High frequency conductance of a quantum point contact

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One of the workhorses for the study of mesoscopic physics is the quantum point contact (QPC). Until now experimental studies have focused only on the quasi DC properties of this device. But a theoretical study [1] of the complex conductance G for alternating voltages at moderately high frequencies predicts apart from an unchanged real part Re(G) an additional frequency dependent imaginary part Im(G), leading to an out of phase current. The imaginary contribution Im(G) is related to the the transmission and reflection properties of the individual channels in the QPC.

We present an experimental study of the AC conductance of an AFM engraved quantum point contact for frequencies up to 200 MHz at temperatures down to 70 mK. The QPC was fabricated from a shallow two-dimensional electron system (2DES) with $n = 3.7\cdot10^{15}\mathrm{m}^{-2}$ and $\mu \approx 100\ \mathrm{m}^2/\mathrm{Vs}$ in an AlGaAs/GaAs heterostructure by direct mechanical patterning with the tip of an atomic force microscope (AFM) [2]. Especially the use of a diamond tip proved to produce nice defect free and reproducible QPCs [3]: A groove in the surface of the sample, achieved by moving the AFM tip with a high force, leads to a depletion of the 2DES underneath, allowing the direct writing of narrow insulating lines. Using this technique we wrote a narrow constriction into the 2DES (inset of Fig. 1a) that acts as QPC. The insulated areas of the 2DES near the constriction act as in plane gates (IPG). A voltage V_{IPG} at the IPG controls the number of conducting channels in the QPC. This is demonstrated in Fig.1a): The conductance G of the QPC displays a step of $2e^2/h$ for each channel added.

For high frequency measurements of the conductance we connected coaxial lines to the source and drain contacts of the QPC. Great care was taken to omit any capacitive coupling of the lines outside of the sample. We realized this setup in a dilution refrigerator and ensured a proper thermal anchoring of the coaxial lines, achieving temperatures down to 70 mK. We applied a sine voltage with a frequency up to 200 MHz to the source contact and measured the resulting current by the voltage drop over the 50 Ω input resistance of a high bandwidth low noise voltage amplifier connected to the drain. The use of a high frequency Lock-In Amplifier supplemented by a careful characterization of the coaxial lines allowed us to measure amplitude and phase of the current. The resulting complex conductance $G_{\mathrm{ac}} = I/V$ is shown in Fig.~2 for 163 MHz.

The real part of G_{ac} is frequency independent for the range exploited in this experiment. Figure 2 shows that our AC measurement reproduces nicely the conductance measured in a DC setup. As predicted by theory we observe an additional imaginary part of the conductance, which depends on frequency f and in plane gate voltage V_{IPG}. Christen and Büttiker [1] predicted Im(G_{ac}) to behave like a capacitance, i.e. linear in frequency: $\mathrm{Im}(G_{\mathrm{ac}}) = f\cdot\mathcal{E}$ with frequency independent but gate voltage dependent emittance $\mathcal{E}(V_{\mathrm{IPG}})$, which we indeed observe in our experiment. The emittance $\mathcal{E}$ is given by the sum $\mathcal{E} = \Sigma\, \mathcal{E}_n$ of the emittances $\mathcal{E}_n$ of the current carrying channels. Different from conventional capacitances these contributions can be positive or negative, depending on the transmission an reflection properties of the channel. As can be seen from Fig. 2 we indeed observe the expected change of Im(G_{ac}) for each addition of a conducting channel to the QPC with increasing V_{IPG}. Applying the calculations of Ref. [1] to our device we expect jumps in the imaginary conductance of $\Delta|\mathrm{Im}(G_{\mathrm{ac}})| \sim 0.01\cdot(2e^2/h)$ for $f = 163$ MHz. This is in good agreement with the experimentally observed steps. Thus our experiment nicely approves these theoretical predictions.

[1] T. Christen and M. Büttiker, Phys. Rev. Lett. **77**, 143 (1996).
[2] H. W. Schumacher *et al.*, Appl. Phys. Lett. **75**, 1107 (1999).
[3] J. Regul *et al.*, Appl. Phys. Lett. **81**, 2023 (2001).

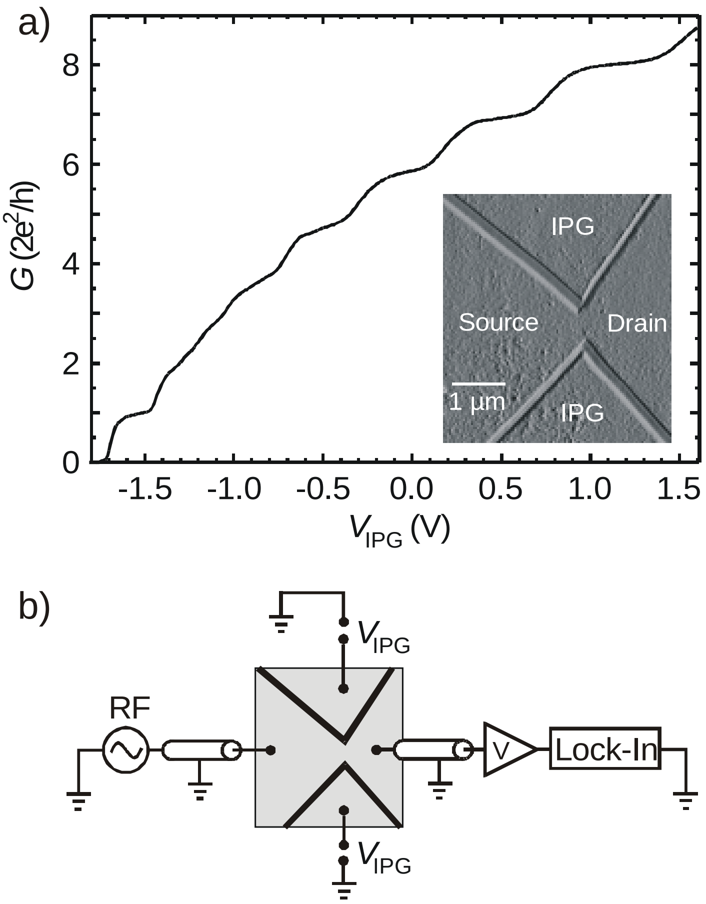

Figure 1: a) DC conductance G vs. in plane gate voltage V_{IPG} for the quantum point contact (QPC) used in these experiments. The *inset* shows an AFM image of the diamond engraved QPC. The in plane gates allow to control the number of transmitted channels.

b) Setup for high frequency conductance measurements: The AC source voltage V is supplied by a radio frequency generator, which is connected by a high frequency coaxial line to the sample. A high frequency voltage amplifier with 50 Ω input resistance acts as current amplifier. Its output voltage, which is proportional to the current I flowing through the QPC, is measured phase sensitively with high phase accuracy using a high frequency Lock-In Amplifier. Careful calibration of the coaxial lines allows a precise measurement of the real (in phase) and imaginary (out of phase) part of the conductance $G_{ac} = I / V$.

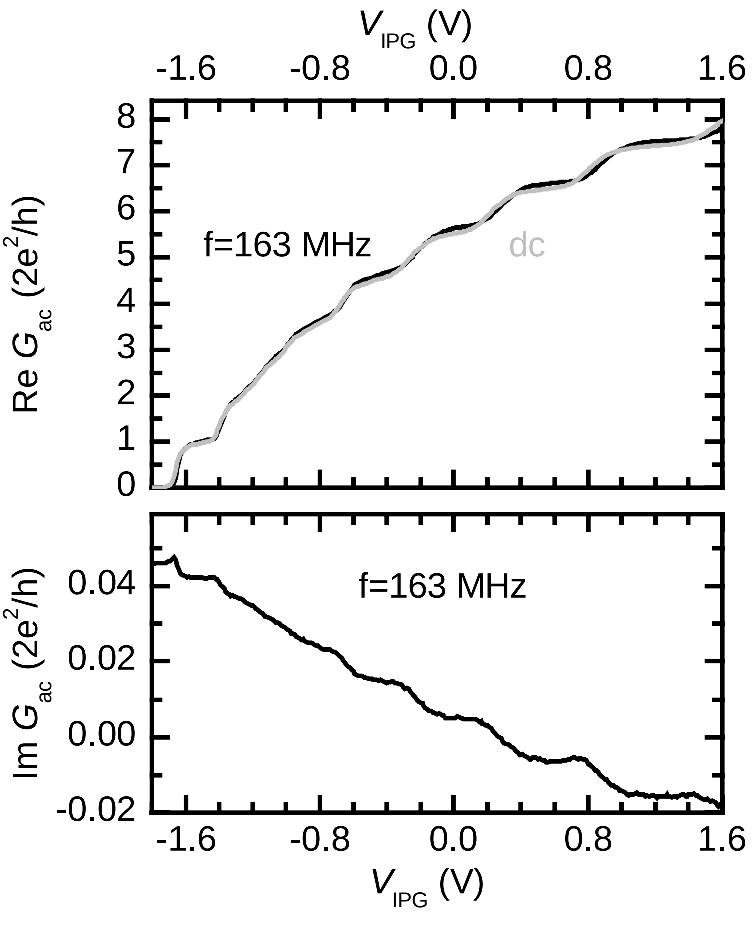

Figure 2: *Top*: Real part of the high frequency conductance G_{ac} at $f = 163$ MHz (black line) compared to the DC conductance (grey line), both plotted as function of the in plane gate voltage V_{IPG}.
Bottom: The imaginary part of the conductance displays steps at the same position as the real part.