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Normal-State Properties of Uniaxially Pressed $\text{Bi}_{1.65}\text{Pb}_{0.35}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ Ceramics

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We have studied the effects of the uniaxial compacting pressure on the physical properties of polycrystalline $\text{Bi}_{1.65}\text{Pb}_{0.35}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ (Bi-2223) superconductors. Powders of this material were pressed at different uniaxial compacting pressures ranging from $\sim 90$ to $\sim 600$ MPa and heat-treated at the same temperature. A characterization of samples by using Scanning Electron Microscopy and X-ray diffractometry indicated an appreciable improvement of the degree of texture with increasing pressure. The temperature dependence of the electrical resistivity $\rho(T)$ exhibits a $T$-linear behavior at temperatures higher than $T^* \sim 235$ K. The deviation of $\rho(T)$ from the linear behavior below $T^*$ indicates the opening of the pseudogap, a feature confirmed by magnetic susceptibility measurements performed in powder samples. From linear fittings of the normal-state electrical resistivity we were able to separate contributions to $\rho(T)$ arising from both the grain misalignment and microstructural defects. The results suggest that the grain orientation and the connectivity between them are improved with increasing compacting pressure. Also, based on the linearity of the electrical resistivity data both the transport electron-phonon coupling constant, $\lambda_{tr}$, and the mean free path, $l$, were estimated. We have found that in the sample with the highest degree of texture $\lambda_{tr} \sim 0.53$, a value comparable with the one obtained in Bi-2223 single crystals. However, the result for $l \sim 12.7$ Å at 300 K, in the same ceramic sample, is close to 3 times lower than the single crystal value. The influence of the intergranular electrical resistivity in determining band-theory parameters was analyzed within the framework of a current conduction model for granular superconducting materials.

I. INTRODUCTION

The presence of grain boundaries in various forms of polycrystalline superconducting samples (bulk sintered material, thick films, tapes, and wires) is a natural consequence of the preparation conditions from powdered precursors. Grain boundaries play an important role in limiting the general transport properties of polycrystalline superconductors. Moreover, it is well established that the properties of grain boundaries mainly control the macroscopic properties of all high-$T_c$ materials.[1] This phenomenon is mainly attributed to the misorientation between the grains usually referred to as the meso-texture.[2] High angle grain boundaries can act as Josephson coupled weak links, leading to a significant field-dependent suppression of the supercurrent across the grain boundary.[1] In order to improve the transport properties of these materials they are subjected to large mechanical deformations. These techniques have proven to be effective in raising the superconducting critical current $I_c$ of the superconducting tapes,[3–5] mainly due to a marked increase in both the meso-texture and the micro-texture, where the latter is related to the orientation of the individual grains regarding the direction in which the mechanical deformation is applied. The combination of the above types of texture gives the macro-texture of the material.[2]

In a previous work, we have described a systematic study concerning the influence of uniaxial compacting pressure on the general superconducting properties of polycrystalline ($\text{Bi-Pb}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ (Bi-2223)) samples.[6] By performing measurements of critical current density as a function of applied magnetic field, $I_c(B_a)$, we have observed three different superconducting levels: the superconducting grains, the superconducting clusters, and the weak links. It was found that properties of the last two levels are very sensitive to the compacting pressure, mostly due to changes in the grain boundary properties. However, a similar systematic study regarding effects of the uniaxial compacting pressure on the normal-state transport properties of the above ceramic material is lacking.

The normal state properties of high-$T_c$ superconductors, such as the temperature dependence of the electrical resistivity, $\rho(T)$, have been an attractive topic for investigations in the last years. This occurs because it is possible to obtain some important parameters such as the electron-phonon coupling constant, $\lambda_{tr}$, and the mean free path, $l$, by correlating transport measurements with band-theory arguments.[7] In granular superconducting materials, studies involving the behavior of $\rho(T)$ present an additional inconvenient due to the complexity of their microstructure in which both intragranular and intergranular contributions as well as the degree of texture and structural defects must be considered.[13] Consequently, estimates of band-theory parameters such as $\lambda_{tr}$ and $l$ from $\rho(T)$ data of ceramic samples require corrections in order to separate the influence of microstructural contributions on the intrinsic electrical resistivity of the Cu-O planes, also referred
TABLE I: Few parameters of the uniaxially compacting pressed samples studied in this work: the compacting pressure, \( P \), the offset superconducting critical temperature, \( T_{c,ff} \), the electrical resistivity at 300 K, \( \rho(300 \text{ K}) \), and the paracoherent electrical resistivity, \( \rho_p \).

<table>
<thead>
<tr>
<th>Sample</th>
<th>( P ) (MPa)</th>
<th>( T_{c,ff} ) (K)</th>
<th>( \rho(300 \text{ K}) ) (mΩ cm)</th>
<th>( \rho_p ) (mΩ cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>98</td>
<td>99.8</td>
<td>2.88</td>
<td>0.69</td>
</tr>
<tr>
<td>P2</td>
<td>196</td>
<td>101.5</td>
<td>2.19</td>
<td>0.54</td>
</tr>
<tr>
<td>P3</td>
<td>294</td>
<td>102.5</td>
<td>1.81</td>
<td>0.42</td>
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<td>P4</td>
<td>490</td>
<td>102.8</td>
<td>1.63</td>
<td>0.36</td>
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<td>P5</td>
<td>588</td>
<td>103.0</td>
<td>1.24</td>
<td>0.28</td>
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</tbody>
</table>


to as in-plane electrical resistivity \( \rho_{ab} \). Within this context, Gurvitch et al.[7] have corrected the electrical resistivity data of both \( \text{La}_{2-x}\text{Sr}_{x}\text{CuO}_4 \) and \( \text{YBa}_2\text{Cu}_3\text{O}_{6-\delta} \) ceramic samples by using a constant factor of ∼2 and comparing the results with data obtained in high-quality ceramics and epitaxial thin films.

In addition, electrical resistivity measurements in the normal-state of cuprates have revealed the presence of electronic correlations at high temperatures, referred to as the pseudogap. Such a pseudogap, which manifests itself as a depletion of the quasiparticle density of states (DOS) below a characteristic temperature \( T^* \).[8] would reflect the creation of a precursor state of the Cooper pairing [9] that acquires long-range coherence order below the superconducting critical temperature, \( T_c \). The pseudogap temperature, \( T^* \), can be estimated by using different techniques such as the temperature dependence of the electrical resistivity, \( \rho(T) \), and magnetic susceptibility, \( \chi(T) \).[8, 10] In fact, \( T^* \) can be inferred from deviations in both \( \rho(T) \) and \( \chi(T) \) data from the expected behavior at temperatures well above \( T_c \).[8] In addition, it is well known that the magnetic susceptibility behavior is related to the Pauli paramagnetic susceptibility of the \( \text{Cu}^{2+} \) spins, which in turn is related to the density of state at the Fermi level.[11, 12]

In this work we focus on the \( \rho(T) \) measurements of polycrystalline \( \text{Bi}_{1.65}\text{Pb}_{0.35}\text{Sr}_{2}\text{Ca}_{2}\text{Cu}_{3}\text{O}_{10+\delta} \) samples subjected to different uniaxial compacting pressures before the last heat treatment. X-ray diffraction patterns, XRD, taken on powder and bulk samples, microographies by Scanning Electron Microscope, SEM, taken on free surface and fracture, and measurements of magnetization versus temperature, \( M(T) \), have been performed as complementary characterizations. The main contribution of this paper is to quantify the effects of uniaxial compacting pressure on the \( \rho(T) \) dependence mainly in the normal-state region. By using the model proposed by Gurvitch et al.[7] some relevant parameters were extracted such as the electron-phonon coupling constant and the mean free path. The resulting values have been also analyzed within the framework of the current conduction model proposed by Diaz et al.[13]

II. EXPERIMENTAL PROCEDURE

Polycrystalline samples of the superconductor \( \text{Bi}_{1.65}\text{Pb}_{0.35}\text{Sr}_{2}\text{Ca}_{2}\text{Cu}_{3}\text{O}_{10+\delta} \) (Bi-2223) were prepared from powders of \( \text{Bi}_2\text{O}_3 \), \( \text{PbO} \), \( \text{SrCO}_3 \), \( \text{CaCO}_3 \), and \( \text{CuO} \), which were mixed in an atomic ratio of \( \text{Pb}:\text{Bi}:\text{Sr}:\text{Ca}:\text{Cu} = 0.35:1:6.5:2:2.3 \). Details of the sample preparation process are described elsewhere.[6] Here, before the last heat treatment, the powders were uniaxially pressed at different compacting pressures ranging from ∼90 to ∼600 MPa (see Table I), and the typical dimensions of the pellets were \( d = 10 \text{ mm} \) in diameter and \( h = 1 \text{ mm} \) in height. The last heat treatment of the pellets was performed in air at 845 °C for 40 h followed by slow cooling.

We have evaluated the phase identification in both powder and bulk samples by means of X-ray diffraction patterns obtained in a Bruker-AXS D8 Advance diffractometer. Also, a qualitative evaluation of the degree of texture in pellet samples was made by using the same technique. These measurements were performed at room temperature using \( \text{Cu} \) K\( _\alpha \) radiation in the 3° ≤ 2θ ≤ 80° range with a 0.02° (2θ) step size and 5 s counting time.

The microstructure of fractured and free surfaces of samples was observed by using a JEOL JSM-5800 Scanning Electron Microscope operating at 25 kV. In the first type of measurement we have observed the shape of the grains, their degree of orientation, and estimated the mean size. From the second one, we qualitatively evaluated the porosity of samples subjected to different compacting pressures.

We have performed dc magnetization measurements \( M(T) \) in powders extracted from each pellet and with identical mass, by using a commercial Quantum Design SQUID magnetometer. The powders were cooled in zero applied magnetic field from room temperature down to 10 K. After this step, zero-field cooled (ZFC) and field-cooled (FC) measurements were performed under applied magnetic fields and up to 300 K.

The temperature dependence of the electrical resistivity, \( \rho(T) \), was measured by using the standard dc four-probe technique in slabs with typical dimensions of \( t = 0.5 \text{ mm} \) (thickness), \( w = 2 \text{ mm} \) (width), and \( l = 10 \text{ mm} \) (length). These measurements were performed by applying the excitation current along the plane of the sample perpendicular to the direction in which the uniaxial compacting pressure has been applied. After cooling the sample in zero applied magnetic field down to 77 K, an excitation current of 1 mA was applied. The specimen was then warmed slowly from 77 K to room temperature and both the voltage across the sample and the temperature were collected.

Current-voltage (I-V) measurements were performed to determine the paracoherent electrical resistivity, \( \rho_p \), of the samples.[13] We have used the so-called quasi-dc four-probe technique in these experiments, as described in Ref. 14. Once the sample was cooled down and fixed at a given temperature close to 103 K, an excitation current, \( I_{ex} \), was applied during 1 sec and the voltage across the sample, \( V \), was measured. After this step, \( I_{ex} \) was turned off during ∼10 sec, avoiding possible Joule self-heating effects, and the voltage was measured again for a new value of \( I_{ex} \). Repetitions of the above steps accom-
accompanied by a continuous increase of the excitation current resulted in several \( I - V \) curves at different temperatures. From the results, \( \rho \) vs. \( J \) curves are built and \( \rho_p \) is extracted from the apparent observed plateau in the \( \rho \) vs. \( J \) dependence.\[13\] By using this procedure, the electrical resistivity of the sample \( \rho \) and the transport current density flowing through the material \( J = I_{ex}/(wt) \) are determined.

III. EXPERIMENTAL RESULTS

Figure 1 displays the X-ray diffraction patterns taken on bulk samples \( P_2, P_3, \) and \( P_5 \), and in a powder sample \( PO \). This powder was prepared from the sample \( P_2 \), that was reground after the last heat treatment. A comparative analysis of these patterns reveals that all samples have similar chemical composition and that all the indexed reflections are related to the high-\( T_c \) Bi-2223 phase. The unit-cell parameters were calculated regarding an orthorhombic unit cell and the obtained values \( a = 5.410 \, \text{Å}, \, b = 5.413 \, \text{Å}, \, \) and \( c = 37.152 \, \text{Å} \) are in excellent agreement with those reported for the same compound elsewhere.\[15\] The values of \( a, b, \) and \( c \) were found to be essentially the same for the samples subjected to different compacting pressures. A careful inspection of these X-ray diagrams also reveal clear effects related to the increase of the compacting pressure. A typical example is associated with changes observed, for instance, in the evolution of the (200) and (0014) peaks. The data indicate a monotonic increase of the relative intensity of the (0014) peak with increasing compacting pressure. This strong suggest that the grains belonging to samples subjected to higher compacting pressures are more aligned along the \( c \)-axis, a feature that is corroborated by the continuous decrease of the relative intensity related to the reflection (200).

In order to quantify these features, we have also computed the relative intensity of both (0010) and (200) Bragg peaks regarding the intensity of the reflection (0012) belonging to the powder sample \( PO \). The compacting pressure dependence of both reflections are displayed in Fig. 2. The data indicate that the relative height of the peak (0010) increases monotonically with increasing compacting pressure suggesting that higher compacting pressures improved the degree of texture and results in a better alignment of the grains. In addition, it seems that grains are aligned with their \( c \)-axis preferentially parallel to the compacting direction. Indeed, such a feature is consistent with the progressive decrease of the relative intensity related to the peak (200), as inferred from the data shown in Fig. 2.

The effect of the compacting pressure has its counterpart in the microstructure of these samples. This can be inferred from the free surface and the fracture micrographs of samples \( P_1 \) and \( P_5 \) which are shown in Fig.3. In both types of micrographs it is possible to observed that the granular morphology of both samples is similar, exhibiting the occurrence of grains with nearly platelet-like shape. Also, a careful inspection of the free surface micrographies of samples \( P_1 \) and \( P_5 \) (see Figs. III and III) reveals that the later is more homogeneous, mostly due to a marked reduction in the porosity level with increasing compacting pressure.

The analysis of fracture micrographies in these samples also indicates changes in both the grain size and the grain orientation. The average grain size in the sample \( P_1 \) was found to be \( L_a = 6 \, \mu \text{m} \) long and as thick as \( L_c = 0.3 \, \mu \text{m} \). For the sample \( P_5 \), the grains were found to have dimensions of \( L_a = 4 \, \mu \text{m} \) long and \( L_c = 0.1 \, \mu \text{m} \) thick. The ratio \( L_a/L_c \), which is referred to as the mean aspect ratio of the grains,\[13\] has been found to be very sensitive to the applied pressure and were \( \sim 20 \) and \( \sim 40 \) for the samples \( P_1 \) and \( P_5 \), respectively. These values are higher than those of 2.5 and 4.5 in ceramic samples of \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \)\[13\] but similar to the one of \( \sim 50 \) estimated in (Bi,Pb)-2223 superconducting tapes.\[2\]

On the other hand, the micrograph belonging to the sample \( P_1 \) (Fig.III) reveals that the grains are random oriented and...
thicker than those, for instance, of the sample P5, which are thinner and aligned parallel to each other. The above results are in excellent agreement with the XRD analysis discussed above, which indicated a continuous increase of the degree of texture with increasing compacting pressure.

FIG. 3: Micrographs of the free surfaces (III and III), and fractured samples (III and III) P1 and P5, respectively, which were subjected to different uniaxial compacting pressures, as displayed in Table I.

It is reasonable to point out that the morphological alterations provoked by increasing the compacting pressure must be reflected in some macroscopic properties of these ceramic samples as the temperature dependence of the electrical resistivity. Following this statement, the temperature dependence of the electrical resistivity $\rho(T)$ of samples P1, P2, P3, P4, and P5 are displayed in Fig. 3. All curves exhibit a transition to the superconducting state below the onset superconducting critical temperature $T_{on} \sim 110$ K. Such a critical temperature is identified as the transition of isolated grains to the superconducting state in granular superconductors. The observation of an almost constant value of $T_{on} \sim 110$ K in all samples suggests that the superconducting grains seem to be insensitive to the increasing of the compacting pressure, at least in the pressure range used in these experiments. In addition, a nearly constant value of $T_{on} \sim 110$ K, combined with the XRD results which exhibited absence of Bragg peaks belonging to extra phases, indicates that the grains of all samples have essentially the same stoichiometry.

We have also found that the temperature in which the zero resistance state is attained, $T_{off}$, slightly increases with increasing compacting pressure (see Table I). Since $T_{off}$ is close related to the intergranular component of these ceramic samples, the $\rho(T)$ data indicate that increasing compacting pressure results in a better connectivity between grains, besides the higher alignment along the $ab$-plane, as inferred from the data shown above. On the other hand, the $\rho(T)$ curves
exhibit a clear metallic-like behavior in the normal-state region. Such a result, along with the progressive decrease of the magnitude of \( \rho(T) \) at 300 K (see Table I), suggests that the electrical current flows preferentially along the \( ab \)-plane of the partially oriented grains in these samples.

The \( \rho(T) \) data were found to obey a linear trend in a well defined temperature range. Thus, a relevant question concerns the procedure to determine the temperature in which \( \rho(T) \) curves start to deviate from linearity. Usually, this temperature is determined by visual localization. However, such a procedure is too subjective to be quantitative, as discussed by Tallon et al.[8] In order to evaluate the deviation from linearity of our \( \rho(T) \) data, we have computed several slopes \( \Delta \rho(T)/\Delta T \) following the relation

\[
m(T) = \frac{\rho(300K) - \rho(T)}{300K - T},
\]

where \( \rho(300K) \) is the electrical resistivity at 300 K (see Table I). The temperature \( T \) was increased from 160 K to 260 K, in step sizes of \( \sim 5 \) K. A linear dependence of \( \rho(T) \) data implies, according to Eq. (1), a temperature-independent behavior of the \( m(T) \) dependence.

![FIG. 5: Normalized values of \( m(T) \), calculated by using the Eq. 1 from 160 to 260 K, as a function of temperature. A constant value of \( m(T) \) is observed for temperatures higher than 235 K, as discussed in the text.](image)

The temperature dependence of the normalized \( m(T) \) curves of the samples P1, P3, and P5 are displayed in Figure 5. The \( m(T) \) curves exhibit a temperature independent behavior from room temperature down to \( T_p \approx 235 \) K. Below \( T_p \), the \( m(T) \) curves of samples P1, P3, and P5 display a similar behavior and start to deviate each other at a lower temperature \( T \approx 210 \) K. Thus, a temperature-independent behavior in the \( m(T) \) dependence indicates that all \( \rho(T) \) curves have a \( T \)-linear behavior in a narrow temperature range, or more appropriately, from \( T_p \approx 235 \) K to 300 K. The data shown in Fig. 4 also indicate that \( T_p \) seems to be insensitive to changes in the compacting pressure.

As already mentioned, it is well accepted that such a \( T \)-linear deviation in \( \rho(T) \) curves at higher temperatures constitutes an evidence of the pseudogap opening. Also, it has been pointed out that this deviation may be reflected in the density of the states at the Fermi surface due to the Cooper pair formation without long-range phase coherence.[9] In order to verify the above statement, magnetic susceptibility measurements were performed in powder samples. Figure 6 displays the temperature dependence of the inverse magnetic susceptibility, \( \chi^{-1}(T) \), of samples P1, P2, P3, and P5. The curves show a clear deviation from linearity of the Curie-type magnetic susceptibility behavior at \( T^* \approx 235 \) K, a feature which is much more pronounced in samples subjected to low compacting pressures as P1 and P2.

With the aim to discuss the differences between the \( \chi^{-1}(T) \) curves of our batch of samples, simple and qualitative arguments can be used. A continuous decrease in temperature would result in two opposite effects on the magnetic susceptibility of the paramagnetic state: (1) a better alignment of the magnetic dipoles along the direction of the applied magnetic field due to the decrease of the thermal energy (Curie law), and (2) a decrease in the number of magnetic dipoles at temperatures below \( T^* \) because part of them participate in the creation of Cooper pairs, which have dipole momentum equal to zero. Within this scenario, the creation of Cooper pairs results in a decrease of the density of states and, consequently, a decrease in the Pauli paramagnetic susceptibility term. On the other hand, the intensity with both effects are reflected in \( \chi^{-1}(T) \) curves depends on the demagnetizing factors of the grains in the powder samples. As shown in figures III and III, the granular morphology of these samples has been altered with increasing compacting pressure: it evolves from grains with nearly ellipsoidal shape (see sample P1) to grains with a platelet-like shape (see sample P5). In fact, the average value of the grain thickness, \( L_{ave} \), for the sample P1 is close to three times larger than the one observed in the sample P5. The other dimensions of the grains were found to be similar in both samples. Therefore, increasing compacting pressure provokes a decrease in the average value of the demagnetizing factor of the grains and, as consequence, a decrease in the
measured values of the magnetic susceptibility. Thus, the deviation from the Curie law below $T^*_K \approx 235$ K is expected to be much less pronounced in samples subjected to higher compacting pressures, as observed in our experiments. Our value of $T^*_K \approx 235$ K agrees well with the pseudogap temperature reported by both Fujii et al. [10] and Yamada et al. [16] in Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ single crystals, as well as by Ekino et al. [17] in (Bi-Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ ceramic samples. Thus, our combined results of transport and magnetic measurements suggest that changes in $T = T^*_p \approx T^*_K \approx 235$ K are related to the opening of the pseudogap at this temperature.

![Image of graph showing $\rho$ vs. $J$ for Bi-2223 compounds](image)

**FIG. 7:** $\rho$ vs. $J$ curves for all samples studied in this work. The paracoherent electrical resistivity $\rho_p$ has been determined from the apparent linear plateau of the $\rho(J)$ curves, as indicated by the dashed line of the curve belonging to the sample P5.

Another important information regarding the effects of compacting pressure on the intergranular features of samples can be extracted from the paracoherent electrical resistivity, $\rho_p$. As reported by Diaz et al., [13] effects arising from the misalignment of grains in transport data can be disregarded in the paracoherent state because the grains are in the superconducting state while the intergranular junctions remain in the normal state. In order to determine the paracoherent electrical resistivity of our samples, $\rho$ vs. $J$ curves were measured and the results are shown in Figure 7. Values of $\rho_p$ were extracted by extrapolating the apparent observed plateau in the $\rho$ vs. $J$ behavior[13] and are shown in Table I. Even when the values of $\rho$ were very scattered we were able to verify the existence of an almost constant value of $\rho$ for $J \leq 45$ A/cm$^2$. In addition, the data indicate a progressive decrease in $\rho_p$ with increasing compacting pressure, as confirmed by the estimated values of $\rho_p = 0.69$ m$\Omega$ cm and $\rho_p = 0.28$ m$\Omega$ cm in samples P1 and P5, respectively. These results indicate that increasing compacting pressure improves the intergranular components of these uniaxially pressed Bi-2223 samples.

The $\rho$ vs. $J$ curves also displays a departure from the plateau observed close to $J \approx 45$ A/cm$^2$ in all samples. As discussed in Ref. 13, such a value would be related to the superconducting critical current density of the grains, $J_c$. However, such a value seems to be very low as compared with those of $J_c \approx 10^3-10^6$ A/cm$^2$ obtained by magnetic measurements in similar temperatures.[18, 19] Such a discrepancy is related to the anisotropic factor $J^{ab}_c/J^c$, where $J^{ab}_c$ and $J^c$ are the in-plane and out-of-plane superconducting critical current densities of grains, respectively. In Bi-2223 compounds $J^{ab}_c/J^c \approx 50$, as reported elsewhere.[20] Within this context, one would expect that the first change in the plateau of $\rho(J)$ curves reflects the dissipation in grains mainly oriented along the $c$-axis parallel to the applied current density, i.e., this value corresponds to $J^{c}_c$. By assuming that the values of the critical current density reported by magnetic measurements [18, 19] mainly reflect the $J^{ab}_c$ component, then our results for the out-of-plane $J_c$ seem to be reasonable.

**IV. DISCUSSION**

The influence of the uniaxial compacting pressure on the normal-state transport properties has been clearly demonstrated in XRD, SEM, and $\rho(T)$ measurements (see Figs. 2-4). The combined results indicate an increase of both the degree of texture (grain alignment) and the grain connectivity of the samples. Thus, a comprehensive analysis of these effects on the transport properties must be considered.

As far as this point is concerned, Diaz et al. [13] have proposed a model in which the $\rho(T)$ data of polycrystalline samples of high temperature superconductors are believed to be strongly influenced by two different contributions: one associated with the misalignment of the grains (texture degree) and the other one related to microstructural defects such as voids and microcracks. Within the context of the model, the $\rho(T)$ dependence can be written as,[13]

$$\rho(T) = \frac{1}{\alpha_n} (\rho_{ab} + \rho_{str}), \quad (2)$$

where

$$\alpha_n = f \alpha_{str}, \quad (3)$$

is a factor that enhances the electrical resistivity due to both the misalignment of the grains $f$; $0 < f \leq 1$; and microstructural defects $\alpha_{str}$; $0 < \alpha_{str} \leq 1$.

In such a model, the grains are believed to behave as a single crystal. Then, the first term in the Eq. (2) is related to the average electrical resistivity of the $ab$-plane, $\rho_{ab}$. The second one, $\rho_{str}$, is the actual average of the intergranular component, which is assumed to be temperature-independent. In our analysis, the term $\rho_{ab}$ has been assumed to be linearly temperature-dependent and zero-residual temperature intercept. In fact, Fujii et al. [10] have reported measurements of both the in-plane $\rho_{ab}(T)$ and the out-of-plane $\rho_p(T)$ electrical resistivity as a function of temperature in Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$
TABLE II: Parameters obtained by the linear fitting of the ρ(T) curves. A is the slope of the electrical resistivity data in the T-linear region and ρ(0) the residual electrical resistivity. We have also included the parameters obtained by using the model proposed in Ref. 13. Here ρstr is the average intergranular electrical resistivity and αf a factor that enhances the electrical resistivity due to the grain misalignment, f, and microstructural defects, αstr.

<table>
<thead>
<tr>
<th>Sample</th>
<th>A(µΩcm/K)</th>
<th>ρ(0)(µΩcm)</th>
<th>ρstr(µΩcm)</th>
<th>αf</th>
<th>f</th>
<th>αstr</th>
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<tbody>
<tr>
<td>P1</td>
<td>5.62</td>
<td>1.19</td>
<td>0.39</td>
<td>0.33</td>
<td>0.58</td>
<td>0.57</td>
</tr>
<tr>
<td>P2</td>
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<td>0.89</td>
<td>0.38</td>
<td>0.43</td>
<td>0.61</td>
<td>0.70</td>
</tr>
<tr>
<td>P3</td>
<td>3.82</td>
<td>0.66</td>
<td>0.32</td>
<td>0.48</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td>P4</td>
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<td>0.28</td>
<td>0.50</td>
<td>0.64</td>
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</tr>
<tr>
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<td>0.40</td>
<td>0.27</td>
<td>0.68</td>
<td>0.71</td>
<td>0.96</td>
</tr>
</tbody>
</table>

single crystals with different oxygen contents. The data related to the single crystal with optimum oxygen content indicate that the slope of the in-plane electrical resistivity, ρstr(T), in the T-linear part, is Astr = 1.84 µΩ cm/K and that the electrical resistivity at 300 K is ρstr(T) ≈ 496 µΩ cm.[21]

Therefore, both αf and ρstr can be obtained by using the appropriate expressions,[13]

$$\alpha_f = \frac{A_{str}}{A}, \quad (4)$$

and

$$\rho_{str} = \alpha_f \rho(0), \quad (5)$$

where A is the slope of the ρ(T) curve in the T-linear region (T > T_F) and ρ(0) the residual electrical resistivity at T = 0. Both parameters were obtained by fitting the electrical resistivity data to the typical linear dependence ρ(T) = AT + ρ(0). The best fitting parameters by using the above linear dependence are displayed in Table II.

As inferred from the analysis of Eq. (5), the residual electrical resistivity ρ(0) cannot be considered as the actual intergranular electrical resistivity of the sample. Moreover, ρ(0) quantifies the influence of both the texture and microstructural defects on the magnitude of the intergranular electrical resistivity of the polycrystalline sample.

The calculated values of αf and ρstr, by using Eqs. (4) and (5), are given in Table II. As expected from the previous analysis, ρstr decreases appreciably (∼ 30 %) with increasing compacting pressure, indicating an improvement of the intergranular component of ρ. Such a decrease in ρstr with increasing compacting pressure is mainly related to two mechanisms: an increase of the degree of texture and a decrease of microstructural defects.

In order to gain further information regarding the above mechanisms, we tentatively try to separate both contributions from the estimated values of αf. Such a separation requires, according to Eq. 3, the determination of f or αstr. As far as this point is concerned, Díaz et al. [13] have proposed an experimental procedure based on measurements of the para coherent electrical resistivity of polycrystalline samples, ρp, to determine these parameters. In such a procedure, it has been assumed that the sample is in the so-called para coherent state. This means that the grains are in the superconducting state but the intergranular junctions remain in the normal-state. Under these circumstances, the first term in Eq. (2) can be neglected and effects arising from the misalignment of grains become irrelevant, i. e., f = 1 and αf = αstr. In this case Eq. (2) is altered and rewritten as

$$\rho_p = \frac{1}{\alpha_{str}} \rho_{str}, \quad (6)$$

where ρp is the para coherent electrical resistivity. By using Eq.(6) in combination with the values of both ρp and ρstr, an estimate of αstr is possible. We have performed these estimates and the obtained values are displayed in Table II. As can be inferred from Eq. (6), the observed decrease in ρp values with increasing compacting pressure (see Table I) is related to a similar behavior observed in ρstr and the progressive increase of αstr (∼ 40 %), which in turn indicates the reduction of microstructural defects. In addition, one may to estimate the values of the grain misalignment factor f by using Eq. (3), knowing both αf and αstr. As displayed in Table II, the grain misalignment factor f increases from f ∼ 0.58 to f ∼ 0.71 for samples P1 and P5, respectively. These results indicate an appreciable increase in the degree of texture with increasing compacting pressure and are in excellent agreement with both XRD and SEM data.

On the other hand, by combining the observed T-linear behavior in the ρ(T) dependence (see Fig. 4) with band-theory arguments, it is possible to obtain additional information regarding the effects of the compacting pressure on the normal-state transport properties.[7] Based on the behavior of A an important information regarding the strength of the electron-phonon interaction can be obtained. By considering that the T-linear behavior of ρ(T) curve is mainly caused by the electron-phonon scattering, then the transport electron-phonon coupling constant λ_tr can be estimated from the expression[7]

$$\lambda_tr = \frac{\hbar \omega_c^2 A}{8 \pi^4 k_B} = 0.246(\hbar \omega_p)^2 A, \quad (7)$$

where $k_B$ is the Boltzmann constant, $\hbar \omega_p$ is the plasma energy expressed in eV, and A is expressed in µΩ cm/K (see Table II). Assuming that the London penetration depth $\lambda_L$ for the BSCCO system is $\sim 2100 \AA$[22] then the plasma frequency can be estimated by using the relation $\omega_p = c/\lambda_L$, where c is the velocity of light, yielding $\hbar \omega_p = 0.893$ eV. Additionally, from the electrical resistivity measurements one can also estimate the mean free path of the carriers, l, following the equation:[7]

$$l(T) = \frac{4 \pi v_F}{\omega_p^2 \rho(T)} = \frac{4.95 \times 10^{-4} v_F}{(\hbar \omega_p)^2 \rho(T)}, \quad (8)$$

where $v_F$ is the Fermi velocity, which for BSCCO materials is $\sim 2.5 \times 10^7$ cm s$^{-1}$.[22] and ρ(T) is given in µΩ cm.
We mention that in Ref. 7, values of \( \rho(T) \) data have been corrected by a factor \( \beta = \rho / \rho_{\text{true}} \) in order to separate the ab-plane electrical resistivity from the measured electrical resistivity of polycrystalline samples. A constant value of \( \beta \sim 2 \) was derived, by comparing the transport data with those from high-quality ceramic and epitaxial thin films. Here we assume that such a correction factor must take into account the granular features of ceramic samples and adopt the form \( \beta = 1/\alpha_T \).

In order to evaluate the influence of the actual intergranular electrical resistivity, \( \rho_{\text{IG}} \), on the mean free path, let us estimate \( l \) by neglecting the contribution arising from \( \rho_{\text{IG}} \) in Eq. (2). By taking the data belonging to the sample P5 and assuming \( \alpha_{\text{tr}} \approx 1 \) (see Table II), one obtains, by using Eq. (8), \( l(300 \text{ K}) \approx 21 \AA \). This value of \( l(300 \text{ K}) \) is closer to the one estimated for Bi-2223 single crystals of \( l \approx 31 \AA \), and over 1.5 times higher than the previous estimate of \( l \) in which the intergranular component of \( \rho(T) \) has been considered.

**V. CONCLUSIONS**

In summary, we have carried out a systematic study on the influence of the uniaxial compacting pressure on the transport properties of Bi\(_{1.65}\)Pb\(_{0.35}\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_{10+\delta}\) ceramic samples subjected to different compacting pressures before the last heat-treatment. Based on the linearity of the electrical resistivity curves and applying appropriate corrections, we have estimated both the transport electron-phonon coupling constant, \( \lambda_{\text{tr}} \), and the mean free path, \( l \). We have found that the extracted \( \lambda_{\text{tr}} \) values in well-compacted samples are in good agreement with similar estimates for single crystals. On the other hand, an appreciable difference was found in the case of the mean free path, \( l \). Such a difference is certainly related to the intergranular electrical resistivity, which is an intrinsic feature of polycrystalline samples. In addition, contributions for the electrical resistivity arising from both the degree of texture and microstructural defects were extracted from a precise analysis of the \( \rho(T) \) dependence by using current models. It was found that increasing compacting pressure results in an increase of both the degree of texture and the grain connectivity of the samples. We have also observed that the electrical resistivity curves in the normal-state region deviate from linearity at \( T^* \sim 235 \text{ K} \), a feature that points out changes in the density of states and is related to the opening of the pseudogap. Such an opening of the pseudogap was confirmed by powder magnetic susceptibility measurements performed in the same samples. The temperature of the pseudogap \( T^* \) resulted to be independent of the applied compacting pressure. This is an expected result considering that changes in the compacting pressure mainly affect the morphology of the grains, but the intragranular properties remain essentially the same.

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