Spring 2019 Purdue University

ECE 255: L3.1

Intrinsic Semiconductors

(Sedra and Smith, 7th Ed., Sec. 3.1)

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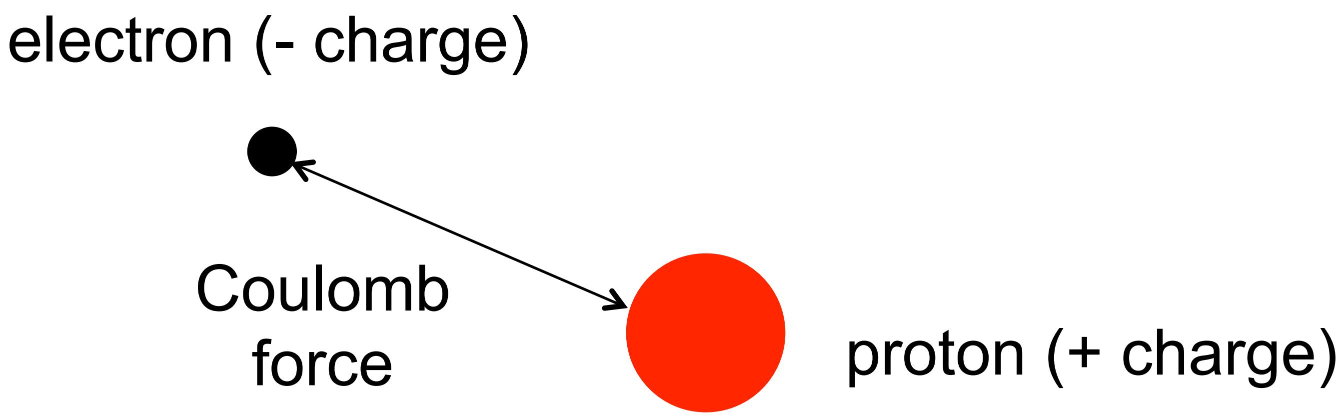
Intrinsic semiconductors

1) Energy levels of atoms
2) Energy bands in crystals
3) Intrinsic carrier concentration
4) Insulators, metals, and semiconductors

The hydrogen atom

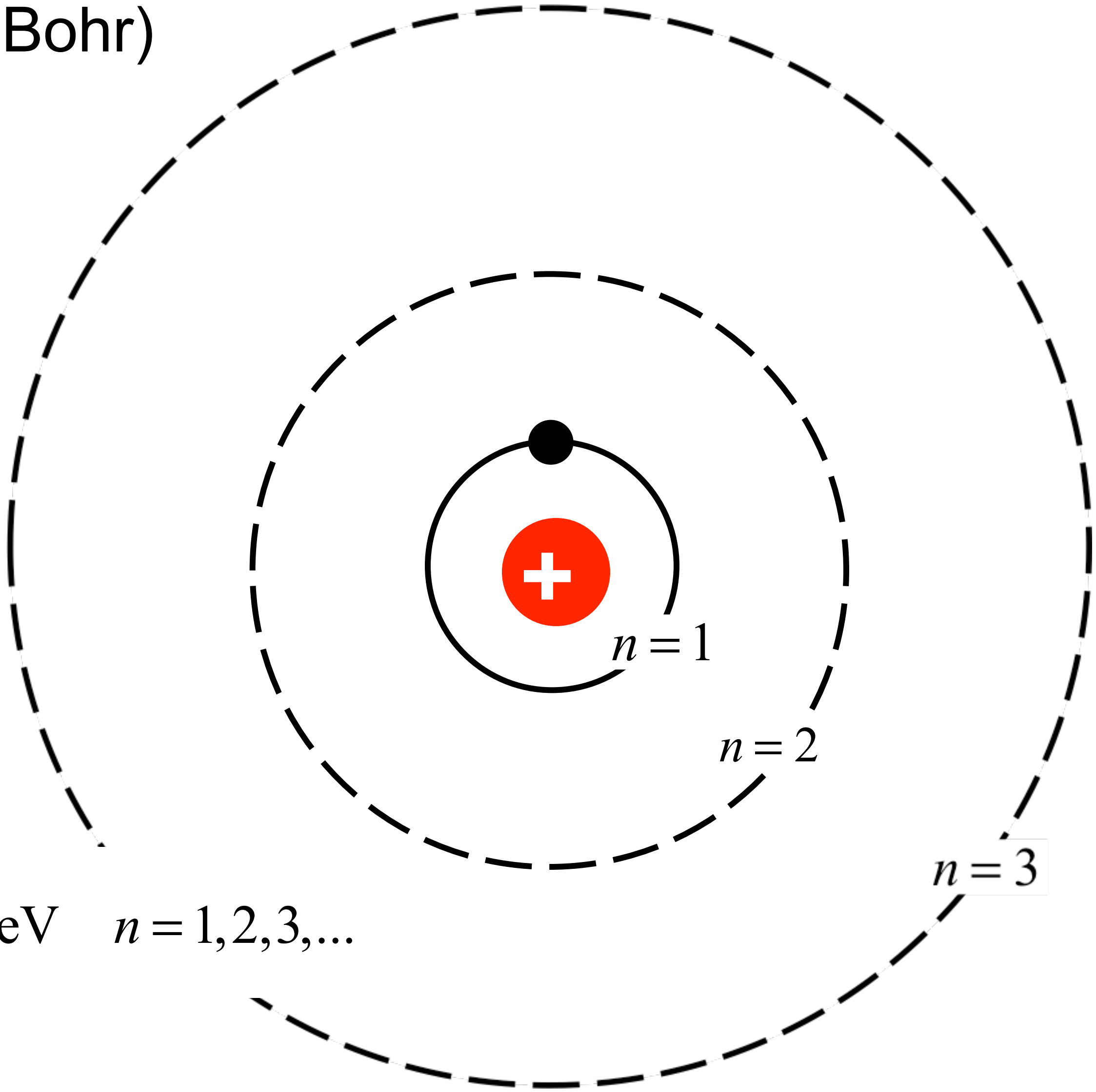


Electrons reside in “orbitals”

https://en.wikipedia.org/wiki/Hydrogen_atom

Quantization of energy levels

Hydrogen (Bohr) atom



$$E_H = -\frac{13.6}{n^2}\,\text{eV} \quad n = 1,2,3,\ldots$$

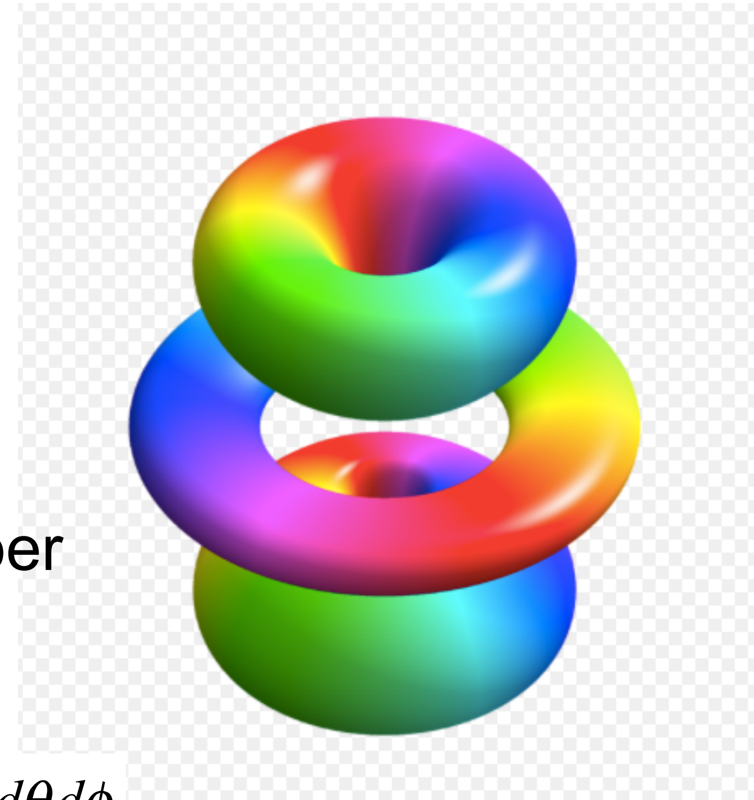
Orbitals

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 - \frac{e^2}{4\pi\varepsilon_0 r}\right)\psi\left(r,\theta,\phi\right) = E\psi\left(r,\theta,\phi\right)$$

$$\psi_{n,\ell,m}\left(r,\theta,\phi\right)$$

n: principle quantum number
l: angular momentum quantum number
m: magnetic quantum number

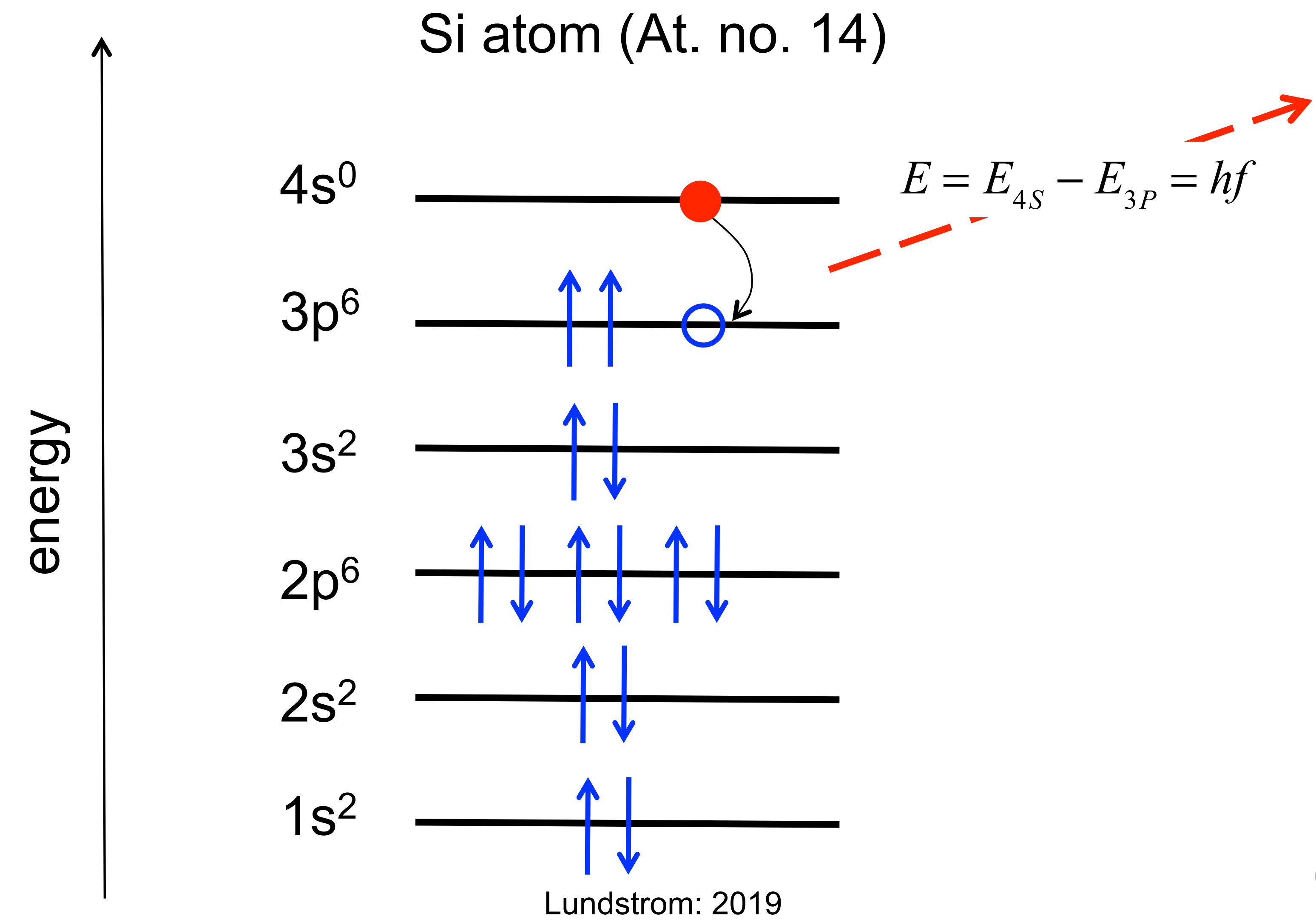
$$P\left(r,\theta,\phi\right)r^2 dr \sin\theta d\theta d\phi = \psi^*_{n,\ell,m}\psi_{n,\ell,m} r^2 dr \sin\theta d\theta d\phi$$



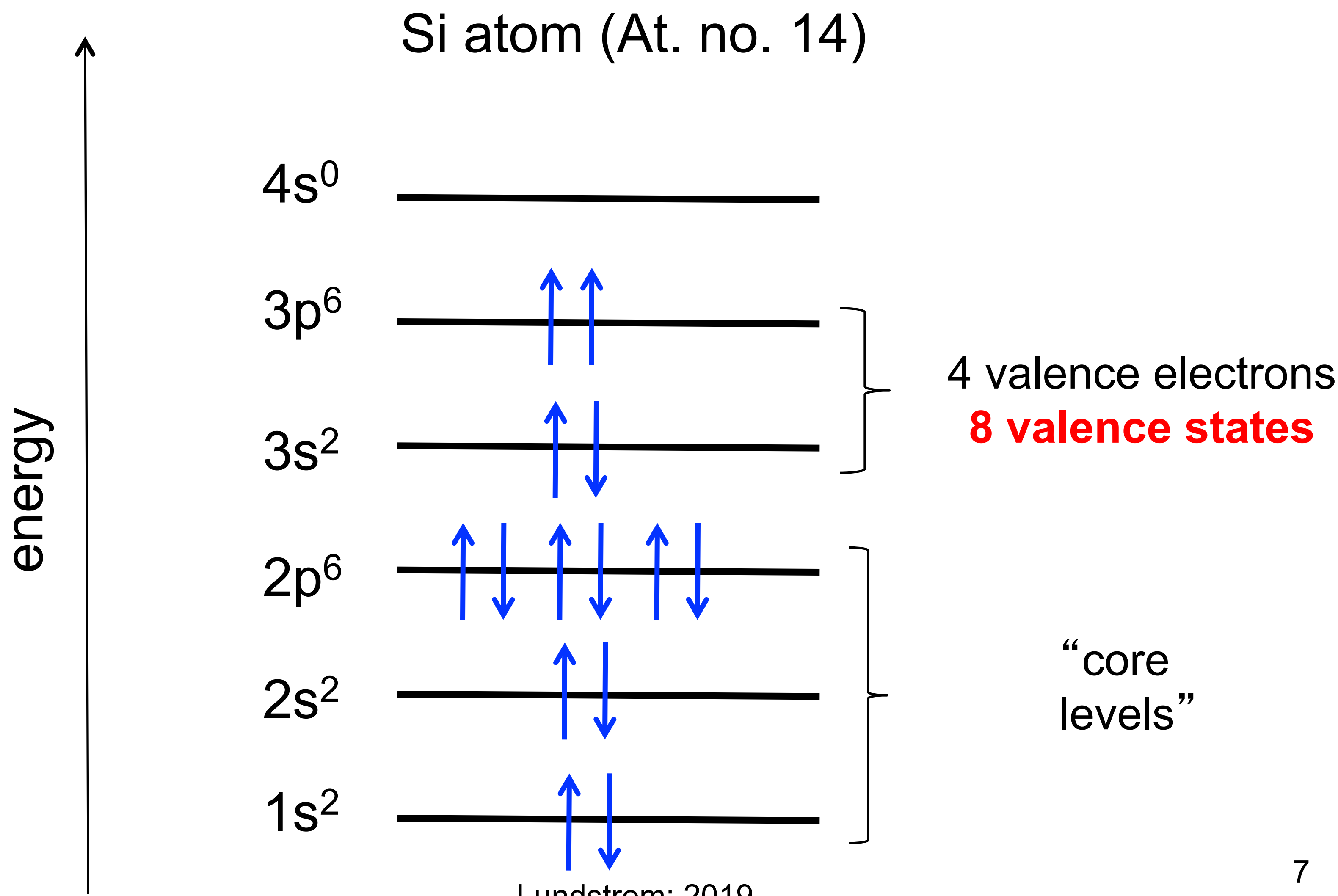
$$\psi_{4,3,1}\left(r,\theta,\phi\right)$$

https://en.wikipedia.org/wiki/Hydrogen_atom

Silicon atom energy levels



Valence vs. core levels



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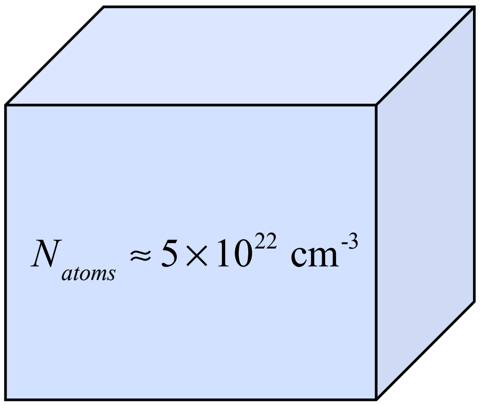
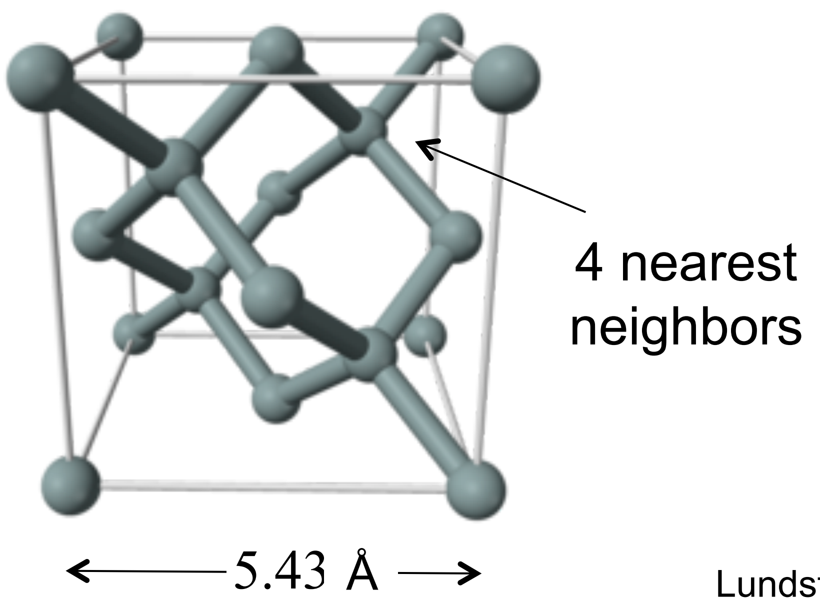
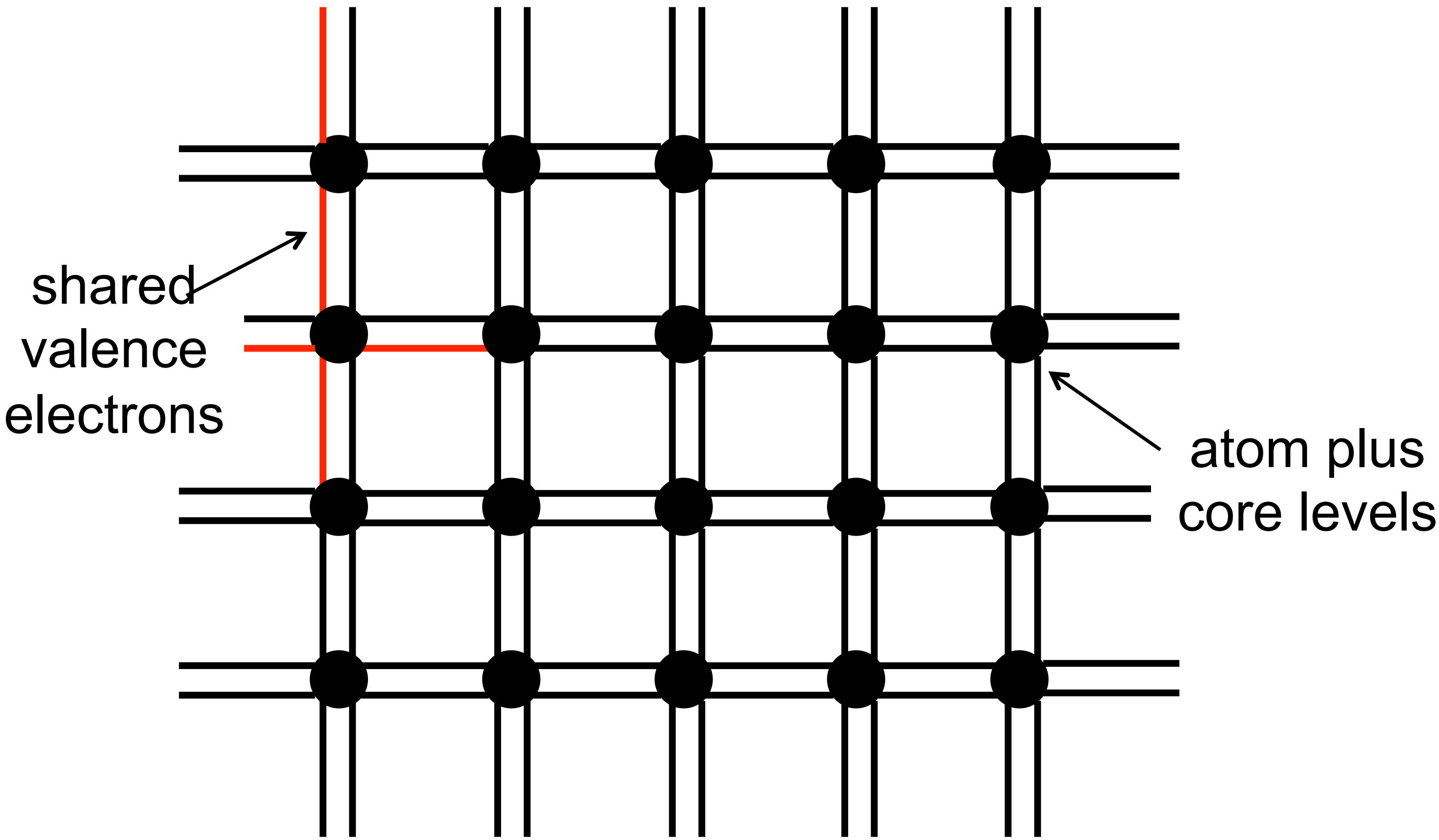
Silicon energy levels / energy bands



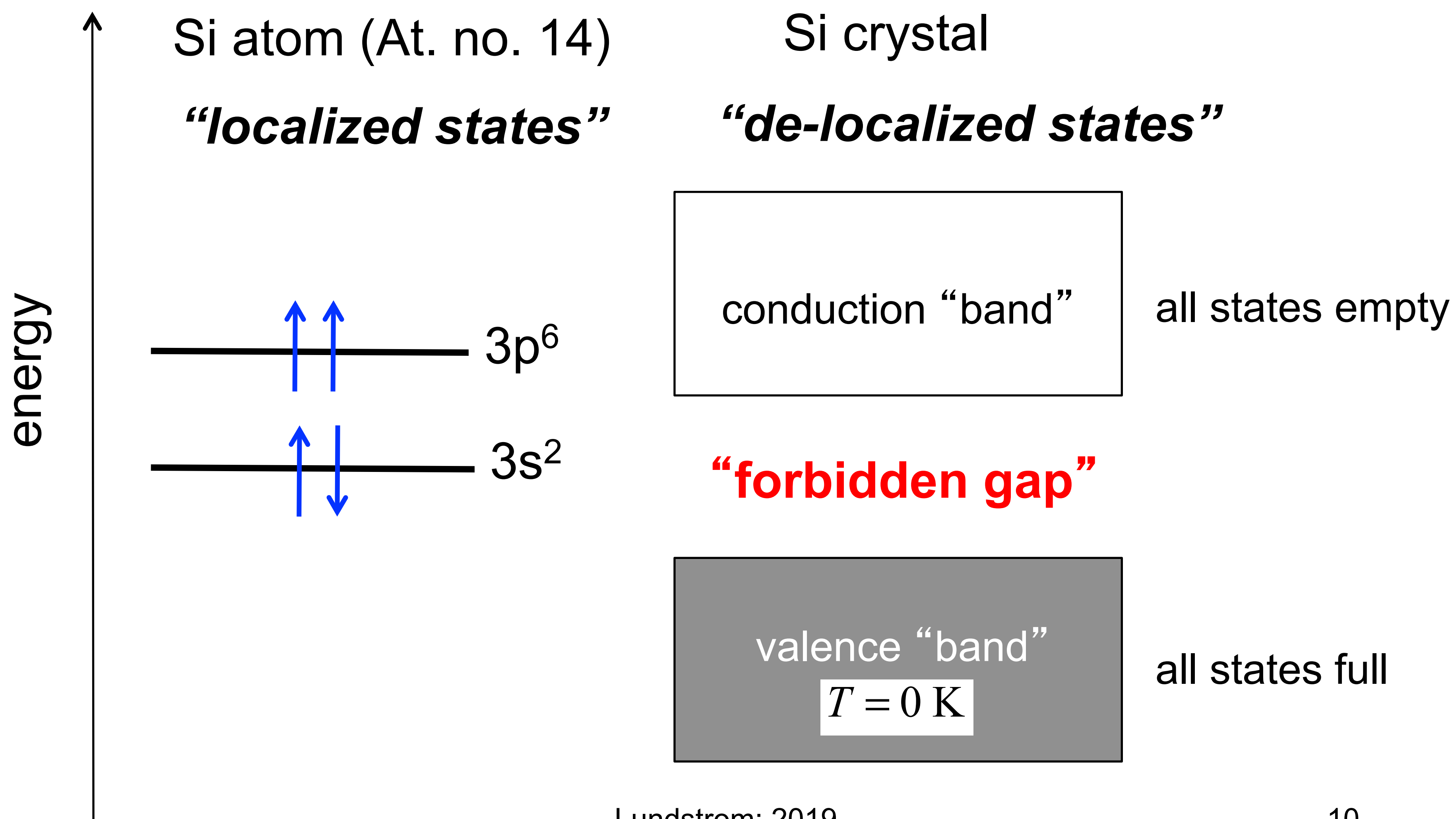


- Only the valence states are of interest to us.
- Each Si atom has 4 valence electrons and 4 nearest neighbors.
- The 8 valence states give rise to $8N_{atoms}$ states per cm^3 in the solid.
- But the **interaction** of the electron wavefunctions alters the discrete energy levels of the isolated Si atoms.

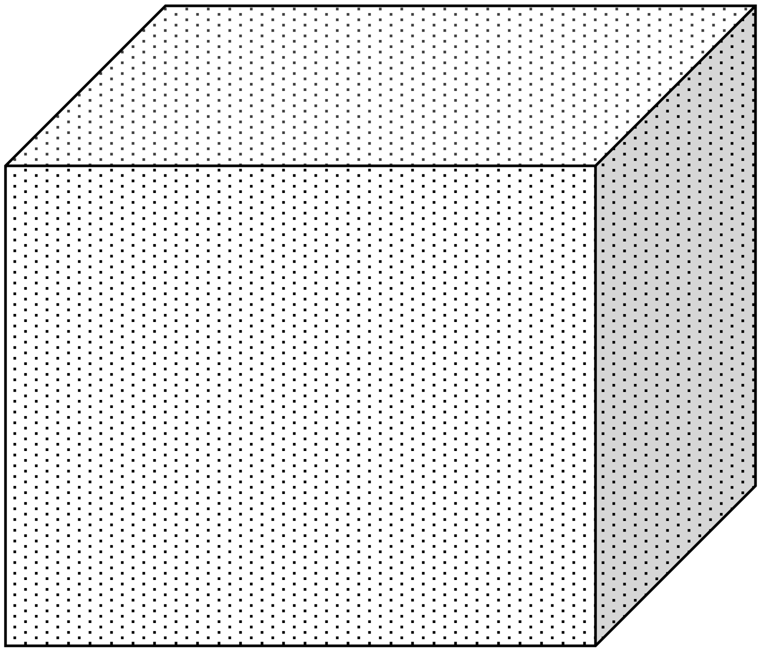
Bonding (cartoon)



Silicon energy levels → energy bands



Aside: Ideal Gas



V: volume
P: pressure
T: temperature
N: number of atoms

$$PV = Nk_B T$$

Maxwellian velocity distribution

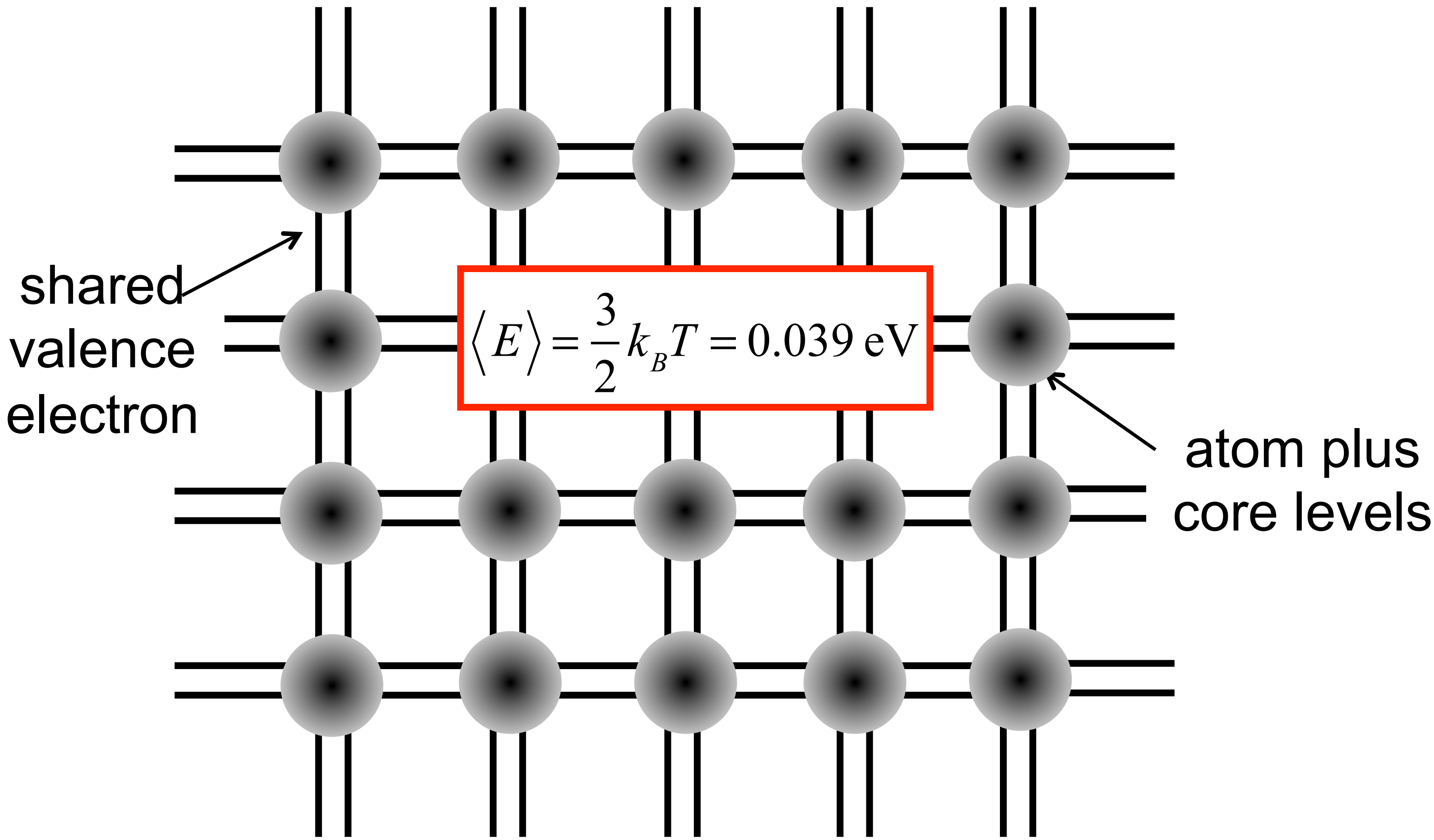
$$f(\upsilon)\,d^3\upsilon = \left(\frac{m}{2\pi k_B T}\right)^{3/2} e^{-\frac{m\upsilon^2}{2k_B T}}\,d^3\upsilon$$

$$f(E)\,dE \propto e^{-\frac{E}{k_B T}}\,dE$$

$$\langle E \rangle = \frac{3}{2} k_B T$$

https://en.wikipedia.org/wiki/Maxwell–Boltzmann_distribution

Bonding (cartoon T >0 K)



$$\langle E \rangle = \frac{3}{2} k_B T = 0.039 \text{ eV}$$

Joules and electron volts

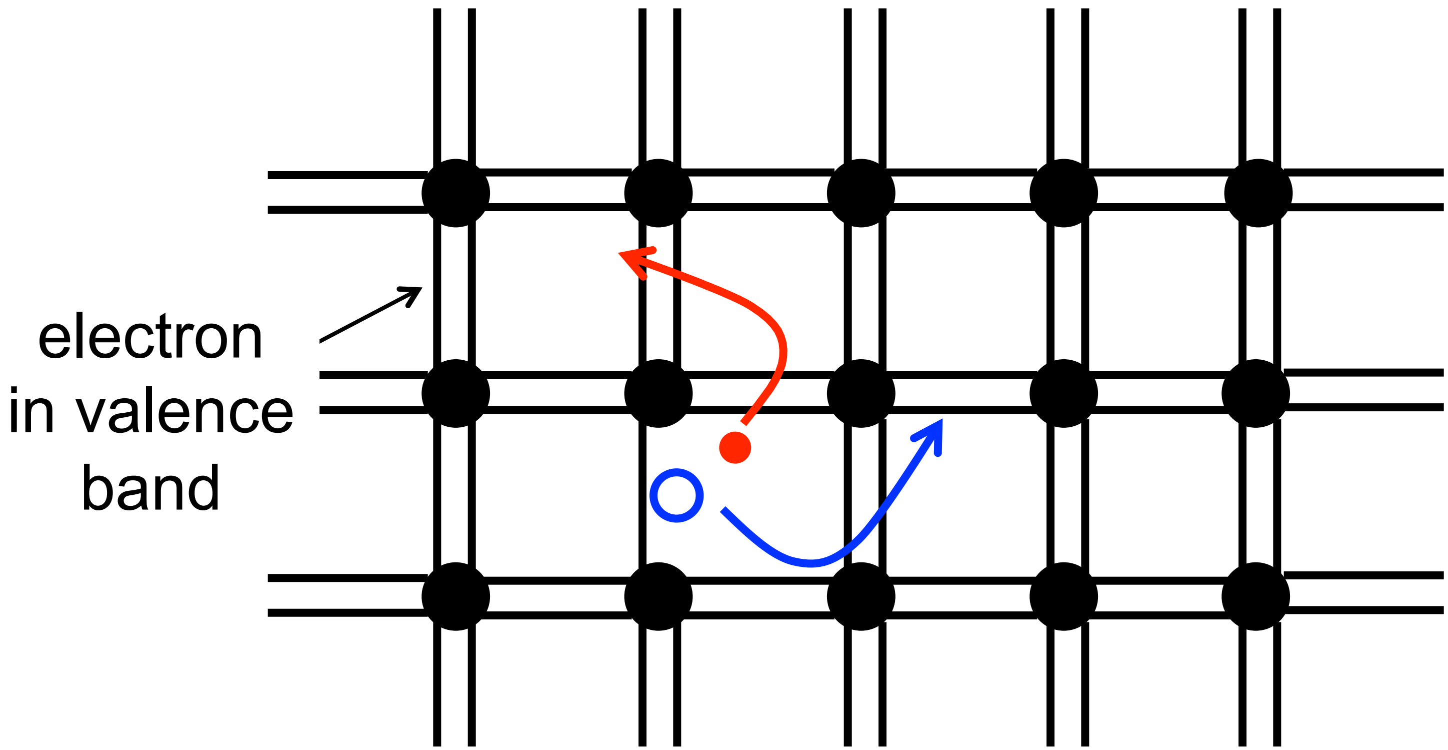
$$\langle E \rangle = \frac{3}{2} k_B T = 0.039 \text{ eV}$$

We should do our calculations in SI (MKS) units, but it is convenient to express energies in electron volts, which is not a proper SI unit. Electron volts should be converted to Joules before using them in calculations.

$$\langle E \rangle = \frac{3}{2}\left(1.38 \times 10^{-23} \text{ J/K}\right) \times 300 \text{ K} = 6.21 \times 10^{-21} \text{ J}$$

$$E(eV) = \frac{E(J)}{q} = \frac{6.21 \times 10^{-21} \text{ J}}{1.6 \times 10^{-19} \text{ C}} = 0.039 \text{ eV}$$

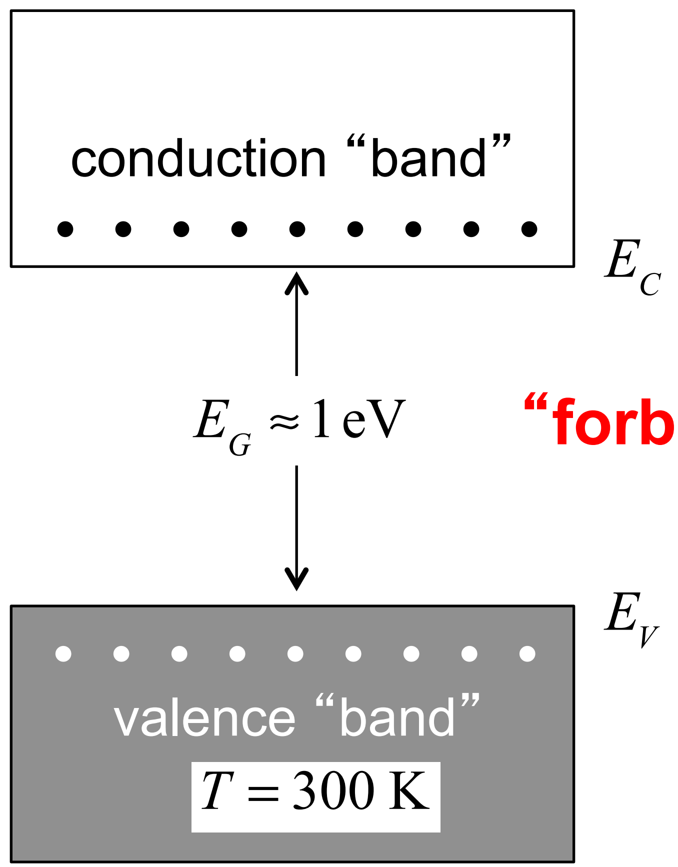
Electrons and holes in semiconductors



1) Electrons in the conduction can move
2) Holes in the valence band can also move
3) Electrons and holes can recombine

Energy band view $T > 0$ K

Si crystal



A few states full

$$\langle E \rangle = \frac{3}{2} k_B T = 0.039\text{ eV}$$

"forbidden gap"

$n = p = n_i$ in an ***intrinsic*** semiconductor

A few states empty

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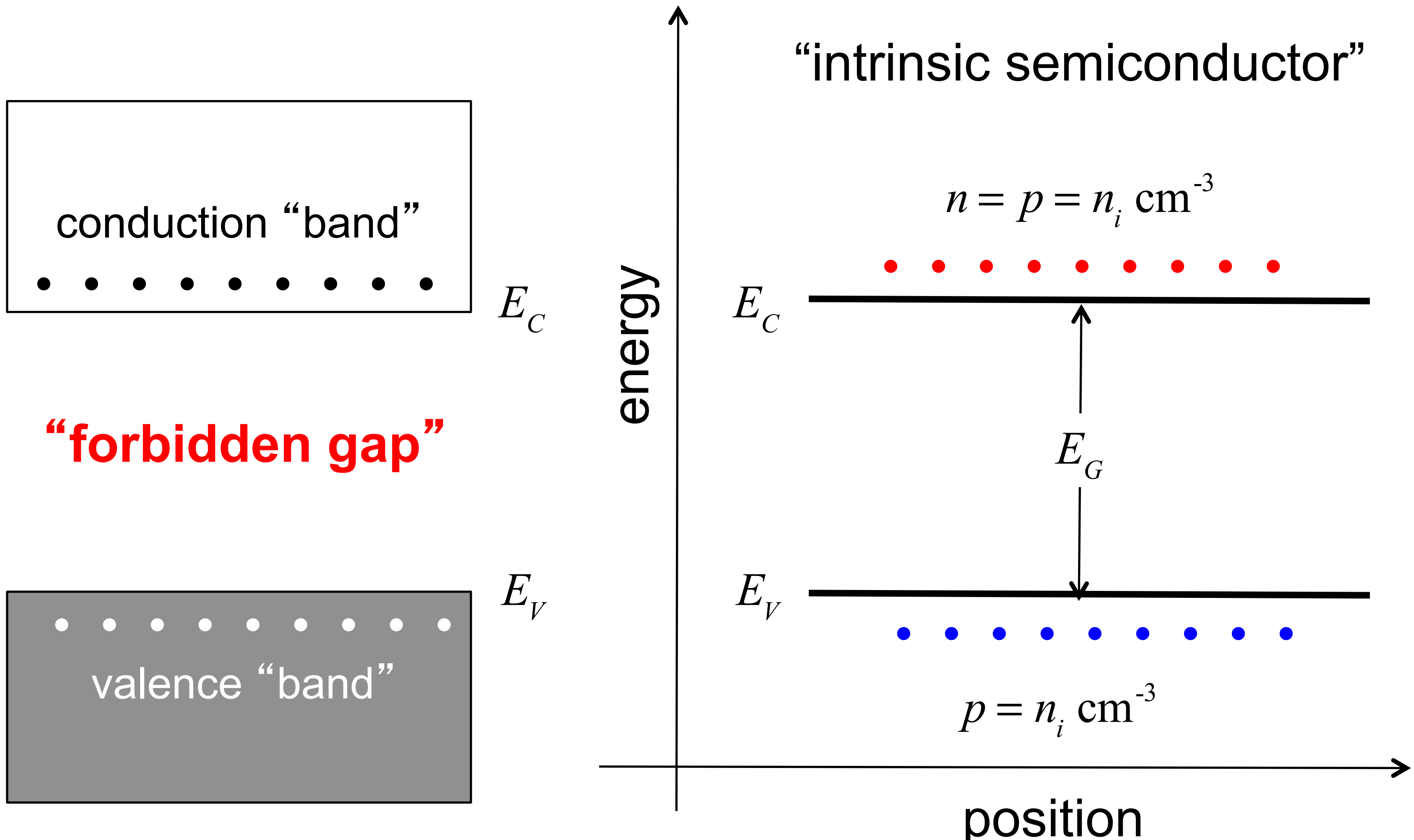
“Energy band diagrams”



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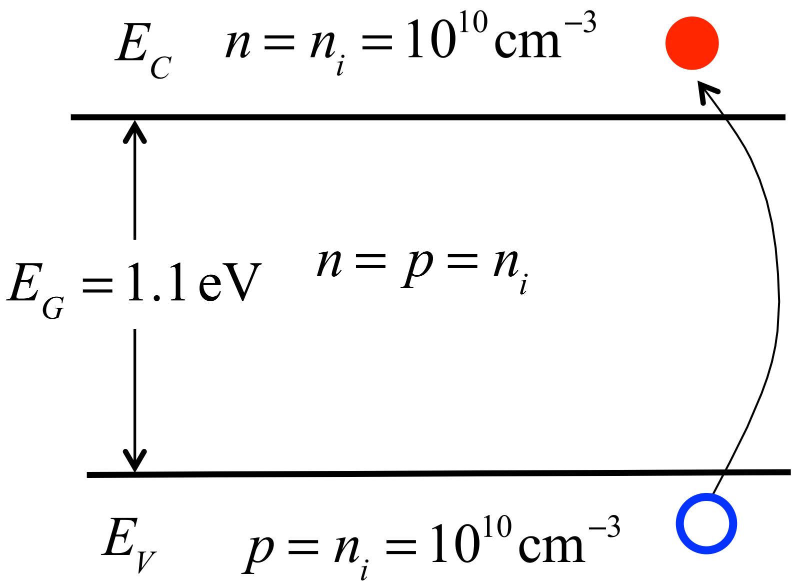
Two key parameters

Intrinsic Si



$$E_G(\mathrm{Si}) = 1.1\,\mathrm{eV}$$

$$E_G(\mathrm{GaAs}) = 1.4\,\mathrm{eV}$$

$$k_B T = 0.026\,\mathrm{eV} \quad (T = 300\ \mathrm{K})$$

$$P \sim e^{-E_G/k_B T}$$

$$n_i(\mathrm{Si}) = 1 \times 10^{10}\ \mathrm{cm}^{-3} \quad (T = 300\ \mathrm{K})$$

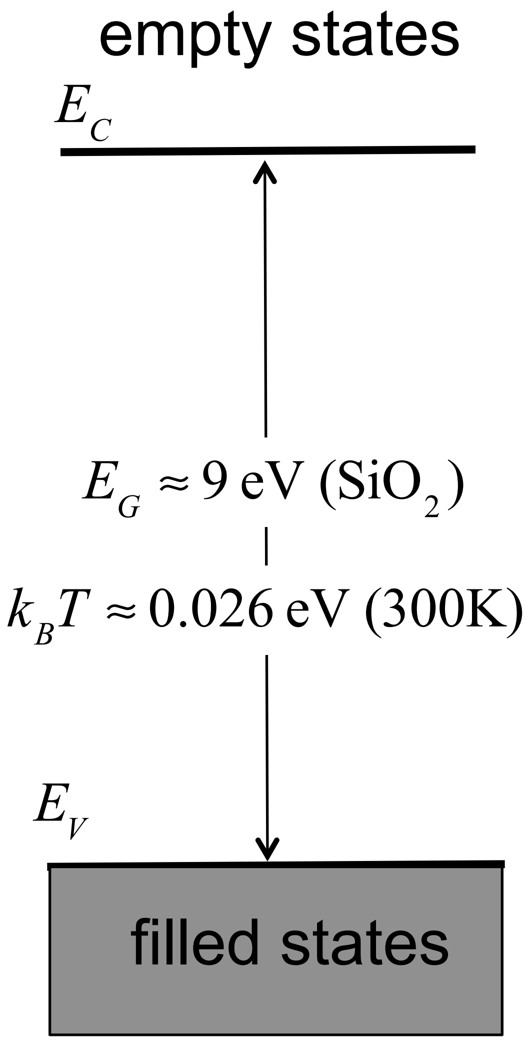
$$n_i(\mathrm{GaAs}) = 2 \times 10^{6}\ \mathrm{cm}^{-3} \quad (T = 300\ \mathrm{K})$$

Metals insulators and semiconductors

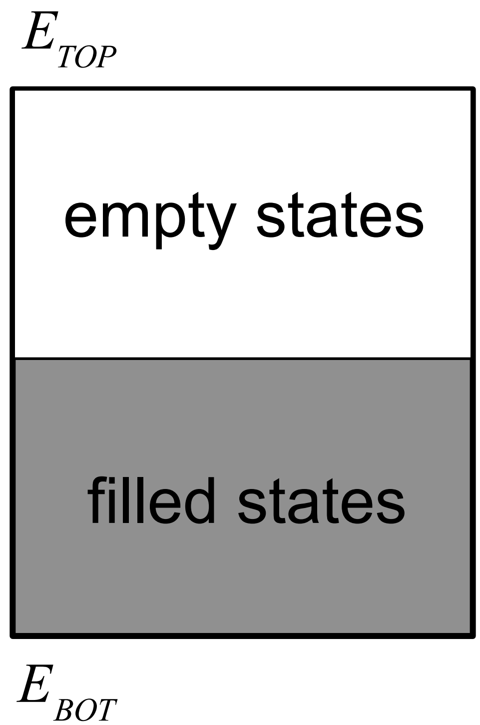
Metals:	conduct electricity (and heat) well.
Insulators:	don’t conduct electricity well usually don’t conduct heat well
Semiconductors:	in-between, **but** their properties can be controlled

Insulators | Metals | Semiconductors

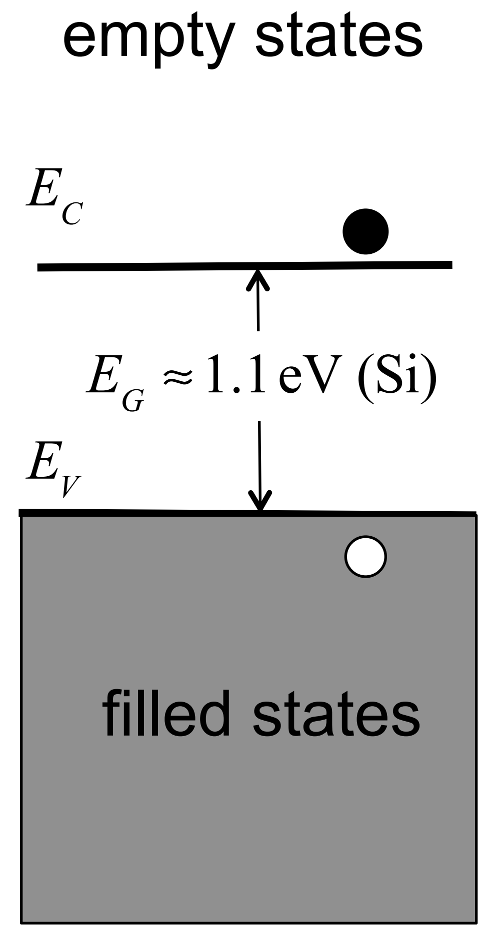
Insulators



Metals



Semiconductors



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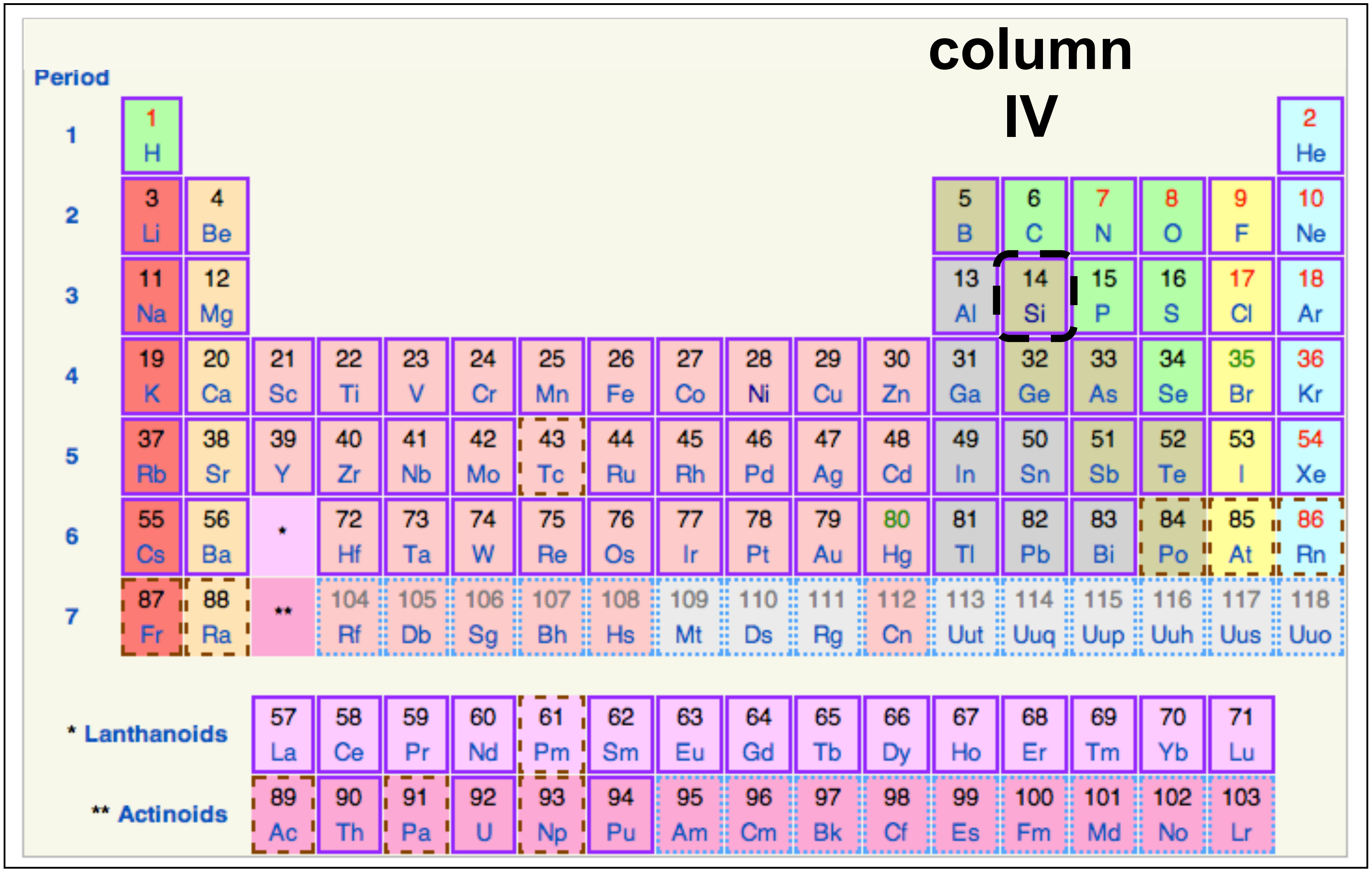
Semiconductors



Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
* Lanthanoids			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
** Actinoids			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

http://en.wikipedia.org/wiki/Periodic_table

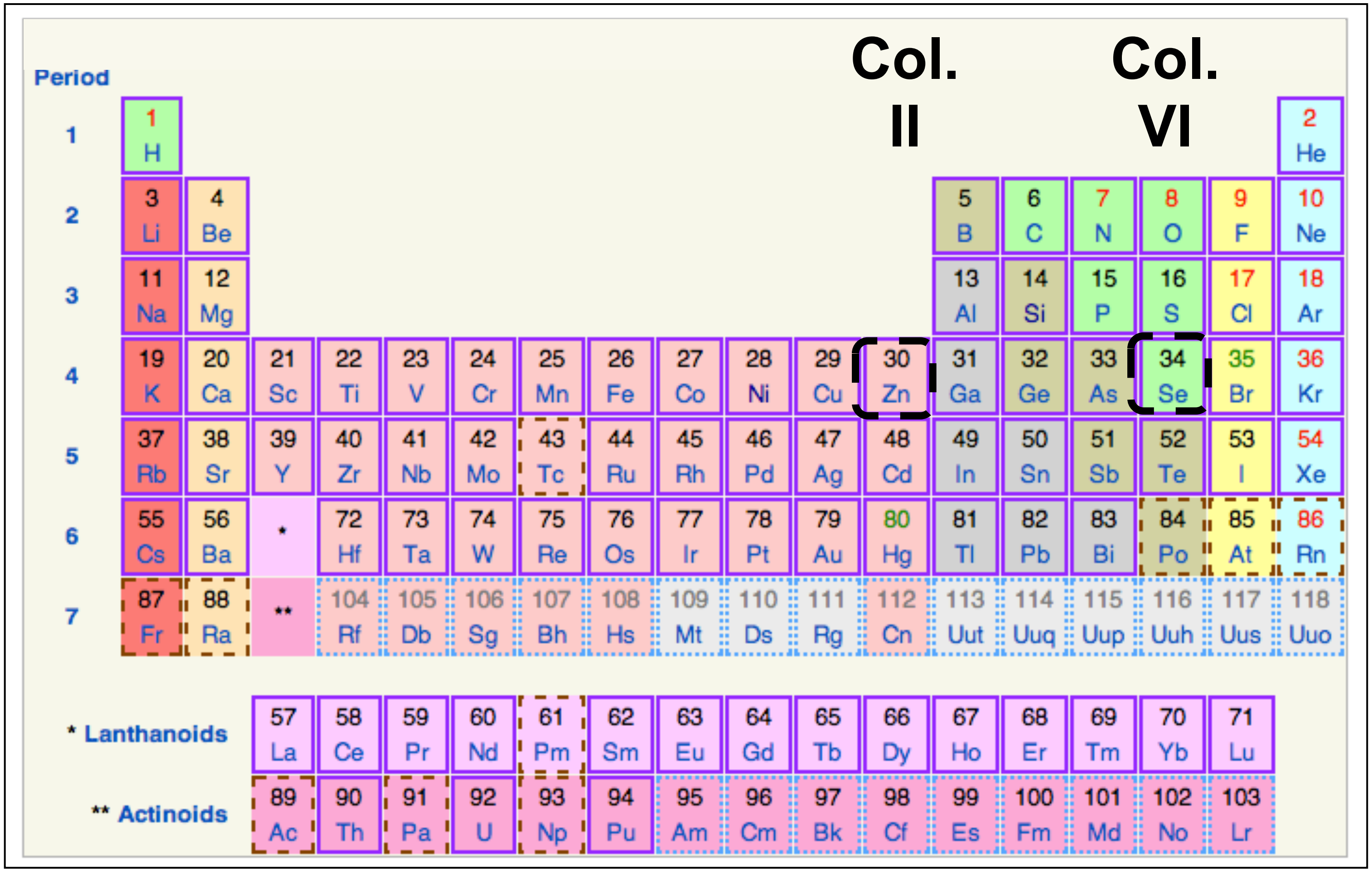
III-V semiconductors

Col. III **Col. V**

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
* Lanthanoids			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
** Actinoids			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

http://en.wikipedia.org/wiki/Periodic_table

II-VI semiconductors



http://en.wikipedia.org/wiki/Periodic_table

Summary

The localized energy levels in isolated atoms become delocalized **energy bands** in a solid.

Everything happens very near the top of the valence band and very near the bottom of the conduction band.

The electrical current in a semiconductor is carried by **electrons in the conduction band** and by **holes in the valence band.**

The **band gap** and **intrinsic carrier concentration** are key parameters for semiconductors.

Intrinsic semiconductors

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2) Energy bands in crystals
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