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Effect of Co addition on the critical current density of MgB_2 superconductor

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ABSTRACT

In this study, the $(MgB_2)_{1-x}Co_x$ samples, where $x=0.0$, 0.1, 0.3, 0.6 and 0.8, were prepared by using the solid-state reaction technique. Effect of the Co-addition on the structural, magnetic, critical current density, J_c, and flux pinning properties of the superconducting MgB_2 system was investigated. A magnetic transition was observed with increasing the Co-concentration in MgB_2. For the pure MgB_2, J_c was obtained to be 2.78×10^4 A cm^{-2} at 5 K and 1.7 kOe, but J_c was suppressed by addition of Co to the system. It was found that a large amount of Co in MgB_2 did not act as pinning centers which improves J_c. The magnetic behavior observed by the Co-addition originates from the magnetic properties of cobalt itself.

1. Introduction

MgB_2 with the superconducting transition temperature, T_c, of 39 K has attracted great attention from experimental and theoretical points of view within the last decade. Nowadays, the MgB_2 system is used in widespread technological applications from magnets to the superconducting fault current limiter (SFCL), power transmissions, motors, etc. The system exhibits low anisotropy, large coherence length and simple crystal structure. Especially, large coherence length eliminates the weak link problems, which allows the possibility of achieving high critical current density, J_c. However, the critical current density in MgB_2 is limited by some factors such as poor connectivity between superconducting grains and chemical heterogeneity at the grain boundaries [1].

Different elements to improve J_c and H_{c2} have been substituted, doped and/or added to the MgB_2 system [1–10]. The substitution/doping elements constitute pinning centers in the system, which lead to the improvement in J_c. The pinning centers reduce the mean free path of the normal electrons, decreasing the coherence length and increasing H_{c2} [7]. When the substituted/doped elements are magnetic such as Mn, Fe, Co and Ni, the superconductivity in the system was suppressed. However, it was found that additional pinning centers between the magnetic moments of the vortex and magnetic particles occurs [8–12]. Magnetic particles interact strongly with magnetic flux lines, which cause a strong force to trap the flux lines [1]. The magnetic part of the pinning force between the vortex and magnetic particles has a range of London penetration depth [11] which is much larger than the depth of usual vortex core-type pinning. Therefore, the magnetic particles in MgB_2 can cause unusual behavior on the superconducting gaps and penetration lengths with temperature [13,14].

Studies on the Co-substituted/doped MgB_2 are present in the literature [2,8,13,15–17]. But, the effects of the highly Co-addition into MgB_2 on the pinning behavior have not been examined. In this study, we have investigated structural, electrical and magnetic properties of $(MgB_2)_{1-x}Co_x$ prepared by the conventional solid-state reaction technique.

2. Experimental Details

$(MgB_2)_{1-x}Co_x$ samples, where $x=0.0$ (pure), $x=0.1$ (90 wt% MgB_2+10 wt% Co), 0.3 (70 wt% MgB_2+30 wt% Co), 0.6 (40 wt% MgB_2+60 wt% Co) and 0.8 (20 wt% MgB_2+80 wt% Co) were prepared by the conventional solid-state reaction method using high purity powders of MgB_2 (Alfa Aesar Co. 99%) and Co (99.999%). The powders were mixed in an agate mortar for 3–5 h under Ar atmosphere and were pressed into pellets under a pressure of 6.5 MPa. The pellets were placed in an α-alumina crucible and then heat treated at 650 °C for 2 h in Ar atmosphere.

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The structural characterization of the fabricated samples was performed using X-ray diffraction (XRD) with a scan speed of $1^{\circ}\,\mathrm{min}^{-1}$ in the range of 3–70°. Rigaku RadB X-ray diffractometer system with CuKα (λ=1.5405 Å) radiation was used during XRD measurements. Rietveld refinement to calculate the unit cell parameters of samples is carried out using the program Jade 5.0 software. Temperature dependence of resistance (*R*–*T*) of samples was measured by the conventional dc four-probe method with a closed cycle He refrigerator (Leybold LT10) system.

Magnetization measurements (*M*–*T* and *M*–*H*) of samples were carried out using Quantum Design PPMS-9 T system. *M*–*T* measurements were performed between 300 K and 5 K at a magnetic field of 50 Oe. Magnetic hysteresis (*M*–*H*) of samples was measured at three different temperatures, 5 K, 20 K and 30 K, up to the magnetic field of 6 T.

3. Results and discussion

XRD patterns of samples are shown in Fig. 1. All peaks in the x=0.0 Co-added sample were matched by pure MgB_2 with hexagonal symmetry and space group P6/mmm as shown in Fig. 1a. Unit cell parameters of the sample were calculated to be a=3.0898 Å (0.12%) and c=3.5359 Å (0.33%), which are close to the typical values of MgB_2. For the x=0.1 Co-added sample, the majority of peaks were indexed to MgB_2 and impurity phases such as MgB_4 and (Mg,Co)O were also detected in the system as shown in Fig. 1b. In the case of the x=0.3 Co-addition to MgB_2, the peak intensities of MgB_2 decreased compared to x=0.0 and 0.1 samples as shown in Fig. 1c. The sample consisted mainly of MgB_2, but small amount of MgB_4 and (Mg,Co)O impurity phases was also found. It is seen that the structural properties changed with the increase of the Co-concentration to x=0.6 as shown in Fig. 1d. Peak intensities decreased further, indicating that the crystal structure was distorted by highly Co-addition. It was observed that the amount of the impurity phases, MgB_4 and (Mg,Co)O, significantly increased although the MgB_2 phase exists in the sample.

Considering difference in the ionic radii of Co^{2+} (r_{Co}=0.72 Å), Mg^{2+} (r_{Mg}=0.66 Å) and B^{+} (r_B=0.35 Å), it is concluded that the addition of Co to the system caused a significant distortion on the crystal structure of MgB_2. It should be mentioned that we were not able to calculate lattice parameters of highly Co-added samples due to the large amount of impurities, so it is difficult to make a discussion on the lattice parameters of samples.

The superconducting transition temperature, T_c, and zero resistance temperature, T_0, obtained from temperature dependence of resistance, (*R*–*T*), of samples are shown in Table 1. T_c and T_0 values of samples decreased with increasing the Co-concentration in the

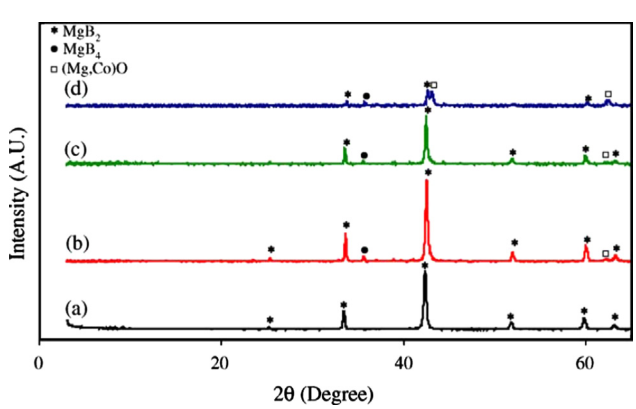

Fig. 1. XRD pattern of the $(MgB_2)_{1-x}Co_x$ system: a) x=0.0, b) x=0.1, c) x=0.3 and d) x=0.6.

Table 1
T_c and T_0 values of the samples fabricated.

Material (x)	T_c (K)	T_0 (K)
0.0	39.8	38.9
0.1	39.4	37.4
0.3	37.9	35.9
0.6	37.0	31.9
0.8	Non-superconducting	Non-superconducting

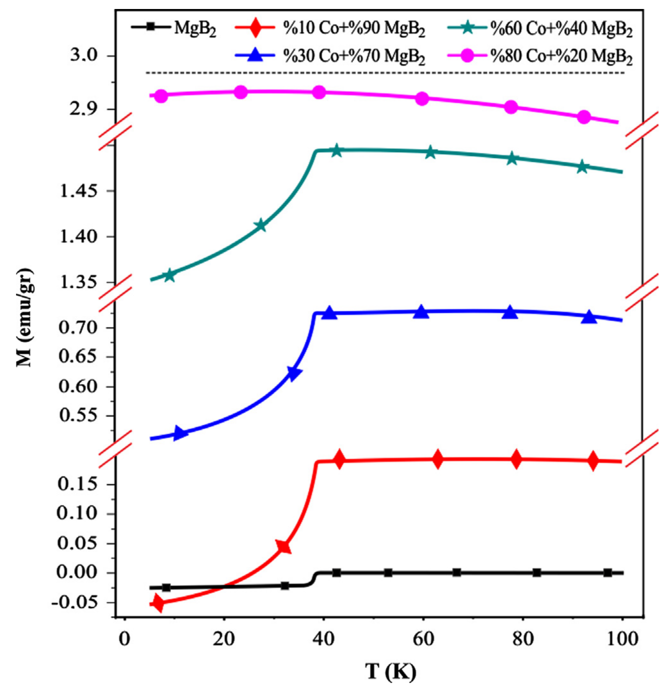

Fig. 2. Temperature dependence of the magnetization of the $(MgB_2)_{1-x}Co_x$ system.

MgB_2 system. Growth of impurity phases, formation of weak coupling between impurities and superconducting grains, disorders (i.e., impurities, defects, imperfections) and structural distortions are main reasons of decrease in the T_c value [18]. This suggests that disorders, impurities and structural distortions induced by the Co addition lead to the increased carrier scattering and thus the decrease of T_c.

Fig. 2 shows temperature dependence of the magnetization of samples. Pure MgB_2 sample showed sharp diamagnetic transition, indicating good homogeneity in the sample. The x=0.1 Co-added sample exhibited a paramagnetic–diamagnetic transition below 38 K. This indicates that superconductivity and paramagnetism coexist in the sample. Completely different magnetic behavior was found in samples for $x \geq 0.3$ Co-addition. Any diamagnetic transition was not obtained. A strong transition to ferromagnetic state was observed in samples. Such a transition is attributed to dissociation of MgB_2 by the Co-addition.

The net magnetic moment in MgB_2 is obviously zero in the superconducting state. The filled electron shells produce diamagnetism in an applied magnetic field, which is apparently observed in the pure MgB_2 as shown in Fig. 2. From the elementary level of magnetization, it is well known that the field dependent diamagnetism is generally not big enough and can easily be destroyed by some effects. From *M*–*T* measurements, one can conclude that the diamagnetism would be reduced due to several reasons: The first and the biggest effect is that the inclusion of Co ions causes a net cancellation in the diamagnetic effects since each Co ion have a net permanent magnetic moment. The second effect is due to the increase of number of the impurity/secondary phases and so the reduction of the superconducting grains