Semiconductors

Astronomy 525

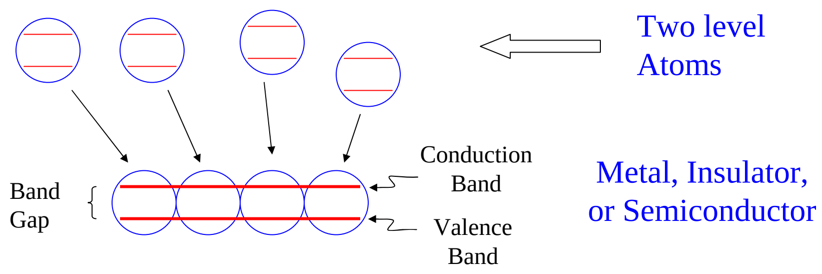
Lecture 18

Outline

- Semiconductor Models
- Pure Semiconductors
- Doped semiconductors
- Bohr model for impurities
- Expected spectral response
- Photoconductivity
- Unwanted impurities
- Photoelectron dynamics
- Photoconductive Gain

The Band Theory of Solids

Tight binding approximation



Two level Atoms

Band Gap

Conduction Band

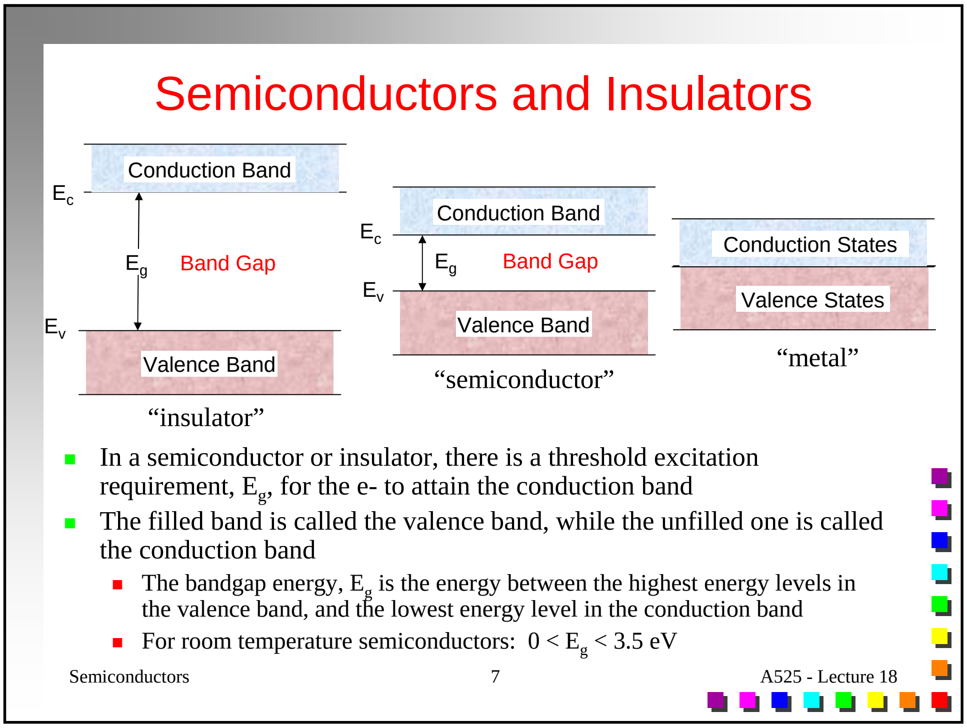
Valence Band

Metal, Insulator, or Semiconductor

- Bring atoms together and the levels merge
- The “valence states” and “conduction states” are analogous to the ground and excited states in the isolated atom.

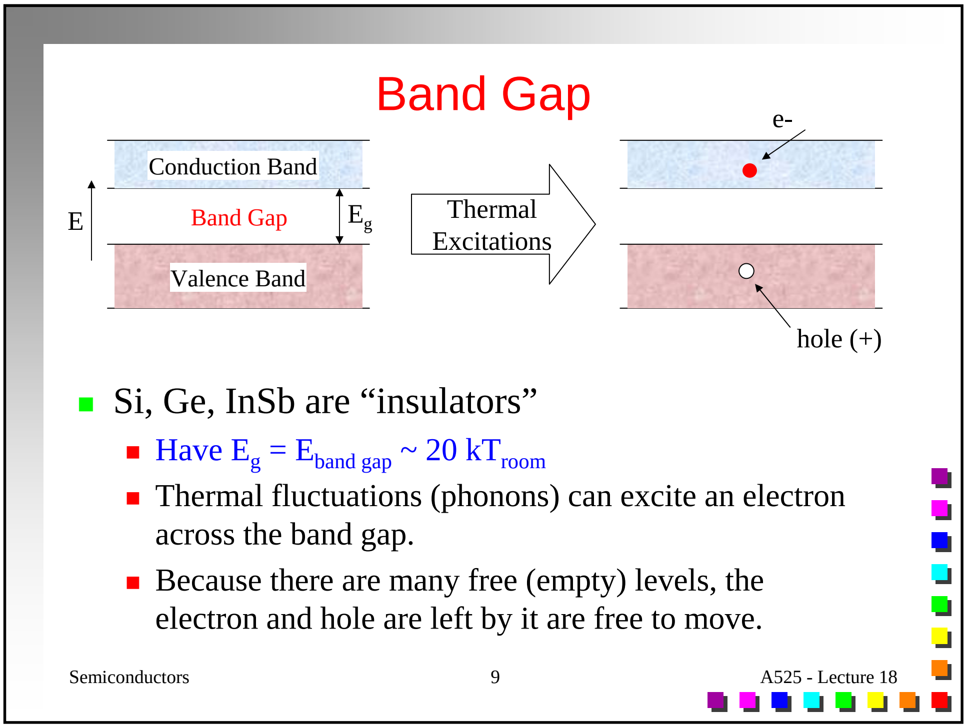
Examples: H and He

- Suppose we start with atomic hydrogen
  - It forms a metallic solid since there are *N* e- and 2 *N* levels for them in the 1s state.
  - An electron can migrate from one atom (proton) to the next with no additional energy.
- If we start w/ helium
  - The “broadened” 1s level is full because of the 2, 1s electrons are present.
  - The e- cannot move ⇒ an insulator
  - To move the e- must move up to the next (2s) level (Band)



Semiconductors and Insulators

- In a semiconductor or insulator, there is a threshold excitation requirement, E_g, for the e- to attain the conduction band
- The filled band is called the valence band, while the unfilled one is called the conduction band
  - The bandgap energy, E_g is the energy between the highest energy levels in the valence band, and the lowest energy level in the conduction band
  - For room temperature semiconductors: $0 < E_g < 3.5$ eV



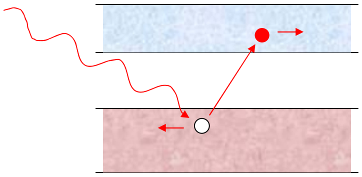
Band Gap

- Si, Ge, InSb are "insulators"
  - Have $E_g = E_{\text{band gap}} \sim 20\ kT_{\text{room}}$
  - Thermal fluctuations (phonons) can excite an electron across the band gap.
  - Because there are many free (empty) levels, the electron and hole are left by it are free to move.

Pure Semiconductors

- Pure semiconductors, i.e. Si and Ge, are called **Intrinsic.**

Material	E_g(eV)	λ_c(μm)
Diamond	5.33	0.23
Si	1.11	1.12
Ge	0.67	1.85
SiC	2.86	0.43



- If the temperature of the material is low
  - There will be few electrons in the conduction band.
- A photon with $E_{ph} > E_g$ E_{ph} (eV) = 1.24/λ(μm)
  - can move an electron from the valence to the conduction band
  - Current can flow
- We have a photon detector !!

Periodic Table

Ia	IIa	III b	IV b	V b	VI b	VII b	VIII b			I b	II b	IIIa	IVa	Va	VIa	VIIa	
H^{1} 1s																	He^{2} $1s^2$
Li^{3} 2s	Be^{4} $2s^2$											B^{5} $2s^2 2p$	C^{6} $2s^2 2p^2$	N^{7} $2s^2 2p^3$	O^{8} $2s^2 2p^4$	F^{9} $2s^2 2p^5$	Ne^{10} $2s^2 2p^6$
Na^{11} 3s	Mg^{12} $3s^2$											Al^{13} $3s^2 3p$	Si^{14} $3s^2 3p^2$	P^{15} $3s^2 3p^3$	S^{16} $3s^2 3p^4$	Cl^{17} $3s^2 3p^5$	Ar^{18} $3s^2 3p^6$
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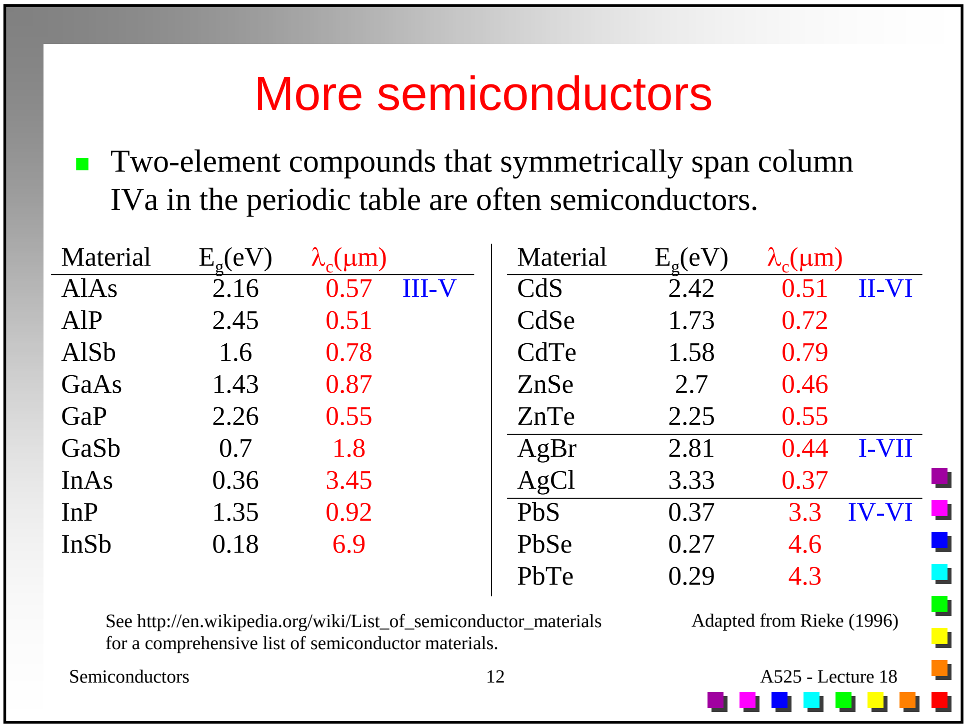
Outer electron configurations of neutral atoms in their ground states are shown.



More semiconductors

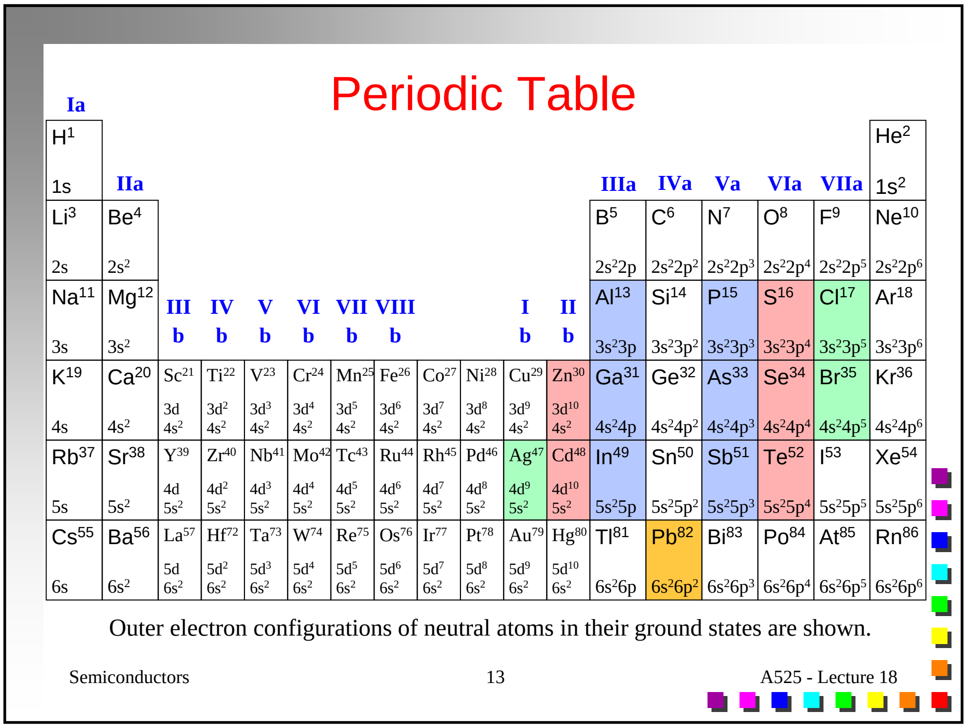
- Two-element compounds that symmetrically span column IVa in the periodic table are often semiconductors.

Material	E_g(eV)	λ_c(μm)	
AlAs	2.16	0.57	III-V
AlP	2.45	0.51	
AlSb	1.6	0.78	
GaAs	1.43	0.87	
GaP	2.26	0.55	
GaSb	0.7	1.8	
InAs	0.36	3.45	
InP	1.35	0.92	
InSb	0.18	6.9	

Material	E_g(eV)	λ_c(μm)	
CdS	2.42	0.51	II-VI
CdSe	1.73	0.72	
CdTe	1.58	0.79	
ZnSe	2.7	0.46	
ZnTe	2.25	0.55	
AgBr	2.81	0.44	I-VII
AgCl	3.33	0.37	
PbS	0.37	3.3	IV-VI
PbSe	0.27	4.6	
PbTe	0.29	4.3	

See http://en.wikipedia.org/wiki/List_of_semiconductor_materials
for a comprehensive list of semiconductor materials.

Adapted from Rieke (1996)



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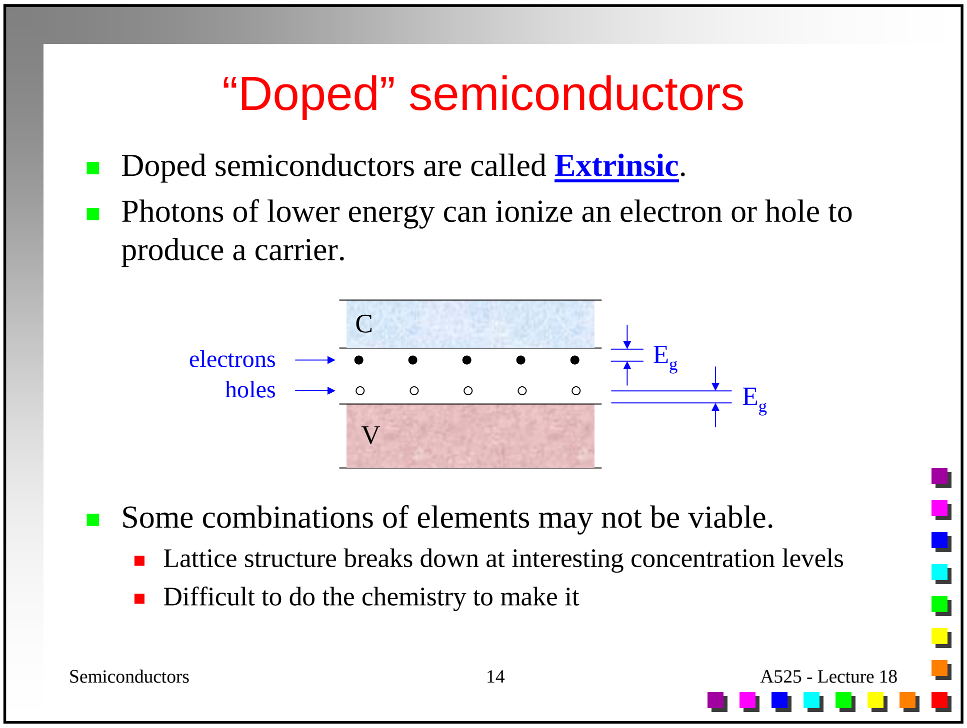
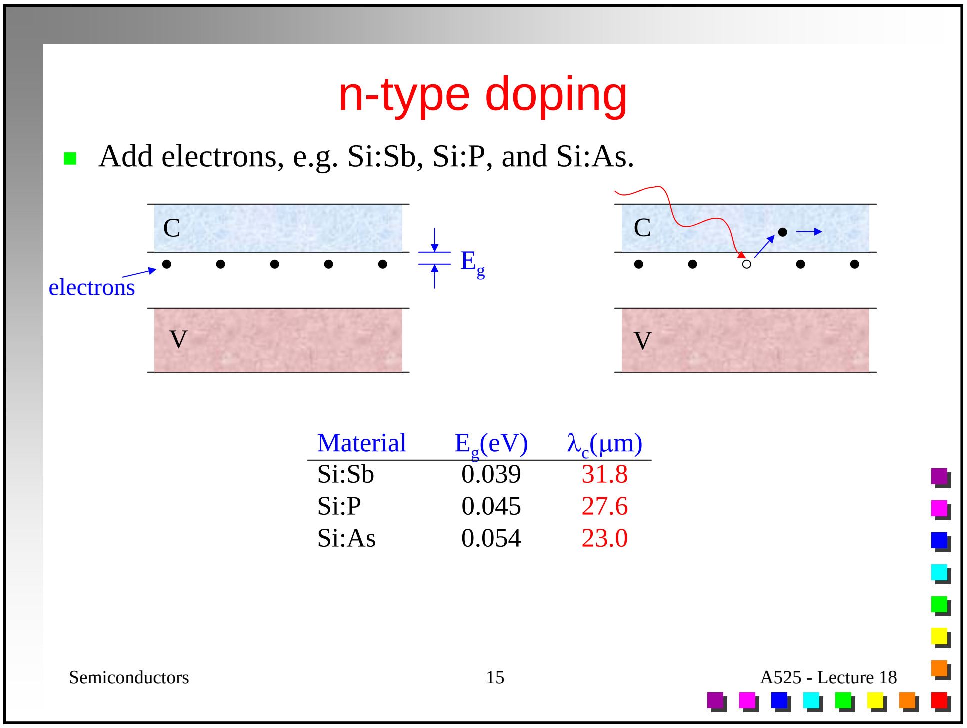


"Doped" semiconductors

- Doped semiconductors are called **Extrinsic**.
- Photons of lower energy can ionize an electron or hole to produce a carrier.

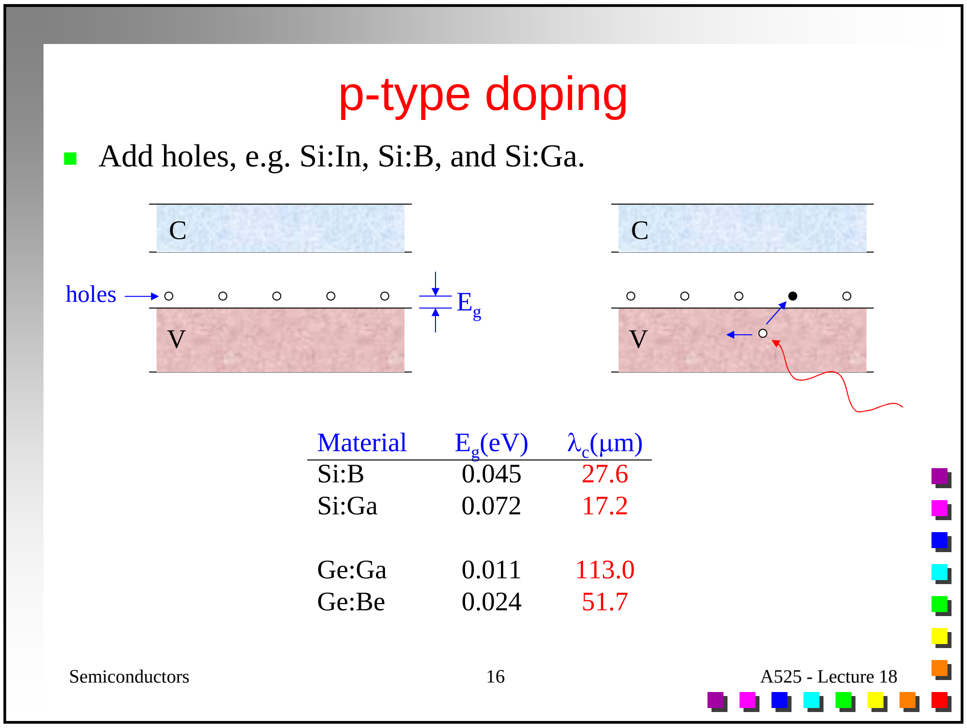
- Some combinations of elements may not be viable.
  - Lattice structure breaks down at interesting concentration levels
  - Difficult to do the chemistry to make it



n-type doping

- Add electrons, e.g. Si:Sb, Si:P, and Si:As.

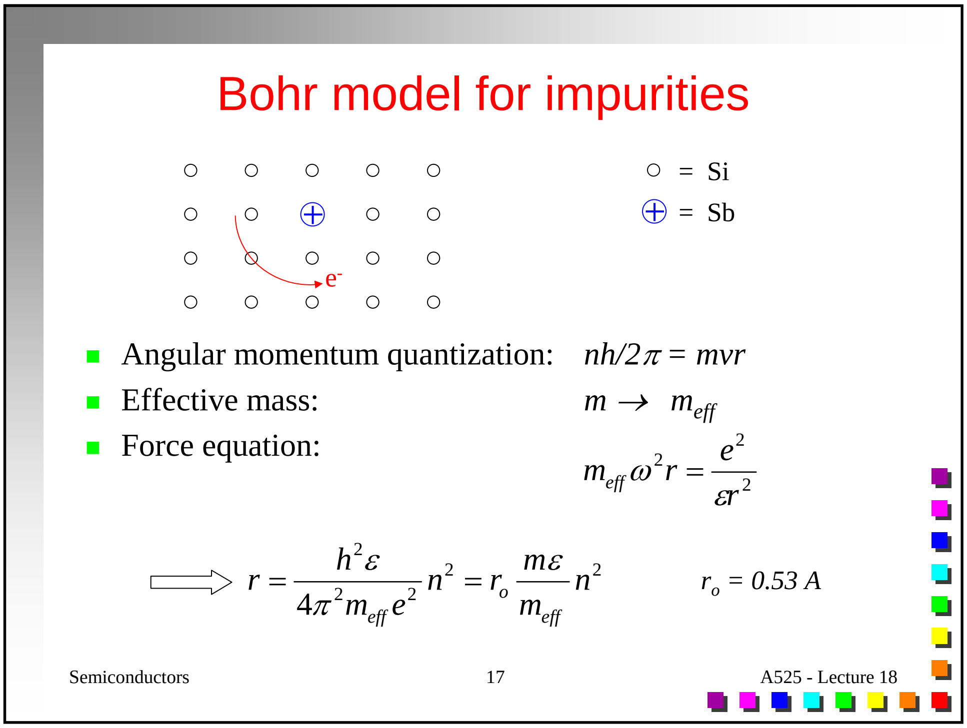
Material	E_g(eV)	λ_c(μm)
Si:Sb	0.039	31.8
Si:P	0.045	27.6
Si:As	0.054	23.0



p-type doping

- Add holes, e.g. Si:In, Si:B, and Si:Ga.

Material	E_g(eV)	λ_c(μm)
Si:B	0.045	27.6
Si:Ga	0.072	17.2
Ge:Ga	0.011	113.0
Ge:Be	0.024	51.7



Bohr model for impurities

○ = Si

⊕ = Sb

- Angular momentum quantization: $nh/2\pi = mvr$
- Effective mass: $m \rightarrow m_{eff}$
- Force equation: $m_{eff}\,\omega^2 r = \dfrac{e^2}{\varepsilon r^2}$

$$\Longrightarrow \quad r = \frac{h^2 \varepsilon}{4\pi^2 m_{eff} e^2} n^2 = r_o \frac{m\varepsilon}{m_{eff}} n^2 \qquad r_o = 0.53\ A$$

Energy levels

$$E = -\frac{e^2}{2\varepsilon r} = -R_o \frac{m_{eff}}{m} \frac{n^2}{\varepsilon^2}$$

$$R_o = 13.6 \text{ eV}$$

	ε	m_{eff}/m	r(A)	$E_{n=1}$(eV)	λ_o(μm)
Si	11.7	0.25	25	0.025	50
Ge	15.8	0.12	70	0.0065	190

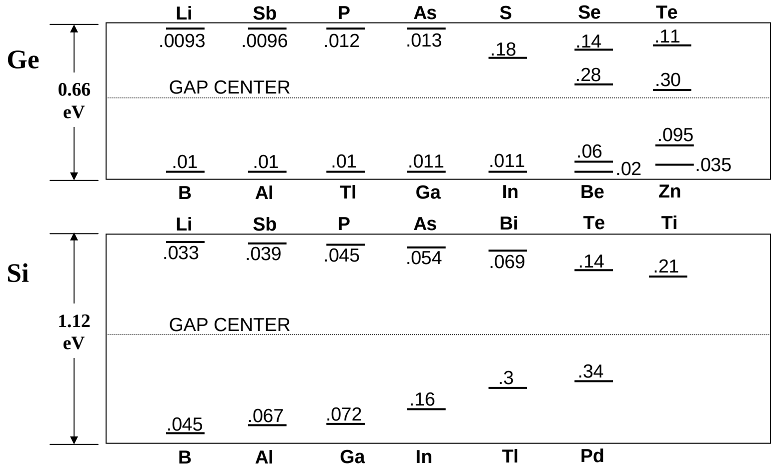
$$\lambda_o = hc/E_1$$

- This is idealized. Not all impurities are the same!
- Some actual values for λ_o.

Si:B ~ 30 μm

Ge:Ga ~ 120 μm

Ionization energies of impurities



See Sze, Physics of Semiconductor Devices

Ideal Photon Detector

- For quasi-monochromatic radiation
  - $P/h\nu$ = # photons/sec (P = power)
- If we have one electron per photon
  - Current = (# e-/sec)·e = $e \cdot P/h\nu$
- Responsivity [Amps/Watt]
  - $R_{max} = e / h\nu = 0.81 \cdot \lambda(\mu m)$ in Amps/Watt
  - The actual responsivity will be

$R = \eta G \cdot R_{max}$

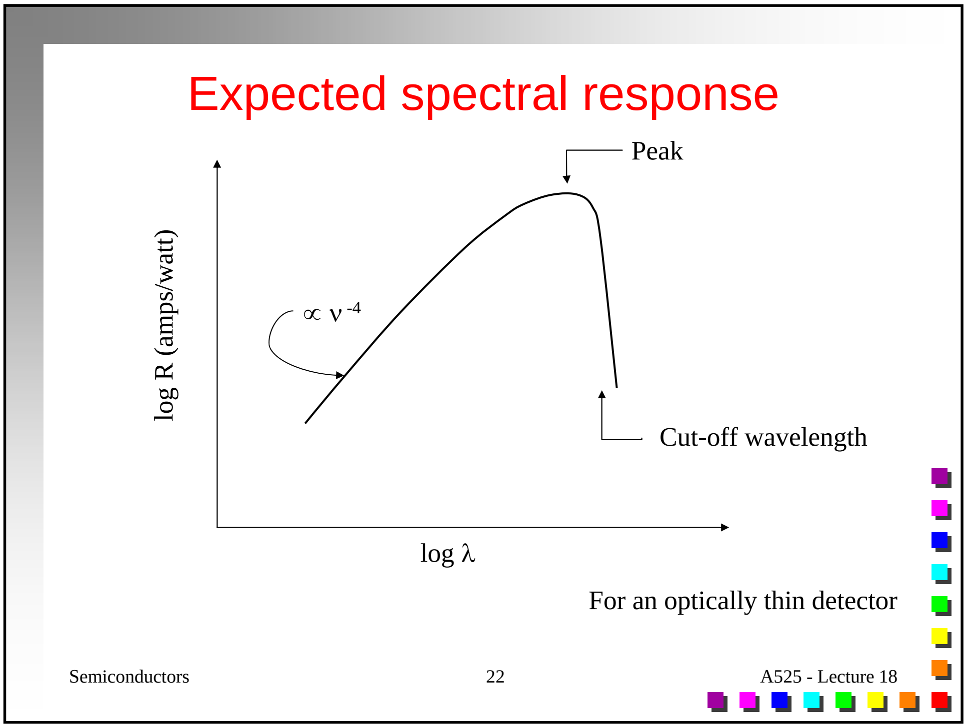
η = Quantum Efficiency

G = Photoconductive Gain

What is the spectral response?

- No (or little) response for $h\nu < E_B$.
- Peak response for $h\nu \sim E_B$.
- Decreasing response for $h\nu > E_B$.
  - Ionization cross-section decreases for $h\nu > E_B$.
    ($\sigma_\nu \propto \nu^{-3}$ like H-atom)
  - Only one e-/photon but more energy per photon

$$\Rightarrow \frac{\text{No. of } e^- / \text{sec}}{\text{watt}} \text{ goes down as } \nu \text{ increases}$$



Expected spectral response

For an optically thin detector

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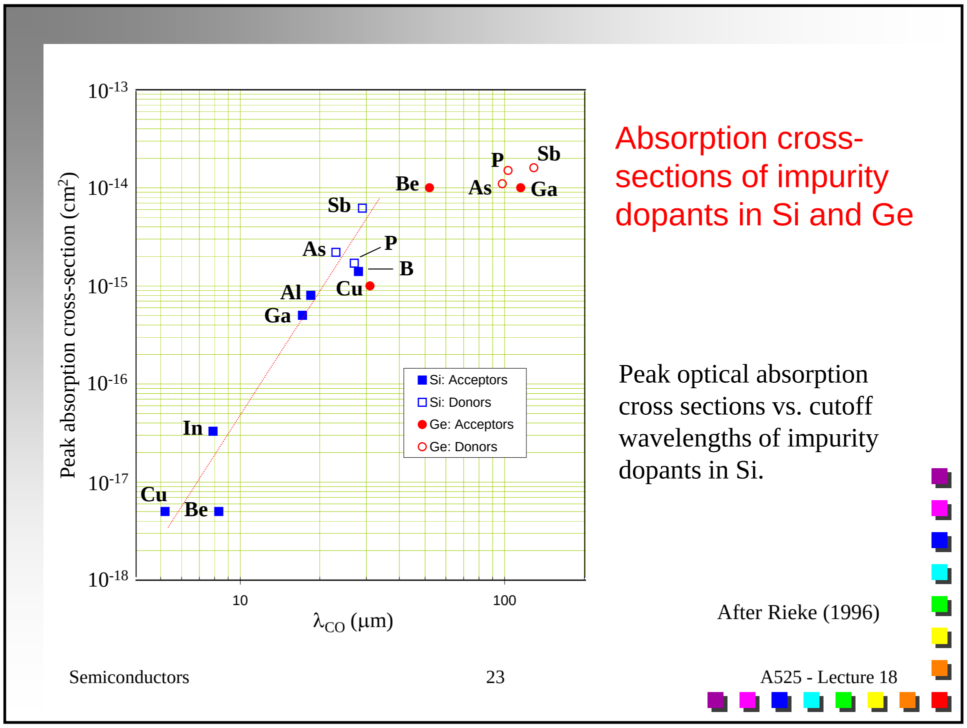

Absorption cross-sections of impurity dopants in Si and Ge

Peak optical absorption cross sections vs. cutoff wavelengths of impurity dopants in Si.

After Rieke (1996)

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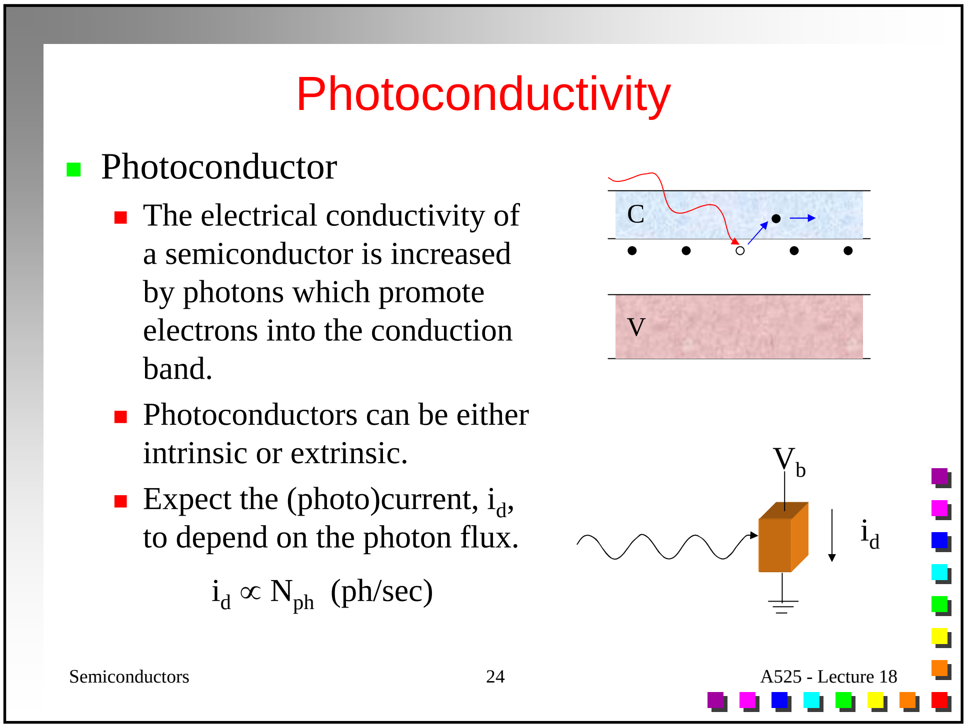
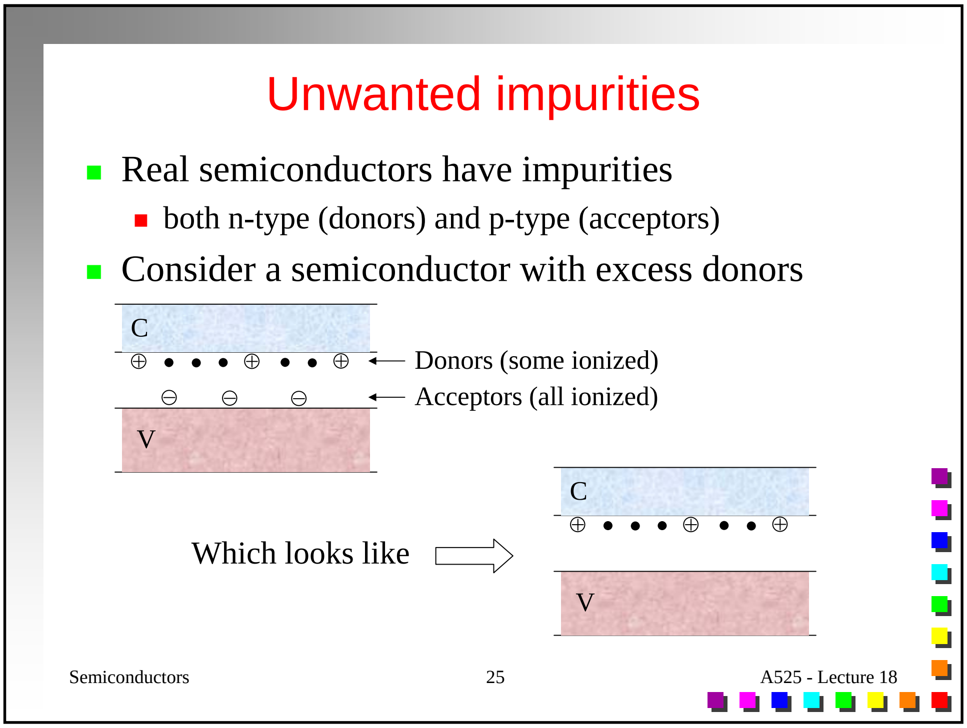


Photoconductivity

- Photoconductor
  - The electrical conductivity of a semiconductor is increased by photons which promote electrons into the conduction band.
  - Photoconductors can be either intrinsic or extrinsic.
  - Expect the (photo)current, i_d, to depend on the photon flux.

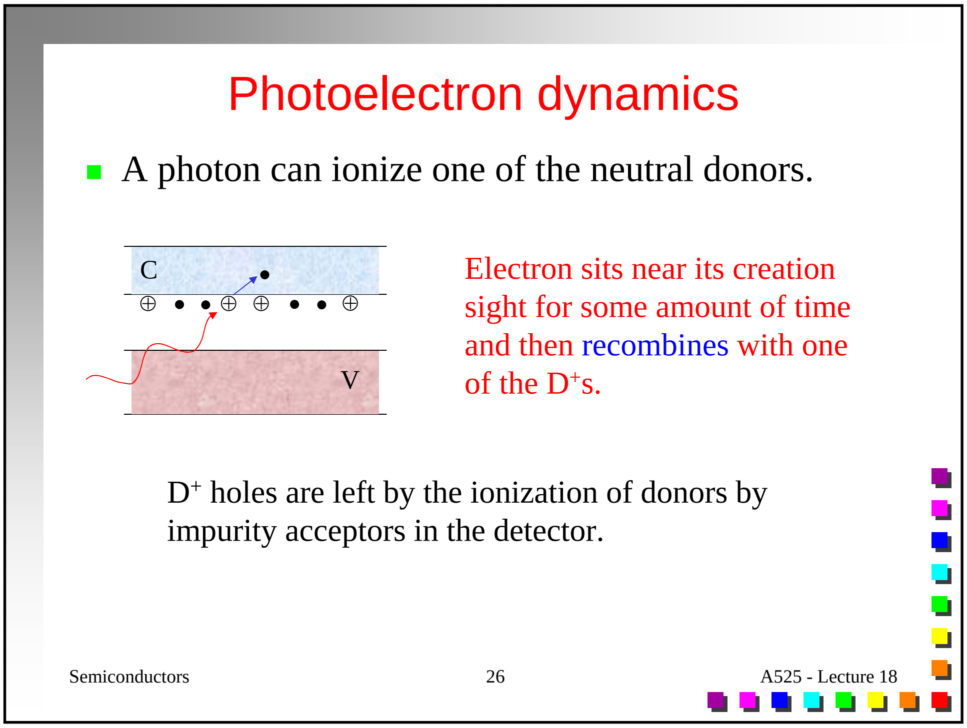
$$i_d \propto N_{ph} \quad \text{(ph/sec)}$$



Unwanted impurities

- Real semiconductors have impurities
  - both n-type (donors) and p-type (acceptors)
- Consider a semiconductor with excess donors

Which looks like

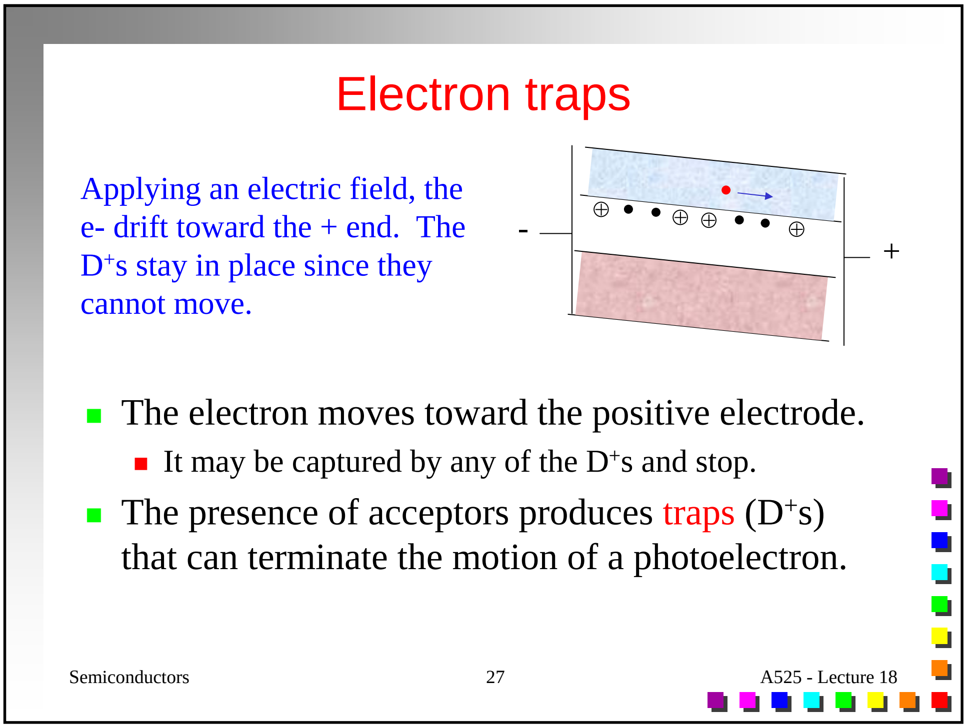


Photoelectron dynamics

- A photon can ionize one of the neutral donors.

Electron sits near its creation sight for some amount of time and then recombines with one of the D^+s.

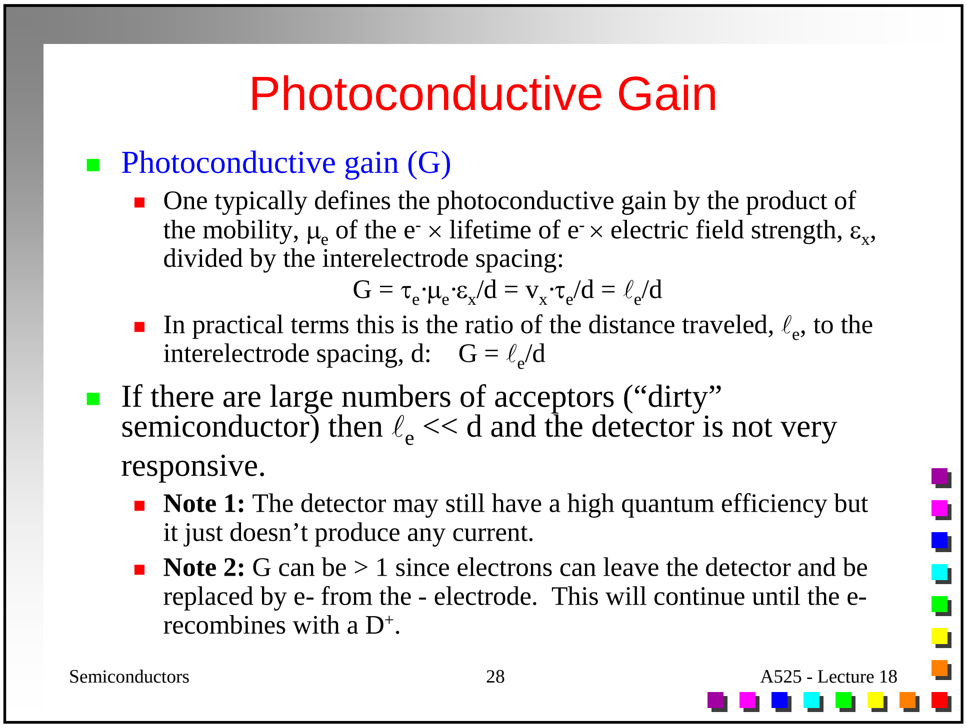
D^+ holes are left by the ionization of donors by impurity acceptors in the detector.



Electron traps

Applying an electric field, the e- drift toward the + end. The D^+s stay in place since they cannot move.

- The electron moves toward the positive electrode.
  - It may be captured by any of the D^+s and stop.
- The presence of acceptors produces traps (D^+s) that can terminate the motion of a photoelectron.



Photoconductive Gain

- Photoconductive gain (G)
  - One typically defines the photoconductive gain by the product of the mobility, μ_e of the e^- × lifetime of e^- × electric field strength, ε_x, divided by the interelectrode spacing:

$$G = \tau_e \cdot \mu_e \cdot \varepsilon_x / d = v_x \cdot \tau_e / d = \ell_e / d$$

  - In practical terms this is the ratio of the distance traveled, ℓ_e, to the interelectrode spacing, d: $G = \ell_e / d$
- If there are large numbers of acceptors ("dirty" semiconductor) then $\ell_e \ll d$ and the detector is not very responsive.
  - **Note 1:** The detector may still have a high quantum efficiency but it just doesn't produce any current.
  - **Note 2:** G can be > 1 since electrons can leave the detector and be replaced by e- from the - electrode. This will continue until the e- recombines with a D^+.