

## Nonlinear transport and noise thermometry in quasiclassical ballistic point contacts

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We study nonlinear transport and nonequilibrium current noise in quasiclassical point contacts (PCs) defined in a low-density, high-quality two-dimensional electron system in GaAs. At not too high bias voltages  $V$  across the PC, the noise temperature is determined by a Joule heat power and is almost independent on the PC resistance that can be associated with a self-heating of the electronic system. This commonly accepted scenario breaks down at increasing  $V$ , where we observe extra noise accompanied by a strong decrease of the PC's differential resistance. The spectral density of the extra noise is roughly proportional to the nonlinear current contribution in the PC,  $\delta S \approx 2F^*|e\delta I| \sim V^2$ , with the effective Fano factor  $F^* < 1$ , indicating that a random scattering process is involved. A small perpendicular magnetic field is found to suppress both  $\delta I$  and  $\delta S$ . Our observations are consistent with a concept of a draglike mechanism of the nonlinear transport mediated by electron-electron scattering in the leads of quasiclassical PCs.

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The Landauer's approach [1] accounts for elastic scattering of the charge carriers (electrons) off the potential inhomogeneities and is applicable in quasi-one-dimensional conductors shorter than the phase-coherence length. Within this framework the temperature ( $T$ ) and bias ( $V$ ) dependencies of the conductance are caused solely by the averaging of the energy-dependent scattering matrices [2]. Being a random process, the resulting reflection (backscattering) of the electrons at the conductor produces nonequilibrium fluctuations of the electric current (shot noise) [3]. Qualitatively, increasing backscattering reduces the current and increases the relative current fluctuation. The same holds true for a backscattering owing to the electron-phonon interaction in classical metallic point contacts (PCs) [4].

A different concept was recently proposed in Refs. [5–7] for inelastic electron-electron scattering ( $e$ - $e$  scattering) nearby a quasiclassical ballistic PC. Counterintuitively, a reduction of the mean free path owing to the  $e$ - $e$  scattering was predicted to give rise to an increase of the PC conductance [5]. In contrast to the backscattering scenario, this can be understood in terms of a draglike interaction between the electrons of the incident and outgoing beams mediated by a nonequilibrium electronic distribution nearby the PC. In the linear response regime the PC conductance was predicted to increase linearly with  $T$ , in qualitative agreement with experiments [8,9]. In the nonlinear transport regime the same mechanism should give rise to the excess current contribution in the PC,  $|\delta I| \propto V^2$ , and the excess shot noise with a spectral density of  $2|e\delta I|$  [6]. Here we attempt to observe these hallmarks of the draglike  $e$ - $e$  scattering mechanism.

So far experimental observations of the leads-related noise were limited to  $1/f$ -like noise in classical metallic PCs with signatures of phonon emission [10] and a trivial self-heating effect owing to Joule heat dissipation in semiconductor PCs [11] and diffusive metallic nanowires [12]. Recently [13] a possibility to create minimal excitation states (called levitons) in a two-dimensional quantum PC was demonstrated using

shot noise spectroscopy. Although one expects a decay of the levitons owing to the inelastic  $e$ - $e$  scattering, it remains unclear as to what extent this could be traced via noise measurements. Other available experiments were not optimized for refined studies of the  $e$ - $e$  scattering in the nonlinear transport regime. Backscattering off the depletion disk in scanning gate experiments [14] and phonon emission by extremely hot electrons in three-terminal devices [15] preclude observation of the extra current contribution predicted in Ref. [6].

Here, we report an experimental study of the nonlinear transport and noise in quasiclassical PCs in a two-dimensional electron system (2DES) in GaAs. Low carrier density, a long elastic mean free path, and suppressed partition noise [3] make our samples well suited for this experiment. On top of the self-heating effect we observe an extra noise contribution with the spectral density  $\delta S$  accompanied by an extra nonlinear current in the PC,  $|\delta I| \sim V^2$ . The extra noise is sub-Poissonian,  $\delta S \approx 2F^*|e\delta I|$ ,  $F^* < 1$ , as expected for a random scattering process. Both  $\delta I$  and  $\delta S$  are suppressed in a small magnetic field perpendicular to the 2DES. In our opinion, these results elucidate the relevance of the draglike  $e$ - $e$  scattering processes for the nonlinear transport in quasiclassical PCs and demonstrate a possibility for their detection via noise thermometry.

Our samples are made from two nominally identical (001) GaAs/AlGaAs heterostructures with 2DES buried 200 nm below the surface. The electron density is about  $0.9 \times 10^{11} \text{ cm}^{-2}$  and the mobility is  $\approx 4 \times 10^6 \text{ cm}^2/\text{Vs}$  at  $T = 4.2 \text{ K}$ , corresponding to an elastic mean free path of  $\approx 20 \mu\text{m}$ . The split gate PCs are obtained with standard  $e$ -beam lithography. We studied three samples with lithographic widths of the PC constriction of 260 and 600 nm. Two (narrower) constrictions I and III had a T-shape geometry similar to that used in Ref. [9], while a (wider) constriction II had a standard symmetric shape. The linear response PC resistance  $R_0$  is controlled by means of gate voltages applied to metallic split gates defining the constriction. The experiments were performed

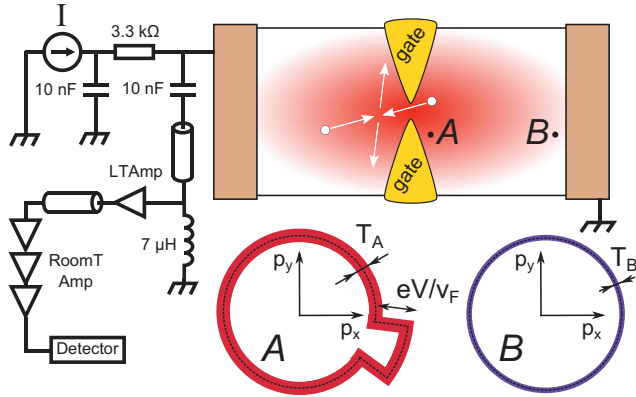


FIG. 1. (Color online) Experimental layout. The PC constriction is formed with the help of split gates on the surface of the crystal. Current  $I$  flows through the sample and drives the electronic distribution out of equilibrium. On top of the trivial self-heating of the 2DES, sketched by a color gradient, we are looking for a contribution of  $e$ - $e$  scattering of counterpropagating beams to current and noise (white circles mimic scattering electrons). The momentum space distributions at points A and B are sketched in the lower part of the figure. In the former case, the distribution is anisotropic with a bump of size  $|eV|/v_F$  and a higher local temperature  $T_A$ , while in the latter case the distribution is locally equilibrium with a lower temperature  $T_B$ . The noise measurement scheme used for sample II is given on the left hand side.

in a  $^3\text{He}/^4\text{He}$  dilution refrigerator (samples I and III) and in a  $^3\text{He}$  insert (sample II) at temperatures  $T \approx 0.1$  K and  $T \approx 0.5$  K, respectively, measured by Johnson-Nyquist noise thermometry. For shot-noise studies we measured voltage fluctuations on a load resistor (1 k $\Omega$  for sample I and 3.3 k $\Omega$  for sample II) within the frequency range 10–20 MHz. In addition, a tank circuit with a resonant frequency of about 13 MHz was used for sample II. In both cases the noise setup was calibrated by measuring the equilibrium Johnson-Nyquist noise of the device in parallel with the load resistor as a function of gate voltage at two different bath temperatures [16]. For samples I and II the nonlinear  $I$ - $V$  characteristics were obtained with a standard two-terminal dc measurement. Sample III was used only for transport measurements in a four-terminal scheme with a small ac modulation. The ohmic contacts to the 2DES were obtained via annealing of AuGe/Ni/AuGe and placed at distances about 1 mm away from the PC. The series resistance of each of the two 2DES regions connecting the PCs to the ohmic contacts is about  $R_{2\text{DES}} \approx 180 \Omega$  for sample I and  $R_{2\text{DES}} \approx 50 \Omega$  for sample II.

A layout of our experiment is shown in Fig. 1. Current flow through the split gate defined PC constriction drives the electronic system out of equilibrium. Farther away from the PC the electronic distribution is of equilibrium Fermi-Dirac type characterized by a local temperature (see a sketch of a momentum space in point B). The local temperature reaches its maximum nearby the PC, as required by a balance of Joule heating and thermal conductivity (sketched by a color gradient in Fig. 1)—a so-called self-heating effect [11]. In addition, next to the orifice, at distances smaller than the mean free path, the electrons originating from different leads are not thermalized. Hence the electronic distribution is anisotropic

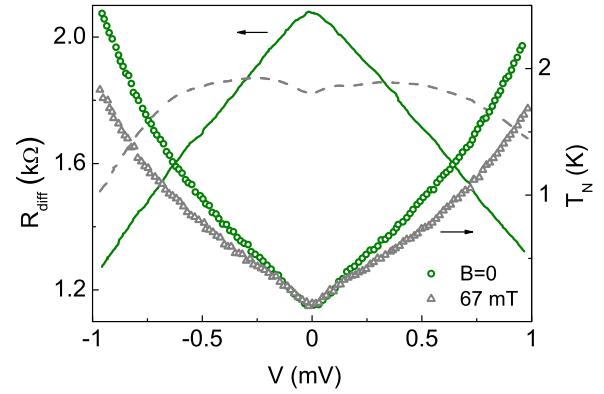


FIG. 2. (Color online) Nonlinear transport regime in a quasiclassical PC.  $R_{\text{diff}}$  (lines, scale on the left) and  $T_N$  (symbols, scale on the right) are plotted as a function of the bias voltage on the PC in sample I. The solid line and circles are taken in the absence of magnetic field, whereas the dashed line and triangles correspond to a perpendicular  $B$  field of 67 mT.

and characterized by a bump (in point A) or a dent of size  $eV/v_F$  in momentum space [2], where  $v_F$  is the Fermi velocity in the 2DES. In what follows we demonstrate that  $e$ - $e$  scattering of counterpropagating beams in the vicinity of the PC orifice predicted in Ref. [6] is responsible for the extra noise on top of the trivial self-heating.

Figure 2 demonstrates typical experimental data for the differential resistance  $R_{\text{diff}} = dV/dI$  and current noise measured simultaneously in the nonlinear transport regime (sample I). Here we express the noise spectral density  $S_I$  in terms of the noise temperature defined as  $T_N = S_I R_{\text{diff}} / 4k_B$ , where  $k_B$  is the Boltzmann constant. At increasing dc bias voltage  $|V|$  across the PC we observe that  $R_{\text{diff}}$  decreases by almost a factor of 2, roughly linear in  $V$  (solid line). This observation is qualitatively analogous to the  $T$  dependence of the linear response PC resistance [9] and signifies a draglike nonlinear contribution  $|\delta I| \sim V^2$  in the  $e$ - $e$  scattering scenario [6]. A similar behavior is observed in all our samples (see the inset of Fig. 3). The decrease of  $R_{\text{diff}}$  in Fig. 2 is accompanied by an increase of  $T_N$  (see the right scale in Fig. 2). At not too high  $V$  the bias dependence of the  $T_N$  is close to linear, whereas an extra, nearly parabolic, contribution is well resolved at  $|V| > 0.5$  mV.

We attribute the increase of  $T_N$  at small  $V$  to the self-heating of the 2DES [11]. In this scenario one expects that  $T_N$  equals the electronic temperature nearby the PC and is determined solely by a Joule heat power  $J = IV \sim V^2$ . To verify this conjecture we plot  $T_N^2$  as a function of  $J$  in Fig. 3. In both samples the data follow a linear dependence at small  $J$ , which is nearly independent of  $R_0$  (shown only for sample II to save space). This is expected for a balance between the Joule heating and Wiedemann-Franz cooling [11]:  $T_N^2 \approx T_0^2 + R_{2\text{DES}} L^{-1} J$ , where  $T_0$  is the bath temperature,  $R_{2\text{DES}}$  is the resistance of each of the two 2DES regions connecting the PC to the ohmic contacts, and  $L$  is the Lorenz number [17]. Quantitatively, the above formula underestimates  $T_N$  in sample II by almost 40%, which might be a result of additional heat resistance of the ohmic contacts, reduced thermal conductivity of the 2DES at higher  $T_0$  [18], or a small residual partition noise. More

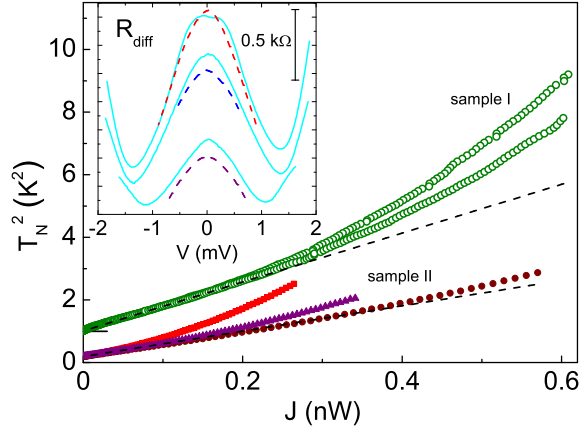


FIG. 3. (Color online) Noise dependence on Joule heat power ( $J$ ). Square of the noise temperature is plotted against  $J$  for the two samples. Open symbols correspond to sample I and  $R_0 \approx 2$  k $\Omega$ . Solid symbols correspond to sample II and  $R_0 \approx 0.5$  k $\Omega$  (circles), 1.5 k $\Omega$  (triangles), and 3.4 k $\Omega$  (squares). In sample I the upper (lower) trace corresponds to  $V < 0$  ( $V > 0$ ), whereas in sample II the bias symmetry is preserved. Dashed lines are extrapolations of the linear dependencies  $T_N^2 - T_0^2 \propto J$  at small  $J$ , where the equilibrium temperature is  $T_0 = 0.1$  K for sample I and  $T_0 = 0.5$  K and  $R_0 \approx 1.5$  k $\Omega$  for sample II. The data for sample I are shifted vertically for clarity, with the zero level indicated by a solid line. In this plot, the data for sample I were obtained in a separate run, compared to Fig. 2. We believe that a difference of 15% in  $T_N$  between the data sets at  $R_0 \approx 2$  k $\Omega$  is an artifact owing to a long-term drift of the gain of the cryogenic amplifier, which was not figured out during the experiment. Inset:  $R_{\text{diff}}$  vs  $V$  for sample II (dashed lines,  $T_0 = 0.5$  K) and  $R_0 \approx 1.5, 2,$  and  $3.4$  k $\Omega$  from bottom to top and for sample III (solid lines,  $T_0 = 0.1$  K) and  $R_0 \approx 1.2, 2.3,$  and  $3.3$  k $\Omega$  from bottom to top. The data are vertically shifted for clarity.

important, however, is a lack of the universality observed in Fig. 3, which becomes clearly visible at higher  $J$  and indicates extra noise on top of the self-heating. This is the same, nearly parabolic in  $V$ , noise contribution we found in Fig. 2. Note that in sample I the extra noise depends on the sign of  $V$ , which correlates with the bias asymmetry of  $R_{\text{diff}}$  in Fig. 2, whereas in sample II the data are almost perfectly symmetric. We evaluate the extra noise temperature  $\delta T_N$  as a difference between the measured  $T_N$  and the self-heating contribution extrapolated linearly to high  $J$  (see the dashed lines in Fig. 3).

In Fig. 4 we plot a spectral density of the extra noise  $\delta S = 4k_B \delta T_N / R_{\text{diff}}$  against a nonlinear current contribution through the PC,  $\delta I = I - V/R_0$ . Our main observation here [19] is that, away from the origin,  $\delta S$  increases approximately linear with  $\delta I$ , that is, both quantities follow nearly the same functional dependence on  $V$ . In the limit of high  $\delta I$  the slope is consistent with the effective Fano factor of  $F^* \approx 0.9$  (the slope of the dashed lines). Such a relation is expected for a random process with sub-Poissonian statistics, meaning that electrons carrying extra current are barely correlated. This is not possible for equilibrium Fermi distributions [20] in the electron beams incident on the PC, suggesting that a random scattering process between the incident and outgoing electron beams in the 2DES nearby the PC is involved. Counterintuitively, such extra

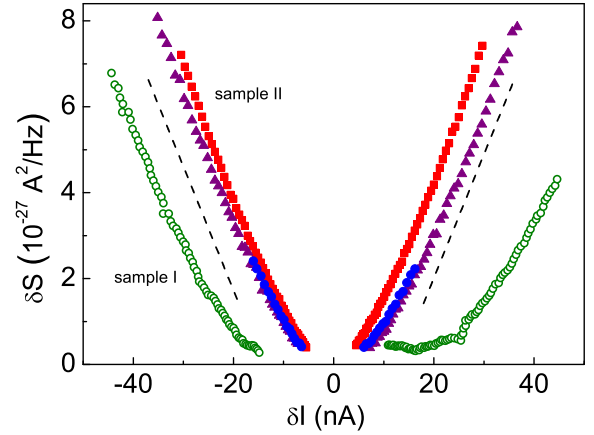


FIG. 4. (Color online) Extra noise vs extra current. The spectral density  $\delta S$  of the extra noise is plotted as a function of the nonlinear current contribution  $\delta I$  for both polarities of  $V$ . Open symbols correspond to sample I and  $R_0 \approx 2$  k $\Omega$  ( $0.5$  mV  $\leq |V| \leq 1$  mV). Solid symbols correspond to sample II and  $R_0 \approx 1.5$  k $\Omega$  (triangles,  $0.4$  mV  $\leq |V| \leq 0.7$  mV),  $2$  k $\Omega$  (circles,  $0.4$  mV  $\leq |V| \leq 0.6$  mV), and  $3.4$  k $\Omega$  (squares,  $0.5$  mV  $\leq |V| \leq 0.9$  mV). Dashed lines are guides with a slope of  $F^* = 0.9$ . For sample I, the data are obtained in the same run as in Fig. 2 and the scales on both axes are reduced by a factor of 2.

scattering gives rise to the decrease of  $R_{\text{diff}}$ , which perfectly fits in the  $e$ - $e$  scattering scenario of the nonlinear transport in quasiclassical PCs [6].

At  $T = 0$  uncorrelated scattering events between the carriers of the incident and outgoing beams result in a nonequilibrium electronic distribution and give rise to the Poissonian extra noise [6]. Sub-Poissonian extra noise in Fig. 4 does not necessarily imply correlations between the individual  $e$ - $e$  scattering events and can be explained by a finite  $T$  effect associated with the self-heating. In our samples the self-heating results in  $|eV|/k_B T < 10$ , a situation for which the numerical calculations predict extra shot noise with  $F^* \approx 0.5$  (see Fig. 2 of Ref. [6]). In spite of a qualitative agreement at higher  $|\delta I|$ , our data appreciably deviate from the expected linear dependence near the origin. On one hand, this deviation might stem from the uncertainty of our procedure to quantify the self-heating. It is this uncertainty that prevents us from analyzing the data at small  $|V|$ . On the other hand, there is an important difference between our experiment and theoretical assumptions. In Ref. [6], the  $e$ - $e$  scattering is assumed to be weak compared to the elastic scattering, which determines the mean free path and cuts off the logarithmic divergence of the collision integral. In contrast, we estimate [21] the  $e$ - $e$  scattering length  $l_{ee} \approx 2$   $\mu\text{m}$  for electrons with an energy of  $|eV| = 0.5$  meV above the Fermi surface, i.e., an order of magnitude smaller than the elastic mean free path in our devices. Still, in the regime  $|eV| \gg k_B T_N$ , the electronic distribution in the vicinity of the PC remains strongly anisotropic (see the sketch in Fig. 1) and the ideas of Ref. [6] are applicable qualitatively. Experimentally, this qualitative picture breaks down at even higher  $|V|$ , typically above 1 mV, where  $l_{ee}$  becomes comparable to the width of

the PC orifice. Here the bias dependence of  $R_{\text{diff}}$  changes sign (observed in all our samples and shown for sample III in the inset of Fig. 3), which can be explained by inelastic backscattering owing to multiple  $e$ - $e$  scattering events in the vicinity of the PC. In support we observe that the upturn of  $R_{\text{diff}}$  shifts towards smaller  $|V|$  with decreasing  $R_0$  (i.e., increasing the width of the PC orifice). At the same time  $T_N$  keeps increasing (not shown), apparently consistent with the suppression of thermal conductivity owing to the  $e$ - $e$  scattering [22].

Finally, we study the effect of a small perpendicular magnetic field  $B$  on the PC noise. The value of  $B$  is chosen such that the cyclotron diameter (about  $1.5 \mu\text{m}$ ) is large compared to the width of the PC orifice and is much smaller than the elastic mean free path. In this case the primary effect of  $B$  is to bend the trajectories of scattering electrons and suppress the  $e$ - $e$  scattering contribution to conductance [7,9]. As shown in Fig. 2, in a magnetic field (triangles) the overall  $T_N$  decreases compared to the  $B = 0$  case (circles). At the same time, the decrease of  $R_{\text{diff}}$  with the bias voltage is suppressed in a magnetic field (see the dashed line in Fig. 2). These qualitative observations strongly support our interpretation of the nonlinear transport regime in terms of the draglike

$e$ - $e$  scattering processes nearby the PC. We do not perform a quantitative account of the self-heating in a magnetic field, which is complicated in the presence of a chiral heat flux along the edges of the sample [23].

In summary, we studied the nonlinear transport regime and noise in quasiclassical ballistic PCs. In addition to the trivial self-heating effect, we observe extra noise with a nearly parabolic bias dependence. The extra contributions to the noise and current in the nonlinear transport regime are related via a sub-Poissonian value of the effective Fano factor, which is most likely a finite temperature effect. In addition, a small magnetic field perpendicular to the 2DES is found to suppress both. These observations provide evidence of the draglike contribution of the  $e$ - $e$  scattering to the nonlinear transport and noise in ballistic PCs.

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