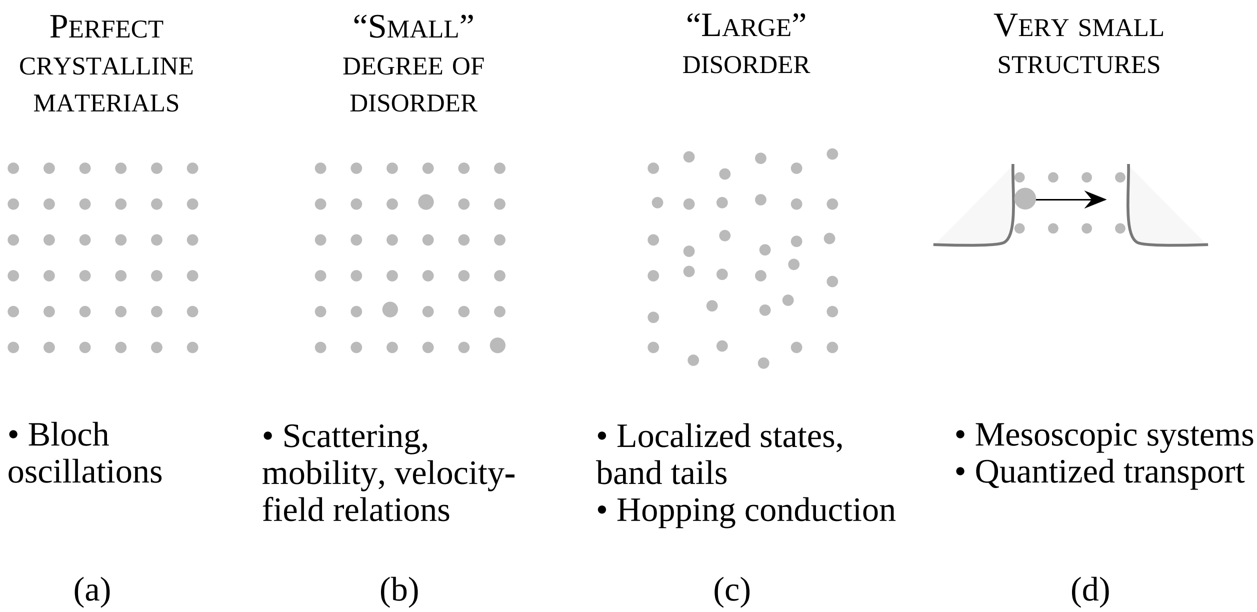
Chapter 8

COHERENCE, DISORDER, AND MESOSCOPIC SYSTEMS



A schematic of how levels of structural disorder and size impact electronic properties of a material.

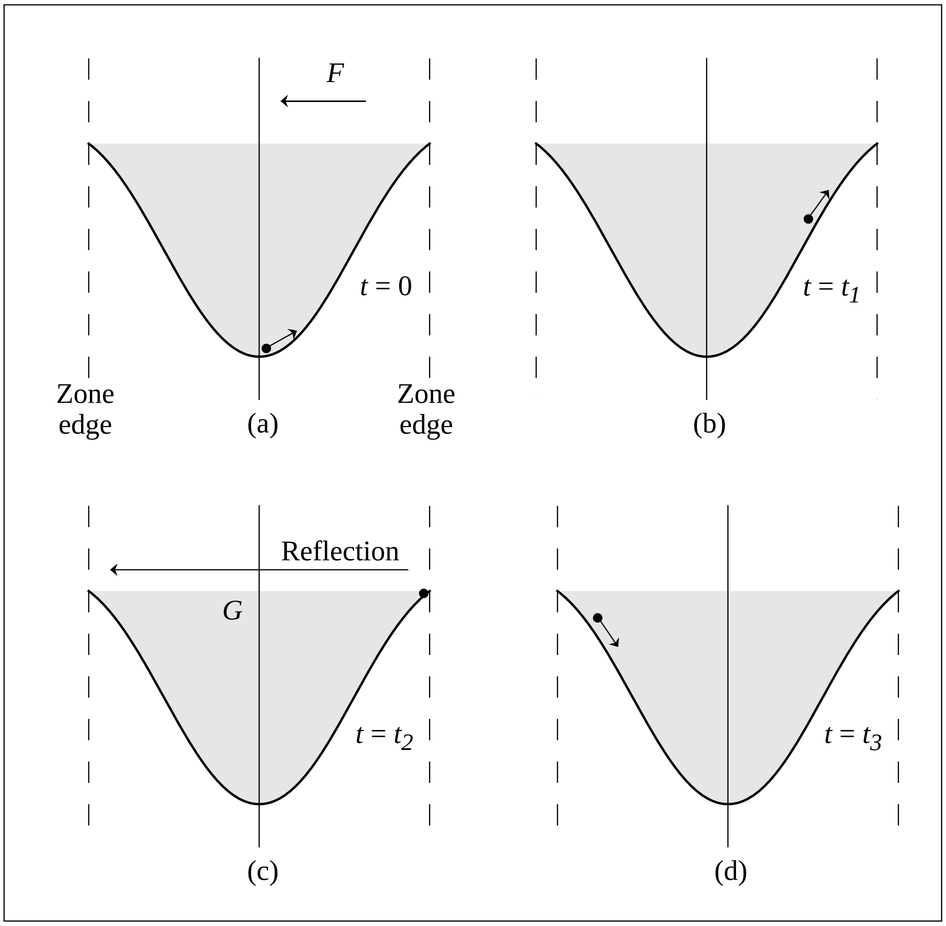
PERFECT PERIODIC STRUCTURE: ZENER-BLOCH OSCILLATIONS

$$\psi_k = u_k \, e^{i(k \cdot r - \omega t)}$$

$$\frac{\hbar dk}{dt} = eF$$

Periodic nature of the bandstructure means electrons will undergo oscillations in k-space.

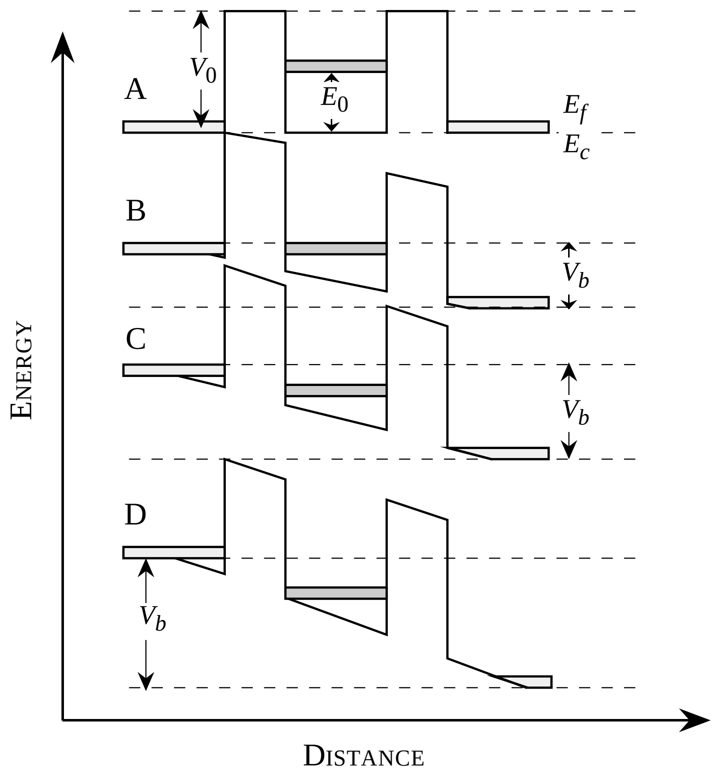
Frequency of oscillation ~ $\frac{eFa}{\hbar}$
a = lattice constant



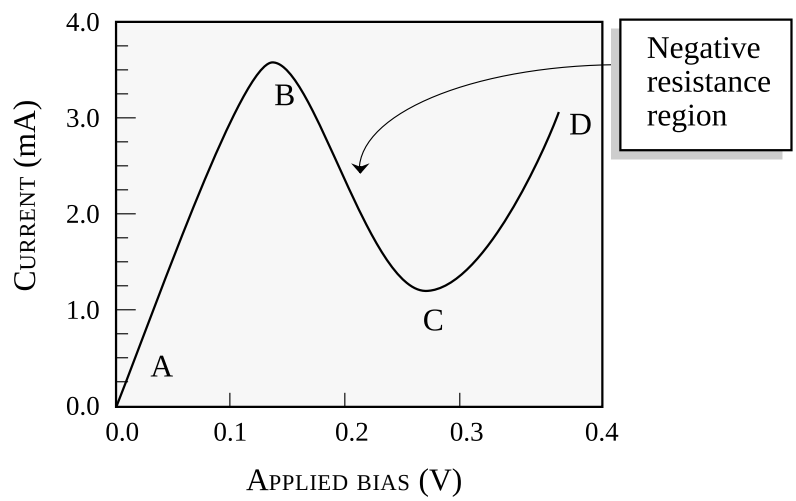
PROBLEM: Scattering causes phase incoherence and Bloch oscillation can be sustained only at very low temperatures for picoseconds.

Coherent transport: Resonant tunneling

Double barrier structures show negative resistance in their I–V characteristics due to resonant tunneling



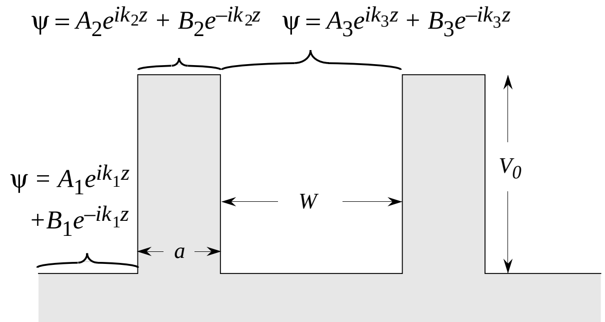
(a)



(b)

(a) Schematic explanation of the operation of resonant tunneling devices showing the energy band diagram for different bias voltages. (b) Typical current–voltage characteristic for the resonant tunneling diode.

Coherent transport: resonant tunneling

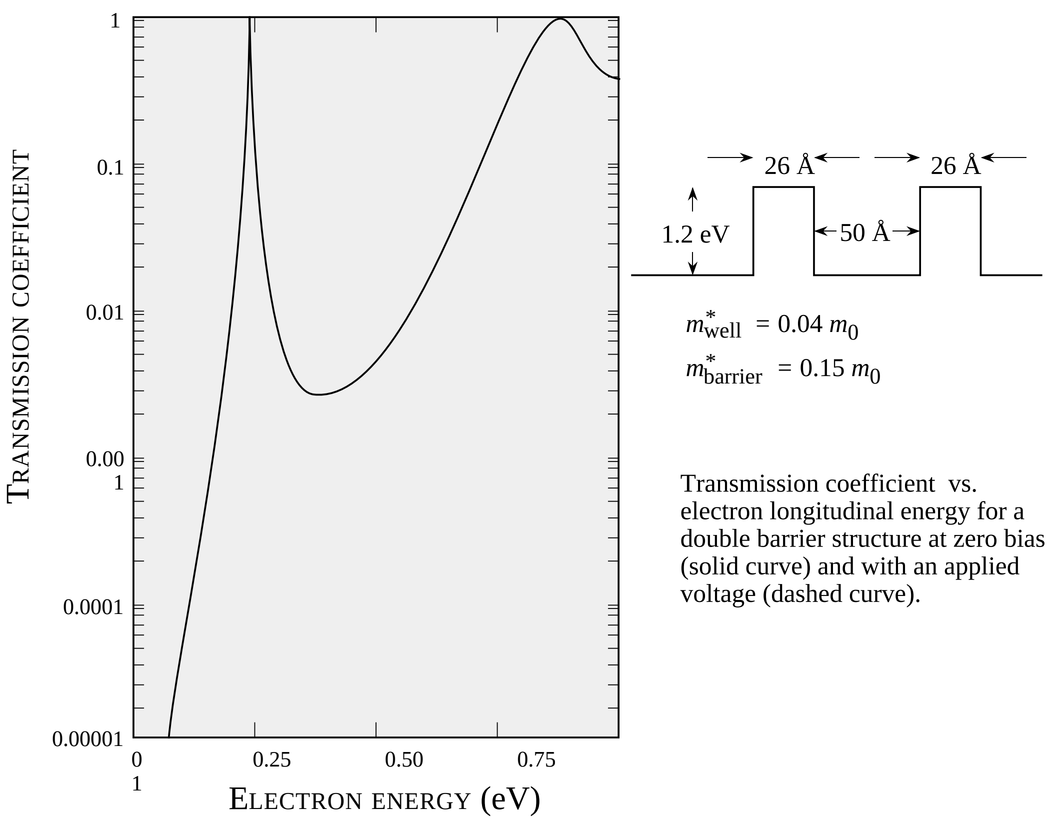


Typical resonant tunneling structure with two barriers. The wavefunction in each region has a general form shown.

$$T_{2B} = \left[1+ \frac{4R_{1B}}{T_{1B}^2} \sin^2(k_1W-\theta)\right]^{-1}$$

$$R_{1B} = \frac{V_0^2 \sinh^2\gamma a}{V_0^2 \sinh^2\gamma a + 4E(V_0-E)} \; ; \; T_{1B} = 1 - R_{1B}; \; \tan\theta = \frac{2k_1 \gamma \cosh \gamma a}{(k_1^2 - \gamma) \sinh \gamma a}$$

$$\gamma^2 = \frac{2m(V_0-E)}{\hbar^2}$$



$m^*_{well} = 0.04\, m_0$

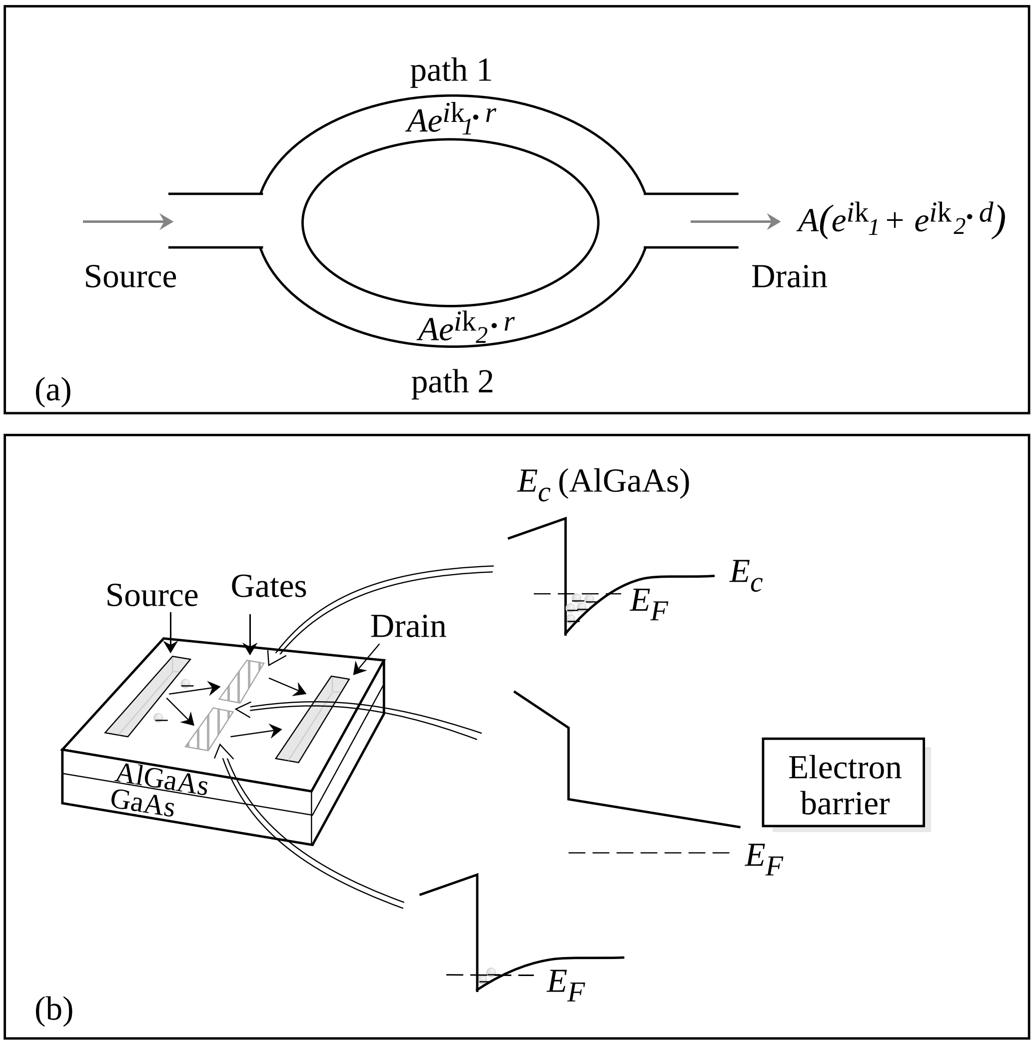
$m^*_{barrier} = 0.15\, m_0$

Transmission coefficient vs. electron longitudinal energy for a double barrier structure at zero bias (solid curve) and with an applied voltage (dashed curve).

COHERENT TRANSPORT: QUANTUM INTERFERENCE

Electron waves traveling coherently in two paths can recombine to cause interference effects

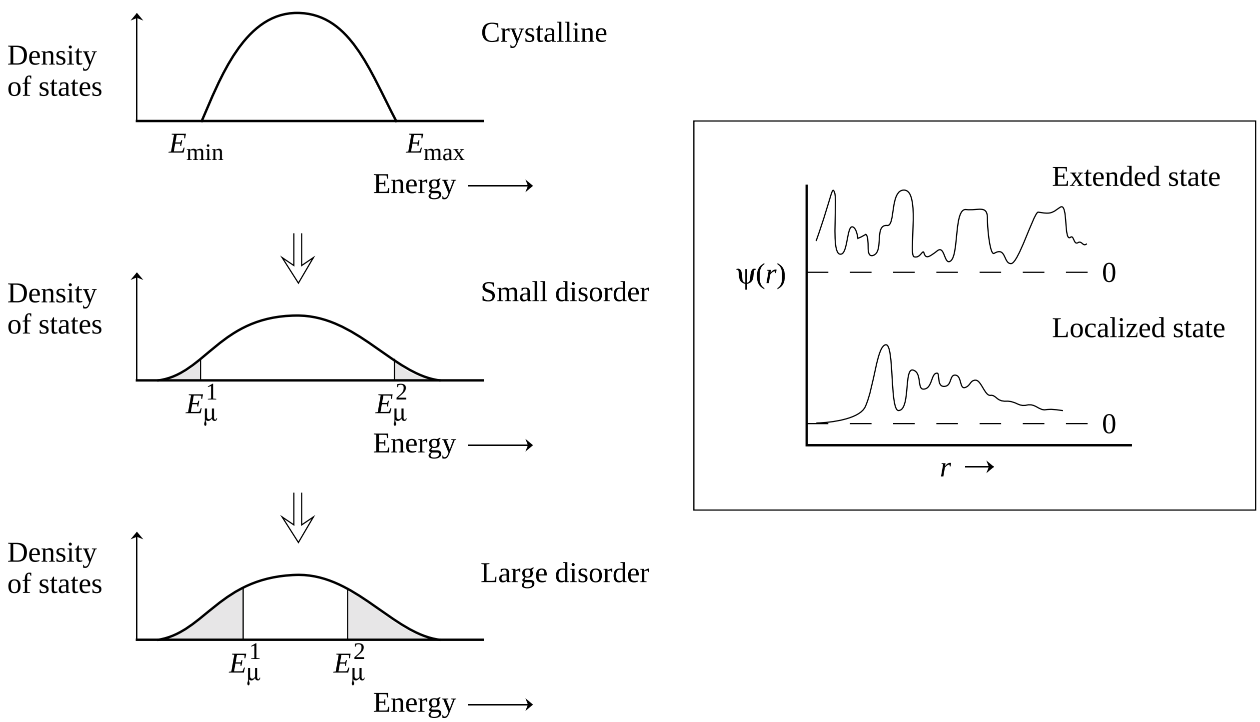
$$I(d) = 2A^2\,[1 - \cos(k_1 - k_2)d]$$



(a) Schematic of a coherent electron beam traveling along two paths and interfering. (b) A schematic of a split-gate transistor to exploit quantum interference effects. Electrons can propagate from the source to the drain under the two gates in the 2-dimensional channel of AlGaAs/GaAs as shown.

DISORDERED SEMICONDUCTORS: LOCALIZED AND EXTENDED STATES

If a structure has a large disorder, i.e., nearly every site deviates from the erfect periodic site, wavefuncitons are no longer Bloch (plane wave) states.

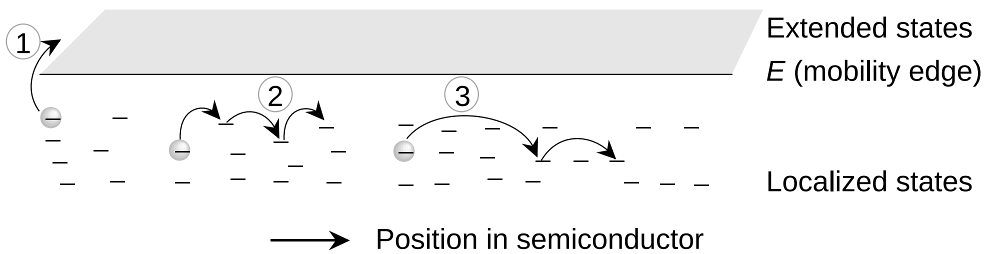


Density of staes and the influence of disorder. The shaded region represents the region where the electronic states are localized in space. The mobility edges E_μ separate the region of localized and extended states. The inset shows a schematic of an extended and a localized state.

DISORDERED SYSTEMS: TRANSPORT

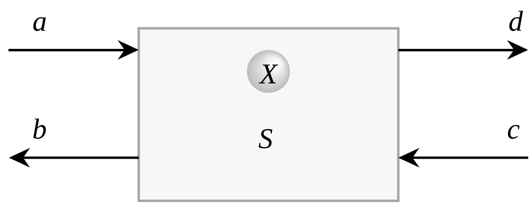
Very low temperatures: Variable range hopping between localized states.

Higher temperatures: Thermally activated transport from localized to extended states.



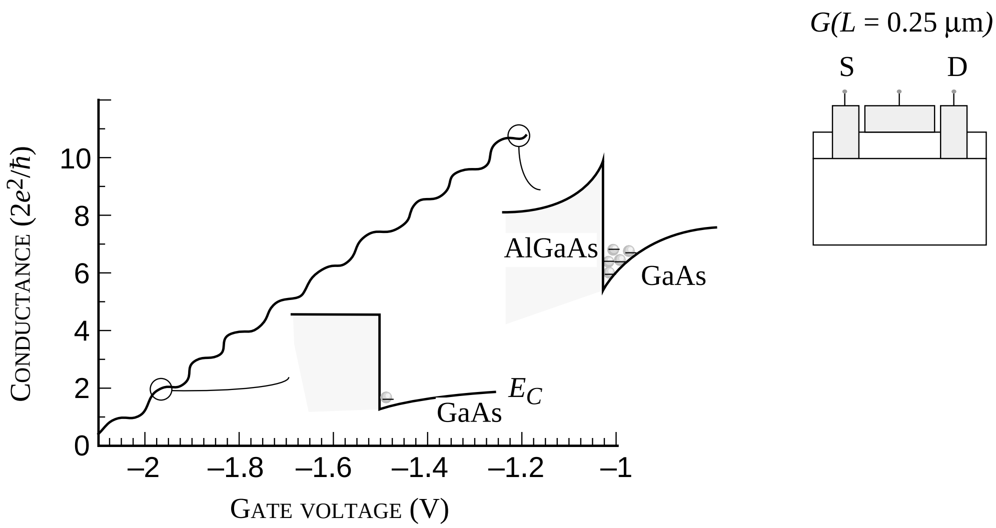
Mechanisms for transport in a disordered system. In case 1, the electron is thermally activated to the states above the mobility edge. In case 2, the electron hops to the nearest localized state, while in case 3, the electron hops to the "optimum" site as explained in the text.

Mesoscopic structures: conductance fluctuations



A schematic showing the effect of the scatternig center S on electron waves *a* and *c* incident from the left and right, respectively. Waves *b* and *d* emerge as a result of reflection and transmission.

Conductance: $G = \frac{2e^2}{h}$; quantized conductance.



Experimental studies on conductance fluctuations arising in a GaAs/AlGaAs channel constricted by the structure shown.
The results are for the channel conductance in units of $e^2/\pi h (=2e^2/h)$.
(From the paper by B. J. Van Wees, et al., Phys. Rev. Lett., **60**, 848 (1988).)

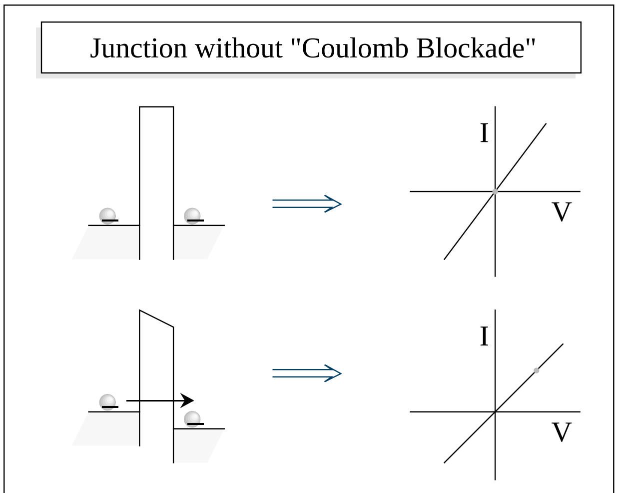
MESOSCOPIC SYSTEMS: COULOMB BLOCKADE

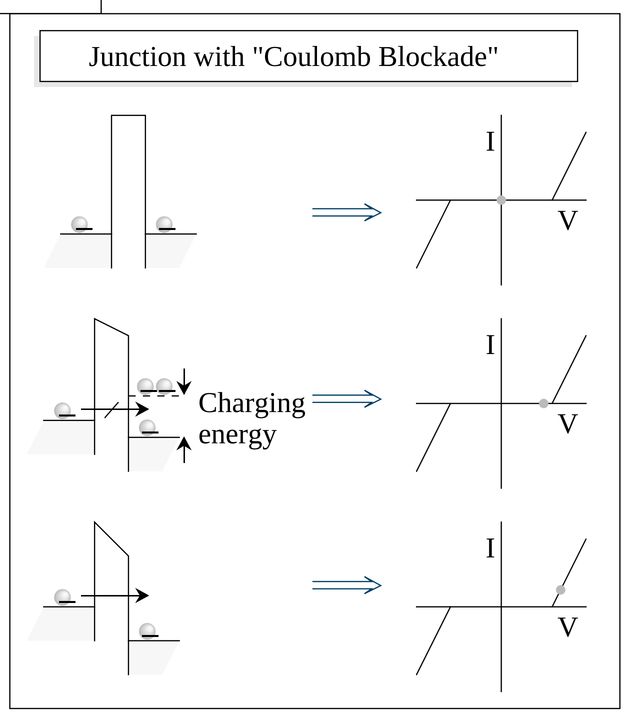
Coulomb blockade occurs in very small capacitors where the addition of a single electron alters the voltage by ~ k_BT/e

ΔE = energy to place an electron on a capacitor

$$= \frac{e^2}{2C}$$

ΔV = voltage needed to place an electron = $\frac{e}{2C} = \frac{80\ \text{mV}}{C(aF)}$





(a) A normal tunnel junction with large capacitance shows ohmic I-V characteristics.
(b) In very small capacitance tunnel junctions the presence of a Coulomb blockade ensures no current flows until the voltage reaches a certain point.