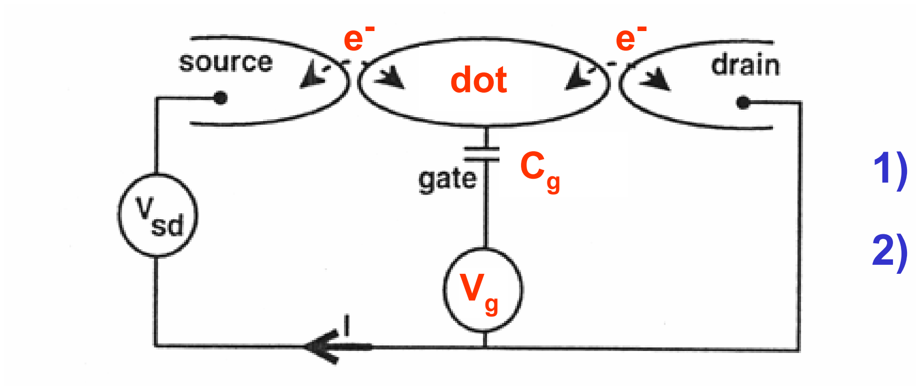
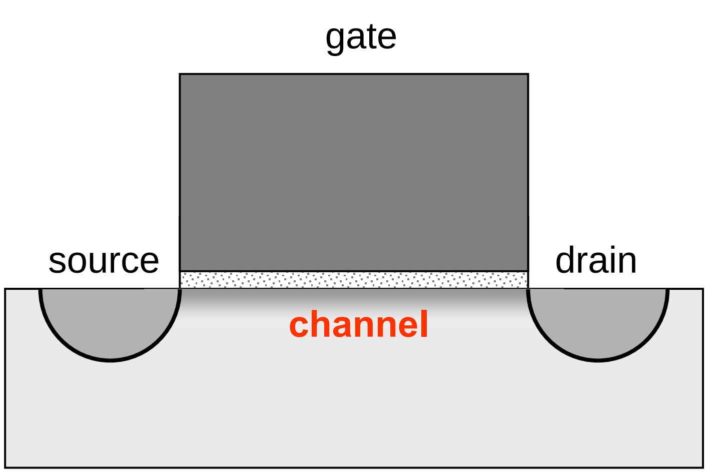
Single Electron Transistor (SET)





A single electron transistor is similar to a normal transistor (below), except

1) **the channel is replaced by a small dot.**

2) **the dot is separated from source and drain by thin insulators.**

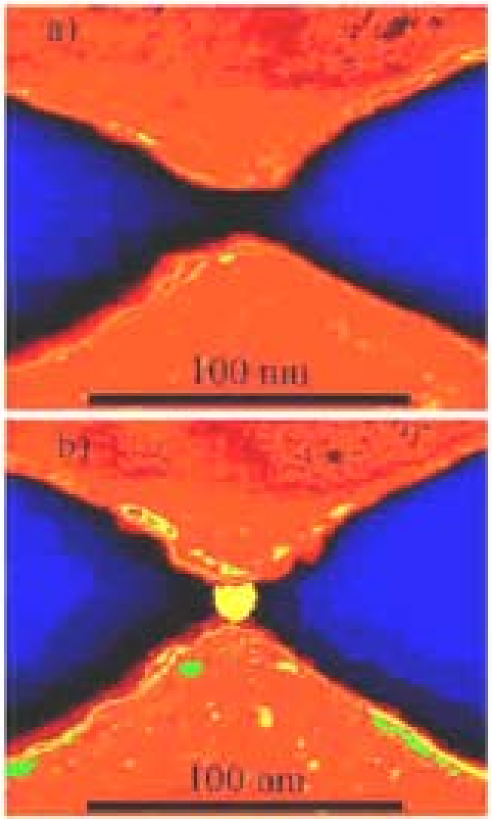
An electron tunnels in two steps:
source $\rightarrow$ dot $\rightarrow$ drain

The gate voltage V_g is used to control the charge on the gate-dot capacitor C_g .

How can the charge be controlled with the precision of a single electron?

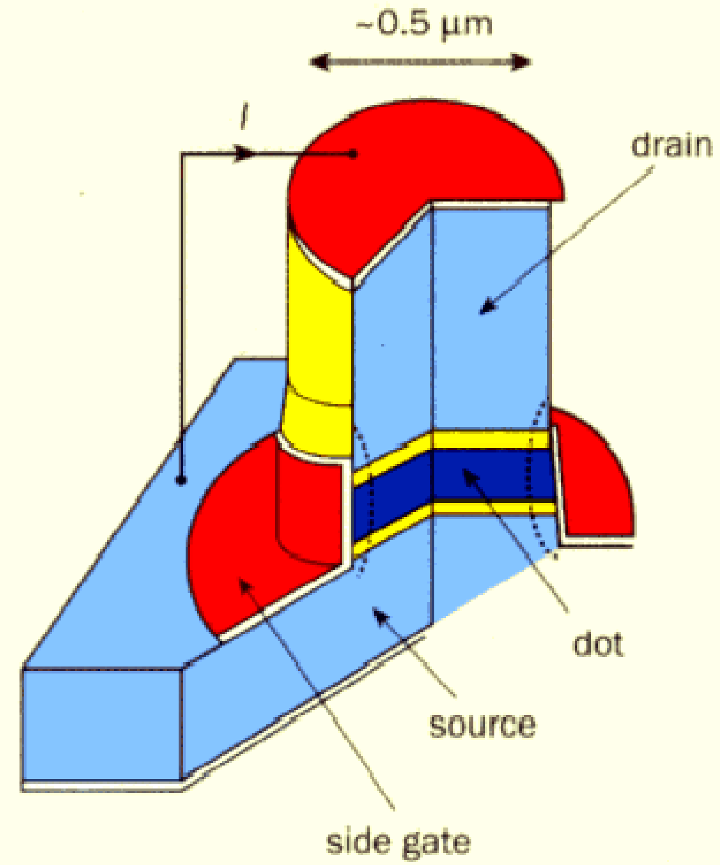
Kouwenhoven et al., *Few Electron Quantum Dots*, Rep. Prog. Phys. **64**, 701 (2001).

Designs for Single Electron Transistors



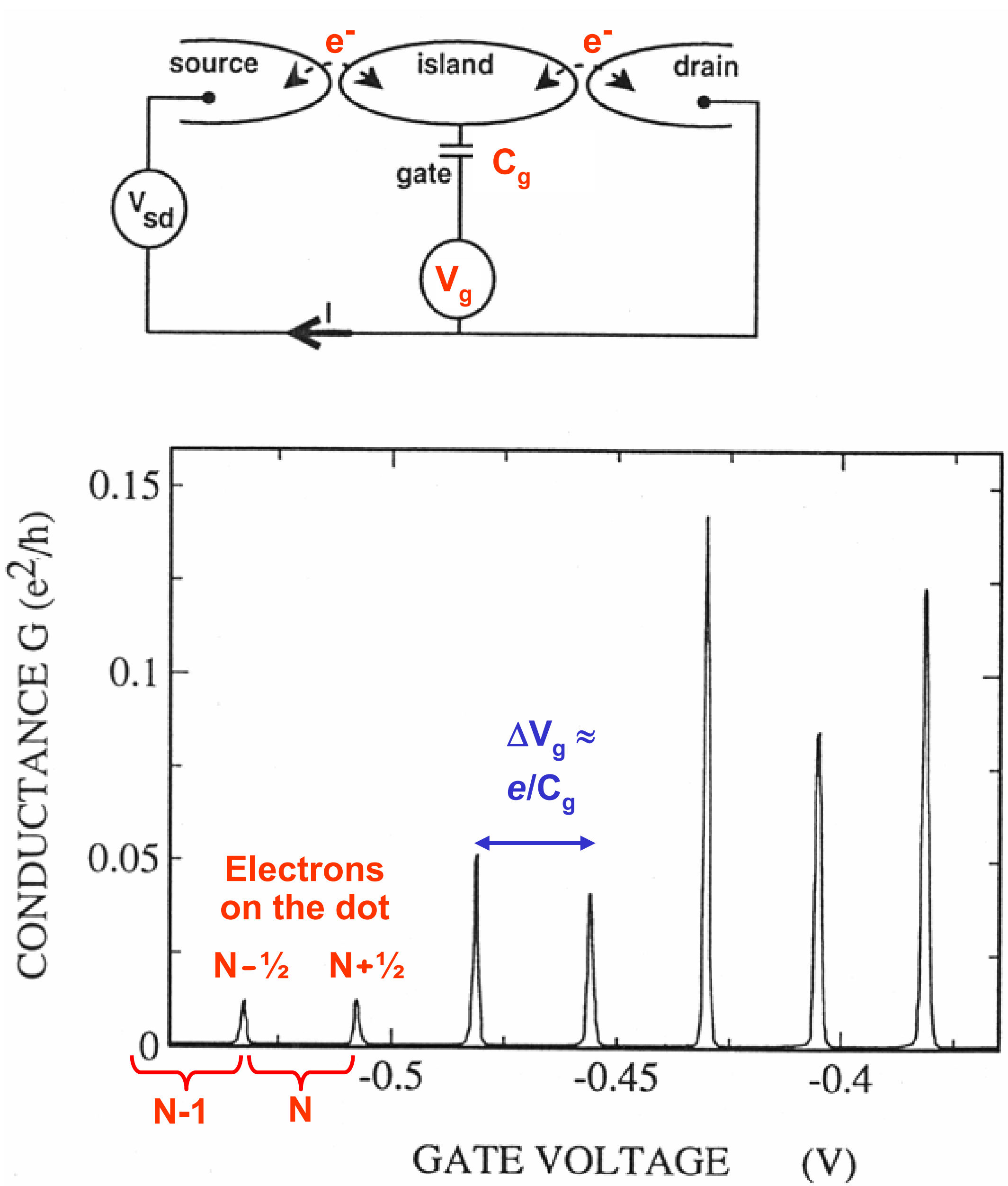
Nanoparticle attracted electrostatically to the gap between source and drain electrodes. The gate is underneath.

1 Vertical quantum dot structure



The quantum-dot structure studied at Delft and NTT in Japan is fabricated in the shape of a round pillar. The source and drain are doped semiconductor layers that conduct electricity, and are separated from the quantum dot by tunnel barriers 10 nm thick. When a negative voltage is applied to the metal side gate around the pillar, it reduces the diameter of the dot from about 500 nm to zero, causing electrons to leave the dot one at a time.

Charging a Dot, One Electron at a Time



Sweeping the gate voltage V_g changes the charge Q_g on the gate-dot capacitor C_g. To add one electron requires the voltage $\Delta V_g \approx e/C_g$ since $C_g = Q_g/V_g$.

The source-drain conductance G is zero for most gate voltages, because putting even one extra electron onto the dot would cost too much Coulomb energy. This is called Coulomb blockade.

Electrons can hop onto the dot only at a gate voltage where the number of electrons on the dot flip-flops between N and N+1. Their time-averaged number is N+½ in that case.

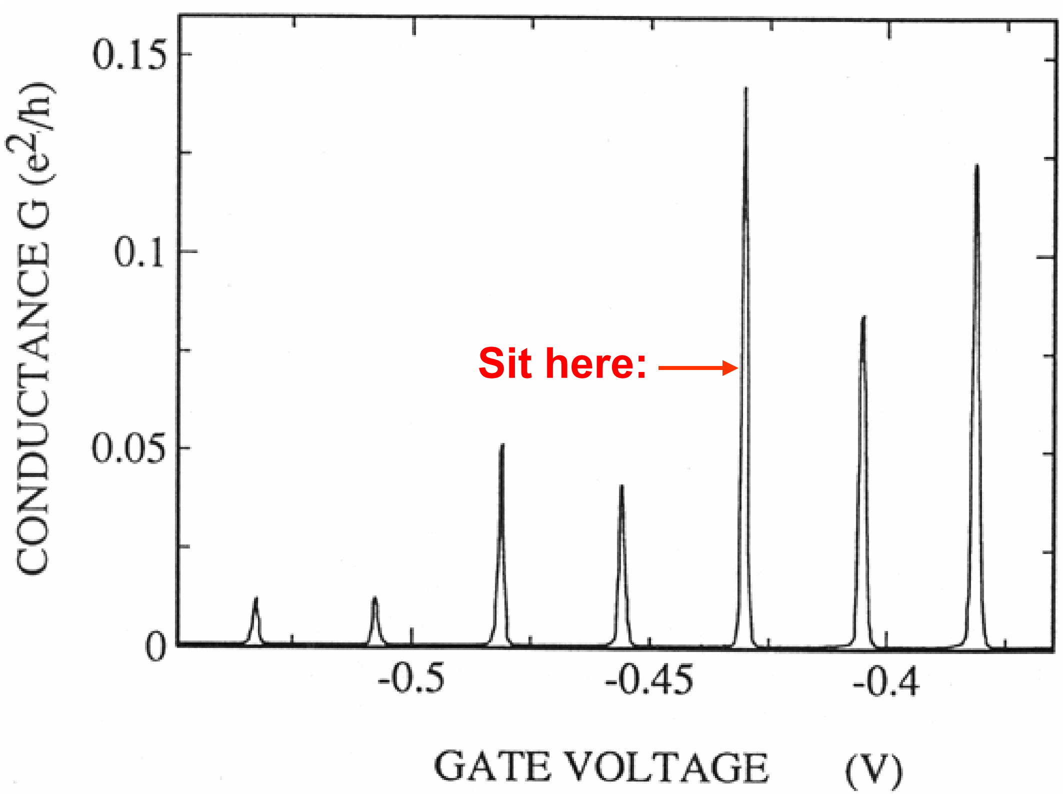
The spacing between these half-integer conductance peaks is an integer.

The SET as Extremely Sensitive Charge Detector

At low temperature, the conductance peaks in a SET become very sharp.

Consequently, a very small change in the gate voltage half-way up a peak produces a large current change, i.e. a large amplification. That makes the SET extremely sensitive to tiny charges.

The flip side of this sensitivity is that a SET detects every nearby electron. When it hops from one trap to another, the SET produces a noise peak.

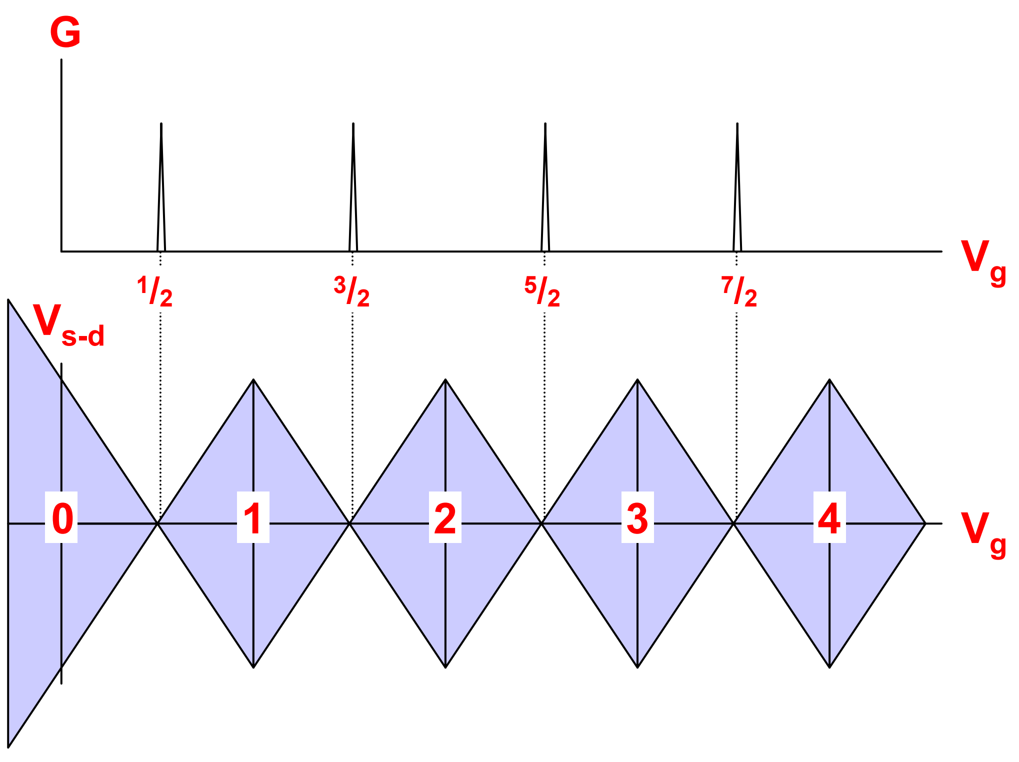


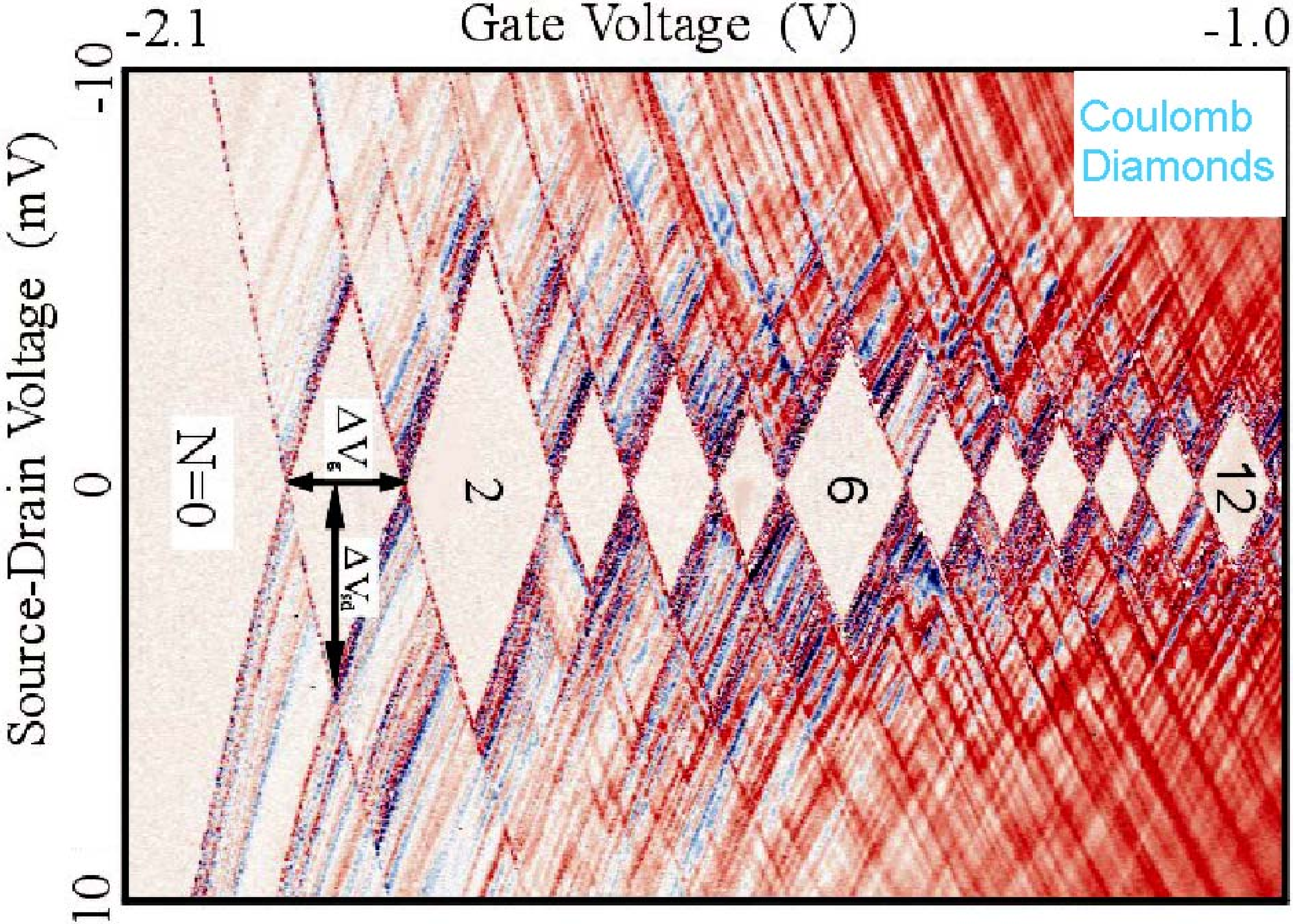
Gate Voltage versus Source-Drain Voltage

The situation gets a bit confusing, because there are two voltages that can be varied, the gate voltage V_g and the source-drain voltage $V_{s\text{-}d}$.

Both affect the conductance. Therefore, one often plots the conductance G against both voltages (see the next slide for data).

Schematically, one obtains "Coulomb diamonds", which are regions with a stable electron number N on the dot (and consequently zero conductance).





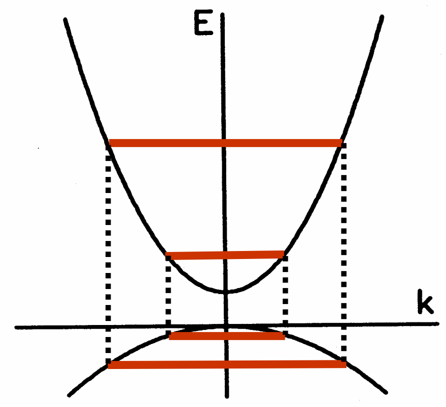
Gate Voltage (V)
-2.1
-1.0
Source-Drain Voltage (mV)
-10
0
10
Coulomb
Diamonds
N=0
2
6
12
ΔV_g
ΔV_{sd}

Including the Energy Levels of a Quantum Dot

Contrary to the Coulomb blockade model, the data show Coulomb diamonds with uneven size. Some electron numbers have particularly large diamonds, indicating that the corresponding electron number is particularly stable.

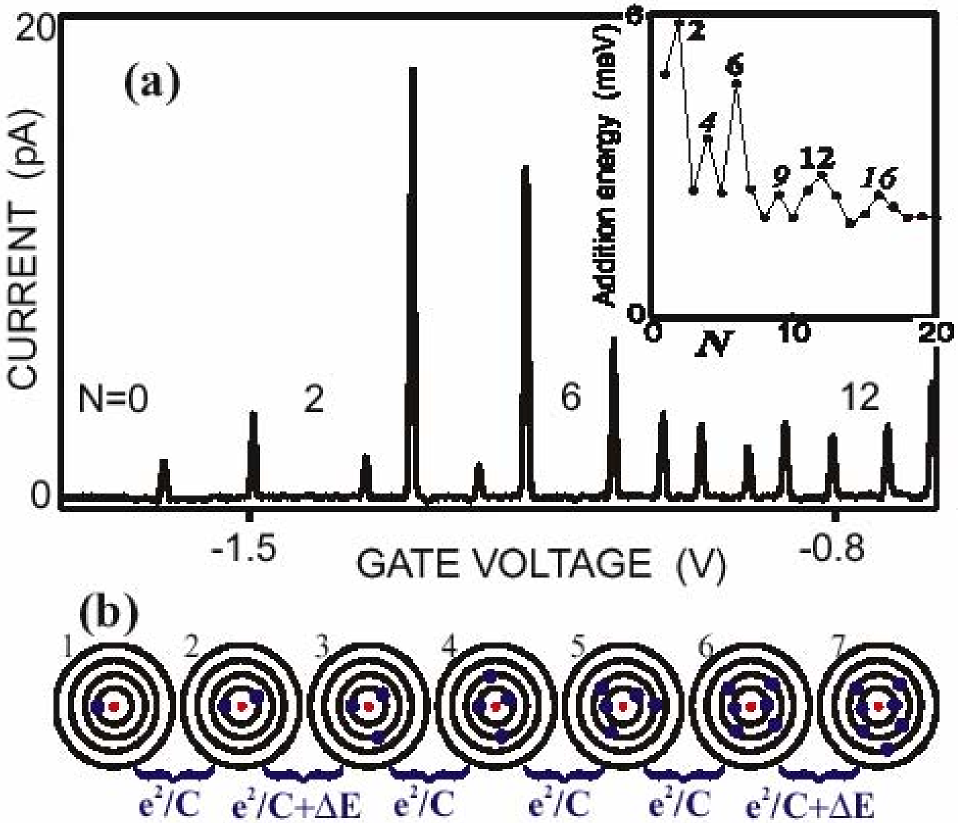
This is reminiscent of the closed electron shells in atoms. Small dots behave like artificial atoms when their size shrinks down to the electron wavelength.

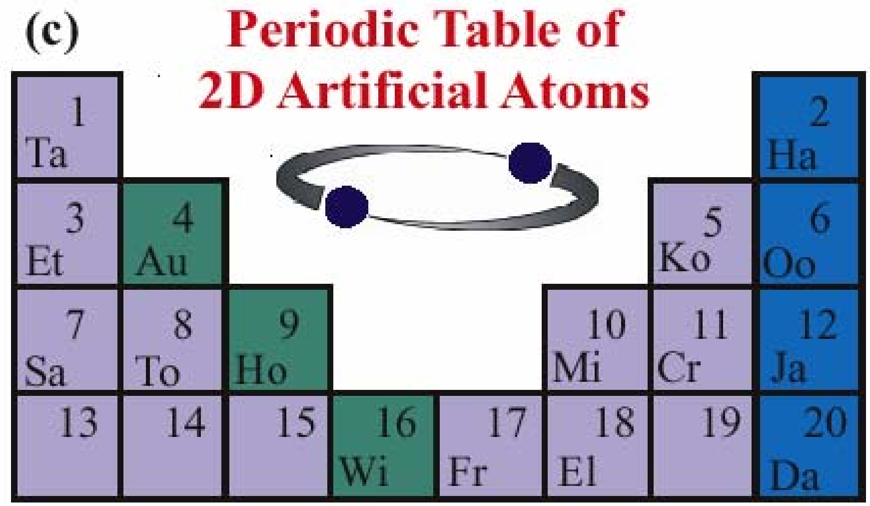
Continuous energy bands become quantized (see Lecture 8). Adding one electron requires the Coulomb energy U plus the difference ΔE between two quantum levels (next slide). If a second electron is added to the same quantum level (the same shell in an atom), ΔE vanishes and only the Coulomb energy U is needed.



The quantum energy levels can be extracted from the spacing between the conductance peaks by subtracting the Coulomb energy $U = e^2/C$.

Quantum Dot in 2D (Disk)

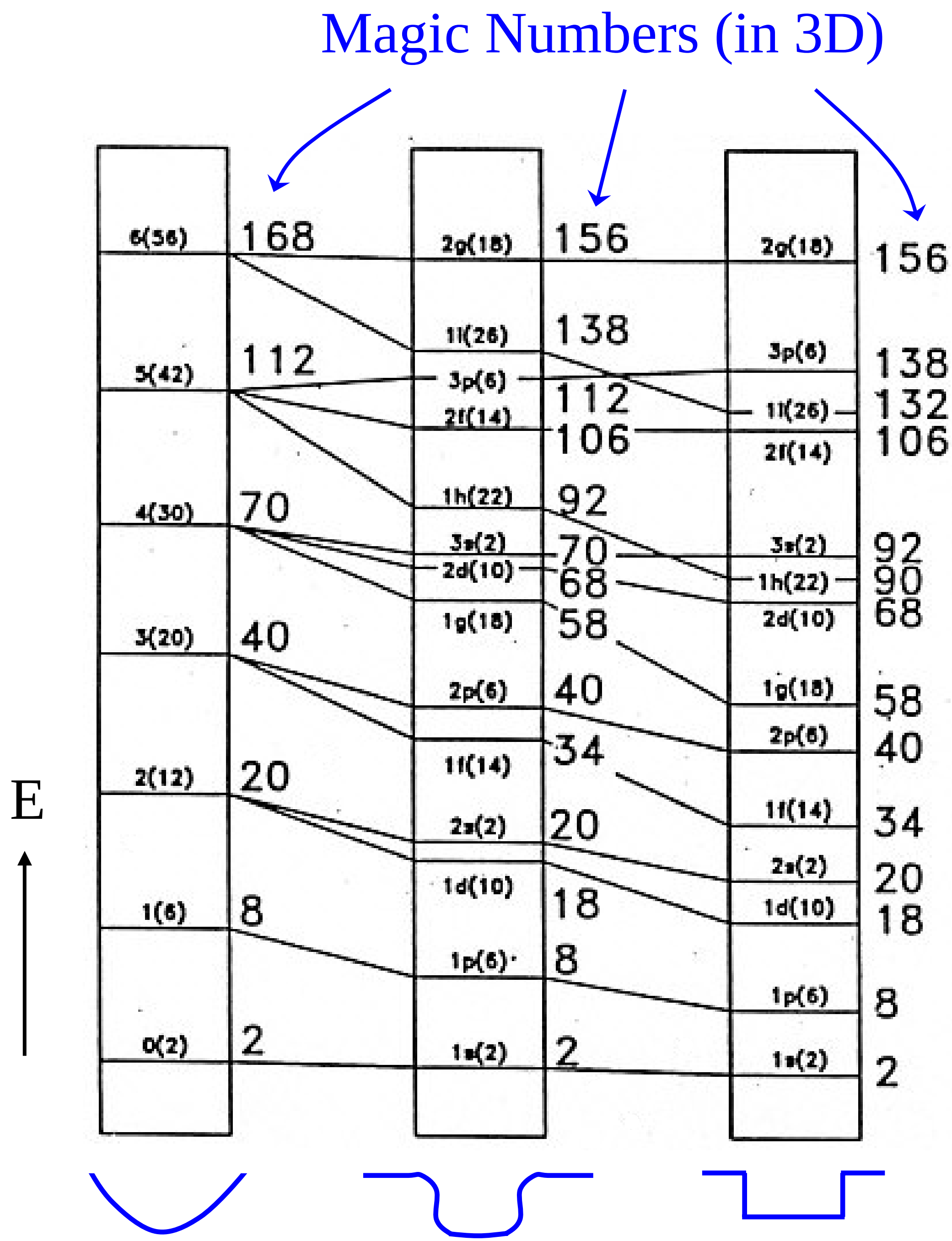




Filling the Electron Shells in 2D

Figure 2. Current flowing through a 2D circular quantum dot when varying the gate voltage. (a) The first peak marks the voltage where the 1st electron enters the dot, and the number of electrons, N, increases by one at each subsequent peak. The distance between adjacent peaks corresponds to the addition energies (see inset). (b) The addition of electrons to circular orbits is shown schematically. The first shell can hold 2 electrons whereas the second shell can contain up to 4 electrons. It therefore costs extra energy to add the 3rd and 7th electron. (c) The electronic properties following from a 2D shell structure can be summarized in a periodic table for 2 D elements. (The elements are named after team members from NTT and Delft.)

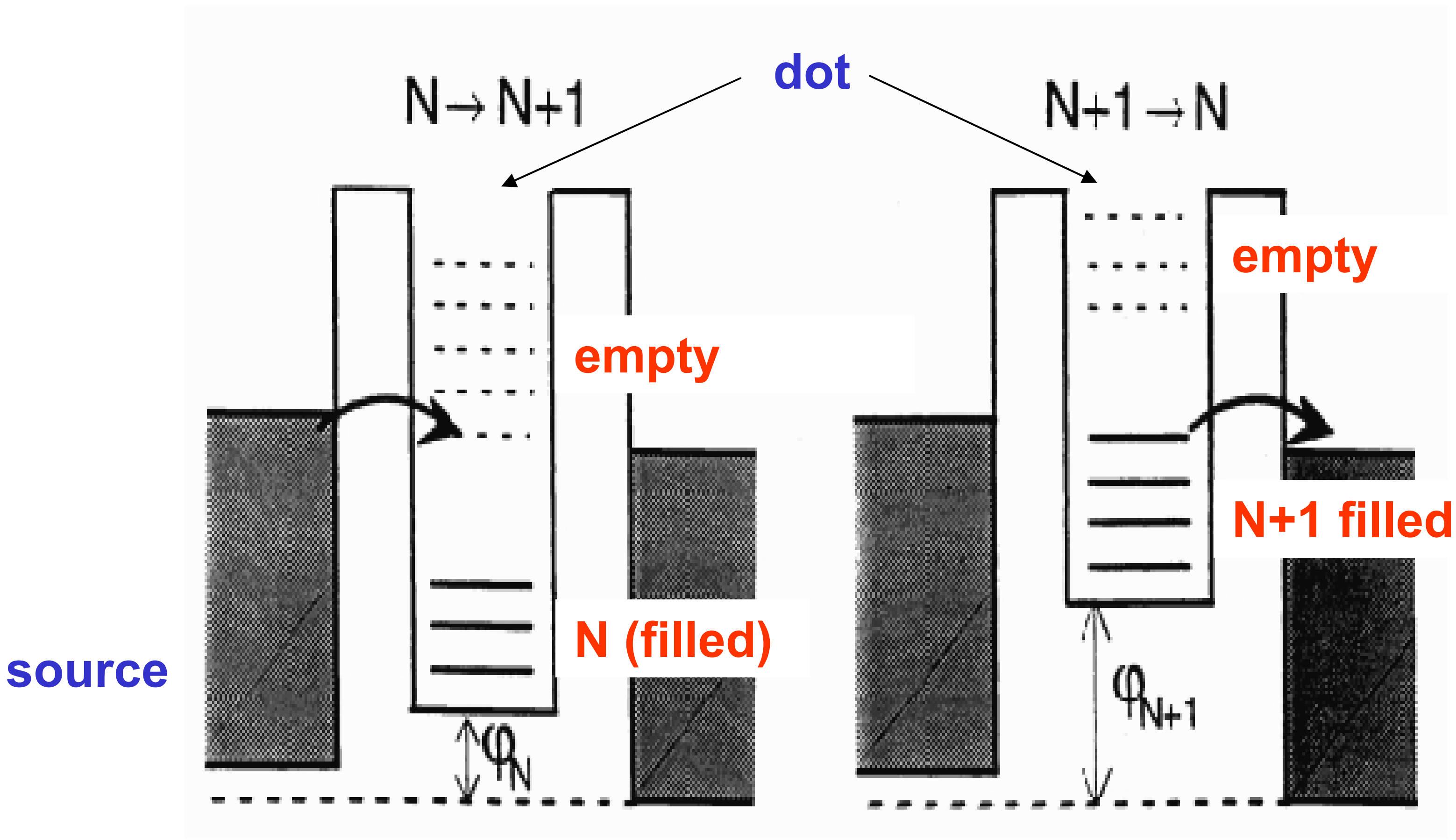
Shell Structure of Energy Levels for Various Potentials



Potentials:

Two Step Tunneling

source → dot → drain

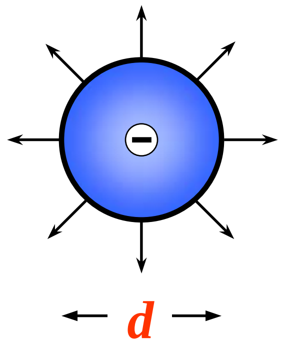


(For a detailed explanation see the annotation in the .ppt version.)

Coulomb Energy U

- **Two stable charge states of a dot with N and N+1 electrons are separated by the Coulomb energy $U = e^2/C$.**
- **The dot capacitance C decreases when shrinking the dot.**
- **Consequently, the Coulomb energy U increases.**
- **When U exceeds the thermal energy $k_B T$, single electron charging can be detected.**
- **At room temperature ($k_B T \approx 25$ meV) this requires dots smaller than 10 nm (Lect. 2, Slide 2) .**

Coulomb energy $U = e^2/C$ of a spherical dot embedded in a medium with dielectric constant ε, with the counter electrode at infinity : $2e^2/\varepsilon d$

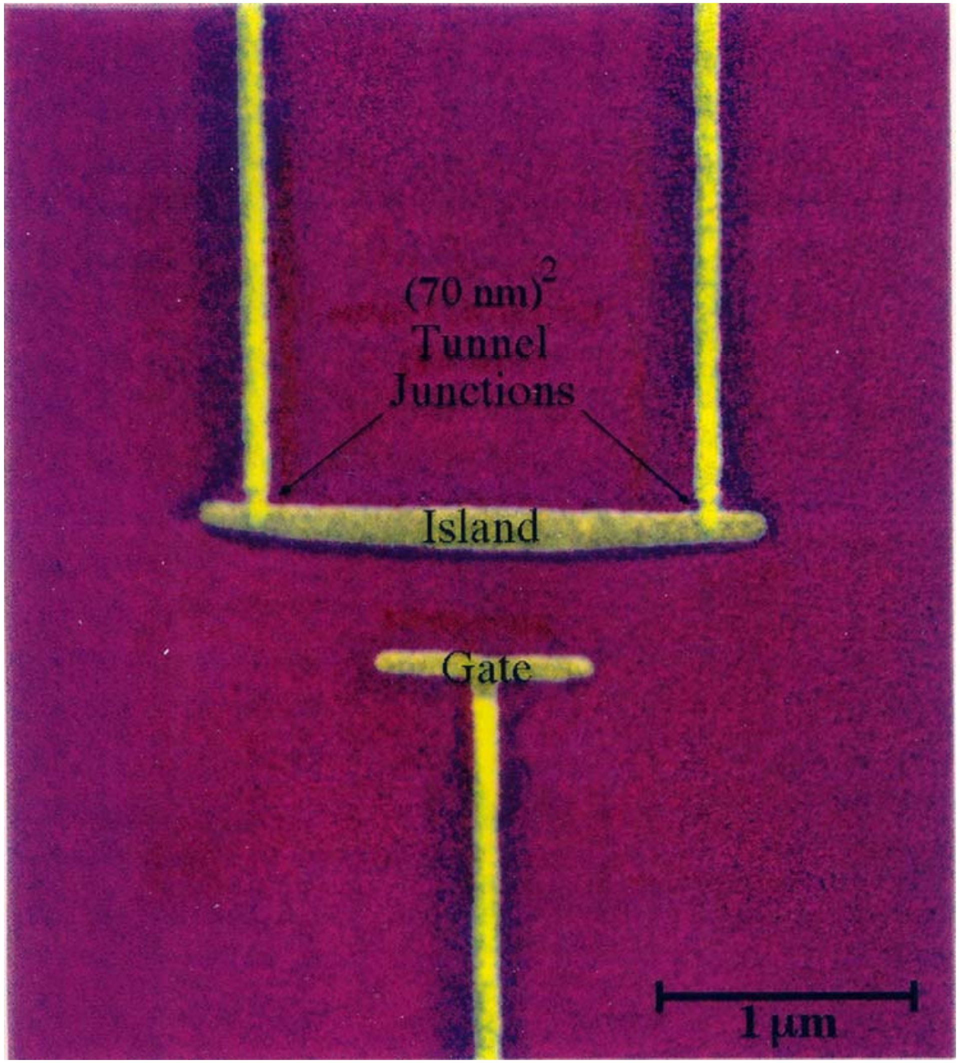


Conditions for a Coulomb Blockade

1) The Coulomb energy e^2/C needs to exceed the thermal energy $k_B T$. Otherwise an extra electron can get onto the dot with thermal energy instead of being blocked by the Coulomb energy. A dot needs to be either small (<10 nm at 300K) or cold (< 1K for a μm sized dot).

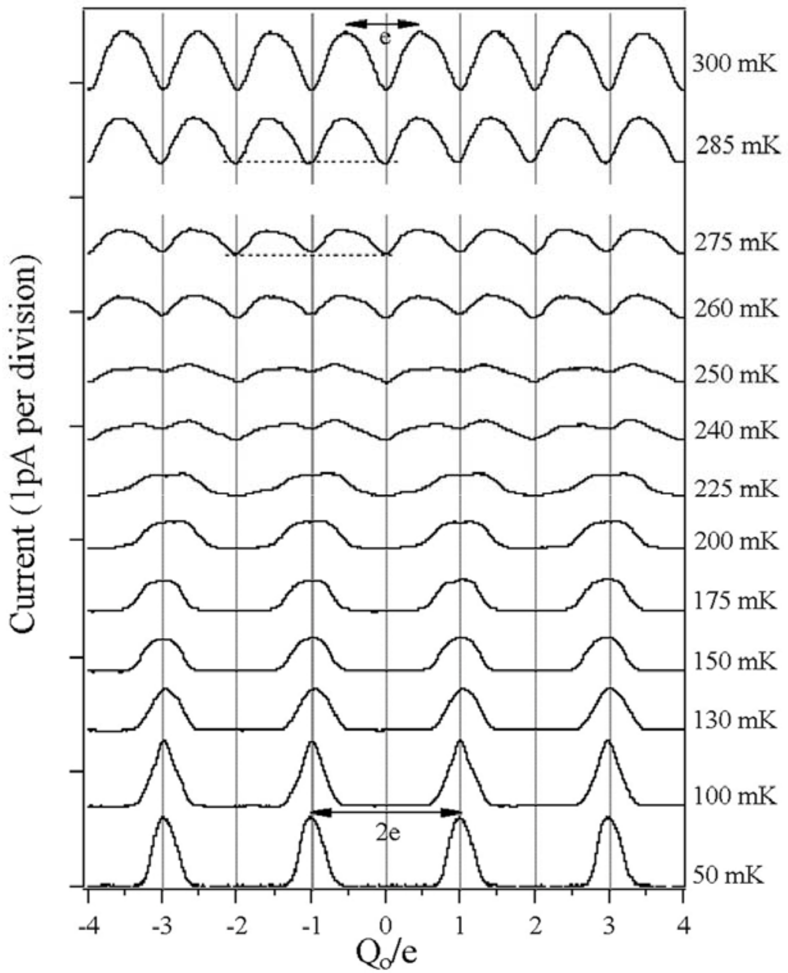
2) The residence time $\Delta t = RC$ of an electron on the dot needs to be so long that the corresponding energy uncertainty $\Delta E = h/\Delta t = h/RC$ is less than the Coulomb energy e^2/C . That leads to a condition for the tunnel resistance between the dot and source/drain: $R > h/e^2 \approx 26\ k\Omega$

Superconducting SET



A superconducting SET sample with a 2 μm long island and 70 nm wide leads.
The gate at the bottom allows control of the number of electrons on the island.

Superconducting SET



Current vs. charge curves for a superconducting dot with normal metals as source and drain. At low temperatures (bottom) the period changes from *e* to 2*e*, indicating the involvement of Cooper pairs.

Single Electron Turnstile

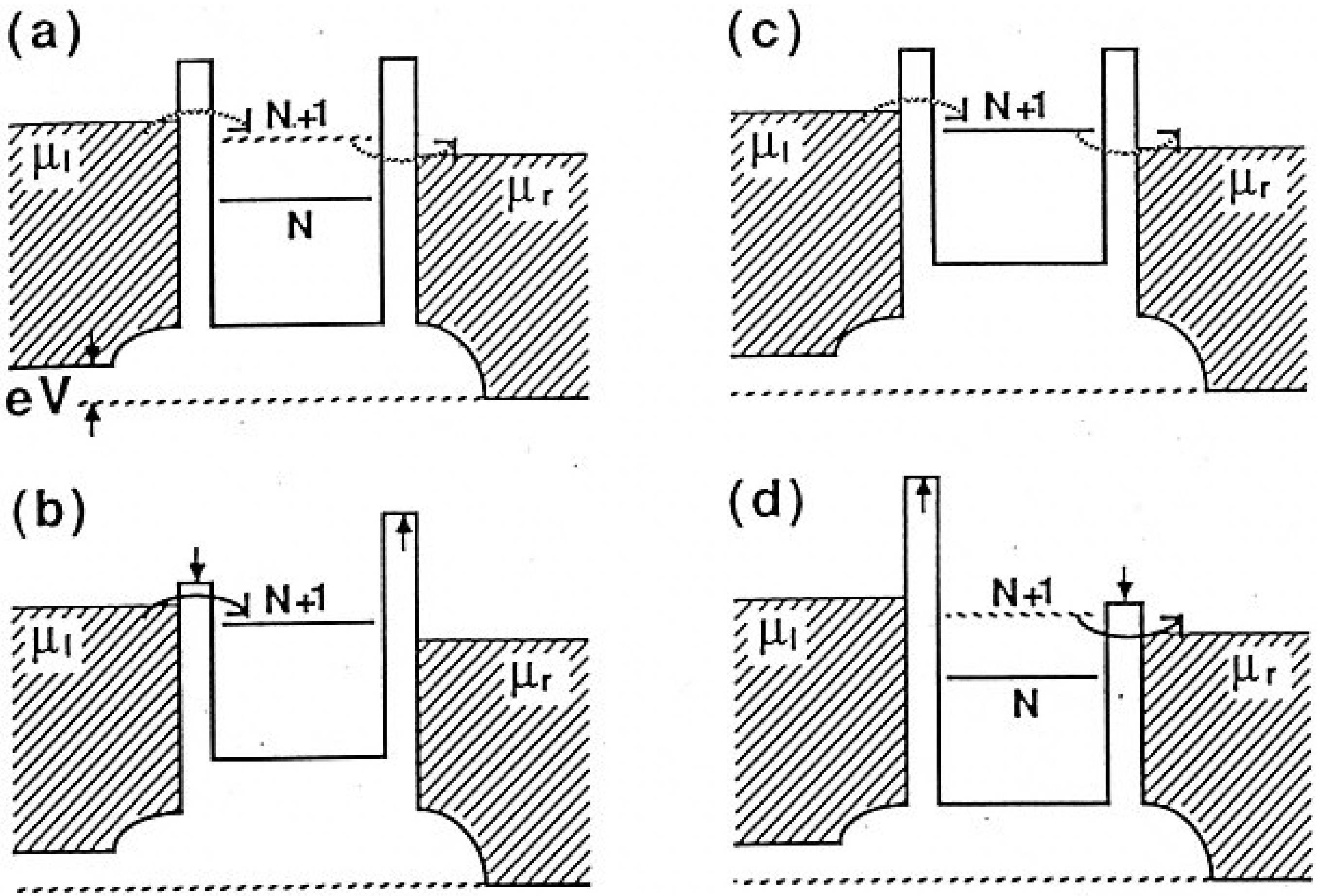


FIGURE 26. Schematic illustration of the four stages of operation of the single-electron turnstile. RF voltages applied to the gates are used to modify the tunneling rates through the barriers. Dashed arrows indicate that the tunneling probability is low; solid arrows indicate that it is high. (a) N electrons occupy the dot. (b) The left barrier is lowered, allowing one electron to tunnel onto the dot. (c) The left barrier is raised; the dot contains $N+1$ electrons. (d) The right barrier is lowered, allowing the electron to tunnel off. The net result is one electron transferred through the dot per RF cycle.

Precision Standards from "Single" Electronics

Count individual electrons, pairs, flux quanta

Current I
Coulomb
Blockade

$I = e\ \mathrm{f}$

Voltage V
Josephson
Effect

$V = h/2e \cdot \mathrm{f}$

$V/I = R = h/e^2$

Resistance R
Quantum Hall
Effect

(f = frequency)