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Resistive transition and flux flow mechanism in $CoFe_2O_4$ nanoparticles added $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ superconductor

M. Waqee-ur-Rehman [a], Irfan Qasim [a], M. Mumtaz [a,*], K. Nadeem [a], S. Qamar [b]

[a] Materials Research Laboratory, Department of Physics, Faculty of Basic and Applied Sciences (FBAS), International Islamic University (IIU), Islamabad 44000, Pakistan

[b] Materials Science Lab, Department of Physics, Quaid-i-Azam University, Islamabad 45320, Pakistan

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$(CoFe_2O_4)_x/Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ {$(CoFe_2O_4)_x$/CuTl-1223}; ($0 \le x \le 2$) nanoparticles-superconductor composites were synthesized by solid–state reaction technique and dissipative mechanism was investigated by infield measurements and analysis. Activation energy {$U_o(H)$} was calculated from Arrhenius plots of infield resistivity measurements. The infield resistive properties of superconductors depend upon the fluxoid motion, which causes resistive transition broadening by shifting T_c (0) towards lower temperature values. The enhancement of transition broadening is attributed to spread of upper critical field in vortex state and dissipation process with applied magnetic field. Addition of magnetic $CoFe_2O_4$ nanoparticles reduces the fluxoid motion by introducing nano-sized defects in the host CuTl-1223 superconducting matrix, which act as effective flux pinning centers. An overall increase in the activation energy $U_o(H)$ has been observed with increasing contents of magnetic $CoFe_2O_4$ nanoparticles, which elucidate the enhanced flux pinning with increasing $CoFe_2O_4$ magnetic nanoparticles content up to x = 1.5 wt. % in CuTl-1223 superconducting matrix.

1. Introduction

The dissipative behavior and response of high temperature superconductors (HTSCs) depend on the quantized fluxoid movement in the presence of magnetic field and current flow. The number of fluxoids is directly related to the external applied magnetic field and HTSCs have a critical role for technological applications as the motion of vortices is dissipative in external magnetic fields. Resistive dissipation can introduce many problems like reduction in efficiency of transmission lines, noise in devices etc [1–4]. To understand the resistive behavior, the properties of the intermediate or mixed state of HTSCs is important as it involves the study of vortex dynamics in the presence of surface current flow and applied field [5,6]. The motion of the vortices may be due to thermal fluctuations in the vortex system and influence of Lorentz force on magnetic vortex, which cause energy dissipation. The dissipative flux motion and flux pinning mechanism have inverse relation, greater the fluxoid movement, lesser is the flux pinning. The peculiar broadening introduced by energy dissipation in resistive curves under the influence of external magnetic field illustrates the vortex motion and flux pinning effectively [7].

The study of resistive broadening and flux pinning reveal that different phenomena are responsible for energy dissipative mechanism in bulk HTSCs. One of the most important parameters is the spatial variation of Ginzburg-Landau parameter, which is associated with the fluctuations in critical temperatures (T_c) known as *k* pinning. Second one is the insertion of non-superconducting materials within the superconducting matrices, which may lead towards scattering of electrons in the lattice and causes the enhanced flux pinning [8]. Many other significant method have been commonly used for generation of these artificial defects in superconducting matrices like ion irradiation, thermal treatments, chemical doping, mechanical methods and addition of nanostructures [9–14].

In cuprates layered superconductors, the energy dissipation mechanism in applied field and resultant vortex dynamics may be interpreted by considering the vortex creep and temperature dependence of resistivity ρ(T). Broadening of superconducting transitions is generally investigated through thermally activated flux flow (TAFF) model. The resistive broadening is clarified in term of energy dissipation because of fluxoid motion due to applied

* Corresponding author.
E-mail address: mmumtaz75@yahoo.com (M. Mumtaz).

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magnetic field. The resistance is generated by the flow of the vortices in the TAFF region. Resistivity can be expressed as;

$$\rho(T, H) = \rho_o exp\{-U_o(T, H)/K_B T\}$$

Here k_B is Boltzmann constant, ρ_o is the normal state resistivity, U_o (T, H) is the activation energy of flux flow, which can be obtained from the slope of linear part of Arrhenius plot [15].

We have studied the thermally activated flux flow effects in $(CoFe_2O_4)_x$/CuTl-1223 nanoparticles-superconductor composites. The literature review suggests that addition of artificial defects in layered superconductors have significant effects for enhancement of flux pinning mechanism [16,17]. Nano-oxides inclusions act as a source of flux pinning, which may enhance the critical current density (J_c) for many HTSCs [18,19]. The addition of specific content of nanoparticles like ZrO_2 and Al_2O_3 showed effective flux pinning in (Bi, Pb)-2223 superconductors and helped in improvement of J_c. The addition of SnO_2 and In_2O_3 in CuTl-1223 superconductor improved the superconducting volume fraction and reduced the porosity [20–22]. The addition of MgO nanoparticles in Bi-2212 superconductors increased the superconductor volume fraction and transition sharpness, decreased the overall value of T_c but has not altered the T_c^{onset} (K) of the material [23]. Recently, it was shown that inclusion of magnetic nanoparticles (MNPs) in HTSCs had played an important role as efficient pinning centers at lower densities [24]. The enhancement in T_c and J_c in parallel applied magnetic fields up to certain level of magnetic Cr content in Pd films was observed [25]. Recently, there has been considerable interest in improvement of flux pinning by the addition MNPs in different bulk HTSCs [26]. Numerous models have been proposed to investigate the effects of MNP's inclusions in HTSCs on their electromagnetic properties [27]. However, magnetic pinning depends on the magnitude and orientation of its magnetization vector, also depends on the size of MNP's, which is still a challenging problem for both theoretical and experimental investigations. We have previously reported the effects of addition of $ZnFe_2O_4$ nanoparticles in the superconducting CuTl-1223 matrix [28].

In this article, we are presenting our new results of inclusion of $CoFe_2O_4$ nanoparticles in CuTl-1223 superconducting matrix for investigation of energy dissipation and flux pinning mechanisms. The non-superconducting $CoFe_2O_4$ MNP's were successfully embedded at inter-crystallite sites of CuTl-1223 superconducting matrix. We have used Physical Property Measurement System (PPMS) for complete infield resistivity measurements and observed the variation of activation energy with inclusion of different concentrations of $CoFe_2O_4$ MNP's in CuTl-1223 matrix. Thermally activated flux flow caused by the vortex dynamics in applied field has also been discussed.

2. Samples synthesis and characterization techniques

$(CoFe_2O_4)_x$/CuTl-1223 ($0 \le x \le 2$) nanoparticles-superconducting composites were synthesized by the two steps solid–state reaction method. Initially, we synthesized $Cu_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ precursor material by mixing Cu(CN), $Ba(NO_3)_2$ and $Ca(NO_3)_2$ compounds as starting materials in suitable ratios in an agate mortar and pestle. We put the ground material into quartz boat and placed it in pre-heated chamber furnace at 860 °C for heat-treatment for 24 h. The furnace was switched off after 24 h heat-treatment and precursor material was cooled down to room temperature in furnace. In the second step, thallium oxide (Tl_2O_3) and $CoFe_2O_4$ nanoparticles were mixed in precursor material in specific ratios and were ground for about 2 h. This uniformly ground resultant material was then palletized under pressure of 3.8 tons/cm^2 and those pellets were later on encapsulated in a gold capsule for sintering process. The pellets were sintered at 860 °C for 10 min and then quenched to the room temperature to get the resultant $(CoFe_2O_4)_x$/CuTl-1223 nanoparticles-superconducting composites samples.

The structure was investigated by X-ray diffraction (XRD) scan from Rigaku X-ray diffractometer having a CuKα source with a wavelength of 1.54056 Å. The cell parameters were calculated by using a cell refinement computer program MDI jade and compared with standard International Center for Diffraction Data (ICDD) record. Morphology of composites was determined by using scanning electron microscopy (SEM). The electrical dc-resistivity measurements of bar-shaped samples were carried out as a function of temperature using four-probe method with the help of Physical Properties Measurement System (PPMS) manufactured by Quantum Design. Transverse magnetic field was applied normal to the surface of the sample.

3. Results and discussion

X-ray diffraction (XRD) patterns of $(CoFe_2O_4)_x$/$Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$; x = 0, 1.0 and 2.0 wt % nanoparticles-superconducting composites samples are shown in Fig. 1. Most of the diffraction peaks are associated with the tetragonal structure of host $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ superconducting phase. The diffraction patterns express the dominance of CuTl-1223 phase with characteristics (0 0 1) peak of this phase at 2θ° = 5.84°. XRD patterns reveal that the structure and symmetry of CuTl-1223 phase had not been changed after the inclusion of $CoFe_2O_4$ nanoparticles, which indicates the presence of these nanoparticles over the intergranular sites [29]. Almost all the diffraction peaks have been well indexed using computer program MDI Jade according to tetragonal structure of CuTl-1223 phase following the P4/mmm symmetry and the cell parameters are a = 4.42 Å, c = 15.00 Å, a = 4.42 Å, c = 14.95 Å and a = 4.45 Å, c = 14.92 Å for the samples with x = 0, 1.0 and 2.0 wt %, respectively. The presence of these nanoparticles at inter-crystallite sites helps in improving the inter-grains weak-links of CuTl-1223 superconducting matrix. Few peaks of very low intensities could not be indexed according to CuTl-1223

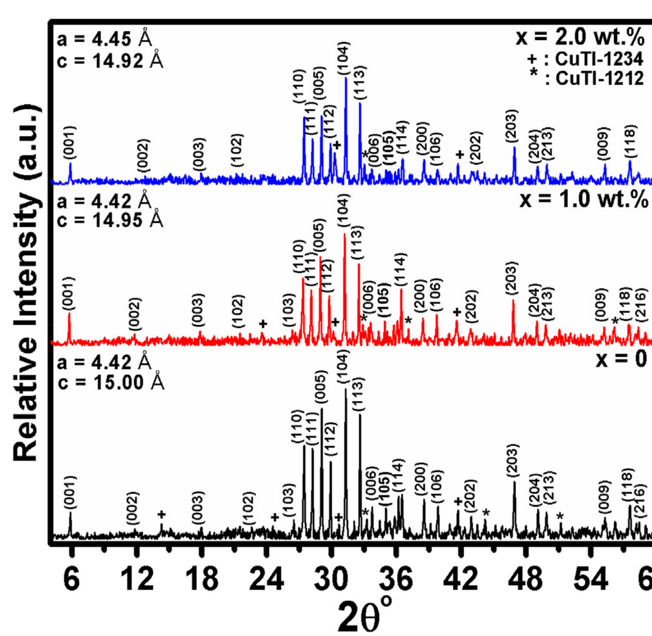

Fig. 1. XRD patterns of $(CoFe_2O_4)_x$/CuTl-1223 nanoparticles-superconductor composites with x = 0, 1.0 and 2.0 wt. %.