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

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Abstract

We study the longitudinal magnetoresistance of 270-nm diameter bismuth nanowire arrays embedded in an alumina matrix which are capped with layers of pure Bi that have low contact resistance. At intermediate fields the LMR presents a broad maximum that is discussed discussed in terms of the interplay between the carrier's cyclotron radius and scattering at the wire walls and the onset of Shubnikov-de Haas oscillations.

Key words: nanowires; Bi;

1. Introduction

Bi is a semimetal that has been extensively employed to explore quantum transport and finite-size effects [?]. It owes its unusual transport properties to its highly anisotropic Fermi surface, low carrier densities, small carrier effective masses, and long carrier mean free path. There is growing interest in Bi nanowires [?],[?]. Arrays of these nanowires are fabricated by a non-lithographic approach, using high pressure injection of molten Bi into insulating nanostructured template or electrochemical growth. Measurements of the longitudinal and transverse magnetoresistance of these nanowires with diameters ranging 30 to 200 nm have been presented that are interpreted in terms of quantum size effects, such as the semimetal-semiconductor transition. The interpretation of the longitudinal magnetoresistance (LMR), that is with a magnetic field along the wire axis in these works, is qualitative. It is observed in most Bi samples that the nanowires longitudinal magnetoresistance conductivity decrease as the magnetic field is increased when the field exceeds a critical field B_c. The critical field is, roughly, the field that makes the cyclotron radius $r_c = h\, k_F/2\pi eB$ of the wire smaller than the wire radius. Here h is Plack constant, k_F is the Fermi wavevector for the appropriate carrier, heavy or light electrons or holes, and e is the electron charge. This property was first observed for fine wires of sodium [?], and was explained using Chambers's kinetic theory of electronic transport in fine wires. According to Chambers, at low fields such that r_c¿d/2, carriers scattering at the wire walls dominate and the resistance is high. As the field increases beyond the value for which r_c¿d/2, scattering by the walls becomes inefective, and the resistance decreases because the mobility increases. The magnetoresistance due to Chambers's mechanism is negative. However, if the nanowire has an intrinsic positive longitudinal magnetoresistance, the resulting LMR would show a mixed behaviour with a maximum occuring, very roughly, for a magnetic field Hc where r_c=d/2. Here, we present results for samples where the crystalline structure is predominantly oriented with the trigonal axis along the wire-length. This particular crystalline orientation is very interesting because the intrinsic longitudinal magnetoresistance (LMR) is much lower than in other samples of comparable diameters that have been studied. Also, the LMR of bulk Bi is very low for this crystalline orientation [?] and therefore the experimental conditions are optimal for the study the Chamber's effect.

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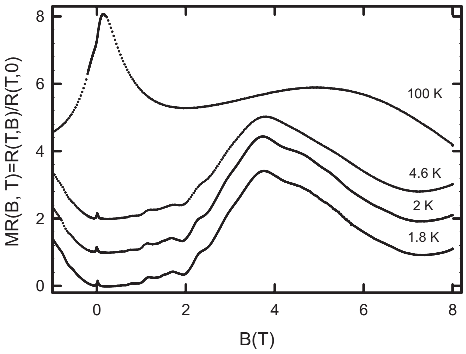

Fig. 1. Longitudinal magnetoresistance of the 200 nm Bi wire array as a function of magnetic field at various temperatures as indicated in the figure. The B=0 array resistance at 1.8 K is 150 micro-ohms. The curves have been displaced arbitrarily for clarity.

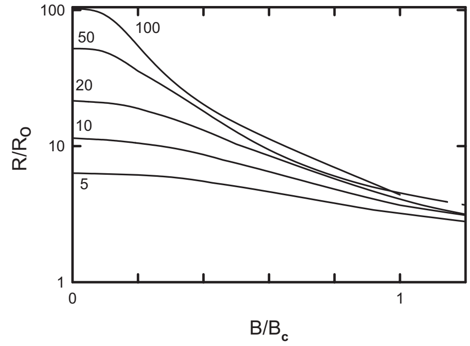

Fig. 2. Chambers's theory results for the longitudinal magnetoresistance of a wire of diameter d as a function of the ratio of the diameter to the cyclotron radius r_c. Full lines: R/R0 for various ratios of mean free path to diameter (100, 50, 20, 10, and 5), as indicated. $B/B_c= d/(2 r_c)$.

2. Results

The nanowires diameter is 270 nm and 50 micrometers long. Our nanowires are capped with a layer of Bi because the number of wires contacted is maximized and the contact resistance to the individual nanowires is minimized if the Bi nanowires are terminated in bulk Bi. Current is injected between two silver epoxy electrodes positioned on opposite sides of the wire array, and we measured the voltage between the other pair of electrodes. Fig. 1 shows the longitudinal magnetoresistance (LMR) at various temperatures. Our 100 K data display a broad maxima at 5 T. At low temperatures, we find a broad maximum at $H_c = 4$ T that is usually interpreted in terms of Chambers's effect. The oscillation of the intensity at high magnetic field including the minimum at 7.5 T is due to Shubnikov-de Haas resonances. The peak at B=0 is a contact effect. A maximum was also observed by Heremans et al [**?**] in 200 nm diameter wire arrays at 3 T at 70 K, the maximum temperature in that study, shifting to lower fields, 2 T at 20 K, and gradually dissapearing at lower temperatures. Fig. 2 shows the results of Chambers's calculations, which are based on kinetic theory assuming random scattering at the walls that display the characteristics described in the Introduction.

Our nanowire crystalline orientation is with the trigonal axis along the wire length. The mass tensor of the electrons M_e and the mass tensor of the holes M_h that contribute to the transport are well known from studies the Shubnikow-de Haas oscillations of the magnetoresistance of bulk. Bi. The cyclotron masses at the Fermi level are found to be around $m_c e = 0.04$ m_e for electrons and $m_c h = 0.3$ m_e for holes. As shown in Fig. 2 the magnitude of Chambers's effect is proportional to the mean free path of the carrier involved. Therefore, in our case, the electron peak would show more prominently. The kinetic energy of electrons K_F is E_F (1+ E_F/E_G) or 83.6 meV. The Fermi wavevector for Chambers's expression, which is $2\pi(2\, m_c\, K_F)^1/2/h$, is found to be $4.21x10^8$/m. For our average diameter d of 270 nm we estimate that Chambers's peaks should appear at B=2.0 T for electrons, in less than fair agreement with the peak location Fig. 1. The shift and broadening of the peak at high temperatures is likely caused by the decrease of the intrinsic LMR at higher temperatures. It has been remarked that systematic discrepancies between the position of the LMR peak and theoretical estimates of Bc have been found [**?**]. Furthermore, it is unclear how to apply Chambers's theoretical results to materials such as Bi that have an intrinsic LMR because the magnetic field dependent resistance R_o increases with magnetic field as B^1.6. The magnetic field dependence of R/R_o shown in Fig 2 is not strong enough to offset the increase with magnetic field of R_0 except at $B = 0.2$ B_c making the discrepancy between calculated and observed maximum more pronounced. We believe that this is not surprising because Chambers's results are obtained assuming that carriers are diffusively reflected at the wire walls, whereas it is well known that the scattering is almost all specular [**?**] for Bi due to the long Fermi wavelength of the charge carriers, in particular for grazing incidence. We believe that this well known mechanism allows electrons to move without scattering even for r_c¿d/2. However, we are not aware on a quantitative theoretical treatment of the LMR of wires that takes into account the specular scattering of carriers. The interpretation of the peak as the onset of Shubnikov-de Haas oscillations is discussed by Brandt et al [**?**].

Acknowledgements

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