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Development of Rotating Box Type Multi-Facing Target Sputtering System for a Multi-layered Structure Device

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We have newly developed a rotating box type multi-facing target sputtering system for fabrication of superconducting tunnel junction devices with both a 1 nm-thick tunnel barrier. For realization of high performance X-ray detector of superconducting tunnel junction devices, a sputtering system has to satisfy conditions such as a low-temperature sputtering, a high plasma density, multi-target sputtering and a compact sputtering. This newly developed rotating box type multi-facing target sputtering system has these characteristics. We have fabricated SiO_2 thin films for insulation layer of superconducting tunnel junction devices using this sputtering system, and clarified the low-temperature characteristics of this sputtering system.
Key words: Superconducting tunnel junction, Josephson junction, X-ray detector, Facing target sputtering

1. INTRODUCTION

A superconducting tunnel junction (STJ) is widely used as a highly sensitive detector for X-rays and particles [1]. This junction was fabricated using a conventional DC magnetron sputtering with the substrate placed opposite to the target [2-4]. Both ion and γ electron bombardments to the substrate in the magnetron sputtering method may cause the thermal and physical damage to the STJ device interface in the fabrication of the STJ device using this sputtering method.

We fabricated Nb/Al-AlOx-Al/Nb STJ devices using a conventional type facing target sputtering (FTS) technique [5,6], and obtained a very small leak current density of 0.13 pA/μm^2 at the bias voltage of 0.1 mV [7-9]. with a pair of targets with the same size arranged oppositely. The ionization of the inert gas is accelerated, and the high-density plasma generated during the sputtering, because γ electrons generated in the plasma, are retained and reciprocated between both targets by the magnetic field. Because a substrate is placed on the outside of the pair of targets, the STJ devices can be fabricated on the substrate not to damage the device interface by both ion bombardment and γ electron.

In the use of a highly sensitive X-ray and particle detector, it is not only necessary to reduce the sub-gap leakage current to the theoretical limit, but also to improve the production-collection efficiency of quasi-particles, which needs for the operation of X-ray detectors. We have proposed a novel structure of STJ devices to improve the production-collection efficiency of quasi-particles [5]. For the fabrication of this newly device structure, four thin films of Nb, Ta, Al and W and a tunnel barrier of AlOx must be prepared in-situ deposition. It is also necessary to deposite two insulation films of Al_2O_3 and SiO_2 as the insulation layer. In order to fabricate this newly STJ devices with a low leak current, a sputtering system with six pairs of facing targets will be needed in the framework of the conventional type facing target sputtering. A multi-facing target sputtering system in the framework of the conventional ones necessarily requires a large cathode volume and consequently a large vacuum chamber for the cathode. Larger systems are disadvantageous both in the initial cost for construction and in the running cost for operation.

2. COMPARISON OF DAMAGE BETWEEN MAGNETRON SPUTTERING AND FACING TARGET SPUTTERING

In order to distinguish the facing target sputtering described in this Section from a rotating box type multi-facing target sputtering described in the Section 4, we define the former as the conventional type facing target sputtering.

It is known that the characteristics of fabricated STJ devices are largely affected by the presence of defects at the junction interface, even in small amounts [4]. The damage of Teflon tapes bound on Si substrates has been investigated after deposition of SiO_2 film at a deposition rate of 13.0 nm/min for comparison between the magnetron sputtering and the conventional type facing target sputtering[7-9]. As shown in Fig.1, In the magnetron sputtering the damage of tape was found after sputtering for 7 min 40 sec. No damage, of course, had been found before sputtering. In contrast, in the facing target sputtering, Teflon tape retained the same shape even after 21 min 30 sec of sputtering. In the usual magnetron sputtering the target faces to the substrate and consequently emitted electrons from the target surface (γ electrons) may arrive on the substrate where a thin film is deposited. γ electrons have high energy and may damage the deposited thin film structure. On the other hand, in the conventional type facing target sputtering, γ electrons and resulting plasma are confined between the facing targets, since magnets are placed just under the respective targets so as to generate opposing magnetic poles. This prevents γ electrons from reaching on the substrate surface and causes much less damage on the deposited film [5,6]. The difference in damage of Teflon tapes clearly shows the difference in performance between these two sputtering method.

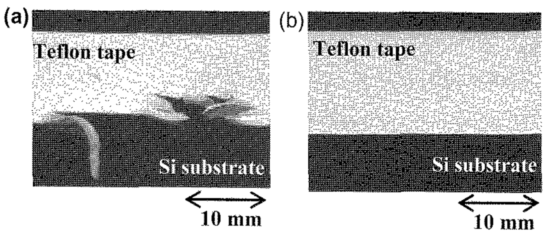

Fig.1 Damage to the Teflon tape placed on the Si substrate during the deposition of the SiO2 film.
(a) Deposition by conventional magnetron sputtering,
(b) Deposition by the facing target sputtering.

3. CHARACTERISTICS OF Nb/Al-AlOx-Al/Nb JUNCTION

The conventional type facing target sputtering system in our laboratory is double target sputtering and has two electric power sources, direct current (DC) and radio frequency (RF). With Nb, Al metal targets (target size: 90 mm ϕ) we fabricated an Nb/Al-AlOx-Al/Nb junction structure and then, replacing the targets by SiO_2, Al_2O_3 oxide targets, deposited an interlayer insulating film. The temperature of substrates during deposition was about 85 ℃. Junction devices were fabricated by photolithography process including the reactive ion etching (RIE) and a newly developed selective anodization method [8]. The fabricated junction area was 50 μm x 50 μm. The gap voltage was about 1.6 mV and the leak current density was 55 nA/μm^2 at 0.1 mV (Fig.2). At 4.2 K the thermal noise was too large to operate as a detector and hence the environmental temperature was lowered to about 0.5 K to reduce the thermal noise. The leak current density at 0.1 mV was as low as 0.13 pA/μm^2, which is smaller than the corresponding value at 4.2 K by about six orders of magnitude[9]. For the operation of detectors the leak current is required at worst to be 40 pA/μm^2 or less. The presently fabricated STJ devices have an extremely high performance of device characteristics. This indicates that the feature of the facing target sputtering, or the low temperature sputtering, contributes considerably to the formation of junction interfaces with little defects.

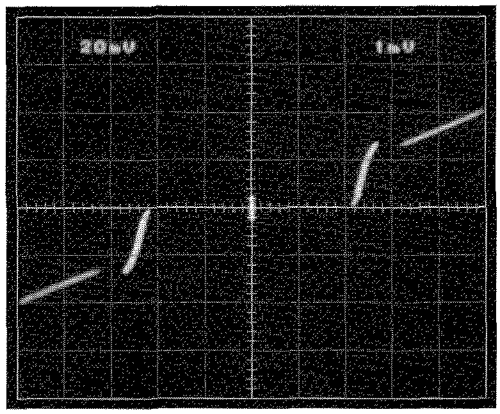

Fig.2 I-V characteristics of STJ device fabricated using the conventional FTS sputtering system, measured at 4.2 K.
Vert. axis: 2 mA/div, hori.axis: 1 mV/div

4. ROTATING BOX TYPE MULTI-FACING TARGET SPUTTERING SYSTEM

4.1 Background of the development of a rotating box type multi-facing target sputtering system

For STJ devices operating as high performance X-ray detectors, the device fabrication technique to reduce the leak voltage to the order of pA/μm^2 or less is very important, as described in Section 3. At the same time, it is also very important to invent a novel junction structure so that quasi-particles excited by X-ray irradiation may tunnel through the barrier without loss. We have proposed a novel structure of STJ devices to improve the production-collection efficiency of quasi-particles (Fig.3), which is necessary for the operation of X-ray detectors [10]. For the fabrication of this device structure, four thin film layers of Nb, Ta, Al and W and a tunnel barrier of AlOx must be prepared in-situ by deposition.

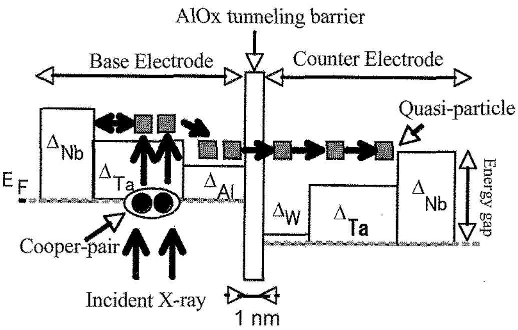

Fig.3 New structure of STJ device to improve the production-collection efficiency of quasi-particles.

In order to fabricate STJ devices of this structure with a low leak current, a system with at least four pairs of facing targets will be needed in the framework of the conventional type facing target sputtering at low temperature. As mentioned in Section 2, the magnetic flux is confined between the facing targets with opposing magnetic poles. However, since the magnetic flux supplied by magnets distant from the targets is not closed, relatively thick iron yokes are equipped to confine the flux. For a four-pair target sputtering system, four target pairs should be arranged parallel in this structure and the total cathode volume will be very large (Fig.4). A multi-facing target sputtering system in the framework of the conventional ones necessarily requires a large cathode volume and consequently a large vacuum chamber for the cathode. A large vacuum chamber naturally needs a large vacuum pump for evacuation and a larger cost for chamber materials. It will cause a larger cost for constant supply of electric power and water for the vacuum pump. Larger systems are disadvantageous both in the initial cost for construction and in the running cost for operation.

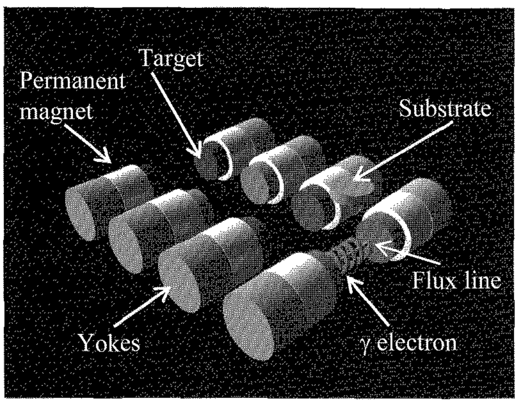

Fig.4 A schematic diagram of total cathode in the case of 4-target sputtering constituted by the conventional FTS system

4.2 Characteristics of a rotating box type multi-facing target sputtering system

Figure 5 shows a schematic diagram of a novel system of rotating box type multi-facing target sputtering, which has characteristics of low temperature sputtering and resolves the disadvantages mentioned above [11]. This system has the following characteristics. The magnets in each box form a closed magnetic circuit and the magnetic poles are opposing for the facing boxes. The facing boxes are rotating so as to make four-facing target sputtering possible. If a single material is used for four pairs of targets, the duration of the targets is extended by four times. In Fig.5, square pillars are presented, but hexagonal or octagonal pillars may also be adopted, if a closed magnetic circuit is formed. Using the finite element method the magnetic field strength was calculated for the conventional type facing target sputtering and the rotating box type multi-facing sputtering system. In the conventional type facing target sputtering, the magnetic flux leaks between a pair of

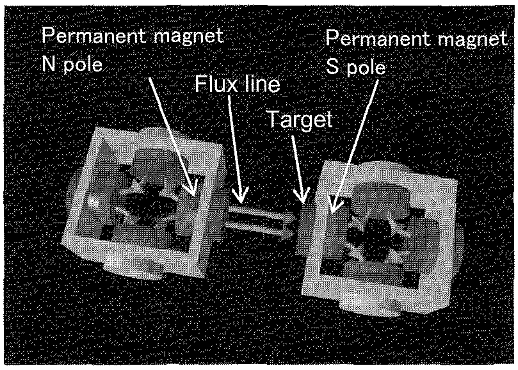

Fig.5 A schematic diagram of a novelty rotating box type multi-facing target sputtering

facing targets, which diminishes the efficiency of the magnets. On the other hand, in the rotating box type multi-facing target sputtering, formation of a closed magnetic circuit reduces the leakage of magnetic flux and consequently the magnetic field strength increases by about 10 % by use of the same magnets. The increase in magnetic field strength brings a better trapping capacity of γ electrons to give (1) a higher plasma density and (2) a higher performance of low temperature sputtering, in comparison with the conventional type facing target sputtering. To obtain the same magnitude of magnetic field strength, the volume of magnets can be reduced, which is another merit. Moreover, iron yokes are unnecessary in principle and the total reduction of magnet size is roughly estimated to be 30%, which will contribute to make a system more compact. The total cathode volume for a four-pair facing target system is estimated as about a half of that for the conventional type facing target sputtering. The reduction of the cathode volume makes it possible to reduce the chamber volume. The size reduction of sputtering systems is advantageous in view of both the initial cost for construction and the running for operation, as well as from the view point of energy saving.

Figure 6 shows the rotating box type multi-facing target sputtering system constructed in the present research. It consists of three chambers, a load-rock chamber with a glove box, a chamber for formation of tunnel barriers, and a main chamber for sputtering. In the sputtering chamber, we can fabricate six layers of films (four layers of Nb, Ta, Al and W films as junction electrodes and two layers of SiO_2 and Al_2O_3 as interlayer insulator films) using six-component sputtering with the facing hexagonal pillar cathodes, which is applicable to the fabrication of a novel STJ device indicated in Fig.3. The pressure reached was 1.0 x 10^{-6} Pa, the Ar pressure during sputtering was 1.0 Pa, the deposition rate was in a range of 50–110 nm/min, and the observed superconductivity transition temperature T_c for Nb was 9.25 K, which was similar to the value for bulk Nb. The substrate temperature was about 80℃ in the conventional type facing target sputtering used to fabricate the STJ devices indicated in Fig.2. On the other hand, the substrate temperature was less than 50℃ in the rotating box type multi-facing target sputtering. These results show that the fabrication of high quality Nb thin films with little inclusion of impurity gases is achieved by low temperature sputtering.

5. CONCLUSION

In order to fabricate high quality and performance STJ devices, we have developed a novel rotating box type multi-facing sputtering system. Its specific features are (a) a high plasma density with multi-facing targets in the magnetron arrangement of high performance, (b) lower temperature deposition (substrate temperature: less than 40 ℃ in the SiO_2 film deposition), and (c) compactification and energy saving by virtue of utilization of the multi-target sputtering with the reduction in cathode volume and running cost by 1/3 of the conventional type facing target sputtering. We expect that high quality STJ devices with both a small leakage current and a high production-collection efficiency of quasi-particles can be fabricated using this rotating box type multi-facing target sputtering system. This system may also be applicable to fabrication of other multi-layer structure devices that require low temperature sputtering, such as ferromagnetic tunnel junctions for magnetic media.

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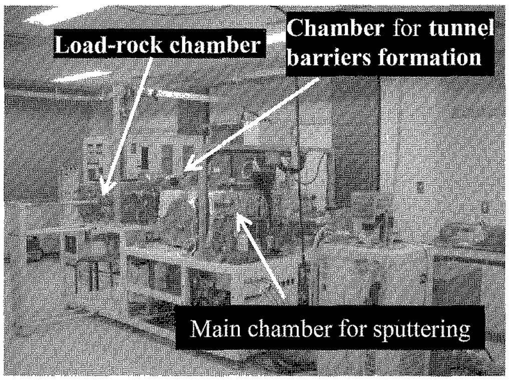

Fig.6 Rotating box type multi-facing target sputtering system. It consists of a road-lock chamber with a glove box, a chamber for formation of tunnel barriers and a main chamber for sputtering. Different six films can be deposited in-situ using a six-component sputtering with the facing hexagonal pillar cathodes.

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