Rapid Communications

Pauli pump for electrons

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Inspired by recent developments in GaAs-Al_xGa_{1-x}As heterostructure fabrication, we propose a simple device based on quantum adiabatic transport that can work as an electron pump. It consists of two gates to which an alternating voltage is applied with a relative phase shift, which breaks the time-reversal symmetry. Its operation relies on the Pauli principle, which leads to a distinction for the electrons transmitted through the device between inelastic emission and absorption processes. Depending on the modulation amplitude, transmission of one electron per photon or a few electrons per cycle can be realized. It is also possible to measure the electron velocity. Since inelastic processes occur in a controlled way, the device can serve to test assumptions about electron reservoirs in the presence of phase breaking.

Recent developments in semiconductor heterostructure fabrication made it possible to study electron transport in low-dimensional nanostructure devices. A wealth of new transport phenomena is observed.1 As long as electron-electron interactions can be neglected, the theoretical understanding of these phenomena can often be based on the fact that (i) quantized-transport channels exist due to confinement of the electron on small length scales; (ii) transport through these channels remains phase-coherent due to the large phase-breaking lengths. Under the conditions of adiabatic transport, mixing of transport channels is suppressed, which among other things accounts for the well-known conductance quantization of a narrow constriction2 at multiples of $e^2/h$.

On the other hand, Coulomb effects have been observed3 in systems consisting of two constrictions. The region in between these constrictions can be charged, which causes a Coulomb blockade, leading to characteristic oscillations of the conductance. There is a strong correspondence between these charging effects and analogous effects observed in small tunnel junctions.4 Here, due to the charging effect, the states with different numbers of electrons on a conducting island have different energies and can therefore be distinguished. This, in combination with an alternating gate voltage, gives the possibility to construct a single electron turnstile or a pump, which transmits only one electron per cycle.5,6 Lead by the analogy with small tunnel junctions, several similar devices, based on the Coulomb blockade, in semiconductor heterostructures have been discussed.7,8

Also in the absence of charging effects, a time-dependent potential can induce a current without a bias voltage.9,10 In this paper we propose an electron pump which is based on a different principle: the controlled inelastic absorption of modulation quanta. Consider a slowly varying narrow channel (see Fig. 1) in a two-dimensional electron gas (2DEG). Along this channel two gates are present, which can be modulated independently by an alternating voltage of amplitude $V_i$ ($i = 1, 2$) and frequency $\omega$. Such a device can simply be fabricated, e.g., with the help of metal gates in a semiconductor heterostructure. The smooth spatial variation allows us to work in the semiclassical approximation. We operate in the situation where all the open transport channels are transmitted with unity probability. The modulation amplitude is small enough in order not to violate this property. If the frequency is low enough to prevent intersubband transitions ($\omega < \Delta E_{\text{sub}}$, where $\Delta E_{\text{sub}}$ is the subband splitting), the

FIG. 1. 2DEG confined to a narrow channel with a double-barrier system. The barriers, situated at $x_1$ and $x_2$, can be modulated independently with amplitude $V_1$ and $V_2$. 
transport remains adiabatic even in the presence of the modulation. The only feature of the modulation is to change the energy of the electron, during transmission through the channel, by an amount $k\omega$, with $k$ an integer; the device is not based on a periodic opening and closing of a transport channel during a cycle. A relative phase shift $\phi$ is applied between the gates, which breaks the time-reversal symmetry. As a consequence, for an electron with a certain momentum going from left to right in the channel, the probability $P_{rl}$ for an inelastic process differs from the corresponding probability $P_{lr}$ for an electron going from right to left. The two reservoirs acting as source and drain for these electrons are both characterized by a Fermi distribution $f(E)$ at chemical potential $\mu$ in case of zero-bias voltage. We assume that the reservoir absorbs incident carriers with probability $1-f(E)$. Hence at low temperatures, Pauli's principle suppresses inelastic emission due to the modulation. As a result, a net current will flow through the device at zero-bias voltage. If the reservoir would absorb all incoming electrons, as assumed by Büttiker, no current would flow in the situation described. The order of magnitude of the current is a few electrons per cycle.

Assume for simplicity that only one subband is occupied in the narrow channel. In the adiabatic approximation,

$$\sigma(x,t;\phi) = -\frac{m}{2} e^{i\tau(x)} \int_{-\infty}^{\infty} dx' e^{i\omega(x')} \left[ V_1(x') + V_2(x') e^{i\phi} \right] + (\omega \to -\omega; \phi \to -\phi).$$

Here $\tau(x) = \int_{-\infty}^{x} dx' m/k_{E}(x')$.

The inelastic contributions to the transmission probability are easily found by calculating the spectral density $|\int dt/2\pi e^{i\omega t} \Psi(x,t;\phi)|^2$ of the time-dependent wave function $\Psi(x,t;\phi)$ at $x = \infty$. The probability $P_{rl}(\pm k\omega)$ for an electron to absorb or emit $k$ modulation quanta during transmission through the device from left to right reads

$$P_{rl}(\pm k\omega) = J_{\delta}[S(\omega,\tau_{trav} + \phi)]$$

$$S = [S_1^2 + S_2^2 + 2S_1S_2\cos(\omega,\tau_{trav} + \phi)]^{1/2},$$

where $J_{\delta}(S)$ is a Bessel function. We defined the action $S = m \int \infty dx V(x)/k_{E}(x)$ and the traversal time $\tau_{trav}$ needed to travel between the gates. Since time-reversal symmetry is broken by the phase difference $\phi$, the time-dependent wave function for an electron going from right to left is given by $\Psi^*(x,t;\phi)$. Therefore, the corresponding probability for an inelastic process for an electron transmitted from right to left $P_{lr}(\pm k\omega) = J_{\delta}[S(\omega,\tau_{trav} - \phi)]$. This leads to an asymmetry for the inelastic probabilities:

$$P_{rl}(\pm k\omega) \neq P_{lr}(-\omega,\phi).$$

We can calculate the net current between the two reservoirs right and left to the narrow channel which act as source and drain for the electrons traversing the system by considering separately the current from left to right $I_{lr}$,

$$I_{lr} = \frac{e}{\pi} \int dE \sum_{k} P_{rl}(k\omega) f_1(E) \left[ f_1(E + k\omega) - f_1(E) \right]$$

and the corresponding current $I_{rl}$ from right to left.

The one-dimensional wave function $\Psi_{E}(x)$ describes the electron in the narrow channel at energy $E$ in this subband. A time-dependent gate modulation couples to the electron via a matrix element $V_1(x) \cos(\omega t)$. We assume that these matrix elements are localized around the gate positions $x_1$ and $x_2$, respectively. The time-dependent wave function can be written as

$$\Psi(x,t;\phi) = e^{-iE_{E}(x)} e^{i\sigma(x,t;\phi)},$$

where we denote the dependence on the phase difference $\phi$ between the gates explicitly. The action $\sigma(x,t;\phi)$ then satisfies the semiclassical equation

$$\frac{\partial}{\partial t} \sigma(x,t;\phi) = -\frac{k_{E}(x)}{m} \frac{\partial}{\partial x} \sigma(x,t;\phi)$$

$$- \left[ V_1(x) \cos(\omega t) + V_2(x) \cos(\omega t + \phi) \right],$$

in which the matrix elements $V_1, V_2(x)$ act as a source term. The local momentum $k_{E}(x) = \sqrt{2m} E - U(x)$, associated with the transport channel, depends on the effective potential $U(x)$ which describes the lateral confinement of the electron. Equation (2) is readily integrated:

$$I = \frac{e}{\pi} \int dE \sum_{k} P_{lr}(k\omega) \left[ f_1(E + k\omega) - f_1(E) \right],$$

with

$$I(S) = \frac{1}{2} S J_{\delta}(S) + J_{\frac{1}{2}}(S) - \frac{1}{2} S J_{\frac{1}{2}}(S) J_{\frac{1}{2}}(S).$$

The magnitude is one electron per absorbed modulation quantum.

In Fig. 2 we plot the number of electrons transmitted per cycle as a function of the modulation amplitude $S_1$ at fixed $\omega$ and for various values of $\phi$ ranging from $\pi/10$ to $\pi/2$. As can be estimated from the asymptotic behavior of $I(S)$, it starts linearly from the origin and saturates for large values of $S_1$ at a value $(4/\pi) S_2 \sin(\omega,\tau_{trav}) \times \sin(\phi)$, which can be of the order one electron per cycle. The maximum saturation is obtained for $\phi = \pi/2$. The frequency dependence is given in Fig. 3, for $\phi$ decreasing from $\pi/2$ to $\pi/10$. The ratio $S_1/S_2$ is 1 for the solid curves and 0.1 for the dashed line. The latter represents the asymptotic behavior discussed above. At saturation the frequency dependence can serve as a means to determine the traversal time $\tau_{trav}$ and hence the semiclassical velocity of the electron in the narrow channel.

We emphasize again the fact that, since the probabili-
FIG. 2. The number of electrons transmitted per cycle through the device as a function of the modulation amplitude \( S_1 \) for various \( \phi \). \( S_2 \) is kept fixed at 10, \( \omega \tau_{\text{trans}} = \pi / 2 \). The curves correspond (from top to bottom) with \( \phi = \pi / 2, 2\pi / 5, 3\pi / 10, \pi / 5 \), and \( \pi / 10 \).

FIG. 3. The number of electrons transmitted per cycle through the device as a function of the modulation frequency \( \omega \tau_{\text{trans}} \) for various \( \phi \). The ratio \( S_1 / S_2 \) is kept fixed at 1, except for the dashed line where it is taken \( 1 / 10 \). This line oscillates as \( \sin(\omega \tau_{\text{trans}}) \). The curves correspond (from bottom to top) with \( \phi = \pi / 2, 3\pi / 10 \), and \( \pi / 10 \) and have been given an offset for clarity.


14R. Landauer (private communication).