Electrical Properties of Nano Bi$_2$O$_3$ Added (Bi,Pb)Sr-Ca-Cu-O Superconductor

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Abstract. In this study, Bi$_2$O$_3$ nanoparticles were added into (Bi$_{1.6}$Pb$_{0.4}$)Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (BPSCCO) superconductor. Ultrafine BPSCCO powders were prepared by the co-precipitation method. Bi$_2$O$_3$ with weight percent (wt. %) 0, 0.04, 0.06, and 0.10 was added during the final heating stage. The samples were investigated by x-ray powder diffraction method. Critical current density, $J_c$ was measured between 40 K and 77 K with the 1 µV/cm criterion. DC electrical resistivity was measured using the four point probe method. This result showed that the highest $J_c$ was observed for sample with 0.06 wt. % Bi$_2$O$_3$. A gradual decrease of $J_c$ and transition temperature $T_c$ was observed for samples with greater than 0.06 wt. % Bi$_2$O$_3$.

1. Introduction

There are many studies done to improve the critical current density of (Bi,Pb)Sr-Ca-Cu-O (BPSCCO) superconductor. The low operating temperature required by low-temperature metallic superconductors (LTS), with transition temperatures below 23 K has limited their practical use in power application [1]. Existing HTS wires technology need to be improved for grid application. The application of superconductor in power grid can be performed at liquid nitrogen temperature [2, 3].

The critical current density, $J_c$ can be determined from the current-voltage characteristics. In transport measurements, electric field criterion such as 1 µV/cm are often used to determine $J_c$ [4]. Addition of other element in BPSCCO can act as impurity for pinning center to improve $J_c$ and transition temperature $T_c$ [5-8]. Among the Bi-based materials, Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi-2223) phase, which is also called high $T_c$ phase, is of great interest due to its higher critical temperature (∼110 K), atmospheric stability and ability to be rolled into long wires or tapes [9].

In application of BSCCO phase superconductor, the major limitation is the intergrain weak links and flux pinning capability. Effective artificial flux pinning is introduced to enhance flux pinning capability. The flux pinning capability could be improved by microstructural control such as concentration of dislocations and planar faults, tiny secondary phase and irradiation damage zones [10]. From a previous study, HTSC tapes were prepared with the optimum amount 0.01 wt. % nano Bi$_2$O$_3$ addition. In the current study nanosize Bi$_2$O$_3$ were added into (Bi,Pb)Sr-Ca-Cu-O with 0 to 0.15 wt. % [11]. The objectives of this study were to investigate the effect of nano Bi$_2$O$_3$ on the transport properties of (Bi,Pb)Sr-Ca-Cu-O superconductor.
2. Experimental Details

Bi(Pb)-Sr-Ca-Cu-O high-temperature superconductor was prepared via the co-precipitation method. The chemicals used in this method were bismuth acetate 99.99 %, strontium acetate, not mentioned percentage (Aldrich), lead acetate 99.5 %, calcium acetate 90 %, (Fluka) and copper acetate 98 % (Alfa Aesar). Oxalic acid, acetic acid, 2-propanol and deionized water were used as solutions in this synthesis. The acetate powders were diluted in acetic acid solution with a stoichiometric amount (solution A). The mixture was stirred for about 2 h at 80 °C to dilute the entire chemical to form dark blue colour solution. Oxalic acid (0.5M) was mixed to the water: isopropanol with ratio 1:1.5 to form solution B.

Solutions A and B were mixed at 0-3 °C for 30 min to form blue navy slurry. The precipitate was filter and dried at 80-100 °C for 8 h. The blue powder was calcined at 730 °C for 12 h. This calcination was to remove impurities from the powder. The powder was reground and calcined again at 845 °C for 24 h. This was followed by the addition of Bi₂O₃ nanopowder Aldrich 99.9 % (0, 0.04, 0.06 and 0.10 wt. %). The powder was pressed into pellets and sintered at 845 °C for 48 h in a furnace. DC electrical resistivity was measured using the four point probe technique in combination with CTI cryogenics closed-cycle refrigerator (Model 22). The transport critical current density \( J_c \) was measured using pellets cut into bar shape using by the four-point probe method with the 1 µV/cm criterion between 40 and 77 K. The XRD patterns of the sample were recorded using a Bruker XRD diffractometer with CuKα radiation.

3. Results and Discussion

Table 1 shows the onset transition temperature (\( T_{c-onset} \)), zero resistance temperature (\( T_{c-zero} \)), transition width \( \Delta T_c \), critical current density \( J_c \) at 77 K and volume fraction of Bi-2212 and Bi 2223 phase. The volume fraction of the highest Bi-2223 phase is the non-added sample. The low \( T_c \) phase of Bi-2212 was observed in the 0.10 wt. % sample.

Figure 1 shows the XRD patterns of the non-added sample, 0.04, 0.06, and 0.10 wt. % Bi₂O₃ added samples. Most of the peaks in both non-added and Bi₂O₃ added samples belong to the high \( T_c \) phase (Bi-2223) with a few peaks corresponding to the low \( T_c \) phase (Bi-2212). The addition at 0.10 wt % sample showed the lowest \( T_c \), which showed the intensity of high phase (Bi,Pb) -2223 (H) decreased with increase of the low phase of (Bi,Pb) -2212 (L). (Bi,Pb) -2212 (L) phase exists at 0.10 wt. % sample much more than other samples. For sample 0.06 wt. % XRD pattern (Bi,Pb) -2223 (H) was nearly same with 0.04 wt% except for (Bi,Pb) -2212 (L) peak 1115L which diminished.

Figure 2 shows the resistance versus temperature curve for all samples. The highest \( T_c \) achieved was at 0.04 wt. % (106 K), with optimum amount of addition during the final processing of BPSCCO samples can effectively improve the flux pinning and increased \( T_c \) as well [14]. Normally, the superconducting transition temperature decreases with the increase of impurities [15]. The sample with 0.10 wt. % showed the lowest \( T_c \) value with 103 K.
Table 1. Onset transition temperature ($T_{c\text{onset}}$), zero resistance temperature ($T_{c\text{offset}}$), transition width $\Delta T_c$ and critical current density $J_c$ at 77 K

| $\text{Bi}_2\text{O}_3$ (wt. %) | $T_{c\text{onset}}$ (K) | $T_{c\text{offset}}$ (K) | $\Delta T_c$ (K) | $J_c$ (mA/cm$^2$) | Volume fraction Bi-2223 | Volume fraction Bi-2212 |
|-------------------------------|-------------------------|--------------------------|-------------------|------------------|-------------------------|-------------------------|
| 0                             | 112                     | 105                      | 7                 | 982              | 89                      | 11                      |
| 0.04                          | 113                     | 106                      | 7                 | 1322             | 85                      | 15                      |
| 0.06                          | 112                     | 105                      | 7                 | 5047             | 82                      | 18                      |
| 0.10                          | 111                     | 103                      | 8                 | 3757             | 77                      | 23                      |

Figure 1. XRD patterns for Bi$_{1.6}$Pb$_{0.4}$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ of the non-added sample and samples added with 0.04, 0.06 and 0.10 wt. % $\text{Bi}_2\text{O}_3$. (H) denotes the high- $T_c$ phase (Bi-2223) and (L) denotes the low- $T_c$ phase (Bi-2212).
Figure 2. Resistance versus temperature curves for Bi$_{1.4}$Pb$_{0.6}$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ of the non-added sample and samples added with 0.04, 0.06 and 0.10 wt % Bi$_2$O$_3$. The inset shows the curve near $T_c$.

The critical current density, $J_c$ of all samples were measured at 40 K, 50 K, 60 K, 70 K and 77 K are shown in Figure 3. The highest $J_c$ was observed at 40 K for 0.06 wt. % with the highest value (7396 mA/cm$^2$). $J_c$ at 77 K for this sample was 5237 mA/cm$^2$. The $J_c$ of the non-added sample showed $J_c$ at 40 K was 1833 mA/cm$^2$ and $J_c$ at 77 K was 982 mA/cm$^2$. The $J_c$ value of 0.10 wt. % sample at 40 K was 5237 mA/cm$^2$ and at 77 K was 3757 mA/cm$^2$. All samples with the addition of nano Bi$_2$O$_3$ showed a higher transport critical current density compared to the non-added sample. Overall, $J_c$ decreased with increasing temperature and this due to the thermally activated flux creep [16].
Figure 3. Critical current density, $J_c$, of Bi$_{1.6}$Pb$_{0.4}$Sr$_2$Ca$_2$Cu$_3$O$_{10}$, of the non-added sample and samples added with 0.04, 0.06 and 0.10 wt. % Bi$_2$O$_3$ at temperature 40, 50, 60, 70 and 77 K

4. Conclusion
Nano Bi$_2$O$_3$ addition in (Bi,Pb)-2223 superconductor improved $J_c$ for all added samples. An appropriate amount of Bi$_2$O$_3$ optimized the critical current density of (Bi,Pb)-2223. The highest $J_c$ was observed in the 0.06 wt. % sample. XRD pattern showed the increase of (Bi,Pb)-2212 phase which lowered $T_c$, but did not affect $J_c$. The excess amount of Bi$_2$O$_3$ for 0.10 wt. % sample contributed to the low $T_c$.

Acknowledgments
This work was supported by Universiti Kebangsaan Malaysia under grant number AP-2015-006 and the Ministry of Higher Education of Malaysia under grant number FRGS/1/2017/STG02/ UKM/01/1.

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