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Controlling the Intrinsic Josephson Junction Number in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ Mesa

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In fabricating $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions in 4-terminal mesa structures, we modify the conventional fabrication process by markedly reducing the etching rates of argon ion milling. As a result, the junction number in a stack can be controlled quite satisfactorily as long as we carefully adjust those factors such as the etching time and the thickness of the evaporated layers. The error in the junction number is within ±1. By additional ion etching if necessary, we can controllably decrease the junction number to a rather small value, and even a single intrinsic Josephson junction can be produced.
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KEYWORDS: intrinsic Josephson junctions, junction number, argon ion etching, etching rates, *I*–*V* curves

1. Introduction

Since the discovery of intrinsic Josephson junctions (IJJs) in 1992,[1)] considerable attention has been attracted and much interest aroused, not only for the rich treasury of nonlinear dynamics of IJJs but also for their possible applications at high frequencies such as terahertz oscillators with high power output and quantum voltage standard. With the strongest anisotropy among high-temperature superconductors, $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) has been proven to be the best material for fabricating IJJs. One of the main challenges in the field is to fabricate such junction stacks in which their number of junctions can be very well controlled. Although the successful fabrication of IJJs containing only a few junctions has been reported, the precise control of junction number (particularly, in making a single intrinsic Josephson junction) seemed difficult.[2–7)]

Recently, we have modified the conventional fabrication process of IJJs by reducing the etching rates of BSCCO and of the covering metal layers during the Argon ion etching process. In a three-terminal mesa we can control the junction number with an error of ±1.[8)] However, the effects of the surface junction and the layer damaged by the ion etching can always be seen in the measured *I*–*V* curves. The former prevents us from obtaining consistently the value of the supercurrent of the first branch, while the latter makes it impossible to reduce the junction number in the stack to below two (the damaged layer is approximately 2.7 nm thick). In this article, we report the fabrication method of four-terminal mesas with further improvement. With reduced etching rates and additional ion etching process, we are now able to control the number of junctions in a stack to the accuracy of one junction in each run. In other words, we can controllably decrease the number of junctions in a stack to a rather small value, and even single intrinsic Josephson junction can be obtained.

2. Experimental and Discussion

BSCCO single crystals with T_c of approximately 90 K are grown using a traveling solvent floating zone (TSFZ) method.[9)] After a small slice (typically of the size of 2 mm × 2 mm × 0.1 mm) is cleaved from a bulk single crystal, a silver layer d_1 thick is evaporated promptly onto the its fresh surface. Then the BSCCO slice is fixed on a Si substrate for further fabrication. With the photoresist sprayed, a square of $16 \times 16\,\mu m^2$ is photolithographically patterned onto the sample. Argon ion milling is then carried out for a time duration of T_1 to make a mesa of BSCCO which is promptly isolated by an evaporated layer of CaF_2. By ultrasonic rinsing in acetone, the top of the mesa becomes free of CaF_2 and the photoresist in a lift-off process. Subsequently, a second silver layer d_2 thick is evaporated onto the sample. Two separate electrodes, 4 μm apart and each of the sizes of $6 \times 16\,\mu m^2$, are photolithographically patterned and electric leads can be glued onto them using the silver paste. For four-terminal measurements, two more electrodes can be easily formed on the base of the BSCCO slice directly. The schematic diagram is shown in Fig. 1.

The above-mentioned top electrodes are made by argon ion milling for a time duration of T_2. In doing so, obviously, not only the top Ag layer (d_2 thick), but also the one under it (d_1 thick) and the BCCCO sample further down will probably be etched as well, depending on the etching time, etching rate, and the thickness of the silver layers. Supposing that the etching rates for Ag and BSCCO are ER_{Ag} and ER_{Bi}, respectively, the junction number in the resulting stack can be estimated to be $(T_1 - d_1/ER_{Ag}) \cdot ER_{Bi}/d_0$ (for $T_2 \le (d_1 + d_2)/ER_{Ag}$) or $(T_1 - T_2 + d_2/ER_{Ag}) \cdot ER_{Bi}/d_0$ (for $T_2 > (d_1 + d_2)/ER_{Ag}$), respectively, where d_0 is the distance between two adjacent superconducting layers along the *c* axis (typically 1.54 nm for BSCCO). Furthermore, our experiments have indicated that the base of BSCCO seems to be damaged during the ion milling, making the stack slightly taller than its geometric height. In other words, an empirical fitting parameter d_{et} should be included to correctly estimate the junction number in a stack. Thus the junction number N is

$$N = [(T_1 - d_1/ER_{Ag}) \cdot ER_{Bi} + d_{et}]/d_0 \quad \text{for} \quad T_2 \le (d_1 + d_2)/ER_{Ag} \tag{2.1}$$

or

$$N = (T_1 - T_2 + d_2/ER_{Ag}) \cdot ER_{Bi}/d_0 \quad \text{for} \quad T_2 > (d_1 + d_2)/ER_{Ag} \tag{2.2}$$

We note that in the fabrication T_1 is always larger than

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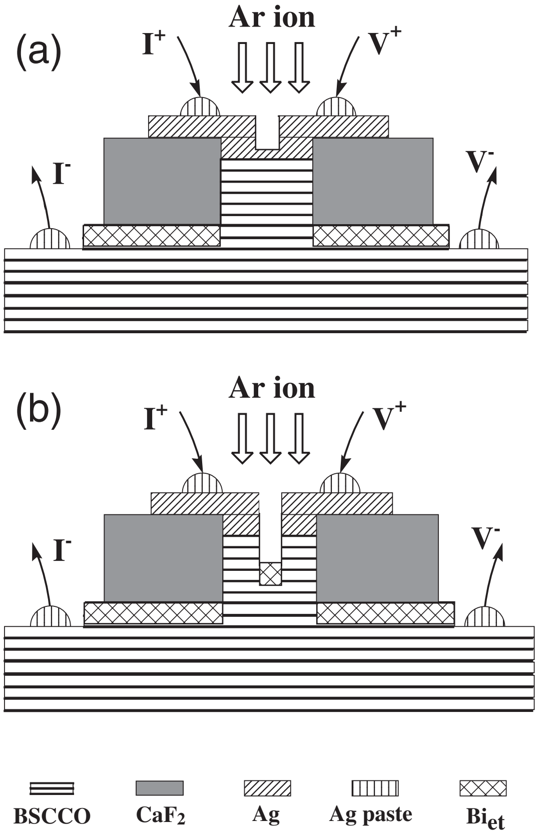

Fig. 1. Schematic view of IJJs of mesa structure. (a) when $T_2 \leq (d_1 + d_2)/ER_{\mathrm{Ag}}$; (b) when $T_2 > (d_1 + d_2)/ER_{\mathrm{Ag}}$, where $\mathrm{Bi}_{\mathrm{et}}$ represents the BSCCO layer damaged during the ion milling.

d_1/ER_{Ag}, thus in the structure described by eq. (2.1) the minimum junction number is determined by d_{et}/d_0, denoting that we cannot obtain a stack with less than d_{et}/d_0 junctions in it. While in the structure described by eq. (2.2), there is no such a minimal limit to the junction number, because that T_1 and T_2 can be adjusted independently, and for sufficiently long T_2 we can certainly break the bound set by d_{et}.

In the ordinary fabrication of IJJs, ion milling is usually carried out at high energy, resulting in high etching rates of both Ag and BSCCO. The typical values were 76 nm/min for Ag and 18 nm/min for BSCCO in our previous work.[10,11] At such high etching rates, it seemed difficult to precisely control the number of junctions in a stack by controlling T_1 and d_1. Besides, to ignore the layer damaged by the ion etching also causes an error in the junction number. In our previous work, the error of the junction number is ±5. The basic idea for the present work is to reduce the rates markedly so that precise control of the junction number becomes feasible. By adopting a neutral ion energy of 250 eV and a flow density of 0.38 mA/cm^2 during the argon ion milling, we lower the etching rates to 9.3 nm/min for Ag and 1.3 nm/min for BSCCO. Accordingly, the empirical fitting parameter d_{et} is 2.7 nm, which is obtained from the statistics of many samples.[8]

The measurements are carried out in a cryocooler with samples kept at typically 25 K. For one of our samples ($d_1 = 68$ nm, $d_2 = 102$ nm, $T_1 = 12$ min, $T_2 = 18$ min), the number of junctions in the mesa is approximately 5 as given by eq. (2.1). Fig. 2 shows the *I–V* curves of the sample.

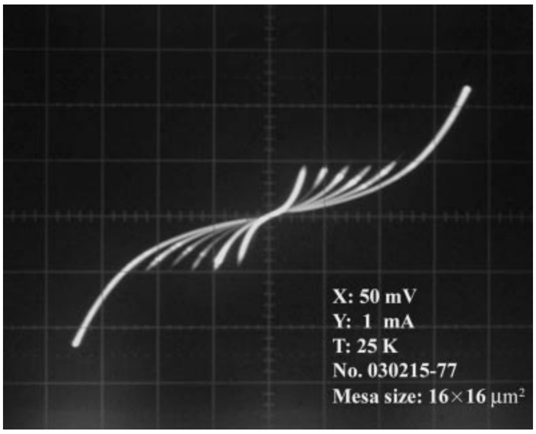

Fig. 2. *I–V* characteristics of a stack with 6 junctions (including a surface junction).

Judging from the quasi-particle branches, there are indeed 5 junctions in the stack, just the same as what eq. (2.1) gives. However, at the interface between the BSCCO mesa and the Ag layer, there exists a surface junction; taking this into account makes a total junction number of 6. Then the error in N is 1. For the more than 30 samples that we have fabricated, the error of N is within ±1 for junction numbers from 3 to 12; this indicates that by controlling T_1, d_1 and the etching rates, the junction number in a stack can really be controlled quite satisfactorily, as shown by eq. (2.1).

Due to the existence of a surface junction, the supercurrent is not registered in the *I–V* curves in Fig. 2, which was discussed in detail by Doh *et al.*[7] In fact, surface degradation reduces the critical temperature of the surface junction; and when the experimental temperature is above it, the junction will manifest itself as a nonlinear resistor, thus quenching the supercurrent in IJJs. If we increase the etching time to $T_2 > (d_1 + d_2)/ER_{\mathrm{Ag}}$, the surface junction will be broken into two parts [Fig. 1(b)], and their resistances will be included in those of the top electrodes accordingly; thus in four-terminal measurements the influence of the surface junction on *I–V* curves will be eliminated. With further etching, the structure becomes U-shaped; under general conditions, the right and left stacks are of equal sizes and act as leads for the measurements, and only the bottom stack is of importance in what follows. The effects of the sizes of the right and left stacks or the effects of their irregularities will be discussed elsewhere.

When $d_1 = 68$ nm, $T_1 = 12$ min, and $d_2 = 102$ nm, $T_2 = 19$ min, we obtain the *I–V* curves of 3 junctions as shown in Fig. 3(a). The junction number in the curves agrees well with the result given by eq. (2.2). If, with this same sample, we increase T_2 by 1 min in each of the following etchings, the junction number in the stack will be reduced to 2 and 1 accordingly as shown by the *I–V* curves in Fig. 3(b) and Fig. 3(c). The *I–V* curves in Figs. 3(a) to 3(c) indicate that, apart from the reduction in junction number, there is no appreciable change in the shape of the *I–V* curves nor in the values of the supercurrent; i.e., no degradation is observed after several etchings and thermal cycles.

From eq. (2.2), we know that the errors of the thickness of the metal layers, the etching rates and the etching time lead to the error of the junction number. The results above show

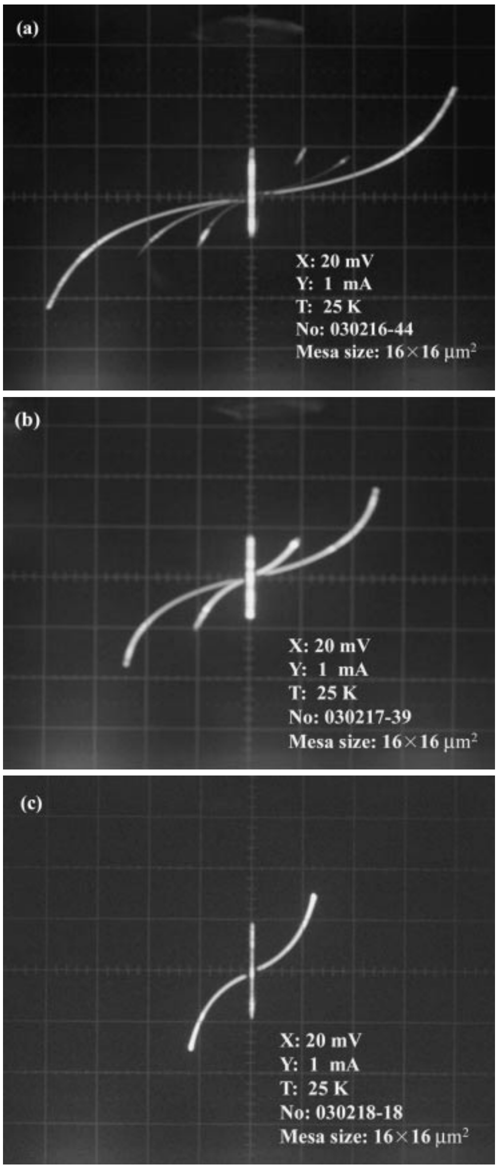

Fig. 3. Current-voltage characteristics of IJJs. Successive etchings reduce the junction number in a stack from (a) 3, to (b) 2, and to (c) 1. Each etching lasts one minute.

that we can precisely control the junction number of IJJs by additional ion etching process, thus successfully eliminate the error ±1 in the junction number. If we want a sample of IJJs containing n junctions, we may set the parameters (T_1, T_2, d_2) in eq. (2.2) to satisfy $N = n + 1$. The obtained junction number N_0 should be between n and $n + 2$ because of the existence of error ±1. Optional additional ion etching process can be adopted to reduce the junction number to n with the accuracy of one junction in each run. This method is so successful that by using it we have successfully fabricated several samples with only one intrinsic Josephson junction of the sizes of $16 \times 16\,\mu\mathrm{m}^2$ or $8 \times 8\,\mu\mathrm{m}^2$.

3. Conclusions

In order to control the junction number in a stack, we can adjust such factors as the etching time, the etching rates and the thickness of the covering Ag layers. In determining the junction number, in principle, they should have equal weight; but in practice, if we want to keep the etching time or the layer thickness within reasonable ranges, a low etching rate is of extreme importance. By markedly reducing the etching rates and carrying out optional additional ion etching processes, we have improved the conventional fabrication process of IJJ in four-terminal structures; thus we are now able to obtain IJJs stacks containing any number of junctions down to only one. This method provides us with the possibility of looking at how the layer number in a IJJs stack affects its dynamical behavior or its superconductivity. Also under way are the studies on the properties of one intrinsic Josephson junction singled out from a stack.

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