Astronomical Observing Techniques

Lecture 9: Silicon Eyes 1

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Overview

1. Solid State Physics
2. Intrinsic Photoconductors
3. Extrinsic Photoconductors
4. Readout & Operations
5. Detector Noise

Modern Detectors

1. Photon detectors

Respond directly to individual photons -> releases bound charge carriers. Used from X-ray to infrared.

Examples: photoconductors, photodiodes, photoemissive detectors

2. Thermal detectors

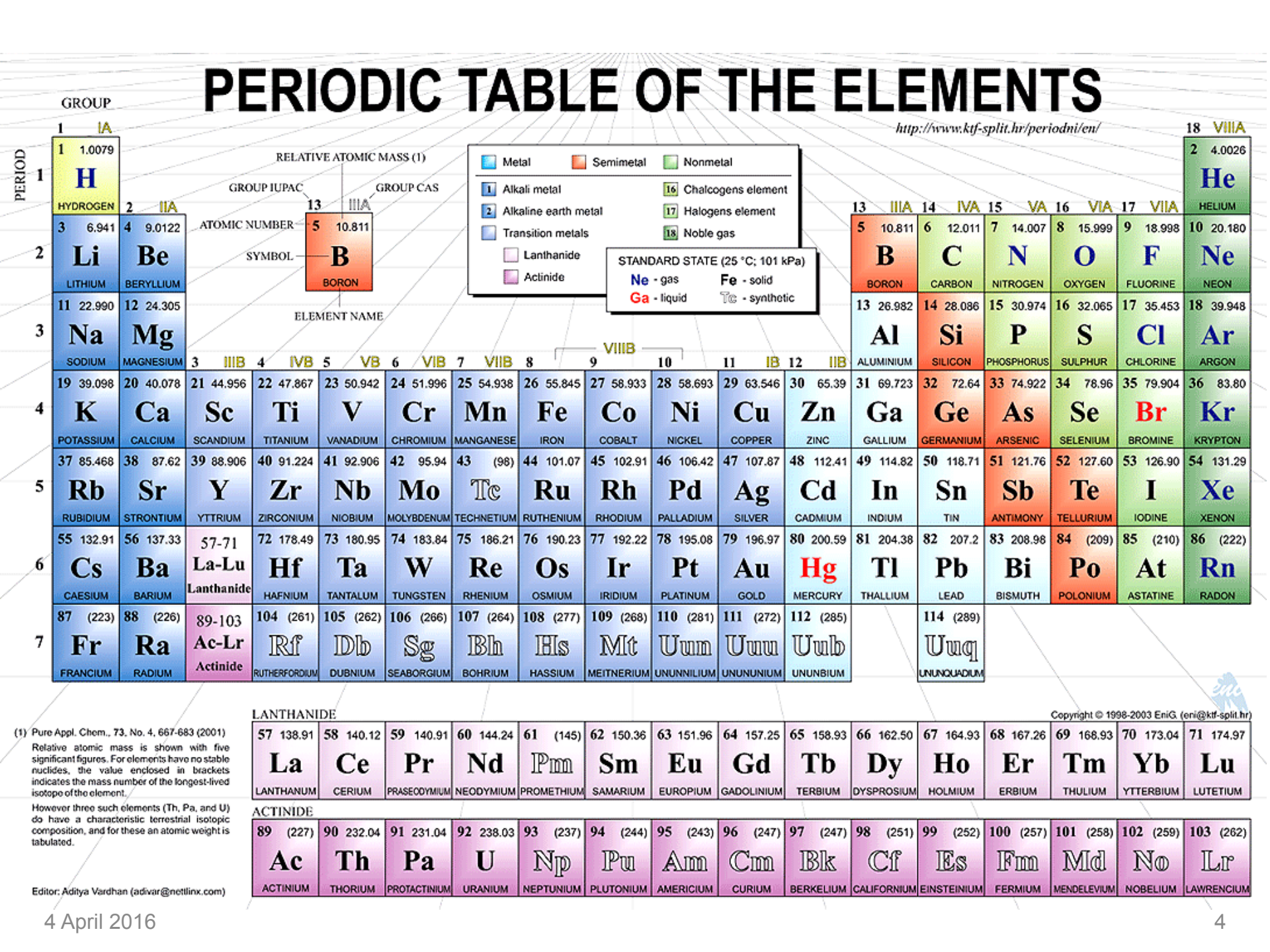
Absorb photons and thermalize their energy-> changes resistance -> modulates electrical current. Used mainly in IR and sub-mm detectors.

Examples: bolometers

3. Coherent receivers

Respond directly to electrical field and preserve phase information (but need a reference phase "local oscillator"). 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
9
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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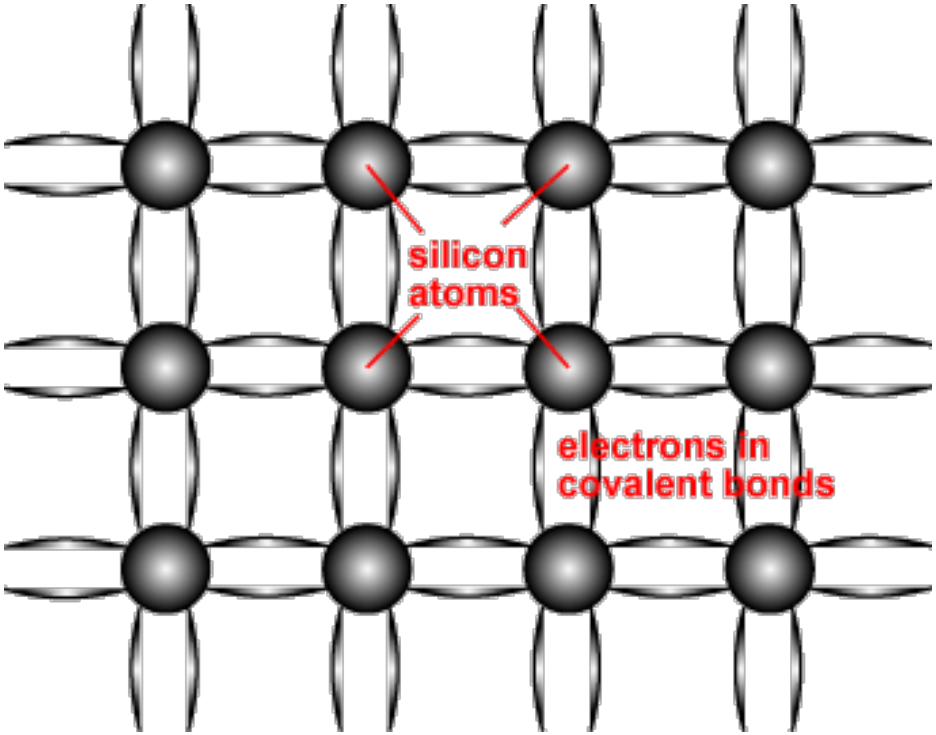
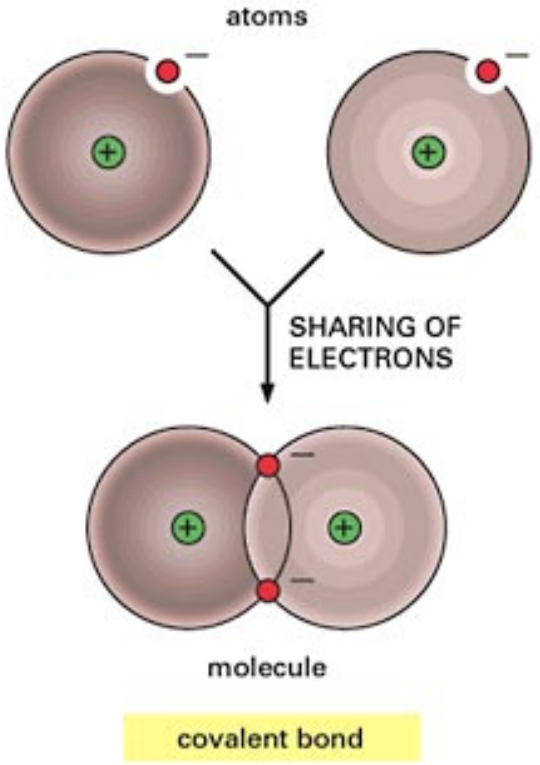
Diamond Lattice

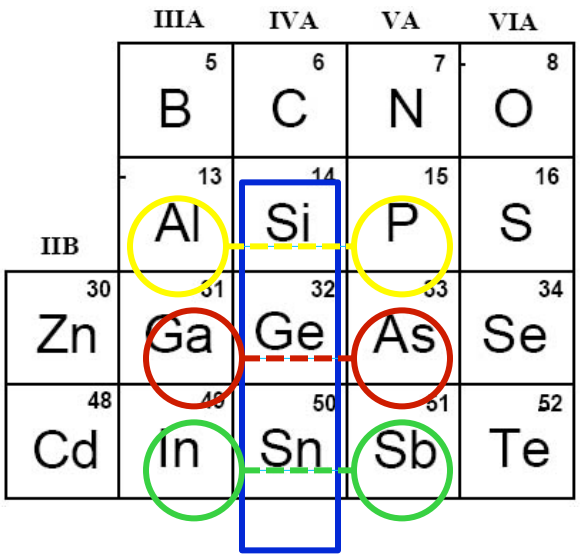
- Elements with 4 e^- in valence shell form crystals with diamond lattice structure (each atom bonds to four neighbors).
- These double-bonds between neighbours are due to “shared” electrons

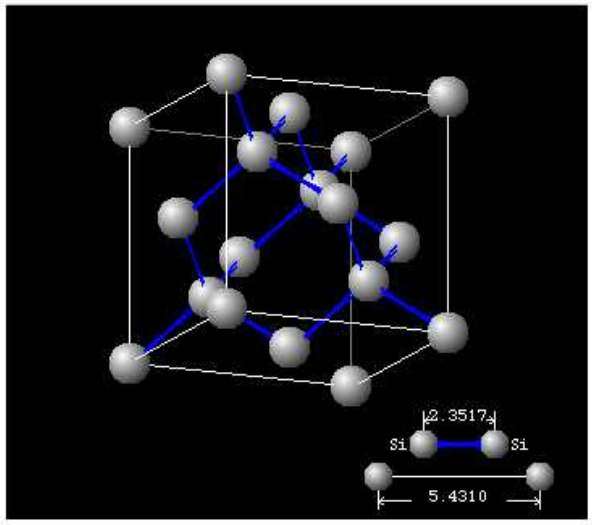


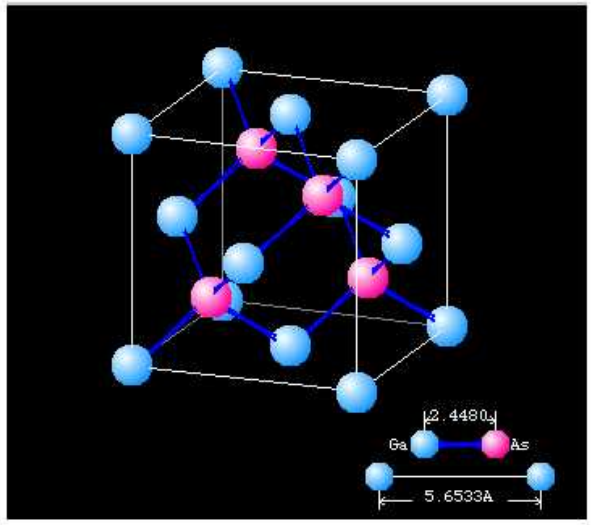


Diamond Lattice

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



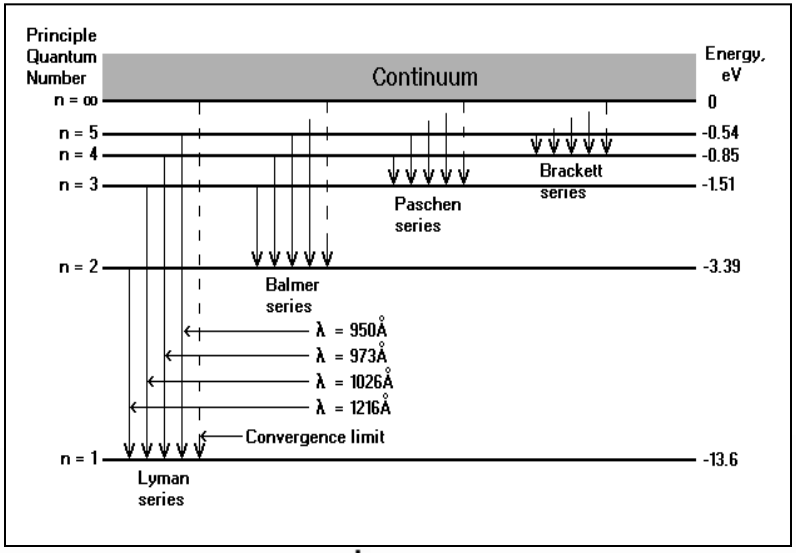


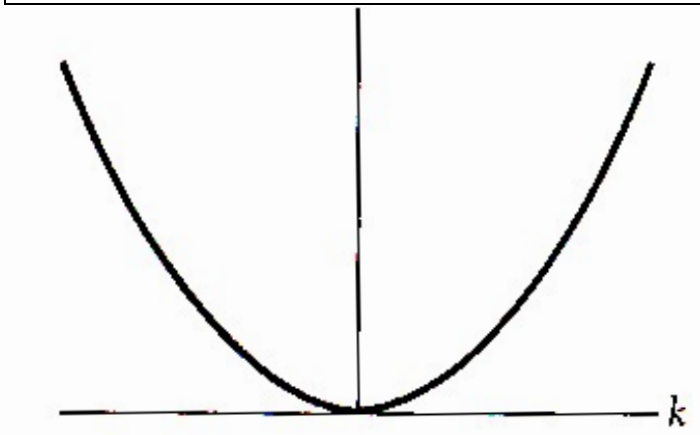


Electronic States and Bands

Single atomic system

Example: H atom



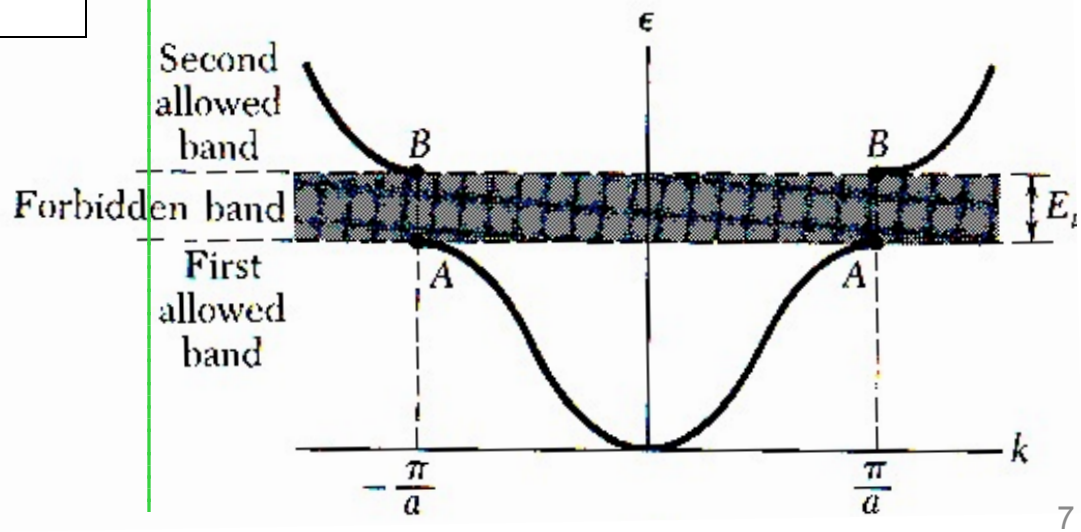


Atomic crystal

Wavefunctions Ψ overlap

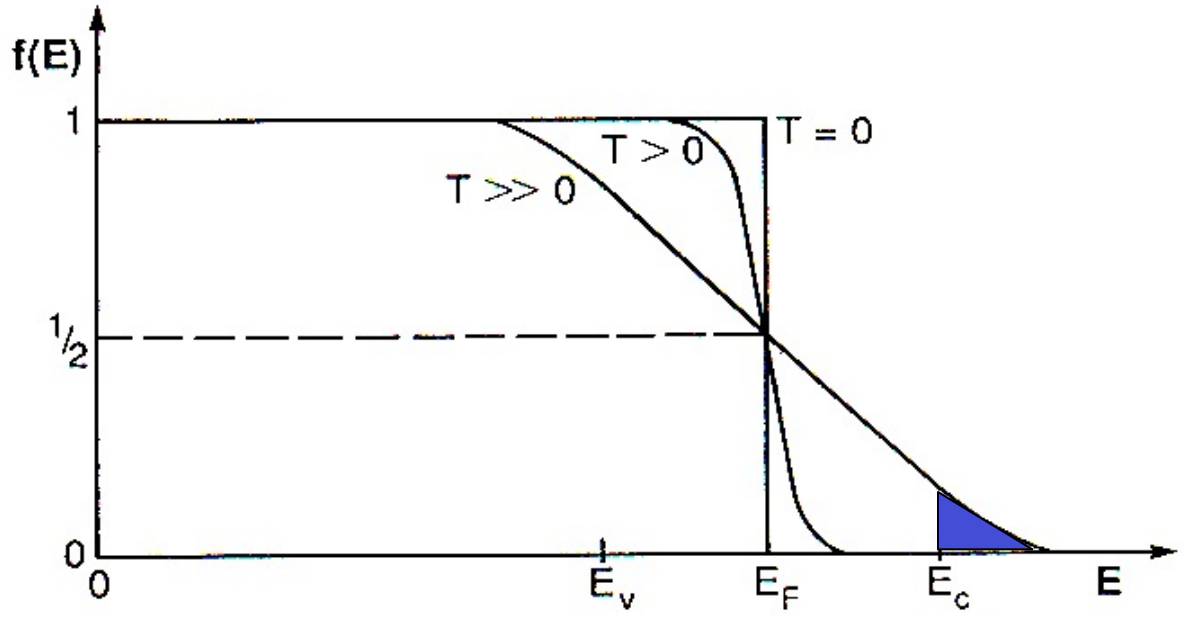
→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

→ Multiple splitting ➔ "bands"



Fermi Energy

- Fermi energy E_F determines concentration of thermally excited electrons in conduction band
- Energy valence band: E_V; Energy conduction band: E_C
- Fermi function f(E): probability that state of energy E is occupied at temperature T.



$$n_0 = N_c f(E_c), N_c = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2}, f(E_c) = \frac{1}{1+e^{(E_c-E_F)/kT}} \overset{E_c-E_F>>kT}{\approx} e^{-(E_c-E_F)/kT}$$

Fermi energy = energy of the highest occupied quantum state in a system of fermions at T=0K

QM: fermions obey the Pauli exclusion principle → two fermions cannot occupy the same quantum state. Fermions consecutively fill up the unoccupied quantum states starting with the lowest energy; when all the particles have been put in, the Fermi energy is the energy of the highest occupied state.

Fermi level = chemical potential

The Fermi level is the energy at which there is a 50% chance of finding an occupied energy state. The Fermi level can be calculated from the density of states in the conduction and valence bands. The Fermi level may increase, remain the same or decrease with increasing temperature, depending on the number of states in the conduction and valence bands.

Fermi energy and Fermi level are only the same at absolute zero. At absolute zero temperature the Fermi level can be thought of as the energy up to which available electron states are occupied. At higher temperatures, the Fermi level is the energy at which the probability of a state being occupied has fallen to 0.5.

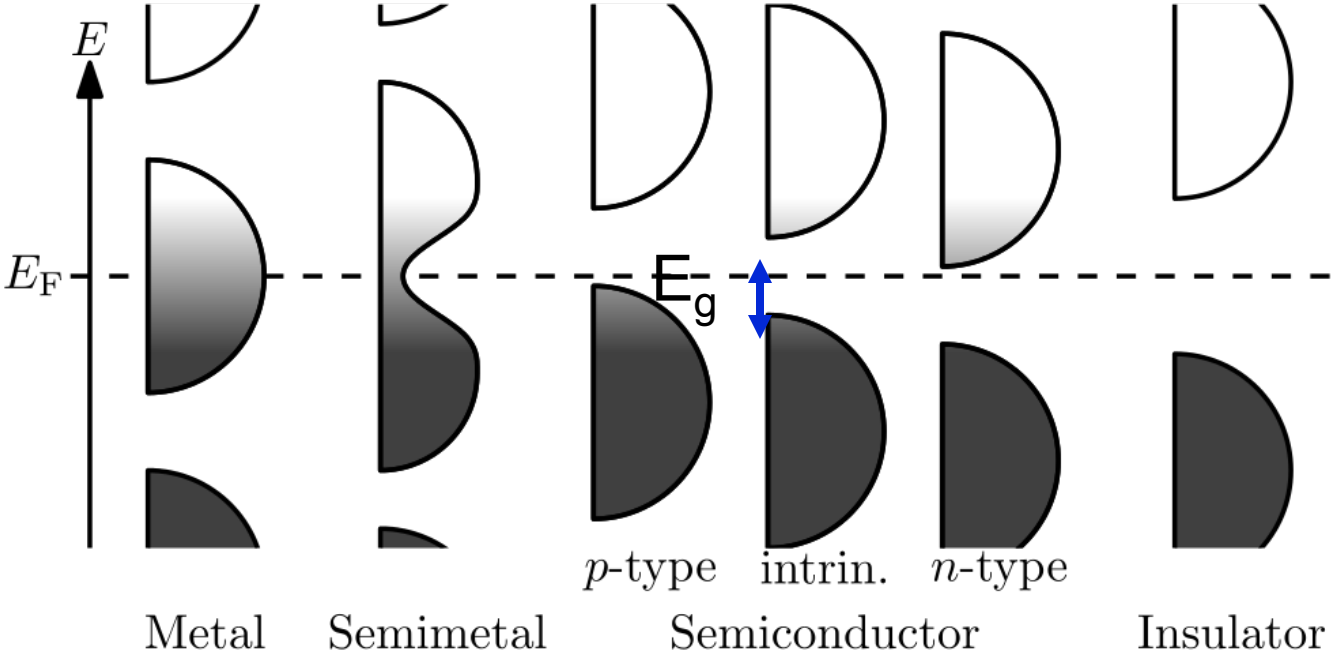
The **Fermi function** f(E) gives the probability that a given available electron energy state will be occupied at a given temperature. Typically, most of the levels up to the Fermi level E_F are filled, and relatively few electrons have energies above the Fermi level.

The population of states depends upon the *product* of the Fermi function and the electron density of states:

- In the gap there are no electrons because the density of states is zero.
- In the conduction band at 0K, there are no electrons even though there are plenty of available states, but the Fermi function is zero.
- At high temperatures, both the density of states and the Fermi function have finite values in the conduction band, so there is a finite conducting population.

Electric Conductivity

Conductivity requires charge carriers in the conduction band



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

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

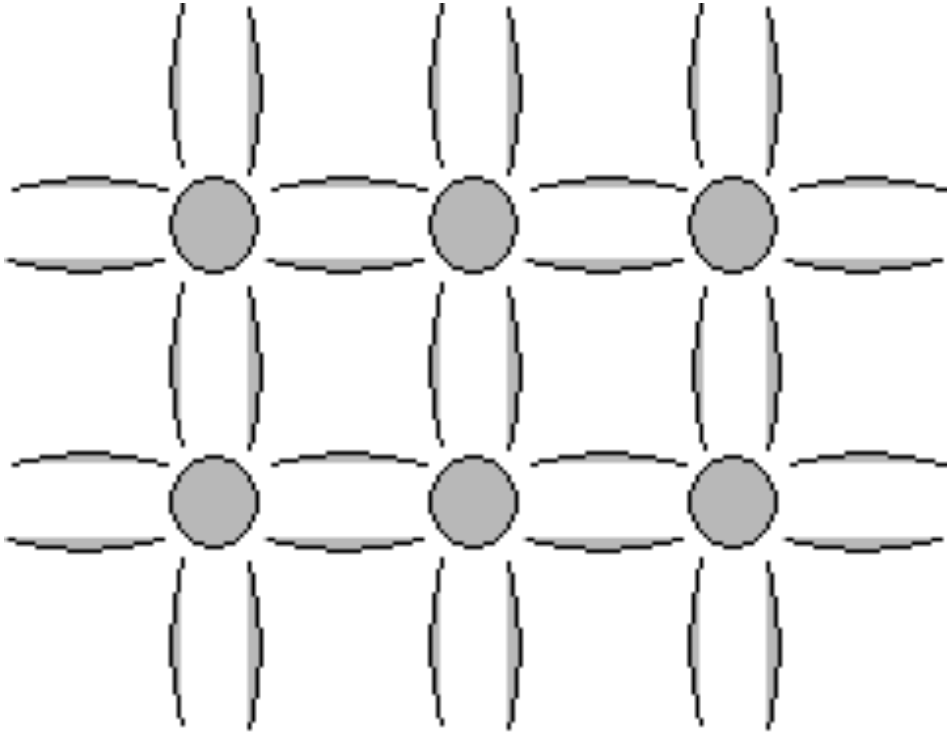
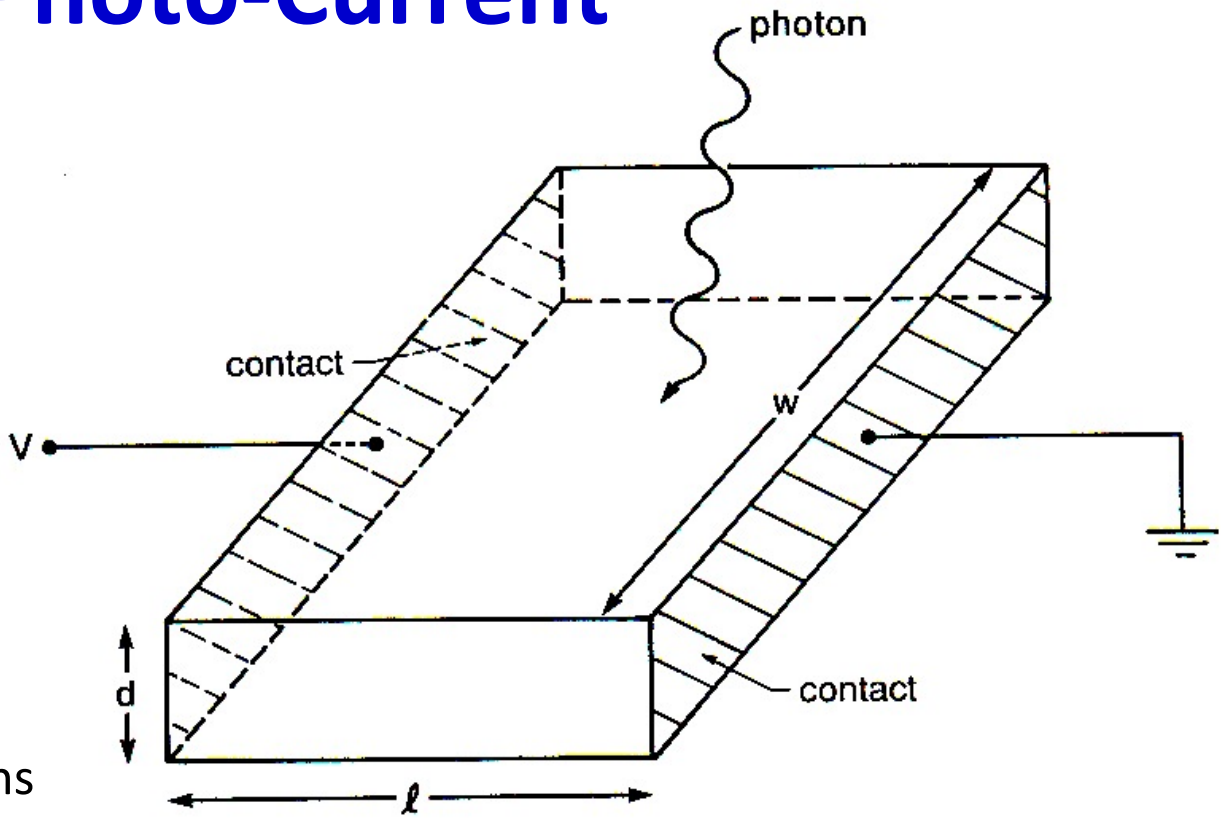


Photo-Current

- Conductivity: $j=\sigma E$
- Current: $I=jwd$
- $V=RI,\ E=V/l$



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

where:

R_d = resistance

w,d,l = geometric dimensions

q = elementary electric charge

n_0 = number density of charge carriers

ϕ = photon flux

η = quantum efficiency

τ = mean lifetime before recombination

μ_n = electron mobility ~ mean time between collisions.

drift velocity $v=\mu_n E$, current density $j=n_0 qv$

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

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

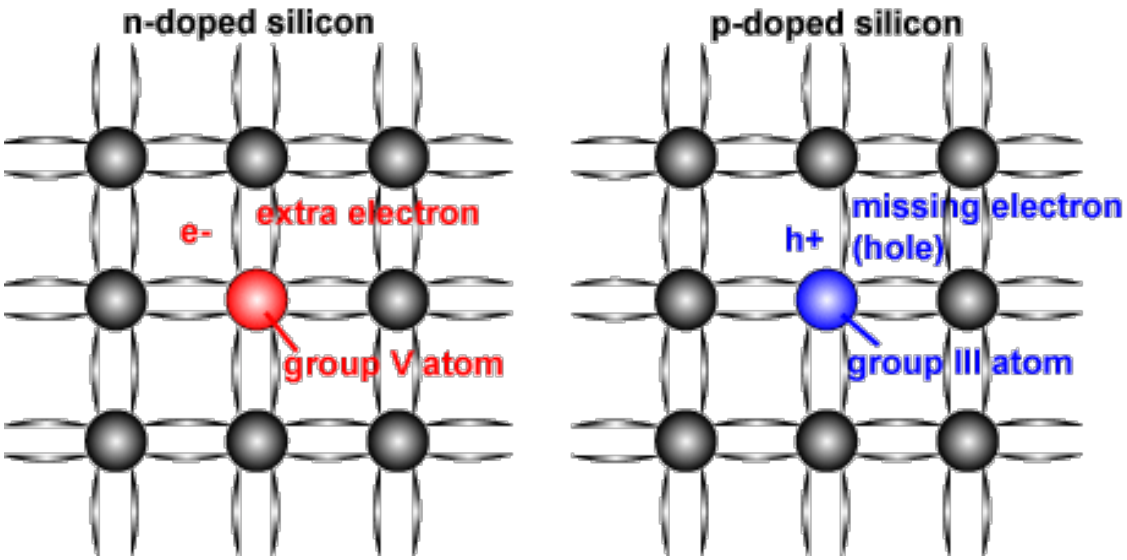
→ GaAs: 0.87μm

- non-uniformity of material
- problems to make good electrical contacts to pure Si
- difficult to avoid impurities and minimize thermal (Johnson) noise

Extrinsic Semiconductors

- extrinsic semiconductors: charge carriers = electrons (n-type) or holes (p-type)
- achieved by 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

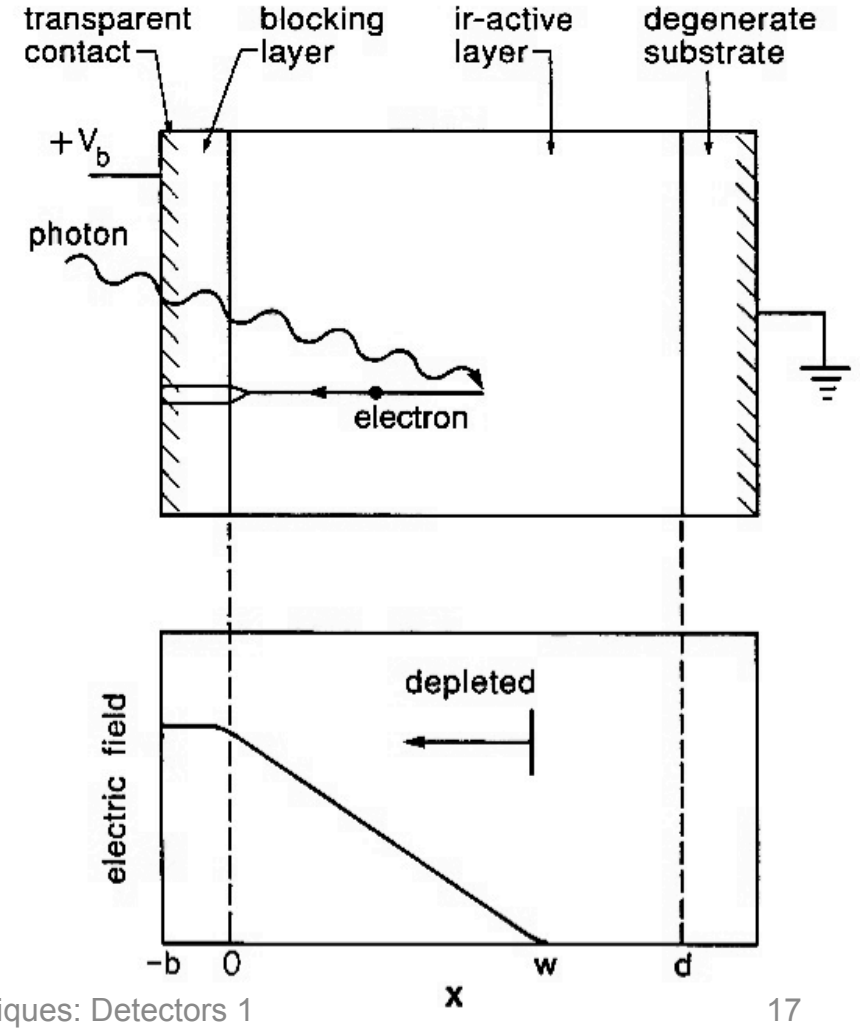
		Ge	Si
Impurity	Type	Cutoff wavelength λ_c (μm)	Cutoff wavelength λ_c (μm)
Al	p		18.5[a]
B	p	119[b]	28[a]
Be	p	52[b]	8.3[a]
Ga	p	115[b]	17.2[a]
In	p	111[b]	7.9[a]
As	n	98[b]	23[a]
Cu	p	31[b]	5.2[a]
P	n	103[b]	27[a]
Sb	n	129[b]	29[a]

Problem: absorption coefficients much less than for intrinsic photoconductors → low QE → active volumes (pixels) must be large

Blocked Impurity Band (BIB) Detectors

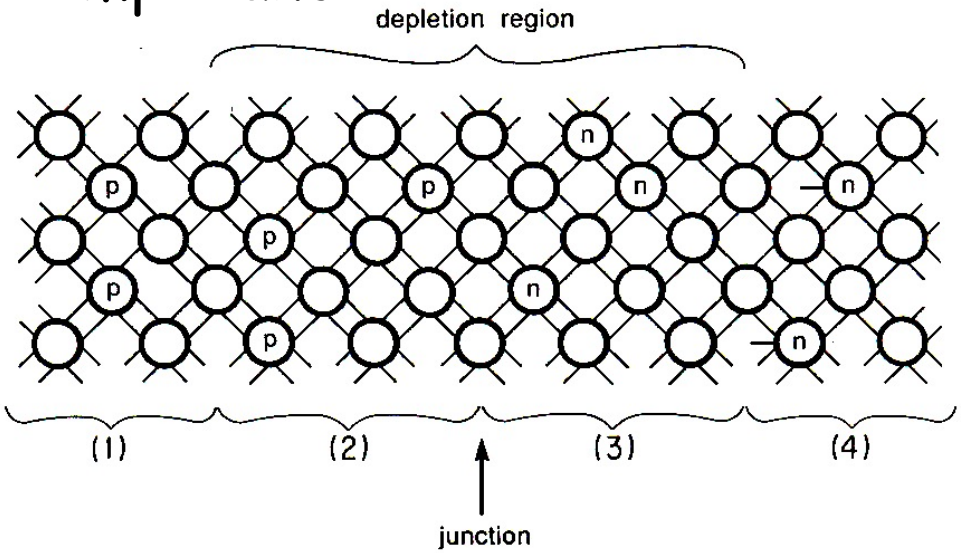
Solution: use separate layers to optimize the optical and electrical properties independently:

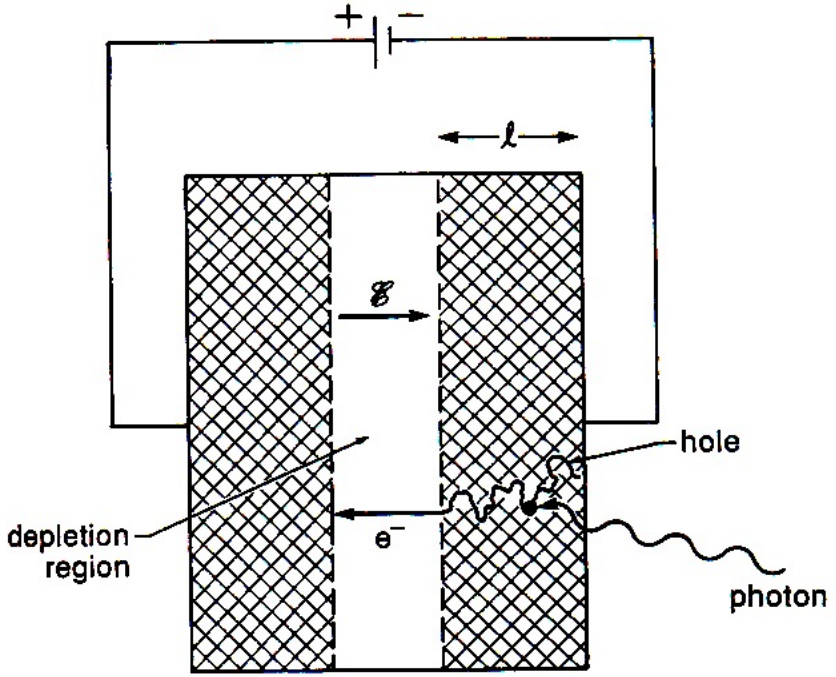
- IR-active layer: heavily doped
- Blocking layer: thin layer of high purity (intrinsic photoconductor)
- *Typical species are Si:As or Si:Sb BIBs*



Photodiodes

- junction between *two* oppositely doped zones
- Two adjacent zones create a depletion region with high impedance



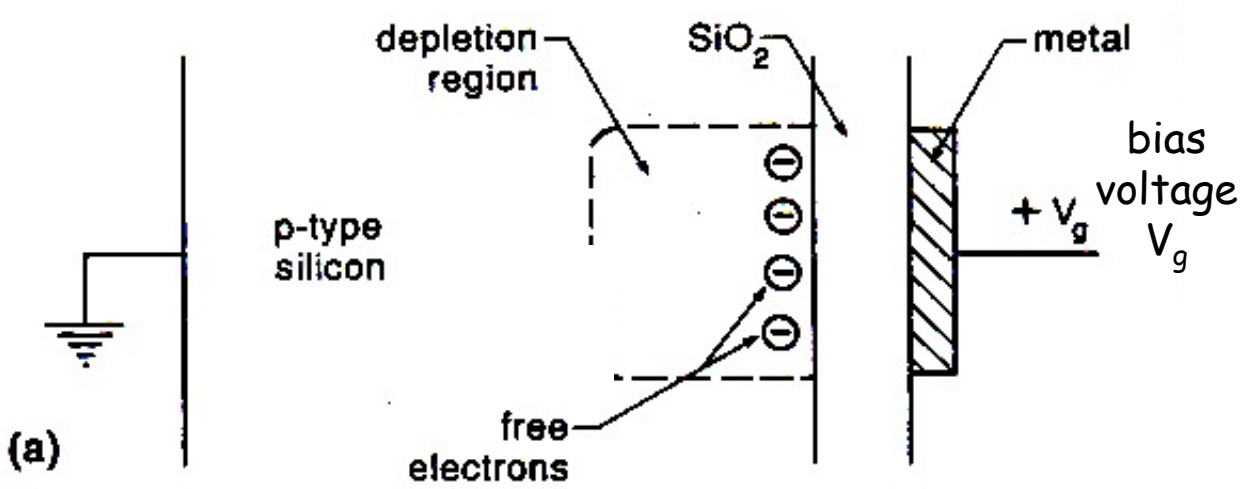


1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^--hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region → photo-current

Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

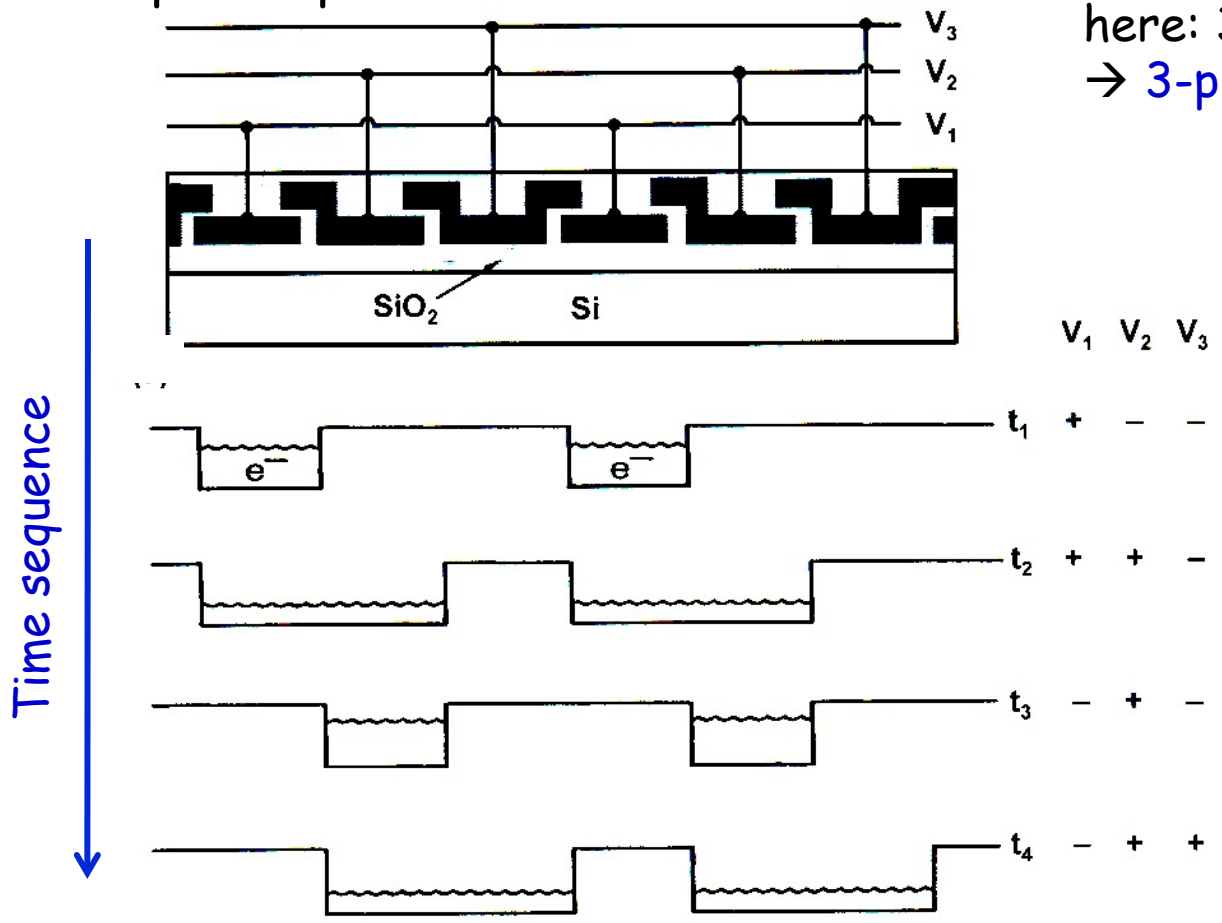
Pixel structure: metal "gate" evaporated onto SiO_2 (isolator) on silicon = MOS



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^-

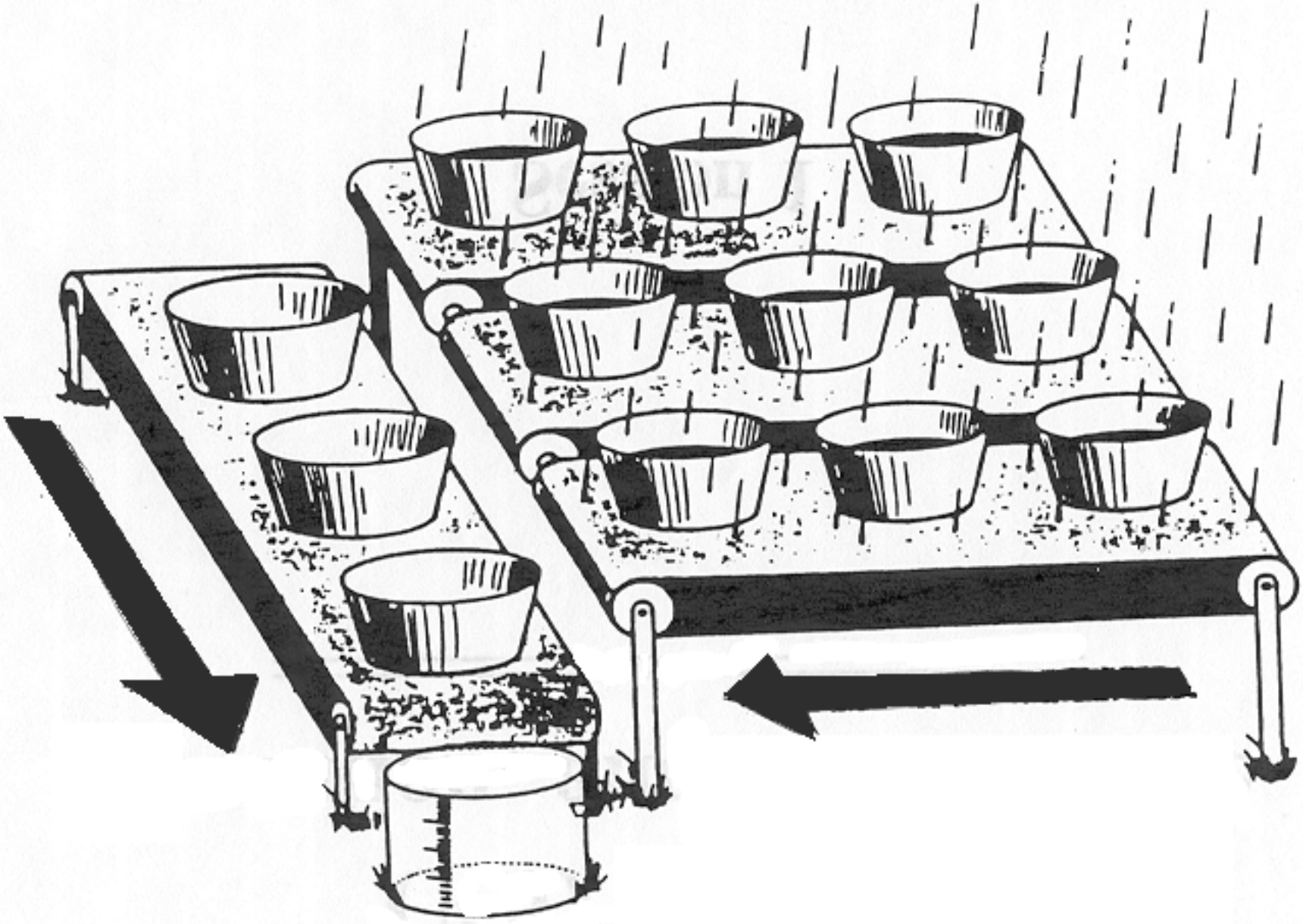
Charge Coupled Readouts

Collected charges are passed along the columns to the edge of the array to the output amplifier.



here: 3 sets of electrodes
→ 3-phase CCD

Be aware of charge transfer (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}.

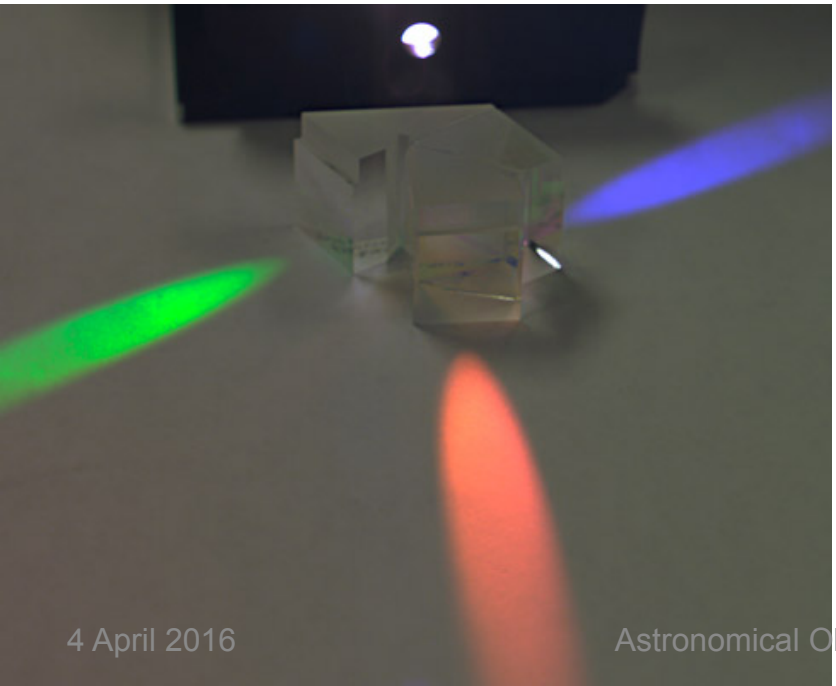
3. "Fringing fields" due to dependency of the well on the voltages of neighbouring electrodes (τ_{ff}).

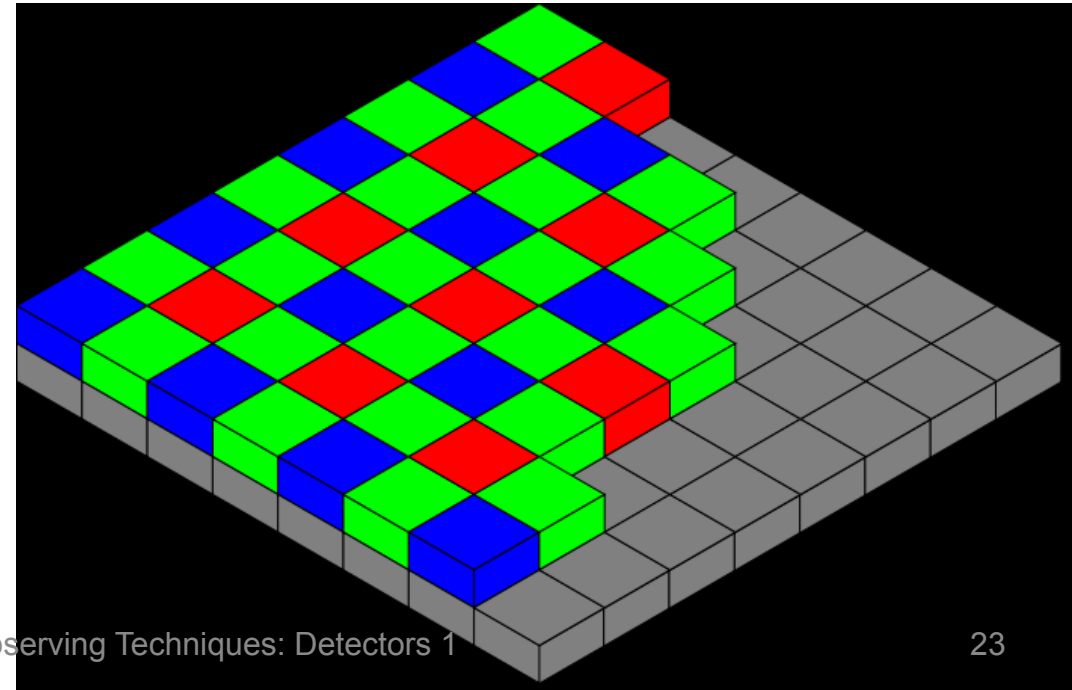
Approximation for the CTE of a CCD with *m* phases: $$CTE = \left(1 - e^{-t/\tau}\right)^m$$

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

CCD Color Sensors

1. Take three exposures through three filters subsequently – only works for fixed targets (standard for astronomy).
2. Split the input beam in three channels, each with a separate and optimized CCD (professional video cameras).
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 generated and recombined holes and electrons.

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

fundamental thermodynamic noise due to the thermal motion of the charge carriers. Consider a photo-conductor as an RC circuit. Since $\langle Q^2 \rangle = kTC$, the charge noise is also called kTC noise or reset noise.

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, …

The total noise in the system is: $\left\langle I_N^2 \right\rangle = \left\langle I_{G-R}^2 \right\rangle + \left\langle I_J^2 \right\rangle + \left\langle I_{1/f}^2 \right\rangle$

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.