

Cryogenic amplifier for fast real-time detection of single-electron tunneling

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The authors employ a cryogenic high electron mobility transistor (HEMT) amplifier to increase the bandwidth of a charge detection setup with a quantum point contact (QPC) charge sensor. The HEMT is operating at 1 K and the circuit has a bandwidth of 1 MHz. The noise contribution of the HEMT at high frequencies is only a few times higher than that of the QPC shot noise. The authors use this setup to monitor single-electron tunneling to and from an adjacent quantum dot. The authors measure fluctuations in the dot occupation as short as 400 ns, 20 times faster than in previous work. © 2007 American Institute of Physics. [DOI: 10.1063/1.2783265]

The conventional method for studying quantum dot properties electrically is to measure electron transport through the dot.¹ An alternative approach is to measure the current through a quantum point contact (QPC) located next to the dot, which is sensitive to the charge dynamics of the quantum dot.^{2–6} This technique is very versatile and has also been used to probe the excited state spectrum of a quantum dot,^{7,8} perform single-shot readout of electron spin states,^{9,10} and observe coherent electron spin dynamics in quantum dots.¹¹

Until now, current fluctuations through such a QPC charge sensor have always been measured using a room temperature (RT) current-to-voltage (*IV*) converter. This limits the measurement bandwidth to several tens of kilohertz,⁴ because of the low-pass (LP) filter formed by the capacitance of the measurement wires to ground and the input impedance of the amplifier. However, increasing this bandwidth is crucial in order to study (real-time) fast electron and nuclear spin dynamics¹² as well as to increase the single-shot spin readout fidelity.⁹ One way to increase the bandwidth is to embed the QPC in a resonant circuit and measure its damping,^{13,14} analogous to the operation of the rf single-electron transistor.¹⁵ In theory such a “rf-QPC” allows for single-shot charge detection within a few tens of nanoseconds.¹⁶ However, this technique requires rf modulation and is experimentally rather involved.

Here, we explore a much simpler approach to increasing the bandwidth, which uses a high electron mobility transistor (HEMT) operated in dc as a cryogenic preamplifier.¹⁷ Compared to a RT amplifier, a cryogenic amplifier can be mounted much closer to the sample, which significantly reduces the capacitance of the measurement wire. The use of a HEMT has the additional advantage that the noise level at cryogenic temperatures is very low (especially at high frequencies), so a better charge sensitivity can be obtained.

The HEMT is connected to the right lead of the QPC, which is also connected to ground via R_c [Fig. 1(a)]. A bias voltage V_{sd} is applied to the left lead and a current $I_{QPC}(t)$ will flow which depends on the QPC conductance $G_{QPC}(t)$. The voltage over R_c is a measure for this current and is

probed via the HEMT. Fluctuations of G_{QPC} result in fluctuations of I_{QPC} , denoted by ΔI_{QPC} . These generate voltage fluctuations on the HEMT gate with respect to the voltage on its source, V_{gs} . The modulation of V_{gs} results in a modulation of the drain-source current I_{ds} through the HEMT channel. This current is measured by an ac-coupled *IV* converter at RT and digitized using a digital oscilloscope (LeCroy WaveRunner 6030A).

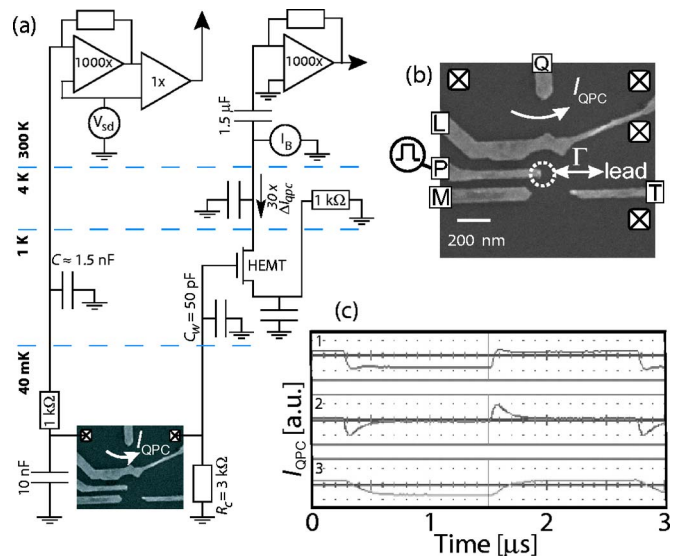


FIG. 1. (Color online) (a) Schematic of the experimental setup. R_c converts fluctuations in I_{QPC} into voltage fluctuations on the HEMT gate. Through its transconductance, the HEMT converts these fluctuations into current fluctuations which are amplified by an additional amplification stage at room temperature. R_c and C_w form a 1 MHz LP filter. (b) Scanning electron micrograph of a similar device as used in the experiment. The dot (dashed circle) and QPC are defined in a 2DEG formed at a GaAs/AlGaAs interface 90 nm below the surface, with an electron density of $1.3 \times 10^{15} \text{ m}^{-2}$ by applying negative voltages to gates L, M, T, and Q. Fast voltage pulses can be applied to gate P. The crosses represent Ohmic contacts. (c) Response to a voltage pulse applied to gate P. Trace 1 shows the total response to a voltage pulse when $G_{QPC} \approx e^2/h$. When the QPC is pinched off, there is still a response due to cross-talk between the pulse line and the HEMT gate wire (trace 2), providing a measure for the bandwidth of the readout circuit from the HEMT gate up to RT (~ 8 MHz). Subtracting trace 2 from trace 1 reveals the signal from the QPC (trace 3) with a rise time of 285 ns, corresponding to a bandwidth of 1 MHz.

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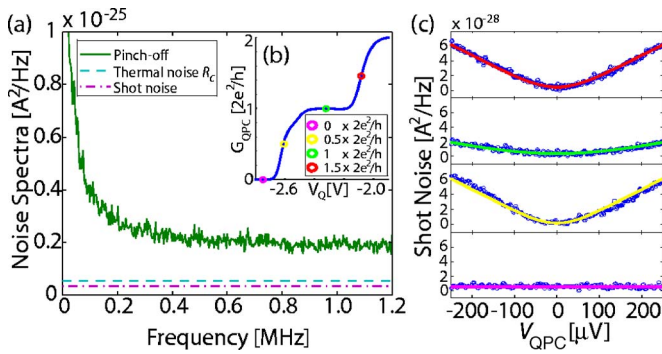


FIG. 2. (Color online) (a) Noise spectrum of the setup including the cryogenic HEMT amplifier. The measured spectrum is taken for the QPC in pinch-off, thereby excluding shot noise and noise coming from the other side of the QPC. The calculated noise contributions from the QPC shot noise and the thermal noise of R_c are plotted for reference (dash-dotted and dashed lines, respectively). (b) QPC conductance as a function of the voltage on gate Q. (c) Measurements of the QPC shot noise power measured at the QPC conductances indicated by the colored markers in (b). Solid lines are fits to Eq. (1).

We use a commercially available HEMT (Agilent ATF 35143) with a $400\ \mu\text{m}$ gate length and a threshold voltage $V_t \approx 0.4\ \text{V}$. When appropriately biased (by controlling I_B), the transconductance of the HEMT is $g_m = 10\ \text{mA/V}$, which relates the drain-source current I_{ds} through the HEMT to V_{gs} as $I_{ds} = -g_m V_{gs}$, implying $\Delta I_{ds} \approx -30 \Delta I_{\text{QPC}}$, using $R_c = 3\ \text{k}\Omega$. The power dissipation of the HEMT is $30\ \mu\text{W}$. In addition to the HEMT, I_{QPC} can also be measured *simultaneously* in a $100\ \text{Hz}$ bandwidth using an *IV* converter at RT which is connected to the left lead of the QPC. We refer to this measured current as the time averaged current.

The quantum dot and the QPC are defined in a two-dimensional electron gas (2DEG) by applying negative voltages to metal surface gates [labeled L, M, T, and Q in Fig. 1(b)]. Gate L completely separates the QPC source and drain electrically from the leads of the dot. The experiment is performed in a dilution refrigerator with a base temperature of $40\ \text{mK}$ and with zero externally applied magnetic field.

First, we characterize the bandwidth of the setup. The bandwidth (BW) is expected to be limited by the resistor R_c and the capacitance C_w of the measurement wire connecting the right lead of the QPC to the HEMT gate [BW = $(2\pi R_c C_w)^{-1}$]. The HEMT is mounted on the $1\ \text{K}$ stage, since this has sufficient cooling power to dissipate the heat generated by the HEMT in operation. The value for C_w is then a trade-off between two requirements: a low capacitance and sufficient thermal anchoring of the wire. The value of R_c is also a trade-off: increasing the value of R_c increases the amplitude of the voltage fluctuations on the HEMT gate ($\Delta V_{gs} = \Delta I_{\text{QPC}} R_c$) but reduces the bandwidth of the setup (for a given value of C_w). Our aim is to detect single-electron tunneling on a submicrosecond time scale. The value for R_c was chosen assuming $\Delta I_{\text{QPC}} \approx 400\ \text{pA}$ and an equivalent input referred voltage noise $0.4\ \text{nV}/\sqrt{\text{Hz}}$. $R_c = 3\ \text{k}\Omega$ then gives signal-to-noise ratio (SNR) ≈ 3 and a bandwidth of $1\ \text{MHz}$. The bandwidth is determined by measuring the QPC response to fast voltage pulses applied to gate P. The measured rise times are $285\ \text{ns}$, yielding a bandwidth of $1\ \text{MHz}$, in excellent agreement with the designed bandwidth [Fig. 1(c)].

The next step is a characterization of the noise level. We measure the total noise spectral density and plot this as an equivalent input referred current noise in Fig. 2(a). A char-

acteristic $1/f$ contribution is present up to $200\ \text{kHz}$. For frequencies above $200\ \text{kHz}$, the spectrum is approximately flat, saturating at $0.2 \times 10^{-25}\ \text{A}^2/\text{Hz}$ ($= 0.4\ \text{nV}/\sqrt{\text{Hz}}$). This is very close to the voltage fluctuations generated by the QPC shot noise (calculated to be $S_I = 0.17\ \text{nV}/\sqrt{\text{Hz}}$, for $1\ \text{mV}$ bias over the QPC⁴). We test this by a *direct* measurement of the QPC shot noise. We measure the rms voltage after bandpass filtering the output of the RT *IV* converter (bandwidth from $500\ \text{kHz}$ to $1\ \text{MHz}$). In Fig. 2(b), we show the QPC conductance G_{QPC} as a function of the voltage on gate Q, determined from the time averaged current. The colored markers indicate the QPC conductances ($G_{\text{QPC}} = ne^2/h$, $n = 0, 1, 2, 3$) at which the shot noise was measured as a function of bias over the QPC, V_{QPC} [see Fig. 2(c)]. V_{QPC} is varied by changing V_{sd} . We verified that the QPC was in its linear regime for the entire range of V_{QPC} . The total shot noise spectral density S_I can be expressed as^{18,19}

$$S_I = \frac{2e^2}{h} \sum_i \mathcal{N}_i \left[eV_{\text{QPC}} \coth\left(\frac{eV_{\text{QPC}}}{2k_B T_e}\right) - 2k_B T_e \right], \quad (1)$$

where $\mathcal{N}_i = T_i(1 - T_i)$ with T_i the QPC transmission coefficient of mode i , V_{QPC} the bias over the QPC, k_B the Boltzmann constant, and T_e the electron temperature. The solid lines in Fig. 2(c) are fits to Eq. (1), yielding $\mathcal{N} = 0.234, 0.090, 0.229$, and 0 from top to bottom, in agreement with the QPC conductances. The measurements prove that the equivalent input referred voltage noise is indeed very close to the shot noise limit in this setup. From the fits, we also extract the electron temperature $T_e = 255\ \text{mK}$, consistent with the value obtained from the width of Coulomb peaks ($T_e = 267\ \text{mK}$).

The noise measurements show that the noise from the HEMT is in agreement with our initial estimation. We therefore expect to have sufficient SNR to detect single-electron tunnel events. To test this experimentally, the dot is tuned to be near the $0 \leftrightarrow 1$ electron transition by adjusting the voltages on gates L, M, and T and to be isolated from the bottom lead.⁷ The dot remains coupled to the other lead with a tunable tunnel rate Γ . An electron is now allowed to tunnel back and forth between the dot and the lead and the QPC current should therefore exhibit a random telegraph signal (RTS). The QPC conductance is set again at approximately e^2/h .

In order to maximize ΔI_{QPC} , we want to apply the highest possible bias, V_{QPC} . However, for $V_{\text{QPC}} > 0.65\ \text{mV}$, we observe a severe change in the dot occupation, most probably due to intradot excitations to the first orbital excited state.²⁰ We therefore restrict ourselves to QPC bias voltages below $0.65\ \text{mV}$. This reduces ΔI_{QPC} to $320\ \text{pA}$, resulting in a lower SNR. Measurements of the RTS are shown in Fig. 3. To verify that the measured RTS originates from electron tunnel events between the dot and the lead, we varied two control parameters, as in Ref. 4: (1) the dot electrochemical potential μ relative to the Fermi level of the lead μ_F and (2) the tunnel barrier between the dot and the lead. The dot potential is changed by changing the voltage on gate M. The dot occupation probability P depends on $\mu - \mu_F$ and the temperature broadening of the lead so it should directly reflect the Fermi-Dirac distribution of electronic states in the lead. We infer the dot occupation from the measured average time the electron spends on (off) the dot, $\tau_{\text{on(off)}}$, as $P = \tau_{\text{off}} / (\tau_{\text{on}} + \tau_{\text{off}})$.⁵ However, since both the HEMT and the RT *IV* converter are ac coupled, signals from the QPC are high-pass filtered ($1.2\ \text{kHz}$ cutoff). We can therefore not use a simple

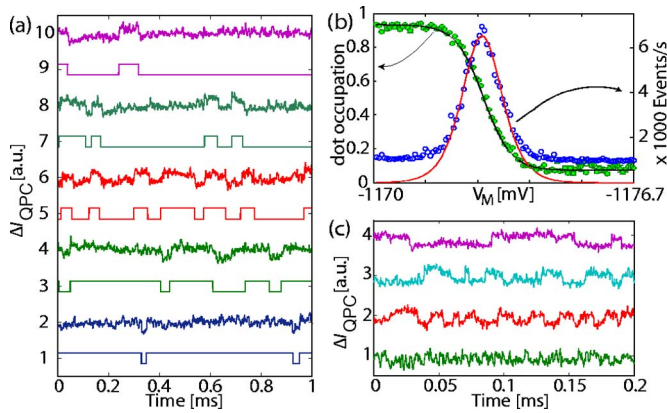


FIG. 3. (Color online) (a) Measured QPC current when increasing the dot potential from top to bottom. The result of our flank detection routine is plotted below each measured trace. An additional bandpass filter (200 Hz–200 kHz) was used for this measurement. (b) Dot occupation extracted from the same data as (a) as a function of V_M . From the same data, we extract the number of tunnel events per second as a function of V_M from which we can extract the tunnel rate.²¹ The solid curves are fits to the data using the Fermi distribution function $f(\mu)$ (black curve) and $\Gamma f(\mu)[1-f(\mu)]$, yielding $\Gamma=26.1$ kHz (red curve). (c) The tunnel rate Γ is increased from top to bottom by decreasing the negative voltage on gate T. Here, the signal was bandpass filtered from 3 kHz to 1 MHz. The shortest detectable events are on the order of 400 ns.

threshold detection scheme⁹ but instead detect the flanks of the steps in ΔI_{QPC} to obtain the single-electron tunneling statistics. In Fig. 3(b), the average dot occupation is plotted versus the voltage on gate M (V_M). At $V_M=-1172.8$ mV, μ is aligned with μ_F . The solid black line is a fit to the Fermi-Dirac distribution function $f(\mu)$, yielding an electron temperature $T_e=275$ mK. The average times $\tau_{\text{on/off}}$ also allow the determination of the tunnel rate Γ . The Fermi distribution and the tunnel rate Γ determine the average number of tunnel events per second as $r_e=1/(\tau_{\text{on}}+\tau_{\text{off}})=\Gamma f(\mu)[1-f(\mu)]$. This is also plotted in Fig. 3(b). The fit to these data yields $\Gamma=26.1$ kHz (solid red line).²¹ The tunnel rate Γ can be varied via the voltage on gate T [Fig. 3(c)]. The shortest detectable events are on the order of 400 ns. The charge sensitivity reached is $4.4 \times 10^{-4} e/\sqrt{\text{Hz}}$ in the range 200 kHz–1 MHz, only 3.8 times larger than the shot noise limit in this setup with $V_{\text{QPC}}=0.65$ mV.

We have demonstrated that a HEMT can be used as a cryogenic amplifier to increase the measurement bandwidth of a QPC charge detection setup. The bandwidth of the setup is 1 MHz and the equivalent input referred voltage noise is measured to be 0.4 nV/ $\sqrt{\text{Hz}}$ above ~ 200 kHz, which is close to the QPC shot noise limit. This allows us to detect fluctuations in the dot occupation as short as 400 ns, 20 times faster than previously achieved using a QPC as a charge sensor. The bandwidth could be further increased by placing the HEMT even closer to the sample (since the dissipation in the HEMT is low enough), which would reduce

the capacitance even more. A lower amplifier noise (both 1/f and base line) could be obtained by using a HEMT with a larger gate area.

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¹L. P. Kouwenhoven, D. G. Austing, and S. Tarucha, Rep. Prog. Phys. **64**, 701 (2001).

²T. Fujisawa, R. Tomita, T. Hayashi, and Y. Hirayama, Science **314**, 1634 (2006).

³S. Gustavsson, R. Leturcq, B. Simovic, R. Schleser, T. Ihn, P. Studerus, K. Ensslin, D. C. Driscoll, and A. C. Gossard, Phys. Rev. Lett. **96**, 076605 (2006).

⁴L. M. K. Vandersypen, J. M. Elzerman, R. N. Schouten, L. H. Willems van Beveren, R. Hanson, and L. P. Kouwenhoven, Appl. Phys. Lett. **85**, 4394 (2004).

⁵R. Schleser, E. Ruh, T. Ihn, K. Ensslin, D. C. Driscoll, and A. C. Gossard, Appl. Phys. Lett. **85**, 2005 (2004).

⁶J. R. Petta, A. C. Johnson, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. **93**, 186802 (2004).

⁷J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, L. M. K. Vandersypen, and L. P. Kouwenhoven, Appl. Phys. Lett. **84**, 4617 (2004).

⁸A. C. Johnson, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Phys. Rev. B **71**, 115333 (2005).

⁹J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, B. Witkamp, L. M. K. Vandersypen, and L. P. Kouwenhoven, Nature (London) **430**, 431 (2004).

¹⁰R. Hanson, L. H. Willems van Beveren, I. T. Vink, J. M. Elzerman, W. J. M. Naber, F. H. L. Koppens, L. P. Kouwenhoven, and L. M. K. Vandersypen, Phys. Rev. Lett. **94**, 196802 (2005).

¹¹J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Science **309**, 2180 (2005).

¹²R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen, Rev. Mod. Phys. (in press); see also e-print arXiv:cond-mat/0610433.

¹³D. J. Reilly, C. M. Marcus, M. P. Hanson, and A. C. Gossard, 0707.2946v1.

¹⁴M. Thalakulam, W. W. Xue, F. Pan, Z. Ji, J. Stettenheim, L. Pfeiffer, K. W. West, and A. J. Rimberg, 0708.0861v1.

¹⁵R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, Science **280**, 1238 (1998).

¹⁶R. J. Schoelkopf (private communication).

¹⁷A. T. Lee, Rev. Sci. Instrum. **60**, 3315 (1989).

¹⁸Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).

¹⁹L. DiCarlo, Y. Zhang, D. T. McClure, D. J. Reilly, C. M. Marcus, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **97**, 036810 (2006).

²⁰E. Onac, F. Balestro, L. H. Willems van Beveren, U. Hartmann, Y. V. Nazarov, and L. P. Kouwenhoven, Phys. Rev. Lett. **96**, 176601 (2006).

²¹For every trace without a tunnel event, the total length of the trace (1 ms) is assigned to $\tau_{\text{on/off}}$. This results in a base line of 1000 events/s instead of 0. To determine Γ , we fit to a subset of the data with a sufficient number of tunnel events.