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Physica E 21 (2004) 916–920
PHYSICA E
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Quantized transport in ballistic rectifiers: sign reversal and step-like output

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Abstract

Tunable ballistic rectifiers with different geometries are investigated. On standard structures with a symmetry-breaking scatterer embedded in a cross-bar geometry, we observe—apart from the usual rectification behavior—oscillations in the output characteristics that show the importance of quantum transport for the understanding of the rectification mechanism. On samples that are designed taking semiclassical and quantum transport into account, we find greatly improved rectification efficiency, accompanied, however, by a surprising reversal of the output polarity. We also observe a pronounced step-like increase in the rectified signal. All observations can be explained by a model that takes into account the interplay between classical diffusive, semiclassical, and quantum transport.

PACS: 73.23.-b; 73.23.Ad; 73.40.Ei; 73.63.Rt

Keywords: Rectification; Ballistic transport; Semiclassical; One-dimensional; Non-linear

1. Introduction

The availability of high-mobility two-dimensional electron gases (2DEGs) and high-resolution lithographic techniques have made it possible to fabricate electronic devices with properties that are determined by *size and shape* rather than materials properties. A number of electrically active structures have been proposed and realized that make use of charge or energy quantization, ballistic transport or self-gating to achieve a desired output characteristic. One such device is the so-called ballistic rectifier [1]. A possible realization is shown in the inset to Fig. 1. Here, a symmetry-breaking scatterer (triangle pointing down), placed inside a cross-shaped 4-probe geometry, will induce a negative voltage between two probes (U–L), when a current is passed through the other two probes (S–D), regardless of the polarity of the current. Even though a simple billiard ball model of scattered electrons (see arrows) can qualitatively account for the experimental findings, the development of a more satisfactory theoretical description that goes beyond the linear Landauer–Büttiker model has proved to be difficult [2–6].

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1386-9477/$ - see front matter
doi:10.1016/j.physe.2003.11.150

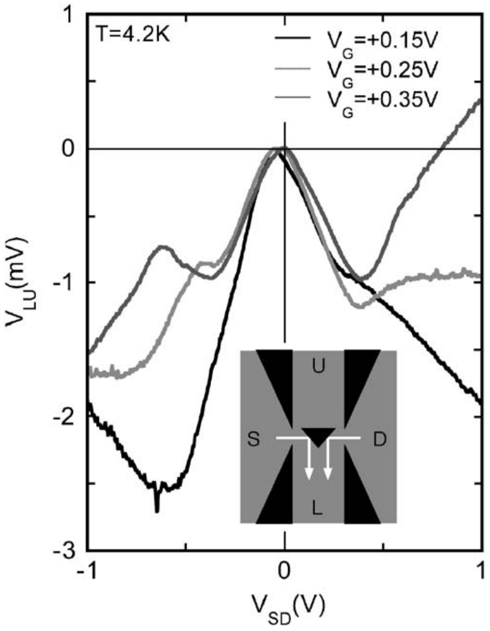

Fig. 1. Inset: Simple visualization of ballistic rectification (arrows) superimposed upon a schematic of the sample layout. The width of the narrow constrictions near the base of the triangle is approximately 500 nm. Main figure: Output voltage (measured between leads L and U) as a function of input bias (applied between leads S and D) for different gate-voltages V_G.

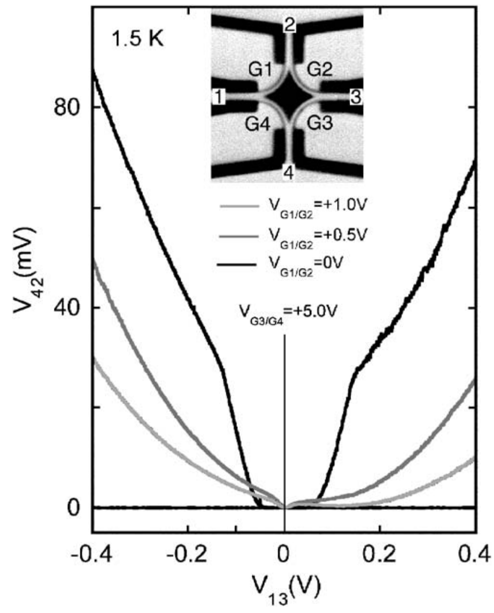

Fig. 2. Inset: Layout of a rectification structure that is symmetric by design but can be tuned to become asymmetric with great flexibility by application of a voltage to the in-plane gates G1–G4. Dark areas are etched away, light areas contain a 2DEG. Main figure: Output voltage (measured between leads 4 and 2) as a function of input bias (applied between leads 1 and 3). The gates were tuned such that the current path 1–2–3 is through narrow constrictions, while the path 1–4–3 is through wide constrictions.

Here we investigate ballistic rectifiers with different geometries and in situ tunability. Apart from the simple rectification behavior, we find—depending on the geometric parameters—oscillatory output characteristics, sign reversal and step-like output. The results can be explained by an interplay between classical diffusive, semiclassical ballistic, and quantum transport.

2. Experimental

The devices are fabricated from $GaAs/Al_xGa_{1-x}As$ heterostructures, containing high-mobility 2DEGs of densities around 4×10^{11} cm^{-2} and mobilities ranging from 3.0 to 8.0×10^5 cm^2/V s at 4.2 K, located 37 nm below the surface. The patterns are defined by electron beam lithography, combined with shallow wet etching (sample A, see Fig. 1) or reactive ion etching (samples B and C, see Figs. 2 and 4), respectively. For sample A, tunability is achieved by evaporation of a homogeneous NiCr gate that can be biased to change the overall carrier density in the unetched areas. Samples B and C make use of so-called "in-plane gates". Here, the cross-bar is defined by etching only narrow channels. The remaining areas of the 2DEG can then be used as side gates (labeled G1, ..., G4 in Figs. 2 and 4) so that the narrow constrictions around the central scatterer can individually be tuned by the application of a suitable bias to the corresponding gate. The samples are characterized by standard DC current and voltage measurements, carried out at liquid He temperatures.

3. Results and discussion

Fig. 1 shows the measured output voltage V_{LU} as a function of the input voltage V_{SD}.[1] At low bias the

[1] Plotting V_{LU} against input *voltage* rather than current (see Ref. [1]) facilitates assessment of the rectification efficiency V_{out}/V_{in}.

results are in good agreement with Ref. [1], where a nearly parabolic characteristic was found. In order to explain this "ballistic rectification", Fleischmann and Geisel have proposed a model [4] that starts from four transport paths between the four leads. It assumes that two of them (here S–L and D–L) are quasi-classical, with a continuum of one-dimensional (1D) transport channels involved, whereas the other two paths (S–U, D–U) are quantized, with few, well-separated 1D channels. Application of a bias will continuously increase the number of 1D channels in one quasi-classical path (say, S–L) and decrease it in the other (L–D). This will lead to a chemical potential in L that is not the arithmetic mean of those in S and D

$$\mu_S - \mu_L < (\mu_S - \mu_D)/2, \quad \mu_L - \mu_D > (\mu_S - \mu_D)/2.$$

The other path with energetically well-separated 1D channels will remain unaffected at moderate bias, so that

$$\mu_S - \mu_U = \mu_U - \mu_D = (\mu_S - \mu_D)/2.$$

This difference in the way the voltage V_{SD} is divided up along the quasi-classical and the quantized transport path will result in a net voltage between U and L. For details of the model, see Ref. [4].

Fleischmann and Geisel further predicted that at high bias the number of 1D channels in the quantized path can be affected, too, leading to an abrupt change or even a reversed sign of the output signal. In agreement with these predictions, we observe pronounced changes in the output voltage at high input voltages, giving support for the theoretical explanation. [2]

To more thoroughly test the above picture, we have fabricated a sample with tunable narrow constrictions as shown in Fig. 2 (inset). Obviously, this device can no longer be understood in the simple ballistic electron picture shown in Fig. 1, because (i) the input leads are not narrow enough to provide for a well collimated electron beam and (ii) the scatterer is not asymmetric.

Fig. 2 displays the rectifying behavior of this device when two of the four constrictions surrounding the scatterer are opened up by a high positive gate voltage, whereas the other two remain narrow (approximately 300 nm, judging from the lithographic width of the etched trench and taking into account lateral depletion). Let us first focus on the curve with the narrowest leads. Compared to Fig. 1, a number of differences can be observed. First, the rectification efficiency (V_{out}/V_{in}) is about an order of magnitude better, showing that indeed quantum transport should be considered for optimization of "ballistic" rectifiers. Second, the output voltage stays almost zero up to a voltage of about ± 150 mV where it increases in a step-like fashion. Third and most important, *the output voltage is reversed with respect to* Fig. 1. This last observation has carefully been checked with different devices. Furthermore, we make use of the tunability of the sample where—because of the symmetric layout—the input/output configuration can be chosen freely and only the gate voltages determine the rectification [7]. This way the possibility that the (reversed) output voltage is caused by spurious effects such as unwanted lithographic asymmetry of random impurities can clearly be excluded.

The reversed output compared to Fig. 1 and compared to the model by Fleischmann et al. has been a great puzzle. As mentioned above, the model assumes that the applied voltage is evenly divided along the two narrow channels but unevenly divided along the wider channels. Recent experiments on a related device [7], however, showed that for very wide channels the drop in the chemical potential becomes symmetric again, as expected for classical diffusive transport.

We have therefore extended the model to also include the situation where the wide channels are classical diffusive, with a resistance that is independent of bias, whereas the narrow channels are in the quantum regime. The output voltage as a function of input bias is determined following the approach of Ref. [4]. We start from the fact that the intermediate voltage probes have equal incoming and outgoing currents (assuming ideal, current-less voltage measurement). Assuming zero temperature to simplify the calculation, from this follows (cf. Eqs. (4) and (7) in Ref. [4])

$$\int_{\mu_1}^{\mu_2} M(E)\,\mathrm{d}E = \int_{\mu_2}^{\mu_3} M(E)\,\mathrm{d}E.$$

Here, μ_1 is the chemical potential in lead 1 and $M(E)$ is the number of 1D channels up to a given energy E, calculated for a hard-wall potential. The input bias is given by $V_{13} = e(\mu_3 - \mu_1)$. This will determine the chemical potential in lead 2, while the

[2] Similar oscillatory output has been observed by Löfgren et al. (see Ref. [3]) and explained in a somewhat different picture of transverse modes in the input leads.

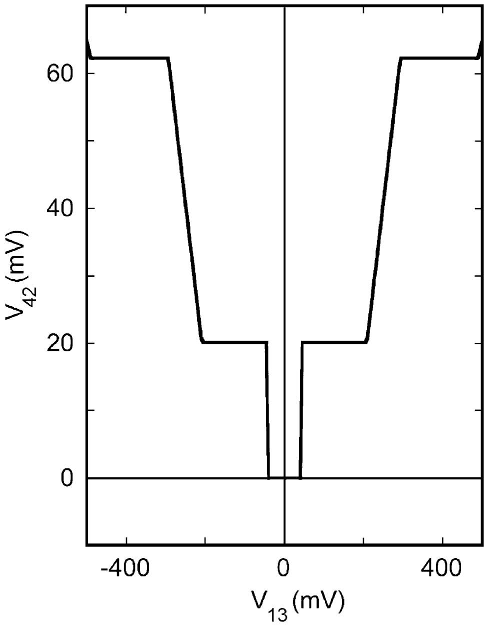

Fig. 3. Calculated output of a rectifier with one quantized path and one classical diffusive path. See text for details.

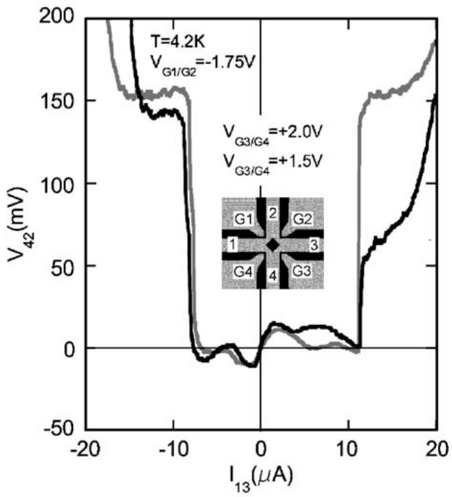

Fig. 4. Inset: Schematic of the layout of a tunable rectification structure with short constrictions. Main figure: Step-like output of the device shown as a function of input current. The gate voltages have been tuned so that the narrow constrictions exhibit quantized transport and the wider constrictions are in the classical diffusive regime. The output increases in a step-wise fashion, reflecting the population of 1D transport channels in the quantized current path.

chemical potential in lead 4 is given by the classical value $(\mu_3 + \mu_1)/2$.

Fig. 3 shows the result of the calculation. As expected, the sign of the calculated output is in agreement with the experimental curve. Furthermore, the model correctly shows the absence of any rectification at low bias. Only when a threshold bias is reached, the output increases abruptly. This abrupt increase takes place when the number of 1D channels differs by ± 1 in the narrow constrictions. The output then remains constant until a next threshold is reached and so on. It should be pointed out that this behavior is qualitatively different from the situation in Fig. 1 and Ref. [3], where the output is oscillatory and not step-like. On the other hand, it is in good qualitative agreement with the data in Fig. 2. Considering the simplicity of our model, even the quantitative agreement between Figs. 2 and 3 is satisfactory: Both the threshold voltage and the step height agree within roughly 30–40%. Also note that the input voltage scale of the steps in Fig. 2 and the oscillations in Fig. 1 are similar, giving support to the assumption that they originate from the same mechanism, i.e. the successive bias-induced opening of 1D channels in the narrow leads.

The plateau region after the threshold predicted by the calculation in Fig. 3 (40 mV $< |V_{13}| <$ 200 mV) is almost completely washed out in Fig. 2. Trying to reproduce this plateau experimentally, we fabricated samples with a layout similar to the one shown in Fig. 2, but with shorter and better defined constrictions (see inset to Fig. 4). Again, the tunability of the device through the in-plane gates G1, ..., G4 is advantageous. When the path 1–4–3 is opened by a positive voltage applied to gates G3 and G4 and a suitable negative gate voltage is applied to gates G1 and G2 the sample shows a clear step-like output (see Fig. 4). Unfortunately, under these conditions the sample is in a state of very high impedance and the output signal is affected by noise and other variations (probably caused by random impurities) in the output. Nevertheless, the vanishing output at low bias and the plateau-like constant output above the threshold voltage can clearly be discerned.

On the other hand, when the quantized paths become wider and wider by biasing the respective gates positively, the steps in the output characteristics become more and more obscured (see gray curves in

Fig. 2). Then the overall shape of the resistance becomes similar to that in Fig. 1, however with a curvature that is opposite to that in Fig. 1, because the roles of the narrow and wide paths are exchanged.

4. Summary and conclusion

In summary, we have realized tunable ballistic rectifiers with different geometries. In the "standard" geometry (Fig. 1) the general output characteristics of other studies [1,8] is reproduced. We have also investigated a novel geometry that is symmetric by design but can be made asymmetric (and thus rectifying) with great flexibility by in-plane gates. Here we find a dramatically improved rectification efficiency, which indicates that the simple billiard picture of ballistic rectification is not applicable and that a model that includes semiclassical and quantum transport is more appropriate. The reversed output polarity in this structure is explained by treating the wide leads as classical diffusive transport paths. The successive population of 1D subbands in the quantized current path then leads to a pronounced step-like rectification characteristic.

Acknowledgements

We would like to thank R. Fleischmann, T. Geisel, and A. Song for valuable discussions. Financial support by the Bundesministerium für Bildung und Forschung (BMBF) is gratefully acknowledged.

References

[1] A.M. Song, et al., Phys. Rev. Lett. 80 (1998) 3831.
[2] A.M. Song, Phys. Rev. B 59 (1999) 9806.
[3] A. Löfgren, et al., Phys. Rev. B 67 (2003) 195309.
[4] R. Fleischmann, T. Geisel, Phys. Rev. Lett. 89 (2002) 016804.
[5] M. Büttiker, D. Sánchez, Phys. Rev. Lett. 90 (2003) 119701.
[6] T. Geisel, R. Fleischmann, Phys. Rev. Lett. 90 (2003) 119702.
[7] S. de Haan, et al., Phys. Rev. Lett., in press.
[8] A.M. Song, et al., Appl. Phys. Lett. 79 (2001) 1357.