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MODELING A.C. ELECTRONIC TRANSPORT THROUGH
A TWO-DIMENSIONAL QUANTUM POINT CONTACT

Author(s):

I. E. Aronov
N. N. Beletskii
G. P. Berman
D. K. Campbell
G. D. Doolen
S. V. Dudiy

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Modeling A.C. Electronic Transport Through a Two-Dimensional Quantum Point Contact

I.E. Aronov^{a,b}, N.N. Beletskii^b, G.P. Berman^{c,d}, D.K. Campbell^{d,e}, G.D. Doolen^{c,d},
S.V. Dudiy^b^aSchool of Physics, Georgia Institute of Technology, Atlanta, GA 30332 USA^bInstitute of Radiophysics and Electronics, National Academy of Sciences of Ukraine,
12 Acad. Proskura St., 310085, Kharkov, Ukraine^cTheoretical Division, T-13, MS B213, Los Alamos National Laboratory,
Los Alamos, NM 87545 USA^dCenter for Nonlinear Studies, MS B258,
Los Alamos National Laboratory, Los Alamos, NM, 87545 USA^eDepartment of Physics, University of Illinois at Urbana-Champaign,
1110 West Green St., Urbana, IL 61801-3080 USA

We present the results on the a.c. transport of electrons moving through a two-dimensional (2D) semiconductor quantum point contact (QPC). We concentrate our attention on the characteristic properties of the high frequency admittance ($\omega \approx 0 - 50\text{GHz}$), and on the oscillations of the admittance in the vicinity of the separatrix (when a channel opens or closes), in presence of the relaxation effects. The experimental verification of such oscillations in the admittance would be a strong confirmation of the semi-classical approach to the a.c. transport in a QPC, in the separatrix region.

The geometry of the QPC, and the classical electron trajectories (a phase space) are shown in Figures 1 and 2. In [1], using a novel variant of the Wigner distribution function formalism, we showed that for low-frequency external a.c. fields, the admittance of a QPC consists of the d.c. conductance (the real part of the admittance) and an "emittance" (the imaginary part of the admittance), which includes both inductive [1] and capacitive [1,2] contributions resulting from quantum transport effects. The emittance is sensitive to the geometry of the QPC and can be controlled by the gate voltage. We demonstrated in [1] that there exist step-wise oscillations in the (quantum) inductance, which are determined by the harmonic mean of the velocities of the "open channels" (electron modes that propagate through the QPC). The (quantum) capacitance is a mesoscopic manifestation of the "closed channels" (electron modes that are reflected by the QPC). The existence of well-defined conductance, capacitance, and inductance implies that (at low

frequencies) a QPC can be considered to be an elementary circuit of the extremely small size, $\sim 0.1 - 1 \mu m$. In [3,4], we extended our analysis to higher frequencies by solving the self-consistent integral equations for the spatial distribution of the electric potential and the electron current within the QPC and obtained the frequency dependence of the admittance for the QPC. We solved these equations numerically for a wide frequency region ($\omega \approx 0 - 50$ GHz) and for different QPC parameters (width, number of open and closed channels, etc.). We found that there exists a characteristic value of the frequency where a crossover behavior of the admittance takes place between a low-frequency regime, in which the effective circuit theory can be applied [1] and a high-frequency regime, in which strongly nonlinear effects as a function a frequency arise [3,4]. For standard QPC dimensions and parameters, this crossover frequency is $\omega = \omega_c \sim 10$ GHz.

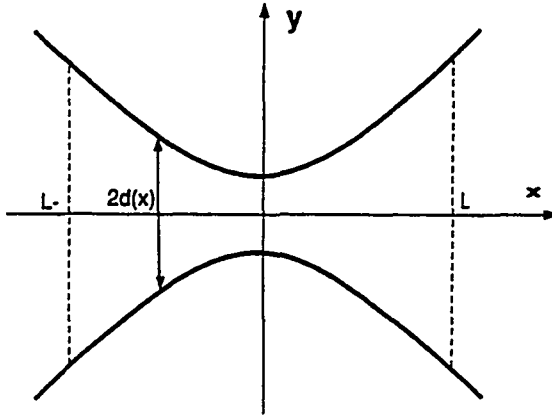


Figure 1. The geometry of the QPC. The width, $2d(x) = 2d(0) \exp(L^2 x^2 / \tilde{L}^2)$. The effective length is $2L$.

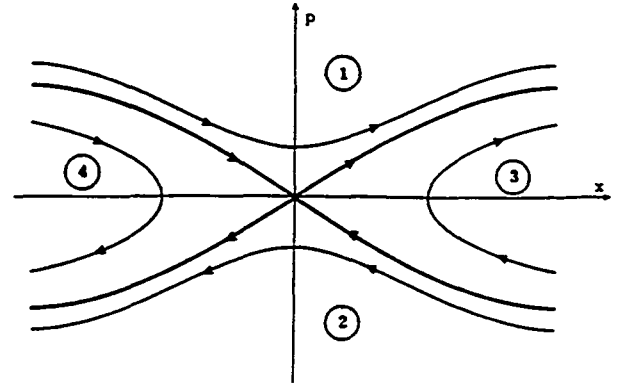


Figure 2. The classical trajectories. The heavy lines are the separatrices that separate the open channels (regions 1 and 2) and closed channels (regions 3 and 4).

Further, our solution shows that in the vicinity of the “opening points” (parameter values at which new “open channels” appear or disappear), the admittance exhibits characteristic oscillations as a function of the parameter $q = k_F d(0) / \pi$ (where k_F is a Fermi wave vector, and $2d(0)$ is the width of a QPC), and on the frequency, ω , of the a.c. field. In the frames of our semiclassical approach, these oscillations arise from the effects of classical trajectories close to the separatrix shown in Figure 2 (quantum tunneling effects are not included). Namely, in the vicinity of the separatrix, the characteristic time-scale, τ , of the quasiclassical dynamics of electrons slows down ($\tau \rightarrow \infty$), and the dimensionless phase factor, $\exp[i\tau(q)\omega]$ which gives a contribution to the oscillations of the admittance, becomes very sensitive to small variations of the system’s parameters, such as q and ω . In Figures 3 and 4 (curves 1), the oscillations of the real and the imaginary parts of admittance, $Y = Y' + iY''$ (normalized by $2e^2/h$) are shown as a function of a real part of a dimensionless frequency β' ($\beta = \beta' + i\beta'' = (\omega + i\nu)L/v_F$). The value $\beta' = 1$ corresponds to $\omega = 26 \times 10^9 s^{-1}$. The imaginary part of the frequency, β'' , describes the

momentum relaxation effects. The following parameters were chosen: $L = \tilde{L} = 10^{-3}\text{cm}$, $d(0) = 2.05 \times 10^{-6}\text{cm}$, $\epsilon = 13$, $v_F = 2.6 \times 10^7\text{cm/s}$, $k_F = 1.5 \times 10^6\text{cm}^{-1}$, $\nu = 10^9\text{s}^{-1}$ ($\beta'' = 0.043$). The parameter $q = 1.96$ is close to an integer, $n_0 = 2$. Figures 3 and 4 show also the contribution to the admittance from the open channels (in our case $N = 1$, curve 2), closed channels ($\tilde{N} = 4$, curve 3), and from $(N+1 = 2)$ closed channel (curve 4).

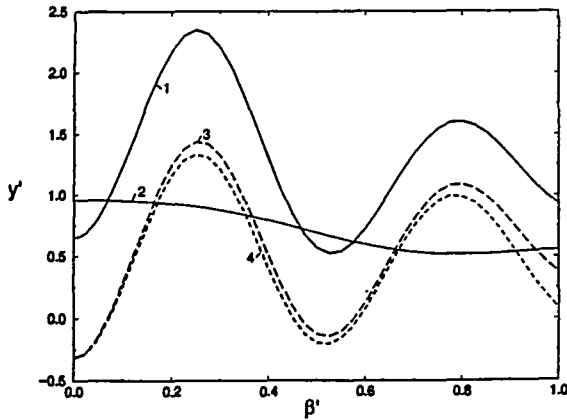


Figure 3. Oscillations of the real part of the admittance on the dimensionless frequency.

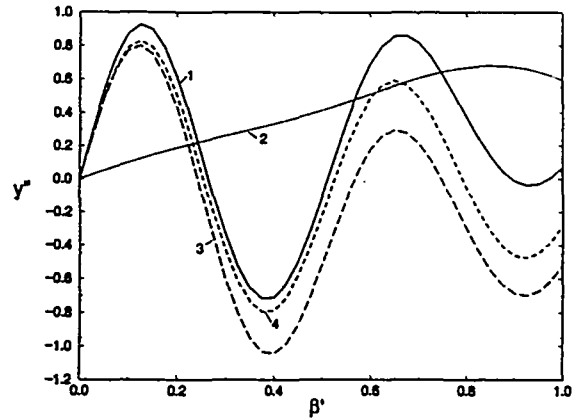


Figure 4. Oscillations of the imaginary part of the admittance on the dimensionless frequency.

Note, that the quantum tunneling effects have not been taken into consideration. That is why, the experimental verification of the described above oscillations in the admittance would be a strong confirmation of applicability of the semi-classical approach to the a.c. transport in a QPC, in the vicinity of the separatrix.

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