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Unconventional magnetoresistance in long InSb nanowires

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Magnetoresistance in long correlated nanowires of degenerate semiconductor InSb in asbestos matrix (wire diameter of around 5 nm, length 0.1–1 mm) is studied over temperature range 2.3–300 K. At zero magnetic field the electric conduction G and the current-voltage characteristics of such wires obey the power laws $G \propto T^{\alpha}$, $I \propto V^{\beta}$, expected for one-dimensional electron systems. The effect of magnetic field corresponds to a 20% growth of the exponents α, β at $H = 10\,\mathrm{T}$. The observed magnetoresistance is caused by the magnetic-field-induced breaking of the spin-charge separation and represents a novel mechanism of magnetoresistance.

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Electron-electron correlation effects being negligible in three-dimensional case play a dominant role in one dimension. One of the most significant consequence of the correlation effect is the absence of quasiparticle excitations in 1D metals. Instead, in 1D case the collective excitations associated with separate spin and charge degrees of freedom are developed and lead to the formation of the so-called Luttinger liquid (LL) (for a review see [1]). The spin-charge separation mentioned above means different velocities for collective charge and spin excitations. Charge transport in LL is of collective nature and cannot be described by the conventional kinetic equations. A charged impurity in a 1D electron system forms a tunneling barrier. The absence of single-particle excitations complicates the tunneling of electrons in LL and leads to a power law dependence of tunneling density of states. Tunneling through this barrier in the case of short-range e-e interaction provides the power laws for the linear conduction [2] $G(T) \propto T^{\alpha}$ and nonlinear I–V curve $I(V) \propto V^{\beta}$, whereas for long-range Coulomb interaction a substantially different functional dependence of type $G \propto \exp\left[-\nu \ln(T_0/T)^{1/3}\right]$ is predicted [3, 4].

Experimental study of 1D behavior remains a challenge. Single-wall and multi-wall carbon nanotubes and various nanowires have been intensively studied last years (see e.g. [5 – 7] and references therein). One of the most dramatical effect of reduced dimensionality on physical properties of long nanowires was reported recently for the electric conduction of InSb nanowires in an asbestos matrix [8]. It was found that G as a function of temperature and electric field follows power laws over 5 orders of magnitude of conduction variation. The effect was considered as a manifestation of the Luttinger-liquid-like behavior of an impure 1D electron system. This conclusion has been supported recently by the measurements of thermoelectric power [9]. Namely, it was found that the Seebec coefficient of InSb nanowires as a function of temperature exhibits a metallic behavior corresponding to n-type conduction, whereas the temperature variation of the electric conduction follows a power law. LL is the only known physical system where these both types of behavior coexist [10].

The physical reason for realization of the LL-like behavior in InSb nanowires is a lucky coincidence of numerous factors [8]. Namely, a very small effective electron mass intrinsic to bulk InSb ($m^* \sim 10^{-2} m_e$) is favorable for a pronounced energy level splitting due to quantum size effect, which was estimated to 10^4 K in our nanowires having 5 nm in diameter [8]. Studied samples consist of about 10^6 of such parallel crystalline [11] InSb nanowires forming hexagonal a lattice with a 30 nm period. Thus, long-range interactions between electrons in each wire may be screened through the Coulomb interaction of these electrons with electrons on neighboring wires. This leads to a short-range intra-wire e-e interactions, which is a basic assumption of the LL theory. In all other respects, the wires can be considered independent of each other. It was argued [8] that the transport properties of individual wires are determined by tunneling through impurities and weak links (e.g. constrictions) introduced during the fabrication process. Thus, such an impure LL may be considered [8] as broken into drops of almost pure LL separated by weak links. "Almost pure" means that the size of most of the drops are

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less than the localization length L_{loc}. If one takes into account the repulsive e-e interaction, L_{loc} may be larger than the mean distance between impurities and the mean free path (weak pinning) [12, 13]. As the mean drop size is $\sim 10^3$ nm [8], this condition can be fulfilled. Then the dominant role in transport is determined by tunneling through weak links which are connected in series by LL drops as it was proposed in [14]. In addition, due to the high density of weak links along each nanowire, contact effects play a negligible role in transport properties.

Study of the magnetoresistance is a powerful tool for investigation of the transport mechanism in physical systems. In the case of LL where charge and spin degrees of freedom are decoupled, magnetic field effect may bring new features which are not observed in other physical systems. In particular, it causes breaking of the spin-charge separation [15]. As a result, the charge mode responsible for electric conduction gets a contribution from the spin mode. This effect is expected to be most pronounced in TDOS and affects the critical indixes [16]. So a novel type of magnetoresistance can be expected in physical systems exhibiting a LL-like behavior whose conduction is dominating by tunneling. In this context InSb nanowires are very perspective objects because of their exceptionally strong spin-orbit coupling which leads to a very high g-factor $g \approx 50$. Below we present magnetoresistance data for InSb nanowires in an asbestos matrix in magnetic fields up to 10 T. The observed magnetoresistance corresponds to a magnetic-field dependence of the exponents α, β caused by magnetic-field-induced breaking of the spin-charge separation, representing a novel mechanism of magnetoresistance.

We have studied the electrical conduction of long InSb nanowires crystallized inside an asbestos matrix as a function of magnetic field, temperature and electric field. Sample preparation and characterization have been described in details elsewhere [8, 11]. The data reported below were obtained for two representative samples demonstrating a LL-like behavior with zero magnetic field exponents $\alpha = 2.2$, $\beta = 2.1$ (sample 1), $\alpha = 4.5$, $\beta = 4.3$ (sample 2). Magnetoresistance of both samples demonstrates a similar behavior.

Fig.1 shows a typical variation of the electric current, I, measured at a set of fixed voltages, *vs.* magnetic field. Magnetoresistance in low magnetic fields is negative, like observed in a network of single-wall carbon nanotubes [17]. Conduction reaches a maximum at $H \approx 1$ T and falls down by a factor of 5 at $H = 10$ T at a given temperature. For relatively small voltages (corresponding to the linear conduction regime) the effect of magnetic field on the conduction is practically independent of the voltage. For larger voltages the magnetoresistance is smaller. The observed magnetoconduction is slightly anisotropic and the ratio $[I(H) - I(0)]/I(0)$ for $H \perp I$ is approximately 20% bigger than for $H \parallel I$.

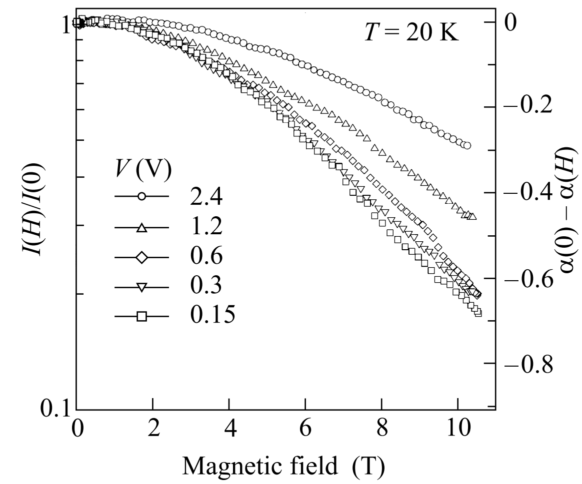

Fig.1. Typical set of $I(H)$ curves measured at different voltages. The right axis scale corresponds to the estimate $\alpha(0) - \alpha(H) = \ln[I(T,H)/(I(T,0)]/\ln(\epsilon/T)$ at $T = 20$ K. $H \perp I$. Sample 2, $\epsilon = 250$ K

Fig.2 shows the effect of the magnetic field on the shape of I–V curves. At relatively high temperatures (80 K curve) the effect of magnetic field is small. At

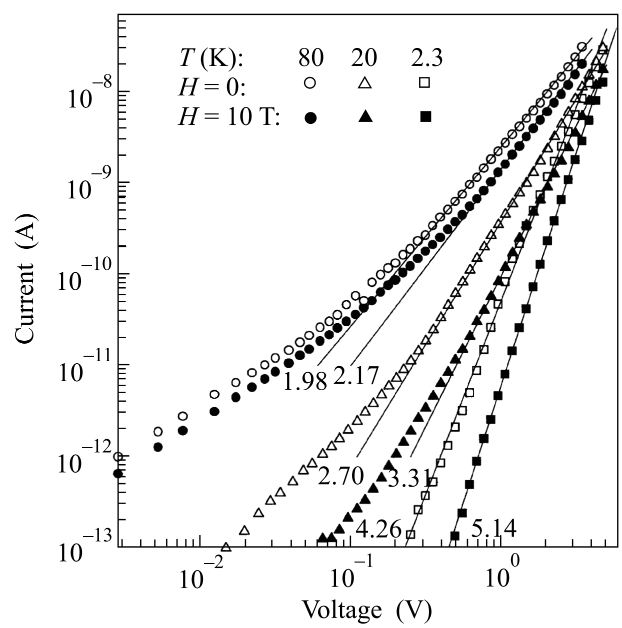

Fig. 2. Temperature set of I–V curves measured at zero magnetic field (empty patterns) and at $H = 10$ T (filled patterns). $H \perp I$. Sample 2. Solid lines show the best fit of the nonlinear part by the power law, $I \propto V^\beta$. The respective exponents, β, are indicated by numbers

lower temperatures the effect is much more pronounced (up to one order of magnitude at $T \leq 5$ K for $H > 10$ T) and is smaller for bigger electric fields. For comparison: measurements on InSb extracted from asbestos cracks showed only a 20% negative magnetoconduction $G(0) - G(H) \propto H^2$ at $T = 4.2$ K and $H = 10$ T, and magnetoresistance of InSb in vycor glass with a 7 nm channel network [18] is negligibly small. The magnetoresistance of a network of carbon nanotubes is also small [19]. These results demonstrate the decisive role of the one-dimensional sample topology. In addition, as seen from the low-temperature curves in Fig.2, the magnetic field changes the slope of the nonlinear part of the curve, i.e. affects the exponent β.

Fig.3 shows the temperature variation of the ratio $G(H = 10\,\mathrm{T})/G(0)$. For sample 2 at $T < 20$ K this ratio

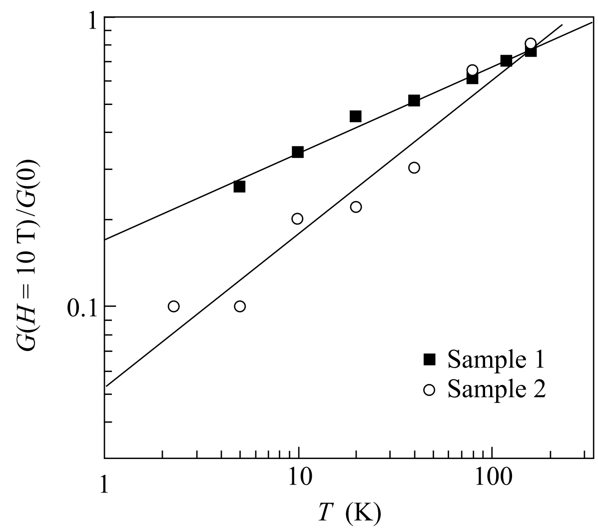

Fig.3. Temperature dependence of the conduction in a magnetic field of 10 T related to its value at $H = 0$ measured at the smallest V. Lines indicate the least-squares fit of the data using the power law (Eq.(1)). $H \perp I$

was estimated from the low-current part of I-V curves. It is clearly seen that the magnetoconduction depends on temperature and grows with lowering temperature approximately as a power function of temperature.

$d\ln G/dH$ at $H = 10$ T as a function of both temperature and electric field is shown in Fig.4. At relatively small voltages $d\ln G/dH$ is practically independent of voltage and forms a limiting dependence. This dependence as a function of the $\ln T$ can be approximated by a straight line, $d\ln G/dH = A - B\ln(T)$ (solid line in Fig.4). At relatively large voltages $d\ln G/dH$ tends to deviate from the limiting dependence upon cooling, the deviation being growing with the voltage.

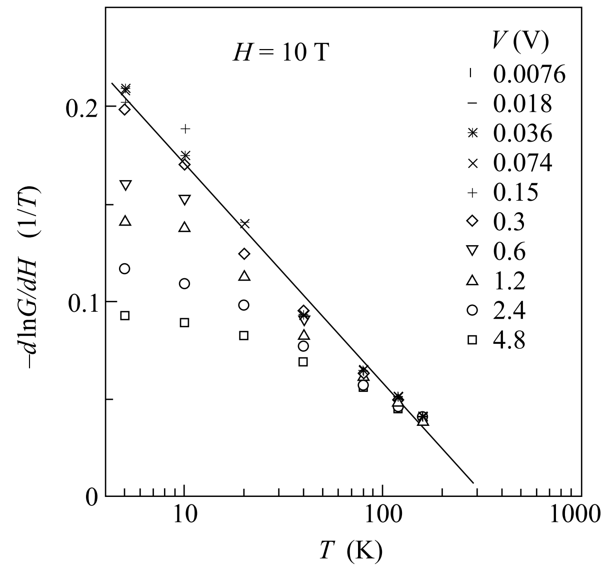

Fig.4. Temperature dependences of the conduction sensitivity to the magnetic field $d\ln G/dH$ at $H = 10$ T for given values of the voltage V. The line corresponds to the power law $d\ln G/dH = 0.048\ln(T/315\,\mathrm{K})$ 1/T. $H \perp I$. Sample 1

Temperature sets of $d\ln G/dH$ plotted *vs.* voltage show a similar behavior (see Fig.5). The high-voltage data form a limiting curve which can be approximated

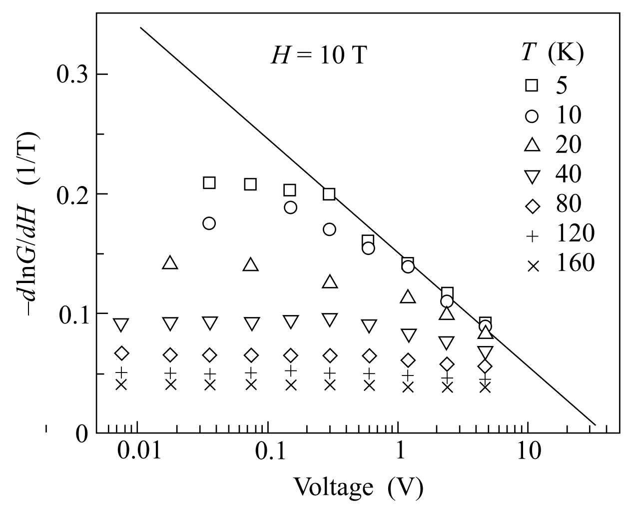

Fig.5. Voltage dependences of the conduction sensitivity to the magnetic field $d\ln G/dH$ at $H = 10$ T for given temperatures. The line corresponds to the power law $d\ln G/dH = 0.041\ln(V/40\,\mathrm{V})$ 1/T. $H \perp I$. Sample 1

by $d\ln G/dH = C - D\ln(V)$ (solid line in Fig.5). Low-voltage data demonstrate a deviation from this limiting curve and are practically independent of voltage at $V \to 0$. Note that the limiting curves in Fig.5 and 4 are formed with different data: namely, the low-voltage data forming the limiting curve in Fig.4 sit on the low-voltage plateaus in Fig.5, and vice versa, the low-temperature data forming the limiting curve in Fig.5 sit on the low-voltage plateaus in Fig.4. Thus Figs.4 and 5 illustrate different features of the observed magnetoresistance.

As it is clear from the data of Figs.2–5, the observed magnetoresistance corresponds to a magnetic-field induced variation of the exponents for $G(T)$:

$$G(T) = G_0 \left(\frac{T}{\epsilon}\right)^{\alpha(H)} \quad (1)$$

and nonlinear I–V curve

$$I(V) = I_0 \left(\frac{V}{V_0}\right)^{\beta(H)} . \quad (2)$$

Indeed, in this case $G(H)/G(0) = T^{\alpha(H)-\alpha(0)}$, in agreement with Fig.3, $d\ln G/dH = (\ln T - \ln\epsilon)d\alpha/dH$ and $d\ln I/dH = (\ln V - \ln V_0)d\beta/dH$, in agreement with Figs.4 and 5 respectively. Eqs.(1), (2) fit the data with $d\alpha/dH = 0.05\,1/\mathrm{T}$, $d\beta/dH = 0.06\,1/\mathrm{T}$ and $\epsilon = 335\,\mathrm{K}$ for sample 1, and 0.11 1/T, 0.12 1/T and 250 K for sample 2 at $H = 10\,\mathrm{T}$. $\alpha(0) - \alpha(H)$ for sample 2 calculated with Eq.(1) and $\epsilon = 250\,\mathrm{K}$ is shown in Fig.1 (right scale).

Magnetic field affects both orbital motion and spin degree of freedom of electrons. While the magnetic length $L_B = \sqrt{c\hbar/eB} > d$, where d is the wire diameter, we cannot expect that orbital effects [20] play a role. In our 5 nm diameter nanowires this condition is broken at $B \sim 40\,\mathrm{T}$, far away from the maximum magnetic field 10 T used in our measurements. Thus we can conclude that Zeeman splitting is responsible for the observed behavior. This splitting in InSb is especially strong due the very big g-factor in InSb ($g \approx 50$).

At present there is no theory describing magnetoresistance in 1D correlated conductors. We expect that magnetic field leads to a variation of α and β. It is known, that magnetic field affects correlation function critical exponents in the 1D Hubbard model [21], so $\alpha(H)$ and $\beta(H)$ dependences are expected. It is also worth to mention that magnetic-field-dependent exponents are observed in a temperature variation of NMR relaxation time of a spin-1/2 Heisenberg ladder gapless phase [22]. Spin-charge separation in the LL model means that only independent collective spin (spinons) and charge (holons) excitations are present at $H = 0$. Magnetic field acting on the spin subsystem mixes spinons and holons and destroys thereby the spin-charge separation [15]. Magnetic-field dependence of holon's characteristics (e.g. velocity) caused by breaking of the spin-charge separation results to a variation of the exponents. In Ref. [16] linear magnetic-field dependences for exponents of spectral functions and bulk density of states, $\rho_{\text{bulk}}(\omega, H)$, are obtained for a pure LL. Namely, magnetic field affects the index for tunneling density of states as

$$\alpha_{\text{bulk}}(H) = \alpha_{\text{bulk}}(0)\left(1 + a\frac{H}{H_c}\right), \quad (3)$$

where $H_c = \epsilon_F/g\mu_B$, and $a \approx 1$ in the strong coupling regime [16]. So despite the absence of theoretical results for $\alpha_{end}(H)$ responsible for tunneling through a single impurity barrier in magnetic field, similar relative variation of α, β is expected. Then the observed 20% variation of exponents in a magnetic field of 10 T corresponds to $H_c \sim 50\,\mathrm{T}$, which is achieved at $\epsilon_F = 0.1\,\mathrm{eV}$ [8].

To our knowledge, a magnetoresistance of observed type and such a large value has not been reported yet for other physical objects exhibiting a LL-like behavior. Namely, magnetoresistance of carbon nanotubes may be interpreted within the framework of the weak localization scenario and Aharonov-Bohm effect [17] and also as due to the change in a magnetic field of the density of states at the Fermi energy [23] for non-interacting electrons. Reported magnetoresistance in Bi [6] and Sb [7] nanowires of comparable diameter (~ 10 nm) is much smaller (15% in Bi and 0.2% in Sb at 5 T) and even has the opposite sign (Sb). Strong anisotropic magnetoresistance of bulk samples of n-InSb with electron densities $n \sim 10^{16}\,\mathrm{cm}^{-3}$ is observed in the quantum limit of applied magnetic field at $T = 1.5\,\mathrm{K}$ [24]. In contrast with our data, it can be explained within a conventional transport theory without taking into account the decisive role of e-e interactions.

We would like to note that the consideration described above is valid while $L_B > d$, i.e. at $H < 40\,\mathrm{T}$. When $L_B < d$, the orbital effects [20] take place. In addition, when $H > H_c \sim 50\,\mathrm{T}$, no spin effect is expected any more. So the physical mechanism of magnetoresistance is expected to be changed at $H = 40{-}50\,\mathrm{T}$.

Thus InSb nanowires exhibit a strong positive magnetoresistance (up to 1 order of magnitude at $H = 10\,\mathrm{T}$) corresponding to a magnetic-field induced variation of the exponents α and β in $G \propto T^{\alpha}$ and $I \propto V^{\beta}$. This variation is a manifistation of a novel physical mechanism of magnetoresistance specific for 1D systems.

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1. J. Voit, Rep. Prog. Phys. **58**, 977 (1995).
2. C.L. Kane and M.P.A. Fisher, Phys. Rev. Lett. **68**, 1220 (1992); Phys. Rev. **B46**, 15233 (1992).
3. L.I. Glazman, I.M. Ruzin, and B.I. Shklovskii, Phys. Rev. **B45**, 8454 (1992).
4. M. Fabrizio, A.O. Gogolin, and S. Scheidl, Phys. Rev. Lett. **72**, 2235 (1994).
5. M. Bockrath, D.H. Cobden, J. Lu et al., Nature, **397**, 598 (1999); C. Schonenberger and L. Forro, Physics World, **13**, 37 (2000).
6. J. Heremans, C.M. Thrush, Yu-Ming Lin et al., Phys. Rev. **B61**, 2921 (2000).
7. J. Heremans, C.M. Thrush, Yu-Ming Lin et al., Phys. Rev. **B63**, 085406 (2001).
8. S.V. Zaitsev-Zotov, Yu.A. Kumzerov, Yu.A. Firsov, and P. Monceau, J. Phys.: Cond. Matter **12**, L303 (2000).
9. M.V. Vedernikov, O.N. Urypin, B.M. Goltsman et al., MRS Fall Meeting, Symp. G (Boston), XI-2001.
10. C.L. Kane and M.P.A. Fisher, Phys. Rev. Lett. **76**, 3192 (1996).
11. S.B. Vakhushev, privite communication.
12. A. Furusaki and N. Nagaosa, Phys. Rev. **B47**, 4631 (1993).
13. H. Maurey and T. Giamarchi, Phys. Rev. **B51**, 10833 (1995).
14. S.R. Renn and D.P. Arovas, Phys. Rev. **B51**, 16832 (1995).
15. T. Kimura, K. Kuroki, and H. Aoki, Phys. Rev. **B53**, 9572 (1996).
16. S. Rabello and Q. Si, Phys. Rev. Lett., submitted (see also cond-mat/0008065).
17. A. Bachtold, C. Strunk, C. Schonenberger et al., Nature **397**, 673 (1999).
18. V.A. Berezovets, privite communication.
19. G.T. Kim, E.S. Choi, D.C. Kim et al., Phys. Rev. **B58**, 16064 (1998).
20. C. Biagini, D.L. Maslov, M.Yu. Reizer, and L.I. Glazman, Eurothys. Lett. **55**, 383 (2001); Shan-Wen Tsai, D.L. Maslov, and L.I. Glazman Phys. Rev. **B65**, 241102 (2002).
21. H. Frahm and V.E. Korepin, Phys. Rev. **B43**, 5653 (1991); M. Ogata, T. Sugiyama, and H. Shiba, Phys. Rev. **B43**, 8401 (1991).
22. G. Chaboussant, Phys. Rev. Lett. **80**, 2713 (1998).
23. S. Roche and R. Saito, Phys. Rev. Lett. **87**, 246803 (2001).
24. S.S. Murzin, A.G.M. Jansen, and E.G. Haanappel, Phys. Rev. **B62**,16645 (2000).