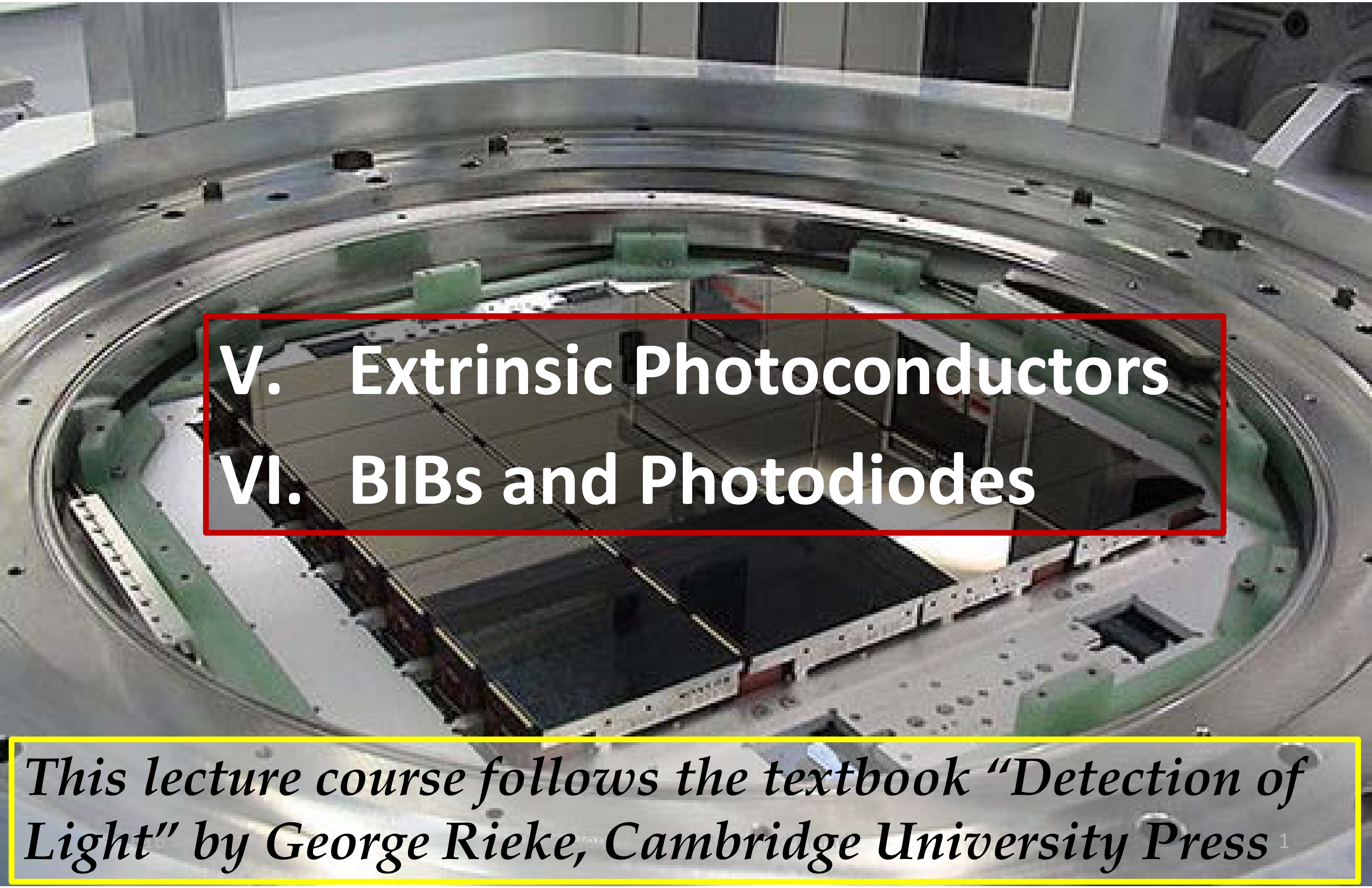
Detection of Light



V. Extrinsic Photoconductors
VI. BIBs and Photodiodes

This lecture course follows the textbook "Detection of Light" by George Rieke, Cambridge University Press

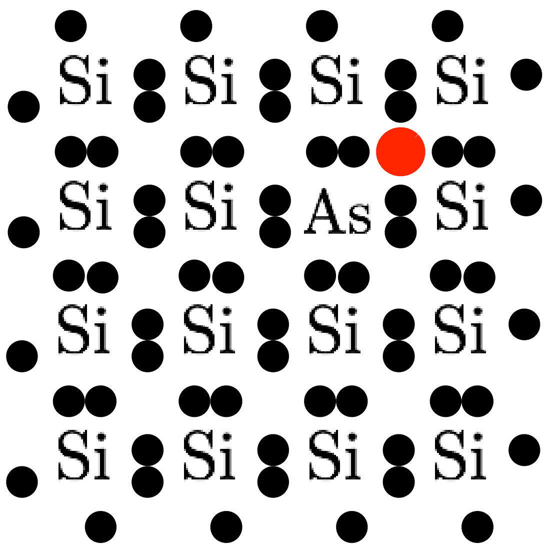
Doping and resulting Bandgaps

What can we do to reduce the Bandgap?

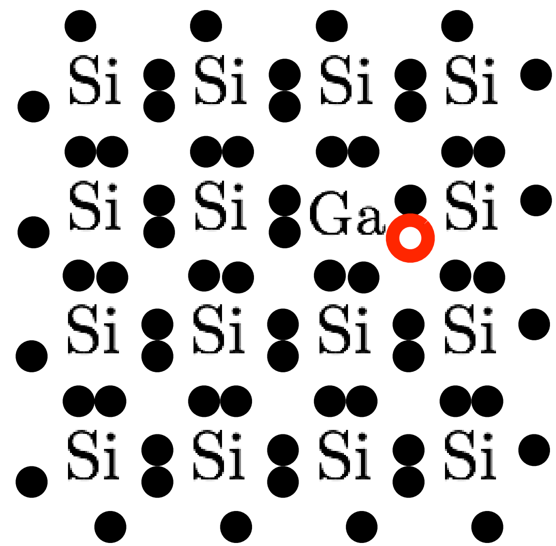
Goal: smaller bandgap = lower excitation energy = detection of lower energies = detection of longer wavelengths photons

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

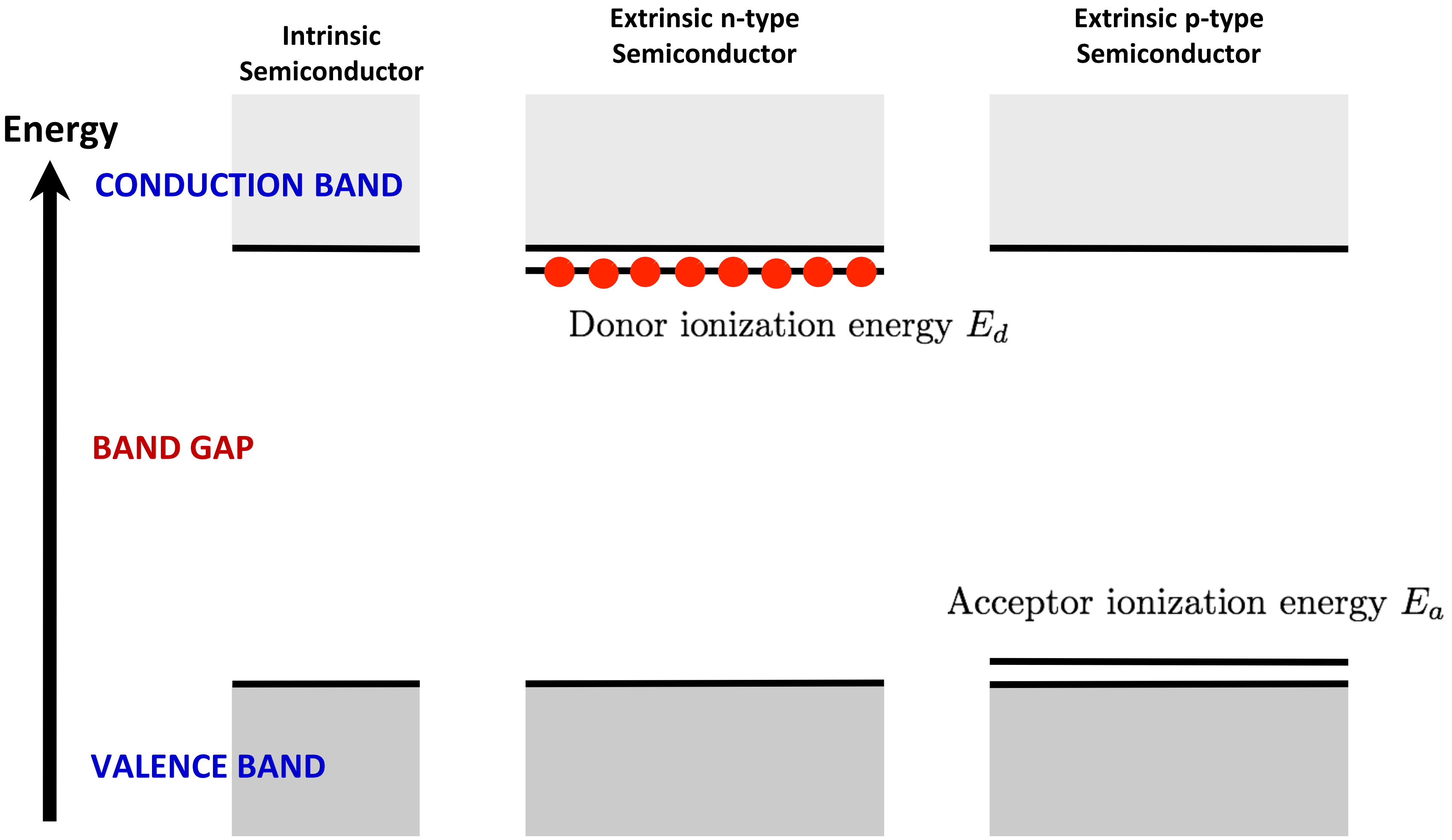
Adding a Group V element ("donor") adds conduction electrons → n-type Si



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

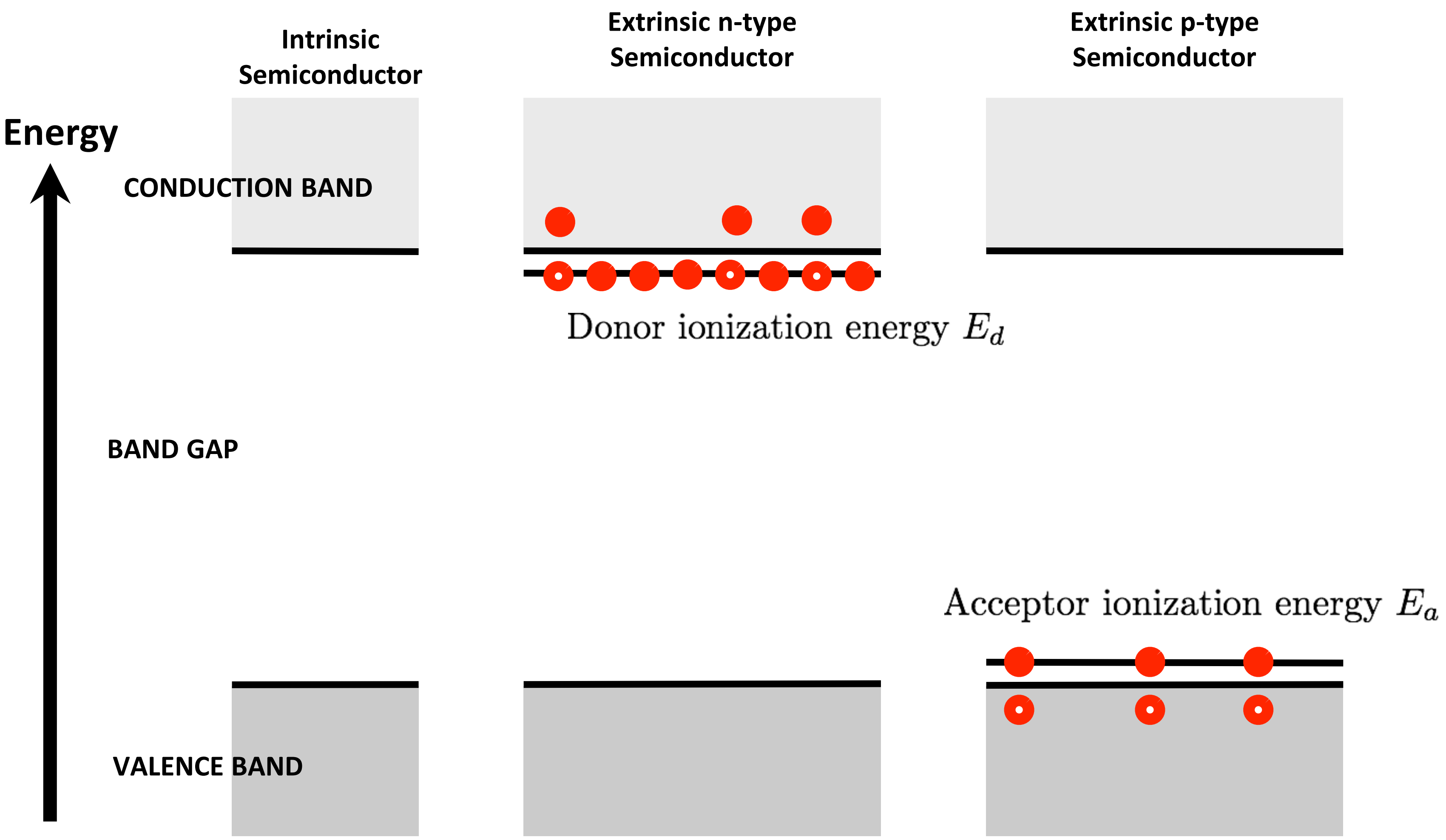


Energy Bandgaps at T = 0 K



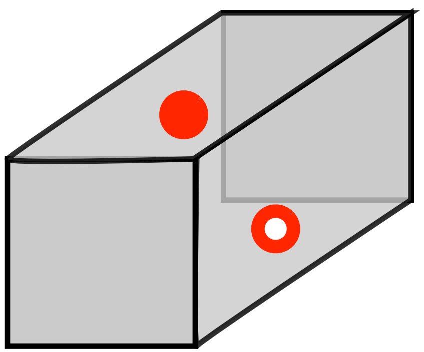
Note: pure semiconductors are called intrinsic, doped semiconductors are called extrinsic.

Energy Bandgaps at T > 0 K

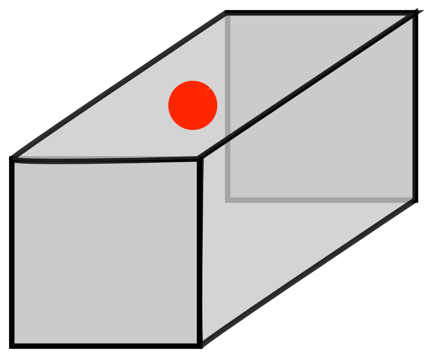


Intrinsic versus extrinsic Carrier Release

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



Intrinsic semiconductor releases an electron and a hole



Extrinsic semiconductor releases ONLY ONE free charge carrier

Properties of Extrinsic Photoconductors

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 = 300K, kT ~ 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

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

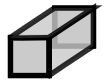
Absorption Coefficients and QE

The absorption coefficient for extrinsic photoconductors is:

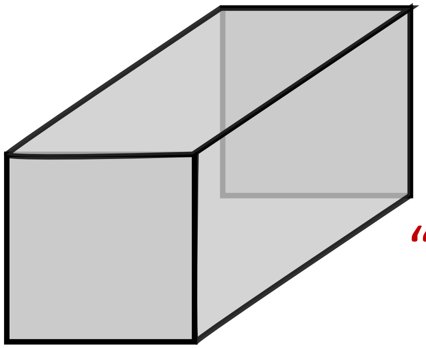
$$a(\lambda) = \sigma_i(\lambda) N_I$$

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

With typical 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.



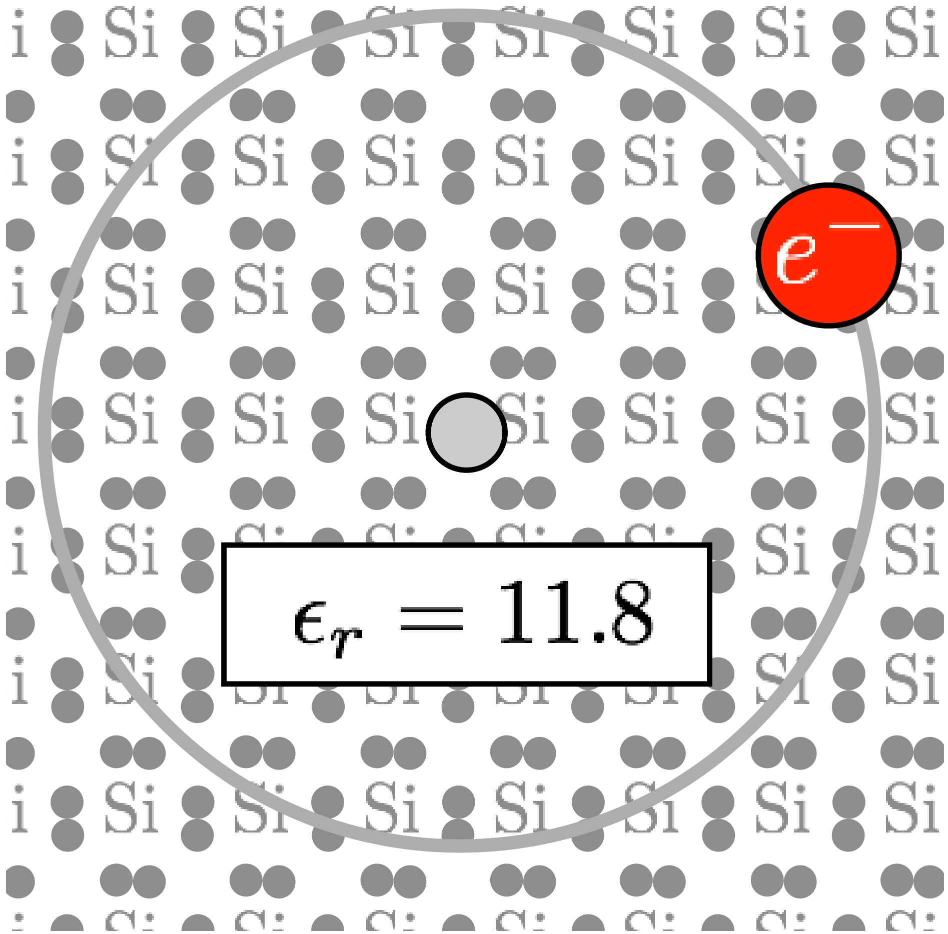
Intrinsic detector



Extrinsic detector

"Bulk Photo-conductor"

Why is a donor easily ionised?



NEP can be improved by increasing the detector resistance

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

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

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

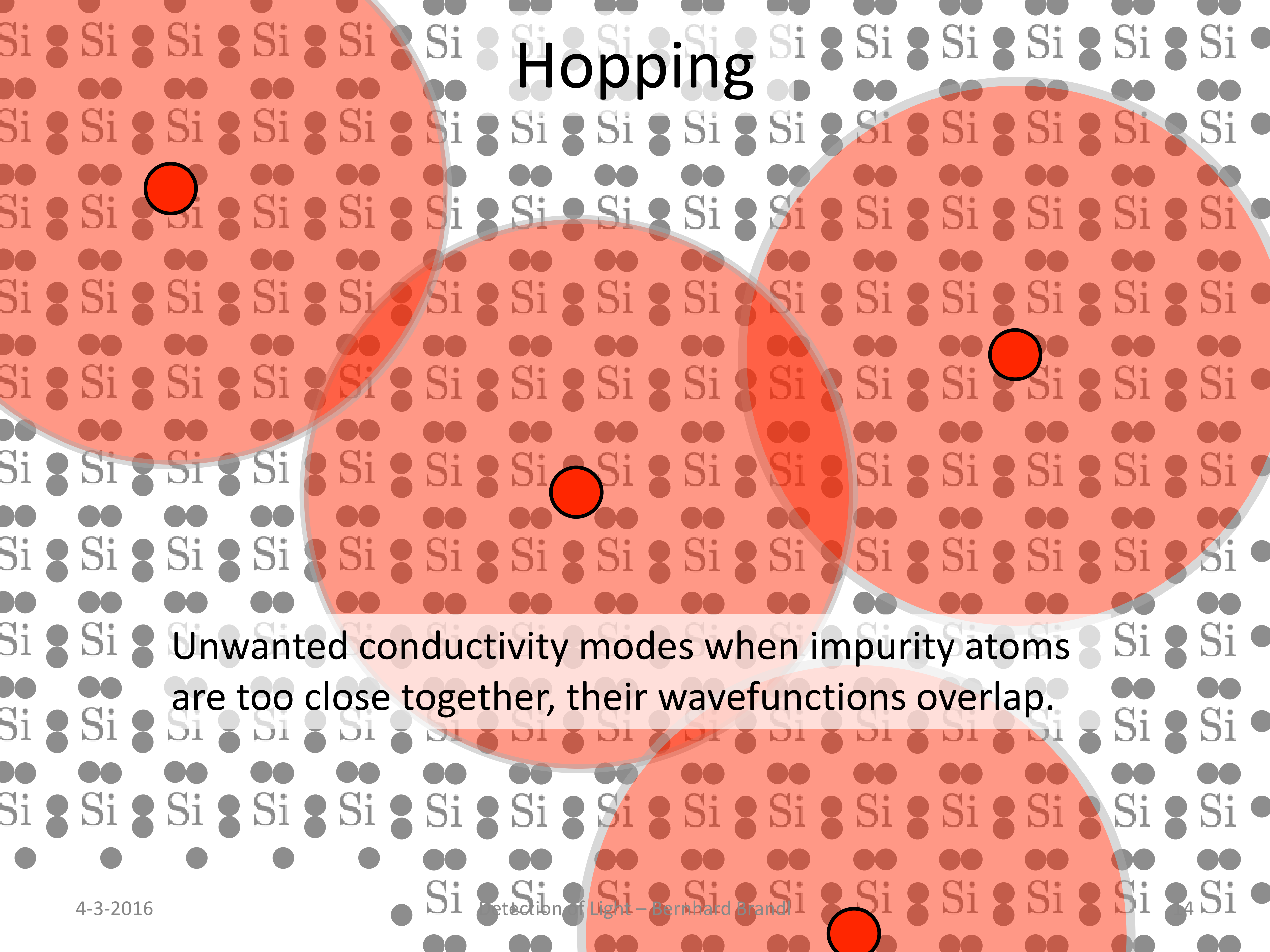
Several options:

- increasing R
- higher QE
- higher G
- lower T

The NEP can be best improved by increasing the detector resistance

Artifacts and Problems of Extrinsic Detectors

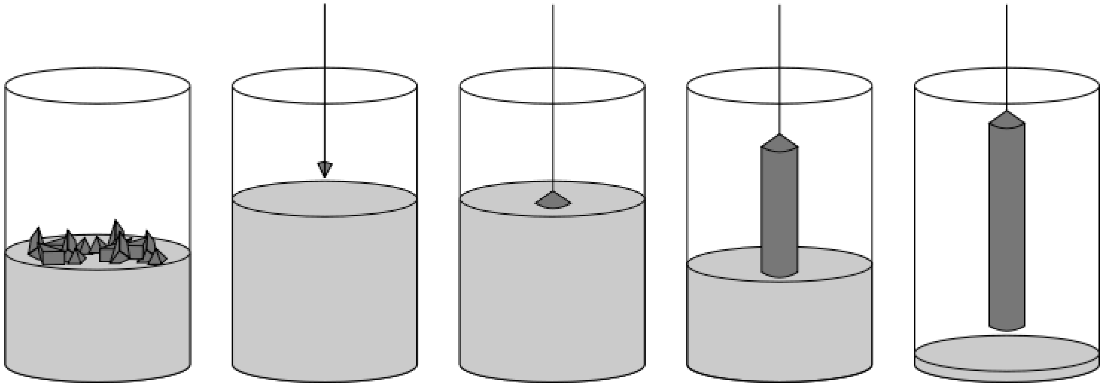
Hopping



Unwanted conductivity modes when impurity atoms are too close together, their wavefunctions overlap.

Growing Crystals

Silicon crystal drawn using the using Czochralski Process

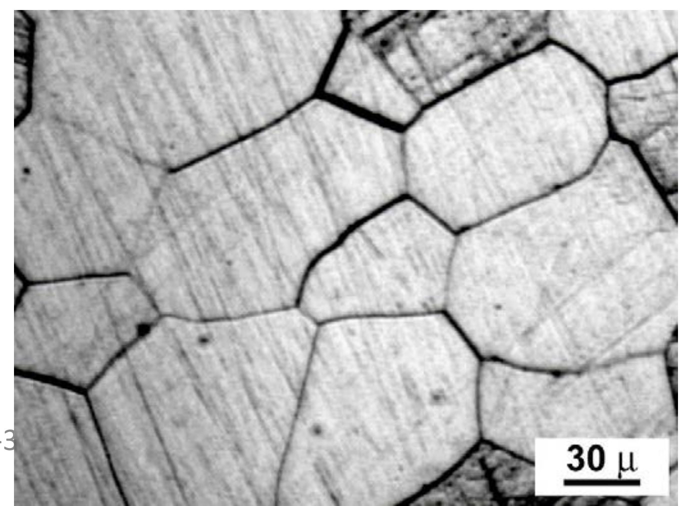


from Wikipedia

See movie at:

http://www.youtube.com/watch?v=cYj_vqcyI78

2m long, about 200kg



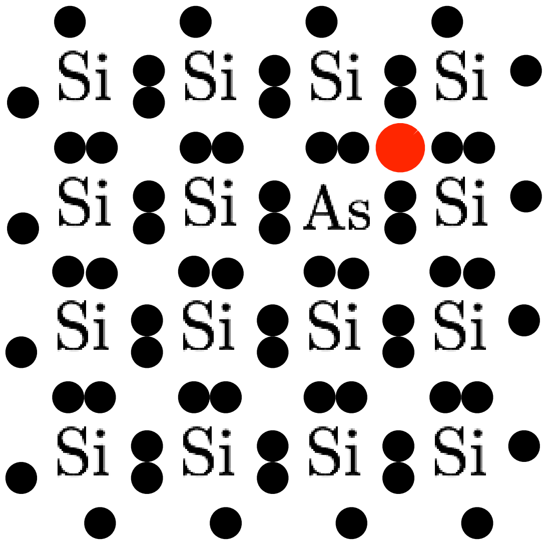
Grain Boundaries

No clean room process is perfect! Oxygen is introduced from dissolved quartz in the heating bowl. Unwanted Boron atoms are present in Silicon at 10^{-13} cm^{-3}.

Intrinsic Absorption in Extrinsic Semiconductors

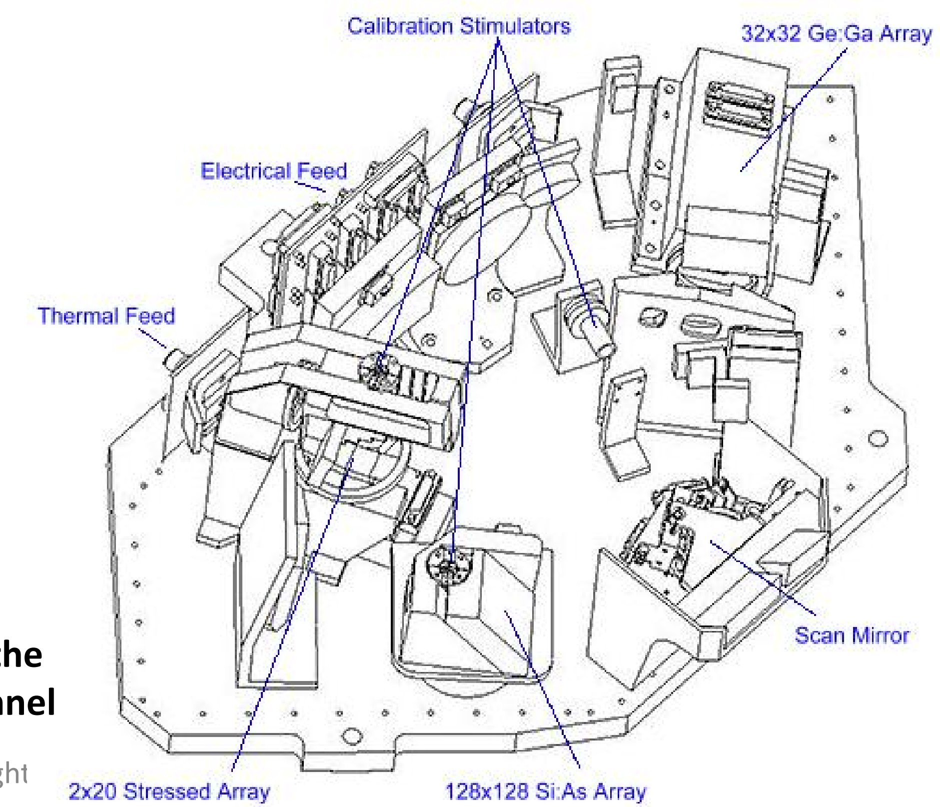
Even though the dopant:intrinsic ratio is typically 1:10000, you MUST USE a filter to make sure intrinsic energy photons don't hit your detector!

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



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

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



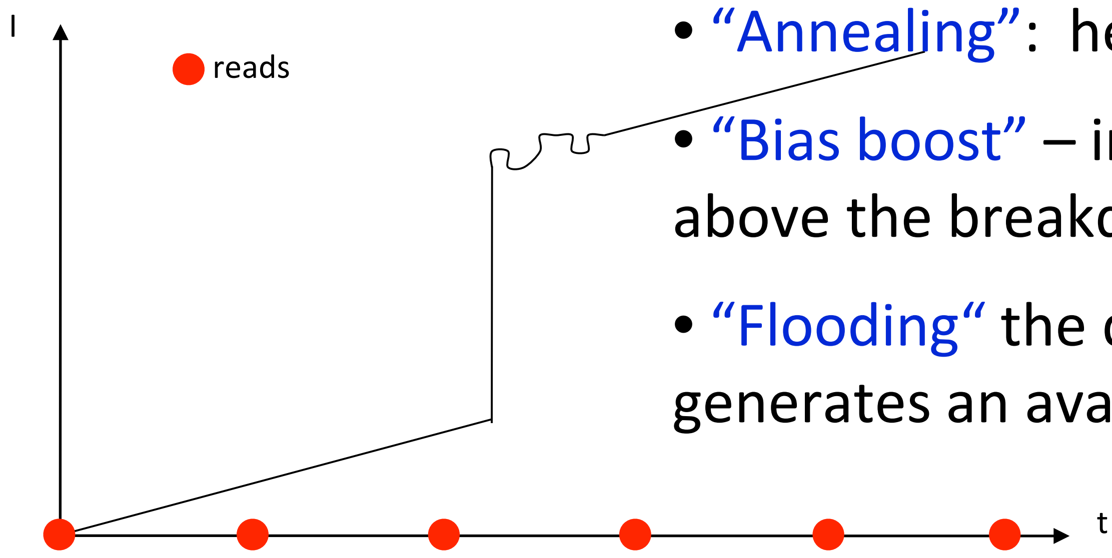
Ionizing Radiation Effects (in Space)

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

However, extrinsic photoconductors are larger (higher probability to get hit) and operate at low backgrounds.

Mitigations *(see lecture #5)*:

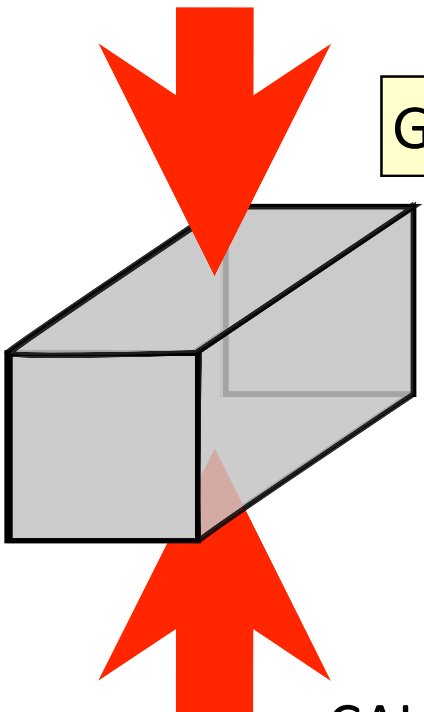
- "Annealing": heat up to 20K (Si) or 6K (Ge)
- "Bias boost" – increase bias voltage to above the breakdown level
- "Flooding" the detector with light generates an avalanche of electrons



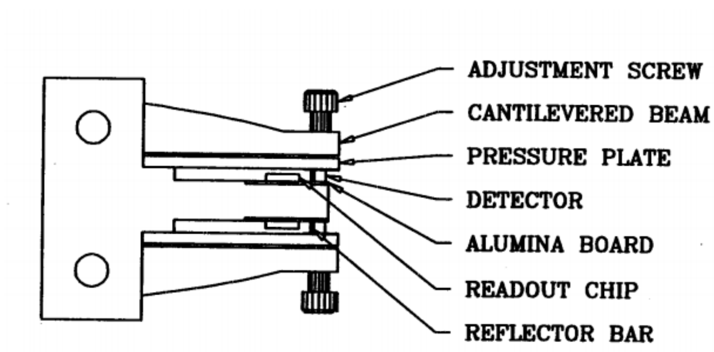
Stressed Detectors

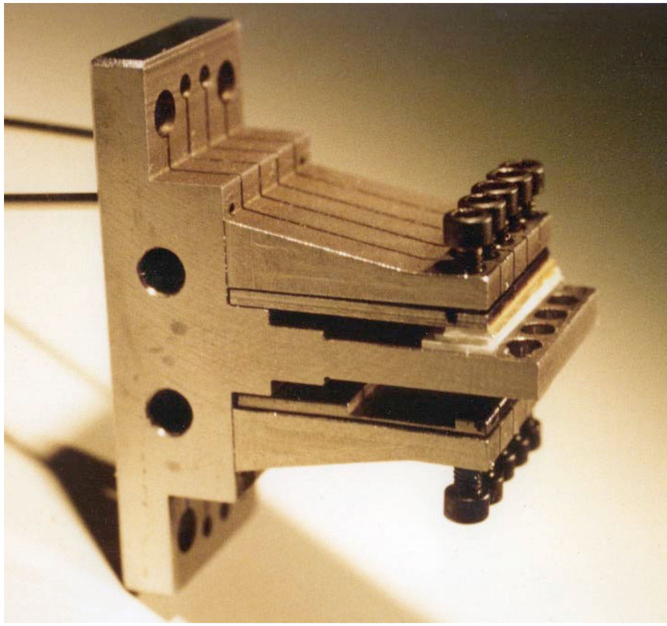
Stressing p-type Photoconductors

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

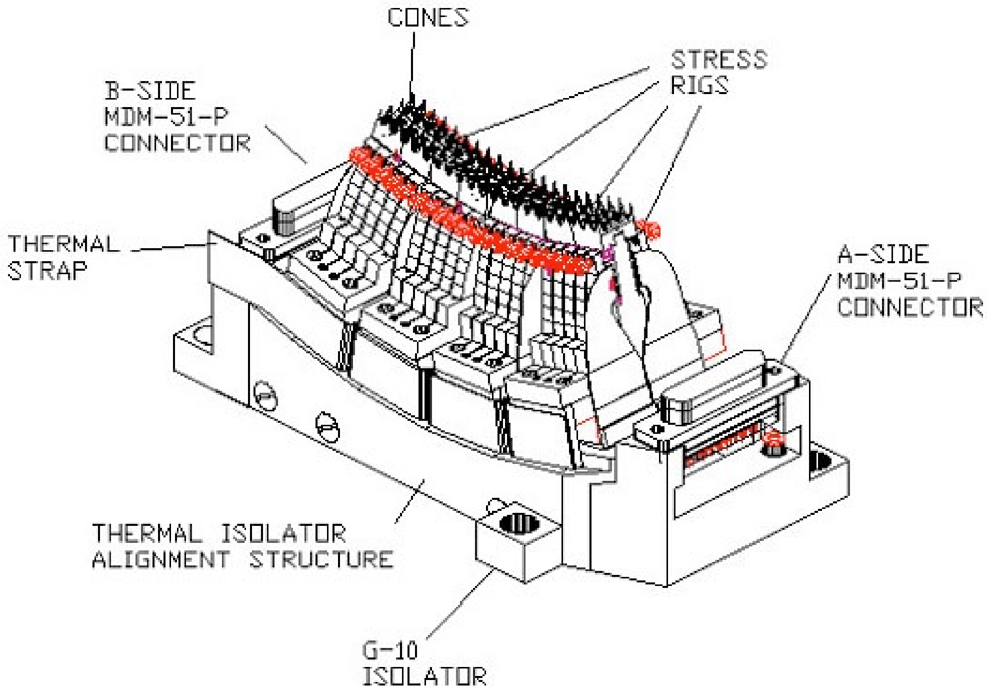




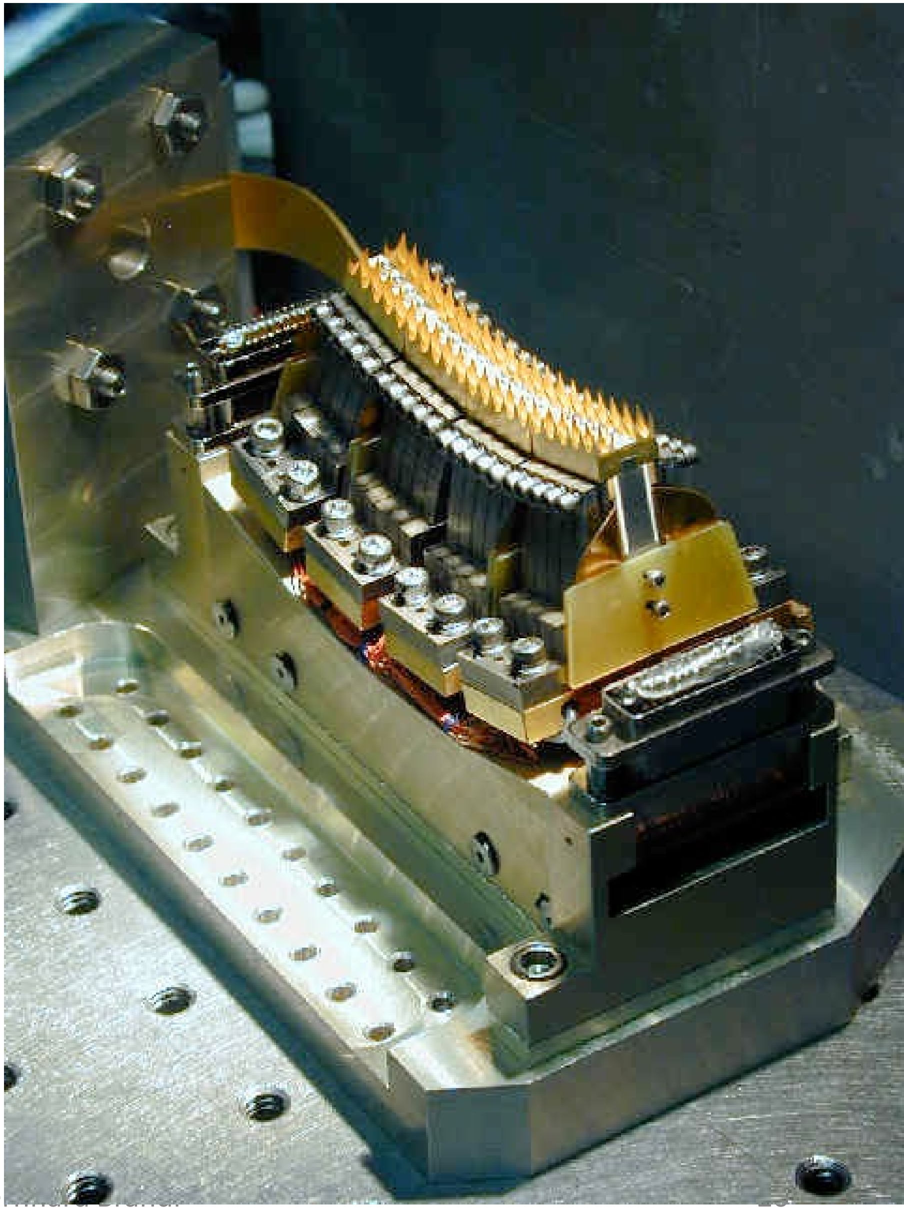
CAUTION: Pressure is 4 tons per square cm!
Apply pressure evenly and consistently.
Don’t be anywhere nearby if it mechanically fails....

Stacking stressed Ge:Ga pixels

2 × 20 pixel of the Spitzer/MIPS



Haller and Richards and the Arizona IR Group



BIB Detectors

Conflicting Requirements of Extr.Ph.

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

BUT

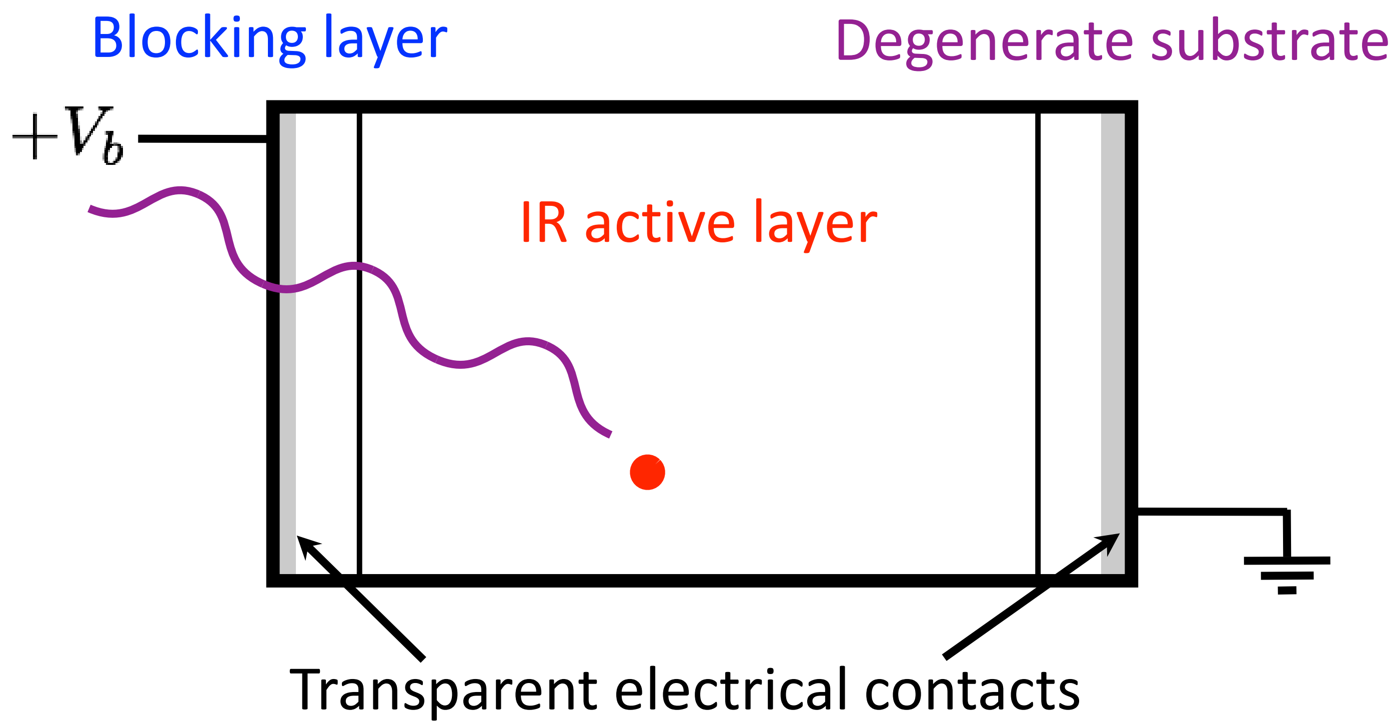
We want lower noise with higher resistance:

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

SOLUTION:

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

Blocked Impurity Band (BIB) Detectors



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 occurs in the low resistance (=high conductivity =no recombination) material, so you only have noise from the Generation statistics.

Unstressed ⇔ Stressed ⇔ BIB

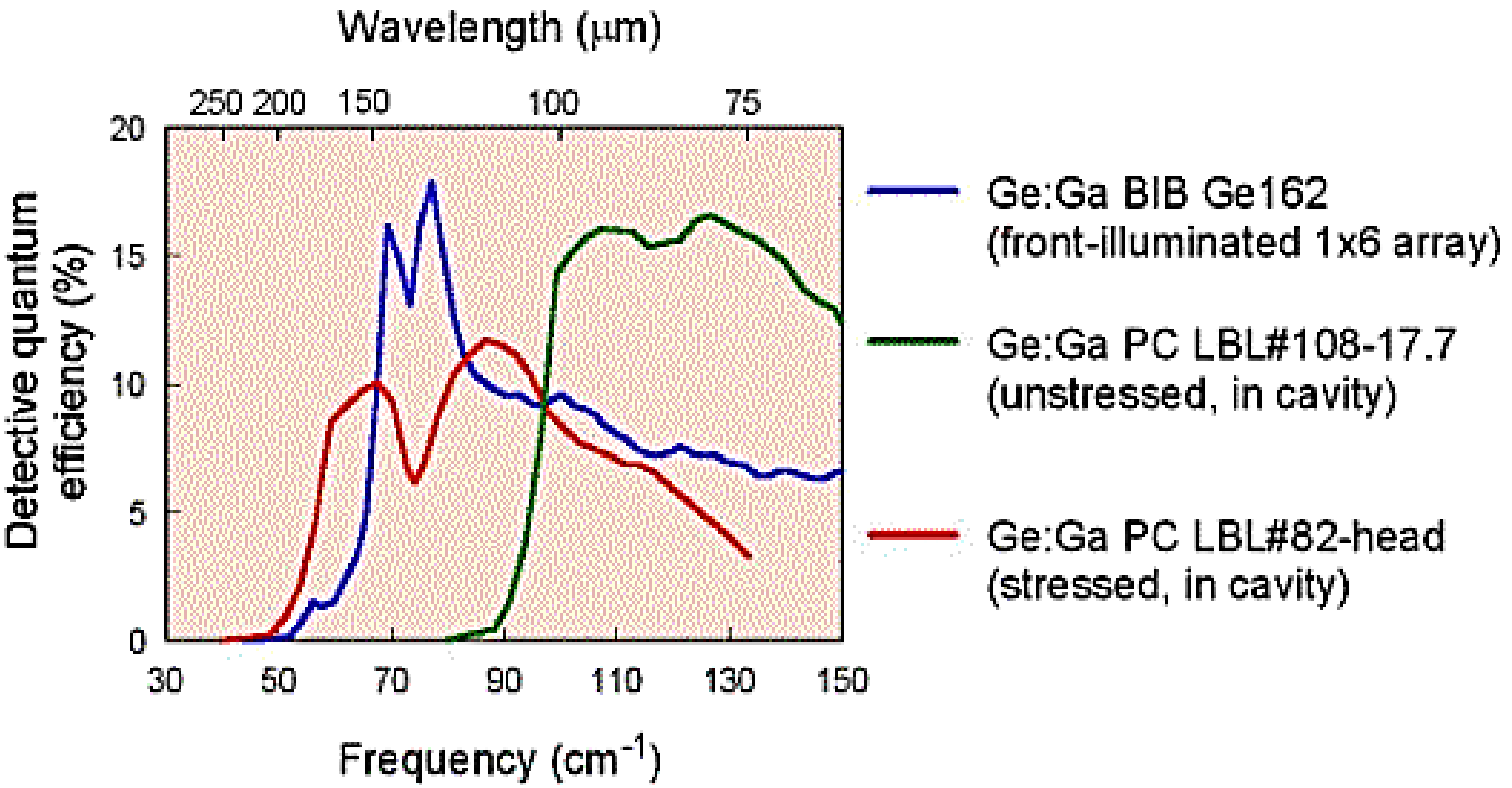


Figure 11. Comparison of Ge BIB and Conventional Photoconductors (D. Watson)

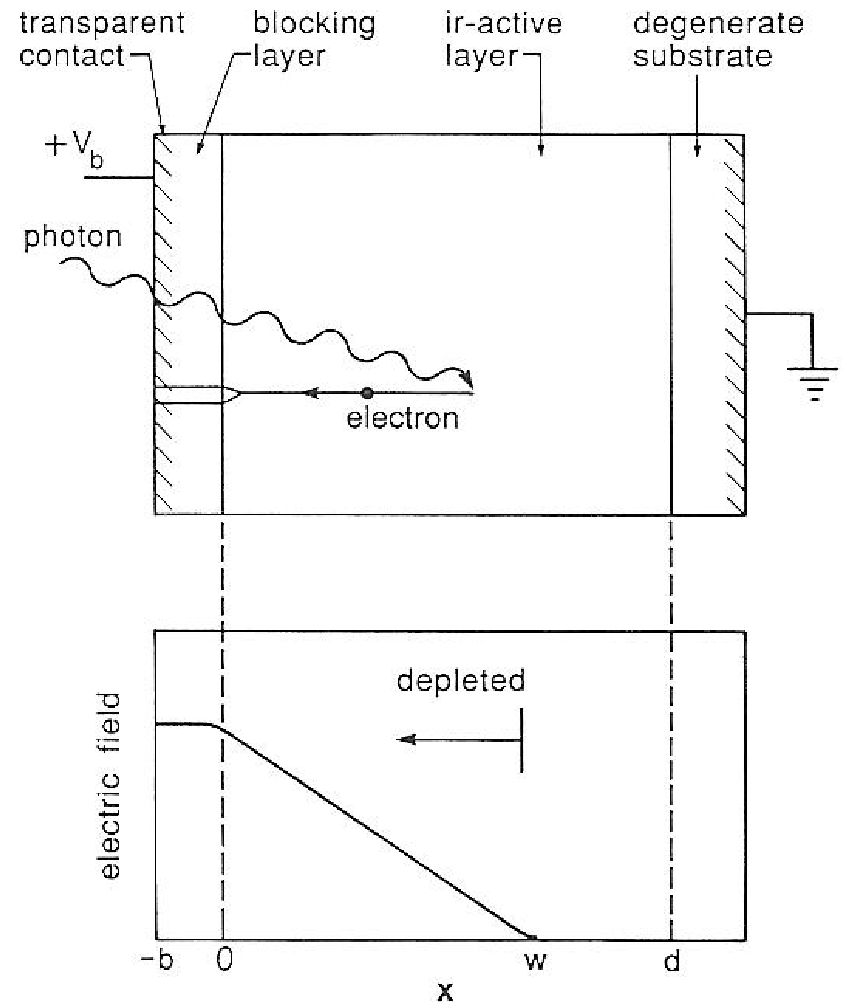
Quantum Efficiency and Bias Voltage

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.

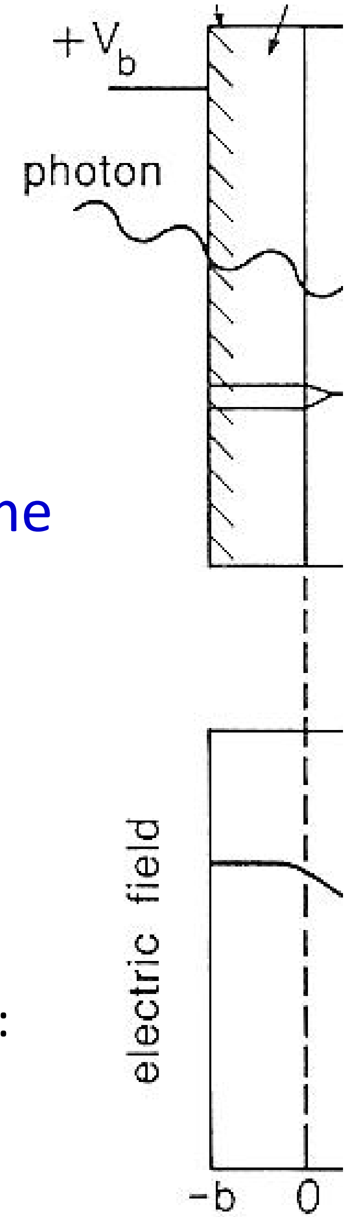
The applied voltage determines the width of the depletion layer (and hence the quantum efficiency of the detector)



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 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 $\beta = \frac{\langle G^2 \rangle}{\langle G \rangle^2}$
- The G-R noise is only G noise and is thus renamed 'shot' noise:

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



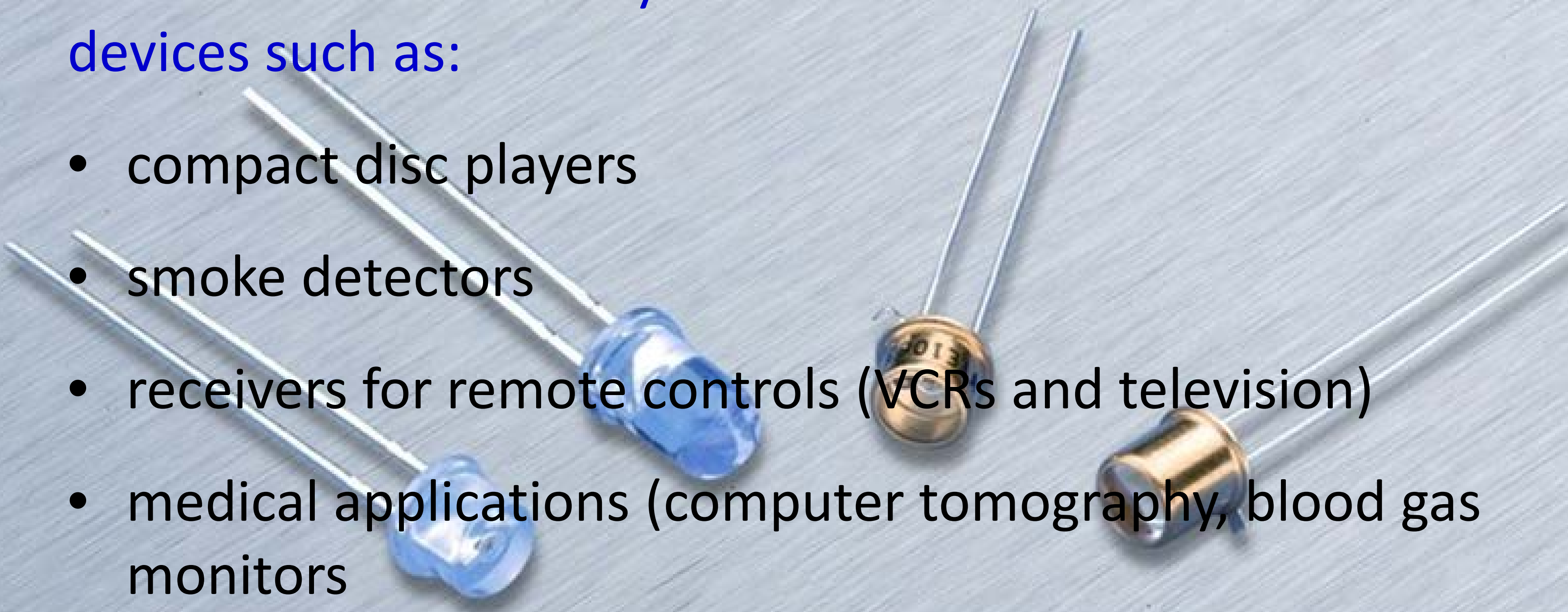
Photodiodes

Photodiodes

From Wikipedia:

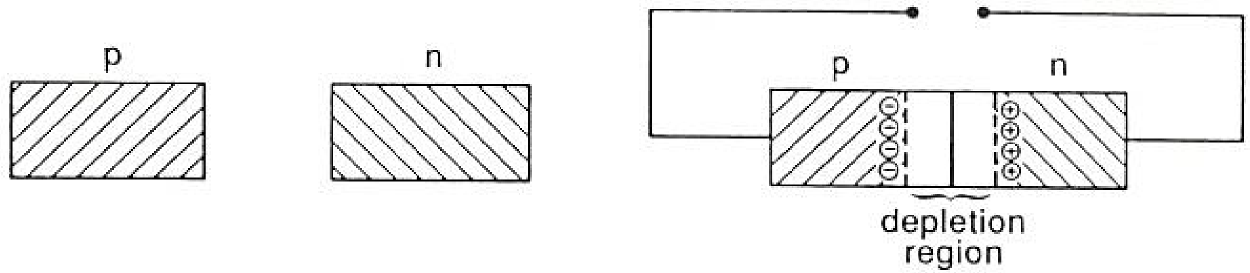
Photodiodes are heavily used in consumer electronics devices such as:

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

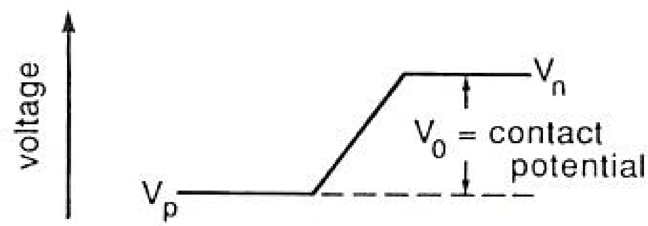


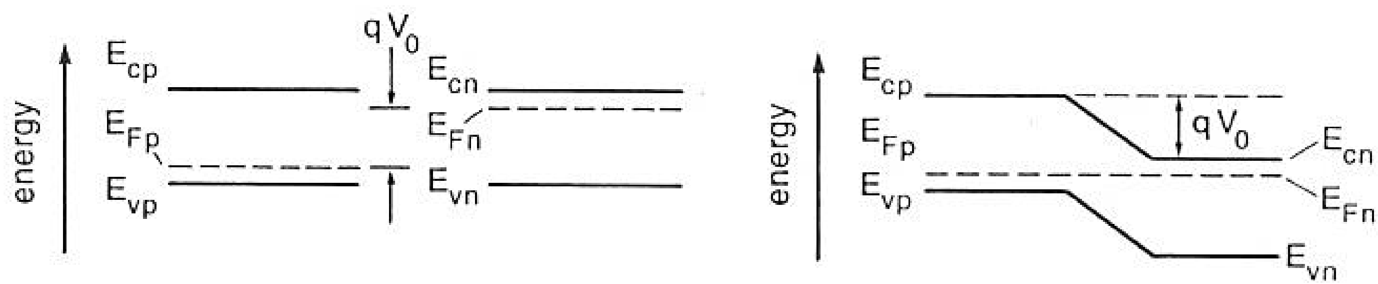
General Principle of a Photodiode

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



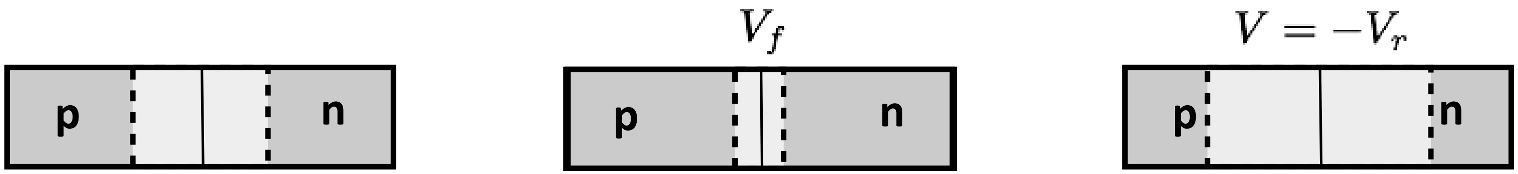


(a) before contact (b) after contact

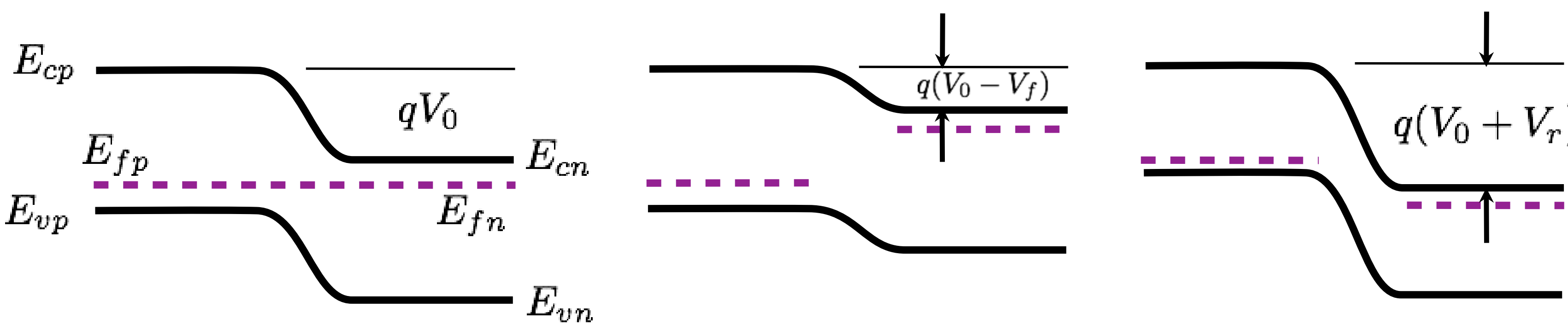
The Effect of the Bias Voltage

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

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

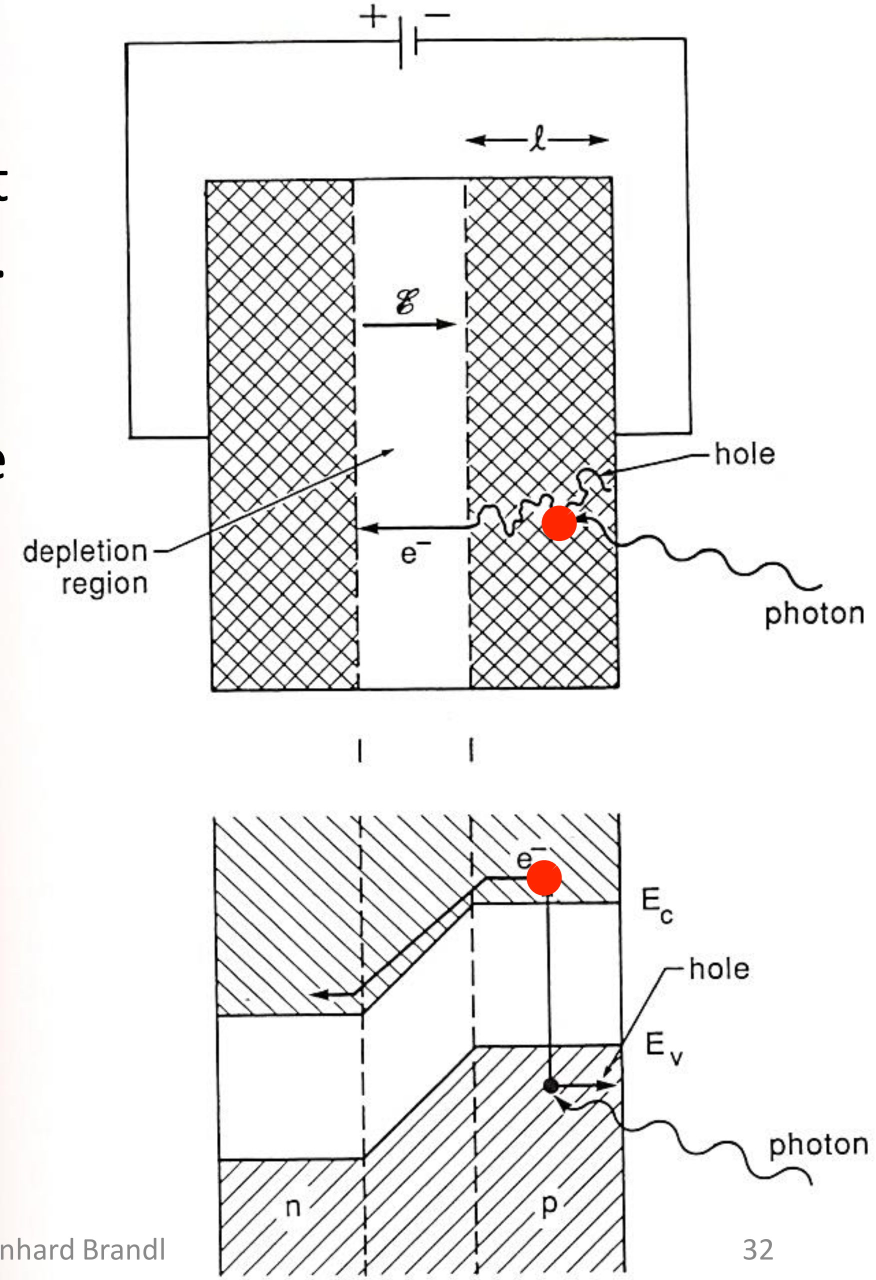


The depletion region increases in size and the resistance increases.



Photoexcitation in Photodiodes

- Photon is absorbed in p-type part and creates an electron-hole pair.
- 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.



Wavelength Range of Photodiodes

Though constructed with extrinsic (doped) material, photodiodes work only through intrinsic absorption.

Typical optical/IR photodiode materials with interesting cutoff wavelengths at room temperature are:

Material	$\sim\lambda_{cutoff}$
Si	1.1 µm
GaInAs	1.7 µm
Ge	1.8 µm
InAs	3.4 µm
InSb	6.8 µm

…and for the near-UV:

Material	$\sim\lambda_{cutoff}$
GaP	0.52 µm
GaN	0.37 µm
$Al_xGa_{1-x}N$	0.2 ... 0.37 µm

Wavelength Range of Photodiodes (2)

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

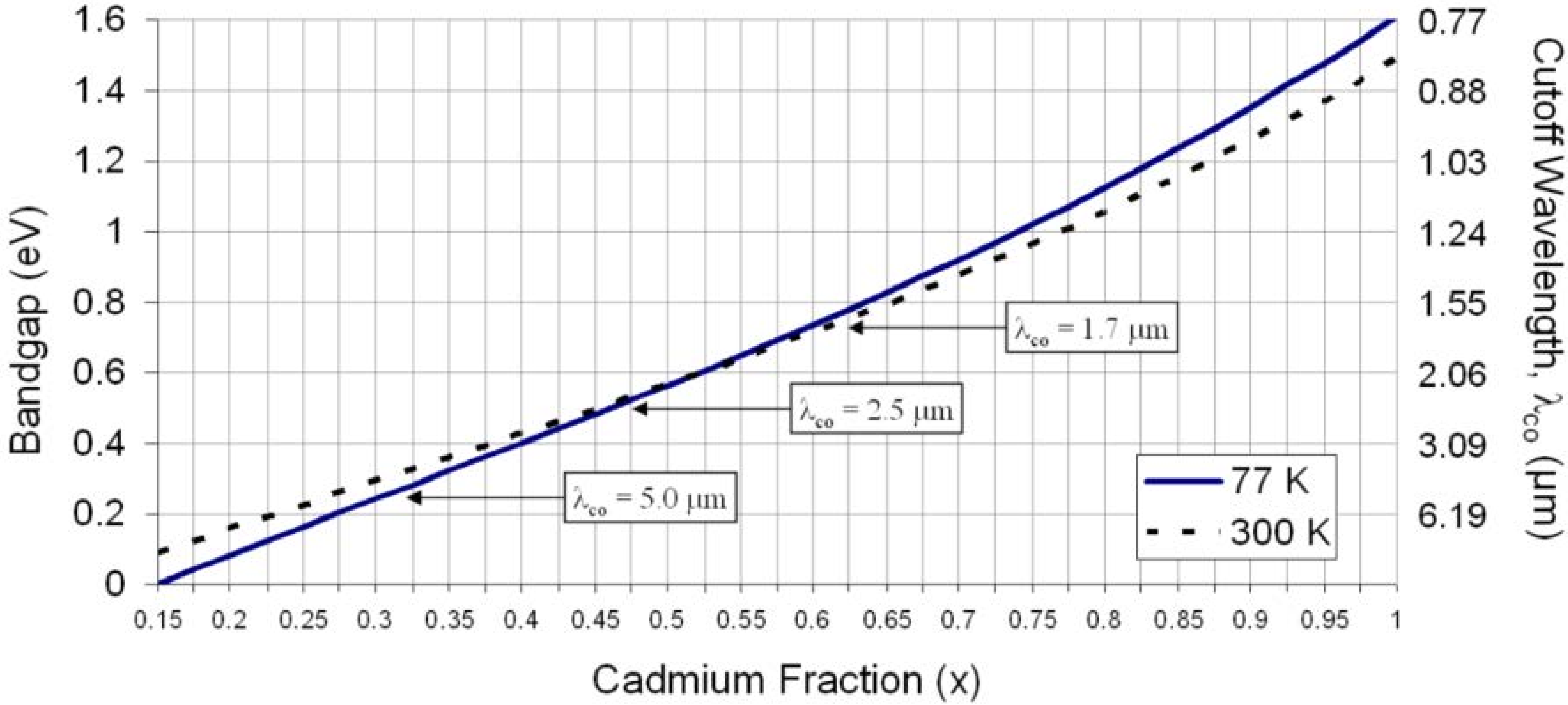


Fig. 3: Bandgap and cutoff wavelength of $Hg_{1-x}Cd_xTe$ as a function of the cadmium fraction, x.

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