# Photoelectric effects in a quantum point contact with an artificial impurity



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**LETTER TO THE EDITOR**

# Photoelectric effects in a quantum point contact with an artificial impurity

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**Abstract.** I present exact numerical calculations on photon induced currents in a quantum point contact configuration with an artificial impurity potential. The presence of the impurity potential induces a net particle current in one direction only. The induced voltages for a corresponding open circuit are estimated. The calculations show that the effect is robust and easily within the experimental range.

Recent photoconductance experiments [1, 2, 3] on quantum point contacts (QPCs) in the two-dimensional electron gas (2DEG) displayed oscillations. The first experiment by Wyss *et al* [1] was motivated by theoretical predictions [4]. The predictions were that additional ministeps should occur in the quantized conductance of the QPC. However, these ministeps were not observed in the experiments, and there has been argument over whether the observed oscillations are the result of photon-assisted transport or merely of heating of the 2DEG. The theoretical work by Grincwajg *et al* [5] gave a different criterion for which contribution to the photoconductance dominates from that used in [4], taking into account the conservation of electronic momentum. This modified the photoconductance oscillations, but the oscillations still had a step-like character. Both these theoretical papers [4, 5] were based on a semiclassical and adiabatic description of electronic motion. In a recent work [6] exact numerical results for the photoconductance were given, and it was shown that in order to have step-like oscillations in the photoconductance, the zero-field conductance steps should be very sharp. From this point of view, it is not surprising that step-like oscillations were not found experimentally. The numerical method used in [6] is the recursive Green function technique applied to the continuous Schrödinger equation in a mixed representation [7] of transverse eigenfunctions and the longitudinal coordinate. Based on the same numerical scheme, I now present calculations for a simple asymmetric configuration. In this *asymmetric* geometry the radiative field does not merely alter the voltage–current characteristics from the zero-field case, it *induces* currents/voltages in situations where, without microwaves, there were none. Photovoltaic effects in asymmetric structures have been considered earlier [8, 9]. These analytic approximate calculations were based on adiabatic theory.

In the following I neglect the electron–electron interaction and assume spin degeneracy. I further study DC transport and assume stationary conditions. Consider a QPC configuration as indicated in figure 1 under the influence of a coherent radiative field with frequency $\omega/2\pi$. Neglecting spontaneous emission, we can write the DC electric current from left (L) to right

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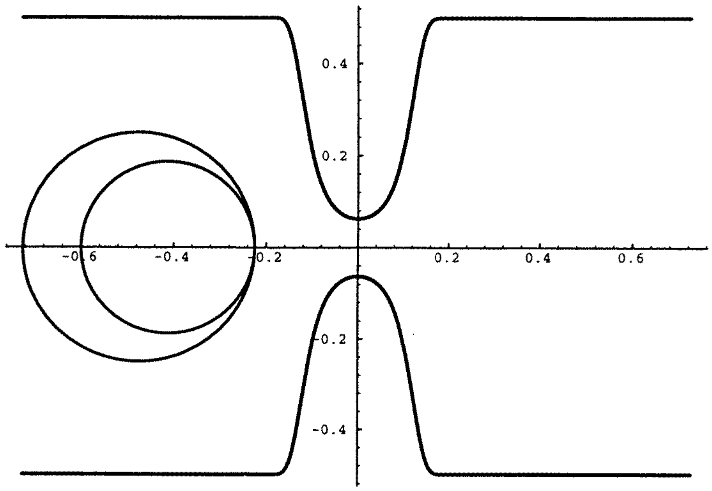


**Figure 1.** A plot of the QPC configuration considered in this paper. The coordinates are in units of the asymptotic width of the channel. The circles indicate the two antidot potentials used in the calculations. The antidot potential should be sufficiently close to the QPC in order to have any influence on the transport properties, but sufficiently far from the QPC that transport is dominated by the QPC.

(R) in the spirit of Landauer and Büttiker [10, 6] as

$$I = \frac{2e}{h}\sum_n \int_0^\infty \left[T_{R,L}(E+n\hbar\omega, E) f_{\mu_L}(E) - T_{L,R}(E+n\hbar\omega, E) f_{\mu_R}(E)\right] \mathrm{d}E \tag{1}$$

where $T_{R,L}(E+n\hbar\omega, E)$ is the sum of transmission probabilities for particles from the left with energy $E$ to the right with final energy $E+n\hbar\omega$. Here, $e$ is the electronic charge. In the following, I shall consider two possibilities. First, I assume that the chemical potentials, $\mu_{L/R}$, are kept equal, and the effect of the radiative field is to induce an electric current, $I$, through the device. From time reversal symmetry (I neglect spontaneous processes) $T_{L,R}(E+n\hbar\omega, E) = T_{R,L}(E, E+n\hbar\omega)$ so (1) reduces to

$$I = \frac{2e}{h}\int_0^\infty \Delta T(E) f_\mu(E)\mathrm{d}E \equiv \frac{2e}{h}\langle \Delta T\rangle E_F \tag{2}$$

where

$$\Delta T(E) = \sum_n \left[T_{R,L}(E+n\hbar\omega, E) - T_{R,L}(E, E+n\hbar\omega)\right]. \tag{3}$$

A positive $\Delta T(E)$ means a positive contribution of *particle* current from left to right.

Second, I consider the case of zero current. The induced voltage in the *right* reservoir (I assume that the chemical potential in the left reservoir is fixed) is now found via the relation

$$T' eV = \langle \Delta T\rangle E_F \tag{4}$$

where

$$T' eV \equiv \sum_n \int_0^\infty T_{L,R}(E+n\hbar\omega, E)\left[f_{\mu+eV}(E) - f_\mu(E)\right] \mathrm{d}E. \tag{5}$$

If $\langle \Delta T\rangle$ is positive, the induced voltage in the right reservoir will be negative. In the following calculations I have considered fields sufficiently weak that only the neighbouring energy levels, $E \pm \hbar\omega$, have to be considered in the calculation of $\Delta T(E)$. That the calculations are in this weak-field regime is checked by reducing the electric field by a factor two and observing that $\Delta T(E)$ is reduced by a factor four.

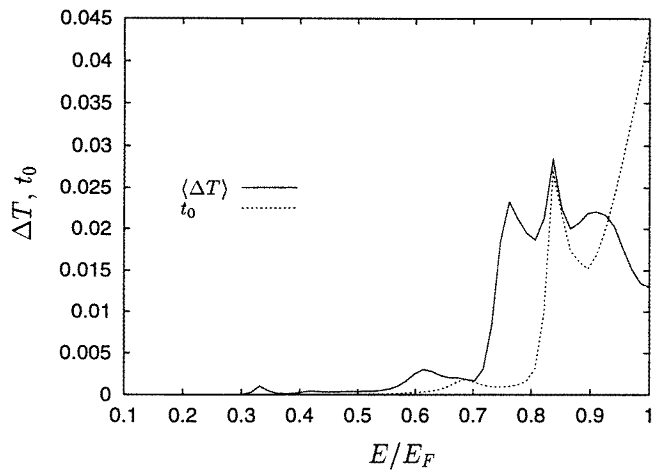


**Figure 2.** A plot of the net transmission (equation (3) in the text) as a function of the scaled energy, $E/E_F$. The solid line displays the average with respect to the polarization angle, $\phi$, of the linear polarized field. The dotted line shows the zero-field transmission. All quantities are in dimensionless units.

The setup consists of a QPC with an artificial impurity potential at one of its sides. The impurity potential is assumed to be placed on the left of the QPC. This potential is taken to be repulsive i.e. it is an antidot. Figure 1 displays a plot of the configurations used in the actual calculations. The antidot should not be too close to the QPC as this would block all transport, but it should be sufficiently near the QPC to have a strong impact on the transport properties.

The basic idea for the setup is very simple. Assume that the QPC is close to the threshold of the first conductance step, so that most of the zero field transport is dominated by the constriction. The artificial impurity breaks the longitudinal mirror symmetry around the centre of the QPC and makes it possible to induce currents in the presence of radiation. The presence of the antidot will now cause additional electron scattering. Electrons will either be scattered to the right, through the point contact, or scattered to the left, away from the QPC region. If the additional scattering is to the left, this will essentially have no effect on the current, since the electrons would very probably have been scattered in that direction by the QPC anyway (remember that the QPC should be close to threshold for the *first* conductance step). Antidot scattering through the QPC will, on the other hand, lead to a real increase in particle current in that direction. This picture may seem simplistic. Nevertheless, all calculations indicate that net particle current is induced only to the right ($\Delta T(E) \geqslant 0$).

As model parameters I have chosen $k_F = 1.3 \times 10^8$ m$^{-1}$, and the minimum width, $W_0$, of the QPC is given by $k_F W_0/\pi = 1.46$. The repulsive potential, $U$, of the circular antidot is $U = 2E_F$. In these calculations, I have assumed that the radiation field is linearly polarized, with a polarization angle, $\phi$, with respect to the longitudinal direction. The electric field has been chosen to be 100 V cm$^{-1}$ and $\hbar\omega = E_F/2$ ($\simeq$5 meV), which is well within experimental realization [3]. I have assumed that the effective electron mass is

$m^* = 0.067m_e$. The confinement potential is given by hard wall boundary conditions: the wavefunction vanishes at $y = \pm W(x)/2$.

Figure 2 displays the energy dependence of the transmission for the configuration with the smallest antidot plotted in figure 1. The solid line shows the photo-induced transmission, $\langle \Delta T \rangle (E)$, averaged over the polarization angle, $\phi$. The dashed line is the zero-field transmission, $t_0$, for the system.

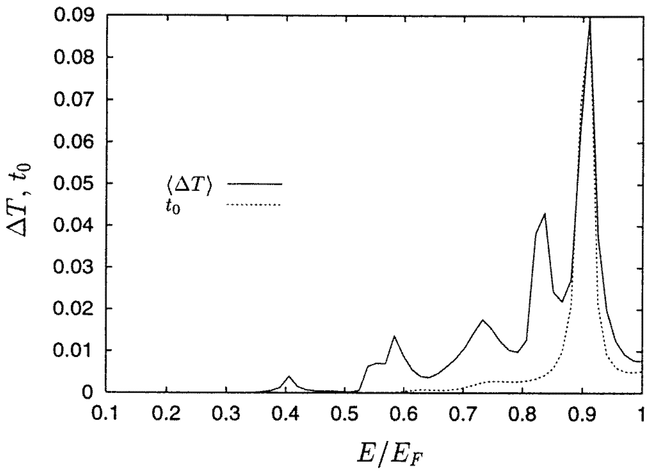


**Figure 3.** The same as figure 2, but for a system with a larger antidot. The radius of the antidot is $\frac{4}{3}$ times the size of that for which calculations are presented in figure 2.

Figure 3 displays the same information as figure 2, but for an antidot where the radius is increased by a factor $\frac{4}{3}$ (corresponding to the largest antidot in figure 1). The distance between the QPC and the antidot is unaltered. On the basis of the calculations, the following observations have been made:

(i) The energy-averaged photo-induced transmission, $\langle \Delta T \rangle_E(\phi)$ does not show any significant dependence on $\phi$;

(ii) The photo-induced transmission, $\Delta T(E)$, is always non-negative (for all choices of $\phi$);

(iii) As can be seen by comparing figures 2 and 3, the larger radius gives the best photoresponse.

One should note that one of the peaks in $\Delta T(E)$ coincides with a peak in $t_0$, in both figures 2 and 3. This is probably not accidental, as a peak in $t_0$ indicates an increase in the local density of states in the region between the QPC and the antidot ('resonant tunnelling'). An increase of the local density of states in this region should in general enhance the probability for photon scattering events and thereby enhance $\Delta T(E)$. For the particular value of electric field chosen here, the amplitudes of $\Delta T(E)$ and $t_0$ are almost equal, but this is only accidental. Also note that the peak in $t_0(E)$ gives rise to a peak in $\langle \Delta T \rangle (E)$ at $E - \hbar\omega$.

It is clear from equations (2) and (4) that although the induced current is small, the induced voltage can be significant. The induced currents for the two examples given here are $I = 0.0058 \times \frac{2e}{h} E_F$ = 4.3 nA for the calculations corresponding to figure 2, and $I = 0.0087 \times \frac{2e}{h} E_F$ = 6.5 nA for figure 3. Estimates of the induced voltages are 1 and 3 mV respectively. Accurate estimates of the induced voltages are not possible since I have not taken into account effects from the high electric field which may be generated by sufficiently large voltage differences in the two reservoirs. This comment applies in particular to the calculation with the largest antidot, which yields the largest induced voltage. A widening of the point contact should result in a larger current and a reduced voltage.

In conclusion, I have presented exact numerical calculations for photon-induced currents due to the presence of an artificial impurity potential in the vicinity of a quantum point contact. The particle current is induced in the direction from the impurity through the constriction. If the antidot potential is defined by means of a metallic gate, it should be possible to turn the effect on and off by switching the gate voltage.

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