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Critical current density of the $(Bi,Pb)_2(Sr,Ca)_3Cu_2O_x$ whiskers

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Abstract. The $(Bi,Pb)_2(Sr,Ca)_3Cu_2O_x$ whiskers with 2212 phase have been grown out by annealing a $Bi_{1.8}Pb_{0.35}Sr_{1.9}Ca_{2.1}Cu_{3.1}O_x$ melt-quenched plate in a stream of O_2 gas at 825 °C for 121 hours. Temperature dependences of the magnetic susceptibility (χ–T) and the critical current density (J_c–T) have been measured. The transition point T_c of the whiskers is 76.2 K, and the J_c value is 29 240 A cm^{-2} at 63.4 K, zero magnetic field. $J_c \propto (1 - T/T_c)^2$ near T_c is found, which hints that there may exist some inner grain Josephson junctions in the whisker.

Since the discovery of the high-temperature superconductors (HTSCs), Bi–Sr–Ca–Cu–O 2212 phase whiskers have been grown out by several groups [1–5] and their crystal structures and superconductivities have been characterized. In recent years, physical properties [6, 7], mechanical properties [8–10] and composites [11] of the 2212 whiskers have been reported. A Bi-based 2212 whisker is a special kind of HTSC single crystal which has a large aspect ratio (length:width >60:1). It is very flexible and exhibits remarkable elastic properties similar to those observed in whiskers of other metallic and alloy materials [12–15]. Moreover, it has a strong current carrying ability. For example, the critical current density J_c value of an Li-doped Bi–Sr–Ca–Cu–O 2212 phase whisker at 77 K is 30 000 A cm^{-2} in a zero magnetic field [2]. Matsubara *et al* prepared $Bi_2Sr_2Ca_2Cu_3O_{10}$ (2223) whiskers by heating the 2212 whiskers inside a calcined $Bi_2Sr_2Ca_4Cu_6Pb_{0.5}O_x$ powder. The 2223 whiskers yielded a maximum J_c of 7.3×10^4 A cm^{-2} at 77 K in zero magnetic field [16]. Therefore, for both applicational and fundamental reasons, investigations of the whiskers represent one of the important approaches to pursue the practical application of the HTSC materials and elucidate the nature of the high-temperature superconducting mechanism. In this letter, the temperature dependence of J_c for a $(Bi,Pb)_2(Sr,Ca)_3Cu_2O_x$ whisker in zero magnetic field is reported and its behaviour near critical temperature T_c is discussed.

Chemically pure powders of Bi_2O_3, PbO, $SrCO_3$, $CaCO_3$ and CuO were weighed in the nominal composition of $Bi_{1.8}Pb_{0.35}Sr_{1.9}Ca_{2.1}Cu_{3.1}O_x$ and mixed thoroughly. The mixture was ground in an agate mortar and melted at 1150 °C for 15 min in air. The melt was rapidly quenched into 0.5 mm thick plates at a fast rate. The plates were annealed at 825 °C for 121 h in a stream of oxygen and furnace cooled. Then several whiskers were grown out on both surfaces of the annealed plates. The whiskers have the dimensions of 1–8 mm long, 10–100 μm wide and 1–10 μm thick. Their composition was $(Bi,Pb)_2(Sr,Ca)_3Cu_2O_x$

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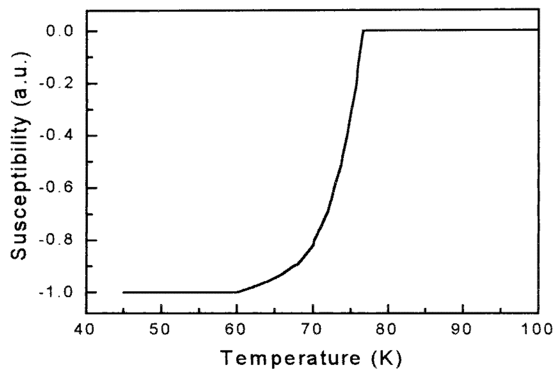

Figure 1. Temperature dependence of the real part of ac susceptibility for the grown whiskers. The applied magnetic field is 0.1 μT, the frequency is 1000 Hz.

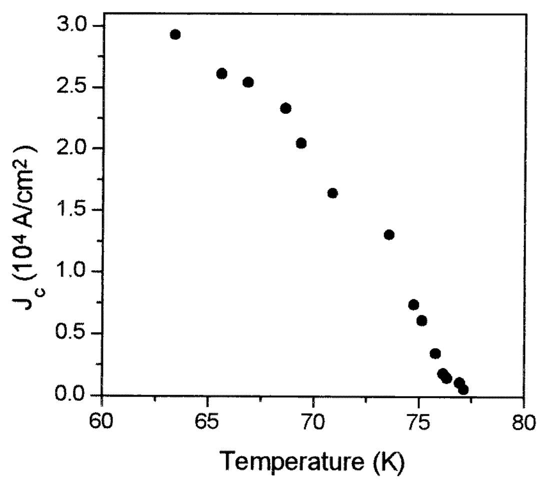

Figure 2. Zero-magnetic-field critical current density J_c against temperature of a $(Bi, Pb)_2(Sr, Ca)_3Cu_2O_x$ whisker.

analysed by EDAX. The crystal structure and orientation of the grown whiskers have been characterized [17, 18]. The whiskers have remarkably oriented structures and they are of 2212 single phase [3, 17]. The axial direction of a whisker is the b axis, the widthwise direction is the a axis and the c axis is perpendicular to the a–b plane [18]. The morphologies of the whiskers was observed by a JSM-T200 scanning electron microscope (SEM). The transition temperature T_c was determined by the ac susceptibility method. Their critical current density J_c was measured by a standard four-probe method with a voltage criterion of 1 μV cm^{-1}.

Figure 1 shows the temperature dependence of the real part of ac susceptibility for the grown whiskers. Their T_c is 76.2 K which is defined as the 10% drop of the susceptibility. The zero-magnetic-field critical current density J_c versus temperature of a whisker is shown in figure 2, which shows the J_c value of the whisker is 29 240 A cm^{-2} at 63.4 K and 20 000 A cm^{-2} at 70 K, which is much larger than that of the corresponding bulk materials. The relatively high critical current density of the whiskers is attributed to

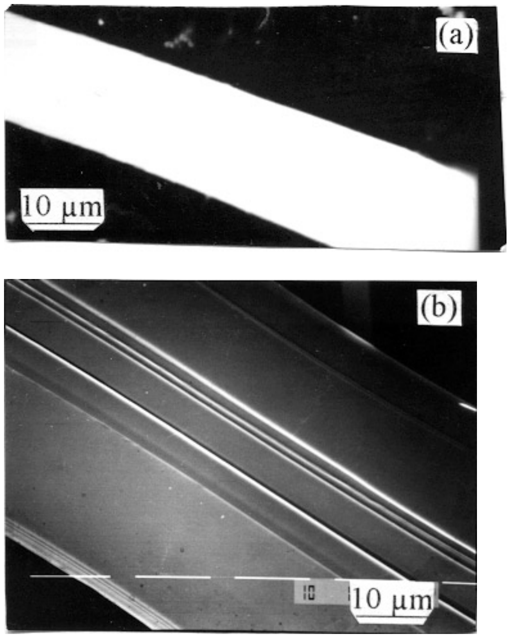

Figure 3. SEM photographs of a narrow whisker (a) and a broad whisker (b).

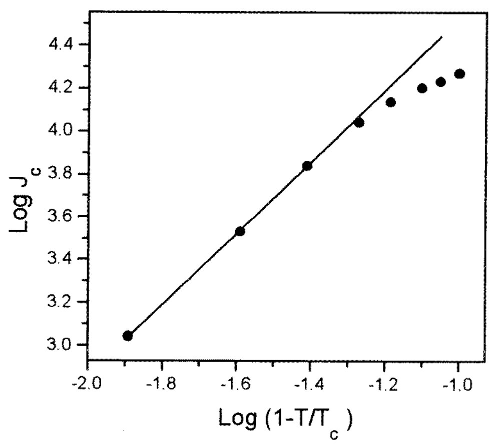

Figure 4. LogJ_c against $\log(1 - T/T_c)$ for the whisker.

their microstructure. Figure 3(a) and (b) show the SEM photographs of a narrow whisker (15 μm wide) and a broad whisker (45 μm wide), respectively. The compositions and microstructures are both well distributed for the two whiskers. The broad whisker seems to be composed of several narrow whiskers which are stacked up strictly parallel with each other and forms into a layered structure. The current carrier plane is along the axial direction of a whisker. Because there is no obvious crystal grain boundary along the current carrying direction, there are no weak links among crystal grains which is inevitable in bulk materials.

Figure 4 depicts the relationship between $\log J_c$ and $\log(1 - T/T_c)$ near T_c of the whisker. The slope of the linear part is 2, then near T_c ($T < T_c$), J_c of the whisker is proportional to $(1-T/T_c)^2$. De Gennes [19, 20] has calculated that near T_c $(T < T_c)$, current density J_c passing through a SNS (superconductor–normal metal–superconductor) junction consisting of conventional low-temperature superconductors is proportional to $(1-T/T_c)^2$, whereas J_c passing through a corresponding SIS (superconductor–insulator–superconductor) junction is proportional to $(1-T/T_c)$. These two conclusions are tenable when the superconducting coherent length is much larger than lattice parameter, the conventional superconductors satisfy this condition. However, the coherent length of a high-temperature oxide superconductor is very small: it is of the order of the size of the unit cell. After the discovery of HTSCs, Deutscher and Müller calculated the current density J_c passing through the SNS and SIS junctions consisting of high-temperature oxide superconductors [21, 22]. Their results indicated that unlike the case of junctions consisting of conventional low-temperature superconductors, J_c passing through the SNS and SIS junctions consisting of high-temperature oxide superconductors were both proportional to $(1-T/T_c)^2$ at temperatures slightly lower than T_c. Matsubara *et al* have also found $J_c \propto (1-T/T_c)^2$ for the $Bi_2Sr_2Ca_2Cu_3O_{10}$ whiskers [16]. Deutscher and Müller proposed that Josephson junctions existed within the superconducting grains [21], and this supposition could explain some experimental results very well which could be hardly explained by the weak-link effect among grains such as magnetic measurement and microwave absorption experiment, etc [22]. They indicated that the inner grain Josephson junctions in a high-temperature oxide superconductor might be taken placed at the defects such as twin boundaries. These defects must be nontetragonal or nonsuperconducting areas although their exact structures still need to be studied further. Among the many planar defects observed nowadays, some are normal metals, and some are insulators. For a conventional superconductor which has a large coherent length, this kind of thin nonsuperconducting area will not affect its superconducting state strikingly. However, this is not the case for a HTSC which has a small coherent length. An insulating area will lead to an SIS junction, and a normal metal area will lead to an SNS junction, and the current density J_c passing through these two kinds of tunnelling junction are both proportional to $(1-T/T_c)^2$ near T_c. This similarity of the behaviour of SIS and SNS junctions in a high-T_c oxide superconductor can be attributed to that the attenuation length of the superconducting wavefunction in both an insulating area and a normal metal area is in the same magnitude order with the coherent length near T_c. The short coherence length of the high-temperature superconductors is shown to induce considerable weakening of the pair potential at surfaces and interfaces. It is argued that this effect is responsible for the existence of internal Josephson junctions, which are at the origin of the superconductive glassy state.

The current density J_c of the present $(Bi, Pb)_2(Sr, Ca)_3Cu_2O_x$ superconducting whisker is proportional to $(1-T/T_c)^2$ near T_c, which is in agreement with the result of other HTSC junction cases proposed by Deutscher, Müller and Matsubara, respectively. This hints that there may exist inner grain Josephson junctions in the present whisker. This deduction is not contradictory to figure 3 which does not show any grain boundary along the current carrying direction. Generally speaking, real crystals are not perfect but contain some crystal imperfections. We have examined the perfection of the whisker by the transmission Laue method [18]. A few Laue spots were found to be split into several small spots along the axial direction of the whisker, suggesting there existed a small amount of mosaic structures or substructures in it. A typical thickness of the normal slab N separating two conventional low-temperature superconductors S is $\sim$1000 Å; their coherence length ξ is $\sim$100 Å. Therefore, a junction thickness in the case of high-T_c superconductors whose coherence length ξ is $\sim$10 Å must be less than 100 Å in order for the junction to be able to carry a finite supercurrent from S to S. Hence the magnification of figure 3 is too small to observe the mosaic structures or substructures in the whiskers. Diminishing of these mosaic structures or substructures by improving the growth technique may be a valuable goal towards practical application of the whiskers.

In summary, the zero-magnetic-field critical current density J_c of a $(Bi,Pb)_2(Sr,Ca)_3Cu_2O_x$ whisker is 29 240 A cm^{-2} at 63.4 K. The high current density of the whisker is closely related to its microstructure, for there is no obvious crystal grain boundary along the *a*–*b* plane of the whisker which is the current carrying plane. The J_c of the whisker is proportional to $(1 - T/T_c)^2$ near T_c, which hints that there may exist some inner grain Josephson junctions in the whisker. The inner grain junctions in the whisker are induced by the short coherence length and they may be taken to be placed at the mosaic structures or substructures.

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