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AUTHOR(S): G.P. Berman, T-13
G.D. Doolen, T-13
R. Mainieri, T-13
I.E. Aronov, Sage Tech Inc
D.K. Campbell, Univ of Il
N.N. Beletskii, S.V. Dudiy, Nat'l Acad of Sci Ukraine

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Los Alamos, New Mexico 87545

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A.C. Transport and Collective Excitations in a Quantum Point Contact

G.P. Berman, G.D. Doolen, R. Mainieri

Theoretical Division and CNLS, Los Alamos National Laboratory, Los Alamos NM 87545

I.E. Aronov

Sage Technology Inc., 1800 Sandy Plains Parkway, Suite 320, Marietta GA 366

D.K. Campbell

Department of Physics, University of Illinois at Urbana-Champaign,

1110 West Green St., Urbana, IL 61801-3080

N.N. Beletskii, S.V. Dudiy

Institute of Radiophysics and Electronics, National Academy of Sciences of Ukraine,

12 Acad. Proskura St., 310085, Kharkov, Ukraine

We calculate the a.c. – admittance of a two-dimensional quantum point contact (QPC) using a Boltzmann-like kinetic equation derived for the partial Wigner distribution function. An integral equation for a potential inside a QPC is solved numerically. The dependence of the admittance on the frequency of the a.c. field is found in a wide frequency range, $\omega \approx 0 - 50$ GHz. The contribution to the imaginary part of the admittance due to the quantum capacitance and inductance is numerically calculated. It is shown that the crossover from localized parameters – quantum capacitance and inductance – to distributed behavior takes place at $\omega \sim 10$ GHz. A transition from 2D plasmons to quasi-1D plasmons is analyzed as a function of two dimensionless parameters: $k_x d_0$ (where k_x is the longitudinal wave vector, and d_0 is the width of the QPC), and the number of open electron channels, N .

Recent technological progress in manufacturing nano-scale solid state structures has made it possible to fabricate semiconductor devices which operate in the quantum ballistic regime. One system which has attracted much attention is the two-dimensional ballistic quantum point contact (QPC) [1-5]. A QPC (see Fig. 1) is one of the basic elements of integrated nano-circuits. It provides the interfaces between nano-devices. A QPC displays unusual behaviors and can itself be considered to be a nano-device. For example, by variation of the gate voltage, one can change the boundaries (shape) of the QPC causing step-like oscillations of the quantum conductance [4,5]. Recently, it was discovered that at low enough frequency, a QPC demonstrates not only the quantum peculiarities in the d.c.-transport, but also has quantum inductance [3] and quantum capacitance [2,3]. This allows one to consider a QPC (in the low frequency regime) as an extremely small elementary circuit, $\sim 0.1 - 10 \mu m$. In this paper, we present the results of numerical simulations of the a.c. transport through a QPC (in the x -direction in Fig. 1), for a wide range of frequencies. We also investigate the crossover behavior of collective excitations in a QPC, from 2D plasmons to quasi-1D plasmons.

In an adiabatic geometry which is smooth on the scale of the Fermi wavelength, the longitudinal and transverse motion of electrons can be separated [1]. In this case, the transverse energy, $\varepsilon_n(x) = \pi^2 n^2 \hbar^2 / 8m d^2(x)$, plays the role of the effective potential energy for one-dimensional longitudinal motion in the n -th channel. (For the numerical simulations we assume a QPC boundary of the form: $d(x) = d_0 \exp(x/\tilde{L})^2$.) At low temperatures ($T \ll \mu$, where μ is the chemical potential), one has a separation between propagating (open) channels ($\varepsilon_n(0) < \mu$), and reflecting (closed) channels ($\varepsilon_n(0) > \mu$) [3]. It was shown in [3], that in the low frequency regime the trajectories belonging to the open channels give a contribution both to the real part of the admittance (conductance) and to the inductance. The trajectories belonging to the closed channels may have the turning points inside the constriction shown in Fig. 1 which are determined by the equation: $\varepsilon_n(x_n) = \mu$. These trajectories give a contribution to the capacitance. The number of open channels is: $N = [q]$, where $q = 2k_F d_0 / \pi$, and $\hbar k_F = \sqrt{2m^* \mu}$ (k_F and m^* are the Fermi wave vector and the effective electron mass). The integer, $\tilde{N} = [q \exp(L/\tilde{L})^2] - N$, is the number of closed channels.

In this paper we use the formalism developed in [3] to calculate the admittance, $Y = I_{tot}/V$, in a wide range of frequencies ($\omega \approx 0 - 50$ GHz), where I_{tot} is the total current through the QPC, and V is the potential difference between the left ($x = -L$) and the right ($x = L$) edges of the constriction shown in Fig. 1. It is assumed that inside the QPC, the electric field has the form: $E(x, t) = -(\partial \Phi(x)/\partial x) \exp(-i\omega t)$. The potential, $\Phi(x)$, inside the QPC, is determined by the solution of the integral equation. (A procedure for deriving this equation will be discussed elsewhere [6].) As one can see from Fig. 2, the real part of the potential has characteristic peaks at the turning points $\xi_n = x_n/L$ corresponding to the closed channels. The real part of the admittance (conductance), y' , is shown in Fig. 3a ($Y = (2e^2/\hbar)y$). The curves (1-3) correspond to different values of the parameter q . For all cases shown in Fig. 3, the number of open channels is $N = 2$. One can see that at $\omega = 0$, the conductance assumes a familiar form, $y' = 2$. When the frequency increases, the dependence $y'(\beta)$ ($\omega = (v_F/L)\beta = 26 \text{ GHz} \cdot \beta$, where v_F is the Fermi velocity) becomes nonlinear due to the contribution of both open and closed channels. More complicated behavior $y'(\beta)$ can be observed in the neighborhood of q approximately equal to an integer. We shall discuss this behavior of the admittance elsewhere [6]. In Fig. 3b, we demonstrate the dependence of the imaginary part of the admittance, y'' on frequency. One can see that the low frequency approximation is valid in the region: $\omega < \omega_c \approx 10$ GHz. In this frequency region, a QPC can be considered as an effective circuit [3]. For $\omega > \omega_c$, one should take into consideration the nonlinear dependence $y''(\beta)$. The contribution to the admittance, $y(\beta)$, of both open and closed channels is significant in the whole frequency region. One can see from Fig. 3b that the effects connected with the imaginary part of the admittance can be large. For example, at $\beta = 1$: $y''/y' \approx 0.8$. Effects connected with the nonlinear behavior $y(\beta)$ are of significant importance in systems with integrated nano-devices. We hope that observation of these effects can be experimentally realized soon.

Finally, for a QPC of a strip form with the width d_0 , we have found that a crossover of the surface plasmon spectrum from 2D to quasi-1D is described by two dimensionless parameters: 1) The number of open channels, N ; 2) The dispersion parameter, $k_x d_0$, where, k_x , is the plasmon wave number. In a quasi two-dimensional case, when $N \gg 1$, and in the long wave regime, ($k_x d_0 \ll 1$), the spectrum of plasmons is of an acoustic type. In the short wave regime ($k_x d_0 \gg 1$), the spectrum of plasmons exhibits a square-root behavior. In the quasi one-dimensional case, ($N \geq 1$), the spectrum of plasmons is of an acoustic type. A detailed analysis of the crossover of the surface plasmon spectrum from 2D to quasi-1D is presented in [7].

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Figure Captions

Fig. 1. The geometry of the micro-constriction. The width is denoted by $2d(x)$, the narrowest width is $2d_0$, and the effective length is $2L$.

Fig. 2. Distribution of the real part of the electric potential, $\Phi'(\xi)$ (normalized by V) inside a QPC ($\xi = x/L$), for five values of the frequency (curves 1-5). The values of parameters are: $q = 1.7$; $N = 1$; $\tilde{N} = 11$; $L/\tilde{L} = 1.4$; $\tilde{L} = 10\mu m$; $d_0 = 1.5 \cdot 10^{-6}$ cm; $k_F = 1.5 \cdot 10^6 cm^{-1}$; $v_F = 2.6 \cdot 10^7 cm/s$; dielectric constant $\epsilon = 13$. (1): $\omega = 0$; (2): $\omega = 9$ GHz; (3): $\omega = 19$ GHz; (4): $\omega = 28$ GHz; (5): $\omega = 37$ GHz.

Fig. 3. Frequency dependence of the admittance $y = (\hbar/2e^2)Y$; (a) y' - real part; (b) y'' - imaginary part of the admittance, for different values of q and $\tilde{N}$. $N = [q] = 1$; $L = \tilde{L} = 10\mu m$; (1) $q = 1.1$, $\tilde{N} = 2$; (2) $q = 1.7$, $\tilde{N} = 3$; (3) $q = 1.75$, $\tilde{N} = 3$. The subscripts (0) and (c) indicate the contributions to the admittance of open and closed channels; $\omega = (v_F/L)\beta = 26GHz \cdot \beta$.

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