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# Nonlinear conductance at small driving voltages in quantum point contacts

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Conductance asymmetry of quantum point contacts at near-zero applied biases is reported. This nonlinearity in the current-voltage characteristics depends in sign and magnitude on the quantization condition of the point contact (i.e., the gate voltage). The variation in the conductance is of the order of tens of ohms against a background of several kΩ, and occurs in a very small bias region, $|V| \ll (E_n - E_{n-1})/e$ around zero bias, where $E_n$ is the $n$th one-dimensional subband energy in the quantum point contacts. The non-Ohmic and asymmetric behavior causes a rectified dc signal as the response to an applied ac current. Second-harmonic-generation measurements also confirm the observation. The phenomenon is discussed in light of recent mechanisms for nonlinearities in point contacts due to the influence of an electric field on a two-level scatterer or on an intermode interference between mode-mixing points.

The observation of the conductance quantization in constrictions, made from $Ga_{1-x}Al_xAs/GaAs$ heterostructures with a high-mobility two-dimensional electron gas (2DEG), has generated considerable interest.[1] The constriction is defined electrostatically by means of a metallic split gate deposited on top of the heterostructure. In such samples, called quantum point contacts (QPC), the number of conducting one-dimensional subbands in the constricted region can be gradually reduced by increasing the negative voltage $V_g$ applied to the metal gate. The conductance $G$ has been found to be quantized as $G = i2e^2/h$, where $i$ is the number of one-dimensional (1D) subbands occupied. The basic behavior of the QPC is well understood by a model of 1D channels of noninteracting electrons based on the adiabatic Landauer approach for the quantum transport.[2] However, the influence of a scatterer in the constricted region is still in its early stages.

In this paper we report the observation of nonlinear and asymmetric conductance oscillations for small bias voltages. A deviation from the linear conductance has been reported earlier[3,4] and attributed to the breakdown of quantization due to a difference in the number of occupied subbands for the two velocity directions.[5] This occurs when the applied voltage across the contact, $eV$, becomes comparable with the subband spacing, which is equal to 1–2 meV. However, the nonlinearities we observe are at bias voltages, which are two orders of magnitude smaller and related to deviation from the simplest adiabatic picture of a quantum point contact, probably due to scattering centers in the contact region. The influence of a single scattering center on the properties of a constriction in a 2DEG (Refs. 6–10) as well as metallic point contacts[11–13] are an issue of much current interest. Nonlinear properties of tiny metallic constrictions due to a single scattering center have been considered theoretically, but so far evaded experimental confirmation.

Our quantum point contacts were made from molecular-beam-epitaxy-grown $GaAs/Al_{30}Ga_{70}As$ heterostructures containing a 2DEG with an electron density of $3.2 \times 10^{15}$ m$^{-2}$ and a mobility of 80 m$^2$ V$^{-1}$ s$^{-1}$. The split gate was prepared by means of electron-beam lithography and the split gates had a lithographic separation of about 0.2 $\mu$m and were 80 nm above the 2DEG. The alloyed Au/Ge/Ni Ohmic contacts had contact resistances which were determined to be less than 1 Ω mm in a separate experiment. Measurements were performed in a four-probe geometry at temperatures down to 300 mK. The samples exhibited clear conductance quantization up to $i = 20$, when measured as a function of the gate voltage $V_g$. The depletion of the 2DEG underneath the gate happened at $V_g = V_d \simeq -0.4$ V and pinch off occurred typically at $V_g = V_p \simeq -1$ V. In this gate voltage range the gate leakage currents were typically below 100 pA.

A conventional small signal lock-in technique was employed for the conductance measurements. We used a constant ac current source, and the measured resistance was converted into conductance. The measurements were done with a slow dc current sweep through $I_{dc} = 0$ for fixed values of the gate voltage far from the pinchoff. Small ac currents of 2–6 nA were used to obtain the derivative of the $V(I)$ versus dc current. Measurements of the differential resistance with an accuracy of few ohms were difficult because of intrinsic noise, which behaved as a random telegraph signal. The amplitude of this noise reached several hundred ohms and we used 1–3-sec time constants for the lock-in to suppress this noisy signal in order to focus on the dc current-voltage characteristics.

Two traces of resistance versus current are shown in Fig. 1 at 0.3 K. Similar traces were measured up to temperatures as high as 4.2 K. Several distinct values of the random telegraph signal could occasionally be observed, but they are not seen on this graph because of the long time constant used. In order clearly to resolve the dc nonlinearity, two or several resistance traces back and forth in $I_{dc}$ were recorded. The two measurements

 

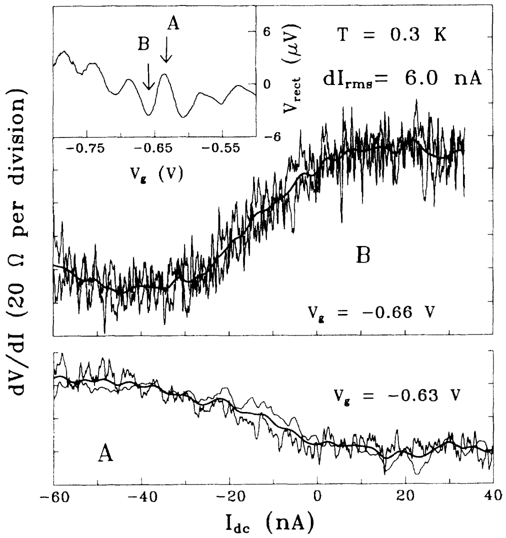


FIG. 1. Different current bias. The differential resistance is measured with lock-in technique with a small (6 nA) added ac excitation current. The noise on the differential resistance is intrinsic and due to a random telegraph signal connected with charging processes. The resistance is measured during two sweeps of the dc current to improve the statistics of the measurements. The thick curve corresponds to a smoothed mean value of the two traces. The two sets of data ( $A$ and $B$) are for different split-gate voltages. The inset shows how the two split-gate voltages are chosen, namely, at a maximum and a minimum of the rectified signal. The nonlinearity in the resistance explains the magnitude of the rectified signal (with the applied ac current $I_{\rm rms}=75$ nA). This ac current corresponds to $eV_{\rm rms}=0.15$ meV to be compared with $k_BT=0.025$ meV.

shown in Fig. 1 ( $A$ and $B$) are taken with the gate voltage chosen at a peak and a valley of the rectified voltage to be considered subsequently. The two gate voltages correspond, respectively, to a plateau and in-between plateau of the quantized conductance.

The rectified signal, i.e., the dc voltage response $V_{\rm rect}$ to a low-frequency oscillating current $I \sin\omega t$, was detected in a configuration where the voltage leads of the Hall bars were connected to a high input impedance nanovoltmeter with differential input terminals, a long time constant, and a battery-driven power supply. A rectified signal as a function of gate voltage is shown in the inset of Fig. 1 with an applied current of $I_{\rm rms}=75$ nA. The 75 nA corresponds, with the actual sample resistance of $\sim 2$ k$\Omega$, to a voltage 0.15 mV$\simeq 6k_BT$. The measured nonlinearity in conductance and the rectified signal was found in all cases to be consistent, yet the rectified signal was much easier to detect. The total resistance swing between positive and negative bias in Fig. 1 is 50 and 100 $\Omega$ for the two gate voltages. This compares favorably to the measured rectified voltage in the inset. We discuss only results for small dc and ac biases; $V \ll 1$ mV and $I_{\rm rms}, I_{\rm dc} \leq 110$ nA, where the difference between electrochemical potentials at the two sides of the QPC was much smaller than the 1D subband separation. However, we should emphasize that the voltage response $eV$ to the applied dc and ac currents was typically larger or comparable to the thermal energy $k_BT$. However, the resistance asymmetry shown in Fig. 1 could also be observed at 4.2 K, where the dc voltage bias at which the asymmetry occurred was considerably smaller than $k_BT/e$. At this temperature the asymmetry was approximately 20 $\Omega$. On increasing the temperature (in the range 0.3–4.2 K) the oscillations of $V_{\rm rect}(V_g)$ and the nonlinearity decrease at the same pace as the smearing of the conductance quantization. The temperature dependence of the rectified signal is shown in Fig. 2. We measured $V_{\rm rect}(V_g)$ for different values of the ac currents and found an overall proportionality between the rectified signal and the ac current amplitude except at small currents. This indicates that $R(I)$ changes over a current range less than 50 nA. The difference between resistance $R^+$ and $R^-$ for large currents on each side of the nonlinear region is $\Delta R = R^+ - R^- = \pi V_{\rm rect}/I$, where $V_{\rm rect}=(I/2\pi)\int_0^{2\pi} R(I\sin\phi)\sin\phi\, d\phi$. Our experiments give $\Delta R \leq 150$ $\Omega$ in agreement with direct observation.

A consequence of the resistance step is the observation of a voltage signal generated at the second harmonics of the applied frequency $\omega$. The second-harmonic voltage $V_{2\omega}$ for one of the samples is shown in Fig. 3. A step in $R$, if alone, would cause the signal to be $V_{2\omega}=\frac{2}{3}V_{\rm rect}$. It is seen that $V_{2\omega}$ definitely possesses the same features as $V_{\rm rect}$ and is of the expected magnitude.

Since the conductance of the QPC is given by the transmission probabilities $T_n$ via the Landauer formula $G=2e^2/h\Sigma T_n$, it is possible and useful to express the nonlinearity in terms of changes in the confinement potential. We have employed a model of parabolic confinement[14,15] $\Phi(x,y)=1/2m\omega_y^2 y^2 - 1/2m\omega_x^2 + \Phi_0$ with transverse and longitudinal oscillator strengths $\omega_x$ and $\omega_y$. In this model $T_n=[1+\exp(-\pi\epsilon_n)]^{-1}$, and $\epsilon_n = 2/\hbar\omega_x[E_F - \hbar\omega_y(n+\frac{1}{2}) - \Phi_0]$. We have related the resistance change to the minimum of the confinement potential, $\delta\phi_0$, as $\Delta R = R^2(dG/d\phi_0)\delta\phi_0$. $dG/d\phi_0$ can be connected to $dG/dV_g$ through known parameters, since $dG/d\phi_0 = (1/2E_F)(dG/dV_g)(V_p - V_d)^2/(V_p - V_g)$ for

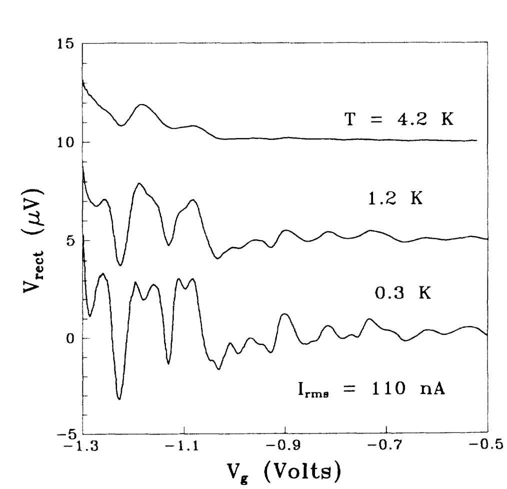


FIG. 2. The rectified voltage vs gate voltage measured at three different temperatures. The three curves are offset vertically by 5 $\mu$V for clarity. Here the quantum point contact was pinched off at $V_g=-1.35$ V.

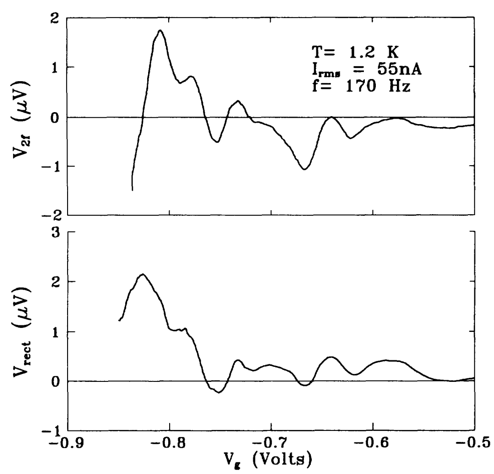


FIG. 3. The second harmonic voltage response $V_{2\omega}$ and the rectified signal for a quantum point contact plotted vs the gate voltage $V_g$. $I_{rms}=55$ nA, $\omega/2\pi=170$ Hz. A steplike change in the contact resistance at zero current bias predicts $V_{2\omega}=2V_{rect}/3$ in rough agreement at all gate voltages. For this point contact $V_d=-0.4$ V and $V_p=-0.85$ V.

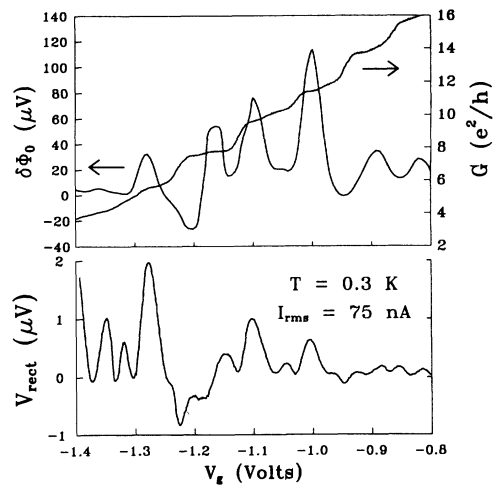


FIG. 4. The phenomenologically calculated difference $\delta\phi_0$ in potential energy of the point conract at a small current bias, the conductance of the quantum point contact $G$ and the rectified signal $V_{rect}$, corresponding to $I_{rms}=75$ nA all plotted as a function of the gate voltage $V_g$. A different resistance $\Delta R$ of a quantum point contact for positive and negative current biases can be related to a difference in transmission through the point contact. If phenomenologically this difference in transmission is ascribed to a different potential $\phi_0^+-\phi_0^-=\delta\phi_0$ of the contact, we can estimate that $\delta\phi_0=\Delta R/(R^2 dR/d\phi_0)$, where $dR/d\phi_0$ is calculated here using a parabolic confinement potential (Refs. 14 and 15). Whereas $V_{rect}$ (from which $\Delta R$ is calculated) has a complicated behavior as a function of $V_g$, $\delta\phi_0$ (top figure) is much simpler with clear maxima at the conductance plateaus $G=2ie^2/h$ ($i=3,4,\ldots,8$). In the calculation we have used $V_p=-1.5$ V; $V_d=-0.4$ V.

the assumption that the width $d_0$ of the construction, defined by $\Phi(0,d_0/2)=E_F$, is proportional to $V_g$. Thus $\delta\phi_0$ versus the gate voltage can be calculated from the measured $G(V_g)$ and $V_{rect}(V_g)$ curves. Whereas there is no clear correspondence between positions of plateaus on the $G(V_g)$ curve and the extrema on the $V_{rect}$ curve, this is certainly the case for $\delta\phi_0(V_g)$ as seen in Fig. 4. $V_{rect}\propto\delta\phi_0(dG/dV_g)$ and the oscillations of the rectified voltage versus $V_g$ are thus due to oscillations in $\delta\phi_0$ as well as $(dG/dV_g)$. For a nonideal QPC, $dG/dV_g$ has many extrema versus $V_g$ giving rise to a complicated dependence $V_{rect}(V_g)$. The behavior of $\delta\phi_0$ itself appears much simpler. An example of its reconstruction is shown in Fig. 4. As is seen, maxima of $\delta\phi_0$ are located at the conductance plateaus. The temperature dependence of $(dG/dV_g)$ dominates the smearing of $V_{rect}(V_g)$.

A known mechanism for generating a nonlinearity in a QPC is due to the different population of the 1D subbands caused by the difference in electrochemical potential, $\Delta\mu=eV$, on the two sides of the QPC.[3] This nonlinearity is observed at a bias level orders of magnitude higher than what we use. An additional nonlinearity in this large bias regime is due to a scheme of electric measurements, where the gate voltage is applied relative to one of the probes and, hence, an additional gate voltage, $\delta V_g\simeq 0.5RI$, is generated by the current $I$ through the QPC. In turn, the change of the gate voltage generates a conductance change. The magnitude of this more trivial effect can be easily calculated. It causes the rectified signal $V_{rect}=R^3(dG/dV_g)I^2$. We observe this nonlinearity at large bias voltages similar to those of Ref. 3, but not in the small bias regimes we describe here.

Our results are most likely related to impurities in the close vicinity of the QPC. It is well known that random charging and decharging of two impurity states can produce switching in the quantum point contact conductance, the so-called random telegraph noise. The alternating occupation of such states near the constriction may be modified by the small electric field in the point contact as suggested by Kozub.[16] Such a slight change in occupational probability of the two states, which generates the random telegraph signal, will in turn lead to a conductance change with bias as observed. If the two-level states are placed near a QPC, they will be coupled to the electron reservoirs with the one-dimensional density of states, and the tunneling probability will reflect the scattering against one or the other level of the one-dimensional channels and thus oscillate with gate voltage depending on which 1D state lies closest to the two-level state. We have tried to find spectral changes in the random telegraph signal and the noise for different bias situations, but have not been able to detect any systematic changes. Another appealing explanation of our measurements has recently been suggested by Zagoskin and Shekhter.[17] The basic idea here is that two impurity scatterers on either side of the quantum point contact (or one scatterer and one sharp end of the constriction) may mix two 1D states. A small electric field across the QPC will give rise to a different quantum-mechanical phase shift along the two 1D states between the scattering centers and lead to interference of the two states as in the electrostatic Bohm-Aharonov effect. Varying the electric field will change the transmission coefficient through these two channels and thus lead to the observed nonlinearity. The fact that the nonlinearity happens at a bias which is much smaller than the 1D subband separation is consistent with experiment. The absolute size of the nonlinearity is more difficult to estimate from this theory since it depends on the degree of mode mixing.

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[1]H. van Houten, C. W. J. Beenakker, and B. J. van Wees, in *Semiconductors and Semimetals,* edited by M. Reed (Academic, Boston, 1992), Vol. 35, pp. 9–112.

[2]L. I. Glazman, G. B. Lesovik, D. E. Kmelnitskij, and R. I. Shekhter, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 218 (1988) [JETP Lett. **48**, 238 (1988)].

[3]L. P. Kouwenhoven, B. J. van Wees, C. J. P. M. Harmans, J. G. Williamson, H. van Houten, C. W. J. Beenakker, C. T. Foxon, and J. J. Harris, Phys. Rev. B **39**, 8040 (1989).

[4]N. K. Patel, L. Martin-Moreno, M. Pepper, R. Newbury, J. E. F. Frost, D. A. Ritchie, G. A. C. Jones, J. T. M. B. Janssen, J. Singleton, and J. A. A. J. Parenboom, J. Phys. C **2**, 7247 (1990).

[5]L. I. Glazman and A. V. Khaetskii, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 546 (1988) [JETP Lett. **48**, 591 (1988)].

[6]G. Timp, R. G. Behringer, and J. E. Cunningham, Phys. Rev. B **42**, 9259 (1990).

[7]Y. P. Li, D. C. Tsui, J. J. Heremans, J. A. Simmons, and G. W. Weiman, Appl. Phys. Lett. **57**, 774 (1990).

[8]D. H. Cobden, N. K. Patel, M. Pepper, D. A. Ritchie, J. E. F. Frost, and G. A. C. Jones, Phys. Rev. B **44**, 1938 (1991).

[9]C. Dekker, A. J. Scholten, F. Lilfrink, R. Eppenga, H. van Hourtten, and C. T. Foxon, Phys. Rev. Lett. **66**, 2148 (1991).

[10]J. A. Nixon, J. H. Davies, and H. U. Baranger, Phys. Rev. B **44**, 12 638 (1991).

[11]R. A. Webb, S. Washburn, and C. P. Umbach, Phys. Rev. B **37**, 8455 (1988).

[12]D. C. Ralph and R. A. Buhrman, Phys. Rev. Lett. **69**, 2118 (1992).

[13]U. Murek, R. Schafer, and W. Langheinrich, Phys. Rev. Lett. **70**, 841 (1993).

[14]H. A. Fertig and B. I. Halperin, Phys. Rev. Lett. **36**, 7969 (1987).

[15]M. Buttiker, Phys. Rev. B **41**, 7906 (1990).

[16]V. I. Kozub, Zh. Eksp. Teor. Fiz. **86**, 2239 (1984) [Sov. Phys. JETP **59**, 1303 (1984)].

[17]A. Zagoskin and R. Shekhter (unpublished).