NOVEL MATERIALS FOR BEAM ACCELERATION*

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Abstract

Bulk niobium is currently the standard material for constructing superconducting radio frequency (SRF) cavities for acceleration in particle accelerators. However, bulk niobium is limited, and new materials and surface treatments may allow greater performance to be reached. We present progress on novel materials and treatments for SRF cavity fabrication.

INTRODUCTION

Superconducting Radio-Frequency (SRF) cavities are the cutting-edge technology that enables high-energy, high efficiency accelerators on a variety of scales for a variety of applications. The standard material for manufacturing of SRF cavities is bulk niobium, a few millimeters thick, with a high residual resistivity ratio (RRR). Though the niobium is thick, the RF field excited in the cavity interacts with the cavity most strongly at the surface, specifically within (approximately) the first 40 nm [1]. Because of this, engineering and optimization of the surface of niobium has become a strong focus of research and development for improving SRF cavity performance [2].

When exposed to atmosphere, niobium forms a complex, multi-phased oxide, a cartoon of which is shown in Fig. 1. The majority of the oxide by volume is composed of the pentoxide, Nb_2O_5, with suboxide phases between the pentoxide and the niobium metal. A powerful tool for studying the different phases and behavior of the oxide is X-Ray Photoelectron Spectroscopy (XPS). When applied to oxidized niobium, XPS imaging results in a recognizable four-peak pattern with background, shown in Fig. 2 [3]. Each phase is associated with two peaks due to spin dynamics, a primary peak and a doublet peak. In Fig. 2, the primary peaks for the metallic Nb and the pentoxide Nb_2O_5 are labeled, and their doublet peaks appear directly to the left of them. As seen in Fig. 2, the other phases typically have smaller XPS peaks which are difficult to distinguish by eye, but can be quantified through a peak-fitting process.

The electronic properties of the oxide, and therefore its interaction with RF fields, are affected in many subtle ways by different cavity treatments. Work at Cornell University and elsewhere proposed to remove the oxide entirely, then replace it with a thin layer of a non-oxidizing normal conductor such as gold [4] [5] [6]. That work showed promise for improving cavity RF performance at very thin (sub-nm) layer thicknesses of gold. We have previously presented preliminary work towards developing a gold passivation technique that could be applied on a full-scale SRF cavity [7]. Here we discuss progress on two main techniques for cavity-scale oxide passivation techniques: thermal oxide passivation and chemical oxide passivation.

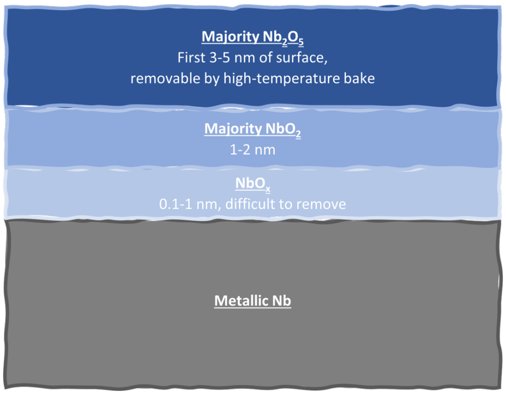

Figure 1: Cartoon of the native niobium oxide structure.

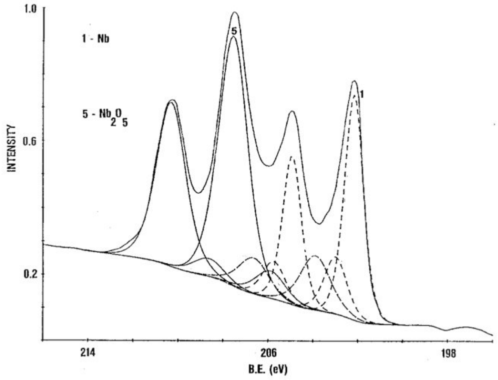

Figure 2: XPS data for a typical oxidized niobium surface, taken from [3].

GOLD PASSIVATION METHODS

Thermal Oxide Passivation

In the thermal oxide passivation method, normal oxidized niobium has a thin layer of gold deposited on it via any applicable method. For this study, we deposited layers of gold via evaporative deposition[1] onto niobium coupon samples 1 cm by 2 cm in size, which had been given the standard set of cavity preparation treatments[2]. Thus, the expected surface

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[1] Evaporative deposition was performed using a CVC SC4500 evaporative deposition chamber.

[2] An approximately 75 µm electropolish, followed by a five-hour ultra high-vacuum bake at 800 C, then a short electropolish of approximately 2 µm

composition of the sample would be metallic niobium as the lowest layer, then the various oxide phases, then a thin layer of gold interfacing with the atmosphere.

Once the samples had received the gold layer, they were imaged using XPS. Then, they were baked in vacuum for 5 hours at 800 C, a temperature high enough to dissolve the majority of the niobium oxide. After the bake, they were imaged again using the same XPS parameters. We expect sufficiently thick layers of gold applied before the vacuum bake to prevent the diffusion of oxygen from the bulk of the niobium back onto the surface once removed from vacuum [8]. A representative set of scans is shown in Fig. 4.

Chemical Oxide Passivation

In the chemical oxide passivation method, normal oxidized niobium is brought into an inert atmosphere of nitrogen, its oxide chemically removed, and a layer of gold is electroplated onto the surface. We utilize an inert-atmosphere glovebox capable of reaching <0.5 ppm of O_2 and H_2O content at peak performance levels. Once in the inert atmosphere, we submerged the samples in dilute 1% hydrofluoric acid for 30 minutes, which is expected to dissolve all phases of the oxide.

A diagram of the electroplating setup is shown in Fig. 3.

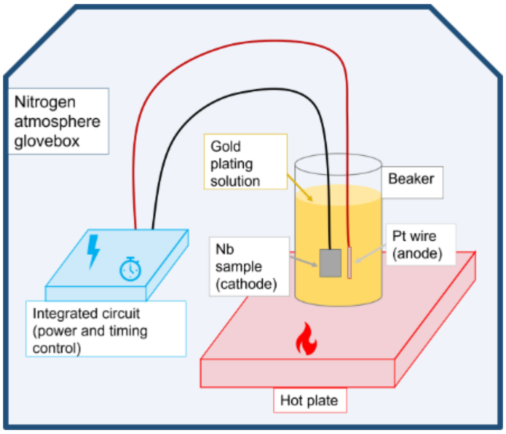


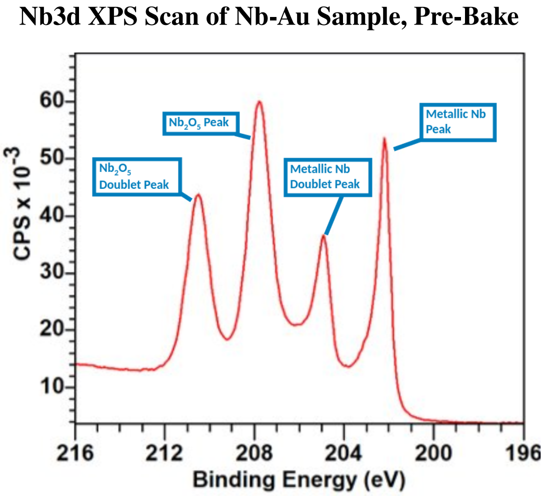
Figure 3: Diagram of the electroplating setup housed inside the inert atmosphere glovebox.

The setup utilizes a custom-built timing circuit[3] to obtain sub-second timing resolution at very low currents. The low deposition currents and times are necessary to obtain the very thin layers of gold recommended by the previous study [5]. The electroplating parameters for our initial sample study were chosen to produce a gold layer thickness of 1 nm of gold[4]. After deposition, the samples are removed from the glovebox and rinsed in deionized water to remove trace amounts of the plating solution. Once the samples are dry, they are scanned with XPS. XPS data from representative samples is shown in Fig. 5.

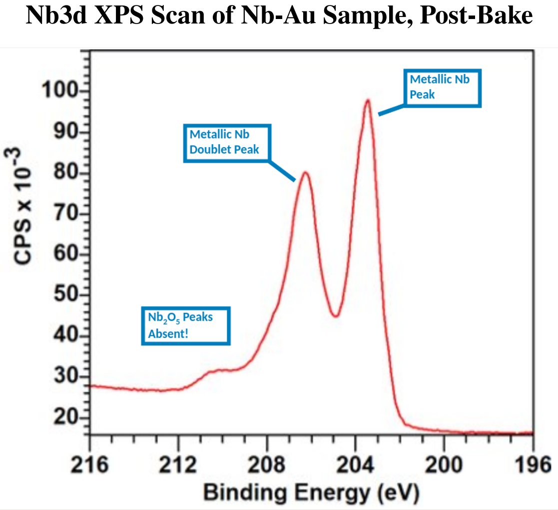
RESULTS AND ANALYSIS

Thermal Oxide Passivation

Exemplary plots from the sample study are shown in Fig. 4. Figure 4a shows the XPS results pre-baking. Both the metallic Nb and pentoxide Nb_2O_5 peaks and doublet peaks can clearly be seen. After baking, the Nb_2O_5 peaks have nearly vanished, as seen in Fig. 4b.


Nb3d XPS Scan of Nb-Au Sample, Pre-Bake

(a) XPS Nb3d scan of a niobium sample given a thin layer of gold. XPS scan was taken after deposition but before baking.


Nb3d XPS Scan of Nb-Au Sample, Post-Bake

(b) XPS Nb3d scan of the same niobium sample given a thin layer of gold. XPS scan was taken after deposition and baking.

Figure 4: XPS Nb3d scans of a niobium sample given a thin layer of gold via evaporation deposition.

Chemical Oxide Passivation

The XPS Au4f scan of the preliminary electroplated sample is shown in Fig. 5. Though the counts per second are quite low (only in the range of 2,000 CPS), there is a clearly distinguishable peak and doublet rising above the level of

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[3] The circuit is based on a 555 timer operating in astable operation mode, and is configurable to a wide variety of voltage, current, and time outputs.

[4] This thickness was calculated using the deposition rate of the electroplating solution as supplied by the manufacturer and assuming a linear scaling relationship between deposition rate and deposition current.

background. Since the sample was rinsed after the electroplating procedure and the electroplating solution is water soluble, we can be confident this signal comes from the surface layer of gold, not trace remnants of the plating solution.

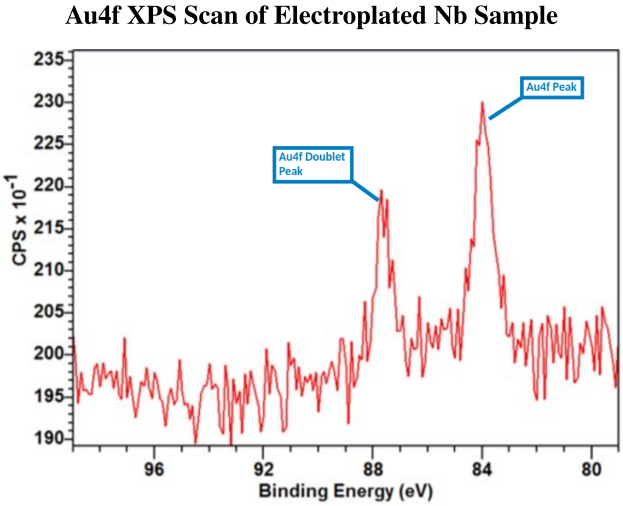

Figure 5: XPS Au4f scan of a niobium sample given a thin layer of gold via electroplating.

CONCLUSION

In conclusion, thermal oxide removal is a promising method for removing niobium oxide, and when performed after a thin gold layer deposition, the oxide remains substantially reduced after exposure to atmosphere. Additionally, the electroplating setup under development shows strong potential to be viable for very thin gold layer deposition on niobium. Future work will comprise of further optimization of the electroplating setup, with the goal of eventually applying the procedure to a full-scale 2.6 GHz SRF cavity.

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