Electro-Dynamics of strongly disordered superconducting TiN films

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Why TiN for KIDs?

- High normal state resistivity ($\sim 100 \, \mu\Omega \cdot \text{cm}$)
  - Efficient far-IR absorption with 20-50 nm thick films
  - Reasonable area filling fraction
  - High kinetic inductance fraction

- $T_c$ varies with stoichiometry (0 - 4.5 K)

- Reasonable quasiparticle lifetime
  - Maximum lifetime varies as $\sim T_c^2$

- Extremely high quality factors (> $10^7$)

- Improved sensitivity / figure of merit: $\mathcal{F} = \alpha_{\text{sc}} \tau_{\text{max}} Q i_{\text{max}} / N_0 V_{\text{sc}}$

Leduc et al, APL 97, 102509 (2010)
Increasing disorder induces a transition from superconductor directly to insulator.
Electronic inhomogeneities

- Superconducting properties become inhomogeneous on a mesoscopic scale
  - Spatial fluctuation of spectral gap $\Delta$
  - Formation of SC islands
  - Not directly linked to microscopic disorder (e.g. grain boundaries)

Local tunneling spectroscopy

TiN, $>1000 \mu\Omega\cdot$cm, 5 nm thick

B. Sacépé et al, PRL 101, 157006 (2008)
How do we describe the electrodynamics of strongly disordered SC TiN films?

- To what degree is TiN (NbTiN, NbN) a well-behaving textbook BCS superconductor like Al?
- To what extent is Mattis-Bardeen applicable for TiN?
- How can we justify the use of a large broadening parameter?
- What kind of problems can the high resistivity in the normal state of TiN films (that we wish to use) pose on the development of KIDs?
Microwave SC Resonators

Complex conductivity: $\sigma_1 - i\sigma_2$

$$Q = \frac{\omega E}{P}$$

$$\omega_0 = \frac{2\pi}{4l \sqrt{(L_g + L_k)C}}$$
Jiansong Gao’s formulas (JLTP 2008)

\[ Q = \frac{2 \sigma_2}{\alpha \beta \sigma_1} \]

\[ \frac{\delta Q}{Q} = - \left( \frac{\delta \sigma_1}{\sigma_1} - \frac{\delta \sigma_2}{\sigma_2} \right) \]

\[ \delta \left( \frac{1}{Q} \right) = \frac{\alpha \beta \delta \sigma_1}{2 \sigma_2} \]

\[ \frac{\delta f_0}{f_0} = \frac{\alpha \beta \delta \sigma_2}{4 \sigma_2} \]
Complex conductivity response: $\sigma_1 - i\sigma_2$

Mattis-Bardeen, Phys. Rev. 111 (1958)

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

\[
\frac{\sigma_2(\omega)}{\sigma_N} = \frac{1}{\hbar \omega} \int_{\max(\Delta-\hbar \omega,-\Delta)}^{\Delta} dE [1 - 2f(E+\hbar \omega)] \frac{1}{i} \left( 1 + \frac{\Delta^2}{E(E + \hbar \omega)} \right) N_S(E)N_S(E + \hbar \omega)
\]

\[
N_S(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}
\]

\[
\frac{\Delta_0 - \Delta}{\Delta_0} \approx 2 \int_{\Delta}^{\infty} dE \frac{1}{\sqrt{E^2 - \Delta^2}} f(E)
\]

$E \rightarrow E - i\Gamma$ or $\Delta \rightarrow \Delta - i\Gamma$

Broadening of the BCS density of states
Results

• TiN (Atomic Layer Deposition)
  • Low Disorder: $\rho = 191 \ \mu \Omega \cdot \text{cm}$, $T_c = 3.2 \ \text{K}$, $t = 55 \ \text{nm}$, $k_Fl = 6.7$
  • High Disorder: $\rho = 309 \ \mu \Omega \cdot \text{cm}$, $T_c = 2.1 \ \text{K}$, $t = 11 \ \text{nm}$, $k_Fl = 3.4$

• NbTiN (Sputtering)
  • Low Disorder: $\rho = 141 \ \mu \Omega \cdot \text{cm}$, $T_c = 13.6 \ \text{K}$, $t = 50 \ \text{nm}$
  • High Disorder: $\rho = 506 \ \mu \Omega \cdot \text{cm}$, $T_c = 11.8 \ \text{K}$, $t = 50 \ \text{nm}$
TiN ALD – series of films with decreasing thickness

Resistivity

Critical temperature
FIG. 4. The broadening factor $2\Gamma$ as a function of the resistivity of the granular Al. The dashed line is the value for the superconducting energy gap $\Delta_{gfr}\text{Al}$. 

Dynes et al., PRL 53 (1984)
Explanations for \( \Gamma \)

- Lifetime broadening (but what determines the lifetime?)
- Electronic inhomogeneities
- Phase fluctuations (breakdown of long range superconducting coherence)
Conclusion

- Low disorder $\rightarrow$
  MB theory + broadening of the BCS density of states

- For increasing disorder $\rightarrow$
  broadening parameter increases

- Broadening is directly related to the increase in disorder

- In agreement with numerical simulations of disordered superconductors
  - Ghosal et al, PRL 81, 3940 (1998)
Outlook

- Microwave properties of a complete series of TiN film with increasing disorder
  - ALD TiN
  - Sputtered TiN (stoichiometry)
  - NbTiN

- Lifetime measurements

- Complete characterization (DC and normal state properties of TiN)
Lifetime measurements
TiN Low Disorder

![Graph showing lifetime measurements for different resonators at various temperatures.]

- Resonator 1: $f_0 = 5.2$ GHz
- Resonator 2: $f_0 = 5.4$ GHz
- Resonator 3: $f_0 = 6.3$ GHz

Graphs at $T = 374$ mK:
- Data points
- Fit line

TU Delft
Lifetime measurements

TiN High Disorder

two decay times!

\[ r_1 \cdot \exp[-t/\tau_1] + r_2 \cdot \exp[-t/\tau_2] \]
Complete characterization

<table>
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<tr>
<th>Film ID</th>
<th>$d$ [nm]</th>
<th>$T_c$ [K]</th>
<th>$\rho$ [$\mu\Omega$cm]</th>
<th>$D$ [cm$^2$/s]</th>
<th>$n$ @10 K [cm$^{-3}$]</th>
<th>$N(0)$ [eV$^{-1}$cm$^{-3}$]</th>
<th>$\xi$ [nm]</th>
<th>$m^*$</th>
<th>$\ell$ [Å]</th>
<th>$k_F \cdot \ell$</th>
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<tr>
<td>ALD1</td>
<td>55</td>
<td>3.2</td>
<td>191</td>
<td>0.94</td>
<td>2.9E+22</td>
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<td>2.8</td>
<td>7.0</td>
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<td>360</td>
<td>0.36</td>
<td>3.2E+22</td>
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<td>100</td>
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<td>4.4E+22</td>
<td>3.9E+22</td>
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<td>2.1</td>
<td>3.3</td>
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</tr>
</tbody>
</table>
Questions
Homogeneously disordered versus granular disordered

**FIG. 3:** Resistance variations with temperature in Pb films upon increasing their thickness (from top to bottom) [12]. (a) Superconductor–insulator transition in finely dispersed quasihomogeneous films deposited on an SiO surface over an intermediate thin layer of amorphous Ge. In the superconducting region, the $R(T)$ curves demonstrate a correlation between the normal resistance and the superconducting transition temperature. (b) Superconductor–insulator transition in granular films deposited directly onto the SiO surface. In such a method of deposition, the lead atoms coalesce into granules. The temperature of the superconducting transition in the film becomes constant at a film thickness exceeding the critical one.

Complex conductivity response: $\sigma_1 - i\sigma_2$

Mattis-Bardeen, Phys. Rev. **111** (1958)

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

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

\[
N_S(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}
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\[
\frac{\Delta_0 - \Delta}{\Delta_0} \approx 2 \int_{\Delta}^{\infty} dE \frac{1}{\sqrt{E^2 - \Delta^2}} f(E)
\]

\[
E \rightarrow E - i\Gamma \quad \text{or} \quad \Delta \rightarrow \Delta - i\Gamma
\]

Broadening of the BCS density of states
$$\frac{\delta f}{f_0}(T) = \frac{\alpha}{2} \sqrt{\frac{\pi \Delta}{2T}} \exp \left( -\frac{\Delta}{T} \right)$$
TiN High Disorder (ALD250)
Resistance (T)

TiN Low Disorder (ALD021)

TiN High Disorder (ALD250)
Atomic Layer Deposition

1. Chemisorption precursor A
   - Dose (TiCl$_4$)

2. Saturation sub-monolayer A
   - Purge

3. Chemisorption precursor B
   - Dose (N$^+$ / H$^+$)

4. Saturation sub-monolayer B
   - Purge
Why Atomic Layer Deposition?

- Very thin layers of TiN
- High resistance per square
- High uniformity
- Possibly superior properties compared to sputtered materials
Roughness and grain size

![Graph showing roughness and grain size](image)
Relative roughness compared to resistivity
ALD021: bring it ON the carpet

- Fitting the amplitude instead of the phase will give a different decay time, roughly a factor of 2 smaller.
- The scatter in the lifetime deduced from the amplitude is very large, although the fits are reasonable.
- Resonator 4 gives a large scattering in the lifetime (phase and amplitude), although the fits are reasonable.
- We cannot really speak of an amplitude or phase response since the data is not properly normalized.
ALD250: two decay times! (unexplained)

- Data is fitted with a double exponential function:
  \[ r_1 \exp\left[-\frac{t}{\tau_1}\right] + r_2 \exp\left[-\frac{t}{\tau_2}\right] \]

- The short time scale is temperature dependent
- The long time scale is roughly temperature independent
ALD250: additional plots

- I have only data of one resonator
- Further, I have only analyzed the ‘phase’ data and no proper normalization was possible
Characterization
Level of disorder

• How close to localization are our TiN films?
  • Anderson localization at $k_F \ell \sim 1$

\[
\begin{align*}
D &= \frac{1}{3} v_F \ell \\
v_F &= k_F^2 / \hbar \pi^2 N(0) \\
\rho^{-1} &= e^2 N(0) D \\
k_F &= \sqrt[3]{3\pi^2 n}
\end{align*}
\]

• Blue Oxford Cryostat
  • Base temperature 1.5 K
  • Magnetic field up to $\sim 13.5$ T

Critical field

R – T Curve

Hall effect
FIG. 3. The density of states $N(E)$ deconvoluted from the data of Fig. 2 (solid line). The dashed line is a BCS density of states broadened by the value of $\Gamma$ shown in the figure for each case.