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2006 J. Phys.: Condens. Matter 18 9651

(http://iopscience.iop.org/0953-8984/18/42/011)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) 9651–9657 doi:10.1088/0953-8984/18/42/011

One-dimensional electron transport and thermopower in an individual InSb nanowire

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Received 6 July 2006
Published 5 October 2006
Online at stacks.iop.org/JPhysCM/18/9651

Abstract

We have measured the electrical conductance and thermopower of a single InSb nanowire in the temperature range from 5 to 340 K. Below temperature (T) 220 K, the conductance (G) shows a power-law dependence on T and the current (I)–voltage (V) curve follows a power-law dependence on V at large bias voltages. These features are the characteristics of one-dimensional Luttinger liquid (LL) transport. The thermopower (S) also shows linear temperature dependence for T below 220 K, in agreement with the theoretical prediction based on the LL model. Above 220 K, the power law and linear behaviours respectively in the G–T and S–T curves persist but with different slopes from those at low temperatures. The slope changes can be explained by a transition from a single-mode LL state to a multi-mode LL state.

(Some figures in this article are in colour only in the electronic version)

Electron transport in one-dimensional (1D) systems has attracted great interest because the peculiar electron–electron interaction (e–e interaction) in 1D systems makes the transport properties distinctly different from bulk metals with a Fermi liquid (FL) of electrons. In 1D systems, the short-range e–e interaction leads to a Luttinger liquid (LL) [1] and long-range e–e interaction results in a Wigner crystal [2]. One of the main features of the LL state is the power-law dependence of tunnelling density of state (DOS) as a function of temperature and bias voltage. This leads to a power-law dependence of the electrical conductance (G) on temperature (T), i.e. $G(T) \sim T^{\alpha}$ at small biases ($eV \ll k_{\mathrm{B}}T$), or a power-law dependence of

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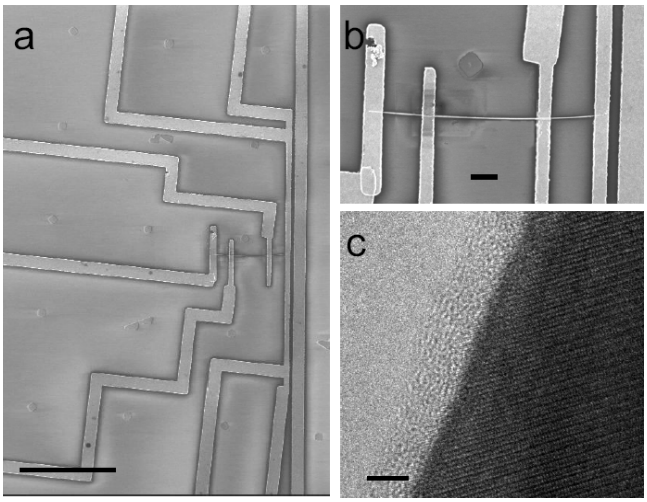

Figure 1. (a) Scanning electron microscopy (SEM) image of the measurement device. Scale bar = 10 μm. (b) Enlarged view of the four electrodes on the InSb nanowire. Scale bar = 1 μm. (c) Transmission electron microscopy (TEM) image of the InSb nanowire. Scale bar = 3 nm.

the differential conductance ($\mathrm{d}I/\mathrm{d}V$) on the bias voltage (V), i.e. $\mathrm{d}I/\mathrm{d}V \sim V^{\gamma}$, at large biases ($eV \gg k_{\mathrm{B}}T$). The LL behaviour has been reported in several 1D systems, such as single-wall and multi-wall carbon nanotubes (SWCNTs and MWCNTs) [3–5, 11], semiconductor nanowires [6–8], polymer nanofibres [9] and fractional quantum Hall edge states [10]. The exponents of the power law depend on the number of 1D channels within the system [12]. A transition from 1D LL to 3D FL has been observed as the number of interacting channels increased in nanowire bundles [13]. However, there has been no report on the energy-induced increase in the number of 1D conducting channels in a single nanowire LL system. In addition, there has been no experimental report of the thermopower of an LL system despite the increasing interest and several theoretical studies devoted to elucidating the thermopower in LLs [14–17].

In this paper we report electrical conductance and thermopower measurement results of a single indium antimonide (InSb) nanowire that was unintentionally doped possibly with tellurium during the vapour–liquid–solid (VLS) growth process [18]. A device fabricated by electron-beam lithography (EBL) was used for the measurements. The nanowire was deposited from a suspension on a 1 μm thick SiO_2 film grown on a silicon wafer. Four metal electrodes were patterned on the nanowire together with a heater line shown as the rightmost metal line in figure 1(a). The contact electrode to the nanowire adjacent to the heater line also served as a resistance thermometer line [19]. For measuring the thermopower, joule heating within the heater line by means of a direct current was used to raise the temperature at the thermometer line, the temperature increase (ΔT) of which was obtained by measuring its resistance change using a four-probe setup. The temperature rise at the leftmost electrode on the nanowire was found to be negligible in a heat conduction simulation. The thermovoltage (ΔV) between these two outer electrodes on the nanowire was measured and used to calculate the thermopower (or Seebeck coefficient) as $S = \Delta V/\Delta T$.

To improve the electrical contact between the nanowire and the metal electrodes, a 3 min immersion of the device in a solution of 23.7% $(NH4)_2S$ in water was used to passivate the surface of the nanowire segments exposed through windows opened in the EBL resist,

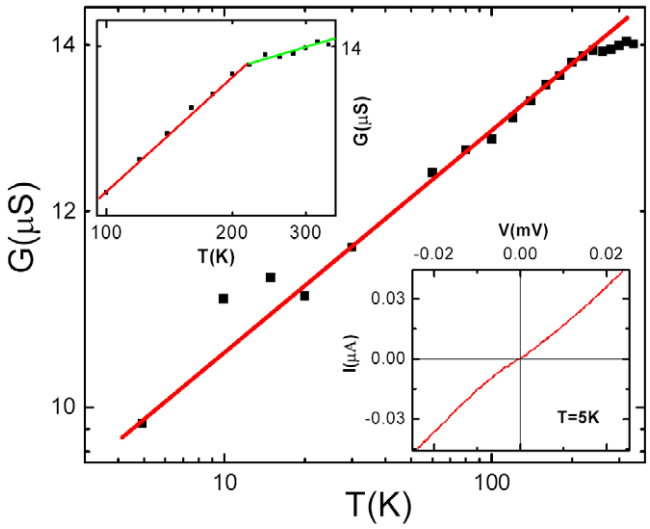

Figure 2. Four-probe electrical conductance (G) as a function of temperature (T). The line is the linear fit to the measurement data (filled squares) below $T = 220$ K. Upper inset: the G–T curve near 220 K. Lower inset: the two-probe I–V curve at $T = 5$ K.

i.e. polymethyl-methacrylate (PMMA). This was done after the PMMA was developed and before the metal deposition so that only the nanowire segments under the metal electrodes were passivated. During the passivation, the native oxide layer on the InSb nanowire was removed and the dangling bonds on the nanowire surface were terminated with a monolayer of sulfur atoms.

In figure 2, the four-point electrical conductance data obtained between the two inner electrodes on the nanowire are plotted on a double-logarithmic scale. The conductance increases with increasing temperature, which appears to be a typical semiconductor behaviour. The thermal activation model ($\ln(G) \propto -1/T$) and the variable-range hopping model ($\ln(G) \propto -1/T^{\delta}$) are widely used to describe the electronic transport in semiconductors [20]. However, neither of these models fits our experimental data. Instead, the conductance can be well fitted with a power-law function of temperature, $G(T) \sim T^{\alpha}$ with $\alpha = \alpha_1 = 0.09$ below temperature $T^* = 220$ K, with the exponent changing to $\alpha = \alpha_2 = 0.03$ for T above T^*. The upper inset of figure 3 shows that the current–voltage (I–V) characteristics also follow a power-law relation $I \sim V^{\beta}$ with $\beta = 0.87$. Thus, the LL model is more accurate in describing the transport mechanism in the InSb nanowire system. Furthermore, the measured I–V characteristics can be fitted well using the scaled master curve given by the LL theory as [3, 9, 13, 21]

$$I = I_0 T^{\alpha+1} \sinh\left(\frac{\gamma eV}{2k_{\mathrm{B}}T}\right)\left|\Gamma\left(1+\frac{\beta}{2}+\mathrm{i}\frac{\gamma eV}{2k_{\mathrm{B}}T}\right)\right| \tag{1}$$

where Γ is a gamma function, I_0 is a proportionality constant, α and β are the corresponding exponents in the power-law relations of $G(T) \sim T^{\alpha}$ and $I \sim V^{\beta}$. As shown in figure 3, all the two-probe I–V curves measured between the two outer electrodes at $T < 220$ K collapse into a single curve described by equation (1) by plotting $I/T^{\alpha+1}$ versus $eV/k_{\mathrm{B}}T$. The fitting parameters are $I_0 = 0.017$ and $\gamma = 0.025$.

The power-law behaviour in the InSb nanowire resembles the typical characteristic of an LL [3–10]. We attribute this power-law feature to single quasiparticle tunnelling processes

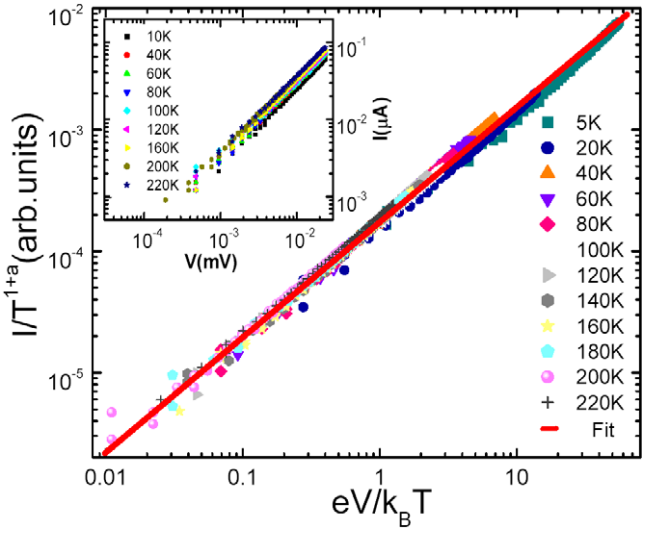

Figure 3. Scaled I–V curves. Inset: I–V curves at different temperatures. The line is the fitting curve based on equation (1).

at some blockade sites along the wire. The fitting parameter γ represents the ratio between the voltage drop across a dominantly resistive tunnelling junction at high bias to the total applied bias voltage across the entire device [3]. A γ value of 0.025 corresponds to about 40 tunnelling junctions along the nanowire. It has been suggested that defects and impurities in a nanowire act as tunnelling junctions between the ends of two LLs [14, 22, 23]. For the InSb nanowire, one possible scenario is that there were about 40 defects or impurity sites acting as tunnelling junctions along the 7.45 μm long nanowire between the two outer electrodes, so that γ was found to be 0.025. The exponent α in the power-law dependence is related to the interaction parameter g of the LL by $\alpha = (1/g - 1)/4$. This equation for end contacts is applicable here because the two middle electrodes in the four-probe configuration of the conductance measurement essentially make end contacts with the LL. Here, $g = g_1 = 0.74$ for $\alpha = \alpha_1 = 0.09$. At temperatures above T^*, the exponent $\alpha = \alpha_2 = 0.03$ corresponds to $g = g_2 = 0.89$. The power-law dependence of the conductance and the master curve fitting indicate that the InSb wire was in the LL state over the entire temperature range of the measurement. The large g values reveal that the electron–electron interaction is relatively weak compared with SWCNTs [3–5] and 16 nm diameter molybdenum selenide (MoSe) nanowire bundles [13].

Now we turn to the change of the power-law exponent at a crossover temperature $T^* = 220$ K (upper inset in figure 2). This change of the exponent has been reported recently in MoSe nanowires [13] as well as CNTs [11] and was interpreted as the transition from a Coulomb blockade (CB) regime to the LL regime [24, 25, 13]. If the CB energy is larger than $k_B T$ at $T = 5$ K for the InSb nanowire, there should be a zero conductance region at low bias voltages, which was not the case in the measured I–V curve (lower inset of figure 2). Hence, the CB energy should not be larger than $k_B T$ at 5 K and cannot be as large as that at 220 K. For CB to occur at $T = 220$ K, moreover, the charging energy E_c should be at least 10 times higher than $k_B T$ at 220 K, or at least 180 meV. The 7.45 μm long nanowire was likely divided into $\sim$190 nm long and 42 nm diameter metallic islands by about 40 impurity or defect sites. If one uses the self-capacitance of a 40 nm diameter spherical island on a dielectric substrate with a dielectric

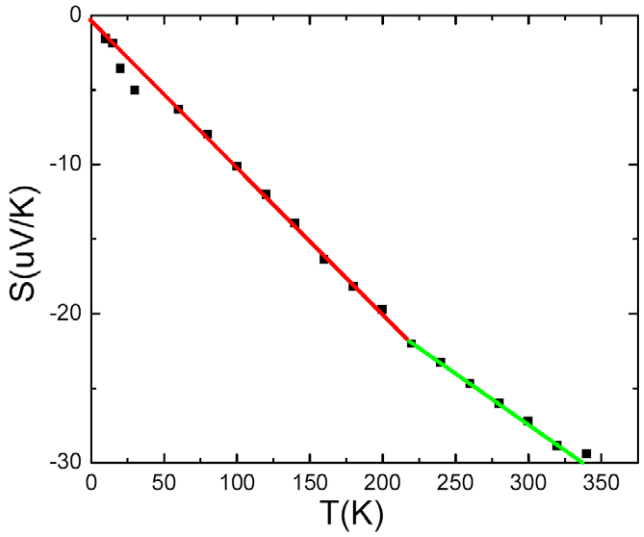

Figure 4. Thermopower as a function of temperature. The lines are the linear fits to the measurement data (squares) below and above $T^* = 220$ K.

constant $\varepsilon = 3$ as a rough estimate ($C \approx 2\pi\varepsilon_0\varepsilon d$, where d is the diameter), the charging energy $E_c = e^2/2C$ corresponds to $k_B T$ at about 10 K. The dimension of the ~40 islands along the nanowire was larger than the 40 nm island in the above estimation, so that the charging energy should be smaller than $k_B T$ at about 10 K and much smaller than that at $T^* = 220$ K. Hence, the possibility of transition to CB at 220 K was ruled out. On the other hand, the energy separation between the first and second quantum channels is $\Delta E = (\pi^2\hbar^2)/2m^*d^2$ [6]. The native oxide layer and potentially a surface charge-induced depletion layer on the nanowire surface can make the effective diameter for electron transport smaller than the nanowire diameter observed by an SEM. The native oxide thickness is typically found to be about 5 nm thick on the InSb nanowire (figure 1(c)), so that the effective diameter for electron transport is estimated to be about 32 nm or smaller for the 41.5 nm diameter nanowire. The effective carrier mass m^* ranges from 0.014 to $0.2m_e$ in bulk InSb, where m_e is the rest mass of a free electron, and the energy spacing ΔE between the two adjacent electron subbands corresponds to a temperature in the range 18–246 K, where the observed crossover temperature $T^* = 220$ K lies in. Hence, for temperature below 220 K the InSb nanowire is essentially a quantum wire with one or two (considering spin) quantum conduction channels. At temperatures above 220 K, the thermal energy $k_B T$ becomes comparable to the subband energy spacing ΔE, increasing the number of the conduction modes. In a single channel mode LL, there are no quasiparticles and only plasmons exist, while in an LL wire with multi-modes, there are excitations with velocities on order of V_F besides plasmons. These excitations represent FL quasiparticles. Hence, both plasmon and quasiparticles are created by the tunnelling electrons in the multi-mode LL [12]. The transition from single-mode transport to multi-mode transport can cause an increase in the interaction parameter g and a decrease of the exponent α for the tunnelling DOS.

We have also measured the thermopower of the same nanowire using the measurement device [19]. The results are shown in figure 4. The negative sign of the obtained thermopower suggests that the dominant carriers are electrons. At temperatures below $T^* = 220$ K, the thermopower decreases linearly with decreasing temperature at a slope of 0.097 μV K^{-2}. The linear dependence persists above T^* with a smaller slope of 0.069 μV K^{-2}. The crossover

temperature in the S–T curve coincides with the crossover temperature in the G–T curve (figure 2). This occurrence suggests that the electronic structure change at T^* causes the slope change in both the G–T and S–T curves.

It has been predicted that the e–e interaction results in the corrections on the electron density of states and thus a change in the conductivity and thermopower [14–17]. However, there have been no measurements of the thermopower of an LL. The thermopower of an LL can be induced by (i) the dispersion of the electron energy spectrum near the Fermi energy and (ii) the backscattering of the electrons by an impurity. The energy dispersion relation is linear near the Fermi energy in LLs, so that the thermopower originating from this term is zero. Although an introduction of higher-order nonlinear electron spectrum can result in thermopower, this term is negligible compared with the thermopower induced by local impurity scattering [14]. For the InSb nanowire, the defects and impurities can be modelled as tunnelling junctions between several decoupled LLs. At low temperature, even a small barrier potential can strongly influence the transport properties in 1D systems, so that the thermopower induced by electron backscattering dominates [17, 26]. The electron–electron interaction in 1D systems enhances the impurity-induced thermopower and renormalizes the thermopower. Correlated with the interaction strength factor g, this enhancement can be written as [17, 26]

$$S(T) \approx S_0(T)/g, \tag{2}$$

where $S_0(T) \propto T$ is the thermopower of a noninteracting electron system. Hence, the thermopower of the nanowire will be enhanced by a factor of g^{-1} and this enhancement effect can be reflected in the slope of the S versus T curve [23]. In order to clarify this enhancement effect in the InSb nanowire, we correlate the slope change at T^* with the interaction strength factor g. The ratio of the slopes of the S–T curve below and above T^* was calculated to be 1.2 according to equation (2). This ratio is 1.4 from the slopes found in figure 4 for the two temperature ranges. The two values are rather close. Hence, the experimental result supports the theory of thermopower of an LL system, where impurity backscattering is considered to be a main origin of the thermopower.

We would like to point out that in this discussion we assume that the electron–phonon (e–p) interaction is very weak compared with the electron–electron interaction. This is because only a small population of phonons with the energy $\hbar\omega_{\mathrm{ph}}$ and wavevector $2k_{\mathrm{F}}$ are available to provide the allowable large momentum transfer $2k_{\mathrm{F}}$ for the back scattering of electrons by phonons to occur [26]. The weak temperature dependence of the conductance also indicates that electron–phonon scattering is suppressed in the thin InSb nanowire compared with its bulk counterpart.

In summary, we measured the I–V characteristics and thermopower of a single 41.5 nm diameter InSb nanowire in the temperature range between 5 and 340 K. It was found that the G–T curve follows the power-law dependence of 1D systems with a slope change at a crossover temperature $T^* = 220$ K. The S–T curve shows a linear temperature dependence also with a slope change at the same crossover temperature $T^* = 220$ K. The transition from a single-channel mode LL to a multi-mode LL state can give a reasonable interpretation of both the observed I–V characteristics and thermopower.

Acknowledgments

The authors acknowledge Dr Natalio Mingo for helpful discussions. This work is supported by NASA under contract No. NNA05BE36C to ELORET. The authors at Austin are supported in part by Office of Naval Research contract No. N00014-04-1-0532 (Program Manager: Dr Mihal E Gross).

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