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Review

Superconducting and normal state properties of carbon doped and neutron irradiated MgB_2

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Abstract

Current research in MgB_2 focuses on the effects various types of perturbations have on the superconducting properties of this novel two-gap superconductor. In this article we summarize the effects of carbon doping and neutron irradiation in bulk MgB_2. Low levels of carbon doping and light neutron irradiation result in significant enhancements in H_{c2}. At high fluences, where superconductivity is nearly fully suppressed, superconductivity can be restored through post exposure annealing. However, this results in a change in the interdependencies of the normal state and superconducting properties (ρ_0, T_c, H_{c2}), with little or no enhancement in H_{c2}.

Keywords: MgB_2; Carbon doping; Neutron irradiation

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1. Introduction

The discovery of superconductivity near 40 K in the relatively simple binary compound MgB_2 [1] garnered a tremendous amount of excitement. This remarkably high T_c nearly doubled the record for traditional phonon mediated BCS superconductors [2]. But MgB_2 is no mere "traditional" superconductor. The existence of two superconducting gaps [3] opens exciting possibilities for studying the interactions between two weakly coupled bands and, from an applied point of view, tuning the superconducting properties for the development of practical devices. MgB_2 has however, proved somewhat difficult to modify. MgB_2 is apparently a line compound, with the highest possible level of Mg vacancies less than 1% [4], and the structure is resistant to most forms of doping. The most successful and widely studied substitutions are Al for Mg and C for B [5].

An alternative route to systematically introduce defects is through irradiation using protons, heavy ions, neutrons, etc. Of these possible routes, neutron irradiation offers the best avenue for uniformly damaging bulk MgB_2. There are two main sources of damage from neutron irradiation of MgB_2. First, fast neutrons deposit energy through inelastic collisions with atoms, creating thermal and dislocation spikes [6]. Second, ^{10}B has a large capture cross section for lower energy neutrons and readily absorbs these thermal neutrons, subsequently α decaying to ^{7}Li. By isotropically irradiating samples whose dimensions are less than the thermal neutron penetration depth, one can ensure uniform damage throughout the sample.

In this article we summarize the effects of carbon doping and neutron irradiation in bulk MgB_2 filaments.

2. Experimental methods

Fully dense wires of superconducting MgB_2 can be synthesized by exposing commercially available boron filaments to magnesium vapor [7,8]. Specialty Materials, Inc. uses chemical vapor deposition (CVD) to deposit solid boron onto tungsten substrates, producing fibers on kilometer length scales [9]. The process can be modified to produce carbon doped boron by simply adding methane into the BCl_3 gas stream. A typical reaction involves flowing 3000 ccpm of BCl_3 over a tungsten filament that is resistively heated to 1100–1300 °C. The samples reported here were doped with carbon by adding methane flow rates up to 100 ccpm. The filaments are converted to MgB_2 by exposure to Mg vapor at elevated temperatures. Details on the synthesis of carbon doped samples can be found in Ref. [10].

For the irradiation studies we placed three fibers, each approximately 1–2 cm in length, under a partial helium atmosphere in quartz ampoules. A water flooded aluminum can containing 25 ampoules was then exposed to an isotropic flux of reactor neutrons, consisting of 98% thermal neutrons ($E = 25$ meV) and 2% epithermal neutrons (ranging in energy up to 10 keV), at the Missouri University Research Reactor (MURR) for time periods of 24 h. For more details see Ref. [11]. The exposure corresponds to a fluence of 4.75×10^{18} cm^{-2}. Post exposure anneals were performed with the samples still sealed within the quartz ampoules for temperatures up to 500 °C in a Lindberg model 55035 Mini-Mite tube furnace. In each case, we annealed an ampoule at a given temperature for a set period of time. Upon removal from the furnace, the ampoules were quenched in air and then opened in order to perform measurements on the individual wires.

Powder X-ray diffraction (XRD) measurements were made at room temperature using Cu Kα radiation in a Rigaku Miniflex Diffractometer. A silicon standard was used to calibrate each pattern. Lattice parameters were determined from the position of the (0 0 2) and (1 1 0) peaks. DC magnetization measurements were done in a Quantum Design MPMS-5 SQUID magnetometer on sets of 8–10 wires each approximately 5 mm in length oriented parallel to the applied field. Transport measurements were done using a four probe technique, with platinum wires attached to the samples with Epotek H20E silver epoxy. Typical samples were 6–8 mm in length with 4–6 mm between voltage leads. Resistivity versus temperature in applied fields up to 14 T were carried out in a Quantum Design PPMS-14 system and resistivity versus field was measured up to 32.5 T using a lock-in amplifier technique at the National High Magnetic Field Laboratory in Tallahassee, FL.

3. $Mg(B_{1-x}C_x)_2$

3.1. Structural properties

In order to estimate the carbon content in the carbon doped MgB_2 filaments, X-ray powder diffraction measurements were made to determine the lattice parameters. Carbon has been shown to contract the *a*-lattice parameter while only slightly expanding the *c*-lattice parameter [12,13]. Avdeev et al. [12] showed a contraction of $|\Delta a| = 0.032$ Å for $x = 0.10 \pm .02$ in $Mg(B_{1-x}C_x)_2$. The (0 0 2) and (1 1 0) X-ray peaks for the entire series are given in Fig. 1. Assuming a linear contraction of the *a*-lattice parameter as a function of carbon content, the level of carbon incorporation can be estimated by comparing the relative positions of the (1 1 0) peaks [13]. Determining Δa relative to a pure sample given the same heat treatment, we estimate the level of carbon in these samples to be $x = 0.004$, 0.021, 0.038, and 0.052.

3.2. Thermodynamic and transport properties

Normalized magnetization and zero field resistance curves for the carbon doped wires are given in Fig. 2. Transition temperatures were defined using a 2% screening from magnetization curves and an onset criteria from resistive measurements. T_c decreased from above 39 K in the case of the pure sample to near 35 K for the sample containing