INFLUENCE OF Er-Ca SUBSTITUTION ON PHASE CONTENT, RESISTIVITY AND PARACONDUCTIVITY OF 2223 Bi-BASED HTSC


Superconductivity and Magnetism Laboratory, State University of Moldova, 60 Mateevici str., MD-2009 Chişinău, Moldova, *Institute of Applied Physics, Academy of Science of the Republic of Moldova, 5 Academiei str., MD-2028 Chişinău, Moldova

The effect of Ca substitution by Er$^{3+}$ in (BiPb)-(SrBa)-Ca-Cu-O superconductor has been investigated by electrical resistance measurements with an analysis of the excess conductivity. Superconducting transition temperature $T_c$ decreases with increasing of Er$^{3+}$ ion concentration and the samples are characterised by a linear temperature dependence of the electrical resistance above $2T_c$.

1. INTRODUCTION

The partial substitution of Cu by 3d elements is important for investigating the nature of superconductivity along with the understanding of the normal state properties of this material. In the ceramic systems the competition of the intra- and intergrain conductivity is strongly temperature dependent and is differently influenced by the 3d ions which substituted in the Cu positions [1, 2].

In this paper the paraconductivity data for 2223 Bi-based HTSC are presented. The phenomenon of paraconductivity is manifested by deviation from the linear dependence of the electrical $\rho(T)$ resistance versus temperature. The study of the temperature dependence of the conductivity excess represents a way by which the dimension of fluctuation of the order parameter can be verified. There are many theoretical models that take into consideration the influence of dimensionality on the paraconductivity fluctuation. The following behaviors were found: two-dimensional (2D) and three-dimensional (3D) fluctuation of order parameter in the $\Delta \sigma$ conductivity excess. Using the Lawrence-Doniach model (LD) [3] the “cross-over” temperature (transition from 2D regime to 3D regime of fluctuations), the coherence length, the conductible interlayer distance, and the constant of interaction between superconductor layers were determined.

2. EXPERIMENTAL RESULTS

$\text{Bi}_{1.6}\text{Pb}_{0.4}\text{Sr}_{1.8}\text{Ba}_{0.2}(\text{Ca}_{1-x}\text{Er}_x)\text{Cu}_3\text{O}_y$ (I) and $\text{Bi}_{1.8}\text{Pb}_{0.46}\text{Sr}_{1.88}(\text{Ca}_{1-x}\text{Er}_x)_{2.06}\text{Cu}_3\text{O}_y$ (II) compounds with $x=0.00, 0.02, 0.05$ were synthesized by solid state reaction of appropriate amounts of the metal oxides and carbonates of 99.99% purity. The chemical composition of synthesized samples is presented in the Table 1.

Table 1

<table>
<thead>
<tr>
<th>Nr. of sample</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}\text{Ca}_2\text{Cu}_3\text{O}_y$</td>
</tr>
<tr>
<td>2</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}(\text{Ca}<em>{0.98}\text{Er}</em>{0.02})\text{Cu}_3\text{O}_y$</td>
</tr>
<tr>
<td>3</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}(\text{Ca}<em>{0.95}\text{Er}</em>{0.05})\text{Cu}_3\text{O}_y$</td>
</tr>
<tr>
<td>4</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}\text{Ca}</em>{2.06}\text{Cu}_3\text{O}_y$</td>
</tr>
<tr>
<td>5</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}(\text{Ca}</em>{0.98}\text{Er}<em>{0.02})</em>{2.06}\text{Cu}_3\text{O}_y$</td>
</tr>
<tr>
<td>6</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}(\text{Ca}</em>{0.95}\text{Er}<em>{0.05})</em>{2.06}\text{Cu}_3\text{O}_y$</td>
</tr>
</tbody>
</table>

The temperature dependence of electrical resistance, the density of critical current $J_c$, critical temperature $T_c$ and the phase content were investigated. The resistivity and critical current $J_c$ were measured by fourth-contact method. The characterization of phase purity was carried out by X-ray diffraction using DRON–3M equipment with Cu$K\alpha$ radiation. The XRD analysis proved the presence of a single 2223 phase in the $x=0$ sample. The parameters of 2223 phase were indexed for a tetragonal
unit cell with $a=5.4$ Å and $c=37.1$ Å. In the sample with $x\geq0.02$ ions Er$^{3+}$ provide changes in the X-ray diffraction pattern. The critical parameters, electrical resistivity $\rho(300K)$ and the phase content of the investigated samples are presented in Table 2. The amount of 2212 phase increases from 0% to 75% with $x$ increasing from 0.00 to 0.05 (I). The content of 2223 phase decreases from 23% for $x=0.02$ to 0% for $x=0.05$ (II). 2212 phase content increases from 70% to 85% for $x=0.02$ and $x=0.05$ respectively.

### Critical parameters, electrical resistivity $\rho(300K)$ and phase content.

<table>
<thead>
<tr>
<th>Nr. of sample</th>
<th>$T_c$, K</th>
<th>$J_c$, A/cm$^2$</th>
<th>$\rho(300K)$, $\times10^{-3}$ Ω·cm</th>
<th>Phase content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106</td>
<td>247</td>
<td>1.58</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>99</td>
<td>456</td>
<td>1.6</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>105</td>
<td>24</td>
<td>3.43</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>98</td>
<td>13</td>
<td>2.0</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>1.3</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 2

The study of paraconductivity in (I) and (II) Bi-based HTSC was carried out taking into account that thermal fluctuations lead to modifications of the ordering parameter. The temperature dependence of electrical resistance $R(T)$ for Er$^{3+}$ doped samples ($0\leq x\leq0.05$) is shown in Fig.1 (I) and Fig.2 (II). In $2T_{cmf}-300K$ temperature range these samples are characterized by a linear temperature dependence of the resistance. Here $T_{cmf}$ is the temperature at which the first derivative $dR/dT$ has maximal value.

The excess conductivity was calculated after a linear regression on $R(T)$ data in $2T_{cmf}$ to room temperature range. Residual resistivity $\rho(T=0K)$ was obtained by extrapolation of the least-squares line to $T=0K$. The analysis of the excess conductivity above mean transition temperature $T_{cmf}$ was performed in the framework of the Lawrence-Doniach model [3]. In this model the excess of
conduction based on the Aslamasov–Larkin fluctuations [4] (which take place in superconducting layers coupled by Josephson tunneling) is

\[
\frac{\Delta \sigma}{\sigma_0} = \frac{A(2D)}{\sqrt{\varepsilon (\varepsilon + 4J)}},
\]

where \( \varepsilon = \left( T - T_{conf} \right) / T_{conf} \) is the reduced temperature, \( J = \left( \xi(0) / d \right)^2 \) is the coupling constant between the superconductor layers and \( A(2D) = \left( \rho_0 \varepsilon^2 \right) / (16 \hbar d) \) is the temperature-independent amplitude, \( \sigma_0 = 1 / \rho_0 \) is the conductivity at \( T = 290 \) K, \( \xi(0) \) is the coherence length and \( d \) is the interlayer spacing. For the weak coupling between CuO₂ blocks (\( J \ll 1 \)) eq.1 reduces to the 2D term

\[
\frac{\Delta \sigma}{\sigma_0} = A(2D) \varepsilon^{-1}.
\]

This feature was speculated to evaluate two Aslamov-Larkin contributions, above and below \( T_0 \), according to the equations:

\[
\frac{\Delta \sigma}{\sigma_0} = Ae^{-\lambda},
\]

where \( \lambda = -1/2 \) for 3D region and \( \lambda = -1 \) for 2D region.

In order to test the dimensionality, the log-log plots of the experimental \( \Delta \sigma / \sigma_0 \) versus the reduced temperature \( \varepsilon \) for the samples of Bi₁₋ₓPbₓSr₁₋ₓBa₂(Ca₁₋ₓErₓ)₂Cu₃O₇ and Bi₁₋ₓPb₀.₄₆Sr₁₋ₓ(Ca₁₋ₓErₓ)₂.₇₆Cu₃O₇ where \( x = 0.00, 0.02, 0.05 \) are shown in Fig.3 and Fig.4 respectively. From the extrapolation of the linear variation \( (\Delta \sigma / \sigma_0)^{-1} \) vs. \( T \) the temperature \( T_{cross-over} \) of crossing from 2D to 3D regime of conductivity was obtained. In \( -5.37 < \ln \varepsilon < -1.5 \) range, an obvious cross-over temperature \( T_{cross-over} \) delimiting the 2D and 3D dimensionalities appears in the sample with \( x = 0.00 \).

The 3D behavior \( (\lambda = -1/2) \) in the \( \ln \varepsilon \) ranges (-5.4 to -4.1), (-5.3 to -3.7) and (-4 to -2.7) for the samples (I) at \( x = 0.00 \), \( x = 0.02 \) and \( x = 0.05 \) was obtained (Fig.3). The 2D behavior with \( \lambda = -1 \) in the \( \ln \varepsilon \) ranges (-4 to -3), (-4 to -3.1) and (-2.2 to -1.3) was obtained. The cross-over temperatures

**Fig.3.** The log-log plot of the paraconductivity \( \Delta \sigma / \sigma_0 \) vs. the reduced temperature \( \varepsilon \) for Bi₁₋ₓPb₀.₄₆Sr₁₋ₓBa₂(Ca₁₋ₓErₓ)₂Cu₃O₇ samples.

**Fig.4.** The log-log plot of the paraconductivity \( \Delta \sigma / \sigma_0 \) vs. the reduced temperature \( \varepsilon \) for Bi₁₋ₓPb₀.₄₆Sr₁₋ₓ(Ca₁₋ₓErₓ)₂.₇₆Cu₃O₇ samples.
of transition from 2D to 3D fluctuation regimes, are 108.4K for $x=0.00$, 104.5K for $x=0.02$ and 86.6K for $x=0.05$. By using equation $T_0 = T_c (1 + 4J)$ from the Lawrence-Doniach model, the coupling constants $J = 0.003$, $J = 0.005$ and $J = 0.022$ were found for the samples with $x=0.00$, $x=0.02$ and $x=0.05$. Some results have been obtained for HTSC of the type II – the 3D behavior ($\lambda = -1/2$) in the $\ln \epsilon$ ranges $(-5.37$ to $-4.00)$, $(-5.4$ to $-3.0)$ and $(-4.7$ to $-3.5)$ for the samples $x=0.00$, $x=0.02$ and $x=0.05$ (Fig.4) and the 2D behavior with $\lambda = -1$ in the $\ln \epsilon$ ranges $(-3.6$ to $-1.6)$ and $(-1.6$ to $-1)$ for $x=0.00$ and $x=0.02$. The parameters of paraconductivity are presented in Table 3.

Table 3

<table>
<thead>
<tr>
<th>Nr. of sample</th>
<th>Chemical composition</th>
<th>$T_{\text{cmf}}, \text{K}$</th>
<th>$T_{\text{cross}}, \text{K}$</th>
<th>$J$</th>
<th>$\xi$, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}\text{Ca}<em>{2}\text{Cu}</em>{3}\text{O}_{y}$</td>
<td>107</td>
<td>108.4</td>
<td>0.0032</td>
<td>2.79</td>
</tr>
<tr>
<td>2.</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}(\text{Ca}<em>{0.98}\text{Er}</em>{0.02})<em>{2}\text{Cu}</em>{3}\text{O}_{y}$</td>
<td>102</td>
<td>104.5</td>
<td>0.005</td>
<td>2.67</td>
</tr>
<tr>
<td>3.</td>
<td>$\text{Bi}<em>{1.6}\text{Pb}</em>{0.4}\text{Sr}<em>{1.8}\text{Ba}</em>{0.2}(\text{Ca}<em>{0.95}\text{Er}</em>{0.05})<em>{2}\text{Cu}</em>{3}\text{O}_{y}$</td>
<td>79.5</td>
<td>86.6</td>
<td>0.022</td>
<td>4.78</td>
</tr>
<tr>
<td>4.</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}\text{Ca}</em>{2.06}\text{Cu}<em>{3}\text{O}</em>{y}$</td>
<td>108.5</td>
<td>114.0</td>
<td>0.013</td>
<td>2.57</td>
</tr>
<tr>
<td>5.</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}(\text{Ca}</em>{0.95}\text{Er}<em>{0.05})</em>{2.06}\text{Cu}<em>{3}\text{O}</em>{y}$</td>
<td>106</td>
<td>108.8</td>
<td>0.009</td>
<td>3.5</td>
</tr>
<tr>
<td>6.</td>
<td>$\text{Bi}<em>{1.8}\text{Pb}</em>{0.46}\text{Sr}<em>{1.88}(\text{Ca}</em>{0.95}\text{Er}<em>{0.05})</em>{2.06}\text{Cu}<em>{3}\text{O}</em>{y}$</td>
<td>78.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

3. CONCLUSIONS

1. The doping of Bi-Sr-Ca-Cu-O samples with Pb and (or) Ba atoms leads to the structural stabilization of 2223 phase.
2. The doping of Bi-based superconductors by Er$^{3+}$ ions changes condition of structural stabilization of the phases. It is established that under action of Er$^{3+}$ ions the decreasing of 2223 phase content from 100% ($x=0.00$) to 50% ($x=0.05$) and the increasing of 2212 phase content from 0% ($x=0.00$) to 50% ($x=0.05$) for samples of type I occur. For the samples of type II 2223 phase content decreases from 33% ($x=0.00$) to 0% ($x=0.05$) and the 2212 phase content changes versus $x$ in the following way: 66% ($x=0.00$), 70% ($x=0.02$), 85% ($x=0.05$).
3. The value of coupling constant $J$ increases from 0.003 ($x=0.00$) to 0.022 ($x=0.05$), the value of coherence length $\xi$ increases from 2.79 Å to 4.78 Å and the cross-over temperature decreases from 108.4K to 79.5K at increasing of Er$^{3+}$ ion concentration in matrix (I). For type II of samples the value of coupling constant $J$ decreases from 0.013 ($x=0.00$) to 0.009 ($x=0.02$), the value of coherence length $\xi$ increases from 2.57 Å to 3.5 Å and the cross-over temperature decreases from 114K to 108.8K in the same conditions as above mentioned.

REFERENCES