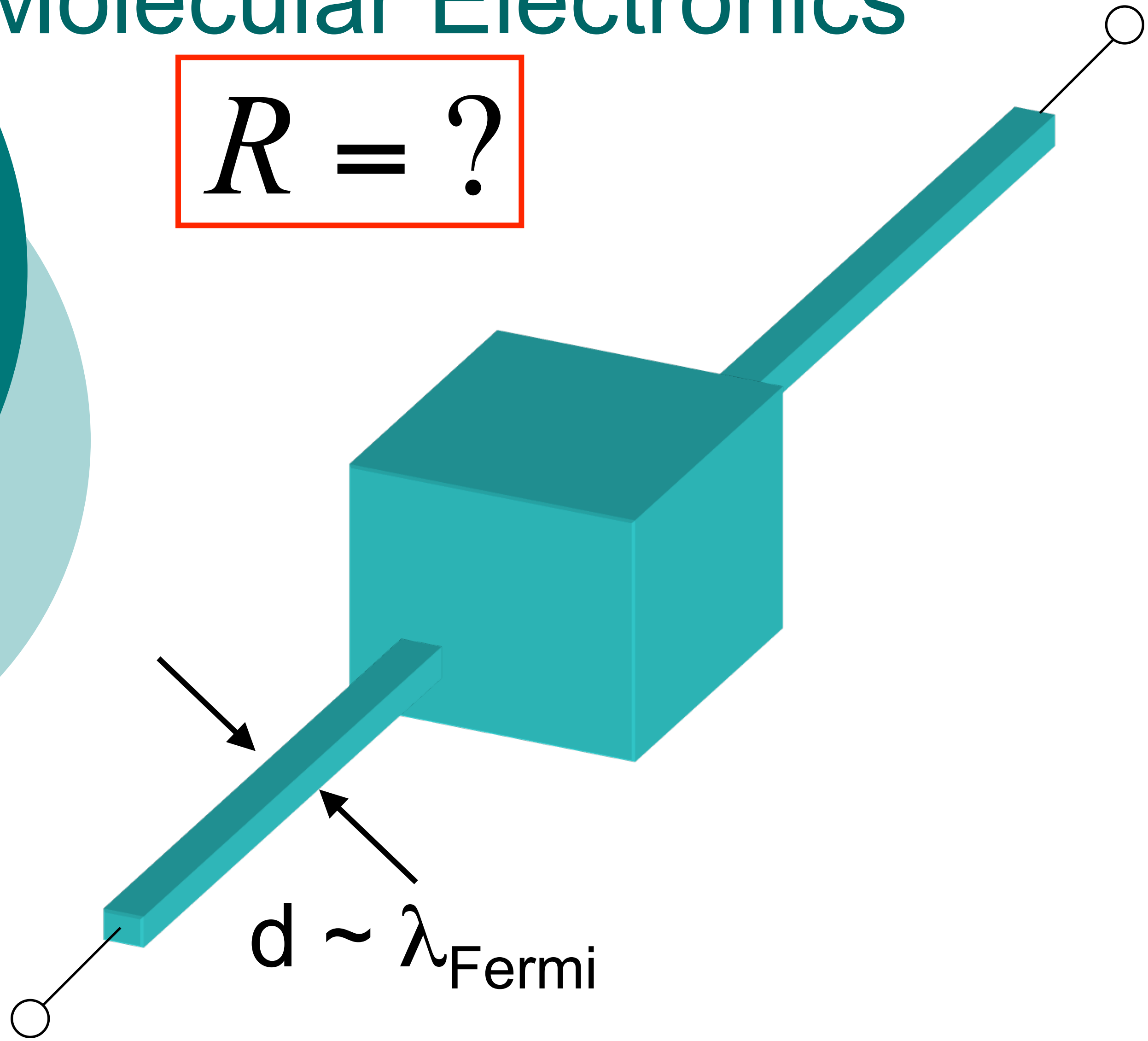
Lecture 13: Quantum dots and Molecular Electronics

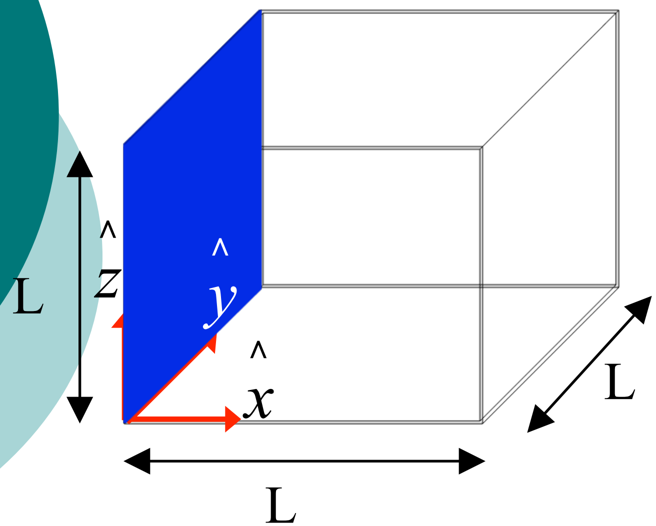
$$R = ?$$



Readings that cover this lecture

- Ferry, pp. 209-226
- Hanson, pp. 125-127

Particle in a box



We can do the same for y, z:

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

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

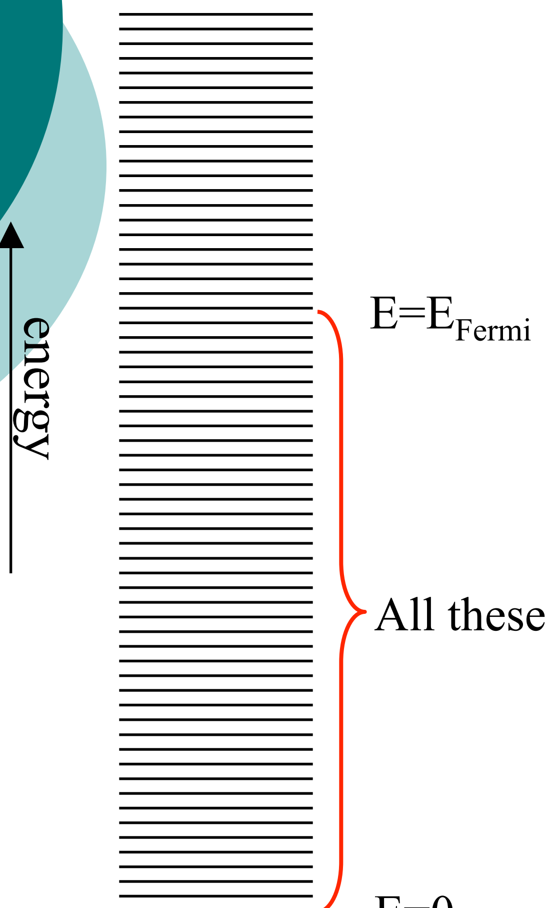
$$k_{n_y} = n_y \pi / L$$

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

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

These are the allowed energy levels, or "quantum states"

Fermi gas

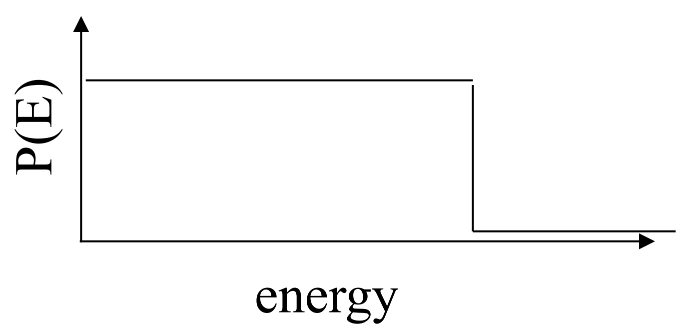


At zero temperature, as we add electrons to the box, we gradually fill up all the states. (DISCUSS PAULI EXCLUSION PRINCIPLE -IMPORTANT!)

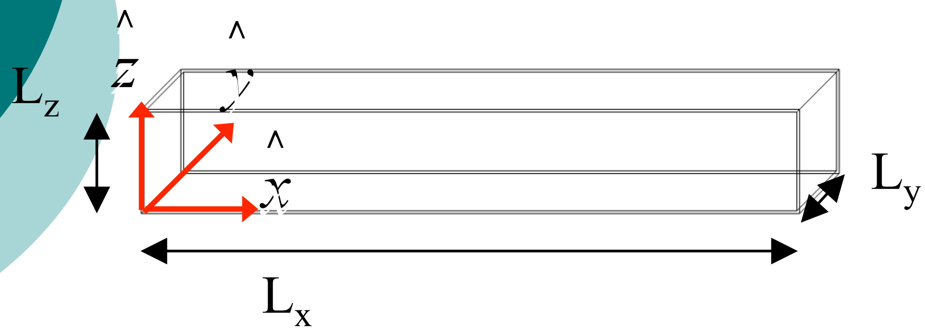
When we are done filling the box, the energy of the last electron is called the "Fermi energy."

"Gas" means we neglect electron-electron interactions.

All these states are filled with electrons.



Particle in a box



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

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

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

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

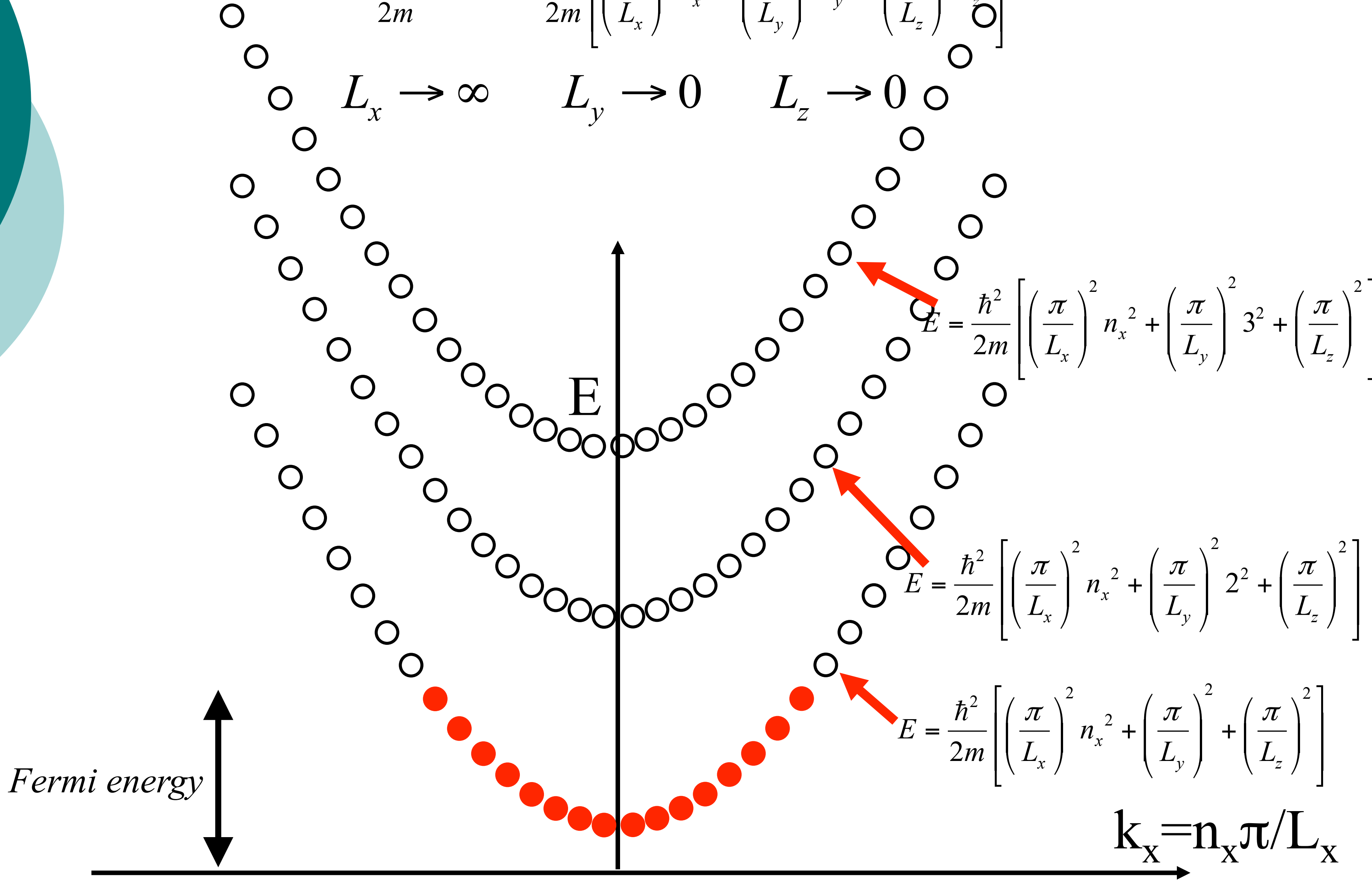
$$E = \frac{\hbar^2 (k_{n_x}{}^2 + k_{n_y}{}^2 + k_{n_z}{}^2)}{2m} = \frac{\hbar^2}{2m}\left[\left(\frac{\pi}{L_x}\right)^2 n_x{}^2 + \left(\frac{\pi}{L_y}\right)^2 n_y{}^2 + \left(\frac{\pi}{L_z}\right)^2 n_z{}^2\right]$$

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

1d system:

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

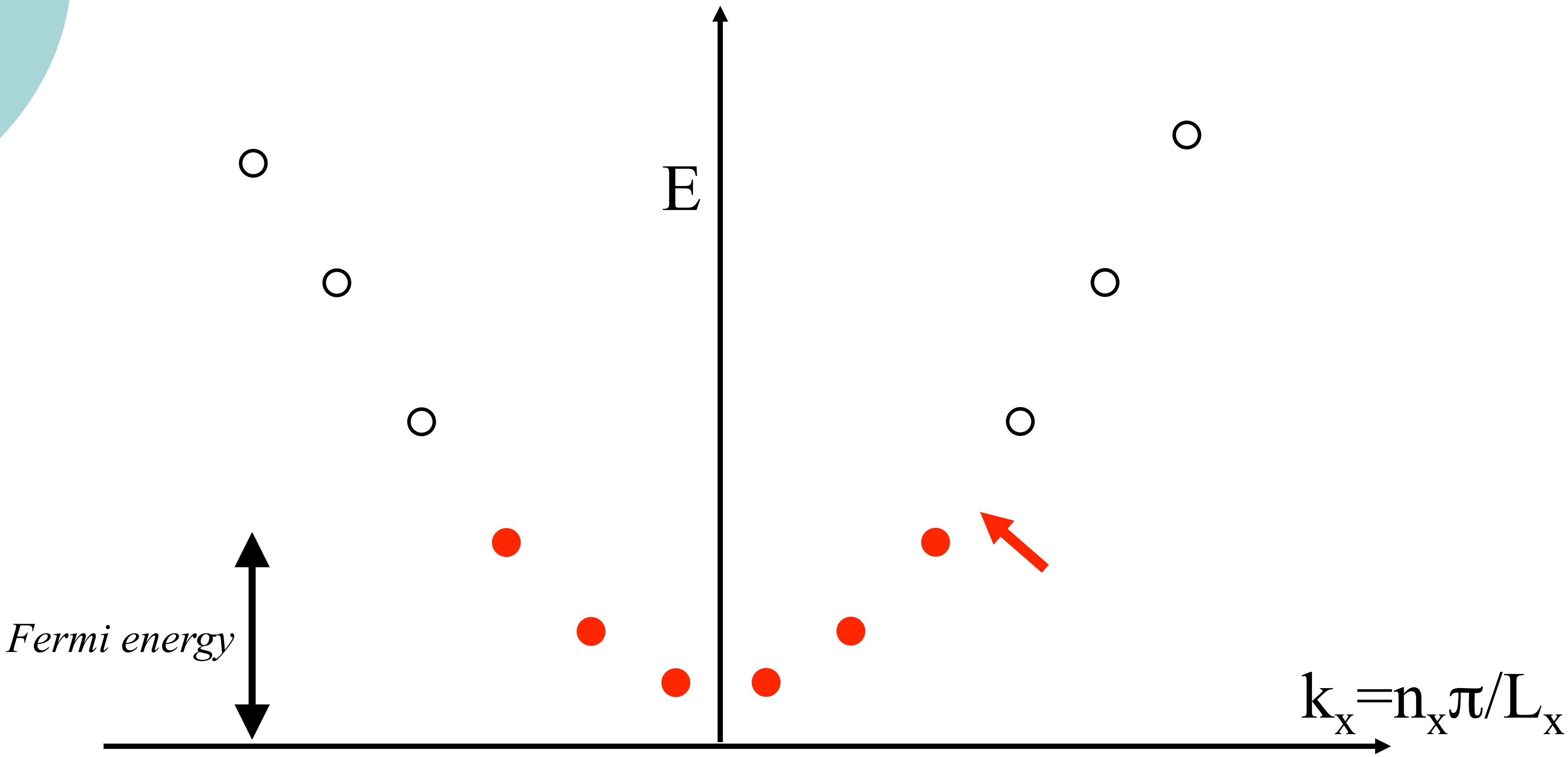
$$L_x\to\infty \qquad L_y\to 0 \qquad L_z\to 0$$



0d system

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

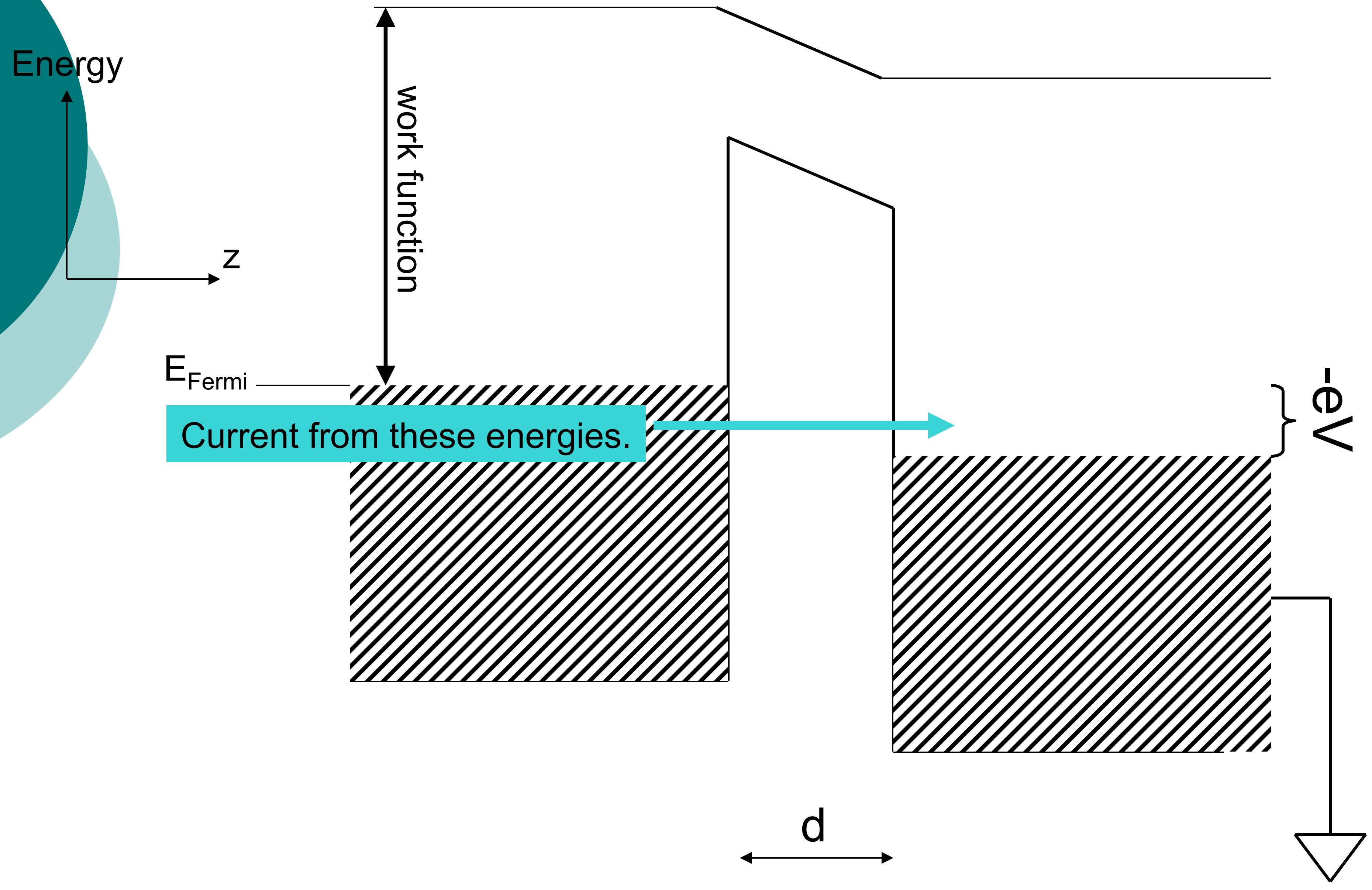
$$L_x \to 0 \qquad L_y \to 0 \qquad L_z \to 0$$



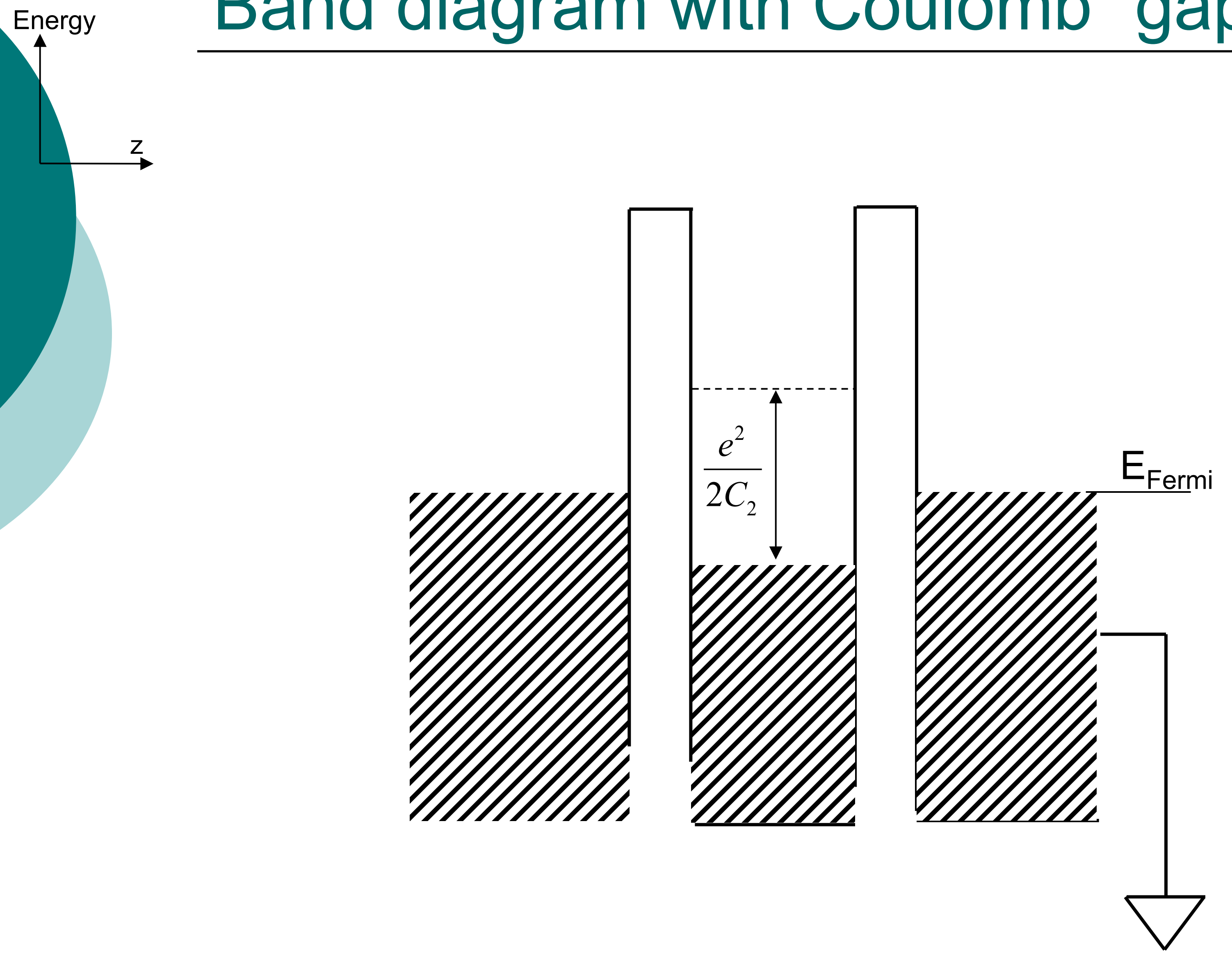
Energy scales

- Charging energy
- Single electron energy level spacing
- Temperature

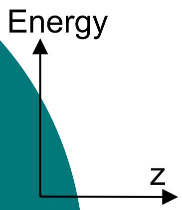
Continuum band diagrams like this no longer apply

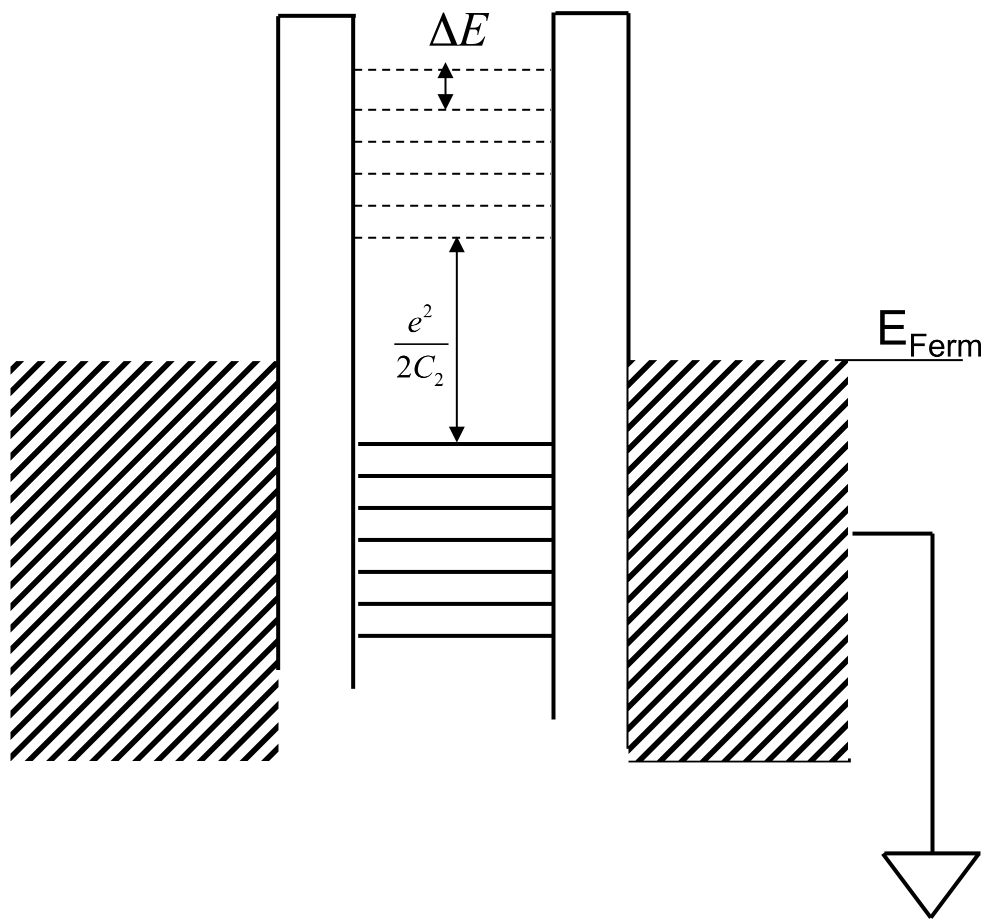


Band diagram with Coulomb "gap"

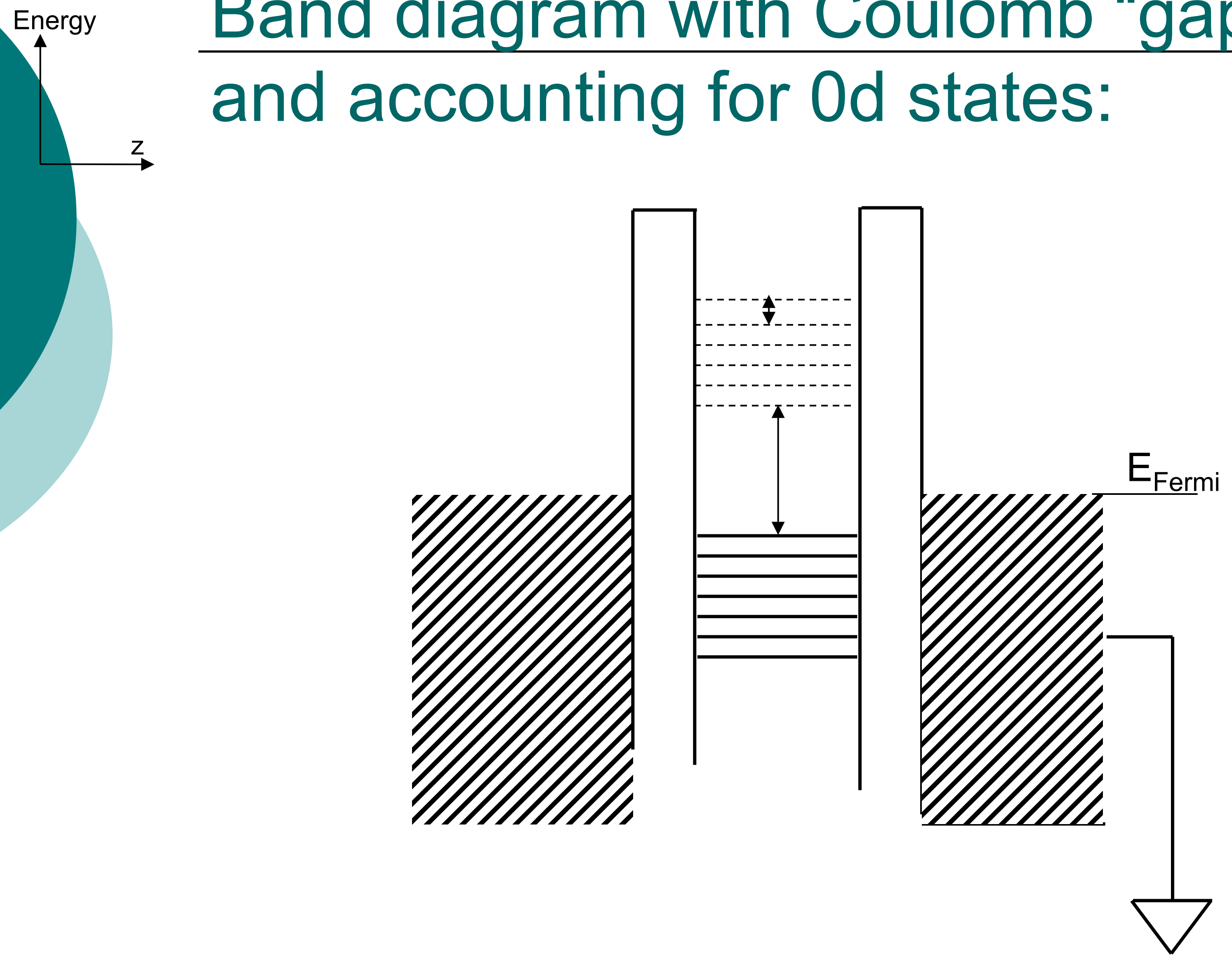


Band diagram with Coulomb "gap" and accounting for 0d states:

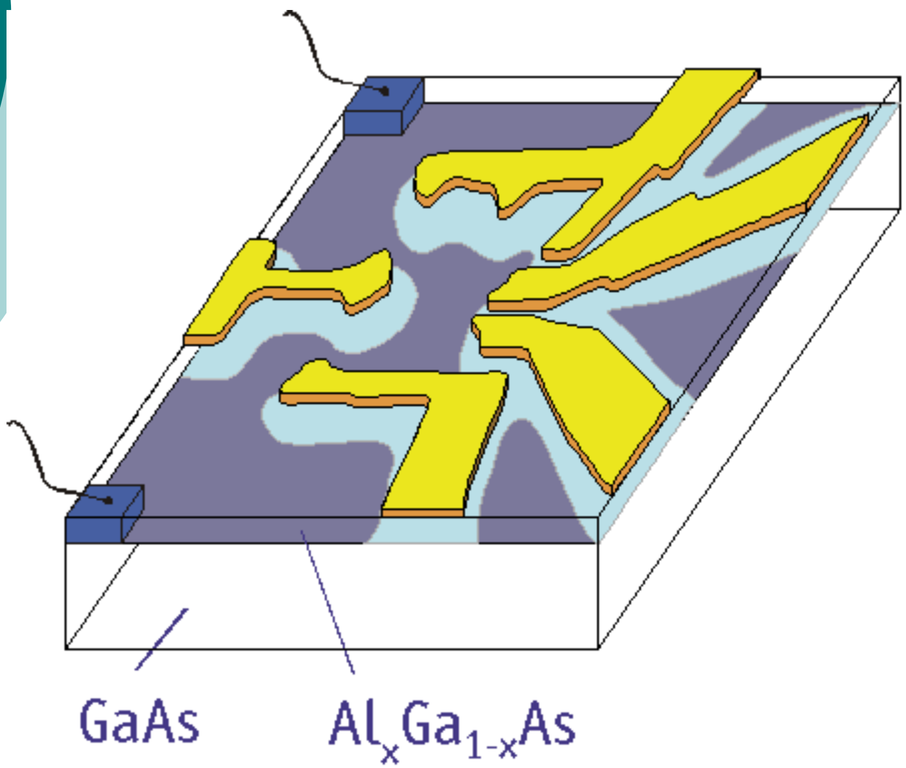


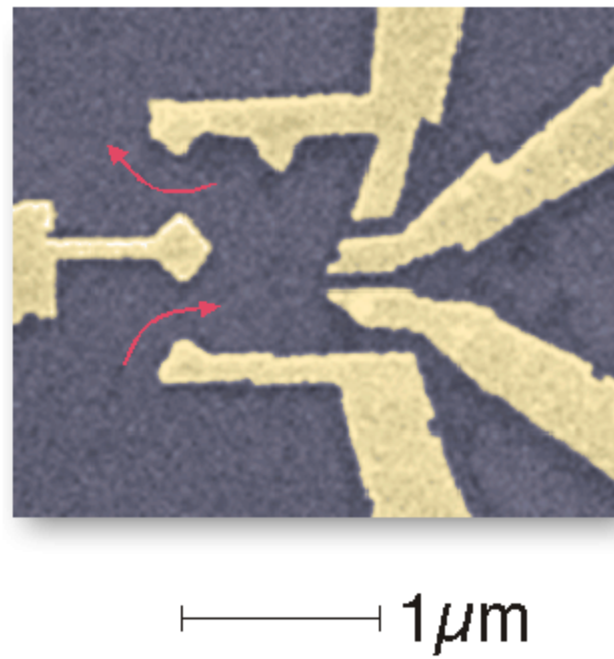


Band diagram with Coulomb "gap" and accounting for 0d states:



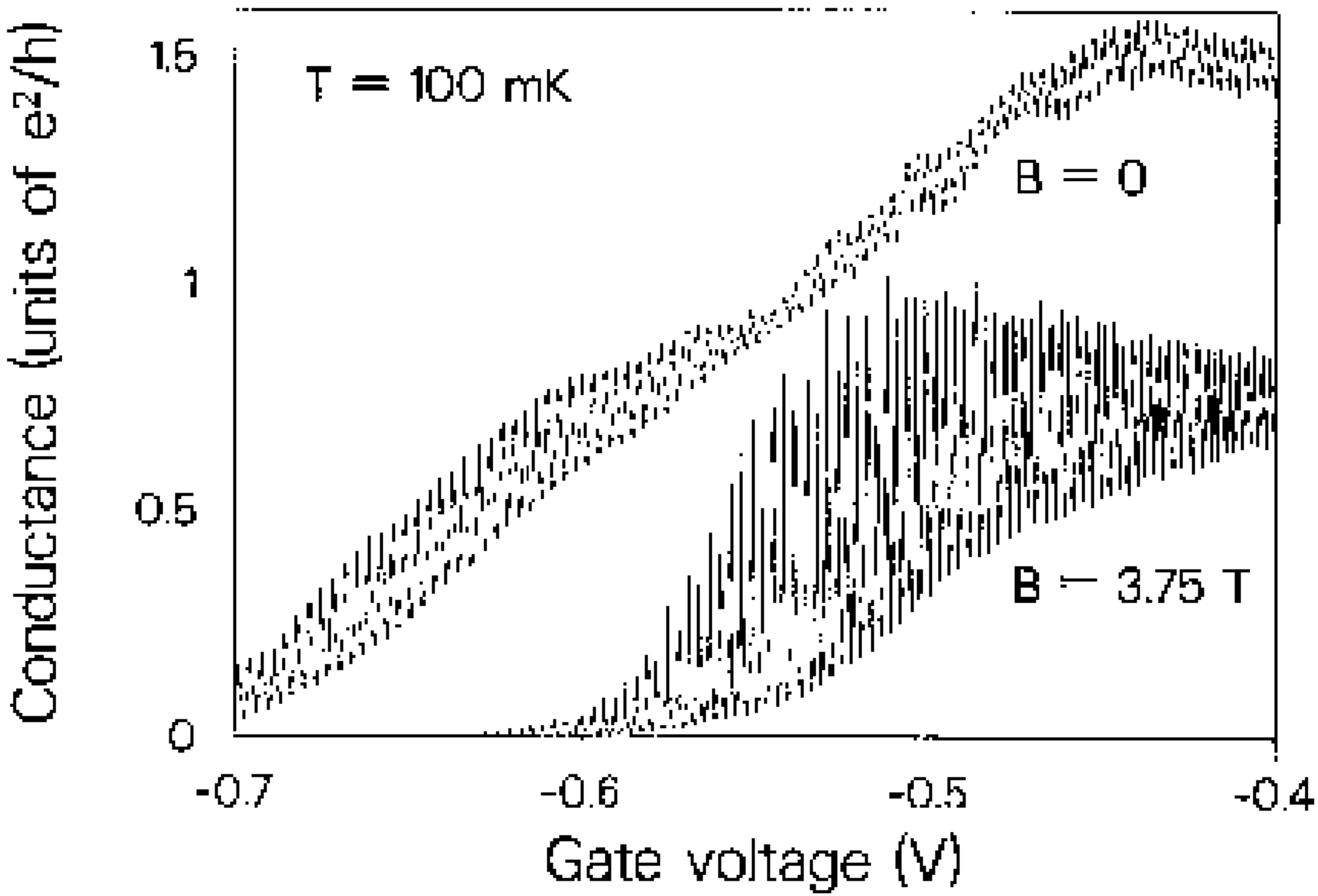
Experimental realization w/2DEGS





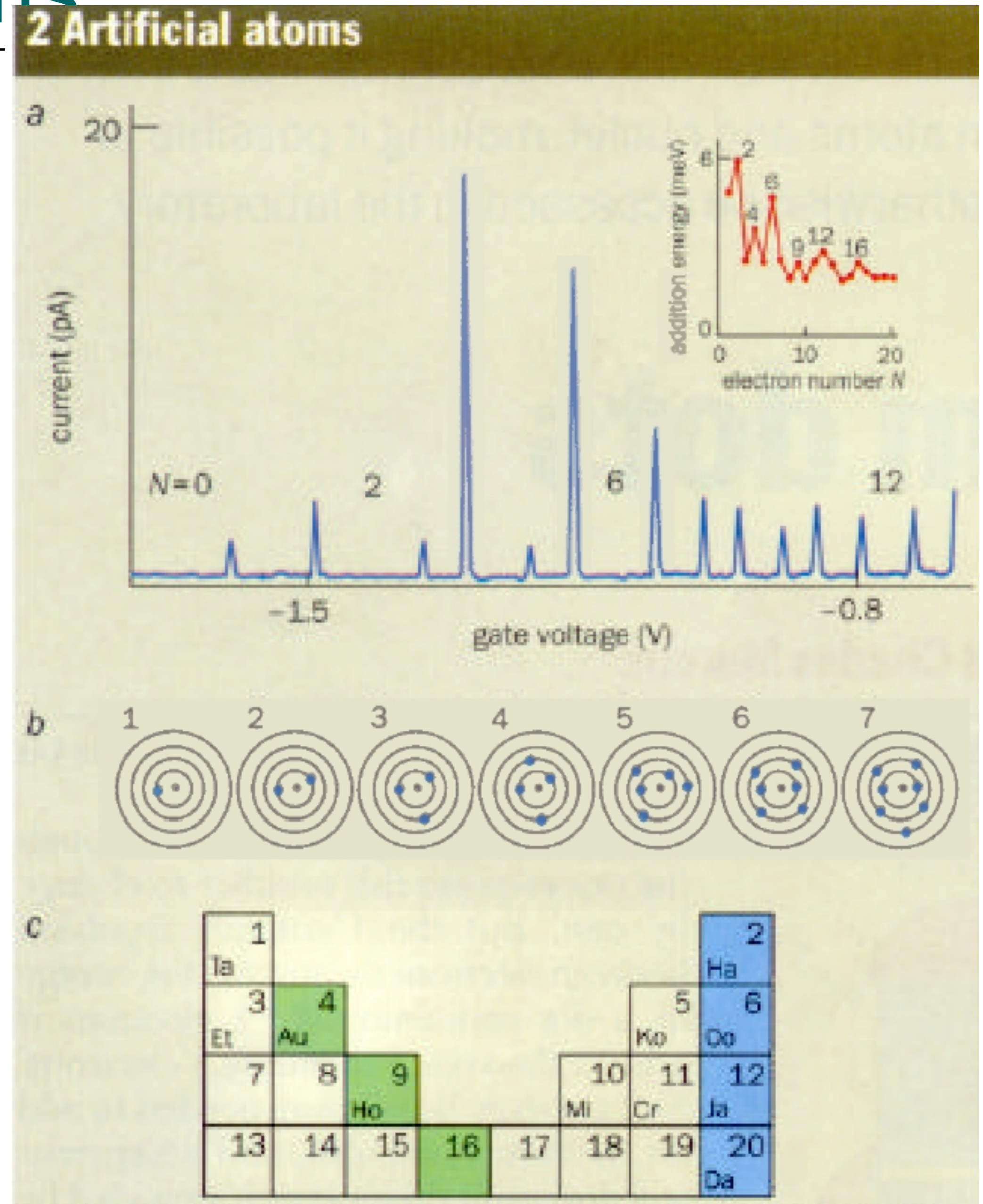
- http://marcuslab.harvard.edu/res.php

Results



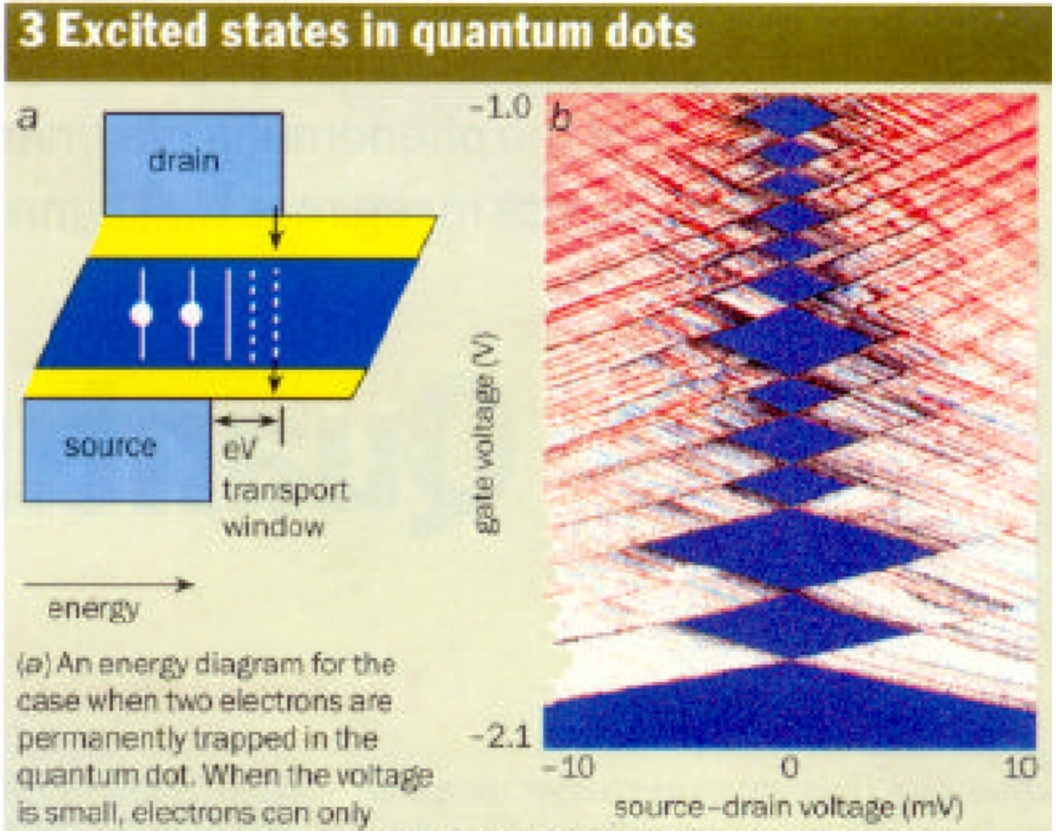
From .P. Kouwenhoven, C.M. Marcus, P.L. McEuen, S. Tarucha, R.M. Westervelt, and N.S. Wingreen
Electron Transport in Quantum Dots
Nato ASI conference proceedings, ed. By L. P. Kouwenhoven, G. Schön, L.L. Sohn (Kluwer, Dordrecht, 1997

Artificial atoms



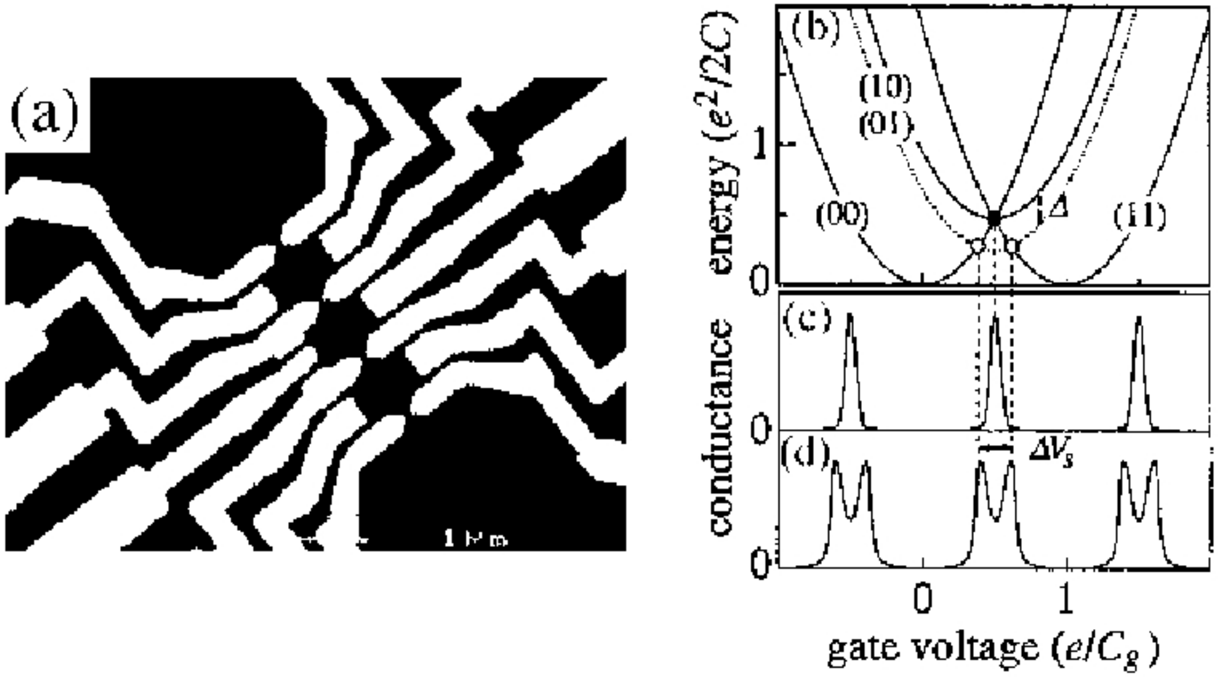
Leo Kouwenhoven and Charles Marcus
Quantum Dots
Physics World, June 1998

Coulomb diamonds



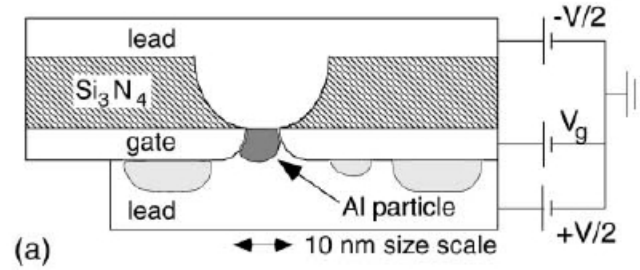
Leo Kouwenhoven and Charles Marcus
Quantum Dots
Physics World, June 1998

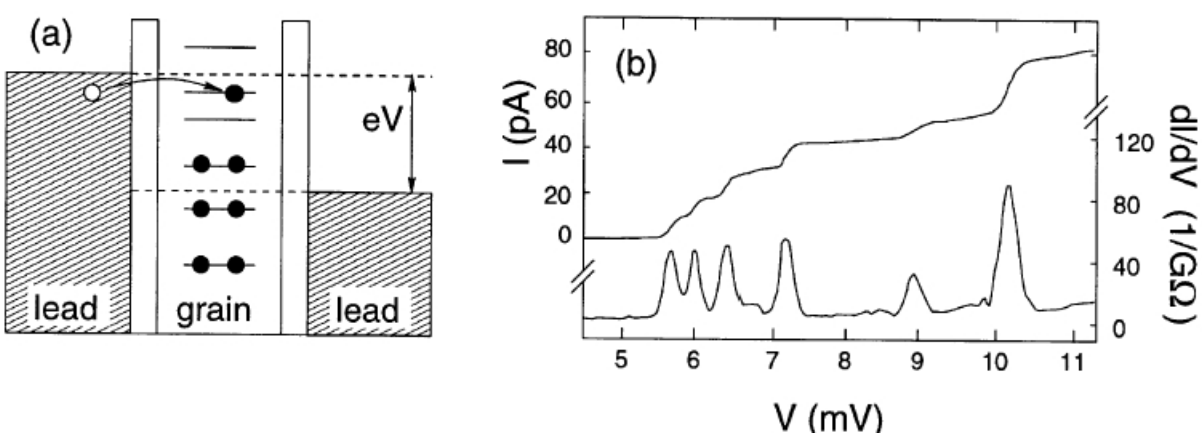
Artificial molecules



From .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. Schön, L.L. Sohn (Kluwer, Dordrecht, 1997

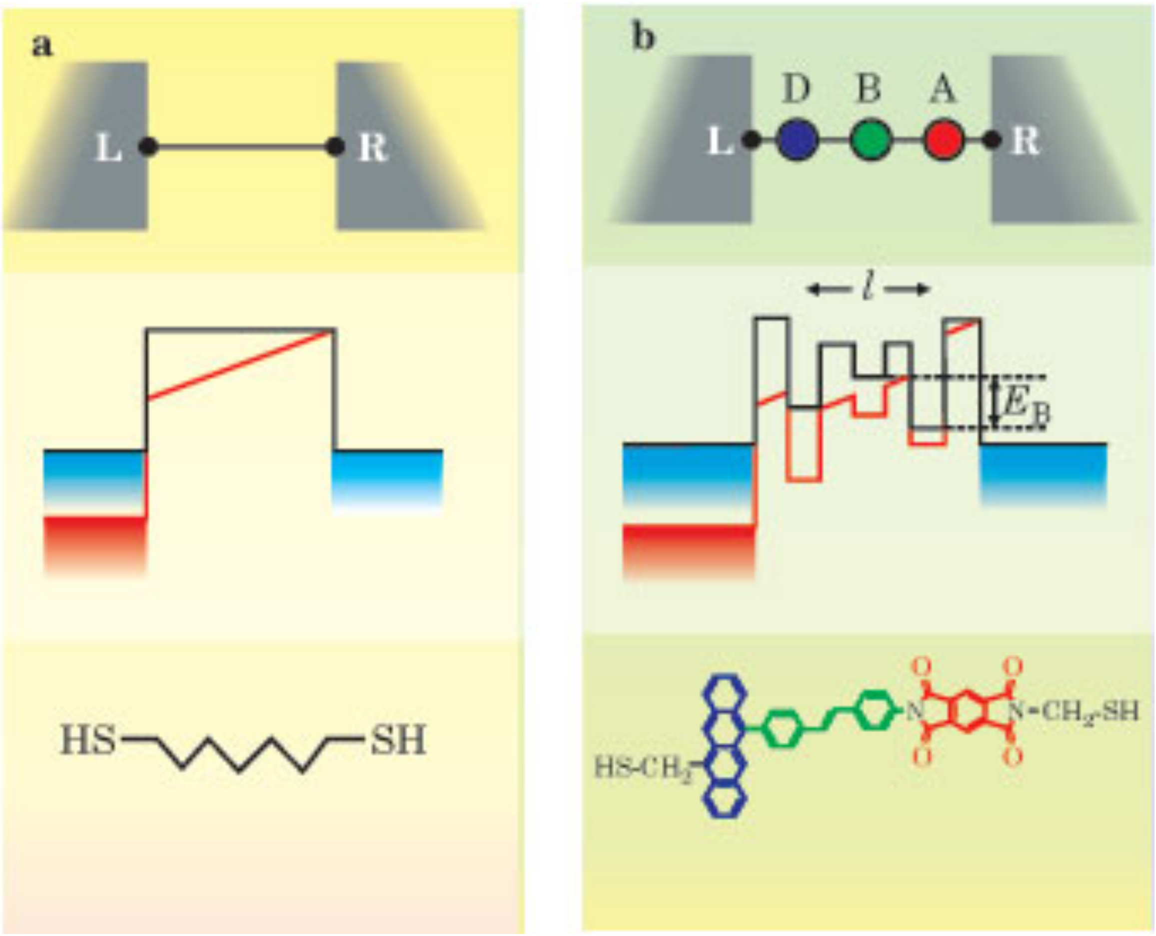
Metallic quantum dots





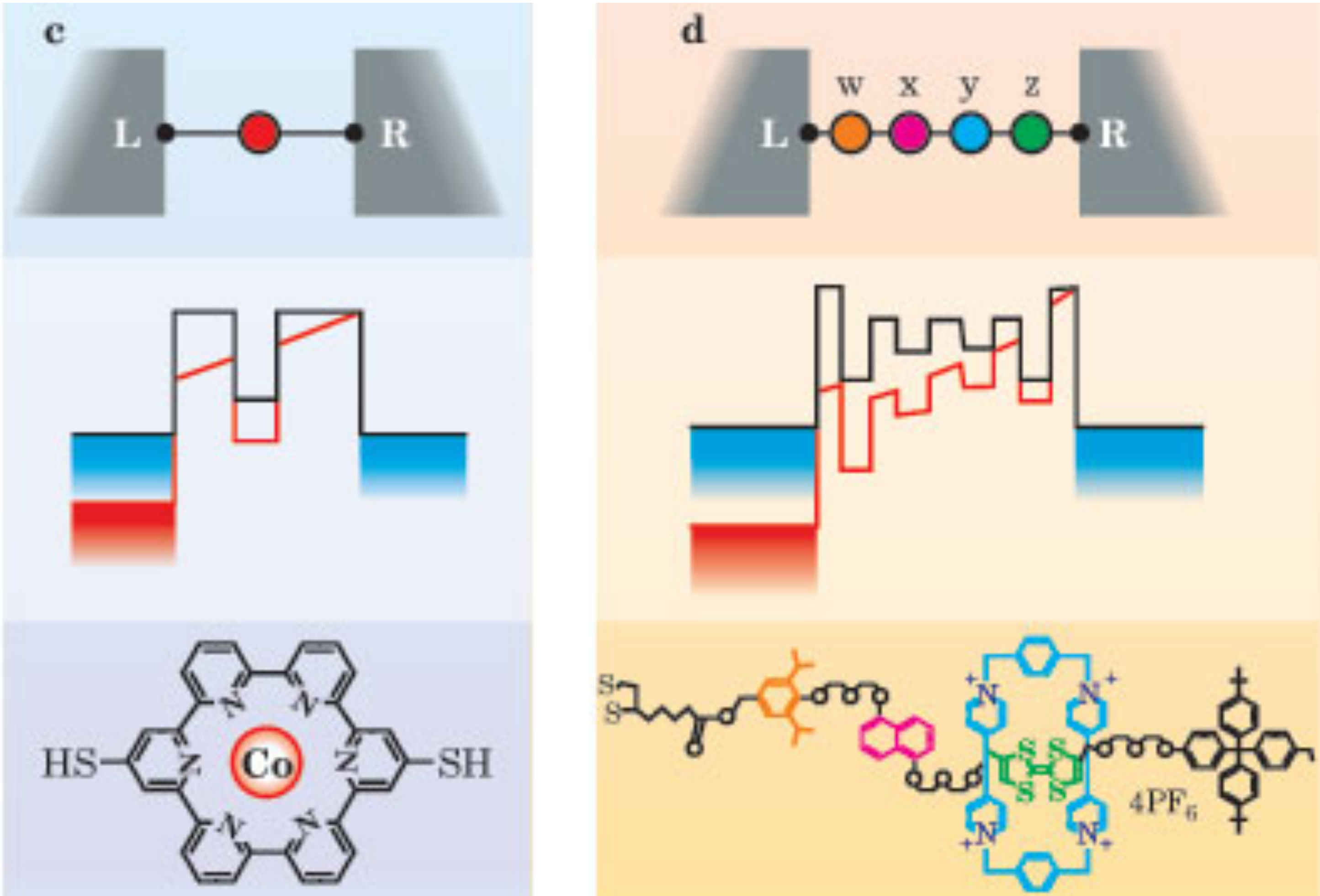
Spectroscopy of Discrete Energy Levels in Ultrasmall Metallic Grains, Jan von Delft and D. C. Ralph, *Physics Reports* **345**, 61 (2001).

Molecular electronics



J. Heath, Physics Today, May 2003

Molecular electronics



J. Heath, Physics Today, May 2003

Molecular electronics

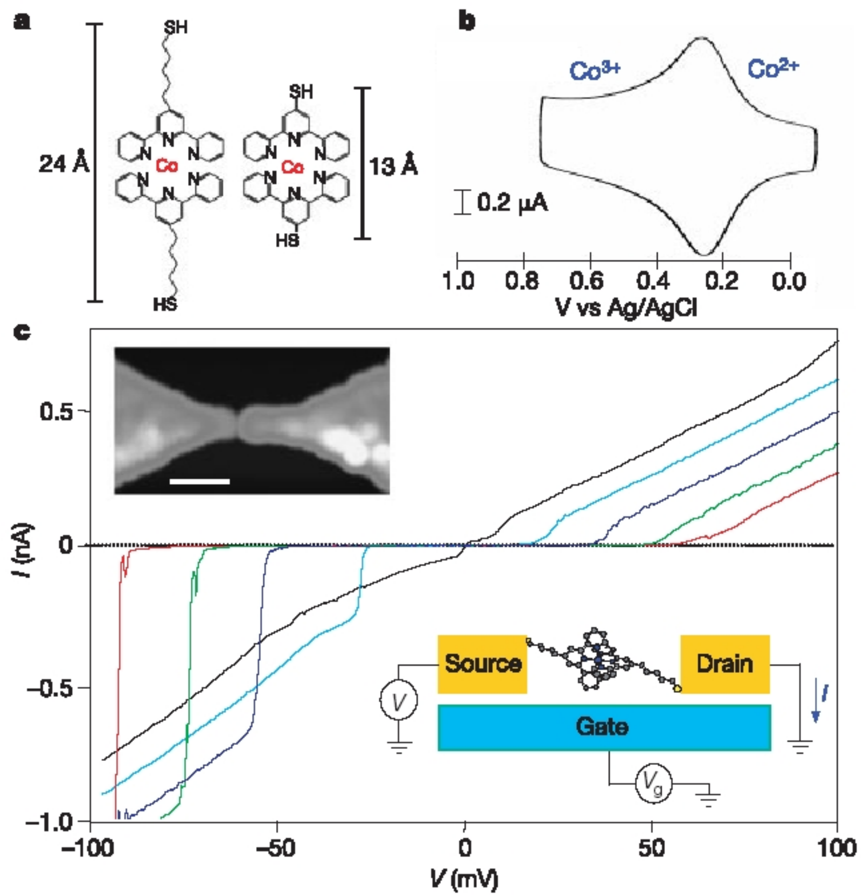
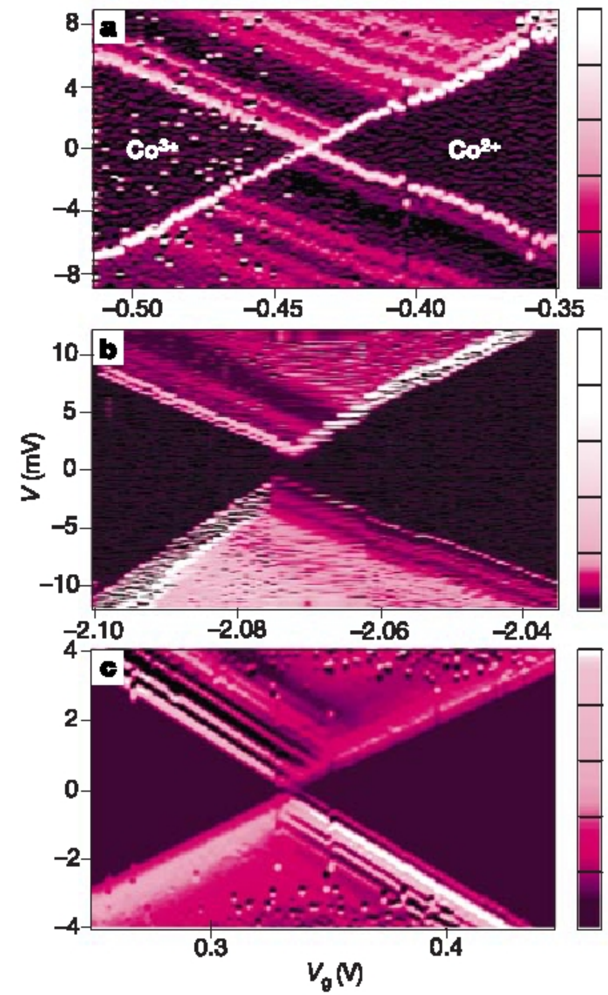


Figure 1 The molecules used in this study and their electronic properties. **a**, Structure of $[Co(tpy\text{-}(CH_2)_5\text{-}SH)_2]^{2+}$ (where tpy-$(CH_2)_5$-SH is 4′-(5-mercaptopentyl)-2,2′:6′,2″-terpyridinyl) and $[Co(tpy\text{-}SH)_2]^{2+}$ (where tpy-SH is 4′-(mercapto)-2,2′:6′,2″-terpyridinyl). The scale bars show the lengths of the molecules as calculated by energy minimization.



"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).