THERMOELECTRIC PROPERTIES OF InSb NANOWIRES ABOVE ROOM TEMPERATURE

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The thermoelectric properties of bandles of indium antimonide nanowires with a diameter of about 5 nm have been measured in the temperature range 80-400 K. Natural chrysotile asbestos consisting of parallel nanotubes was used for nanowire preparation. The temperature dependences of the thermoelectric power and the electrical conductance of these samples have been measured. It is shown that the electrical conductance of nanowires increases very rapidly with increasing temperature and the thermopower grows almost linearly in the whole temperature range studied. These specific features of the thermopower and conductance of InSb nanowires, observed earlier below room temperature, are retained up to 400 K. The thermoelectric properties of studied nanowires can be described in the framework of the Luttinger liquid theory (instead of the Fermi-liquid theory) taking into account enhancement of the electron-electron interaction in one-dimensional conductors. The high thermopower and a very rapid growth of the power factor $S^2\sigma$ (S is the thermopower, σ is the electrical conductivity) with increasing temperature indicate that the Luttinger liquid state of nanowires is very promising for thermoelectric applications.

In recent years, different low-dimensional structures attract the great attention due in particular to possible increasing their thermoelectric figure of merit. Among these structures, electronic properties of quasi-one-dimensional wires are of special interest because the enhanced electron-electron interaction results in formation of the unusual state of their electronic subsystem called Luttinger liquid [1]. The characteristic features of the transport properties of Luttinger liquid were revealed during measurements of the electrical conductance and current-voltage characteristics in InSb [2-4], BiSb alloy [5], $NbSe_3$ [6], and MoSe nanowires [7]; polymer nanofibers [8]; carbon nanotubes [9-11]; fractional quantum Hall edge states [12]. Luttinger liquid behavior of the thermoelectric power was revealed also in InSb nanowires [3, 4] and carbon nanotubes [11].

The important feature of Luttinger liquid is very rapid growth of its power factor with increasing temperature that is favorable for thermoelectric applications. However, up to now, the Luttinger liquid was observed at temperatures being no more than 300 K. In this work, we have measured the thermopower and the electrical conductance of bundles of InSb nanowires embedded into asbestos matrix in the temperature range 80-400 K. It has been shown that the absolute values of these transport coefficients grow monotonically in the whole temperature range studied.

The method of nanowire preparation has been described earlier [13, 14]. Here we remind only that the employed natural chrysotile asbestos consists of long nanotubes with diameters depending on the origin of the mineral. We used asbestos with the channel diameter of about 5 nm. The channels in the asbestos matrix were filled with the molten InSb under a pressure of ~15 kbar. The samples had typical cross-section of ~0.01 mm^2 and length of ~1 mm along a nanowire direction. The electric resistance was measured by the two-probe method. It is possible because of the high resistance of individual nanowires.
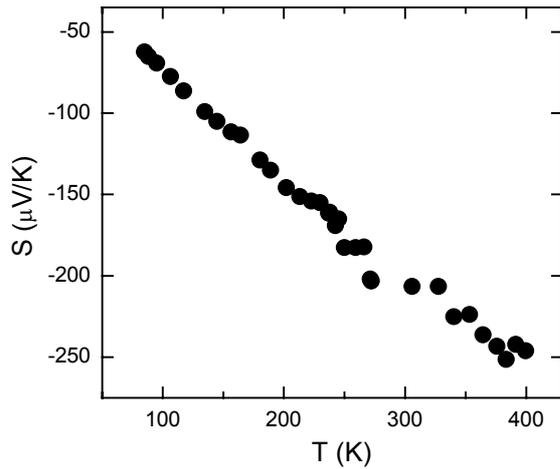
Fig. 1. The temperature dependence of the thermoelectric power of a bundle of InSb nanowires.

The temperature dependences of the thermoelectric power S and the differential electrical conductance G of a bundle of InSb nanowires in an asbestos matrix are presented in Fig. 1 and Fig. 2, respectively. The thermopower is almost a linear function of temperature in the whole measured range. The conductance increases rapidly with increasing temperature. The dependence presented in Fig. 2 is close to a power-law function of temperature in the range ~80-300 K (see also Ref. [2]).
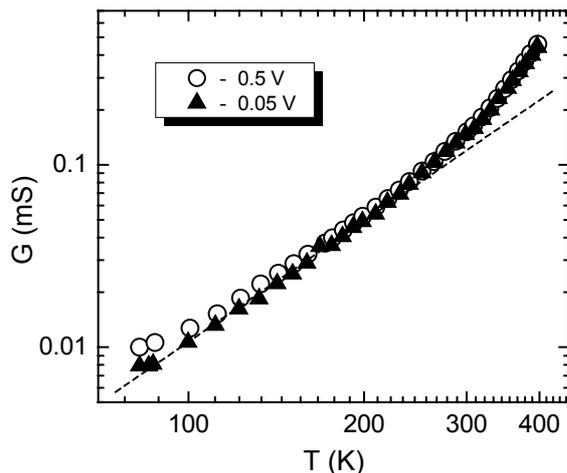

Fig. 2. The temperature dependence of the differential conductance of a bundle of InSb nanowires plotted for two voltages in a double logarithmic scale. The dotted line is the function $G \propto T^{2.2}$.

At present it is impossible to account for the obtained results rigorously. However, there is no doubt that Coulomb interaction has decisive effect upon the electronic transport properties of one-dimensional conductors [1, 15]. The simplest version of the Luttinger liquid theory taking into account an electron-electron interaction describes spinless electrons in a one-dimensional conductor, which are scattered by the single potential barrier. In accordance with the theory, the electrical current $I \propto V_1 T^\alpha$ and the conductance $G \propto T^\alpha$ [9, 10, 15] in the limiting case, when $k_B T \gg eV_1$. Here V_1 is the voltage drop across the single potential barrier[1], $-e$ is the electron charge, k_B is the Boltzmann constant, and the exponent α (>0) depends on the strength of the electron-electron interaction. In other words, the current-voltage characteristics are linear and the conductance is described by a power-law dependence on temperature in this limit. In the opposite case, when $eV_1 \gg k_B T$, the current $I \propto V_1 |V_1|^\beta$ and the differential conductance $G \propto |V_1|^\beta$ [9, 10, 15], where $\beta \equiv \alpha$. This limit leads to a power-law variation of I-V characteristics of a one-dimensional conductor and independence of the conductance on the temperature.

The presented relations describe an electron transport in nanowires with small number of independent defects (impurities, constrictions, etc.). In the opposite case of large density of defects, the nanowire can be modeled as a chain of quantum dots divided by potential barriers [16]. In this model, the electrical current may be described by the same power-law dependences $I(V,T)$ mentioned above. However, the exponents α and β depend on disorder and satisfy the condition $\alpha \gg \beta$. This approach takes into account the Coulomb interaction quasiclassically.

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[1] V_1 coincides with the total voltage drop across a nanowire V, if there is only one potential barrier. If there are N identical independent barriers, $V = NV_1$.

Much less is known about realistic one-dimensional systems, which require closer inspection of both interaction and disorder. It is hoped that the rigorous dependences $I(V,T)$ will be also close to the power law in the indicated limits. However, the exponents α and β should depend on both interaction and disorder [17].
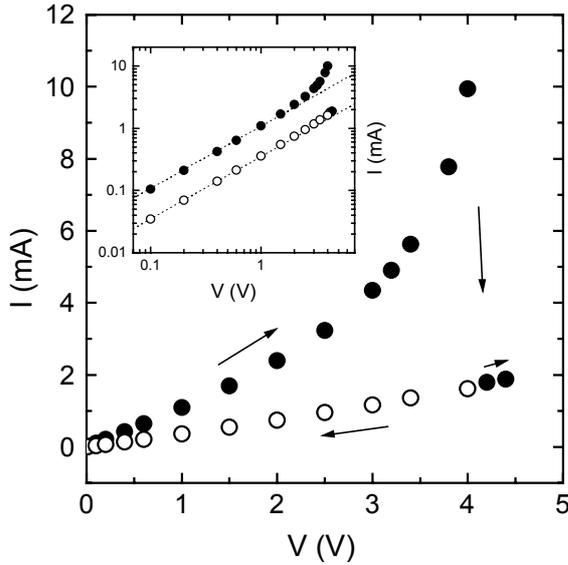

Fig. 3. The current-voltage characteristic of a bundle of InSb nanowires at 300 K before an irreversible change of the sample (solid circles) and after it (open circles). The arrows indicate the consecutive order in which the experimental values were measured. The insert shows the same dependence plotted in a double logarithmic scale. The dotted lines are the dependences $G \propto T$.

In the framework of Luttinger liquid theory, the thermoelectric power is a linear function of the temperature [18, 19]. Note that according to the same estimations, the thermopower of nanowires can be enhanced by the electron-electron interaction in comparison with that calculated by means of the Fermi-gas model.

The dependence presented in Fig. 1 satisfies the theoretical predictions within the limits of experimental errors. Moreover, this thermopower exceeds that measured in the ~40-nm-diameter InSb nanowire [4] by about 7 times. It is known that the electron-electron interaction (and the exponent α) increases with decreasing a nanowire diameter [7]. Therefore, the high thermopower of our nanowires compared with that measured in Ref. [4] can arise because of large electron-electron interaction.

The temperature dependence of the electrical conductance shown in Fig. 2 can be described by the simplest Luttinger liquid theory at temperatures up to about 300 K. This part of the curve is well fitted by power-law function $G \propto T^{2.2}$ with $\alpha = 2.2$. At temperatures ~80 K, the small deviation of the upper curve from power-law behavior appears because of violation of the inequality $k_B T \gg eV_1$. The increase of the curve slope at temperatures above 300 K (in some samples a deviation from the power law begin near 200 K) is not clear now. One of possible explanations is a filling of the second subband of the quantized spectrum by electrons at high temperatures.

The current-voltage characteristics of InSb nanowires exhibit also Luttinger liquid behavior. The measured *I-V* dependences are linear at small voltages but transform into almost power-law functions at high voltages, when $eV_1 \gg k_B T$. Moreover, the samples with a less resistance (that is the samples with less number of defects) reveal a nonlinearity of *I-V* characteristics at less applied voltages V because the voltage drop across one defect V_1 is greater in this case. In Fig. 3, the current-voltage characteristic of such a low-resistance sample is shown (upper curve). One can see that the characteristic is nonlinear at $V > 1$ V. When we increased the voltage, the low-resistance nanowires had been destroyed at $V \approx 4$ V because of electromigration of impurities or melting by Joule heat. After this irreversible change of the sample, the average density of defects in the remaining nanowires and their resistance sharply increase. As a result, the condition $eV_1 \gg k_B T$ was apparently violated and a following reduction of the voltage has revealed the

almost linear *I-V* characteristic of the sample (see the lower curve in Fig. 3).

In summary, we have shown that the electrical conductance and an absolute value of the thermopower of InSb nanowires increase monotonically with increasing temperature in the range from 80 to 400 K. The thermopower varies almost linearly with temperature. The temperature dependence of the conductance is close to the power law with exponent $\alpha > 2$. Such behavior results in a very rapid growth of the power factor of these structures with increasing temperature. The *I-V* characteristics of studied nanowires are nonlinear in general case. The nonlinearity of the characteristics depends on the applied voltage and defect structure of nanowires.

On the one hand, the obtained results indicate that many features of transport properties of nanowires may be at least qualitatively described by Luttinger liquid theory. This theory in particular predicts enhancing thermopower by interaction and our measurements ($S = -250\ \mu V/K$ at 400 K) confirm this prediction. On the other hand, it means that Fermi-liquid (Fermi-gas) approach is not applicable at least to one class of low-dimensional structures – to one-dimensional conductors.

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