Resistive superconducting films for photonsensing devices

*conventional superconductivity in ‘bad metals’*

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Thanks to the members of my group at Delft and my collaborators at SRON
Electrodynamics of the superconductor

Recombination rates; disorder dependent

\[
\frac{\tau_0}{\tau_r(\Delta)} = \sqrt{\pi} \left( \frac{2\Delta}{kT_c} \right)^{5/2} \sqrt{\frac{T}{T_c}} e^{-\Delta/kT} = \frac{(2\Delta)^2}{(kT_c)^3} \frac{\tau_{qp}}{2N^a(0)}
\]

R. Barends et al, PRL 100, 257002 (2008); PRB 79, 020509 (2009)
Power dependence quality factor

NbTiN

$\langle n_{\text{photons}} \rangle$

$T_{\text{bath}} = 310 \text{ mK}$
Materials in use NbN, NbTiN, TiN

- **Hot-electron bolometers** (HEB’s): 4 nm thick, $R=100\,\Omega/sq$, $\rho=250\,\mu\Omega cm$
- **Superconducting single photon detectors** (SSPD’s): >4 nm thick, $R\leq100\,\Omega/sq$, $\rho\leq250\,\mu\Omega cm$, narrow: 90 nm; uniformity
- **Microwave kinetic inductance detectors** (MKIDs): Al, Ta, Nb, NbN, NbTiN, TiN, in search of optimal parameters: 60 nm thick, $R=10\,\Omega/sq$, $\rho=100\,\mu\Omega cm$, uniformity

Conventional superconductivity in ‘bad metals’
Superconductor single-electron detector

Lupascu et al, arXiv; Rosticher et al, to be publ.
Spatial pattern of optical and electron QE in NbN and NbTiN

Dorenbos et al, APL 93, 131101(2008): NbTiN

Rosticher et al, to be published
Thin NbN films and quench-condensed films; superconductor-insulator transition

- Disorder driven
- Magnetic field driven

Su et al., SST 9, A152 (1996)  
Haviland, Jaeger, Goldman, 1986/1989
Superconductor differs from a resistive metal!!

- Electron temperature vs distribution function
- Resistance *not* simply due to single-electron backscattering processes, but:
  - Current conversion processes (static)
  - Phase-slip/flux-flow (dynamic)

Microwave impedance????

TU Delft
Resistance of a NSN structure: static resistance of S (temperature close to Tc)

Boogaard et al, 2004?
Electrodynamics of superconducting thin films

\[ k_F l = 1 \]

\[ \sigma = 2e^2 N(0) D \]

- Localization: D
- Correlations: N(0)

\[
\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar \omega} \int_\Delta \left[ f(E) - f(E + \hbar \omega) \right] g_1(E) dE \\
+ \frac{1}{\hbar \omega} \int_{-\Delta}^{\Delta} \left[ 1 - 2f(E + \hbar \omega) \right] g_1(E) dE \\
\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar \omega} \int_\Delta \left[ 1 - 2f(E + \hbar \omega) \right] g_2(E) dE
\]

\[ g_1(E) = \left( 1 + \frac{\Delta^2}{E(E + \hbar \omega)} \right) N_S(E) N_S(E + \hbar \omega) \]

\[ g_2(E) = \frac{E(E + \hbar \omega) + \Delta^2}{\sqrt{(E + \hbar \omega)^2 - \Delta^2 \sqrt{\Delta^2 - E^2}}} = -ig_1(E) \]

\[ \Gamma = 17 \, \mu eV \]

E to E + i\Gamma

Dynes broadening parameter
Good quality NbN: too much surface resistance
Macroscopic quantum state

\[\psi = |\psi| e^{i\varphi}\]

\[|\psi| = \sqrt{n_s}\]

\[j_s \propto \nabla \varphi\]

\[\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}\]
Vortex core on the scale of $\xi$ and circulating current

$$B(r) = \frac{\Phi_0}{2\pi \lambda^2} K_0 \left( \frac{r}{\lambda} \right) \approx \sqrt{\frac{\lambda}{r}} \exp \left( -\frac{r}{\lambda} \right),$$

Rainer et al, PRB 1996
Dynamics of flux flow

\[ \frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} \]
Berezinskii-Kosterlitz-Thouless transition in 2D superconducting films

\[ \lambda_\perp = 1.78 \frac{\Phi_0^2}{4\pi^5} \frac{e^2}{\hbar k_B T_\infty} \frac{R_\square}{f^{-1}\left(\frac{T}{T_\infty}\right)} \]

\[ \frac{T_{KT}}{T_\infty} f^{-1}\left(\frac{T_{KT}}{T_\infty}\right) = 2.18 \frac{R_\square}{R_c} \]

\[ k_B T_{KT} = \frac{1}{2\pi \hbar^2 n_s^{2D}} \frac{m^*}{m} \]

\[ \begin{cases} \frac{\Delta(T)}{\Delta(0)} \tanh \left[ \frac{\beta \Delta(T)}{2} \right] \\ \end{cases} \]
Coulomb blockade and Josephson coupling

\[ H \sim \frac{1}{2} \sum_{i,j} Q_i C_{ij}^{-1} Q_j - \frac{E_J}{2} \sum_{\langle i,j \rangle} (\phi_i - \phi_j)^2 \]

\[ \frac{d\phi_i}{dt} = \frac{2e}{\hbar} V_i = \frac{2e}{\hbar} C_{ij}^{-1} Q_j \]

\[ H = H_{ch} + H_J \]

\[ = \frac{1}{2} \sum_{i,j} (Q_i - Q_{x,j}) C_{ij}^{-1} (Q_j - Q_{x,j}) - E_J \sum_{\langle i,j \rangle} \cos(\phi_i - \phi_j - A_{ij}) \]
Three competing processes

\[
\sigma = 2e^2 N(0) D
\]

1. Disorder: quantum coherent elastic scattering: localization
2. Electron-correlations: opening of a Coulomb gap
3. Superconducting correlations

- Superconducting state disappears by decrease of *amplitude*
- Superconducting state disappears by *phase fluctuations*
Evolution in time

Josephson coupled

Coulomb coupled
Dissipation in electromagnetic environment

Rimberg et al, PRL 78, 2632 (1997)
Example N(0): superconductor-metal-insulator transition: Nb(x)Si(1-x)

Bishop, Dynes et al, 1983/1985
Disordered superconducting films: intrinsic inhomogeneous pair-density

- Localization: electrons get ‘trapped’
- Correlations: reduction in density of states at Fermi level
- Superconducting correlations

\[ T_c = \frac{\hbar}{\tau_s} \left[ \frac{\sqrt{2\pi g} - \ln(\hbar / T_{c0} \tau_s)}{\sqrt{2\pi g} - \ln(\hbar / T_{c0} \tau_s)} \right]^{\sqrt{2\pi g}/2} \]

Density of states: bandstructure calculations; combined electronic structure and many-body approach.

Crystalline?

\[ a = 7.65a_0 = 0.4 \text{ nm} \]

Allmaier et al, PRB 79, 235126 (2009)
Mott correlation gap in ordered TiN

Our results suggest that TiN is a peculiar metal with a pseudogap at the Fermi level, indicating the proximity to a metal-insulator transition. In our calculations the pseudogap regime is best described for a value of $U=8.5$ eV for the Coulomb interaction.

Consequences for superconductivity?
Summary

- NbTiN and TiN have quality factors over 1 M
- These superconductors are ‘bad metals’
- Superconducting properties may be non-uniform
- Surface resistance in good quality NbN might be an indication
- Dynes parameter in Mattis-Bardeen might signal the same
- However, the films might be well-ordered.
Thermally activated phase slip (1 dimension)

$$\left| \psi(x) \right|^2 \frac{d\varphi}{dx} = \text{constant} \propto I$$

$$\Delta F_0 = \frac{8\sqrt{2}}{3} \frac{H_c^2}{8\pi} A\xi$$

$$\delta F = \Delta F_- - \Delta F_+ = \frac{\hbar}{2e} I$$

$$\frac{d\varphi_{12}}{dt} = \Omega [\exp(-\frac{\Delta F_0 - \delta F/2}{kT}) - \exp(-\frac{\Delta F_0 + \delta F/2}{kT})] = 2\Omega e^{-\Delta F_0/kT} \sinh \frac{\delta F}{2kT}$$
Superconductor-insulator transition

- Phase-coherence: phase-fluctuations
- Disorder
- Coulomb interactions: electron-electron interactions
- Berezinskii-Kosterlitz-Thouless vortices: flux flow
- Anderson-localization
- Mott-insulator

\[ \frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} \]
Conclusions

• Superconductors at these 100 mK temperatures with so few qp’s are poorly explored territory

• Nonuniformity which is not microstructure related?

• Characterization might provide interesting data relevant outside the engineering community

• Example: why does $T_c$ decrease so nicely with N-content in TiN?

\[
T_c = \frac{h}{\tau^*} \left[ \frac{\sqrt{2\pi g} - \ln(h/T_c \tau^*)}{\sqrt{2\pi g} - \ln(h/T_c0 \tau^*)} \right]^{\sqrt{\pi g}/2}
\]