Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Vacuum 80 (2006) 1288–1293
VACUUM
SURFACE ENGINEERING, SURFACE INSTRUMENTATION & VACUUM TECHNOLOGY
www.elsevier.com/locate/vacuum

Deposition of superconducting niobium films for RF cavities by means of UHV cathodic Arc

J. Langner[a,*], R. Mirowski[a], M.J. Sadowski[a], P. Strzyzewski[a], J. Witkowski[a], S. Tazzari[b], L. Catani[b], A. Cianchi[b], J. Lorkiewicz[b], R. Russo[c]

[a]*The Andrzej Soltan Institute for Nuclear Studies, Swierk near Warsaw 05-400, Poland*
[b]*INFN Roma2 and University Tor Vergata, Roma, 001333 Italy*
[c]*Seconda Università di Napoli, INFN-NA, Napoli, Italy*

Abstract

The Ultra-High-Vacuum (UHV) arc technology was proposed as an alternative for depositing thin superconducting films of pure niobium on the internal surfaces of RF cavities for particle accelerators. The paper describes status of research on the deposition of such films for the RF accelerating cavities. UHV arc-based devices, equipped with planar- or cylindrical-cathodes, are described. The main results of experiments and some characteristics of the arc-deposited thin Nb-films, as well as results obtained recently with the formation of such films, are also presented. The critical temperature T_c of the deposited Nb-films appeared to be very close to that of pure bulk niobium ($T_c = 9.26\,K$) and the transition to the superconducting state was very narrow. The deposited Nb-films had higher residual resistivity ratio (RRR) values (up to 80) and larger grains sizes, as compared with those sputtered at the same temperature. The paper also presents recent results of the Cu-cavity coating by means of an UHV linear (cylindrical) arc, operated at IPJ in Poland.

Keywords: Cathodic arc; Arc deposition; Superconducting film; RF cavity

1. Introduction

The superconducting RF-cavities with high electric fields, needed for the acceleration of charged particles in high-energy accelerators, are made of purified (Residual Resistivity Ratio: RRR$\geqslant$300) niobium (Nb). Copper cavities coated with thin niobium film have many merits in a comparison with bulk-Nb ones. Since the late 1980s the magnetron sputtering technology has been applied for the coating of copper RF cavities. This technology is based on the deposition of pure niobium at 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 solving 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 of a Cu-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 fluxion leading to the energy dissipation [2]. It has also been shown [3] that superconducting properties of the film depend on the film purity only, and therefore on the mean free path λ. Hence, the purer is the film, the closer are its parameters to those of the bulk metal.

The present magnetron sputtering techniques appears to have some evident drawbacks. First of all, the magnetron-sputtered cavities, coated in an atmosphere of an inert gas (usually Ar), are inevitably contaminated by auxiliary gas itself. In addition, the observed film porosity, caused not only by the substrate roughness but also by angles of incidence of Nb atoms upon the cavity walls, added to the low energy of the deposited metal ions, may be important

*Corresponding author. Fax: +48 22 7193481.
E-mail address: langner@ipj.gov.pl (J. Langner).

0042-207X/$ - see front matter
doi:10.1016/j.vacuum.2006.01.057

factors limiting the cavities performance. Both drawbacks (if not eliminated) are 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 pure metal-, alloy- and compound-films at very high rates, and with the excellent adhesion and density [4]. Its main disadvantage, the production of micro-droplets, can be overcome due to recent progress in magnetic filtering of arc plasmas. The UHV cathodic-arc technique for the coating of cooper RF cavities was proposed in 2000 [5–6]. Since that time some progress has been achieved. The paper describes the developed technique, its advantages and some technical problems. Moreover, the recent result—the first coating without any micro-droplet filtering of a single-cell designed for 1.5 GHz—is presented.

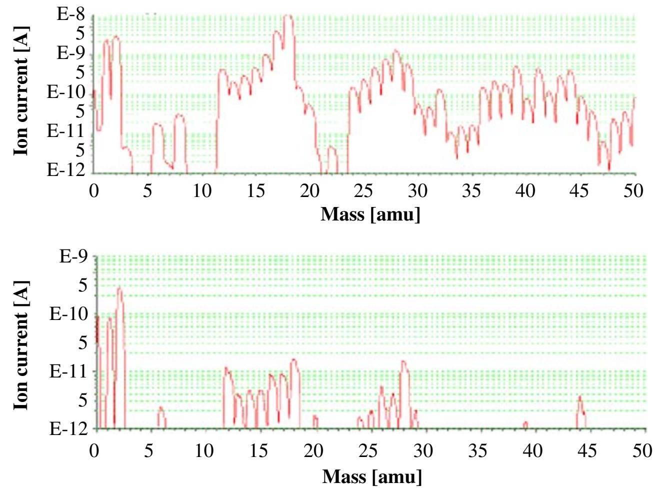

Fig. 1. Typical RGA mass-spectra recorded before (upper) and after 24-h baking at 150 °C (bottom).

2. UHV arc deposition

The facts that the ion energy value is relatively high (in the range of 10–100 eV), as compared with that (5–10 eV) observed in the magnetron-sputtering technique, and the produced ions have high average charge, are the main features of the vacuum arc process. Due to 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 can 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 denser films. Many cathodic-arc deposition systems are in use in industry and research, but they usually work at relatively high pressures (10^{-3}–10^{-4} Pa). In such conditions water vapors and hydro-carbides are important sources of film contaminations.

During the formation of thin superconducting niobium layers the crucial role is played by cleanliness of their deposition process. In order to achieve good properties of the deposited superconducting film, the partial pressures of water, nitrogen, oxygen, CO_2, hydro-carbides etc., must remain below 10^{-7} Pa during the whole deposition process.

Several of UHV arc-based devices, equipped with planar- and cylindrical-cathodes, have been designed, constructed and investigated since 2000. The pumping systems, in our case, have been oil-free ones, and all parts of the deposition devices were designed and built in accordance with the UHV-technology requirements. All the vacuum chamber components and accessories, as well as all vacuum connections, were fabricated using only high purity materials: stainless-steel, oxygen free (OFHC) copper and high-quality ceramics (shielded from the arc). The cathode and all the parts accessible for the arc itself are made of pure Nb with RRR $\geqslant 250$ only. The basic pressure of the order of 10^{-8} Pa was reached after one-night baking of the whole system at a temperature of 150 °C. The typical mass-spectra of residual gases before baking and after 12-h baking, which were recorded by a Residual Gas Analyzer (RGA), are shown in Fig. 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 UHV arc ignition more difficult.

After testing different triggering methods from the point of view of the operational reliability and cleanliness, we have finally decided to use a laser beam introduced through a vacuum-tight glass window and focused upon the cathode surface. Under such conditions the arc is triggered very reliably, without introducing additional impurities [7]. Recently, all our arc-sources have been equipped with Nd:YAG lasers (operated at 50–100 mJ, in 10 ns pulses), and the mastering of the laser ignition technique has appeared to be decisive for improving properties of the deposited superconducting films.

At present seven different UHV-arc systems, equipped with planar- or cylindrical-cathodes made of pure niobium, are in the operation at the Tor Vergata University in Rome, Italy, and at IPJ in Swierk, Poland. In order to enable a comparison of the deposited films (produced with and without filtering), some of the investigated systems have been equipped with knee-shaped magnetic filters, designed especially for the operation under the UHV conditions. An exemplary scheme of the UHV arc-source