PHYSICAL REVIEW B VOLUME 44, NUMBER 16 15 OCTOBER 1991-II

Rapid Communications

Rapid Communications are intended for the accelerated publication of important new results and are therefore given priority treatment both in the editorial office and in production. A Rapid Communication in **Physical Review B** *should be no longer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Pauli pump for electrons

Frank Hekking
Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands

Yu. V. Nazarov
Division of Microelectronics, Nuclear Physics Institute, Moscow State University, Moscow 119 899 GSP, U.S.S.R.
(Received 21 June 1991)

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 constriction[2] at multiples of e^2/h.

On the other hand, Coulomb effects have been observed[3] 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 ω. 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 ($\omega < \Delta E_{sub}$, where ΔE_{sub} is the subband splitting), the

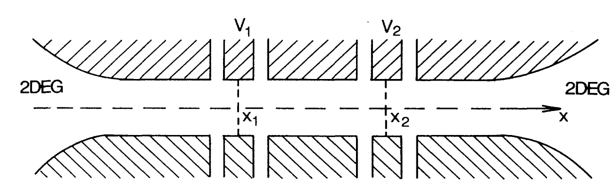

FIG. 1. 2DEG confined to a narrow channel with a double-barrier system. The barriers, situated at x_1 and x_2, can be modulated independently with amplitude V_1 and V_2.

transport remains adiabatic even in the presence of the modulation.[10] 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 ϕ 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_{lr} for an inelastic process differs from the corresponding probability P_{rl} 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 μ 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,[11] 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[12] a 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 $V_i(x)\cos(\omega t)$.[13] 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

$$\Psi(x,t;\phi)=e^{-iEt}\Psi_E(x)e^{i\sigma(x,t;\phi)}\,, \tag{1}$$

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

$$\frac{\partial}{\partial t}\sigma(x,t;\phi)=-\frac{k_E(x)}{m}\frac{\partial}{\partial x}\sigma(x,t;\phi)-[V_1(x)\cos(\omega t)+V_2(x)\cos(\omega t+\phi)]\,, \tag{2}$$

in which the matrix elements $V_{1,2}(x)$ 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:

$$\sigma(x,t;\phi)=-\frac{m}{2}e^{i\omega t-i\omega\tau(x)}\int_{-\infty}^{x}dx'\frac{e^{i\omega\tau(x')}}{k_E(x')}[V_1(x')+V_2(x')e^{i\phi}]+(\omega\to-\omega;\phi\to-\phi)\,. \tag{3}$$

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 (1) at $x=\infty$. The probability $P_{lr}(\pm k\omega)$ for an electron to absorb or emit k modulation quanta during transmission through the device from left to right reads

$$P_{lr}(\pm k\omega)=J_k^2[S(\omega\tau_{\rm trav},+\phi)]\,,$$
$$S=[S_1^2+S_2^2+2S_1S_2\cos(\omega\tau_{\rm trav}+\phi)]^{1/2}\,, \tag{4}$$

where $J_k(S)$ is a Bessel function. We defined the action $S_i=m\int_{-\infty}^{\infty}dx\,V_i(x)/k_E(x)$ and the traversal time $\tau_{\rm trav}$ needed to travel between the gates. Since time-reversal symmetry is broken by the phase difference ϕ, 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 $P_{rl}(\pm k\omega)=J_k^2[S(\omega\tau_{\rm trav},-\phi)]$. This leads to an asymmetry for the inelastic probabilities:

$$P_{rl}(k\omega)\neq P_{lr}(-k\omega)\,. \tag{5}$$

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},

$$I_{lr}=\frac{e}{\pi}\int dE\sum_k P_{lr}(k\omega)f_l(E)[1-f_r(E+k\omega)] \tag{6}$$

and the corresponding current I_{rl} from right to left.[13] The left and right reservoir are characterized by the Fermi distributions f_l and f_r respectively. At zero temperature and zero-bias voltage inelastic emission processes (negative k) are suppressed: all states below the Fermi level in both reservoirs are occupied. Inelastic absorption (positive k), however, is allowed, and since $P_{rl}\neq P_{lr}$ we find a net current flowing between both reservoirs:

$$I=\frac{e}{\pi}\omega\{I[S(\omega\tau_{\rm trav},+\phi)]-I[S(\omega\tau_{\rm trav},-\phi)]\}\,, \tag{7}$$

with

$$I(S)=\tfrac{1}{2}S^2[J_0^2(S)+J_1^2(S)]-\tfrac{1}{2}SJ_0(S)J_1(S)\,.$$

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 $\omega\tau_{\rm trav}=\pi/2$ and for various values of ϕ ranging from $\pi/10$ to $\pi/2$. As can be estimated from the asymptotic behavior of (7), it starts linearly from the origin and saturates for large values of S_1 at a value $(4/\pi)S_2\sin(\omega\tau_{\rm trav})\times\sin(\phi)$, 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 ϕ 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 $\tau_{\rm trav}$ and hence the semiclassical velocity of the electron in the narrow channel.

We emphasize again the fact that, since the probabili-

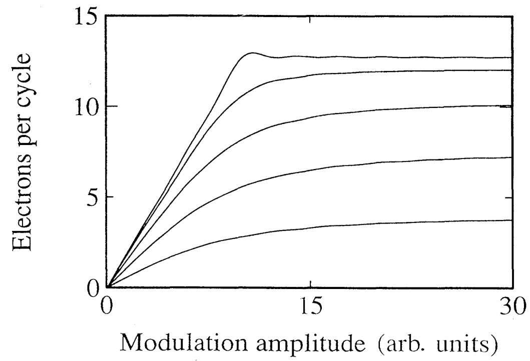

FIG. 2. The number of electrons transmitted per cycle through the device as a function of the modulation amplitude S_1 for various ϕ. S_2 is kept fixed at 10, $\omega\tau_{trav}=\pi/2$. The curves correspond (from top to bottom) with $\phi=\pi/2$, $2\pi/5$, $3\pi/10$, $\pi/5$, and $\pi/10$.

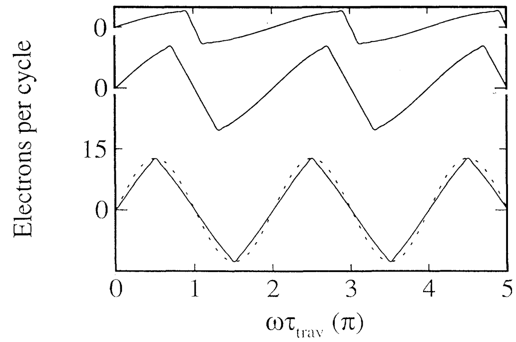

FIG. 3. The number of electrons transmitted per cycle through the device as a function of the modulation frequency $\omega\tau_{trav}$ for various ϕ. The ratio S_1/S_2 is kept fixed at 1, except for the dashed line where it is taken $\frac{1}{10}$. This line oscillates as $\sin(\omega\tau_{trav})$. The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

ties for inelastic absorption and emission are equal, we need to be able to distinguish between these processes in order to get a net current. This possibility is offered by introducing reservoirs, which determine the allowed inelastic processes by selecting *incoming* electrons according to their energy as indicated by (6). There is some controversy concerning this point.[14] In the formalism of Büttiker *et al.*[15] an electron reservoir, kept at chemical potential μ, has the property that, at zero temperature, it feeds the lead connected to it with carriers up to energy μ, while every carrier coming from the lead is absorbed irrespective of the phase *and energy* of the incident carrier.[11] This notion of a reservoir clearly differs from (6), which we take as an expression for the current in the presence of inelastic events. In our opinion, defining a reservoir corresponds to imposing a boundary condition on the incoming and outgoing states, which can be done in several ways. In the formalism of Büttiker *et al.*, the carriers leave the system through infinitely long leads as free particles. Equation (6) describes outgoing electrons that enter a region characterized by a Fermi distribution. So far, the boundary conditions in the presence of real inelastic processes have not been tested. The pump would provide an experimental test for the validity of the definition (6) of an electron reservoir in a two-terminal measurement in case of inelastic events. In the absence of inelastic processes our definition of an electron reservoir should be replaced again by the one in the formalism of Büttiker *et al.*, as was discussed by Sturman.[16] He showed that terms nonlinear in $f(E)$ cancel if elastic scattering in the absence of detailed balance is treated in all orders in the Born approximation. If this would not be the case, Boltzmann's H theorem would be violated for these systems.

In conclusion we propose a simple device that can work as an electron pump. It is based on time-reversal symmetry breaking, provided by a phase-shifted modulation of two independent gates. Reservoirs are introduced which favor inelastic absorption over emission at low temperatures due to the Pauli principle for the charge carriers. As a result a net current can be produced with a magnitude which is one electron per absorbed modulation quantum and which has a tuneable value of the order of a few electrons per cycle. Since the inelastic processes occur in a controllable way, an experimental realization of such a pump would enable one to check assumptions concerning the reservoirs. Furthermore, it would offer the possibility to measure the velocity of the transport electrons in the device.

Note added in proof. After the manuscript was accepted, R. Landauer kindly pointed out that applications of the kind discussed in the text were anticipated in Ref. 17.

We would like to thank M. Büttiker, L. Kouwenhoven, A. van Otterlo, G. Schön, and B. van Wees for valuable discussions. One of us (Yu.N.) acknowledges the hospitality of Delft University of Technology. This research was financially supported by the Stichting FOM.

[1] See, for a recent review, C. W. J. Beenakker and H. van Houten, Solid State Phys. **44**, 1 (1991).

[2] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988); D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peanock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).

[3] U. Meirav, M. A. Kastner, and S. J. Wind, Phys. Rev. Lett. **65**, 771 (1990).

[4] See, for a recent review, D. V. Averin and K. K. Likharev, in *Mesoscopic Phenomena in Solids,* edited by B. L. Altshuler, P. A. Lee, and R. A. Webb (Elsevier, New York, in press), Vol. 30, Chap. 6.

[5]L. J. Geerligs, V. F. Anderegg, P. A. M. Holweg, J. E. Mooij, H. Pothier, D. Esteve, C. Urbina, and M. H. Devoret, Phys. Rev. Lett. **64**, 2691 (1990).

[6]H. Pothier, P. Lafarge, P. F. Orfila, C. Urbina, D. Esteve, and M. H. Devoret (unpublished).

[7]A. A. Odintsov, Appl. Phys. Lett. **58**, 2695 (1991); L. P. Kouwenhoven (unpublished).

[8]L. P. Kouwenhoven, A. T. Johnson, N. C. van der Vaart, C. J. P. M. Harmans, and C. T. Foxon, Phys. Rev. Lett. **67**, 1626 (1991).

[9]Q. Niu, Phys. Rev. Lett. **64**, 1812 (1990); B. J. van Wees, Phys. Rev. Lett. **66**, 2033 (1991); and (unpublished).

[10]F. Hekking and Yu. V. Nazarov (unpublished).

[11]M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).

[12]L. I. Glazman, G. B. Lesovik, D. E. Khmel'nitskii, and R. I. Shekter, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 218 (1988) [JETP Lett. **48**, 238 (1988)].

[13]F. Hekking, Yu. V. Nazarov, and G. Schön, Europhys. Lett. **14**, 489 (1991).

[14]R. Landauer (private communication).

[15]M. Büttiker, Y. Imry, R. Landauer, and S. Pinhas, Phys. Rev. B **31**, 6207 (1985).

[16]B. I. Sturman, Usp. Fiz. Nauk **144**, 497 (1984) [Sov. Phys. Usp. **27**, 881 (1984)].

[17]R. Landauer, in *Analogies in Optics and Micro Electronics,* edited by W. van Haeringen and D. Lenstra (Kluwer Academic, The Netherlands, 1990).