Synthesis and pinning properties of the infinite-layer superconductor \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \)

C. U. Jung, J. Y. Kim, Mun-Seog Kim, Min-Seok Park, Heon-Jung Kim, Yushu Yao, S. Y. Lee, and Sung-Ik Lee

National Creative Research Initiative Center for Superconductivity
and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

We report the high-pressure synthesis of the electron-doped infinite-layer superconductor \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) and its superconducting properties. A Rietveld analysis of X-ray powder diffraction data showed that, within the resolution of the measurement, the sample had purely an infinite-layer structure without any discernible impurities. The superconducting volume fraction and the transition width were greatly improved compared to those in previous reports. The irreversibility field line and the intragranular critical current density were much higher than those of \( \text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4 \) and \( \text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4 \). The stronger pinning behaviors are consistent with the strong interlayer coupling due to the short distance between \( \text{CuO}_2 \) planes.

I. INTRODUCTION

The electron-doped infinite-layer compounds (Sr\(^{2+}\), Ln\(^{3+}\))\(\text{CuO}_2 \) (Ln = La, Sm, Nd, Gd, etc.) consist of an infinite stacking of \( \text{CuO}_2 \) planes and metallic (Sr) layers. \(^{[1, 2]}\) The charge reservoir block common to other cuprate superconductors does not exist in these compounds. Since their structure is so simple, these compounds provide a unique opportunity to explore the fundamental nature of high-temperature superconductor.

Although electron-doped infinite-layer compounds have existed for quite a while, not many studies of their properties have been done because of the lack of high-quality bulk samples. In the case of films of these compounds, the superconducting transition temperatures, \( T_c \), are reported to be much lower than those of bulk samples. For example, the \( T_c \) of a (Sr\(_1-x\)Nd\(_x\))\(\text{CuO}_2 \) film is reduced by about one half compared to that of the bulk \(^{[3, 4]}\). High-pressure synthesis is known to be a unique method that stabilizes the bulk form of infinite-layer compounds with larger superconducting volume fractions \(^{[5, 6]}\).

Nonetheless, several interesting properties have been observed for these compounds. Since the distance between \( \text{CuO}_2 \) planes is short (3.41 Å) due to the absence of the charge reservoir block, the interlayer coupling, and thus the superconductivity is expected to be quite strong. However, the \( T_c \) is only about 43 K, \(^{[7, 8]}\) and neither the ionic radius, the magnetic moment, nor the concentration of Ln ions at Sr sites affects \( T_c \). \(^{[3]}\) Moreover, the oxygen has been found to be very stoichiometric; neither vacancies nor interstitial oxygens exist.

Pinning is another measure of the strength of interlayer coupling. It has been reported that pinning is enhanced by reducing the thickness of the charge reservoir block \(^{[9]}\). However, the pinning properties of infinite-layer superconductors have not been well studied. Strangely enough, the reported irreversibility field line, \( H_{\text{irr}} \), of \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) (La-112) is more than two times higher than that of \( \text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4 \) (La-214) while the intragranular critical current density \( J_c \) is smaller than that of La-214 \(^{[10]}\).

In this research, we used high-quality samples to study the pinning properties of the infinite-layer superconductor La-112. The superconducting volume fraction and the transition width were determined from the low-field magnetization data and were found to be improved over previous reported values and a Rietveld analysis of the X-ray powder diffraction data confirmed that the samples were of high quality. The pinning properties were studied by measuring the irreversibility field line and the intragranular critical current density. Contrary to a previous report, \(^{[7]}\) both values were higher than those for La-214 and \( \text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4 \) (Nd-214), supporting the stronger interlayer coupling between \( \text{CuO}_2 \) planes due to the absence of the charge reservoir block.

II. EXPERIMENTALS

A cubic multi-anvil-type press was used to synthesize La-112 \(^{[11]}\). The precursors were prepared by using the solid-state reaction method \(^{[12]}\). Starting materials of \( \text{La}_2\text{O}_3 \), \text{SrCO}_3, and \( \text{CuO} \) were mixed to the nominal composition of \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \). The mixture was then calcined at 950 °C for 36 hours with several intermittent grindings. The pelletized precursors sandwiched by Ti oxygen getters were put into a Au capsule in a high-pressure cell. A D-type thermocouple was used to monitor the temperature.

The pressure cell was compressed up to 4 GPa and then heat-treated using a graphite-sleeve heater. The temperature of the Au capsule was calibrated to the heating power, which allowed us to use the heating power to control the temperature. However, much of the power from the power supply was lost to the stray resistance (\( R_{\text{stray}} \sim 10^{-2} \, \Omega \) ) between the power supply and the graphite heater (\( R_{\text{heater}} \sim 10^{-2} \, \Omega \) ). Even though the power was supplied at a constant rate by the power supply, the actual heating power of the sample fluctuated because \( R_{\text{heater}} \) changed during the synthesis; \( \Delta R_{\text{heater}}/R_{\text{heater}} \sim 0.1 \). The amount of fluctuation...
was roughly proportional to $R_{\text{stray}}/R_{\text{heater}}$. To solve this problem, we controlled the heating power across the sample, instead of the main power. With this method, a temperature stability of $\pm 2 ^\circ C$ was obtained for a two-hour heating time under high-pressure conditions.

The heating power was increased linearly and then maintained constant for 2 hours. The synthesizing temperature was about 1000 $^\circ C$. Then, the sample was quenched to room temperature after an additional postannealing at 500 $\sim$ 600 $^\circ C$ for 4 hours. Two conditions were important in obtaining higher quality samples. One was the long-term stability of the synthesizing temperature, and the other was the uniformity of the temperature inside the sample cell, the former being more important. The pressure cell and the heating conditions were optimized after hundreds of trials, and very homogeneous samples larger than 200 mg were obtained. The size of the as-grown polycrystalline samples was about 4.5 mm in diameter and 2.8 mm in height.

The structural analysis of an infinite-layer compound can also give valuable information about the doping concentration because the lattice constants are sensitive to the doping concentration. The lattice constants are known to behave in opposite ways with increased doping; the $a$-axis expands while the $c$-axis shrinks [3]. The Rietveld refinement showed that the doping concentration in our Sr$_{1-x}$La$_x$CuO$_2$ was approximately $x = 0.1$, which was the same as the nominal composition.

### III. DATA AND DISCUSSION

#### A. Structure

The Rietveld refinement profile with the tetragonal space group $P4/mmm$ of our sample is shown in Fig. 1. The value of the diffraction angle $2\theta$ was varied from 20$^\circ$ to 140$^\circ$ in steps of 0.02$^\circ$, and the integration time was 15 seconds at each point. The Rietveld refinement program RIETAN-94 with 50 parameters was used for the analysis [13]. In that analysis, the thermal factors were assumed to be isotropic, and the coordination of each atom was fixed. We constrained the Sr : La ratio to the nominal stoichiometry of the precursor [1]. The values obtained for the lattice constants, $a = b = 3.950$ Å and $c = 3.410$ Å, agree quite well, within 0.001 Å, with those obtained using neutron powder diffraction [1], Within the resolution of this refinement, no discernible amounts of impurities were observed. The agreement factors, $R$, between the measured and the calculated diffraction intensities were quite small, and the goodness of fit was excellent ($S = 4.0008$). The refined structural parameters are summarized in Table 1.

A structural analysis of an infinite-layer compound can also give valuable information about the doping concentration because the lattice constants are sensitive to the doping concentration. The lattice constants are known to behave in opposite ways with increased doping; the $a$-axis expands while the $c$-axis shrinks [3]. The Rietveld refinement showed that the doping concentration in our Sr$_{1-x}$La$_x$CuO$_2$ was approximately $x = 0.1$, which was the same as the nominal composition.

#### B. Superconducting properties

Low-field susceptibility $4\pi \chi(T)$ data for good samples are shown in Fig. 2. In this figure, the curves labeled $\chi_{\text{zfc}}$ and $\chi_{\text{fc}}$ were measured in the zero-field-cooled (zfc) and the field-cooled (fc) states, respectively. The nominal superconducting volume fraction was calculated from $f_{\text{nom}} = -4\pi \chi_{\text{zfc}}(T \ll T_c)$ and was not corrected for the demagnetization factors [10]. The superconducting volume fractions were higher, especially in the high magnetic field region than previous results [11, 12, 13].

The superconducting transition onset in Fig. 2 appears at 43 K, which is the value typically reported for the La-112 compound [11, 12]. However, we can see some notable differences from previous reports. One is a very sharp transition near $T = 43$ K, and another is a well-developed saturation of the susceptibility at low temperatures, which reflects the formation of a high-quality superconducting La-112 phase. The saturated values of $4\pi \chi_{\text{zfc}}$ at low temperatures are about $-1.0$, $-1.17$, and $-1.22$ for samples A, B, and C, respectively.

For a superconducting sphere with a radius $R$, $4\pi \chi_{\text{zfc}}(T)$ is given by the Shoenberg formula [14]

$$
-3/2(1 - (3/x) \coth x + 3/x^2),
$$

where $x = R/\lambda_{\text{avg}}(T)$ and $\lambda_{\text{avg}}(T)$ is the average magnetic penetration depth, i.e., $\lambda_{\text{avg}} = (\lambda_{ab}^2 \lambda_c)^{1/3}$. In the limit of $x \gg 1$, the absolute value of $-4\pi \chi$ is not 1, but 1.5, due to the demagnetization effect [11]. If we take the typical value of $\lambda \sim 2000$ Å for high-$T_c$ cuprates and the grain size $R \approx 5$ μm obtained from the SEM image, the value of $4\pi \chi$ is estimated to be about $-1.3$, which is close to the above measured value. Thus, the real superconducting volume fraction of our sample should be close to 100%, especially for sample C. Our values were also confirmed using fine-powdered samples, thus avoiding the possibility of weak links. Also the zfc signal of the low-field magnetization $\chi_{\text{zfc}}(T = 5 \text{ K} \ll T_c)$ was basically the same for 10 Oe as it was for 10 Oe, as can be seen in Fig. 2 which was quite typical for all of our samples, irrespective of the sample quality.
The irreversible field line, $H_{\text{irr}}(T)$, from the high-field magnetization up to 5 T showed that pinning was very strong in the infinite-layer La-112 compound. In Fig. 3, the magnetization curves for fields higher than 1 T and the resulting $H_{\text{irr}}(T)$ are presented. The criterion for the reversible point was set as $|M_{\text{rel}} - M_{\text{irr}}| = 0.1$ emu/cm$^3$. The irreversible field was fitted with $H_{\text{irr}}(T)=H_0(1-T/T_c)^n$. The best parameters were $H_0 = 55.7$ T, $T_c = 42.6$ K, and $n = 1.99$. Our measured value of the irreversible field is about same order of magnitude as previous results [7].

Magnetic hysteresis curves $M(H)$ were measured at temperatures between 5 and 30 K, as shown in Fig. 4 (a). The intragranular critical current density was obtained from the relation $J_c \approx 17(M_L-M_I)/R$, where $M_L$ is the magnetization in the increasing (decreasing) field branch in Gauss (emu/cm$^3$) and $R$ is the average radius of the grains, and is plotted in fig. 4 (b). Our value of $J_c$ is nearly one order of magnitude larger than previous values [7]. As an example, $J_c(5$ K, 4 T) $\approx 1.2 \times 10^6$ A/cm$^2$ compared to the previous value of $2 \times 10^5$ A/cm$^2$.

The choice of $R$ was rather reasonable because the largest grains found in the SEM images on many cleaved surfaces have $R_{\text{max}} \approx 7.5$ $\mu$m, which guarantees the correct order of magnitude of our $J_c$ value. Also this $J_c$ value was nearly same order of magnitude as that obtained for powders using a sieve with the average size $R \approx 3$ $\mu$m [21]. The high-$T_c$ cuprate superconductors have strongly 2-dimensional character, short coherence length, and ‘high’ $T_c$. Due to these, vortex lines become ill-defined and transform into pancake vortices confined within the CuO$_2$ planes, which couple only weakly between the layers. Thus the critical current density suffers great decrease at higher temperatures due to the flux flow driven by a strong thermal fluctuation effect. There are several extrinsic methods to enhance $J_c$. Correlated defect was known to increase the pinning at higher temperatures and high fields while point defects have been known to be efficient only at low temperature and low fields [22]. The former such as columnar defects generated by heavy-ion irradiation not only increases just pinning centers but also could be thought to increase the coupling between vortices along the irradiated trajectory. This is because the relatively strong pinning centers are produced along straight line across CuO$_2$ plane. The behavior of $J_c$ of La-112 here resembles the former case, namely the critical current density does not decays fast as temperature and field increases. For example, at $T \sim T_c/2$, $J_c$ decreases by much less than factor of 2 when the field is increased from 1 and 4.5 Tesla, which is just typical behavior expected for Bean’s critical state model [23]. Correlated defects are generally inserted into the sample on purpose, surely absent in our samples. All these arguments suggest that the behavior of $J_c$ of our sample is highly intrinsic because Jorgensen et al. showed that defects, most probably the oxygen defects and vacancies, do not exist for this compound [6,7].

The samples studied here were made with in-situ annealing and showed that the nearly uniform-sized grains were separated well from each other by wide cracks. The uniform size made the superconducting transition sharp in the low-field magnetization, and the cracks made the resistivity drop in the transport measurement nearly invisible. Actually we tried to make samples without in-situ annealing after sintering. This sample showed many smaller grains between larger grains, which resulted in broad superconducting transition in the low-field magnetization but with a clearer resistivity drop due to a better connectivity between the grains. These suggest that the use of grain radius not the sample radius is reasonable for the calculation of $J_c$, like the previous report [7]. The different $J_c$ values between us and previous result seems to be partly due to the uniformness of the grain size and/or the existence of many smaller grains.

Now let’s compare the above values with those of compounds having a charge reservoir block, whose average distance between CuO$_2$ planes is larger. Optimally doped (La,Sr)$_2$CuO$_4$ and (Nd,Ce)$_2$CuO$_4$ are the most suitable for comparison with our electron-doped infinite-layer superconductors because the former has nearly the same $T_c$ as our sample while the latter is an electron-doped cuprate superconductor similar to ours.

First, $H_{\text{irr}}(T/T_c)$ of La-112 is more than 2 times higher than that of (La,Sr)$_2$CuO$_4$ and one order of magnitude larger than that of Nd-214 [20,22]. Similarly, our measured value of $J_c$ for the La-122 compound is much higher than the value reported for polycrystalline La-214, $J_c \sim 1.7 \times 10^5$ A/cm$^2$ at 4.2 K and 4 T [14]. As for the Nd-214 compound, the reported $J_c \sim 8 \times 10^5$ A/cm$^2$ at 4.2 K and 0 T was obtained using a form of only a thin film not a bulk, [23] so a direct comparison is impossible. However, if the fact that the $J_c$ of high-$T_c$ cuprates decreases by nearly one order of magnitude when the magnetic field is increased from 0 to $\sim 5$ T is considered, the intragranular critical current density of La-112 should be much larger than that of Nd-214 [24].

The above comparisons of $H_{\text{irr}}(T)$ and $J_c$ support the conclusion that the interlayer coupling of an infinite-layer superconductor is stronger due to the absence of a charge reservoir block. Such a stronger interlayer coupling was also found with previous observation of the 3D antiferromagnetic structure for an undoped infinite-layer compound, i.e., $\text{Ca}_{0.85}\text{Sr}_{0.15}\text{CuO}_2$. This material has been reported to have a stronger 3-dimensional character than other parent insulators of cuprate superconductors, such as YBa$_2$Cu$_3$O$_6$, $\text{La}_2\text{CuO}_4$, and Sr$_2$CuO$_2$Cl$_2$ [27,30]. For example, an estimate of the ratio of the out-of-plane and the in-plane coupling constants for $\text{Ca}_{0.85}\text{Sr}_{0.15}\text{CuO}_2$ was two to three orders of magnitude larger than corresponding values for YBa$_2$Cu$_3$O$_6$ and $\text{La}_2\text{CuO}_4$ [27]. From our study, we claim that the pinning properties of high-$T_c$
cuprates is improved at the extreme limit of reducing the thickness of the charger reservoir block, i.e., at a cuprate superconductor without a charger reservoir block.

IV. SUMMARY

We synthesized the infinite-layer compound Sr0.9La0.1CuO2. The quality of the samples was confirmed by using a structural analysis and low-field magnetization measurements. Both the irreversibility field, \( H_{irr}(T) \), and the intragranular critical current density, \( J_c \), were found to be much higher than the values for \((\text{La, Sr})_2\text{CuO}_4\) and \((\text{Nd, Ce})_2\text{CuO}_4\). And \( J_c \) does not decay fast as temperature and magnetic field increases, unlike other cuprate superconductors. These indicate an enhanced interlayer coupling between the CuO2 planes due to a shortening of the \( c \)-axis lattice constant.

ACKNOWLEDGMENTS

We are thankful to K. Kadowaki, R. S. Liu, and D. Pavuna for useful discussions on infinite-layer superconductors. We also greatly appreciate our valuable discussions with P. D. Han, D. A. Payne, C. E. Lesher, M. Takano, and A. Iyo on the general aspects of high-pressure synthesis. This work is supported by the Ministry of Science and Technology of Korea through the Creative Research Initiative Program.

* Electronic address: jungking@postech.ac.kr

[1] T. Siegrist, S. M. Zahurak, D. W. Murphy, and R. S. Roth, Nature 334 (1988) 231.
[2] M. G. Smith, A. Manthiran, J. Zhou, J. B. Goodenough, and J. T. Markert, Nature 351 (1991) 549.
[3] Bobuyuki Sugii, H. Yamauchi, and Mitsuru Izumi, Phys. Rev. B 50 (1994) 9503.
[4] Edwin C. Jones, David P. Norton, David K. Christen, and Douglas H. Lowndes, Phys. Rev. Lett. 73 (1994) 166.
[5] N. Ikeda, Z. Hiroi, M. Azuma, M. Takano, and Y. Bando, Physica C 210 (1993) 367.
[6] J. D. Jorgensen, P. G. Radaelli, D. G. Hinks, J. L. Wagner, S. Kikkawa, G. Er, and F. Kanamaru, Phys. Rev. B 47 (1993) 14 654.
[7] P. Kobayashi, K. Kishio, B. Ni, K. Yamafuji, G. Er, F. Kanamaru, S. Kikkawa, and M. Takano, Physica C 235 (1994) 2863.
[8] G. Er, S. Kikkawa, F. Kanamaru, Y. Miyamoto, S. Tanaka, M. Sera, M. Sato, Z. Hiroi, M. Takano, and Y. Bando, Physica C 196 (1992) 271.
[9] G. Er, Y. Miyamoto, F. Kanamaru, and S. Kikkawa, Physica C 181 (1991) 206.
[10] For a brief review of infinite-layer superconductors, see, for example, J. T. Markert, K. Mochizuki, and A. V. Elliott, J. Low. Temp. Phys. 105 (1996) 1367.
[11] Xingjiang Zhou, Yushu Yao, Cheng Dong, Jingwei Li, Shunlian Jia, and Zhongxian Zhao, Physica C 219 (1994) 123.
[12] G. Er, S. Kikkawa, M. Takahashi, F. Kanamaru, M. Hangyo, K. Kisoda, and S. Nakashima, Physica C 290 (1997) 1.
[13] D. H. Kim, K. E. Gray, R. T. Kampwirth, J. C. Smith, D. S. Richeson, T. J. Marks, J. H. Wang, J. Tallvacchio, and M. Eddy, Physica C 177 (1991) 431.
[14] S. Senoussi, M. Oussena, M. Pribault, and G. Collin, Phys. Rev. B 36 (1987) 4003.
[15] K. Kinoshita, F. Izumi, T. Yamada, and H. Asano, Phys. Rev. B 45 (1992) 5558.
[16] We should be cautious with polycrystalline samples because the microscopic (\( \mu \m) shape of each grain and its angle with the external magnetic field, not the macroscopic (\( mm \) scale) shape of the sample, is important in selecting the actual demagnetization factor.
[17] S. Tao, H.-U. Nissen, C. Beeli, M. Cantoni, M. G. Smith, J. Zhou, and J. B. Goodenough, Physica C 204 (1992) 117.
[18] B. Wiedenhorst, H. Berg, R. Gross, B. H. Freitag, and W. Mader, Physica C 304 (1998) 147.
[19] D. Shoenberg, Superconductivity (Cambridge University, Cambridge, 1954), p. 164.
[20] John R. Clem and V. G. Kogan, Jpn. J. Appl. Phys. 26 (1987) 1162.
[21] Mun-Seog Kim, C. U. Jung, et al., unpublished.
[22] I. Chong, Z. Hiroi, M. Izumi, J. Shimoyama, Y. Nakayama, K. Kishio, T. Terashima, Y. Bando, and M. Takano, Science, 276, (1997) 770 and references therein.
[23] C. P. Bean, Rev. Mod. Phys. 36 (1964) 31.
[24] L. Fábrega, J. Fontcuberta, S. Piñol, C. J. van der Beeck, and P. H. Kes, Phys. Rev. B 46 (1992) 11 952.
[25] Charles P. Poole, Handbook of Superconductivity (Academic Press, San Diego, 2000), p. 466.
[26] D. M. Ginsberg, Physical Properties of High Temperature Superconductors I (World Scientific, Singapore, 1989), p. 278.
[27] A. Lombardi, M. Mali, J. Roos, and D. Brinkmann, Phys. Rev. B 54 (1996) 93.
[28] D. Vaknin, E. Caignon, P. K. Davies, and J. E. Fischer, D. C. Johnston, and D. P. Goshorn, Phys. Rev. B 39 (1989) 9122.
[29] A. Keren, L. P. Le, G. M. Luke, B. J. Sterlinlieb, W. D. Wu, Y. J. Uemura, S. Tajima, and S. Uchida, Phys. Rev. B 48 (1993) 12 926.
[30] R. Pizz, M. Mali, M. Matsumura, F. Raffa, J. Roos, and D. Brinkmann, Phys. Rev. B 56 (1997) 759.
FIG. 1. Rietveld refinement of the X-ray powder diffraction pattern of sample A. The dots are the raw data including background, and the solid line is the calculated profile. The vertical tick marks below the profile represent the positions of allowed diffractions in the tetragonal $P4/mmm$ space group. A difference curve (observed pattern minus calculated pattern) is also plotted at the bottom.

FIG. 2. Magnetic susceptibility, $4\pi \chi(T)$, of Sr$_{0.9}$La$_{0.1}$CuO$_2$ for zero-field-cooling and field-cooling from the low-field magnetization $M(T)$ at 10 and 100 Oe. For calculating the nominal superconducting volume fraction, $f_{\text{nom}}$, we used a low-temperature density of 5.94 g/cm$^3$ from Ref. 12. (a) Sample A, $f_{\text{nom}} = 100\%$, (b) Sample B, $f_{\text{nom}} = 117\%$, and (c) Sample C, $f_{\text{nom}} = 122\%$.

FIG. 3. $4\pi M(T)$ curves of sample A at fields higher than 1 Tesla and irreversibility field $H_{\text{irr}}(T)$: (a) $4\pi M(T)$ curves at 1, 2, 3, 4, and 5 Tesla and (b) irreversible field fitted with $H_{\text{irr}}(T) = H_o(1 - T/T_c)^n$. The criterion was chosen as $|M_{\text{zfc}} - M_{\text{fc}}| = 0.1$ emu/cm$^3$. The uncertainty in terms of temperature is less than 0.2 K. The fit was excellent with the parameters $H_o = 55.7$ Tesla, $T_c = 42.6$ K, and $n = 1.99$. The top axis denotes the normalized temperature $T/T_c$. The filled triangles were obtained with the criterion $|M_{\text{zfc}} - M_{\text{fc}}| = 0.01$ emu/cm$^3$.

FIG. 4. (a) Magnetic hysteresis curves of sample A at 5, 10, 20, and 30 K. (b) The field and the temperature dependences of the intragranular critical current density $J_c$ were calculated by using $J_c \approx 17(M_\uparrow - M_\downarrow)/R$, where $M_\uparrow(M_\downarrow)$ is the magnetization in the increasing (decreasing) field branch in Gauss (emu/cm$^3$) and $R \sim 5 \times 10^{-4}$ cm is the average radius of the grains.

TABLE I. Structural parameters for Sr$_{0.9}$La$_{0.1}$CuO$_2$ from Rietveld refinement using the X-ray powder diffraction pattern for sample A. The values in parentheses are reported ones based on the neutron powder diffraction data in Ref 6.

| Parameter | Value |
|-----------|-------|
| $a = b$ (Å) | 3.9502 (3.95068) |
| $c$ (Å) | 3.41020 (3.40902) |
| $V$ (Å$^3$) | 53.219 (53.212) |
| $\alpha = \beta = \gamma$ | 90.000 0 |
| Sr, La$^a$ | $x = y = z$ |
| Cu | $x = y = z$ |
| O | $y = z$ |
| | $n$ |
| | 1 |
| Sr, La$^a$ | $x = y = z$ |
| Cu | $x = y = z$ |
| O | $y = z$ |
| | $n$ |
| | 1 |
| | 0.5 |
| | 2 |
| Agreement factor | Value(%) |
| $R_{wp}$ (%) | 7.48 (16.0) |
| $R_p$ (%) | 4.68 |
| $R_m$ (%) | 2.21 |
| Goodness of fit, $S$ | 3.3853 |

$^a$Constraint: n(Sr):n(La)=0.9:0.1.
Figure 1: Temperature dependence of the magnetic susceptibility for various samples.

(a) Sample A: 
- $\chi_{fc}$ for 10 Oe (solid squares)
- $\chi_{zfc}$ for 100 Oe (solid circles)

(b) Sample B: 
- $\chi_{fc}$ for 10 Oe (solid squares)
- $\chi_{zfc}$ for 100 Oe (solid circles)

(c) Sample C: 
- $\chi_{fc}$ for 10 Oe (solid squares)
- $\chi_{zfc}$ for 100 Oe (solid circles)
