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SUPERCONDUCTING FILM INJECTED BY IONS FROM PULSED ENERGETIC DENSE PLASMA SOURCE*

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The oxygen and silicon ions have been obtained respectively from pulsed energetic dense oxygen plasma and silane plasma generated by electrodeless discharge. The oxygen ions have been injected into superconducting Nb films, and the Si ions into superconducting YBCO films in order to investigate the variation of their superconductivity with the ions injected into them. Auger profile data show that the injection depths range from 20 to 40nm in the films, depending on the injection condition and film material. The resistance–temperature relations (R-T curves) indicate that the superconductivity remains unchanged in the photoresist-masked part of the film, but is significantly changed in the exposed part. The evenness of the film surface remains unchanged after injection. This technique may serve as an alternative to the planar inhibiting fabrication technique in the fabrication of the multi-layer structure of superconducting films, and also possibly to the conventional plasma source ion implantation technique in material surface processing.

Keywords: superconducting film, ion injection, pulsed energetic dense plasma source
PACC: 7475

I. INTRODUCTION

The ion injection technique has been extensively employed in material processing and microelectronics, particularly in the semiconductor industry.[1−3] Recently, this technique has been adopted to improve the characteristics of superconductive materials, such as controlling the electric resistance of superconducting YBCO film by Ni ion injection,[4] improving the critical current density of single-crystal YBCO[5] using oxygen ion injection, and supplementing the oxygen content lost in YBCO film during annealing[6] by means of oxygen ion injection. In addition, the ion injection technique has also been extended to the fabrication of high-temperature superconducting electronic devices. In this case, the ion injection is specifically termed a planar inhibiting fabrication technique.[7,8] With this technique, the Si ion beam produced from an accelerator bombards a YBCO film, resulting in the implantation of Si ions into it.[7] It is found that the film after Si ion injection becomes neither superconducting nor antimagnetic, while its crystal structure and surface evenness remain unchanged. These results indicate that the planar inhibiting fabrication is a good technique for the epitaxial growth of the subsequent superconducting and insulating films on the processed film surface for fabricating high-temperature superconducting multi-layer structure compared with the conventional lithography in the surface evenness of the processed film. As is well known, in conventional lithography, chemical etching or dry etching is used. Therefore, the exposed part of the film is etched away and only the masked part remains. As a result, the processed film is not as even as the original one. The unevenness of the film is unfavourable for fabricating the multi-layer structure of high-temperature superconducting films. The etched film surface must be evened up by filling insulator into its etched part, prior to another coating. This procedure will complicate the fabrication. What is more, both the film surface of the high-temperature oxide superconductor and the fresh interface resulting from etching are prone to contamination by water, acid, aqueous alkali, which finally may deteriorate the superconducting properties. The planar inhibiting fabrication technique may be free from the above difficulties imposed by the conventional lithography used to fabricate the multi-layer structure of superconducting films.

However, with the planar inhibiting fabrication technique, the equipment for supplying the ion beam

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is costly and difficult for unskilled staff to run. In addition, it takes time to treat a sample for using this technique. These weak points may preclude this technique from being extensively employed in the fabrication of the multi-layer structure of high-temperature superconducting films and also the material surface processing.

In this paper, we develop a pulsed energetic dense plasma source by a linear theta-pinch discharge, and utilize the ions from the source to be injected into the superconducting films. The characteristics of the injected films show that this technique may serve as an alternative to the planar inhibiting fabrication technique in creating a multi-layer structure of superconducting films, and also possibly to the conventional ion injection technique in material processing.

II. PULSED ENERGETIC DENSE PLASMA SOURCE

The pulsed energetic dense plasma is produced by the electrodeless discharge of a capacitor bank, which is based on the theta-pinch effect. The experimental set-up is schematically depicted in Fig.1, and its principle is briefly described as follows.

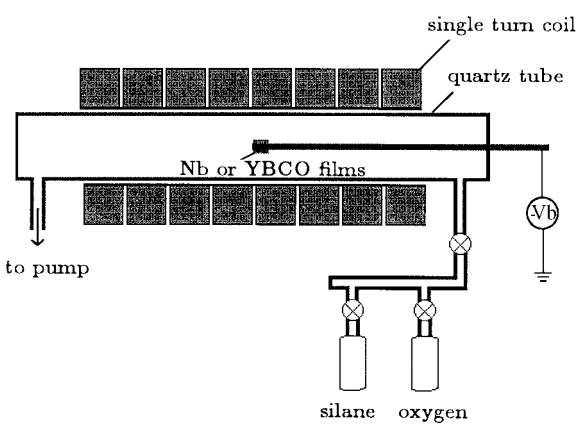


Fig.1. Schematic diagram of the experimental set-up.

A capacitor bank (C) charged up to 25–50kV discharges through a spark gap (G) into a single turn coil, after the spark gap is triggered. A fast-rising large current I_θ is established in the azimuth of the coil and simultaneously induces a fast-rising magnetic field in the axial direction. Assuming that the magnetic field is symmetric in the azimuth and only dependent on radius r spatially, it may be written as $B_z = B_z(r,t)$. The axial magnetic field induces an azimuthal electric field E_θ at a radius r, which is expressed as

$$E_\theta(r,t) = -\frac{1}{2\pi r}\frac{\mathrm{d}}{\mathrm{d}t}\left(\int_0^r B(R,t)2\pi R\mathrm{d}R\right), \quad (1)$$

where the negative sign indicates the direction of E_θ opposite to that of the azimuthal current in the coil. Obviously, $E_\theta(r,t)$ is maximal near the wall of the discharge tube coaxially located inside the coil, as far as the area within the tube is concerned. Therefore, when $E_\theta(r,t)$ reaches a value sufficient to ionize the gas in the tube, the ionization must first take place near the tube wall. The azimuthal E_θ induces an azimuthal plasma current $I_P(r,t)$ near the wall, accordingly, resulting in the formation of a thin current sheath there. The direction of the plasma current in the sheath is opposite to that of the azimuthal current in the coil. A force F_r is created by the I_P and B_z and is expressed as

$$F_r(r,t) = I_P(r,t)B_z(r,t). \quad (2)$$

This force directs to the tube axis, thus the current sheath is pinched inwardly, which is the so-called theta pinch effect, as illustrated in Fig.2. The neutral particles encountered by the imploding current sheath are ionized. Then the ions are swept toward the axis by the imploding current sheath. Thereby, the plasma density and the plasma temperature are both enhanced as the current sheath further moves inwards. The rising of the discharge current is fast in the initial stage of discharge but gradually becomes slow. The plasma correspondingly undergoes shock wave heating initially and adiabatic heating later. Finally, the energetic and dense plasma is swept into the region of the tube axis, where the superconducting film to be treated is located. In order to enhance the kinetic energy of the ions bombarding the film and get rid of the effect of electrons, the film is negatively biased. Consequently, the film is bombarded by the energetic and dense ions.

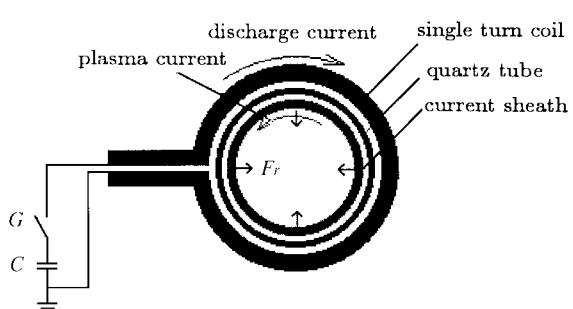


Fig.2. Illustration of generation of pulsed energetic dense ions.

In our equipment, the capacitor bank consists of four capacitors, each with 4μF and a holding-off voltage of 50 kV. Thus the capacitance of the bank totals 16μF. The single turn coil consists of eight pieces of narrow single turn coils, which are connected in parallel to a current collecting plate, each being 6.4 cm in width, 13.5 cm in diameter with 0.6 cm spacing in-between, thus totalling 55.4 cm in length. The discharge tube is of quartz, 12 cm in diameter and 120 cm in length. The spark gap is pressurized field-distorted. When the capacitor bank is charged to 50 kV, the peak discharge current is 380kA and the corresponding axial magnetic field is 0.83T, which are measured with a Rogowski coil and a magnetic probe located in the mid-plane of the coil. The azimuthal electric field strength E_θ is calculated to be 165V/cm. The discharge period is 11.6μs. The plasma temperature and the plasma density range respectively from a few eV to tens of eV and from $10^{15}\,\mathrm{cm}^{-3}$ to $10^{17}\,\mathrm{cm}^{-3}$, depending on working gas pressure and species, which are measured by plasma optical emission spectroscopy.

Different ions can be conveniently created using different gas species. For example, oxygen and silicon ions can be obtained when O_2 and silane are respectively used as the working gas in the discharge. Moreover, their energy and density may be changed simply by adjusting the experimental parameters such as capacitance, discharge voltage, bias potential and working gas pressure. Thereby, the injection depth and ion concentration in the film can be controlled.

Ⅲ. EXPERIMENTAL RESULTS

The oxygen and silicon ions have been obtained respectively from the oxygen plasma and the silane plasma created by the above technique. They have also been respectively injected into the superconducting Nb and YBCO films at the ambient temperature.

A. Oxygen-ion-injected Nb film

The surface of the niobium (Nb) film is prone to being oxidized, when exposed to the air. The oxidization depth could reach 2–3nm into the film. For a high-quality Nb film, the oxygen content inside quickly reduces with the depth. The critical temperature of the Nb film is sensitive to the oxygen content inside. As long as the oxygen atom fraction reaches 5%, the Nb film is no longer superconducting at 4.2K.[9] Therefore, the injection of oxygen ions into the Nb film is expected to change its superconductivity.

The oxygen ions are obtained from the oxygen plasma that is produced by the discharge of the capacitor bank (where only two pieces of capacitors are used instead of the whole capacitors, thus totalling 8μF capacitance) into oxygen gas at a pressure of 0.3 Pa. The discharge voltage of the bank is 28 kV. A dc bias potential applied to the film-holder is -26 kV. The repetitive discharge interval is 25s. The number of discharges is 100 in total; i.e. the film is bombarded by the oxygen ions 100 times. The oxygen ions are expected to be injected into the film at the energetic bombardment. Auger profile data show that the oxygen ions reach 40 nm deep in the film, as shown in Fig.3. It is also found from the Auger measurements that carbon and aluminium contents exist as impurities in the film. The carbon and the aluminium originate from the oil vapour of the pumping system and the aluminium sample holder, respectively. It is believed that the carbon impurity may be reduced by improving the vacuum in the discharge tube, and the aluminium impurity by modifying the structure of the sample holder. In order to clearly indicate the injected oxygen ion profile, the profiles for carbon and aluminium are neglected in this figure. Figure 4 indicates the variation of electric resistance of the Nb film with temperature (R-T curve) before and after the injection of oxygen ions. The Nb film before the injection has a superconducting transition at 8.4 K (curve a). After injection, however, it no longer shows a transition at the same temperature but keeps almost its original electric resistance, which is over one order of magnitude higher than that of the original film at the temperature just above the transition point (curve b). Therefore, the superconductivity of the Nb film is significantly changed after the injection of oxygen ions.

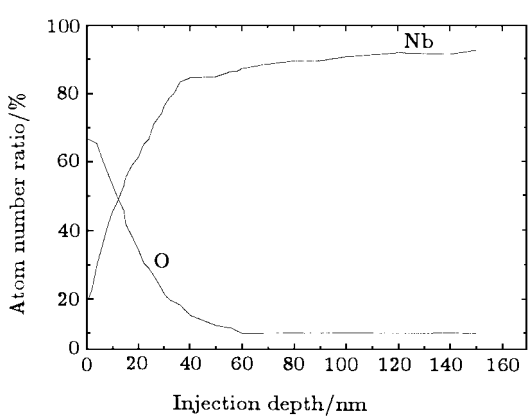


Fig.3. Auger electron spectrum of Nb film with oxygen ions injected into it.

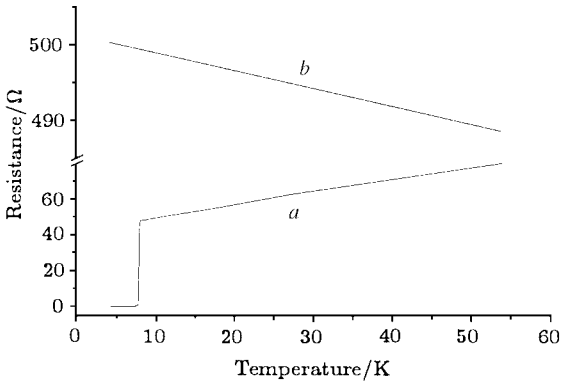


Fig.4. Variation of electric resistance of Nb film with temperature before (a) and after (b) oxygen injection. The electric resistance is enhanced by more than one order of magnitude and almost remains unchanged against temperature after the injection of oxygen ions.

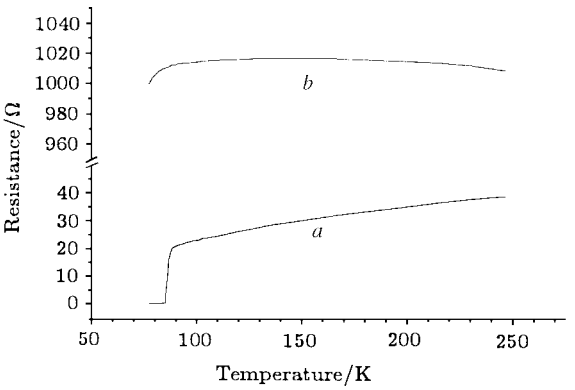


Fig.5. R-T relation of the YBCO film processed in 4.5 Pa silane with a discharge number of 130. The photoresist-masked part of the film is still superconducting (a) and the exposed part is turned into an insulating film (b).

B. Si-ion-injected YBCO film

The superconducting characteristics of the YBCO film sensitively depend on the quantities of Al and Si contents in the film. Si ions can be easily produced by discharge in silane. Therefore, we have chosen Si ions to be injected into YBCO films in our experiment. The YBCO film has some parts masked with the photoresist and is located on the holder that is negatively biased to -2 kV. The Si ions are obtained from the silane plasma produced with the discharge of one capacitor of the capacitor bank, which is 4μF in capacitance and charged to 28 kV, in a 4.5 Pa silane gas. The number of discharges is 130.

Figure 5 shows the R-T curves of the processed YBCO film. It is clearly seen that the masked parts (curve a) and the exposed parts (curve b) of the film exhibit different characteristics after the injection of Si ions. The masked parts of the film become superconducting at about 87 K. However, the resistance of the exposed parts is significantly enhanced and almost does not vary with temperature in the measurement range, indicating that these parts become almost nonconducting.

Another YBCO film which also has some parts masked with the photoresist is processed under the same conditions but at a pressure of 3.5 Pa and with a discharge number of 80 in order to test whether the ion injection effect is sensitive to the experimental parameters. The results show that the processed film remains superconducting in the masked parts, but becomes insulating in the exposed parts. Thus, the injection effect is not very sensitive to the slight variation of working gas pressure and discharge number, indicating that this technique is practical.

It is more important that the evenness of the whole surface of the film has changed little after the ion bombardment, which provides an even surface for coating another layer on it. These results are significant in the sense of the fabrication of the multi-layer film structure.

As the silane plasma is relatively easy to create, both the discharge energy and the bias potential adopted in the silane gas discharge are relatively low compared with those in the oxygen gas discharge.

IV. CONCLUSIONS AND DISCUSSION

It is seen from the above experiments that energetic and dense ions can be easily obtained from the plasma created through the theta-pinch discharge in a gas. Also, their energy and density, thus the injection depth and ion concentration in the film, can be controlled by adjusting the discharge energy, gas pressure, and bias potential. The superconductivity of Nb and YBCO films with oxygen ions and Si ions respectively injected into them is significantly changed in the exposed parts, but remains unchanged in the photoresist-masked parts. Moreover, the film surface is still even after the injection. These results have demonstrated the feasibility of this technique used for fabrication of the multi-layer film structure. Simple structure, easy manipulation and low cost are the merits of the equipment used, compared with the conventional ion injection equipment used in the planar inhibiting fabrication.

Our technique may be extended to the applications in material surface processing. If a work piece

needs to be processed on one part, it may be positioned near the end of the coil and the part to be processed is located perpendicular to the tube axis. The ions may bombard this part of the work piece. In this case, the equipment works in conventional ion injection mode. If it is required to be processed in all parts, the work piece may be located within the coil region. The ions can be implanted into the whole surface of the work piece. In this case, this equipment works in PSII-like mode, where PSII stands for plasma source ion implantation. The PSII-like mode here refers to the mode where the ion source from the plasma is pulsed, while bias potential is constant, which is opposite to the case in conventional PSII where the plasma is steady and the bias is pulsed. Since the ions created with our technique possess high density and high kinetic energy, the pulsed ion implantation is effective. Again, the simple structure, easy operation, and low cost are the merits over the conventional PSII.

Therefore, this technology can serve as an alternative not only to the planar inhibiting fabrication technique in constructing a multi-layer structure of superconducting films, but also to the conventional PSII technique for material processing.

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