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Comparison of physical properties for carbon nanotube doped MgB_2 superconductors synthesized with different process

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Abstract

Carbon nanotubes (CNT) doping of magnesium diboride with a nominal stoichiometry of $MgB_{1.9}C_{0.1}$ synthesized under ambient pressure (AP) and high pressure (HP) leads to an improvement in the critical current density J_c and the upper critical field $H_{c2}(T)$ with a slight depression in the superconducting transition temperature. The anomalous temperature dependence of $H_{c2}(T)$ with a positive curvature implies the existence of two gaps in both samples. At elevated fields, the fact of the current density decays as $J_c(H) \propto H^{-\beta}$ in HP samples suggests a possible route to overcome $J_c(H)$ decreasing rapidly with increasing fields.

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Keywords: Two-gap superconductivity; Critical current density; Carbon nanotubes doping

1. Introduction

A crucial challenge for the potential application of magnesium diboride is to increase its small upper critical magnetic fields H_{c2} and critical current densities J_c [1,2]. By analogy with the study in high-T_c cuprates, the chemical substitution could introduce the non-magnetic impurities. The existence of these impurities results in the enhancement of pinning effect and quasiparticle scattering, thus the physical properties such as J_c and H_{c2} can be improved. But in the case of MgB_2, chemical substitution appears to be a difficult task [3]. Carbon substitution of boron is one of few successful examples [4–8], and a lot of materials acted as the

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carbon precursors, such as amorphous carbon, diamond, B_4C and carbon nanotubes (CNT) etc. Among various precursors, CNT are particularly interesting with their high aspect ratio and nanometer size in diameter. Earlier than ten years ago, there was a report on the effect of embedding CNT in $Bi_2Sr_2CaCu_2O_{8+x}$, which resulted in an enhancement of flux pinning in Bi2212 [9], and the CNT acted as strong columnar-defect-like pinning centers similar to the same kind defects introduced by heavy ion irradiation. As for MgB_2, Dou et al. showed that carbon substitution for boron by CNT doping enhanced the critical current density J_c whereas depressed the critical temperature T_c [8]. However, their samples were synthesized under ambient pressure and low temperature condition (AP). Synthesizing MgB_2 under a higher temperature and high pressure condition (HP) is another important method, we are not aware of any reports on doping CNT of MgB_2 under HP. In this paper, CNT doping of magnesium diboride with a nominal stoichiometry of $MgB_{1.9}C_{0.1}$ synthesized at HP condition is first reported here. Comparing to the samples synthesized under AP condition, some intriguing characteristics are also first reported. Similar to other carbon doping MgB_2, the decrease on the lattice parameter a of both samples indicates the carbon substitution of boron, and the fact that only little MgO phase can be observed by XRD indicates the HP sample with better developed MgB_2 phase. With a slight decrease of superconducting transition temperature, both $H_{c2}(0)$ and J_c are improved in AP and HP samples, and the anomalous temperature dependence $H_{c2}(T)$ of a positive curvature indicates that two-gap behaviour retains in these samples. Based on the Bean model, the magnetic measurements demonstrate the dependent relation of J_c versus applied field H. At any precise temperatures, when the applied field is lower than a magnitude H_{sb}, the $J_c(H)$ of both AP and HP samples show a common plateau, and then $J_c(H) \propto H^{-\beta}$ is only observed in HP sample, while in AP sample, $J_c(H)$ follows an exponential decay. Here, H_{sb} is a characteristic field denoting the single vortex pinning mechanism is predominant, correspondingly, the critical current densities under H_{sb} are written as J_{sv}. Extrapolating these plateaus to the zero applied field to get $J_{sv}(0\ T)$ at different temperatures, $J_{sv}(0\ T)$ in HP sample follows an approximate linear decay with the increasing temperatures, while for AP sample, $J_{sv}(0\ T)$ against temperature diverges from the linear relation. It is worth pointing that the decay speed of power law is slower than that of exponential law, which suggests a possible method of retarding the current density decay with increasing fields for practical applications.

2. Experimental

High purity powders of magnesium, amorphous boron and purified carbon nanotubes (diameter 10–20 nm) were weighed out according to the nominal atomic ratio of $MgB_{1.9}C_{0.1}$ for HP process, while magnesium must be slight excessive for ambient pressure treatment, and well-mixed through grinding. Then the grind powders were pressed into pellets of 11 mm in diameter and 3 mm in thickness using a hydraulic press. Polycrystalline HP samples were fabricated at 1700 °C for 0.5 h under the pressure $P = 5$ GPa, and the AP samples were sintered at 900 °C for 120 min among the ambience of high purity Ar, both samples were followed a slow furnace cooling to room temperature. The undoped sample (pure) fabricated through HP process was used as a reference sample. The mass density of AP sample is about 1.8 g/cm^3, while for the HP sample, the mass density is about 2.3 g/cm^3. Fig. 1 shows the comparisons at different peaks of X-ray diffraction (XRD) analysis. Fig. 1(a) for peak (1 0 0), which denotes the lattice parameter a of AP sample decreases from 3.087 Å to 3.074 Å, while HP sample does from 3.087 Å to 3.067 Å; Fig. 1(b) for peak (0 0 2), the parameter c of these samples are almost same (3.522 Å); Fig. 1(c) for peak (1 0 1), both pure and AP samples demonstrates a shoulder beside the peak (1 0 1), and the existence of these shoulders results from the MgO phase [5,10]. But for the HP sample, its peak (1 0 1) displays a symmetric shape, which indicates the MgB_2 phase is well developed. The magnetization measurements were carried out over a temperature range of 4.2–30 K by VSM (Oxford) in a time-varying magnetic field with a sweep rate 25 Gs/s and amplitude 8 T. The