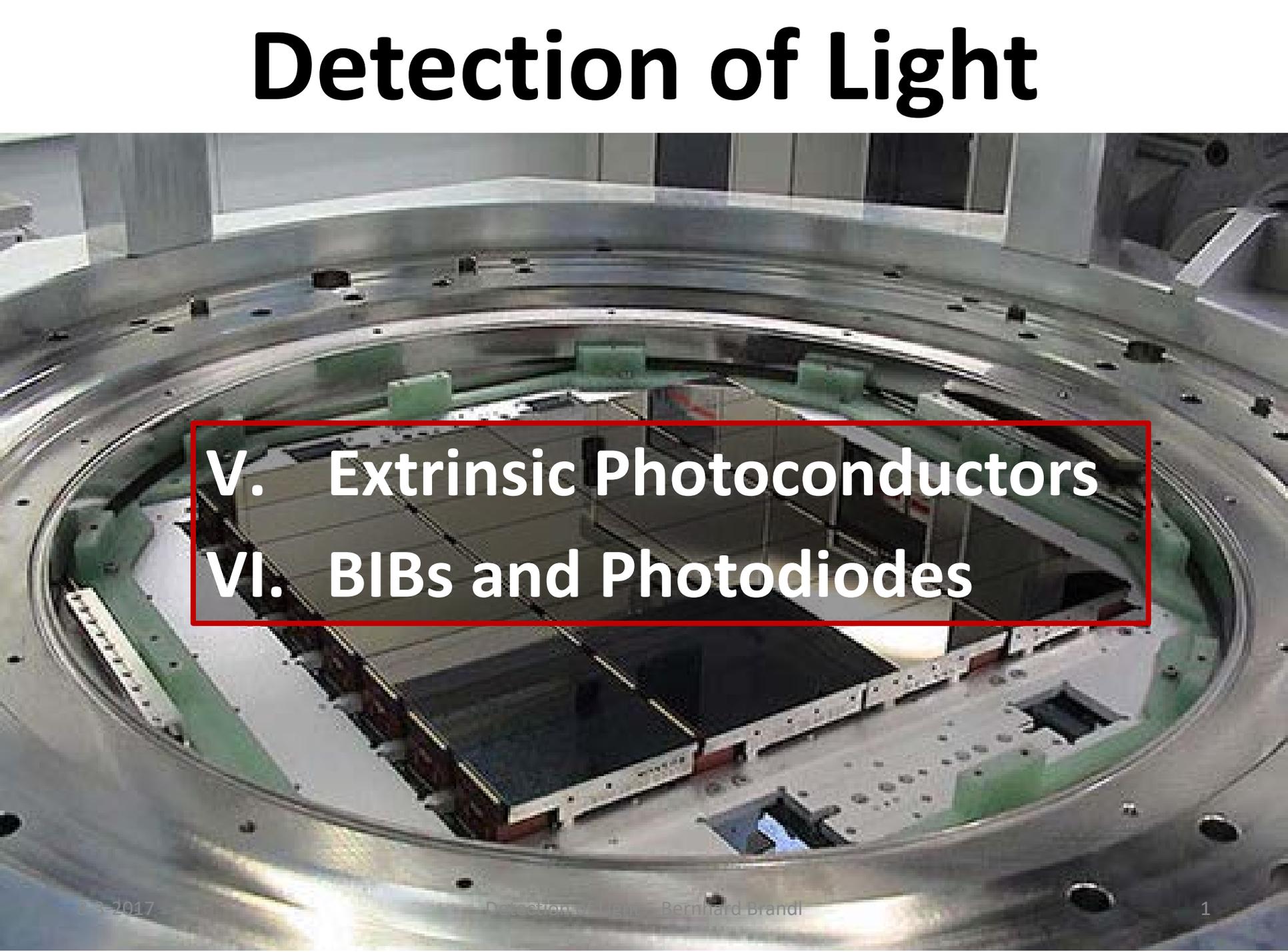


# Detection of Light



**V. Extrinsic Photoconductors**  
**VI. BIBs and Photodiodes**

# Doping and resulting Bandgaps

# The Problem we need to solve

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

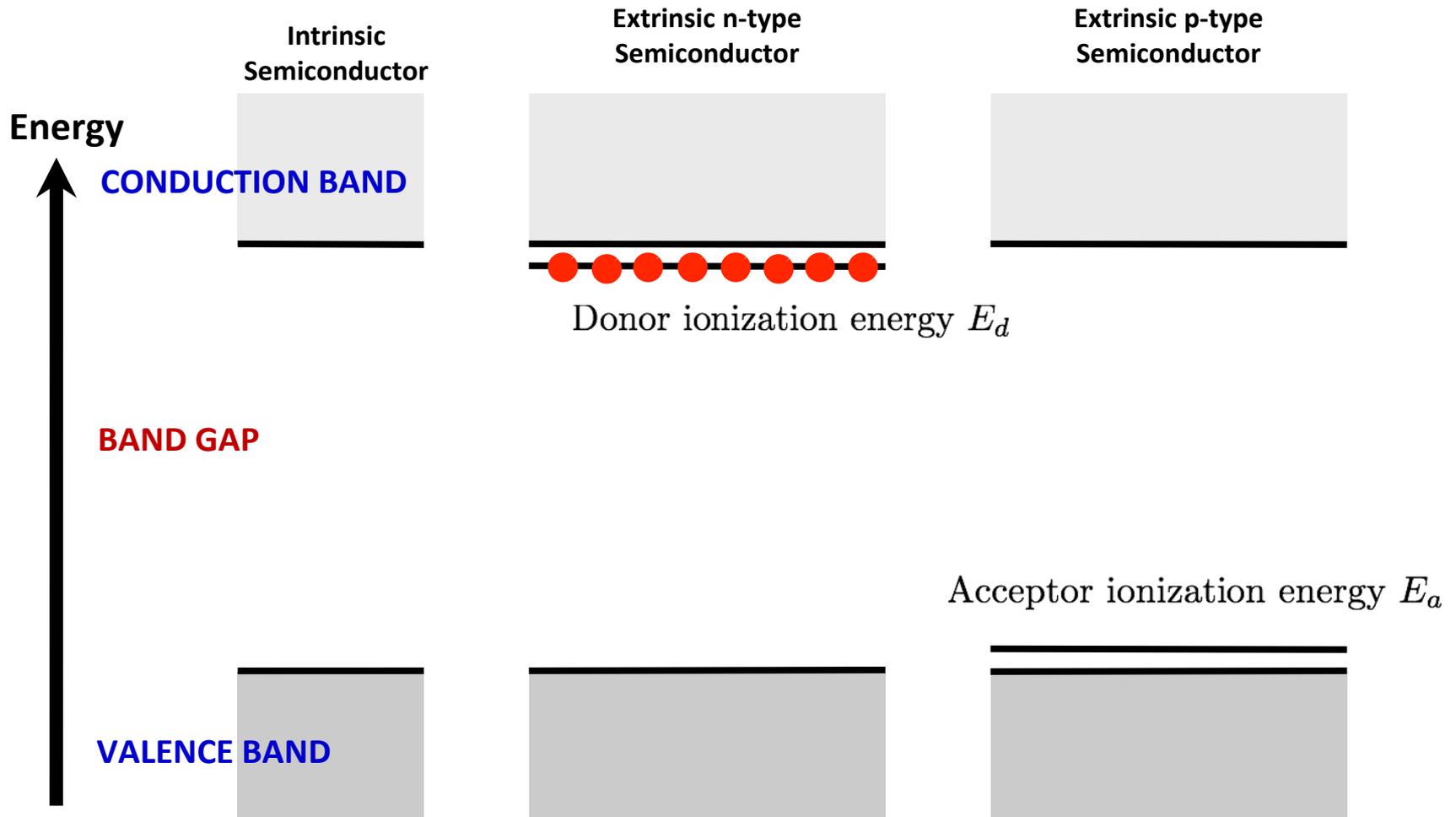
→ Germanium: 1.85 $\mu$ m

→ Silicon: 1.12 $\mu$ m

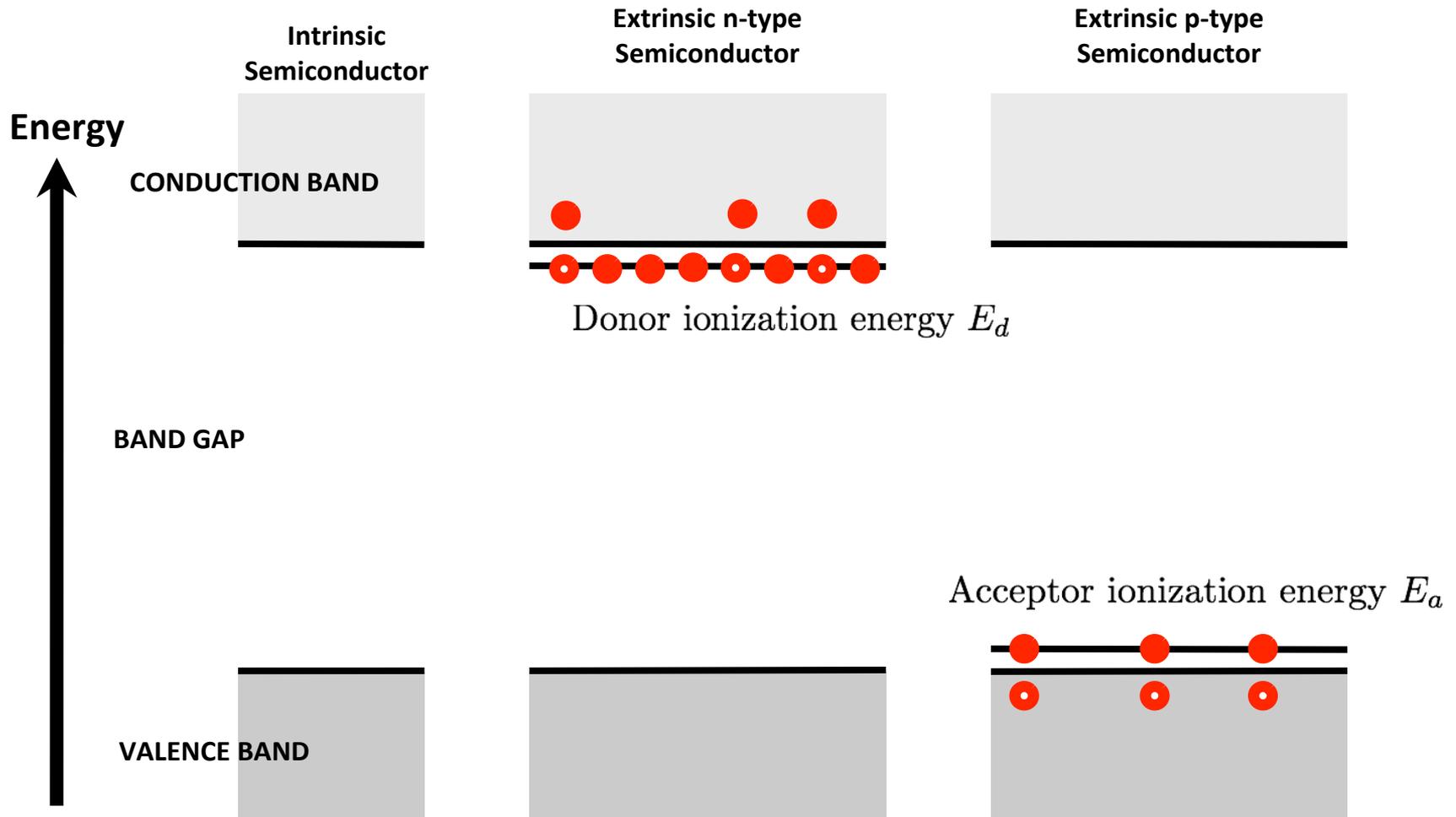
→ GaAs: 0.87 $\mu$ m

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

# Energy Bandgaps at T = 0 K



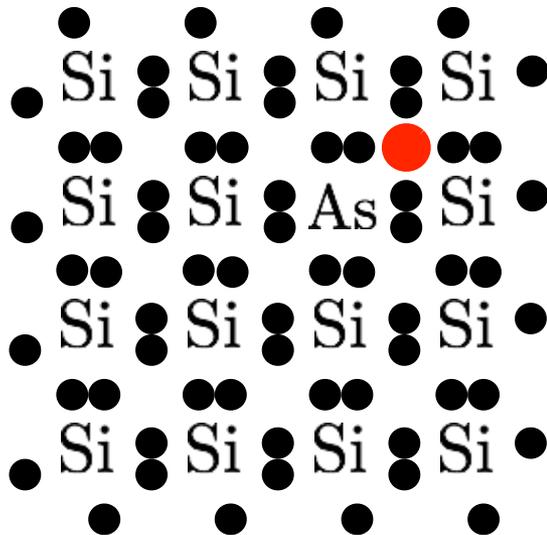
# Energy Bandgaps at $T > 0$ K



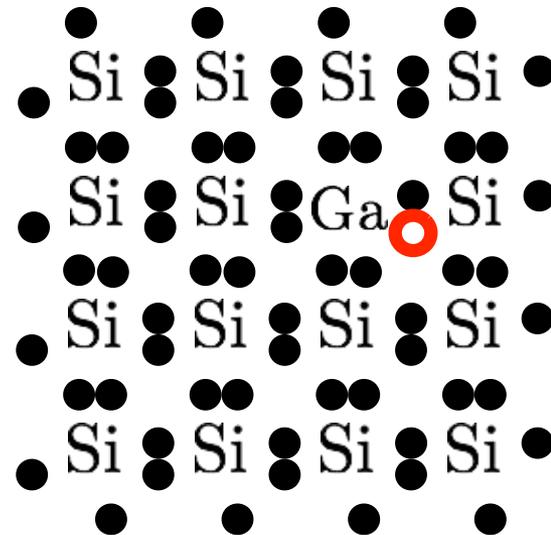
# How can we practically do that?

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  $\rightarrow$  **n-type** Si

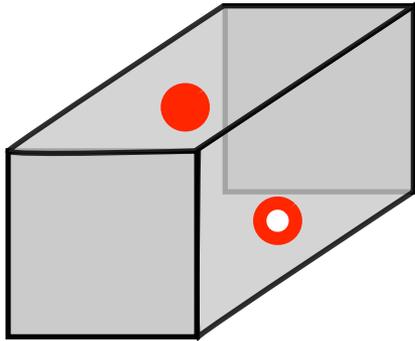


Adding a **Group III** element (“acceptor”) adds a missing electron = “hole”  $\rightarrow$  **p-type** Si

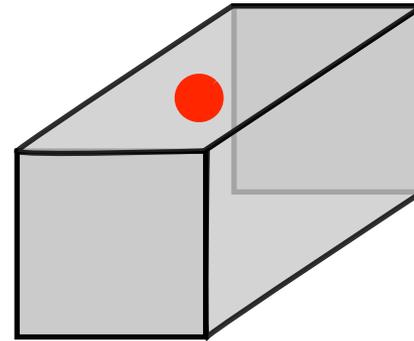


# Intrinsic versus extrinsic Carrier Release

Note: 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

# 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:  $25 \times$  smaller bandgap means  
 $25 \times$  longer wavelength coverage  
of the detector!

Note: for  $T = 300\text{K}$ ,  $kT \sim 26 \text{ meV} \rightarrow$  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		Si	
		Cutoff wavelength $\lambda_c$ ( $\mu\text{m}$ )	Photoionization cross section $\sigma_i$ ( $\text{cm}^2$ )	Cutoff wavelength $\lambda_c$ ( $\mu\text{m}$ )	Photoionization cross section $\sigma_i$ ( $\text{cm}^2$ )
Al	p			18.5 <sup>a</sup>	$8 \times 10^{-16b}$
B	p	119 <sup>b</sup>	$1.0 \times 10^{-14c}$	28 <sup>a</sup>	$1.4 \times 10^{-15b}$
Be	p	52 <sup>b</sup>		8.3 <sup>a</sup>	$5 \times 10^{-18a}$
Ga	p	115 <sup>b</sup>	$1.0 \times 10^{-14c}$	17.2 <sup>a</sup>	$5 \times 10^{-16b}$
In	p	111 <sup>b</sup>		7.9 <sup>a</sup>	$3.3 \times 10^{-17b}$
As	n	98 <sup>b</sup>	$1.1 \times 10^{-14b}$	23 <sup>a</sup>	$2.2 \times 10^{-15a}$
Cu	p	31 <sup>b</sup>	$1.0 \times 10^{-15b}$	5.2 <sup>a</sup>	$5 \times 10^{-18a}$
P	n	103 <sup>b</sup>	$1.5 \times 10^{-14b}$	27 <sup>a</sup>	$1.7 \times 10^{-15b}$
Sb	n	129 <sup>b</sup>	$1.6 \times 10^{-14b}$	29 <sup>a</sup>	$6.2 \times 10^{-15a}$

# Absorption Coefficients and QE

The **absorption coefficient** for extrinsic photoconductors is:

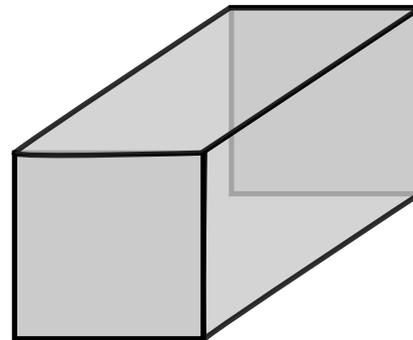
$$a(\lambda) = \sigma_i(\lambda)N_I$$

...where  $\sigma_i$  is the photoionization cross section  
and  $N_I$  is the impurity concentration.

With typical impurity concentrations of  $10^{15} - 10^{16} \text{ cm}^{-3}$ , and typical photo-ionization cross sections of  $10^{-15} - 10^{-17} \text{ cm}^2$ , the **absorption coefficients of extrinsic photoconductors are 2 – 3 orders of magnitude less** than those for direct absorption in intrinsic photoconductors.



Intrinsic  
detector

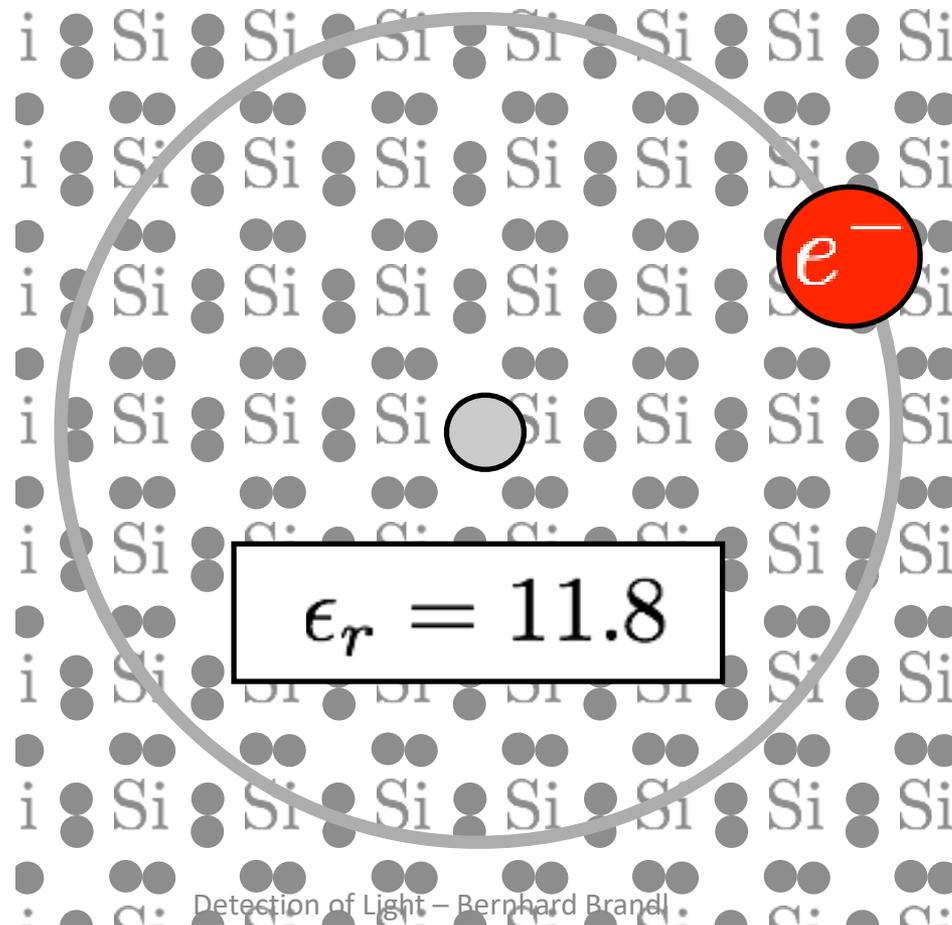


Extrinsic  
detector  
“Bulk Photo-  
conductor”

# Why is a donor easily ionised?

The Bohr radius  $a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2}$  depends on the permittivity of free space,  $\epsilon_0 = \frac{1}{\mu_0 c^2}$ .

In a crystal  $\epsilon_0$  is much larger  $\rightarrow \epsilon_r$



# NEP and the Detector Resistance

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

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

How can we improve the NEP? (*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

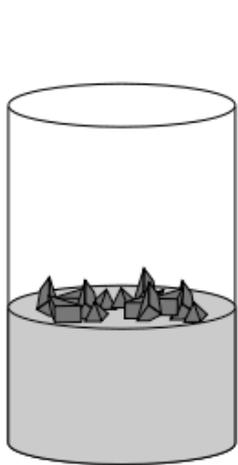
# Problem 1: Hopping



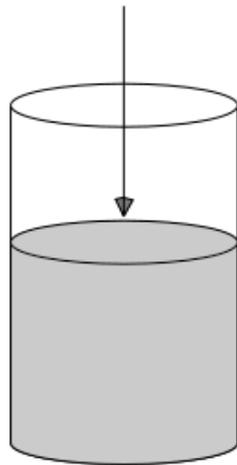
Unwanted conductivity modes when impurity atoms are too close together, their wavefunctions overlap.

# Side note: Growing Si Crystals

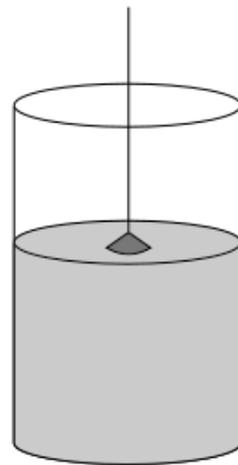
Silicon crystal drawn using the using **Czochralski** Process



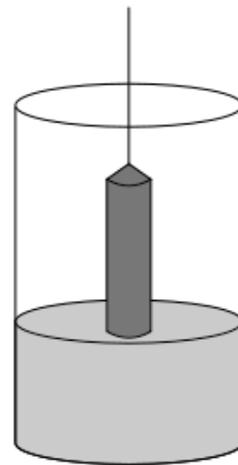
Melting of polysilicon, doping



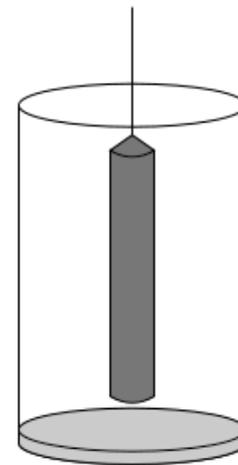
Introduction of the seed crystal



Beginning of the crystal growth



Crystal pulling



Formed crystal with a residue of melted silicon

*from Wikipedia*



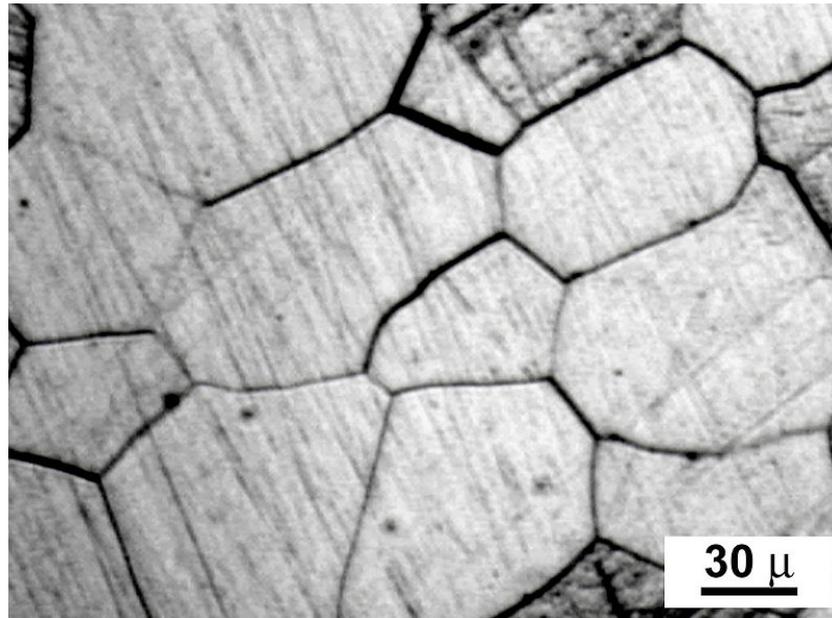
2m long, about 200kg

# Side note: Growing Si Crystals

# 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  $10^{-13} \text{ cm}^{-3}$
- Crystal shows **grain boundaries** rather than perfect homogeneity



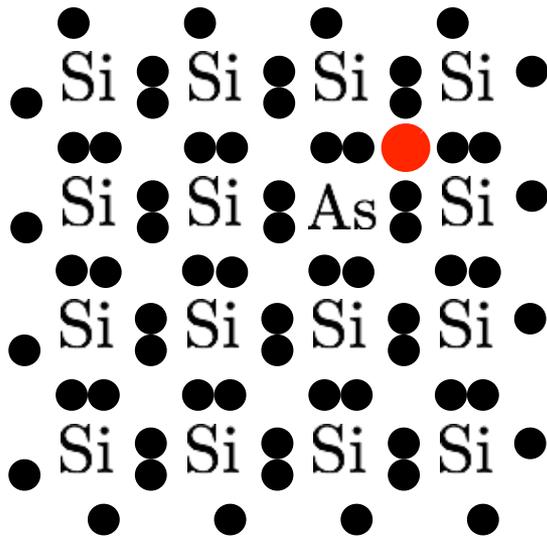
Grain Boundaries

# Problem 3: Intrinsic Absorption

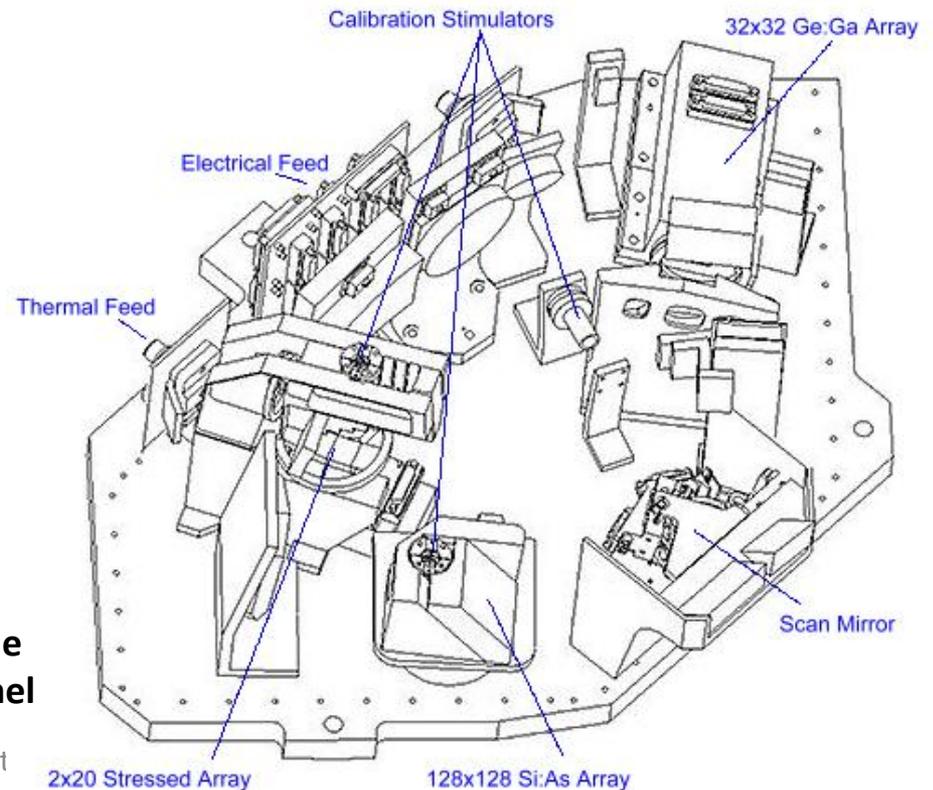
Even though the dopant:intrinsic ratio is typically 1:10000, you **MUST USE** a filter to make sure intrinsic energy photons don't hit your detector!

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



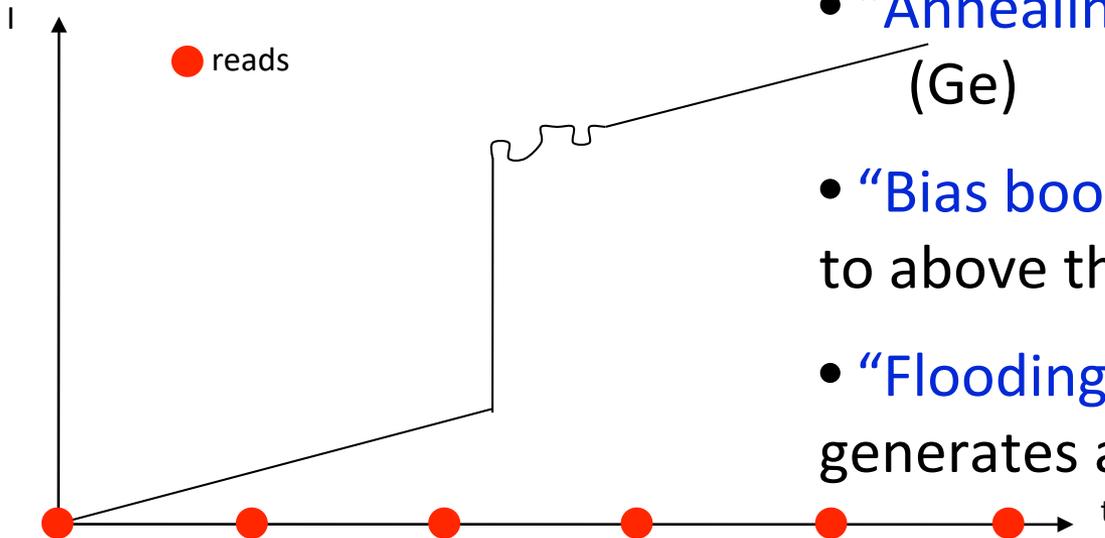
# Problem 4: Ionizing Radiation Effects

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

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

Mitigations (*see lecture #5*):

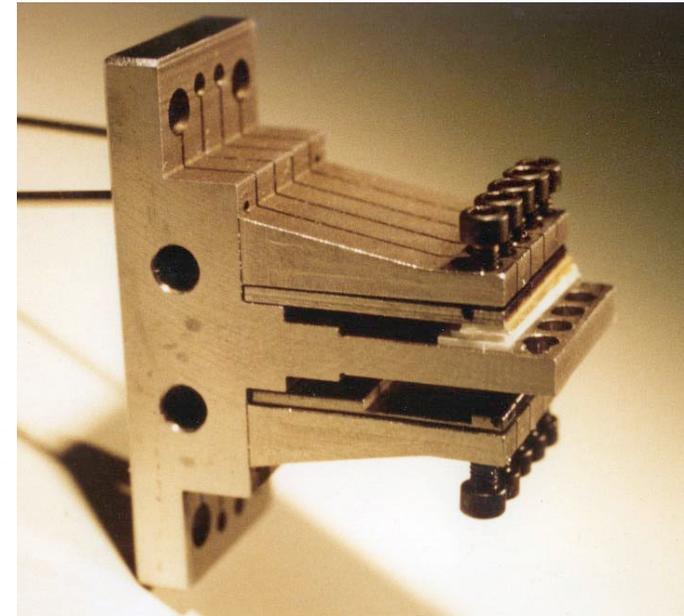
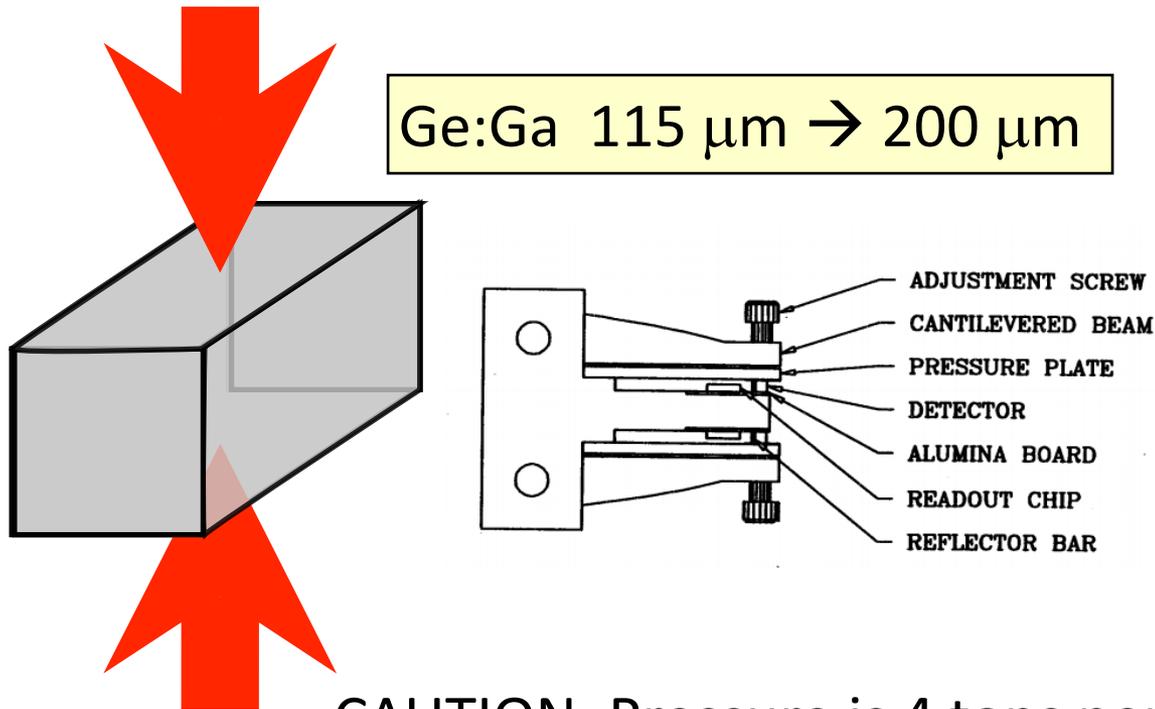
- “**Annealing**”: heat up to 20K (Si) or 6K (Ge)
- “**Bias boost**” – increase bias voltage to above the breakdown level
- “**Flooding**” the detector with light generates an avalanche of electrons



# Stressed Detectors

# Stressing p-type Photoconductors

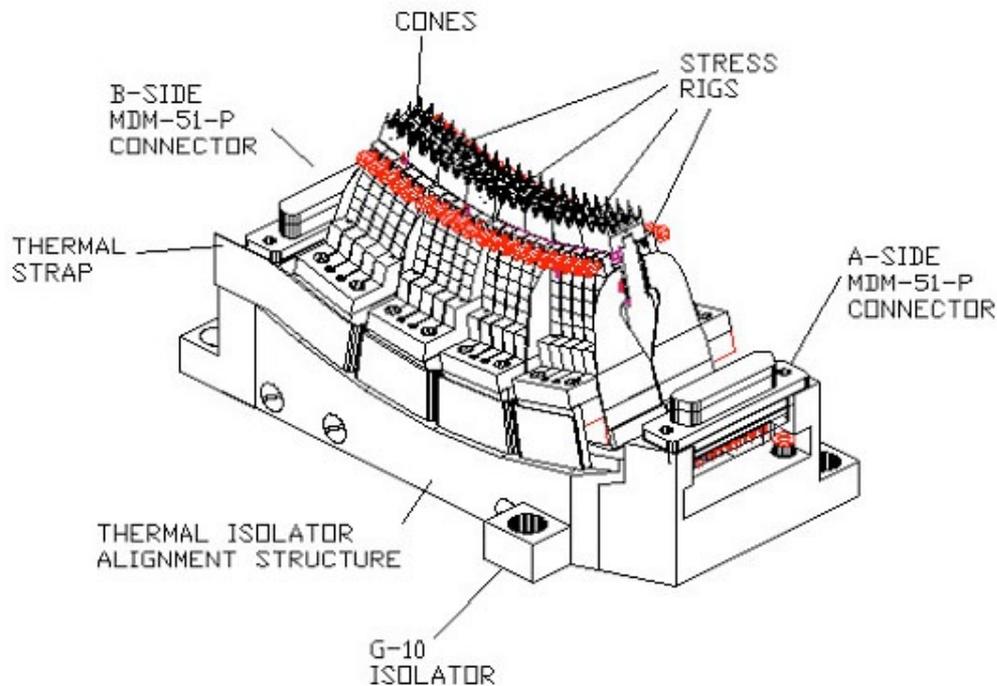
Applying a mechanical force to extrinsic p-type material “helps” break inter-atomic bonds. (p-type has conduction by migrating holes).



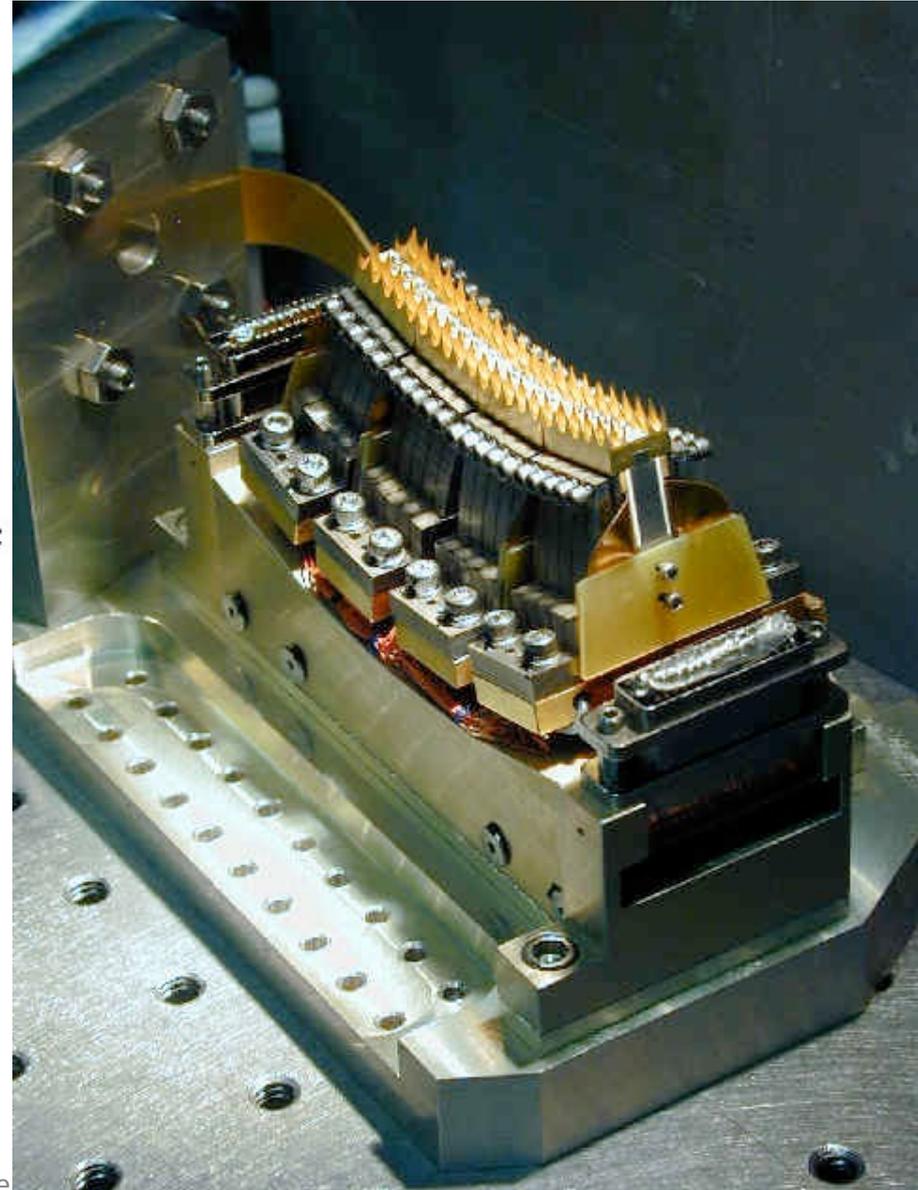
**CAUTION:** Pressure is 4 tons per square cm!  
Apply pressure evenly and consistently.  
*Don't be anywhere nearby if it mechanically fails....*

# Stacking stressed Ge:Ga pixels

2 × 20 pixel of the Spitzer/MIPS



**Haller and Richards  
and the Arizona IR Group**



# BIB Detectors



# Conflicting Requirements

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

**BUT**

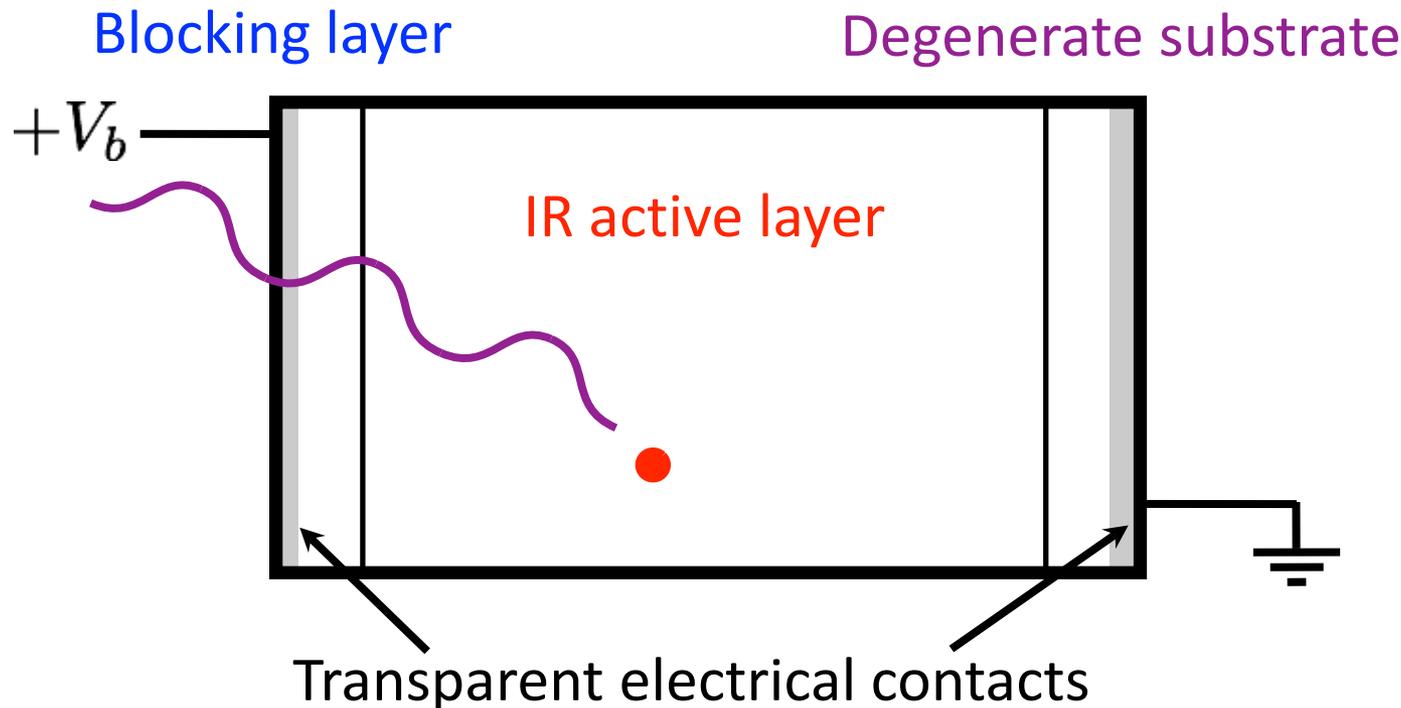
We want lower noise with higher resistance:

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

**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 $\leftrightarrow$ Stressed $\leftrightarrow$ BIB

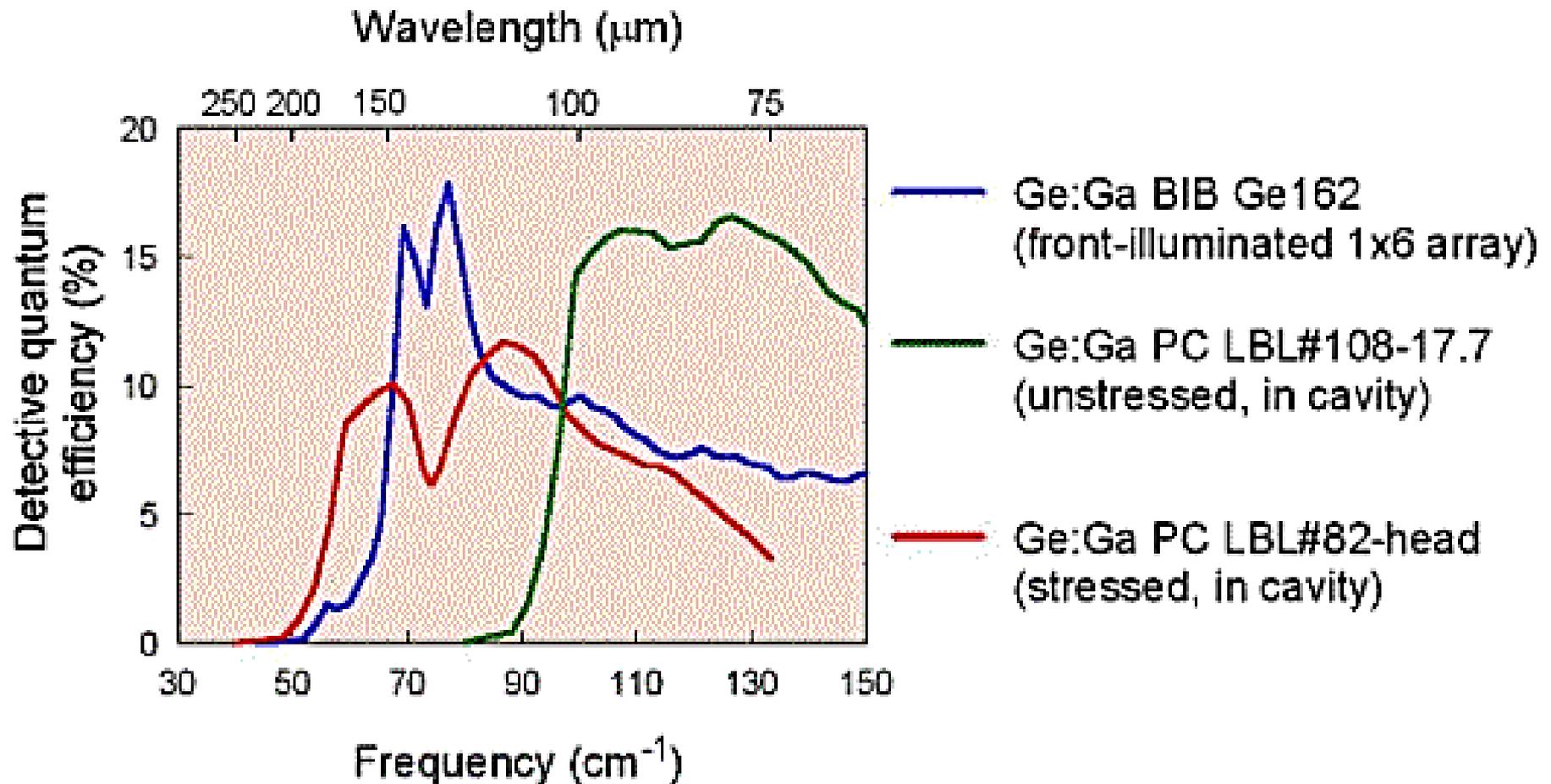


Figure 11. Comparison of Ge BIB and Conventional Photoconductors (D. Watson)

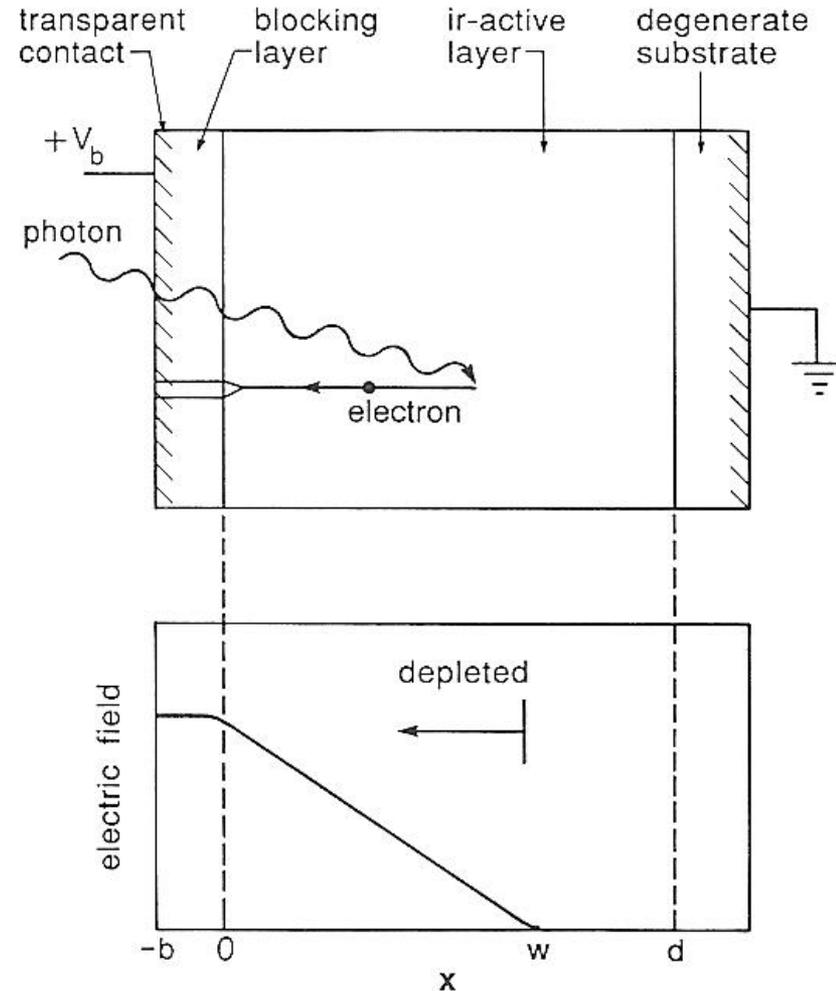
# Quantum Efficiency and Bias Voltage

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  $\rightarrow$  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.

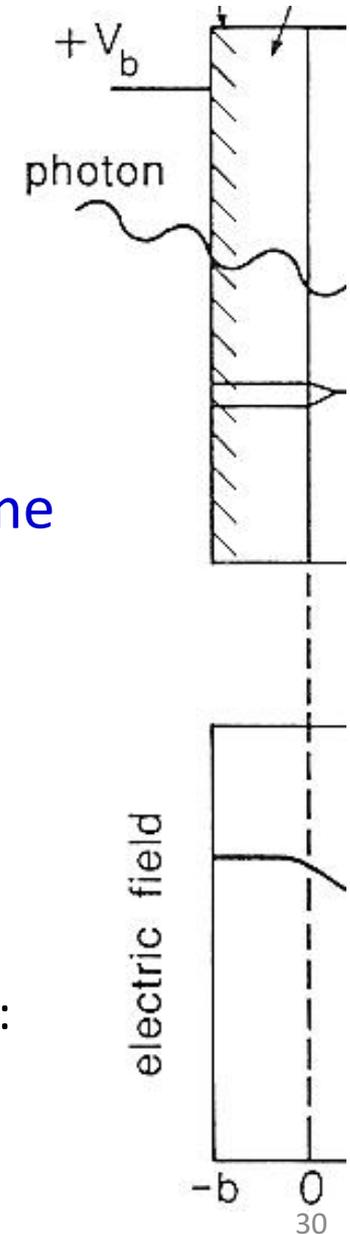
The applied voltage determines the width of the depletion layer (and hence the quantum efficiency of the detector)



# 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**:

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



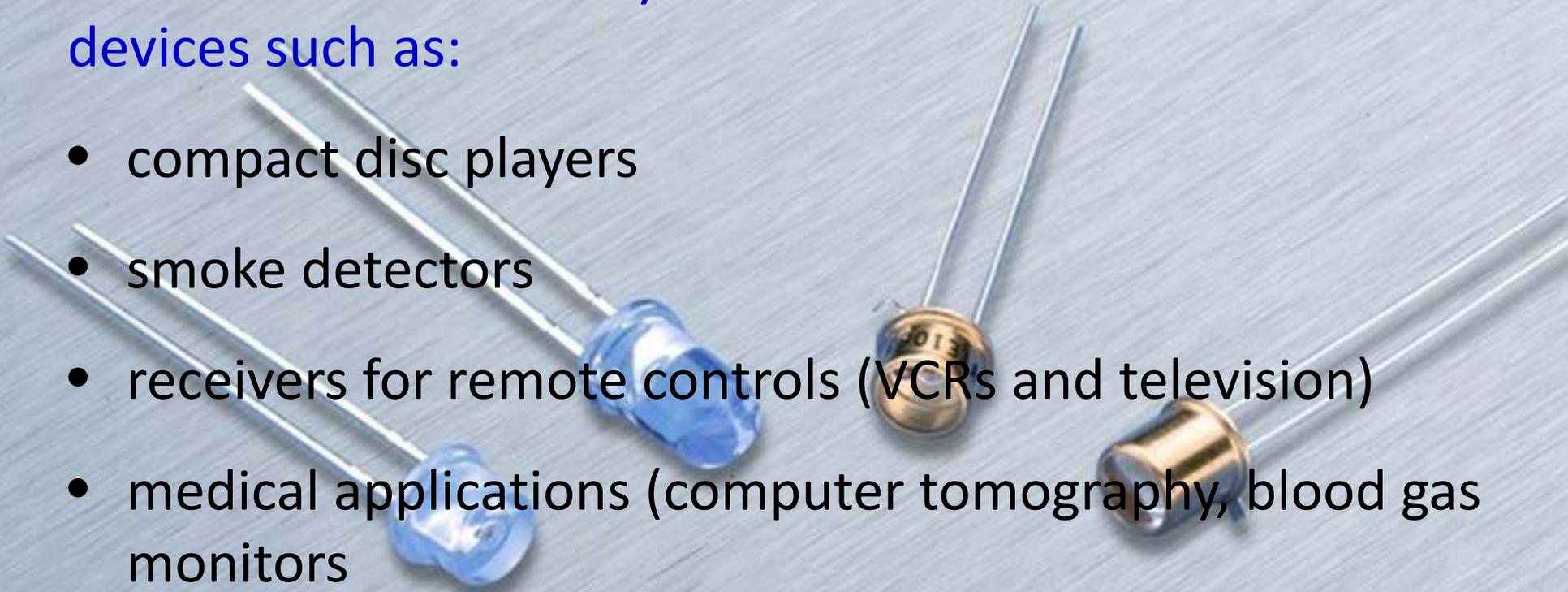
# Photodiodes

# Photodiodes

*From Wikipedia:*

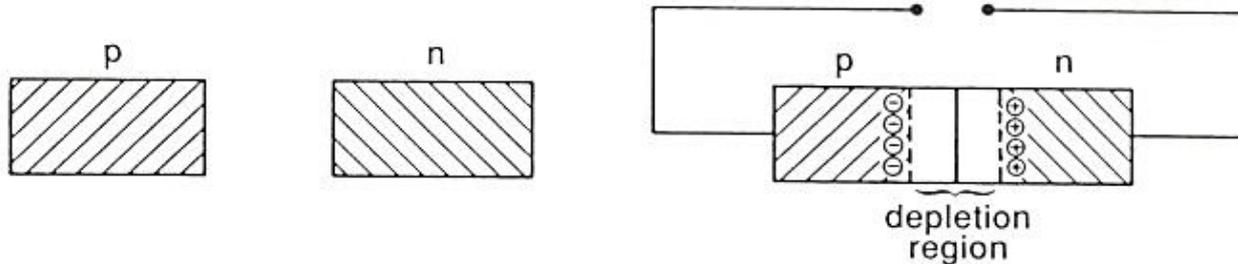
Photodiodes are heavily used in consumer electronics devices such as:

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

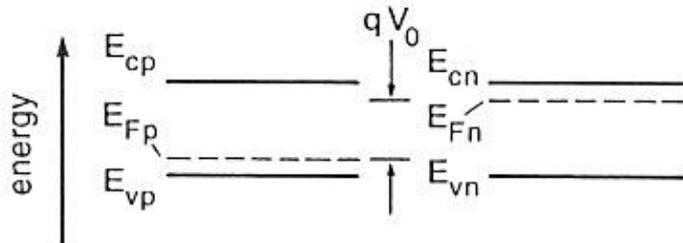
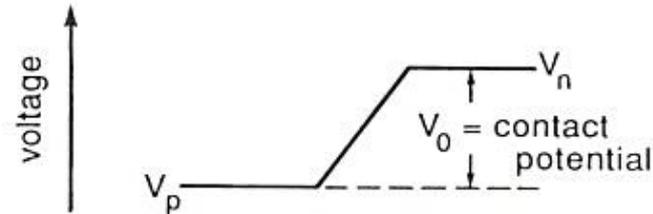


# General Principle of a Photodiode

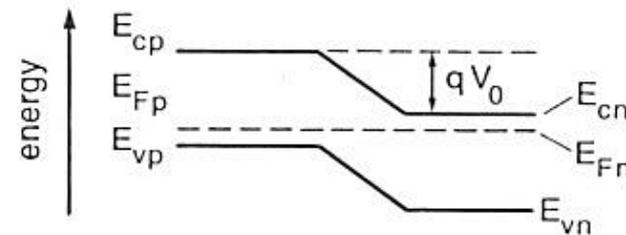
Bringing a **p-type and n-type semiconductor together** (“p-n junction”) creates a depletion region with **high R**.



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



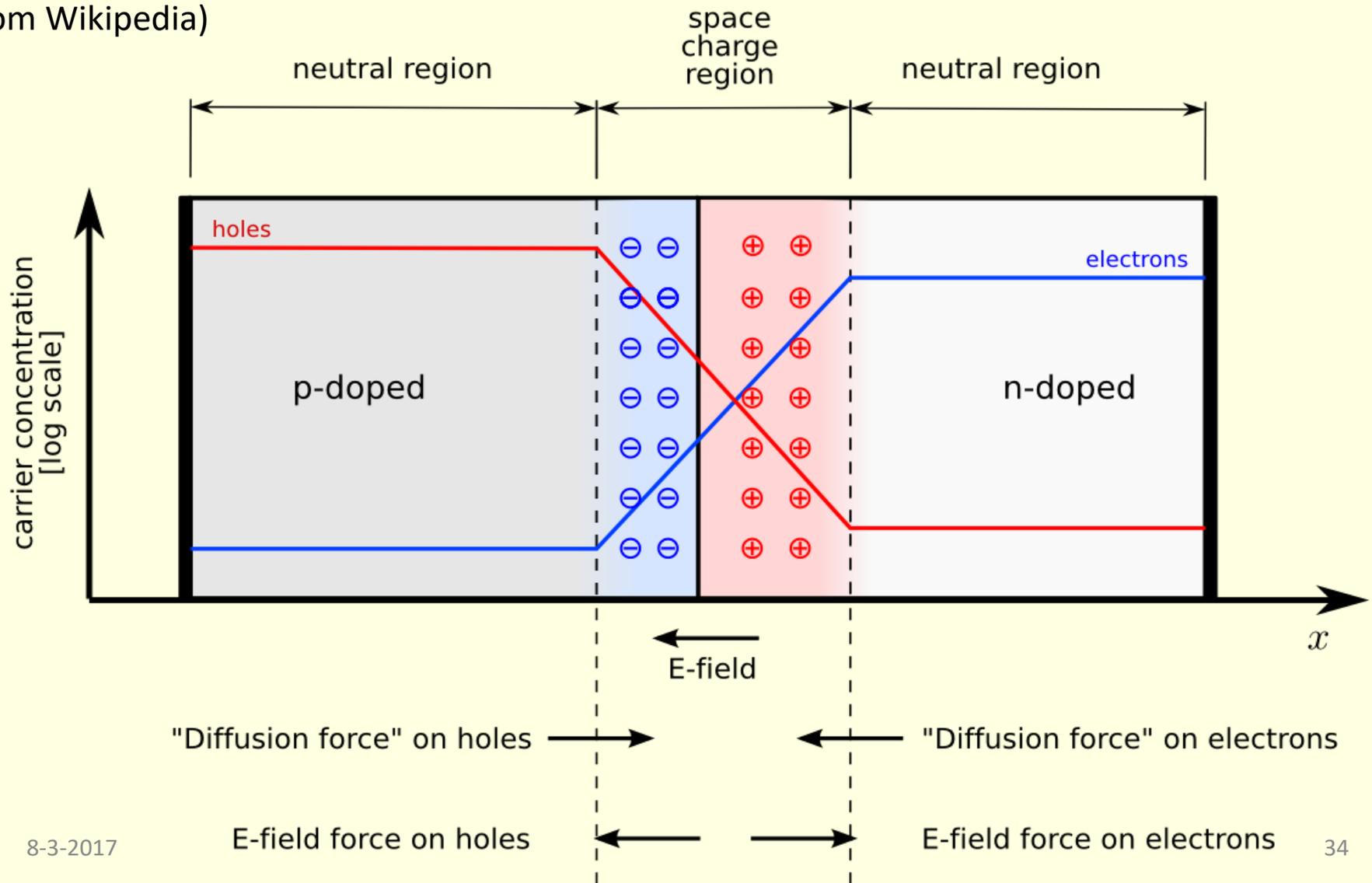
(a) before contact



(b) after contact

# General Principle of a Photodiode (2)

(from Wikipedia)



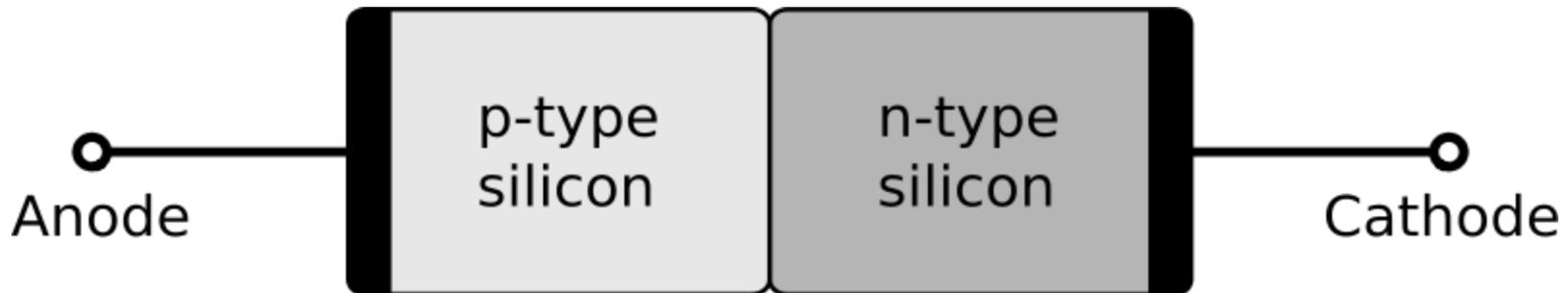
# Photodiodes – Please Note!

A **diamond lattice** can be formed by IV elements (C, Si, Ge) or by combining elements from the 3<sup>rd</sup> and 5<sup>th</sup> group of elements.

This has nothing to do with PIN diodes!

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

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



p-n junction → photodiode

# The Effect of a Bias Voltage

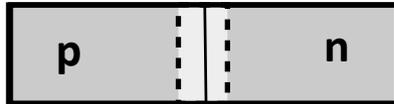
The bias voltage dramatically changes the behavior of the p-n junction:

**Equilibrium**



**Forward bias**

$$V_f$$

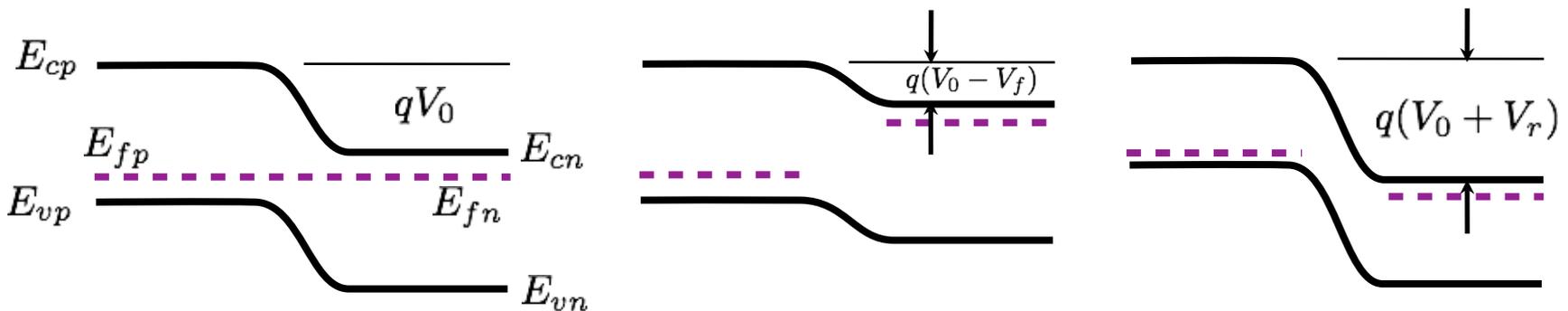


**Reverse bias**

$$V = -V_r$$

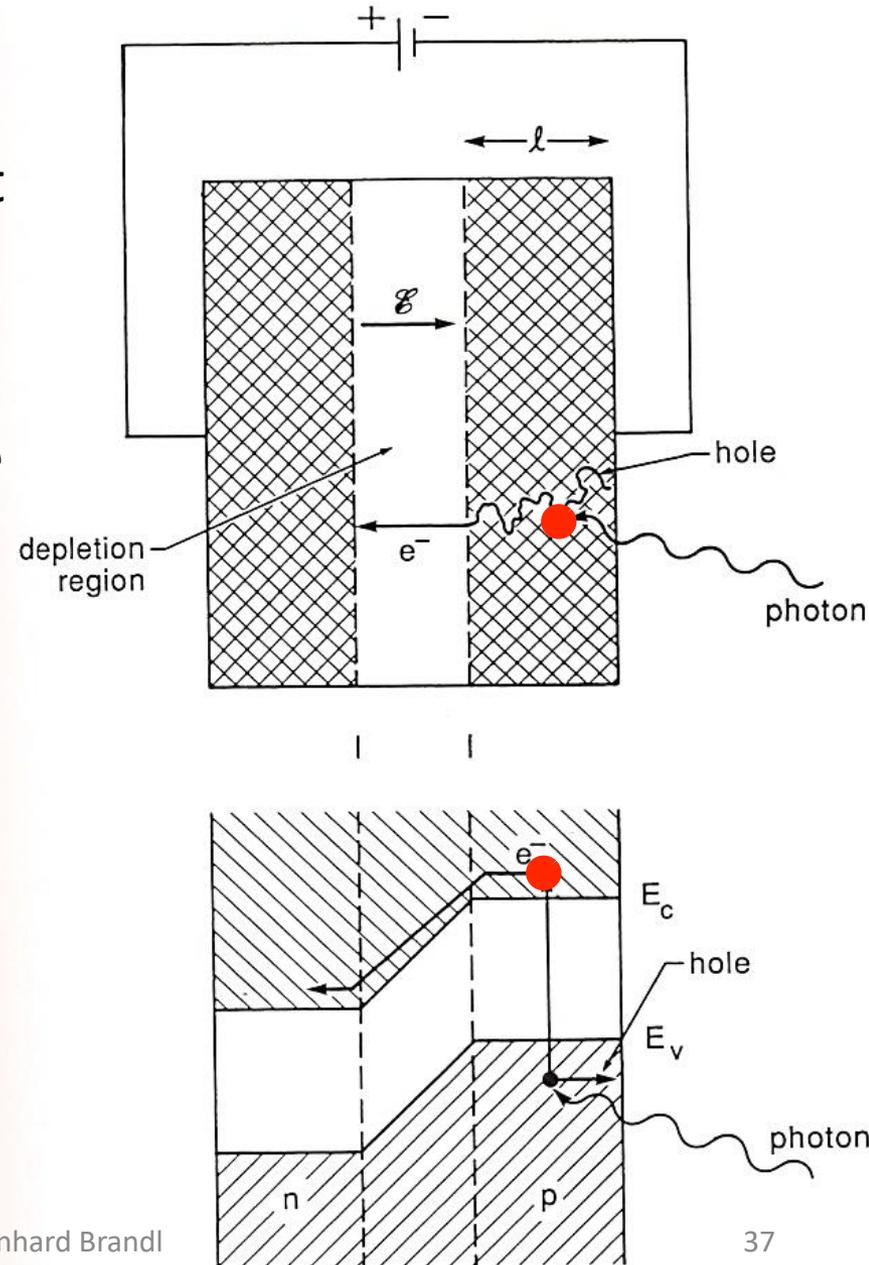


The depletion region increases in size and the resistance increases.



# 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	$\sim\lambda_{\text{cutoff}}$
Si	1.1 $\mu\text{m}$
GaInAs	1.7 $\mu\text{m}$
Ge	1.8 $\mu\text{m}$
InAs	3.4 $\mu\text{m}$
InSb	6.8 $\mu\text{m}$

...and for the **near-UV**:

Material	$\sim\lambda_{\text{cutoff}}$
GaP	0.52 $\mu\text{m}$
GaN	0.37 $\mu\text{m}$
$\text{Al}_x\text{Ga}_{1-x}\text{N}$	0.2 ... 0.37 $\mu\text{m}$

# Wavelength Range of Photodiodes (2)

$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35 \times 10^{-4} T(1 - 2x)$$

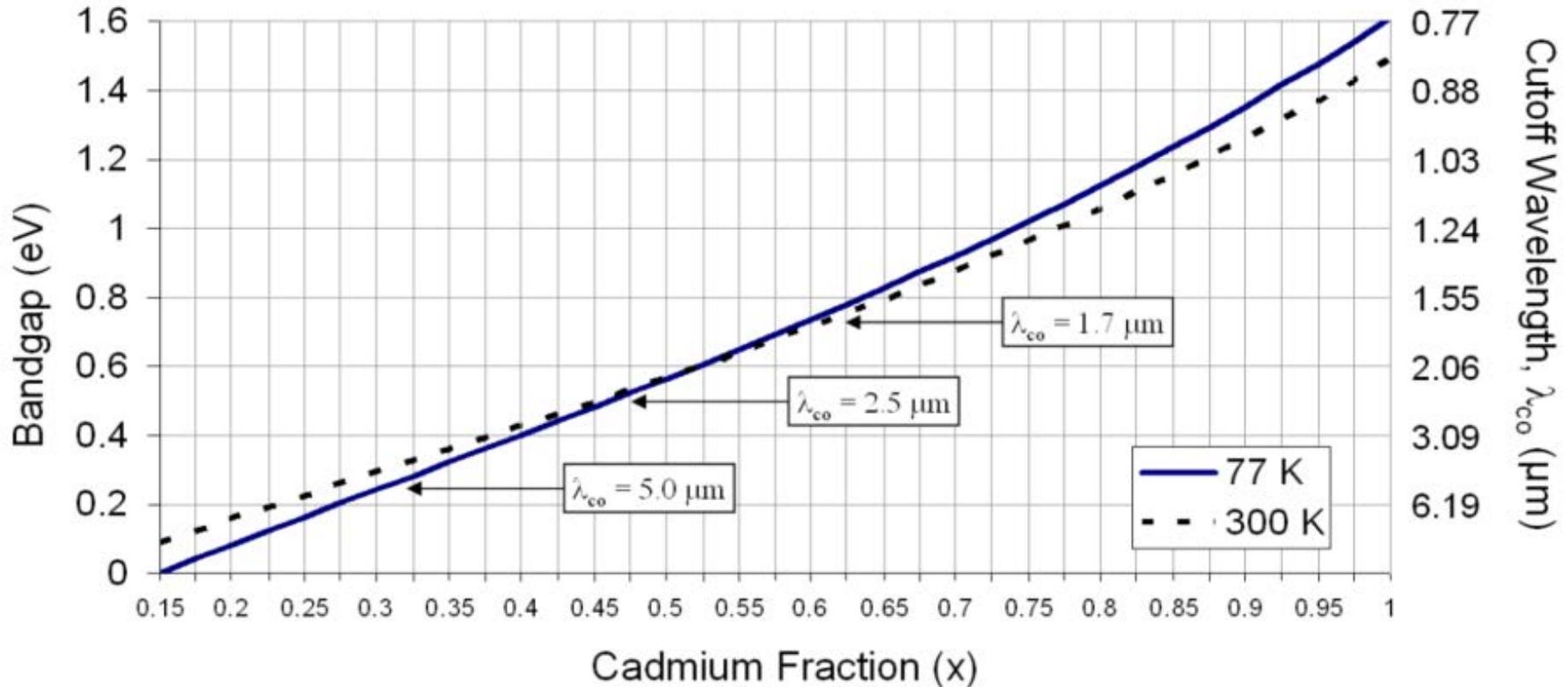
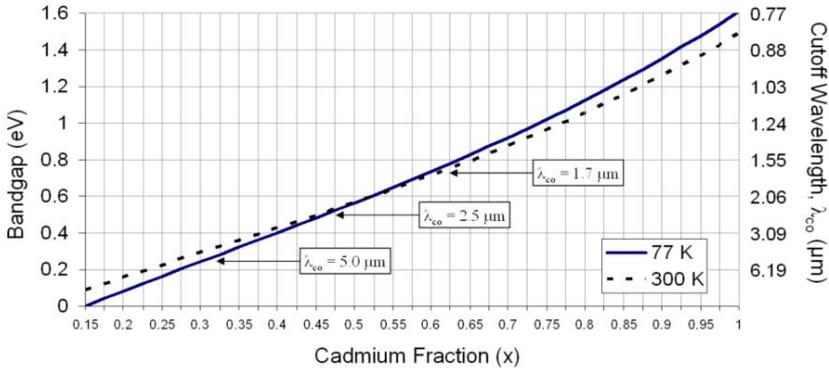


Fig. 3: Bandgap and cutoff wavelength of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  as a function of the cadmium fraction, x.

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

# Photodiodes (4)

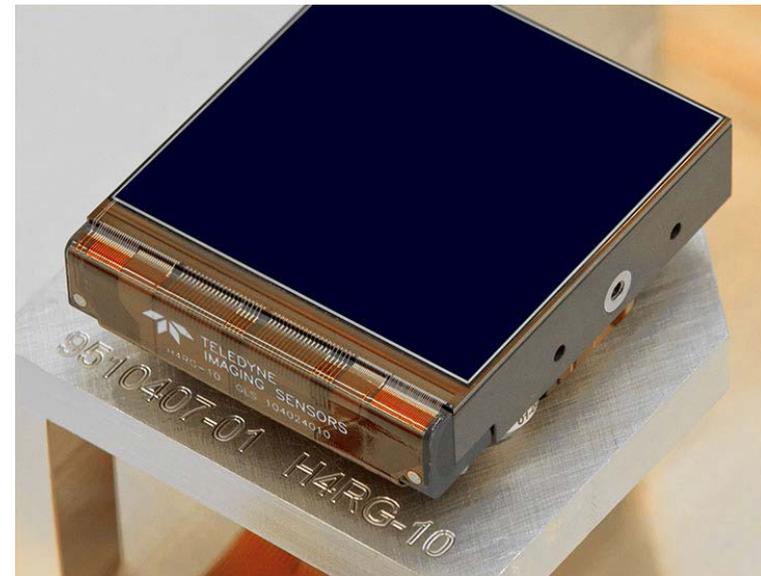
Popular example: HgCdTe  
(used in the HAWAII-4RG arrays)



										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	

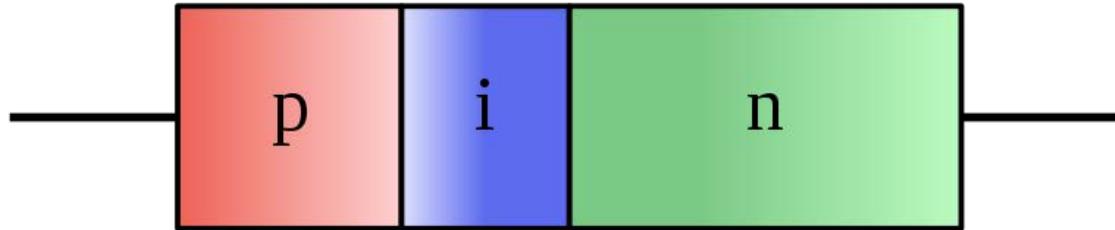
However, to make it **photodiode**, the HgCdTe still needs to be doped:

- n-type: typically **In** at  $5 \times 10^{14} \text{ cm}^{-3}$
- p-type: typically **As** at  $5 \times 10^{15} \text{ cm}^{-3}$



# PIN Diodes

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



In any case, since the photon is **absorbed in the doped region**, its *extrinsic* material properties count:

Material	$\sim \lambda_{\text{cutoff}}$
GaInAs	1.7 $\mu\text{m}$
InAs	3.4 $\mu\text{m}$
InSb	6.8 $\mu\text{m}$

