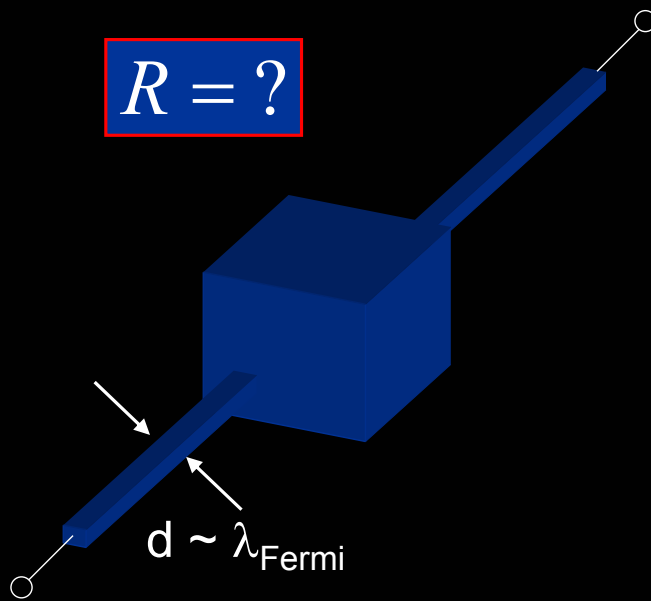


Announcements

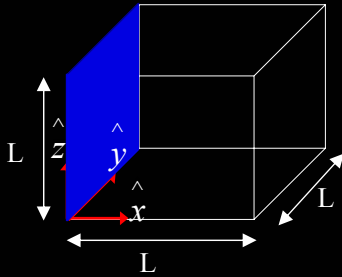
- Reading list now posted online
- Today's lecture online less copyrighted figures
- Today's full lecture @ copy center

Lecture 11: Quantum dots

$$R = ?$$



Particle in a box:



$$\psi(\vec{r}) = (2i)^3 A \cdot \sin(k_{n_x} x) \cdot \sin(k_{n_y} y) \cdot \sin(k_{n_z} z)$$

$$k_{n_x} = n_x \pi / L$$

$$k_{n_y} = n_y \pi / L$$

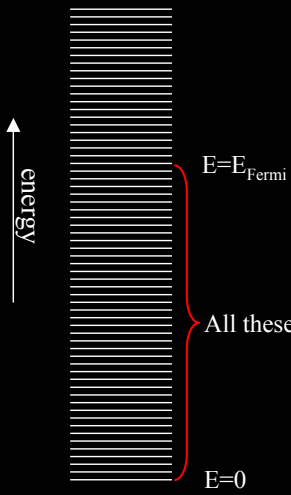
$$k_{n_z} = n_z \pi / L$$

$$E = \frac{\hbar^2 (k_{n_x}^2 + k_{n_y}^2 + k_{n_z}^2)}{2m} = \frac{\hbar^2 (\pi / L)^2}{2m} (n_x^2 + n_y^2 + n_z^2)$$

These are the allowed energy levels, or “quantum states”

Fermi gas:

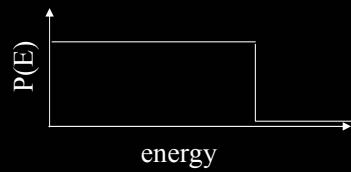
At zero temperature, as we add electrons to the box, we gradually fill up all the states.
(DISCUSS PAULI EXCLUSION PRINCIPLE -IMPORTANT!)



When we are done filling the box, the energy of the last electron is called the "Fermi energy."

"Gas" means we neglect electron-electron interactions.

All these states are filled with electrons.



Particle in a box:

$$\psi(\vec{r}) = (2i)^3 A \cdot \sin(k_{n_x} x) \cdot \sin(k_{n_y} y) \cdot \sin(k_{n_z} z)$$



$$k_{n_x} = n_x \pi / L_x$$

$$k_{n_y} = n_y \pi / L_y$$

$$k_{n_z} = n_z \pi / L_z$$

$$E = \frac{\hbar^2 (k_{n_x}^2 + k_{n_y}^2 + k_{n_z}^2)}{2m} = \frac{\hbar^2}{2m} \left[\left(\frac{\pi}{L_x} \right)^2 n_x^2 + \left(\frac{\pi}{L_y} \right)^2 n_y^2 + \left(\frac{\pi}{L_z} \right)^2 n_z^2 \right]$$

These are the allowed energy levels, or “quantum states”

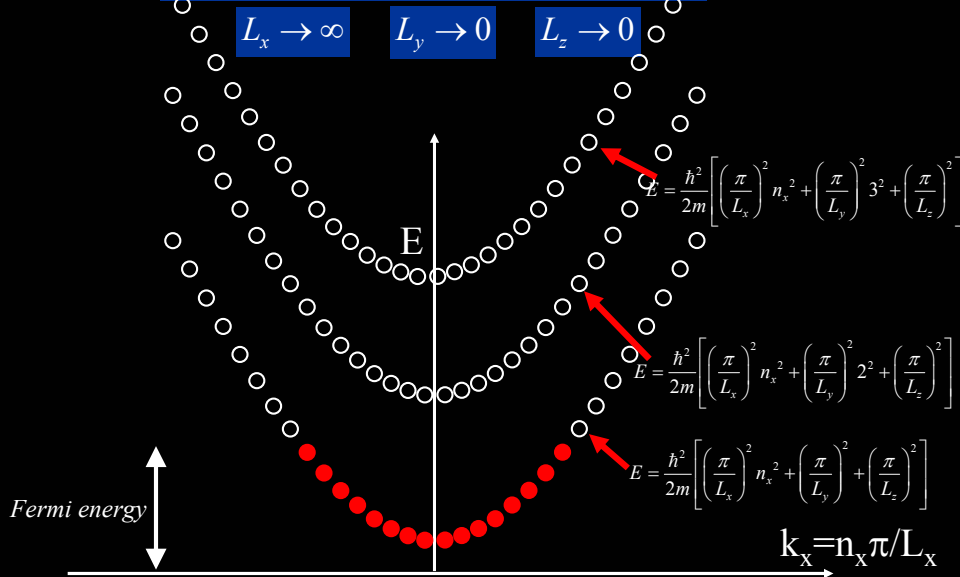
1d system:

$$E = \frac{\hbar^2(k_{n_x}^2 + k_{n_y}^2 + k_{n_z}^2)}{2m} = \frac{\hbar^2}{2m} \left[\left(\frac{\pi}{L_x} \right)^2 n_x^2 + \left(\frac{\pi}{L_y} \right)^2 n_y^2 + \left(\frac{\pi}{L_z} \right)^2 n_z^2 \right]$$

$$L_x \rightarrow \infty$$

$$L_y \rightarrow 0$$

$$L_z \rightarrow 0$$



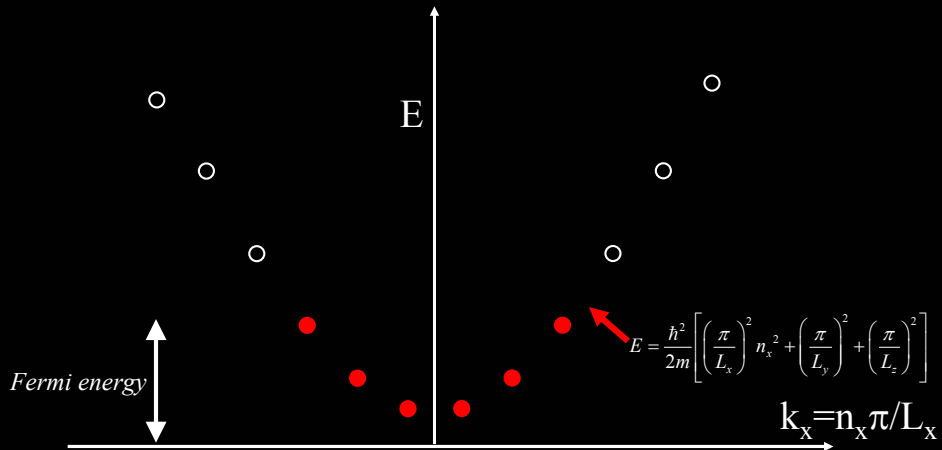
0d system:

$$E = \frac{\hbar^2(k_{n_x}^2 + k_{n_y}^2 + k_{n_z}^2)}{2m} = \frac{\hbar^2}{2m} \left[\left(\frac{\pi}{L_x} \right)^2 n_x^2 + \left(\frac{\pi}{L_y} \right)^2 n_y^2 + \left(\frac{\pi}{L_z} \right)^2 n_z^2 \right]$$

$$L_x \rightarrow 0$$

$$L_y \rightarrow 0$$

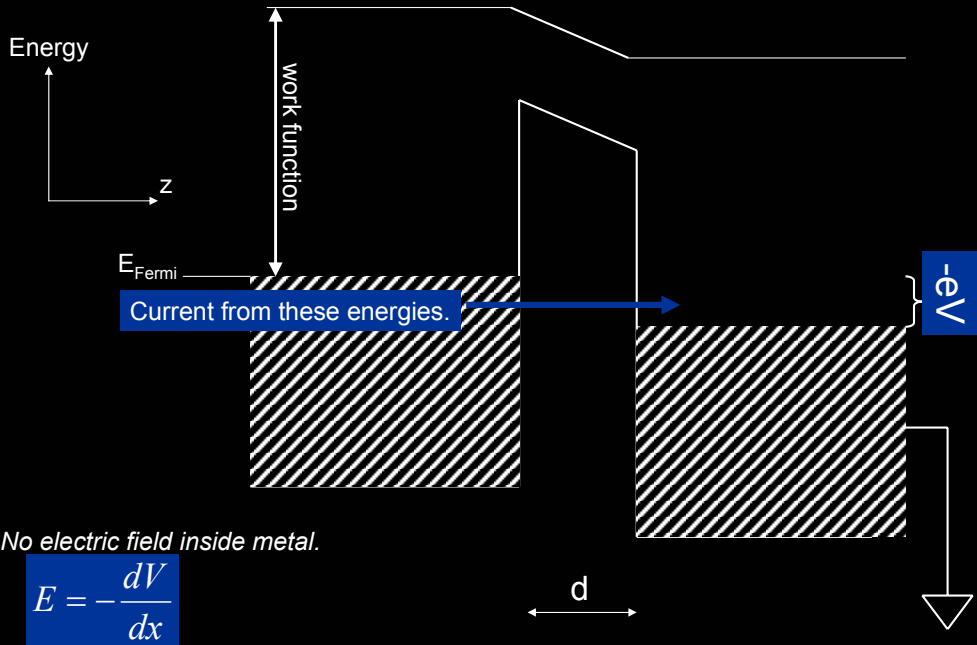
$$L_z \rightarrow 0$$



Energy scales

- Charging energy
- Single electron energy level spacing
- Temperature

Continuum band diagrams like this no longer apply



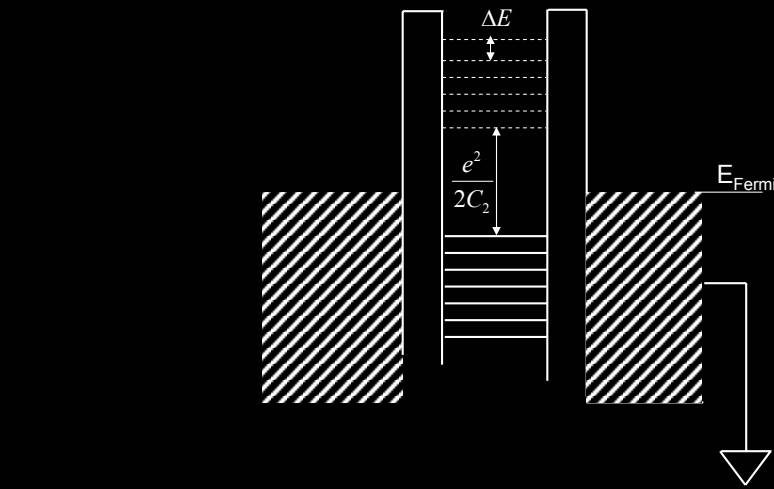
No electric field inside metal.

$$E = -\frac{dV}{dx}$$

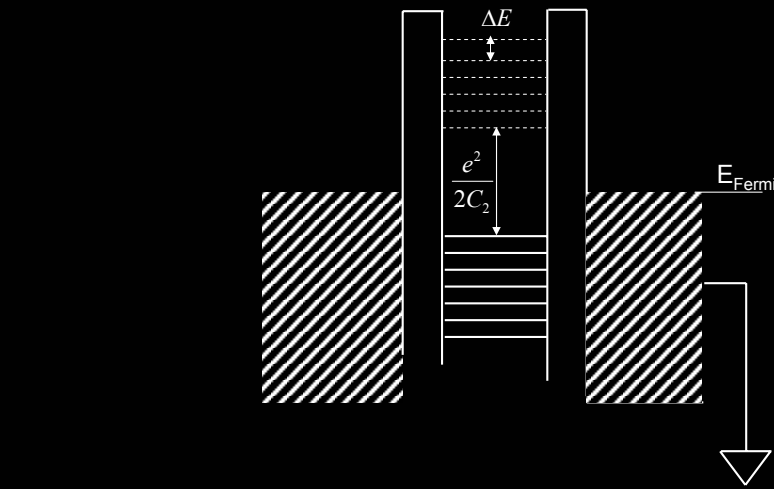
Band diagram with Coulomb "gap"



Band diagram with Coulomb "gap" and accounting for 0d states:



Band diagram with Coulomb "gap" and accounting for 0d states:



Experimental realization w/2DEGS

- <http://marcuslab.harvard.edu/res.php>

Results

From J.P. Kouwenhoven, C.M. Marcus, P.L. McEuen, S. Tarucha, R.M. Westervelt, and N.S. Wingreen
Electron Transport in Quantum Dots
Nato ASI conference proceedings, ed. By L. P. Kouwenhoven, G. Schöen, L.L. Sohn (Kluwer, Dordrecht, 1997)

Artificial atoms

Leo Kouwenhoven and Charles Marcus
Quantum Dots
Physics World, June 1998

Coulomb diamonds

Leo Kouwenhoven and Charles Marcus
Quantum Dots
Physics World, June 1998

Artificial molecules

From J.P. Kouwenhoven, C.M. Marcus, P.L. McEuen, S. Tarucha, R.M. Westervelt, and N.S. Wingreen
Electron Transport in Quantum Dots
Nato ASI conference proceedings, ed. By L. P. Kouwenhoven, G. Schönik, L.L. Sohn (Kluwer, Dordrecht, 1997)

Metallic quantum dots

Spectroscopy of Discrete Energy Levels in Ultrasmall Metallic Grains, Jan von Delft and D. C. Ralph, [Physics Reports 345, 61 \(2001\)](#).

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Molecular electronics

J. Heath, Physics Today, May 2003

Molecular electronics

J. Heath, Physics Today, May 2003

Molecular electronics

"Coulomb blockade and the Kondo effect in single-atom transistors," Jiwoong Park, Abhay N. Pasupathy, Jonas I. Goldsmith, Connie Chang, Yuval Yaish, Jason R. Petta, Marie Rinkoski, James P. Sethna, Hector D. Abruna, Paul L. McEuen & Daniel C. Ralph, *Nature*, 417, 722-725 (2002).