EUROPHYSICS LETTERS 14 January 1992

Europhys. Lett., 17 (3), pp. 249-254 (1992) *published in December 1991*

Single-Electron Pump Based on Charging Effects.

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(received 5 August 1991; accepted in final form 7 October 1991)

PACS. 73.40G – Tunnelling: general.
PACS. 06.20H – Measurement standards and calibration.
PACS. 73.40R – Metal-insulator-metal structures.

Abstract. – We have designed and operated a device consisting of three nanoscale tunnel junctions biased below the Coulomb gap. Phase shifted r.f. voltages of frequency f applied to two gates «pump» one electron per cycle through the device. This is shown experimentally by plateaus in the current-voltage characteristic at $I = \pm ef$, the sign of the current depending on the relative phase of the r.f. voltages and not on the sign of the bias voltage.

Although electric charge is quantized in units of e, the current in usual electronic circuits behaves as the flow of a continuous fluid. Discrete charge carriers do not manifest themselves directly at this macroscopic level because the total charge that has passed through a given section of the circuit at one instant of time fluctuates by many charge quanta, both thermally and quantum-mechanically. In nanoscale tunnel junction arrays, however, recent theoretical and experimental investigations of charging effects [1] have led to experiments showing that electron transfers can be time-correlated [2] or even controlled one by one [3]. The latter work is based on a «turnstile» device consisting of a linear array of normal tunnel junctions in which the charge on the middle electrode is changed by a gate voltage applied through a capacitor. When the gate voltage alternates between properly chosen values, electrons are transferred through the array one per cycle, in the direction imposed by the bias voltage. The turnstile principle is a first step towards the achievement of a current standard based on charge transfer controlled at the single-electron level.

In this letter, we present a new type of single-charge controlling device which, in contrast with the turnstile, operates reversibly. The direction of electron transfer is not determined by the sign of the bias voltage but by the phase relationship between two gate voltages, which provide the energy required for the transfer. We have called this device an electron «pump» because it is the electron fluid analog of the peristaltic pump. The ability to reverse the current delivered by the pump is an important feature in the design of metrological experiments.

A common basis to the turnstile and the pump principles is the blockade [1] of electron tunnelling in multi-junction circuits first demonstrated experimentally with two planar tunnel junctions by Fulton and Dolan [4]. Consider a general linear array built, like our device shown in fig. 1*a*), with N normal tunnel junctions of capacitance $C^{(j)}$ and with true capacitors C_i connected to the metallic «islands» between junctions. A bias voltage source is connected to the end junctions and gate voltage sources are connected to the capacitors. The state of the circuit at a given instant of time is entirely determined by its electronic «configuration» which is given by the set $(n_1, n_2, \ldots, n_{N-1})$ of the numbers of extra electrons on the islands between junctions and by the sum n_0 of the numbers of electrons which have passed through the two end junctions. We call two electronic configurations «neighbours» if they can be transformed one into the other by a single tunnel event on one junction. For fixed-bias and gate voltages, each configuration is characterized by an energy which is the sum of the electrostatic energy of the charges stored on the capacitances and of the work performed by the voltage sources to reach that configuration. When the bias voltage is zero, the typical energy difference ΔE of two neighbouring configurations is of the order of $e^2/2C$, C being the largest of capacitances $C^{(j)}$ and C_i. Thus, at temperatures T satisfying $k_B T \ll e^2/2C$, the circuit will adopt a configuration such that all neighbouring configurations have a higher energy. The configurations having this property are called «stable». The stability of a configuration depends on the gate voltages. When the bias voltage is increased without exceeding a threshold voltage—the Coulomb gap—of order $e/2C$, the circuit will remain trapped in the initial stable configuration and tunnelling will be blocked. No current will flow through the array, even though a finite voltage is applied to it. This analysis neglects of course transitions between nonneighbouring configurations occurring by coherent multiple tunnelling events (co-tunnelling) [5] which are «forbidden» in a theoretical treatment of tunnelling by second-order perturbation theory.

When the gate voltages are changed while keeping the bias voltage well under the Coulomb gap, the stability property may go to different configurations. In that case the circuit will adopt a new stable configuration by undergoing a sequence of tunnel events. The rate of tunnel events across a given junction, *i.e.* the transition rate between neighbouring configurations, is $\Gamma = (\Delta E/e^2 R_T)[1 - \exp[-\Delta E/k_B T]]^{-1}$, where R_T is the tunnel resistance of the junction and where ΔE is the difference in energy of the configurations before and after the event [1]. The energy drop ΔE is converted by the tunnelling process into electron kinetic energy. It is easy to show that as the gate voltages are changed slowly, a quasi-reversible charge transfer will occur if and only if the array is such that stability goes from the initial configuration to one of its neighbours, *i.e.* if the new stable configuration can be reached by *only one tunnel event*. In contrast with the turnstile, the pump was designed so that this criterion is true whatever trajectory is followed in gate voltage space. An electron can thus be transferred reversibly around the circuit with a properly chosen sequence of such slow gate voltage changes.

The pump is a particular case of the general array considered above: it consists of three junctions with capacitances C, C' and C'', and two gates whose capacitances C_1 and C_2 are much smaller than the junction capacitances (see fig. 1*a*)). The bias voltage and the two voltages applied to the gate capacitors are denoted by V, U_1 and U_2. The configuration of the circuit is given by the island integer charges (n_1, n_2) and by n_0. Figure 1*b*) shows, for $V = 0$ and $C = C' = C''$, which configuration is stable for a given value of U_1 and U_2. We have represented this information by drawing, for each island charge configuration (n_1, n_2), the domain in the $C_1 U_1 \otimes C_2 U_2$ plane (gate voltage space) inside which the configuration is stable. These domains are elongated hexagons and they tile the plane to form a lattice with quadratic symmetry, the periods being e along both axes. Neighbouring domains in gate voltage space thus correspond to neighbours in configuration space. Three mutually neighbouring domains share a triple point: for example, point P of fig. 1*b*) is shared by domains (0, 0), (1, 0) and (0, 1). The pumping of electrons is based on this topological property, which does not depend on the precise values of the capacitances. Note that there are two triple points per unit cell of the lattice (see points P and N in fig. 1*b*)). Every «P type» triple point is linked to three «N type» triple points and *viceversa*. At finite bias voltage V, the honeycomb pattern of fig. 1*b*) is distorted: the triple points are replaced by triangle-shaped regions inside which no stable configurations exist and where conduction thus takes place. The size of these regions increases linearly with the bias voltage.

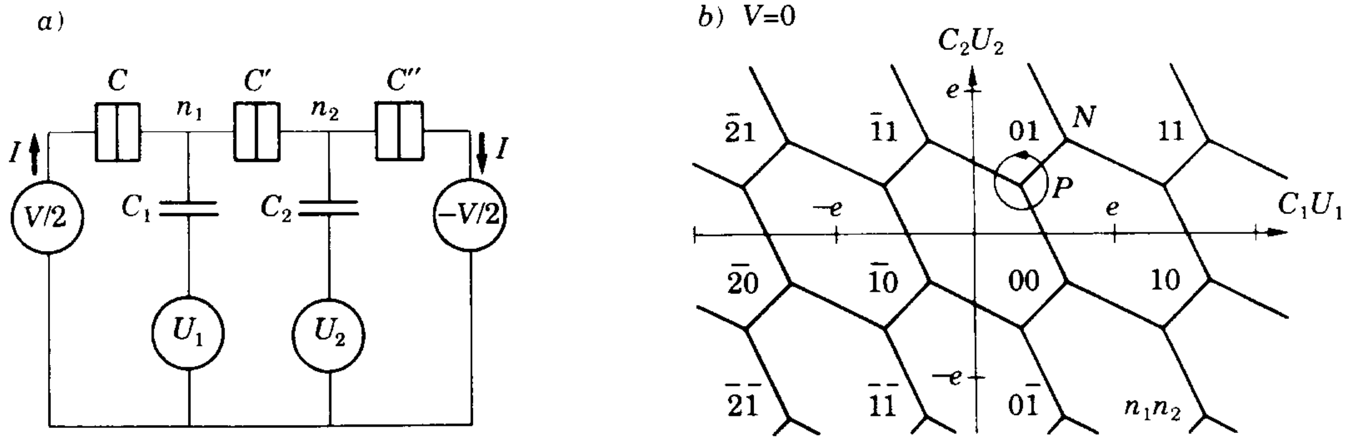

Fig. 1. – Principle of reversible transfer of a single electron using a «pump» controlled by two gate voltages U_1 and U_2. *a)* Circuit schematic: the nanoscale junctions constituting the pump are represented by double-box symbols. *b)* Stable configuration diagram for $V = 0$ and $C = C' = C''$. One turn around a triple point such as P or N, obtained by modulating the gate voltages by two phase-shifted signals, induces one electron to go around the circuit.

The pump is operated by first applying d.c. voltages to the gates so as to place the circuit in the vicinity of a triple point, the bias voltage being much lower than the Coulomb gap voltage, which is given by $e/3C$ when $C = C' = C''$ ([1]). Two periodic signals with the same frequency f but dephased by $\Phi \sim \pi/2$ are then superimposed on the gate voltages. The circuit then follows a closed trajectory like the circle shown around point P in fig. 1*b*). If the frequency f is low enough $(f \ll (RC)^{-1})$, the system remains in the stable configuration associated with its location in gate voltage space. This configuration changes along the trajectory when domain boundaries are crossed. Suppose that the initial island configuration is (0, 0) and that the trajectory is followed counterclockwise. The circuit goes first from (0, 0) to (1, 0) by letting one electron tunnel through the leftmost junction. Then the island configuration changes to (0, 1) when one electron goes through the central junction. Finally, the system returns to its initial island configuration (0, 0) by letting one electron out through the rightmost junction. In a complete cycle one electron is transferred from the left end to the right end of the device. If the sense of rotation in gate voltage space is reversed, in practice by adding π to the phase shift Φ, the electron transfer will take place in the opposite direction. Note that the same original positive rotation around a «N type» triple point also produces a transfer in the opposite direction. In summary, these geometrical considerations show that for zero bias voltage V, two r.f. gate voltages induce a current $I = ef$ around the circuit, provided that the d.c. gate voltages are set in the vicinity of a triple point. The direction of current is determined solely by the phase shift Φ and the type of the triple point.

As the voltage V is increased, electrons can still be pumped, even if V and I have opposite signs, provided that the trajectory followed in gate voltage space encloses the conduction regions. Numerical simulations have shown that regular electron transfers can persist up to one-fifth of the Coulomb gap voltage for an optimal r.f. amplitude. Co-tunnelling events [5], which provide the mechanism for transitions between nonneighbour configurations, are expected to slightly degrade the regularity of the pump. If the electrodes of the pump were in an ideal superconducting state with all electrons paired (no quasi-particle present), the same type of gate voltage modulation around a triple point of the pair configuration stability

([1]) The critical charge (see ref. [3]) of each junction of the pump is found to be $e/3$ when $C = C' = C''$.

diagram should in principle lead to a current $I = 2ef$, *i.e.* the pumping of Cooper pairs instead of electrons. By contrast, the principle of the turnstile cannot be directly generalized to Cooper pairs, since it involves dissipative tunnel events. Finally, let us mention for completeness that a pump for normal electrons based on a heterojunction structure and operating on a totally different principle has been considered by Niu [6].

We have fabricated devices implementing the schematic of fig. 1*a*) using e-beam nanolithography and shadow evaporation as in ref. [7]. Preliminary results have been presented elsewhere [8]. We report here measurements on a device with an improved gate capacitor design. The two islands between the three $(100 \times 100)\,\mathrm{nm}^2$ $Al\text{-}Al_2O_3\text{-}Al$ tunnel junctions are 1500 nm long. We have carefully designed the two interdigitated gate capacitors, which are placed on opposite sides of the axis running through the junctions, in order to minimize the stray capacitance C_x between island 1 (2) and gate 2 (1). Fabrication details can be found in ref. [9]. The total normal resistance of the device was 380 kΩ. It was cooled down to 20 mK with a dilution refrigerator, and current measurements were performed as in ref. [3]. The aluminium electrodes were kept in their normal state with a 0.5 T magnetic field. The average junction capacitance was estimated from the Coulomb gap to be about 0.4 fF. In fig. 2 we show the results of an experiment in which the current through the array was recorded as the d.c. gate voltages $U_1^{\text{d.c.}}$ and $U_2^{\text{d.c.}}$ were scanned. The bias voltage V was set to zero, and two 0.3 mV amplitude r.f. signals in quadrature with frequency $f = 4$ MHz were superimposed on the d.c. gate voltages. Only in some regions of the $U_1^{\text{d.c.}} \otimes U_2^{\text{d.c.}}$ plane did the current exceed the noise. In the top panel of fig. 2 we show the result of a scan of $U_1^{\text{d.c.}}$, $U_2^{\text{d.c.}}$ being kept constant. This panel represents a cut through the current surface which is presented in the bottom panel, the position of the cut being indicated by a dotted line. For clarity, we have represented the «hills» and «basins» in the current by using the following convention: a black dot means a positive current between $+0.8ef$ and $+1.05ef$ (upper pair of dashed lines in top panel), a white dot means a negative

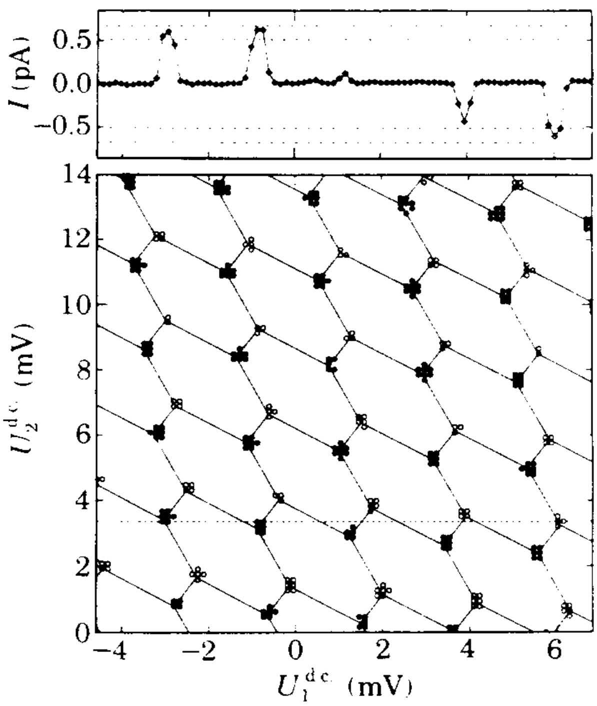

Fig. 2. – Current, at zero bias voltage, through the device as a function of the d.c. gate voltages, for r.f. signals with amplitude 0.3 mV and frequency 4 MHz. In the bottom panel, black (white) dots denote a current between the upper (lower) pair of dashed lines in the top panel. Full lines: calculated ground-state diagram that best fits the experimental data.

current between $-0.8ef$ and $-1.05ef$ (lower pair of dashed lines) and the absence of dots means a current between $-0.8ef$ and $+0.8ef$. Apart from a slight global deformation and an overall translation, the pattern of hills and basins reproduces the honeycomb pattern of fig. 1*b*), a hill (basin) corresponding to a *P*-type (*N*-type) triple point. We attribute the slight deformation of this experimental honeycomb pattern to the stray capacitance C_x, which is the only capacitance not included in the schematic of fig. 1. We have calculated the stability diagram for arbitrary C_1, C_2, C_x, $(C+C'')/C'$ and $(C-C'')/C'$. The best fit to the data is shown in the bottom panel of fig. 2 and corresponds to $C_1 = 74 \pm 2a$ F, $C_2 = 61 \pm 2a$ F, $C_x = 7 \pm 1a$ F, $(C+C'')/C' = 2.1 \pm 0.5$ and $(C-C'')/C' = -0.3 \pm 0.06$. In the fitting, we have allowed an overall translation of the diagram corresponding to arbitrary offset charges [7] on the gate capacitors. Although these offset charges were found to be constant on the time scale of a few hours, abrupt shifts of the pattern on longer time intervals were often observed. The capacitances that we obtain from the fit agree with the values estimated from the geometry of the nanolithographic mask. Figure 3 shows the bias voltage dependence of the current at a «*P* type» triple point with $f = 4$ MHz and for two phase shifts separated by π; a plateau is observed near the centre of the *I*-*V* curve. The sign of the height of the plateau reverses abruptly as the phase shift between the r.f. voltages is varied continuously from $+\pi/2$ to $-\pi/2$. The dashed line marks the current $I = \pm ef$. We also show for comparison the *I*-*V* curve with no r.f. signals. The pronounced conductivity at $V = 0$ is due to the suppression of the Coulomb gap at the triple point.

In order to quantitatively compare experiment and theory we show in fig. 3 the result of a finite-temperature numerical simulation which takes into account co-tunnelling through two junctions (full line). To fit the experimental results the capacitance values were allowed to vary inside the error bars of the measurement described above. The phase shift was the only true free parameter since it had only been determined by r.f. measurements at room temperature. The extent of the plateau on either side of the inflexion point is well explained by the double-tunnel events. At the precision level of the simulation, which was 10^{-3}, the tangent to the calculated curve at the inflexion point is the line $I = ef$. We attribute the deviation between experiment and theory at larger voltages mostly to higher-order co-

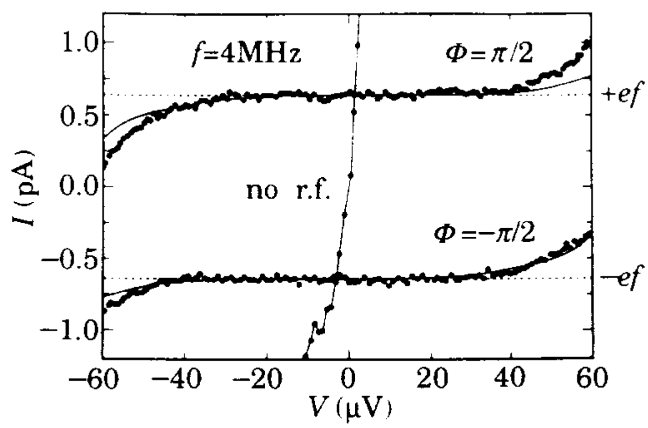

Fig. 3.

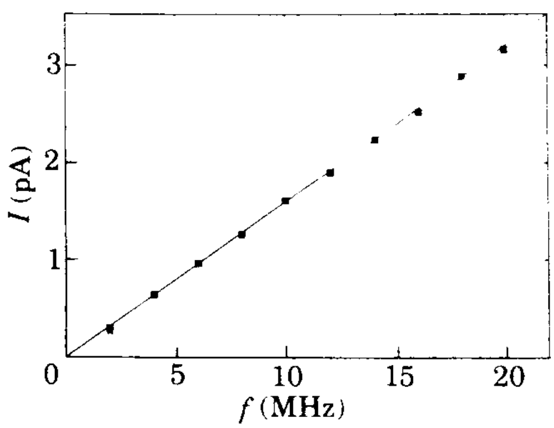

Fig. 4.

Fig. 3. – Current-voltage characteristics with and without a $f = 4$ MHz gate voltage modulation around a «*P*-type» triple point. The U_1 and U_2 r.f. amplitudes were 1 mV and 0.6 mV, respectively. Current plateaus are seen at $I = \pm ef$ (marked with dashed lines), the sign depending on the phase shift Φ between the two r.f. signals. Results of numerical simulations including co-tunnelling events are shown in full lines.

Fig. 4. – Current at the inflexion point of the plateaus of fig. 3 *vs.* r.f. frequency. Full line: theoretical prediction $I = ef$.

tunnelling processes not taken into account by the simulation, although it is possible that hot electron effects [10] could also play a role. We have measured the current at the inflexion point for various frequencies between 2 and 20 MHz. As shown in fig. 4, we find that this current satisfies the expected relation $I = ef$ (full line) within the experimental uncertainty $\Delta I = 0.05$ pA. We have calculated that the co-tunnelling rate and hence, the pump error rate, could be considerably diminished with a pump having more than two stages. Every additional stage improves the transfer accuracy by a factor of roughly $e^2/\pi hCf$, but requires a supplementary r.f. gate voltage.

By reducing the magnetic field to zero, we have placed the pump into the superconducting state. In both current *vs.* d.c. gate voltages and current *vs.* bias voltage measurements, the results are *not* simply the normal-state results transformed according to $e \to 2e$ [11]. Although current plateaus have been observed at $2ef$, there are many unexplained features which we tentatively attribute to a small fraction of long-lived quasi-particles and to co-tunnelling events which, in the superconducting case, may play an important role. Further experiments are in progress to test these hypotheses.

In conclusion, we have fabricated a device producing a current whose magnitude and sign are determined, respectively, by the frequency and phase shift of two r.f. gate voltages. Charge transfer is controlled at the level of single electrons in the normal device and should in principle be controlled at the level of Cooper pairs in a superconducting device with no quasi-particles. The quantitative agreement between the experimental and predicted extent of the current plateaus in the normal case shows that accuracy-limiting tunnelling processes are being understood.

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This work was supported by the Commissariat à l'Energie Atomique (CEA). We thank V. Anderegg, L. J. Geerligs, H. Grabert, J. E. Mooij, S. M. Verbrugh and E. Williams for valuable discussions, P. F. Orfila for technical assistance and A. Cleland for his critical reading of the manuscript.

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