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Improvements of performance on sputter-coated niobium films for superconducting cavities by adding a NbN interlayer

Jiankui Hao *, Fei Jiao, Datao Xie, Kui Zhao

MOE Key Laboratory of Heavy Ion Physics, Institute of Heavy Ion Physics, Peking University, Beijing 100871, PR China

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Abstract

A new type of superconducting film is studied at Peking University in order to improve the properties of sputter-coated films for superconducting cavities. NbN film and NbN–Nb film have been prepared by DC diode sputtering technology at certain nitrogen content and temperature. NbN film is prepared between copper and Nb film as a barrier against copper diffusion into Nb. Micro-structure analyses show that the NbN–Nb films grow well on the copper substrate. The T_c of the Cu–NbN–Nb increases to 9.5 K compared to the 9.2 K transition temperature of bulk Nb.

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Keywords: NbN thin film; Superconducting cavity; Sputtering

1. Introduction

RF superconducting cavities are used more and more widely in accelerators due to the very low loss at liquid helium temperature [1,2]. The niobium is the usual material for the superconducting cavities. The surface resistance R_s of the superconducting cavity consists of BCS resistance R_{BCS} and residual resistance R_{res} [3]:

$$R_s = R_{BCS} + R_{res} = \frac{A}{T} f^2 \exp\left[-\frac{\Delta(0)}{k_B T_c}\frac{T_c}{T}\right] + R_{res} \quad (1)$$

where R_{res} is only related with the material, A is a material parameter, T is the temperature in K, f is the resonant frequency of the cavity, $\Delta(0)$ is the energy gap of the superconducting material, k is the Boltzmann constant and T_c is the critical temperature of a superconductor.

From Eq. (1), we can see that the surface resistance increases with the square of the frequency. For low frequency superconducting cavities, the surface resistance is not as high as the high frequency superconducting cavities. The low frequency superconducting cavities can run at 4.2 K so that the cost of the cryogenic system can be reduced greatly. It is very important to improve the thermal conductivity of the superconducting cavities since the thermal conductivity of niobium is not so good.

Niobium film superconducting cavities are developed in the past years at CERN, INFN-LNL, JAERI, ANU, etc. [4–7]. Niobium-sputtered copper cavities are the typical film cavities. A few microns of niobium films are coated on the surface of oxygen free high conductance (OFHC) copper cavities by sputtering technology. The high thermal conductivity of OFHC copper can improve the whole thermal conductivity of the cavity. At the same time, the cost of the cavity is also decreased. Niobium-sputtered cavities can also be used for high frequency conditions. However, the accelerating gradient of sputtered cavities is not as high as bulk niobium cavities. For 1.5 GHz cavities, the highest gradient is about 20 MV/m which is far below the gradient of bulk niobium cavities, ~40 MV/m.

Peking University has done a lot of researches on niobium-sputtered quarter wave resonator (QWR) [8]. A lot

* Corresponding author. Tel.: +86 10 62767160; fax: +86 10 62758849.
E-mail address: jkhao@pku.edu.cn (J. Hao).

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of work has been carried out to improve the quality of niobium film. One idea is to add an interlayer between the copper and the niobium film. The niobium nitride is selected as the interlayer. NbN is a superconductor with the T_c of about 16 K. Investigations indicate that the NbN and other nitrides can act as the diffusion barrier material [9–11]. The performance of niobium film can be improved by reducing the diffusion of the copper into the niobium.

In this paper, we report the researches on Cu–NbN–Nb multilayer films for superconducting cavities.

2. Experimental

NbN films and NbN–Nb films were prepared by DC diode sputtering technology. Fig. 1 is the principle to prepare the films. NbN films were prepared by DC diode reaction sputtering. A high pure niobium disc target with diameter of 200 mm is the cathode. An OHFC copper disc substrate mounted with several samples acts as the anode. A heater is mounted above the copper disc. There are two gas inlets in the vacuum chamber, one is for argon and the other is for nitrogen. Negative high voltage is applied on the niobium target. Argon is ionized under certain pressure when high voltage is applied. The niobium atoms are bombarded out by the argon ions. If the pressure of nitrogen is available, the NbN films can be deposited on the substrate. A small bias voltage is applied on the substrate to eliminate the contaminants on the surface of the substrate. Experiments showed that the films generated with bias voltage were better than those without bias voltage [8].

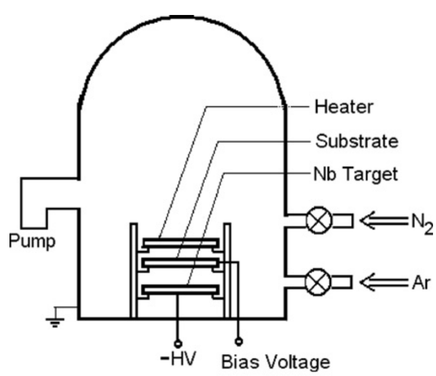

Fig. 1. Schematic drawing of the sputtering system for preparation of NbN and NbN–Nb film.

Sputtering parameters such as sputtering voltage, sputtering current, gas pressure, the ratio of Ar versus N_2 and the sputtering temperature are changed to get the optimal conditions. The background vacuum is better than 5×10^{-6} Pa. The sputtering voltage is 0.9–1.4 kV. The gas pressure is about 8–15 Pa during the sputtering. To prevent the target from overheating, interval sputtering method are adopted. It takes 20–25 min for each sputtering. There are 2 h between each two sequential sputtering.

Silicon and OFHC copper samples are installed on the surface of the substrate to get the NbN and NbN–Nb films. The films on silicon are used to do X-ray diffraction (XRD) analysis and scanning electron microscope (SEM) measurements. The films on copper samples are used for T_c and residual resistance ratio (RRR) tests.

When the parameters of preparing the NbN film are optimized, studies on NbN–Nb films are carried out. After one layer of NbN film is coated on the substrate samples, the N_2 gas flow is stopped so that Nb films are prepared on top of the NbN films. The argon pressure is 10–14 Pa. The NbN layer is about 100–200 nm. SEM and T_c measurements are carried out for different NbN–Nb film samples.

3. Results and discussion

Fig. 2 gives the result of XRD analysis of NbN films prepared at different gas ratio and different substrate temperature. The ratio of N_2 and Ar changes from 1:12 to 1:5. The substrate temperature varied from room temperature to 300 °C. From Fig. 2, we can see that higher substrate temperature helps to form NbN films. At 200 °C, we mainly get Nb_2N films. At 300 °C, we obtain NbN film

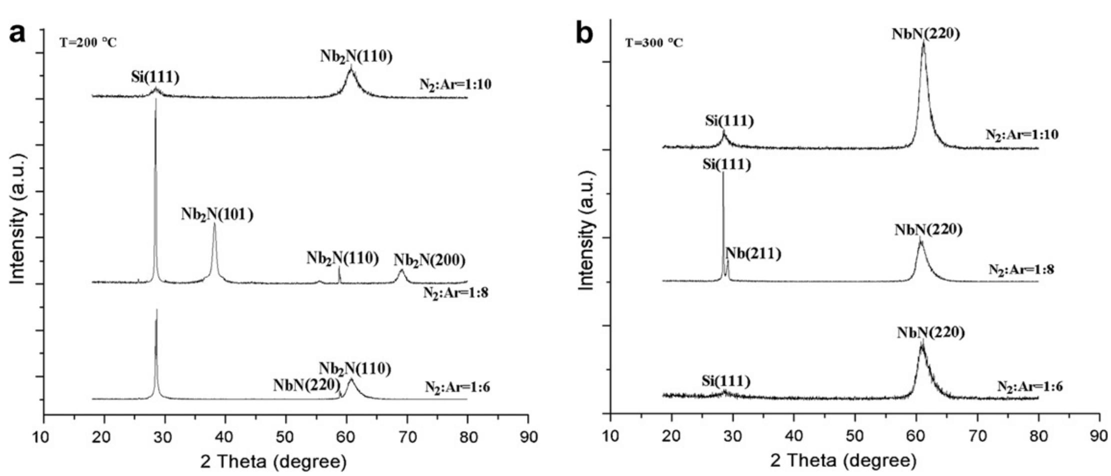

Fig. 2. XRD analysis of NbN films prepared on silicon at different temperature and N_2 content. (a) $T = 200$ °C and (b) $T = 300$ °C.