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INVESTIGATION OF SIS MULTILAYER FILMS AT HZB

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Abstract

The systematic study of multilayer SIS films (Superconductor-Insulator-Superconductor) is being conducted in Helmholtz-Zentrum Berlin. Such films theoretically should boost the performance of superconducting cavities, and reduce some problems related to bulk Nb such as magnetic flux trapping. Up to now such films have been presented in theory, but the RF performance of those structures has not been widely studied. In this contribution we present the results of the latest tests of AlN-NbN films, deposited on micrometer-thick Nb layers on copper. It has, also, been shown previously at HZB that such SIS films may show some unexpected behaviour in surface resistance versus temperature parameter space. In this contribution we continue to investigate those effects with the variation of different parameters of films (such as insulator thickness) and production recipes.

INTRODUCTION

Previous measurements [1, 2] of the first SIS structure at HZB with the Quadrupole Resonator (QPR) [3] have shown unusual behaviour of the surface resistance in temperature dependant parameter space. To study this effect further 3 more SIS layered samples have been coated by the University of Siegen [4] within the ARIES program [5]. The samples are listed in the Table 1. The first SIS sample measured at HZB, prior to ARIES, was prepared at Jefferson Lab (JLab) using DC MS sputtering technology [1, 2]. It is included in the table as well for comparison.

The ARIES SIS samples were the consequent study of the niobium films on copper [5]. Partially due to this reason the structure of the samples was chosen to be NbN-AlN-Thick Nb layer on copper (see Fig. 1). The copper surface of all substrates for the ARIES samples was prepared by INFN with electropolishing (see Fig. 2) [6].

The reasoning behind the choice of the respective layer thicknesses was initially based on Kubo's paper [7]. Moreover, the choice of NbN layer thickness was based on results from the VSM measurements performed within ARIES [8] and then thirdly, we did variations in the thin AlN layer according to advice and feedback session with Gurevich.

First ARIES sample was coated with the DC MS sputtering technology (similar to the SIS films described in [8]). For this sample prior to NbN-AlN coating the RF test of the base Nb layer was performed. The sample with 4 μm Nb layer on copper was transported to HZB from Siegen in a sealed container with a neutral gas (Argon). Then the sample was tested with the QPR, and sent back to Siegen for the subsequent NbN-AlN coating. As a result the Nb layer was exposed to air between the coatings.

The second and third ARIES samples were coated in one run with HiPIMS method [4].

Table 1: SIS Samples Structure

Sample	Sample structure	Layers thickness [nm]
J-Lab SIS [1]	NbTiN/AlN/Nb(bulk) DC MS	75/15/bulk Nb
ARIES 1st SIS	NbN/AlN/Nb/Cu DC MS	197/35/3000 Nb
ARIES 2nd SIS	NbN/AlN/Nb/Cu HiPIMS	180/8/4000 Nb
ARIES 3ed SIS	NbN/AlN/Nb/Cu HiPIMS	180/24/4000 Nb

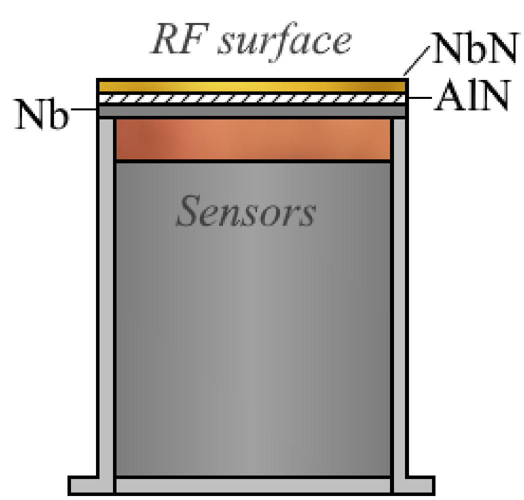

Figure 1: Structure of ARIES samples.

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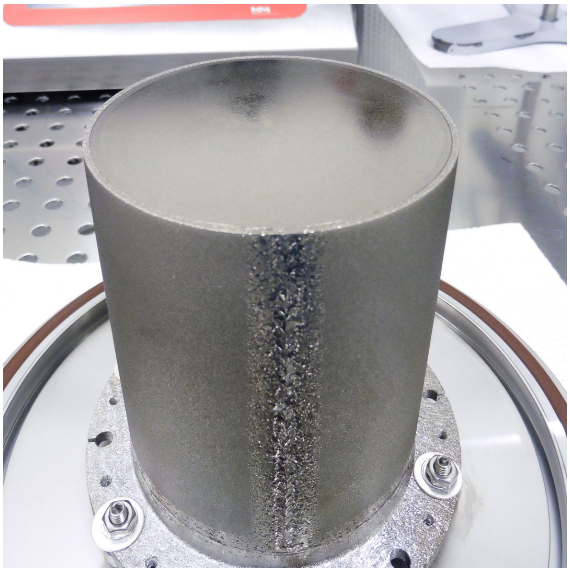


Figure 2: Picture of one of the ARIES samples.

SURFACE RESISTANCE VERSUS TEMPERATURE MEASUREMENTS

The measurement setup of the Quadrupole Resonator is comprehensively described in [3].

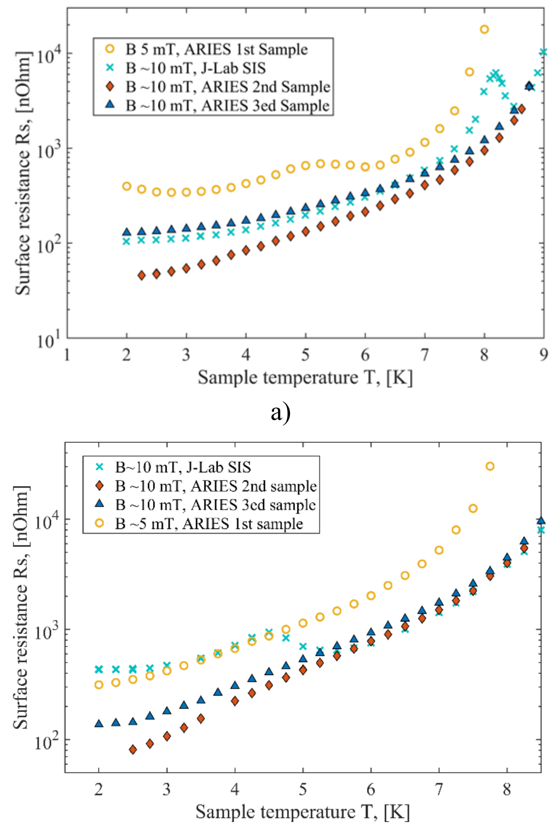
The surface resistance values versus temperature for all samples are plotted in Fig. 3. It can be seen that HiPIMS coated samples with thinner insulator layer generally exhibit a lower surface resistance. The data show (see also Table 2) that the surface resistance is better, the thinner the insulator layer is. The probable explanation for this behavior is that there are some possible dielectric losses in the insulator layer which are increasing with the thickness of the layer.

Table 2: SIS Samples Estimated Residual Resistance

Sample	Residual resistance at 416 MHz [nOhm]	Layers thickness [nm]
Bulk Nb	23	Bulk
ARIES 1st	>400	197/35/3000 Nb
ARIES 2nd	≈45	180/8/4000 Nb
ARIES 3ed	≈128	180/24/4000 Nb

Since the purpose of the insulating layer is to decrease the flux trapping, suppress the proximity effect between the superconducting layers and to avoid a Josephson junction between them, any value above ~1 nm is acceptable. On the other hand the bottom limit for the thickness might come from the coating facility capabilities. For those ARIES samples the limitation was in the order of 8 nm.

The measured surface resistance curves exhibit a second feature: A non-monotonic temperature behavior that was first discovered in the early JLab sample and then also seen in the first ARIES sample. This feature was very pronounced in the JLab sample at around 8 K and less pronounced and shifted to around 5 K in the 1st ARIES sample. At around 850 MHz the surface resistance peak was not observed on the ARIES sample (contrary to JLab sample, where it shifted to lower temperatures)



b)

Figure 3: Surface resistance versus temperature for all samples, measured at: a) ~415 MHz b) ~850 MHz.

In Fig. 4 the 3d reconstruction of the surface resistance is presented for the 1st ARIES sample. It is clear that this peak appears at low fields and looks like an additional plateau at higher fields. The origin of the feature was unclear and it was decided to investigate it further, in particular since the underlying theory did not allow for a decrease of surface resistance with temperature.

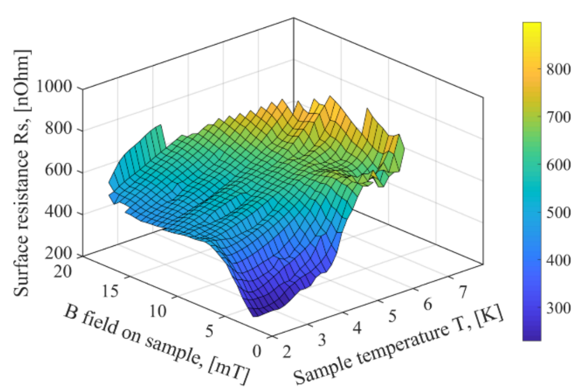


Figure 4: 3d reconstruction (Rs-T-B) of the surface resistance of the 1st ARIES sample for 415 MHz.

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Therefore, in the second ARIES sample the insulator thickness was made as small as possible with the methods at hand (i.e. 8 nm). As a result, any peaks disappeared from the surface resistance versus temperature curve. However, since the production method was changed from DC MS to HiPIMS, it was unclear if this improvement was due to the layer thickness or the production method itself. Therefore, it was decided to coat another (3ed ARIES) sample with HiPIMS and make an intermediate insulator layer thickness around 25 nm (something between JLab and 1st ARIS sample) to check if the peak appearance is due to that layer thickness.

As can be seen in Fig. 3 the peak was not observed. Although the appearance of the peaks in the early samples is still not entirely understood, it was suggested that their appearance is an indicator of the extrinsic performance bias (i.e., poor film quality or trapped flux), rather than an intrinsic property of multilayer structures in general. Moreover the surface resistance of the 1st ARIES sample was much higher than expected at low temperatures (the region where this peak appeared). From Fig. 5 it can be seen that at 416 MHz the surface resistance before 4.5K is even higher than at 850 MHz, and clearly deviates from a standard BCS behavior.

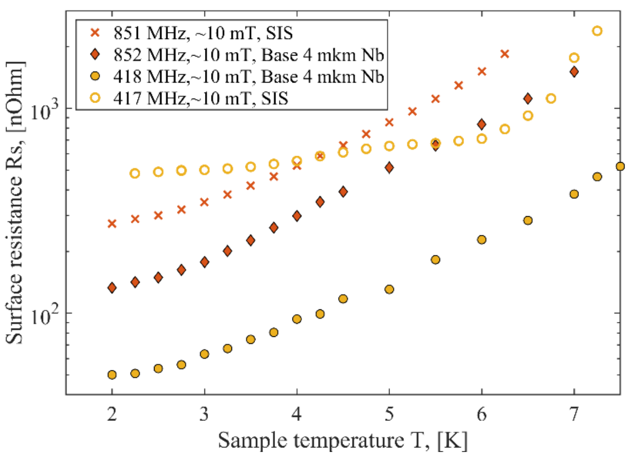

Figure 5: Measurement results for the 1st ARIES sample in comparison with the measurements of its base 4 mkm Nb film (1st layer of Nb on Cu).

In order to investigate that extrinsic impact on the unusual behavior of the 1st ARIES sample further it was thermally cycled. In Fig. 6 the effect of thermal cycling on the surface resistance is illustrated. The yellow curve shows the surface resistance after the initial cooldown, the red curves show a subsequent measurement run after warm-up to the room temperature. The sample had not been touched before the second cooldown, but had been exposed to air for short time. The time passed between the cooldowns was about 4 month. Nevertheless, the curves look very different: Although all curves exhibit the non-monotonic behavior, the peaks are at different temperatures and involve different changes in surface resistances. For the initial cooldown the peak occurred at 5.5 K and 700 nOhm and is followed by a drop to 660 nOhm at 6 K. The edge of the yellow curve towards small temperatures suggests the existence of another peak which could not be fully measured due to limitations of the cryoplant. In the second experiment the peak was shifted to a temperature of 3.5 K and smaller surface resistance of 420 nOhm and dropped below 400 nOhm towards 4.5 - 5.5 K.

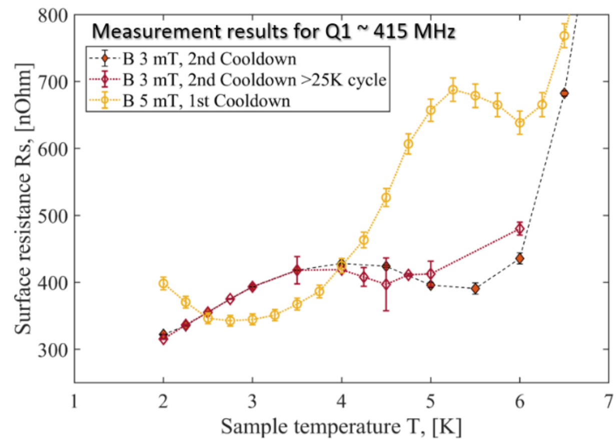

Figure 6: Thermal cycling of the cavity and sample. The error bars obtained by averaging of the statistical oscillations for each measured point only. They come from the thermal stability of the liquid helium system which may change with time. The solid lines are not a mathematical fit and shown only for visual purpose.

In order to test if the change of the curve was caused by magnetic flux trapping, a short warmup of the full cavity above Tc was performed (>25 K thermocycle). The resulting surface resistance vs temperature curve was almost identical up to temperatures of 3.5 K. Above 3.5 K the curves begin to differ. However, these changes are not strongly significant and only slightly beyond the statistical error bars (which are obtained from statistical averaging).

The second thermocycle did not make a big difference, however, the peak was clearly reproducible within one cooldown and independent on the sample thermocycling above Tc. Therefore, the source of the change of the curve and the non-monotonic behavior is still unclear.

During the tests of samples ARIES-2nd-SIS and ARIES-3rd-SIS more promising results were obtained. Those 2 samples coated in 1 run with thinner insulator represent lower residual resistance (see Table 2). Figure 7 shows their respective surface resistance minus residual resistance versus temperature together with a bulk Nb sample for comparison. From the plot we can extract that the temperature dependent part is growing slower than bulk Nb (which is expected due to higher Tc of the NbN top film), which gives the advantage of about 20 nOhm of the temperature dependent component compared to Nb at 4.5 K.

Another satisfying result was achieved with the ARIES-2nd-SIS sample particularly, which showed lowest residual resistance (about 45 nOhm). The residual resistance of the bulk Nb, presented here was about 23 nOhm.

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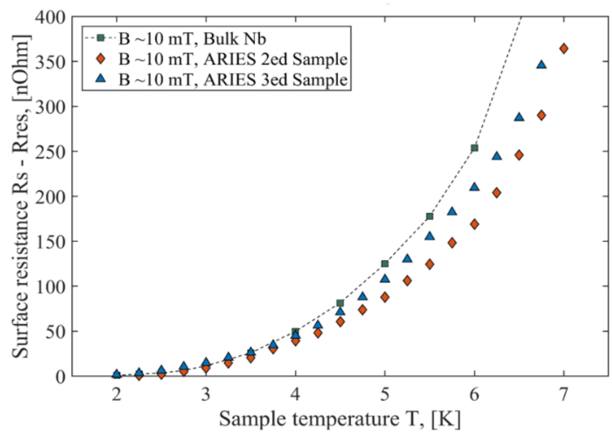

Figure 7: Temperature-dependant component of surface resistance with subtracted residual resistance for 415 MHz.

SURFACE RESISTANCE VERSUS FIELD MEASUREMENTS

On the Surface resistance versus field parameter space 1st ARIES sample also showed non-monotonic behaviour (although those features are not unexpected and can be explained by known effects such as “Q-switches”) the result of the measurements is presented on Fig. 8.

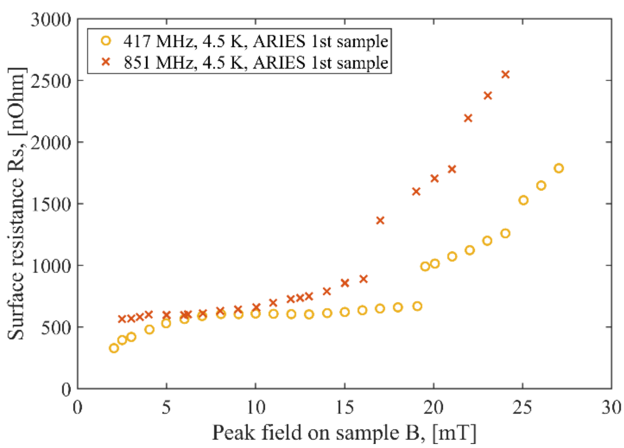

Figure 8: Measured surface resistance vs. peak field for 1st ARIES sample at 4.5 K

The best result of the field dependant component of the Surface resistance was also achieved by the 2nd ARIES sample, which showed quite low “Q-slope” (apart from the lowest Residual resistance), equivalent to bulk Nb (see Fig. 9). The only drawback of the film was that the maximum achieved magnetic field for NbN top layer was about 30-35 mT. For two frequencies: 415 and 850 MHz.

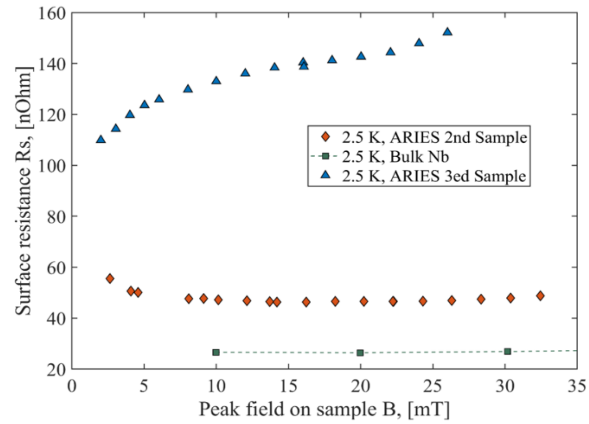

Figure 9: Measured surface resistance vs. peak field for 2nd and 3ed ARIES samples at 4.5 K, 415 MHz, compared to Bulk Nb.

To test if the quench event at 30-35 mT was related to the NbN top film, single pulse measurements at different temperatures were performed. The fit attempt of the empirical expression Eq. (1) to measured maximum field suggests that Tc of the quenching layer is somewhere beyond 9.3 K (see Fig. 10).

$$B_c(T) = B_0\left(1 - \left(\frac{T}{T_c}\right)^2\right) \quad (1)$$

Considering the fact that this field limit was achieved for all NbN samples we make a suggestion that this limitation indeed comes from the NbN film itself. To bypass this limit further study and improvements in the used coating procedures are possibly required.

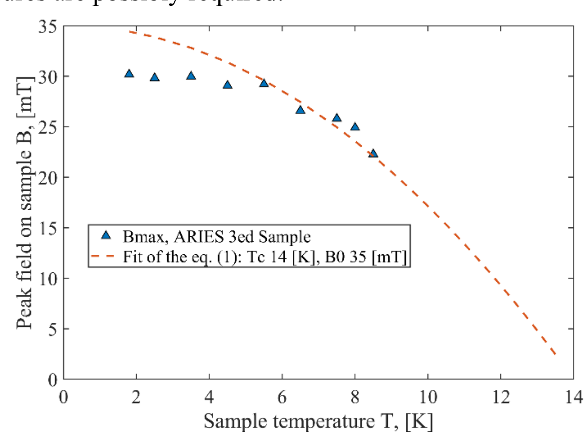

Figure 10: Max field achieved for 3ed ARIES sample as a function of temperature for 415 MHz with fit attempt of Eq. (1).

CONCLUSIONS

A systematic study of multilayer SIS films (Super-conductor-Insulator-Superconductor) is being conducted within the ARIES collaboration. During this study several SIS samples coated with different methods were already tested. Some of them presented unusual (never observed)

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behaviour on the surface resistance versus temperature parameter space. The nature of this feature is still not entirely understood, however, the result of this phase of the study suggests that its appearance is an indicator of the extrinsic performance bias (i.e. poor film quality), rather than an intrinsic property of multilayer structures in general.

Another interesting result was obtained from the measurements of the samples with different insulator layer thickness. As a general trend, the surface resistance is better, the thinner the insulator layer is. The likely explanation for this behaviour is that the dielectric losses in the insulator layer are proportional to the layer thickness. Also, measurements showed that HiPIMS coated samples generally exhibit a better (i.e. smaller) surface resistance.

The latest satisfying result was achieved with one of the SIS samples, which exhibited a comparably low residual resistance (about 45 nOhm compared to 23 nOhm, measured for bulk Nb) and low "Q-slope" or field dependent increase of surface resistance, equivalent to bulk Nb. The only drawback of that film (and one of the feature of all other films) was that the maximum achieved field for NbN top layer was about 35 mT, which also needs to be studied and improved.

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