Quantum effects in linear and non-linear transport of T-shaped ballistic junction

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We report low-temperature transport measurements of three-terminal T-shaped device patterned from GaAs/Al0.8Ga0.2As heterostructure. We demonstrate the mode branching and bend resistance effects predicted by numerical modeling for linear conductance data. We show also that the backscattering at the junction area depends on the wave function parity. We find evidence that in a non-linear transport regime the voltage of floating electrode always increases as a function of push-pull polarization. Such anomalous effect occurs for the symmetric device, provided the applied voltage is less than the Fermi energy in equilibrium.

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Recently, nanotechnology advances have led to a growing interest in electrical transport properties of the so-called three-terminal ballistic junctions (TBJs). As the name indicates, such structures consist of three quantum wires connected via a ballistic cavity to form a Y-shaped or T-shaped current splitter. One motivation is that in principle such systems can operate at high speed with a very low power consumption. Therefore, interesting and unexpected nonlinear transport characteristics of TBJs are intensively investigated due to possible applications as high frequency devices or logic circuits [1, 2].

Another reason for the increased number of studies devoted to TBJs are quantum mechanical aspects of carrier scattering, which dominate at low temperatures in the linear transport regime. This applies especially to T-shaped splitters. For example, it is expected that a T-branch switch, made of materials with a significant spin-orbit interactions, can act as an effective spin polarizer [3]. Also, for such geometry an ideal splitting of electrons from a Cooper pair is expected, provided the lower part of the letter T is made of a superconducting material [4]. Both effects rely very strongly on the perfect shape of the devices and high enough transparency of individual wires. Unfortunately, experimental data available for the lithographically perfect T-branch junctions are limited mostly to a non-linear transport regime [5]. Quantum linear transport is usually studied for less symmetric structures, typically consisting of short point contact attached to a side wall of a wider channel [6].

In this work we report on fabrication and low temperature transport measurements of T-shaped three-terminal devices, for which we take a special care to preserve the perfect symmetry and reduce the geometrical disorder. By comparing our data to conductance modeling by the recursive Green-function method, we find out that quantum effects dominate up to source-drain voltages equal to the Fermi energy. In particular, we show that the non-linear response of symmetric TBJ behaves in a non-classical way and is highly tunable with carrier density.

The three-terminal ballistic junctions are made of a GaAs/AlGaAs:Si heterostructure with electron concentration n_{2D} = 2.3 \times 10^{11} \text{ cm}^{-2} and carrier mobility \mu = 1.8 \times 10^{6} \text{ cm}^{2} / \text{Vs}. The interconnected wires of equal length L = 0.6 \mu m and lithographic width W_{\text{th}} = 0.4 \mu m are patterned by e-beam lithography and shallow-etching techniques to form a T-shaped nanojunction (see inset to Fig. 1). The physical width of all branches is simultaneously controlled by means of a top metal gate which is evaporated over the entire structure. The differential conductances have been measured in a He-3/He-4 dilution refrigerator, by employing a standard low-frequency lock-in technique. We have also studied non-linear transport in the typical for TBJs, so-called push-pull bias

![FIG. 1: (Color online) Currents \( I_{ij} \) vs gate voltage \( V_g \) at temperature \( T \approx 0.3 \text{ K} \). \( I_{ij} \) is defined as current flowing from contact \( j \) when voltage \( V_i \) is applied to terminal \( i \) (see the measurement scheme). Upper inset shows scanning electron micrograph of the T-junction device, top metal gate is not visible here.](image-url)
regime, when equal but opposite in sign $dc$ voltages are simultaneously applied to the opposite input contacts.

The application of a metal gate over the active region of the device helps to symmetrize transmission coefficients by smoothing the confinement potential [7]. Nevertheless, even a perfectly shaped and gated junction may remain disordered at low electron densities, when screening effects are weak. Figure 1 shows linear currents flowing from each of three terminals for negative gate voltages. The structure at the threshold voltage, for $V_g > 0.05$ V they oscillate exactly in phase. It means that starting from a disordered structure at the threshold voltage, for $V_g > 0$ the device becomes more symmetrical and experimental data can be compared with the theory of ballistic transport.

We model TBJ by three semi-infinite strips of “atoms” and the square coupling region. Calculations have been performed at temperature $T = 0$, using a tight-binding approach and a recursive Green functions technique [9]. To determine a local current intensity inside the junction we have incorporated parts of each wire to the coupling region and used a newly developed, so-called knitting algorithm [10]. Results of this modeling are presented in Fig. 3(a) and 3(b). Transmission coefficients $T_{ij}$ between $j$-th and $i$-th electrode are calculated for disorder free and symmetric device with rounded corners in the coupling region. Note that the value of $T_{21}$ increases almost monotonically as a function of energy, whereas $T_{32}$ oscillates strongly. This is the so-called bend resistance effect. $T_{32}$

FIG. 2: (Color online) $G_{ij} = I_{ij}/V_i$ plotted vs gate voltage at $T \approx 0.3$ K. (a) $G_{23}$ and $G_{21}$, (b) $G_{12}$ and $G_{13}$, here both conductances involve transmission to side terminal 3. Inset: comparison between $G_{23}$ and $G_{13}$ oscillations, a smooth background has been removed from the original data ($\Delta G$ is in $2e^2/h$ units, $V_g$ is in volts).

FIG. 3: (Color online) (a) Local current intensity (upper panel) and transmission coefficients $T_{ij}$ vs Fermi energy $E_F$ (below). Lines $A$, $B$ and $C$ mark energy values for which the local current densities have been calculated. Black color in density plot corresponds to zero current and bright areas to maximal current intensity. (b) Conductance $G_1 = G_{12} + G_{13}$ vs gate voltage, $T \approx 0.3$ K. Only oscillating part is shown, a smooth background has been removed. Arrows on both subfigures indicate backscattering at even mode numbers.
reaches maximum when the upper, just populated sub-band, is almost fully transmitted to the terminal 3 (see intensity plot A). For higher kinetic energies, however, coupling becomes weaker and as a result $T_{32}$ decreases, leading to the non-monotonic behavior as a function of Fermi energy $E_F$.

Presented calculations are consistent with the experimental data obtained at electron densities high enough. For $V_g > 0$ the curve $G_{21}$ is similar to $T_{21}$ and rather smooth as compared to $G_{32}$, which (like $T_{32}$) shows deeper minima due to the bend resistance effect (see Fig. 2). Note also, that calculated energy dependence of transmission coefficients differ for odd and even channel numbers. For example, the backscattering for $N = 2$ and $N = 4$ channels is stronger, as indicated with arrows in Fig. 3. This effect was already predicted for a perfect T coupler [8] and is apparently enhanced by the rounding of the “corners” in a junction area. For even parity modes electron has high probability density at the center of the device and therefore is more likely transmitted (to see this compare density plots B and C). We believe that such conductance dependence on wave function parity is also observed in the experiment. It is especially well resolved for the total conductance $G_1 = I_1/V_1 = G_{12}+G_{13}$. Relevant data are presented in Fig. 3(b).

Next we consider the measurement scheme where stub terminal (3) acts as a floating voltage probe (see this compare density plots $B$ and $C$). This effect was already predicted for a perfect T coupler [8] and is apparently enhanced by the rounding of the “corners” in a junction area. For even parity modes electron has high probability density at the center of the device and therefore is more likely transmitted (to see this compare density plots B and C). We believe that such conductance dependence on wave function parity is also observed in the experiment. It is especially well resolved for the total conductance $G_1 = I_1/V_1 = G_{12}+G_{13}$. Relevant data are presented in Fig. 3(b).

Conductance data shown in Fig. 2(b) indicate that on average $G_{31}$ is smaller than $G_{32}$. Therefore, to imitate the real sample, we rounded the junction “corners” of a model device in such a way that $T_{31} < T_{32}$. The shape of the coupling area and results of calculations are shown in Fig. 3(a). Ratio $V_3/V_1$ is on average below 1/2 but oscillates as energy increases. Very similar dependence is observed in the experiment. The measured value of $V_3/V_1$ ratio reaches maximum, each time a new one-dimensional level becomes occupied. Interestingly, theory also predicts the occurrence of additional asymmetric and very narrow resonances when a new conduction channel opens to transport in stub terminal. They are probably related to the so-called Wigner singularities, which exist when the energies of quantized levels in a side probe differ from those in the rest of the device[9]. Similar features are also visible in the experiment, especially for $-0.1 < V_g < 0$, but their possible connection to Wigner resonances requires further studies.

Now let us turn to the non-linear transport regime where the probabilities of transmission from input terminals to a floating contact may differ, even for a perfect device. In such case, when $V_1$ is large enough and positive, then $V_3/V_1$ is less then 1/2. Equivalently, if $V_1 = V_{pp}$ and $V_2 = -V_{pp}$ (push-pull bias regime) then $V_3 = V_C$ is always negative, as it was predicted in [11] and then proved experimentally [12]. Using the quantum scattering approach Csontos and Xu [13] extended the calculation range to a low temperature regime. They showed that $V_C$ may be also positive, provided $\partial T_{31}/\partial E_F = \partial T_{32}/\partial E_F < 0$ and $kT < E_F$. To our knowledge, however, the predictions of Ref. [13] have not been confirmed experimentally.

Figure 4(a) shows measurement schematics and corresponding $V_C$ data obtained when $|V_{pp}| < 15$ mV. $V_C$ is not a symmetric function of $V_{pp}$, yet above a certain threshold, data — as expected — bend towards negative values of $V_C$. Such behavior is often observed in experiments [12] because $T_{31} \neq T_{32}$ due to imperfections which are always present in the real devices. Apart from such asymmetry, however, data reported here behave in an anomalous way. When a linear trend has been removed, $V_C$ first increases with $|V_{pp}|$, and then goes down reaching maximum at $\sim 7$ mV. To investigate this effect in more detail we have used a modulation method to measure the switching parameter $\beta = \partial V_C/\partial V_{pp}$ directly with a better voltage resolution. Figure 4(a) explains the measurement idea and Fig. 4(b) shows values of parameter $\beta = \beta_a - \beta_s$ as a function of $V_{pp}$ for a different gate voltages. Here $\beta_s$ is the mean value of switching parameter calculated at each $V_g$ for $|V_{pp}| < 15$ mV. Subtracting $\beta_s$ is equivalent to removing a linear trend from the dc data and therefore reduces the influence of the $T_{31}$ vs $T_{32}$ asymmetry.

To compare the experimental findings with theory we
FIG. 5: (Color online) (a) Stub voltage \(V_C\) vs push-pull polarization \(V_{pp}\) at \(V_g = 0\) (dotted line). The same data with a linear trend removed are also shown (solid line). Below: experimental setup; small \(V\) range. When \(\partial T / \partial E\) and \(\partial T / \partial V\) are calculated, we conclude that the behavior of \(V_C\) in Fig. 5 cannot be explained by a single particle transmission approach. Probably, as suggested in [11], the non-linear transport regime requires a self-consistent calculations.

In summary, we have shown that long transport in T-shaped ballistic junction can be successfully described by quantum scattering effects and weak disorder in a cavity area. We have shown for the first time, that stub voltage can increase as a function of push-pull polarization in a non-linear transport regime, however, the energy dependence of such non-equilibrium effect is inconsistent with the standard single-particle picture of electron transmission. Nevertheless, novel applications of symmetric TBJ structure, for example as the component of a multilogic device, are still possible.

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[1] H. Q. Xu, Nat. Mater. 4, 649 (2005).
[2] L. Worschech, D. Hartmann, S. Reitzenstein, and A. Forchel, in J. Phys.: Condens. Matter 17, R775 (2005).
[3] A. A. Kiselev and K. W. Kim, Appl. Phys. Lett. 78, 775 (2001).
[4] A. Bednorz, J. Tworzydlo, J. Wróbel, and T. Dietl, Phys. Rev. B 79, 245408 (2009).
[5] D. Wallin, I. Shorubalko, H. Q. Xu, and A. Cappy, Appl. Phys. Lett. 89, 092124 (2006); D. Spanheimer, C. R. Muller, J. Heinrich, S. Hofling, L. Worschech, and A. Forchel, Appl. Phys. Lett. 95, 103502 (2009).
[6] T. Usuki, M. Saito, M. Takatsu, R. A. Kiehl, and N. Yokoyaana, Phys. Rev. B 52, 8244 (1995); A. Ramamoorthy, J. P. Bird, and J. L. Reno, J. Phys.: Condens. Matter 19, 276205 (2007).
[7] J. Liu, W. X. Gao, K. Ismail, K. Y. Lee, J. M. Hong, and S. Washburn, Phys. Rev. B 50, 17383 (1994).
[8] H. U. Baranger, Phys. Rev. B 42, 11479 (1990).
[9] B. R. Bulka and A. Tagliazucchi, Phys. Rev. B 79, 075436 (2009), and references therein.
[10] K. Kazymyrenko and X. Waintal, Phys. Rev. B 77, 115119 (2008).
[11] H. Q. Xu, Applied Physics Letters 78, 2064 (2001).
[12] I. Shorubalko, H. Q. Xu, I. Maximov, P. Omling, L. Samuelson, and W. Seifert, Applied Physics Letters
79, 1384 (2001); L. Worschech, H. Q. Xu, A. Forchel, and L. Samuelson, Appl. Phys. Lett. 79, 3287 (2001).

[13] D. Csortos and H. Q. Xu, Phys. Rev. B 67, 235322 (2003).

[14] M. Büttiker and D. Sánchez, Phys. Rev. Lett. 90, 119701 (2003).