Structure of Matter
The Solid State

WS 2013/14

Lectures (Tuesday & Friday)

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www.ph2.uni-koeln.de
http://www.ph2.uni-koeln.de/527.html

Last time:

Metals (free electron model) cont'd

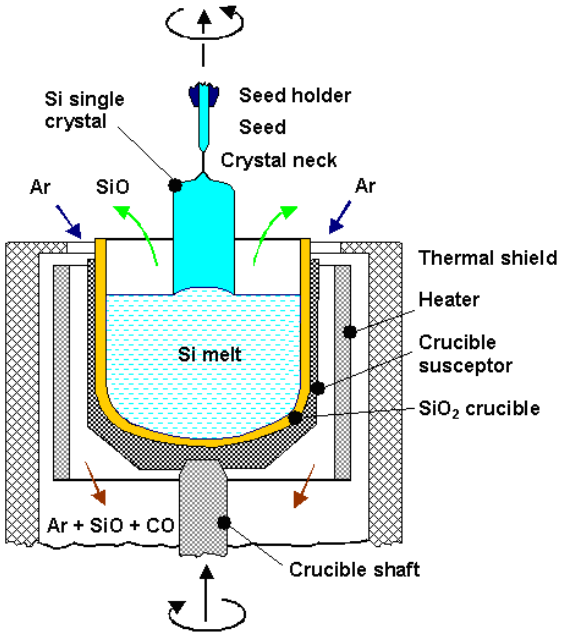
Band structure

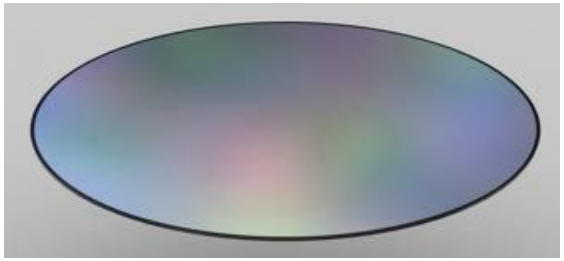
Today:

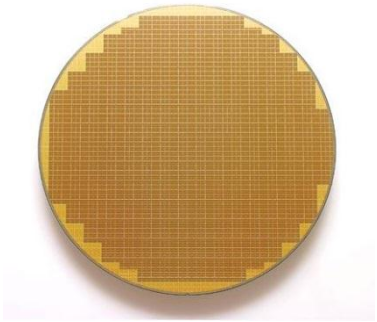
Band structure cont'd, semiconductors

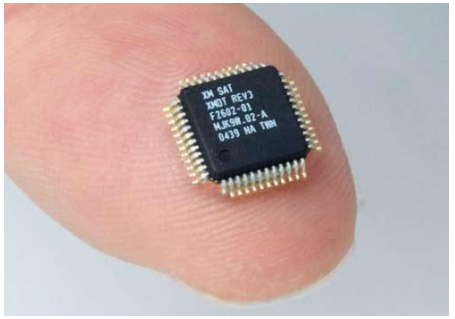
Today

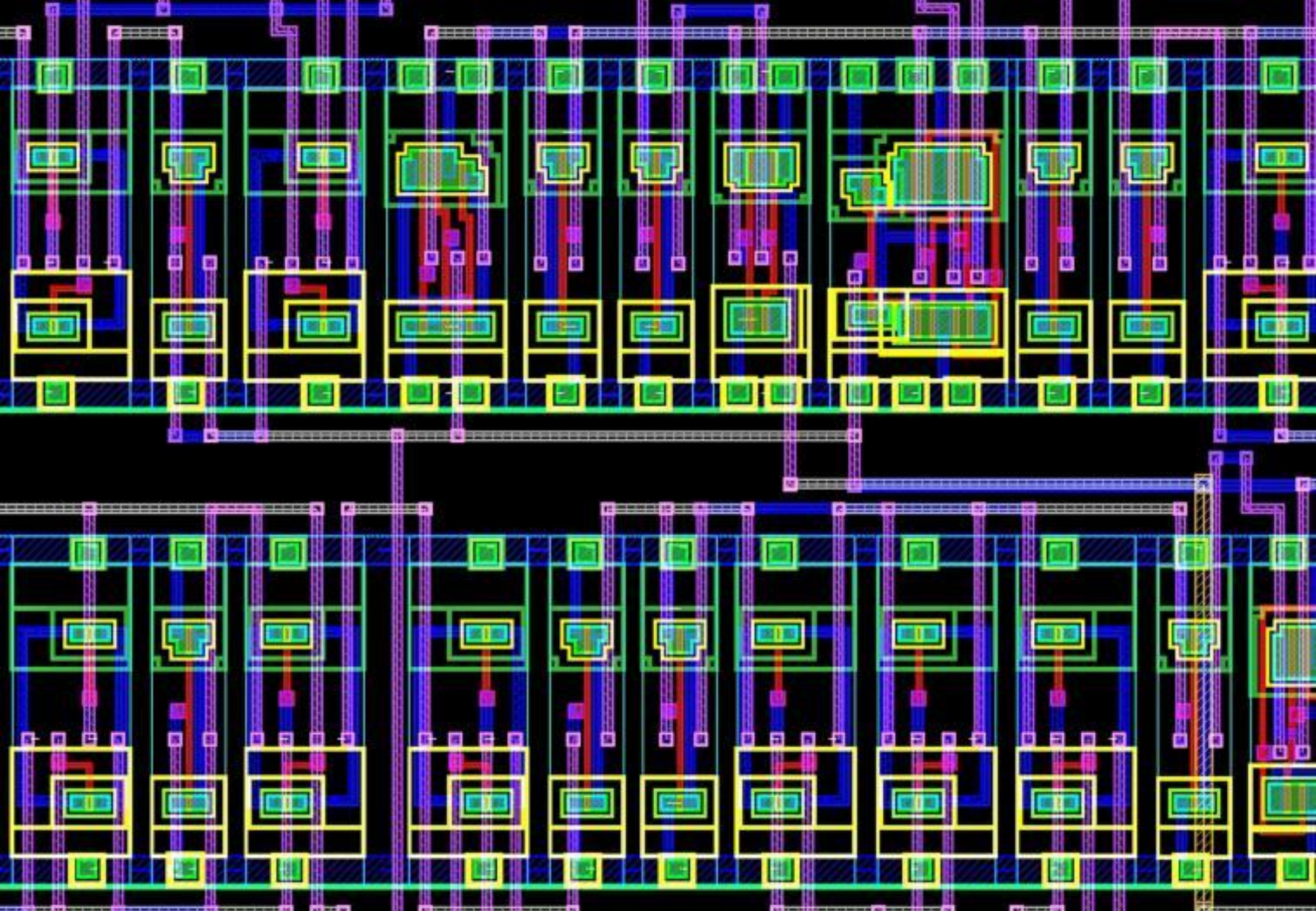
- Semiconductors and semiconductor devices







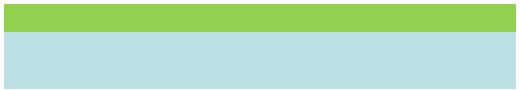




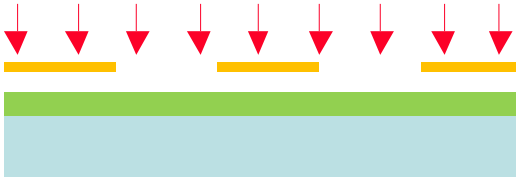
The etching process

Wafer

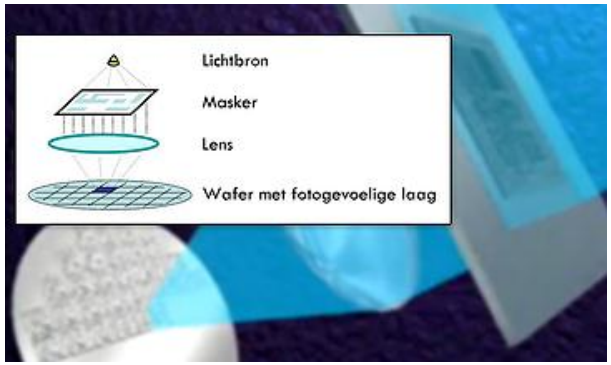
Coating with Photoresist



Bake



Expose mask image



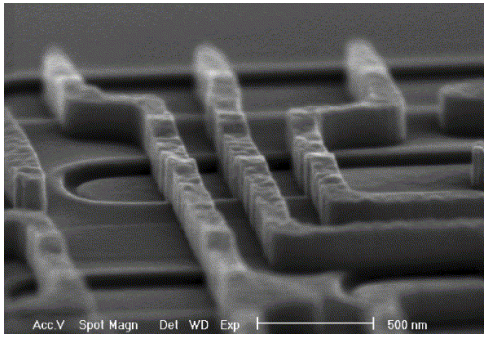
Post-Exposure Bake

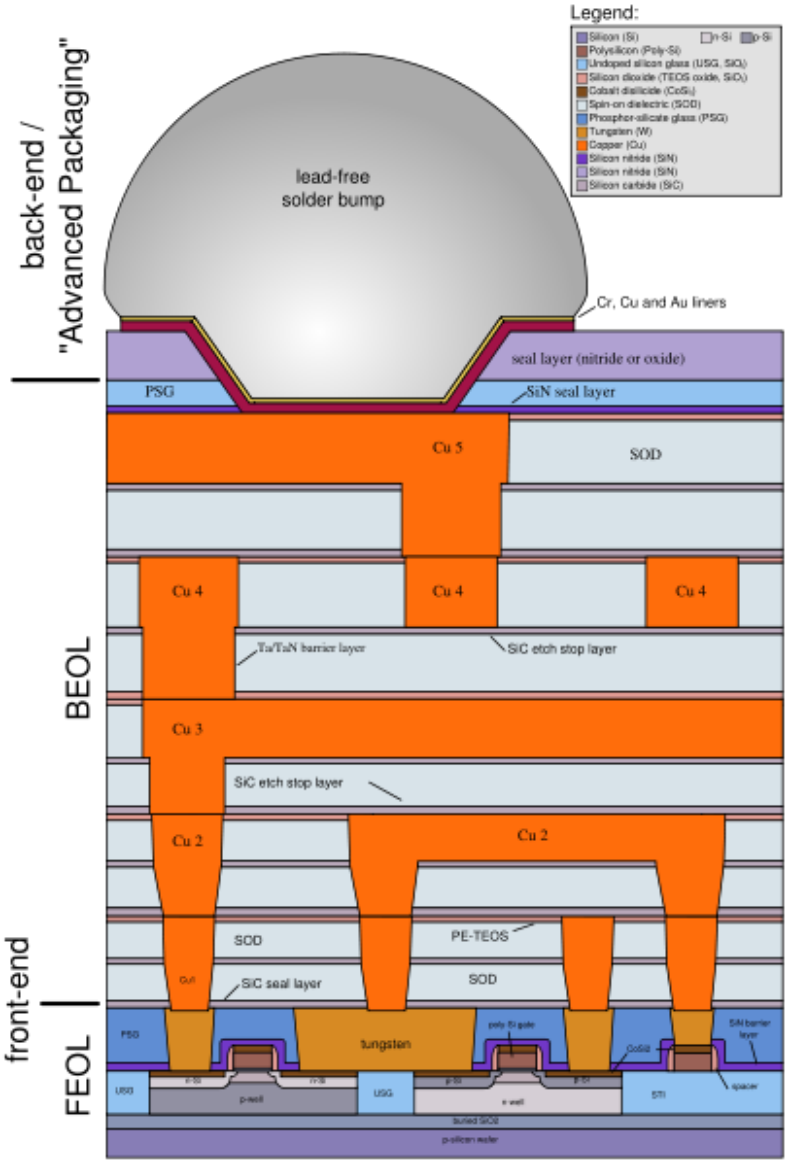
Develop

Etch, Implant, etc.

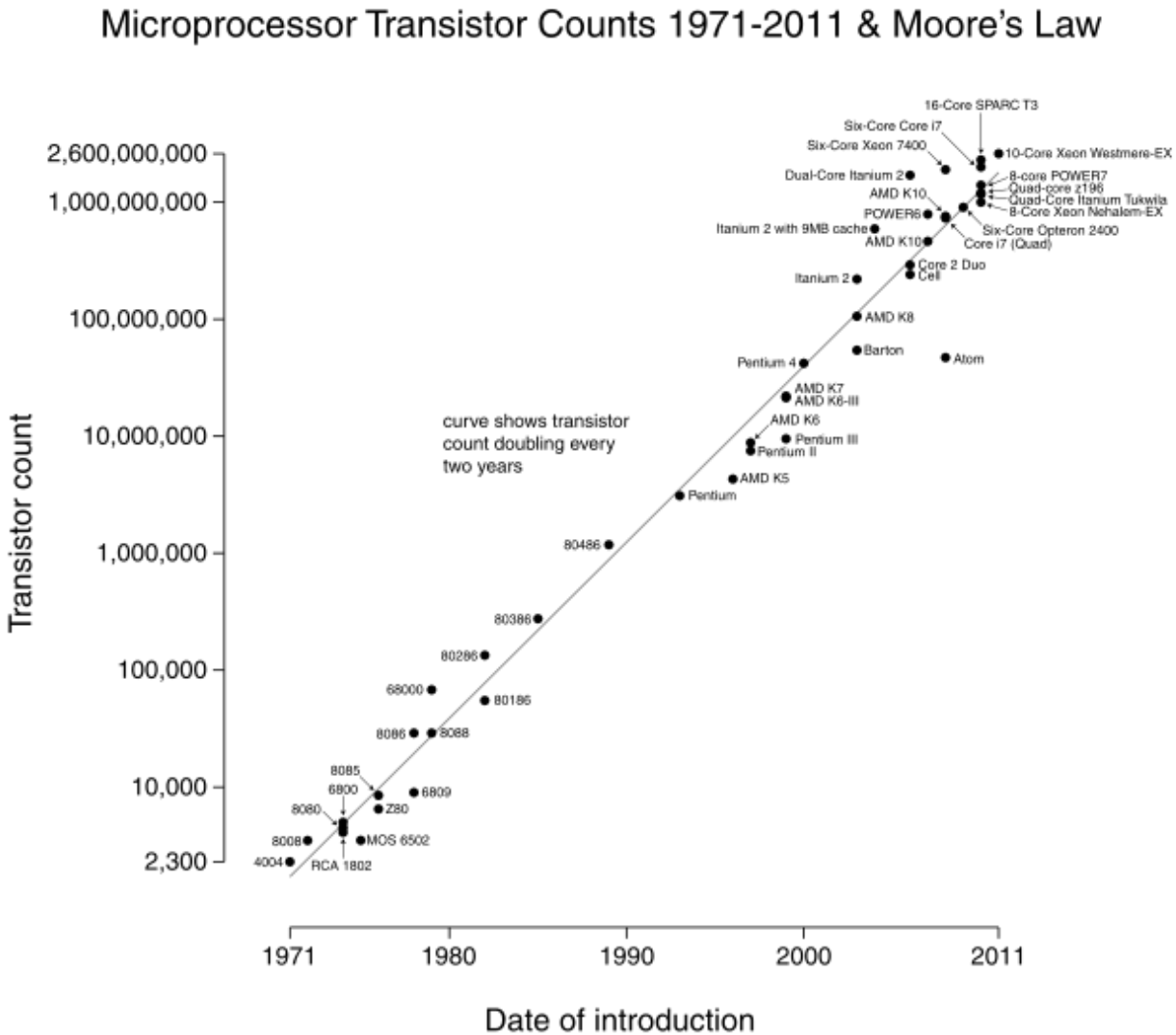
Remove PR

ASML · World leader in waferstepper





Moore law



transitors on a chip doubles every 2 years

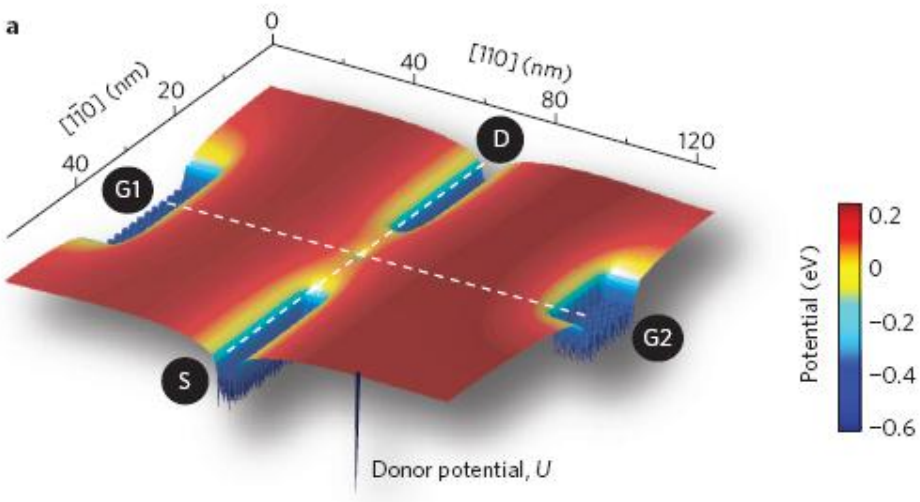
In 2020's:
single atom level

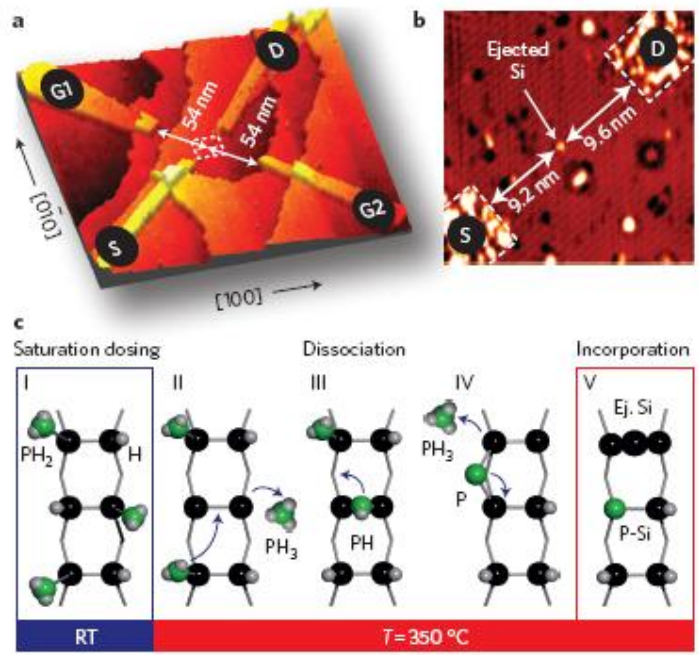
Single atom transistor

LETTERS
PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21
nature nanotechnology

A single-atom transistor

Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*





Semiconductors

Direct gap / Indirect gap
Intrinsic / Extrinsic
Homogeneous / Inhomogeneous

Diamond band structure

VOLUME 16, NUMBER 9 PHYSICAL REVIEW LETTERS 28 FEBRUARY 1966

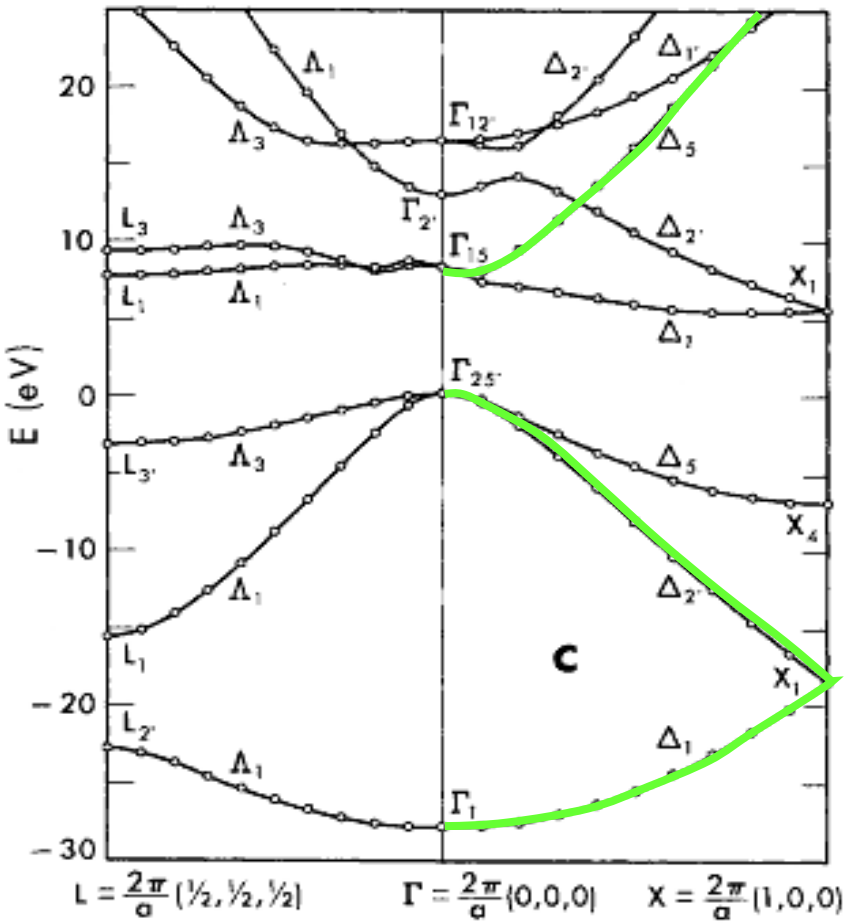


FIG. 1. The electronic band structure of diamond.

BAND STRUCTURE AND OPTICAL PROPERTIES OF DIAMOND*

W. Saslow,† T. K. Bergstresser, and Marvin L. Cohen‡
Department of Physics, University of California, Berkeley, California
(Received 27 January 1966)

Diamond band structure

VOLUME 16, NUMBER 9 PHYSICAL REVIEW LETTERS 28 FEBRUARY 1966

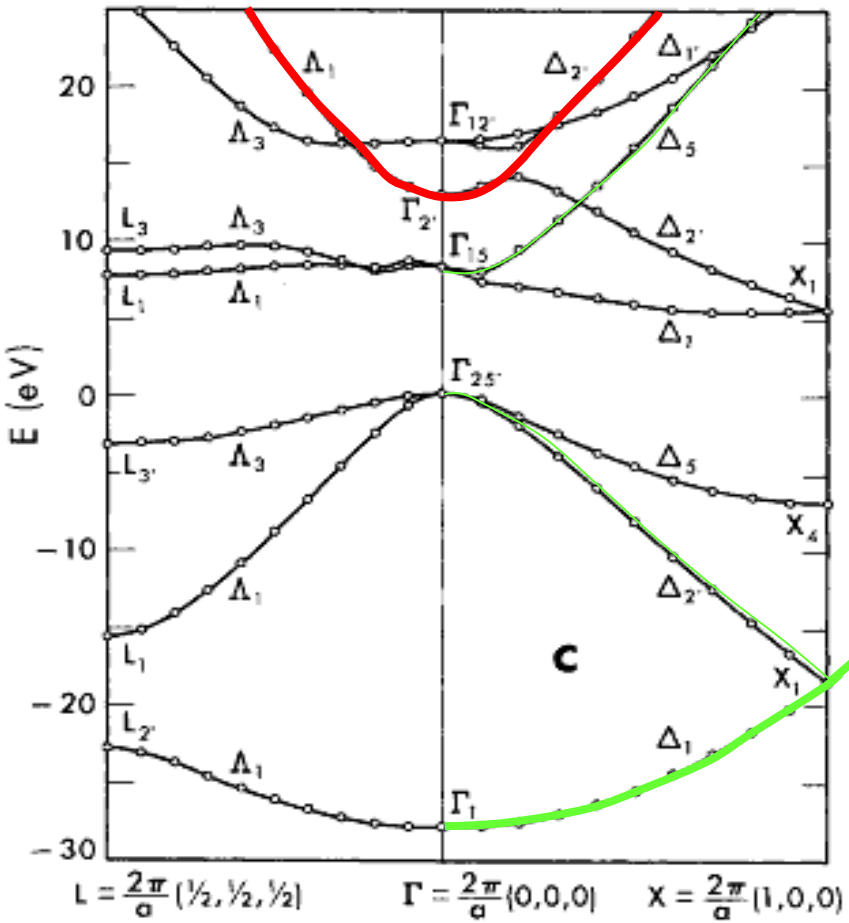
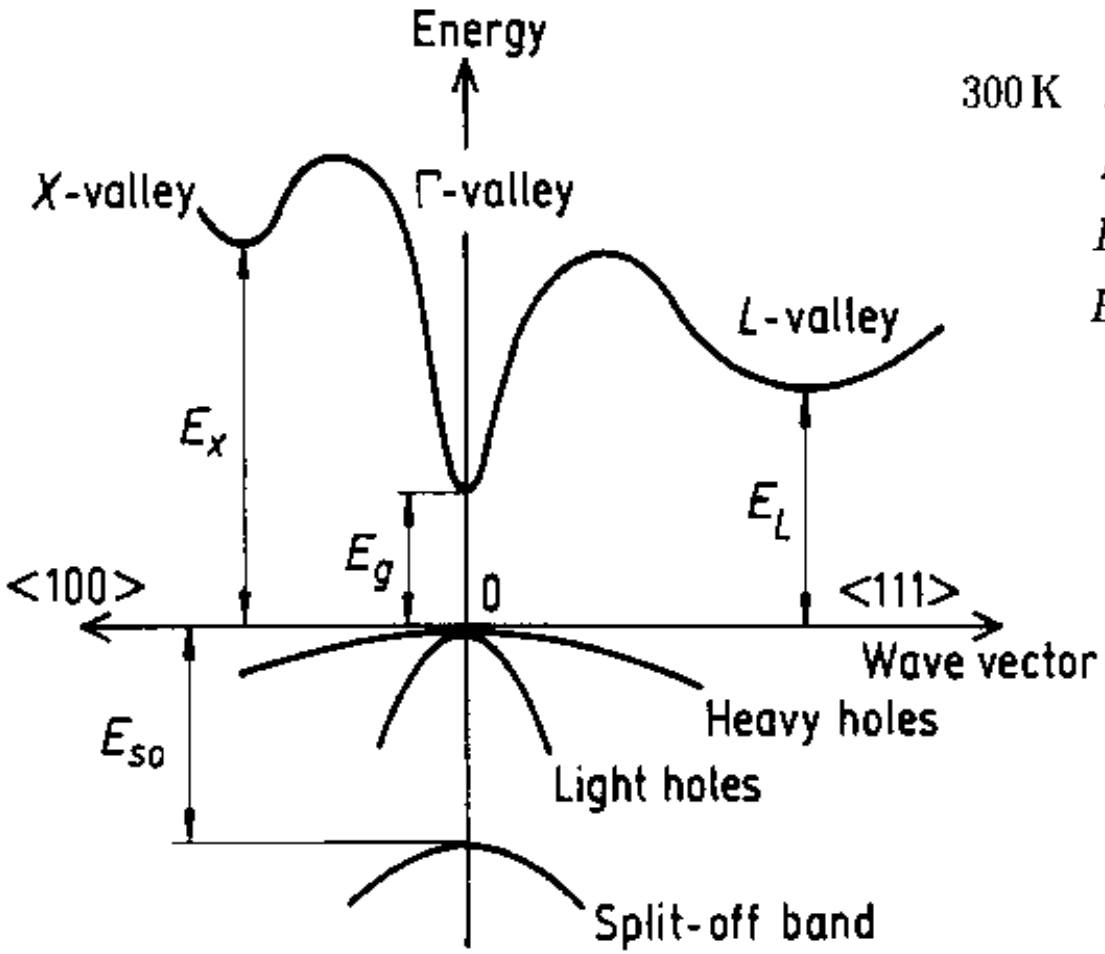


FIG. 1. The electronic band structure of diamond.

'Quadratic' dispersion in extended scheme

Direct gap: GaAs



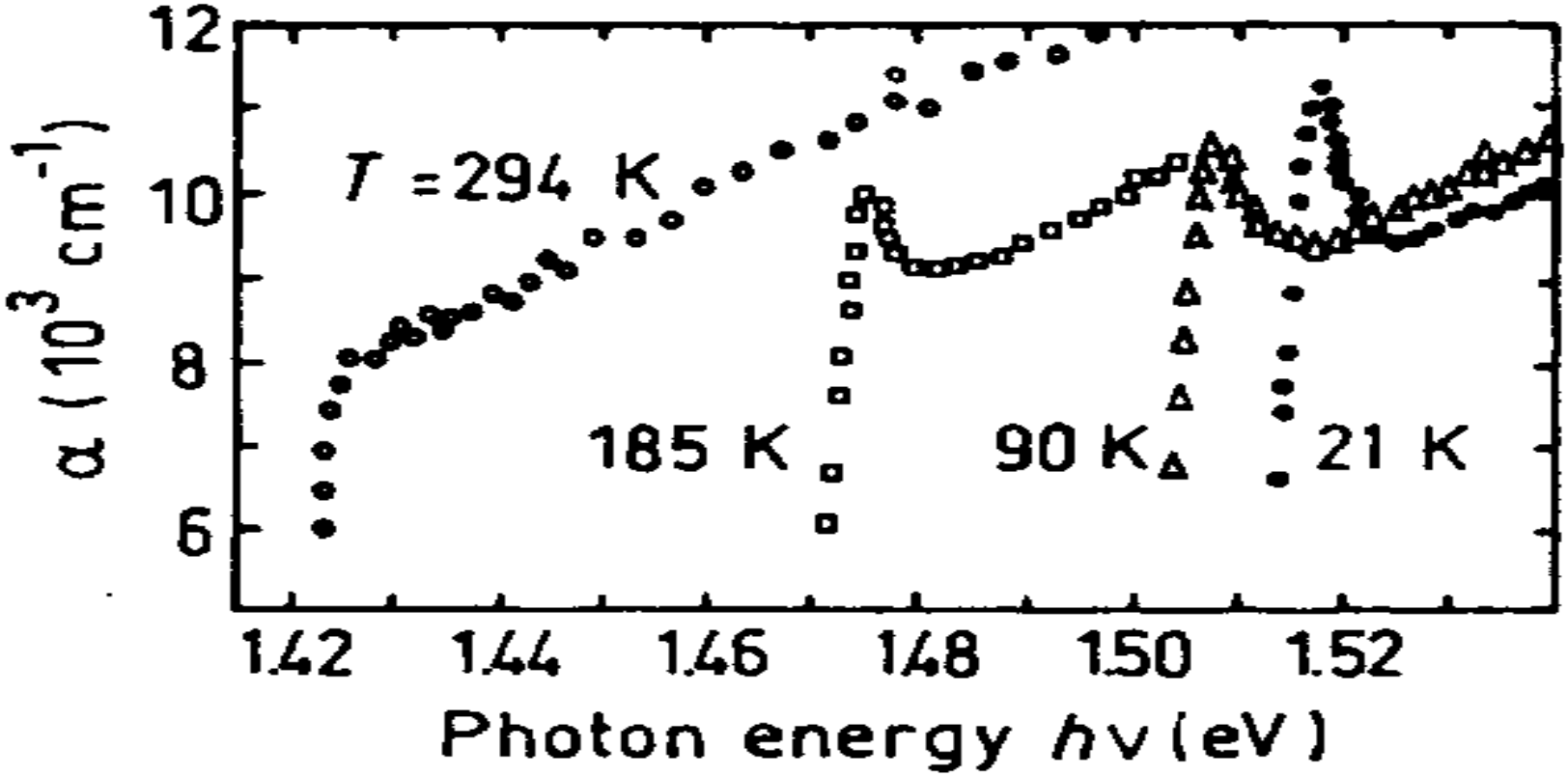
300 K $E_g = 1.42$ eV

$E_L = 1.71$ eV

$E_X = 1.90$ eV

$E_{so} = 0.34$ eV

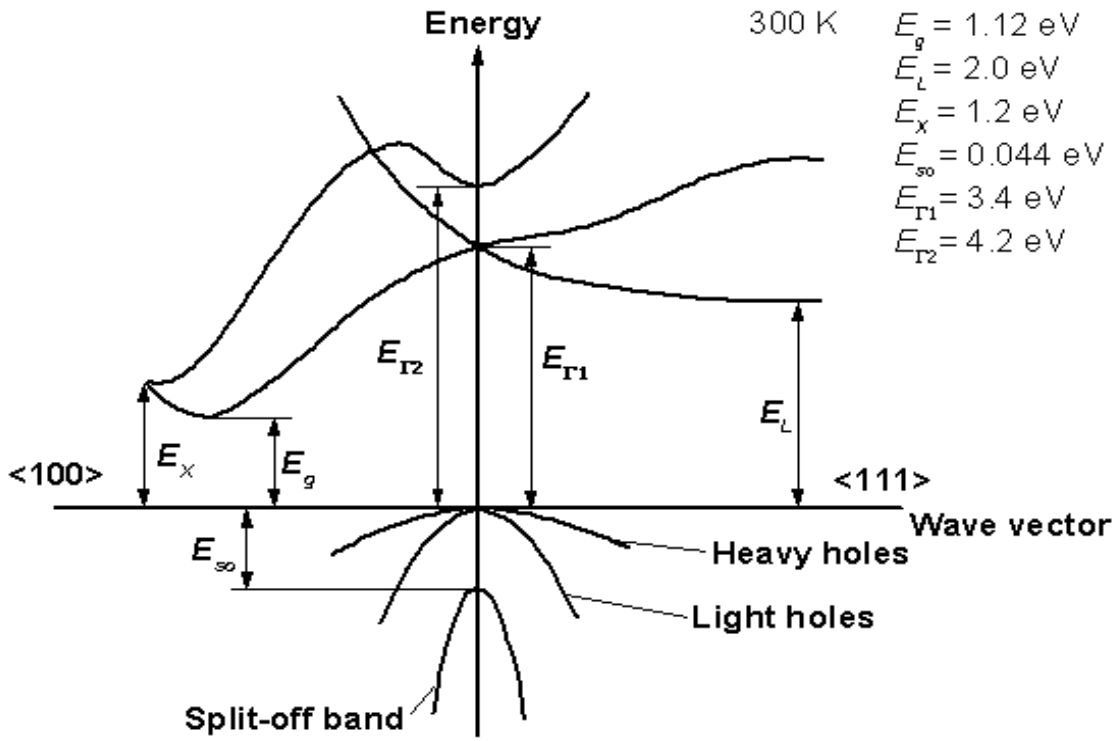
Direct gap: GaAs, absorption



$$I(\omega) = I_0 e^{-\alpha(\omega)\cdot d}$$

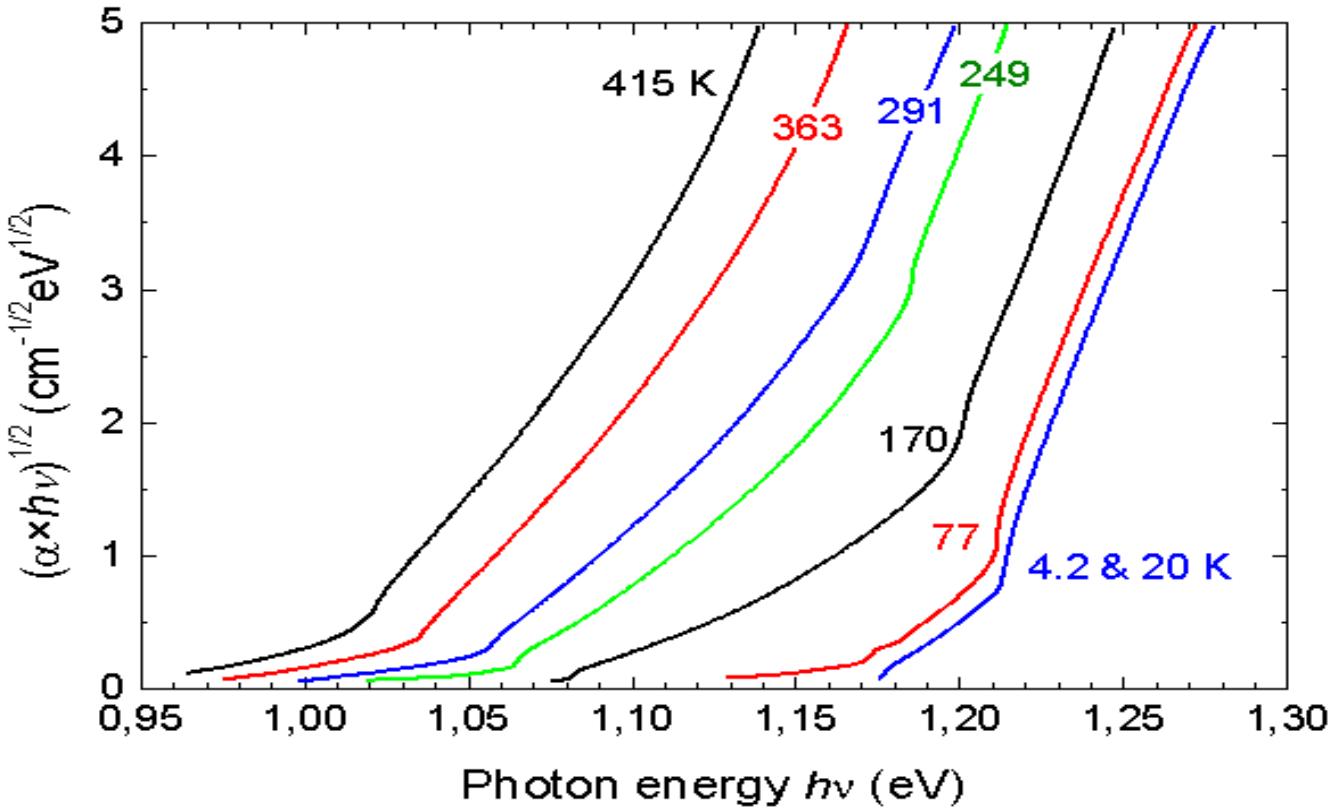
Direct optical transitions
Onset at E_g

Indirect gap: Silicon



Indirect bandgap,
optical transitions need an additional phonon for momentum

Indirect gap, Si absorption



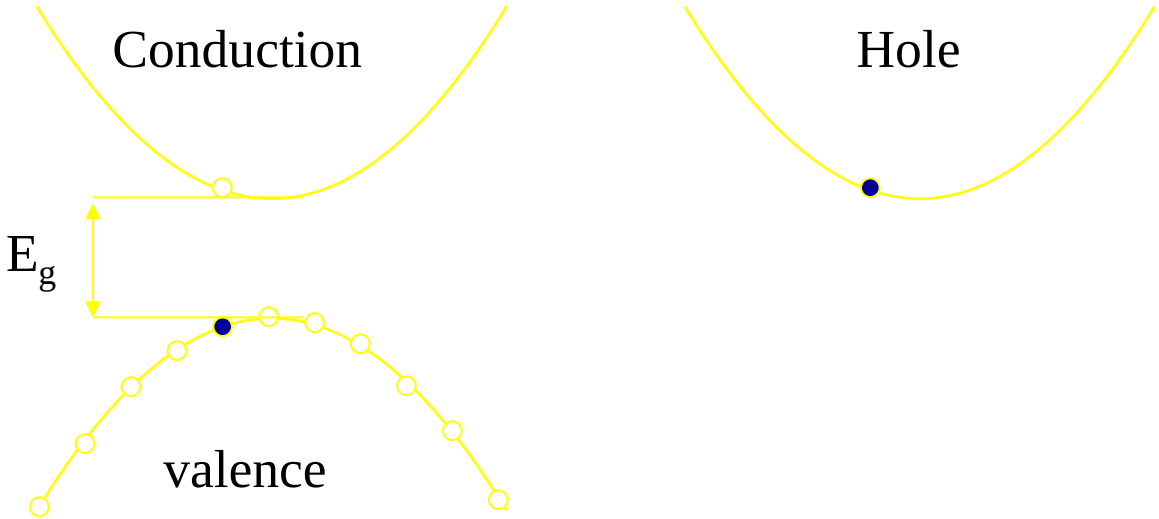
Phonon assisted transitions

Onset at E_g-E_{phonon}

Holes

Missing electron in a filled band
acts as a particle (*hole*) with:

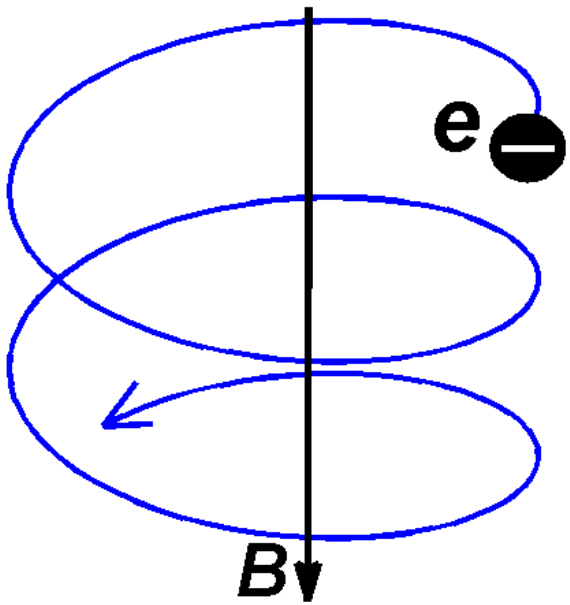
- $k_h = -k_e$
- $E_h = -E_e$
- $v_h = v_e$
- $m_h = -m_e$
- $f_h = 1-f_e$



Both electron and hole conduction (bipolar conduction)

Measuring the electron mass: Cyclotron resonance

$$\omega_c = \frac{eB}{m^*}$$



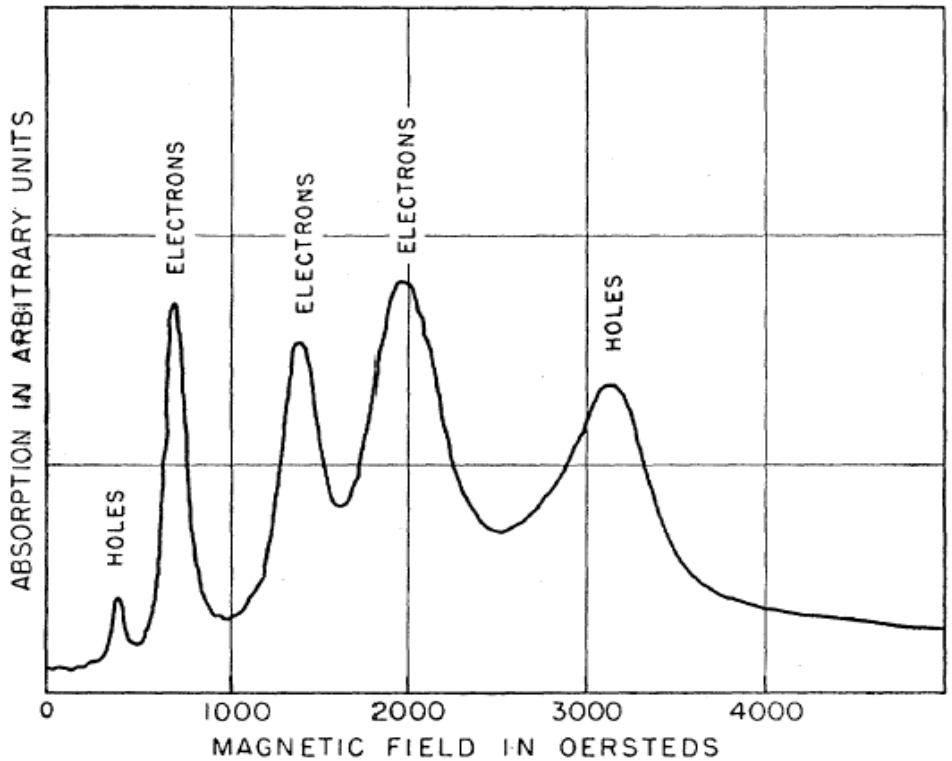
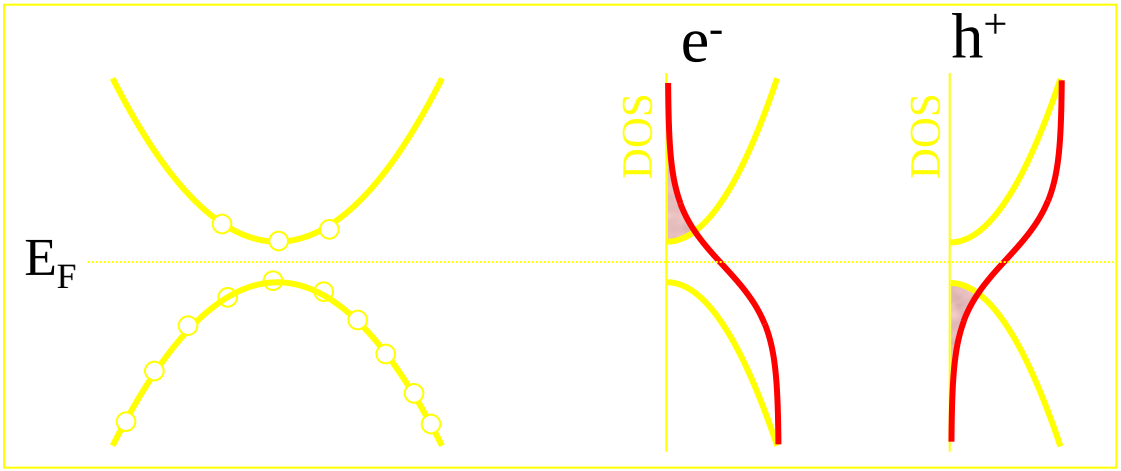


FIG. 2. Typical cyclotron resonance results in germanium near

Dresselhaus et al., Phys. Rev. **98**, 368 (1955)

Carrier density



$$n = \int_{E_c}^{\infty} dE\, D_c(E) \cdot f_c(E) \overset{k_bT \ll E_c - \mu}{\approx} n_0 \cdot e^{\frac{\mu - E_c}{k_bT}} \quad \text{with } n_0 = 2\left(\frac{m_c^* k_bT}{\pi\hbar^2}\right)^{\frac{3}{2}}$$

$$p = \int_{-\infty}^{E_v} dE\, D_v(E) \cdot f_v(E) \approx p_0 \cdot e^{\frac{E_v - \mu}{k_bT}} \quad \text{with } p_0 = 2\left(\frac{m_v^* k_bT}{\pi\hbar^2}\right)^{\frac{3}{2}}$$

$$\boxed{n \cdot p = n_0 p_0 \cdot e^{-\frac{E_g}{k_bT}}}$$

Independent of μ or doping

Intrinsic case: temperature dep. E_F

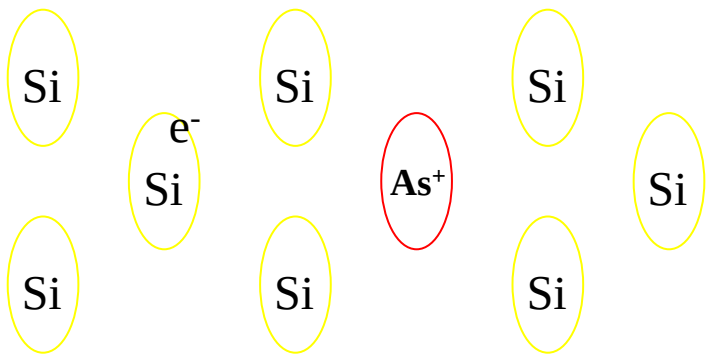
Density: $n_i \equiv p_i \approx \sqrt{n_0 p_0} \cdot e^{-\frac{E_g}{2k_b T}}$

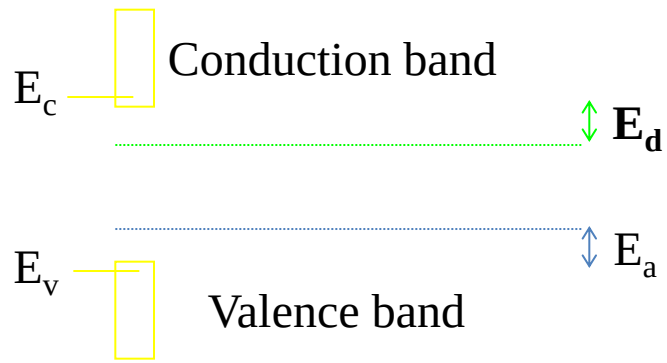
From n = p :

$$n_0 \cdot e^{\frac{\mu - E_c}{k_b T}} = p_0 \cdot e^{\frac{E_v - \mu}{k_b T}}$$

$$E_F = \mu = \frac{1}{2}E_v + \frac{1}{2}E_c + \frac{1}{2}k_b T \ln\left(\frac{n_0}{p_0}\right) = \frac{1}{2}E_G + \frac{3}{4}k_b T \ln\left(\frac{m_h^*}{m_e^*}\right)$$

Extrinsic case





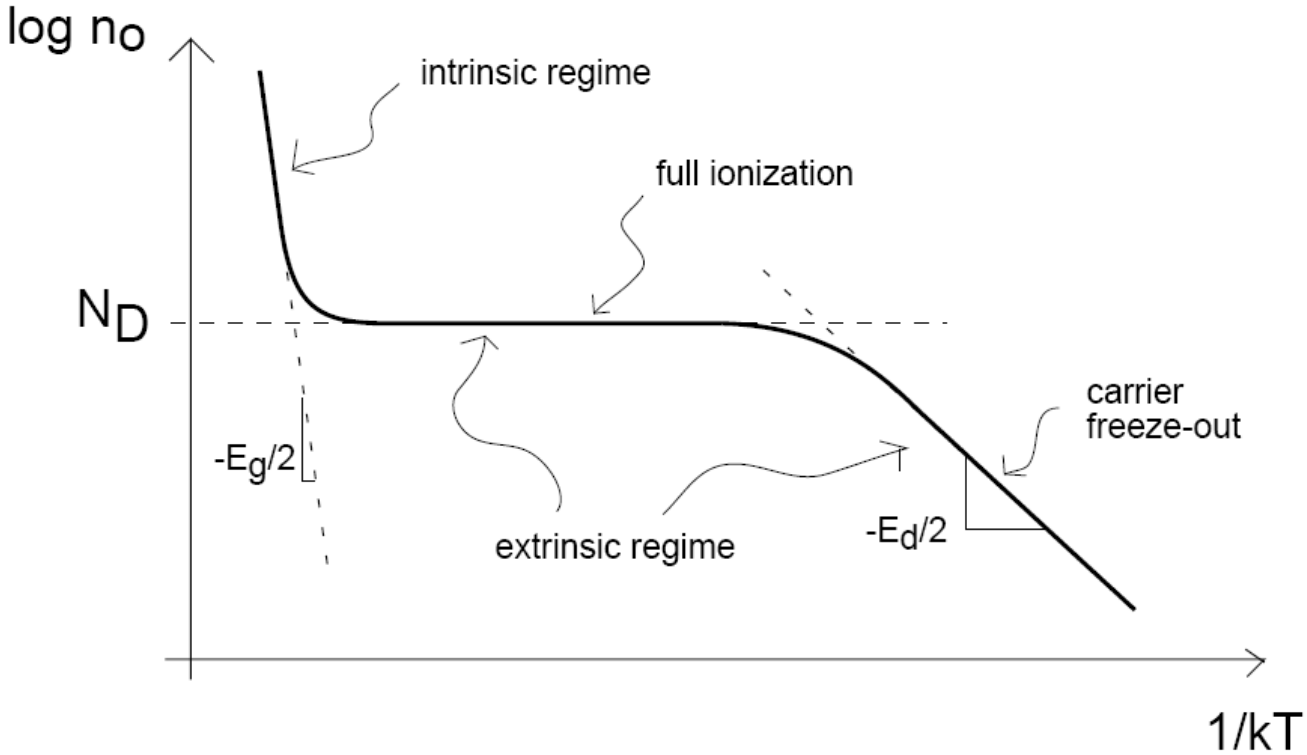
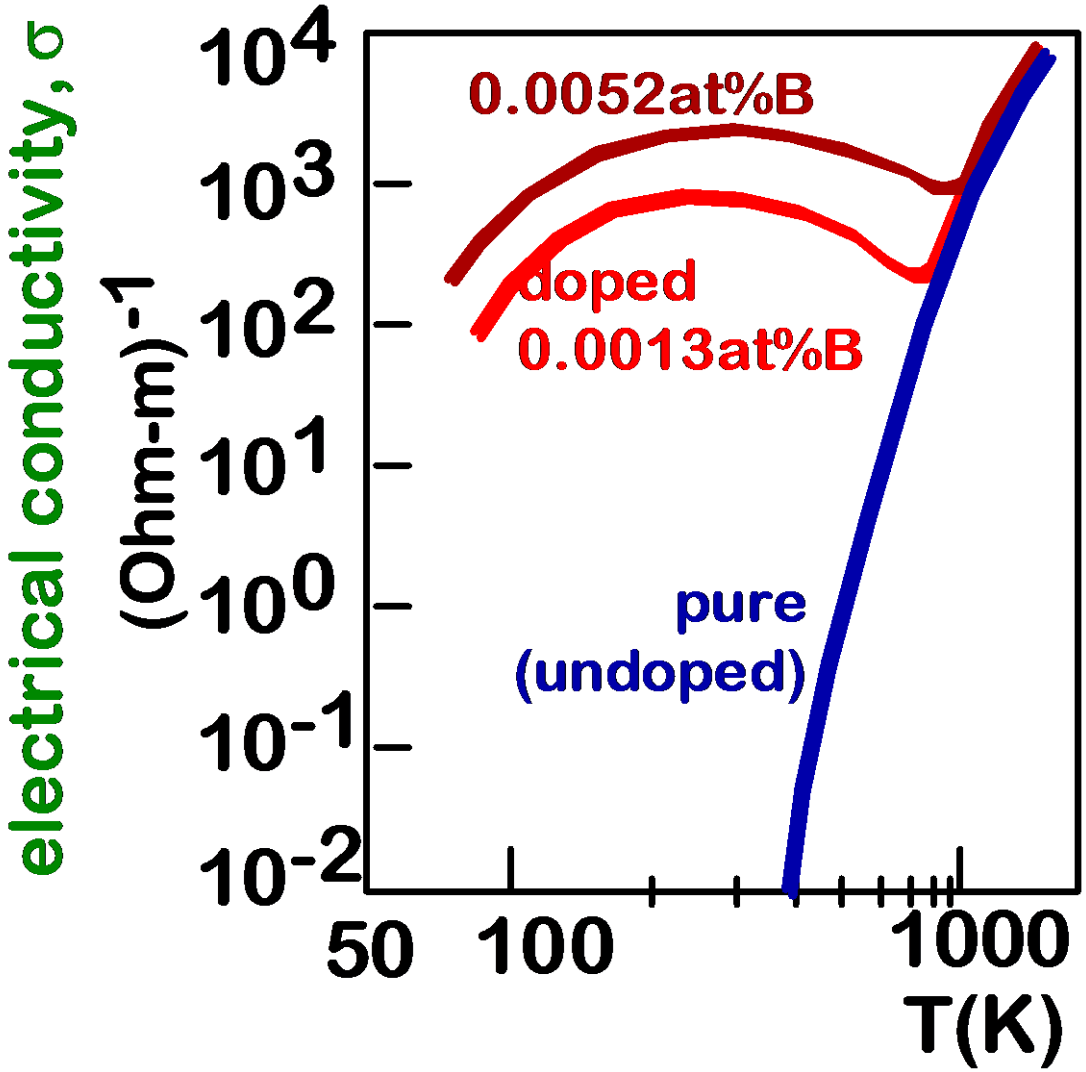
'H problem' with $e^2 \rightarrow e^2/\varepsilon \;\; \& \;\; m \rightarrow m^*$

Ionization energy 1 'Ry': $E_d = \dfrac{m^* e^4}{2\hbar^2 \varepsilon^2} = \dfrac{m^*}{m_o}\dfrac{1}{\varepsilon^2} \cdot 13.6\ eV$

'Bohr' radius: $r_d = \dfrac{\hbar^2 \varepsilon}{m^* e^2} = \dfrac{m_o}{m^*}\varepsilon \cdot a_o$

Doped semiconductors

Binding energies typical 10-60 meV
Bohr radius typical ~10 nm



Conductivity