Fabrication of Niobium Nanobridge Josephson Junctions

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Abstract. To realize antenna-coupled Josephson detectors for microwave and millimeter-wave radiation, planar-type Nb nanobridge Josephson junctions were fabricated. Nb thin films whose thickness, the root mean square roughness and the critical temperature were 20.0 nm, 0.109 nm and 8.4 K, respectively were deposited using a DC magnetron sputtering at a substrate temperature of 700°C. Nanobridges were obtained from the film using 80-kV electron beam lithography and reactive ion-beam etching in CF₄ (90%) + O₂ (10%) gases. The minimum bridge area was 65 nm wide and 60 nm long. For the nanobridge whose width and length were less than 110 nm, an I-V characteristic showed resistively-shunted-junction behaviour near the critical temperature. Moreover, Shapiro steps were observed in the nanobridge with microwave irradiation at a frequency of 6 - 30 GHz. The Nb nanobridges can be used as detectors in the antenna-coupled devices.

1. Introduction

It is well known that the Dayem bridge has one of the simple device structures which show the Josephson effect. The bridge width and length should be comparable to the coherence length \( \xi \) of a superconducting material. Since \( \xi \approx 38 \) nm for Nb, this bridge is called nanobridge [1]. Recently, nanobridges can be successfully obtained, because electron beam lithography (EBL) technology is highly developed, e.g. the minimum width of a line pattern < 10 nm [2].

The nanobridge Josephson junction is a planer junction. This junction is suitable to fabricate the antenna-coupled detector compared to a conventional vertical junction such as a superconductor-insulator-superconductor junction, because a high-frequency current induced in a thin-film planer antenna such as slot, bow-tie and spiral antennas is strongly coupled to the Josephson current flowing along the planer junction [3]. Using the antenna-coupled detector, it is expected to realize a harmonic mixer that detects microwaves and millimeter-waves with low local oscillator (LO) power and low LO frequency.

To fabricate nanobridges from Nb thin films, a thickness of the film should be less than 20 nm, because an aspect ratio of the thickness to the bridge width (or length) can hardly exceed 0.5 due to reactive ion etching. In this study, deposition conditions for 20-nm-thick Nb-sputtered thin films were evaluated. And then Nb nanobridges were fabricated from the thin films, and their electrical properties were evaluated for the evidence that the nanobridges acted as Josephson junctions.

2. Fabrication of 20-nm-thick Nb thin films

Superconducting Nb thin films less than 20 nm with a flat surface morphology is required to fabricate Nb nanobridges. The thin films were deposited onto 10×10-mm² SiO₂/Si substrates by a DC
magnetron sputtering system with a DC power of 200 W and 100-mm target-substrate distance in the Ar atmosphere of 0.8 Pa. The base pressure of the system was $7.0 \times 10^{-6}$ Pa. Under these conditions, a deposition rate was 0.2 nm/s, and 20 nm-thick Nb films having the critical temperature $T_c$ of 7.3 K were obtained. In order to improve $T_c$, a substrate temperature $T_s$ was increased from room temperature to 700°C [4]. Figure 1 shows dependencies of $T_c$ and the residual resistance ratio (RRR) on $T_s$. RRR is defined as $R(273$ K) / $R(10$ K). $T_c$ increased with increasing $T_s$ and almost saturated around 700°C. The maximum $T_c$ of 8.4 K was obtained at $T_s = 700$°C. Therefore, the films have a sufficient value of $T_c$ even if the films are slightly degraded during the fabrication process of the nanobridge described below. Since $T_s$ dependence of $T_c$ is similar to that of RRR, the origin of $T_c$ degradation is residual impurities such as Niobium oxide in the films.

Figure 2 shows an atomic force microscope (AFM) image of the Nb film deposited at $T_s = 700$°C. Dense Nb grains with diameters of 40 – 100 nm were formed, as shown in the figure. The root mean square (RMS) of surface roughness in the film was 0.109 nm. This value was half of the RMS in the film deposited at room temperature.

From these results, the obtained films are applicable to the nanobridge Josephson junctions.

Figure 1. Dependencies of critical temperature and residual resistance ratio (RRR) on substrate temperature.

![Figure 1](image1.png)

Figure 2. AFM image of 20-nm-thick Nb thin film deposited at a substrate temperature of 700°C.

![Figure 2](image2.png)

3. Fabrication and electrical properties of Nb nanobridges

Nb nanobridges were fabricated from the 20-nm-thick Nb thin films mentioned above. The device structure of the nanobridge is shown in figure 3 (a). The bridge length $\ell$ and width $w$ are defined in the magnified view in the figure. The taper angle of Nb banks, $\theta = 45^\circ$, was selected to avoid the microloading effect [5] in reactive ion-beam etching (RIBE), i.e. decrease in an etching rate of the Nb film around the nanobridge.

3.1. Device fabrication

Prior to the nanobridge fabrication, Nb contact pads and wires, as shown in figure 3 (a), were patterned on the Nb thin film by conventional photolithography. Then, the film was etched using RIBE by EIS-200ER (Elionix Co.) in a mixture of CF$_4$ (90%) and O$_2$ (10%) gases. The ion acceleration voltage and the ion current density were 400 V and 1.05 mA/cm$^2$, respectively. EBL process was performed by ELS-7800 (Elionix Co.) to form a nanobridge pattern onto an EB positive resist ZEP-520A (ZEON Co.) on the film. The electron acceleration voltage and the electron beam...
dose were 80 kV and 204 μC/cm², respectively. After the EBL process, the film was etched using RIBE under the same condition as the first RIBE process.

The minimum bridge area of 65 nm in width and 60 nm in length was obtained. These bridge sizes are comparable to the coherence length of Nb near \( T_c \). This means that these nanobridges are regarded as weak links in the Nb films and act as Josephson junctions [6]. The nanobridges whose width and length were less than 110 nm actually showed the Josephson effect as described below. An SEM image of typical Nb nanobridge is shown in Figure 3 (b). The width and length of this nanobridge were 110 nm and 51 nm, respectively.

3.2. I-V and microwave response characteristics

Figure 4 graphs typical I-V characteristics of the fabricated nanobridge shown in figure 3 (b) at 7.1 K (a) without and (b) with microwave irradiation at 6.2 GHz. As shown in figure 4 (a), the I-V characteristic displays the resistively shunted junction (RSJ)-like behaviour. For this junction, the critical current \( I_c \) and the normal resistance \( R_n \) were 450 μA and 1.2 Ω, respectively. From these values, the \( I_cR_n \) product was estimated to be 540 μV.

With the microwave irradiation at a frequency in the range from 6 to 30 GHz, constant current steps were observed. The microwaves were directed from a semi-rigid cable with an open end onto the nanobridge by a signal generator (SG). Each irradiation frequency \( f \) and a voltage interval \( \Delta V \) between the steps well satisfied the Josephson voltage-frequency relation. This implies that these steps are Shapiro steps and that the nanobridge acts as a Josephson junction. The highest order of the step was 7 at \( f = 6.2 \) GHz and a SG power of -0.3 dBm as shown in figure 4 (b). However, the order can increase and the maximum response frequency \( f_{max} \) can be much higher than \( 7 \times 6.2 \) GHz = 43.4 GHz, if coupling efficiency between the junction and microwaves are improved by introducing the antenna-coupled structure into the device.

Although \( f_{max} \) can increase by improving the microwave coupling, \( f_{max} \) is probably lower than the characteristic frequency \( f_s = (2e/h) I_cR_n = 260 \) GHz. This implies that the observed \( I_c \) includes the excess current which is a supercurrent except the Josephson current. An EB resist pattern of the nanobridge whose width and length are less than 40 nm can be formed by our EBL system, whereas it
is difficult to fabricate the Nb nanobridge with no etching error and no film damage by the RIBE in the present stage. The nanobridge Josephson junctions can respond to higher frequency signals when the excess current component decreases by improving the RIBE process.

Figure 4. I-V characteristics of the fabricated nanobridge at 7.1K (a) without and (b) with 6.2-GHz microwave (MW) irradiation. The right figure graphs the I-V characteristic in the positive bias region.

4. Conclusion
Nb nanobridge Josephson junctions were fabricated from 20 nm-thick Nb thin films in order to realize antenna-coupled Josephson detectors for microwave and millimeter-wave radiation. The Nb-sputtered thin films whose thickness, the RMS and $T_c$ were 20.0 nm, 0.109 nm and 8.4 K, respectively were obtained at $T_s = 700^\circ$C. Nanobridges were obtained from the film using 80-kV EBL and RIBE in CF$_4$ + O$_2$ gases. The minimum bridge area was 65 nm wide and 60 nm long. For the nanobridge whose width and length were less than 110 nm, the I-V characteristic showed RSJ-like behaviour near $T_c$. Moreover, Shapiro steps were observed in the nanobridge with microwave irradiation at a frequency in the range from 6 to 30 GHz. These results are useful to realize Josephson detectors in the antenna-coupled devices. For the other application, the junctions are applicable to nano-SQUIDs [7].

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