Charge transport in InAs nanowire Josephson junctions

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We present an extensive experimental and theoretical study of the proximity effect in InAs nanowires connected to superconducting electrodes. We fabricated and investigated devices with suspended gate controlled nanowires and non-suspended nanowires, with a broad range of lengths and normal state resistances. We analyze the main features of the current-voltage characteristics: the Josephson current, excess current, and subgap current as functions of length, temperature, magnetic field and gate voltage, and compare them with theory. The Josephson critical current for a short length device, \( L = 30 \text{ nm} \), exhibits a record high magnitude of 800 nA at low temperature that comes close to the theoretically expected value. The critical current in all other devices is typically reduced compared to the theoretical values. The excess current is consistent with the normal resistance data and agrees well with the theory. The subgap current shows large number of structures, some of them are identified as subharmonic gap structures generated by Multiple Andreev Reflection. The other structures, detected in both suspended and non-suspended devices, have the form of voltage steps at voltages that are independent of either superconducting gap or length of the wire. By varying the gate voltage in suspended devices we are able to observe a cross over from typical tunneling transport at large negative gate voltage, with suppressed subgap current and negative excess current, to pronounced proximity junction behavior at large positive gate voltage, with enhanced Josephson current and subgap conductance as well as a large positive excess current.

I. INTRODUCTION

Semiconducting nanowires (NW) have been a focus of intensive research for their potential applications as building blocks in nano-scale devices. The nano-scale dimension of the semiconducting nanowires, comparable to the electronic Fermi wave length, also makes them an attractive platform for studying the fundamental phenomena of quantum transport. By tuning the Fermi wavelength by means of electrostatic gates one gets access to such quantum phenomena as conductance quantization and quantum interference effects.

Another research interest has been the proximity effect in nanowires induced by connecting them to superconducting electrodes (S). In such devices, S-NW-S, the nanowire serves as a weak link through which a supercurrent can flow due to the presence of the phase difference between the superconducting condensates. Among a variety of nanowires tested in experiments, nanowires of InAs play a central role. This is due to their material properties: high electron mobility, low effective mass, and pinning of the Fermi level in the conduction band that permits highly transparent galvanic S-NW contacts. Hybrid devices of InAs nanowires have demonstrated Andreev subgap conductance, Josephson field effect and Cooper-pair beam splitting. More recently, the nanowire hybrid devices attracted new attention following theoretical predictions of Majorana bound states in NW-S proximity structures.

In spite of intensive research, no systematic investigation of the proximity effect in InAs nanowires has been reported, leaving open important questions about consistency of the observed transport phenomena and theoretical views of the proximity effect.

In this paper, we report on extensive experimental studies of current-voltage characteristics (IVC) of a large variety of hybrid devices made with InAs nanowires connected to aluminum electrodes. These Al-InAs NW-Al devices include suspended and non-suspended nanowires, nanowires with different lengths, and tested at different temperatures, magnetic fields, and gate voltages. We measured the main proximity effect characteristics: Josephson critical current, excess current, and subgap current features, and we make a quantitative comparison with relevant theoretical models.

Our main conclusion is that the most properties of the proximity effect can be qualitatively understood and quantitatively reasonably well fit on the basis of existing theory. In particular, the record high Josephson critical current of 800 nA, observed in the shortest studied nanowire (with 30 nm separation between superconducting electrodes) is close to the theoretical bound for ballistic point contacts. In longer devices, the decay of the critical current with length is consistent with a cross over from ballistic to diffusive transport regime, followed by cross over from a short- to long-junction behavior.

In the gate controlled suspended devices we observe a cross over from a distinct S-normal metal-S (SNS) type behavior with large positive excess current and en-
hanced subgap conductance to tunneling S-insulator-S (SIS) type behaviour in accordance with gradual deple-
tion of the conducting channels by the gate potential and
increase of the wire resistance.

We also observe subgap current features associated
with Multiple Andreev Reflection (MAR) transport. In addi-
tion to those MAR features we systematically
observe subgap features, which are not associated with
MAR but have some different origin. These features are
not related to phonon-induced resonances, and they do
not seem to have an electromagnetic origin. They ap-
pear on the IVCs as voltage steps, strikingly similar to
the voltage steps generated by phase slip centers in su-
perconducting whiskers.

The structure of the paper is as follows: After de-
scribing the device fabrication and experimental setup
in Section II, we summarize the normal state conduction
properties of the devices in Section III, which give the
necessary input for choosing an appropriate theoretical
model of the proximity effect described in Section IV.
Then in the following sections we discuss the supercon-
ducting transport properties: excess current in Section
V, Josephson current in Section VI, sub gap current, and
variation of the current under the gate potential in Sec-
tion VII. Section IX contains conclusive remarks.

II. EXPERIMENTAL DETAILS

A. Sample Fabrication

The devices we have investigated are of three types:
nanowires placed directly on the substrate with either
a) two superconducting contacts or b) multiple contacts,
and c) suspended devices with local gates (Fig. 1). All
devices are made on standard Si substrates capped by
400 nm thick SiO$_2$.

The nanowires are grown by chemical beam epitaxy. In
the growth process, metal-organic gaseous sources are
thermally cracked to their components and the growth
materials are directed as a beam towards an InAs sub-
strate placed in the growth chamber. At the optimal
temperature, the nanowire growth is catalyzed by Au
aerosol particles that have been distributed on the sub-
strate. The sizes of the Au-seeds determine the diameter
of the nanowires. In this paper, the nanowires are taken
from a single growth batch with an average diameter of
80 nm.

To fabricate the non-suspended devices, InAs
nanowires are first transferred to a Si substrate and their
relative positions with respect to predefined marks are
determined with the help of scanning electron microscope
(SEM) images. The extracted locations are then used to
pattern superconducting Ti/Al (5/150 nm thick) con-
tacts on top of the nanowires. Depending on the intended
device length, i.e. distance between source and drain
electrodes, the superconducting contacts are defined by
either single-step or double-step electron beam (e-beam)
lithography. The shorter devices ($L < 100 \text{ nm}$) are defined
by the double-step e-beam lithography whereas the longer
devices ($L \geq 100 \text{ nm}$) are defined by the single-
step e-beam lithography. A SEM image of a typical two
terminal device ($L \approx 100 \text{ nm}$ defined by the single e-beam
lithography) is shown in Fig. 1. The inset image shows
a short length device of $L \approx 60 \text{ nm}$ defined by the double-
step e-beam lithography.

To fabricate the suspended devices, a standard Si
substrate is first patterned with interdigitated Ti/Au strips.
InAs nanowires are then transferred to the al-
faces, an ammonium polysulfide solution (NH$_4$S) has been used prior to evaporation of the interdigitated metal stripes. The stripes are patterned in a two-step fabrication process in order to get a height difference of 15 nm between every two adjacent stripes. This allows the nanowires to rest on the thicker electrodes (65 nm thick) while being suspended above the substrate and the thinner electrodes (50 nm thick). With the help of SEM images, the positions of suitable nanowires are found and superconducting electrodes Ti/Al (5/150 nm thick) are defined on sections of suitable nanowires. A SEM image of a suspended device is shown in Fig. 1c.

To get good transparency of the metal-nanowire interfaces, an ammonium polysulfide solution (NH$_4$S$_x$) cleaning process has been used prior to evaporation of the superconducting contacts. The samples are then characterized at room temperature and stored in a vacuum box before further measurements at low temperatures.

B. Experimental setup

Current-voltage characteristics of the devices are measured in a dilution refrigerator with a base temperature of 15 mK. The IVCs are recorded in either current or voltage bias configuration. In the current-bias mode, the current is determined by a high resistance bias resistor in series with the device. As we increase the current, the voltage across the device is simultaneously measured with a differential amplifier. In the voltage-bias mode, a voltage is directly applied across the device while the current is measured simultaneously by a transimpedance amplifier. To decrease noise coupling to the devices, the electrical lines in the measurement set up are well filtered and thermally anchored at different temperature stages of the refrigerator. The measurement setup is also designed to measure IVCs as a function of temperature and magnetic field.

C. Current-voltage characteristics

A typical IVC is shown in Fig. 2 for a device of length $L \approx 150$ nm (sample B$_{5a}$ in Table I). Above the critical temperature the IVC (blue) exhibits Ohmic behavior with a normal-state resistance of $R_n = 1.07$ kΩ. The critical temperature, $T_c = 1.1$ K, for the devices was determined from samples with shorted electrodes, i.e. without any nanowire. This value agrees well with the temperature at which the Josephson current disappears in the samples with strong Josephson coupling. At temperatures well below $T_c$, the IVC (red) shows three distinct conductance regimes. i) For voltages $|V| > 2\Delta/e$, the IVC shows a linear behavior with the same resistance as in the normal state, $R_n$. ii) For smaller voltages, $|V| < 2\Delta/e$, the resistance is approximately $R_n/2$ and exhibits subgap features. iii) At the zero voltage $V = 0$, the device switches to zero-resistance, exhibiting a Josephson current.

In the next sections we perform quantitative analysis of the IVC, based on a detailed characterization of the normal state current transport in the wire.

III. NORMAL STATE TRANSPORT

In order to characterize the normal-state properties of the junctions, dc-measurements have been performed on several devices with a broad range of lengths and resistances. Measurement results for representative devices are summarized in Table I. The devices are divided into three groups: A, B, and C corresponding to the two-terminal, multi-terminal and suspended devices as shown in Fig. 1.

The normal state resistance as a function of length for devices B$_5$ and B$_6$ is plotted in Fig. 3. The resistance of each device increases linearly with length with approximately the same resistance per unit length, $R/L \approx 6$ Ω/nm. Here, the resistance values are taken from the two-point measurements that also include interface resistance. From the length dependence of the resistance in Fig 3, we extract the contact resistance by extrapolating to zero length. For device B$_5$, we find that contact contribution is less than 180 Ω, while for device B$_6$, it is approximately 1.2 kΩ.

Taking advantage of multiple contacts of the B type devices we perform two- and four-point measurements of the resistance, which allows us to determine the number of conducting channels and the channel average transparency. The two- and four-point resistance expres-
The average transparency is close to unity. For the same junction we find that our nanowires have a spread in the number of channels. Taking two- and four-branch junctions we measured contact resistance, less than 180 Ω for B5, and 1.2 kΩ for B6, ranging between 50 and 100 channels. For junctions B1−B5 we measured R2p = 1.34 kΩ, and R4p = 1.18 kΩ, giving the number of channels

\[ N = \frac{R_q}{R_{2p} - R_{4p}} \approx 80. \]  

This is consistent with the contact resistance found for device B5, and implies perfect S-NW interfaces with transparency close to unity. For the same junction we can then extract the average transparency \( T_i \) = 0.12 for the channels.

Assuming only a surface layer of nanowire to be conducting, in analogy with the 2DEG conductivity in planar InAs devices, such a large amount of conducting channels would give unrealistically small value for the Fermi wavelength. On the other hand, assuming the whole bulk of the wire to be conducting we find the electronic Fermi wave length \( \lambda_F \) to depend logarithmically on the number of channels, as

\[ \lambda_F(N) = \frac{2\pi r_w}{\alpha_{l,n}} \approx A - B \ln(N). \]  

This result is arrived at by solving the Schrödinger equation in a cylinder of radius \( r_w \) and counting the number of modes (channels) that cross the Fermi level. In Eq. \( \lambda_F(N) \) are functions of the nanowire radius; for \( r_w = 40 \) nm, \( A = 42.4 \) nm and \( B = 7.63 \) nm, and varying the radius by ±10% will change both coefficients approximately by ±2%. We can bracket the Fermi wave length between, \( \lambda_F \approx 17\) nm (100 channels) and \( \lambda_F \approx 22\) nm (50 channels) for \( r_w = 40 \) nm. Our values are consistent with the ones reported for planar InAs 2DEG (\( \lambda_F \approx 18 \) nm) and for InAs nanowires (22 nm ≤ \( \lambda_F \) ≤ 33 nm)\(^{27}\). In the further discussions we adopt the values, \( \lambda_F = 22 \) nm, and \( N = 55 \) for all the junctions.

Furthermore we use the measured resistance per unit length, \( R/L = 6 \) Ω/nm, together with the expression for the Drude conductivity, \( \sigma = n e^2 \tau/m^* \), to evaluate a mean free path for the nanowires of \( \ell_{m} = 46 \) nm. The corresponding Fermi velocity \( v_F = \hbar k_F/m^* \approx 1.3 \times 10^6 \) m/s is evaluated by using an electronic effective mass \( m^* = 0.02\)me of bulk InAs, where \( m_e \) is the free electron mass. The effective mass of electrons \( m^* \) for planar InAs 2DEG has been estimated to be in a range from 0.024 to 0.04 \( m_e \). The normal state properties of the nanowires are summarized in Table II.
The current is calculated at the nanowire, and the applied voltage to drop at the defect. This defect is assumed to be in the centre of the nanowire, and the applied voltage to drop at the defect. The majority of the junctions are in the intermediate transport regime, and describe and tractable model, with which we can bridge between the ballistic and diffusive transport regimes, and describe the cross over to the long junction behavior. The model setup is shown in Fig. 4. We assume that the two superconducting leads are connected to the nanowire by perconducting leads are connected to the nanowire by disordered nanowires.

**TABLE II. Summary of the extracted parameters for the nanowires.**

| Parameter                        | Value  |
|----------------------------------|--------|
| Fermi wavelength $\lambda_F$     | 22 nm  |
| Fermi wavevector $k_F$           | 2.9 \cdot 10^6 m^{-1} |
| Fermi velocity $v_F$             | 1.3 \cdot 10^6 m/s |
| Mean free path $\ell_e$          | 46 nm  |
| # conducting channels           | 55     |
| Superconducting gap $\Delta$     | 160 µeV |
| Clean coherence length $\xi_0$   | 1300 nm |
| Diffusive coherence length $\xi_D$| 245 nm |
| Diffusion constant $D_{\text{diff}}$| 200 cm²/s |
| $\varepsilon \Delta / \pi \hbar$ | 12.6 nA |

**IV. THEORETICAL MODEL**

The major difficulty for theoretical interpretation of the experimental data is the very large spread of the wire lengths. Indeed, the shortest wire (30 nm) is in the ballistic point contact regime ($L < \ell_e$, $\xi_0$, with $\xi_0 = h v_F / 2 \pi k_B T_e$), while the longest wire is in the diffusive long junction regime ($L > \ell_e$, $\xi_D$, with $\xi_D = \sqrt{\ell_0} \xi_0$). The majority of the junctions are in the intermediate cross over region. Furthermore, all the tested junctions exhibit the Josephson effect. This implies that the current transport is fully coherent and requires theoretical modeling within the framework of the coherent MAR theory. To overcome this difficulty, we adopt a simple and tractable model, with which we can bridge between the ballistic and diffusive transport regimes, and describe the cross over to the long junction behavior. The model setup is shown in Fig. 4. We assume that the two superconducting leads are connected to the nanowire by highly transmissive contacts, which are treated as fully transparent. The nanowire is disordered due to elastic scattering by impurities and crystal imperfections. This is treated in the Born approximation and the mean free path estimated from the experiments $\ell_e = 46$ nm infers a scattering rate $\Gamma = v_F / \ell_e \approx 2.8 \cdot 10^{13}$ s⁻¹. Strong defects are included and treated as a single interface having the same effective transparency $\mathcal{D}$ for all conducting channel. This defect is assumed to be in the centre of the nanowire, and the applied voltage to drop at the defect.

Using the quasi-classical Green’s function methods described in Refs. 44 and 45, we calculate the IVC as function of device length and transparency by solving the coherent MAR problem. The current is calculated at the scattered, and expressed through the boundary values, $\mathcal{G}_R/L = \hat{g}(\hat{p}_F, x = \pm 0; \omega)$, of the quasi-classical Green’s function for a given channel,

$$\hat{g}(\hat{p}_F, x; \omega) = \begin{pmatrix} \hat{f}(\hat{p}_F, x; \omega) \\ \hat{f}(\hat{p}_F, x; \omega) - g(\hat{p}_F, x; \omega) \end{pmatrix}, \quad \hat{g}^2 = -\pi^2. \tag{3}$$

The Green’s function is computed by solving the Eliashberg equation in the right and left parts of the nanowire,

$$i \hbar \sigma_F \cdot \partial_x \hat{g}(\hat{p}_F, x; \omega) + \varepsilon(x; \omega) \hat{g}(\hat{p}_F, x; \omega) = 0, \tag{4}$$

complemented with the Zaitsev boundary conditions at the scatterer and NW-S interfaces. The third Pauli matrix in Nambu space. In Eq. (4) we introduce the impurity scattering via the impurity self-energies

$$\varepsilon(x; \omega) = \hbar \omega - \hbar \Gamma (g(\hat{p}_F, x; \omega))_{PF}, \tag{5}$$

$$\hat{\Delta}_\text{imp}(x; \omega) = \hbar \hat{f}(\hat{p}_F, x; \omega))_{PF}, \tag{6}$$

$\langle \cdots \rangle_{PF}$ is average over directions ($\pm \hat{p}_F$). The matrix $\hat{f}$ is the anomalous (off-diagonal) part of the Green’s function $\hat{g}$. The components $(f, \hat{f})$ of $\hat{f}$ describe the pairing correlations leading in to the nanowire and two are related by symmetry as $\hat{f}(\hat{p}_F, x; \omega) = -f^*(-\hat{p}_F, x; -\omega^*)$.

**V. EXCESS CURRENT**

We start with a discussion of the excess current at large voltage, which is a robust feature of the proximity IVC. The excess current, $I_{\text{exc}}$, is extracted from the current-voltage characteristics at large voltage bias using the asymptotic form $I(V > 2 \Delta / e) \approx V / R_N + I_{\text{exc}} + O(\Delta / eV)$. The excess current contains contributions both from the single-particle and from the two-particle Andreev currents, and it linearly scales with the energy gap $\Delta(T)$ (see e.g. Ref. 57). In Fig. 5, the excess current is obtained for the device $B_{36a}$ by extrapolating a linear fit of the IVC measured at $V > 2 \Delta / e$ (blue dashed line) giving $I_{\text{exc}} = 150$ nA. To verify that the measured excess current derives from Andreev scattering processes the experimentally extracted excess current is plotted as a function of temperature in Fig. 5b. As can be seen the amplitude of the excess current follows the temperature dependence of the superconducting gap $\Delta(T)$.

The excess current also depends on the transparency and the length of the nanowire device. In Fig. 6 we present the computed excess current as function of device length $L$. The amplitude of the excess current shows a linear behaviour with $L$, which is in agreement with the theoretical prediction for the superconducting gap $\Delta(T)$.

**FIG. 4.** A schematic picture of the theoretical model for the nanowire junctions: Superconducting electrodes (S) are connected by a disordered nanowire of length $L$, which also contains crystalline defects; the latter are modeled with a lumped scatterer situating in the middle of the wire and having effective transparency $\mathcal{D}$; the applied voltage is assumed to mostly drop at the scatterer.
FIG. 5. a) Current-voltage characteristics of the device B5 with length \( L = 150 \text{ nm} \) and normal state resistance \( R_n = 1.07 \text{k}\Omega \). The excess current is extracted by extrapolating the IVC from high voltage to zero voltage. b) Excess currents as a function of temperature are shown for device B5 (L= 150 nm, 170 nm, 180 nm, and 190 nm). The excess currents follow the superconducting energy gap \( \Delta(T) \) (light green).

length together with \( I_{\text{exc}} \) extracted from the measurements. The maximum values of the theoretical curves correspond to the point contact limit \( (L = 0) \), and they are in a good agreement with analytical results,\(^{37} \) \( I_{\text{exc}} = \frac{8}{3\pi}(e\Delta/h) \) per channel for \( D = 1 \), and \( I_{\text{exc}} \approx D^2(e\Delta/h) \) for \( D \ll 1 \). When the wire length is increased the excess current decreases. This was also found, experimentally and theoretically, in ballistic 2DEG InAs\(^{27} \) and computed for fully diffusive junctions.\(^{55,59} \) In our case, the experimental values fall on curves with a typical effective transparency between 0.2 and 0.4 being only weakly device dependent between batches of nano wires. These values compare favorably with \( T_r = 0.12 \) extracted from the 2-point and 4-point measurements in the normal state.

One device, \( A_1 \) (L=30 nm), however, stands out showing a high transparency of \( D \approx 0.87 \). For this junction, highly transmissive ballistic point contact, one should anticipate the largest critical current.

VI. JOSEPHSON CURRENT

Next, we discuss the Josephson critical current as a function of length, temperature, and magnetic field. The maximum values of the Josephson current, \( I_m \), are extracted from the experimentally obtained IVC at the base temperature of 15 mK and shown in Table I. The maximum currents exhibit a range of values depending on the resistance and length of the devices, from a few nA to 800 nA. Similarly, the characteristic voltage, the \( I_m R_n \)-product, also exhibits a range of values, from 20 \( \mu \text{V} \) to 130 \( \mu \text{V} \).

Theoretically, the Josephson current-phase relation is
computed using boundary values of the Green’s function, \( \hat{g}(\hat{p}_F, x; \omega) \), in Eqs. (3) and (4), the expression reads,

\[
I_s(\phi) = \frac{8\pi e T D}{h} \sum_{\omega_n > 0} \left( 2 - \mathcal{D}(g_R L - f_R f_L \cos \phi + 1) \right) \left( \frac{f_R f_L}{p_F} \right). 
\]

The sum is over all Matsubara frequencies, \( \omega_n = \pi k_B T (2n + 1) \), \( T \) is the temperature, \( \phi \) the phase difference over the junction. The critical current is obtained by maximizing the supercurrent.

The maximum Josephson currents presented in Table I, together with a theoretical critical current fit, as a function of length, are plotted in Fig. 7. The shortest junction exhibits the largest Josephson current, as expected, with the theoretical fit of the transparency, \( D \approx 0.65 \). This is very close (75%) to the theoretical limit defined by the transparency extracted from the analysis of the excess current. The other junctions fall in the transparency region \( 0.05 < D < 0.1 \), which is smaller (approximately by a factor of 4) compared to the transparency extracted from the excess current.

Similar or even larger reduction of Josephson current is commonly observed in nanowires, and it is also common in 2DEG InAs Josephson junctions\(^{27} \). Such an effect is not well understood, perhaps it could be related to some deparing mechanism, for example due to magnetic scattering.

One would expect a certain suppression of the Josephson current extracted from the IVC measurement compared to the equilibrium critical current due to the effect of phase fluctuations. However, our analysis shows that majority of our junctions are overdamped, and the suppression of the critical current in this regime is relatively small and cannot account for the whole suppression effect. Indeed, the capacitances of the devices are estimated in the range, \( C \sim 1-5 \) fF, cf. Ref. 11. Assuming \( C = 5 \) fF and the junction resistance, \( R_0 \sim 100 \Omega \) at plasma frequency \( \sim 1 \) GHz corresponding to the free space impedance, we estimate the quality factor \( Q = \sqrt{2eI_c C/\hbar R_0} \lesssim 0.1 \) for the representative junction with critical current, \( I_m = 50 \) nA. This estimate refers to an unbiased junction, the Q-factor further decreases when the current bias is applied. For such an overdamped regime, \( Q \ll 1 \), the switching probability is significantly suppressed\(^{42} \), and IVC can be modeled with the Ambegaokar-Halperin theory\(^{11} \). This conclusion is supported by the absence of hysteresis on IVC. The IVC measurement takes approximately 1 minute, so that the sample spends approximately few seconds close to Ic. Assuming the temperature of electromagnetic fluctuations being close to the base temperature of 15 mK due to a careful noise filtering\(^{12} \) we find that the suppression effect accounts for approximately 20% of the theoretical value for the majority of the junctions with critical currents exceeding 10 nA. For the shortest junction with \( I_m = 800 \) nA the suppression is even smaller, about few percent.

The maximum Josephson current is also investigated as a function of temperature for several devices. The maximum currents for the shortest length device A1 (\( L \approx 30 \) nm and \( R_n = 0.16 \) kΩ), and for the somewhat longer device B5c, (\( L \approx 170 \) nm and \( R_n = 1.15 \) kΩ), are shown in Fig. 8. At the base temperature \( T = 15 \) mK, the devices have maximum Josephson currents of \( I_m = 800 \) nA and 40 nA, respectively. The data for the shortest device agree well with theory in a broad range of temperatures. The longer device exhibits a concave shaped decay at higher temperatures and deviates from the theoretical fit. Qualitatively similar shape of \( I_s(T) \) has been theoretically found for diffusive junctions with highly resistive interfaces (SINIS)\(^{43} \) and explained with enhancement of electron-hole dephasing in the proximity region due to large dwell time. Such an effect is similar to the effect of increasing length of the junction (cf. Ref. \( \text{39} \)). Given such a similarity we may conclude that although device B5c has transparent S-NW interfaces, the model\(^{43} \) might better capture the effect of the junction length.
FIG. 8. Maximum Josephson current as a function of temperature for two devices of length $L = 30$ nm and $L = 170$ nm. Note the different scales for the current magnitude. Theoretical fits to the critical current for both devices are shown. The transparency chosen to fit the data is taken from the low-temperature values for $I_m$ in Fig. 7.

At the base temperature of 15 mK, we also have obtained IVCs as a function of magnetic field. The magnetic field is applied perpendicular to the superconducting leads. The normalized maximum Josephson current and the superconducting energy gap as a function of magnetic field are plotted in Fig. 9 for device B$_{3b}$ with $L = 170$ nm. The superconducting gap $\Delta(B)$ is fitted to the expression $\Delta(B) = \Delta(0)\sqrt{1 - (B/B_c)^2}$ from which we extract $B_c = 67$ mT. The maximum current decreases and is totally suppressed above $B_c$. No Fraunhofer oscillations are observed in any of the devices, consistent with a suppression of superconducting energy gap in the leads.

VII. SUBGAP CURRENT

Now we proceed with discussion of the IVC in the subgap region, $V < 2\Delta/e$, as function of temperature and magnetic field, and for different nanowire lengths. A typical plot of the differential resistance as a function of voltage is presented in Fig. 10. The resistance drops from $R_n = 1.15$ k$\Omega$ at $V \gg 2\Delta$ to $R_{SG} \approx 0.7$ k$\Omega$ at $V \approx 260 \mu$V, which corresponds to the gap value, $2\Delta/e$. Such a drop of resistance in the subgap region is a characteristic of Andreev transport in transmissive SNS junctions. Furthermore, the differential resistance shows a second feature at approximately half the gap voltage, $V \approx 130 \mu$V = $2\Delta/2e$ (shown by arrow in Fig. 10).

Positions of both these features scale with the temperature dependence of the superconducting gap $\Delta(T)$, as shown on Fig. 10. This unambiguously indicates the MAR transport mechanism. Similar features associated with MAR are observed in all measured devices, in some devices we also observed a third MAR feature at $2\Delta/3e$.

We have also measured the dependence of positions of the resistance features as a function of magnetic field. The differential resistance of device A$_4$ as function of magnetic field is shown in Fig. 11. In this device, the three MAR features are present (marked by arrows), which move smoothly towards lower voltages following the magnetic field dependence of the gap $\Delta(B)$.

Besides the MAR features, the IVC of all the measured devices exhibit a number of structures at lower voltages, whose positions are independent of both temperature and magnetic field, see Fig. 10 and Fig. 11. These structures are therefore not associated with MAR. However, they are related to the superconducting state in the electrodes since they do not persist above the critical temperature.
and critical magnetic field and even disappear somewhat earlier.

The origin of these structures is not clear. In Ref. 20 similar structures were reported for suspended NW devices and attributed to resonances resulting from coupling of the ac Josephson current to mechanical vibrations in the wire. The fact that we observe such structures not only in suspended but also in non-suspended wires rules out this explanation. Furthermore, the phonon resonances would appear at voltages corresponding to the phonon eigen-frequencies, i.e. depend on the wire length ($\propto 1/L$). We systematically measured the length dependence of the low-voltage, temperature independent structures, the results are presented in Fig. 12. The positions of the structures do not depend on the wire lengths neither for suspended nor non-suspended devices. The positions are given by the integer multiples of the same voltage, $V \approx 24 \mu V$.

The fact that the positions of the temperature-independent structures are the same in different junctions makes it unlikely that they are related to external electromagnetic resonances, but rather result from some general intrinsic mechanism. To get a better insight in the origin of the temperature independent subgap structures we analyzed the shape of the IVC, see Fig. 13. In all investigated junctions the IVC have a staircase shape and consist of a number of successive voltage steps. Between the steps, the current continuously grows with the differential resistance increasing after every step. Such a behavior may be explained by successive emergence of normally conducting domains in the wire as soon as the current exceeds the critical value. This picture closely resembles the resistive states in superconducting whiskers containing phase slip centers (PSC)\(^{21,22}\). Although one cannot in a straightforward way extend the PSC scenario in truly superconducting whiskers\(^{23}\) to the proximity induced superconductivity in nanowires, one cannot exclude the possibility of formation of some kind of spatially inhomogeneous resistive state in the proximity region.

**VIII. GATE DEPENDENCE**

In this section, we investigate the gate dependence of the IVC in the superconducting state of suspended de-
FIG. 12. Voltage positions of the temperature independent
differential conductance peaks as function of length for devices
of type A, B and C. Horizontal lines indicate the multiples of
the voltage $V \approx 24\mu V$.

devices of type C shown in Fig. 1c and in Table I. The data
presented in the in the previous sections are obtained
at the zero gate voltage for the conduction regime with
multiple open conducting channels. Here we discuss the
change of the IVCs in this regime with variation of the
gate voltage. An opposite, few-channel transport regime
at large negative gate voltage, showing quantization of
the normal conductance and the Josephson critical cur-
tent was investigated in Ref. 11.

In our device, the gate voltage controls the local car-
rier concentration in the nanowire and thereby affects the
strength of the proximity effect. Due to a strong capac-
tive coupling of the gate to the wire, this variation is
significant allowing us to observe a cross over from the
SNS to SIS type regime of the current transport at low
temperature. According to the theory, the IVC of the
transparent wire should exhibit, besides a large Joseph-
son current, a large excess current both in the subgap
voltage region and at the large voltage. On the other
hand, more resistive wires should exhibit a small Joseph-
son current, a suppressed subgap current, and a cross
over to deficit (negative excess) current at large voltage.

The dependence of the maximum Josephson current
on the gate voltage is shown in Fig. 14 for the suspended
device $C_{11}$ ($L \approx 150$ nm). The change of the maximum
current (blue) varies in tact with the change of the dif-
erential conductance (red). Owing to the n-type na-
ture of the nanowires, the conductance and the maximum
Josephson current are strongly suppressed at large nega-
tive gate voltages, $V_g < -5$ V. Changing the gate voltage
towards positive values results in linear increase of the
averaged conductance and maximum Josephson current,
the latter reaching the value of $I_m = 4$ nA at $V_g = 3$ V.
Simultaneously, the $I_m R_n$ product saturates at the value,
$I_m R_n = 12.5 \mu V$, and remains constant over a wide range
of gate voltages, as shown in the inset in Fig. 14.

In Fig. 15 we present a set of IVCs for the suspended
device $C_{12}$ ($L \approx 200$ nm and $R_n = 3.6$ k$\Omega$) for gate volt-
ages ranging from $V_g = -2.16$ V to $V_g = +0.92$ V. At
large positive gate voltage, i.e. at large conductance,
the IVC shows significant excess current and enhanced
subgap conductance, indicating highly transmissive SNS
regime. In the opposite limit of large negative gate volt-
age (small conductance), the IVC has a typical form for
SIS tunnel junctions with negative excess current and
strongly suppressed subgap conductance. The suppres-
sion of the subgap conductance is explained by small
probability of MAR processes at small voltage, which
scales with $D^n$, where $n = 2\Delta/eV$ is the number of Au-
dreev reflections. In the tunneling regime with small
$D \ll 1$ the subgap conductance is exponentially small.
At the intermediate gate voltages the device exhibits con-
tinuous crossover between these two regimes in accor-
FIG. 14. Normal state conductance and maximum Josephson current as a function of a local-gate voltage for device C_{11}. After opening of the first conducting channel at $V_g \approx -5$V, the overall conductance and critical current increase linearly with the gate voltage. In the inset the $I_m R_n$ product as a function of gate voltage. The constant value indicates that the maximum current is correlated with the normal state conductance.

FIG. 15. Current-voltage characteristics for device C_{12} of length $L = 200$ nm. for different gate voltages, $V_g = -2.16, -1.86, -1.64, -1.40, -0.93, 0.92$V (from bottom to top). The IVC exhibit cross over from the tunneling regime with small subgap current and negative excess current to the SNS regime with enhanced subgap conductance and positive excess current.

IX. CONCLUSION

We have investigated, both experimentally and theoretically, proximity effect in InAs nanowires connected to superconducting electrodes. We have fabricated and investigated a large number of nanowire devices with suspended gate controlled nanowires and non-suspended nanowires, with a broad range of lengths and normal state resistances. We measured current-voltage characteristics and analyzed their main features: the Josephson current, excess current, and subgap current as functions of length, temperature, magnetic field and gate voltage, and compared them with theory. The devices show reproducible resistance per unit length, and highly transmissive interfaces. The measured superconducting characteristics are consistent and agree reasonably well in most cases with theoretically computed values. The maximum Josephson current for a short length device, $L = 30$ nm, exhibits a record high magnitude of 800 nA at low temperature that comes close to the theoretically expected value. The maximum Josephson current in other devices is typically reduced compared to the theoretical values. The measured excess current in most of the devices is consistent with the normal resistance data and agrees well with the theory. The subgap current shows large number of structures, some of them are identified as subharmonic gap structures generated by MAR. The other structures, detected in both suspended and non-suspended devices, have the form of the voltage steps at voltages that are independent of either the superconducting gap or the length of the wire. By varying the gate voltage in suspended devices we were able to observe a cross over from typical tunneling transport, with suppressed subgap current and negative excess current, at large negative gate voltage to pronounced SNS-type behavior, with enhanced subgap conductance and large positive excess current, at large positive gate voltage.

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