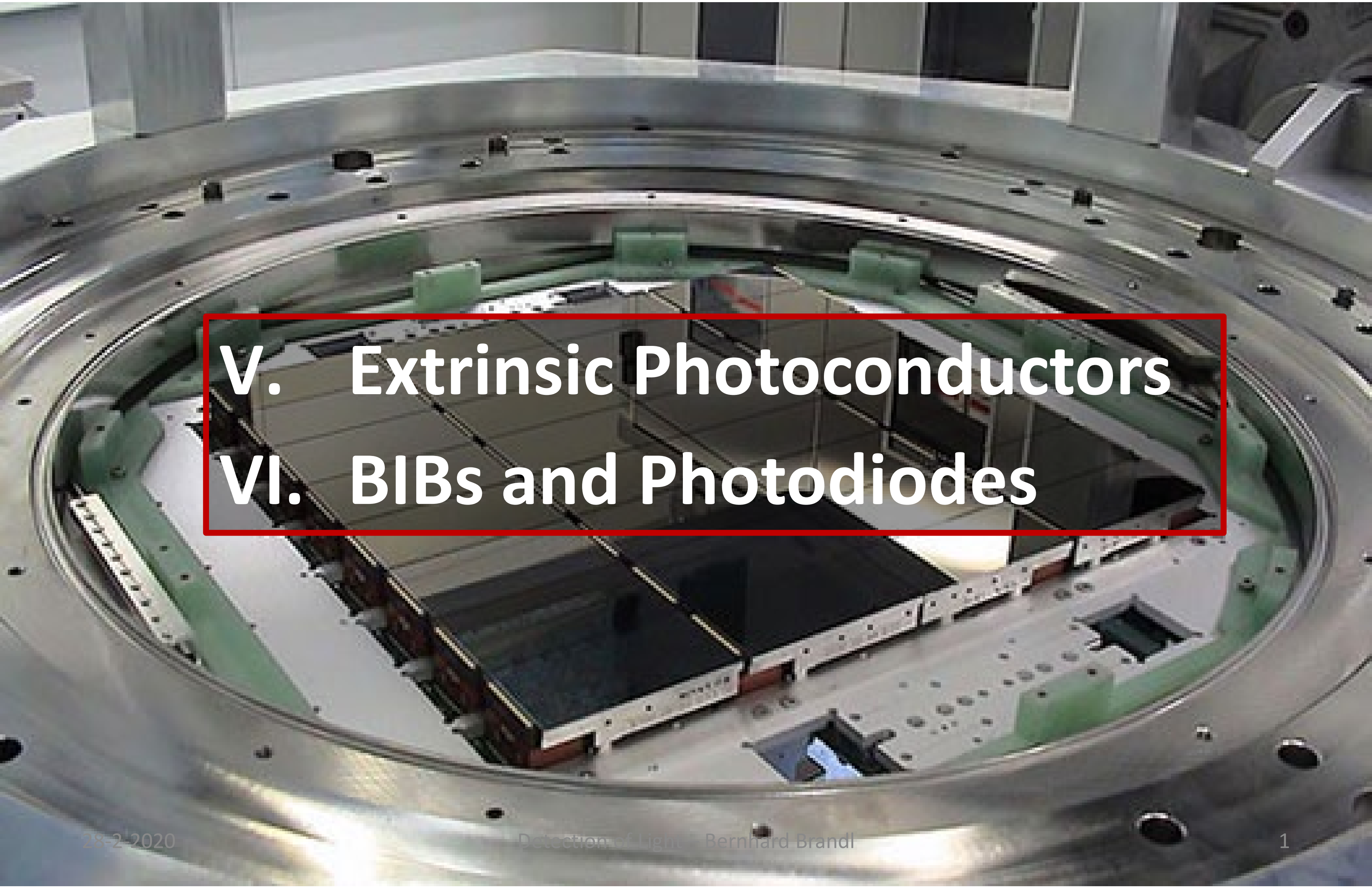
Detection of Light



V. Extrinsic Photoconductors

VI. BIBs and Photodiodes

Doping and resulting Bandgaps

Reminder: Bandgaps

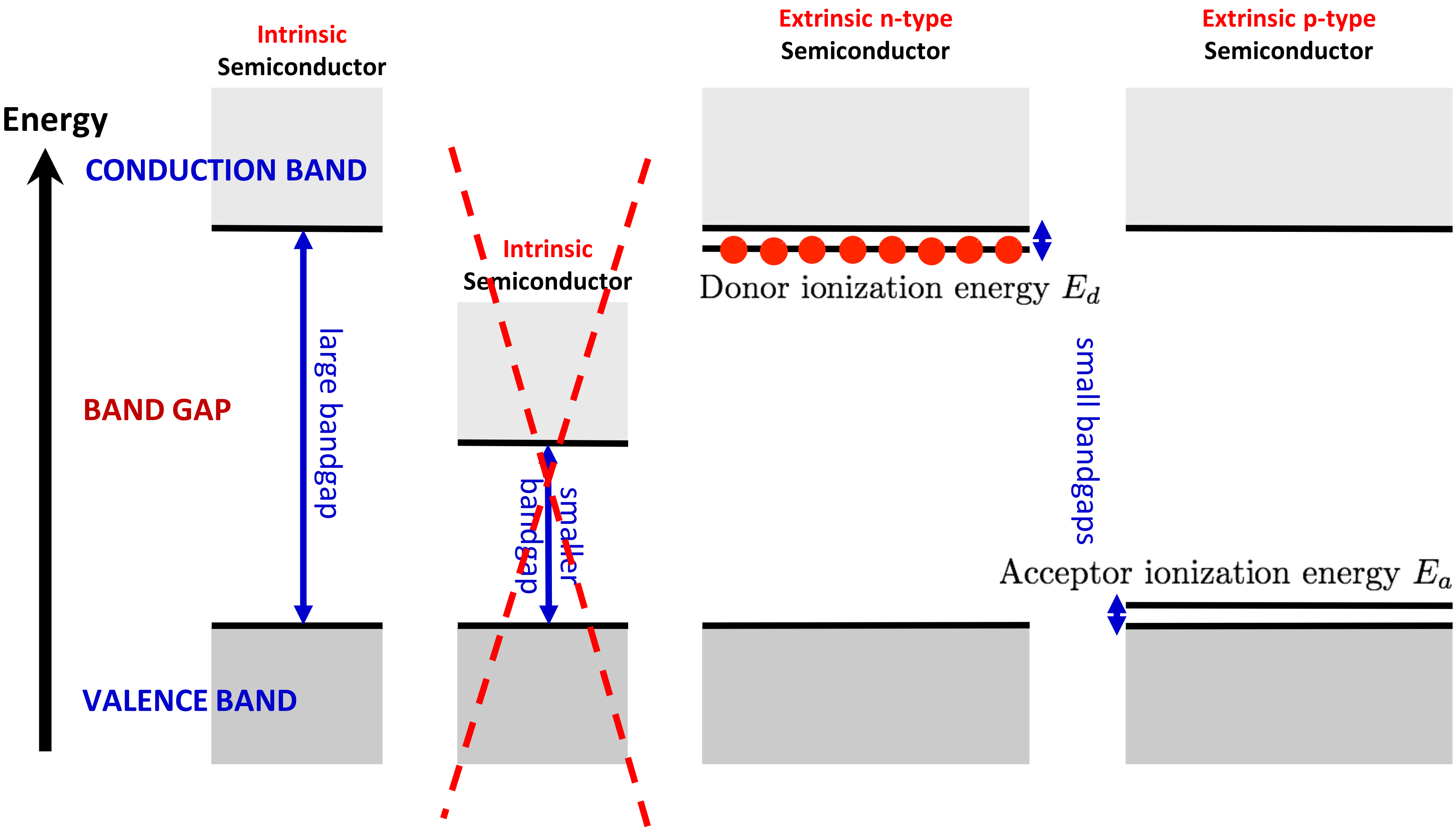
$$E_\gamma = \frac{hc}{\lambda} > E_{bandgap}$$

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

Germanium (0.67eV):	1.8 µm
Silicon (1.14eV):	1.1 µm
InAs (0.35eV)	3.4 µm
InSb (0.17eV):	6.8 µm

Goal: smaller bandgap = lower excitation energy = detection of lower energies = detection of longer wavelengths photons

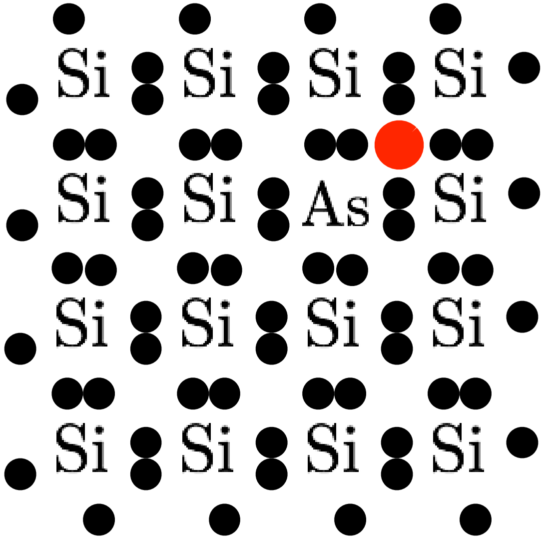
Energy Bandgaps (idealized at T = 0 K)



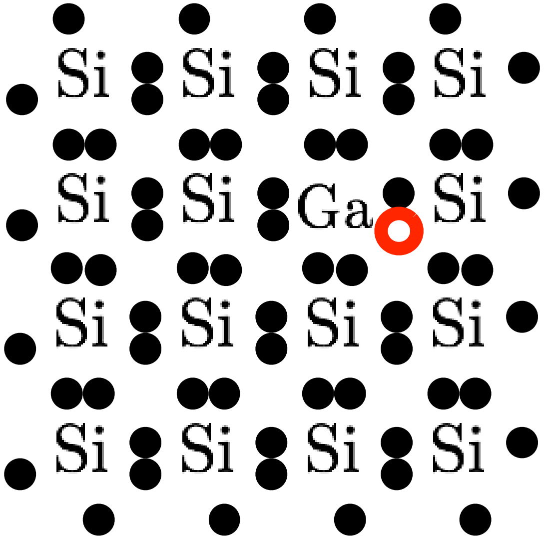
How can we practically do that?

Consider “doping” a pure silicon crystal with small amounts of Group V or Group III elements:

Adding a Group V element (“donor”) adds conduction electrons → n-type Si



Adding a Group III element (“acceptor”) adds a missing electron = “hole” → p-type Si



Bandgaps in extrinsic Semiconductors

Measured donor E_d and acceptor E_a ionization energies:

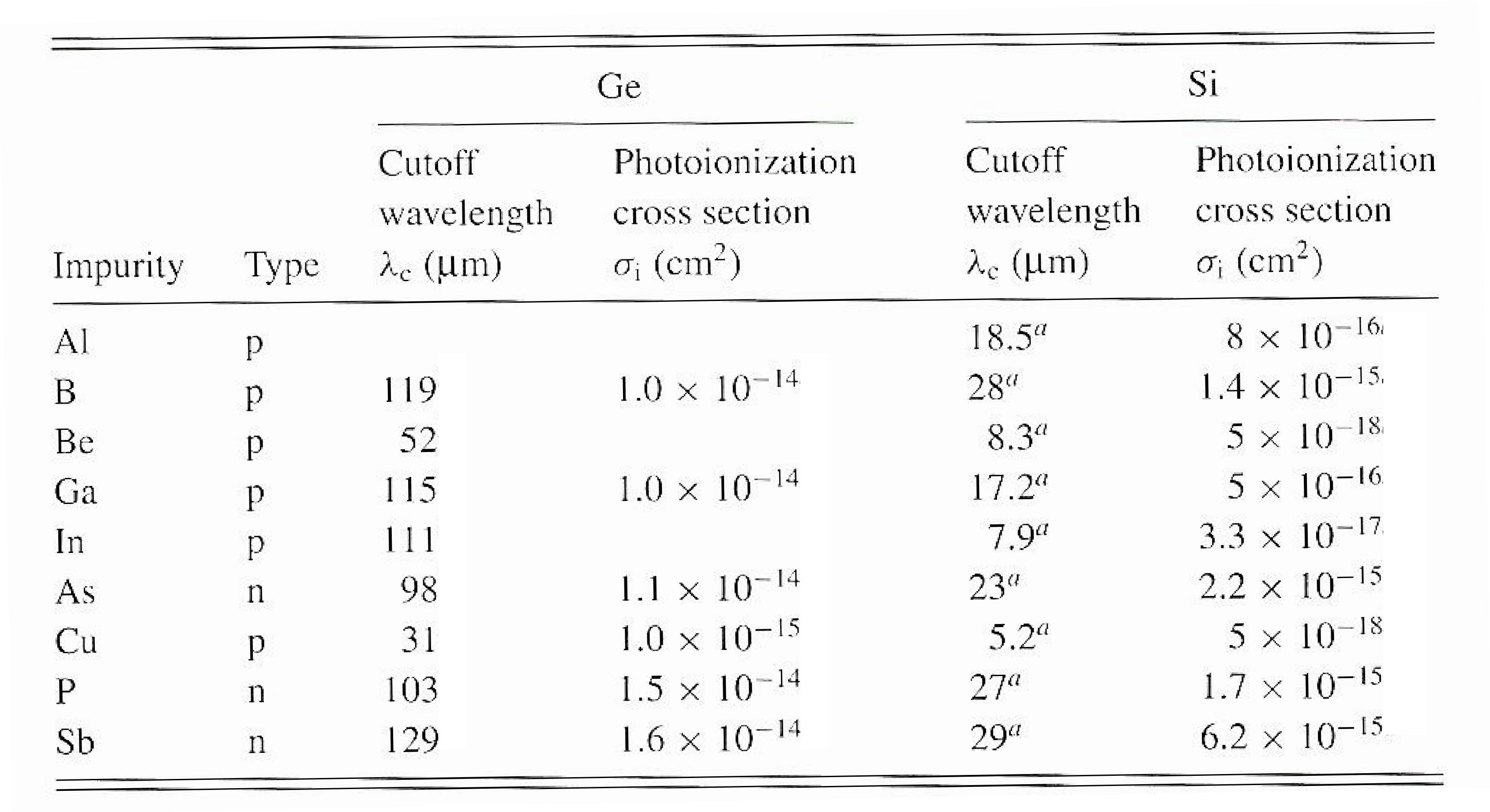
Donor	Si (meV)	Ge (meV)
intrinsic	1100	700
P	45	12
As	49	13
Sb	39	10
B	45	10
Ga	65	11
In	157	11

Note: 25 × smaller bandgap means 25 × longer wavelength coverage of the detector!

Note: for $T = 300\text{K}$, $kT \sim 26$ meV → cooling of detector is crucial

Sensitivity to Longer Wavelengths

The notation for extrinsic materials is given as semiconductor:dopant, e.g. Si:As, Si:Sb, Ge:Ga

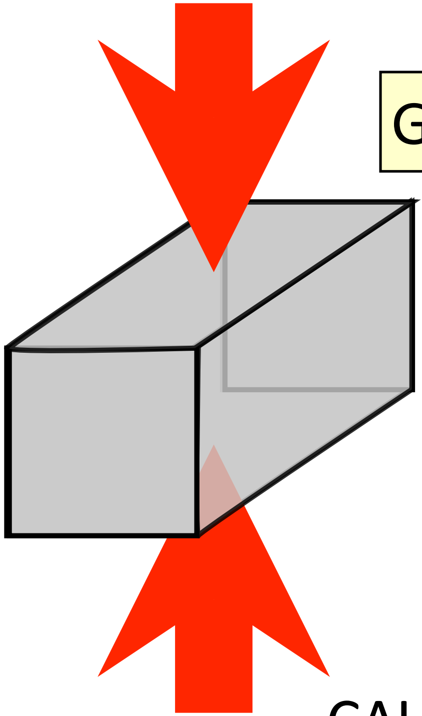


Impurity	Type	Ge: Cutoff wavelength λ_c (μm)	Ge: Photoionization cross section σ_i (cm^2)	Si: Cutoff wavelength λ_c (μm)	Si: Photoionization cross section σ_i (cm^2)
Al	p			18.5[a]	8×10^{-16}
B	p	119	1.0×10^{-14}	28[a]	1.4×10^{-15}
Be	p	52		8.3[a]	5×10^{-18}
Ga	p	115	1.0×10^{-14}	17.2[a]	5×10^{-16}
In	p	111		7.9[a]	3.3×10^{-17}
As	n	98	1.1×10^{-14}	23[a]	2.2×10^{-15}
Cu	p	31	1.0×10^{-15}	5.2[a]	5×10^{-18}
P	n	103	1.5×10^{-14}	27[a]	1.7×10^{-15}
Sb	n	129	1.6×10^{-14}	29[a]	6.2×10^{-15}

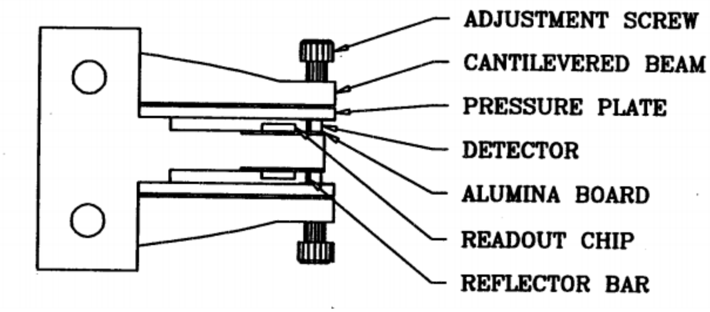
Mechanical Stress

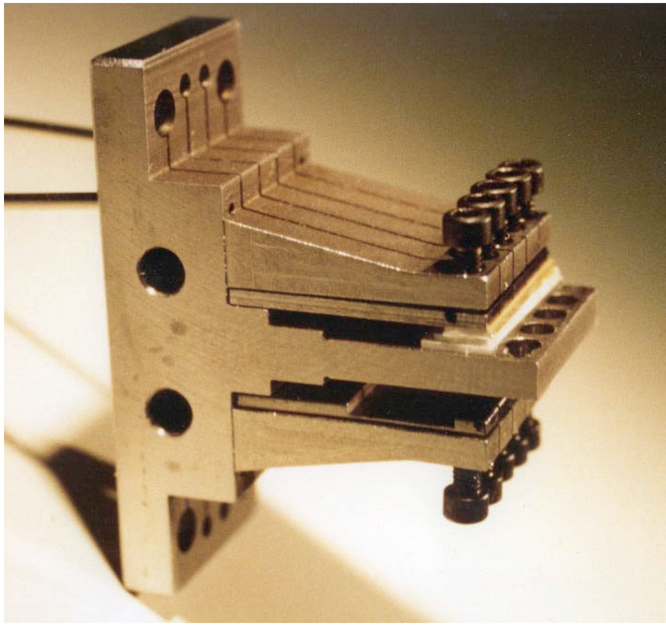
Stressing p-type Photoconductors

Applying a mechanical force to extrinsic p-type material “helps” break inter-atomic bonds. (p-type has conduction by migrating holes).



Ge:Ga 115 µm → 200 µm

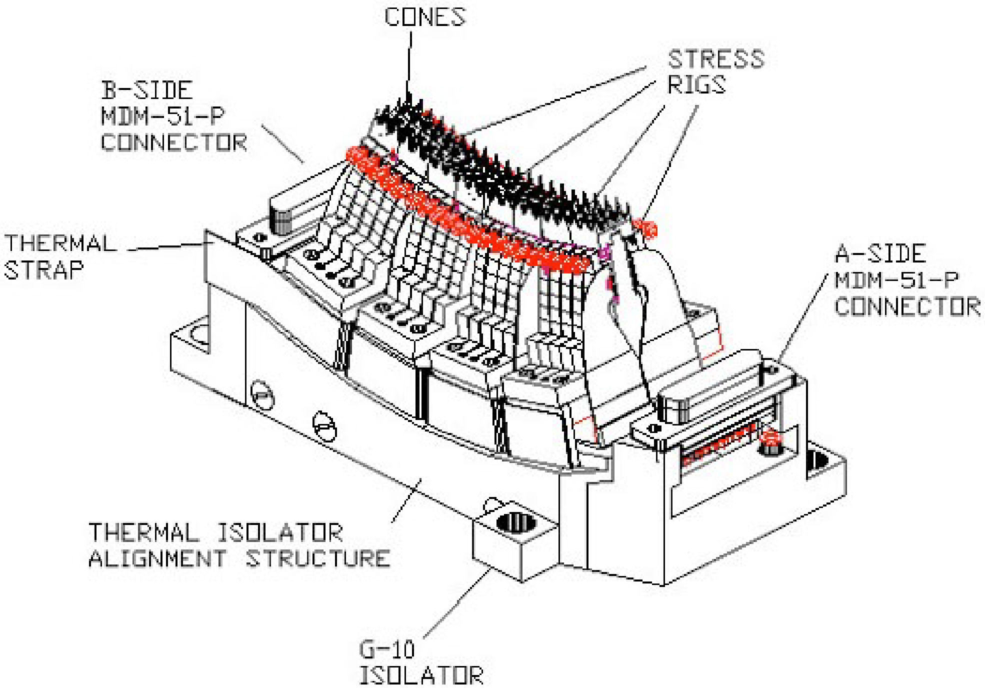




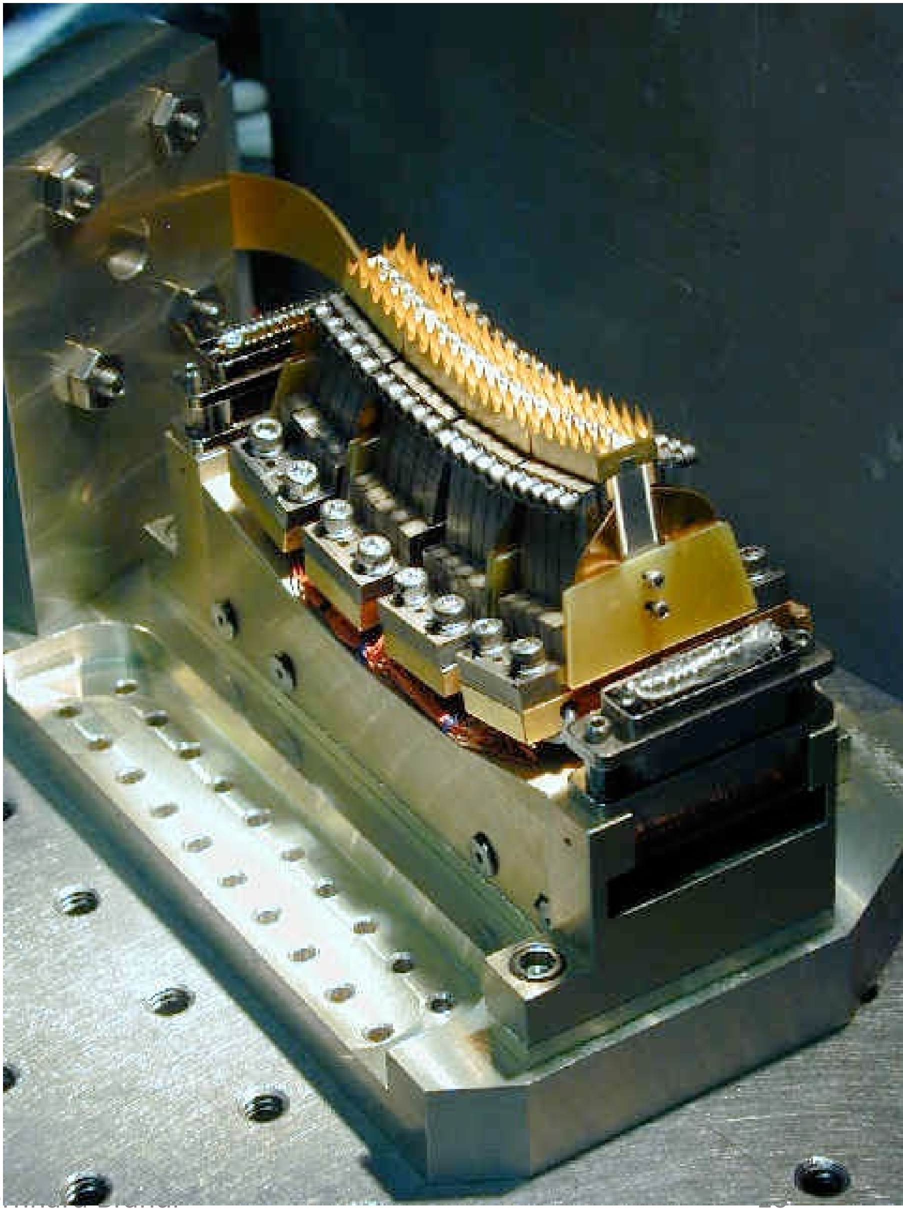
CAUTION: Pressure is 4 tons per square cm!
Apply pressure evenly and consistently.
Don’t be anywhere nearby if it mechanically fails....

Stacking stressed Ge:Ga pixels

2 × 20 pixel of the Spitzer/MIPS



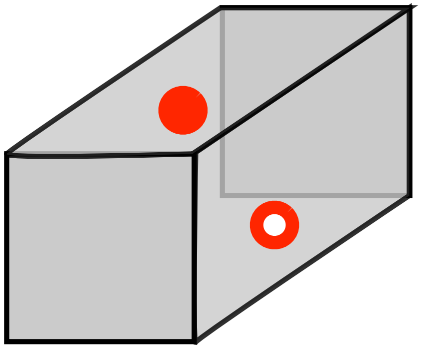
Haller and Richards
and the Arizona IR Group



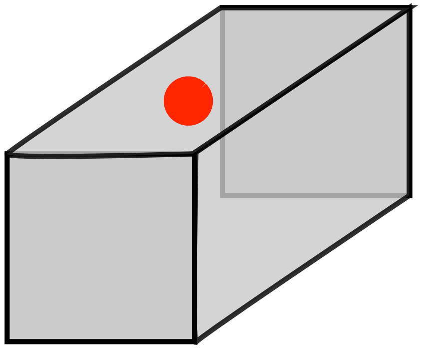
Some Properties of Extrinsic Photoconductors

Intrinsic versus extrinsic Carrier Release

Pure semiconductors are called intrinsic,
doped semiconductors are called extrinsic.



Intrinsic semiconductor releases an electron and a hole

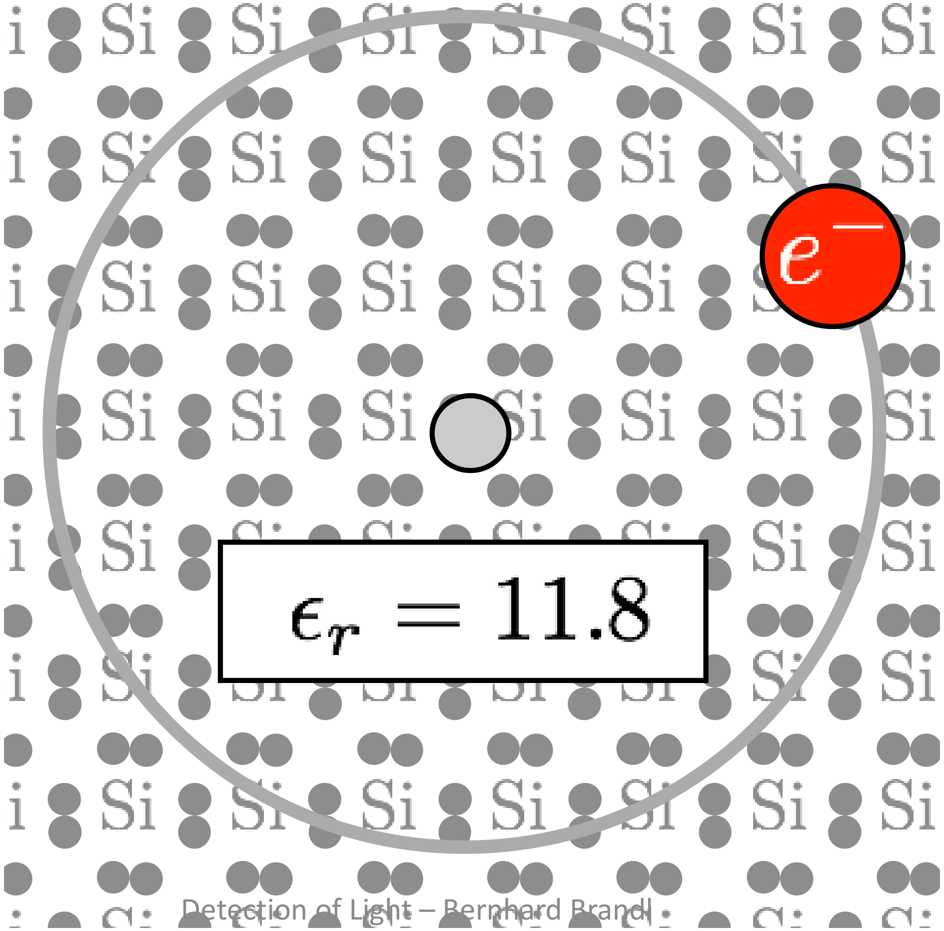


Extrinsic semiconductor releases ONLY ONE free charge carrier (either electron or hole)

On the ionization Cross-Section…

The Bohr radius $a_0 = \frac{4\pi\varepsilon_o h^2}{m_e e^2}$ depends on the permittivity of free space, $\varepsilon_o = \frac{1}{\mu_o c^2}$.

However, in a crystal a_0 is very different, since $\varepsilon_o \rightarrow \varepsilon_o\,\varepsilon_r$ is. In vacuum $\varepsilon_r = 1$.



$\epsilon_r = 11.8$

Doping Concentrations

A few numbers for reference for crystalline silicon (**from Wikipedia 'Doping (semiconductor)'**):

- Intrinsic silicon has ~5×10^{22} atoms cm^{-3}
- At T=300K, the intrinsic carrier concentration is ~1.1×10^{10} cm^{-3}
- Typical doping concentrations: 10^{13} cm^{-3} (light) – 10^{18} cm^{-3} (heavy)
- Doping concentrations >> 10^{18} cm^{-3} are considered degenerate
- Note: degeneracy already starts at concentrations of $1 : 10^4$

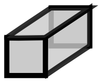
Absorption Coefficients and QE

The absorption coefficient *a* for extrinsic photoconductors is:

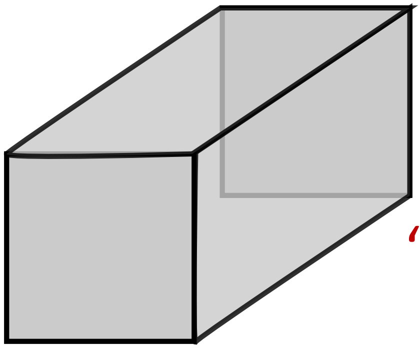
$$a(\lambda) = \sigma_i(\lambda) N_I$$

...where σ_i is the photoionization cross section and N_I is the impurity concentration.

For an impurity concentrations of $10^{15} – 10^{16}$ cm^{-3}, and typical photo-ionization cross sections of $10^{-15} – 10^{-17}$ cm^2, the absorption coefficients of extrinsic photoconductors are 2 – 3 orders of magnitude less than those for direct absorption in intrinsic photoconductors → make them big!



Intrinsic detector

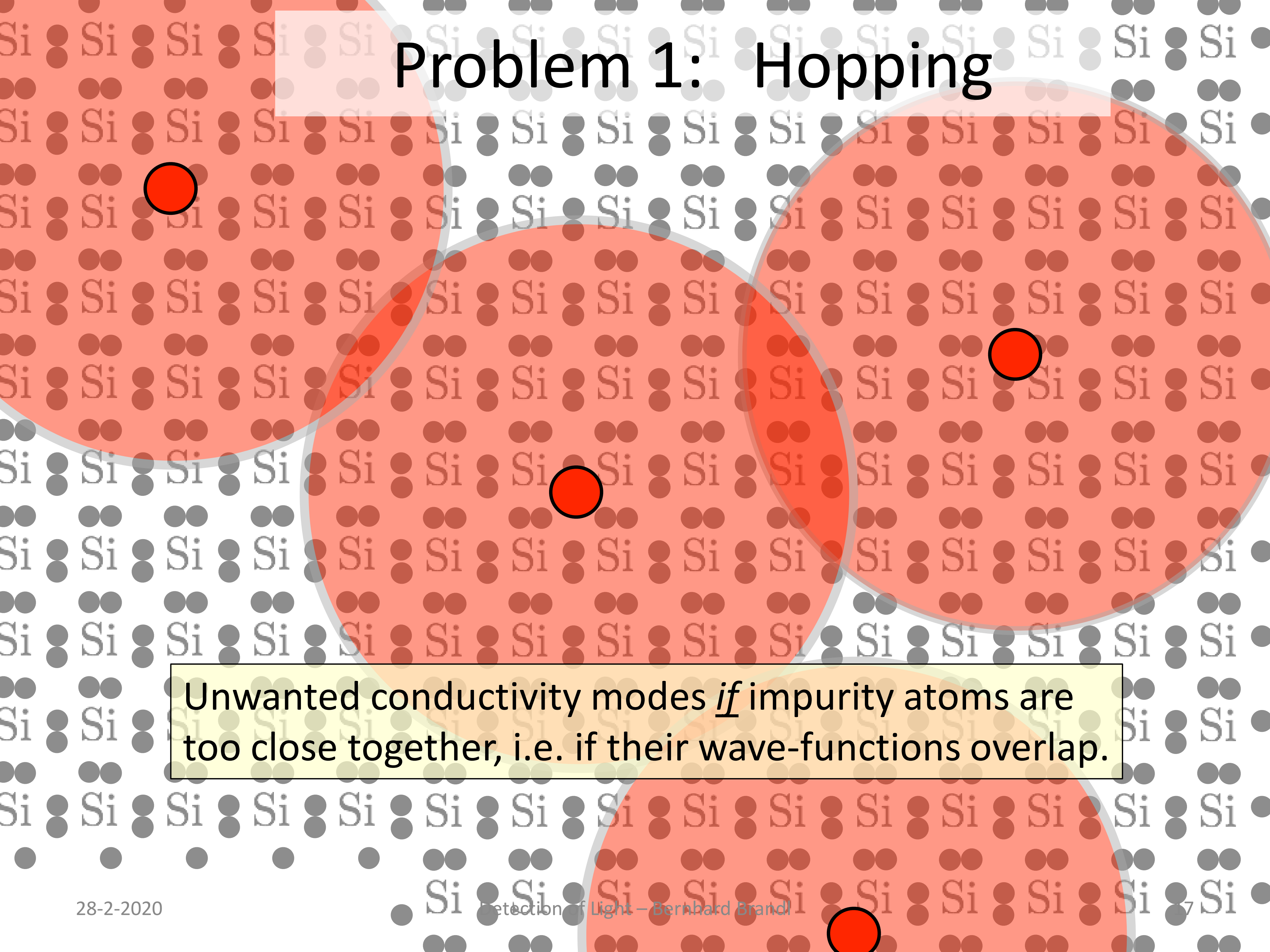


Extrinsic detector

“Bulk Photo-conductor”

Specific Issues of Extrinsic Detectors

Problem 1: Hopping

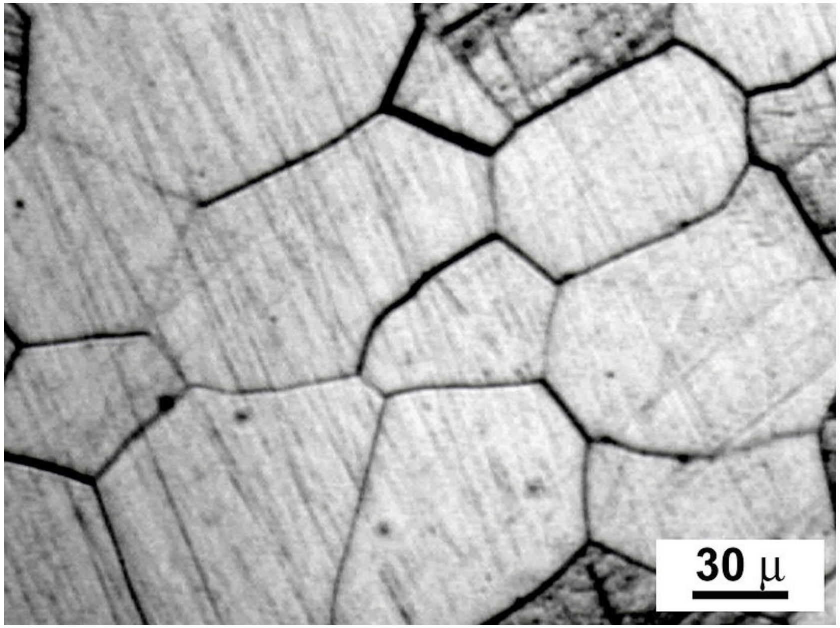


Unwanted conductivity modes *if* impurity atoms are too close together, i.e. if their wave-functions overlap.

Problem 2: Impurities

No clean room process is perfect! For instance:

- Oxygen is introduced from dissolved quartz in the heating bowl
- Unwanted Boron atoms are present in Silicon at 10^{-13} cm^{-3}
- Crystal shows grain boundaries rather than perfect homogeneity



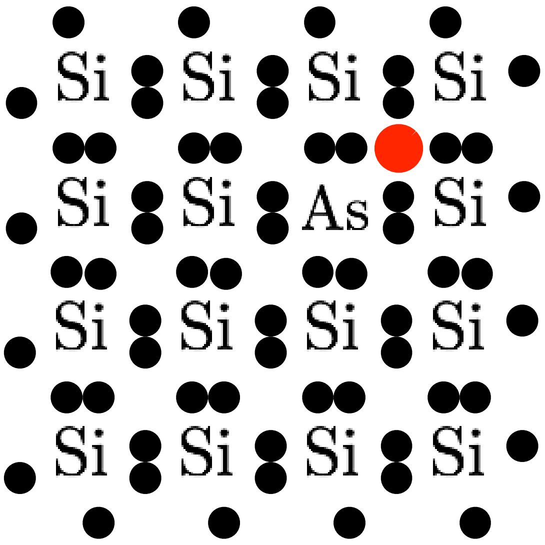
Grain Boundaries

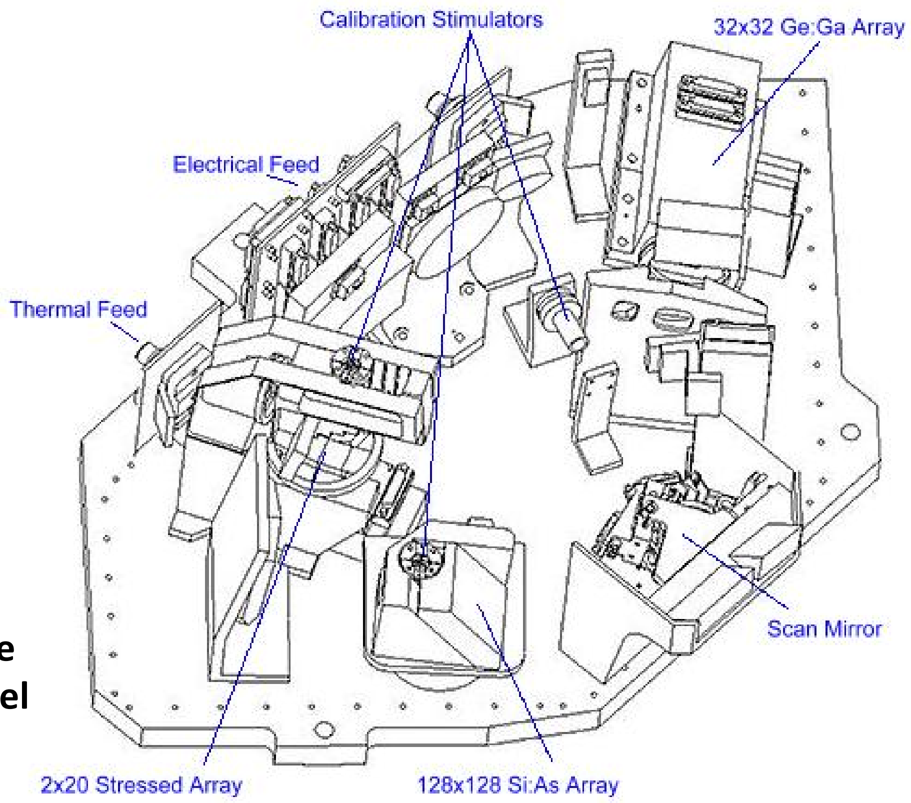
Problem 3: Intrinsic Absorption

Even though the dopant:intrinsic ratio is typically 1:10000, you MUST USE a filter to make sure intrinsic energy photons don't hit your detector!

There are MANY more intrinsic absorbers than extrinsic absorbers...

...so you need a light-blocking filter for short wavelengths



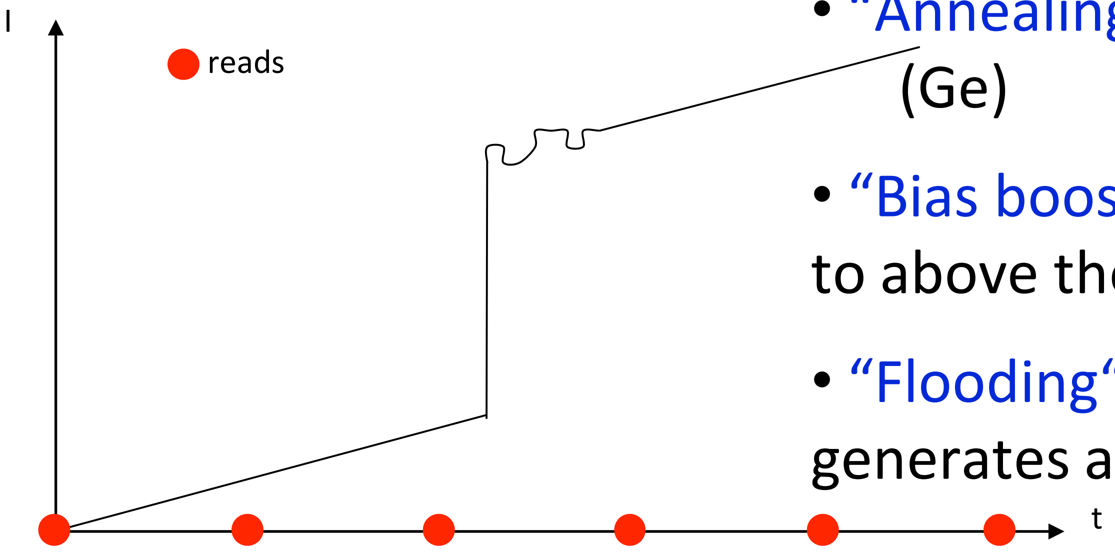


Example: The "light leak" in the Spitzer-MIPS 160 micron channel

Problem 4: Ionizing Radiation Effects

High energy particles create large numbers of free charge carriers (electron/hole pairs) in any solid state detector.

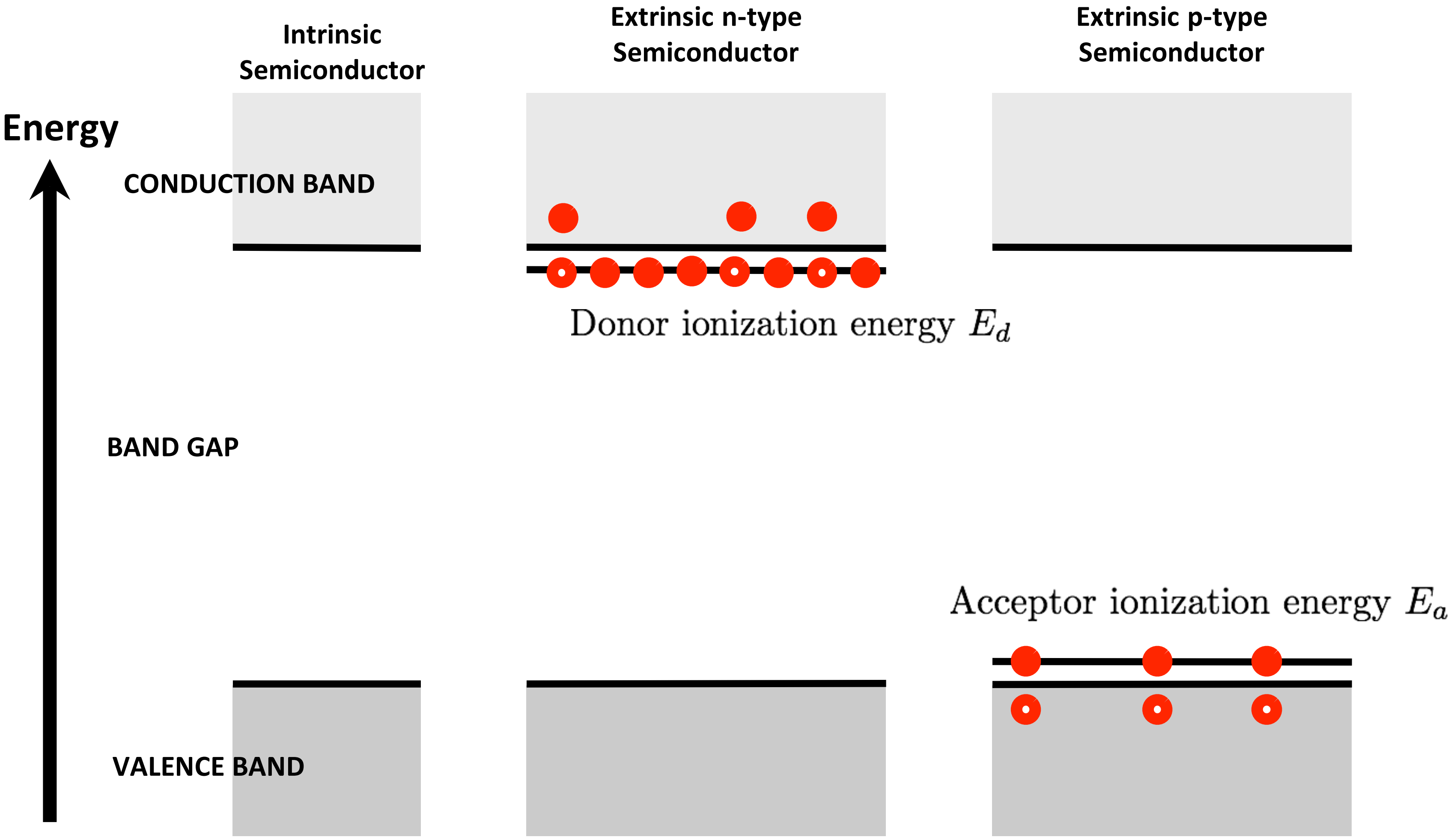
However, extrinsic photoconductors are larger and have a higher probability to get hit. In space they also operate at low backgrounds.



Mitigations *(see lecture #5)*:

- "Annealing": heat up to 20K (Si) or 6K (Ge)
- "Bias boost" – increase bias voltage to above the breakdown level
- "Flooding" the detector with light generates an avalanche of electrons

Problem 5: Dark Current at T > 0 K



Intrinsic Semiconductor

Extrinsic n-type Semiconductor

Extrinsic p-type Semiconductor

Energy

CONDUCTION BAND

Donor ionization energy E_d

BAND GAP

Acceptor ionization energy E_a

VALENCE BAND

BIB Detectors

Ways to improve the NEP

Remember: If $\langle I_J^2 \rangle >> \langle I_{G-R}^2 \rangle + \langle I_{1/f}^2 \rangle$, the detector performance is limited by its internal thermodynamic properties (Johnson noise).

Then: $\mathrm{NEP}_J = \dfrac{2hc}{Gq\eta\lambda}\left(\dfrac{kT}{R}\right)^{1/2}$

How can we improve the NEP? *(Remember: Smaller NEP is better)*

Several options:

- increasing R ⇔ doping levels
- higher QE
- higher G
- lower T

The NEP can be best improved by increasing the detector resistance

Conflicting Requirements

Efficient absorption requires large N_I (where $a(\lambda) = \sigma(\lambda) N_I$) which leads to large conductivity (and low R)

BUT

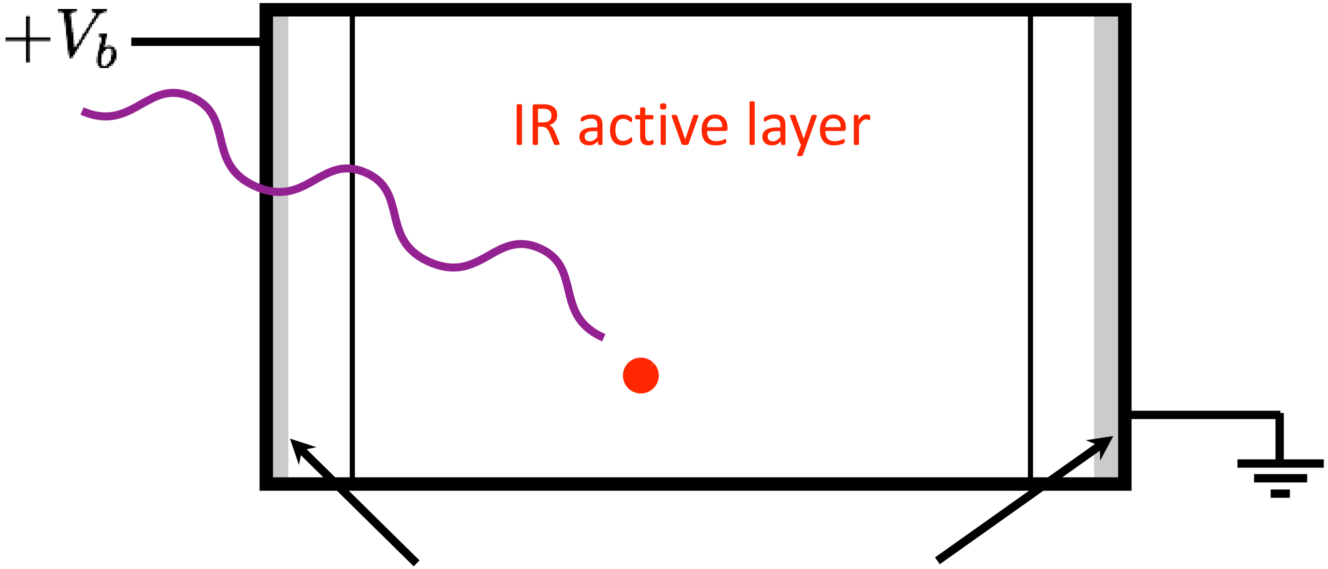
We want lower noise with higher resistance:

$$\mathrm{NEP}_J = \frac{2hc}{Gq\eta\lambda} \left(\frac{kT}{\enclose{circle}{R}} \right)^{1/2}$$

SOLUTION:

Use different layers in the detector to optimize for the electrical properties and the photodetection properties *independently.*

Blocked Impurity Band (BIB) Detectors



Blocking layer

Degenerate substrate

$+V_b$

IR active layer

Transparent electrical contacts

IR active layer is a heavily doped extrinsic semiconductor (e.g. Si:As or Si:Sb)

Blocking layer is a thin layer of high purity intrinsic semiconductor providing large electrical resistance

Degenerate substrate is very heavily doped, electrically conducting material

BIB Advantages

- If the IR layer is heavily doped (N_I is large) it can be relatively thin compared to extrinsic photoconductors → good for space (high ionizing environment)
- Longer cutoff wavelength due to the heavy doping
- Operates over a broader spectral range
- Lower impedances lead to reduced dielectric relaxation effects → faster response times
- The G-R noise is smaller by a factor of $\sqrt{2}$

In bulk photoconductors the recombination occurs in high resistance material and so you have both Generation and Recombination noise; In BIB detectors the recombination may only occur in the low resistance (=high conductivity =no recombination) material, so you only have noise from the Generation statistics.

Unstressed ⬄ Stressed ⬄ BIB

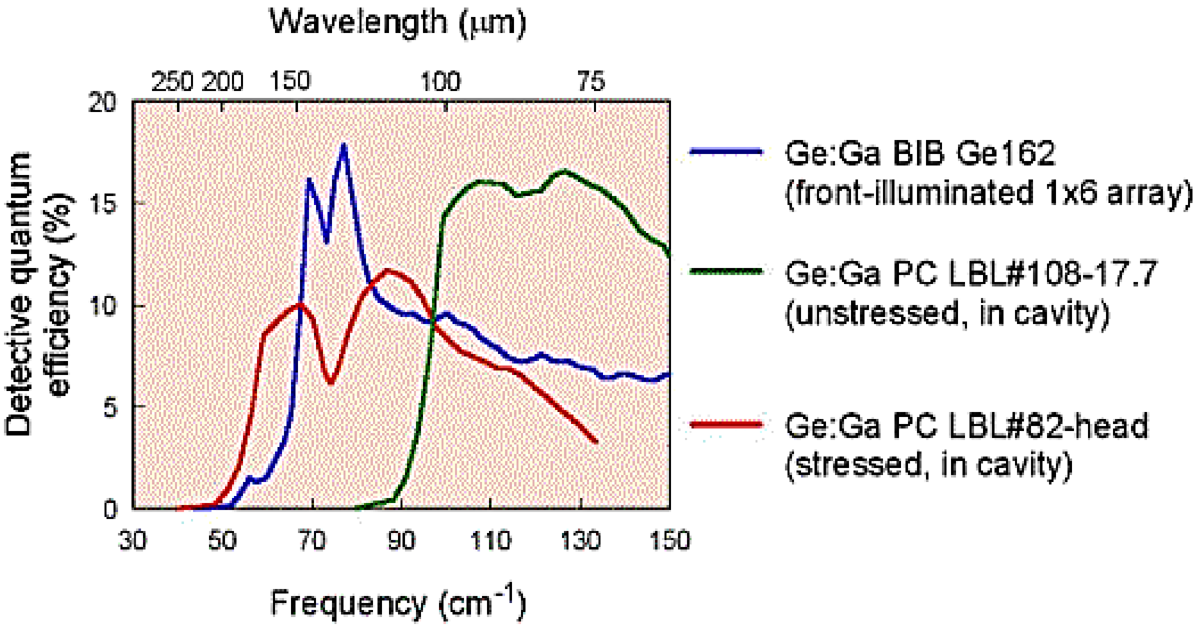


Figure 11. Comparison of Ge BIB and Conventional Photoconductors
(D. Watson)

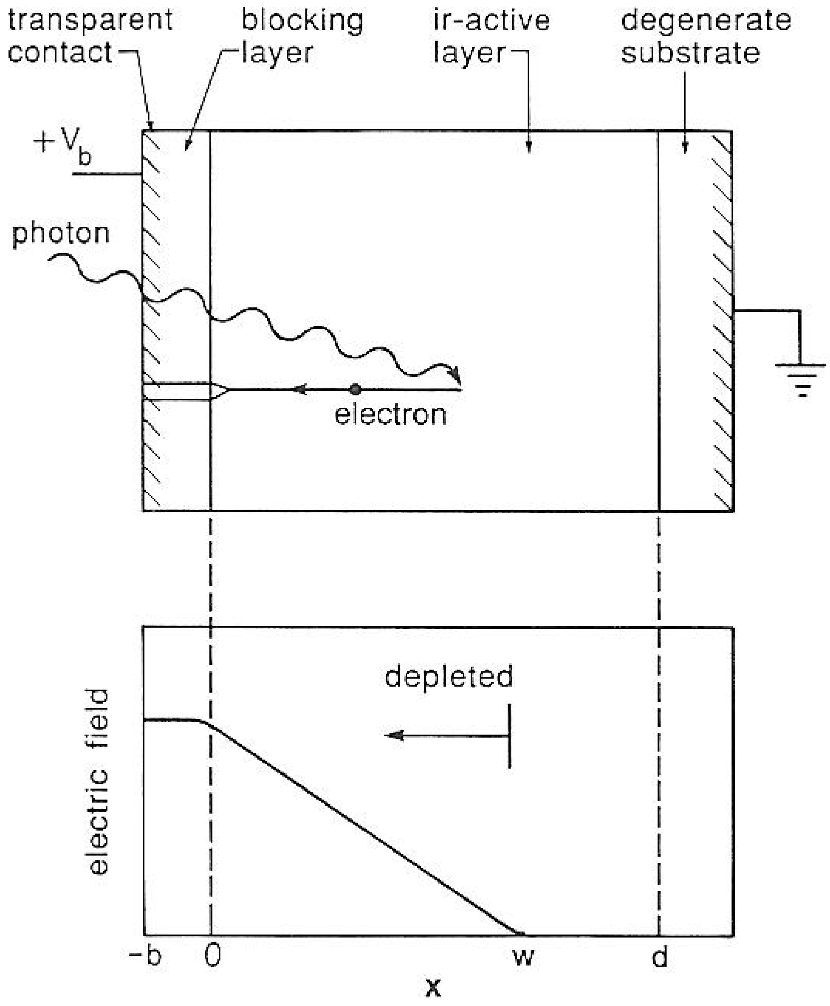
Quantum Efficiency and Bias Voltage

To drive electrons from the IR active layer to the electrodes, we need an electric field with voltage V_b.

IR layer is low R, blocking layer is high R → most of the electric field is across the blocking layer.

A depletion layer forms in the IR active layer as electrons from the n-type dopant follow the electric field.

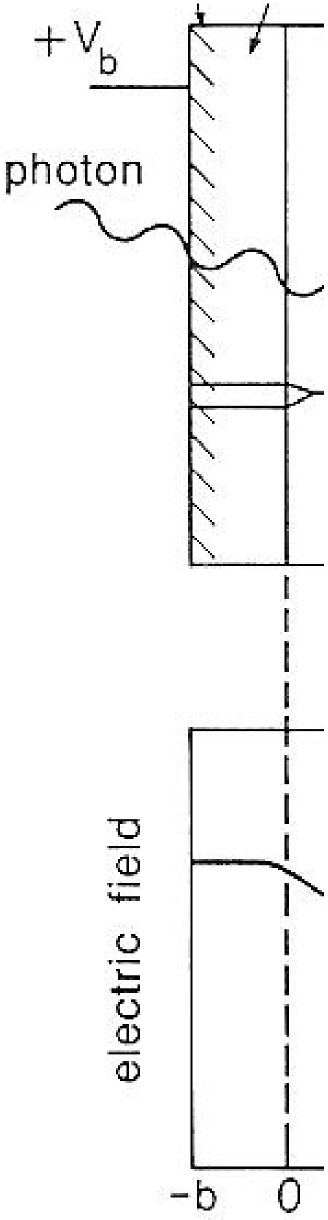
The applied voltage determines the width of the depletion layer (and hence the quantum efficiency of the detector)



Avalanche Effects in BIBs

- High E field in the blocking layer means that we can accelerate electrons to create secondary electrons → Avalanche effect.
- Carefully tuning the bias voltage leads to G > 1
- BIB detectors are usually operated at G of 5 – 50 to overcome amplifier noise
- But we get additional noise because of statistics of avalanche generation:
- The quantum efficiency is reduced by a factor $\beta = \dfrac{\langle G^2 \rangle}{\langle G \rangle^2}$
- The G-R noise is only G noise and is thus renamed 'shot' noise:

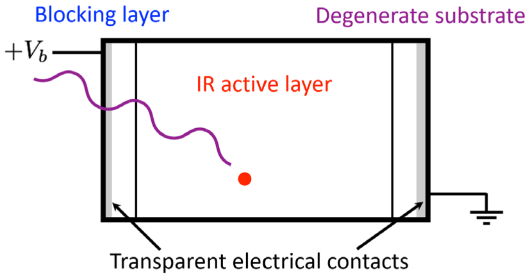
$$\langle I^2_{shot} \rangle = 2q^2 \varphi \frac{\eta}{\beta} (\beta G)^2 \Delta f$$

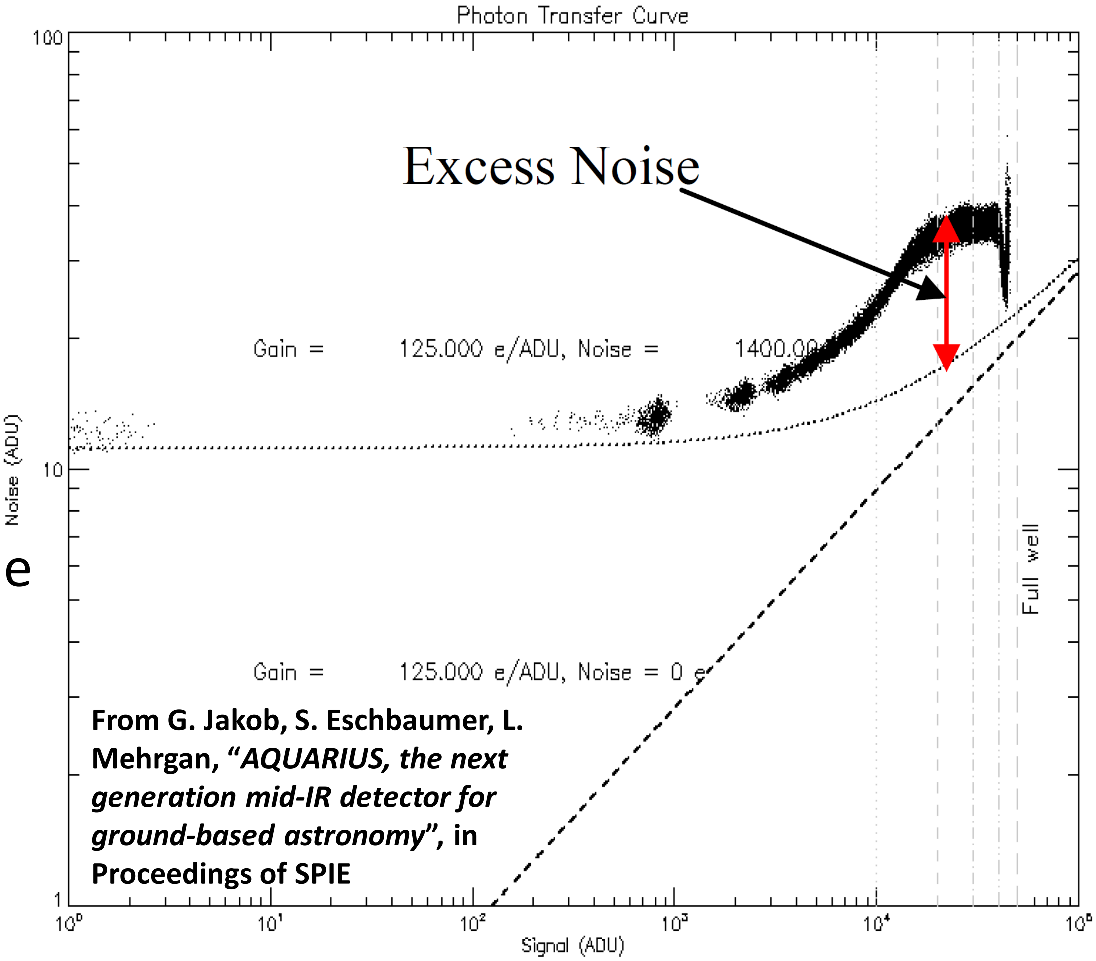


Example: The Raytheon Aquarius Detector

The Aquarius is a Si:As BIB detector, which was designed for space (JWST-MIRI) and adopted to high-flux ground-based applications

Unfortunately, it suffers from excess low frequency noise due to a too thick blocking layer





From G. Jakob, S. Eschbaumer, L. Mehrgan, *"AQUARIUS, the next generation mid-IR detector for ground-based astronomy"*, in Proceedings of SPIE

Photodiodes

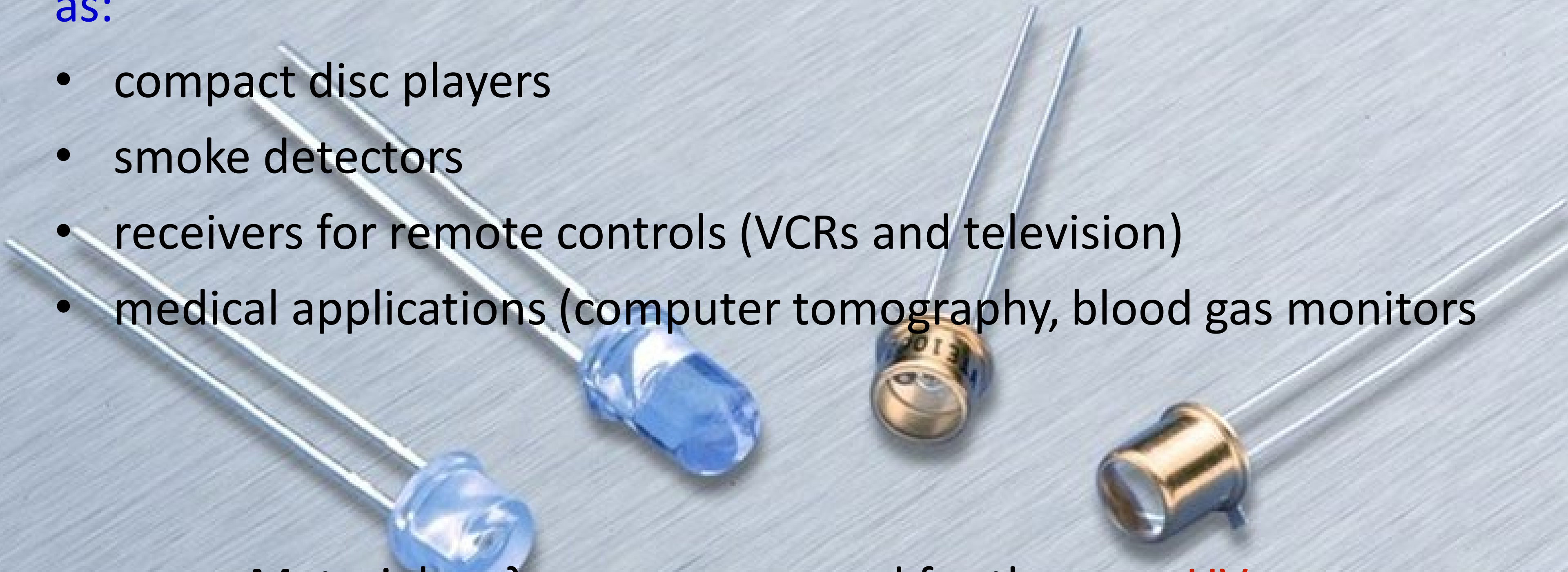
!!! WARNING !!! (to avoid confusion:)

Photodiodes work through intrinsic absorption. They are discussed in *this* lecture because they require doped materials to work.

Side note: Photodiodes as Emitters

From Wikipedia:

Photodiodes are heavily used in consumer electronics devices such as:



- compact disc players
- smoke detectors
- receivers for remote controls (VCRs and television)
- medical applications (computer tomography, blood gas monitors

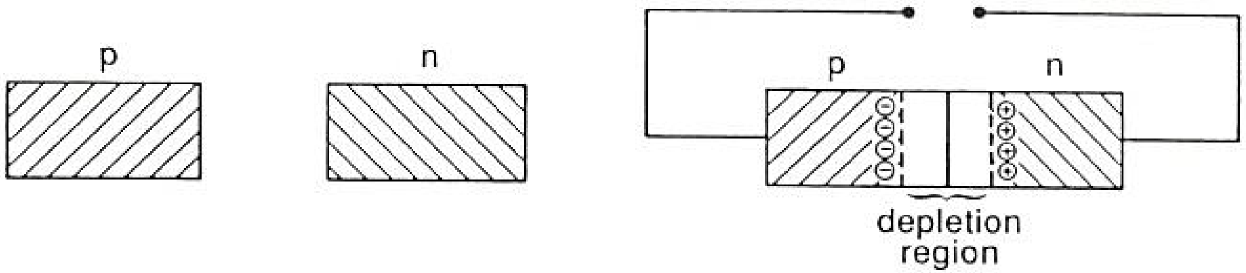
Material	~λ_{cutoff}
GaInAs	1.7 µm
Ge	1.8 µm
InAs	3.4 µm
InSb	6.8 µm

…and for the near-UV:

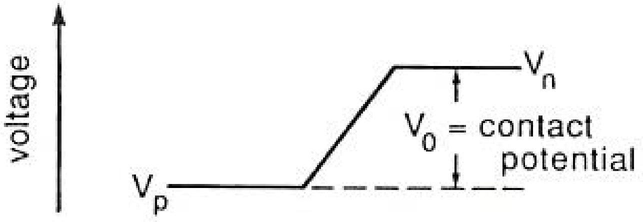
GaP	0.52 µm
GaN	0.37 µm
$Al_xGa_{1-x}N$	0.2 ... 0.37 µm

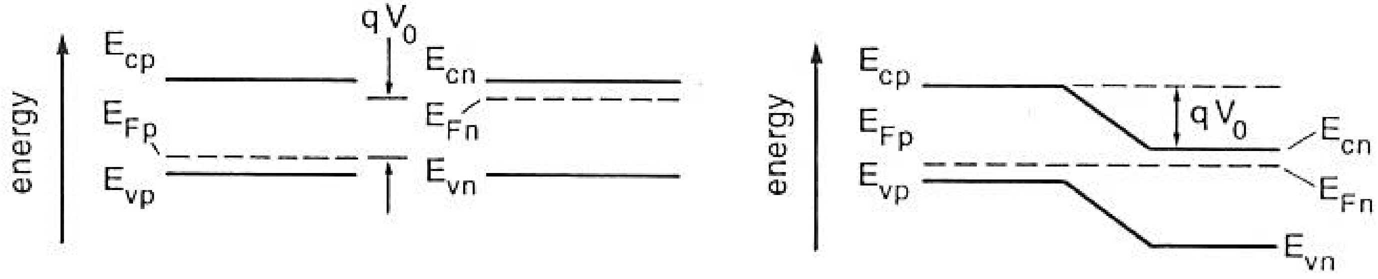
General Principle of a Photodiode

Bringing a p-type and n-type semiconductor together ("p-n junction") creates a depletion region with high R.



Fermi energy levels get equalized, moving the band structures with respect to each other



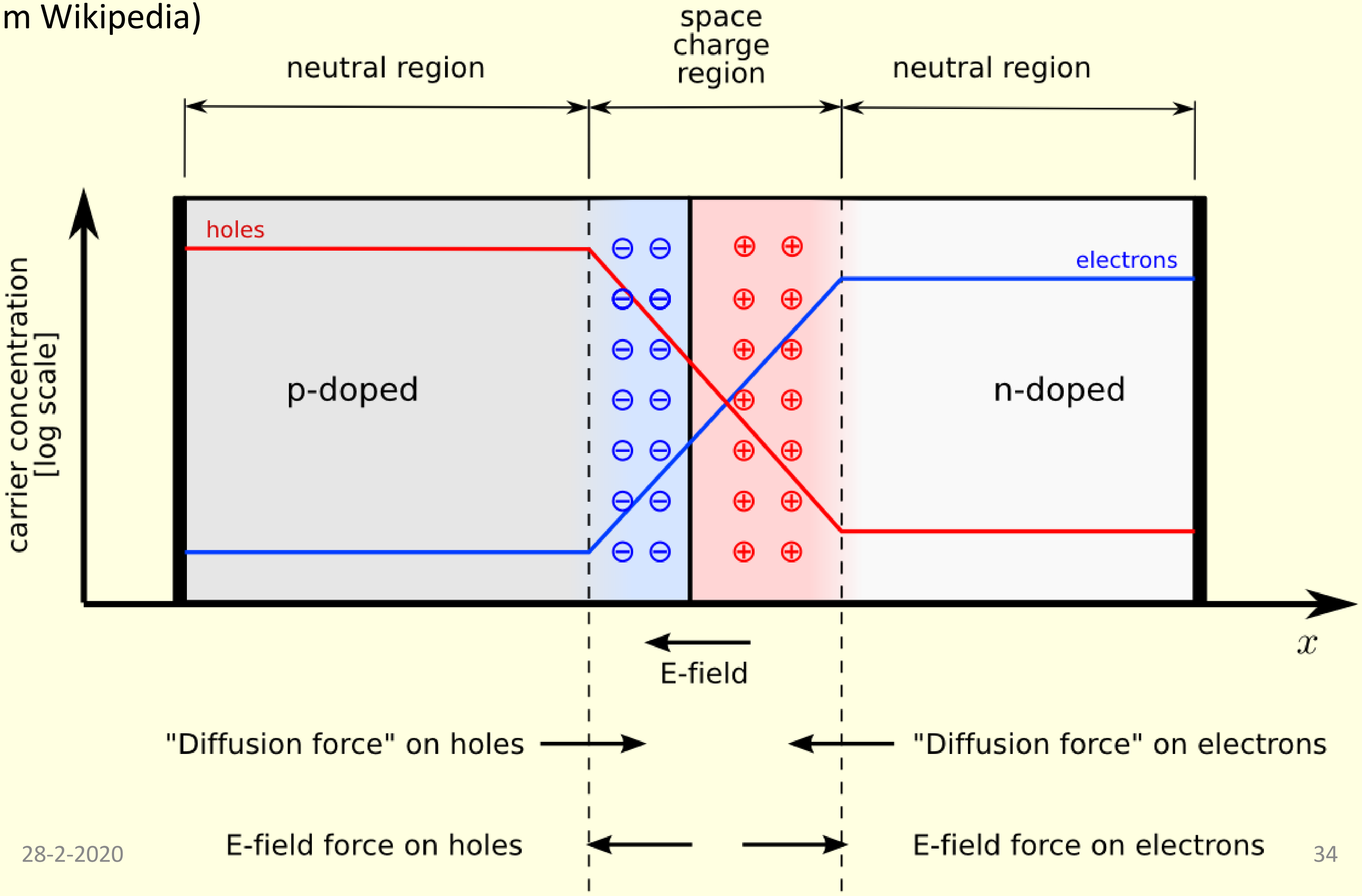


(a) before contact

(b) after contact

General Principle of a Photodiode (2)

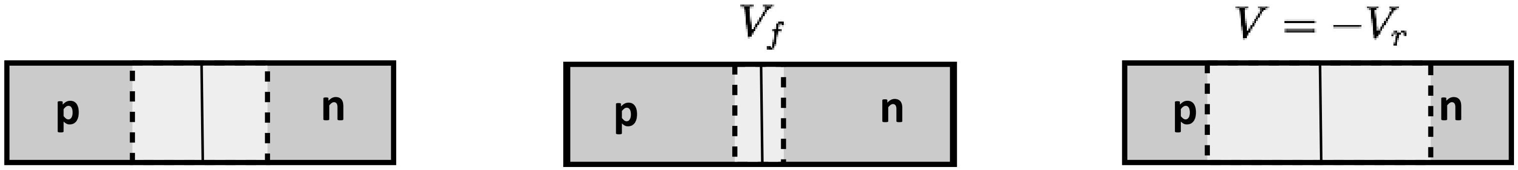
(from Wikipedia)



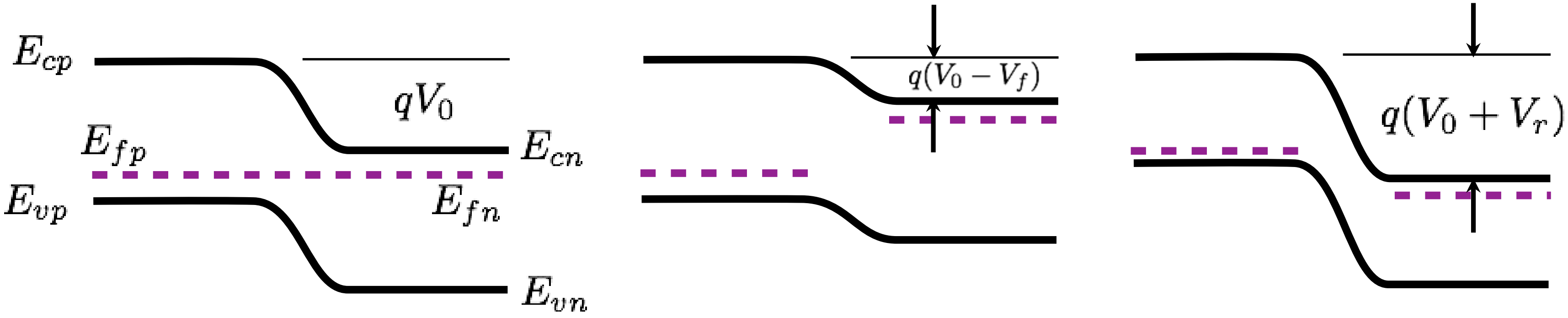
The Effect of an applied Bias Voltage

The bias voltage dramatically changes the behavior of the p-n junction:

Equilibrium **Forward bias** **Reverse bias**

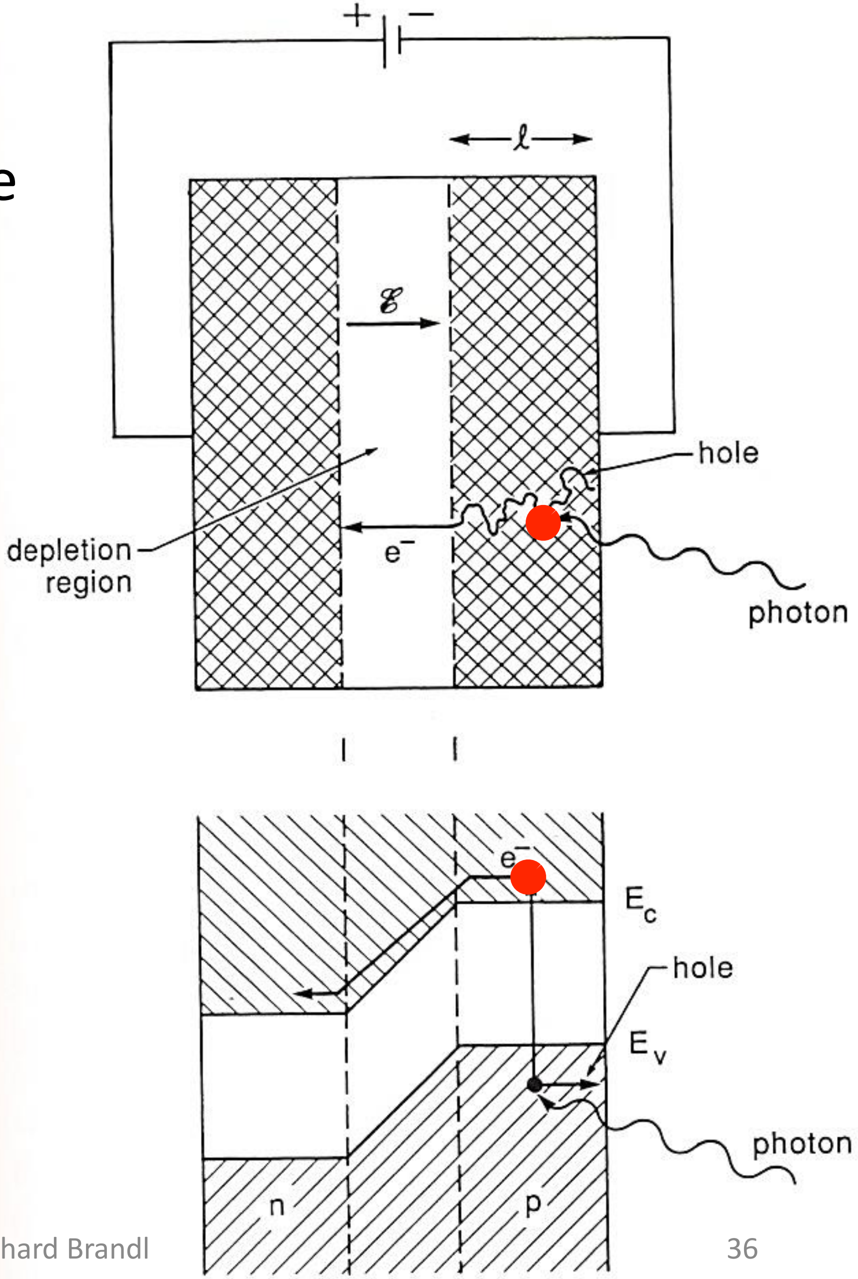


The depletion region increases in size and the resistance increases.



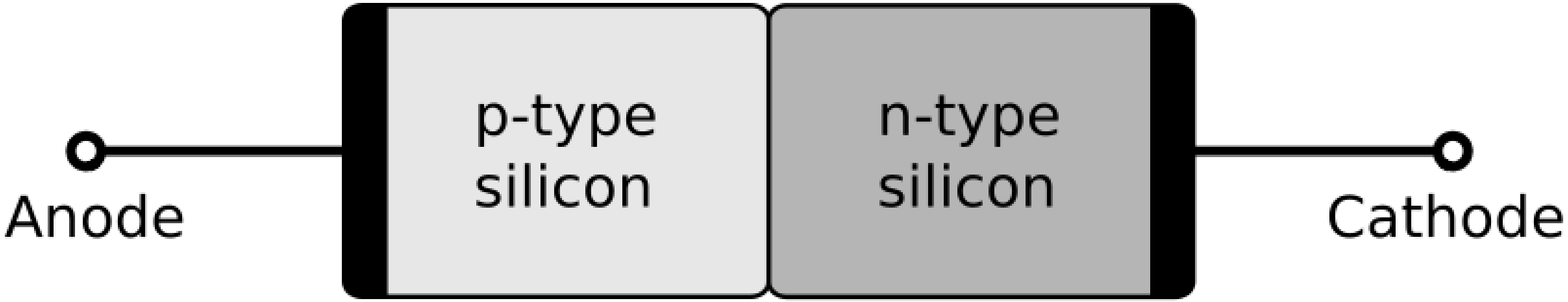
Photoexcitation in Photodiodes

- Photon is typically absorbed in the doped part and creates an electron-hole pair (intrinsic photoconductor).
- All photo-generated e^- diffuse through the material to reach the junction.
- The voltage drives the e^- across the depletion region and is measured as a photo-current.



Keep in mind!

Photodiodes are based on a p-n junction: a p-type doped semiconductor attached to an n-type (of the same material):

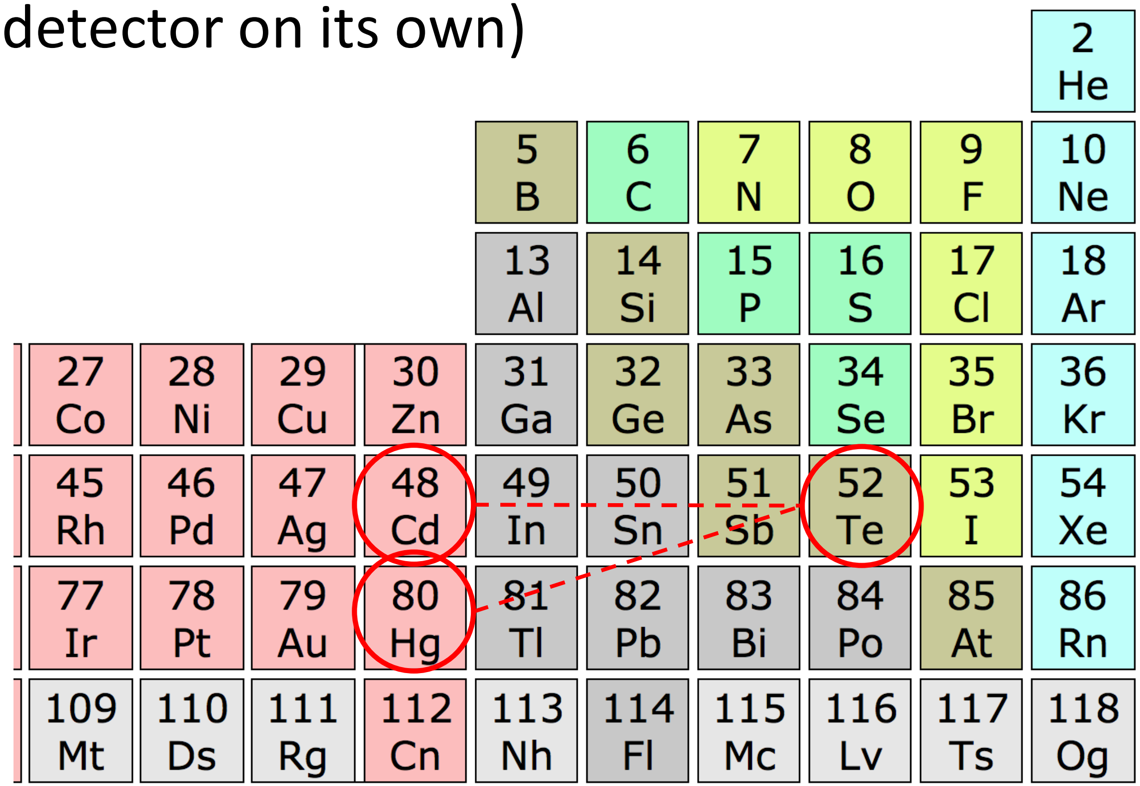


The doping is done to create a p-n junction = high resistance = good electrical properties = low noise!

The material itself is that of an intrinsic semiconductor = high QE

The Magic of $Hg_{1-X}Cd_XTe$

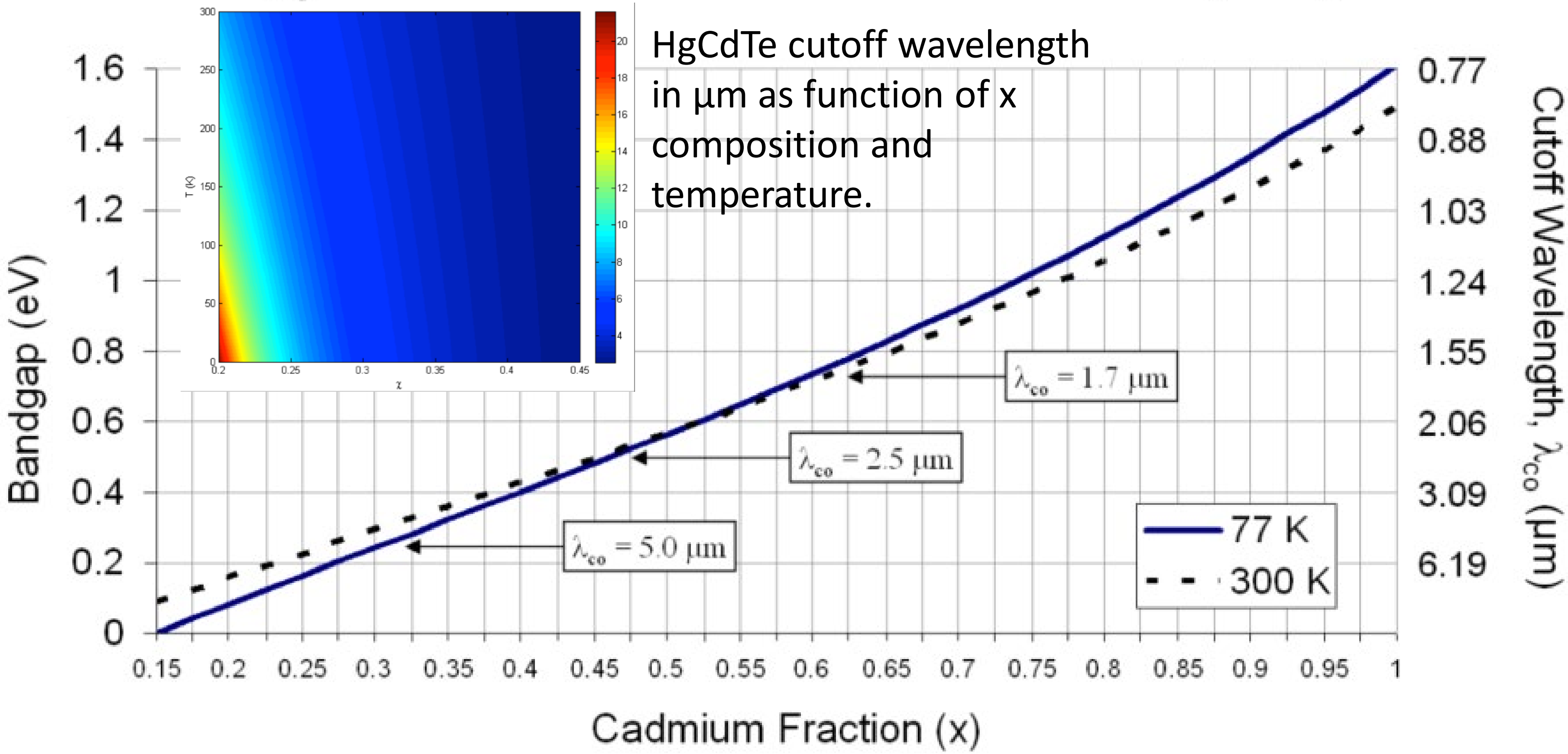
- $Hg_{1-X}Cd_XTe$ is a mixture of CdTe and HgTe
- CdTe is a semiconductor with a bandgap of 1.5eV
- HgTe is a semimetal (extremely small bandgap, not useful as a photon detector on its own)



									2 He
				5 B	6 C	7 N	8 O	9 F	10 Ne
				13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Wavelength Range of HgCdTe

$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35\times10^{-4}\,T(1-2x)$$



HgCdTe cutoff wavelength in µm as function of x composition and temperature.

Fig. 3: Bandgap and cutoff wavelength of $Hg_{1-x}Cd_xTe$ as a function of the cadmium fraction, x.

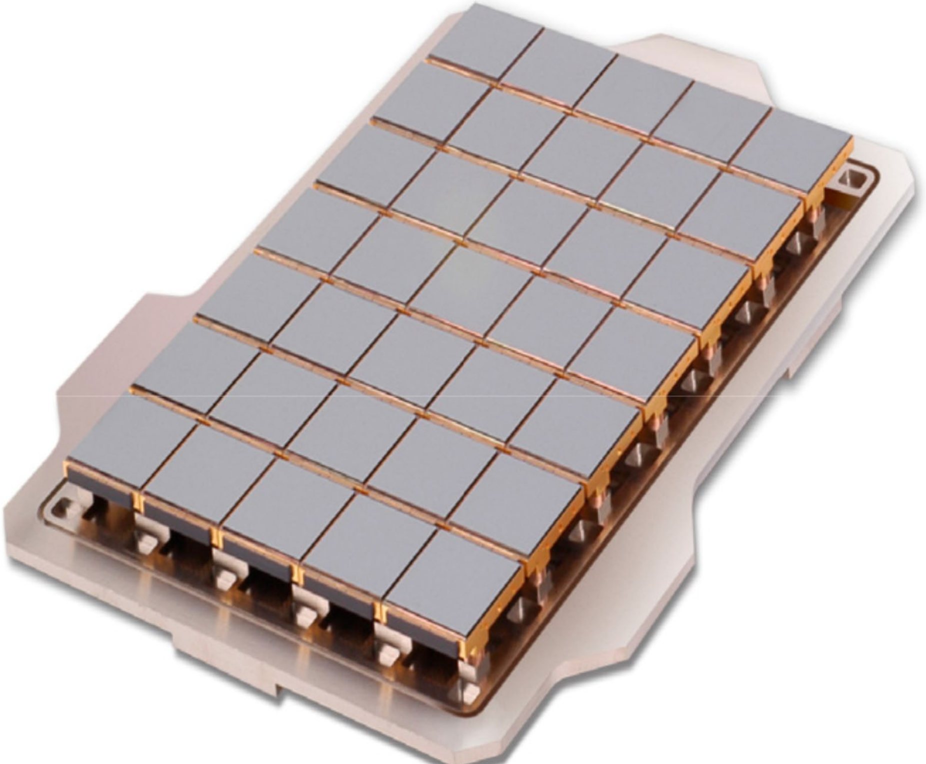
© J.W. Beletic et al., Teledyne Imaging Sensors

HgCdTe as Photodiode

To make it a photodiode, the HgCdTe still needs to be doped:

- n-type: typically In at 5×10^{14} cm^{-3}
- p-type: typically As at 5×10^{15} cm^{-3}

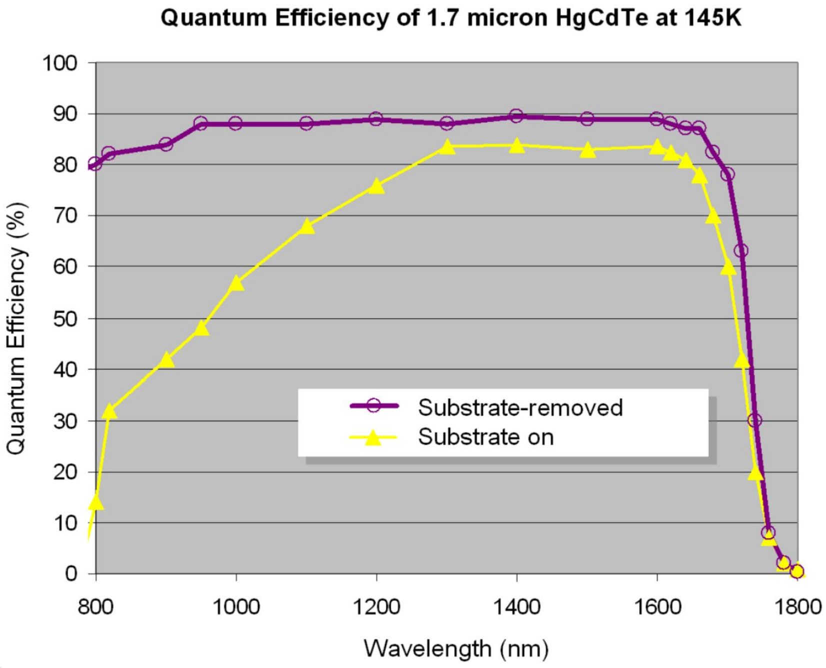
HgCdTe (or “MCT”) photodiodes have become the most popular choice for astronomical detectors in the 1 – 5 µm range



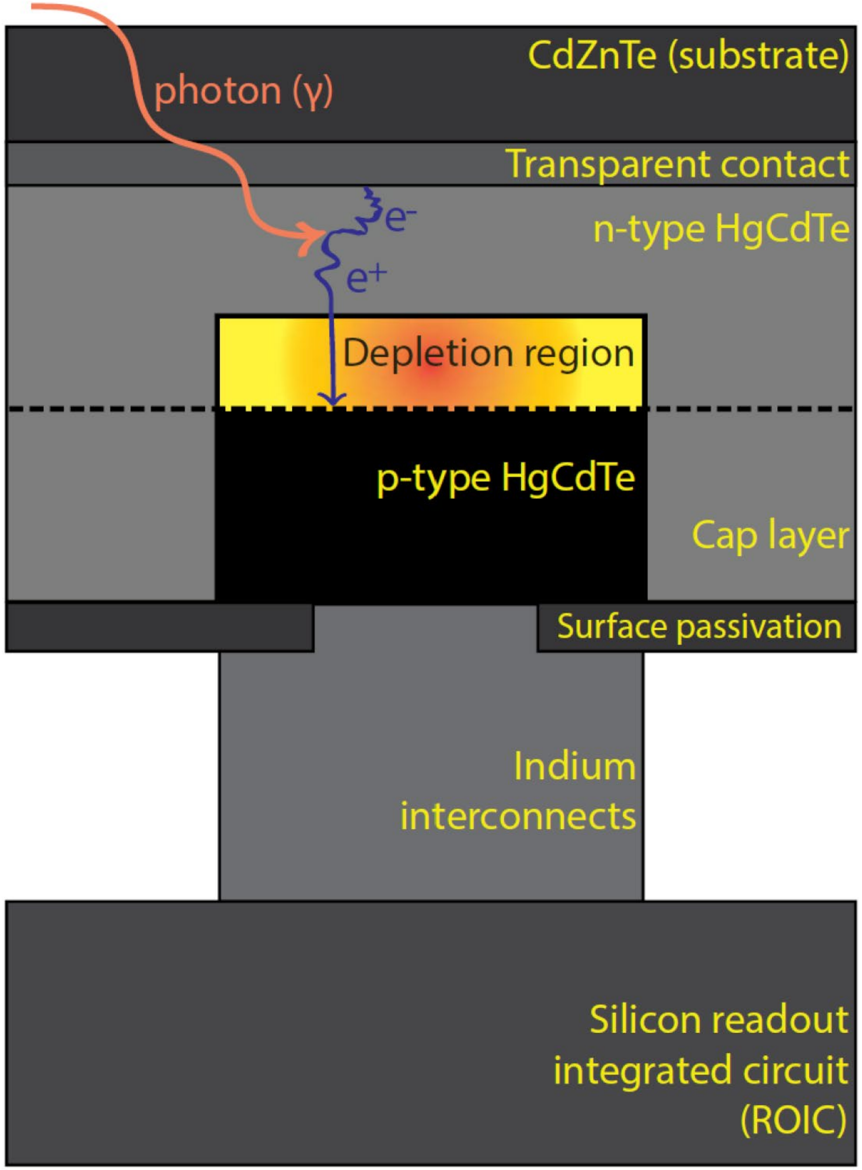
5×7 mosaic of H2RGs (engineering model)

Cut through a HgCdTe Pixel

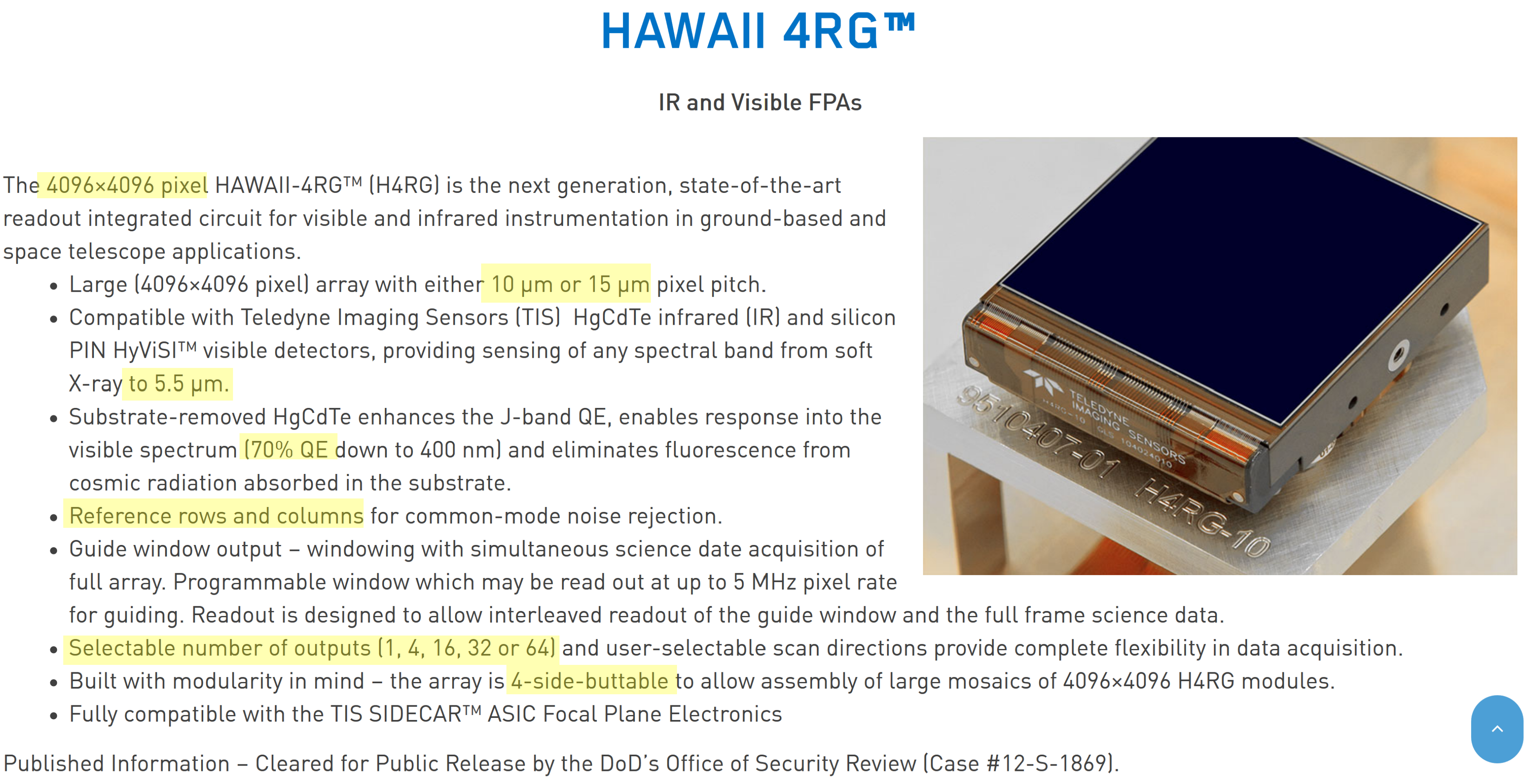
From AA Plazas, C Shapiro, R Smith, J Rhodes, and E Huff. *Nonlinearity and pixel shifting effects in HXRG infrared detectors*. Journal of Instrumentation, 12(04):C04009, 2017.



From Paul Jerram & James Beletic, *"Teledyne's High Performance Infrared Detectors for Space Missions"*c



The HAWAII-4RG from Teledyne Imaging Systems



HAWAII 4RG™

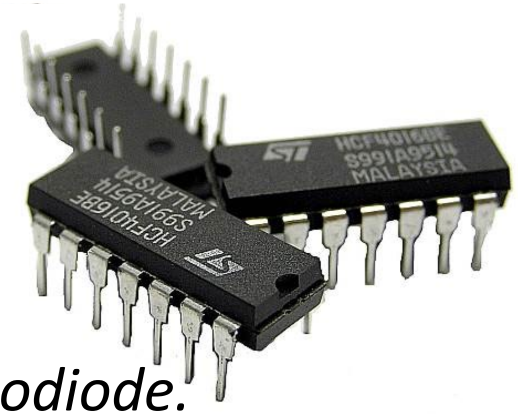
IR and Visible FPAs

The 4096×4096 pixel HAWAII-4RG™ (H4RG) is the next generation, state-of-the-art readout integrated circuit for visible and infrared instrumentation in ground-based and space telescope applications.

- Large (4096×4096 pixel) array with either 10 µm or 15 µm pixel pitch.
- Compatible with Teledyne Imaging Sensors (TIS) HgCdTe infrared (IR) and silicon PIN HyViSI™ visible detectors, providing sensing of any spectral band from soft X-ray to 5.5 µm.
- Substrate-removed HgCdTe enhances the J-band QE, enables response into the visible spectrum (70% QE down to 400 nm) and eliminates fluorescence from cosmic radiation absorbed in the substrate.
- Reference rows and columns for common-mode noise rejection.
- Guide window output – windowing with simultaneous science date acquisition of full array. Programmable window which may be read out at up to 5 MHz pixel rate for guiding. Readout is designed to allow interleaved readout of the guide window and the full frame science data.
- Selectable number of outputs (1, 4, 16, 32 or 64) and user-selectable scan directions provide complete flexibility in data acquisition.
- Built with modularity in mind – the array is 4-side-buttable to allow assembly of large mosaics of 4096×4096 H4RG modules.
- Fully compatible with the TIS SIDECAR™ ASIC Focal Plane Electronics

Published Information – Cleared for Public Release by the DoD's Office of Security Review (Case #12-S-1869).

Side note: p-n junctions as unwanted detectors



From Wikipedia:

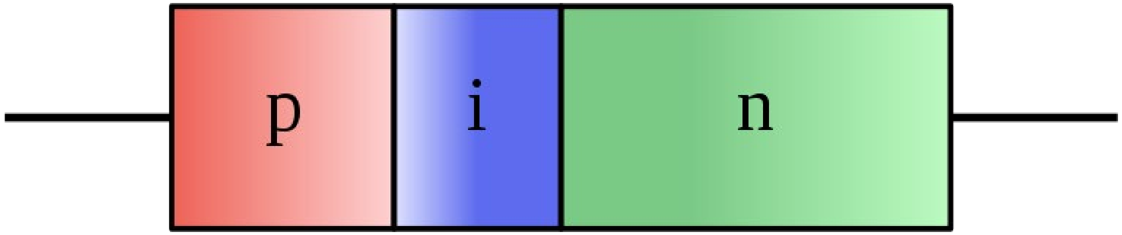
"Unwanted photodiode effects

Any p–n junction, if illuminated, is potentially a photodiode. Semiconductor devices such as diodes, transistors and ICs contain p–n junctions, and ***will not function correctly if they are illuminated by unwanted electromagnetic radiation (light)*** *of wavelength suitable to produce a photocurrent; this is avoided by encapsulating devices in opaque housings."*

PIN Diodes

from Wikipedia:

A PIN diode is a p-n photodiode with an *additional* intermediate region of intrinsic material to increase the charge storage capacity:



As a photodetector, the PIN diode is reverse-biased. The diode ordinarily does not conduct (save a small dark current or I_s leakage). When a photon of sufficient energy enters the depletion region of the diode, it creates an electron, hole pair. The reverse bias field sweeps the carriers out of the region creating a current. Some detectors can use avalanche multiplication.

A PIN photodiode can also detect X-ray and gamma ray photons.