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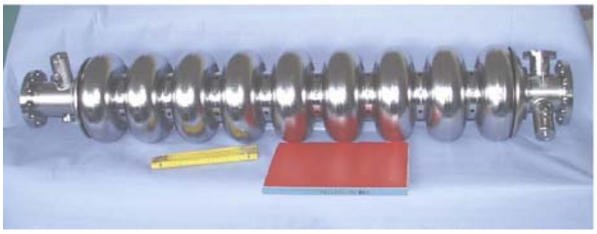

UHV Arc Deposition of Superconducting Niobium Films for RF Application

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Abstract

Recently the UHV arc technology was proposed as a possible alternative for depositing thin superconducting films of pure niobium on the inside surface of RF cavities for particle accelerators. The paper describes status of research on deposition of superconducting films for RF accelerating cavities. New UHV arc based devices with planar and cylindrical niobium cathodes are presented. The main results and characteristics of arc deposited thin superconducting niobium films as well as the progress obtained recently in formation such films are also shown.

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ABSTRACT

Recently the UHV arc technology was proposed as a possible alternative for depositing thin superconducting films of pure niobium on the inside surface of RF cavities for particle accelerators. The paper describes status of research on deposition of superconducting films for RF accelerating cavities. New UHV arc based devices with planar and cylindrical niobium cathodes are presented. The main results and characteristics of arc deposited thin superconducting niobium films as well as the progress obtained recently in formation such films are also shown.

KEYWORDS: Catodic arc, arc deposition, superconducting film, RF cavity

1. INTRODUCTION

The superconducting RF-cavities with high electric fields for the acceleration of charged particles in high-energy accelerators are made of purified (RRR $\geq$ 300) niobium (Nb). Copper cavities coated with thin niobium film have many merits if compared to bulk ones. Since the late 80s the magnetron sputtering technology has been applied for coating copper RF cavities. This technology is based on the deposition of pure niobium, in ultra-high vacuum (UHV) conditions by means of a cylindrical magnetron [1]. The main advantage of the Nb/Cu cavities, besides possible reduction of the fabrication costs, is to solve the problem of the heat dissipation, which is induced by the low heat conductivity of pure Nb. A thin Nb film determines the cavity superconducting behavior, while the high heat-conductivity copper substrate, thick enough to provide mechanical stability, does effectively transfer the heat produced inside the cavity to the liquid-He bath. It significantly increases the tolerable heat production level. In addition, the film magnetic field pinning energy is very high (of the order of 10^9 N/m^3), so that external magnetic fields of the order of the Earth-field do not create free fluxons leading to the energy dissipation [2]. It has also been shown [3] that superconducting properties of the film such as H_{c1}, R_{BCS}, T_c and R_{fl}, depend on the film purity only, and therefore on the mean free path λ, so that the purer the film the closer are its parameters to those of the bulk metal.

The present magnetron sputtering techniques appears to have some drawbacks. First of all, the magnetron-sputtered cavities, coated in an atmosphere of inert gas (typically Ar), are inevitably contaminated by the auxiliary gas itself. In addition, the observed film porosity, caused not only by the substrate roughness but also by angles of incidence of the Nb atoms on the cavity walls, added to the low-energy of the metal ions - may possibly be an important factor limiting the cavities performance. Both drawbacks are (if not eliminated) expected to be strongly reduced by depositing the Nb film by means of the UHV cathodic-arc technique. The cathodic arc deposition offers an excellent approach to producing, at very high rates, pure metal, alloy and compound films with excellent adhesion and density [4]. Its main disadvantage, productions of micro droplets, can be overcome, thanks to recent progress in magnetic filtering of arc plasma. In 2000 UHV cathodic-arc technique to the coating of cooper RF cavities was proposed [5-6].

2. UHV ARC DEPOSITION

The facts that the ion energy is relatively high, in the range of 10-100 eV, as compared to 5-10 eV observed in the magnetron-sputtering technique, and the ions have high average charge, are the main features of the vacuum arc process. Because of a high degree of the ionization, energies of the ions may be further increased by applying a negative bias to a conducting substrate. Such ions thus have sufficient energy to clean contaminant atoms off the surface prior to forming the coating, and sufficient mobility to diffuse to low free energy sites. High ion energy is thus the main factor responsible for much compacter films. Many cathodic arc deposition systems are actually in use in industry and research. They all work under (high) vacuum conditions (10^{-5}-10^{-6} hPa). In such conditions water vapors and hydro-carbides are important source of film contamination.

The crucial role during the formation of a thin superconducting niobium-layer is played by cleanliness of the deposition process. In order to achieve good properties of the superconducting film, the partial pressures of water, nitrogen, oxygen, $CO_{2,}$ hydro-carbides etc., must remain below ≈ 10^{-9} hPa during the deposition process.

Several of UHV arc-based devices with planar and cylindrical cathodes have been designed, constructed and investigated in the period from 2000. The pumping systems, in our case, are totally oil-free and all parts of the deposition devices are designed and built in accordance with the UHV-technology requirements. All vacuum chamber components and accessories, as well as all vacuum connections, are fabricated using only high purity materials: stainless-steel, OFHC copper and high-quality ceramics shielded from the arc. The cathode and all parts accessible to the arc are made of pure Nb with RRR ≥ 250 only. The basic pressure of the order of 10^{-10} hPa is reached after one night baking of the whole system at a temperature of 150 ^{0}C. The typical composition of residual gases before and after baking, recorded by a Residual Gas Analyzer (RGA), is shown in **Figure 1**.

The presented mass-spectra demonstrate very well differences between HV and UHV conditions, which are of primary importance for the deposition of pure metallic films. Another question is the initiation of vacuum arc discharges.

The reliable triggering (ignition) of the arc discharges is often a problem, even in industrial arc-based devices. In HV systems, thin layers of gasses and impurities formed upon the surface of electrodes, are beneficial in that sense that they facilitate the starting of an arc discharge. Under UHV conditions the high-temperature baking of the vacuum chamber removes almost totally such layers. These effects, as well as requirements that all other sources of impurities must be effectively removed, make the arc ignition more difficult.

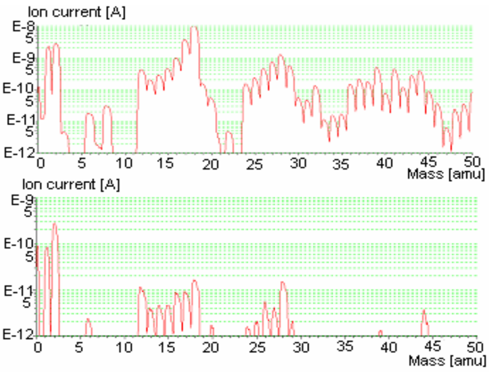


Fig.1 Typical RGA mass-spectra recorded before and after 24-hour baking at 150 ^{0}C.

After testing many known triggering methods from the point of view of operational reliability and cleanliness, we have finally decided to use a laser beam focused upon the cathode through a vacuum-tight glass window. Then the arc is triggered extremely reliably without introducing any additional impurity whatsoever [7]. Recently, the all our arc sources are equipped with Nd:YAG lasers (50-100mJ, 10ns), and the mastering of the laser ignition technique was decisive for improving properties of superconducting films.

At present seven different UHV arc based systems with planar or cylindrical niobium cathodes are in the operation at the University of Rome "Tor Vergata" and at IPJ in Swierk. Some of the investigated systems have been equipped with knee-shaped magnetic filters, specially designed for work under the UHV conditions, in order to enable a comparison of the deposited films (produced with and without filtering). A scheme of the UHV arc source with the planar cathode equipped with the magnetic filter is shown in **Figure 2**. Such systems we use for a deposition of thin niobium films on various substrates to study properties of formed superconducting layers. In future we will try to introduce niobium plasma into a copper cavity by means of magnetic and electric fields. Special UHV system for this purpose is under constructing in Rome.

An alternative being explored is that of using a linear geometry arc (cylindrical cathode) device that ideally meets the requirement of easily coupling to a single or multiple-cell cavity. The cylindrical cathode of such a system can in fact be placed along the cavity axis (like that of a cylindrical magnetron), with the arc discharge moving along it, either spontaneously or being magnetically driven. The new UHV device with the linear-arc source for single-cell cavity coating has been put into operation in Swierk in 2005, **Figure 3**.

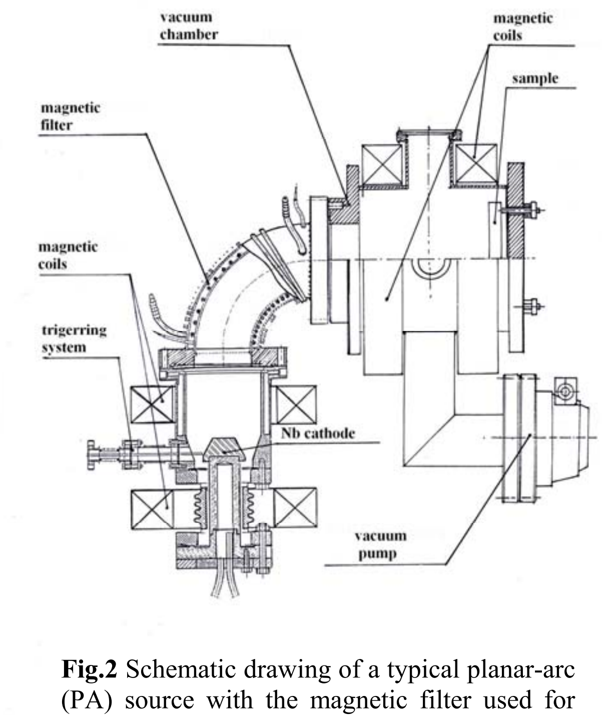


Fig.2 Schematic drawing of a typical planar-arc (PA) source with the magnetic filter used for the elimination of micro-droplets emitted from the cathode surface.

Fig. 3 UHV system with a linear-arc.

3. FORMATION OF NIOBIUM FILMS

In the planar arc systems there can be coated up to six sapphire- and Cu-substrates simultaneously. They can be mounted upon a sample holder consisting of a massive Cu (OFHC) flange, placed at a distance of about 50 cm from the cathode and kept at a constant temperature during the whole deposition process. The sample holder is electrically insulated from walls of the vacuum chamber, so that a bias of 20-100 V can be applied to the coated substrates. The lowest possible arc current for the stable operation in the present DC mode has been found to be about 60 A, while the available cooling system of the cathode has an upper limit of the arc current equal to about 140 A. The deposition rate achievable with the unfiltered PA source can be very high and its value depends on many factors, such as the arc current intensity, the cathode material, geometry, applied fields, etc. In our unfiltered system operated with arc currents of 120-140 A the deposition rate is 10nm/s, while within the present not-optimized FPA configuration it is about 5 times lower.

The sample temperature during depositions is usually recorded by means of thermocouples. Most samples have so far been deposited at temperatures close to the room temperature, and only a few ones have been investigated at higher temperatures (100-200 ^{o}C). As mentioned above, the residual pressure in our systems is usually set within the 10^{-10} hPa range. The pressure increases up to 10^{-6} -10^{-7} hPa when the arc discharge starts, and it remains almost stable at the latter value throughout the deposition process. The gas pressure rise during the arc discharge is found to be almost exclusively caused by hydrogen, which partial pressure is usually more than 3 orders of magnitude higher than that of other contaminants, as shown in **Figure 4**.

4. PROPERTIES OF SUPERCONDUCTING FILMS

The UHV arc-deposited Nb-layers on sapphire substrates have been characterized by measuring their critical temperature T_c and Residual Resistivity Ratio (RRR: defined as the resistivity at room temperature divided by the resistivity at 10 K). The critical temperature of the deposited material is in general very sensitive to impurities, e.g. very small amounts of oxygen in the Nb-film can lower its T_c value significantly. The Nb RRR is also very sensitive to impurities. Typical RRR values for Nb-films deposited by sputtering at a room temperature range from 2 to 10, and the Nb-films with RRR ≈ 25 are obtained either using as the auxiliary gas Kr instead of Ar or raising the substrate temperature to ≈ 250 °C.

The RRR values of our 1.5-µm-thick Nb films, deposited by means of vacuum arc upon the sapphire substrates at a room temperature, under the typical UHV conditions described above, range from 20 up to 50. A record value of RRR = 80 are obtained by heating up the substrate to the temperature of 150^{0} C.

The critical temperature (T_c) and critical current density (J_c) values of the deposited Nb films were measured by means of an inductive method. The best samples have shown the values identical to bulk Nb, i.e. $T_c = 9.26$ K, $\Delta T_c = 0.02$ K and $J_c = 3x10^{7}$ A/cm^2. Typical results, as obtained for several samples, are shown in **Figure 5** [8].

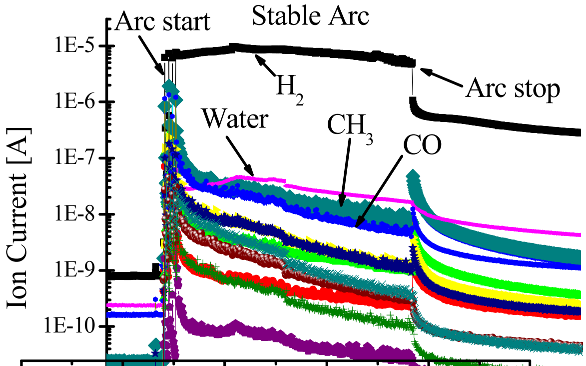
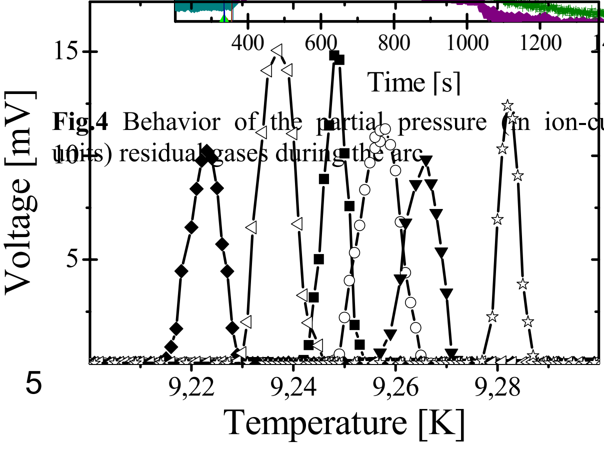


Fig.4 Behavior of the partial pressure (in ion-current units) residual gases during the arc.



The observed differences in T_c value, as compared to that of the high-purity bulk Nb value equal to 9.26 K, are small and can partially be attributed to small temperature differences between the thermometer and the investigated sample.

The main inconvenience of the arc coating is the production of micro-droplets. In our case, micro-droplets composed of high purity molten Nb are not expected to contaminate the film, but they increase its surface roughness, and in a high electric field environment they may become field-emitters. The presence of micro-droplets upon the surface of our films was studied by means of optical- and electron-microscopy. Using a 500X magnification optical microscope, pictures of the sample surface were taken at 10 different randomly chosen locations and analyzed using a LabView computer code. It measured and recorded the number and size of the droplets present in the microscope (fixed area) observation field. The distribution of the droplet density as a function of the droplet size, as measured upon the surface of 4 different samples deposited under comparable conditions, is shown in **Figure 6.** When the magnetic filter is applied, the deposition rate is reduced by a factor of 5 with respect to that of the unfiltered system, as it was mentioned above, however the magnetic filter can reduce the number and dimensions of the deposited micro-droplets (macro-particles) drastically, as one can observe in **Figure 7**.

Fig.5 Transition curves measured for several samples of Nb-layers deposited upon Cu- and sapphire-substrates by means of UHV arc discharges.

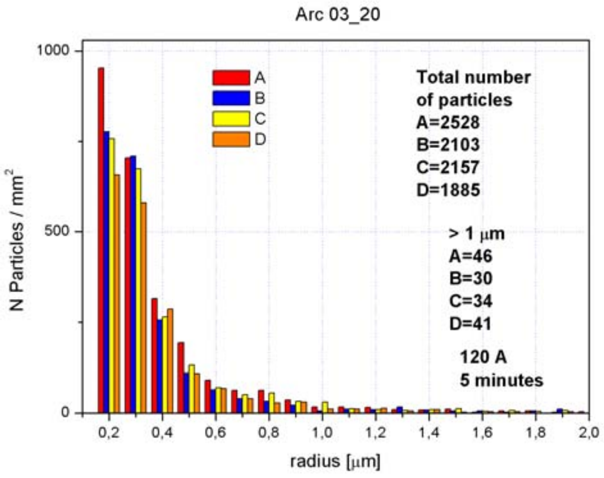


Fig.6. Typical histogram showing the surface density of the micro-droplets visible upon surfaces of four UHV arc-deposited samples (denoted by A, B,C and D).

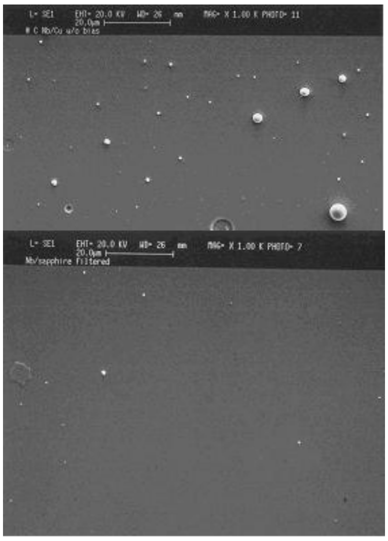


Fig.7 Surface of the Nb coating obtained with the use of the unfiltered UHV arc (upper) and filtered UHV arc (bottom).

5. CC

The paper presents status of research on deposition of Nb films for superconducting RF accelerating cavities. Several cathodic-arc sources working in UHV conditions have been designed and constructed to study the deposition of super conducting Nb films. Performed studies have already shown that thin niobium films, which were deposited by arc-discharges under UHV conditions, demonstrate similar properties to pure bulk niobium. Their RRR values and critical temperature are better, as compared to Nb magnetron sputtered films deposited at the same temperature. The filtered UHV arc system was also used to produce quasi micro-droplet-free samples. Coating of the inner surface of the copper 1.5GHz single cell cavity is currently under development.

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