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Interaction between optical phonons and ac Josephson oscillations in intrinsic Josephson junctions of $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$

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We have investigated the subgap structures in the current-voltage (*I-V*) characteristics of intrinsic Josephson junctions in $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$ (x = 0.15, 0.2) single crystal mesas. The subgap structures appear pronouncedly on each quasiparticle branch in the *I-V* characteristics below T_c (~85K), independently of sample geometry and x. The structures ranging from 6.3 to 26.2 mV have been successfully observed on the first quasiparticle branch. The voltages of the structures correspond relatively well to the frequencies of Raman-active optical phonons in the materials. Moreover, a strong correlation between peak currents of the pronounced structures and critical currents of intrinsic Josephson junctions, which reveals a phonon assisted tunneling of Cooper pairs in the junctions, has been found. The observed subgap structures have been interpreted to be due to the interaction between the Raman-active optical phonons and ac Josephson oscillations in the intrinsic Josephson junctions.
Key words: $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$, intrinsic Josephson junction, subgap structure, optical phonon

1. INTRODUCTION

The transport properties in the c-axis direction of strongly anisotropic high-temperature (T_c) superconductors such as $Bi_2Sr_2Ca_nCu_{n+1}O_{2(n+3)+\delta}$ (n = 1,2) and $Tl_2Ba_2Ca_nCu_{n+1}O_{2(n+3)+\delta}$ (n =1,2) can well be described by the intrinsic Josephson effect of a stack of superconducting metallic CuO_2 multilayers alternating with other nonmetallic layers [1-4]. Recently, the specific subgap structures have been observed as current peaks on each quasiparticle branch in the *I-V* characteristics of intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_y$ (BSCCO) and $Tl_2Ba_2Ca_2Cu_3O_y$ (TBCCO) [5-8]. It has been observed that they appear independently of sameple geometry, oxygen doping, weak magnetic field, and temperature up to $\sim0.6T_c$ by Schlenga et al. [6,8]. Other similar geometry- and gap parameter-independent subgap structures have also been observed on the *I-V* characteristics of BSCCO single crystal break junctions by Ponomarev et al. [9]. Indeed, Ponomarev et al. reported that the voltages of the subgap structures correspond relatively well to the frequencies of Raman-active optical phonons in BSCCO. Up to now, the origin of this structure is not clear although two possible mechanisms have been proposed to explain it. Helm et al. proposed the resonant coupling mechanism between infrared-active optical phonons and oscillating Josephson currents in the intrinsic Josephson junctions [10,11]. On the other hand, Maksimov et al. proposed that it is attributed to the phonon assisted tunneling due to the coupling of the ac Josephson current to the Raman-active optical phonon modes at the corresponding Josephson frequencies in the junctions [12]. The former mechanism can not be applied to the latter mechanism, but either leads to the appearance of current peaks on the *I-V* characteristics when the voltage satisfies the condition of $2eV=\hbar\omega_{ph}$, where ω_{ph} is the frequency of the infrared-active optical phonon for the former mechanism or that of the Raman-active optical phonon for the latter mechanism.

More recently, we have also successfully observed pronounced subgap structures in $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$ (BPSCCO) (x = 0, 0.15, 0.2) [13,14]. The structures appeared on each quasiparticle branch in the *I-V* characteristics, and their peak positions in voltage were independent of x for $0\leq x\leq 0.2$, junction geometry, weak magnetic field and temperature. Furthermore, the voltages of the subgap structures corresponded relatively well to the frequencies of Raman-active optical phonons in B(P)SCCO. These features of subgap structures in the intrinsic Josephson junctions resemble those of fine structures in the break junctions [9]. This suggests the possibility of phonon assisted tunneling mechanism rather than the resonant coupling mechanism for the subgap structures in the intrinsic Josephson junctions. However, the subgap structures have been observed only below 13mV. Now, assuming that Raman-active optical phonon contributes to the subgap structures, more peaks are expected to be observable over higher voltage region, because the frequencies of the Raman-active optical phonon ranges over higher frequency (voltage) region. However, no current peaks at high voltage region have yet been observed for BPSCCO intrinsic Josephson junctions with relatively large junction area ($>30\times15\mu m^2$) due to a negative dynamic resistance, which is caused by self-heating effect [13]. It is hoped to observe them to make the origin of the subgap structures clearer.

From this point of view, we have fabricated small-sized BPSCCO intrinsic Josephson junctions. In this paper, we report the first observation of subgap structures over higher voltage region and discuss the origin of the subgap structures in intrinsic Josephson junctions in the BPSCCO ($x \leq 0.2$) system.

2. EXPERIMENTAL

BPSCCO (x = 0.15, 0.2) single crystals with critical temperature T_c of 80-90K were grown from the molten state of mixtures of Bi_2O_3, $SrCO_3$, $CaCO_3$, CuO and PbO powders by the ordinary self-flux method reported elsewhere [4]. After the as-grown single crystals were cleaved in air, ~30nm thick gold films were deposited on the cleaved surfaces, and then mesas were fabricated on them by means of electron-beam lithography, photolithography and Ar ion milling. Lateral size S of the mesas were (40×1)-(40×3)μm^2 in ab-plane. The I-V characteristics in the c-direction of the mesas were measured between 4.2K and T_c by a four-terminal method.

3. RESULTS AND DISCUSSION

Fig. 1(a) shows a typical I-V characteristic of a BPSCCO (x = 0.15) mesa with S = 40×2μm^2 at 4.2K. The I-V curve shows multiple branches with hysteresis consisting of a superconducting and several quasiparticle branches. This structure is typical for intrinsic Josephson junctions and is due to individual switching of junctions in the mesa into the resistive state. Furthermore, no negative dynamic resistance is observed because self-heating effect is reduced by decreasing a mesa size. Figs. 1(b) and 1(c) show I-V characteristics on expanded two different voltage and current scales for the first quasiparticle branch shown in Fig. 1(a). The subgap structures appeared at the positions of the indicated arrows. Here, the voltage positions of the mth subgap structre on the nth quasiparticle branch are denoted V_{nm}. Moreover, the subgap structures were also observed on each higher order quasiparticle branch, e.g., V_{21} and V_{22}. These peaks are understood as the summation of the subgap structures in each quasiparticle branches, i.e., $V_{21} = V_{11} + V_{11}$, $V_{22} = V_{11} + V_{12}$ [8,13]. Therefore, for data evaluation of the subgap structures we pay attention to the only first quasiparticle branch. The voltages of the peak positions are observed to be V_{11}~6.3mV, V_{12}~8.2mV, V_{13}~10.8mV, V_{14}~11.7mV, V_{15}~21.1, V_{16}~26.2mV, respectively. To our knowledge, this is the first observation of the subgap structures appearing over higher voltage region with accompanying V_{15} and V_{16}, although the observation of the subgap structures from V_{11} to V_{14} were reported previously [14]. We also observed the same subgap structures in other samples with different mesa sizes and x, and confirmed that their voltage positions were independent of temperature, mesa size and x. From our experimental results, we can say that the above-mentioned features of the subgap structures are essential in intrinsic Josephson junctions of BPSCCO.

Next, we discuss the origin of the subgap structures.

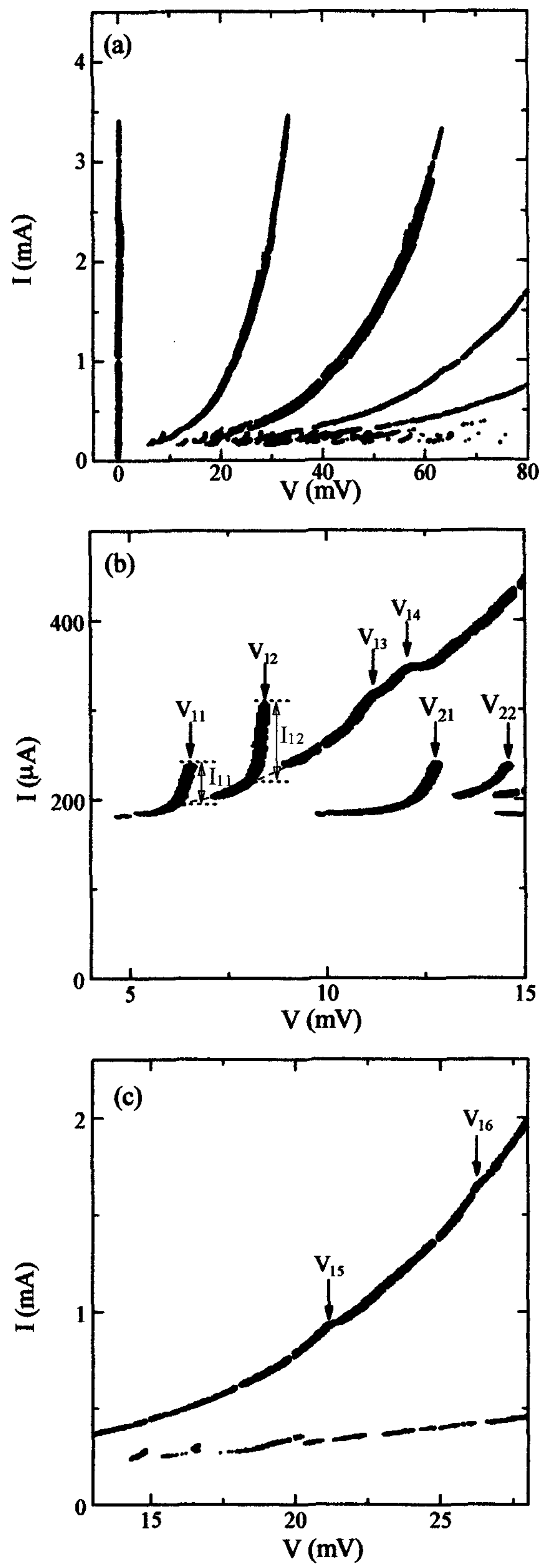

Fig. 1. I-V characteristic of a BPSCCO (x = 0.15) mesa with S = 40×2μm^2 at 4.2K. (a) on large current and voltage scales, and on expanded current and voltage scales in (b) low and (c) high current region. No all branches are traced out.

At present, the subgap structures are considered to originate from an interaction between optical phonons and ac Josephson oscillations [10-12]. Thus, we compare the voltage positions of subgap structures which appeared on the *I-V* characteristics with the frequencies of optical phonons of B(P)SCCO. Table I shows the voltages and corresponding frequencies for the subgap structures on the first quasiparticle branch, together with recent data of the Raman-active optical phonons and the infrared-active optical *c*-axis phonons in the same frequency region of B(P)SCCO [15-19]. From this table, it is found that the voltages of the subgap structures correspond relatively well to the frequencies of Raman-active optical phonons in B(P)SCCO. This result suggests that the Raman-active optical phonon contributes to the subgap structures and hence the phonon assisted tunneling mechanism can be expected. According to Maksimov et al., the amplitude of the current peak due to the phonon assisted tunneling is proportional to the square of critical current I_c^2 [12]. Figs. 2(a) and 2(b) show peak currents I_{11} and I_{12} as a function of critical current I_c. Here, we defined the peak currents I_{11} and I_{12} as the excess currents from the non-linear extrapolated unperturbed characteristic (background current) as shown in Fig. 1(b). From this figure, it is found that I_{11} and I_{12} obey approximately the theoretical relation and hence these correlate strongly with I_c. The above-mentioned results give a evidence for the contribution of the Raman-active phonons to the subgap structures.

4. CONCLUSION

We have investigated the subgap structures in the current-voltage (*I-V*) characteristics of intrinsic Josephson junctions in $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$ (x=0.15, 0.2) single crystal mesas. The subgap structures appear pronouncedly on each quasiparticle branch in the

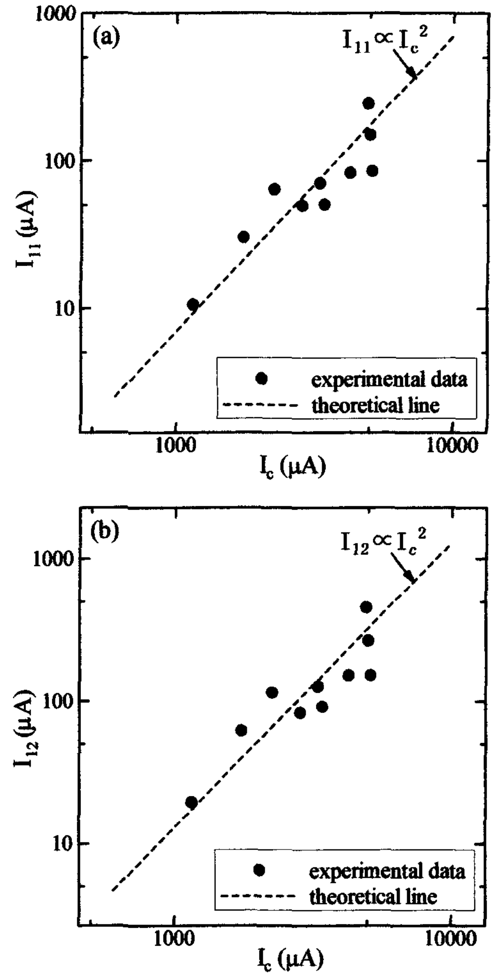

Fig. 2. Subgap peak currents I_{11} and I_{12} as a function of I_c at 4.2K.

Table I. Voltages and corresponding frequencies of subgap structures on the first quasiparticle branch in the *I-V* characteristics of intrinsic Josephson junctions in BPSCCO at 4.2K in comparison with frequencies of the Raman-active optical phonons and infrared-active optical *c*-axis phonons in the same frequency region of B(P)SCCO.

intrinsic Josephson junctions		Raman-active optical phonons				infrared-active optical phonons		
Present work		Kakihana et al.[15]	Liu et al. [16]	Kedziora et al. [17]		Tsvetkov et al. [18]		Tajima et al. [19]
BiPb		Bi	Bi	BiPb	Bi	BiPb	Bi	Bi
V [mV]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]	ω [cm^{-1}]
		24	28					
		48	47	41				
		59	62	60	60			
6.3	103	105	109	109			95	97
		117	119		118			
8.2	132	129	129	130				
		145						
10.8	176	175	180	182	180		177	175
11.7	188	195						
						208	220	218
		287	285	290	292			
		323				333	330	327
21.1	340	353	355					
						380	373	380
26.2	422	409	400					
			465	460	465		467	470

I-V characteristics below T_c (~85K), independent of sample geometry and *x*. The subgap structures ranging from 6.3 to 26.2 mV have been successfully observed on the first quasiparticle branch. The voltages of all subgap structures have been confirmed to be independent of temperature, mesa size and *x*. The voltages for the subgap structures correspond relatively well to the frequencies of Raman-active optical phonons in $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$. Moreover, a strong correlation between peak currents of the pronounced structures and critical currents of intrinsic Josephson junctions has been found. This reveals that the subgap structure is due to a phonon assisted tunneling of Cooper pairs in the junctions. From these results, the observed fine structures have been interpreted in terms of the interaction between the Raman-active optical phonons and ac Josephson oscillations in intrinsic Josephson junctions of $(Bi_{1-x}Pb_x)_2Sr_2CaCu_2O_y$.

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