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Microwave Properties of Intrinsic $Bi_2Sr_2CaCu_2O_y$ Josephson Junctions on Off-axis Substrates

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Abstract. **The transport and microwave properties of $Bi_2Sr_2CaCu_2O_y$ (BSCCO) intrinsic junction on off-axis substrates were investigated. The off-axis BSCCO thin films have been prepared on tilted $LaAlO_3$ (001) substrates with 6 ° toward [110] by molecular beam epitaxy (MBE). The anisotropic transport properties along the c axis and the a-b plane of BSCCO thin films could be changed by the oxygen content by high vacuum (HV) annealing. Josephson self-radiation powers of frequency f=1.7 GHz were directly observed for the sample patterned into an area of 20×40 μm^2. The microwave self-generation properties and the current-voltage characteristics of BSCCO intrinsic junctions on off-axis substrates are discussed in relation to the anisotropic transport properties.**

1. Introduction

The electronic and superconducting properties of layered BSCCO material have proved to be a possible source of microwave Josephson junction devices because the layered anisotropic BSCCO HTSC material exhibit the intrinsic Josephson effect [1] . The Josephson tunneling in this compound is believed to occur between the superconducting double layers of 3 Å thickness separated by the intermediate Sr-O and Bi-O layers of thickness of 15 Å which act as Josephson weak links or insulating layers. For the large energy gap of BSCCO compound. the high frequency applications of a series array of intrinsic Josephson junctions up to the THz frequency range can be expected. Recently, various types of intrinsic Josephson junctions, such as a mesa structure in thin film [2] , a step stack structure [3] and a mesa structure on BSCCO single crystal surface [4] , have been studied. However. in order to use the intrinsic Josephson junctions for the practical on-chip device application, some reliable thin-film fabrication technology is required.

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In this paper, we report on the intrinsic Josephson characteristics of well-defined BSCCO thin-film stacked junctions on tilted $LaAlO_3$ (001) substrates. The intrinsic junctions on a tilted substrate were formed along the c-axis with its direction 6 ° tilted from normal-axis to the substrate surface. The microwave Josephson radiation from the stacked intrinsic BSCCO junctions on tilted $LaAlO_3$ substrates was observed by using a non-resonant detection method, which demonstrated the direct verification of Josephson coupling along the c-axis.

2. Experimental

The epitaxial twin-free BSCCO thin films have been grown by a MBE method with a sequential deposition technique. The BSCCO films could be controlled sequentially by modulating the shutters of four K-cells. The detailed preparation technique has been reported elsewhere [5]. The substrates $LaAlO_3$ (001) with the tilted angle of 6 ° toward [110] azimuth were used. X-ray diffraction (XRD) method and reflection high energy electron diffraction (RHEED) method were applied to analyze the crystalline orientation. The transport property was measured by four probe method, and the transport anisotropy was changed by an annealing in high vacuum (HV) of 10^{-8} Torr at 350-400 °C. The BSCCO films of 100-200 nm thick were patterned into an antenna structure with constriction area of 20×40 μm^2 by the conventional photolithography and wet-etching process. The sample was mounted in a microwave cavity equipped with a microstrip connecting to a coaxial cable. The radiation power from the junction was measured by a superheterodyne detection technique with a non-resonant broad-band matching system at receiving frequency f_{REC}=1.7 GHz with a bandwidth ΔB=800 MHz. The sensitivity of the receiver was dS=3×10^{-24} W/Hz at an integrating time t=1 s. The absolute values of the self-radiation power emitted from the junctions were exactly calibrated by a standard noise source installed inside the microwave receiver system. All electrical connections were carefully filtered by a low pass filter and the sample holder was magnetically shielded by a μ-metal.

3. Results and Discussion

The transport property along c-axis of BSCCO thin films was investigated taking advantage of the structure that the a-b planes are inclined to the substrate normal. The epitaxial relationship was confirmed by XRD and RHEED as shown in Fig.1, and it is the same as the case of $SrTiO_3$ reported in refs. [5, 6]. The resistivity along c-axis could be estimated from the resistivity along [$11sin\theta$] substrate that is contributed from the resistivity along b- and c-axis, where θ is tilted angle and [11sin6 °] is in-plane direction perpendicular to [$1\bar{1}0$] as shown in Fig.2. Figure 3 shows typical temperature dependence of resistance for a line with a width of 20 μm. Thin fims used in this experiment had Tc of 50 $\sim$ 60 K. In normal state, a semiconducting behavior attributed from the constituent along c-axis is observed. In Table 1, we present data of anisotropic transport properties of as grown (sample A) and HV annealed BSCCO films (sample B and C). The anisotropy parameter $\gamma = (\rho_c / \rho_a)^{1/2}$ is given by [7]

$$\rho_{[11sin\theta]} = \rho_{[110]} cos^2\theta + \rho_c sin^2\theta = \rho_{[110]}(cos^2\theta + \gamma^2 sin^2\theta) \quad (1)$$

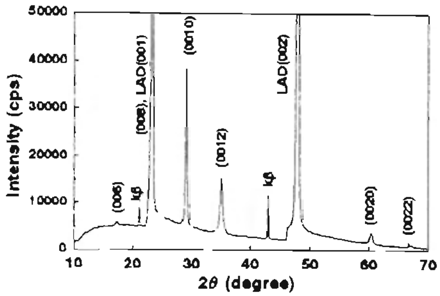

Fig.1 XRD pattern of BSCCO thin film prepared on tilted $LaAlO_3$ substrate.

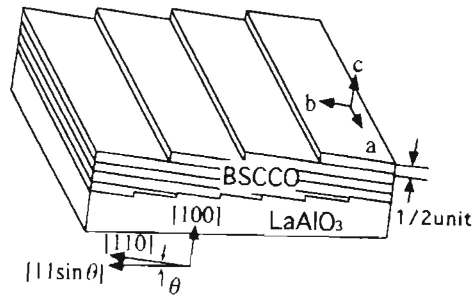

Fig.2 Epitaxial relationship between BSCCO thin film and tilted $LaAlO_3$.

where $\rho_{[11sin\theta]}$ and $\rho_{[110]}$ are experimentally obtained. The large anisotropy in resistivity was observed for sample C, and the anisotropic parameter was estimated to be 38. This value is larger than that of samples A and B. This fact indicates that the oxygen in the crystal can be removed at temperature more than 300 °C and the anisotropy parameter can be changed. This value is, however, small as compared with those of single crystals ($\gamma = 50 \sim 280$). [1, 2] These results indicate a possibility of existence of defects and/or intergrowth in the films grown on the tilted substrates.

Table 1. Anisotropic transport properties of 2212 thin films.

sample	anneal temp. (°C)	$\rho_{[11sin\theta]}$ (mΩ-cm)	ρ_a (mΩ-cm)	ρ_c (mΩ-cm)	γ
A	asgrown	7.2	4.2	68	8.2
B	300	8.0	4.0	77	9.6
C	400	23	1.4	220	38

Figure 4 shows the typical current-voltage(I-V) characteristic and the voltage-dependent Josephson radiation spectral power at receiving frequency f_{REC}= 1.7 GHz for the junction annealed at 400 °C for 1 h. The I-V characteristic was flux-flow type without hysteretic behavior. Unsymmetric Josephson emission powers P(V) appeared at low voltage region. Note that, for a single junction at receiving frequency f_{REC} =1.7 GHz, the Josephson radiation peak should appear at V=3.5 μV, corresponding to the Josephson fundamental voltage-frequency relation f_{REC}=(2e/nh)V, where f_{REC} is the central frequency of a receiver and n is an integer. This fact reflects that the Josephson emission power may originate from the mutual phase locking of the series-connected Josephson junctions. As regards to our sample in the resistive state, the net voltage drop across the junction is the total sum of the voltage drops in individual stacked intrinsic junctions along the current path. Thus, the Josephson radiation power spectrum of the junction should be delivered from the total voltage across the series array junctions according to the Johnson-Nyquist formula. From the peak voltage, we deduce that the coherence state may come from the localized phase-locked junction.

It indicates that the small amount of localized junctions are in phase. The observed

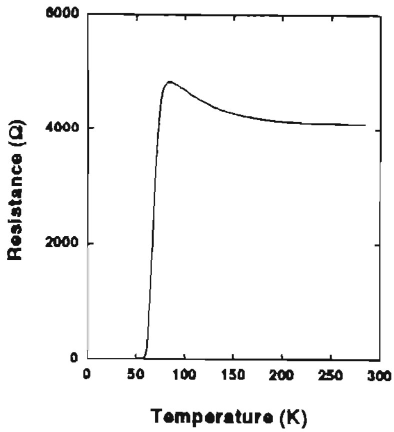

Fig.3 T-dependence of Resistance along [11sinθ] for BSCCO thin film on tilted $LaAlO_3$.

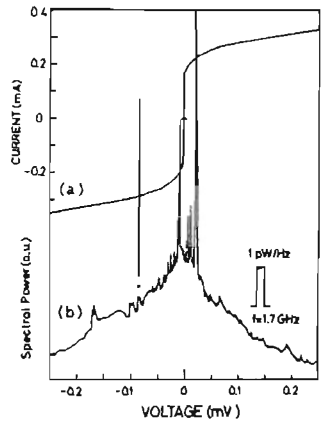

Fig.4 I-V characteristic and the Josephson microwave radiation power P(V) at 4.2 K. The inset bar indicates the calibrated spectral power.

intensity of spectral power was P(V)= 1.0×10^{-12} W/Hz at V=25μV. Note that, for a single BSCCO bicrystal junction, the observed maximum output level for this frequency was recorded about P(V)=1.6×10^{-13} W/Hz [8] . The Josephson radiation power of BSCCO intrinsic Josephson junction on a tilted substrate has about one or two orders of magnitude higher than that of the single bicrystal junction.

4. Conclusion

In summary, we have investigated the intrinsic Josephson effect of well-defined BSCCO stacked junctions on a tilted $LaAlO_3$ (001) substrate with 6 ° toward [110] direction. The observation of coherent Josephson microwave radiation at frequency f_{REC}=1.7 GHz directly showed the occurrence mutual phase locking of the stacked series array of intrinsic junctions along the c-axis. Considering an improvement of the intrinsic Josephson effect, the efforts are now underway to prepare the highly anisotropic BSCCO films.

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