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Fabrication and transport studies on $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_7$: $\text{M} = \text{Ga}, \text{Zn}, \text{and Co}$

U. Tipparach ^{a,*}, T.-P. Chen ^a, J.L. Wagner ^a, K. Wu ^a, Q.Y. Chen ^b, Q. Li ^c,
J.T. Wang ^d, H.C. Yang ^e, H.-E. Horng ^f

^a Department of Physics, University of North Dakota, Grand Forks, ND 58202-7129, USA

^b Texas Center for Superconductivity and Department of Physics, University of Houston, Houston, TX 77204-5932, USA

^c Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

^d Department of Physics, Southern University and A&M College, Baton Rouge, LA 70813, USA

^e Department of Physics, National Taiwan University, Taipei 116, Taiwan, ROC

^f Department of Physics, National Taiwan Normal University, Taipei 116, Taiwan, ROC

Abstract

We have fabricated M-doped $\text{PrBa}_2\text{Cu}_3\text{O}_7$ (Pr123), i.e. $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_7$ for $\text{M} = \text{Zn}, \text{Ga}, \text{and Co}$, with $x = 0.05, 0.10, 0.15, \text{ and } 0.20$. Experimental data indicates single phase samples for the Ga and Co doping up to 20% level. Second phases appear in Zn-doped samples when the doping level reaches 0.15. At 77 K the electrical resistivity of these compounds is several orders of magnitude higher than that of undoped Pr123. We also found no orthorhombic to tetragonal phase transition in the doped samples with all samples remaining in orthorhombic. Their lattices parameters are very close to those of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y123). For this reason these compounds may serve as improved buffer-layer materials for Y123 superconducting electronic circuits and devices. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

$\text{PrBa}_2\text{Cu}_3\text{O}_7$ (Pr123) has been reported to be an insulator [1]. Experiments on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y123)/Pr123 superlattices [2,3], on the other hand, indicate that Pr123 is incapable of insulating Y123 layers in superlattices. Based on the optical reflectivity data of Takenaka et al. [4] and by using the results of electronic structural calculations, Fehrenbacher and Rice [5] argued that CuO_2 planes in Pr123 are non-conducting but the CuO chains, which have 0.5 hole per Cu atom, may be

locally conducting. Blackstead and Dow [6] believe that Pr123 can be made superconducting if the number of Pr atoms occupying Ba sites can be reduced. They later reported [7] observations of inhomogeneous superconductivity in Pr123 with $T_c = 92$ K. Using a traveling-solvent-floating-zone (TSFZ) method, Zou et al. [8] have grown bulk superconducting Pr123 of $T_c \sim 80$ K.

Usagawa et al. [9] performed electrical resistivity measurement on a Pr123 and YBCO combined systems obtained by fabricating a Pr123 film on top of a Y123 single crystal coated with a Y123 film. They found two superconducting transitions for the system. A higher transition, which occurs at 92 K, was identified to be the superconducting

* Corresponding author.

transition of the bulk Y123 single crystal. For a 300 Å thick Pr123 film, the lower transition occurs at 89.9 K while it is 75.5 K for a 2200 Å thick Pr123 film. It is believed that the lower transition comes from the hybridization of the electron energy band associated with the electrons in the chains of Pr123. The hybridization of the Pr123 energy band occurs due to the presence of superconducting electrons in the Y123, i.e. from the proximity effect of the YBCO superconducting electrons to the electrons in the chain sites of the Pr123. This strongly suggests that Pr123 films cannot insulate Y123 layers effectively if they are brought in good contact with Y123 films. Improvement in buffer-layer materials is a necessity for making Y123 SIS, NIS junctions and other electronic circuits and devices.

There are two ways to improve the insulation property of Pr123. One way is to replace the Ba atoms by Pr atoms as was proposed by Blackstead et al. However, there is no controllable method being proposed to replace Ba atoms effectively. Another way is to substitute Cu by other atoms of higher valence. Transport studies on the Cu substituted Y123 usually show higher resistivity. Such a scheme should also work for Pr123. It is our belief that when a sufficient fraction of holes are filled, Pr123 should be a true insulator even in good contact with a Y123. Another mechanism to make Pr123 a true insulator via substitution is that substitution of other atoms for Cu may change the orthorhombic structure of the undoped Pr123 to a tetragonal [10,11]. Such a orthorhombic–tetragonal structural transition will increase the dielectric constant of Pr123. With this motivation we fabricated a series of $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_7$ (PBCMO) ($\text{M} = \text{Co}, \text{Zn}, \text{Ga}$ and $x = 0.05, 0.10, 0.15$, and 0.20) Pr123 compounds and performed electrical resistivity and X-ray measurements. The results of these studies are reported in this paper.

2. Results and discussion

Fig. 1 shows the X-ray spectra for 0%, 5%, 10%, 15%, and 20% Zn, Ga, and Co-doped Pr123. For the Co and Ga doped samples no second phases were found up to 20% doping level. For the 5%

Fig. 1. X-ray diffraction patterns of $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_7$ for $\text{M} = \text{Zn}, \text{Ga}, \text{Co}$, and $x = 0.00$ (Pr123), 0.05, 0.10, 0.15, and 0.20.

incremented Zn-doped samples, no second phase is present until the doping level reaches 15% indicating that the maximum doping of Zn is between

Table 1

Lattice parameters for $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_7$ ($\text{M} = \text{Zn}$, Ga , and Co)

Sample	a	b	c
$\text{YBa}_2\text{Cu}_3\text{O}_7$	3.8932(7)	3.9026(6)	11.4926(11)
$\text{PrBa}_2\text{Cu}_3\text{O}_7$	3.9060(5)	3.9250(4)	11.6338(13)
$\text{PrBa}_2(\text{Cu}_{1-x}\text{Zn}_x)_3\text{O}_7$			
$x = 0.05$	3.9050(5)	3.9274(4)	11.6454(14)
$x = 0.10$	3.9051(5)	3.9223(4)	11.6775(14)
$x = 0.15$	3.9088(7)	3.9213(6)	11.6857(19)
$x = 0.20$	3.9103(9)	3.9226(8)	11.6889(25)
$\text{PrBa}_2(\text{Cu}_{1-x}\text{Ga}_x)_3\text{O}_7$			
$x = 0.05$	3.9109(6)	3.9163(5)	11.7026(17)
$x = 0.10$	3.9174(5)	3.9244(4)	11.7046(13)
$x = 0.15$	3.9205(9)	3.9307(8)	11.6994(25)
$x = 0.20$	3.9203(6)	3.9338(6)	11.6972(17)
$\text{PrBa}_2(\text{Cu}_{1-x}\text{Co}_x)_3\text{O}_7$			
$x = 0.05$	3.9143(6)	3.9193(6)	11.7267(19)
$x = 0.10$	3.9180(1)	3.9210(1)	11.7294(19)
$x = 0.15$	3.9251(1)	3.9307(6)	11.7193(19)
$x = 0.20$	3.9348(9)	3.9367(8)	11.7167(28)

10% and 15%. The X-ray data was analyzed to obtain the structure of the samples and their lattice parameters. Structural parameters were refined using the general structure analysis software (GSAS) suite of programs [12].

Table 1 lists the crystal structure and lattice parameters of all PBCMO samples. The crystal structure and the lattice parameters of YBCO and Pr123 are also listed for comparison. The crystal structure for all samples remains orthorhombic with space group symmetry of Pmmm.

Yang and Lin [10] show that Cu substituted by other metallic elements may induce an orthorhombic to tetragonal (O–T) phase transition. Our experimental data show that for 5% Zn substitution the three peaks (006), (020), and (200) in the region $45^\circ < 2\theta < 50^\circ$ individually are resolved indicating large orthorhombicity. These peaks begin to merge when doping level is increased indicating a decreasing orthorhombicity with increasing doping level. In the Ga-doped case although the values for lattice parameters show that $a \neq b$, the three peaks in $45^\circ < 2\theta < 50^\circ$ region are nearly degenerate indicating that Ga substitution is more effective in decreasing the orthorhombicity. These results agree well with that of Yang and Lin. Tarascon et al. [11] found that Cu substituted

Fig. 2. Electrical resistivity as a function of temperature for PBCMO samples.

by Co induces an O–T transition. Our results show that Co-doped samples remain orthorhombic ($a \neq b$) for doping level as high as 20%. The lattice calculated parameters a and b also. We conclude that the crystal structure for all Co-doped samples remain orthorhombic, however, the orthorhombicity is much less than in undoped PBCMO. The lattice parameters a , b , and c of Co-doped PBCMO samples are also very close to that of Y123.

Fig. 2 shows the plots of electrical resistivity ρ vs. T for all PBCMO samples. Below 100 K the electrical resistivity for all doped Pr123 are orders of magnitude higher than that of the undoped Pr123 indicating the doped samples are much better insulators than the undoped Pr123. In view of their excellent match in lattice parameters between YBCO and PBCMO and their much higher electrical resistivity, all of the doped Pr123 could be better buffer layers than Pr123 for Y123 multilayers.

Among the doped samples, Co has magnetic moment while Zn and Ga are non-magnetic. The electrical resistivity of Zn-doped samples is the

lowest among all the doped samples. In addition, Zn-doped YBCO was found to reduce the T_c of Y123 substantially. If Zn migrates from the $\text{PrBa}_2(\text{Cu}_{0.8}\text{Zn}_{0.2})_3\text{O}_7$ side to the YBCO side then $\text{PrBa}_2(\text{Cu}_{0.8}\text{Zn}_{0.2})_3\text{O}_7$ may not be an ideal buffer layer for YBCO multiplayer systems. The electrical resistivity of Co-doped PBCO samples are the second highest. However, Co is magnetic. At this time it is not known to what exact the magnetic moment of Co affects the T_c of YBCO. Ga-doped samples have the highest electrical resistivity and Ga has no magnetic moment. It is our belief that among all PBCMO samples, the Ga-doped ones may be best suited for making buffer layers for YBCO/PBCMO multiplayer/superlattice.

3. Conclusion

In conclusion, we have fabricated 5%, 10%, 15%, and 20% Zn, Ga and Co-doped Pr123 and performed resistivity and X-ray studies. The X-ray results indicate that the no second phases for Ga and Co-doped samples up to 20%. Second phases appear in Zn-doped sample at 15% doping level. The crystal structure for the doped samples remains orthorhombic and the lattice parameters of these doped materials are very close to that of Y123. The electrical resistivity on the other hand is

much higher than the undoped Pr123. These materials therefore are better suited for buffer layers in Y123 superlattice/multiplayer than the undoped Pr123.

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