Electronic transport in a 3-D network of 1-D Bi and Te-doped Bi quantum wires

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Abstract

The resistance (R) and transverse magnetoresistance (TMR) of a high density network of 6 nm diameter wires of Bi and Bi doped with 0.138 % Te in porous Vycor glass were measured. For pure Bi R increases as T decreases from 300 K to 0.3 K. Below 4 K, where R varies approximately as ln(1/T), the order-of-magnitude of the resistance rise and the behavior of the MR are consistent with localization and electron-electron interaction theories of a one-dimensional disordered conductor in the presence of strong spin-orbit scattering. Addition of Te, an electron donor, reduces the amount by which the resistivity increases with decreasing temperature, and the magnitude of the magnetoresistance is substantially enhanced.

Key words: localization; nanowires; Bi;

1. Introduction

The semimetal bismuth has been extensively studied for quantum confinement effects due to the very small effective masses and long mean-free-paths of the charge carriers. In addition to thin films and single wires[1], recent studies have also looked at the transport properties of large scale networks[2] and arrays of nanowires[3][4]. Because they combine reduced dimensionality with bulk fabrication technology, the latter materials have additional interest due to their possible application as efficient thermoelectric materials. Recently it was shown[2] that a high density three-dimensional network of 6nm diameter Bi wires in a host template of porous Vycor glass (Bi-PVG) exhibits low dimensional electronic transport behavior. Resistance is a monotonically increasing with decreasing temperature, and a sharp upturn at low temperatures is consistent with combined electron interaction in a disordered conductor and weak localization effects. Because localization is strongly affected by magnetic fields, magnetoresistance is a useful measurement to distinguish these two competing effects. The small (2 % at 3T) positive magnetoresistance (MR) observed for Bi-PVG provided evidence that in fact we observe antilocalization, as expected in the presence of strong spin-orbit coupling. The MR data yielded phase-breaking (l_ϕ) and spin-orbit scattering (l_{so}) lengths of 80 nm and 30 nm, respectively.

2. Results

In this work we present new data for the temperature dependent resistivity and transverse magnetoresistance of Bi, doped with 0.14 at. % Te, into porous Vycor glass (BiTe-PVG). Te is an electron donor, so we expect the effects to be two-fold, modifying both the carrier density and the scattering. The sample was made via the same pressure-injection of molten material into the Vycor host as described in our earlier work[2]. The room temperature resistivity of the BiTe-PVG composite (50 mΩ-cm) is comparable to that for

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Bi-PVG (20 mΩ-cm), but the fairly large geometric uncertainties make a precise quantitative comparison impossible. BiTe-PVG and Bi-PVG have a monotonically increasing resistance with decreasing temperature, and exhibit a sharp upturn below 5 K. The upturn is ascribed to a competition between antilocalization (positive dρ/dT) and interaction effects (negative dρ/dT). In Fig. 1, the low-temperature (0.3 K $\leq$ T $\leq$ 10 K) fractional change of the temperature-dependent resistivity (relative to the resistivity at 10 K) is plotted versus the natural logarithm of temperature. The relative upturn is much weaker for the BiTe-PVG than for Bi-PVG, and does not vary logarithmically with T. The weaker upturn indicates that antilocalization effects play a larger role than interaction effects for the Te-doped sample as compared to the pure Bi sample. Since dρ/dT remains negative, interaction effects are still dominant for BiTe-PVG.

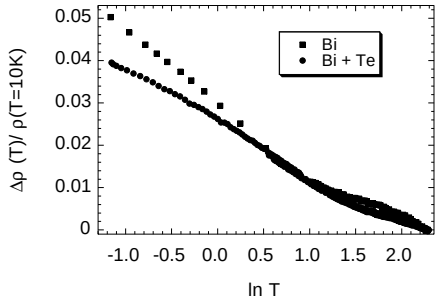

Fig. 1. The fractional change in resistivity, relative to the resistivity at 10 K versus temperature for Bi (squares) and Bi doped with 0.14 at. % Te (circles).

In Fig. 2 we show the fractional change in resistance relative to the zero-field resistance (transverse magnetoresistance, or TMR), at 1.8 K for the BiTe-PVG composite. Note that while the macroscopic current flows perpendicular to the applied field, the wires in the network have random orientation. The data are well-described by the standard expression for low dimensional systems with strong spin-orbit coupling[5], and by fitting the TMR for the BiTe-PVG composite we extract values for l_ϕ and l_{so} of 61 nm and 23 nm, respectively. These are comparable to the values for Bi-PVG (80 nm and 30 nm). However, we see that the magnitude of the BiTe-PVG TMR is more than a factor of 6 larger than for Bi-PVG. TMR measurements taken at 0.5 K yield a slightly larger l_ϕ of 64 nm, and the magnitude of the TMR at 3 Tesla is increased from 12 % to 14 %.

The large positive TMR for BiTe-PVG supports our conjecture from the previous paragraph: Te-doping enhances the role of antilocalization relative to Coulomb interaction effects. Since electron-electron scattering is believed to be the dominant inelastic process at low temperatures, it is tempting to ascribe the change to

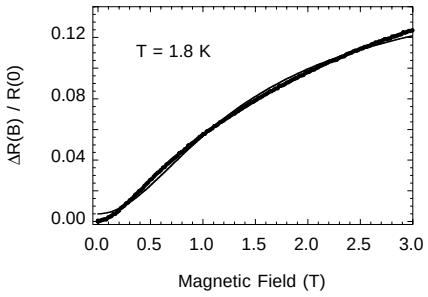

Fig. 2. The fractional change in resistivity, relative to zero magnetic field, versus magnetic field Bi doped with 0.14 at. % Te at 1.8 K. The solid line is a fit to the theoretical expression for quasi-1D wires with strong spin-orbit coupling[5]

a change in carrier concentration. One should be cautious in interpreting the data, however. In recent studies of Bi and Bi - 0.1 at. % Te nanowire arrays[4], it was shown that while unannealed Bi-Te arrays exhibited low-temperature metallic behavior, with positive dρ/dT, annealing restored a negative dρ/dT. This was speculated to result from removal of Te from the Bi during annealing. While our samples are not annealed, this effect may be present in our samples to a certain degree if our cooling rates are considerably slower than those for the samples studied in Ref. 4. Also, because the TMR down to 2 K of the nanowire arrays studied in Ref. 3 was independent of temperature, it was interpreted as being determined by classical effects. Our TMR data at 0.5 K and 1.8 K show only a modest difference, and so may contain both quantum and classical contributions. Nonetheless, the large differences in the magnitude of the TMR and low-temperature, temperature-dependent resistivity for our samples lead us to believe that Te is actually in the Bi nanowire network, and the systematic changes are consistent with quantum effects.

Acknowledgements

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