: $W$
2. Thermal energy: $k_B T$

No conducting state (metal) at 1D or 2D!
Disordered materials

ii. Coulomb interactions

Explanation:
Diminution of e- screening
Disordered materials

iii. Example: Metal to Insulator Transition

FIG. 1. Resistivity $\rho$ vs temperature $T$ for several samples of Si:P with donor density $n$ above and below the critical density $n_c = 3.74 \times 10^{18}$ cm$^{-3}$. Near $n_c$ a small change in $n$ has a large effect on $\rho(T)$.

FIG. 2. Divergence of the $T=0$ K donor dielectric susceptibility $4\pi\chi$ in the insulator [open circles, Ref. 34; solid circles, Ref. 32; solid line, Eq. (6)] and the $T=0$ K conductivity $\sigma(0)$ in the metal [solid circles, Ref. 36; open circles, Ref. 24; solid line, Eq. (4)] as a function of phosphorus donor density $n$. Together these results characterize the metal-insulator transition in a disordered system.
### Summary of the situation

**Different phenomena involved**

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<tr>
<th>Phenomenon</th>
<th>Lengthscales</th>
<th>Energy Scales</th>
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</thead>
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<td><strong>Superconductivity</strong></td>
<td>Coherence length $\xi_{SC}$ ~ 50 nm</td>
<td>SC Gap $\Delta$ ~ 0.5K</td>
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<td><strong>Localization</strong></td>
<td>Localization length $\xi_{Loc}$ ~ 100 nm</td>
<td>Disorder potential $W$ ~ 0.5K</td>
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<td>Mean free path $l$</td>
<td>~ 0.1 nm</td>
<td></td>
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<tr>
<td><strong>Coulomb interactions</strong></td>
<td>Thermal length $L_T$ ~ 50 nm</td>
<td>Interaction potential $U$ ~ 0.5K</td>
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<td><strong>Thermal excitations</strong></td>
<td></td>
<td>Thermal energy $k_B T$ 10mK-1K</td>
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</table>

+ **Dimensionnality**

| Competition between all these scales |
Summary of the situation
The Superconductor-Insulator Transition

Phase transitions between different ground states
Quantum Phase Transitions

i. CPT and QPT

Classical Phase Transitions

- Competition between characteristic energy and $k_B T$
- Ground state governed by thermal fluctuations

Magnetic energy $\mu_B B$ VS Thermal energy $k_B T$:

Quantum Phase Transitions

- Happens only at $T=0$ K
- Competition between 2 (or more !) characteristic energies
- Ground state governed by quantum fluctuations
- Thermal energy $k_B T$ only tampers the transition
Quantum Phase Transitions

ii. CPT and QPT: application to the SIT

SC – Normal State Transition
- CPT
- Competition SC gap VS $k_B T$
- Occurs at finite temperature

SC – Insulator Transition
- QPT
- Competition SC gap VS disorder
- Occurs at $T=0$ K
Quantum Phase Transitions

iii. Properties of QPT

Quantum Phase Transitions

- Happens only at $T=0$ K
- Transition between different ground states
- At the transition: existence of scaling laws (universality of the transition)

Universality at the transition

- No relevant lengthscale
- All quantities only depend on the distance to the transition
- Ex:

$$\rho_{L/H}(B, T, \omega) = f_{L/H}(\frac{\hbar \omega}{k_B T}, \delta/T^{1/\nu_z})$$
iv. Scaling Laws

\[ (H - H_c)T^{-\frac{1}{\nu z}} \]

Magnetic field B

Resistance (Ohms)

Temperature (K)

\( \text{Nb}_{15}\text{Si}_{85} \)

125A

0-35 kOe

\[ R(\delta_K, T) = R_c f(\delta_K T^{-\frac{1}{\nu z}}) \]
Quantum Phase Transitions

v. Examples of QPT

- Quantum Hall Effect
- Metal-to-Insulator Transition
- Superconductor-to-Insulator Transition
- Cuprates
- ….

**BUT**

Physics governed by the different phenomena in competition
NbSi thin films

Synthesis
DC Transport measurements

i. Set-up

16/04/2015  MPO - Séminaire
DC Transport measurements

ii. Different SITs

- **SMI Transitions**
  - 3D: \( d > 100 \text{ nm} \)

- **SI Transitions**
  - 2D, 18%
  - \( \xi \sim 50 \text{ nm} \)

- **Destruction of SC**
  - \( d = 12.5 \text{ nm}, 18\% \)
DC Transport measurements

iii. How does the superconductivity disappear?

*Three different phase transition diagrams*

- **Split**
- **Single**
- **Overlapped**
iv. Unexpected metallic states in 2D systems

Disorder measured by:

\[
\kappa_F l = \frac{1}{R_{\square,N}} \frac{h}{e^2}
\]

\[R_{\square,N} = R_{\square}(500 \text{ mK})\]
AC Reflectrometry Measurements
i. Electrodynamics of superconductors

Two Fluids Model

Complex Conductance
\[ G(\omega) = G_1 - iG_2 \]

Dissipative Response
Quasiparticules
\[ n_e (T), \tau_N \]

Inductive Response
Cooper Pairs
\[ n_s (T) \]

Nature and characteristic times of the excitations
AC Reflectrometry Measurements

ii. Set-up (1)

[100MHz – 2 GHz]
AC Reflectometry Measurements

ii. Set-up (3)

[100MHz – 2 GHz]

Complex Reflection Coefficient \( \Gamma = \frac{\text{Reflected wave}}{\text{Incident wave}} \)

Vector Network Analyser

Lock-in Amplifier

RF Amp. 40dB

-3 dB

-20 dB

-20dB Dir. Coupl.

Bias T

Sample

70 K

4 K

20 mK

16/04/2015
AC Reflectrometry Measurements

ii. Set-up (2)

[100MHz – 2 GHz]

Vector Network Analyser

Lock-in Amplifier

RF Amp. 40dB

-3 dB

-20 dB

-20dB Dir. Coupl.

Sample

Bias T

70 K

4 K

20 mK

130 µm 130 µm

385 µm 385 µm

Au

Pt

NbSi

Au

16/04/2015
AC Reflectrometry Measurements

 iii. Results

STRF 35

$R_\square = 1020 \, \Omega$/sq

$T_c = 215 \, \text{mK}$
SIT in NbSi applied to detectors

i. Bolometers = particule detectors

2. Structure of current bolometers

- Absorber (response time $\propto$ volume)
- Thermal sensor
- Thermal decoupling

Problems to solve

- **Ultimate sensitivity** limited by $NEP^2 = 4k_B T^2 G$
- $G=10^{-11}$ W.K$^{-1}$ for Planck experiment (dependent on the membrane)
- All use **phonons** as vectors for energy transport
SIT in NbSi applied to detectors

ii. Superconducting sensor + absorber

**Case 1:** Absorber = thermometer = superconducting NbSi

\[ \approx 1 \text{ mm} \approx \lambda \text{ for IR absorption} \]

\[ h\nu \gg k_B T_c \]

**Advantages**
- Composition and thickness adjustable for operating temperature of 50-100 mK
- Optimal thermal decoupling (10^{-11} W.K^{-1} for a typical film of 100 \( \mu \text{m} \times 100 \mu \text{m} \times 100 \text{ nm} \) at 70 mK)
- Short response time (\( \approx 1 \text{ ms} @ 70 \text{ mK} \))
- Read-out via interdigitated electrodes \( \rightarrow \) SQUID-based electronics
- Read-out via meander-shaped electrodes \( \rightarrow \) transistor-based electronics

**Absorption**
Square R meets vacuum impedance (377 \( \Omega/\square \))
- Maximum wave absorption
SIT in NbSi applied to detectors

iii. Superconducting sensor

**Case 2:** absorption through antennas; thermometer = superconducting NbSi (TES)

- **IR photons**
- **TES**
  - Measurement of $R$
- **Antennas**
  - High selectivity for the energy spectrum & polarization
  - Good filling factor
  - Smaller NbSi film $\rightarrow$ lower $G$
- **NbSi film**
  - Good matching impedance with antennas $\rightarrow$ transfer of the absorbed energy directly into TES’ electrons via tunable normal $R$ of the film
SIT in NbSi applied to detectors

iv. Insulating sensor

Case 3: absorber = thermometer = Anderson insulating NbSi

- DC measurement of $R$
- Heating due to incoming photons
- Suitable for JFET readout

Absorption

$$R(T_0, h\nu) = R\left(\frac{h\nu}{k_B}\right)$$

- Square $R$ may meet vacuum impedance ($377 \Omega/\square$)
- Maximum wave absorption