RF SURFACE IMPEDANCE CHARACTERIZATION OF POTENTIAL NEW MATERIALS FOR SRF-BASED ACCELERATORS*

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Abstract

In the development of new superconducting materials for possible use in SRF-based accelerators, it is useful to work with small candidate samples rather than complete resonant cavities. The recently commissioned Jefferson Lab RF Surface Impedance Characterization (SIC) system [1] can presently characterize the central region of 50 mm diameter disk samples of various materials from 2 to 40 K exposed to RF magnetic fields up to 14 mT at 7.4 GHz. We report the recent measurement results of bulk Nb, thin film Nb on Cu and sapphire substrates, Nb_3Sn sample, and thin film MgB_2 on sapphire substrate provided by colleagues at JLab and Temple University.

INTRODUCTION

SRF accelerating cavities for particle accelerators made from bulk niobium materials are the state-of-art for particle accelerators. Other materials, like thin film Nb on Cu, Nb_3Sn, and MgB_2 are of interest because of their potential cost and performance benefits in SRF applications. In this paper, we report the measurement results from bulk Nb, thin film Nb on Cu substrates and thin film MgB_2 on sapphire provided by colleagues at JLab and Temple University.

DESCRIPTION OF APPARATUS

The sample has been put at the open end of a TE_{011} cylindrical Nb cavity with a sapphire rod inside, described in [1] . The system provides a resonant field at 7.4 GHz. The cavity body, from which the sample is thermally isolated, is surrounded by liquid helium during the test, which differs from the previous measurements [2-4] by making the RF effect on sample the only contribution to the induced heat and resonance frequency change. Heat can be conducted from the sample only via the calorimeter. The effective surface impedance of the sample is derived by directly substituting heater heat for RF heat under controlled RF field and temperature conditions. This system can detect as little as 1 μW dissipated on the sample, enabling the resolution of surface resistance as low as 1.2 nΩ at 5 mT peak magnetic field. A cross-section of the SIC system is shown in Figure 1.

The effective surface impedance can be calculated from:

$$Z_s = \frac{E_Z}{H_Y} = \frac{P_{rf}}{\frac{1}{2}\int H^2(S)dS} + i\omega\mu_0\lambda = \frac{P_{rf}}{kB_{pk}^{\ 2}} + i\omega\mu_0(\lambda_{ref} + \frac{f - f_{ref}}{M})$$

with: $k = \frac{1}{2}\int B^2(S)dS \Big/ (\mu_0 B_{pk})^2$

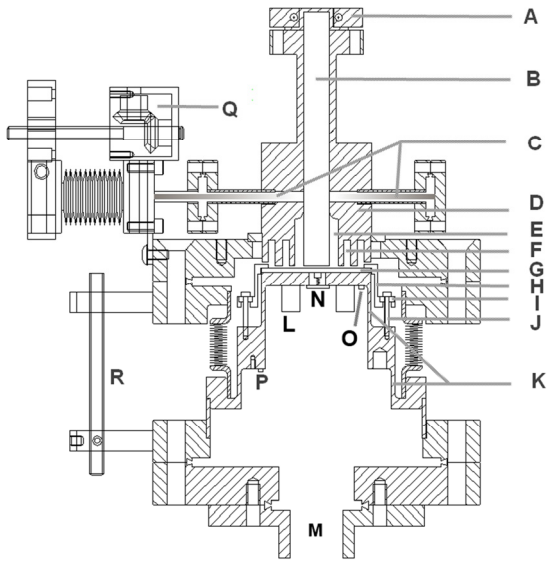

Figure 1: SIC system cross-section. A. Cap for sapphire rod, B. Sapphire rod, C. RF coupler, D. Nb cavity body, E. TE_{011} cavity, F. Double choke joints, G. Sample on top of copper sample holder, H. Stainless steel sample clamp, I. G-10 washer, J. Aluminium bolt, K. Upper and lower thermal insulators, L. Ring heater, M. Port for vacuum and wires. (Vacuum port of the cavity is not shown), N. Thermal sensor mounted on spring, O&P. Thermal sensor, Q. Coupler tuning mechanism, R. Gap tuning mechanism (1 of 3).

The real part is the effective surface resistance and imaginary part is the effective surface reactance. P_{rf} is the RF induced heat, $B(S)$ is the magnetic field distribution on the sample, M is the tuning sensitivity that represents the ratio between frequency change and penetration depth change. k and M are geometry dependent coefficients and ω is the resonant circular frequency. The RF induced heat is calculated from the difference between the power from the heater required to keep a constant sample temperature without RF fields in the cavity and the power from the heater required to keep the sample's equilibrium temperature unchanged when RF fields are present, so called power compensation technique. The change of effective surface reactance is proportional to the change of penetration depth. It may be discerned from the

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frequency dependence of the TE_{011} mode as a function of sample temperature.

EXPERIMENT

A set of commissioning measurements (Fig. 2) have been accomplished using bulk niobium, thin film niobium grown by energetic condensation (EC) on polycrystalline copper substrates, a Nb_3Sn film on niobium, and MgB_2 films on single crystal sapphire. The EC film samples were drawn from a batch produced by extracting niobium ions from an ECR plasma onto a biased and heated substrate [5].

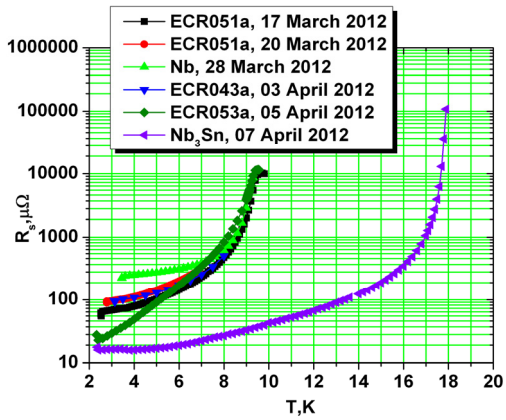

Figure 2: Measured surface resistance of several EC films, bulk Nb sample and Nb_3Sn sample.

Assuming 5% error in power measurement, 1% in current and voltage and 10% in loaded quality factor, the R_s measurement error is estimated to be ~ 20% (not shown). The measurements show high and inconsistent residual resistance at low temperature which is not yet understood.

Several EC samples were characterized with SIC the system. All samples show BCS resistance similar to that of bulk niobium. From the RF surface resistance at ~ 9.5 K in the normal conducting state, surface RRR of the films was estimated and is presented in Table 1 together with DC RRR measurements of co-deposited films. The difference between RF and DC measurement suggests variation in RRR values across the film.

Table 1: Transition temperatures, superconducting transition widths and surface RRRs of measured samples estimated from the data close to the transition temperature.

	RRR_{RF}	RRR_{DC}	T_c, K	ΔT, K
Bulk Nb	~ 60	>250	9.24	0.01
ECR051a	~ 40	54	9.30	0.30
ECR053a	~ 35	182	9.31	0.05
ECR043a	~ 50	289	9.29	0.20
Nb_3Sn			17.80	0.20

A Nb_3Sn sample that was produced at Jefferson Lab by a vapor deposition method was measured in the SIC system directly after the deposition. The R_s measurement shows the transition temperature of about 18 K, consistent with DC magnetization measurements. The film shows high RF surface resistance at the transition temperature suggesting a suboptimal film. This is consistent with the measurements done at Wuppertal University, which indicated that up to 0.5 μm needed to be oxypolished in order to achieve optimal RF performance. We plan to oxypolish the sample and measure the change in low temperature surface resistance as a function of removal.

MgB_2 on Sapphire

The principles of the HPCVD system used to produce the MgB_2 samples were described in references [6, 7]. Three 5 cm diameter samples were fabricated for SRF property characterization, two 200 nm thick (labelled MgB_2-200-I and MgB_2-200-II) and one 350 nm thick (labelled MgB_2-350). Small samples with 1×1 cm^2 size and 350 nm thickness have been fabricated for surface characterization.

The transition temperatures of MgB_2-200-I and MgB_2-200-II were both 39.3±0.2 K, while that of MgB_2-350 was 39.5±0.2 K.

The penetration depth λ_s may be derived from the effective penetration depth of thin films using the expression $\lambda_{eff} = coth(d/\lambda_s)$ [8] with d the film thickness. The results are plotted in Figure 3. The measurement errors of penetration depth and sample temperature are 5% and 0.01 K, respectively. Theoretical value based on BCS theory and Mattis-Bardeen's anomalous skin effect of a superconductor may be calculated using a code SRIMP, written by Halbritter [9]. Using the fitting routine developed by Ciovati [10], we find the suggested BCS model parameters for these MgB_2 samples $\Delta/kT_c = 1.08$, London penetration depth = 180 nm, coherence length = 6 nm, and mean free path = 38 nm.

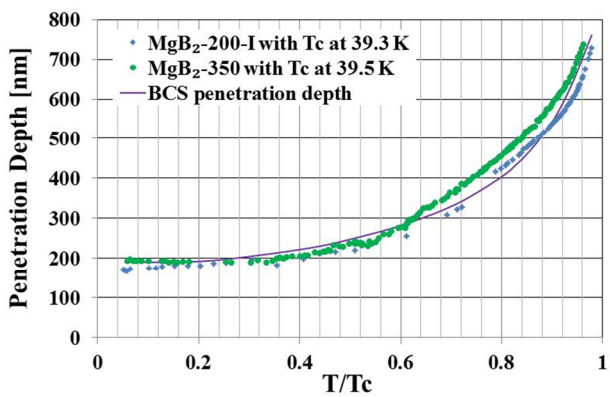

Figure 3: ◆MgB_2-200-I with T_c 39.3 K ● MgB_2-350 with T_c 39.5 K penetration depth versus sample temperature of MgB_2 on sapphire substrate – BCS penetration depth.

Figure 4 shows the effective surface resistance at 7.4 GHz of the MgB_2 samples, measured at temperatures between 2.1 K and 40 K, with peak fields between 0.6 mT

ISBN 978-3-95450-122-9

and 3.7 mT. The surface resistance of a large-grain Nb sample prepared by BCP etch, measured using the same apparatus, is plotted as a reference. At temperatures above 4 K, the MgB_2-350 sample has a lower surface resistance than Nb. At 2.2 K, the effective surface resistance decreased from 20 μΩ to 9 μΩ with the film thickness increase from 200 nm to 350 nm. The lowest effective surface resistance measured was 9±2 μΩ at 2.2 K, which is consistent with the previous best reported results [4, 11, 12] (using the f^2 rule for normalization) and with smaller systematic errors. We note that the 350 nm sample is less than two penetration depths thick at low temperatures and much less at higher temperatures. This must be taken into account when interpreting the effective surface resistance with respect to a BCS model. The microstructural defects or impurities revealed by XRD might explain why the samples' SRF performance <4K is not yet better than that of a near-perfect single crystal bulk Nb. These XRD measurements have been reported elsewhere [13] and suggest that the crystal quality of the epitaxial films may yet be improved. For the MgB_2-350 sample, the effective surface resistance versus magnetic field was measured with fields up to 10 mT at 3 K sample temperature. Results are shown in Figure 5. Effective surface resistance increased from 10 μΩ to 35 μΩ with increased fields from 0.5 mT to 10 mT.

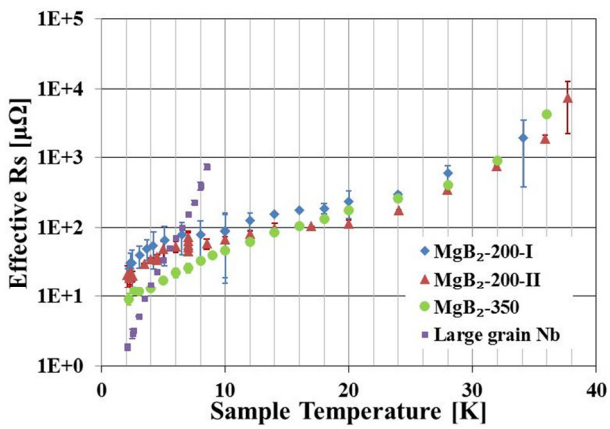

Figure 4: ◆MgB_2-200-I ▲MgB_2-200-II ●MgB_2-350 Effective surface resistance of MgB_2 on sapphire substrate ■Surface resistance of large grain Nb sample.

SUMMARY

The surface impedance characterization (SIC) system at Jefferson lab has been used to measure a variety of thin films on different substrates. In some circumstances the system appears to indicate anomalously high residual resistances that remain yet to be understood. From the data surface RRR values of the films were estimated. The first RF measurement of Nb_3Sn film produced at Jefferson Lab by the vapor diffusion method shows critical temperature of about 18 K consistent with DC magnetization measurements, but also suggests that the film performance may be improved by oxypolishing.

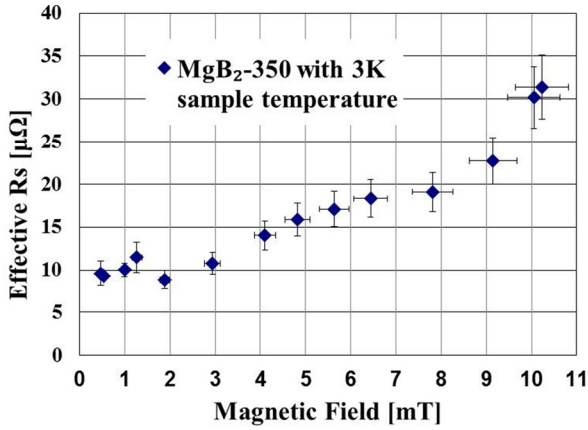

Figure 5: Effective surface resistance of MgB_2-350 versus magnetic field at 3 K.

Quality surface impedance characterization of MgB_2 films of two thickness has been accomplished. Extensive use of the SIC system for SRF material development is anticipated in the future.

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