Astronomical Observing Techniques 2017

Lecture 9: Silicon Eyes 1

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2. Crystal Lattices
3. Electronic Bands
4. Fermi Energy and Fermi Function
5. Intrinsic Photoconductors
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7. Readout & Operations
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Modern Detectors

Photon detectors

Responds to individual photons, releases electrons, X-rays to IR

Examples: photoconductors, photodiodes, photoemissive detectors

Thermal detectors

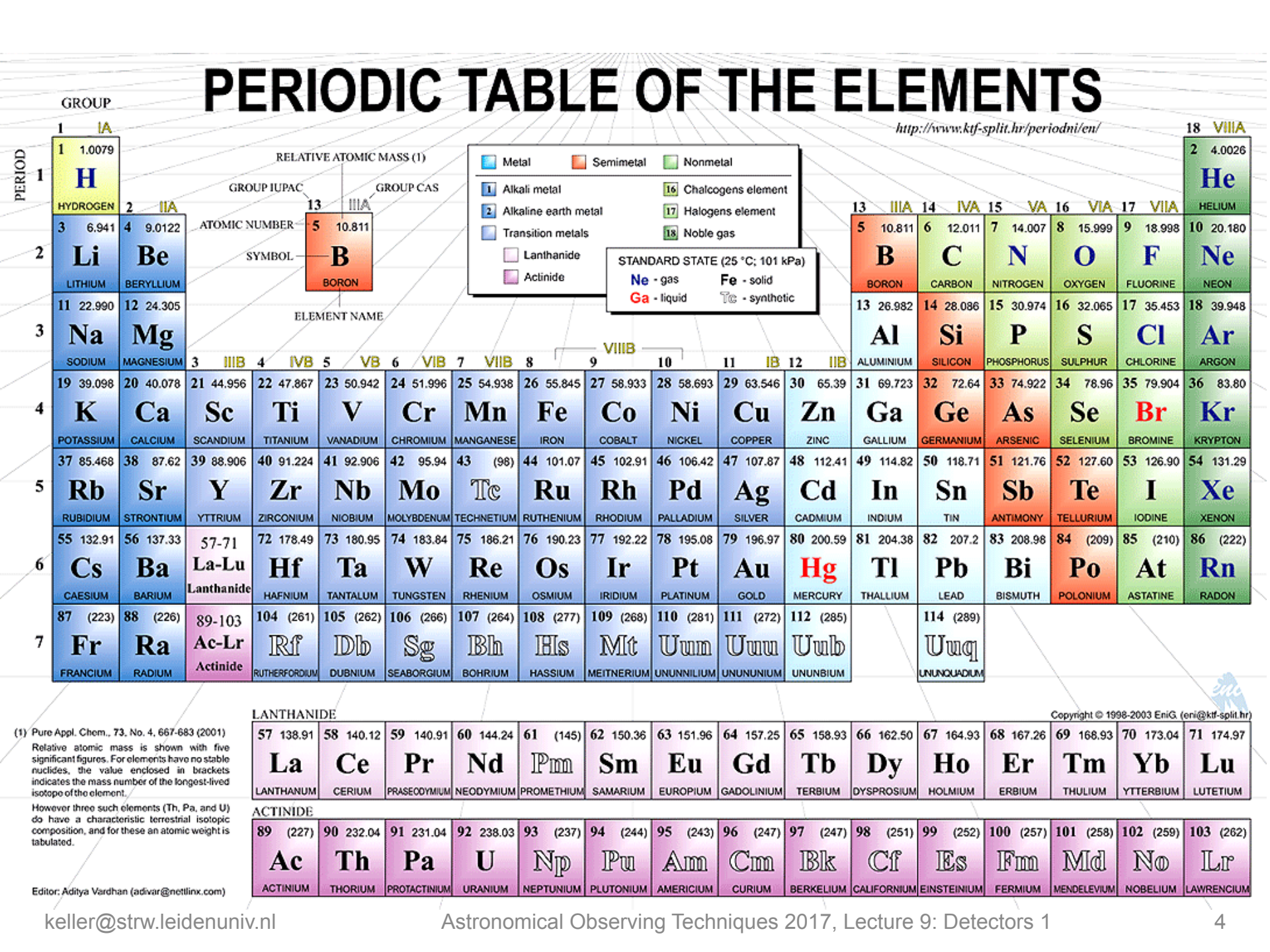
Absorbs photons, changes temperatures, changes resistance, IR and sub-mm detectors

Examples: bolometers

Coherent receivers

Responds directly to electrical field and preserve phase, mainly used in the sub-mm and radio regime

Examples: heterodyne receivers


PERIODIC TABLE OF THE ELEMENTS
http://www.ktf-split.hr/periodni/en/
GROUP
PERIOD
RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME
Metal
Semimetal
Nonmetal
1 Alkali metal
2 Alkaline earth metal
Transition metals
Lanthanide
Actinide
16 Chalcogens element
17 Halogens element
18 Noble gas
STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic
1 IA
2 IIA
3 IIIB
4 IVB
5 VB
6 VIB
7 VIIB
8 VIIIB
9 VIIIB
10 VIIIB
11 IB
12 IIB
13 IIIA
14 IVA
15 VA
16 VIA
17 VIIA
18 VIIIA
1 1.0079 H HYDROGEN
2 4.0026 He HELIUM
3 6.941 Li LITHIUM
4 9.0122 Be BERYLLIUM
5 10.811 B BORON
6 12.011 C CARBON
7 14.007 N NITROGEN
8 15.999 O OXYGEN
9 18.998 F FLUORINE
10 20.180 Ne NEON
11 22.990 Na SODIUM
12 24.305 Mg MAGNESIUM
13 26.982 Al ALUMINIUM
14 28.086 Si SILICON
15 30.974 P PHOSPHORUS
16 32.065 S SULPHUR
17 35.453 Cl CHLORINE
18 39.948 Ar ARGON
19 39.098 K POTASSIUM
20 40.078 Ca CALCIUM
21 44.956 Sc SCANDIUM
22 47.867 Ti TITANIUM
23 50.942 V VANADIUM
24 51.996 Cr CHROMIUM
25 54.938 Mn MANGANESE
26 55.845 Fe IRON
27 58.933 Co COBALT
28 58.693 Ni NICKEL
29 63.546 Cu COPPER
30 65.39 Zn ZINC
31 69.723 Ga GALLIUM
32 72.64 Ge GERMANIUM
33 74.922 As ARSENIC
34 78.96 Se SELENIUM
35 79.904 Br BROMINE
36 83.80 Kr KRYPTON
37 85.468 Rb RUBIDIUM
38 87.62 Sr STRONTIUM
39 88.906 Y YTTRIUM
40 91.224 Zr ZIRCONIUM
41 92.906 Nb NIOBIUM
42 95.94 Mo MOLYBDENUM
43 (98) Tc TECHNETIUM
44 101.07 Ru RUTHENIUM
45 102.91 Rh RHODIUM
46 106.42 Pd PALLADIUM
47 107.87 Ag SILVER
48 112.41 Cd CADMIUM
49 114.82 In INDIUM
50 118.71 Sn TIN
51 121.76 Sb ANTIMONY
52 127.60 Te TELLURIUM
53 126.90 I IODINE
54 131.29 Xe XENON
55 132.91 Cs CAESIUM
56 137.33 Ba BARIUM
57-71 La-Lu Lanthanide
72 178.49 Hf HAFNIUM
73 180.95 Ta TANTALUM
74 183.84 W TUNGSTEN
75 186.21 Re RHENIUM
76 190.23 Os OSMIUM
77 192.22 Ir IRIDIUM
78 195.08 Pt PLATINUM
79 196.97 Au GOLD
80 200.59 Hg MERCURY
81 204.38 Tl THALLIUM
82 207.2 Pb LEAD
83 208.98 Bi BISMUTH
84 (209) Po POLONIUM
85 (210) At ASTATINE
86 (222) Rn RADON
87 (223) Fr FRANCIUM
88 (226) Ra RADIUM
89-103 Ac-Lr Actinide
104 (261) Rf RUTHERFORDIUM
105 (262) Db DUBNIUM
106 (266) Sg SEABORGIUM
107 (264) Bh BOHRIUM
108 (277) Hs HASSIUM
109 (268) Mt MEITNERIUM
110 (281) Uun UNUNNILIUM
111 (272) Uuu UNUNUNIUM
112 (285) Uub UNUNBIUM
114 (289) Uuq UNUNQUADIUM
LANTHANIDE
57 138.91 La LANTHANUM
58 140.12 Ce CERIUM
59 140.91 Pr PRASEODYMIUM
60 144.24 Nd NEODYMIUM
61 (145) Pm PROMETHIUM
62 150.36 Sm SAMARIUM
63 151.96 Eu EUROPIUM
64 157.25 Gd GADOLINIUM
65 158.93 Tb TERBIUM
66 162.50 Dy DYSPROSIUM
67 164.93 Ho HOLMIUM
68 167.26 Er ERBIUM
69 168.93 Tm THULIUM
70 173.04 Yb YTTERBIUM
71 174.97 Lu LUTETIUM
ACTINIDE
89 (227) Ac ACTINIUM
90 232.04 Th THORIUM
91 231.04 Pa PROTACTINIUM
92 238.03 U URANIUM
93 (237) Np NEPTUNIUM
94 (244) Pu PLUTONIUM
95 (243) Am AMERICIUM
96 (247) Cm CURIUM
97 (247) Bk BERKELIUM
98 (251) Cf CALIFORNIUM
99 (252) Es EINSTEINIUM
100 (257) Fm FERMIUM
101 (258) Md MENDELEVIUM
102 (259) No NOBELIUM
103 (262) Lr LAWRENCIUM
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.
Editor: Aditya Vardhan (adivar@netlinx.com)
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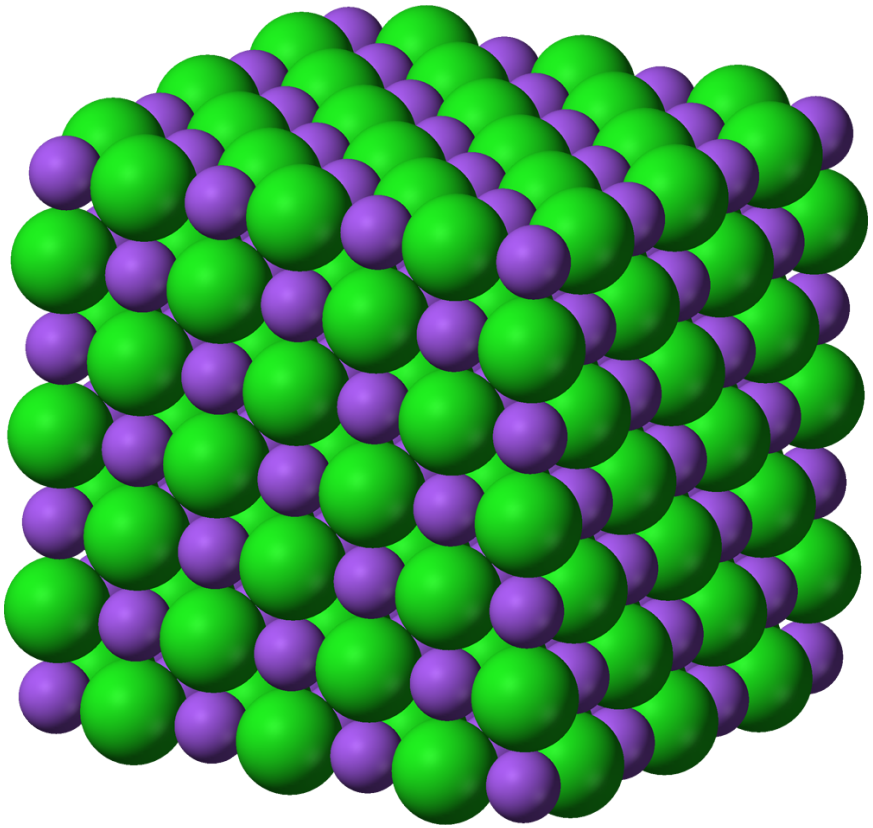
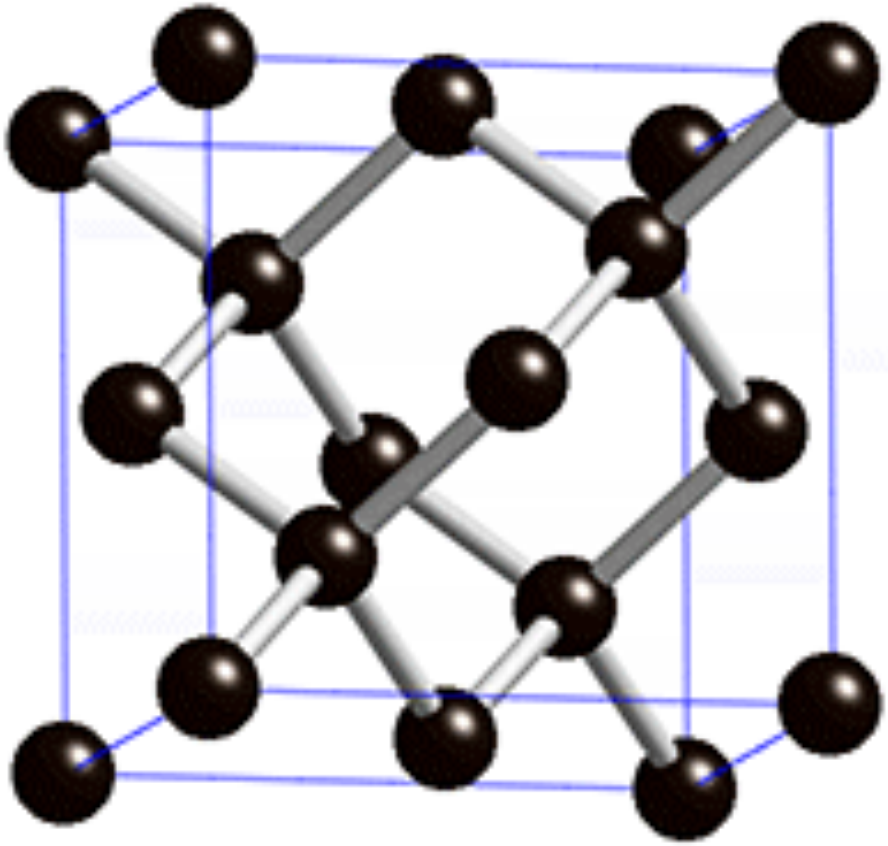
Crystal Lattice

- crystals: periodic arrangement of atoms, ions or molecules
- smallest group of atoms that repeats is unit cell
- unit cells repeat at lattice points
- crystal structure and symmetry determine many physical properties



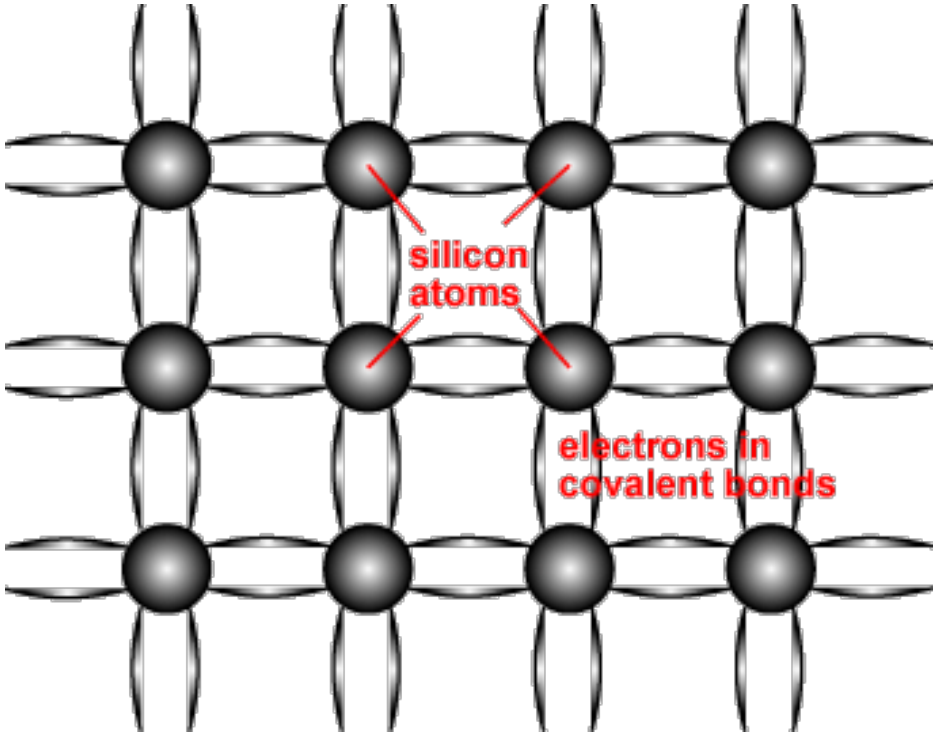
purple:Na^+, green: Cl^-

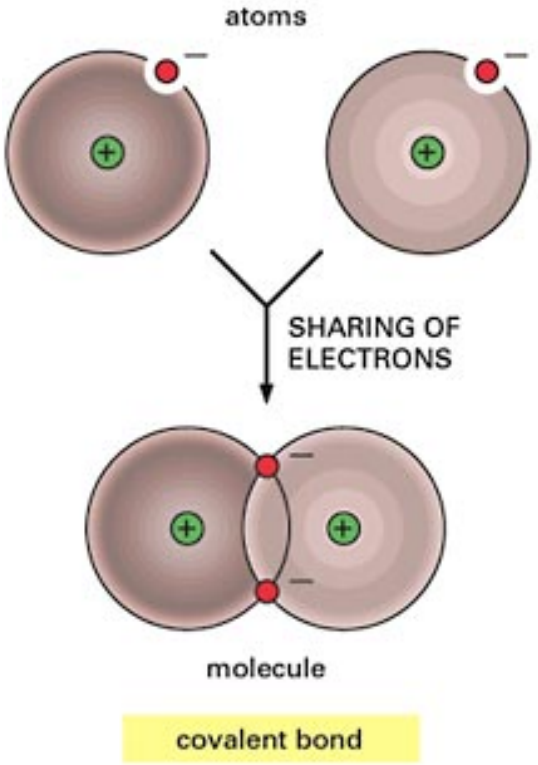
Diamond Unit Cell



Covalent Bond

- Elements with 4 e^- in valence shell form crystals with diamond lattice structure (each atom bonds to four neighbors).
- Double-bonds between neighbours due to “shared” electrons

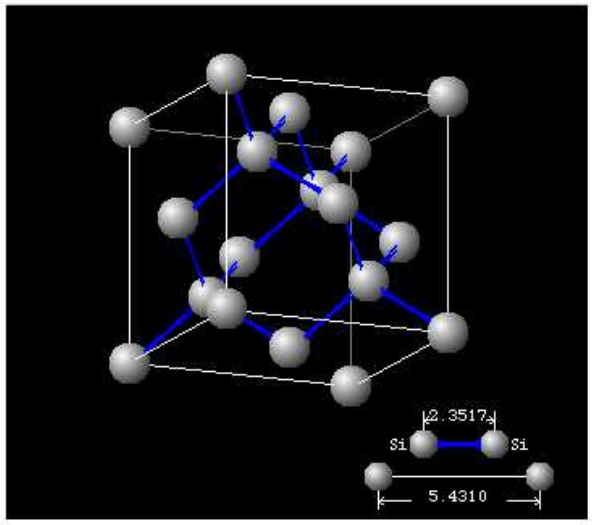


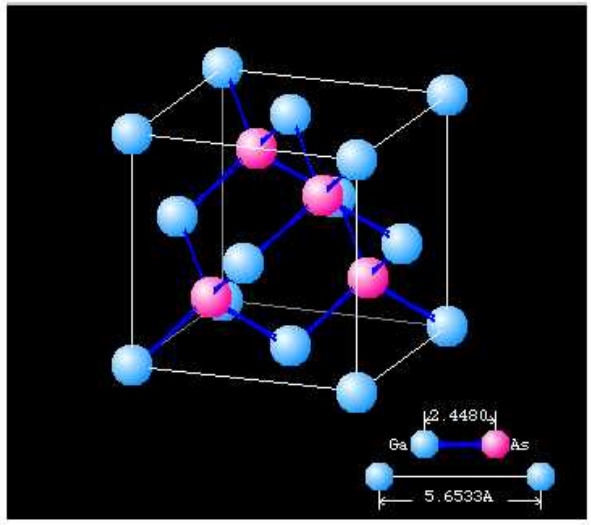


Diamond Lattice with 2 Elements

Diamond lattice not only formed by group IV elements (C, Si, Ge) but also by III-V semiconductors (InSb, GaAs, AlP)

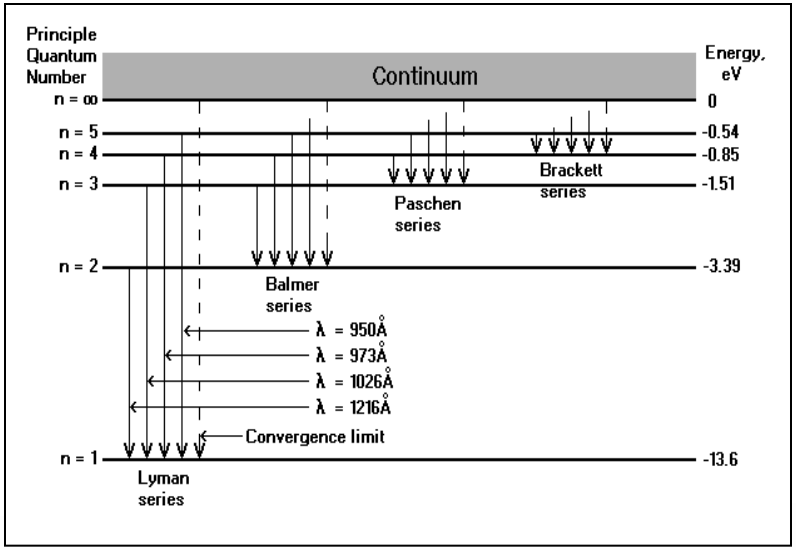
	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
IIB	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te





Electronic States and Bands

Single (Hydrogen) Atom

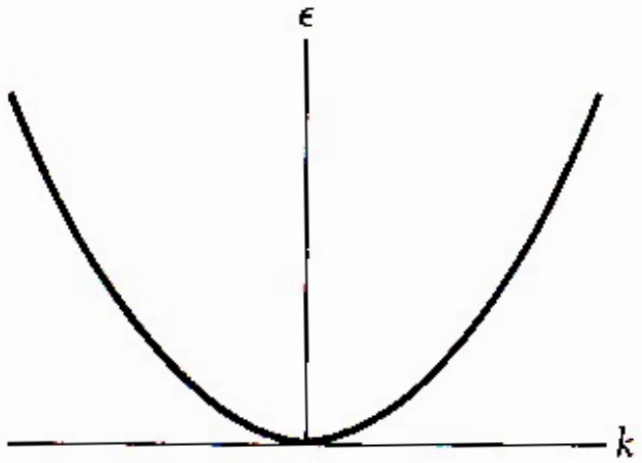


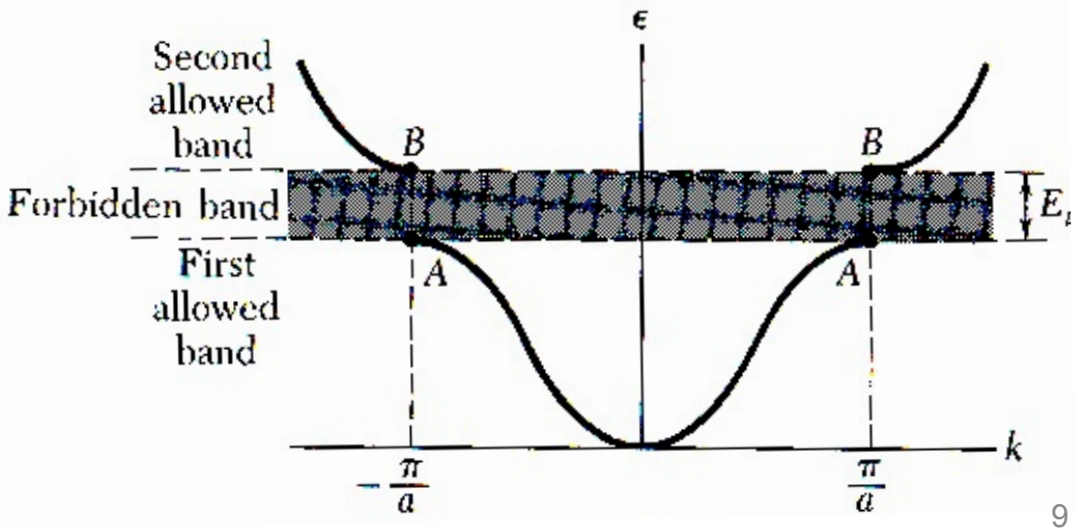
Atoms in crystal

Wavefunctions Ψ overlap

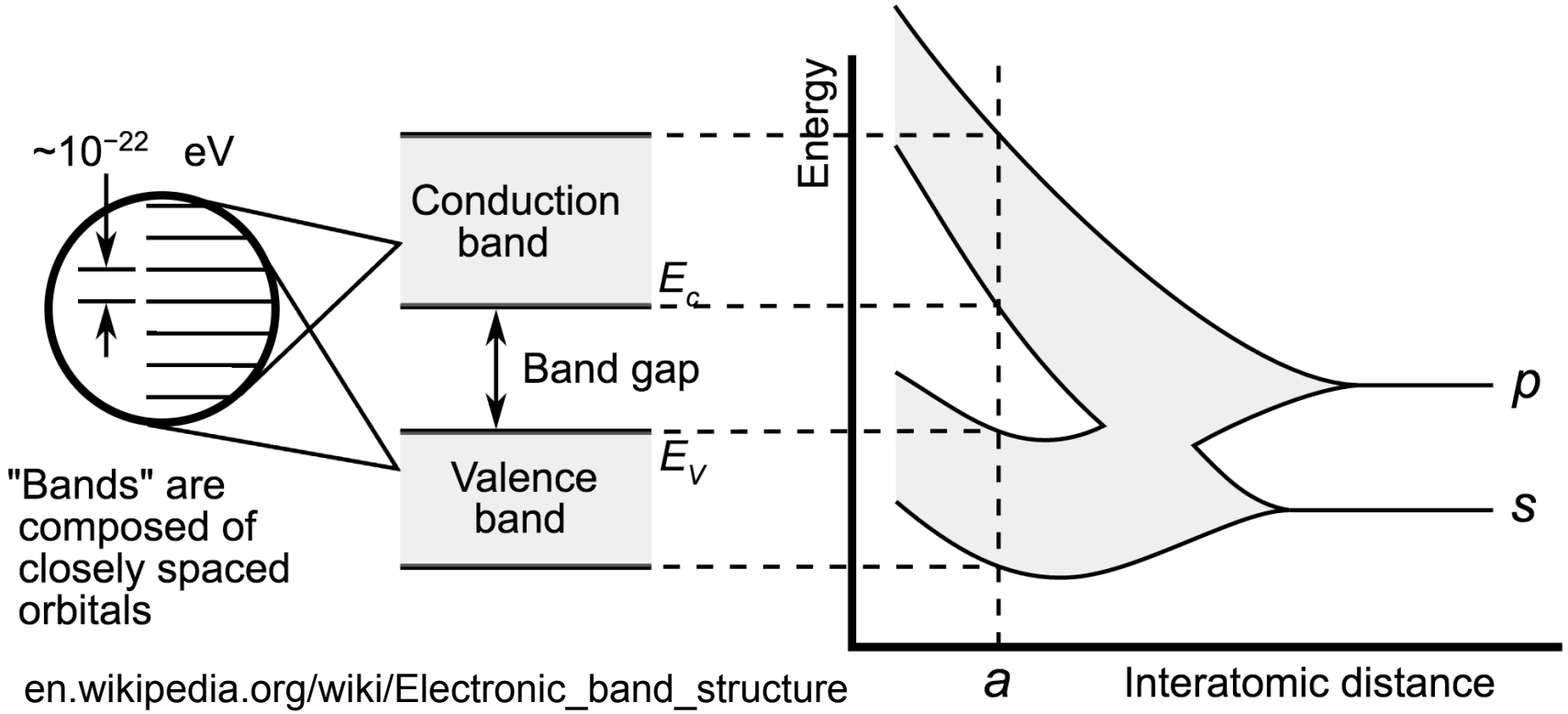
→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

→ Multiple splitting ➔ "bands"





Electron Energy Levels in Carbon

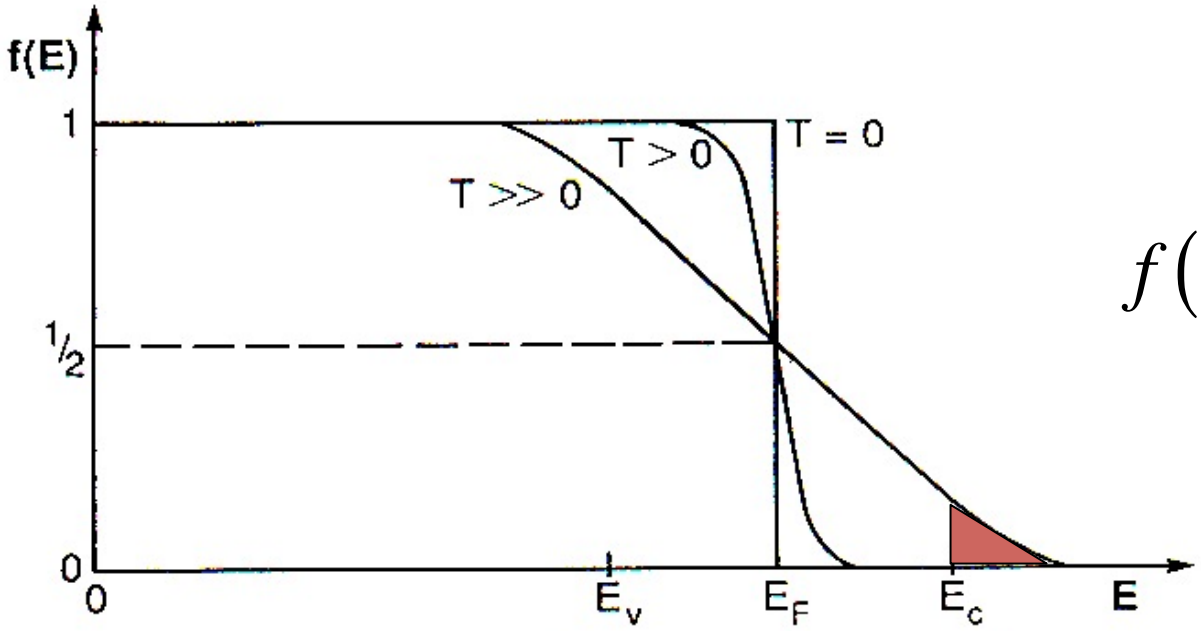


en.wikipedia.org/wiki/Electronic_band_structure

- possible energy levels of electrons in diamond lattice
- Pauli exclusion principle leads to splitting of energy states
- electrons in conduction band can move freely

Fermi Energy

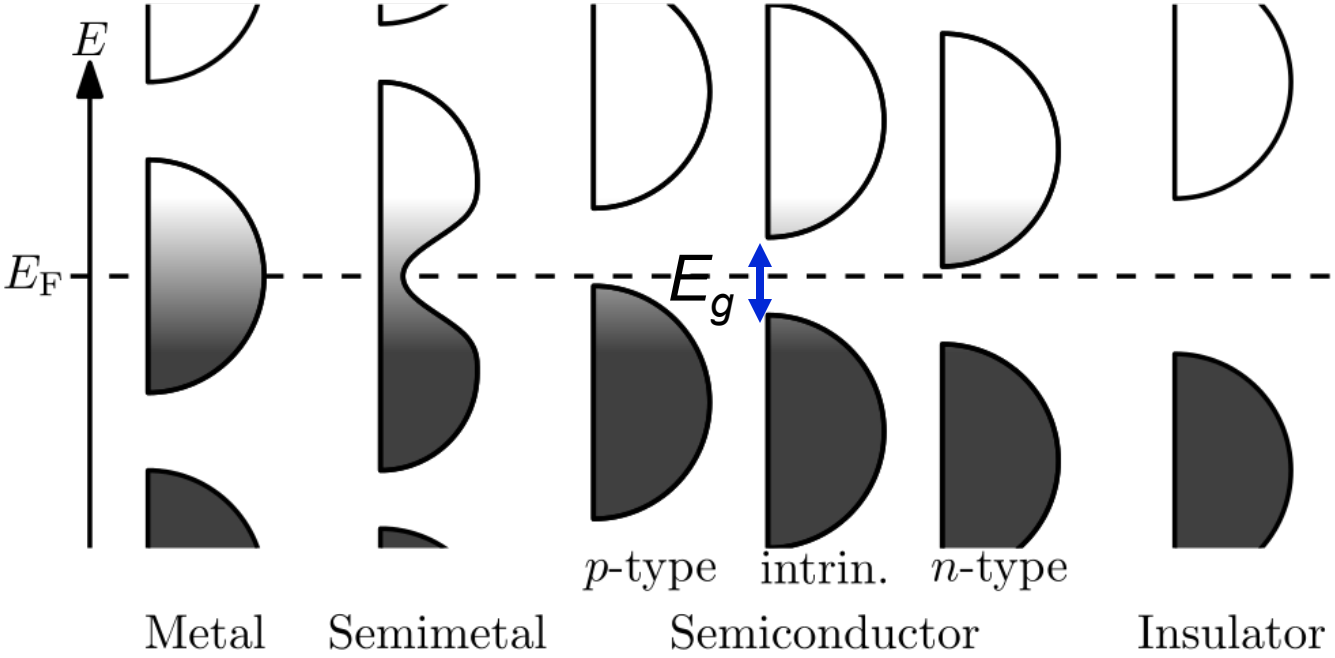
- Pauli exclusion principle 2 fermions cannot occupy same quantum state; fill up unoccupied quantum states
- Fermi energy E_F is energy of highest occupied quantum state in a system of fermions at T = 0K
- Fermi function $f(E)$ is probability that state of energy E is occupied at temperature T; $f(E_F) = 0.5$



$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

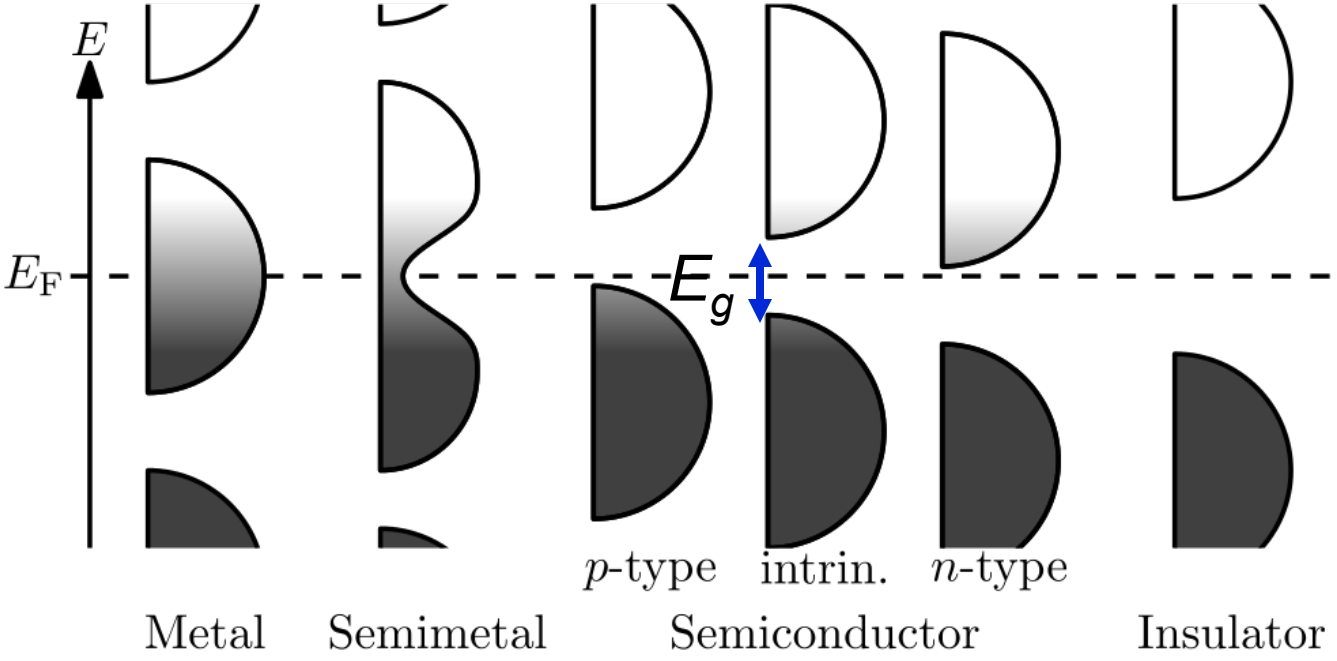
Electric Conductivity

Conductivity requires charge carriers in the conduction band



- Metal: Fermi energy in the middle of conduction band -> free electrons at all temperatures
- Insulator: large band gap and Fermi energy between bands
- Semiconductor: narrow band gap and Fermi energy between bands

Overcoming Bandgap



Overcome bandgap E_g to lift e^- into conduction band:

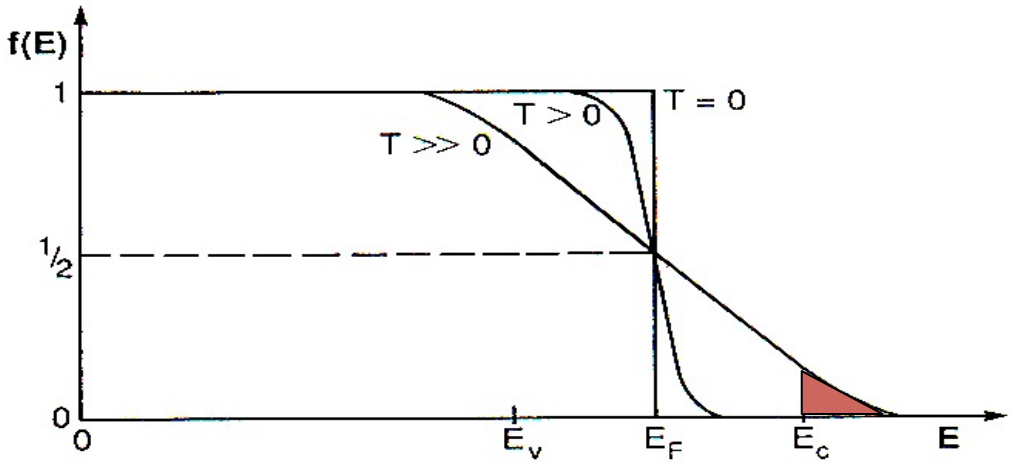
1. external excitation, e.g. via a photon ←photon detector
2. thermal excitation
3. impurities

Electrons in Conduction Band

- Number of occupied states in conduction band is given by product of number possible states N_c in conduction band times the probability $f(E_c)$ that they are occupied
- For silicon, temperature increase of 8K doubles number of electrons in conduction band

$$n_0 = N_c f\left(E_c\right)$$

$$N_c = 2\left(\frac{2\ \ m_{eff} kT}{h^2}\right)^{3/2}$$



$$f\left(E_c\right) = \frac{1}{1+e^{\left(E_c - E_F\right)/kT}} \overset{E_c - E_F >> kT}{\approx} e^{-\left(E_c - E_F\right)/kT}$$

Intrinisic Photo-Conductors: Basic Principle

- semi-conductor: few charge carriers → high resistance
- charge carriers = electron-hole pairs
- photon lifts e^- into conduction band
- applied electric field drives charges to electrodes

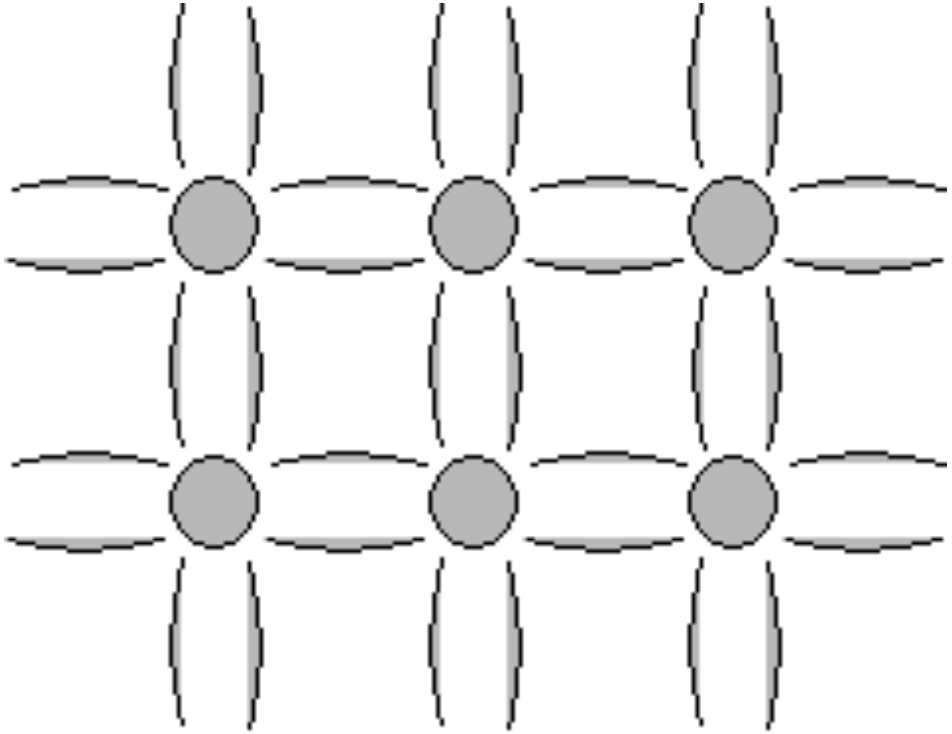
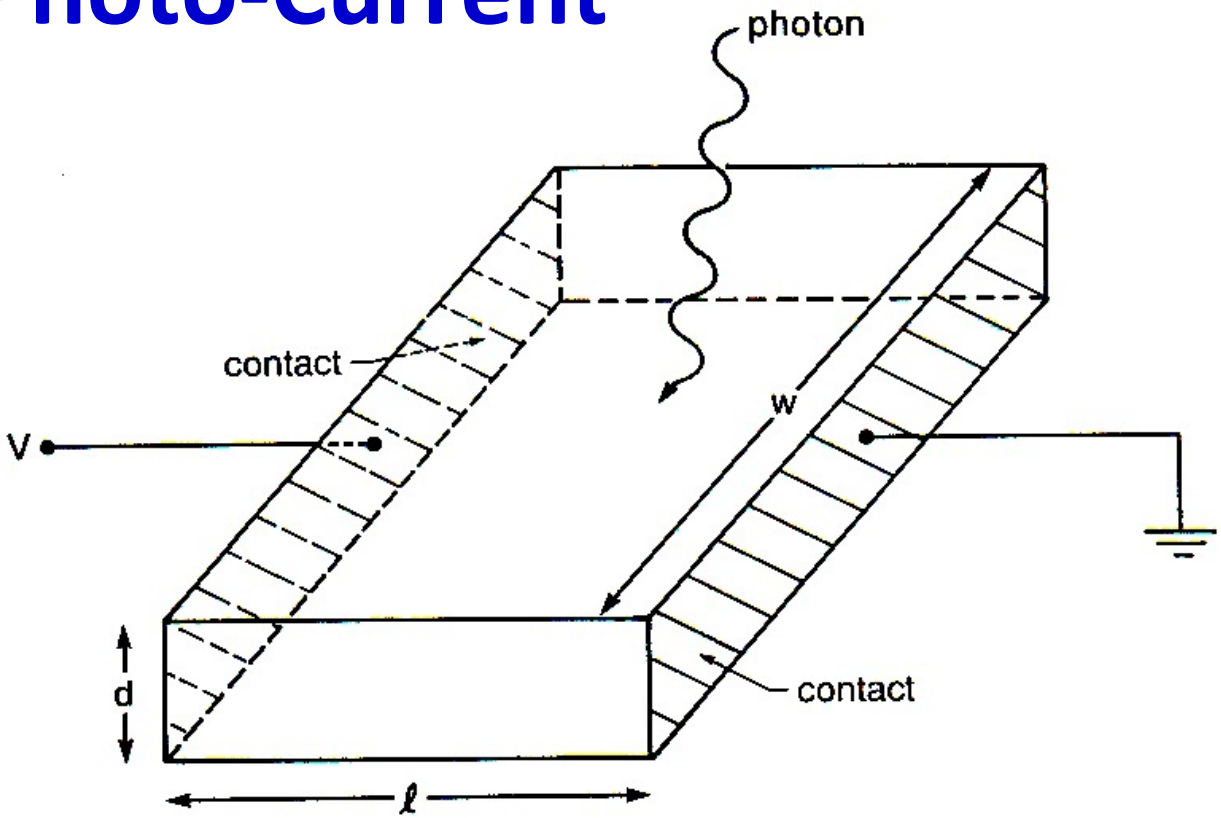


Photo-Current

- Conductivity: $j=\sigma E$
- Current: $I=jwd$
- $V=RI,\ E=V/l$
- $\sigma=j/E=jl/V=jl/(RI)$
  $=jl/(Rjwd)$
  $=1/R\times l/wd$



$$\sigma = \frac{1}{R_d}\frac{l}{wd} = qn_0\mu_n$$

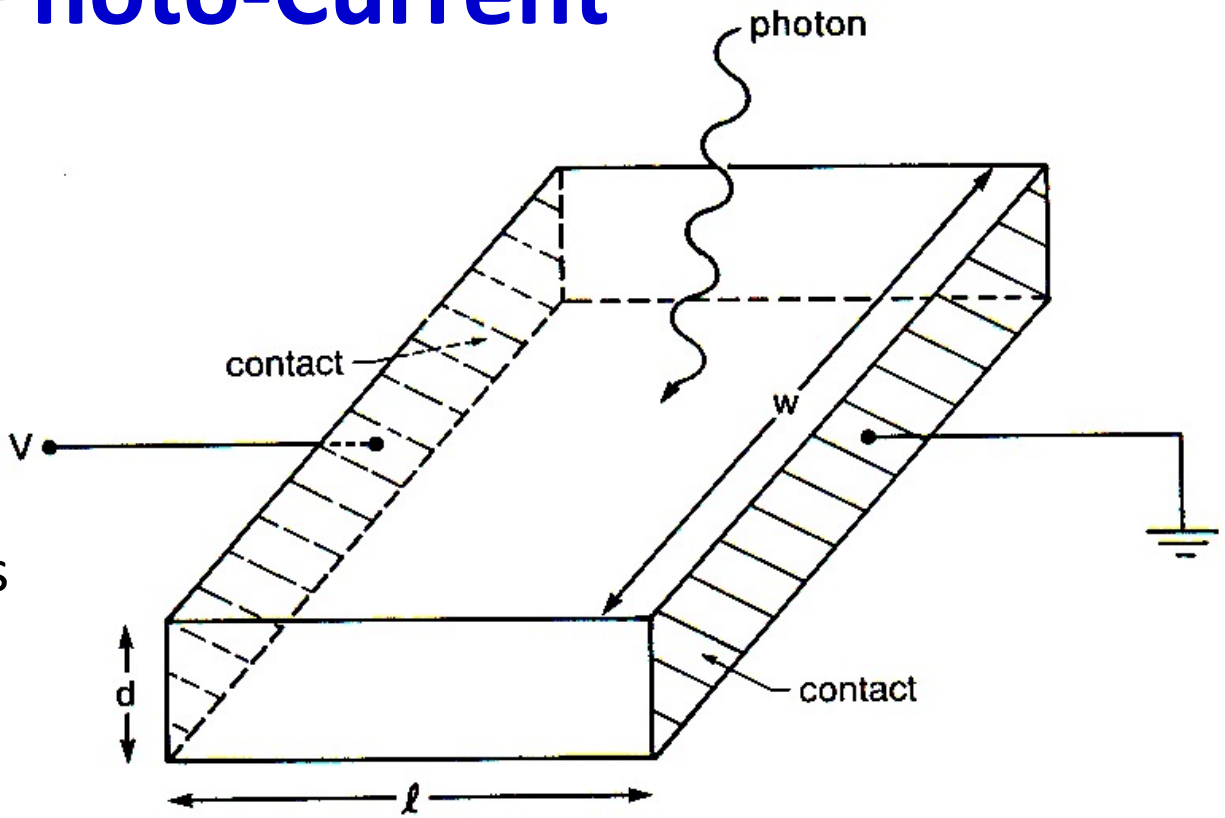
where:

R_d = resistance

w,d,l = geometric dimensions

Photo-Current

$$\sigma = \frac{1}{R_d}\frac{l}{wd} = qn_0\mu_n$$



where:

R_d = resistance

w,d,l = geo. dimensions

q = elementary charge

n_0 = number density of charge carriers

ϕ = photon flux

η = quantum efficiency

τ = mean lifetime before recombination

$$n_0 = \frac{\varphi\eta\tau}{wdl}$$

μ_n = electron mobility; drift velocity $v=\mu_n E$, current density $j=n_0 q v$, $\sigma=j/E=n_0 q\mu_n E/E=qn_0\mu_n$

Important Quantities and Definitions

Quantum efficiency η = $\dfrac{\#\text{ absorbed photons}}{\#\text{ incoming photons}}$

Responsivity S = $\dfrac{\text{electrical output signal}}{\text{input photon power}}$

Wavelength cutoff: $\lambda_c = \dfrac{hc}{E_g} = \dfrac{1.24\,\mu m}{E_g[eV]}$

Photo-current: $I_{ph} = q\varphi\eta G$

Photoconductive gain G: $G = \dfrac{I_{ph}}{q\varphi\eta} = \dfrac{\tau}{\tau_t} = \dfrac{\text{carrier lifetime}}{\text{transit time}}$

The product ηG describes the probability that an incoming photon will produce an electric charge that will reach an electrode

Limitations of Intrinsic Semiconductors

- long-wavelength cutoffs

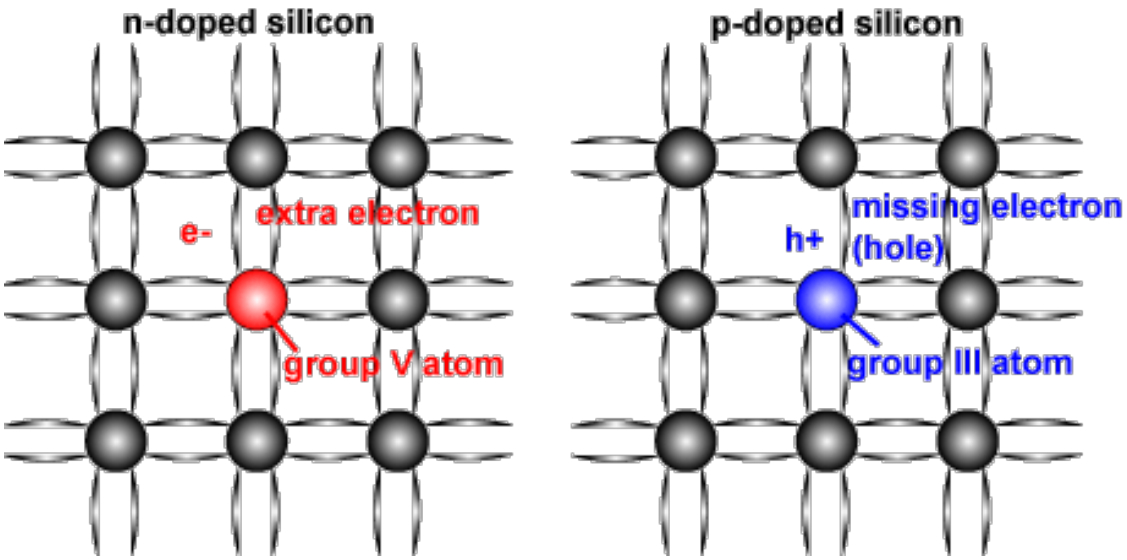
$$\lambda_c = \frac{hc}{E_g}$$

Germanium:	1.85µm
Silicon:	1.12µm
GaAs:	0.87µm

- difficult to create completely pure material
- problems to make good electrical contacts to pure Si
- difficult to avoid impurities and minimize thermal noise

Extrinsic Semiconductors

- extrinsic semiconductors:
  charge carriers = electrons (n-type) or holes (p-type)
- addition of impurities at low concentration to provide excess electrons or holes
- much reduced bandgap -> longer wavelength cutoff



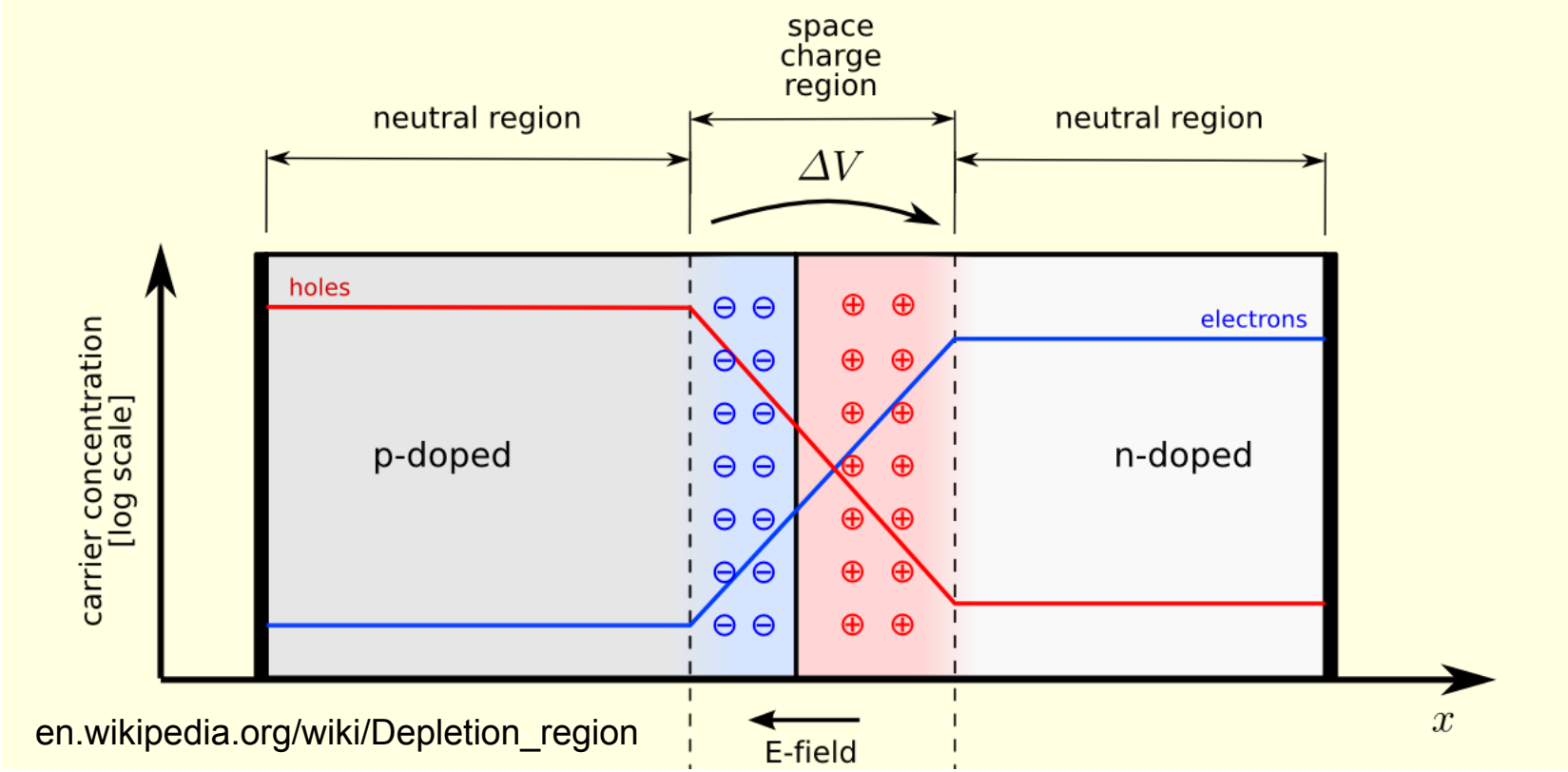
Example: addition of boron to silicon in the ratio 1:100,000 increases its conductivity by a factor of 1000!

Extrinsic Semiconductor Band Gaps

		Ge	Si
Impurity	Type	Cutoff wavelength λ_c (μm)	Cutoff wavelength λ_c (μm)
Al	p		18.5[a]
B	p	119[b]	28[a]
Be	p	52[b]	8.3[a]
Ga	p	115[b]	17.2[a]
In	p	111[b]	7.9[a]
As	n	98[b]	23[a]
Cu	p	31[b]	5.2[a]
P	n	103[b]	27[a]
Sb	n	129[b]	29[a]

Problem: absorption coefficients much less than for intrinsic photoconductors → low quantum efficiency → active volumes of pixels must be large

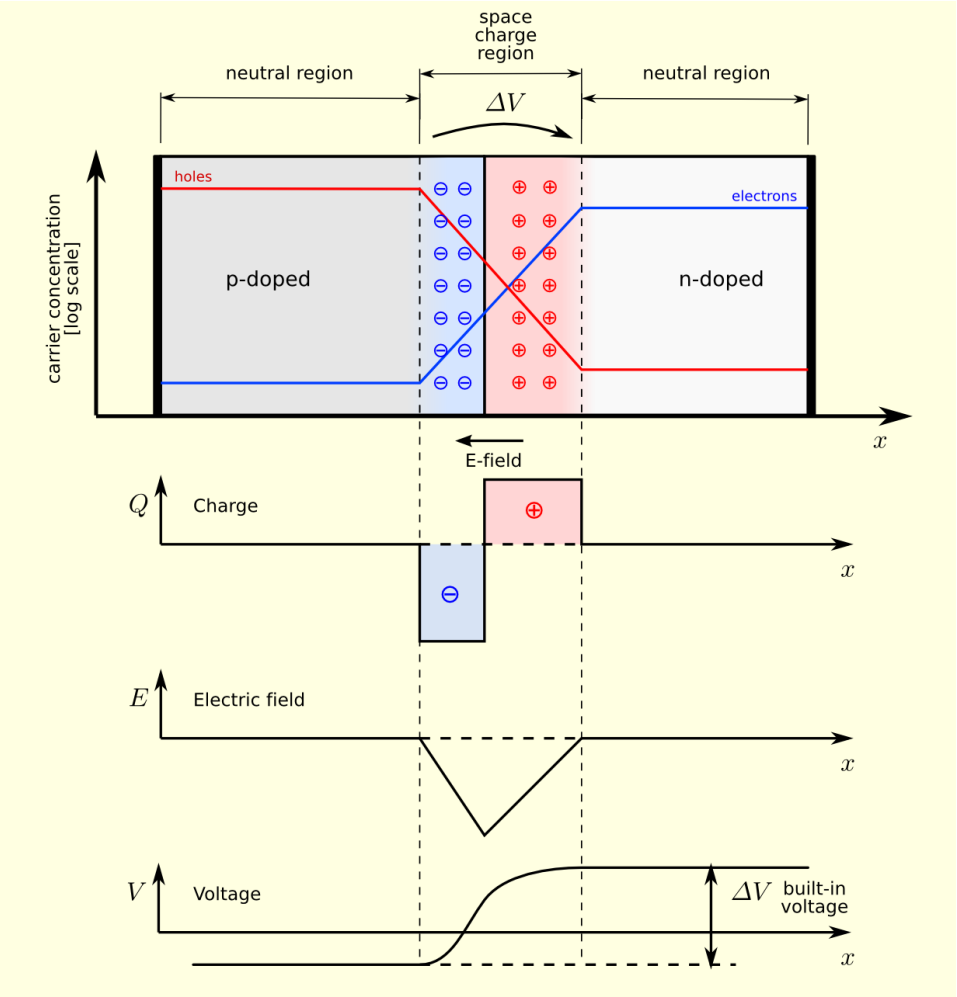
Depletion Zone / PN Junction



- junction between p- and n-doped Si (both are electrically neutral)
- e^- migrate to P-side, holes migrate to N-side
- e^- can only flow over large distances in n-type material, holes can only flow in p-type material

Depletion Zone / PN Junction

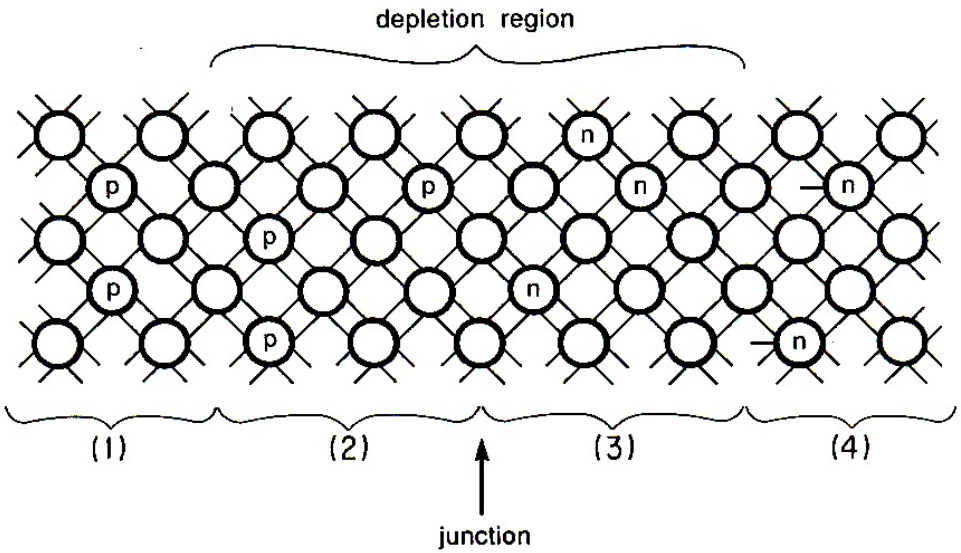
- migrating e^- from N-side to P-side produces positive donor ion on N-side; migrating hole produces negative acceptor ion on P-side
- migrating e^- recombine with holes on P-side; migrating holes recombine with e^- on N-side
- migrating e^- and holes, mobile charge carriers are depleted
- charged ions remain adjacent to interface

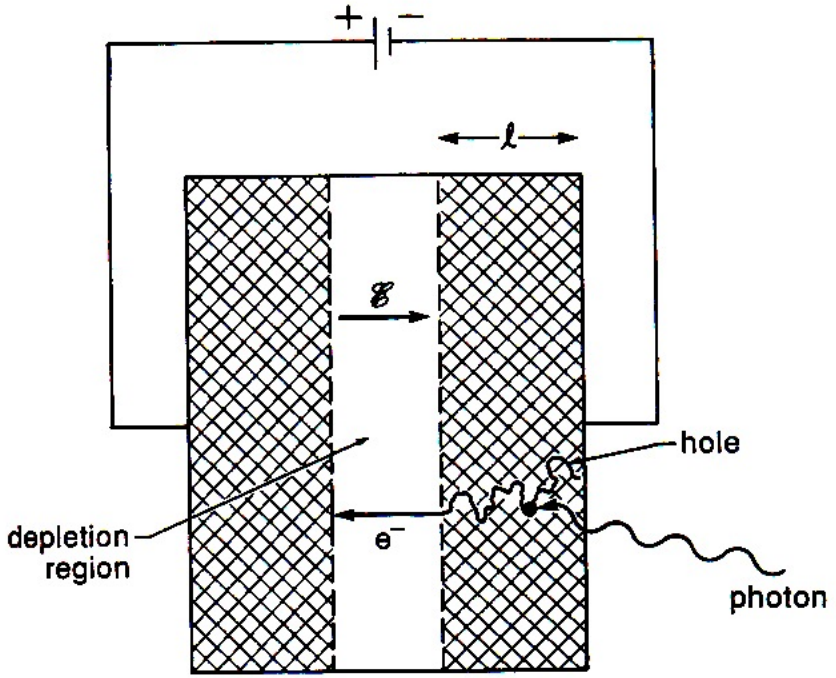


en.wikipedia.org/wiki/Depletion_region

Photodiodes

- junction between *two* oppositely doped zones
- 2 adjacent zones create a depletion region



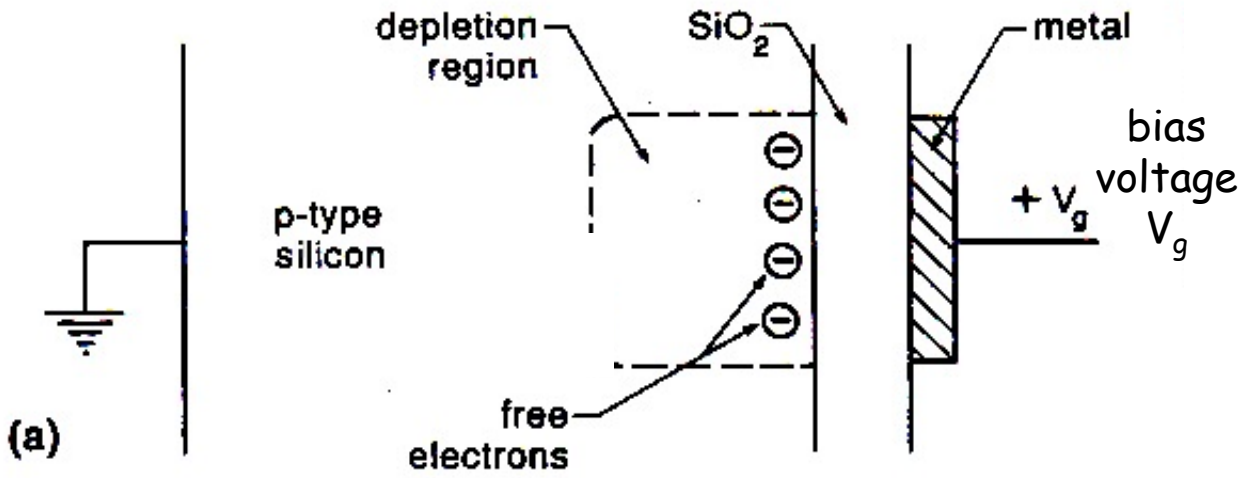


1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^--hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region → photo-current

Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

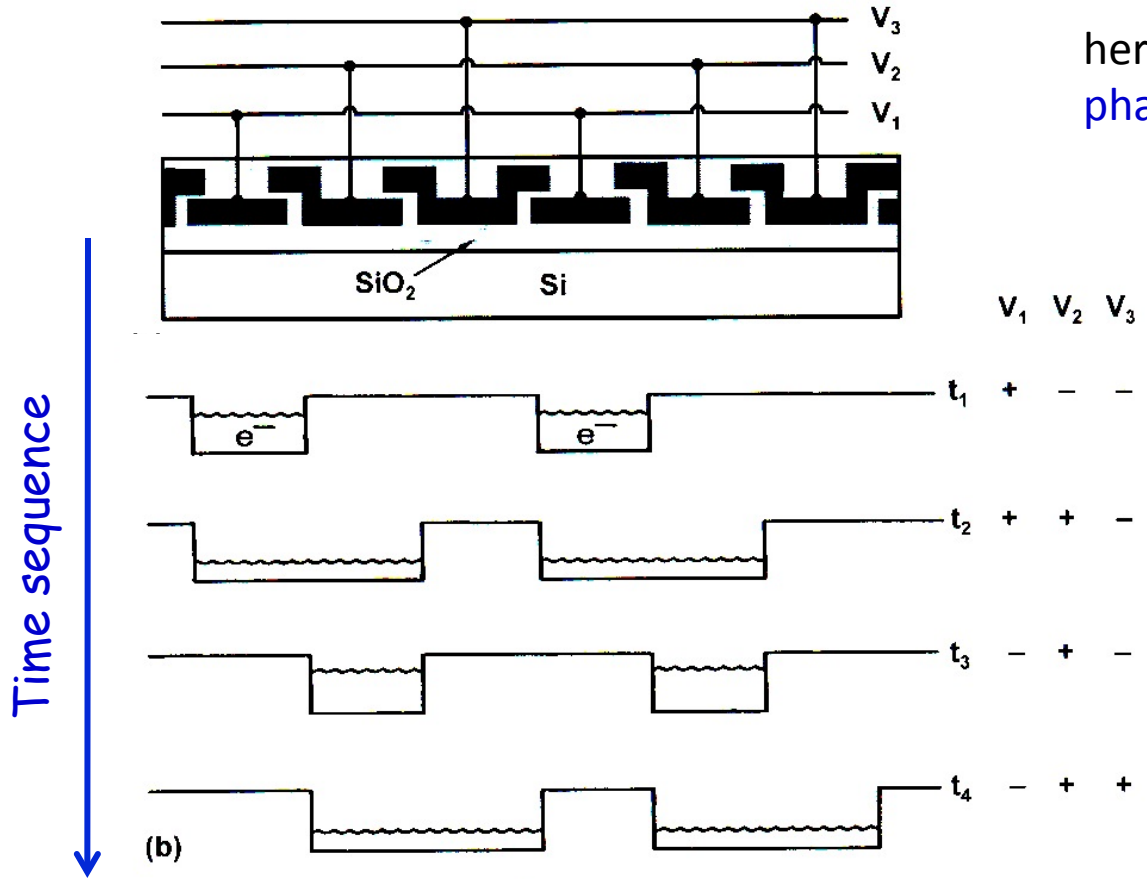
Pixel structure: metal "gate" evaporated onto SiO_2 (isolator) on silicon = MOS



1. photons create free e^- in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO_2 layer
3. e^- accumulate at the Si—SiO_2 interface
4. total charge collected at interface measures number of photons during the exposure
5. → read out the number of e^-

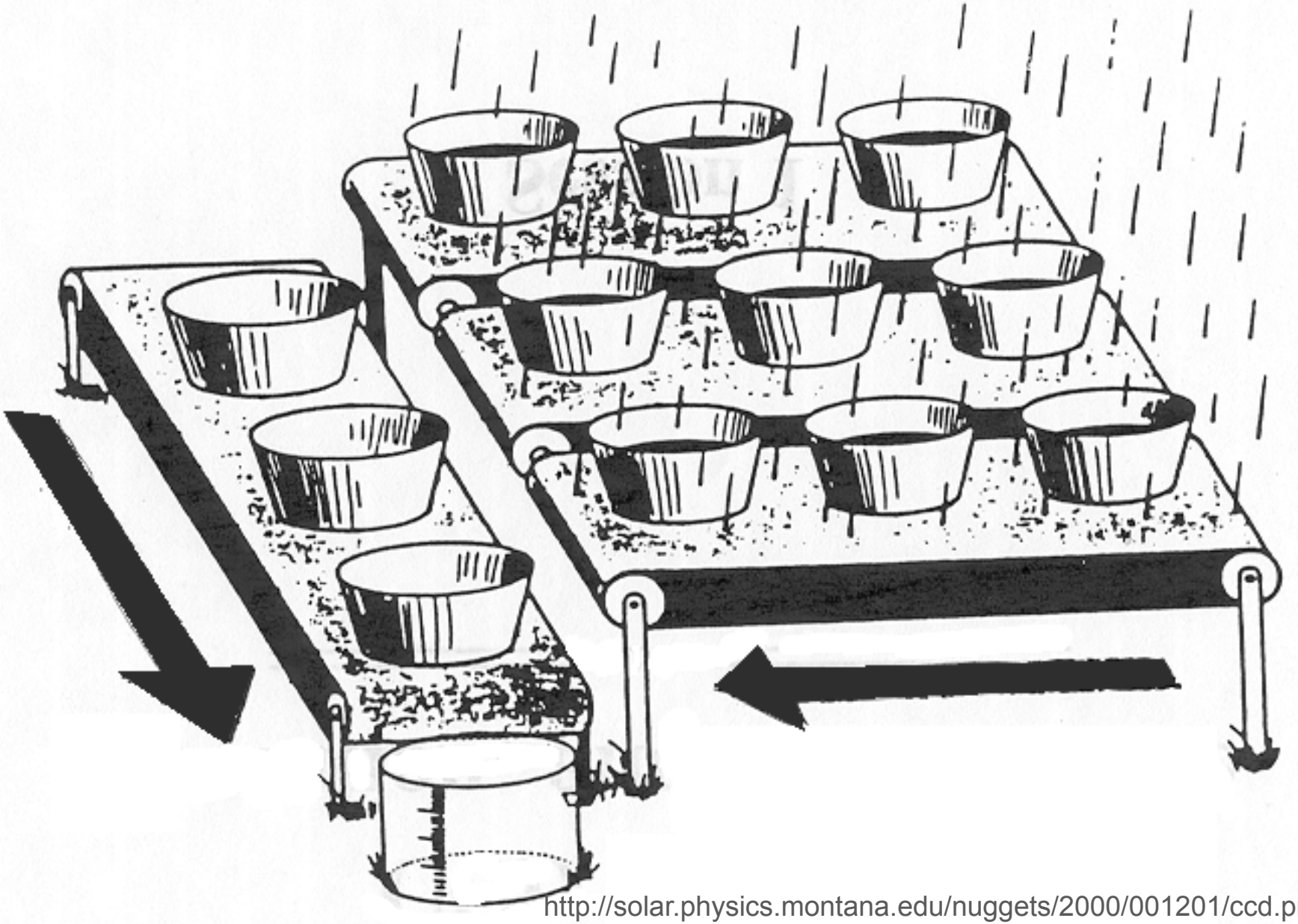
Charge Coupled Readouts

Charges are moved along columns to the edge of the array to the output amplifier



here: 3 sets of electrodes → 3-phase CCD

Charge transter (in-)efficiencies (CTEs) due to electrostatic repulsion, thermal diffusion and fringing fields



http://solar.physics.montana.edu/nuggets/2000/001201/ccd.png

Charge Transfer Efficiency (CTE)

Time-dependent mechanisms that influence the CTE:

1. Electrostatic repulsion causes electrons to drift to the neighbouring electrode with time constant for charge transfer τ_{SI}.

2. Thermal diffusion drives electrons across the storage well at τ_{th}.

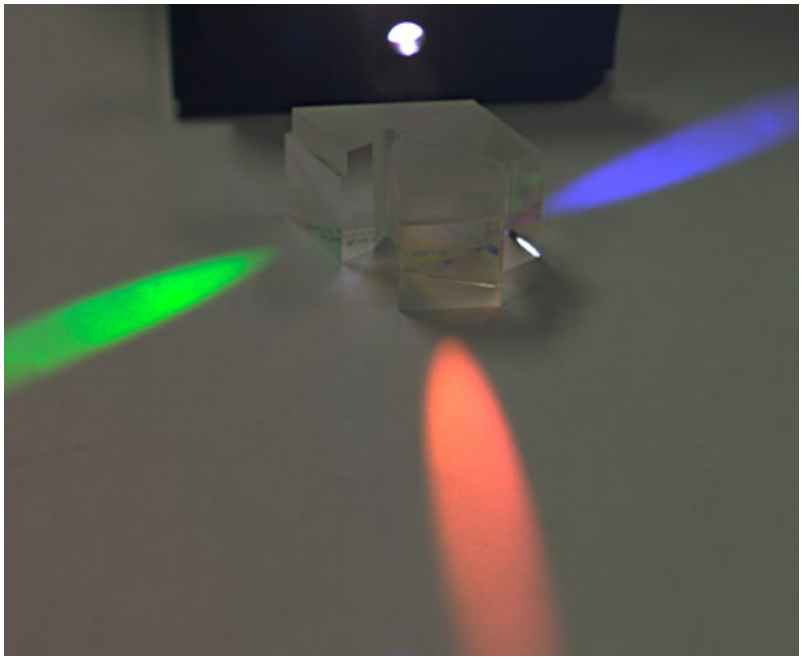
3. "Fringing fields" due to dependency of the well on the voltages of neighbouring electrodes (τ_{ff}).

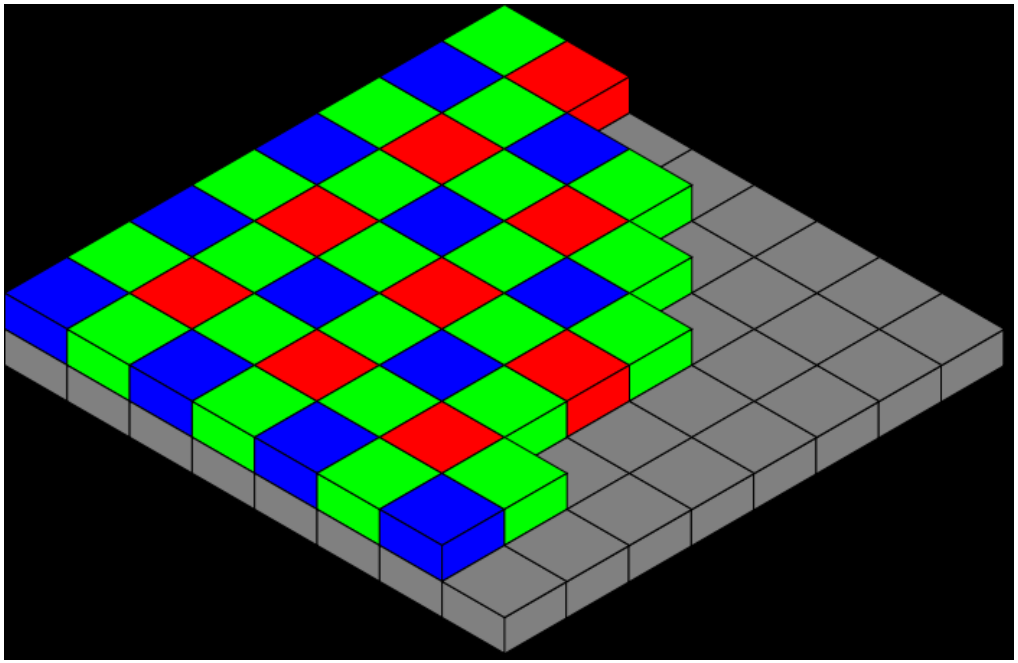
Approximation for the CTE of a CCD with *m* phases: $$CTE = \left(1 - e^{-t/\tau}\right)^m$$

Noise from charge transfer inefficiency: ε = (1-CTE)

CCD Color Sensors

1. Three exposures through 3 filters – only works for fixed targets
2. Split input into 3 channels with separate filter and CCD
3. Bayer mask over CCD – each subset of 4 pixels has one filtered red, one blue, and two green





Main Detector Noise Components

G-R noise $\left\langle I_{G-R}^2 \right\rangle = 4q^2 \varphi \eta G^2 \Delta f$

Fundamental statistical noise due to the Poisson statistics of the photon arrival → transferred into the statistics of the **g**enerated and **r**ecombined holes and electrons

Johnson or kTC noise $\left\langle I_J^2 \right\rangle = \frac{4kT}{R} \Delta f$

Fundamental thermodynamic noise due to thermal motion of charge carriers. Photo-conductor is an RC circuit where $\langle Q^2 \rangle$ = kTC

1/f noise $\left\langle I_{1/f}^2 \right\rangle \propto \frac{I^2}{f} \Delta f$

increased noise at low frequencies, due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, and JFETs, …

Total noise: $\left\langle I_N^2 \right\rangle = \left\langle I_{G-R}^2 \right\rangle + \left\langle I_J^2 \right\rangle + \left\langle I_{1/f}^2 \right\rangle$

BLIP and NEP

Operationally, background-limited performance (BLIP) is always preferred:

$$\left\langle I_{G-R}^2 \right\rangle >> \left\langle I_J^2 \right\rangle + \left\langle I_{1/f}^2 \right\rangle$$

The noise equivalent power (NEP) is the signal power that yields an RMS S/N of unity in a system of Δf = 1 Hz:

$$NEP_{G-R} = \frac{2hc}{\lambda}\left(\frac{\varphi}{\eta}\right)^{1/2}$$

In BLIP the NEP can only be improved by increasing the quantum efficiency η as background photon noise dominates