Luttinger-liquid-like transport in long InSb nanowires

2000 J. Phys.: Condens. Matter 12 L303

(http://iopscience.iop.org/0953-8984/12/20/101)

J. Phys.: Condens. Matter **12** (2000) L303–L309. Printed in the UK PII: S0953-8984(00)11990-3

LETTER TO THE EDITOR

Luttinger-liquid-like transport in long InSb nanowires

S V Zaitsev-Zotov†, Yu A Kumzerov‡, Yu A Firsov‡ and P Monceau§

† Institute of Radioengineering and Electronics, Russian Academy of Sciences, Mokhovaya 11, 103907 Moscow, Russia

‡ Ioffe Physico-Technical Institute, Russian Academy of Sciences, Polytekhnicheskaya 26, 194021 St Petersburg, Russia

§ Centre de Recherches sur Les Très Basses Températures, CNRS, BP 166, 38042 Grenoble Cédex 9, France

E-mail: serzz@mail.cplire.ru

Received 21 February 2000

Abstract. Long nanowires of degenerate semiconductor InSb in asbestos matrix (wire diameter about 50 Å, length 0.1–1 mm) have been prepared. The electrical conduction of these nanowires has been studied over a temperature range 1.5–350 K. The zero-field electrical conductance is a power function of temperature $G \propto T^{\alpha}$ with a typical exponent $\alpha \approx 4$. Current–voltage characteristics of such nanowires are nonlinear and, at sufficiently low temperatures, follow the power law $I \propto V^{\beta}$. The electrical conduction of the nanowires cannot be accounted for in terms of ordinary single-electron theories and exhibits features expected for impure Luttinger liquid (LL). For the simple approximation of an impure LL as a pure liquid broken into drops by weak links, the estimated weak-link density is around 10^3–10^4 cm^{-1}.

1. Introduction

Being negligible in the three-dimensional case, electron–electron correlation effects play the dominant role in one dimension. As a result, the physical properties of a one-dimensional (1D) metal are expected to be dramatically different from those of usual metals with a Fermi liquid of electrons. One of the main consequences of the electron–electron Coulomb repulsive interaction is that the energy density of states around the Fermi energy decreases. The resulting electron state depends on details of the electron–electron interaction. In the absence of a long-range interaction, an 1D electron liquid (so-called 'Luttinger liquid' (LL) [1]) is formed, while with long-range Coulomb interaction we have a 1D Wigner crystal [2]. The transport properties of 1D electron systems are a subject of very intense interest. It has been shown that in Coulomb blockade systems the tunnelling transparency of a barrier vanishes owing to the electron–electron interaction, resulting in a power-law zero-bias anomaly for the conduction [3] (see also [4]). For the particular case of LL, a similar result has also been obtained by stronger methods [5–9]. The role of impurity scattering in the presence of short-range [7, 10] and long-range [9, 11] interactions has also been intensively studied.

A Luttinger-liquid-like behaviour for tunnelling into fractional Hall edge states, predicted in [8], was recently observed in a GaAs-$Al_{0.1}Ga_{0.9}As$ heterostructure in the quantum Hall regime with a filling factor $\nu = 1/3$ [12]. However, each of these edge states has properties of the so-called 'chiral Luttinger liquid' but not those of LL. They are similar but not identical. For a continuum with a filling factor $1/4 \leqslant \nu \leqslant 1$, the experimental I–V curves [13] are not in full correspondence with the theoretical predictions. A Luttinger-liquid behaviour has also been predicted for carbon nanotubes [14, 15].

0953-8984/00/200303+07$30.00

Small (within about an order of magnitude) variations with voltage and temperature of the tunnelling conductance from the current leads into ropes of single-walled nanotubes in the Coulomb blockade regime were found [16] to be consistent with the expectations for LL. No LL behaviour has been observed in single nanowires (except in carbon nanotubes mentioned above) and quasi-one-dimensional systems like Bi nanowire arrays [17].

In the present Letter, we report on a study of the electrical conductance of InSb nanowires in an asbestos matrix. It has been found that it follows the power law over 5 orders of conductance variation and can be described as a conductance of a pure LL broken into drops by weak links, the estimated weak-link density being about 10^3–10^4 cm^{-1}.

2. Experimental details

Natural asbestos is a mineral very convenient for nanowire preparation. It is a crystal-like package of long fibre-like tubes roughly 300 Å in diameter with a central hole of 20–200 Å in diameter [18, 19], depending on a geological deposit. Almost any material can fill the holes at sufficiently high pressure and temperature. Since the distance between thus prepared nanowires is large, they are independent of one another in contrast to numerous quasi-one-dimensional conductors where the overlapping of wave functions of electrons on metal chains leads to 3D-ordered charge-density waves. Previously, superconducting properties of In, Sn and Hg nanowires [20–22], weak localization phenomena [23] and the first-order melting transition in Hg nanowires in asbestos [24] have been studied.

The asbestos used in the present work was characterized by electron microscopy to have a 50±10 Å central hole diameter and 300 Å package period. It was filled with InSb under a pressure of 15 kbar at a temperature of 550 °C. A preliminary vacuum treatment was undertaken to remove gases absorbed by asbestos. In contrast to many other filling materials [20–24], InSb nanowires were stable at room temperature even after removing the pressure.

Samples were cut from big asbestos crystals filled with InSb. The samples studied were typically 0.01–0.1 mm wide and thick and 0.1–1 mm long in the direction along the asbestos fibres. Thus each sample contained 10^5–10^7 nanowires 50±10 Å in diameter separated by 250 Å asbestos walls. In most cases, such samples also had longitudinal cracks filled with InSb. To eliminate the influence of such cracks, the samples were etched in a 1:1 mixture of HCl and HNO_3 for 10–40 minutes. As such a procedure also removes InSb from the ends of asbestos filaments, the samples were shortened after etching, to remove empty ends.

In most cases, the current leads were made by vacuum deposition of indium, in a few cases In-Ga amalgam was used for this purpose. A two-terminal technique was used to measure the electrical conductance of both pure asbestos and InSb in asbestos. No difference was found between conduction data for samples with both types of contacts, but the vacuum-deposited ones were much more stable. The electrical conductance of bulk InSb samples was measured by both the two- and four-terminal technique. No substantial contact effects were observed. Temperature dependences of conductance and current–voltage characteristics (I–V curves) were measured in the voltage-controlled regime. A U5-11 electrometric amplifier and Keithley 617 electrometer were used to measure currents as low 10^{-15} A.

3. Results

We prepared more than 80 samples of InSb in asbestos and measured their room-temperature conductance. About 50 of them were chosen for detailed investigation of temperature and electric field dependences of conductance. For comparison, we also measured the electrical conductance of InSb in a multifilamentary glass (vycor) with a typical pore diameter of about 70 Å, bulk pieces of InSb extracted from cracks, and empty asbestos.

We found that all the measured samples can be divided into three groups in accordance with the temperature evolution of their conductance. The first group consists of samples with $G(300\text{ K})/G(4.2\text{ K}) \lesssim 100$. Practically all unetched samples with vacuum-deposited contacts belong to this group. For samples of this kind, a rapid initial decrease of G upon cooling saturates at some temperature so that their low-temperature $G(T)$ is similar to the $G(T)$ of bulk InSb. We concluded, therefore, that in these samples the dominant contribution to low-temperature conductance comes from InSb-filled longitudinal cracks in asbestos. The second group is formed by samples whose conductance has strong temperature dependence down to the lowest measurement temperature (1.5 K). In our opinion, the conductance of these samples is due to InSb nanowires in the asbestos matrix. The physical properties of such samples are the main subject of the present Letter. In addition, some samples have very low room-temperature conductance (about $10^{-12}\ \Omega^{-1}$) and very strong temperature dependence of conductance which goes out of the range of the present measurements ($\sim 10^{-15}\ \Omega^{-1}$) at temperatures below 100–200 K. We believe that InSb nanowires are not continuous in these samples. Their properties are beyond the scope of the present Letter. In addition, the conductance of some samples was unstable and switched between two or more different conducting states belonging to one of the conduction groups described above. Such samples do not provide any new information, and the temperature evolution of their conductance will not be described here.

The current–voltage characteristics of samples of the second group are highly nonlinear in the entire temperature range studied. In addition, application of a sufficiently large voltage may irreversibly modify the shape of the I–V curve, the result of such a modification being dependent on a particular sample. The conductance of some samples was stable at voltages of up to 30 V, but only 3 V was enough to irreversibly modify the conductance of other samples. Irreversible increase or decrease of conductance was observed. The physical reasons for such an irreversible behaviour may be related to electromigration of impurities. The data reported below refer to the reversible part of the I–V curves.

Figure 1 shows typical temperature dependences of the linear conductance G for a representative set of samples of InSb-filled asbestos. The typical room-temperature resistance of such samples is 10 kΩ–10 MΩ. The $G(T)$ for InSb extracted from a crack in asbestos (broken curve in figure 1) and for InSb in vycor (dotted curve in figure 1) are shown in the same plot for comparison. First of all, the $G(T)$ of all samples is at least three orders of magnitude smaller than the conductance of bulk InSb from a crack, multiplied by the filling factor for asbestos $(50\text{ Å}/300\text{ Å})^2$, and the conductance of InSb in vycor. Second, the temperature dependence of their conductance is much stronger. The most remarkable feature is the approximately linear shape of $G(T)$ in the log–log coordinates (see figure 1). This means that $G(T) \propto T^{\alpha}$. A large group of the samples studied (six samples) had $\alpha = 4 \pm 0.5$. In addition, one sample had $\alpha \approx 2$; and another, $\alpha \approx 7$.

Figure 2 gives a typical temperature set of I–V curves. The I–V curves are nonlinear at any temperature. The nonlinearity becomes more pronounced with lower temperature. The power law, $I \propto V^{\beta}$, with $\beta \approx 4.4$ fits the low-temperature data over seven orders of current variation. Other samples reveal a similar behaviour with $2 \lesssim \beta \lesssim 6$. Only a minor nonlinearity (10%) was observed for InSb in vycor at $T = 4.2$ K in electric fields $E < 10\text{ V cm}^{-1}$.

4. Discussion

The doping level of InSb from cracks in asbestos is expected to be close to that for InSb in nanowires. The weak temperature dependence of the conduction of bulk InSb indicates

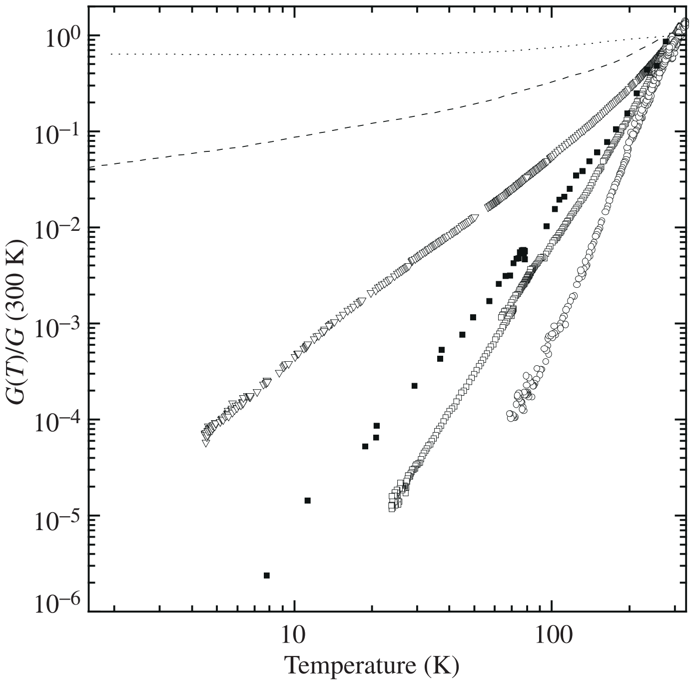

Figure 1. Log–log plot of the temperature variation of the linear conductance of InSb nanowires. The broken curve shows the conductance of bulk InSb extracted from a crack in asbestos. The dotted curve represents the conductance of InSb in vycor.

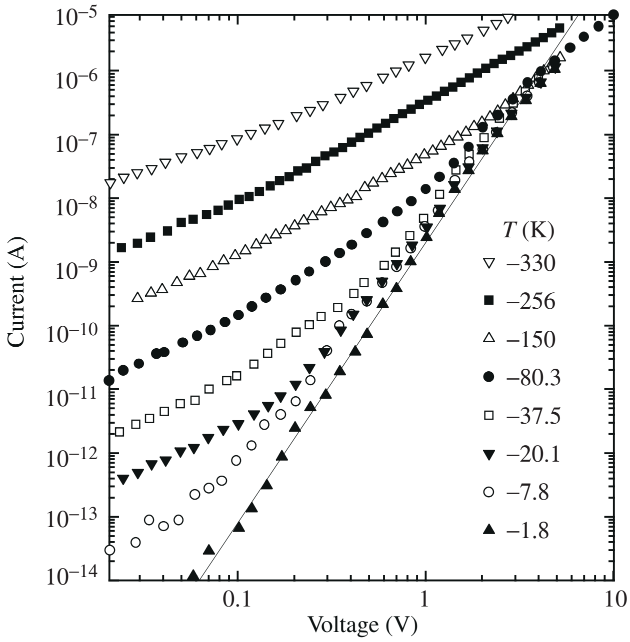

Figure 2. Typical temperature set of I–V curves for a sample of InSb in asbestos. The full curve shows $I \propto V^{4.4}$. The sample length is 0.2 mm.

that InSb nanowires consist of heavily doped degenerate InSb with carrier concentration n exceeding 10^{17} cm^{-3}. The fundamental difference between the temperature dependences of the conductance of InSb in vycor glass and InSb nanowires indicates dramatic changes in the physical properties of InSb nanowires, associated with the 1D nature of electron states, rather than with the finite-size effect only. For an InSb wire with diameter $d = 50$ Å and the effective carrier mass $m^* = (0.014\text{–}0.2)m_e$, the energy separation between the first and the second quantum levels $\Delta E = (\pi\hbar)^2/2m^*d^2 = 800\text{–}20\,000$ K, which much exceeds T for the examined temperature range. So the electron band structure of 50 Å InSb nanowires is essentially one-dimensional. Other details of the band structure are not very certain. In particular, the Fermi energy $E_F = (\pi\hbar n d^2)^2/8m^*$ depends on uncertain parameters m^* and n. If $n \leqslant 2/d^3 \sim 2 \times 10^{19}$ cm^{-3}, then $E_F < \Delta E$, i.e. there is a single quantum conduction channel.

Thus, the samples studied consist of long quantum wires with one or few quantum conduction channels. Since the interwire distance is ≈ 250 Å, no electron tunnelling between the wires is expected and the wires can be considered independent. The wires are composed of a degenerate semiconductor and contain a large amount of impurities and defects. The single-electron 1D variable-range hopping conduction $G \propto \exp[-(T_0/T)^{1/2}]$ apparently does not fit the data. In principle, $I \propto V^\beta$ characteristics with $\beta = 1.5\text{–}3$ are known for charge-limited injection currents in semiconductors and dielectrics [25]. Similar dependences were really observed by us for empty asbestos and for asbestos with broken nanowires, with $\beta = 1.5\text{–}2.5$. As for InSb nanowires, $\beta > 3$ observed for some samples is out of the range for the current-injection case [25].

The power dependence $G \propto T^\alpha$ is predicted for tunnelling between two drops of pure LL [5–7], for LL in a long wire with impurities [26], and for a 1D Wigner crystal [9]. Similarly, $I \propto V^\beta$ is predicted for tunnelling between two drops of pure LL [5, 6, 7], for LL in a long wire with impurities [26], and for the Coulomb blockade effect [3, 4, 11]. However, the dependence $G \propto \exp[-\nu \ln(T_0/T)^{3/2}]$ is predicted for tunnelling 1D Coulomb gas [27], Wigner crystal [28, 29], and pure LL in the presence of a long-range Coulomb interaction [27]. We suppose that long-range interactions in our multiwire samples between electrons in each wire may be screened through Coulomb interaction of these electrons with electrons of neighbouring wires. This leads to a short-range intrawire e–e interaction, which is the basic assumption of the LL theory. In all other respects, the wires can be considered independent of one another. The transport properties of individual wires are determined by impurities and weak links (e.g. constrictions) appearing during the fabrication process. For an infinite wire, the Anderson localization leads to a threshold-like dependence of $I(V)$ [9, 10], not observed in our case. Therefore, we can conclude that the dominant role is played in our samples by tunnelling through weak links. In this case, we can approximate every wire by a system of LL drops connected in series by weak links. For every drop, a power-like behaviour of the density of states near the Fermi level takes place.

For a sample consisting of N identical quantum wires, each with M independent weak links, $G(T)$ and $I(V)$ [5, 6] can be rewritten as

$$G(T) = C_T N \frac{e^2}{\hbar} \left[\sum_{j=1}^{M} \left(\frac{\tilde{\varepsilon}}{t_j} \right)^2 \right]^{-1} \left(\frac{kT}{\tilde{\varepsilon}} \right)^{\alpha} \tag{1}$$

and

$$I(V) = C_I N \frac{e^2}{\hbar} \left(\frac{\tilde{\varepsilon}}{e} \right) \left[\sum_{j=1}^{M} \left(\frac{\tilde{\varepsilon}}{t_j} \right)^{2/\beta} \right]^{-\beta} \left(\frac{eV}{\tilde{\varepsilon}} \right)^{\beta} \tag{2}$$

where $C_T, C_I \sim 1$, t_j is the measure of the tunnelling transparency of jth weak link, $\tilde{\varepsilon} \sim E_F$ is the energy scale for LL, and $\alpha = 2/g - 2$ and $\beta = 2/g - 1$, where g is a bare dimensionless constant. The results obtained, (1) and (2), correspond to a pure LL. For an impure LL or a system of in-series LL drops, scattering of t_j changes the exponents. According to [26], g in β should be substituted by its renormalized value g^*, which results in a departure from the $\beta = \alpha + 1$ law. Thus, the power-law behaviour can be expected for both $G(T)$ and $I(V)$ for the cases of a weak link between two pure LLs [5, 6], impure LL or drops of LL in series connected by weak links [26], and our multiwire model.

The absence of LL-like behaviour in 280±30 Å and 700±100 Å Bi nanowire arrays [17] may be associated with too large nanowire diameters.

The observed values are 2.3 and 2.3, 3.4 and 4.4, 4.5 and 3.8, 4.6 and 3.0, for α and β, respectively; $\alpha = 4$ corresponds to $g = 1/3$, considered a typical value for the LL theory [5, 6]. If $\beta = \alpha + 1$ and all wires are identical, M can be estimated from equations (1) and (2) without fitting parameters by comparing I–V curves and $G(T)$. For a sample with $\alpha = 3.4$ and $\beta = 4.4$, $M \approx 20$, which corresponds to 10^3 weak links per cm per wire. Taking for other samples $\tilde{\varepsilon} \sim 10^3$ K and using the experimental values $I(5\ \mathrm{K}, 1\ \mathrm{V}) = 10^{-12},\ 10^{-9},\ 2 \times 10^{-13}$ A, $G(5\ \mathrm{K}) = 10^{-15},\ 2 \times 10^{-9},\ 10^{-14}\ \Omega^{-1}$, we have $M = 2 \times 10^3, 5 \times 10^3, 5 \times 10^3$, respectively. The corresponding weak link density per wire is about 10^4 cm^{-1}. The variation of α, β from one sample to another may result from the nanowire diameter scattering and/or doping level variation.

Our experimental results furnish no arguments in favour of possible double-well barrier formation at current contacts [15]. Therefore, we do not consider here the effect of electron tunnelling through these barriers [15] but suggest that electron to charged boson excitation conversion occurs in the contact area. Then two kinds of contact effects are expected to affect the transport properties of quantum wires. The first of these, caused by electron reflection from the contact, can be described as an additional contact resistance of the order of $h/2e^2 = 12.3\ \mathrm{k}\Omega$ per each quantum wire [30]. This contribution is negligible in the low-temperature region. The second, associated with interaction of electrons with image charges induced in the contacts, leads to potential redistribution along a nanowire [31, 32]. In accordance with [31, 32], at sufficiently low temperatures even in the case of a quantum wire with a single barrier, the major contribution comes from the barrier rather from the contact effect. This is even truer for our multibarrier samples.

5. Conclusions

The LL theory, therefore, provides a plausible explanation of our experimental data. It should be noted that LL is mostly a convenient theoretical approximation: long-range Coulomb interaction, backscattering and interference effects modify the theory. One can expect, however, that a more realistic description of InSb nanowires is possible without substantial modification of the predicted $G(T)$ and $I(V)$ dependences.

Three of us, SVZ-Z, YuAK and YuAF, are grateful to CRTBT-CNRS for hospitality during the initial stage of the research. We wish to thank S N Artemenko and V Ya Pokrovskii for their interest in this work, and A M Nikitina for assistance in sample etching. The work has been supported by CNRS through jumelage 19 between CRTBT and IRE RAS, the Region Rhone-Alpes through the program Tempra, the Russian Foundation for Basic Research (grants 97-02-18267, 98-02-16667) and MNTP 'Physics of Solid State Nanostructures' (grants 99-1112 and 97-1052).

References

[1] Haldane F D M 1981 *J. Phys. C: Solid State Phys.* **14** 2585
[2] Schultz H J 1993 *Phys. Rev. Lett.* **71** 1864
[3] Girvin S M, Glazman L I, Jonson M, Penn D R and Stiles M D 1990 *Phys. Rev. Lett.* **64** 3183
[4] Matveev K A, Yue D and Glazman L I 1993 *Phys. Rev. Lett.* **71** 3351
[5] Kane C L and Fisher M P A 1992 *Phys. Rev. Lett.* **68** 1220
[6] Kane C L and Fisher M P A 1992 *Phys. Rev. B* **46** 15233
[7] Furusaki A and Nagaosa N 1993 *Phys. Rev.* B **47** 4631
[8] Wen X-G 1991 *Phys. Rev.* B **44** 5708
[9] Maurey H and Giamarchi T 1995 *Phys. Rev.* B **51** 10833
[10] Giamarchi T and Schultz H J 1988 *Phys. Rev.* B **37** 325
[11] Maurey H and Giamarchi T 1997 *Europhys. Lett.* **38** 681
[12] Chang A M, Pfeiffer L N and West K W 1996 *Phys. Rev. Lett.* **77** 2538
[13] Grayson M, Tsui D C, Pfeiffer L N, West K W and Chang A M 1998 *Phys. Rev. Lett.* **80** 1062
[14] Egger R and Gogolin A 1997 *Phys. Rev. Lett.* **79** 5082
[15] Kane C, Balents L and Fisher M P A 1997 *Phys. Rev. Lett.* **79** 5086
[16] Bockrath M, Cobden D H, Lu J, Rinzler A G, Smalley R E, Balents L and McEuen P 1999 *Nature* **397** 598
[17] Heremans J, Trush C M, Zhang Z, Sun X, Dresselhaus M S, Ying J Y and Morelli D T 1998 *Phys. Rev.* B **58** R10091
[18] Pundsak F L 1961 *J. Phys. Chem.* **65** 30
[19] Yada K 1967 *Acta Crystallogr.* **23** 704
[20] Bogomolov V N and Kumzerov Yu A 1975 *JETP Lett.* **21** 198
[21] Bogomolov V N, Klushin N A and Kumzerov Yu A 1977 *JETP Lett.* **26** 72
[22] Bogomolov V N, Kolla E V and Kumzerov Yu A 1983 *Solid State Commun.* **46** 383
[23] Bogomolov V N, Kolla E V and Kumzerov Yu A 1983 *Solid State Commun.* **46** 159
[24] Bogomolov V N, Kolla E V and Kumzerov Yu A 1985 *JETP Lett.* **41** 34
[25] Lampert M A and Mark P 1970 *Current Injection in Solids* (New York: Academic)
[26] Renn S R and Arovas D A 1995 *Phys. Rev.* B **51** 16832
[27] Nagaosa N and Furasaki A 1994 *J. Phys. Soc. Japan* **63** 413
[28] Glazman L L, Ruzin I M and Shklovskii B I 1992 *Phys. Rev.* B **45** 8454
[29] Fabrizio M, Gegolin A O and Schedel S 1994 *Phys. Rev. Lett.* **72** 2235
[30] Maslov D L and Stone M 1995 *Phys. Rev.* B **52** 5539
[31] Sablikov V A and Shchamkhalova B S 1999 *Phys. Rev.* B **58** 13847
[32] Egger R and Grabert H 1999 *Phys. Rev.* B **58** 10761