A METHOD OF EVALUATING MULTILAYER FILMS FOR SRF APPLICATIONS *

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Abstract

The lower critical magnetic field of an SRF cavity may be increased by screening the interior fields from the cavity bulk. This screening could be accomplished by coating the interior of a cavity with alternating layers of insulator and superconductor, each of which is thinner than the London penetration depth of the superconductor. This idea has been proposed by Gurevich [A. Gurevich, *Appl. Phys. Lett.* **88**, 012511 (2006)]. We have developed a method for measuring the behavior of such a multilayer system. A superconducting disk resonator is deposited on top of a small multilayer sample. The small sample approach allows for flexibility in the evaluation of many different materials and configurations. The onset of magnetic flux penetration in the superconductor can be observed from the change in resonator Q and the detection of flux flow voltages. Since the disk resonator applies a known field to the multilayer system, the lower critical magnetic field of the system may be measured. This paper presents design analysis for an experimental program for multilayer film evaluation.

INTRODUCTION

Gurevich [1] has proposed a method for raising the effective lower critical magnetic field H_{c1} of a superconducting radio frequency (SRF) cavity by means of a multilayer thin film coating on the inner surface. The coating consists of alternating layers of insulating and and superconducting films, where the superconducting layer thickness is less than the London penetration depth. In principle, this type of coating on an elliptical cavity could increase the peak magnetic field (and therefore the accelerating gradient) past the ∼180 mT limit for bulk Nb. This paper presents the experimental design for an evaluation of the multilayer approach.

An overview of [1] is presented in this section. We treat the example of a multilayer structure composed of layers of Nb-Ti and aluminum oxide. The superconducting layers screen the cavity fields from the bulk, as shown in Figure 1. The field decays exponentially across the superconducting film, establishing a current imbalance between the top and bottom and skewing the free energy per unit length G/L for flux vortex motion [1, 2]:

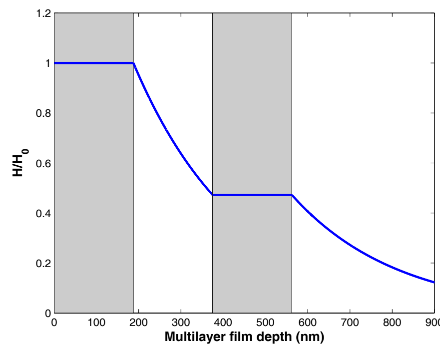

Figure 1: As in [1], the normalized field H/H_0 as a function of sample depth for alternating layers of Nb-Ti and Al_2O_3. $\lambda \sim 250$ nm and the layer thickness $d \sim 0.75\lambda$.

$$G/L = \frac{\phi_0^2}{4\pi\mu_0\lambda^2} \ln\left[\frac{d}{1.07\xi}\cos\left(\frac{\pi u}{d}\right)\right] - \phi_0 \int_u^{d/2} J(z)dz.$$

The first term represents the kinetic energy of a moving vortex, and the second term is the Lorentz force contribution from the net current across the film. u is the depth of the vortex in the superconducting layer, ξ is the coherence length (≈ 0.7 nm for Nb-Ti), and we assume a penetration depth $\lambda \sim 250$ nm [2]. This skewing of the free energy is shown in Figure 2.

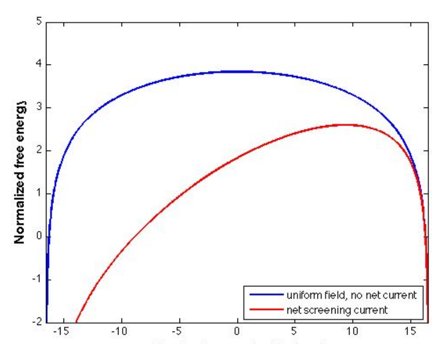

Figure 2: As in [1], the normalized vortex free energy G/G_0 as a function of displacement u from the center of a superconducting Nb-Ti film. The red line represents the barrier to flux motion arising from a net current across the film.

As the current work is an evaluation of the multilayer

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approach, we use Nb-Ti thin films for their relatively low value of H_{c1}. The objective is to quantify the performance of the multilayer approach by exceeding $H_{c1} \approx 50 - 100$ Oe in small multilayer samples, rather than to achieve fields comparable to those in elliptical high-gradient cavities. This paper presents the experimental design for such a proof-of-principle study.

EXPERIMENTAL DESIGN

Any RF structure designed to evaluate multilayer films must satisfy several basic requirements. First, the applied field must be parallel to the sample surface. H_{c1} for a thin film is significantly higher for parallel than for oblique fields [3]. Parallel magnetic fields also mimic the field distribution for the TM_{011} accelerating mode of a typical elliptical cavity.

In addition, the onset of flux penetration in the sample should be the only factor influencing resonator performance. We therefore require the magnetic field to be strongest on the sample surface, ensuring that any dissipation from RF vortex motion occurs within the multilayer structure. Equivalently, the sample must have a lower H_{c1} than any other part of the experimental apparatus. Sample geometry should be flat, with minimal surface area to facilitate film quality control and analysis. And finally, multipacting should be minimized so that the onset of flux penetration and subsequent vortex motion are relatively strong contributors to RF losses. The issue of vortex dissipation will be discussed in more detail below.

To satisfy the above requirements, we have designed a microstrip disk resonator that mounts on top of interchangeable flat multilayer samples.

Disk Resonator

The disk operates in the TM_{01} mode, such that the magnetic field is everywhere parallel to the sample. Figure 3 shows the magnetic fields from a simulation of this configuration for a 4 cm diameter disk operating in the TM_{01} mode at 2.9 GHz. Note that the magnetic field vanishes at the disk edge, as do the corresponding electric currents. This minimizes radiation losses from edge effects [4]. Since the disk is flat, field emission is minimized. Also, since the disk is immersed directly in liquid helium with no cavity enclosure, multipacting is minimized. The disk is made from high-RRR bulk niobium, so that it can reliably produce magnetic fields well above the lower critical field of the Nb-Ti multilayers while itself remaining free of flux penetration.

Sample Design

Samples are 8 cm square and of varying thickness, depending on the penetration depth of the superconductor used. For Nb-Ti ($\lambda \sim 250$ nm) the film and dielectric layers are each 190 nm thick. To obtain a value of H_{c1} which is significantly lower than that for the bulk Nb disk resonators, these films are sputtered rather than using the energetic deposition methods available at Jefferson Lab [6]. At least initially, film surface roughness and texture are of little concern.

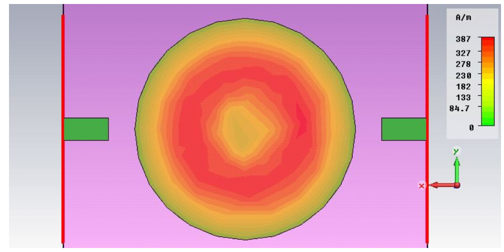

Figure 3: CST Microwave Studio finite element simulation of the magnetic field from a microstrip disk resonator. The field is entirely tangential to the disk surface, with no radial or longitudinal components. Stripline for capacitive RF coupling is seen on either side of the disk.

Each multilayer sample is, via masking, deposited simultaneously with a control sample on the same substrate, as shown schematically in Figure 4. The control sample is a single thin layer of Nb-Ti, identical to that of the multilayer sample, but lacking the bulk Nb ground plane. This effectively forms a traditional disk resonator, as in [5]. Depositing both multilayer and control samples simultaneously in the same chamber eliminates variations in film quality and thickness, allowing for a direct comparison of, for example, Q vs. E curves.

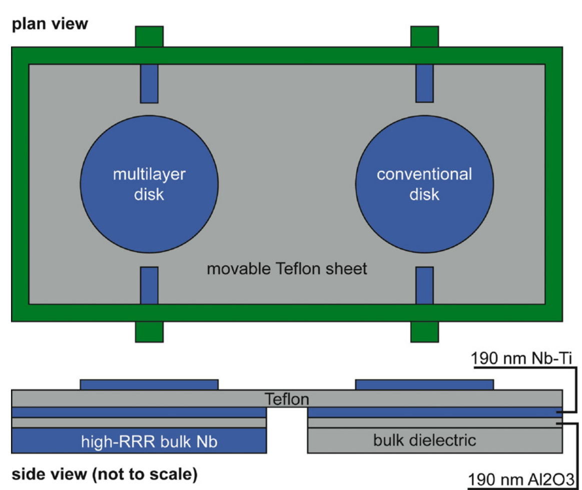

Figure 4: Schematic of the experimental apparatus. Multilayer and "control" samples are deposited simultaneously on the same substrate.

RF Coupling

To allow the simultaneous evaluation of multilayer and control samples, two high-RRR bulk Nb disk resonators are positioned side-by-side on a movable Teflon sheet, as in Figure 4. RF power is capacitively coupled to the resonators via Nb stripline [7]. Variable coupling is achieved by mounting movable Nb plates above the gap between resonator and stripline, creating a variable gap capacitance. The Teflon sheet is used to help match the relatively large edge impedance of the disk resonator to the 50Ω input and output couplers. In this arrangement, RF power can be supplied to one or the other disk resonator without removing the samples from the liquid helium or disturbing the coupling.

The disks, Nb stripline, and Teflon sheet together make up a movable module. Fixed SMA-type RF connectors are used to couple power to the resonators. Using the same fixed resonator and coupler scheme ensures that field strength and coupling constants do not vary between samples.

MEASUREMENTS

The RF breakdown field is characterized by entrant flux vortices in the thin superconducting layers. The onset of flux penetration in these layers can be measured via two related phenomena: flux flow voltage signals propagating in the thin dielectric layer, and a change in the Q of the resonator.

Flux Flow Voltage

A transport current density $\vec{J}$ on the thin film surface generates a Lorentz force per unit vortex length $\vec{F}/L = \vec{J}\times\vec{\phi}_0$, where $\vec{\phi}_0$ is the flux quantum. If the Lorentz force is larger than the vortex pinning force, the fluxoid will exhibit viscous flow across the film surface, perpendicular to $\vec{J}$. This flux motion, in turn, induces a dissipative electric field parallel to $\vec{J}$. Essentially, the motion of flux lines across the film creates a propagating voltage signal in the dielectric, which may be measured at the sample edge [3, 8].

Resonator Q

Because vortex motion is dissipative, flux flow voltage signals can be directly correlated with a drop in resonator Q. Below H_{c1} we calculate $Q_0 \approx 6 \times 10^7$. After the onset of flux penetration, we can use the thermal feedback model for vortex dissipation to calculate the extent of Q degradation [1, 2]. This approach requires knowledge of the temperature dependence of the thin film surface impedance, as well as the penetration depth. Therefore, measurements must be made for each film. The new surface impedance characterization (SIC) facility [9] at Jefferson Lab will be useful in making such measurements.

CURRENT AND FUTURE WORK

Experimental design is complete and construction of the apparatus is underway. We are currently assembling the cryostat insert and the RF couplers. In parallel with this, we have begun sample preparation. Note that the Nb-Ti films discussed here are a preliminary effort. In principle, any superconductor of any thickness less than λ may be used with this system. We intend to evaluate as many superconducting materials as possible.

Calculations of loaded Q and RF breakdown field depend heavily on the thin film penetration depth, coherence length, and thickness. Very rough *a priori* estimates are possible, but accurate predictions of these values require TEM and SIC measurements of prepared samples. Furthermore, analytic calculations of the RF breakdown field [1] use a vortex image approach that assumes a microscopically flat film surface. We would like to model the effect of film roughness on the multilayer breakdown field.

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