Nonlinear Electron Transport in an Asymmetric Microjunction: A Ballistic Rectifier

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(Received 1 December 1997)

An asymmetric artificial scatterer in a semiconductor microjunction is shown to dramatically affect the nonlinear transport of ballistic electrons. The chosen device geometry, defined in a GaAs-AlGaAs heterostructure, successfully guides carriers in a predetermined spatial direction, independent of the direction of the input current I. From the nonlinear current-voltage characteristic we obtain unusual symmetry relations for the four-terminal resistances with $R_{ij,kl}(I) \approx -R_{ij,kl}(-I)$ and $R_{ij,kl}(B) \gg R_{kl,ij}(-B)$ even at zero magnetic field B. The *ballistic rectifier* thus realized relies on a new kind of rectification mechanism entirely different from that of an ordinary diode. [S0031-9007(98)05927-4]

PACS numbers: 73.23.Ad, 73.40.Ei, 73.50.Fq

The high mobilities of state-of-the art two-dimensional electron gases in semiconductor heterostructures, combined with device fabrication technologies with high spatial resolution, have made it possible to study electron transport through semiconductor devices in which characteristic feature sizes are small in comparison with the elastic mean free path between scattering events caused by residual impurities. In such microstructures, electrons do not propagate diffusively as in traditional semiconductor devices but instead ballistically, with their path largely determined by specular reflection from device boundaries. Based on ballistic electron transport, a variety of novel phenomena have been observed in such microdevices. Examples are electron focusing [1], bend resistances [2], and a quenched or negative Hall effect [3,4]. Within the framework of the Landauer-Büttiker formalism, models have been developed to explain the above linear transport phenomena [5]. However, comparatively less attention has been given to the nonlinear ballistic transport regime in which electric fields or currents become so large that they significantly affect the momentum distribution of the carriers without destroying ballistic motion by inelastic scattering processes. Only recently has it been recognized in both theoretical and experimental studies that it is rather challenging to also investigate the nonlinear ballistic transport regime [6–8]. Even though several groups have realized that the introduction of artificial asymmetries should have a significant effect on nonlinear ballistic transport [9–11], so far, no strong nonlinear effects induced by a broken device symmetry have been observed.

Here we introduce a novel device geometry which is particularly suitable to study the effects of reduced symmetry on the nonlinear ballistic transport properties. By inserting an asymmetric scatterer into the center of a ballistic cross junction, we observe unusual nonlinear current-voltage characteristics which we show to be dominated by the symmetry properties of the scatterer. The size of the artificial scatterer is much larger than the Fermi wavelength λ_F of the conducting electrons and comparable to their elastic mean free path l_e ($l_e \gg \lambda_F$). We demonstrate a successful guidance of ballistic electrons to a predetermined spatial direction independent of input current direction. As a result, the device works as a *ballistic rectifier* with a mechanism entirely different from that of an ordinary diode. We would like to point out that here we tailor the momentum distribution of carriers rather than their band structure.

The observed drastic dependence of the transport properties on lead currents and magnetic fields is reflected in unusual symmetry relations of the four terminal resistance $R_{ij,kl} \equiv V_{kl}/I_{ij}$, defined by the voltage V_{kl} measured between terminals k and l, divided by the current I_{ij} flowing from i to j. In particular, we can achieve $R_{ij,kl}(I) \approx -R_{ij,kl}(-I)$ and $R_{ij,kl}(B) \gg R_{kl,ij}(-B)$ even at zero magnetic field B. An extended Landauer-Büttiker formula, which includes the dependence of the transmission coefficients on lead currents, is employed and describes well our observations.

The preparation of the device starts from a modulation-doped GaAs-AlGaAs heterostructure with a two-dimensional electron gas located 37 nm below the surface. On the unprocessed wafer, the carrier density is about 5×10^{11} cm^{-2} with a mobility of about 5×10^5 cm^2/V s at 4.2 K. The left inset of Fig. 1(a) is an atomic force micrograph of the central part of the device. Using electron beam lithography and shallow wet etching, a triangular antidot is defined in a cross junction formed by two wide channels (labeled "upper" U and "lower" L) and two narrow channels (labeled "source" S and "drain" D). The antidot has an upper sidelength of 2 μm and a height of 1 μm. The lithographic width of the source and drain channels is 700 nm, while the electronic width is about 400 nm due to the carrier depletion along the channel edges. The designed width of the upper and lower channels is 3.2 μm. The horn-shaped openings of the S and D channels are used to collimate electrons

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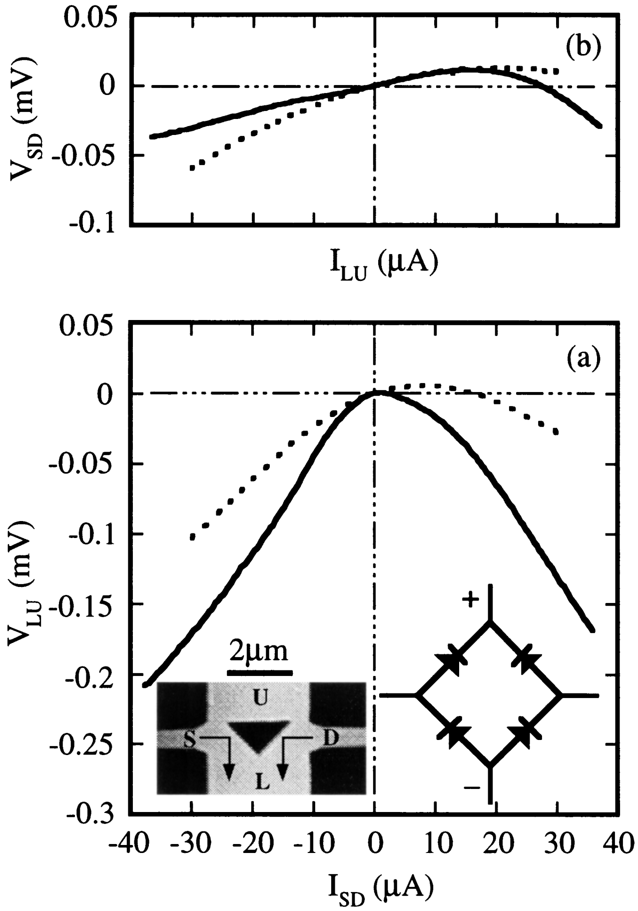

FIG. 1. *I*-*V* curves of a typical device at 4.2 K (solid lines) and 77 K (dashed lines). In the geometry where the symmetry is broken with respect to the current path, V_{LU} vs I_{SD} (a), a much more pronounced nonlinear characteristic is observed than in the complementary geometry, V_{SD} vs I_{LU} (b). The left inset in (a) is an atomic force micrograph of the central part of the sample. Arrows indicate typical trajectories of electrons ejected through *S* and *D* channels, respectively. The right inset represents a bridge rectifier.

[4]. Since the elastic mean free path l_e of our sample (about 6 μm) is larger than the central part of the device, specular electron scattering from the etched boundaries dominates the transport properties.

For the present device geometry, a naive ballistic single particle picture appears to predict a *nonlinear* response [arrows in the left inset in Fig. 1(a)]: For a net flow of electrons from *S* to *D* (negative I_{SD}), the majority of the electrons ejected through *S* into the junction will be specularly deflected towards *L*, thus inducing a negative voltage V_{LU} between the *L* and *U* voltage probes. For the reverse source-drain current and perfect symmetry of the sample, the electrons ejected through *D* and deflected by the scatterer will result in the *same* negative voltage V_{LU}, or, expressed in terms of the four-terminal resistance,

$$R_{SD,LU}(I_{SD}) = -R_{SD,LU}(-I_{SD}). \qquad (1)$$

This is opposite to the case of *linear* ballistic transport where any four-terminal resistance $R_{ij,kl}$ is independent of I_{ij}; i.e., $R_{ij,kl}(I) = +R_{ij,kl}(-I)$ holds, corresponding to an antisymmetric V_{kl} vs I_{ij} curve. However, we emphasize that, in general, this naive picture is wrong, but in the presence of nonlinear transport, we will demonstrate below that it turns out to be correct.

The V_{LU} vs I_{SD} curve of our device measured at 4.2 K [solid line in Fig. 1(a)] almost perfectly [12] exhibits the symmetry breaking response of Eq. (1). The slight deviations from Eq. (1) observed in the experiment are attributed to an unintentional breaking of the desired symmetry along the *L*-*U* axis. We wish to point out that even in the limit where dissipation dominates the resistance, we expect the four-terminal resistance $R_{SD,LU}$ to vanish for a device with perfect symmetry. A number of other devices with similar geometries were fabricated on the same and other wafer material. Even though most of these devices show stronger antisymmetric contributions, all samples exhibit a strong symmetric contribution to the *I*-*V* characteristic, as expressed in Eq. (1) and observed in Fig. 1(a).

This fact demonstrates that the guidance of electrons by the artificial scatterer (which can be thought of as a kind of "momentum tailoring") has resulted in a device characteristic similar to that of a bridge rectifier [see the right inset of Fig. 1(a)]. However, only a single device is used here rather than four diodes as in a bridge rectifier. The mechanism and the major characteristics of the present device make it entirely different from a common semiconductor diode. First, no doping junction or barrier structure along the current direction is used in our devices at all. The rectification effect comes only from the artificial scatterer which breaks the symmetry of the device with respect to the *S*-*D* axis. Second, as there is, under ideal conditions, no *intrinsic* lower current limit for nonlinear ballistic transport, no obvious threshold working current or voltage is expected for the present rectification scheme. Indeed, in an ac measurement (not shown here), a clear rectification effect is observed even when the applied ac source-drain voltage is well below 1 mV. Thus, the working principle of our device might be suitable for detection and mixing of ultraweak signals. Finally, because of the small feature size and the low in-plane capacitance of the device as well as its ballistic nature, the rectification is expected to operate up to very high frequencies. On a related device with an array of triangular scatterers, a nonlinear response was observed in the THz regime [10]. On the present device, initial high frequency measurements up to 2 GHz showed no significant decrease in the rectification efficiency.

Even though the present device works best at liquid helium temperatures, a weaker rectification can also be observed at 77 K [dotted line in Fig. 1(a)]. The reduced nonlinear behavior is attributed to the shorter l_e (about 1–2 μm) at 77 K, which is still comparable to the distance between the openings of the *S* or *D* channels and the antidot. At room temperature, when the transport becomes diffusive on the scale of the junction's dimension, we recover the conventional antisymmetric *I*-*V* characteristics.

To confirm that the above effect is indeed caused by the artificial scatterer and the broken symmetry for current flow along the S-D direction, we also measured the complementary case, V_{SD} vs I_{LU}. For an ideal device geometry that is symmetric along the U-L axis, $V_{SD} = 0$ is expected at any I_{LU}. Experimentally, we observe a nonzero response [solid line in Fig. 1(b)]. However, for the same applied current, V_{SD} is almost an order of magnitude lower than V_{LU}. Again, we attribute the deviation from the ideal response to imperfections in the fabricated geometry. It is worth noting that the quasilinear part of the I-V curve in Fig. 1(b) extends to much higher currents than in Fig. 1(a). This implies that through the suitably designed device geometry and the measurement configuration, our experiment is particularly sensitive to nonlinear effects. This allows for a detailed study of the nonlinear properties at low current densities, where, e.g., heating effects are negligible.

For ballistic transport in the *linear regime,* the Landauer-Büttiker formalism [5],

$$I_i = (e/h)\left[(N_i - R_{ii})\mu_i - \sum_{j \neq i} T_{ij}\mu_j \right], \qquad (2)$$

has been very well developed. Here, N_i is the number of conducting channels in lead i, R_{ii} is the coefficient for carriers in lead i to be reflected into lead i, μ_i is the chemical potential of lead i, and T_{ij} is the transmission coefficient of carriers from probe j to i ($T_{i \leftarrow j}$). Similar to the Onsager-Casimir relations of the resistivity [13], a reciprocity symmetry relation of the four-terminal resistance,

$$R_{ij,kl}(B) = R_{kl,ij}(-B), \qquad (3)$$

was derived based on time-reversal symmetry in the presence of a magnetic flux, $T_{ij}(B) = T_{ji}(-B)$ [5].

The clear nonlinear effects observed in our experiment, however, are not described by Eq. (3). We are able to generate a system where $R_{SD,LU}$ is considerably larger than $R_{LU,SD}$ and $R_{SD,LU}(I) \approx -R_{SD,LU}(-I)$ even at zero magnetic field.

To account for the experimental observations within the Landauer-Büttiker picture, we assumed that Eq. (2) still holds in a generalized form, at least to a good approximation, also in the nonlinear ballistic transport regime. To include nonlinear effects, however, we allow the transmission coefficient T_{ij} to be a function of the lead current I_j. This reflects the fact that in general the transmission coefficients are dependent on the momentum distribution of the carriers. Since I_j determines the momentum distribution of electrons in lead j, it also determines the transmission probabilities of electrons from lead j to the other leads. Here, we take into account only the dependence of T_{ij} on the current of the lead j, where the electrons are ejected from [14]. For example, in the linear transport case (around zero lead currents), the electrons in the S channel of our device have the same probability of moving towards the antidot as that of moving towards the source contact. In the nonlinear transport case, the applied current in the S channel causes an electric field along the channel direction (defined to be the x direction). This will not affect the velocity distribution of the electrons in the y direction which is from $-v_F$ to $+v_F$. Here we assumed that the y axis is in the device plane and perpendicular to the current direction, the temperature $T = 0$ K, and v_F is the Fermi velocity. However, the velocity distribution in the x direction becomes from $(-v_F + \Delta)$ to $(v_F + \Delta)$. Here Δ is the change of velocity due to the acceleration (in one direction) or deceleration (in the opposite direction) effect of the electric field. The accelerated electrons will then be ejected in a smaller angle with respect to the x axis due to the enhanced velocity component in the x direction, i.e., *collimated* by the electric field, while the decelerated electrons will move into a larger angle, i.e., *decollimated* by the electric field. If the current in the S channel is applied in such a direction that the electrons coming out of it are accelerated by the electric field, clearly the collimation effect will increase the transmission probability from S to L and suppress the transmission probability from S to U, and vice versa. Therefore, in general, the transmission coefficient T_{ij} is a function of the lead current I_j in the nonlinear transport regime.

In complete analogy to the derivation in the linear transport case [5], the four-terminal resistance formula follows:

$$R_{SD,LU} = (h/e^2 D)[T_{LS}(I,B)T_{UD}(-I,B) - T_{LD}(-I,B)T_{US}(I,B)]. \qquad (4)$$

Here, we define $I \equiv I_{SD}$ and a positive lead current as a current flowing into the device. The determinant D is a positive factor, relatively insensitive to lead currents [5]. Around zero current (i.e., in the linear regime) and at zero magnetic field, $T_{LS} = T_{LD}$ and $T_{US} = T_{UD}$, so that $R_{SD,LU} = 0$ is expected in the case of a device with perfect symmetry along the U-L axis. However, if $I_{SD} > 0$ (net flow of electrons from D to S), the electrons coming out of the D channel are accelerated by the electric field in the channel D. This collimation effect enhances the transmission coefficient from D to L, T_{LD}, and suppresses T_{UD}. The transmission coefficients T_{LS} and T_{US} are determined by the electrons coming out of the S channel. Since the electric field decelerates these electrons in the direction from the S channel to the antidot, this decollimation effect suppresses T_{LS} and increases T_{US}. As a result, we find from the Eq. (4) that $R_{SD,LU} < 0$, which corresponds to the negative slope in the right part of the V_{LU} vs I_{SD} curve in Fig. 1(a). Similarly, for $I_{SD} < 0$, we obtain $R_{SD,LU} > 0$, corresponding to the positive slope in the left part of the V_{LU} vs I_{SD} curve in Fig. 1(a). A more detailed discussion of the transmission coefficients as a function of lead currents, which takes into account the change of the number of electrons ejected from the channels with lead currents, will be given elsewhere [15].

To gain further insight into the effects caused by the artificial scattering geometry, magnetic fields were

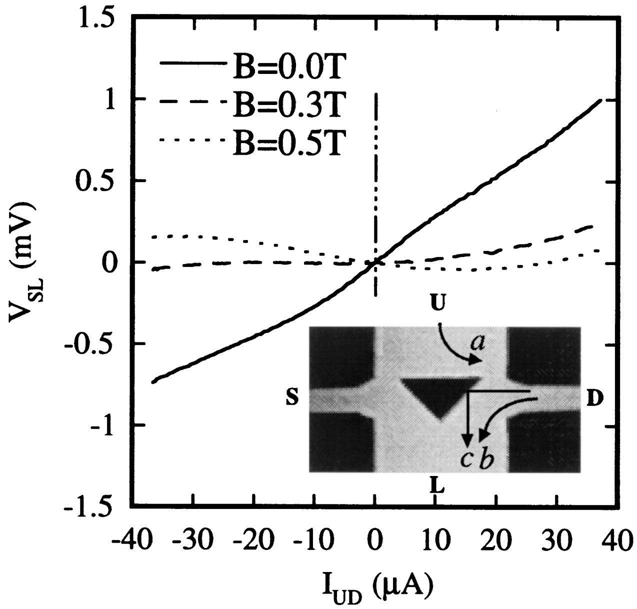

FIG. 2. V_{SL} vs I_{UD} curves in different magnetic fields B at 4.2 K. The inset shows some typical trajectories, a, b, and c associated with the transport discussed in the text.

applied normal to the sample surface. Since in a magnetic field, a large Hall effect dominates the above four-terminal resistance ($R_{SD,LU}$) measurement, we will focus in the following on $R_{UD,SL}$, the so-called "bend resistance." Figure 2 shows V_{SL} vs I_{UD} traces at $B = 0$, 0.3, and 0.5 T with the magnetic field pointing out of the plane of the two-dimensional electron gas. The most prominent effect of the magnetic field in Fig. 2 is its strong influence on the slope of the I-V curve, which changes sign around $B = 0.3$ T. Similar to Eq. (4), we can obtain the four-terminal resistance

$$R_{UD,SL} = (h/e^2D)[T_{SU}(I,B)T_{LD}(-I,B) - T_{SD}(-I,B)T_{LU}(I,B)]. \quad (5)$$

Here, $I \equiv I_{UD}$. When $B = 0$, the antidot blocks the direct path of electrons from D to S so that $T_{SD} \approx 0$ and very straightforwardly from Eq. (5) we find $R_{UD,SL} > 0$. With increasing magnetic field, T_{SU} will strongly decrease as shown by the typical trajectory a of electrons in the inset of Fig. 2. The transmission coefficient T_{LD}, however, is not as much affected by the magnetic field. As depicted in the inset of Fig. 2, trajectory b in a magnetic field contributes as much to T_{LD} as trajectory c in zero magnetic field. Therefore, the product $T_{SU}(I,B)T_{LD}(-I,B)$ will decrease with increasing magnetic field. More importantly, at $B =$ 0.3 and 0.5 T, the classical cyclotron radii, R_C, are about 370 and 220 nm, respectively, which are comparable to the distance between the antidot and the conducting channels. Therefore, the curved orbits allow the electrons to bypass the antidot or use it as a "bridge" between D and S. Thus, $T_{SD} > 0$ and the second product in the bracket of Eq. (5) will increase. As a result, $R_{UD,SL}$ decreases and eventually becomes negative, as observed in the experiment. This further confirms the dominant influence of the triangular antidot on the transport behavior of our device.

In conclusion, we wish to emphasize the possibility of using artificial scatterers to achieve and study novel transport behavior of ballistic electron devices. Our finding not only has important implications for the understanding of nonlinear transport in semiconductor microstructures, but also could open a great number of novel routes for the design of detection, mixing, and other nonlinear devices, since the investigated nonlinear behavior does not rely on a mechanism intrinsic to semiconductors or even solids.

We acknowledge valuable discussions with A. Govorov, S. E. Ulloa, M. Wagner, and W. Zwerger and excellent technical advice from S. Manus, B. Jager, and M. Streibl. One of us (A. M. S.) is supported by the Alexander von Humboldt Research Foundation. The work is supported through the Deutsche Forschungsgemeinschaft (SFB 348).

[1] H. van Houten *et al.*, Phys. Rev. B **37**, 8534 (1988); L. W. Molenkamp *et al.*, Phys. Rev. B **41**, 1274 (1990); J. Spector *et al.*, Appl. Phys. Lett. **56**, 1290 (1990).
[2] G. Timp *et al.*, Phys. Rev. Lett. **60**, 2081 (1988).
[3] M. L. Roukes *et al.*, Phys. Rev. Lett. **59**, 3011 (1987); C. J. B. Ford *et al.*, Phys. Rev. Lett. **62**, 2724 (1989).
[4] C. W. J. Beenakker and H. van Houten, Phys. Rev. B **39**, 10 445 (1989).
[5] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).
[6] R. Taboryski *et al.*, Phys. Rev. B **49**, 7813 (1994).
[7] R. I. Hornsey, A. M. Marsh, J. R. A. Cleaver, and H. Ahmed, Phys. Rev. B **51**, 7010 (1995).
[8] A. Messica *et al.*, Phys. Rev. Lett. **78**, 705 (1997).
[9] M. Büttiker, J. Phys. Condens. Matter **5**, 9361 (1993); T. Christen and M. Büttiker, Europhys. Lett. **35**, 523 (1996).
[10] A. Lorke *et al.*, Physica B (to be published).
[11] H. Linke, P. Omling, H. Xu, and P. E. Lindelof, in *Proceedings of the 23rd International Conference on the Physics of Semiconductors*, edited by M. Scheffler and R. Zimmermann (World Scientific, Singapore, 1996), p. 1593; H. Linke, Ph.D. thesis, Lund University, 1997.
[12] To account for spurious thermal voltages, the I-V curves displayed here were offset by a small constant amount.
[13] L. Onsager, Phys. Rev. **38**, 2265 (1931); H. B. G. Casimir, Rev. Mod. Phys. **17**, 343 (1945).
[14] In the case of very strong lead currents, one might need to include the dependence on all lead currents or treat the system self-consistently as done in Ref. [9].
[15] A. M. Song *et al.* (to be published).