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Role of anti-ferromagnetic Cr nanoparticles in CuTl-1223 superconducting matrix

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Anti-ferromagnetic chromium (Cr) nanoparticles were added to $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ (CuTl-1223) superconducting matrix to synthesize $(Cr)_x$/CuTl-1223 (x = 0, 0.5, 0.75, and 1.0 wt.%) nano-superconductor composites. Different experimental techniques were used to study the structural, morphological, compositional and superconducting transport properties of these composites. It was observed that the addition of Cr nanoparticles had not altered the crystal structure of the host CuTl-1223 superconducting matrix, which indicates the presence of these nanoparticles at the grain-boundaries. Suppression of superconducting transport properties can be attributed to two factors (i) spins scattering by net magnetization due to uncompensated spins on the surface of these anti-ferromagnetic Cr nanoparticles and (ii) oxygen imbalance due to formation of Cr_2O_3 surface layers on these nanoparticles. The prominent reduction in the diamagnetic signal was also observed, which had indicated the decrease of superconducting volume fraction after the inclusion of Cr nanoparticles in the composites. Superconducting microscopic parameters such as coherence length $\{\xi_c(0)\}$, inter-layer coupling (J), Fermi velocity (V_F) and Fermi energy (E_F) of the carriers were determined as a function of Cr content in $(Cr)_x$/CuTl-1223 nano-superconductor composites by excess conductivity analyses in three dimensional (3D), two dimensional (2D) and short wave dimensional (0D) fluctuation regions.

1. Introduction

To enhance the performance of bulk high temperature superconductors (HTSCs) from application point of view, it is required to improve their inter-grains connectivity and superconducting volume fraction. In literature, different techniques have been employed in this regard [1–9]. But the inclusion of nanostructures of different elements and compounds of different sizes in bulk superconducting matrix is an efficient, cheap and easy technique [10]. The increase of critical current density (J_c) was attributed to improved inter-grains connectivity of the host bulk Bi-2223 superconducting matrix after the addition of $Co_{0.5}Ni_{0.5}Fe_2O_4$ and Co_3O_4 nanoparticles [11,12]. Improvement in superconducting properties of (Bi, Pb)-2223 system was observed after the addition of appropriate amount ($x \leq 0.5$ wt.%) of Cr_2O_3 nanoparticles [13]. Ultra fine MgO nanoparticles were added to enhance the superconducting properties of Bi-2212/Ag tapes [14]. The effect of Al_2O_3 nanoparticles on superconducting properties of $YBa_2Cu_3O_{7-\delta}$ was investigated and reduction in T_c was observed, which was attributed to the insulating nature of these nanoparticles [15].

The effects of nano-sized NiO addition in $(Bi_{1.8}Pb_{0.4}Sr_2Ca_{2.2}Cu_3O)_{1-x}(NiO)_x$ with different concentration were investigated and improvement in flux pinning was observed for x = 0.002 wt.% [16]. Superconducting properties of $Bi_{1.6}Pb_{0.4}Sr_2CaCu_2O_y$ were enhanced after the addition Y_2O_3 nanoparticles up to 0.7 wt.% [17]. Different wt. % of Fe_3O_4 nanoparticles were added to $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10}$ superconductors, and enhanced J_c both in absence and presence of magnetic was reported [18]. Nano-sized Co_3O_4 and MgO particles were added to Bi(Pb)–Sr–Ca–Cu–O superconductors and improved superconducting properties were observed [19,20].

$(Cu_{0.5}Tl_{0.5})Ba_2Ca_2O_{10-\delta}$ (CuTl-1223) phase of CuTl-based superconducting family is a potential candidate from application point view due to its relatively higher superconducting properties

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[21–23]. The inclusion effects of Al_2O_3 nanoparticles on structural and superconducting properties of CuTl-1223 matrix were studied [24]. The addition of noble metals (Ag, Au) nanoparticles up to certain optimum level has significantly improved the superconducting transport properties of CuTl-1223 matrix without changing the crystal structure of the host bulk CuTl-1223 phase. The improvement in superconducting transport properties of CuTl-1223 matrix was attributed to the enhanced inter-grains connectivity by these nanoparticles [25]. The suppression of superconducting properties after the addition of magnetic core–shell nickel/nickel-oxide (Ni/NiO) and $ZnFe_2O_4$ nanoparticles in CuTl-1223 superconductors was observed [26,27].

In present work, we have investigated the effects of anti-ferromagnetic Cr nanoparticles addition on structural, compositional, morphological and superconducting transport properties of CuTl-1223 matrix by different experimental techniques. Anti-ferromagnetic Cr nanoparticles can improve the inter-grains connectivity by filling the pores in the bulk CuTl-1223 matrix but at the same time these nanoparticles may act as scattering centers due to uncompensated spins on their surfaces. Anti-ferromagnetic nature of Cr nanoparticles with strong affinity of oxygen can create oxygen disorder within the superconducting regions, which can definitely affect the carriers density in the CuO_2 planes. Therefore, this study can be very interesting and useful to explore the dependence of superconducting properties of CuTl-1223 matrix.

2. Experimental details and characterization techniques

$Ba(NO_3)_2$, $Ca(NO_3)_2$ and $Cu_2(CN)_2$ compounds were mixed in appropriate ratios and ground for 2 h in an agate mortar and pestle. The mixed and ground powder was loaded in quartz boats and heat-treatment was carried out at 860 °C in a chamber furnace for 24 h followed by furnace cooling to room temperature (i.e. 300 K). After 24 h heat-treatment, the material was again ground for 1 h and loaded in ceramic boats for second time heat-treatment under similar conditions. Later on, the appropriate amounts of Tl_2O_3 and Cr nanoparticles of size 100 nm were mixed and ground for about 1 h. The ground material was then pelletized under 3.8 tons/cm^2 pressure and the pellets were gold encapsulated for sintering at 860 °C for 10 min followed by quenching to room temperature to get $(Cr)_x$/CuTl-1223 nano-superconductor composites.

The structure and phase purity of Cr nanoparticles, CuTl-1223 matrix and $(Cr)_x$/CuTl-1223 nano-superconductor composites were determined by X-rays diffraction (XRD). We used scanning electron microscopy (SEM) for surface morphology, energy dispersive X-ray spectroscopy (EDX) for compositional analysis and Fourier transform infrared spectroscopy (FTIR) to study the different oxygen phonon modes. We determined dc-resistivity of the samples with the help of commercial physical properties measurement system (PPMS). Pellets were cut in rectangular bar shapes with 1.6 mm × 1.1 mm × 2.9 mm dimensions and silver paste was used to make four low resistance contacts on the surface of sample. During dc-resistivity measurements, the current was kept contact at 10 μA. Ac-susceptibility measurements were carried out by the mutual inductance method using Lock-in Amplifier at a frequency of 270 Hz with H_{AC} = 0.07 Oe of primary coil. Excess conductivity $\Delta\sigma$ is determined by the expression;

$$\Delta\sigma = \sigma_m(T) - \sigma_n(T) = \rho_m^{-1}(T) - \rho_n^{-1}(T) \quad (1)$$

where $\rho_m(T)$ is the actually measured resistivity and ρ_n(T) is the normal-state resistivity obtained from extrapolated resistivity at 0 K; $\rho_n(T) = \alpha + \beta T$, α is an intercept and β is a slope of straight line. According to the Aslamazov–Larkin (AL) model, the normalized excess conductivity $\Delta\sigma/\sigma_{room}$ was determined by applying a microscopic approach in the mean field region [28], where the fluctuation are small and given by the relation;

$$\Delta\sigma_{AL} = A\varepsilon^{-\lambda} \quad (2)$$

where A is fluctuation amplitude, $\varepsilon = \ln\left[\frac{T - T_c^{mf}}{T_c^{mf}}\right]$ is reduced temperature and T_c^{mf} is usually referred to as the mean field critical temperature [29,30]. Dimensional exponent is determined from the slope of ln(ε) versus ln($\Delta\sigma$) plot. All physical parameters depend on the dimensionally exponentλ, which is expressed as;

$$\lambda = 2 - \frac{D}{2} \quad (3)$$

where λ is equal to [31–33];

$$\lambda = \begin{cases} -0.50 \ for\ (3D) Fluctuations \\ -1.00 \ for\ (2D) fluctuations \\ -3.00 \ for\ (sw) fluctuations \end{cases} \quad (4)$$

According to Lawrence–Doniach (LD) model, a cross-over from two dimensional (2D) to three dimensional (3D) conductivity occurs at a cross-over temperature;

$$T_o = T_c\left[1 + \left(\frac{2\xi_c(0)}{d}\right)^2\right] \quad (5)$$

The inter-layer coupling strength is given by second term, which is related to the reduced temperature ε by J = ε/4 and d is the distance between the conducting layers of adjacent unit cells, which is approximately equal to c-axis length of unit cell. Alexei Abrikosov applied Ginzburg–Landau theory to explain the experimental data of superconductors. He analyzed that high magnetic field in a type-2 superconductor penetrates in the form of magnetic flux quanta Φ_o. The thermodynamic critical magnetic field $B_c(0)$ can be estimated from Ginzburg number N_G, which is given by Refs. [34,35].

$$N_G = \left|\frac{T_G - T_c^{mf}}{T_c^{mf}}\right| = 1/2\left(\kappa_B T_c \gamma \Big/ \{B_c(0)\}^2\{\xi_c(0)\}^3\right)^2 \quad (6)$$

where $\gamma = \xi_{ab}(0)/\xi_c(0)$ is an isotropy [36] and T_G is the cross-over temperature from critical to 3D regime. We can estimate penetration depth $\lambda_{p.d.}$, lower critical magnetic field B_{c1} upper critical magnetic field B_{c2} and the critical current density J_c after determination of B_c as follows [37–40].

$$B_c = \frac{\Phi_o}{2\sqrt{2}\pi\lambda_{p.d.}\xi_{ab}(0)} \quad (7)$$

$$B_{c1} = \frac{B_c}{\kappa\sqrt{2}}\ln\kappa \quad (8)$$

$$B_{c2} = \sqrt{2}\kappa B_c \quad (9)$$

$$J_c = \frac{4\kappa B_{c1}}{3\sqrt{3}\lambda_{p.d.}\ln\kappa} \quad (10)$$

where $\Phi_o = \frac{h}{2e}$ is the change quantum andκ is the GL factor which is comparison of penetration depth to coherence length.