The electronic transport of top subband and disordered sea in an InAs nanowire in the presence of a mobile gate

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Received 11 October 2013, revised 23 December 2013
Accepted for publication 8 January 2014
Published 3 April 2014

Abstract
We performed measurements at helium temperatures of the electronic transport in an InAs quantum wire ($R_{\text{wire}} \sim 30 \, \text{k}\Omega$) in the presence of a charged tip of an atomic force microscope serving as a mobile gate. The period and the amplitude of the observed quasi-periodic oscillations are investigated in detail as a function of electron concentration in the linear and non-linear regime. We demonstrate the influence of the tip-to-sample distance on the ability to locally affect the top subband electrons as well as the electrons in the disordered sea. Furthermore, we introduce a new method of detection of the subband occupation in an InAs wire, which allows us to evaluate the number of electrons in the conductive band of the wire.

Keywords: scanning gate microscopy, atomic force microscopy, InAs nanowire, mesoscopics

1. Introduction
In the past decade an increasing number of investigations have been dedicated to the electronic transport in semiconductor nanowires [1–4]. Nanowires based on III–V semiconductors, e.g. InAs are especially attractive as conductive channels in devices for nano-electronic applications [5, 6]. Apart from more application-driven investigations, InAs nanowires are also very suitable objects to study fundamental quantum phenomena, i.e. single electron tunneling [7, 8] or electron interference [9–12], at low temperatures. At helium temperatures the transport in InAs nanowires is mostly diffusive and typical values of the elastic mean free path $l_e$ are of the order of a few tenths of nanometers [9–11]. Information on electron phase coherence can be extracted from the temperature dependence of universal conductance fluctuations [11, 12].

In order to gain detailed information of local conductance features in low-dimensional systems, mobile gate measurements employing a charged AFM tip (scanning gate microscopy measurements or SGM measurements) have been established as a standard method. Quantum point contacts [16–18], quantum rings [19], quantum dots based on heterojunctions [20–22], graphene [23], and carbon nanotubes [24–26] have been investigated comprehensively using SGM. Investigations of local electronic transport in InAs nanowires with scanning gate microscopy were performed at room temperature [27, 28] as well as at He temperatures [29–33, 37]. However, these studies mostly focused on wires with initially existing [29–32] or artificially created [33] defects, i.e. potential barriers made of InP, which divided the nanowire into a series of quantum dots.

Essential efforts have been made in the theoretical understanding of the problem of electronic transport in systems perturbed with a charged AFM tip [34–36] as well. In [34] two regimes with weak and strong influences of AFM tip on electronic system of the wire are discussed. [35] gives a detailed explanation of methods used to extract the structure of electron wavefunction from SGM measurements. [36] gives an
explicit interpretation of SGM measurements on point contacts in 2D electron systems.

Recently, in InAs nanowires without defects with characteristic resistance values of 30 kΩ, unexpected quasi-periodic oscillations of the resistance along the wire were observed in SGM scans [37]. The non-monotonic dependence of the period of observed oscillations on the back-gate voltage made it possible to associate them with electrons in the top subband with a small Fermi wavelength comparable with the length of the wire ($\lambda_F \sim l_{\text{wire}}$) altering the resistance of the whole system. These electrons do not scatter on the surface of the nanowire and do not mix with other free electrons of the lower laying mixed subbands (disordered sea). However, the experiment reported in [37] left the mechanism behind the oscillations as an open question.

Here, we present a detailed investigation of the resistance oscillations in an InAs nanowire, namely the tracing of the oscillation from a clearly defined two-nodes state through a three-nodes one to a state where minima split. Furthermore the stability of two-nodes oscillations in the non-linear regime is discussed. We demonstrate the influence of the tip-to-sample distance on the ability to locally influence the top subband electrons as well as the electrons in the disordered sea. We suggest a new method to determine the occupation of the topmost subband using a line trace of a charged AFM tip along the wire. This method allows us to evaluate the number of conductive electrons added to the InAs wire on applying a positive back-gate voltage.

2. Experimental details

In our experiment we study a nominally undoped InAs nanowire grown by selective-area metal-organic vapor-phase epitaxy [38]. The diameter of the wire is 100 nm. The wire was placed on an n-type doped Si (100) substrate covered by a 100 nm thick SiO$_2$ insulating layer. The Si substrate served as the back-gate electrode. The evaporated Ti/Au attached to the back-gate electrode. The evaporated Ti/Au attached to the wire as well as the markers of the search pattern were defined by electron-beam lithography. The evaporated Ti/Au attached to the back-gate electrode. The evaporated Ti/Au attached to the wire as well as the markers of the search pattern were defined by electron-beam lithography. The distance $l_{\text{wire}}$ between the contacts is 2.6 μm. A scanning electron-beam micrograph of the sample is shown in figure 1(a). The source and drain metallic electrodes connected to the wire are marked by S and D.

All measurements were performed at $T = 4.2$ K. The charged tip of a home-built scanning probe microscope [39] is used as a mobile gate during scanning gate imaging measurements. All scanning gate measurements are performed by keeping the potential of the scanning probe microscope tip ($V_{\text{tip}}$) as well as the back-gate voltage ($V_{\text{BG}}$) constant. The conductance of the wire during the scan is measured in a two-terminal circuit by using a standard lock-in technique. Here, a driving AC current with an amplitude of $I_{\text{AC}} = 1$ nA at a frequency of 231 Hz is applied while the voltage is measured by a differential amplifier. Two typical tip-to-SiO$_2$-surface distances were chosen for the scanning process: the tip is far from the surface means $h_{\text{tip}} = 300$ nm, and the tip is close to the surface means $h_{\text{tip}} = 220$ nm.

![Figure 1](image_url)

Figure 1. (a) Scanning electron microscope image of the InAs nanowire. The source and drain contact pads are marked by S and D. The scale bar corresponds to 1 μm. The positions of the tip during the transport measurements versus $V_{\text{BG}}$ performed equidistantly along the wire are marked by a dashed line, the position of the tip for the reference is marked by ‘★’. (b) Dependence of $2.1 \, \mu \text{m}/l_{\text{node}}$ where $l_{\text{node}}$ is the distance between nodes of the resonances extracted from the set of SGM images. Bright and dark symbols show $l_{\text{node}}$ for $N_{\text{node}} = 2$ and 3, respectively. (c)–(h) SGM images measured at $V_{\text{BG}} = 8.98, 9.14, 9.50, 9.62, 9.94$ and 10.40 V, respectively, depicting the nanowire resistance at different tip positions ($V_{\text{tip}} = 0$ V). Brighter color means higher resistance. The driving current is $I_{\text{AC}} = 1$ nA. The tip to surface distance is $h_{\text{tip}} = 300$ nm. The positions of the nodes are marked with pink and blue triangles for two-nodes and three-nodes patterns, respectively. The scale bar corresponds to 1 μm. The scale is the same for all SGM images from (c) to (h). The solid lines in each SGM image traces the edges of the metallic contacts while the dashed line marks the wire axis. (i) Crosscut of (h) along the wire axis with minima marked by triangles.
3. Experimental results

In figures 1(c)–(h) scanning gate microscopy images in the linear regime are shown which are obtained at back-gate voltages of \( V_{\text{BG}} = 8.98, 9.14, 9.50, 9.62, 9.94 \) and 10.40 V, respectively, keeping the tip voltage \( V_{\text{tip}} \) fixed at zero. The tip-to-surface distance during these measurements was kept at \( h_{\text{tip}} = 300 \) nm. Increasing the back-gate voltage the situation develops through a well-defined two-nodes pattern (see figures 1(c), (d)), then passing a two-to-three node regime (see figures 1(e), (f)) and subsequently to a well-defined three-nodes one (see figure 1(g)). The corresponding positions of nodes in the SGM scans are marked by pink and blue triangles for two-nodes and three-nodes patterns, respectively. At \( V_{\text{BG}} = 9.14 \) and 9.94 V in the single resonance regime (see figures 1(c), (g)) the oscillations are well-defined, while in the intermediate regime the oscillations are slightly less visible (see figures 1(e), (f)). It is worth noting that at \( V_{\text{BG}} = 9.62 \) V two-nodes and three-nodes patterns are resolved simultaneously. Finally, at the highest back-gate voltage of 10.40 V, the pattern evolves into a four-nodes regime with split minima, as can be inferred from figure 1(h). A crosscut of this pattern along the wire axis is shown in figure 1(i). The resulting eight quasi-periodic minima are marked by inverted triangles.

In order to access the rigidity of the observed oscillations we calculated the ratio \( l_{\text{eff}}/l_{\text{node}} \), with \( l_{\text{eff}} \) the effective wire length and \( l_{\text{node}} \) the distance between the nodes. As can be seen in figure 1(b), the ratio defined above strongly depends on the back-gate voltage \( V_{\text{BG}} \) and resembles a staircase shape with well developed plateaus. In order to adjust the position of the lower step to an integer node number \( N_{\text{node}} \), we used a value of 2.1 \( \mu \)m for the effective wire length \( l_{\text{eff}} \). This value is slightly smaller than the geometrical length of the wire \( l_{\text{wire}} = 2.6 \) \( \mu \)m but looks reasonable keeping in mind the presence of the depletion regions at the interfaces between the wire and the metallic contacts.

Next we present scanning gate measurements, where the driving current through the nanowire was increased stepwise. The images shown in figure 2(a)–(d) correspond to a \( I_{\text{AC}} = 1, 4, 12.5 \) and 50 nA, respectively. These measurements were obtained by applying a back-gate voltage of \( V_{\text{BG}} = 8.7 \) V and setting \( V_{\text{tip}} \) to zero. Once again the tip is kept far from the surface (\( h_{\text{tip}} = 300 \) nm). It is worth noting that while in figures 2(a)–(c) the energy corresponding to the typical source-to-drain voltage is smaller than the thermal energy \( eV_{\text{SD}} < k_{\text{B}}T \), for the case of figure 2(d) the situation is opposite, i.e. \( eV_{\text{SD}} > 1.6 \) meV \( > k_{\text{B}}T \), with \( k_{\text{B}} \) the Boltzmann constant. Crosscuts of figures 2(a)–(d) along wire axis are shown in figure 2(e). As can be seen, no significant deviations of the node positions and the amplitude of the oscillations are found up to \( I_{\text{AC}} = 12.5 \) nA. However, a slight suppression of the oscillations and a decrease of the resistance are observed in the strong non-linear regime at \( I_{\text{AC}} = 50 \) nA.

For the next two sets of SGM images shown in figures 3(a)–(f) a closer tip-to-surface distance of \( h_{\text{tip}} = 220 \) nm was chosen. These measurements were performed in the linear regime by using a driving current of 1 nA. The first set, shown in figures 3(a)–(c), is measured at smaller back-gate voltages of \( V_{\text{BG}} = 3.97, 3.98 \) and 3.99 V. The triangles mark the nodes of three-nodes pattern created by conductive electrons of the top subband. The second set of scans, depicted by figures 3(d)–(f), taken at the higher back-gate voltage of 8.51, 8.52 and 8.53 V, respectively. Here, the smooth background was subtracted, in order to emphasize the small scale ripples on the scan. As a reference, figure 3(g) shows crosscuts along the wire axis of pristine SGM data (without subtraction) at the different back-gate voltages.

The next set of experimental data is dedicated to resistance versus back-gate dependencies for different charged tip positions. Once again, for all measurements the tip voltage is set to zero. First, in figure 4(a) the dependence of the normalized reciprocal wire resistance \( 1/(h/e^2/R_{\text{ref}}) \) i.e. the normalized conductance, on the back-gate voltage \( V_{\text{BG}} \) is shown, where the tip is placed at a fixed location far from the wire. The location of the spot is indicated by a \( \bullet \) in figure 1(a). The trace shown in figure 4(a) will serve as a reference for the later position dependent measurements. The fluctuating conductance can be assigned to the phenomenon of universal conductance fluctuations [40, 41]. The corresponding fluctuation amplitude can be determined by first subtracting the background conductance \( (h/e^2)/R_{\text{lim}}(V_{\text{BG}}) \) obtained from a linear fit of \( (h/e^2)/R_{\text{ref}}(V_{\text{BG}}) \). The remaining fluctuations \( \Delta((h/e^2)/R) = (h/e^2)/(1/R_{\text{ref}} - 1/R_{\text{lim}}) \) are shown in the inset of the figure 4(a). Here, a typical value of fluctuation amplitude of 0.1\( (h/e^2) \) for the back-gate voltage
using driving currents of (a)–(c) SGM images of the InAs wire resistance made Figure 3. J. Phys.: Condens. Matter 26 (2014) 165304

(a)–(c) SGM images of the InAs wire resistance made using driving currents of $I_{AC} = 1$ nA. A shorter tip-to-surface distance of $h_{tip} = 220$ nm was chosen. The tip voltage is $V_{tip} = 0$ V for all scans. Back-gate voltages are of $V_{BG} = 3.97, 3.98$ and $3.99$ V for (a)–(c), respectively. The side scale bar represents the color to resistance mapping in quantum resistance units $(h/e^2)$. Triangles mark nodes of three-nodes pattern. (d)–(e) are SGM images of the InAs nanowire resistance made using driving currents of $I_{AC} = 1$ nA after subtraction of the smooth background $\Delta R = R - R_{smooth}$ in quantum resistance units $(h/e^2)$. Back-gate voltages are of $V_{BG} = 8.51, 8.52$ and $8.53$ V for (d)–(f), respectively. The side scale bar represents the color to $\Delta R/(h/e^2)$ map. The horizontal scale bar in all SGM scans corresponds to $1$ µm. The solid lines in each SGM image trace the edges of the metallic contacts and the dashed line marks the wire axis. (g) represents crosscuts of SGM scans (d)–(f) normalized on quantum resistance $(h/e^2)$ before background subtraction.

range of $0$ V $\leq V_{BG} \leq 12$ V. This value fits well to comparable measurements on InAs nanowires [11, 12]. Next we will present a set of measurements, where the tip is placed equidistantly from source to drain at fixed positions $i = 1 \ldots 11$ along the dashed line indicated in figure 1(a). In figure 4(b) the deviation of the conductance with respect to the conductance with a tip positions far from the wire $R_n^{-1}(V_{BG}) - R_{ref}^{-1}(V_{BG})$ is plotted as a function of back-gate voltage for the different positions $i$. Three well-defined minima in the conductivity (grooves) are observed around $V_{BG} \approx 2.7, 7.5$ and $10.5$ V marked by I, II and III in figure 4(b).

4. Discussion

In our previous work SGM experimental data with 10, 2, 3 and 4 standing wave nodes ($N_{node}$) have been presented [37]. The transition from $N_{node} = 10$ to $N_{node} = 2$ was interpreted as the formation of a new top subband and while the previous top subband sinks into ‘disordered sea’. ‘Disordered sea’ contains conductive 3D electrons with mean free path governed by wire diameter, while electrons in the top subband are 1D electrons demonstrating ballistic transport. Experimental results in paper [37] were obtained in the previously mentioned resonance condition $N_{node}/I_{node} = I_{wire}$. While the nodes are the most pronounced features, no information about $I_{node}(V_{BG})$ in between resonances were provided. It was found in [37], that the oscillation amplitude drops as $N_{node}$ increases, thus the transformation from $N_{node} = 2$ to $3$ was chosen in this study as the preferable $V_{BG}$ range to extract $I_{node}(V_{BG})$ in out-of-resonance condition. The observed staircase shape dependence of $1/I_{node}$ versus $V_{BG}$, as indicated in figure 1(b), is qualitatively in good agreement with the model of standing waves of ballistic electrons in the top transverse quantization subband. Standing waves are the result of the presence of potential barriers at metal–semiconductor interfaces. In the models of Wigner crystallization of Luttinger liquid and Friedel oscillations a similar dependence of $1/I_{node}$ versus $V_{BG}$ is expected [42]. One finds, that the kinetic energy $E_k(N_{node} = 3) = [(3\pi/I_{wire})h^2/(2m^*)] = 21$ µeV is essentially less than $k_BT$ even for the three-nodes resonant state. Here, $m^* = 0.023 m_e$ is the effective mass of electron in InAs, $m_e$ is the free electron mass, $h$ is the Planck constant. In addition, the thermal length $L_T(N_{node} = 3) = h^2/(2\pi m^* k_BT (2I_{wire}/3)) \sim 30$ nm is considerably smaller than the length of the wire $I_{wire} = 2.6$ µm. The energy difference between the two-nodes and three-nodes
resonance states is less than $k_BT$ because both states are resolved simultaneously at a back-gate voltage $V_{BG} = 9.62 \text{ V}$ (see figure 1(f)). The Coulomb energy of the electron–electron interaction, $\Delta = 2e^2d_L^2/(4\pi \varepsilon_0 \varepsilon)\varepsilon_{wire}/3$, even for the three-nodes resonant state is less than $k_BT$ as well. Here, $\varepsilon = 15.15$ is the static dielectric constant in InAs, $d_L \sim 150 \text{ nm}$ is the distance from the center of the wire to the doped back-gate, and $\varepsilon_0$ is the vacuum permittivity. Thus, the ability of Wigner crystallization, Friedel oscillations and standing wave scenarios looks rather doubtful for $N_{node} = 2$ and 3. Temperature dependence of Friedel oscillations, but for coherent Luttinger liquid is discussed in detail in [43]. The Coulomb interaction between electrons becomes comparable to the temperature $\Delta = 0.16 \text{ meV}$ only at $V_{BG} = 10.40 \text{ V}$ when the average distance between the electrons is around 250 nm. We may speculate that the formation of a Wigner crystal in the top subband happens at this back-gate voltage with a $2k_T$ to $4k_T$ transformation of the oscillations.

SGM images presented in figure 2 demonstrate the robustness of the two-nodes resonant state to application of source to drain voltage. As it was mentioned above, no significant deviations of the node positions and the amplitude of the oscillations are found as long as $\varepsilon_{VSD} \leq k_BT$. Only the application of a large current of $I_{AC} = 50 \text{ nA}$ resulting in $\varepsilon_{VSD} \sim 1.6 \text{ meV} \gg k_BT$ suppresses the oscillations and decreases the resistance (see figure 2(e)).

The results of the SGM scans made when the tip to surface distance is 220 nm, i.e. the closest distance from tip to the wire axis is 170 nm, are presented in figures 3(a)–(g). As previously stated, if the distance from the tip to the wire axis $l_{tip} \gg d$ the density oscillations of the top subband are probed while at $l_{tip} \sim d$ the charged tip disturbs the disordered sea as well. The pattern of the ripples in figures 3(d)–(f) changes essentially when $V_{BG}$ rises for 10 mV while SGM images are obtained with the scanning tip placed close to the nanowire ($l_{tip} \sim d$). Thus, figure 3 presents a solid confirmation that electrons in the disordered sea are not localized. The characteristic deviation of the back-gate voltage inducing the redistribution of conductivity maxima and minima in SGM images when the tip is scanning over the nanowire ($l_{tip} \sim d$) is about 10 mV.

In contrast to that, the width of the step in dependence of $I_{node}(V_{BG})$ is more than a hundred millivolts. The irregular pattern observed in SGM scans governed by the disordered sea has the smallest typical length scale of 200 nm, which is in accordance with the expected spatial resolution of the experimental set up for $h_{tip} = 220 \text{ nm}$. The amplitude of the deviations of resistance (see figure 3(g)) is comparable with the amplitude of the universal conductance fluctuations shown in figure 4(a) (inset).

In [37] the abrupt increase of the $I_{node}$ was interpreted as the formation of the new subband in the InAs wire. The instance of subband formation electrons are loaded simultaneously to the disordered sea and to the band with the increase of back-gate voltage. Electrons loaded to the new subband are blocked because of the potential barriers at the wire contact with the interfaces forming a semi-opened quantum dot. This dot decreases the total conductance of the wire at a certain range of back-gate voltage, namely from $V_{BG}$ of quantum dot formation to the value of the back-gate voltage when the barriers become transparent. Let us call the center of this range $V_{BG1}$. It is possible to slightly alter $V_{BG1}$ with the charged AFM tip. Taking into account that electrons in a quantum dot are concentrated in the center of the wire, $V_{BG1}$, as a function of the tip position along the wire, must have one maximum [26, 35]. This maximum is traced by the dashed line in figure 4(b). Thus, three subbands are formed and marked as I, II and III in the region of back-gate voltage of $0 \text{ V} < V_{BG} < 12 \text{ V}$ at $V_{BG} \approx 2.7$, 7.5 and 10.5 V, respectively. There is some discrepancy for back-gate voltages less than 1 V in the determination of the formation of the second subband when comparing to the data in [37], where the formation was determined directly from SGM scans. This originates from the hysteresis in $R_{wire}(V_{BG})$ of the sample.

Observation of the formation of three subbands in the $0 \text{ V} < V_{BG} < 12 \text{ V}$ back-gate region means that the total number of loaded subbands may be evaluated as 4 or 5 and, thus, the total number of conductive electrons loaded into wire containing 1D electrons of top subband and 3D electrons of the ‘disordered sea’ is less than 100. The total number of electrons added to wire calculated from the capacitance is around 2000 [37]. It means that most of the electrons in the wire are probably trapped because of interface states charged by changing the back-gate voltage. Thus, all electrons in InAs wire are of three types, namely, 1D conductive electrons of top subband, 3D conductive electrons of ‘disordered sea’ and localized electrons in the traps. This also means that the value of mean free path must be recalculated as well. It seems $l_e$ is actually larger than the typically used value of 40 nm even for disordered sea. A value of $l_e \sim 200 \text{ nm}$ was measured by Zhou et al [47] at room temperature.

5. Conclusion

We performed measurements at helium temperatures of the electronic transport in an InAs nanowire ($R_{wire} \sim 30 \text{ k}\Omega$) in the presence of a charged tip of an atomic force microscope serving as a mobile gate. The period and the amplitude of previously observed quasi-periodic oscillations are investigated in detail as a function of back-gate voltage in the linear and non-linear regime. None of the scenarios such as Friedel oscillations, Wigner crystallization or standing wave looks applicable to explain the origin of observed oscillations at $N_{node} = 2$ and 3. We demonstrate the influence of the tip-to-sample distance on an ability to influence locally the top subband electrons as well as the electrons in the disordered sea. We suggest a new method of evaluation of the number of conductive electrons in an InAs wire. This method leads to the conclusion that most of the electrons added to nanowire conductive band on applying a positive back-gate voltage are trapped.

Acknowledgments

This work is supported by the Russian Foundation for Basic Research programs of the Russian Academy of Science, the Program for Support of Leading Scientific Schools, and by the International Bureau of the German Federal Ministry of Education and Research within the project RUS 09/052.
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