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Sign reversal and tunable rectification in a ballistic nanojunction

B. Hackens,^{a)} L. Gence, and C. Gustin

CERMIN, PCPM and DICE Labs, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

X. Wallart, S. Bollaert, and A. Cappy

IEMN, Cité Scientifique, Villeneuve d'Ascq, France

V. Bayot

CERMIN, DICE Lab, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

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Low-temperature measurements show that an asymmetric mesoscopic junction patterned in a two-dimensional electron gas can exhibit tunable rectification, including sign reversal. Strikingly, we observe that the amplitude and sign of the effect are governed by the conductances of the channels and that rectification is reversed without reversing the asymmetry of the device. Based on the temperature dependence of the rectified voltage, we show that the effect is ballistic and exhibits unexpected features with respect to predictions of available models. © 2004 American Institute of Physics. [DOI: 10.1063/1.1814803]

Obtaining a rectification effect from a geometrical asymmetry was proposed as early as in 1920, when Nikola Tesla patented the “valvular conduit.”¹ The device consists of a channel with asymmetric loops on its sides and presents a resistance which depends on the direction of the fluid flow. Eighty years later, a similar rectification effect was obtained for electrons (different electrical resistance for different current directions), using an asymmetric ballistic nanochannel patterned in a semiconductor heterostructure.² In the last few years, a wealth of ballistic rectification effects have also been predicted and evidenced in junctions of three³ and four^{4–6} nanochannels with different geometries and different degrees of asymmetry. Pioneering works have also shown that the very high frequency operation of these devices is feasible and very promising.^{7,8} In such applications, tuning the ballistic rectification effect *in situ* would be highly valuable.

In this letter, we examine nonlinear rectification effects in the four-terminal device shown in Fig. 1(a), inspired by the model of Fleischmann and Geisel.⁶ As current flows between source and drain [S and D on Fig. 1(a)], this model predicts an accumulation of electrons (higher local electron density than the equilibrium value) at the wider voltage probe (labeled “lower,” L), provided that the narrow and wide channels of the device show quantized and ballistic transport, respectively. However, a recent experiment on a similar device geometry⁵ revealed an accumulation of electrons at the opposite (narrower) voltage probe (labeled “upper,” U), i.e., $V_{LU} = V_L - V_U > 0$. The apparent discrepancy between Refs. 5 and 6 was attributed to the fact that the narrow and wide channels in the experiment were in the ballistic and diffusive regimes, respectively, in opposition to model assumptions.

In our device, we show that the sign and amplitude of the transverse nonlinear voltage V_{LU} can be tuned by illuminating the sample as well as by biasing in-plane gates. We further demonstrate that the effect is ballistic and that sign reversal of the rectified voltage cannot be understood within the framework of existing models.^{5,6,9} Moreover, we show

that the channels’ conductances govern the sign and amplitude of the rectification effect.

The four-terminal junction studied here, shown on Fig. 1(a), is fabricated from a δ -doped InGaAs/InAlAs heterostructure. The two-dimensional electron gas (2DEG) is confined in a 15-nm-thick In₇₀Ga₃₀As layer located 20 nm below the surface, and separated from the semi-insulating InP substrate by a 400-nm-thick InAlAs buffer layer. Electron-beam lithography and wet etching were used to pattern the junction, formed by three wide channels (S, D, and L) and one narrow channel (U). A diamond-shaped etched antidot is shifted from the center of the junction and defines two narrow branches joining channels S-U and D-U (width ~ 140 nm) and two wider branches (width ~ 300 nm) joining S-L and D-L. It therefore breaks the symmetry of the device with respect to the S-D axis. A control over the width of each branch of the device is provided by four in-plane gates patterned in the 2DEG, separated from the junction by 150 nm wide etched trenches.

The measurements on this sample were performed at temperatures T between 4.2 and 130 K. The low-temperature

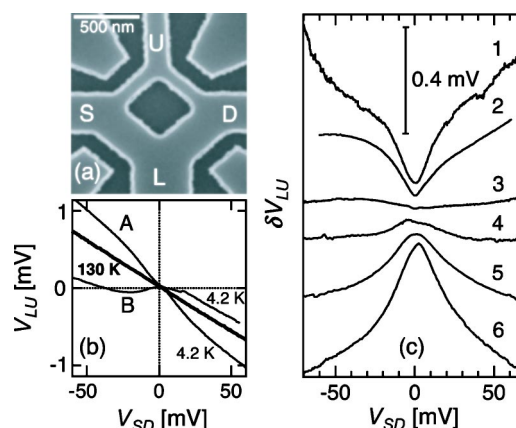


FIG. 1. (Color online) (a) Electron micrograph of the device (dark regions have been etched). (b) V_{LU} vs V_{SD} at 130 K (bold curve) and at 4.2 K with (curve A) and without (curve B) high temperature illumination by a LED. (c) δV_{LU} vs V_{SD} at 4.2 K for different combinations of in-plane gate voltages and different cooldown conditions (curves 1 and 2 have been obtained after illumination). The curves have been offset for clarity.

^{a)}Electronic mail: hackens@pcpm.ucl.ac.be

electron sheet density in the 2DEG is $n_s = 1.6 \times 10^{12} \text{ cm}^{-2}$. Illuminating the sample with a red light emitting diode (LED) resulted in a $\sim 25\%$ increase of n_s . At 4.2 K, the electron mobility is $\mu = 4 \times 10^4 \text{ cm}^2/\text{Vs}$, equivalent to an electron mean free path $l_\mu = 0.8 \text{ }\mu\text{m}$, larger than the device size. The current-voltage characteristics are obtained using a “push-pull” measurement setup: opposite dc voltages are applied on channels D and S . We measure the resulting transverse voltage V_{LU} . As two measurement branches are available for each channel, we also simultaneously measure the source and drain voltages V_S and V_D at $2 \text{ }\mu\text{m}$ from the junction, ensuring that $V_S = -V_D$. Therefore, $V_{SD} = V_S - V_D$ does not include any contribution of lead or contact resistance.

For each configuration of in-plane gate biases and illumination, the four-contacts conductances G_{IJ} between channels I and J have been measured at 4.2 K using a lock-in technique.¹⁰ We observed differences of up to 20% between G_{LS} and G_{LD} and up to 15% between G_{US} and G_{UD} , indicating that the device is slightly asymmetric with respect to the U - L axis. In order to quantify the opening of the upper part of the device, formed by the branches S - U and U - D , we define $G_U = (G_{US} + G_{UD})/2$. Similarly, the opening of the lower part of the device is proportional to $G_L = (G_{LS} + G_{LD})/2$.

Figure 1(b) shows V_{LU} vs V_{SD} measured using the push-pull method. At high temperature (130 K), V_{LU} depends linearly on V_{SD} . This linear contribution is a classical (ohmic) effect, arising from the unintentional asymmetry of the device with respect to the U - L axis (it was similarly observed at different levels in almost all previous experimental works on three- and four-terminals nanojunctions).^{3–5} As the temperature decreases, a nonlinear contribution of growing amplitude superimposes on the temperature-independent linear background. Most importantly, changing the sample cooldown conditions tremendously affects this nonlinear contribution. Curves A and B on Fig. 1(b), both measured at 4.2 K, show opposite nonlinear contribution to V_{LU} vs V_{SD} . Curve A was obtained after a brief illumination at 60 K by the LED, while curve B was obtained without illumination.

In order to shed light on the striking behavior shown in Fig. 1(b), we carefully investigate correlations between device parameters and the sign and amplitude of the nonlinear effect. In addition to illumination, biasing the in-plane gates also affects the nonlinear effect. This is clearly evidenced on Fig. 1(c), where δV_{LU} vs V_{SD} —obtained by subtracting the linear contribution from the V_{LU} vs V_{SD} data—is displayed for different values of in-plane gate voltages. The amplitude of the nonlinear signal δV_{LU} changes between $\sim +0.5$ and ~ -0.5 mV at $V_{SD} = 70$ mV. As both illumination and side gate biasing influence the conductance of the channels, it is tempting to present the amplitude of the nonlinear effect versus G_L and G_U .

Figure 2 gathers all our measurements of $\delta V_{LU}^{30 \text{ mV}} = [\delta V_{LU}(V_{SD} = 30 \text{ mV}) + \delta V_{LU}(V_{SD} = -30 \text{ mV})]/2$ for different combinations of G_U and G_L , using a color map where positive values are shown in red and negative in blue.¹¹ Clear trends are observed: positive $\delta V_{LU}^{30 \text{ mV}}$ values concentrate at the large G_{LU} side of the graph and negative $\delta V_{LU}^{30 \text{ mV}}$ values group at the small G_{LU} side. Furthermore, Fig. 2(inset) shows that $\delta V_{LU}^{30 \text{ mV}}$ vs G_L is linear, with a transition between positive and negative $\delta V_{LU}^{30 \text{ mV}}$ around $G_L = 8 \times 2e^2/h$. The trend is similar in the case of $\delta V_{LU}^{30 \text{ mV}}$ vs G_U . In summary, widening all device branches leads to an accumulation of

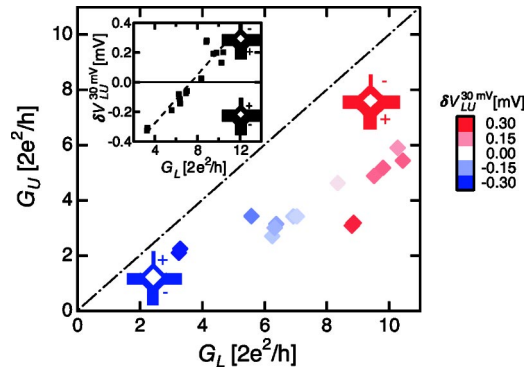


FIG. 2. (Color online) Color plot of $\delta V_{LU}^{30 \text{ mV}}$ vs G_U and G_L at 4.2 K (see color scale at the right of the graph). Schematic representations of the device are drawn in the corners of the graph, with the sign of the accumulated charge at contacts U and L . The dash-dotted line corresponds to $G_U = G_L$. Inset: $\delta V_{LU}^{30 \text{ mV}}$ vs G_L at 4.2 K. The dashed line is a linear fit to the data.

electrons at the narrow channel, and narrowing the branches results in accumulation of electrons at the wide one.

Importantly, we note in Fig. 2 that all our data points fall on the same side of the dash-dotted line (corresponding to $G_U = G_L$), so that G_U is always smaller than G_L . Since branches L - S and L - D always remain wider than branches U - S and U - D , whatever the biases applied on in-plane gates, the observed sign reversal of δV_{LU} cannot originate from an asymmetry reversal of the device (in contrast to Ref. 5, where sign reversal is always observed as device asymmetry is reversed). Indeed, red data points on Fig. 2 correspond to negative charge accumulation at the narrower side of the device, similar to data in Ref. 5. Conversely, blue data points correspond to accumulation of negative charges at the wider side of the device, similar to predictions of Fleischmann and Geisel.⁶ We point out that our high conductance data show the same rectification sign as in Ref. 5, where $G_{U,L}$ are always larger than in our sample.¹² This work is therefore consistent with Ref. 5, while unveiling new features in an uncovered range of $G_{U,L}$.

In a first analysis, the transition from negative to positive output voltage could be viewed as a transition between the two different transport mechanisms, described in Refs. 5 and 6. Within the framework of these models, the change from negative to positive δV_{LU} could in principle be explained, but only under specific conditions, i.e., widening the branches should cause a concomitant change of transport regime: from quantized to ballistic in the narrow branches, and from ballistic to diffusive in the wide ones. While unlikely, we now test this explanation in view of all available data.

The temperature dependence shown in Fig. 3(c) is clearly related to that of the electron mean free path, measured on an unpatterned part of the same wafer. This indicates that the nonlinear rectification is governed by ballistic effects, both for $\delta V_{LU} > 0$ and $\delta V_{LU} < 0$.¹³ This observation rules out the explanation given in the previous paragraph, since the T^{-1} dependence expected for thermal broadening of the quantum steps¹⁴ is not observed. On the other hand, our results show that, in addition to quantum transport,⁶ ballistic effects can give rise to the accumulation of electrons in the wider branch of an asymmetric cross-junction device, and that the direction of accumulation can be reverted *in situ*. However, the understanding of the sign reversal and the tunability of the effect remains to be theoretically investigated.

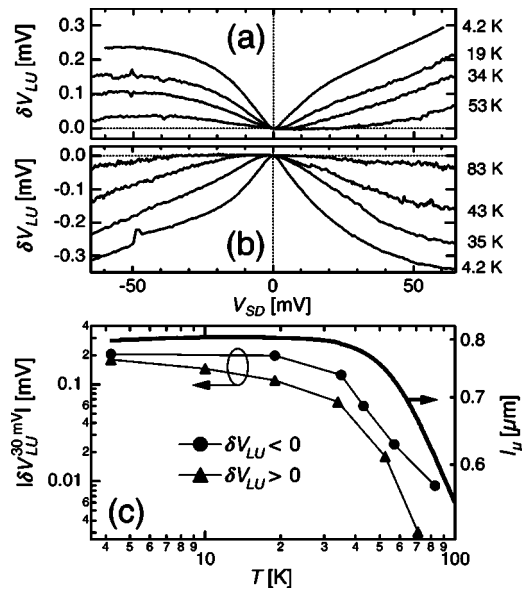


FIG. 3. Temperature dependence of δV_{LU} vs V_{SD} in the case of (a) positive δV_{LU} and (b) negative δV_{LU} . (c) I_μ (bold curve, right axis) and $|\delta V_{LU}^{30 \text{ mV}}|$ (left axis) as a function of the temperature for positive and negative δV_{LU} .

In conclusion, we demonstrated the tunability of the sign and amplitude of the nonlinear transverse voltage of a four-terminal nanojunction in the ballistic regime. The tunability was found to be governed by the conductances of the channels. Electrons accumulate in the wide (narrow) part of the device in the case of small (large) average conductance. Data suggest that both the upper and lower part of our device are in the ballistic (but not quantum) regime of transport, which differs from previously reported works.^{5,6,9} In our case, the real geometry of the sample should be taken into account, and not only the width of the branches. This could be accomplished by means of Monte Carlo simulations, which already proved successful with similar devices.⁷

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¹⁰Note that, for adjacent channels I and J, G_{IJ} is the conductance of the branch I-J in parallel with the conductance of branches I-K, K-M, and M-J in series (where K and M are the other channels).

¹¹The choice of $V_{SD}=30$ mV is arbitrary. Choosing another value for V_{SD} would not change our conclusions.

¹²As inferred from μ , n_s and device size in Ref. 5.

¹³The current used in our experiment can be large enough to induce Joule heating of the electron system, so that it is logical to consider thermal voltages as a potential explanation to the observed nonlinear transverse voltage. However, an earlier work (Ref. 9) showed that a necessary condition for the occurrence of such a thermal voltage in a four terminal configuration is a quantized regime of transport, at least in the narrower part of the device. As the temperature dependence of the effect is consistent with a ballistic regime of transport (and not with a quantized regime), we can exclude a thermal origin for the nonlinear effect.

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