Detection of Light

STRESSED AND BIB DETECTORS AND PHOTODIODES

08 Oct 2009

See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Nobel Prize 2009

To Willard S. Boyle and George E. Smith (Bell Laboratories) *"for the invention of an imaging semiconductor circuit – the CCD sensor"*

Bell Labs researchers Willard Boyle (left) and George Smith (right) with the charge-coupled device, which transforms patterns of light into useful digital information and is the basis for many forms of imaging, including camcorders and satellite surveillance. Photo taken in 1974 (Alcatel-Lucent/Bell Labs)

Stressed Detectors

Reminder: Extrinsic PC → Longer Wavelengths

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24\mu m}{E_g[eV]}$$

Requires smaller E_g to get response to longer wavelengths

		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	8×10^{-16}
B	p	119	1.0×10^{-14}	28[a]	1.4×10^{-15}
Be	p	52		8.3	5×10^{-18}
Ga	p	115	1.0×10^{-14}	17.2	5×10^{-16}
In	p	111		7.9	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	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}

Not beyond 130µm!

Stressed Detectors

Long λ cut-off of a p-type photoconductor can be modified by applying physical stress on the crystal.

Principle: p-type → conduction via migrating holes → external stress "helps" the inter-atomic bonds to break

Most effective: the [100] axis of the diamond lattice:

GeGa 115μm ➔ >200μm

the practical yield stress of Ge:Ga is ~ 700 N mm^{-2}!

Important when applying forces:

- uniform pressure ("flat-field")
- constant pressure (thermal effects!)
- non-destructive!

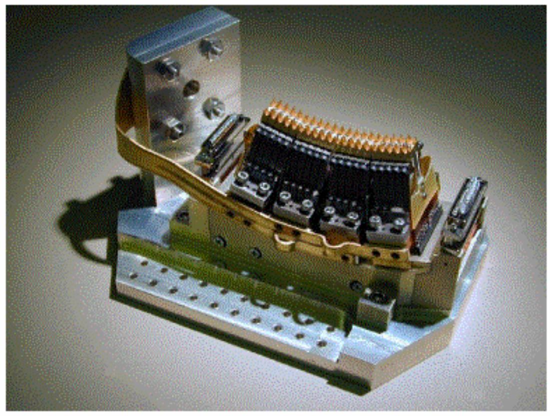
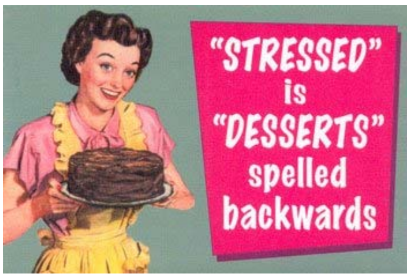
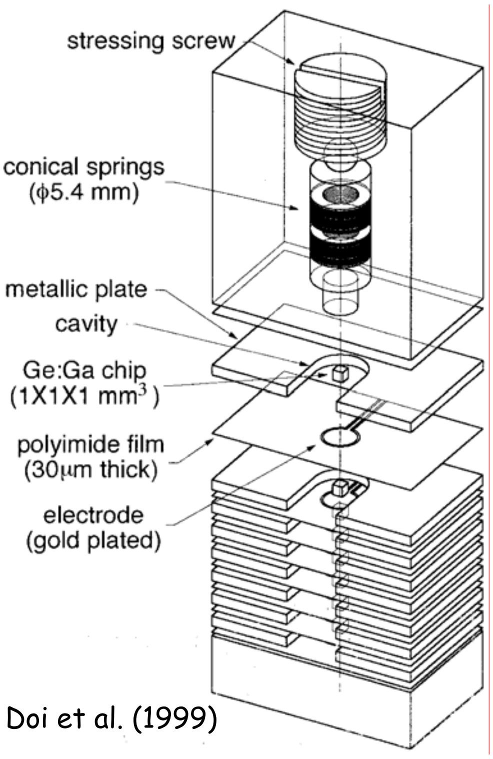


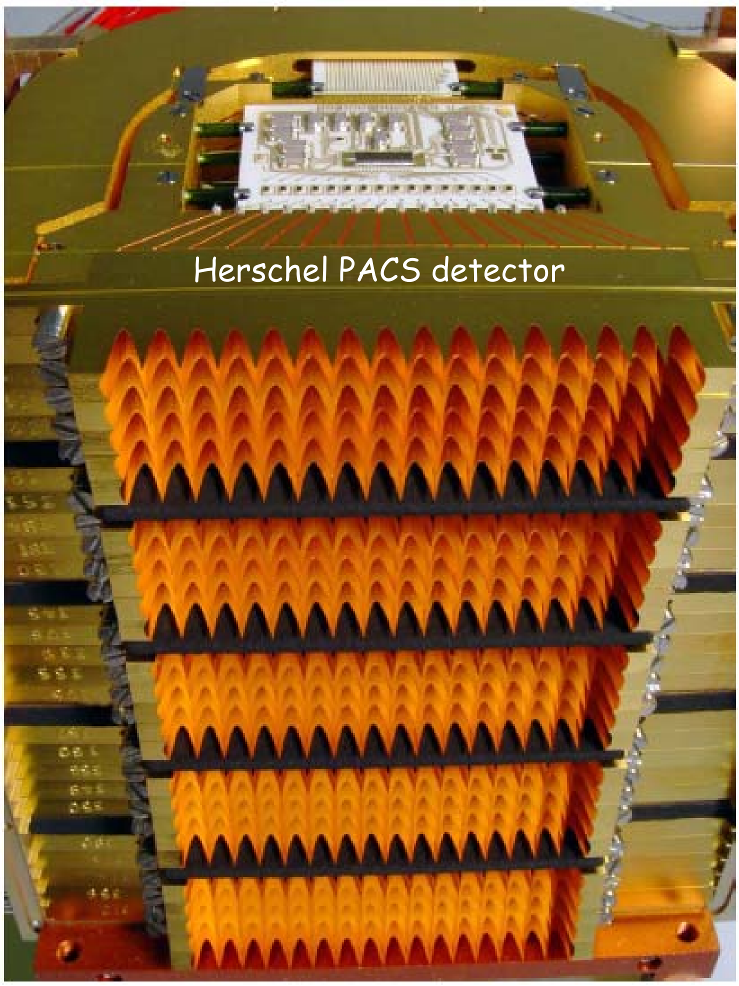
Figure 6. MIPS 160 μm Stressed Ge:Ga Array



Stressed Detectors (2)



Doi et al. (1999)



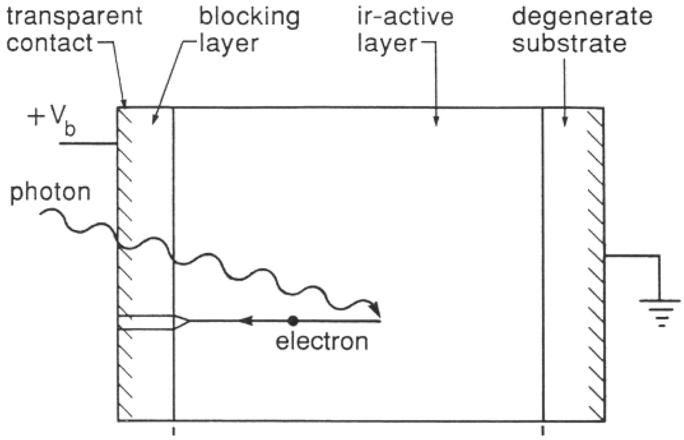
Blocked Impurity Band (BIB) Detectors

Working Principle of BIB Detectors

BIB = Blocked Impurity Band

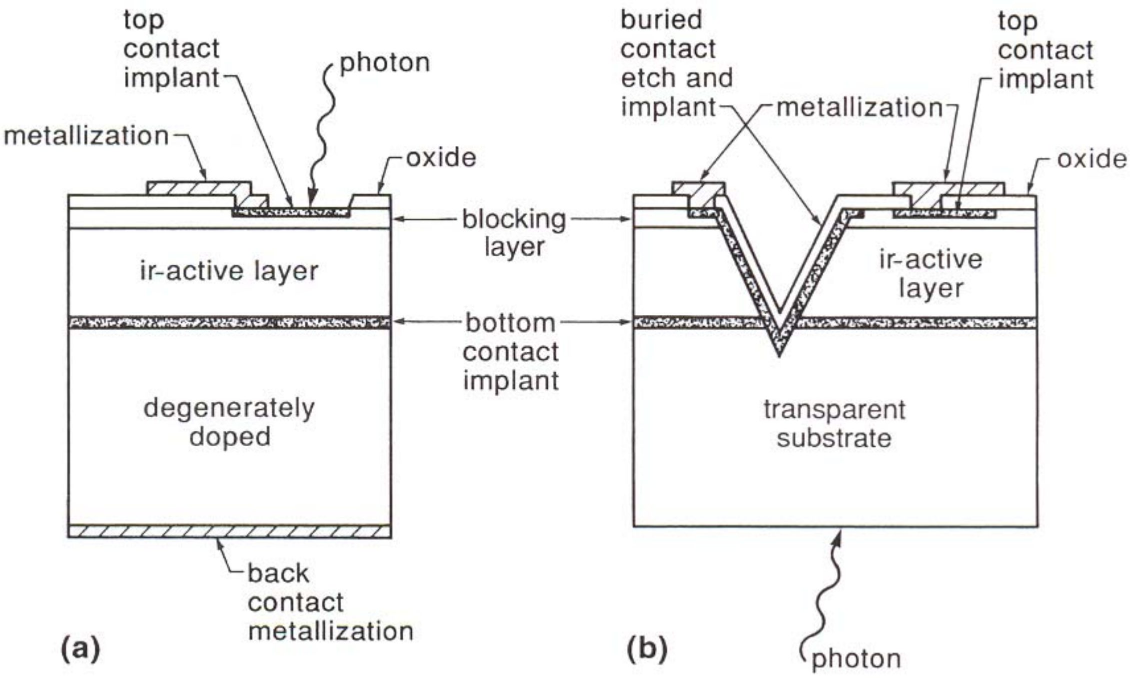
Conflicting requirements in extrinsic semiconductors:
Efficient absorption [$a(\lambda) = \sigma(\lambda)\, N_I$] requires large N_I → *high* conductivity
Minimizing noise requires high resistance → *low* conductivity

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



IR-active layer: heavily doped, typical species: Si:As, Si:Sb
Blocking layer: thin layer of high purity (intrinsic photoconductor)

Two Types of BIB Detectors



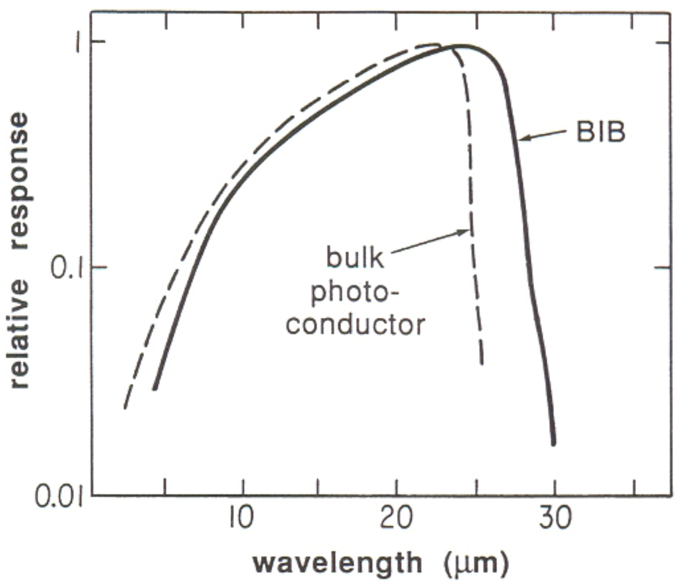
(a) Front illuminated: transparent contact implanted into the blocking layer; back contact by growing detector on extremely heavily doped (conducting) substrate

(b) Back illuminated: thin, transparent contact layer is grown underneath the active layer on a high-purity, transparent substrate.

BIB Detectors and Cut-off Wavelength

Heavy doping widens the impurity band and reduces the gap between impurity and conduction band.

→ Minimum required photon energy is slightly lower for BIB detectors than "bulk photoconductors" → response extends to longer wavelengths.

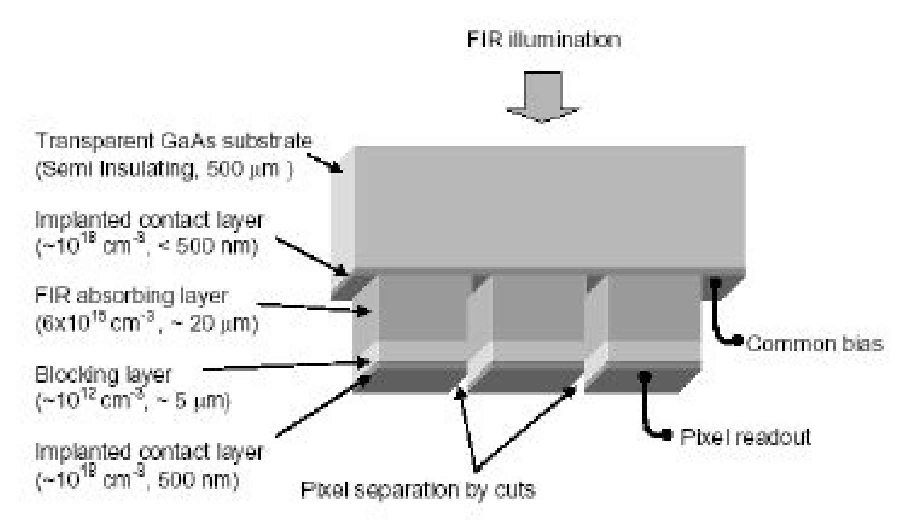


Some Advantages of BIB Detectors

• IR active layer is heavily doped → can be very thin (good for space!)

• extended coverage to longer wavelengths
• high impurity concentrations (without degraded dark current) → high quantum efficiency at shorter wavelengths
→ operation over broader spectral range

• lower impedances → reduced dielectric relaxation effects



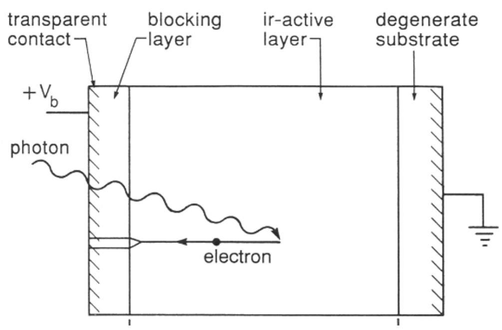
Sketch of a GaAs BIB pilot sample from the MPE GaAs BIB detector development program.

Noise of BIB Detectors

In bulk photoconductors the recombination occurs in the *high* resistance material → G-R noise from photon statistics (G) + random recombinations (R)

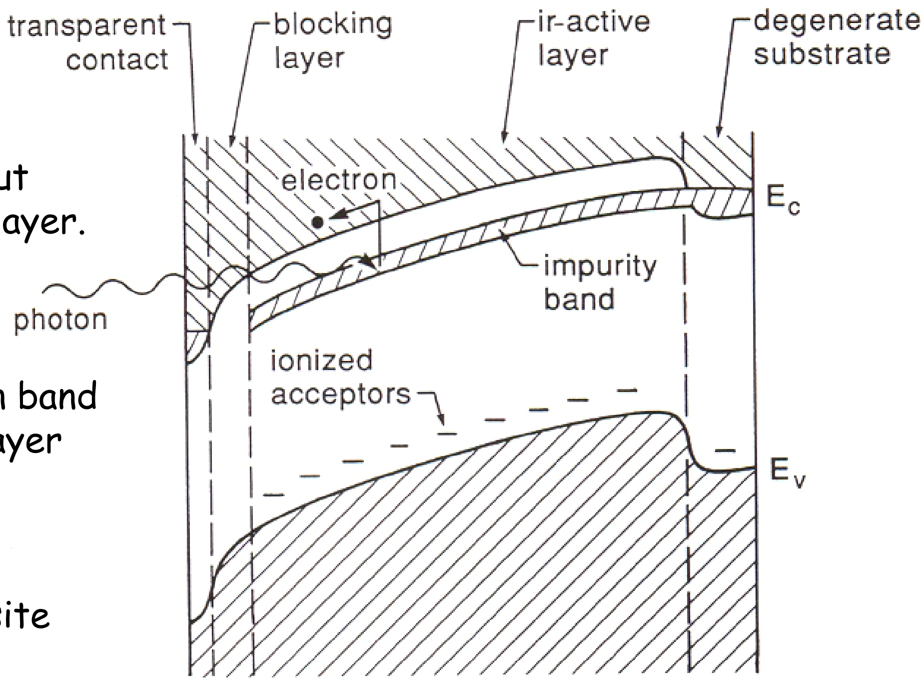
In BIB detectors the recombination occurs in the *low* resistance material → just noise from photon statistics (G)

→ The rms noise current is reduced by a factor $1/\sqrt{2}$
→ This "generation only" noise is termed shot noise.



Operation of BIB Detectors

Apply positive bias voltage to blocking layer of n-type BIB detector. (*BIB detectors are electrically asymmetric*).



e^- move in impurity band but cannot cross the blocking layer.

e^- raised to the conduction band will move to the blocking layer and pass through it to the contact.

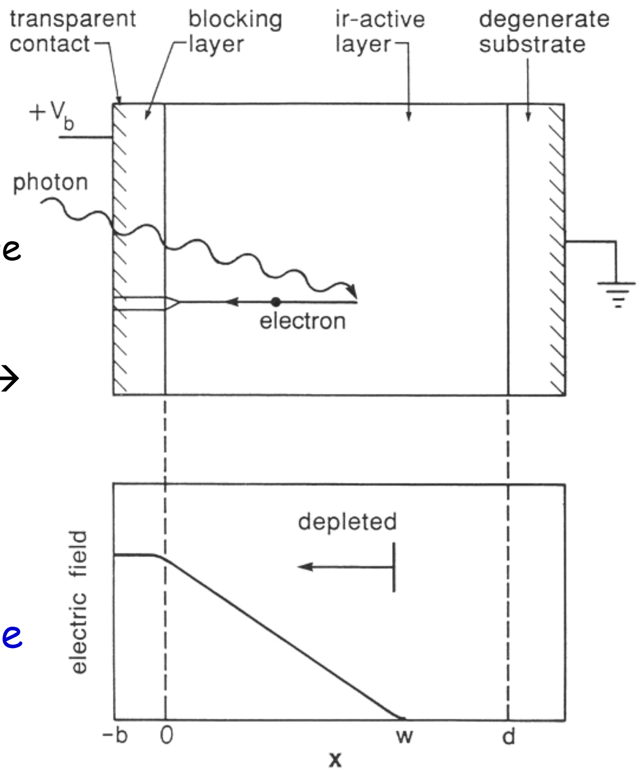
holes migrate to the opposite contact.

Quantum Efficiency of BIB Detectors

Remember: area close to the interface IR-active/blocking layer is depleted of charge carriers.

Depleted region → high Ē-field → any charge will drift rapidly – as it should be!

Beyond depleted region → reduced Ē-field → inefficient collection of charges → low QE.



In other words:

- The quantum efficiency depends on the width of the depletion region.

- The width of the depletion region depends on the bias voltage.

Importance of the Depletion Region

Density of charges is described by Poisson's equation: (where κ_0 = dielectric constant, ρ = charge density, ε_0 = permittivity of free space, and N_A is the density of the minority (p) carriers that get compensated (by the As) and contribute a counteracting space charge. Typically $N_A \sim 10^{13}$ cm^{-3}).

$$\nabla D = \rho \Rightarrow$$

$$\frac{dE_x}{dx} = \frac{\rho}{\kappa_0 \varepsilon_0} = -\frac{qN_A}{\kappa_0 \varepsilon_0}$$

Width = distance from interface to where the Ē-field becomes zero (with $dV/dx = -E_x$): (where t_b = thickness of blocking layer, and V_b = bias voltage).

$$w = \left(\frac{2\kappa_0 \varepsilon_0}{qN_A} |V_B| + t_B^2 \right)^{1/2} - t_B$$

Note: the width of the depletion region (and hence the quantum efficiency) will increase with the bias voltage until it reaches the size of the IR-active layer t_{IR}.

The maximum useful ("critical") bias voltage is: $V_{bC} = \frac{qN_A}{2\kappa_0 \varepsilon_0} \left(t_{ir}^2 + 2 t_{ir} t_B \right)$

Pros and Cons of a high Bias Voltage

Cosmic rays damage blocking layer crystal structure → increases I_{dark}.

Mitigation: use very pure blocking layers with $N_A < 10^{12}$ cm^{-3}
→ reduces required V_b to reach a certain depletion width
→ lowering V_b reduces I_{dark}.

Typical V_b are in the order of a few Volts.

Typical mean free path in Si:As is ~200nm.
Given a strong local Ē-field the e$^-$ may gain sufficient energy to ionize neutral As impurity atoms.
➔additional atoms in the conduction band
➔this process may repeat → cascade of electrons created by a single photon.

Careful choice of V_b will produce photoconductive gains $G > 1$.
Practically, one operates BIB detectors at $G \sim 5$-10 to overcome amplifier noise.

G > 1 and the Noise

High gains come with additional noise due to:
- statistics of the "avalanche"
- local effects of the "gain region"

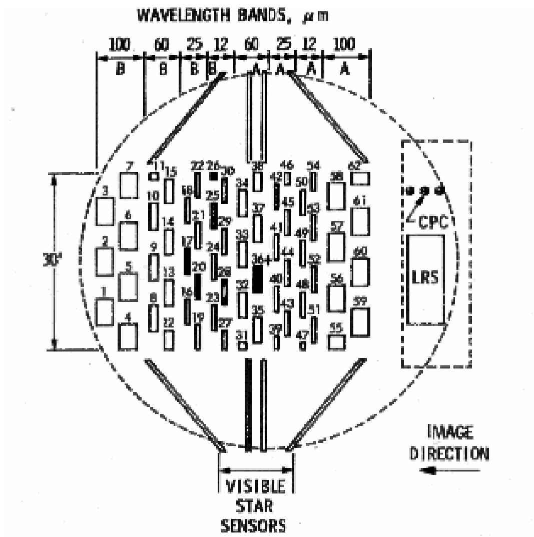
Increase in noise is described by the gain dispersion β: $\beta = \frac{\langle G^2 \rangle}{\langle G \rangle^2}$

...which reduces the quantum efficiency η: $DQE = \frac{\eta}{\beta}$

Because BIB detectors have no recombination noise $\langle I_{G-R} \rangle$ is reduced by $\sqrt{2}$:

$$\langle I_{G-R}^2 \rangle = 4q^2 \varphi \eta G^2 \Delta f \rightarrow \boxed{\langle I_{shot}^2 \rangle = 2q^2 \varphi \frac{\eta}{\beta} (\beta G)^2 \Delta f}$$

Question about IRAS (1983) detectors



62 detectors covering 4 bands:

12μm	Si:As
25μm	Si:Sb
60μm	Ge:Ga
100μm	Ge:Ga

From the book "Ripples in the Cosmos: View Behind the Scenes of the New Cosmology " on COBE and IRAS by Michael Rowan-Robinson:
[describing problems of IRAS before launch]
"As the launch date approached a group of detectors failed due to a shortcut. Jim Houck, a member of the US team from Cornell University, had the rescuing idea to reverse the detector polarity and to ground them again – and it worked."

Question: Could the IRAS detectors have been BIB detectors?

BIB and Stressed Detectors – a Comparison

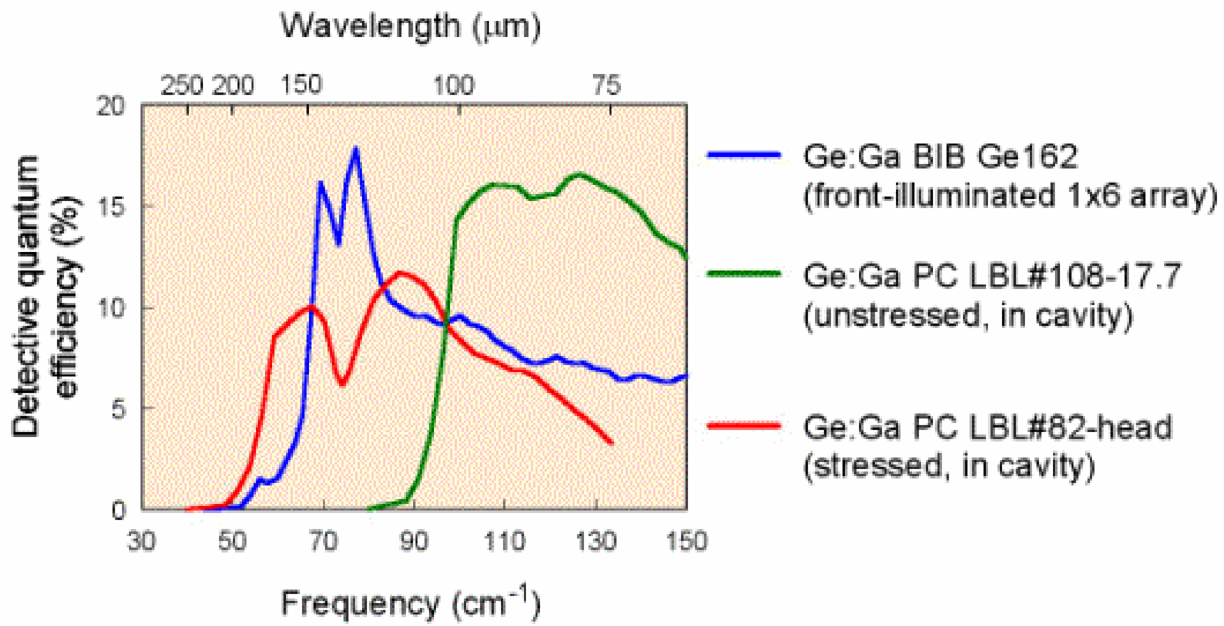


Figure 11. Comparison of Ge BIB and Conventional Photoconductors (D. Watson)

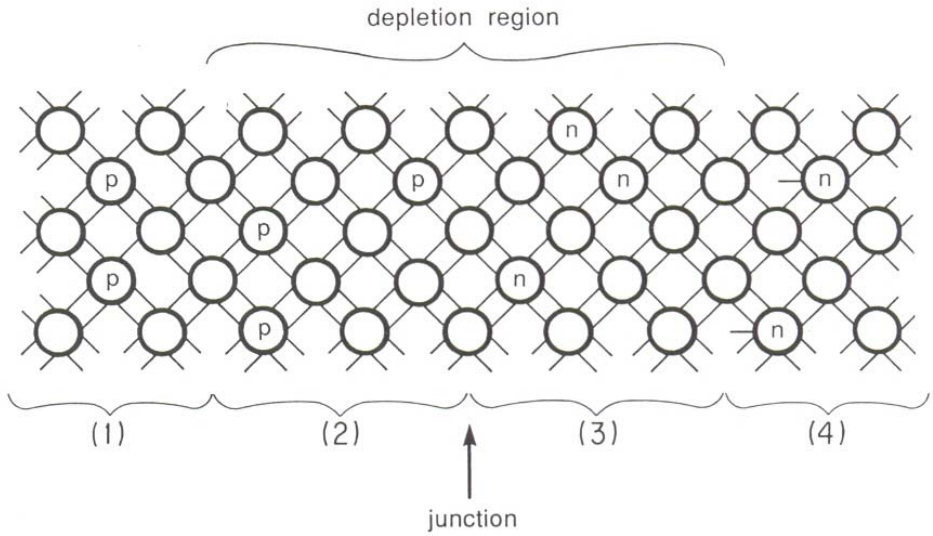
Figure taken from "Germanium Detectors for the Far-Infrared" by Erick T. Young

Now: FIR → Vis/NIR

Photo-Diodes

General problem of near-IR detectors: impossibility to achieve *simultaneously* high sensitivity (high G) *and* low noise (large R).

Basic Principle: p-n Junction

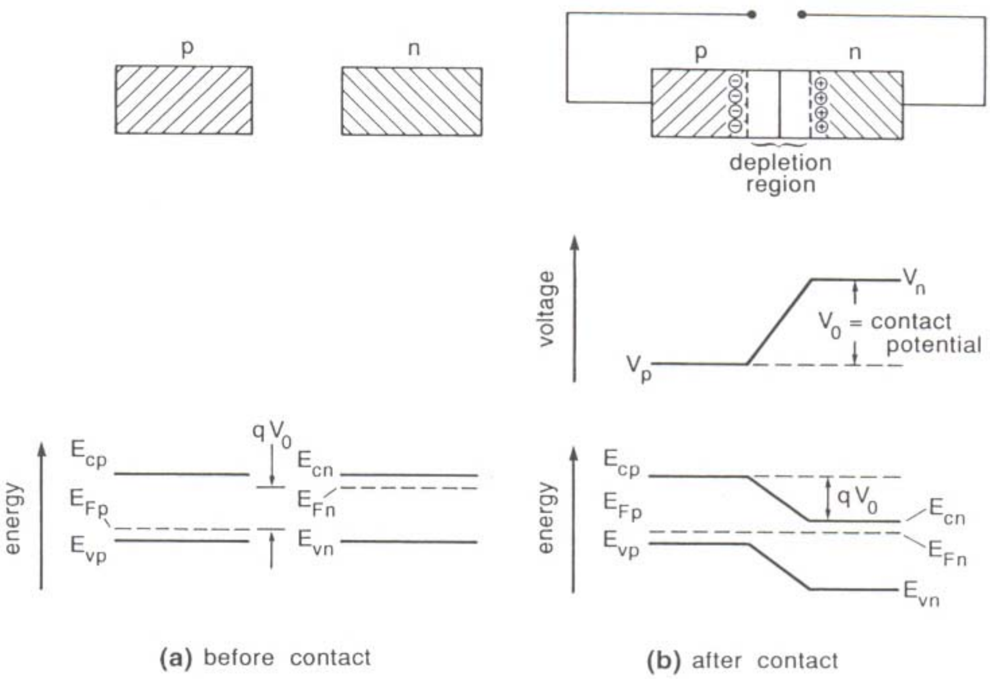


n-type: surplus of e^- p-type: lack of e^-
Thermal excitation → e^- diffuse into p-type region → space charge region → depletion of charge carriers → high resistance.

Diffusion process results in a voltage difference across the junction : contact potential V_0.

Outside the depletion region (due to high doping levels): R and $\bar{E}$ are low

Contact Potential across a Junction



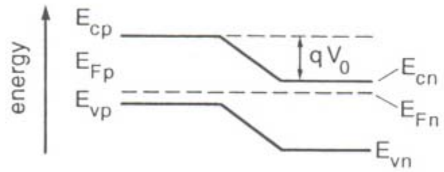
The contact potential V_0 is determined by the difference in the Fermi levels:

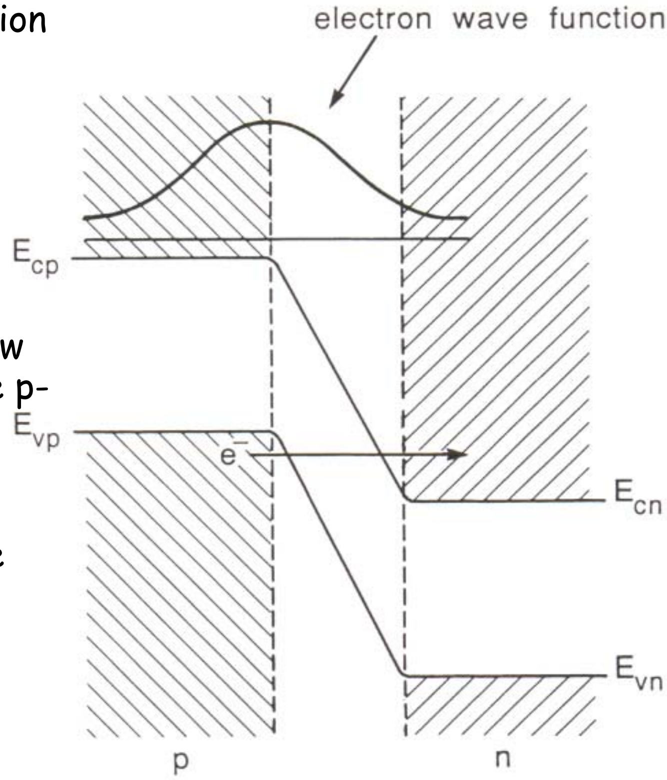
$$\Delta E_F = q\,V_0$$

Applying Reverse Bias

1. Apply voltage such that it adds to the contact potential → reverse bias (positive voltage to n-type material)

Increases potential across depletion region → increases width and resistance





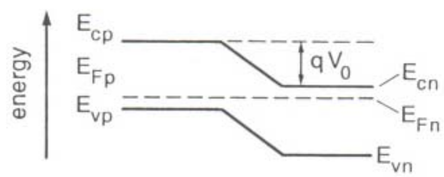
A modest reverse bias can bring E_{cn} below E_{vp} (conduction band in n-type below the p-type valence band).

Now, an e^- does not need to move to the conduction band (E_{cp}) – if the depletion region is thin (relative to the e^- wavefunction) tunneling can occur.

Applying Forward Bias

1. Apply voltage such that the contact potential is reduced → forward bias

Reduces potential across depletion region



A forward bias with $V > V_0$ will make $E_{vn} > E_{Fn}$, and the junction is strongly conducting.

General behaviour of a diode:

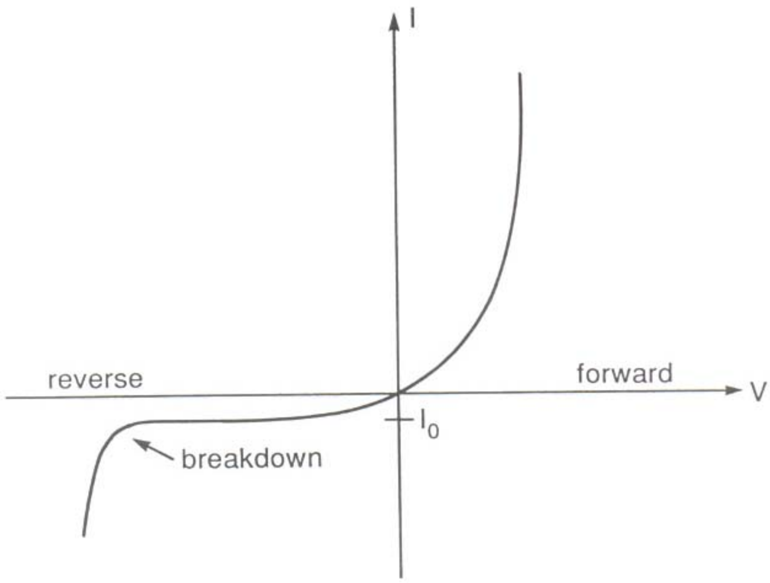
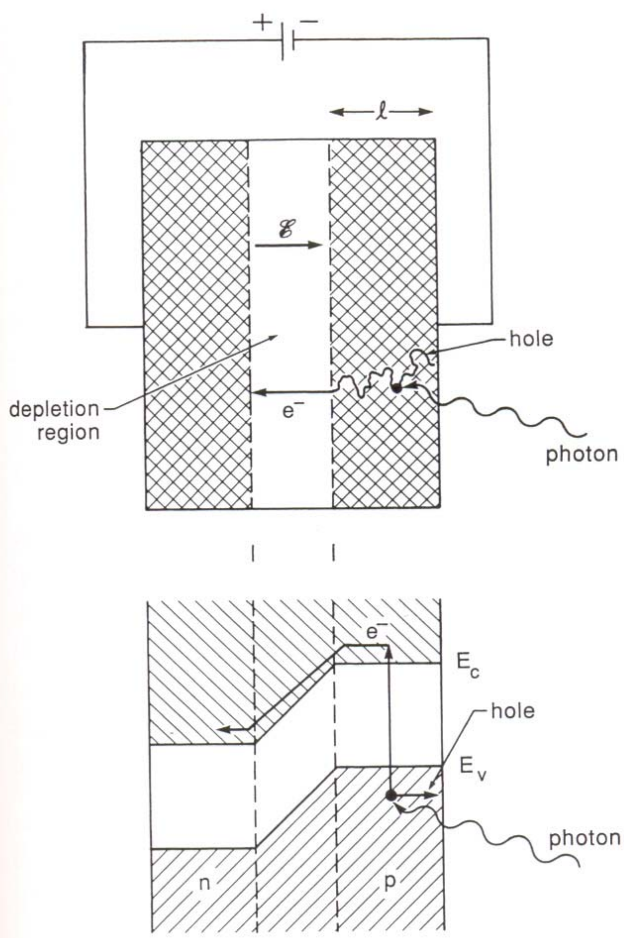


Photo-excitation in Photodiodes

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

Same if absorbed in n-type part but then the hole migrates through junction.



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

$Hg_{1-x}Cd_xTe$ → λ_{cutoff} = 1 … 15 μm

Varying x you can tune your HgCdTe detector response:

$$E_g(x,T) = -0.303 + 1.816x - 0.0962x^2 + 0.189x^3 + \frac{\left(6.3 - 15.84x + 6.29x^2\right)\cdot 10^{-4} T^2}{11 + 67.7x + T}$$

Commercial Applications of Photodiodes

From Wikipedia:

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).

Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a better, more linear response than photoconductors.

For higher temporal frequencies (e.g. optical communications) PIN diodes (see below) are preferred.

Wikipedia also writes: *"P-N photodiodes are not used to measure extremely low light intensities. Instead, if high sensitivity is needed, avalanche photodiodes, intensified charge-coupled devices or photomultiplier tubes are used for applications such as astronomy, spectroscopy, night vision equipment and laser range finding."* – not quite, though!

Summary: Properties of Photodiodes

Summary of characteristics of Photodiodes:

- Based on junction between *two* oppositely doped zones
- Two adjacent zones create depletion region with high impedance
- Can operate at high sensitivity at room temperature
- Intrinsic absorption → high quantum efficiency in small volumes
- Limited to $\lambda < 15\mu m$
- Can be constructed in arrays of millions of pixels
- Detectors of choice for 1 – 6 µm, visible and near-UV