Interlayer Coupling and Superconducting Critical Temperature of $Bi_2Sr_{1.5}La_{0.5}CuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$: Incommensurate Effects of Pressure

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The c-axis interlayer coupling of $Bi_2Sr_{1.5}La_{0.5}CuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals was changed by means of hydrostatic pressure $P < 1$ GPa resulting in a drastic increase of the c-axis critical current I_c (up to 270% GPa^{-1}) and decrease of the normal state resistance R_n (down to -60% GPa^{-1}). The superconducting critical temperature only slightly increases with a rate of $\approx 2\%-6\%$ GPa^{-1}. The much stronger effect of pressure on I_c and R_n in $Bi_2Sr_{1.5}La_{0.5}CuO_{6+\delta}$ implies that the CuO-interlayer coupling has little effect on T_c in this compound. [S0031-9007(99)08906-1]

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The interlayer tunneling (ILT) model developed by Anderson and collaborators is one of the leading candidates for explaining high-temperature superconductivity [1]. In this model, the energy gain that drives the formation of the pairs is associated with a decrease of the kinetic energy due to the easy motion of the pairs accompanied by the impeded single-particle tunneling along the c axis. The model in its current version predicts an increase of the condensation energy E_c proportionally to the interlayer Josephson coupling $t_\perp^2$, or to the inverse square of the c-axis penetration depth λ_c. A conclusive experimental check of this prediction for different single-layer high-T_c materials would provide a critical test of the ILT model. Practically, E_c and λ_c are rather difficult to measure directly on one and the same specimen, and one has to compare results obtained on different samples and sometimes from indirect measurements. A large sample-to-sample variation common to the majority of high-T_c materials can, thus, make the comparison meaningless.

Recently, a Tl-based single-layer compound $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) has been a subject of intensive experimental investigations [2,3]. In direct measurements of λ_c using scanning SQUID microscopy, it was unambiguously shown that the c-axis penetration depth λ_c in Tl-2201 is at least 1 order of magnitude larger than it has been calculated theoretically within the ILT model. This discrepancy has also been acknowledged by Anderson [4]. Up to now, the Tl-2201 compound is, however, the only exception among other well-characterized single-layer materials, such as $(La,Sr)_2CuO_4$ (La-214) or $HgCa_2CuO_4$ (Hg-1201) which show a more of less satisfactory agreement with the ILT model [5].

Here, we report on the c-axis critical current I_c (as a direct measure of the interlayer coupling) and its correlation to the superconducting critical temperature T_c (as a measure of the condensation energy) of a Bi-based single-layer compound $Bi_2(Sr_{1.5}La_{0.5})CuO_{6+\delta}$ (Bi-2201), and its double-layer ally, $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212). We use hydrostatic pressure $P \leq 1$ GPa as a tool to alter the interlayer coupling in the single crystals. We observed that while the interlayer coupling (I_c) increases dramatically with pressure (up to 270% GPa^{-1}), the critical temperature only slightly increases at a rate of 2%–6% GPa^{-1}. These incommensurate effects of pressure suggest that the CuO-interlayer coupling has little effect on T_c of the Bi compounds, in contrast to the ILT model.

To study the c-axis transport properties, we used a technique of making small mesas with typical areas of 200–600 μm^2 and heights <200 Å on the surfaces of Bi-2201 and Bi-2212 single crystals [6]. Several electrical contacts on top of every mesa allowed us to perform four-probe measurements of the c-axis superconducting and normal state transport properties.

Hydrostatic pressure up to 1 GPa was applied in a common piston-cylinder-type high pressure chamber with a 1:1 mixture of kerosene and light-fraction oil as a pressure-transmitting medium. Such a mixture has been proven to preserve the hydrostatic properties during cooling [7]. The pressure was deduced from the change with pressure of the resistance R_m of a manganin wire ($d \ln R_m/dP \approx 2.5\%$ GPa^{-1}) at $T = 293$, 77, and 4.2 K.

It has been established that Bi-2212 single crystals can be viewed as one-dimensional (1D) series arrays of intrinsic Josephson junctions (IJJ) [8]. Atomic-scale IJJ are presumably formed by the CuO bilayers (3 Å thick) acting as planar superconducting electrodes and poorly conducting BiO and SrO layers acting as barrier layers of a thickness of 12 Å [8]. Thus, a 150 Å high mesa consists of ten intrinsic Josephson junctions in a series. They show up as different branches in the current-voltage

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(I-V) characteristics, each corresponding to one, two, three, etc. IJJ subsequently switching to the quasiparticle state as the bias current exceeds the corresponding critical current [8,9].

Typical I-V characteristics of a stack of ten Bi-2212 IJJ, at two pressures, are represented in Fig. 1(a). Only two out of ten branches are shown. The characteristics are highly hysteretic, which is typical for a superconductor-insulator-superconductor-type of Josephson junction. The strong effect of pressure is also seen in Fig. 1(a). I_c nearly doubles at $P = 0.8$ GPa. Such an observation seems to be missing in the literature [10].

Our Bi-2201 samples also show hysteretic multibranched I-V characteristics in the c-axis direction; see Fig. 1(b). This is the first direct observation of the intrinsic Josephson effect in single-layer Bi-2201. There are several closely spaced sub-branches in place of usually well-defined individual branches of I-V characteristics of Bi-2212 IJJ. Switching between the sub-branches takes place stochastically and it is hard to trace them individually. This may be due to more pronounced charging [11] and nonequilibrium effects, since the effective thickness of planar "electrodes" of IJJ in Bi-2201 is much smaller than in Bi-2212. A detailed study of this issue is to be published elsewhere. Of most significance for the present experiments, though, is the presence of a zero-voltage state with a well-defined critical current, characterizing the c-axis interlayer coupling in Bi-2201. In Fig. 1(b), it is seen that the c-axis critical current of Bi-2201 increases more than 2 times at $P = 0.85$ GPa and $T = 4.2$ K.

Figures 2(a) and 2(c) show the temperature dependence of I_c at different pressures. I_c drastically increases with pressure at all temperatures. The relative change of I_c with pressure, $S_I = 1/I_c(0)\delta I_c(P)/\delta P$ is about 120% GPa^{-1} for Bi-2212, and 270% GPa^{-1} for Bi-2201 at 4.2 K. There are small "glitches" in the $I_c(T)$ curves for Bi-2212; see Fig. 2(a). These may qualitatively be explained by a presence of different configurations of Josephson vortices in stacks of coupled IJJ [12].

Figures 2(b) and 2(d) show the temperature dependence of the c-axis normal state resistance R_n. Data were taken at different pressures, determined at 77 K for Bi-2212 and at 4.2 K for Bi-2201. The change of pressure upon cooling from room temperature down to $T = 77$ K has not been taken into account. The relative change of R_n for Bi-2212, $S_R = -1/R_n(0)\delta R_n(P)/\delta P$, was estimated to be about 60% GPa^{-1} at $T = 90$ K and is *decreasing* with increasing temperature, which differs from the experiments by Forró *et al.* [13]. For Bi-2201,

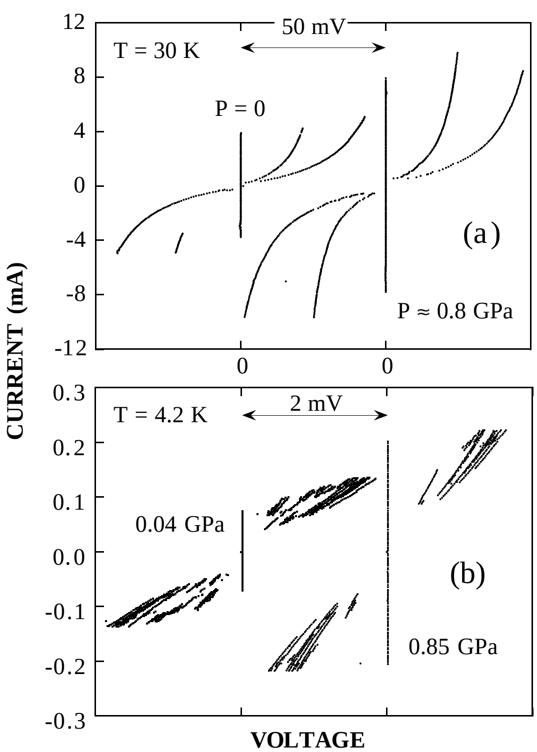

FIG. 1. Typical multibranch I-V characteristics of two stacks of intrinsic Josephson junctions at the two pressures indicated in the panels. (a) Bi-2212: Area of junctions is 600 μm^2. Two out of ten branches at $P = 0$ and 0.8 GPa are shown. (b) Bi-2201: Area of junctions is 450 μm^2. Note that the individual branches are not as well developed as in Bi-2212. The characteristics are shifted along the voltage axis by (a) 50 mV and (b) 2 mV for clarity.

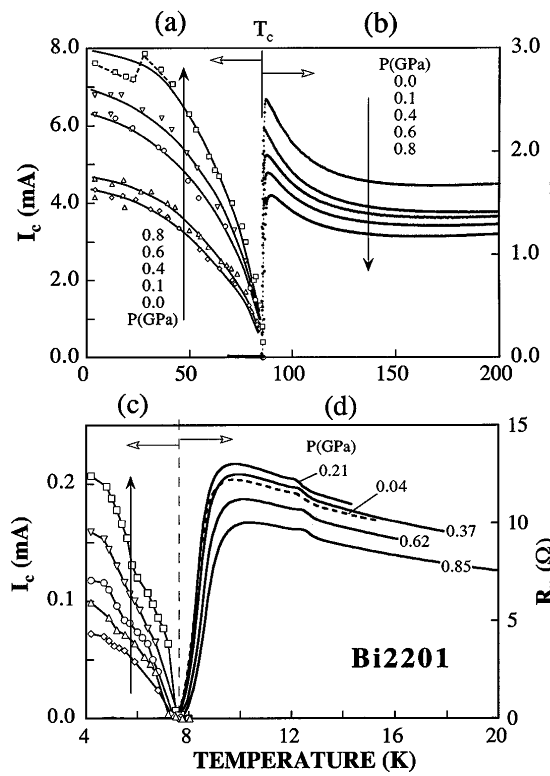

FIG. 2. Temperature dependences of [(a),(c)] the c-axis critical current I_c and [(b),(d)] the normal state resistance R_n at different pressures for Bi-2212 [(a),(b)] and Bi-2201 [(c),(d)]. Solid lines are guides for the eye.

a correct estimate is difficult to obtain correctly as $R_n(P)$ is nonmonotonic at low pressure. The dashed line corresponds to the last measurement, when the pressure was finally released from 0.8 down to 0.04 GPa. It lies below the solid curves corresponding to 0.21 and 0.37 GPa. The reason for this needs more study [14]. At high pressures, $S_{R(P\to 0.8\ \mathrm{GPa})}$ can be estimated to be $\sim 50\%\ \mathrm{GPa}^{-1}$; see Fig. 2(d).

The pressure dependence of R_n of a common metal is usually explained by a change in the Debye temperature with pressure [15]. The same effect of pressure-induced stiffening of the crystal lattice is responsible for the *decrease* of T_c with pressure for common-metal superconductors, like Al, In, Tl, and Sn. In contrast, the high-T_c compounds show much larger effects of pressure on their normal state resistances. This is hard to explain merely by changes in the phonon system. For example, compare $d(\ln R)/dP \approx -1.9\%\ \mathrm{GPa}^{-1}$ for copper with the above mentioned $S_R \sim -60\%\ \mathrm{GPa}^{-1}$ for Bi-2212.

It is widely accepted that holes created in the two-dimensional CuO_2 planes through electron transfer to the charge reservoirs are responsible for superconductivity in the cuprate superconductors [16]. Pressure may affect the charge transfer, resulting in a change of the hole concentration and an increase of T_c. However, the pressure experiments by Sieburger *et al.* on Bi-2212 samples with different oxygen content have shown that the increase of T_c is almost the same for all samples: underdoped, optimally doped, and overdoped [17]. This observation clearly indicates that it is impossible to explain the increase of T_c with pressure by a change in carrier concentration only.

In the ILT model, it is the interlayer coupling which dictates the superconducting transition temperature. This would explain the increase of T_c with pressure, since the hydrostatic pressure, in general, is expected to increase the interlayer coupling. From the experiment on single-layer Bi-2201 we see that the superconducting critical current, which we believe reflects the interlayer coupling, increases about 2 orders of magnitude faster than T_c; see Fig. 3 [18]. This implies that T_c in Bi-2201 does not correlate with the interlayer coupling, in contrast to the ILT model.

In Bi-2212 though, one has to distinguish the interlayer coupling within the block of the CuO-Ca-CuO layers (intrablock coupling) and the (cell-to-cell) coupling between these blocks across BiO layers (interblock coupling). The c-axis critical current is determined by the weakest of the two, most likely by the interblock coupling, while it is the intrablock coupling which determines high T_c in the ILT model. This does not allow one to make certain conclusions on the validity of the ILT model in Bi-2212 [19].

Even for the single-layer "2201" compounds, there exists another hypothetical explanation of the results obtained. If the BiO(TlO) layers were superconducting [9], the pairs formed in the CuO planes would have a fair change to escape to the former layers thus providing some saving of the kinetic energy, and making the coupling between adjacent BiO(TlO) and CuO layers responsible for high T_c in the ILT model. Furthermore, if the c-axis critical current (and hence, λ_c) were dictated by the bottleneck of the likely weak BiO(TlO)-to-BiO(TlO) coupling, the experimentally measured I_c and λ_c would not have probed the "active" coupling. This would explain the difference between the 2201-compounds, and the Hg-1201/La-214 systems, which have no "doubling" of blocking layers, and where the ILT model seems to work [5]. The "negative" for the ILT model results of our present study and experiments of Refs. [2,3] may turn out to be not as conclusive as they seemed to be. However, this purely speculative suggestion needs more study.

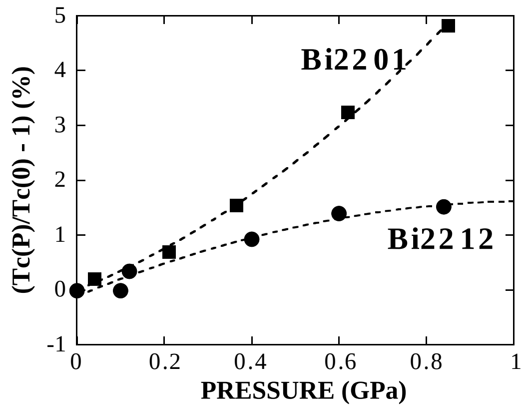

FIG. 3. The pressure dependence of the superconducting critical temperature T_c. The midpoints of the transition curves $R_n(T)$ have been adopted as T_c's. The zero-pressure transition temperatures were 88.4 and 8.2 K for Bi-2212 and Bi-2201, respectively. Dashed lines are guides for the eye.

In conclusion we have experimentally demonstrated that the interlayer coupling in Bi-2201 and Bi-2212 single crystals may be drastically increased by applying hydrostatic pressure. A relatively small change of T_c with pressure in Bi-2201 suggests that the interlayer coupling has little effect on T_c in the Bi system.

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into agreement. They argue that, for instance, taking into account fluctuation effects should result in prediction of a larger λ_c.

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