SOLID-STATE PHYSICS

Passing electrons one-by-one

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CURRENT in electrical devices is most often thought of as if it were the flow of a continuous, charged fluid. It is usually safe to ignore the actual discrete nature and charge ($-e$) of the individual electrons in this way because large numbers tend to be involved. Moreover, they screen each other, so that it is mostly just the average behaviour that is apparent. Recently, however, some small circuits cooled below 1 K have been devised in which current flow goes to the opposite extreme. In these 'single-electron' devices the electrons instead move one at a time in stepwise fashion, with the charge e playing a controlling role. One much sought result is to make this flow of electrons occur in lock-step with an applied radiofrequency signal, one electron per period, forming an ideal current source. A group from Chalmers and Moscow State Universities has already observed the onset of such behaviour[1], and now a team from Delft and Saclay has developed a circuit[2], called the single-electron turnstile, in which the synchronization is nearly complete, to about 1 part per 10^3. Provided that this can be extended to 1 part per 10^7 or so, such a device could become the standard of current, much as the Josephson effect is the modern standard of voltage.

Single-electron circuits employ tunnel junctions of the sort used in Josephson work. These thin-film structures consist of an ultra-thin (1–3 nm) insulating layer sandwiched between two metal electrodes. At random times electrons will pass from one electrode to the other by quantum-mechanical tunnelling through the insulator. If a bias voltage V is applied between the electrodes, these discrete, random events add up to a net current I through the junction, with a kinetic energy increment eV given to each tunnelling electron.

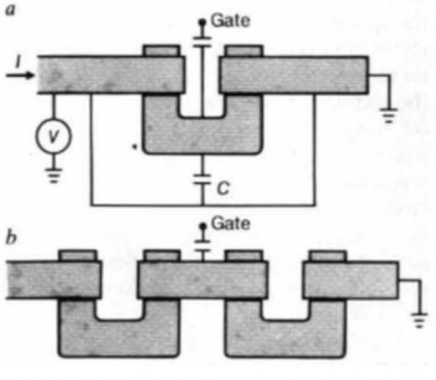

FIG. 1 *a*, Schematic of a one-electron device, comprising overlapping two Josephson junctions, metal electrodes separated by a thin layer of insulating material, with the central electrode connected to an external gate through a small capacitance (=). That electrode also has a small capacitance C. *b*, New turnstile device, an elaboration of the standard one-electron device. (⏚, Electrical earth.)

The essence of a single-electron device is that the current is required to pass, via tunnel junctions, through a region having low capacitance, C, to the rest of the circuit. One such configuration, of which the turnstile is an elaboration, has two closely adjacent junctions in series, with their common electrode forming the required region of low-capacitance (Fig. 1*a*). As current flows, tunnelling electrons come and go, and this region is repeatedly charged and discharged by an amount e. Each incoming electron must be able to supply an electrostatic energy of $e^2/2C$ to be allowed to enter. With junction dimensions at around 0.1 μm one can obtain $C<1$ fF (femtofarad) which makes $e^2/2C$ equivalent to thermal energies at around 1 K. At temperatures well below 1 K and with bias $V \ll e/C$ there is too little energy available to overcome this barrier and the tunnelling rate is greatly reduced. This effect, now known as the Coulomb blockade[3], was first observed many years ago in granular materials[4].

The blockade can be lifted by lowering the electrostatic potential of the low-capacitance region using capacitative coupling to a nearby gate electrode. In this case an otherwise blockaded electron borrows part of the energy needed to surmount the barrier from the gate voltage supply. This transistor-like control of the current by the gate was exploited by the Delft–Saclay group. Their turnstile device (Fig. 1*b*) had four adjacent aluminium junctions in series (total $R \sim 1$ MΩ) interconnecting three such similar low-capacitance regions ($C \approx 0.5$ fF), and was operated at about 0.03 K. With this design they achieved a sort of one-electron shift-register by applying a low static bias across the four junctions from left to right plus a radiofrequency (f) gate voltage V_G coupled to the central low-capacitance region. The electrostatic energies work out such that when the gate voltage is maximum, one electron (only) can transfer to the central region through the two left-most junctions, but not farther. As the gate voltage decreases, it becomes possible for an electron to leave the centre and escape to the right. The two conditions do not overlap, so only one electron is transferred in each cycle.

In practice all this seems to have worked well. The current–voltage characteristics with $V_G = 0$ show a Coulomb blockade region of much enhanced resistance (greater than 1 GΩ) at low bias, less than 0.2 mV. With a radiofrequency gate voltage running at a few megahertz, the I–V curve in this region develops a nice constant current step at $I = ef$, about 0.16 pA MHz^{-1}, with a shape closely matching simulations based on a semiclassical model (Fig. 2). The precision with which I/f could be measured for 4 MHz$<f<$30 MHz was limited by the difficulty in measuring the currents, a few picoamps, to within more than a few femtoamps. To give some idea of what more is needed before a standard of current can be achieved, the authors point out that for a precision of 10^8, the frequency should be less than $10^{-3}/RC$, so that sufficient time is allowed in each cycle to be confident that the random tunnelling events do take place. This probably means that the frequency should be less than 100 MHz.

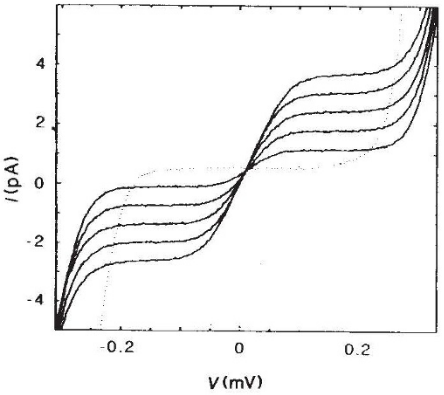

FIG. 2 Current–voltage characteristics of the new single-electron turnstile (from ref. 2). Dotted curve, no radiofrequency voltage applied. Solid curves, with applied radiofrequency voltage: current plateaus are seen at $I = ef$, where f is the applied frequency (4, 8, 12, 16 and 20 MHz) and e is the electron charge.

At the same time the number of electrons that leak through by some other path than through the turnstile mechanism must be less than $10^{-8}f$, or less than one per second. Within the semiclassical model, the only leakage is by thermally excited electrons passing over the Coulomb barrier. The authors calculate that a temperature of 15 mK would suffice to suppress these for the present device. As they note, however, it is uncertain whether a fuller quantum treatment will preserve this favourable prognosis. The Coulomb barrier itself has some spread in energy owing to its finite lifetime and the uncertainty principle, and this may cause an unavoidable leakage current. We shall have to wait and see. □

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