UC Davis
UC Davis Previously Published Works

Title

Giant positive magnetoresistance of Bi nanowire arrays in high magnetic fields

Permalink

https://escholarship.org/uc/item/0f92n04k

Journal

Journal of Applied Physics, 85(8)

ISSN

Authors

Hong, Kimin
Yang, FY
Liu, Kai
et al.

Publication Date

1999-04-15

DOI

Peer reviewed

Giant positive magnetoresistance of Bi nanowire arrays in high magnetic fields

Kimin Hong,[a] F. Y. Yang, Kai Liu, D. H. Reich, P. C. Searson, and C. L. Chien
The Johns Hopkins University, Baltimore, Maryland 21218

F. F. Balakirev and G. S. Boebinger
Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 07974
and Los Alamos National Laboratory, MS E534, Los Alamos, New Mexico 87545

We have studied the magnetoresistance of electrodeposited Bi wires with diameters between 200 nm and 2 μm in magnetic fields up to $B = 55$ T. In zero field, the resistance increases with decreasing temperature, indicating that the mean free path is strongly influenced by the nanowire geometry. The high-field magnetoresistance shows strong dependence on field orientation; typically 200% for B parallel to the wires, and 600%–800% for B perpendicular to the wires. The perpendicular magnetoresistance is well described by a modified two-current model which suggests that the high-field response of the arrays is fairly insensitive to the wire diameter, and is dominated by bulk properties of Bi. © *1999 American Institute of Physics.* [S0021-8979(99)69908-X]

Recently, giant magnetoresistance (GMR) has attracted much interest because of its intricate physics and applications in nonvolatile memory and field-sensing devices.[1] In GMR, spin-dependent charge transport in heterogeneous magnetic materials results in a large change of resistance upon the application of a magnetic field. In nonmagnetic materials, the magnetoresistance of semimetals such as bismuth (Bi) has long been a subject of interest because of the unusual properties of their charge carriers.

Crystalline Bi exhibits anisotropic magnetoresistance which depends on the direction of the applied field with respect to the crystal axes.[2] This is due to its complex Fermi surface, which has elongated pockets of both holes and electrons with different effective masses. Since the carriers of Bi have a very long Fermi wavelength $\lambda_F \approx 40$ nm, it is particularly interesting to study thin films and wires with physical sizes approaching λ_F. In low-dimensional systems, phenomena such as quantum size effects have been observed.[3] Usually, thin films of Bi have been obtained by vacuum deposition techniques such as thermal evaporation and sputtering. One of the drawbacks of these films is that they tend to have very small grain sizes,[4,5] and the magnetoresistance is in general very small. Recently, electrodeposition using nanoporous templates has provided an enticing means of fabricating arrays of narrow wires composed of a variety of metals.[6] This method has enabled us to obtain Bi nanowires with large grains.[7] In this paper, we report the first magnetoresistance measurements of electrodeposited Bi nanowires under very high magnetic fields up to $B = 55$ T.

Bi wires with diameters $d = 200$ nm, 400 nm, 1 μm, and 2 μm were made by electrodeposition into pores produced by nuclear particle track etching in polycarbonate membranes. The membranes are approximately 10 μm thick with pore density $\sim 10^7 - 10^8$ cm^{-2}. The pores are nominally parallel with some spread in angles as large as 15° from the normal to the plane of the membranes. Transmission electron

microscopy (TEM) and electron diffraction have shown that the wires are polycrystalline, with grain sizes up to $\sim 2 - 4$ times the pore diameters with no preferred orientation.[7] Electrical contacts were made on both sides of the membranes with vacuum-deposited Au layers and silver epoxy. The temperature dependence of the resistance at zero field was measured at $T = 4.2 - 290$ K. High-field magnetoresistance was measured in fields up to $B = 55$ T using a pulsed magnet at various temperatures between $T = 4.2$ K and 290 K in both longitudinal ($B \parallel$ wires) and transverse ($B \perp$ wires) orientations.

The temperature dependence of the resistance $R(T)/R(290$ K) for arrays of Bi wires with diameters 200 nm, 400 nm, 1 μm, and 2 μm is shown in Fig. 1. In all the arrays, $R(T)$ increases monotonically as the temperature decreases, and there is generally a larger change in $R(T)$ as the wire size is reduced. In Bi, the resistance is determined by a fairly delicate balance between the carrier concentration $n(T)$, which decreases with decreasing T, and the mobility $\mu(T)$, which generally increases with decreasing T as the mean free path $l(T)$ grows. In bulk single crystal samples, $l(T)$ grows from ~ 0.2 to 0.3 μm at room temperature to as
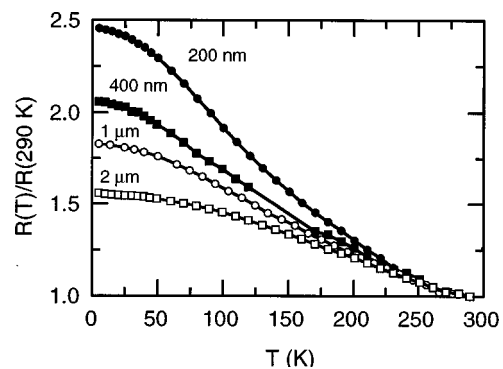

FIG. 1. Temperature dependence of zero-field resistance $R(T)/R(290$ K) of Bi nanowires with $d = 200$ nm, 400 nm, 1 μm, and 2 μm. The lines are guides to the eye.
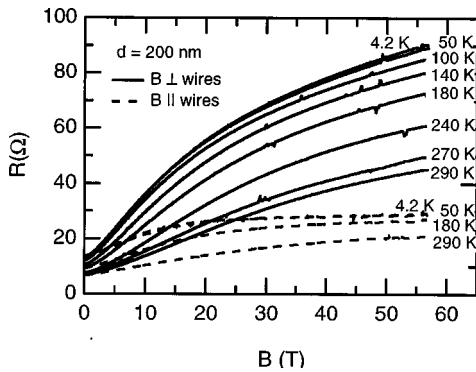
[a]Electronic mail: kimin@pha.jhu.edu

FIG. 2. Field dependence of resistance for $B \perp$ wires (solid lines) and $B \parallel$ wires (dashed lines) at fixed T for $d = 200$ nm.

FIG. 3. (a) Transverse magnetoresistance ΔR of (a) 200 nm Bi wires and (b) 400 nm Bi wires at $T = 4.2$ and 290 K.

large as $\sim 100 \, \mu$m at $T = 4.2$ K, and the resistance decreases with decreasing T. In thin films, however, $l(T)$ has less temperature dependence so that $n(T)$ has a larger effect on $R(T)$.[8] In our nanowire arrays, the increase of resistance at low temperatures shown in Fig. 1 indicates that $l(T)$ is cut off in the wires as well, that $n(T)$ also determines $R(T)$ in our samples.

The high-field resistance $R(B)$ for a 200 nm wire sample at several fixed temperatures between $T = 4.2$ K and 290 K is shown in Fig. 2 for both the perpendicular (solid lines) and parallel (dashed lines) field orientations. There is clearly a dramatic difference between the two orientations, with the parallel resistance $R_\parallel$ saturating near $B = 20$ T as the temperature is reduced, and the perpendicular resistance $R_\perp$ continuing to rise at the highest field measured. In both orientations, there is a strong temperature dependence in $R(B)$ down to $T \approx 100$ K, but little temperature dependence below $T \approx 50$ K. The small spikes visible on some of the traces are due to electronic noise, and are not intrinsic to the samples.

These data are representative of the behavior of $R_\perp$ in all the samples measured, as will be discussed in more detail below. There is somewhat more variability in $R_\parallel$. In all the samples $R_\parallel$ shows most of its change with field below $B = 20$ T at low temperatures, but in some samples it continues to rise slowly at higher fields. This may be attributable to small misalignments of the samples, which would mix in a contribution from $R_\perp$. In the perpendicular orientation, on the other hand, the effects of misalignment are much less pronounced. In the remainder of this paper, we will focus on analyses of $R_\perp$.

To illustrate the magnetoresistance (MR) we show, in Fig. 3(a), $\Delta R = R(B) - R(0)$ derived from the data on the $d = 200$ nm sample at $T = 4.2$ K and 290 K. In this plot, only every tenth data point from the traces in Fig. 2 is shown. Figure 3(b) shows the corresponding data for a $d = 400$ nm sample. At each temperature, the curves for the two samples look very similar, and in fact they differ only by a scale factor. At $T = 4.2$ K, MR rises more steeply at lower fields. This is characteristic of all the samples we have measured, as will be demonstrated below.

The large ΔR leads to large magnetoresistance ratio, $\Delta R/R$, typically 600%–800%. These values are very large, but small compared to that reported for single-crystal Bi in
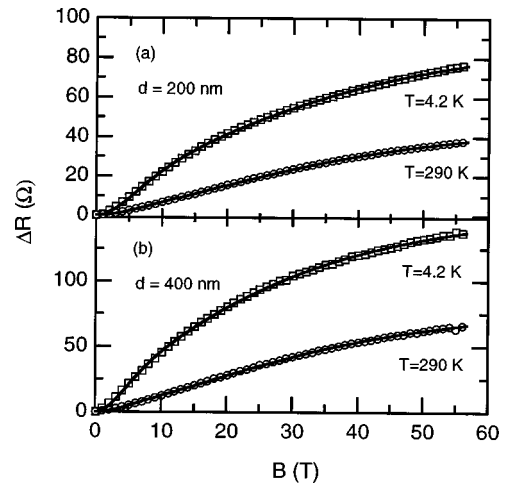
high fields. The general shape of the perpendicular MR in our samples is similar to that of single-crystal Bi up to $B = 30$ T,[9,10] but the large decrease around 40 T seen therein is not observed in our samples. In the absence of a detailed theoretical framework based on the microscopics of Bi, we resort to the standard description of magnetoresistance at high fields using the Frank's formula,[11,12] $\Delta R \propto B^2 / [1 + (\mu B)^2]$, where the constant μ is related to the carrier mobility. This formula alone does not adequately describe our data. Very good fits may be obtained, however, by a two-term generalization of the Frank's formula, which we write as

$$\Delta R = R_1 \frac{(\mu_1 B)^2}{1 + (\mu_1 B)^2} + R_2 \frac{(\mu_2 B)^2}{1 + (\mu_2 B)^2}.$$

The solid lines in Fig. 3 are examples of these fits. The agreement with the data is excellent even at the lowest fields where the agreement is still very good.

The parameters derived from fitting data of five samples with varying wire diameter are shown in Fig. 4. The self-consistency of all parameters lend credence to the generalized Frank's formula. The two ''mobilities'' are effectively independent of both temperature and wire size, with values $\mu_1 \approx 0.12 \, \text{m}^2$/V s and $\mu_2 \approx 0.03 \, \text{m}^2$/V s. This lack of variation with T is consistent with the picture of a temperature-independent mobility (or mean free path) restricted by the wire geometry and/or grain size. The two values of μ_1 and μ_2 differing by about a factor of 4 suggests that there are two different species of carriers.

The ratio R_1/R_2 indicates the relative importance of the two species of carriers. As shown in Fig. 4(c), the ratio R_1/R_2 displays a remarkable similarity for all the samples measured, increasing from roughly 0.2 to 0.5 with decreasing T. This reflects the growth in importance of the high-mobility term, μ_1, at low temperatures which is responsible for the faster rise of the MR in the low-T data.

In summary, we have reported the first high-field magnetoresistance measurements of bismuth nanowire arrays. The dependence of MR on temperature and magnetic field can be well described by the generalized Frank's formula with two mobilities which are essentially temperature inde-
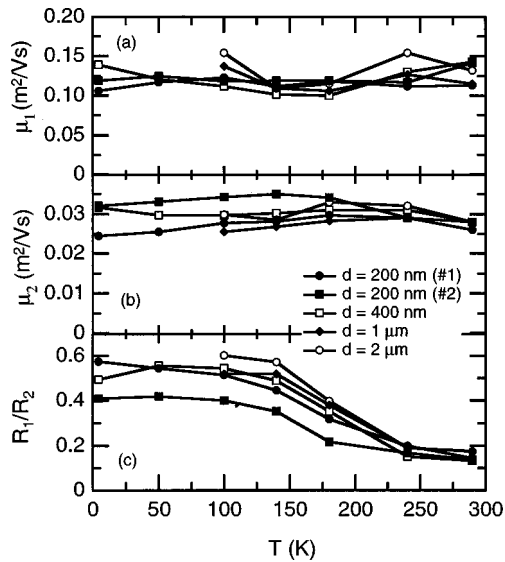
FIG. 4. The best-fit results of (a) μ_1, (b) μ_2, and (c) R_1/R_2 obtained by using the generalized Frank's formula for Bi wires of diameters 200 nm, 400 nm, 1 μm, and 2 μm. (The two $d = 200$ nm samples were cut from the same membrane.)

pendent due to constraints imposed by the wires. Further experiments, including measurements on thin films, are clearly necessary to elucidate the high-field behavior of electrodeposited bismuth.

[1] M. N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988).

[2] L. S. Lerner, Phys. Rev. **127**, 1480 (1962).

[3] Yu. F. Komnik, E. I. Bukhshtab, Yu. V. Nikitin, and V. V. Andrievskii, Sov. Phys. JETP **33**, 364 (1971).

[4] D. E. Beutler, T. L. Meisenheimer, and N. Giordano, Phys. Rev. Lett. **58**, 1240 (1987).

[5] N. O. Birge, B. Golding, and W. H. Haemmerle, Phys. Rev. Lett. **62**, 195 (1989).

[6] T. M. Whitney, J. S. Jiang, P. C. Searson, and C. L. Chien, Science **261**, 1316 (1993).

[7] K. Liu, C. L. Chien, P. C. Searson, and Kui Yu-Zhang, Appl. Phys. Lett. (to be published).

[8] N. Garcia, Y. H. Kao and M. Strongin, Phys. Rev. B **5**, 2029 (1972).

[9] N. Miura, R. G. Clark, R. Newbury, R. P. Starret, and A. V. Skougarevsky, Physica B **194-196**, 1191 (1992).

[10] K. Hiruma and N. Miura, J. Phys. Soc. Jpn. **52**, 2118 (1983).

[11] A. Sommerfeld and N. H. Frank, Rev. Mod. Phys. **3**, 1 (1931).

[12] J.-P. Jan, Solid State Phys. **5**, 1 (1957).