Magnetoresistivity and $H_{c2}(T)$ in MgB$_2$

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Detailed magnetotransport data on dense wires of MgB$_2$ are reported for applied magnetic fields up to 18 T. The temperature and field dependencies of the electrical resistivity are consistent with MgB$_2$ behaving like a simple metal and following a generalized form of Kohler's rule. In addition, given the generally higher-T_c values and narrower resistive transition widths associated with MgB$_2$ synthesized in this manner, combined with applied magnetic fields of up to 18 T, an accurate and complete $H_{c2}(T)$ curve could be determined. This curve agrees well with curves determined from lower field measurements on sintered pellets and wires of MgB$_2$. $H_{c2}(T)$ is linear in T over a wide range of temperature (7 K$\leq T \leq$32 K) and has an upward curvature for T close to T_c. These features are similar to other high κ, clean limit, boron-bearing intermetallics: YNi$_2$B$_2$C and LuNi$_2$B$_2$C.

I. INTRODUCTION

The recent discovery[1] of superconductivity in MgB$_2$ has lead to a flurry of activity. Measurements of the boron isotope effect[2] show that there is a shift in T_c from 39.2 to 40.2 K (for Mg^{11}B$_2$ and Mg^{10}B$_2$, respectively), a result consistent with electron phonon mediated BCS superconductivity. Measurements[2–7] of the upper critical field, $H_{c2}(T)$, and the thermodynamic critical field, $H_c(T)$, as well as the specific heat are all consistent with MgB$_2$ being a fairly typical intermetallic superconductor with an atypically high transition temperature. Although single crystal samples are not yet available, it has recently been found that dense, very high quality, wire samples of MgB$_2$ can be made.[4] These samples have a superconducting transition temperature above that found for Mg^{11}B$_2$, as would be expected based on the natural abundance of ^{10}B. These samples allow for the direct measurement of electrical resistivity and, given that the width of the superconducting transition is narrower in MgB$_2$ wire than in powder or sintered pellet samples, wire samples allow for an accurate determination of the upper critical field $H_{c2}(T)$. In this communication we present data on the magnetotransport of MgB$_2$ wires for applied magnetic fields of up to 18 T and over the temperature range 1.5–300 K. By a careful analysis of the resistivity data we are able to conclude that MgB$_2$ behaves like a simple metal in the normal state with all of our magnetoresistance data collapsing onto a single curve in accordance to Kohler's rule. In addition we are able to construct the full $H_{c2}(T)$ curve. We find that $H_{c2}(T)$ is linear over a much larger temperature range than would be expected,[8] leading to a $H_{c2}(0) \approx 16.4$ T.

II. EXPERIMENTAL METHODS

MgB$_2$ wire was produced[4] by sealing 100 μm diameter boron fiber and Mg into a Ta tube with a nominal ratio of Mg$_2$B. Given that MgB$_2$ is the most Mg rich binary Mg-B compound known, it was felt that excess Mg would aid in the formation of the proper, stoichiometric phase. The sealed Ta tube was itself sealed in quartz and then placed into a 950 °C box furnace for 2 h. The reaction ampoule was then removed from the furnace and quenched to room temperature. Whereas the boron fiber has a diameter of 100 μm, the MgB$_2$ wire has a diameter of approximately 160 μm. Although the MgB$_2$ wires are somewhat brittle, the integrity of the filament segments is preserved during the exposure to the Mg vapor; i.e., the fibers did not decompose, fragment, or turn into powder. The resulting wire has over 80% the theoretical density of MgB$_2$ and measurements of the temperature-dependent resistivity reveal that MgB$_2$ is highly conducting in the normal state. The room temperature resistivity has a value of 9.6 μOhm-cm; whereas the resistivity at $T = 40$ K is 0.38 μOhm-cm. The zero-field T_c value for the wire sample is higher than that found for Mg^{11}B$_2$, a result consistent with the natural abundance of ^{10}B. It should be noted that both the wire and sintered pellet samples synthesized in this manner tend to have very high and sharp superconducting transitions.

Magnetoresistivity measurements utilizing a 20 T, superconducting magnet were performed at the National High Magnetic Field Laboratory (NHMFL), Pulsed Facility. A standard four-probe ac method was used, utilizing Epotek H20E silver epoxy for making electrical contacts. The contact resistance was approximately 1 Ohm. Given the well-defined geometry of the samples, accurate measurements of resistivity were possible. The ac current was applied along the wire and the magnetic field was applied perpendicular to the current direction. The sample was mounted in a flow cryostat able to regulate the temperature from 1.4 K to room temperature.

III. DATA AND ANALYSIS

Figure 1 presents temperature-dependent electrical resistivity data for a MgB$_2$ wire sample taken at a variety of applied fields for $H \leq 18$ T. Two features are clearly seen:
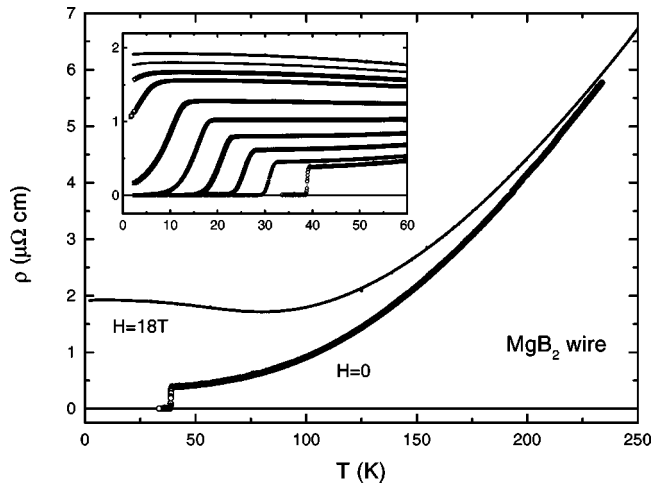
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FIG. 1. Temperature-dependent resistivity of the MgB$_2$ wire in zero and 18 T applied fields. Inset: low-temperature $\rho(T)$ data in applied fields of (from bottom right to top left) 0, 2.5, 5, 7.5, 10, 12.5, 15, 16, 17, and 18 T.

there is a suppression of the superconducting phase to lower temperatures for increasing applied field, and there is a clear, large magnetoresistivity in the normal state. Looking first at the suppression of superconductivity, the inset to Fig. 1 presents an enlarged view of the low-temperature resistivity data. Using these data, three temperatures can be extracted from each curve: onset temperature, temperature of maximum $d\rho/dT$, and completion temperature, where onset and completion temperatures are determined by extending the maximum $d\rho/dT$ line up to the normal state and down to zero resistivity.

Figure 2 presents the $H_{c2}(T)$ curve that we deduce from these data. In addition to the high-field data taken at the NHMFL (shown as open symbols), data taken in a Quantum Design Physical Property Measurement System (PPMS) at
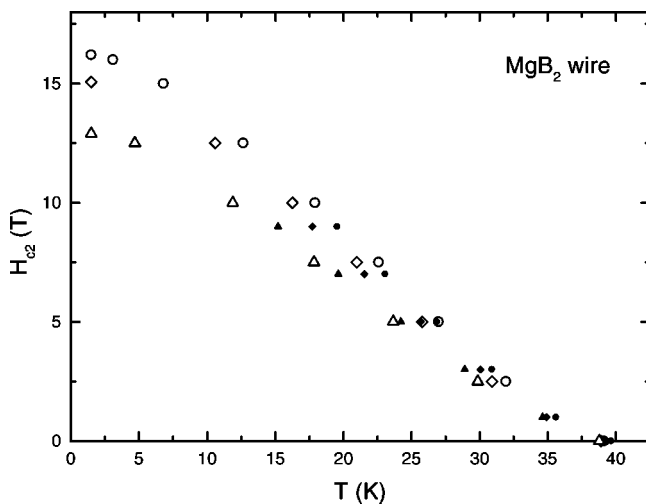

FIG. 2. Upper critical field of MgB$_2$ wires. Different symbols represent different criteria (onset, maximum of $d\rho/dT$ and completion) as described in text. Data at 1.5 K are from $\rho(H)$ measurements (not shown). Open symbols—this work (Fig. 1), filled symbols—from Ref. 4.
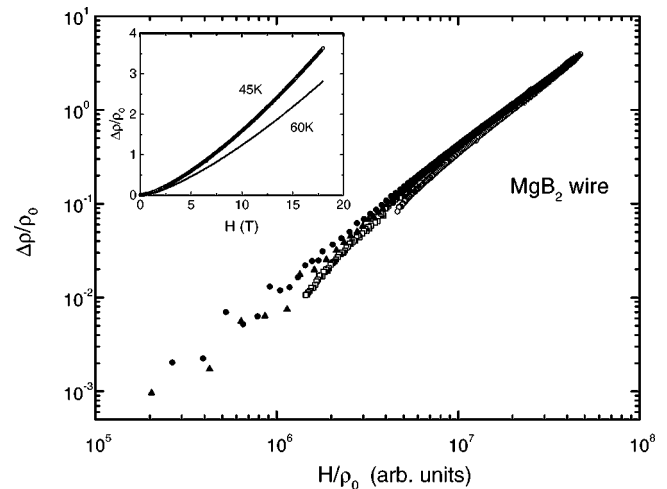

FIG. 3. Kohler's plot for MgB$_2$ wires: open symbols from temperature-dependent resistivity; filled symbols from field-dependent resistivity at 45 and 60 K. Inset $\Delta\rho(H)/\rho_0$ at 45 and 60 K.

lower fields on a sample from the same batch are also shown (filled symbols). Several features of this curve are worth noting. First of all it has a large temperature/field range over which it is linear ($7 \ K \leqslant T \leqslant 32$ K). Below approximately 7 K $H_{c2}(T)$ starts to roll over and saturate. This leads to a low-temperature value of $H_{c2}(1.5 \ K) = 16.2$ T, which is significantly larger than estimates[3] based on the assumption[8] that the low temperature $H_{c2}(0) = 0.71T_c[dH_{c2}(T)/dT] = 12.5$ T. Secondly, at high temperatures ($T \geqslant 32$ K) there is a distinct positive, upward curvature associated with the $H_{c2}(T)$ curve. This is not unique to the current form of our sample but was also seen in resistively determined $H_{c2}(T)$ for sintered pellets of Mg^{10}B$_2$.[3] Taken as a whole, the temperature dependence of H_{c2} for MgB$_2$ is remarkably similar to that recently found for other nonmagnetic, intermetallic, boride superconductors: LuNi$_2$B$_2$C and YNi$_2$B$_2$C.[9–11] In these cases $H_{c2}(T)$ is linear over an extended region of T and near T_c there is a distinct upward curvature. In both the case of MgB$_2$ as well as in the case of Y/LuNi$_2$B$_2$C the material is a high κ, type-II superconductor and in both cases the as grown compounds are well within the clean limit.[3,4,9–11]

Turning to the normal-state magnetoresistivity, Fig. 3 shows $\Delta\rho/\rho_0$ vs H/ρ_0 on a log−log plot to demonstrate that all of the data presented in Fig. 1, as well as the two isothermal $\rho(H)$ plots shown in the inset of Fig. 3, are broadly consistent with the generalized form of Kohler's rule. The fact that all of these data fall (roughly) onto a single curve implies that there is a single salient scattering time in the normal-state transport of MgB$_2$.[12] This is what would be anticipated for a simple nonmagnetic intermetallic sample. It is worth noting that such a clear magnetoresistance would be much harder to detect in samples with enhanced impurity or defect scattering.[13]

The isothermal $\Delta\rho(H)/\rho_0$ data shown in the inset of Fig. 3 can be fit to $\Delta\rho(H)/\rho_0 \propto H^\alpha$ with $\alpha = 1.4$–1.5. In addition, the temperature-dependent normal-state resistance of sintered Mg^{10}B$_2$ pellets as well as the resistivity of wire

samples in zero field can be fit to a power law between $T^{2.6}$ and T^3 at low temperatures ($T \lesssim 200$ K).[3,4]

Finally, there is a slight upturn observed in the low-temperature $\rho(T)$ data taken in high applied magnetic fields (Fig. 1). Although the origin of this feature is not completely understood, similar features have been observed for other high purity, nonmagnetic intermetallic compounds.[14,15]

IV. CONCLUSIONS

In this communication we present detailed magetoresistivity data on dense (over 80%), high quality samples of MgB$_2$. In the normal state we find that MgB$_2$ has a temperature- and field-dependent resistivity that is consistent with MgB$_2$ being a highly conducting intermetallic compound that can be synthesized so as to achieve very low residual resistivities. This allows the large values of $\Delta\rho/\rho_0$ to reveal themselves. The fact that the magnetoresistivity data follow Kohler's rule is consistent with MgB$_2$ behaving like a simple metal with one dominant scattering time.[12]

In the superconducting state we find that MgB$_2$ has a relatively linear $H_{c2}(T)$ curve with slight deviations from linearity at both high and low temperatures. This leads to a relatively high value of $H_{c2}(0) = 16.4$ T. The linear behavior of $H_{c2}(T)$ as well as the upward curvature in $H_{c2}(T)$ for T near T_c is similar to behavior seen in other boron bearing intermetallic compounds (YNi$_2$B$_2$C and LuNi$_2$B$_2$C) that have large κ values and are within the clean limit. This similarity brings up the obvious question of whether such temperature dependencies of $H_{c2}(T)$ are a generic feature associate with this subclass of intermetallic superconductors.

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