Characterizing thin films by RF and DC methods

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Outline

• Cavity measurements
  – Example: Nb on Cu (HiPIMS)

• Sample measurements with the Quadrupole Resonator
  – Example: Nb on Cu (ECR)

• Point contact tunneling
  – Example: Nb on Cu (HiPIMS)

• Muon Spin Rotation
  – Example 1: Nb on Cu (HiPIMS)
  – Example 2: NbTiN/Nb
Cavity measurements

• The $Q$ vs $E$ measurement of an accelerating cavity is a critical milestone for any thin film development.

• Sputter coated Nb films on Cu cavities have been used in the past for LEP-II and currently for LHC and HIE-Isolde.

• In the 1990s the dcMS technology has been investigated in depth for 1.5 GHz cavities.

• More recently energetic condensation techniques such as HiPIMS are investigated as an alternative approach to overcome the current limitation of this technology, i.e. the field dependent residual surface resistance.
HiPIMS: Motivation

By applying pulses of high power the sputtered target material atoms are ionized and applying biasing potential we can achieve:

- Target material ions can be accelerated towards the substrate, higher kinetic energy upon arrival
- Ions are directed to the surface, thus non-flat surfaces can be sputtered with good uniformity of the film
HiPIMS: Status at CERN

- So far only tests without biasing
- SEM images show more ordered surface structure
- RF performance equal to dcms with same surface preparation
  - Biasing could be the key
- RRR of about 20-30

Magnetron  HiPIMS

1μm

dcMS: 1.5 GHz
HiPIMS: 1.3 GHz
Electron Cyclotron Resonance (ECR) at JLAB

• Another technique to create Nb films with high RRR and large grain size
• Deposition in vacuum with no sputter gas
• Deployment for deposition on cavities has just been initiated
• Tests on flat samples are necessary to probe the RF performance
Quadrupole Resonator (CERN/HZB)

![Diagram of Quadrupole Resonator]

**Equation:**

\[ P_{RF} = P_{DC,1} - P_{DC,2} \approx \frac{1}{2} R_{Surface} \int_{Sample} H^2 dS \]

**Measurement:**

- Measurement of transmitted power \( P_t \)
- \( P_t = c \int H^2 ds \), \( c \) from computer code

**Diagram Explanation:**

- Shielding Cavity
- Nb Rods/Transmission Line
- Pole Shoes, illuminating the Sample with RF Field
- Sample Surface
- T-Diode
- Heater

**Graph:**

- Temperature vs. Power
- Time scale: DC on \( \approx 60 \) s, RF on \( \approx 40 \) s
- Temperature of Interest
- Bath Temperature
- Power levels: \( P_{DC,1} \), \( P_{DC,2} \), \( P_{RF} \)
Quadrupole Resonator (CERN)

Features:

- Sample tests over a parameter range inaccessible to elliptical cavities
- Niobium and copper substrates can be used
- Three different RF frequencies, with almost identical magnetic field configuration
- Wide temperature range (2-20K)
- Precise calorimetric measurement (Accuracy about 0.05 nΩ)

Results on an ECR sample
RRR=53
Q-slope mitigated

400 MHz, 4K
DC measurement techniques

• There are several thin film coatings which might be potentially interesting for SRF application but cannot yet be deposited on cavities

• Additional to RF sample tests there are several DC techniques, which can give invaluable information to optimize coating parameters and provide an understanding of loss mechanism

• Point contact tunneling can be used to measure the density of states directly

• Low energy muon spin rotation can be used to directly probe the field penetration
Point contact tunneling

$$\frac{dI}{dV} = N(E) \frac{f(E+eV)}{(eV)} dE$$

Smeared BCS DOS

$$N(E) = \text{Re} \left[ \frac{|E| i}{\sqrt{|E| i}^2} \right]$$

Measurement on a HiPIMS sample

Some zero bias peaks: Magnetic impurities?
Muon Spin Rotation ($\mu$SR)

- Muons are deposited one at a time in a sample
- Muon decays emitting a positron preferentially aligned with the muon spin
- Right and left detectors record positron correlated with time of arrival
- The time evolution of the asymmetry in the two signals gives a measure of the local field in the sample

\[ a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R} \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
Depth dependent (low energy) $\mu$SR

Superconductor in the Meissner State

$$\omega_\mu(z) = \gamma_\mu B_{\text{loc}}(z)$$
Measuring fluctuating field

Polarization function for different fluctuation rates. The “0” function corresponds to a Gaussian distribution of random fields.

Slow Fluctuations
Main effect is relaxation of the $\frac{1}{3}$ tail at long times, because $1/3$ of the muons see a field in spin direction and do not process

Fast Fluctuations
No recovery. For faster fluctuations slower depolarization (motional narrowing)
Can be due to muon diffusion or paramagnetism
Hints for magnetic impurities from PCT

Growing a N\textsubscript{2} overlayer on top of Nb and stop muons close to Nb

Dynamic response rules out diffusion

Crosscheck with Ni confirms that muon is static in N\textsubscript{2}

Combined results strongly suggest paramagnetic impurities in HiPIMS sample

MOTIVATION

• T. Kubo suggests the use of a bilayer system without insulator to reach high accelerating gradients

• He first calculates the penetration profile within London theory with appropriate boundary conditions

• He uses this result to calculate the forces acting on a vortex on the surface

• He concludes: A boundary of two SCs introduces a force that pushes a vortex to the direction of the material with larger penetration depth
We observe a single exponential decay with $\lambda_0 = 223(7)$.

Proximity effect? Dirty Nb due to diffusion?

To benefit from the counter current flow, an insulating layer is essential at least for the NbTiN/Nb system.

Measure above $T_c$ of Nb
- Field enters from both sides
- Comparison with SIS sample (no proximity)
- Significantly different $\lambda_0$ and $d$ support proximity for SS
Conclusion

• RF sample tests enable
  – Testing materials which are not yet ready for deposition on cavities
  – Having a faster turnaround than cavity tests, providing feedback for coating optimization
  – Accessing a parameter space inaccessible to cavity tests

• DC methods
  – Can measure superconducting and material parameters
  – Provide information for coating parameter optimization
  – Can give insight which material/structures are potentially useful for SRF application