Anomamous skin effect in superconducting films

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Outline

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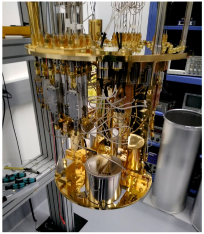
Motivation

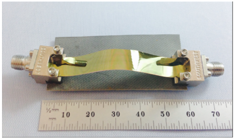
With the ever growing application of superconducting technology, the need for a better understanding of the superconducting thin film is also growing

CERN Nb Coated QWR cavity.[1]



Nb resonators for quantum memory[2]

Fermi Nb_3Sn Cavity.[3]



Flexible Nb film Transmission Line[4]

Outline

Theoretical model

Assume the normal incidence of the RF wave on the superconducting surface, the electric field $E(z)e^{i\omega t}$ is governed by the following equation:

$$E''(z) + k^2 E(z) = i\omega\mu_0 J(z) \quad (1)$$

However the current $J(z)$ here is not solely determined by the local E field:

$$J(z) = \int_0^\infty k_a(z - z_1)E(z_1)dz_1 \quad (2)$$

The key part here is the kernel function k_z which essentially describes how far the information of field variation will propagate across the depth of the film.

Theoretical model

In the normal conducting metal, the kernel is:

$$k_a = \frac{3}{4\rho l} \int_1^\infty e^{-|z|sa/l} \left(\frac{1}{s} - \frac{1}{s^3} \right) ds \tag{3}$$

where $a = 1 + i\omega l / v_F$ is the scaling factor, l is the mean free path and v_F is the Fermi velocity of the electron. In the superconducting, the k_a does not have the closed form, instead, we need to numerically find it by inverse Fourier transform the following expression[5]:

$$K(p) = -\frac{3}{4\pi\hbar v_F \lambda_L^2} \int_0^\infty \int_{-1}^1 e^{ipRu} e^{-\frac{R}{l}} \left(1 - u^2\right) I(\omega, R, T) du dR \tag{4}$$

Theoretical model

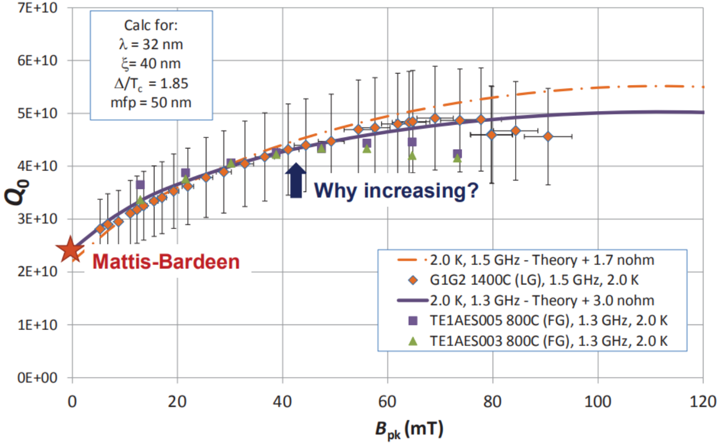
The integrand $I(\omega, R, T)$ is the following[6]:

$$I(\omega, R, T) = -\pi i \int_{\Delta-\hbar\omega}^{\infty} \left[1 - 2f(E+\hbar\omega)\right]\left[g\cos(\alpha\epsilon_2) - i\sin(\alpha\epsilon_2)\right] e^{i\alpha\epsilon_1}\, dE$$
$$+\pi i \int_{\Delta}^{\infty} \left[1 - 2f(E)\right]\left[g\cos(\alpha\epsilon_1) + i\sin(\alpha\epsilon_1)\right] e^{-i\alpha\epsilon_2}\, dE$$

Where
$f(E) = \frac{1}{1+e^{\frac{E}{k_B T}}}$,
Δ is the superconducting gap,
$\alpha = \frac{R}{\hbar v_F}$,
$\epsilon_1 = \sqrt{E^2 - \Delta^2}$,
$\epsilon_2 = \sqrt{(E+\hbar\omega)^2 - \Delta^2}$,
$g = \frac{E(E+\hbar\omega)+\Delta^2}{\epsilon_1\epsilon_2}$,
λ_L is the London penetration depth.

Application of model in bulk material

The model was first applied to the bulk material aiming to explain the increase of Q in low field region.



Theoretical model

The kernal function K(p) has to be calculated numerically. Then the kernel function k_a real space can be aquired by performing a inverse FFT. Plug the k_a at each location into the differential equation (1), we can solve the 1D field distribution in the film

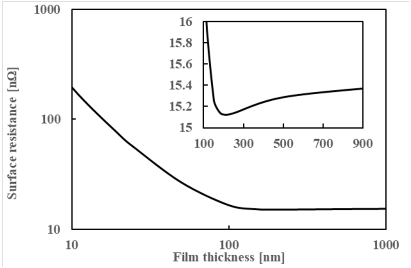
$$E_n + \sum_{m=n}^{K} (n-m) \left[k^2 l^2 E_m + i\omega\mu_0 l^3 D^3 \sum_{j=0}^{K} E_j k_a((m-j)l) \right] = E_d - lD(K-n)E_d' \quad (5)$$

Here we divide the 1D problem region into K equally spaced sections, $k = \omega/c$ is the wave number of the RF wave, $D = d/l/K$ is the normalized coordinate.

Theoretical model

Two interesting predictions from the model:

- Impedance dip。
  There is a 10% dip along the Z vs d curve which means that under certain condition the impedance of the film could have a convex shape instead of monotonically decreasing.



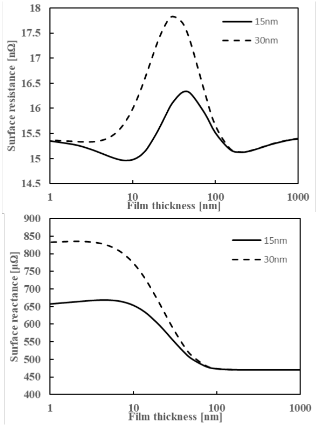
Impedance of Nb film vs the thickness of the film at 1.5 GHz under 2k. The mean free path was assumed to be 500 nm and the substrate was chosen to be Al_2O_3

Theoretical model

Two interesting predictions from the model:

- Anomalous impedance of Nb film in SIS structure.。

Impedance of Nb film vs the thickness of the film at 1.5 GHz under 2k. The insulator layer was chosen to be sapphire with two different thickness, 15 and 30 nm respectively. The mean free path was set to 500 nm (RRR 50).



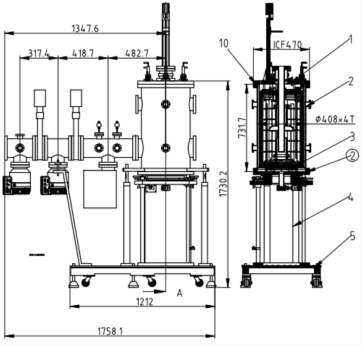
Outline

Sputtering System

Collaborating with Haichang Duan, Yuchen Yang, Jiawen Kan, Jin Dai, Ping He and Pei Zhang, we are working on a sputtering system for the Nb film fabrication.

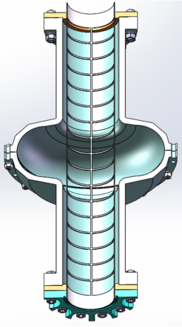
- Sputtering system。

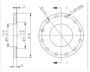
  Upgraded magnetron sputtering system driven by the new HiPIMS power source.



HiPIMS with Grid

In order to improve the quality of the film, a bias grid was added between the target and the samples (dummy cavity).

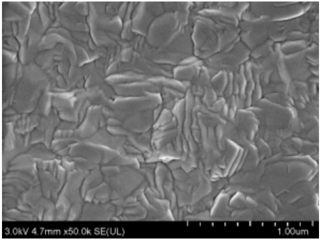




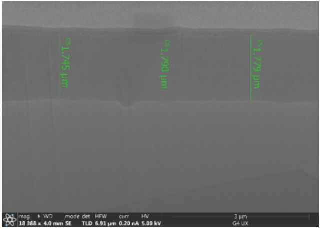
Courtesy of Haichang Duan

Nb film on Copper Substrate

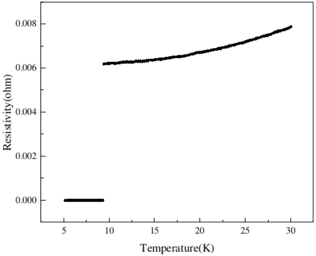
SEM of surface



FIB-SEM of cross section



Tc measurement



Tc = 9.24 K;

$\Delta T = 0.1K$

RRR = 15

Courtesy of Haichang Duan

Outline

Next step

- Design and manufacture the coaxial device for the impedance measurement;
- Measurement on the RF impedance of the film with different thickness and possiblly different RRR;

Thank you for your attention.
Ready to field the questions.

Outline

Sergio Calatroni Cern.
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