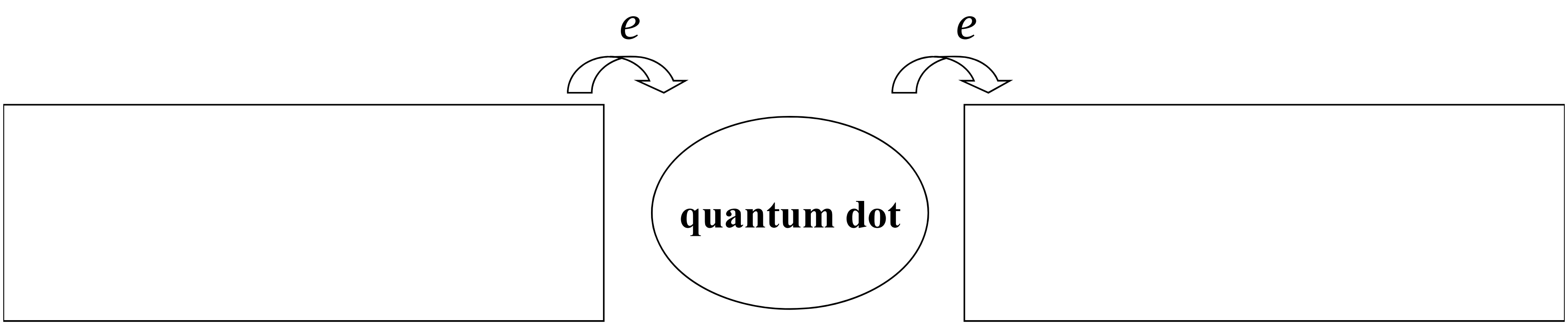
Single-electron effects

Charging effects

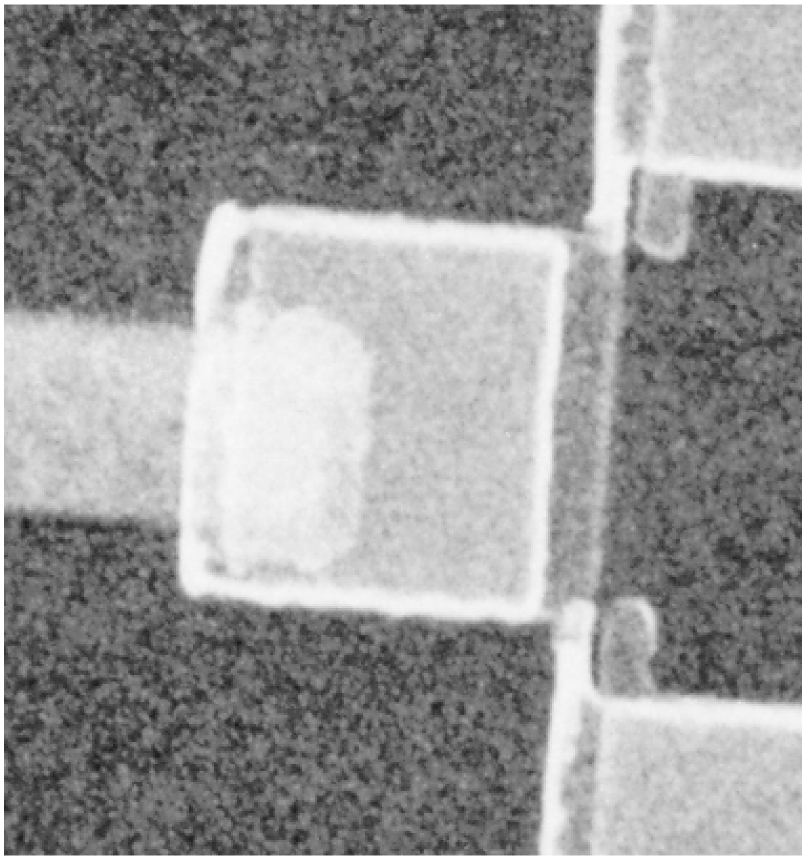
After screening, the next most simple approach to describing electron-electron interactions are charging effects.

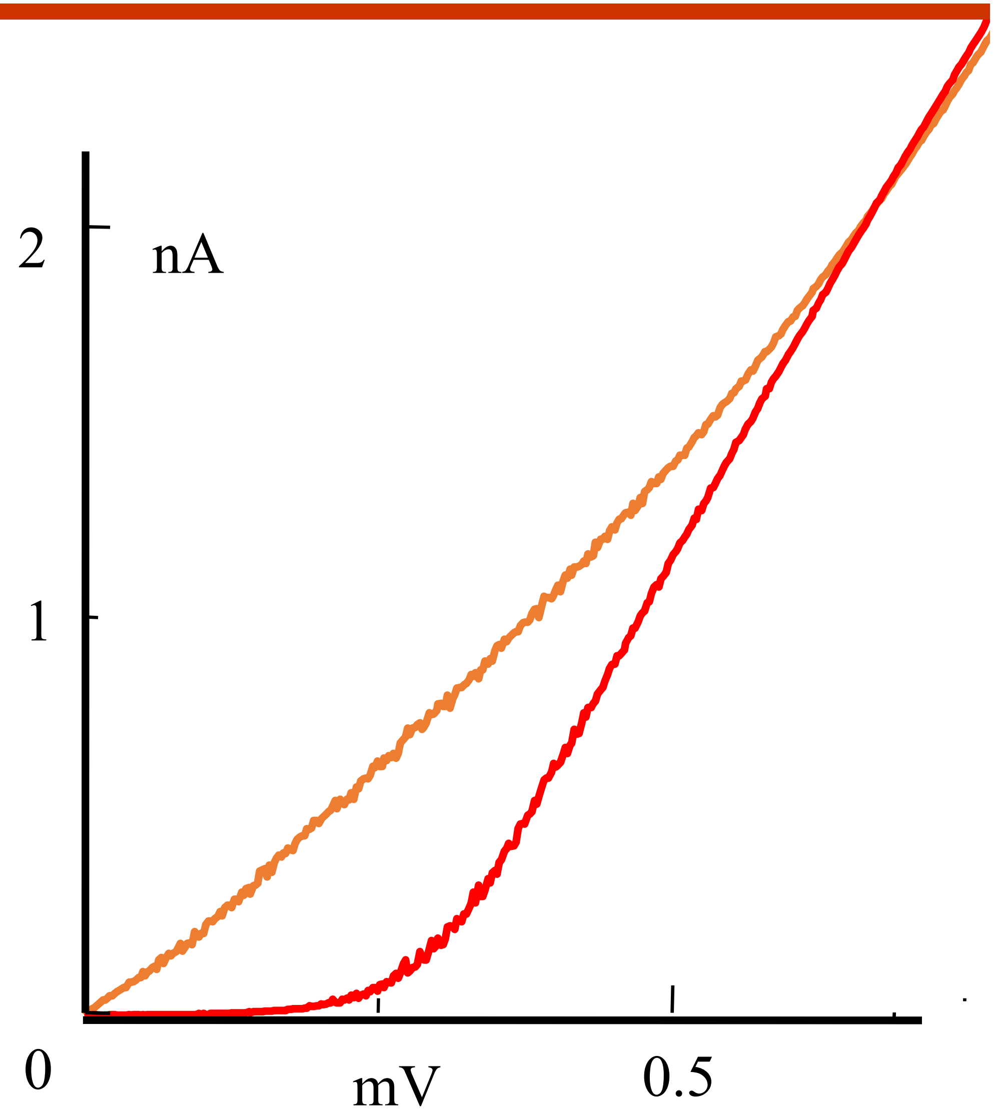


The motion of electrons through a single quantum dot is correlated.

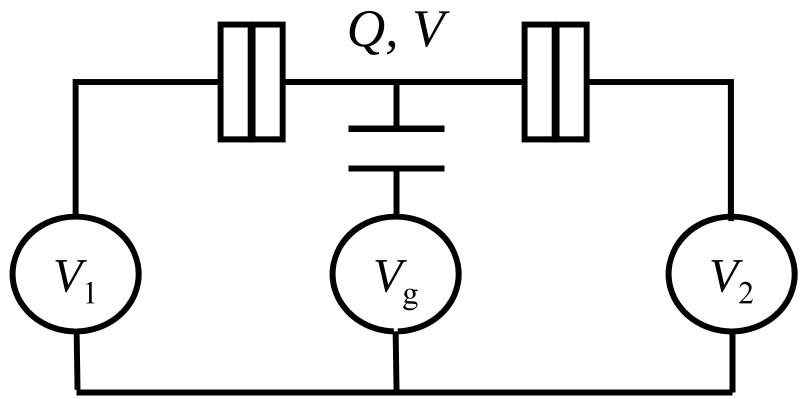
$$Q = CV$$

Single electron transistor





Single electron transistor



$$Q = C_1(V - V_1) + C_2(V - V_2) + C_g(V - V_g)$$

$$Q = -ne$$

$$V(n) = \left(-ne + C_1V_1 + C_2V_2 + C_gV_g\right) / C_\Sigma$$

$$C_\Sigma = C_1 + C_2 + C_g$$

Single electron transistor

The potential of the island with *n* electrons on it:

$$V(n) = \left(q - ne + C_1V_1 + C_2V_2 + C_g\right) / C_\Sigma$$

The energy needed to add an infinitesimal charge *dq* to an island at voltage *V*(*n*) is *V*(*n*)*dq*. The energy needed to add a whole electron is:

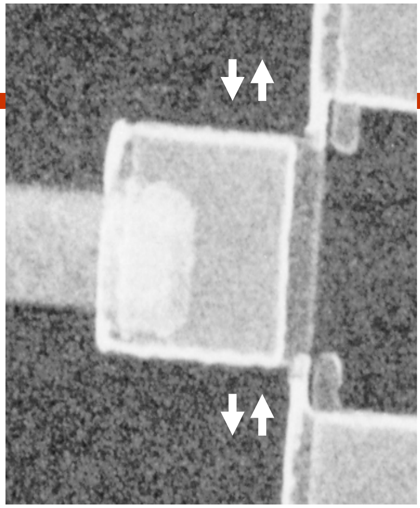
$$\Delta E = \int_0^{-e} V(n)dq = -eV(n) + \frac{e^2}{2C_\Sigma}$$

Charging energy

The energy needed to remove a whole electron is:

$$\Delta E = \int_0^{e} V(n)dq = eV(n) + \frac{e^2}{2C_\Sigma}$$

Single electron transistor



The possible tunnel events are:

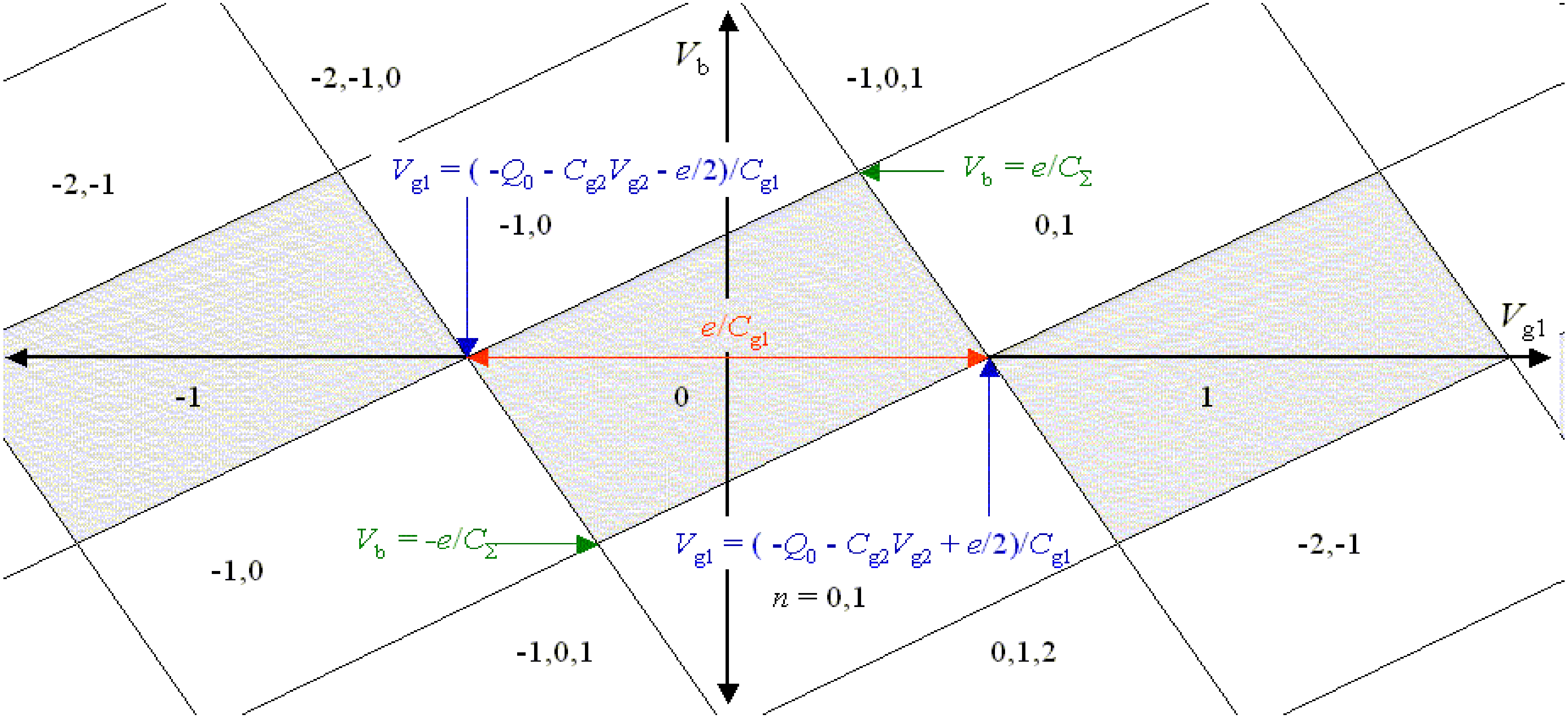
$$\Delta E_{1R}(n) = eV_1 - e\left(-ne + Q_0 + C_1V_1 + C_2V_2 + C_{g1}V_{g1} + C_{g2}V_{g2}\right)/C_\Sigma + \frac{e^2}{2C_\Sigma}$$

$$\Delta E_{1L}(n) = -eV_1 + e\left(-ne + Q_0 + C_1V_1 + C_2V_2 + C_{g1}V_{g1} + C_{g2}V_{g2}\right)/C_\Sigma + \frac{e^2}{2C_\Sigma}$$

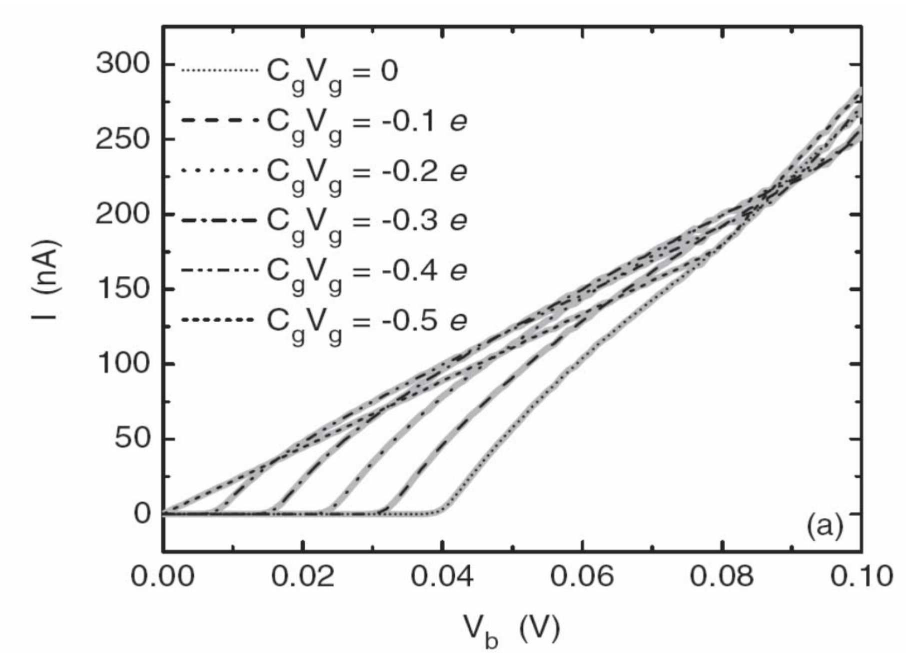
$$\Delta E_{2R}(n) = -eV_2 + e\left(-ne + Q_0 + C_1V_1 + C_2V_2 + C_{g1}V_{g1} + C_{g2}V_{g2}\right)/C_\Sigma + \frac{e^2}{2C_\Sigma}$$

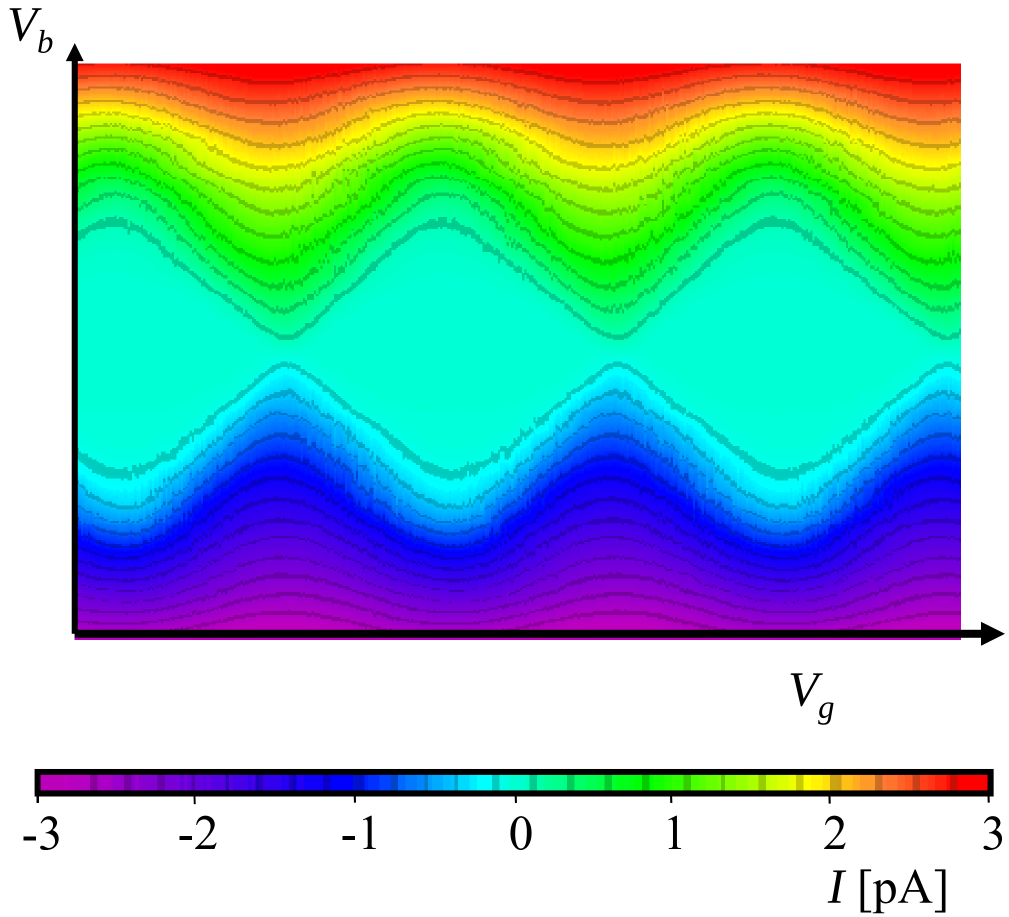
$$\Delta E_{2L}(n) = eV_2 - e\left(-ne + Q_0 + C_1V_1 + C_2V_2 + C_{g1}V_{g1} + C_{g2}V_{g2}\right)/C_\Sigma + \frac{e^2}{2C_\Sigma}$$

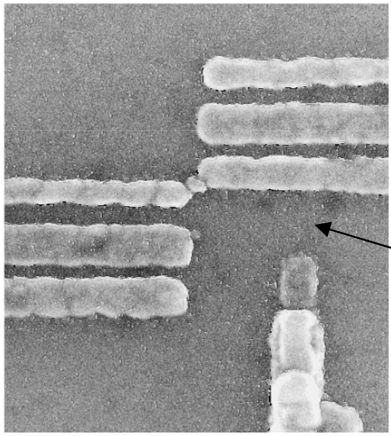
Coulomb blockade



Coulomb blockade

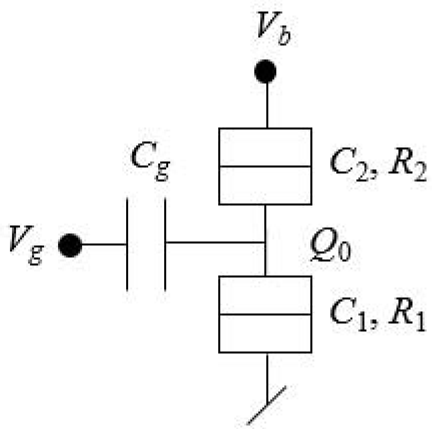


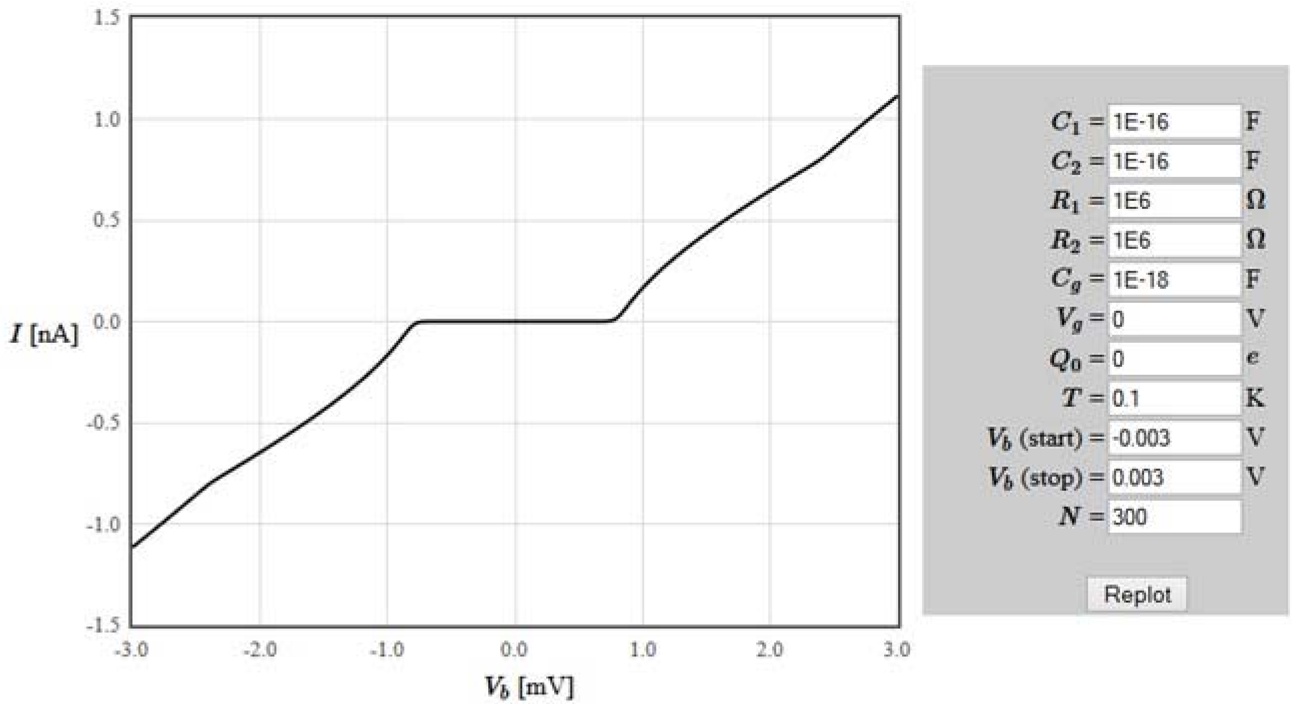




2 nm room temperature SET Pashkin/Tsai NEC

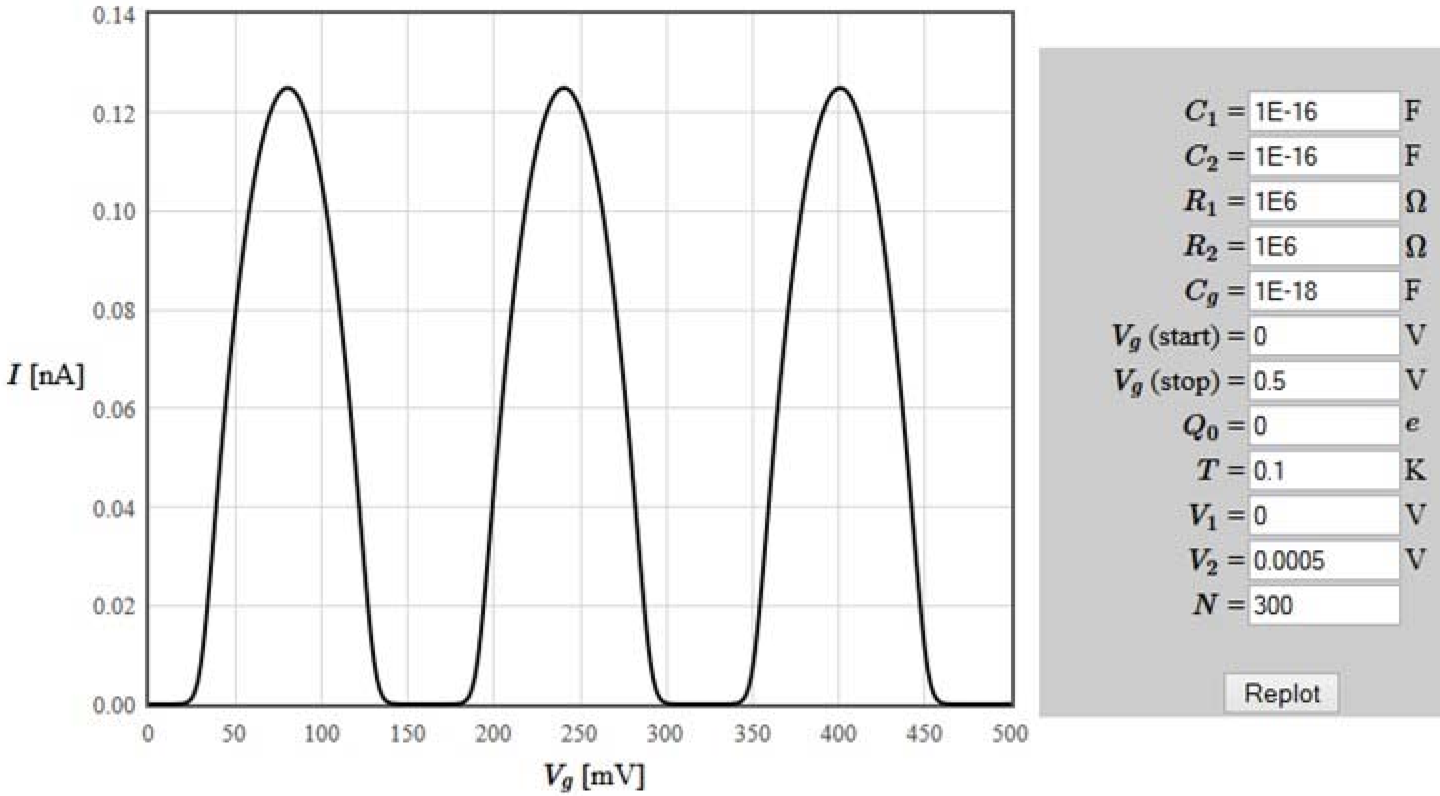
Single electron transistors





http://lamp.tu-graz.ac.at/~hadley/set/asymIV/SETIV.html
http://lamp.tu-graz.ac.at/~hadley/set/symIV/SETIV.html

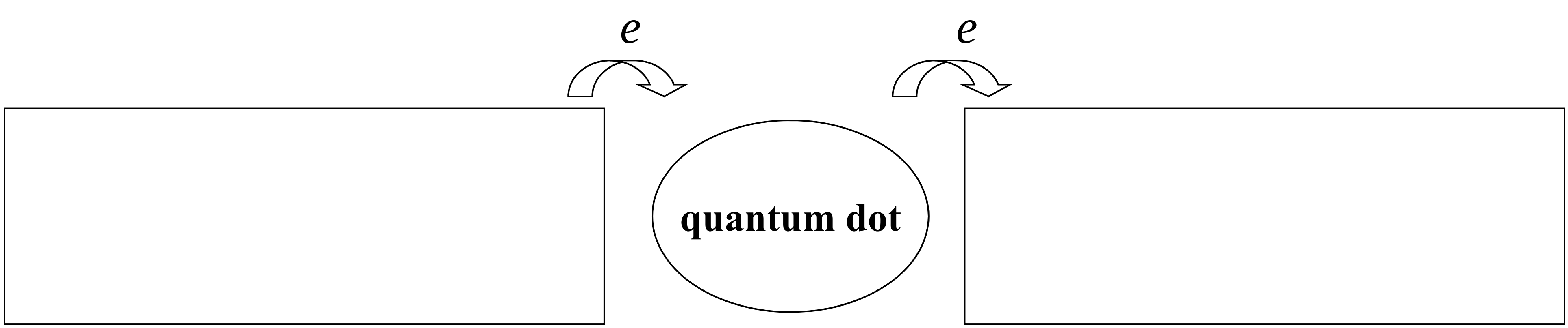
Single electron transistors I-V_g



http://lamp.tu-graz.ac.at/~hadley/set/ivg/ivg.html

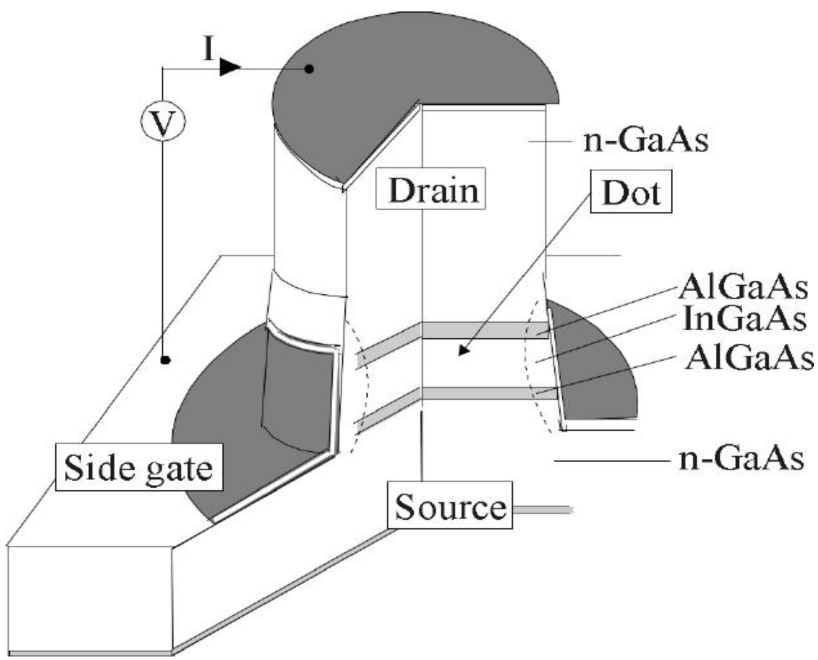
Charging effects

After screening, the next most simple approach to describing electron-electron interactions are charging effects.

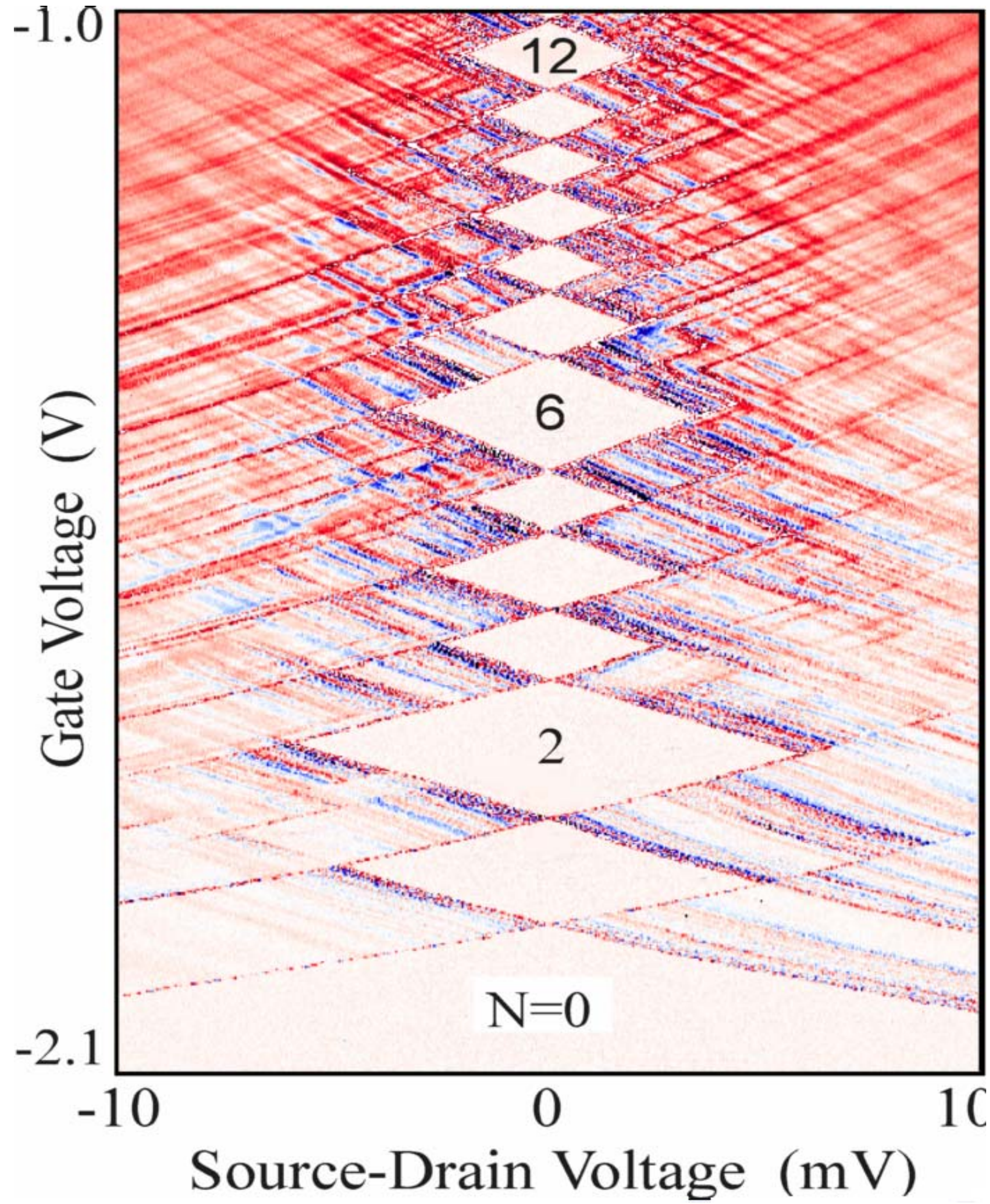


The motion of electrons through a single quantum dot is correlated.

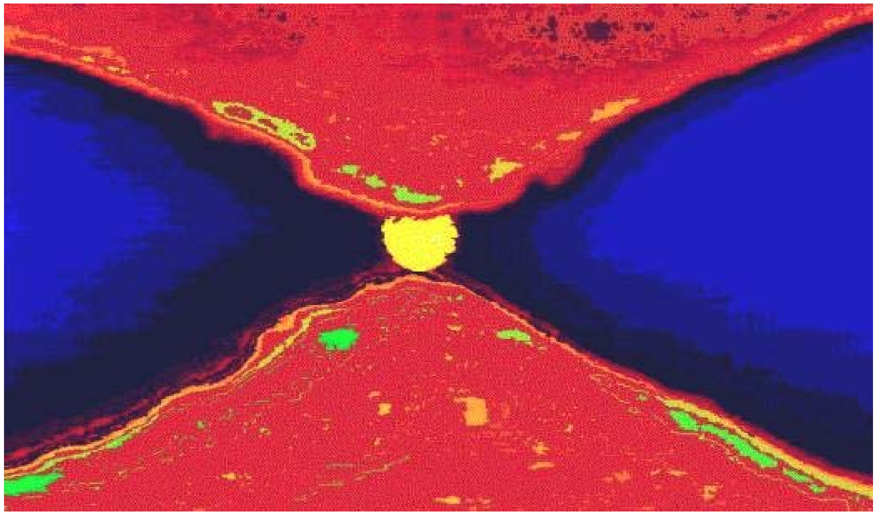
Quantum dot

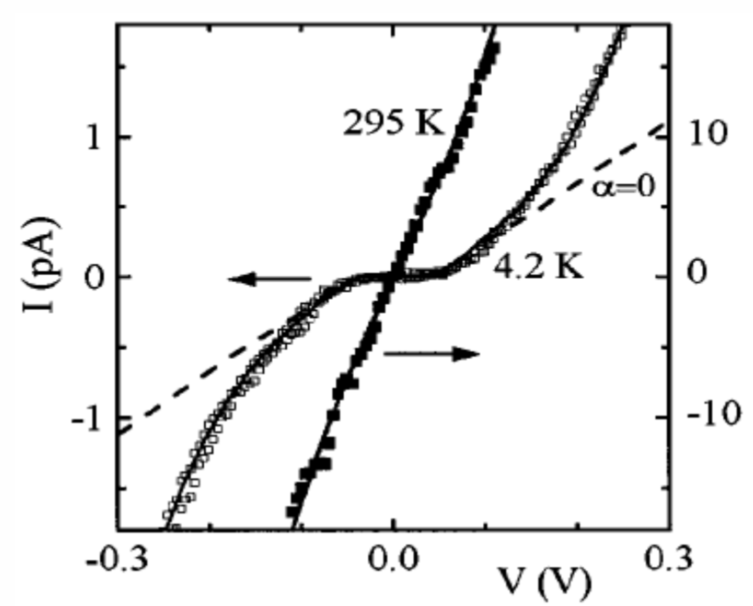


I
V
n-GaAs
Drain
Dot
AlGaAs
InGaAs
AlGaAs
Side gate
n-GaAs
Source

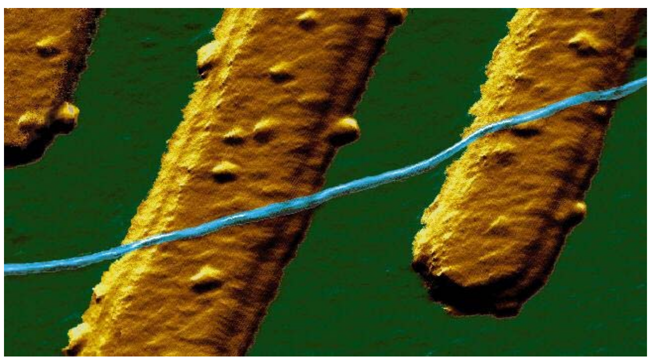


-1.0
-2.1
12
6
2
N=0
Gate Voltage (V)
-10
0
10
Source-Drain Voltage (mV)

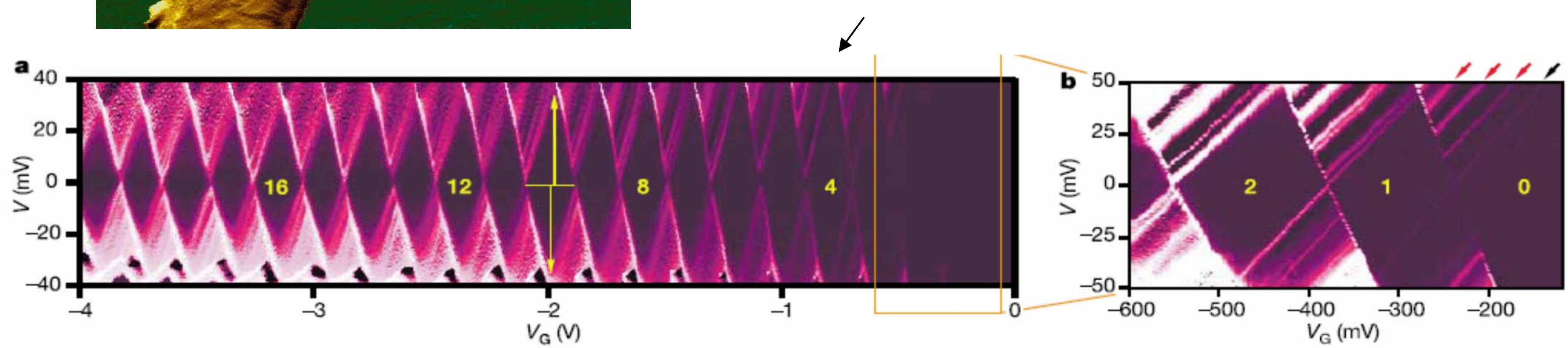




A. Bezryadin et al. Appl. Phys. Lett., 71, p. 1273.



Jarillo-Herrero, et al., Nature 429, 389 (2004).



Coulomb blockade suppressed by thermal and quantum fluctuations

Thermal fluctuations $\frac{e^2}{2C_\Sigma} >> k_B T$ Quantum fluctuations $\Delta E \Delta t > \hbar$

Duration of a quantum fluctuation: $\Delta t \sim \frac{\hbar 2 C_\Sigma}{e^2}$

RC charging time of the capacitance: RC_Σ

Charging faster than a quantum fluctuation $RC_\Sigma < \frac{\hbar 2 C_\Sigma}{e^2}$

$$R < \frac{2\hbar}{e^2} \approx 8 \text{ k}\Omega$$

$$\frac{h}{e^2} \approx 25.5 \text{ k}\Omega$$

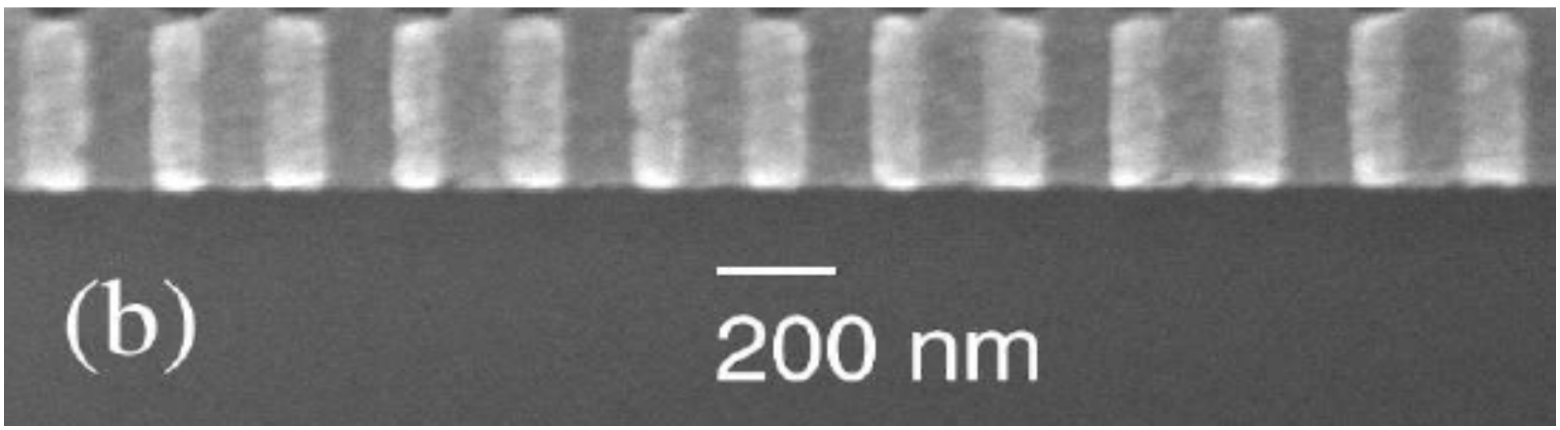
Resistance quantum

Metal - insulator transition in 1-d arrays

Charging energy $\Delta E = e^2/2C$

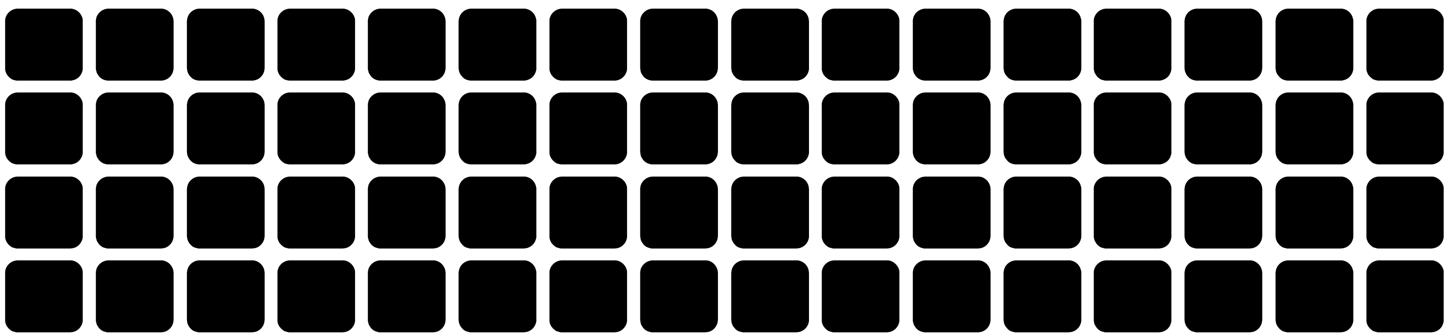
$$\Delta t = \frac{\hbar}{\Delta E} = \frac{2C\hbar}{e^2} > \frac{1}{\Gamma} = RC$$

$$R < \frac{2\hbar}{e^2}$$ extended state



Metal insulator transition

If the tunnel resistances between the crystals is > 25 kΩ, the material will be an insulator at low temperature



Strong coupling of metal particles results in a metal.
Weak coupling of metal particle results in an insulator.