Rectification in Mesoscopic Systems with Broken Symmetry: Quasiclassical Ballistic Versus Classical Transport

S. de Haan,[1] A. Lorke,[2] J. P. Kotthaus,[1] W. Wegscheider,[3] and M. Bichler[4]

[1]*Sektion Physik and CeNS, LMU, Geschwister-Scholl-Platz 1, 80539 München, Germany*
[2]*Institut für Physik, Universität Duisburg-Essen, Lotharstrasse 1, ME245, 47058 Duisburg, Germany*
[3]*Institut für Angewandte und Experimentelle Physik, Universität Regensburg, 93040 Regensburg, Germany*
[4]*Walter Schottky Institut, TU München, Am Coulombwall 3, 85748 Garching, Germany*

(Received 17 July 2003; published 6 February 2004)

In suitably designed mesoscopic semiconductor structures, the phenomenon of ballistic rectification can be observed. A currently discussed microscopic model relates the observations to the interplay between fully quantized and quasiclassical current paths. We present measurements that contribute substantially to the clarification of the fascinating topic. In particular, we observe the opposite sign of the output voltage as compared to the prediction. Demonstrating the basic principle upon which the rectification is based—the asymmetry of the voltage drop in a quasiclassical wire—and extending the model to the classical transport regime, we can well explain our experiments as being caused by the interplay of quasiclassical ballistic and classical transport. Tunable ballistic rectifiers generating very large output signals and operating at room temperature raise the hope for future applications.

DOI: 10.1103/PhysRevLett.92.056806 PACS numbers: 73.23.Ad, 73.40.Ei

The combination of state-of-the-art nanoelectronic fabrication techniques with high mobility two-dimensional electron gases (2DEGs) based on semiconductor heterostructures made it possible to study the transport properties of devices with feature sizes smaller than the elastic mean-free path of the electrons. In such mesoscopic systems, transport is determined by reflection from the device boundaries rather than by scattering events caused by residual impurities. Because of the ballistic nature of transport, the shape of the conducting region plays a crucial role for the functioning of a device.

A prominent example is the so-called "ballistic rectifier," introduced by Song *et al.* [1]. There, the symmetry of a crosslike device is intentionally broken with respect to the source-drain axis by embedding a triangular scatterer in the center. Driving a current through the source-drain path results in a nonzero voltage between the upper and lower voltage probes that is independent of the direction of the input current. Another example is the influence of broken symmetry on quantum transport as observed, e.g., by Linke *et al.* [2] and theoretically treated by Reimann *et al.* [3].

Though at first glance the ballistic rectification can be understood in a simple billiardlike picture of deflected electrons [1], the underlying mechanisms are more complex. A full theoretical understanding of the phenomenon is still missing, even though the experimental facts are reproducible and widely accepted. Recently, Fleischmann and Geisel introduced a microscopic model based on the Landauer-Büttiker approach [4] and including the energy dependence of the number of modes propagating in different current paths [5]. Here, rectification is attributed to the interplay of fully quantized and quasiclassical ballistic transport channels in the system. The model stimulated further, ongoing discussion [6,7], as well as our present experimental studies. As predicted by the model, an oscillatory output was found in recent measurements. However, in some experiments the sign of the rectified voltage seems to be controversial [8,9].

In this Letter, we present measurements that serve as a direct test of the model of Ref. [5] and via new experimental information shed light on the mechanisms underlying ballistic rectification. As will be shown in detail, investigating a device with an optimized design, we obtain the surprising result that the output voltage has a sign opposite to what has been theoretically predicted in Ref. [5]. Determining the chemical potentials of the voltage probes independently in a suitable experiment, we demonstrate that this sign reversal can be explained extending the scope of the approach of Fleischmann and Geisel by introducing a classical current path [10]. We further show measurements on improved, tunable structures strengthening the confidence in this interpretation.

In the first step, we investigated a ballistic rectifier with a design following the proposal in Ref. [5]. The devices are fabricated from a δ-doped $GaAs/Al_xGa_{1-x}As$ heterostructure with a two-dimensional electron gas located 60 nm below the surface, a typical carrier density of 5×10^{11} cm^{-2}, and a typical mobility of 7.5×10^5 cm^2/V s at 4.2 K. High-resolution electron beam lithography and wet chemical etching techniques are used to define the central region of the device. As seen in the atomic force micrograph (inset of Fig. 1), it is formed by four electronic channels. Two of them are narrow, two of them wide. In order to avoid strong depletion effects, the trenches are only shallowly etched (≈ 30 nm). Evaporating a NiCr gate, we are able to vary the electron density and to control the effective electronic widths of the channels. Adopting the notation of Ref. [1], the contacts are labeled "source" S, "drain" D, "upper" U,

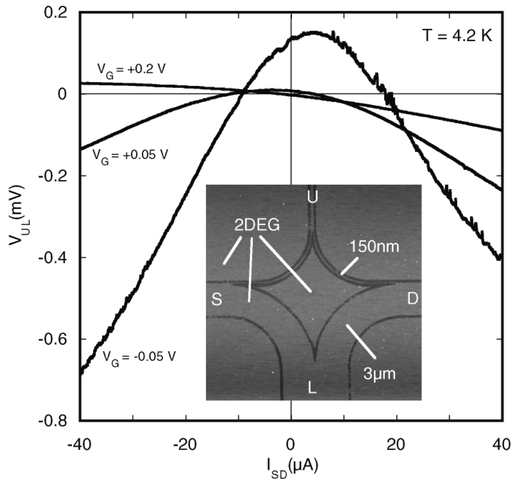

FIG. 1. *I-V* curves of a device combining 150 nm and 3 μm wide leads for different gate voltages at 4.2 K. If the gate voltage is sufficiently low, strong nonlinear effects can be observed, and the external current is rectified. The inset is an atomic force micrograph of the active part of the sample, illustrating the geometry and the labeling of the contacts.

and "lower" L. The lithographic width of the narrow leads, coupling the upper contact to source and drain, is 150 nm, whereas the leads connecting the lower contact are 3 μm wide.

In Fig. 1, we present V_{UL} vs I_{SD} curves of the device at 4.2 K for different gate voltages. If we apply a sufficiently large positive gate voltage, the *I-V* characteristic is almost linear. A decrease of the gate voltage, resulting in better defined and narrower channels, leads to strong symmetric contributions. At negative gate voltages, we observe distinct nonlinear behavior caused by breaking the symmetry of the device. Although the curves are not perfectly symmetric and slightly shifted with respect to the $V_{UL} = 0$ line (effects that are probably caused by imperfections in device fabrication and thermal voltages), at first sight our experimental results seem to be in perfect agreement with the predictions of Fleischmann and Geisel. Note, however, that they cannot be explained in an illustrative single particle picture [1] relying on guidance and reflection of ballistic electrons and collimation effects.

The experimental data of Fig. 1 exhibit a crucial difference as compared to theory [5]. The sign of the output voltage is reversed. In contrast to both the calculations and the experiments with triangular scatterers, in our structure negative charge is accumulating at the *upper* contact, i.e., the contact coupled to source and drain via *narrow* leads. In order to confirm this unexpected result, various samples, including devices without top gate and devices combining 300 nm and 3 μm wide channels, have been thoroughly examined. Although some samples exhibit weaker nonlinear contributions than those to be seen in Fig. 1, the curvature of the V_{UL} vs I_{SD} curves is always negative, supporting the presented data without exception.

According to Ref. [5], understanding the behavior of the chemical potential of a voltage probe P that is connected by identical boxlike leads to a source contact S and a drain contact D can serve as a key for understanding the process of rectification as a whole. The authors argue that, in the quantum-mechanical case, when the number of modes is constant in the energy interval between the chemical potential of the source contact μ_S and the chemical potential of the drain contact μ_D, this quantity reads $\mu_P = (\mu_S + \mu_D)/2$. In "quasiclassical" (wider but ballistic) leads, however, where the number of occupied modes increases as the square root of the energy and current at higher energies is carried by a greater number of modes, the chemical potential must shift to higher values, $\mu_P > (\mu_S + \mu_D)/2$. Similar phenomena have recently been reported in nanoscale devices connecting three quantum point contacts via a ballistic cavity [11,12].

The direct measurement of the chemical potential μ_P in a suitable layout provides essential information for the interpretation of our results. We therefore fabricated three terminal devices consisting of a single electronic channel with a source contact, a drain contact and a voltage probe that is located in the middle of the wire (see insets of Fig. 2). Applying an external source-drain bias, we can now directly determine the voltage drops between S and P and between P and D, respectively.

Several devices with a 3 μm "wide" channel, representing the lower half of the device shown in Fig. 1, and samples with a 300 nm "narrow" channel, representing the upper half, have been investigated. Typical results are presented in Fig. 2. In the case of a 3 μm wide lead, the voltage measured between S and P and the voltage measured between P and D are virtually equal; i.e., the

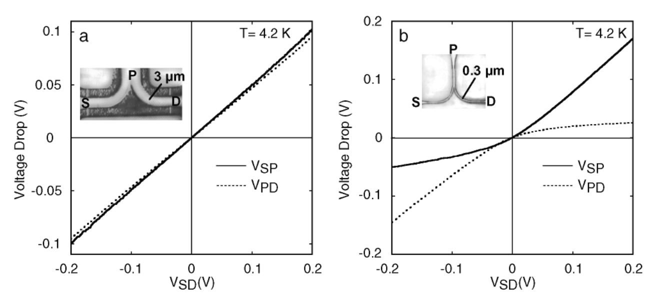

FIG. 2. Determination of the chemical potential of a voltage probe P that is connected by identical leads to a source contact S and a drain contact D for different channel widths. The central parts of the devices are shown in the insets. (a) In the case of a 3 μm wide channel, the source-drain voltage drops symmetrically as expected for a classical conductor. (b) In the case of a 300 nm wide channel, the potential of the voltage probe is shifted towards that of the negatively biased reservoir. Compared to (a), the chemical potential μ_P is raised, corresponding to quasiclassical behavior.

voltage drop is almost perfectly symmetric [see Fig. 2(a)] as expected for a classical conductor. As can be seen in Fig. 2(b), showing the experimental results for a 300 nm wide channel, a reduction of the wire width causes significant changes. Applying a negative voltage between the source and the drain contact, the voltage drop measured between S and P is smaller than the voltage drop measured between P and D, $|V_{SP}| < |V_{PD}|$. In the case of positive source-drain voltages, this relation is reversed, $|V_{SP}| > |V_{PD}|$; the two curves are bent into opposite directions.

The fact that the voltage difference $|V_{SP}| - |V_{PD}|$ undergoes a change in sign, when the source-drain bias is swept through zero, clearly indicates that the reduction of the channel width leads to a fundamental change in the transport mechanism. Extending the considerations of Fleischmann and Geisel to the classical transport regime [10], we can explain our observations. The relation $\mu_P = (\mu_S + \mu_D)/2$ should be valid not only in a narrow quantum-mechanical lead with a constant number of modes, but also in the classical case. This is a trivial consequence of the fact that the resistance of a classical wire grows linearly with its length. Accordingly, from the symmetric voltage drop illustrated in Fig. 2(a) , it follows that the 3 μm channel in our experiment exhibits classical behavior. In the case of a 300 nm lead, however, the chemical potential of P is shifted to higher values, $\mu_P > (\mu_S + \mu_D)/2$—the fingerprint of a quasiclassical current path, in perfect agreement with the predictions of Ref. [5].

Based on this experimental data, we understand the results presented in Fig. 1. The device designed to test the theoretical model of Ref. [5] clearly works as a rectifier, but it is operating in a different transport regime. Whereas in the model rectification arises from the interplay of *quasiclassical* and *fully quantized* transport channels, the rectification effect observed in the experiment can be attributed to the coupling of *classical* and *quasiclassical* channels. Surprisingly, the fundamental ability of the sample to rectify an external current remains unchanged, but the sign of the output voltage is reversed when measuring between corresponding probes:

$$\mu_{P,\,\mathrm{wide}} - \mu_{P,\,\mathrm{narrow}} > 0,$$

if wide represents the quasiclassical, ballistic and narrow the quantum-mechanical transport regime;

$$\mu_{P,\,\mathrm{wide}} - \mu_{P,\,\mathrm{narrow}} < 0,$$

if wide represents the classical and narrow the quasiclassical, ballistic regime.

Responsible for this striking result are the properties of the chemical potential μ_P. Comparing a classical wire and a quantum-mechanical wire with very few occupied modes [9], this quantity adopts the same value. In between those limits, in the quasiclassical ballistic case with a large number of occupied modes, one finds deviations, both in the model and in the experiment.

To test our explanation in detail and to further demonstrate that the rectification is given by the width of the different leads rather than spurious effects such as nonlinear contacts or random impurities, we have finally fabricated samples with a geometry that can be adjusted *in situ* by means of external gate voltages.

The active region of the sample is now symmetric. It is formed by a central scatterer, surrounded by four 700 nm wide electronic channels that are electrically separated from the remaining two-dimensional electron gas by 300 nm wide etched trenches. In analogy to a variety of fascinating experiments dealing with Y-branch switches [13–15], the parts of the 2DEG that are adjacent to the channels act as in-plane gates (IPGs) that can be used to tune the width of each constriction separately (see the schematic insets of Fig. 3). The basic processing steps are the same as for the first generation of devices described in the beginning. However, in this new layout the effective electrical isolation of the IPGs and the minimization of leakage currents across the etched barriers are essential for the performance, especially at room temperature. To optimize these parameters, we chose a shallow GaAs/Al$_x$Ga$_{1-x}$As heterostructure with a 37 nm deep

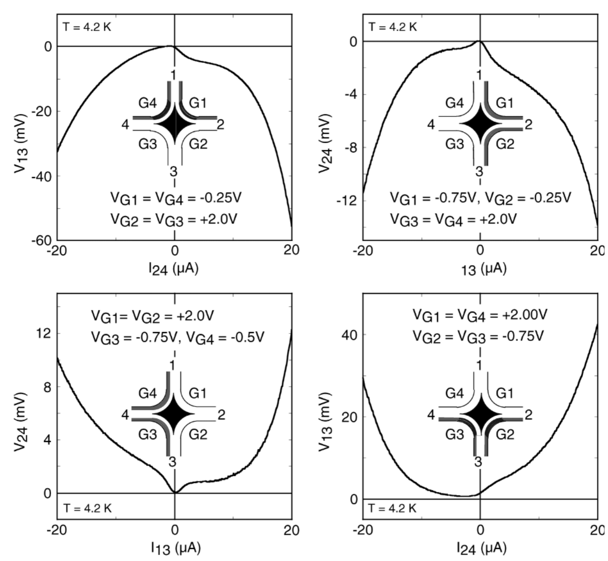

FIG. 3. Transverse current-voltage characteristics of a tunable ballistic rectifier for four equivalent gate configurations. The basic layout of the device and the operating principle of the in-plane gates are schematically illustrated in the insets. Whenever the gate-induced asymmetry is sufficiently large, rectification can be observed. In the experiments shown in the upper left and the lower right, the external current is injected into contact 2 and drawn out at contact 4, and the rectified voltage is measured between the contacts 1 and 3. In the other two measurements, current and voltage contacts are exchanged. Comparing the diagonally opposing curves, one can see that a reversal of the channel widths results in a reversal of the output signal.

two-dimensional electron gas as a starting material. Reactive ion etching ($SiCl_4$ and Ar) at very small acceleration voltages ($V_{acc} < 20$ V) is used to transfer the resist mask into the electron gas. Thanks to these improvements, we are able to fabricate highly isolating trenches with sufficiently low depletion lengths that allow for the application of large gate voltages and offer a wide-range tunability of the channel widths.

The measurements presented in Fig. 3 demonstrate the enormous flexibility of this type of devices. Here, we show the transverse current-voltage characteristics for specific gate configurations at 4.2 K. If the gate-induced asymmetry of the system becomes sufficiently large, resulting in narrow channels on one side of the structure and wide channels on the other, the sample again works as a rectifier.

Because of the fourfold symmetry of the layout, the tunability of the channels enables us to access four equivalent measurement configurations that are schematically sketched in the insets. It is possible not only to reverse the output signal simply by reversing the gate voltages (see the upper left and the lower right curves in Fig. 3), but also to exchange current and voltage contacts (see the upper left and upper right curves in Fig. 3). In any of the different setups, we observe clear rectification. Agreeing with the results obtained from the fixed geometry, negative charge is *always* accumulating at the voltage probe that is connected to the current contacts via the *narrow* channel pair, i.e., the channel pair formed by smaller gate voltages. Confirming the previous measurements, again the sign of the rectification signal is reversed, as compared to the calculations in Ref. [5]. However, the ability to invert the output signal of our tunable ballistic rectifier *in situ* by adjusting the individual gate voltages, strongly supports the approach of the authors that rectification arises as a consequence of different widths of the channels.

In addition to this, both the absolute value of the rectified voltage and the temperature dependence of the effect illustrate that our interpretation of the experiments, involving classical and quasiclassical current paths, is correct. In comparison to the devices consisting of a triangular scatterer, we could increase the output signal by 3 orders of magnitude, both at liquid helium and at liquid nitrogen temperatures. With appropriate gate voltages, output voltages of more than 100 mV can easily be achieved. Even at room temperature, we observe a strong rectification effect, opening up chances for future applications. The parameter limiting the device performance at high temperatures is the stability of the in-plane gates against breakthrough. If the thermally activated leakage currents between the gates and the electronic channels become too large, it is no longer possible to generate an adequate gate-induced asymmetry in the sample. Hence, the decrease of the attainable output voltage with increasing temperature is due to a fabrication process, which can still be optimized, rather than due to a fundamental operating principle.

In conclusion, we have investigated novel types of symmetry-broken mesoscopic semiconductor structures. Extending a recent theoretical proposal, our experiments show that the phenomenon of ballistic rectification can be understood within the framework of different transport regimes. The suggestion that the mechanism of rectification relies on an asymmetric potential drop in a quasiclassical wire could be verified. Our finding, that the functionality of the new devices is based upon the interplay of quasiclassical and classical transport channels, will have important implications on the exploitation of the effect.

We would like to thank M. Büttiker, R. Fleischmann, T. Geisel, and A. Song for valuable discussions. The work was supported by the Bundesministerium für Bildung und Forschung (BMBF) under Grant No. 01 BM 914.

[1] A. M. Song, A. Lorke, A. Kriele, J. P. Kotthaus, W. Wegscheider, and M. Bichler, Phys. Rev. Lett. **80**, 3831 (1998).
[2] H. Linke, T. E. Humphrey, A. Löfgren, A. O. Sushkov, R. Newbury, R. P. Taylor, and P. Omling, Science **286**, 2314 (1999).
[3] P. Reimann, M. Grifoni, and P. Hänggi, Phys. Rev. Lett. **79**, 10 (1997).
[4] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).
[5] R. Fleischmann and T. Geisel, Phys. Rev. Lett. **89**, 16804 (2002).
[6] M. Büttiker and D. Sánchez, Phys. Rev. Lett. **90**, 119701 (2003).
[7] T. Geisel and R. Fleischmann, Phys. Rev. Lett. **90**, 119702 (2003).
[8] A. Löfgren, I. Shorubalko, P. Omling, and A. M. Song, Phys. Rev. B **67**, 195309 (2003).
[9] S. de Haan, A. Lorke, J. P. Kotthaus, M. Bichler, and W. Wegscheider (to be published).
[10] By "classical" we mean that the observed behavior is as expected for a classical conductor with diffusive transport, even if the origin of this behavior may be nonclassical. It may be caused, e.g., by screening in a multichannel ballistic conductor as discussed by Büttiker *et al.* [6,7].
[11] H. Q. Xu, Appl. Phys. Lett. **78**, 2064 (2001).
[12] I. Shorubalko, H. Q. Xu, I. Maximov, P. Omling, L. Samuelson, and W. Seifert, Appl. Phys. Lett. **79**, 1384 (2001).
[13] J.-O. J. Wesström, Phys. Rev. Lett. **82**, 2564 (1999).
[14] K. Hieke and M. Ulfward, Phys. Rev. B **62**, 16727 (2000).
[15] L. Worschech, B. Weidner, S. Reitzenstein, and A. Forchel, Appl. Phys. Lett. **78**, 3325 (2001).