Physica C 495 (2013) 208–212

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Enhancement of critical current density for nano (n)-ZnO doped MgB_2 superconductor

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ARTICLE INFO

Article history:
Received 15 June 2013
Accepted 1 October 2013
Available online 10 October 2013

Keywords:
Critical current density
Vortex-avalanches
Residual resistivity ratio
Magnetization

ABSTRACT

Doping effect of ZnO-nanoparticles on the superconducting properties of MgB_2 has been studied. The 2% nano-ZnO doped MgB_2 shows the excellent J_c and H_{irr} at all temperatures and magnetic fields amongst the doped and undoped sample. The lattice parameter-*c* shows the higher value for 2% ZnO doped MgB_2 sample, which clearly demonstrates the presence of the lattice strain in doped samples. The residual resistivity ratio was increased as the nano-ZnO doping level increased. Very slight variation in T_c is observed from the temperature dependence of resistivity plot of nano-ZnO doped MgB_2. In M (H) plot at low applied fields, we have observed large vortex instabilities (vortex-avalanches) associated with 2% and 4% doped samples. Vortex avalanche effect is diminishes with increasing temperature and disappears near 15 K. The results are discussed in terms of local-vortex instabilities caused by doping of ZnO nanoparticles. Scanning electron microscopy studies show that the synthesized samples are well adherent and grains are uniformly distributed with an average particle size of ~5–10 μm.

1. Introduction

Since the discovery of superconductivity at 39 K in layered transition metal boride MgB_2 [1], led a rush among the scientific community due to its fundamental properties as well as practical applications [2–4]. The two-gap property is one of the most unusual aspects of the MgB_2 that is very important to its high-field performance [5–7]. This superconducting material exposed the simple chemical composition, somewhat high transition temperature (T_c), lower anisotropy, large coherence length and better current flow across the grain boundaries [8]. However, in bulk MgB_2, one of the most important challenges is to enhance the upper critical field (H_{c2}) along with improving the critical current density (J_c). As we know that MgB_2 have poor grain coupling and a lack of pinning centres, it normally shows a rapid decrease in J_c in high magnetic fields [9,10]. Furthermore, the reported result of very high H_{c2} and relatively large J_c in dirty thin film grasped the interest of the scientists towards its practical use of high field applications [11,12]. Enormous efforts have been made on the way to the fabrication of high-quality MgB_2 superconductor. In order to enhance the J_c, H_{c2}, and the irreversibility field (H_{irr}), enormous chemical doping [13–21], different routes [22–25], and thermo-mechanical processing techniques [26,27] have been adopted. Remarkably, chemical doping particularly using nano-particle doping has revealed the great promise in improving the J_c–H behavior due to form a high density of nano-inclusions in MgB_2 matrix and provides a strong flux pinning force (F_p). Amongst nano-dopants, the nano (n)-ZnO has been taken into account because the local structure of MgB_2 should be affected by Mg–O interaction on the ZnO. In the recent years, various studies have been reported experimentally [28–34] and theoretically [35–39] for the enhancement of superconducting properties in Zn-doped MgB_2 superconductor. Various attempts have been made for enhancing J_c, H_{c2} and H_{irr} by doping different organic and inorganic Zn-containing materials in MgB_2 as reported earlier [40,41].

The purpose of the present study is, therefore, to investigate electrical, structural and magnetic properties of n-ZnO *doped* MgB_2 superconductor. We ascertain that inclusion of n-ZnO in MgB_2 support eloquently improving J_c and H_{irr} in high applied fields. This is due to large vortex instabilities at $T = 10$ K up to 10 KOe applied field for all the doped samples. The XRD measurements were carried out to evaluate the percentage of Zn doping in MgB_2. Here, we observed that Zn atom forms solid solution in the Mg site of MgB_2. Magnetization measurement as a function of field at different temperature from 4 to 30 K have been studied for different percentage of n-ZnO doped MgB_2 samples. In comparison to the pure sample, the 2% n-ZnO doped sample show the excellent

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http://dx.doi.org/10.1016/j.physc.2013.10.001

J_c–H properties. Irreversibility field H_{irr} for $Mg_{1-x}Zn_xB_2$ were obtained from the M–H hysteresis plots and found that 2% n-ZnO doped sample shows the excellent H_{irr} at all the temperatures. The results were further correlated with the images of scanning electron microscopy (SEM).

2. Experimental details

In the present report, synthesis of n-ZnO doped MgB_2 for nominal composition of x = 0%, 2%, 4% and 6% were attempted by standard solid state reaction method. Highly pure starting materials Mg powder (Sigma Aldrich, >99% purity), B amorphous powder (Sigma Aldrich, >99% purity), and n-ZnO powder (Sigma Aldrich, >99% purity) were mixed with stoichiometric ratio, ground in room temperature with the agate mortar and pestle up to 1 h and pressed with hydraulic press in the pellets size of $20 \times 10 \times 3$ mm^3. These pellets were encapsulated in different soft Fe-tube and its subsequent heating to 750 °C for two and half hours in an evacuated (10^{-5} Torr) quartz tube and quenching to liquid nitrogen temperature. Finally, we have to find a bulk polycrystalline and quite porous sample of n-ZnO doped MgB_2.

The XRD patterns of the samples were recorded using Cu Kα radiation within 2θ range of 20–70°. Temperature dependence of resistivity $\rho(T)$ from the room temperature to 13 K were investigated by standard four-probe method. The magnetizations of these samples were measured using PAR-4500 Vibrating Sample Magnetometer (VSM) at various temperatures in magnetic fields up to 70 kOe. The J_c values were deduced from M–H loops using the Bean's Critical State Model. Irreversibility fields (H_{irr}) were measured from the highest magnetic field where the magnetization was irreversible. Additionally, the morphologies were observed by SEM (JEOL, JSM-6360) operating with a 20 kV accelerating voltage.

3. Results and discussion

The XRD of the samples were carried out using Cu Kα radiation for a 2θ range of 20–70° with a step time of 1 s/0.02 step each. The XRD patterns for the samples used in the present study are shown in Fig. 1. The presence of the small amount of MgO and unreacted Mg are seen in the pattern near about 2θ = 62.2° and 2θ = 36.8°, which are marked by the symbol "∗" and "#", respectively in Fig. 1. The impurity phase MgO might arise during the reaction because Mg is highly reactive with oxygen. No other impurity except MgO and unreacted Mg are seen in the XRD plots of n-ZnO doped MgB_2 samples. The total XRD plot shows the fine doping of n-ZnO in the stoichiometry of Mg and B. The MgO impurity phase has been also observed in our earlier reported paper for n-alumina doped MgB_2 superconductor [15].

The lattice parameters estimated from the XRD plot show a slight decrease in the a-axis parameter. The lattice parameter a decreases from 3.0825 Å for the pure sample to 3.0806 Å for the sample with highest concentration, as can be seen in Fig. 2. On the contrary, quite improvement in the c-axis parameter up to 2% Zn concentration has been observed as shown in Fig. 2. The variation in the lattice parameter-a is negligible with respect to ZnO concentration. The (100) peak leads the a-axis parameter and the (002) peak represents the c-axis parameter. Fig. 2 evidently reveals the presence of the lattice strain in doped samples. The lattice parameters a and c were manually refined by using the Windows-based PowderX software.

The Full Widths at Half Maximum (FWHM) were determined with the program PowderX by using X-ray diffraction data. These FWHM data were used to evaluate the grain size and strain of different doped samples using the Williamson and Hall model [42]:

$$\mathrm{FWHM} \times \cos(\theta) = \frac{0.94\lambda}{(\mathrm{Grain\ size})} + 4 \times \mathrm{Strain} \times \sin(\theta)$$

where λ is the wavelength of monochromatic Cu Kα radiation (1.540598 Å) and θ is the angle of peak position at X-ray plot. The above relation encompasses the combination of Scherrer equation for size broadening and Stokes and Wilson expression for strain broadening. After plotting the FWHM × cos(θ) vs. sin(θ) and fitting the straight line as shown in Fig. 3. Finally, we have calculated the variation of crystalline size and strain as a function of different doped samples of ZnO with MgB_2 as indicated in Figs. 4 and 5. The average gain size for the doped samples is found to be between 20 nm and 21 nm.

The temperature dependence of resistivity, $\rho(T)$ of n-ZnO doped MgB_2 is shown in Fig. 6 at different doping level. It is evident from the $\rho(T)$ plot that the all samples shows the sudden transition up to ρ = 0. This study endorsed the slight variation of T_c with the n-ZnO doping. Residual resistivity ratio (RRR) values varies from 1.65 to 3.67 with the increase of the doping level from pure sample to 6% doped n-ZnO. The T_c of n-ZnO doped MgB_2 varies very slightly with increasing doping level as shown in the inset of Fig. 6. The variation of T_c (onset), T_c (ρ = 0) and ΔT_c are described in Table 1

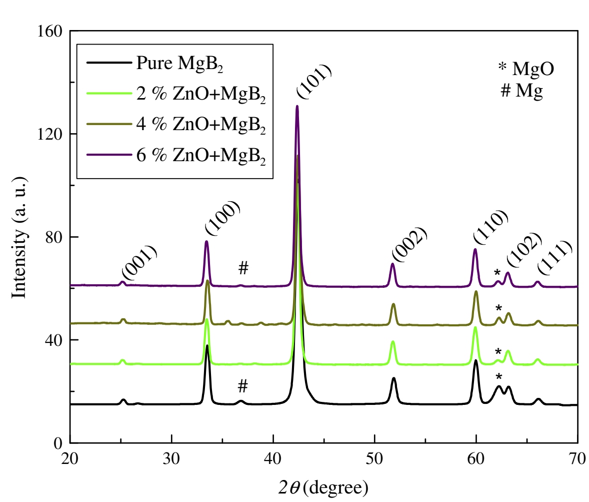

Fig. 1. XRD pattern of 0%, 2%, 4% and 6% n-ZnO doped MgB_2.

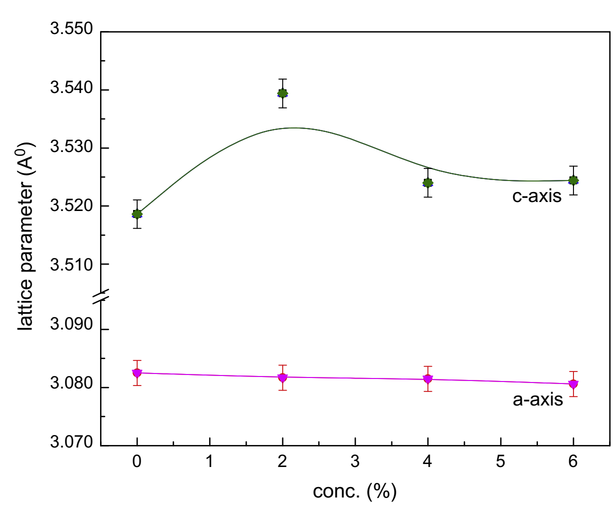

Fig. 2. Variation of a-axis and c-axis lattice parameter with different Zn-doping concentration.