Longitudinal magnetothermopower and magnetoresistance of pure bismuth nanowires

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Interest in the physical properties of bismuth nanowires has grown considerably in recent years, mainly due to their technological promise as very efficient thermoelectric elements in solid-state cooling devices. Theoretical calculations predict that Bi nanowires should have an enlarged thermoelectric figure-of-merit, which comes as a result of the enhancement in the thermopower (TEP), S, due to an increase of the electronic density of states. Up to date, however, there is no reliable experimental evidence showing an improved thermoelectric efficiency in low-dimensional Bi strucures.

We have measured the thermopower (TEP), S, and electrical resistivity, r, of single bismuth nanowires with diameters $d = 100-200$ nm in longitudinal magnetic fields up to $B = 20$ T at low temperatures. Our wires were fabricated by glass-coated melt spinning method. For these nanowires, the frequencies and phases of the observed Shubnikov-de Haas (SdH) oscillations are in good agreement with the accepted values for bulk bismuth crystals. Nonetheless, as compared with quantum oscillations in the longitudinal magnetoresistance of good-quality bulk crystals, the SdH peaks are much broader with small relative amplitude at any field. The significantly broadened Landau levels result from the small-scale sample inhomogeneities created by relaxation of stresses. These stresses are generated by the expansion of bismuth (3.32%) upon crystallization as well as by the differences in thermoelastic properties of materials used in the fabrication of Bi/Pyrex composites. The existing nanowires with $d \geq 100$ nm are too defective and/or thick to allow for a direct observation of the quantum-size effects, which were predicted to decrease the frequencies of magnetic quantum oscillations.

We found that the pure Bi nanowires with residual resistivity ratios ρ(0,300K)/ρ(0,4.2K)= $2-4$ exhibit very large values of zero-field thermopower at $4.2 < T < 26$K, which is dominated by diffusion ($S \propto T$) with no phonon drag being evident. The TEP stays positive over the whole temperature and magnetic field ranges investigated. The positive sign of the diffusion TEP suggests that hole carriers dominate the conduction mechanism in pure Bi nanowires at low T. Our analysis indicates that the anomalous thermopower is a consequence of the complex microstructure rather than the result of the strong scattering of electrons by the wire boundaries. Using the measured values of $S \approx +100\mu$V/K and $\rho \approx 100$ $\mu\Omega\cdot$cm, we obtained the large values of the thermoelectric power factor $S^2/\rho \sim 100\mu$W/cm·K^2 at $T \approx 25$K.

We have shown that the curves of longitudinal magnetoresistance have a maximum for a field of $B_m \approx cp_F/e(ld)^{1/2}$ and an inflection point at $B_d \approx 2cp_F/ed$, which allow to extract information on the Fermi momentum p_F and mean free path l of the charge carrier group, which undergoes the most intensive diffusive surface scattering in a wire with $d \ll l$. The values of p_F and $l \sim 1$ μm for our pure Bi nanowires apply to hole carriers. In distinction from the resistance data, the curves of the longitudinal magnetothermopower offer the possibility of identifying the characteristic field, where the diameter of hole Larmor orbit equals d, as an extremum.

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