Quantum interference effects in InAs semiconductor nanowires

Citation for published version (APA):

DOI:
10.3938/jkps.54.135

Document status and date:
Published: 01/01/2009

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Quantum Interference Effects in InAs Semiconductor Nanowires

Yong-Joo Doh
Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands and National CRI Center for Semiconductor Nanorods, Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang 790-784

Aarnoud L. Roest and Erik P. A. M. Bakkers
Philips Research Laboratories, Professor Holstlaan 4, 5656 AA Eindhoven, The Netherlands

Silvano De Franceschi
LaTEQs laboratory, DSM/DRFMC/SPSMS, CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble, France and TASC laboratory, CNR-INFM, S.S. 14, Km 163.5, 34012 Trieste, Italy

Leo P. Kouwenhoven
Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

(Received 26 September 2008)

We report quantum interference effects in InAs semiconductor nanowires strongly coupled to superconducting electrodes. In the normal state, universal conductance fluctuations are investigated as a function of the magnetic field, the temperature, the bias and the gate voltage. The results are found to be in good agreement with theoretical predictions for weakly disordered one-dimensional conductors. In the superconducting state, the fluctuation amplitude is enhanced by a factor up to 1.6, which is attributed to a doubling of the charge transport via Andreev reflection. At a temperature of 4.2 K, well above the Thouless temperature, conductance fluctuations are almost entirely suppressed and the nanowire conductance exhibits anomalous quantization in steps of $e^2/h$.

PACS numbers: 73.23.-b, 74.25.Fy, 85.30.St, 85.25.Cp

Keywords: InAs, Semiconductor nanowires, Universal conductance fluctuations, Superconductors, Conductance quantization

I. INTRODUCTION

Chemically grown semiconductor nanowires can provide a mesoscopic system to study quantum confinement and interference effects at low temperature, which is a promising platform to develop novel quantum devices. In the Coulomb blockade regime, single-electron tunneling devices [1,2] and few-electron quantum dots [3] have been realized successfully from various nanowires. In the strong coupling regime, the Kondo effect [4], weak localization [5] and universal conductance fluctuations [4-6] have been observed using InAs nanowires. With highly transparent contacts to conventional superconductors, a supercurrent can flow through the semiconductor nanowire to enable Josephson field-effect transistors [6,7] and gate-tunable superconducting quantum interference devices [8] on a nanoscale.

Universal conductance fluctuations (UCF) are caused by the quantum interference of multiply scattered electronic wavefunctions in a weakly disordered conductor, giving rise to aperiodic conductance fluctuations as a function of the magnetic field and the Fermi energy [9, 10]. As the sample size, $L$, becomes smaller than the phase coherence length $L_\phi = (D\tau_e)^{1/2}$, where $D$ is the electron diffusion constant and $\tau_e$ is the inelastic scattering time, the root-mean-square (rms) amplitude of the fluctuations is of order $e^2/h$, independent of the degree of disorder [9,10]. Here, $e$ is the electric charge and $h$ is Planck’s constant. When a mesoscopic normal conductor is brought into contact with a superconductor, the phase-coherent electronic transport is expected to incorporate superconducting correlations [11], resulting in a
combination of UCF and Andreev reflection [12]. Following some initial pioneering work [13] based on all-metallic systems, further investigation of such a fundamental phenomenon has remained an experimental challenge [14].

Here, we investigate the conductance fluctuations of InAs nanowires contacted with superconducting Al electrodes as a function of the magnetic field $B$, the backgate voltage $V_g$, the bias $V$ and the temperature $T$. The magnetococonductance data show reproducible and aperiodic fluctuations with a characteristic amplitude of order $e^2/h$. We estimate the phase-coherence length to be $L_\phi \approx 100$ nm at $T = 30$ mK. The autocorrelation function of the magnetococonductance data decays on a field scale consistent with this value of $L_\phi$. In the superconducting state, the amplitude of conductance fluctuations is enhanced by a factor of up to $\sim 1.6$ at low bias below the superconducting energy gap $2\Delta/e$, which is attributed to the participation of Andreev reflected holes in the UCF.

As we increase the temperature above the Thouless temperature, $E_{T\phi}/k_B \sim 1.2$ K, where $k_B$ is the Boltzmann constant, the conductance fluctuations are suppressed by thermal dephasing. With the UCF being almost washed out at $T = 4.2$ K, anomalous conductance plateaus at multiples of $e^2/h$ are observed as a function of $V_g$, which are insensitive to the application of a perpendicular magnetic field up to $B \sim 2$ T. The possible origin of this anomalous quantization is discussed.

II. EXPERIMENTS

Single-crystalline InAs nanowires are grown via a laser-assisted vapor-liquid-solid method. After the nanowires had been deposited on a degenerately doped p-type silicon substrate with a 250-nm-thick surface oxide, superconducting contacts were formed using Ti(10 nm)/Al(120 nm). Details on the nanowire growth and device fabrication have been published elsewhere [6].

The linear conductance $G$ of the nanowire device, corresponding to the inverse of the dynamic resistance $|dV/dI|^{-1}$, was measured using an AC lock-in technique, in which the AC voltage across the sample was kept below $k_BT/e$ to avoid electron heating. To reduce the external noise effects, we filtered the measurement leads by using II filters at room temperature and by using low-pass RC and copper powder filters at the temperature of the mixing chamber in a dilution refrigerator.

III. RESULTS AND DISCUSSION

Typical magnetococonductance data at $T = 30$ mK are shown in Figure 1(a). The magnetic field, $B$, was applied parallel (perpendicular) to the nanowire axis for device D1 (D2). The overshoot of the $G(B)$ curve near $B = 0$ T is due to a supercurrent induced by the superconducting proximity effect. Regardless of the fields direction, reproducible and aperiodic conductance fluctuations are observed as a function of the magnetic field. The peak-to-peak variation of the magnetococonductance is about $e^2/h$, consistent with theoretical predictions [9,10]. The $G(B)$ curve is symmetric upon field reversal, as expected for a mesoscopic two-probe measurement [15]. The rms magnitude of the magnetococonductance fluctuations is defined as $\text{rms}(G_B) = <(G(B) - <G(B)>)^2>^{1/2}$, where the angular brackets refer to an average over magnetic field, resulting in $\text{rms}(G_B) = 0.29 \pm 0.03 \ e^2/h$ for D1 (D2) for a perpendicular magnetic field. In this average, we disregarded the low-field data range ($|B| < 0.5$ T) where the magnetococonductance was affected by weak localization/antilocalization [5] and superconducting prox-
The phase coherence length $L_\phi$ can be obtained from an analysis of the autocorrelation function of $G(B)$, which is defined as $F(\Delta B) = \langle G(B)G(B + \Delta B) \rangle - \langle G(B) \rangle^2$ with $\Delta B$ being a lag parameter in the magnetic field [9,10]. $F(\Delta B)$ is expected to have a peak at $\Delta B = 0$. The half-width at half height of this peak corresponds to the magnetic correlation length, $B_c$, over which the phases of the interference paths become uncorrelated with those at the initial field. Figure 1(b) shows the positive side $(\Delta B > 0)$ of the autocorrelation function.

From the data obtained in a perpendicular magnetic field (open dots) we find $B_c = 0.21 \text{T}$ and $0.18 \text{T}$ for devices D1 and D2, respectively. According to theoretical calculations for a quasi-one-dimensional conductor [11], the correlation field is expected to be inversely proportional to the coherence length, i.e. $B_c = 0.42 \Phi_0/(wL_\phi)$, where $\Phi_0 = \hbar/e$ is the one-electron flux quantum and $w$ is a width corresponding to the nanowire diameter (80 nm). From $B_c \approx 0.2 \text{T}$, we find $L_\phi \approx 100 \text{ nm}$. This value is smaller than the one obtained from weak localization/anticontinullization measurements in similar nanowires [5]. Since the Fermi wave number, $k_F$, is estimated to be $\sim 5 \times 10^6 \text{ cm}^{-1}$ from the carrier concentration as $\sim 6 \times 10^{18} \text{ cm}^{-3}$ [6], our assumption of a quasi-one-dimensional conductor is satisfied with $k_F l \gg 1$, where $l = 10 - 100 \text{ nm}$ is the elastic mean free path [5,6]. Similar $F(\Delta B)$ curves are obtained with the magnetic field applied parallel to the nanowire axis, in contrast with previous results for multi-walled carbon nanotubes [15]. We argue that the seemingly weak dependence of $B_c$ on the field direction reflects the fact that $L_\phi$ is very close to the nanowire diameter.

The obtained values of $L_\phi$ can be used to verify the consistency between the observed UCF amplitude and the corresponding theoretical expectation. When the coherence length $L_\phi$ is much shorter than the sample size $L$, the nanowire can be considered as a series of uncorrelated segments of length $L_\phi$. The fluctuations are described by $\text{rms}(G_B) = 2.45(L_\phi/L)^{3/2}$ [16], resulting in $0.27 e^2/h$ for D1 and $2.1 e^2/h$ for D2. While the first value is in good agreement with the measured UCF amplitude, in the second case we find a significant discrepancy, which we interpret to be the result of the effective channel length being substantially larger than the lithographic distance between the contacts. To support this interpretation, we note that the contact electrodes were 500 nm wide, so within the same contact, the transparency of the metal-nanowire interface could be strongly inhomogeneous. The hypothesis of a larger channel length for D2 is further substantiated by the relatively small value of the conductance ($\sim 36 e^2/h$) as compared to D1 ($\sim 22.5 e^2/h$).

In the absence of a magnetic field, the conductance fluctuations are observed as a function of $V_g$, since a change of chemical potential induced by $V_g$ is equivalent to a change in impurity configuration in the nanowire.
measure 1(a). We ascribe this residual enhancement mostly to the presence of time-reversal symmetry at zero magnetic field. The enhancement factor in the normal state, \(\text{rms}(G_g)|_{V=-0.44\text{mV}}/\text{rms}(G_B)\), is about 1.7 for D1, which is quite close to the theoretical expectation of 1.41 \([11]\).

We suggest that another enhancement of the \(\text{rms}(G_g)\) value at low bias below \(V_{\text{gap}}\) is direct evidence of the interplay between the UCF and the Andreev reflection. The inset of Figure 2(b) shows a typical dynamic conductance \(dI/dV(V)\) curve at a low temperature far below the superconducting transition temperature, \(T_c = 1.1\text{ K}\), of the Al electrode. The overall conductance enhancement at low bias below \(V_{\text{gap}}\) is caused by the Andreev reflection at the interface between the InAs nanowire and the superconducting electrodes, where the incident normal electron is retro-reflected as a phase conjugated hole \([12]\). Multiple conductance peaks at \(V_m = V_{\text{gap}}/m\) with \(m = 1, 2, 3\) occur when the Andreev-reflected hole is reflected again as a normal electron at the opposite interface, or vice versa \([18]\). Finally additional elementary charges of Andreev-reflected holes are driven into a weakly disordered system of the InAs nanowire to increase the \(\text{rms}\) amplitude of the conductance fluctuations at low biases below \(V_{\text{gap}}\). For a phase-coherent segment of \(L_0\) near the interface, the enhancement factor, \(\alpha\), of the \(\text{rms}\) amplitude of the UCF in the superconducting state relative to that in the normal state is about \(\alpha = 2.08\) in theory with the assumption of time reversal symmetry \([11]\). Thus, for the whole nanowire segment of \(L\) between two superconducting contacts, the total enhancement factor, \(\gamma\), is \((1 + 2(2^2 - 1))/N_0)^{1/2}\), with \(N_0 = L/L_0\), giving rise to \(\gamma = 1.59\) for D1, which is quite close to the experimental value of \(\text{rms}(G_g)|_{V=0.1\text{mV}}/\text{rms}(G_g)|_{V=-0.44\text{mV}} = 1.57\) in Figure 2(b).

Another characteristic length scale determining coherent electronic transport is the thermal length, defined as \(L_T = (\hbar D/2k_BT)^{1/2}\). Using \(D = 80\text{ cm}^2/\text{s}\) \([6]\), we obtain \(L_T = 1.3\ \mu\text{m}\) at \(T = 30\text{ mK}\). Since this is much longer than \(L\) and \(L_0\), we have so far ignored thermal smearing as a dephasing mechanism. We now discuss the effect of temperature. To investigate the \(T\)-dependence of the conductance fluctuations in the absence of superconductivity we applied a perpendicular magnetic field of \(B = 0.1\text{ T}\), corresponding to a magnetic flux of \((0.2-0.9)\Phi_0\) in the nanowire segment. The ac bias for the lock-in measurement was kept below \(10\ \mu\text{V}\) in order to minimize the electron heating effect. The results are shown in Figure 3(a). As temperature increases, \(\text{rms}(G_g)\) is almost constant up to a critical temperature \(T^* = 1.2\text{ K}\), above which it decreases substantially. Highly reproducible fluctuations of \(\delta G(V_g)\) for \(T < T^*\) are displayed in the inset of Figure 3(a) over a large \(V_g\) range. The critical temperature \(T^*\) is linked to the Thouless energy, a characteristic energy scale \(E_T\) for diffusive transport, which is defined as \(E_T = \hbar D/2mL^2\) \([19]\). For D4, \(E_T\) is found to be 0.14 mV, compared to \(k_BT^* = 0.10\text{ mV}\).

As the fluctuations have almost disappeared at \(T = 4.2\text{ K}\), a conductance plateau emerges clearly at \(G = \text{me}^2/h\) with \(m = 3, 4, 5\) in the \(G(V_g)\) curve, as shown in Figure 3(b). The conductance steps remain almost unaltered, even after the application of a perpendicular magnetic field at values up to \(B = 2.33\text{ T}\). The conductance values in the zero-field \(G(V_g)\) curves of Figure 3(a) are displayed as an intensity plot in Figure 3(c), thereby emphasizing the anomalous conductance quantization in units of \(e^2/h\). Here, it should be noted that the linear conductance was measured in a four-terminal configuration to avoid any non-linear effects from the contact resistance. Two-terminal measurements for the nanowire segment (B-C) and (C-D), however, show similar con-
conductance plateaus after subtracting a contact resistance of 100 Ω, as shown in the upper inset of Figure 3(b) for the segment (C-D).

There are two distinctive features in our measurements, which differ from the quantized conductance of quantum point contacts in a two-dimensional electron gas [20]. Firstly, we utilized only a back gate for the electrostatic depletion. An arbitrary quantum point contact is thought to be formed in the middle of the nanowire segment due to a nonuniform distribution of the electrostatic potential with the application of $V_{g}$ [21]. Secondly, the unit of the conductance steps is $e^2/h$ rather than $2e^2/h$, where the factor of 2 corresponds to the spin degeneracy of the one-dimensional subbands [20]. It should be noted that at $B = 2.33$ T, the Zeeman splitting, $|g_{\mu B}B| = 2.02$ meV, is larger than the thermal energy broadening, $3.5k_BT = 1.26$ meV, at $T = 4.2$ K (based on previous experiments [8] we have taken $g \approx -15$, the Lande g-factor in bulk InAs, while $\mu_B$ is the Bohr magneton). Similar anomalies in the conductance quantization have been reported for other one-dimensional nanostructures, such as carbon nanotubes [22], Ge/Si nanowires [23] and GaAs quantum wires [24]. The origin of the apparent lack of spin degeneracy is currently not understood. It has been proposed that a spontaneous spin polarization may occur in a one-dimensional electron gas at zero magnetic field [25-27]. More in-depth studies are necessary to shed light on this open issue.

IV. CONCLUSION

In summary, we have investigated quantum interference effects in InAs semiconductor nanowires connecting superconducting metal contacts. In the normal state, conductance fluctuations as a function of the magnetic field or the gate voltage are in good agreement with theoretical predictions for a weakly disordered one-dimensional conductor. In the superconducting state, we have presented strong evidence of the interplay between the UCF and the phase-coherent Andreev reflection phenomenon. Finally, following the temperature-induced suppression of UCF, we have observed an anomalous conductance quantization, whose physical origin remains to be clarified.

ACKNOWLEDGMENTS

We gratefully acknowledge helpful discussions with C. W. J. Beenakker, J. A. van Dam, Y. V. Nazarov and G.-C. Yi. We acknowledge financial support from the EU through the HYSWITCH project and from the EUROCORES FoNE program and from the National Creative Research Initiative Project (R16-2004-004-01001-0) of the Korea Science and Engineering Foundations.

REFERENCES