Thin Film Applications for SRF

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Daniel Bowring (TJNAF, UVA)
Why Thin Films?

- Thermal conductivity of, e.g., Cu is much larger than Nb - helps prevent hot spot quenches.
- Cheaper to use less Nb
- Possibility of other materials (MgB$_2$, NbN)
- Improved shielding from Earth’s B-field
- Improved BCS surface resistance

Overview

• Some history
• Where is thin film SRF now?
• How thin/thick is too thin/thick?
• $Q$-slope and possible sources
LEP II: 1998-2000

- Industry produced 272 Nb/Cu cavities
- 352 MHz (big!) for 200 GeV (CM)
- Avg. gradient 6-10 MV/m, depending
- Magnetron sputtering

“High field” $Q$-Slope

Measured $Q_0$ of LEP 2 Nb/Cu Cavities

A quote from Enzo

“... experimentalists will never benefit simultaneously [from] extremely high Q values and high fields. ... Niobium sputtered cavities will never be usable at high accelerating gradients, unless Residual Resistivity Ratio values of at least 100 [are] achieved in the niobium film growth.”

## Thin Film SRF Today

<table>
<thead>
<tr>
<th>Machine</th>
<th>What/Where</th>
<th>Approx. Gradient</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>LHC</td>
<td>CERN</td>
<td>5 MV/m</td>
<td>400 MHz</td>
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<tr>
<td>SOLEIL</td>
<td>St.-Aubin, France</td>
<td>5 MV/m</td>
<td>352.2 MHz</td>
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<tr>
<td>ALPI</td>
<td>Legnaro, Italy</td>
<td>4-6 MV/m</td>
<td>80 MHz</td>
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$Q_0$ vs. Gradient, LHC

MgB$_2$

- First published in 2001
- $T_c = 39$ K
- Theoretical max. gradient $\sim 77$ MV/m
- $R_{\text{BCS}}(4 \text{ K}, 500 \text{ MHz}) = 2.5$ n$\Omega$

Coating SRF Cavity with a Two-Step Process

Coating cavity with B layer at ~400-500°C using CVD

Reacting with Mg to form MgB₂ at ~ 850-900 °C in Mg vapor

How thin is too thin?

- Absolute lower limit is set by the London penetration depth. For Nb, this is ~36 nm.
- Practical lower limit set by substrate avg. surface roughness + concentration gradient.
- fcc to bcc transition

How thin is thin enough?

• LEP 2 experience suggests excessive film stresses at >10µm, causing problems during HPR.

• These limits likely dependent on deposition technique. YMMV.

• **Useful range: 2 < d < 10 µm.**
Possible Sources of Q-drop

• **DISCLAIMER**: Strong disagreement about role of grain boundaries in film quality.

• I will discuss (not endorse!) the findings/theories of various groups.

• Evidently lots of interesting work to be done here.
Role of Mean Free Path

Dependence of $R_{\text{BCS}}$ on mean free path

Trapped Magnetic Flux

- Flux vortices “pinned” by lattice defects.
- As $T$ drops below $T_c$ this pinned flux is trapped.
- Simple model for DC fields assumes all flux trapped.

$$R_{mag} = \frac{H_{DC, ext}}{2H_{c2}} R_n$$
Trapped Flux, cont’d.


- Thermometry measurements map “hot spots” in cavity due to trapped flux.

- Flux oscillates at pinning site, gives resistive losses.

- Authors: *Q*-drop might come from vortex penetration due to “reduced surface barrier” (lattice defects)
Trapped Flux, cont’d.


• Comparative thermometry studies of large and small grain cavities suggest crystal defects play a role in flux pinning.

• This experiment discounts role of field enhancement at grain boundaries, suboxide layer.

• But...
Theories / Experiments Comparison


<table>
<thead>
<tr>
<th></th>
<th>Q-Slope Fit</th>
<th>Q-Slope before baking (EP = BCP)</th>
<th>Q-Slope Improvement after baking</th>
<th>Q-Slope after baking (EP &lt; BCP)</th>
<th>No change after 4 yr. air exposure</th>
<th>Exceptional Results (BCP)</th>
<th>Q-Slope unchanged after HF chemistry</th>
<th>Q-Slope &gt; EP</th>
<th>BCP Quench unchanged after baking</th>
<th>TE@11 Q-Slope after baking</th>
<th>Quench EP &gt; BCP</th>
<th>BCP Quench unchanged after baking</th>
<th>Argu Validity</th>
<th>Fudal Disagree Exper. # Theory</th>
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<tbody>
<tr>
<td>Magnetic Field Enhancements</td>
<td>Y</td>
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<td>N</td>
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<td>Thermal Feedback</td>
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<td>Magnetic Field Dependence of ( \Delta )</td>
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<td>Segregation of Impurities</td>
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<td>Bad S.C. Layer Interstitial Oxygen Nb(_{s+O})</td>
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Y / N = theory in **agreement** / **contradiction** with experimental observation

/ = undisputable disagreement with experiment
• Paper *unique*: presents close approximation of an outright theory.

\[ R_{BCS} \propto \exp - \left[ (\Delta - p_F v_s) / kT \right] \]
where \[ p_F v_s / kT \propto \sqrt{\coth(\ell / \xi_0)} \]

\[ \ell \approx (24 \, \text{Å}) \times (\beta - 1) \]

• As RRR drops below \(~100\), “parasitic” term starts to wreck \( R_{BCS} \).

• This theory describes *medium-field* \( Q \)-slope.
Conclusions

• Parameter space of SRF thin film development is huge.

• Clearly lots of interesting work still to be done in this field.

• Thank you for your attention.