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Anisotropic I–V characteristics of spontaneously emerged periodic stripes of superconducting NbN thin films on Si trench sidewall by RF magnetron sputtering

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ABSTRACT

To realize a highly integrated thin film superconductive coil, sputter-deposition of NbN on a trench sidewall of Si substrate was examined. A trench of 0.2 mm in depth was fabricated by Si Deep-RIE. A Nb target was sputtered in Ar/N_2 mixed gas flow. Thanks to the periodic corrugated structure formed by repeated Deep-RIE process, it was found that NbN superconducting lateral stripes connected with each other with thinner NbN thin film were spontaneously emerged. The superconducting properties along and across the stripes were completely different. Along the stripes, the *I–V* curves showed supercurrent. Additionally, the undulations were observed in *I–V* curves below Tc indicating the existence of the inhomogeneity of such as thickness, having different J_c depending on the position in the stripes. The normal conductivity along the stripes is almost five times higher than that across the stripes. Across the stripes, clear supercurrent was observed in the films formed in N_2 flow rate lower than 12%, indicating the stripes were connected with a thin superconductive layer in between. In the films formed in N_2 flow rate over 14%, no supercurrent was observed but the conductance increased with temperature indicating tunneling conduction. The obtained novel structure can be looked upon as a spontaneously emerged multifilamentary superconducting wire possibly applicable to produce high magnetic field.

1. Introduction

Electrical energy storage is getting more and more importance in accordance with increase in renewable energy electrical power sources which is inevitably accompanied with serious fluctuations. There are typically four means to store electricity, such as, (1) pumping-up hydroelectric power plant, (2) rechargeable battery, (3) flywheel energy storage system and (4) superconducting magnetic energy storage (SMES). By introducing electrical current into a superconducting coil, the electrical current is ideally preserved eternally without resistive loss. Here, the energy is stored substantially as a magnetic field generated by the eternal current in the coil. There are three advantages in SMES as follows, (1) Energy dissipation is negligibly small because of zero resistivity for the stored eternal current, (2) Since the inlet and outlet of energy from SMES is done only through electricity accompanied by no chemical reaction process, degradation of the system is expected to be fairly limited, (3) It is possible to extract very large current from SMES in very short time. However, conventional SMES is fabricated winding superconducting wire which is essentially stiff and difficult to be deformed, resulting in a large system with its capacity as large as 1 GJ [1]. Because of the high cost of construction together with high running cost of refrigeration, applications of superconducting coils and magnets are very limited only for medical application such as MRI and high magnetic field apparatuses for research purposes.

To open a new door to the application of SMES, a much more compact one with higher energy storage density was designed and proposed here based on the planar micro-fabrication technology prevalently used in semiconductor process. Let it be called as micro SMES, here. The idea is basically a usage of superconducting thin films patterned into spiral shape which essentially works as

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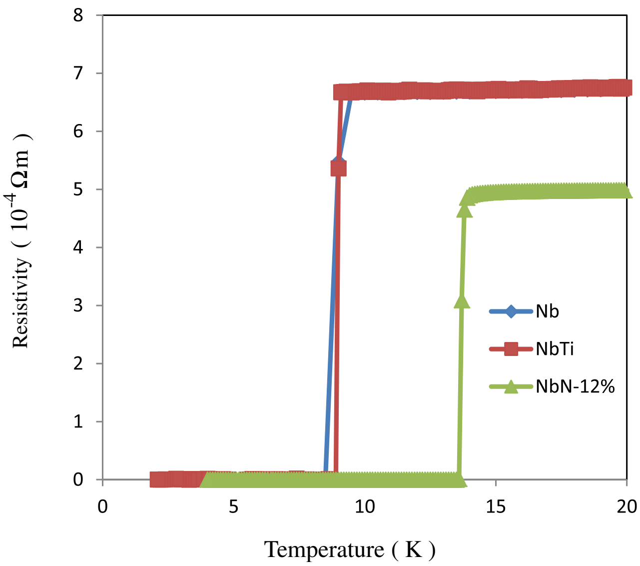

Fig. 1. Temperature dependence of resistivity of Nb, NbTi, NbN12% thin films sputtered on Si substrate.

a superconducting magnet. However, the superconducting permanent current stored in the coil make magnetic field which in turn induces an expansive force (hoop force) on the coil toward radial direction, forcing the superconductive thin film to peel off from the substrate. To avoid this, filling up a coil-shaped trench fabricated on Si wafer with superconducting substance (damascene process) is attempted, resulting in the compensation of expansive force (hoop force) induced on the superconducting substance in the trench by reaction force from the trench sidewall. This planar micro-fabrication process is well established in semiconductor process and easier than the fabrication process of conventional superconducting coil made of brittle superconductive wires.

As for superconductive substance, NbTi and NbN are surveyed because of their mechanical strength and superconductivity even in the high magnetic field as high as 10 T [2,3]. The metallic Nb is also tested for reference.

There can be several methods to fill up the trench with superconductive substances, such as sputter deposition, electroplating, electroless plating, etc. In this work, sputter deposition is employed and the superconductive properties of the initial stage of deposition were evaluated.

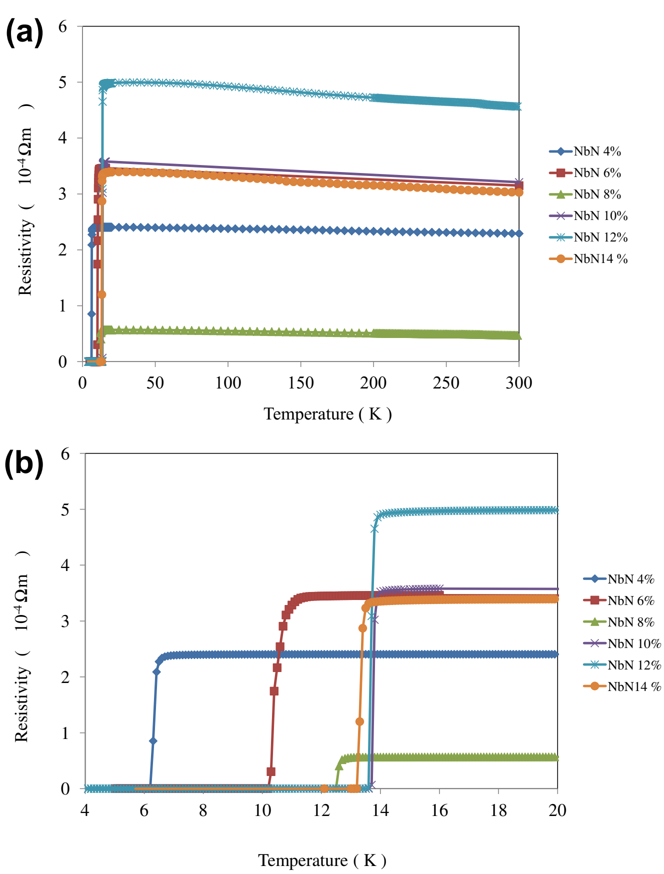

Fig. 2. Temperature dependence of resistivity of NbN 4–14% thin films sputtered on Si substrate. (a) 4–300 K, (b) 4–20 K.

2. Experimental

2.1. Fabrication of Nb, NbTi and NbN thin films on planar Si(110) wafer substrate by sputter-deposition

A sputtering target such as Nb or NbTi of 4 inches in diameter was located under the substrate at a distance of 180 mm with its surface normal inclined at an angle of 30° form the surface normal of the substrate so as to prevent the reversely accelerated ionized particles from hitting the substrate. RF power of 1 kW was applied to the magnetron type sputter target by matching the impedance to have negligibly small reflected power. Before deposition experiment, sputtering vacuum chamber was evacuated up to 2×10^{-5} Pa using a cryopump so as to eliminate water vapor content as low as possible. The substrate is heated to keep 423 K during the deposition and rotated around vertical axis at 20 rpm.

The deposition of Nb or NbTi films was performed at an ambience of 0.5 Pa Ar gas by setting the Ar gas flow at 50 sccm with a mass-flow meter. This realized the growth of thin films at a rate of 20 nm/min. As for NbN films, N_2 gas flow was added to Ar gas flow so as to keep total gas flow at 50 sccm. Here, the conditions of N_2 gas flow were chosen to be 4%, 6%, 8% 10% 12% and 14% of the total gas flow of Ar and N_2. The deposition rate decreased with the increase of N_2 gas flow. The total deposition time was fixed to 60 min.

2.2. Trench formation on Si(110) wafer substrate by Deep-RIE (reactive ion etching)

As a model of the targeting trench structure for thin film deposition, a photo-resist pattern was formed in accordance with the conventional photo-process using i-line stepper. Using this pattern as a mask, reactive-ion-etching of naked Si surface based on Bosch method [4] was repeatedly performed to result in formation of a deep trench of 0.1 mm in width and 0.2 mm in depth in 30 min. A high speed RIE apparatus: MUC-21 by Sumitomo Precision Products was used for this Deep-RIE process.

2.3. Evaluation of superconducting properties

A low temperature prober system TTP4 by Lakeshore Inc. and PPMS system by Quantum Design Ltd. were used for evaluation of superconducting properties of the film samples mentioned above. The conditions of measurements were 4–300 K, 0–1 T in the former apparatus TTP4 and 2–300 K, 0–9 T in the PPMS system, respectively.