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Full Length Article

Room-temperature growth of thin films of niobium on strontium titanate (0 0 1) single-crystal substrates for superconducting joints

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ABSTRACT

With the eventual aim of forming joints between superconducting wires of $YBa_2Cu_3O_{7-\delta}$ (YBCO), thin films of Nb were grown at room-temperature on $SrTiO_3$ (STO) (0 0 1), a single-crystal substrate that shows good lattice matching with YBCO. The crystallinity, surface morphology, and superconducting properties of the Nb thin films were investigated and compared with those of similar films grown on a silica glass substrate. The Nb thin films grew with an (*hh*0) orientation on both substrates. The crystallinity of the Nb thin films on the STO substrate was higher than that on the silica glass substrate. X-ray diffraction measurements and observation of the surface morphology by atomic-force microscopy indicated that Nb grew in the plane along the [1 0 0] and [0 1 0] directions of the STO substrate. This growth mode relaxes strain between Nb and STO, and is believed to lead to the high crystallinity observed. As a result, the Nb thin films on the STO substrates showed lower electric resistivity and a higher superconducting transition temperature than did those on the silica glass substrates. The results of this study should be useful in relation to the production of superconducting joints.

1. Introduction

Wires made of rare-earth-type high-temperature superconductors $REBa_2Cu_3O_{7-\delta}$ (REBCO) are expected to be used in the next generation of high-magnetic-field magnetic resonance imaging (MRI) equipment [1–5]. Consequently, a technique for fabricating superconducting joints is required for the development of the next generation of MRI equipment [6]. There are two possible schemes for producing superconducting joints on REBCO wires. The first is the formation of direct joints between the REBCO layers of the wires. The superconducting properties of REBCO are strongly influenced by the direction and the composition of the crystals [6]. Consequently, there is a concern that the superconducting characteristics might deteriorate as a result of deviations in the direction of the REBCO crystals in the joint portion, and of deoxidation as a result of high-temperature heat treatment [6]. Although a direct-joint method for joining REBCO wires has been reported, it involves a complicated technique, and prolonged heat treatment is necessary [7,8].

The second scheme for forming superconducting joints involves the formation of an indirect joint in which the REBCO layers in the wire are bridged and joined through another superconductor. We recently studied this joint scheme and found that a thin film of Nb might be a suitable superconductor for forming joints. Nb is a typical superconductor that has high chemical stability and good processability; it is used in superconducting quantum-interference devices and in rapid single-flux quantum circuits [9–12]. In joints formed from Nb, although the superconducting transition temperature (T_c) of Nb is approximately 9 K [13], its superconducting properties are unaffected by crystal orientation compared with that of REBCO. Furthermore, heat treatment of the joint is unnecessary because it is possible to form superconducting thin films of Nb by deposition at room-temperature [14,15]. Formation of joints at room-temperature suppresses the production of oxygen vacancies in REBCO, and prevents deterioration of its superconducting properties.

To use thin films of Nb as joints for REBCO superconducting wires, it will be necessary to form the Nb thin films on the REBCO substrate. However, the growth of Nb thin films on REBCO has not been investigated in detail. For this reason, information on the growth of Nb thin films is required first. Single-crystalline $SrTiO_3$ (STO) (0 0 1) is a typical perovskite substrate that shows good lattice matching with REBCO (0 0 1). For example, the lattice mismatch between $YBa_2Cu_3O_{7-\delta}$ (0 0 1) and STO (0 0 1) is approximately 1.2% [16,17].

In the present study, Nb was deposited on $SrTiO_3$ (STO) (0 0 1) as a preliminary study for the deposition of Nb on REBCO. We investigated the crystallinity, the surface morphology, and the

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superconducting properties of a Nb thin film deposited on an STO substrate at room-temperature. In addition, to evaluate the comparative effects of the substrate material, we also examined a Nb film deposited on a silica glass substrate.

2. Experiments

The Nb thin films were deposited on STO (0 0 1) single-crystal substrates and silica glass substrates by radio-frequency (RF) magnetron sputtering using a Nb (99.9%) target of φ = 2.54 cm. The sputtering chamber was evacuated to 10^{-5} Pa, and Ar gas was introduced into the chamber to maintain a pressure of 1.0 Pa. The RF power was set to 70 W, and the distance between the target and the substrate was set to 25 mm. The substrate was at room-temperature. The final film thickness for each sample was typically 400 nm.

The X-ray diffraction (XRD) patterns of the thin films were measured by a θ–2θ scan and by a φ scan, which were obtained by using an X'Pert diffractometer (Malvern PANalytical B.V., Almelo, Netherlands) and a SmartLab diffractometer (Rigaku Corp., Tokyo, Japan), respectively, with Cu Kα radiation sources. The surface crystallinity of the thin films was investigated by reflection high-energy electron diffraction (RHEED) (kSA 400; k-Space Associates, Inc., Dexter, MI, USA). The crystallinity inside the thin film was evaluated by observing cross-sections of the thin films by scanning transmission electron microscopy (STEM) (JEM-ARM 200F; JEOL Ltd., Tokyo, Japan). The surface morphologies of the thin films were observed by atomic-force microscopy (AFM) (SPM-9700; Shimadzu Corp., Kyoto, Japan). To evaluate the superconducting properties, the electric resistivity in the absence of a magnetic field was measured from 300 K to 2 K by a four-terminal method using a physical-property measurement system (PPMS; Quantum Design Inc., San Diego, CA, USA).

3. Results and discussion

Fig. 1(a) shows the XRD patterns of the Nb thin films deposited on STO and silica glass at room-temperature. Peaks attributable to (*hh*0) of Nb were observed on the STO substrate and also on the silica glass substrate, showing that the Nb thin films crystallized at room-temperature. The Nb crystal, which has a body-centered cubic lattice, was oriented in the (*hh*0) direction, even on amorphous silica glass, because (*hh*0) is the densest plane in the Nb crystal. Intensities and full widths at half maximum (FWHM) of the Nb 110 peaks were 72,000 cps and 0.26° for the Nb thin film on the STO substrate, 4000 cps and 0.42° for that on the silica glass substrate, respectively. The stronger peak intensity and narrower FWHM of the Nb thin film on the STO substrate indicate higher crystallinity of that on the STO substrate. Fig. 1(b) shows the φ scan XRD pattern of the Nb thin film on the STO substrate, measured to investigate the in-plane orientation. In the φ scan measurement, a tilt angle of the sample stage and a θ–2θ angle were set so that the diffraction peak from Nb (*h*00) was measured. Subsequently, the XRD pattern was obtained by rotating the sample stage while maintaining the tilt angle and the θ–2θ angle. Consequently, if all the Nb lattices were arranged in the same direction in the plane, peaks should have been detected every 180° of rotation, whereas they were actually detected every 90°. This suggests that some of the Nb lattices were rotated by 90° in the (*hh*0) plane. In addition, the intensities of all the peaks were similar, showing that almost identical numbers of rotated and nonrotated Nb lattices were present. Fig. 1(c) shows the RHEED pattern of the STO substrate sample. The presence of a streak pattern showed that the Nb thin film has a high crystallinity up to the surface.

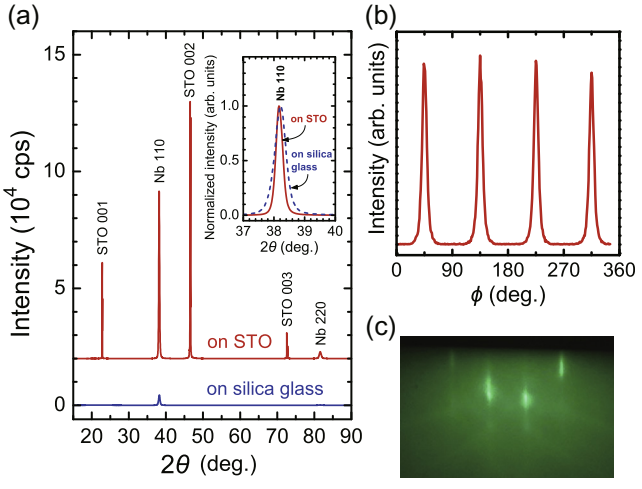

Fig. 1. (a) θ–2θ scan XRD patterns of thin films of Nb deposited on an STO substrate and a silica glass substrate. The XRD pattern of the thin film on the STO substrate is shown shifted by 20,000 cps. The inset shows a magnification of the Nb 1 1 0 peaks normalized by the Nb 1 1 0 peak intensities. (b) φ scan XRD pattern of the Nb thin film on the STO substrate. XRD peaks were detected every 90°. (c) RHEED pattern of the Nb thin film on the STO substrate. A streak pattern was observed.

To investigate the atomic arrangement inside the Nb thin film on the STO substrate, we recorded the cross-sectional STEM image shown in Fig. 2. The regularly aligned white stripes were attributed to Nb atoms. The spacing between the stripes is 0.24 nm, which corresponds to the interplanar spacing of Nb (1 1 0). The cross-sectional STEM image confirmed that (*hh*0)-oriented growth of Nb had occurred. The observed Nb atoms were not spherical, but were connected in lines. This indicated that the front Nb lattices overlap the rear Nb lattices with a different in-plane orientation. The cross-sectional STEM image is consistent with the results obtained from XRD.

Fig. 3 shows the surface AFM images of the Nb thin films on the STO substrate and the silica glass substrate. The average roughness R_a was 0.9 nm for the STO substrate sample and 1.0 nm for the silica glass substrate sample, confirming that the surfaces of both films were flat. Mesh-like elongated grains were observed in the Nb thin film on the STO substrate, and the mesh was oriented along the [1 0 0] and [0 1 0] directions of the STO substrate. On the other hand, in the Nb thin film on the silica glass substrate, elongated grains oriented in random directions were observed.

The difference between the surface morphology of the sample on the STO substrate and that on the silica glass substrate is due to the different structures of the substrates. The mesh structure observed for the Nb thin film on the STO substrate is considered to arise from the lattice structure of the STO (0 0 1) and the Nb (1 1 0) planes (Fig. 4). The STO (0 0 1) lattice is a square lattice of 0.39 nm on each side, whereas the Nb (1 1 0) lattice is rectangular with a long side of 0.47 nm and a short side of 0.33 nm [16,18]. In other words, the length of the long sides of the rectangular lattice is longer than the length of the sides of the square lattice, whereas the length of the short sides of the rectangular lattice is shorter than that of the sides of the square lattice. The mismatch between the length of the sides of the square and those of the rectangle have large values of 19.9% for the long side and −15.2% for the short side. Consequently, it is difficult for Nb to grow in a consistent in-plane direction on the STO because a large strain accumulates. Actually, as shown in the XRD φ scan, half the Nb lattices were rotated by 90°. The lengths of the diagonals of the lattices were 0.55 nm for STO and 0.57 nm for Nb. The mismatch is as small as 3.8%. The existence of the Nb lattices mutually rotated by 90° is considered to be effective in relaxing the distortion of the interface as a whole. The mesh shape of the thin film surface was caused by