Superconductor-Insulator Transitions in 2D Films

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Outline

Introduction and Motivation

Experiments on Granular and Homogeneous Films

Expanding the parameter space

Discussion: Fate of the phase-only model, intermediate metallic phase, and electron heating
Introduction

Transition temperature does not usually depend on concentration of non-magnetic impurities in superconductors.

With high enough disorder, Anderson localization occurs.

Under strong conditions of electron localization, superconductivity should disappear, even with an attractive interaction.

Obvious question: How does superconductivity disappear with increasing disorder?
Transition is continuous, so that there should be strong fluctuations.

At $T = 0$ fluctuations should be quantum mechanical.

Above and outside the critical region conductivity is determined by fermionic excitations.

Inside the critical region, charge transfer due to Cooper pairs is more important.

In some approximation these pairs may be viewed as Bosons. This is the basis of some models of the SI transition. The other approach treats Fermions.

Two dimensions is special for superconductors: Kosterlitz-Thouless-Berezinskii Transition
Approach: Study transport properties of ultrathin films

Old subject: more than 60 years old -- Shal’nikov

Interest heightened by prospect of a quantum critical point and possible dissipation controlled phase transition

Materials Studied:

Quench evaporated films (films grown on substrates held at liquid helium temperatures.

Ultrathin sputtered films such as In$_x$O$_y$ or Mo$_x$Ge$_y$

Layered cuprate superconductors
Transition temperature vs. sheet resistance in $\text{Mo}_x\text{Ge}_y$

Experiment by Graybeal and Beasley, theory by Finkel’shtein
Amorphous Ga grown on a glass substrate.

Clear evidence of metallic behavior at low temperatures.

Also have local superconductivity.

Motivated early work of Chakravary et al. On dissipation-controlled transitions.

Jaeger ~ 1989
Metals quench-evaporated on glass are “granular.”

*In-situ* STM of a “granular” film (Valles)

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**FIG. 3.** *In situ* STM images of a QC Pb film on HOPG as its thickness $d$ is varied for a transition from an insulating to a metallic phase. (a),(b) $d = 3.0$ nm. Scan areas $675 \times 675$ nm (a) and $130 \times 130$ nm (b). (c) $d = 4.8$ nm. Scan area $240 \times 240$ nm. (d) A cross section of the film in (c). (e),(f) $d = 6.1$ nm. Scan areas same as those in (a) and (b). A plateau edge on the substrate is apparent in (e). The gray scale height range is set to $\pm 5.0$ nm for all images.
Amorphous Bi grown on amorphous Ge at liquid helium temperatures.

Cyclic evaporation leads to evolution of superconductivity with thickness.

Apparent separation between superconducting and insulating behavior.

Critical resistance close to $\frac{h}{4e^2} = 6450 \ \Omega$
Data Suggested that there is a Quantum Critical Point

Have divergent correlation lengths, for the spatial, $\xi$, and for the temporal direction, $\xi_t$. The latter is associated with a vanishing energy scale

$$\xi \sim |\delta|^{-\nu}, \text{ and } \xi_t \sim \xi^z$$

The correlation length exponent is $\nu$ and the dynamical critical exponent is $z$. Have interplay of dynamics and thermodynamics. $d$-dimensional quantum systems at finite temperature in the $T \to 0$ limit become classical with $d + 1$ dimensions. (Actually $d + z$ dimensional)

The scaling form for resistance in two dimensions is

$$R = R_c F(\delta/T^{1/z})$$

The control parameter $\delta = |t - t_c|$ or $|H - H_c|$, where $t$ is thickness, and $H$ is magnetic field, and $t_c$ and $H_c$ are critical thickness and critical fields.

Other parameters such as stress and charge density, or disorder at fixed thickness, might also be effective tuning parameters.

Close enough to the transition it probably does not matter what tuning parameter is used.
Phase Diagram Proposed by Fisher and Co-workers

Also proposed universal limiting resistance at criticality.
Work based on Bose-Hubbard model. Have both disorder- and magnetic field-tuned transitions.
**Various Values of “Critical” Resistance.**

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_0 (k\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoC</td>
<td>3.2 ± 0.4</td>
</tr>
<tr>
<td>Bi on Ge</td>
<td>6.42 ± 0.2</td>
</tr>
<tr>
<td>Pb</td>
<td>6.75 ± 0.8</td>
</tr>
<tr>
<td>In-InO$_x$</td>
<td>6.97 ± 1.4</td>
</tr>
<tr>
<td>Ga on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Bi on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Pb on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Nb</td>
<td>6.4</td>
</tr>
<tr>
<td>DyBaCuO</td>
<td>6.4</td>
</tr>
<tr>
<td>NdCeCuO</td>
<td>6.4</td>
</tr>
<tr>
<td>Pb on Ge</td>
<td>9.94 ± 0.4</td>
</tr>
<tr>
<td>Bi on Sb</td>
<td>10</td>
</tr>
<tr>
<td>Pb</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>Al on Ge</td>
<td>18.6 ± 1.7</td>
</tr>
</tbody>
</table>

Obviously not Universal
Can interpret as evidence against Bose picture as coherence peak vanishes in insulator.

Similar data for the disorder driven transition by Dynes group.
Issues

Reconciliation of Bose-only picture with obvious presence of Fermi excitations on the insulating side of the transition resulted in much theoretical work.

Most works predicted exponents and the critical resistance. Experiment was never able to resolve the systematics of the critical resistance.

The most quantitative feature of data was the apparent success of finite size scaling.
Scaling of the field-driven transition of $\alpha$-MoGe

(Kapitulnik et al. and Hebard and Palaanen earlier)

$\nu z = 1.2, \ z = 1$
Thickness Driven Transition in Different Magnetic Fields (a-Bi on a-Ge) (Markovic)

$\nu_z = 1.2$ in zero field

$\nu_z = 1.4$ in field

$z = 1$
Magnetic Field Scaling at one Thickness
Phase Diagram in Field and Thickness

**Boundary cannot be a real phase boundary**
New System for Quench-Deposited Films

0.004K limiting temperature
15T field
Sample rotator
Aside: Thinnest Films: appear “glassy” in a magnetic field

Upper curve is in a 12T parallel magnetic field

Lower curve is in zero field

Temperature is 50mK.

Disappears as films get thicker and above 200mK.
Resistance vs. Temperature at Various Thicknesses
All films appear metallic in the limit of zero temperature!
(actually measured down to the bottom T << 50mK)
Reminiscent of behavior of granular films, which exhibit metallic regime at much higher temperatures.

Limiting resistance for superconductivity
\[ R_{sq} \approx R_Q \left[ \frac{R_n}{R_c} - 1 \right]^{2\nu} \]

Also: D. Dalidovich and P. Phillips, and T. Ng and D. Lee

Bose Metals
I-V Characteristic of a Low-Resistance Film

I-V Characteristic of a High Resistance Film
Magnetic Field Dependence of Bi Films grown on a - Ge Substrates

Flat region appears to depend on magnetic field.

Maximum domain of flatness is very close to 12,900$\Omega$.

This is $h/2e^2$.

Accidental?

Have not attempted scaling because of limited range of data.

I-V Characteristics are linear down to $10^{-10}$A.
Width of Flat Regime vs. Field for a Film in a parallel field

Peak also corresponds to a resistance of $12,900\Omega$
Width of Flat Regime vs. Parallel Magnetic Field

![Graph showing the relationship between T_{\text{flat}} (mK) and Field (Tesla)]
Largest flat regime corresponds to 12,900 Ω.

This is $\frac{h}{2e^2}$.

Field is not quite aligned parallel.
Systematics of $R(T)$ with different fields and thicknesses suggest that resistance by itself does not determine the shape of the curve.

Two curves below are both at 9T. One is 9.19Å in thickness, the other is 9.25Å.
Optical Transmission of Pb and Au films grown on a-Ge (Tu and Strongin) (between 100 to 500cm\(^{-1}\))

Quench condensed films exhibit divergence in real part of the dielectric constant.

This suggests a M/I transition at a sheet resistance of order of 3000 \(\Omega\). This is interpreted as a percolation transition.

The implication of these results is that films with resistances of order 6-10,000 \(\Omega\) are all insulators!

This M-I transition is likely to be percolative.

The S-I transition then occurs with uncoupled clusters and must involve the substrate.
Implications: So-called homogeneous films are clustered. 
\( \alpha \)-Ge underlayer may play a very important role. Annealing associated with warming may change resistance, but not mesoscale structure.
Tentative Conclusions

1. S-I transition as evidenced from finite size scaling does not necessarily tell you what happens in the zero temperature limit.

2. Can have scaling, and then other physics can intervene at low temperatures. In this case appear to get a metal on both the insulating and superconducting sides of the transition. Data are completely consistent with what was previously reported, and resemble what is found for films grown on glass, where effects are seen at high temperatures.

3. These films are 1/3 to 1/10 the thickness of In$_2$O$_3$ or Mo$_x$Ge$_y$ films, and the action occurs at higher resistances. Their heat capacities are almost nothing.
3. Apparent metallic behavior persists to higher temperatures at or near what would be the marginal resistance, which for these samples is close to $h/2e^2$ for both thickness and field-driven transitions.

4. Caveats: Are the electrons really cooling? Can have heating from electromagnetic environment despite the best intentions on shielding. Electrons can be hot. Don’t yet have clear (clean and independent) way to determine electron temperature to prove that there is this extended metallic phase. Metallic behavior would look the same as not cooling!

5. But, this all may be intrinsic as width of flat region systematically varies with magnetic field and is not monotonic in field. There are also different size flat regions for different films with the same resistance. The considerations relating to dissipation that will be discussed in the following talk may be relevant here as well.

6. Role of a-Ge underlayer is important. If the physics of granular and nominally homogeneous films is the same, then it is the difference.