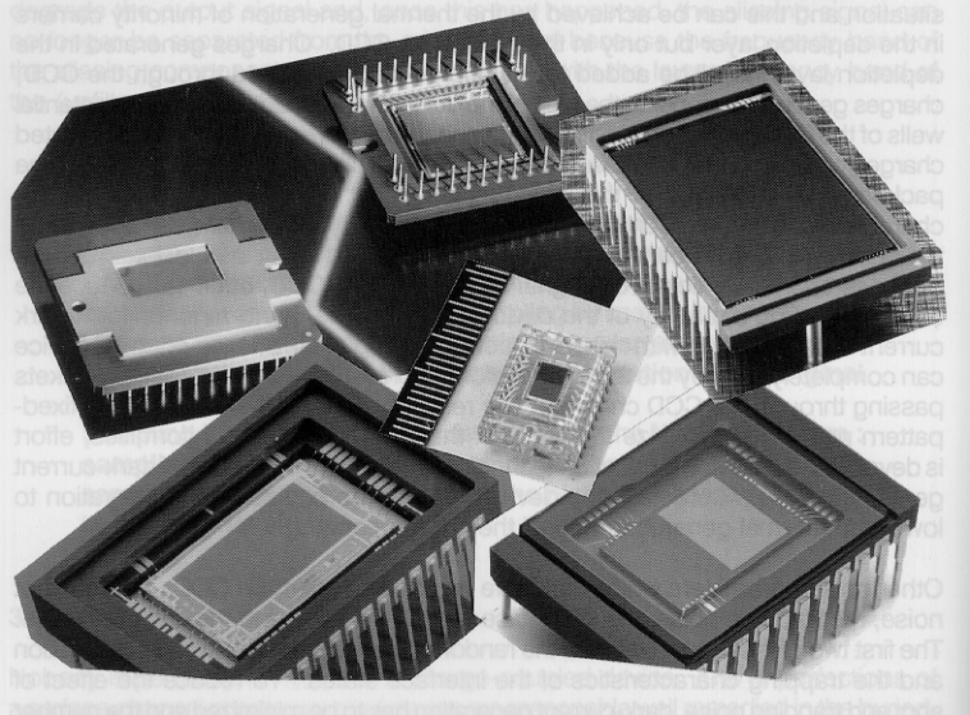
Astronomische Waarneemtechnieken
(Astronomical Observing Techniques)

Based on lectures by Bernhard Brandl



Lecture 9: Detectors 1

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

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

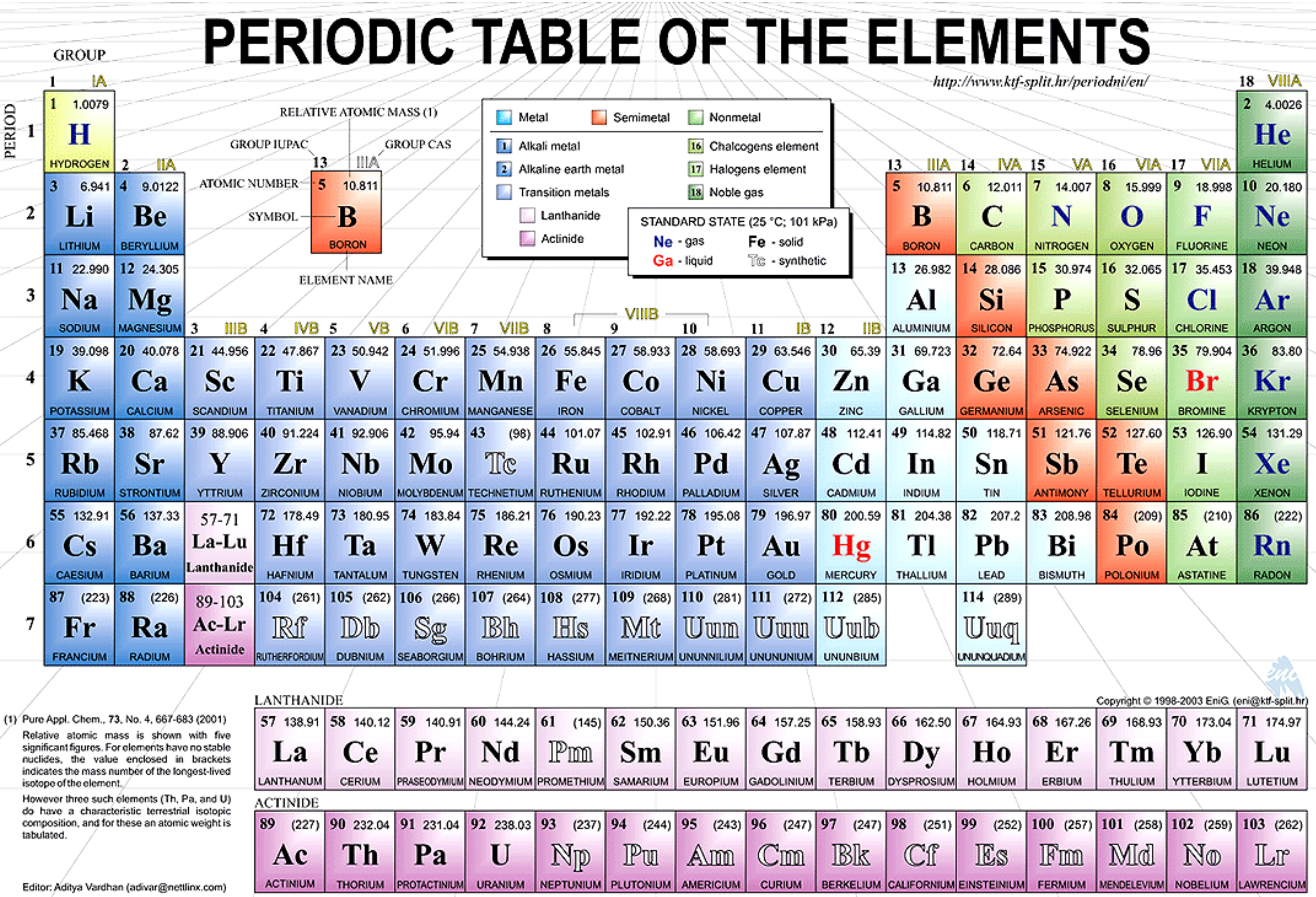
3. **Coherent receivers**

   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/



RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME

13	IIIA
5	10.811
B	
BORON	

- 🟦 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

GROUP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PERIOD	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	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
3	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
4	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
5	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
6	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
7	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

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(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.

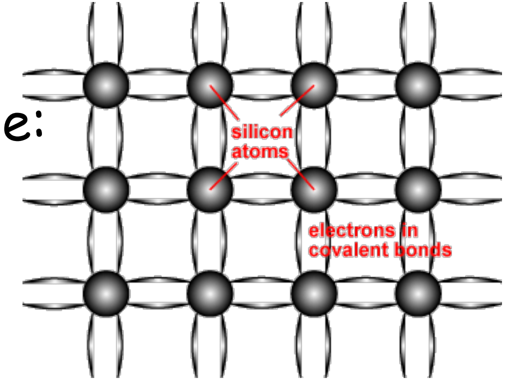
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

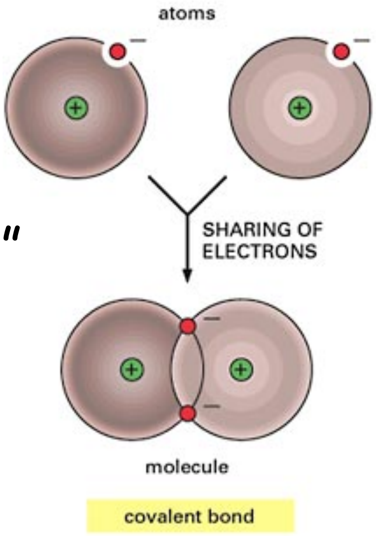
Diamond Lattice

Elements with 4 e^- in valence shell form crystals with diamond lattice structure (each atom bonds to four neighbors).

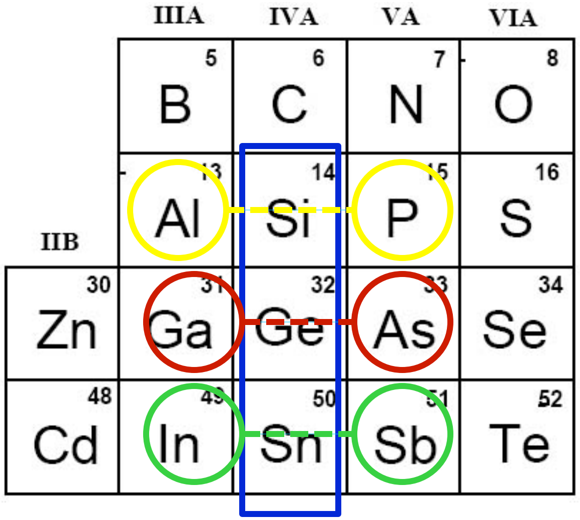
Example:



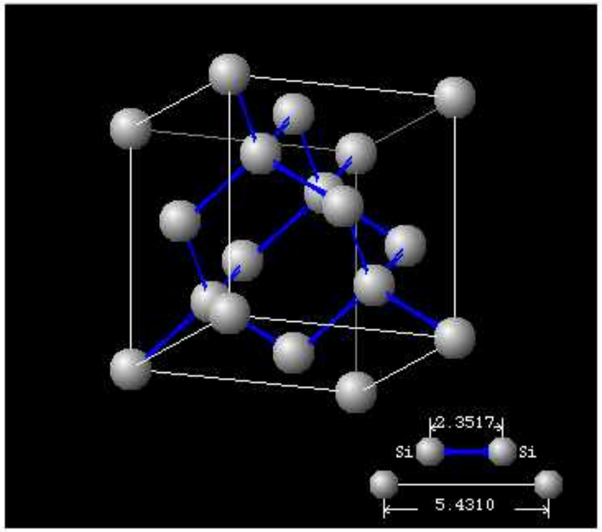
These double-bonds between neighbours are due to "shared" electrons

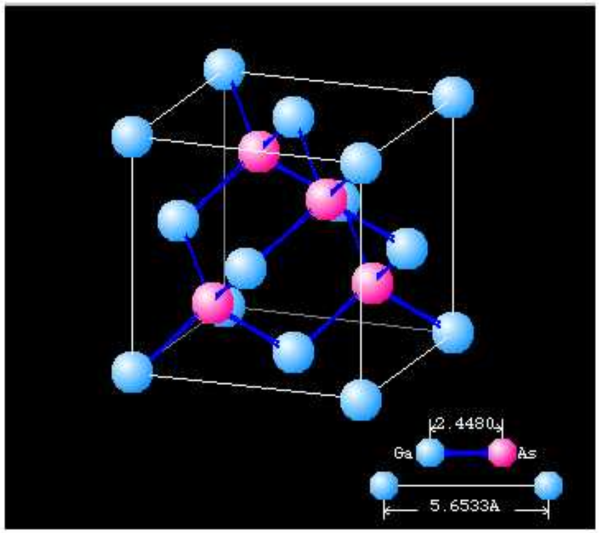


Diamond lattice not only formed by IV elements (C, Si, Ge but also by III-V semiconductors (InSb, GaAs, AlP)



IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	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

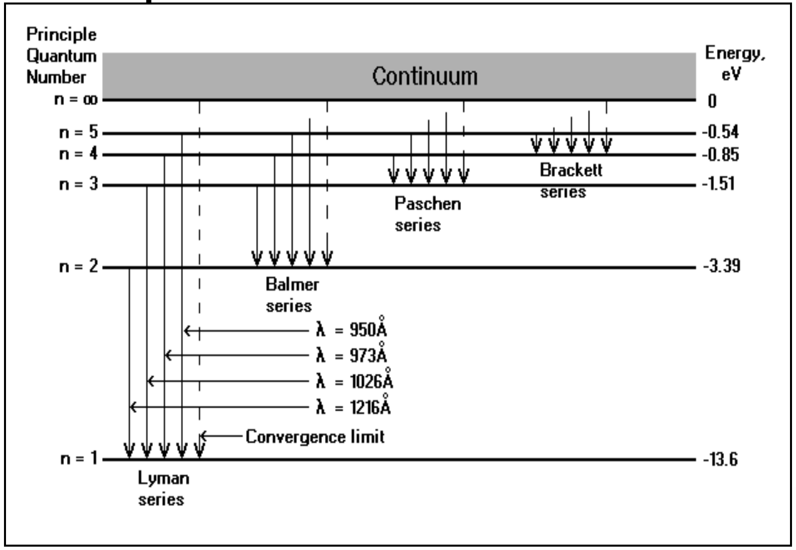




Electronic States and Bands

Single atomic system

Example: H atom

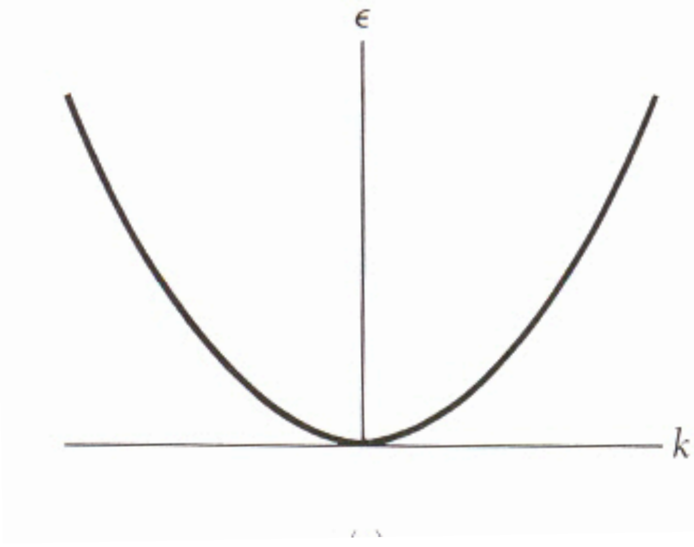


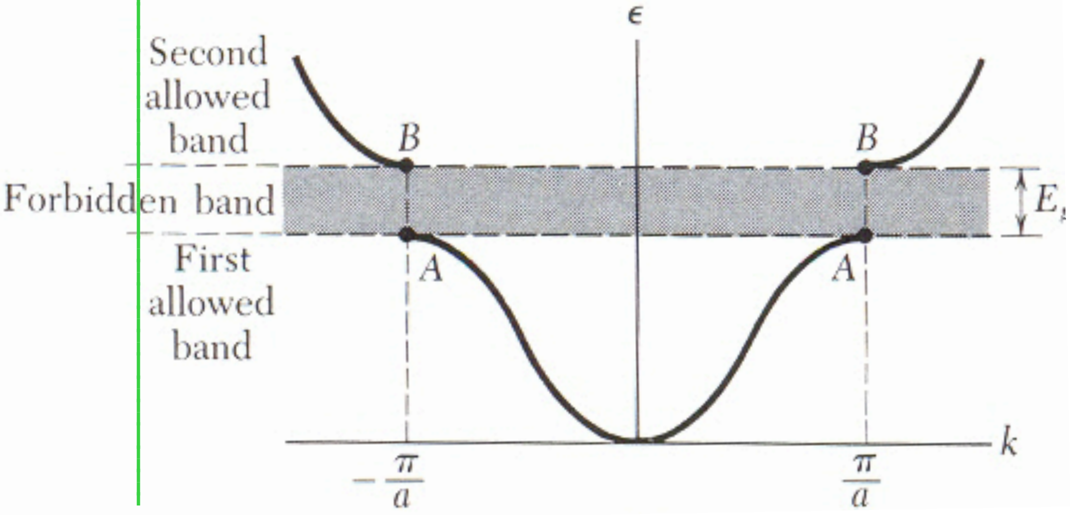
Atomic crystal

Wavefunctions Ψ overlap

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

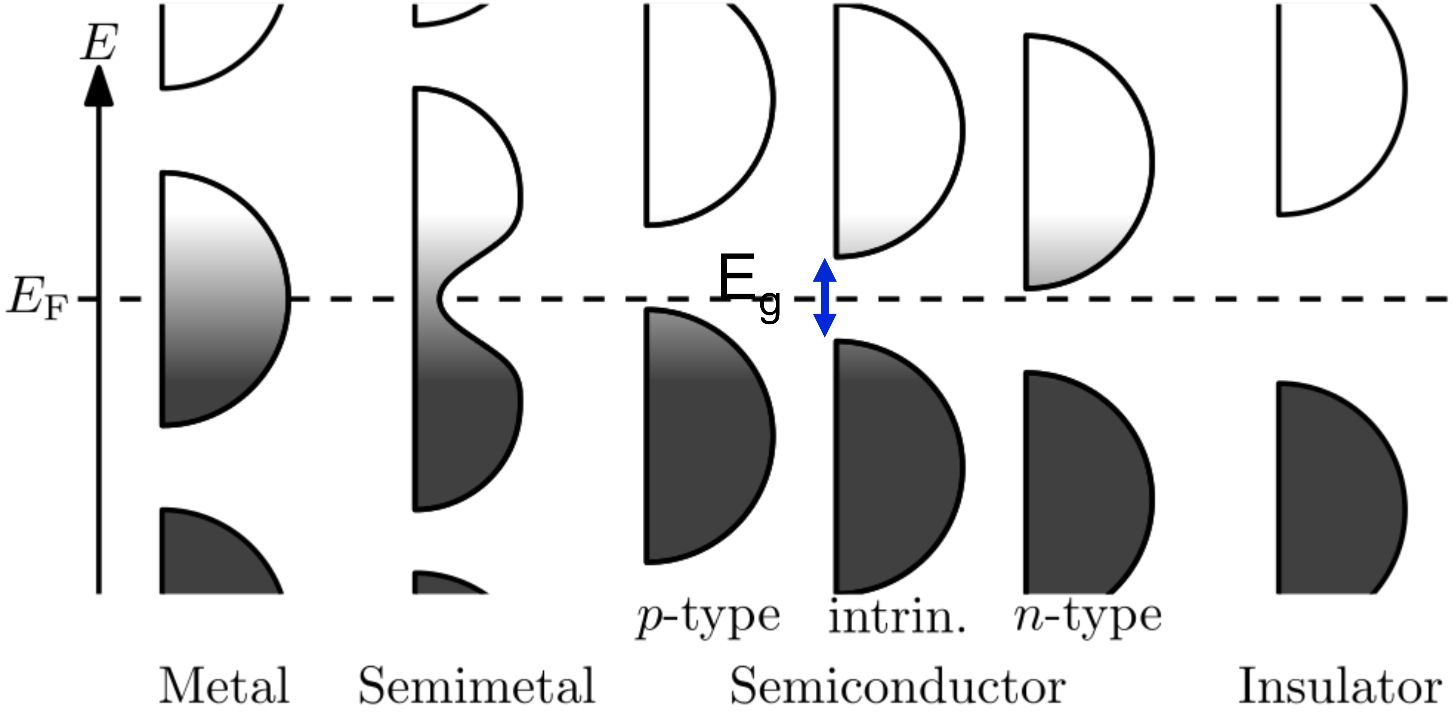
→ Multiple splitting ➔ "bands"





Electric Conductivity

Conductivity requires charge carriers in the conduction band



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

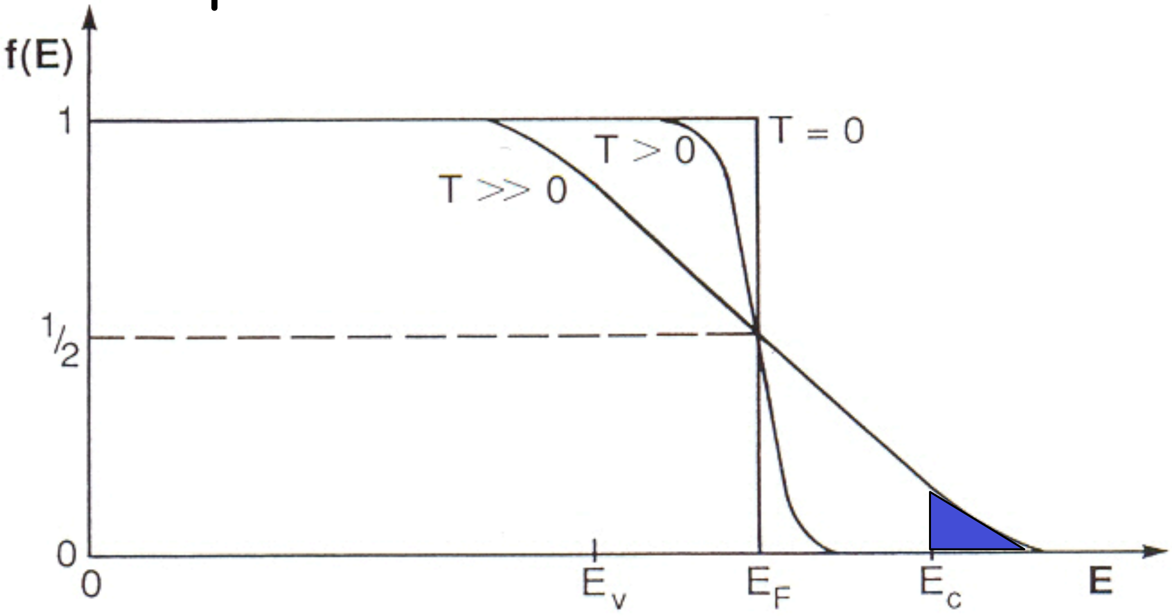
1. external excitation, e.g. via a photon ←photon detector
2. thermal excitation
3. impurities

Fermi Energy

The Fermi energy E_F determines the concentration of thermally excited electrons in the 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 below 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 $E\text{-}_F$ 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.

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

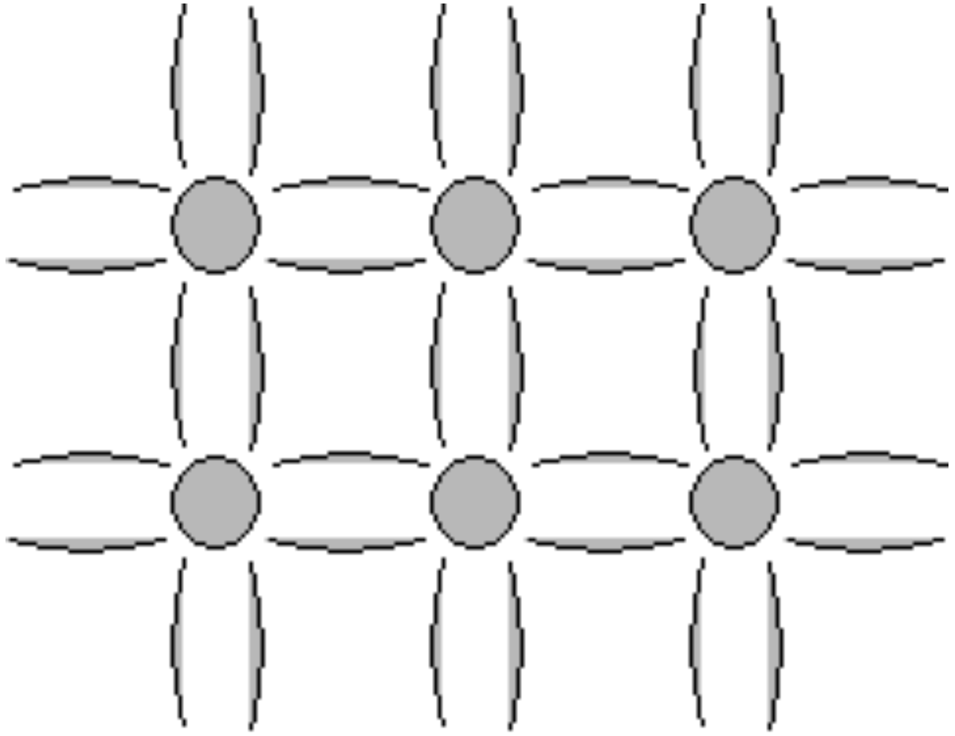
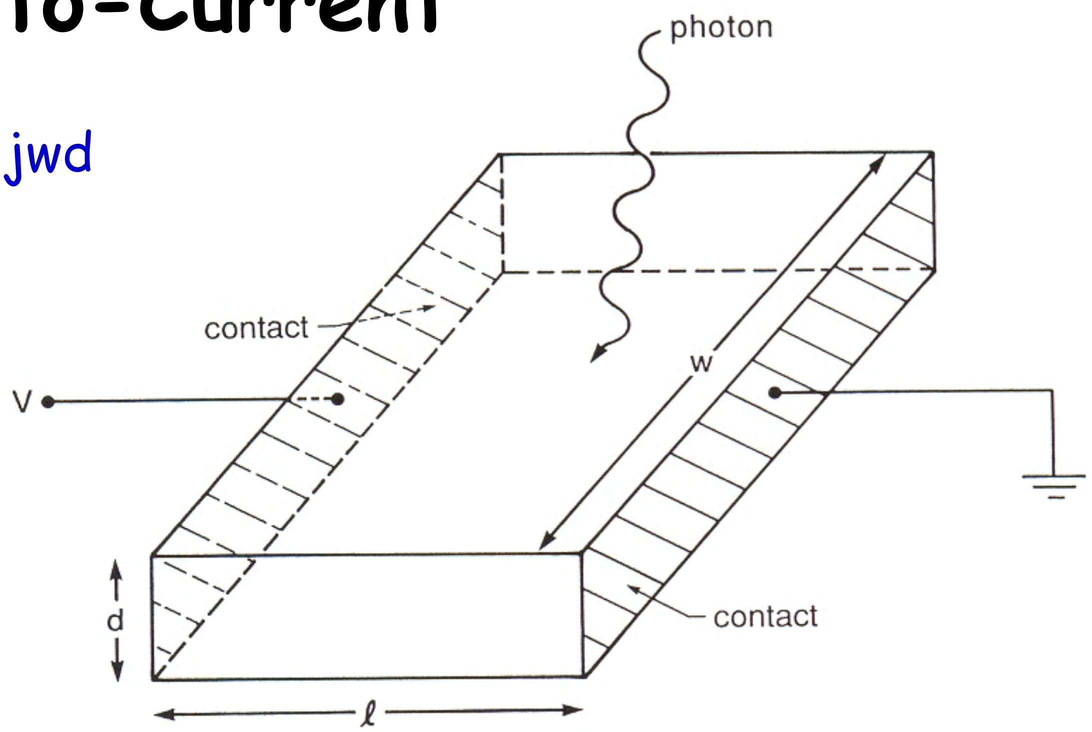


Photo-Current

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

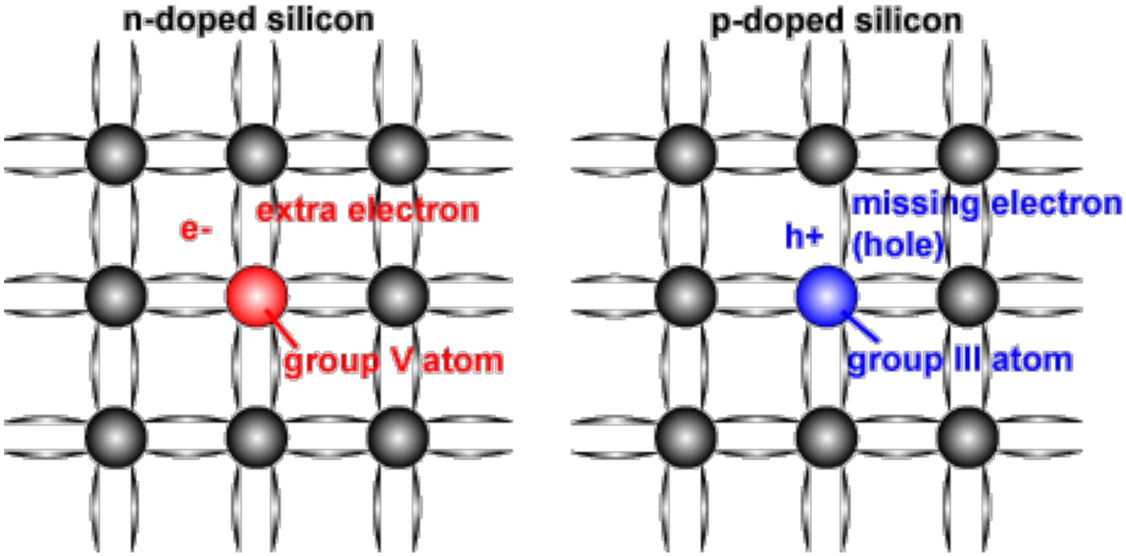
$$\lambda_c = \frac{hc}{E_g}$$

    - → 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

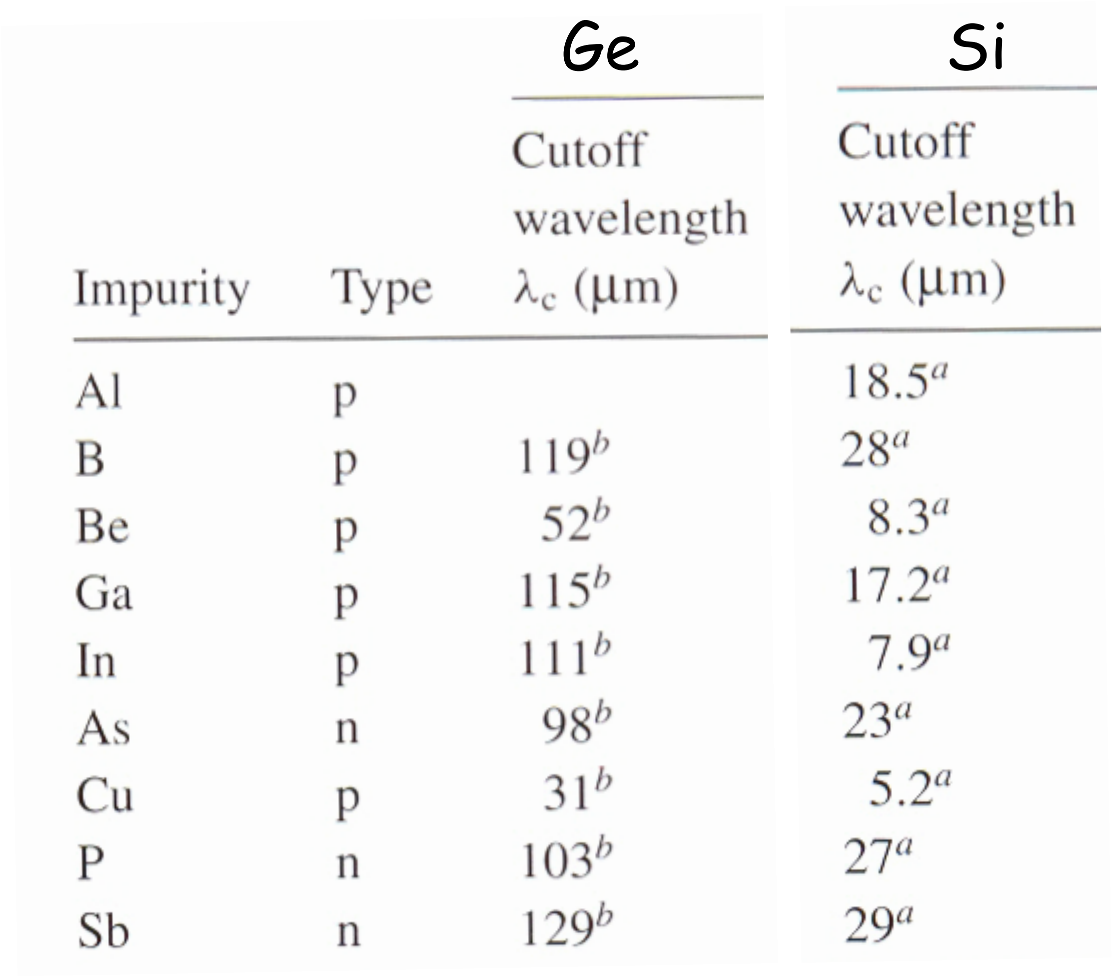
- extrinsic semiconductors: charge carriers = electrons (n-type) or
- holes (p-type)
- achieved by addition of impurities at low concentration to provide excess electrons or holes

→ 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



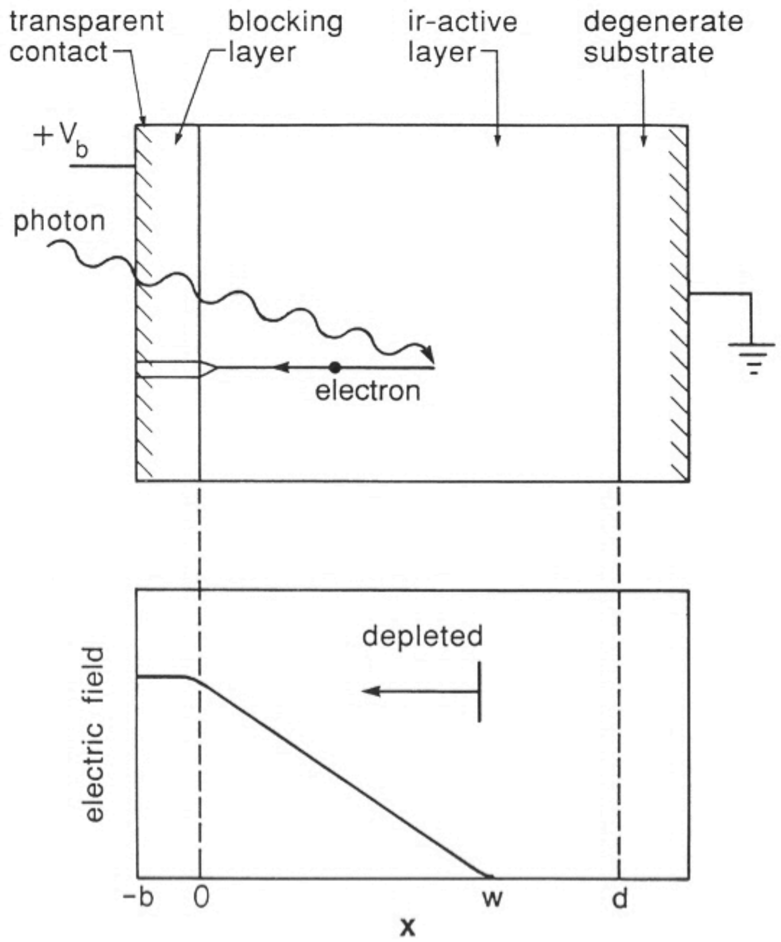
		Ge	Si
Impurity	Type	Cutoff wavelength λ_c (μm)	Cutoff wavelength λ_c (μm)
Al	p		18.5[a]
B	p	119[b]	28[a]
Be	p	52[b]	8.3[a]
Ga	p	115[b]	17.2[a]
In	p	111[b]	7.9[a]
As	n	98[b]	23[a]
Cu	p	31[b]	5.2[a]
P	n	103[b]	27[a]
Sb	n	129[b]	29[a]

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

Blocked Impurity Band (BIB) Detectors

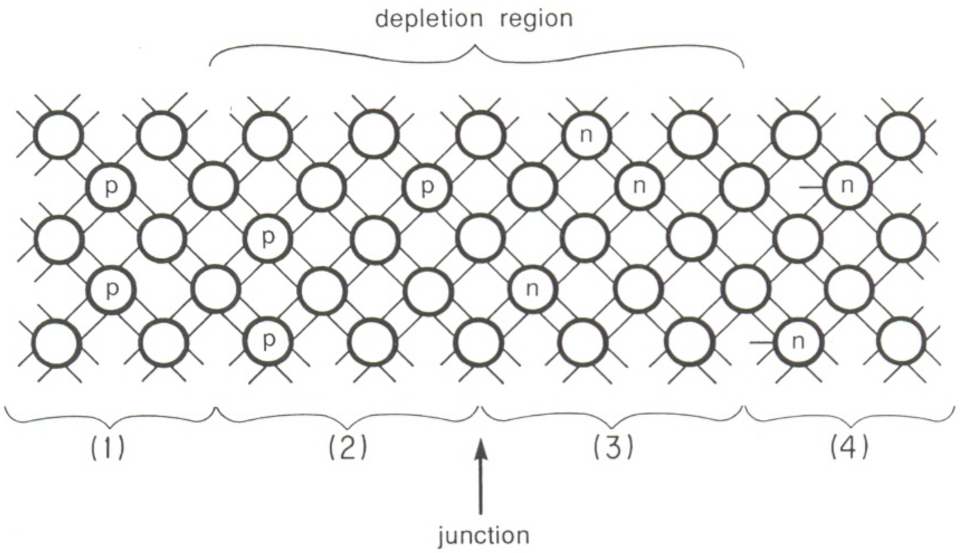
Solution: use separate layers to optimize the optical and electrical properties independently:

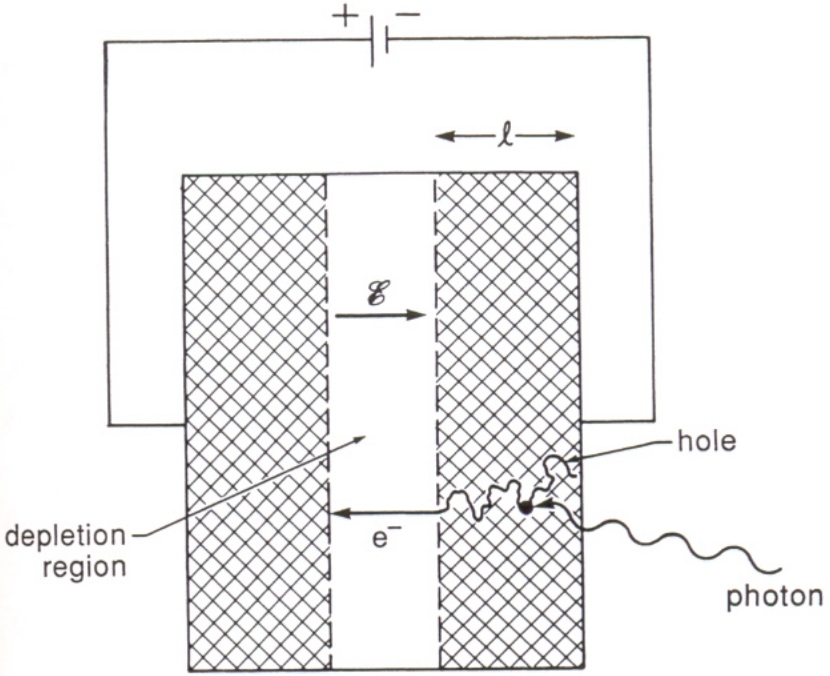
- IR-active layer: heavily doped
- Blocking layer: thin layer of high purity (intrinsic photoconductor)
- *Typical species are Si:As or Si:Sb BIBs*



Photodiodes

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



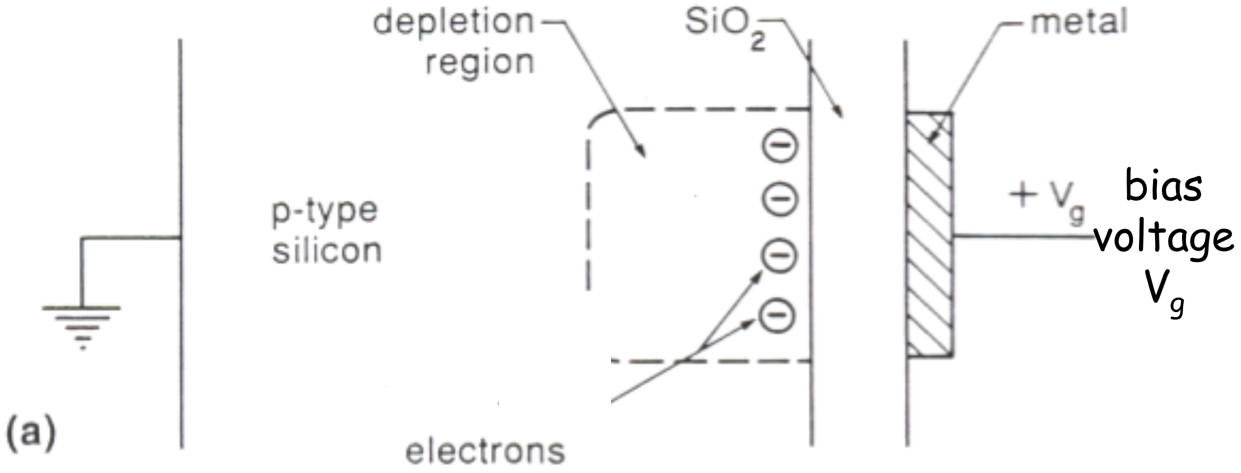


1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^--hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region → photo-current

Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

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

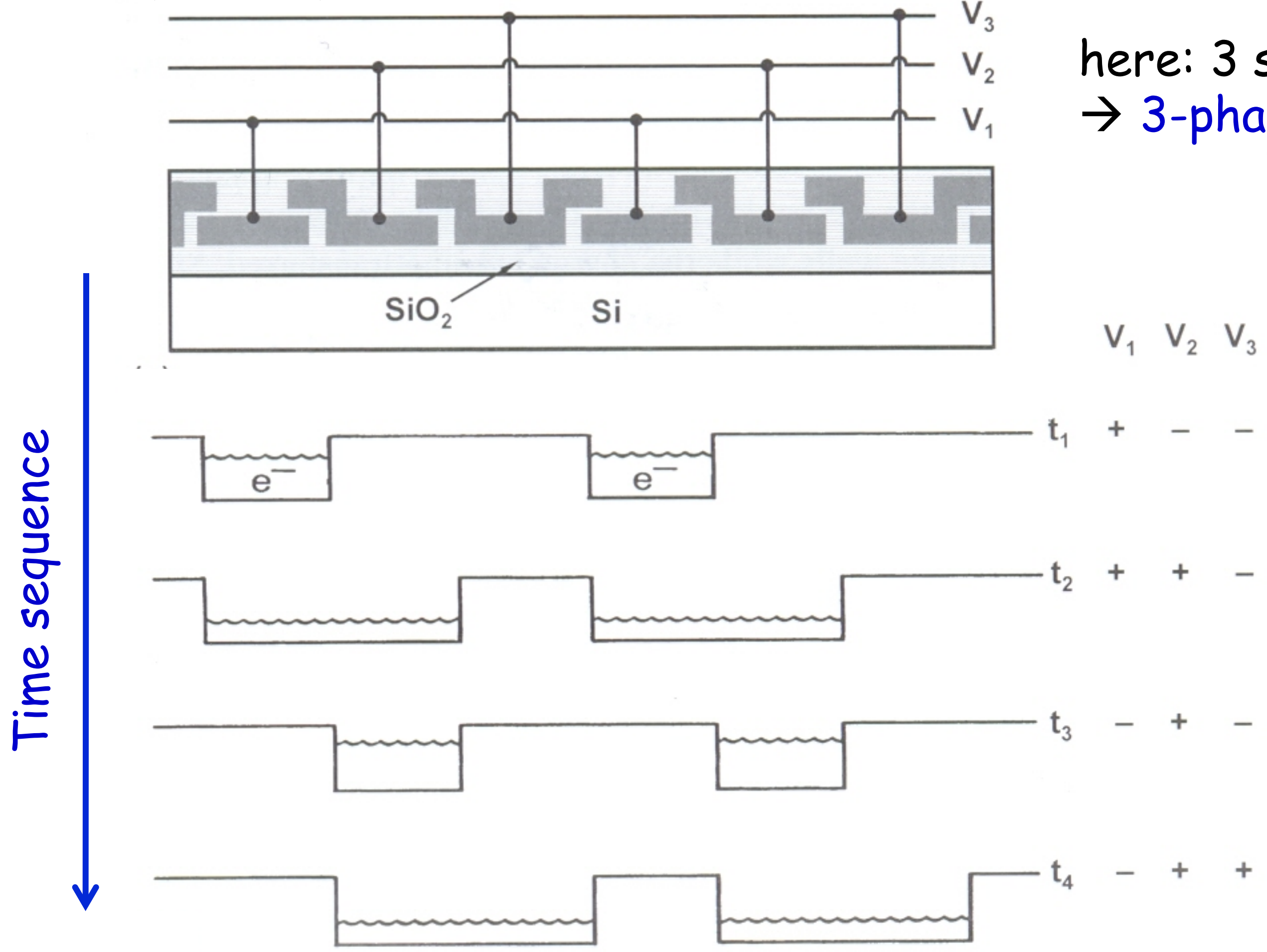


1. photons create free e^- in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO_2 layer
3. e^- accumulate at the Si—SiO_2 interface
4. the total charge collected at the interface is a measure of the number of photons during the exposure
5. → read out the number of e^-

Charge Coupled Readouts

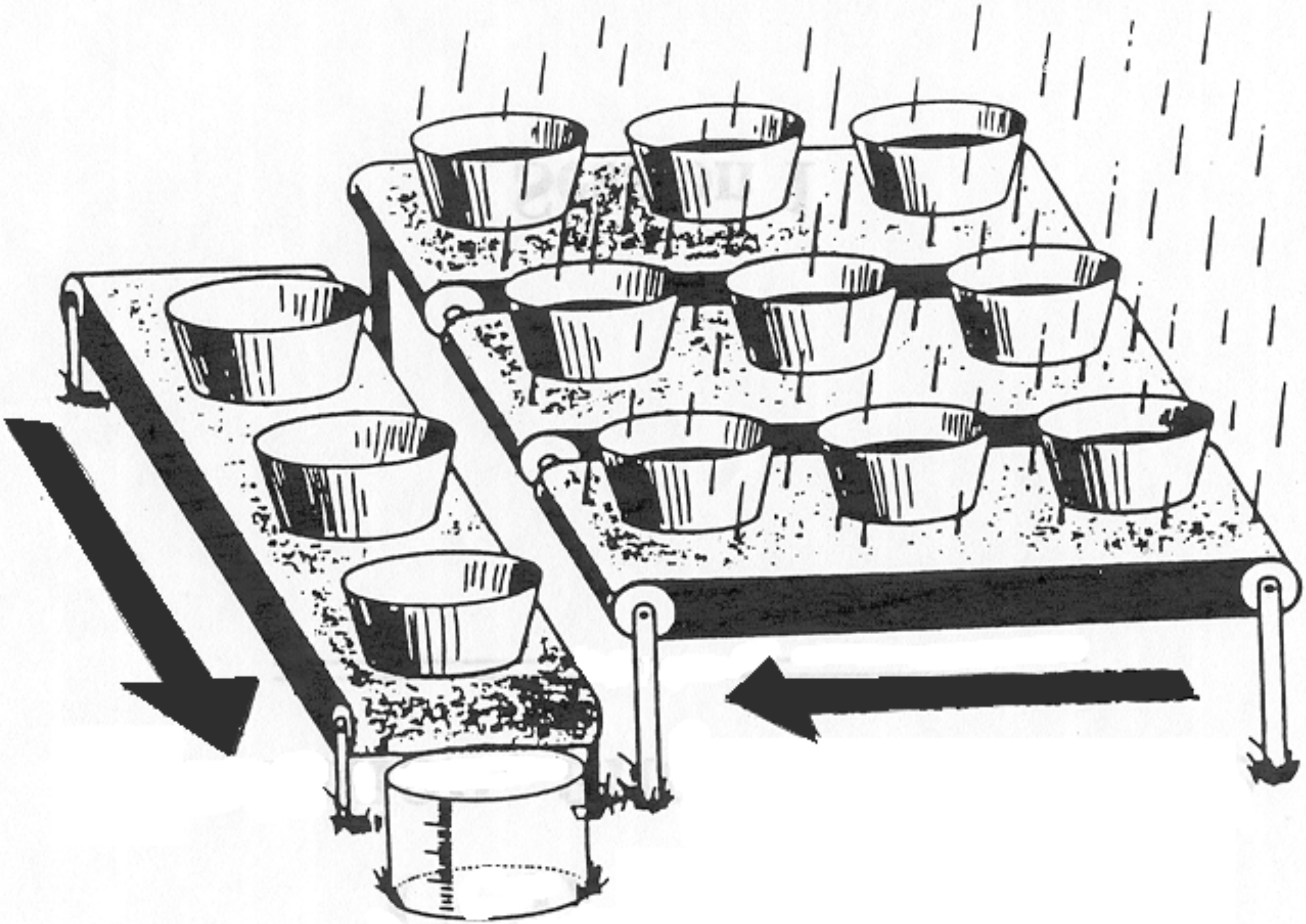
Collected charges are passed along the columns to the edge of the array to the output amplifier.

here: 3 sets of electrodes
→ 3-phase CCD



	V_1	V_2	V_3
t_1	+	–	–
t_2	+	+	–
t_3	–	+	–
t_4	–	+	+

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: $\varepsilon = (1\text{-}CTE)$

Orthogonal Transfer CCDs (OTCCD)

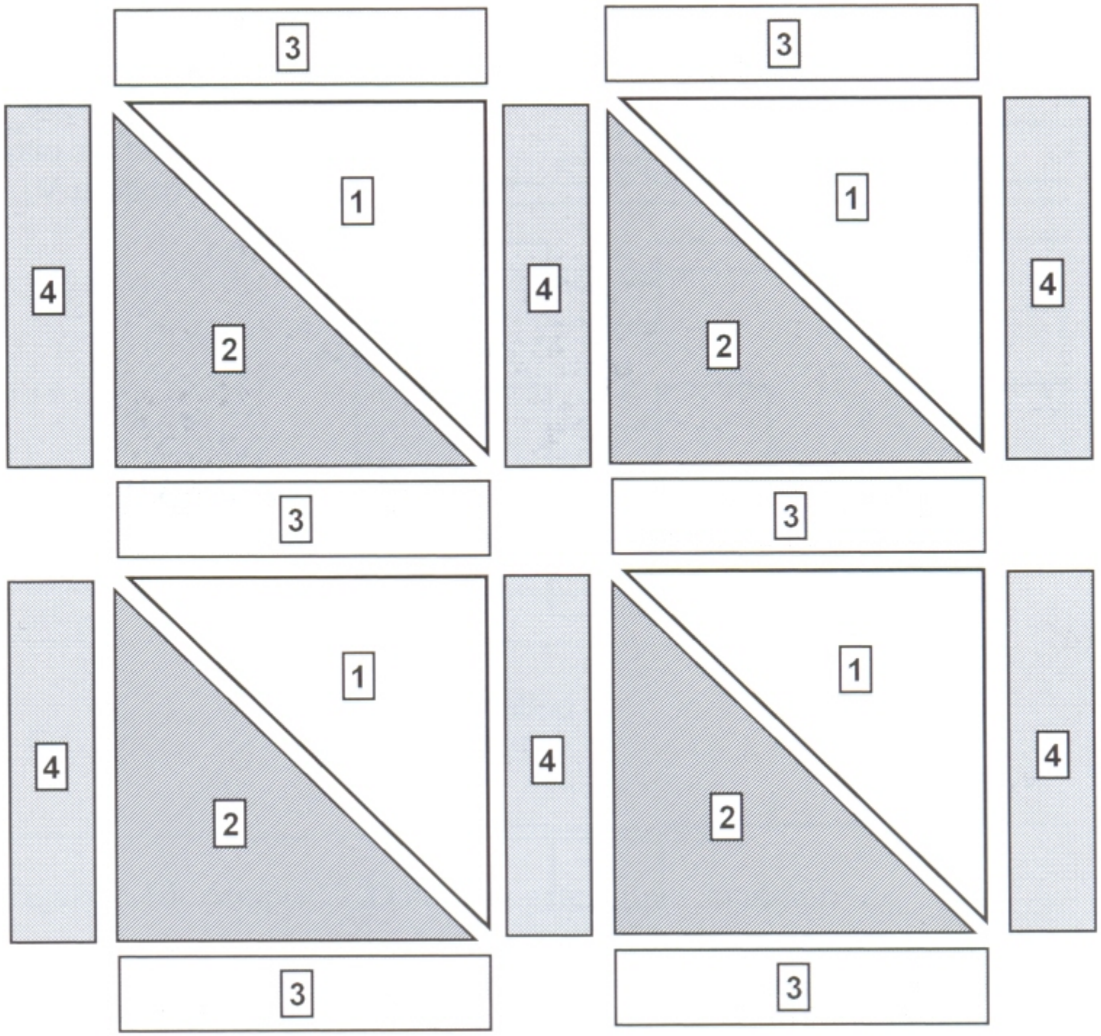
For TDI it would be desirable to move the charges in *any* direction to follow the image motion. This can be done with the OTCCD.

OTCCD operation:

To move a charge to the right, `3' is negative to act as channel stop, `1', `2', and `4' are operated as a conventional CCD.

To move a charge up, `4' is negative to act as channel stop, `1', `2', and `3' are operated as a conventional CCD.

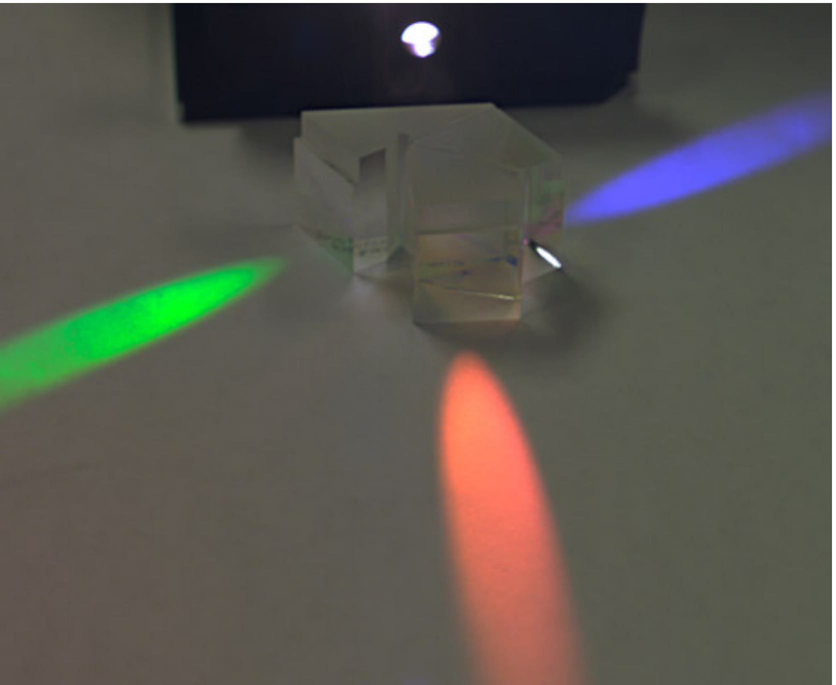
Moving to the opposite directions: reversing the clocking.

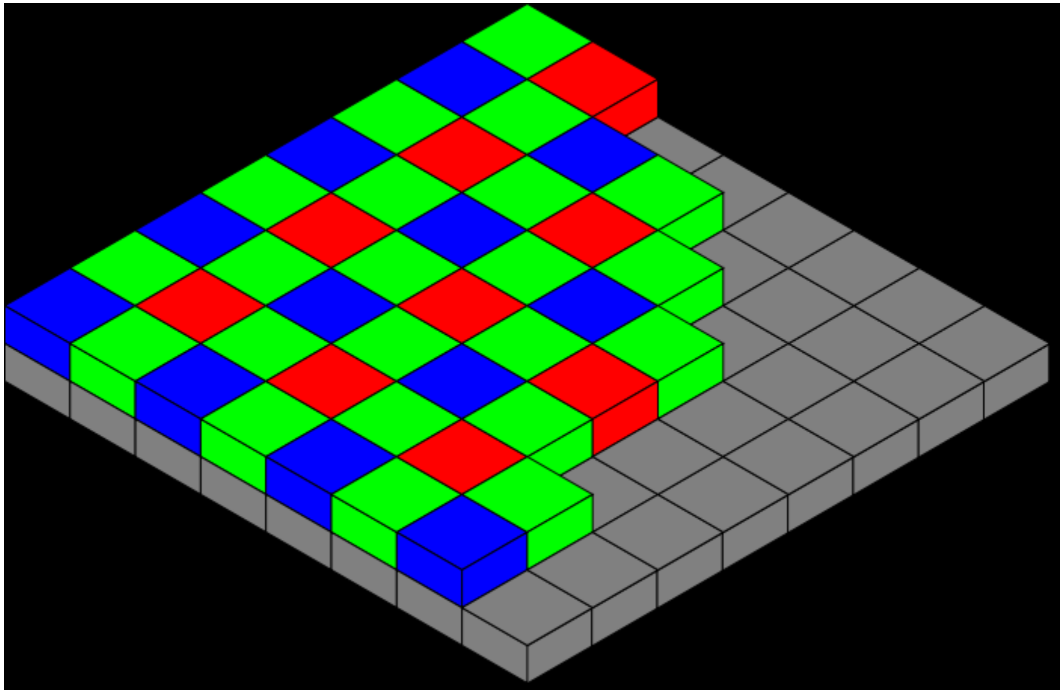


CCD Color Sensors

Essentially three ways to do it (from Wikipedia):

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 **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 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)

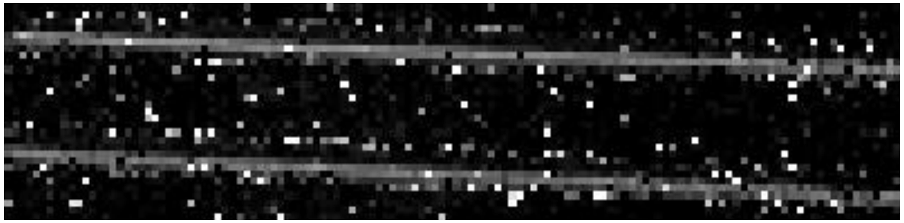
is always preferred: $\left\langle I_{G-R}^{2}\right\rangle >> \left\langle I_{J}^{2}\right\rangle + \left\langle I_{1/f}^{2}\right\rangle$

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

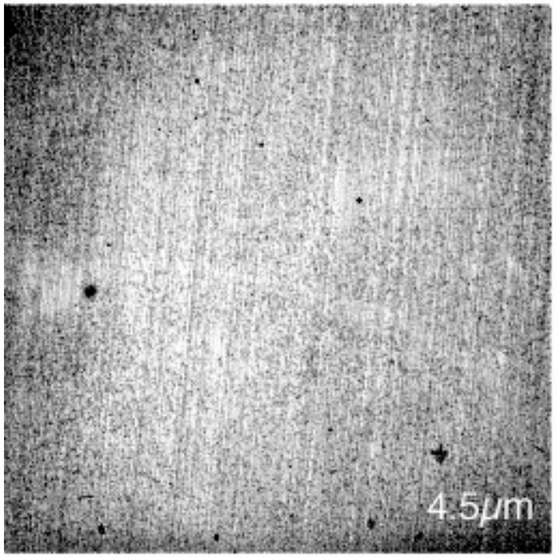
$$NEP_{G-R} = \frac{2hc}{\lambda}\left(\frac{\varphi}{\eta}\right)^{1/2}$$

In BLIP the NEP can only be improved by increasing the quantum efficiency η.

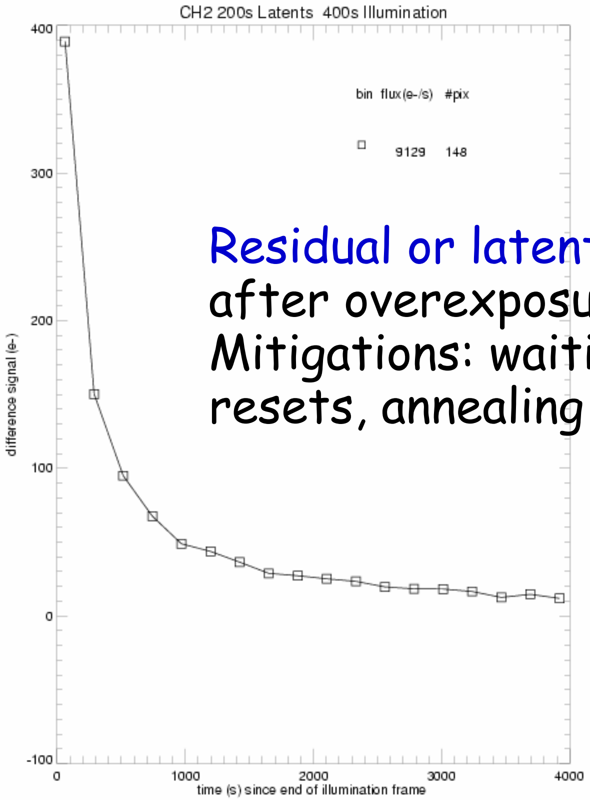
Detector Artefacts (1)



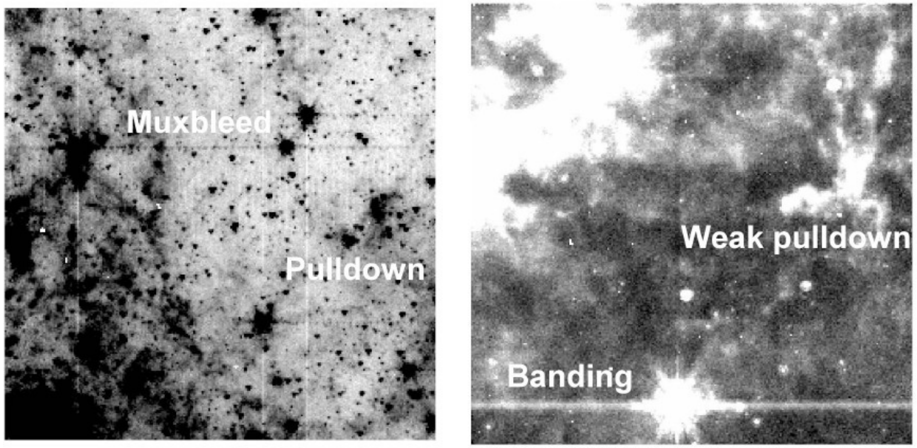
Dead, hot and rogue pixels.
Mitigation: subtract off-source image and/or reduce bias voltage



Fixed pattern noise.
Mitigation: "flat-fielding"



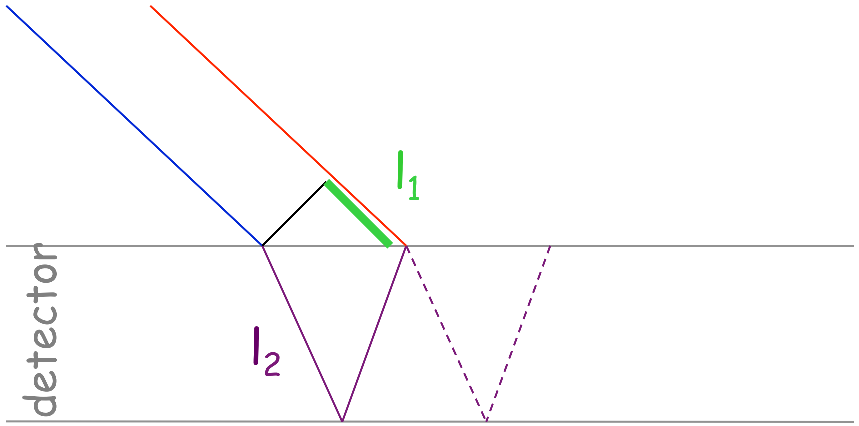
Residual or latent images after overexposure.
Mitigations: waiting, frequent resets, annealing

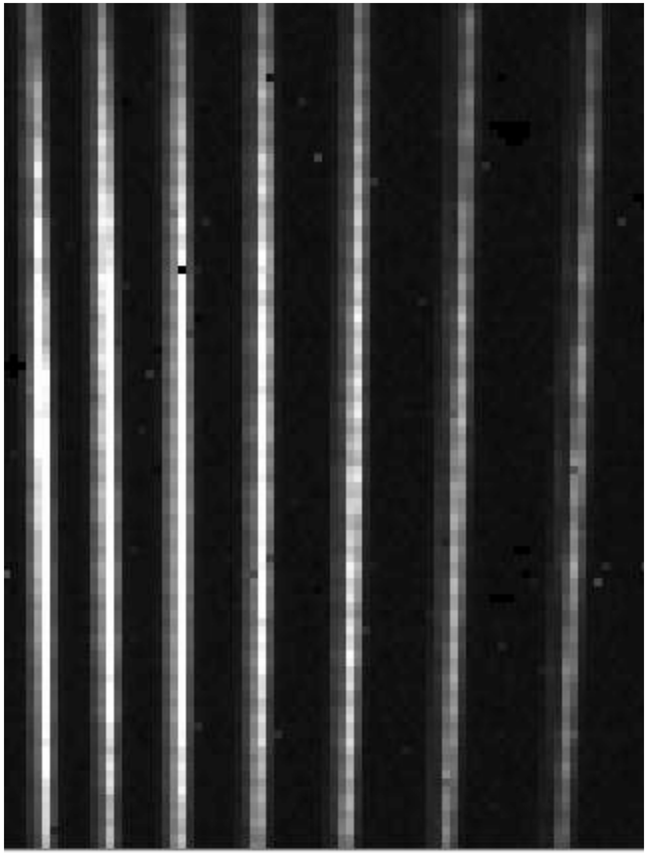


Muxbleed, pulldown and banding.
Mitigation: avoid bright sources, short exposures.

Detector Artefacts (2): Fringing

In spectrographs: photons reflect off the back of the detector and interfere with the incoming light.





If the phase difference between l_1 and $n \cdot l_2$ is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs → fringes = wave pattern.

General Flatfielding

Detector response (QE, bias) varies slightly from pixel to pixel → image has "structure", even with flat illumination
→ flat-fielding; common methods are:

1. Dome flats: illuminate a white screen within the dome (can be done during the day, but may introduce spectral artifacts)

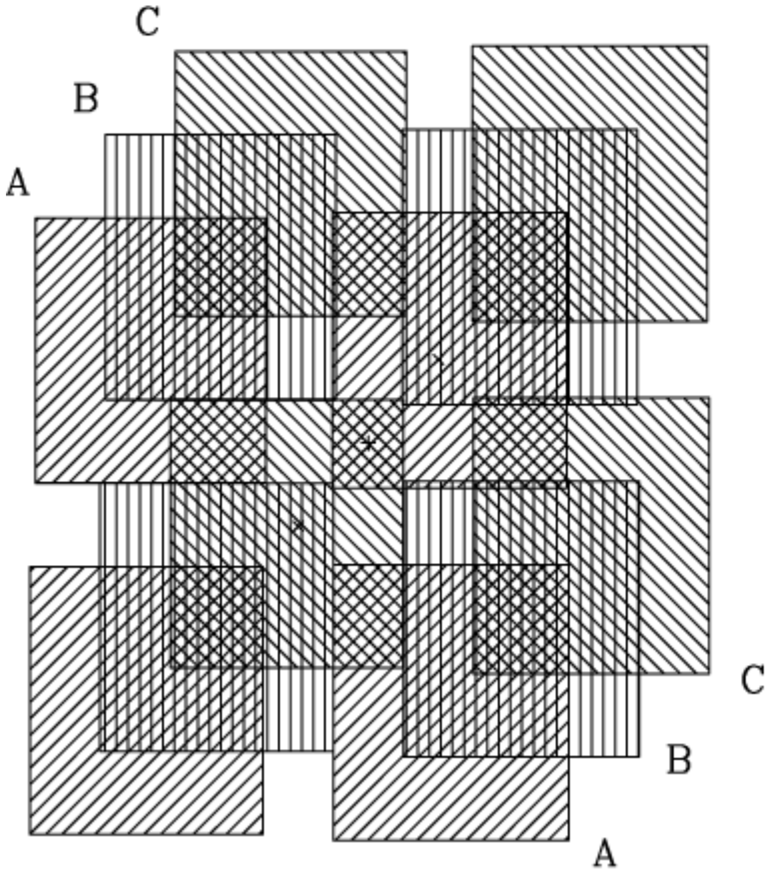
2. Twilight flats: observe the twilight sky at two times during sunrise or sunset (high S/N but time is often too short to get FFs for all filters)

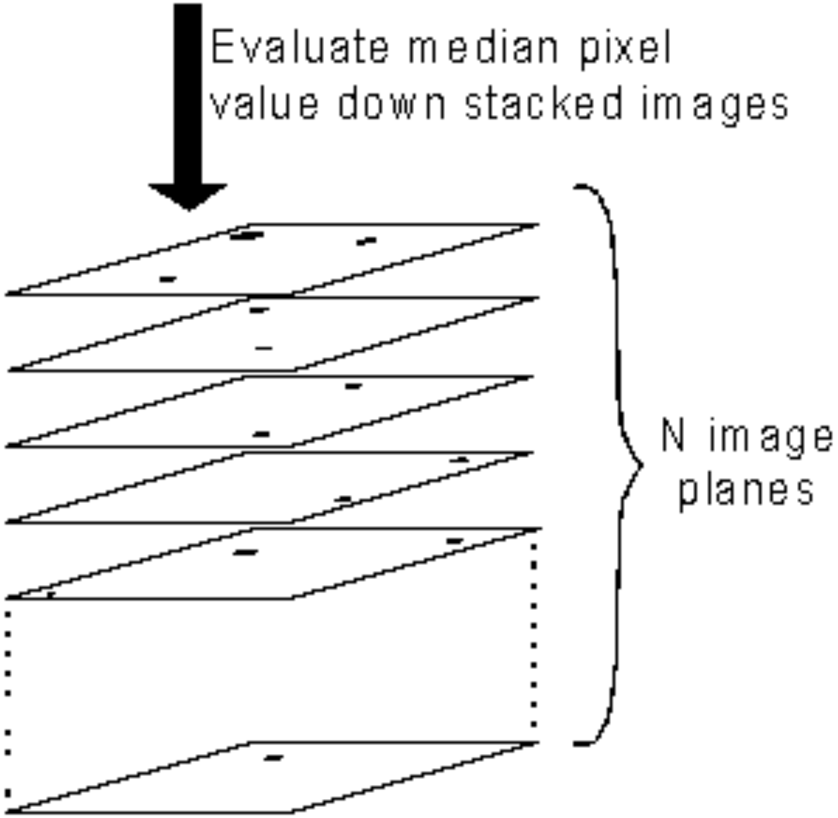
3. Sky flats: use the observations themselves (spectrally best, but often low S/N)

In all cases: use the difference between two flux levels F_1, F_2 to compute the flatfield $FF = \left(\frac{F_1 - F_2}{\text{median}(F_1 - F_2)} \right)^{-1}$ with which all images have to be multiplied.

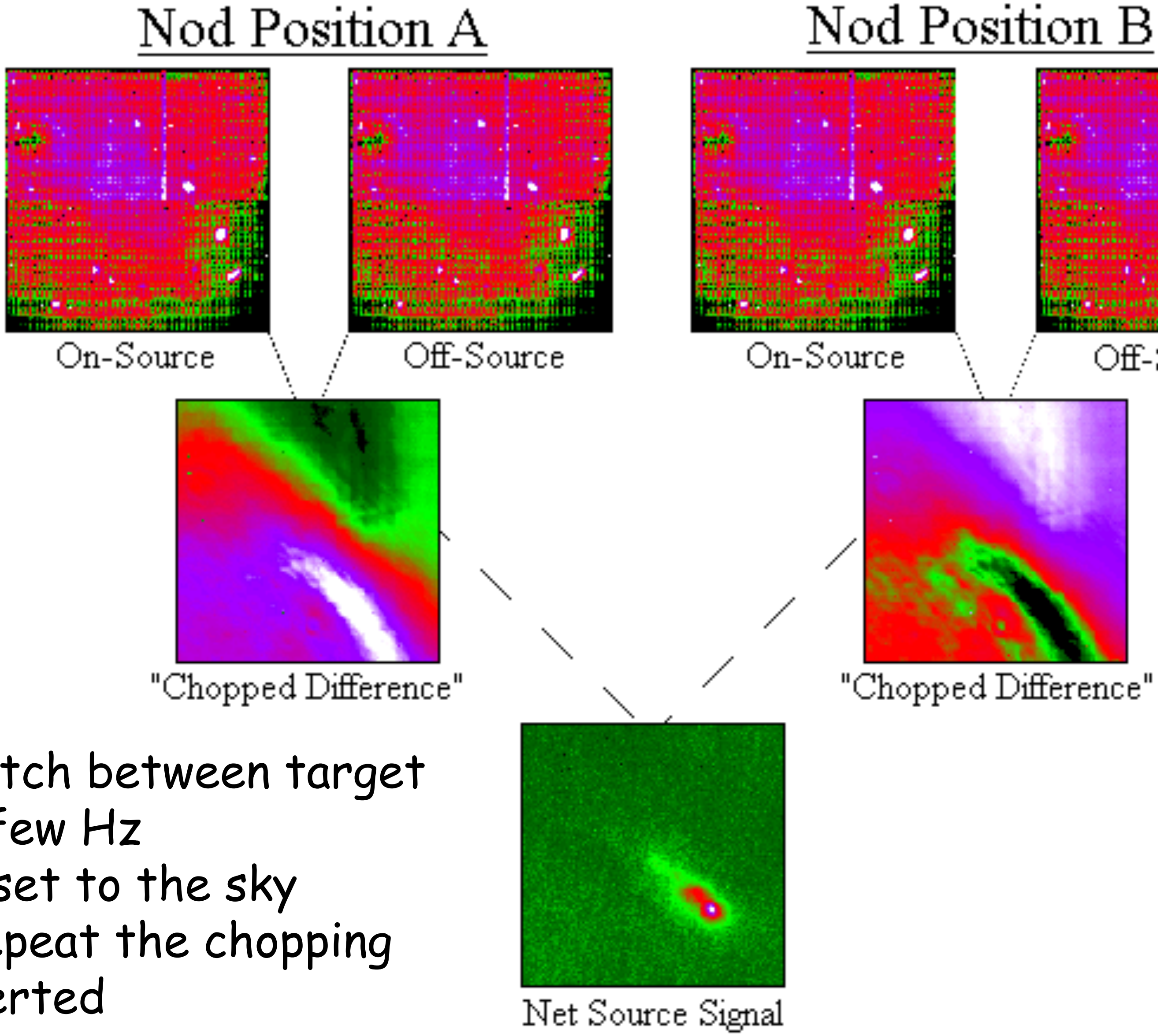
Dithering / Jittering

1. Observe the same field with many exposures, each offset by a small amount
2. Combine the image e.g., via median filtering





Chopping / Nodding



Chopping: switch between target and sky at a few Hz
Nodding: offset to the sky position to repeat the chopping sequence inverted