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Center for Advanced Sensor Systems

Semiconductor Scintillator and 3D Integration

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ECE Department and Sensor CAT

Radiation Detection for Homeland Security:

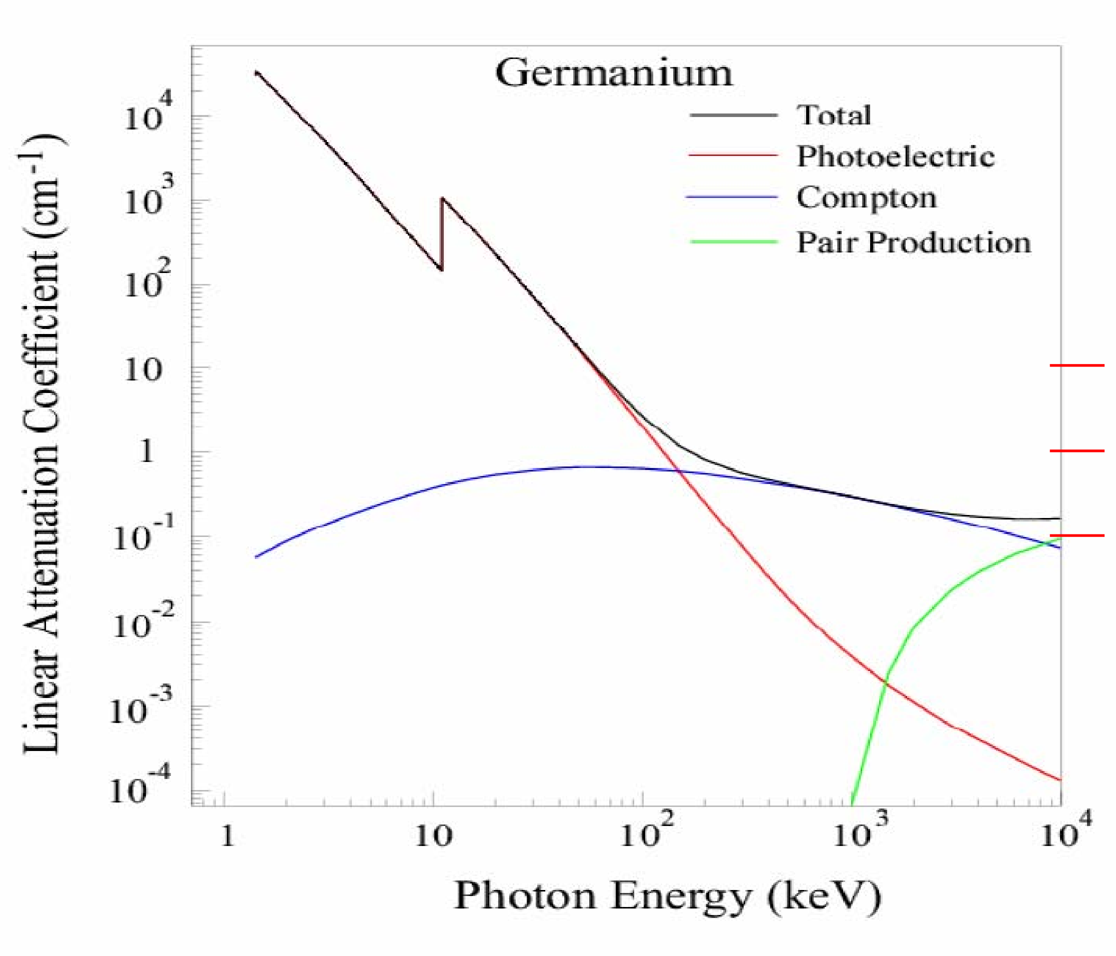
- Isotope identification

  spectroscopic energy resolution

- Direction to source

  angular resolution

X-ray (γ-ray) attenuation



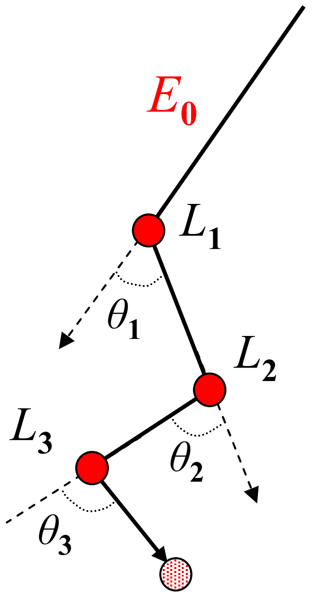
absorption length

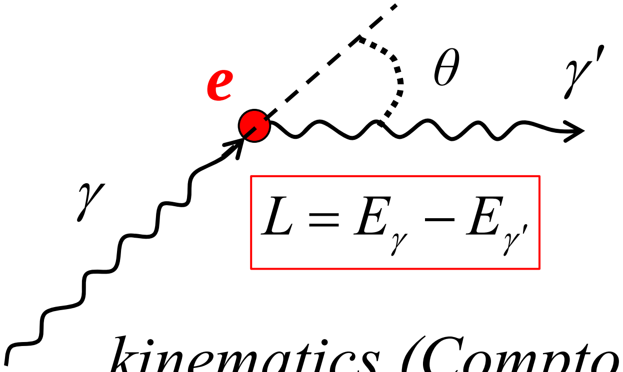
1 mm

1 cm

1 dm

Compton Scattering





$$\boxed{L = E_\gamma - E_{\gamma'}}$$

$$m_e c^2 = 511\,\mathrm{KeV}$$

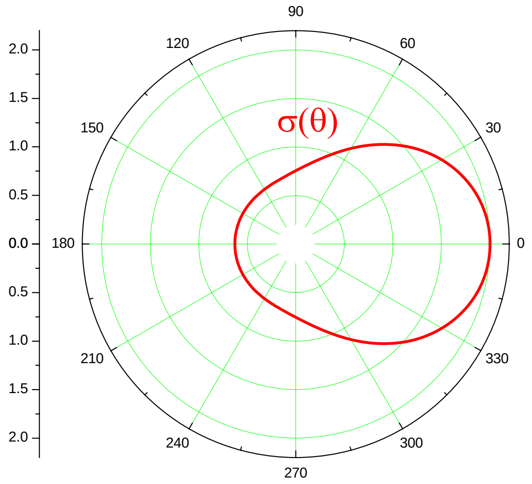
$$E_\gamma = 662\,\mathrm{KeV}\ \ (\mathrm{Cs}^{137})$$

kinematics (Compton):

$$\cos\theta = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E_{\gamma'}}$$

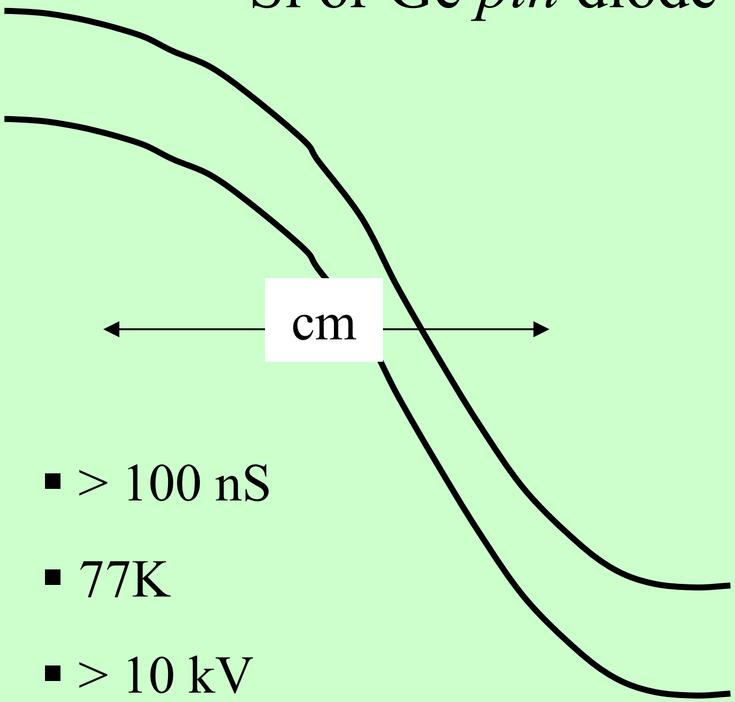
dynamics (Klein-Nishina):

$$\sigma(\theta) = \sigma_0 \left(\frac{E_{\gamma'}}{E_\gamma}\right)^2 \left(\frac{E_{\gamma'}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma'}} - \sin^2(\theta)\right)$$



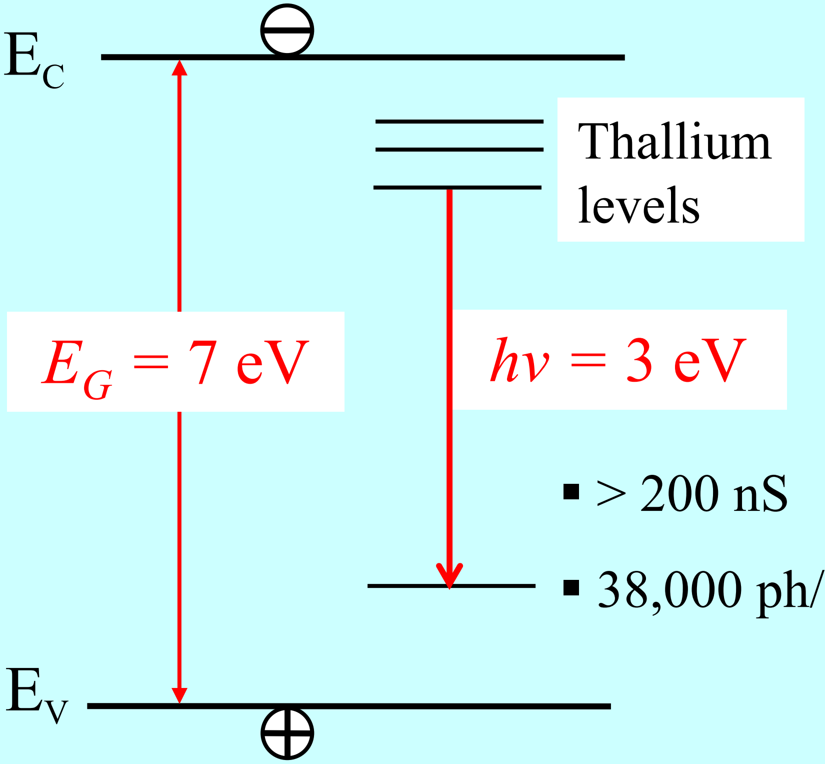
Diodes and scintillators

Si or Ge *pin* diode



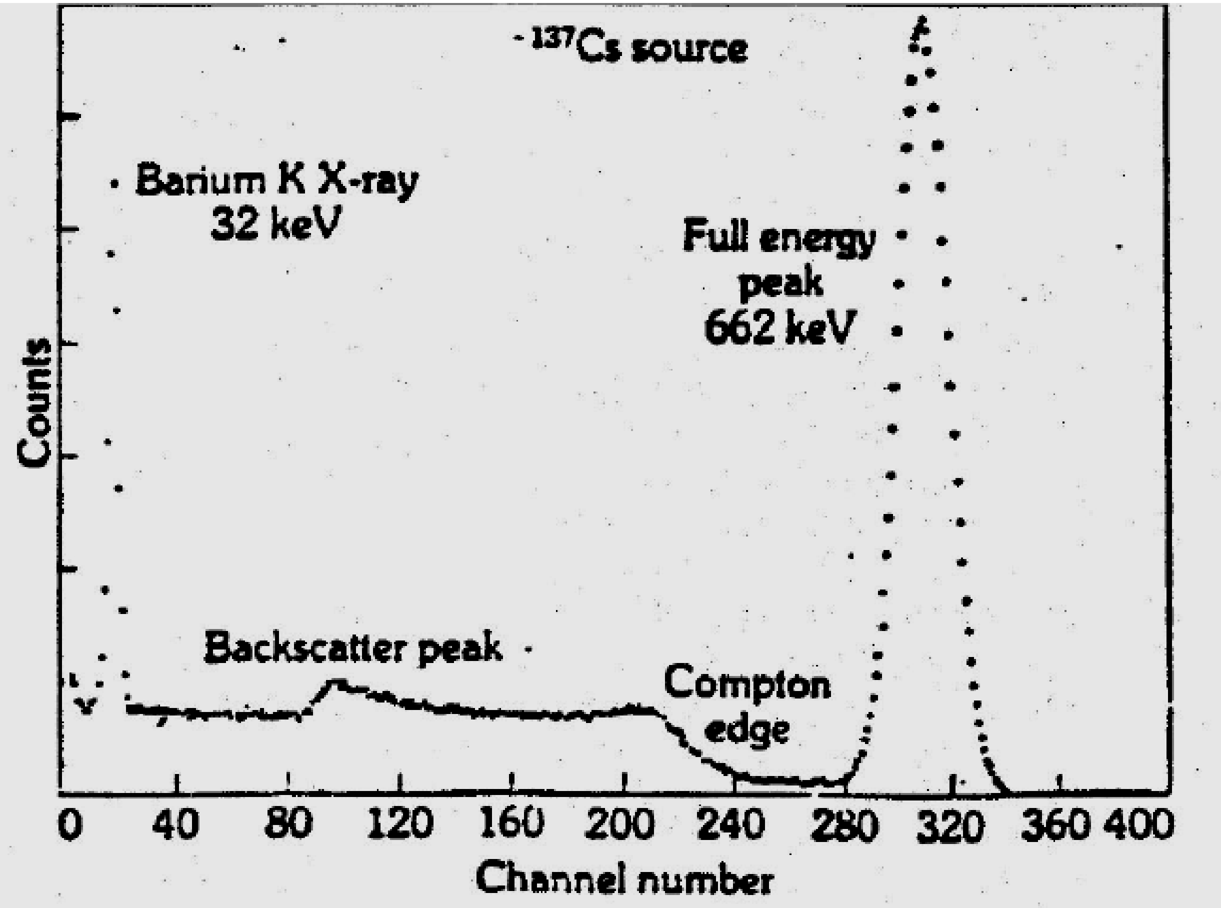
- > 100 nS
- 77K
- > 10 kV
- up to 300,000 e-h/MeV

NaI scintillator

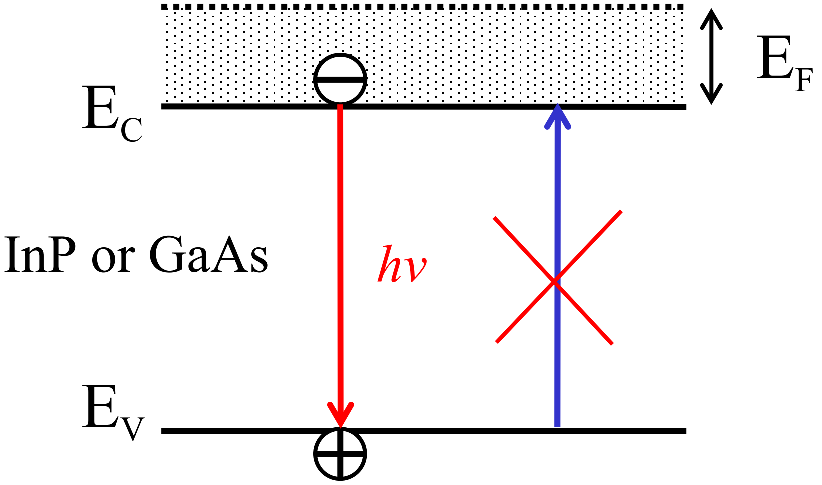


- > 200 nS
- 38,000 ph/MeV

Gamma spectroscopy



Main Idea*



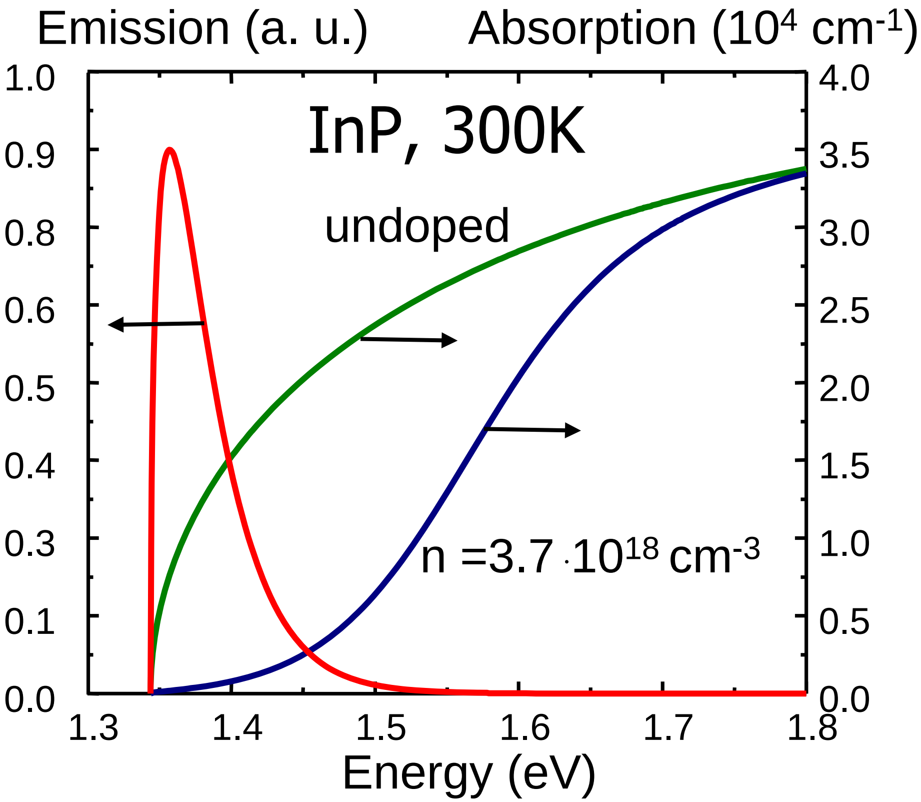
- Radiative decay time ≈ 1 ns
- Photon re-absorption suppressed due to high Fermi level (Burstein shift)
- Expected light yield ≈ 100%
- Absolute yield ≈ 240,000 ph/MeV

material transparent to its own fundamental light emission

photons are delivered to the surface from deep inside the semiconductor

*A. Kastalsky, S. Luryi, B. Spivak, *Nucl. Instr. and Methods in Phys. Research* **A 565**, pp. 650-656 (2006)

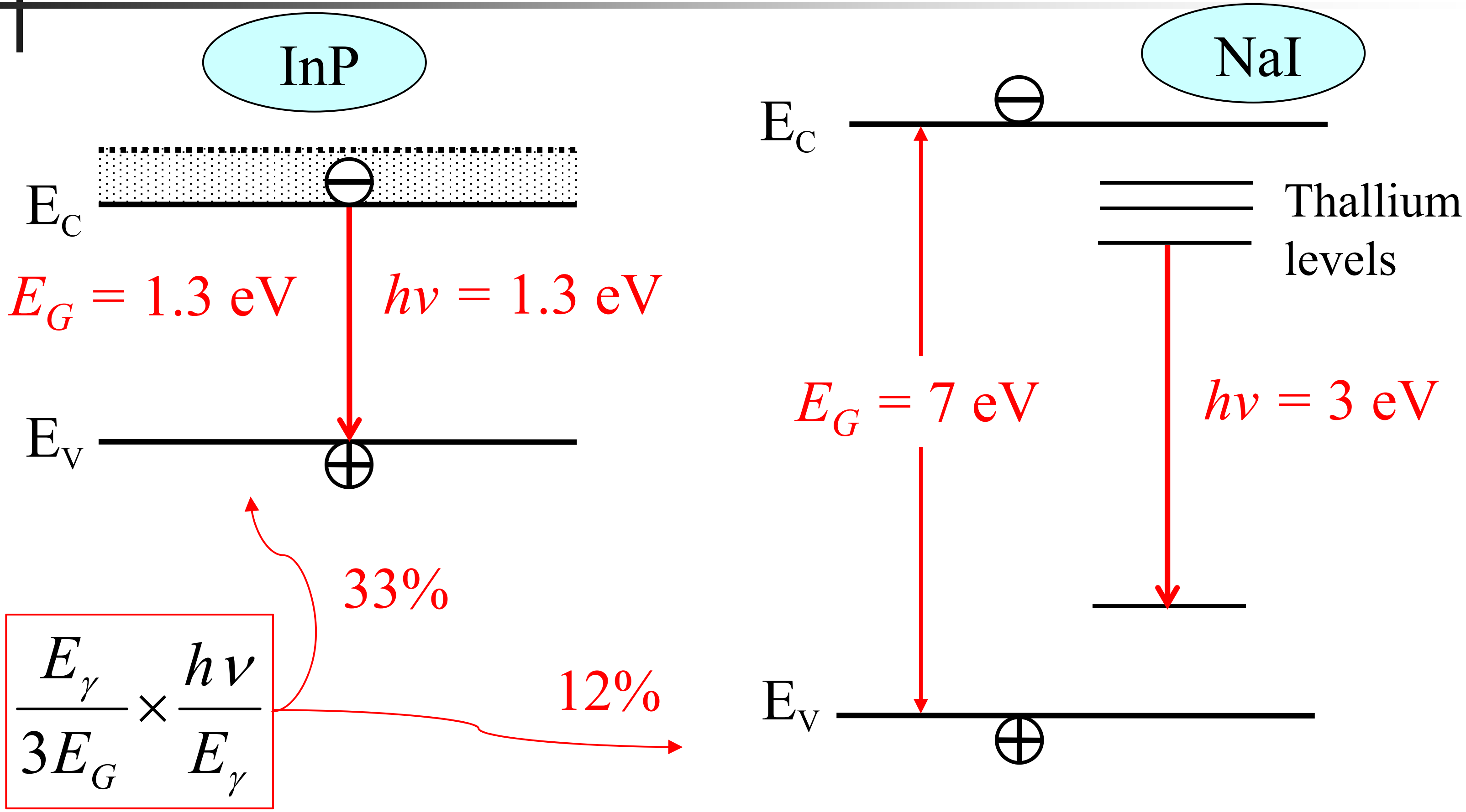
Burstein shift



$$\lambda \approx \lambda_0 \, e^{E_F/kT}$$

absorption mean free path λ *is exponentially enhanced compared to* $\lambda_0 \approx 1\ \mu\text{m}$

Comparison of InP scintillator with activated crystalline NaI



InP

E_C

$E_G = 1.3$ eV

$h\nu = 1.3$ eV

E_V

33%

12%

$$\frac{E_\gamma}{3E_G} \times \frac{h\nu}{E_\gamma}$$

NaI

E_C

Thallium levels

$E_G = 7$ eV

$h\nu = 3$ eV

E_V

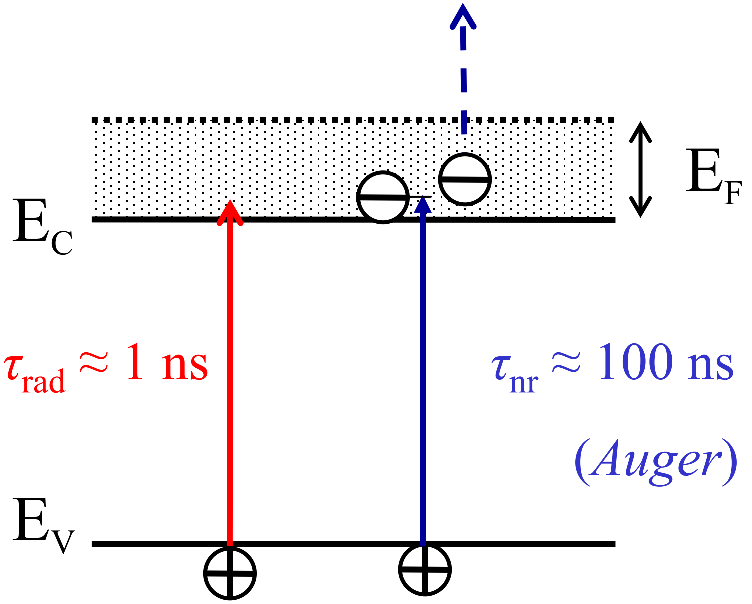
Response time

Radiative recombination

$$\boxed{R = Bnp = \frac{p}{\tau_{\text{rad}}}}$$

Nonradiative recombination

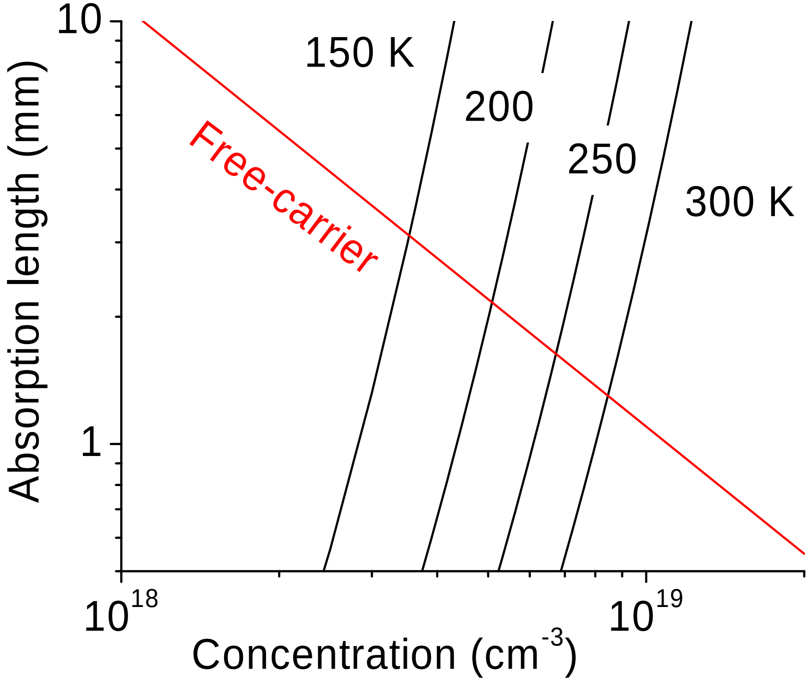
$$\boxed{R_{\text{nonrad}} = Cn^2 p \equiv \frac{p}{\tau_{\text{nr}}}}$$

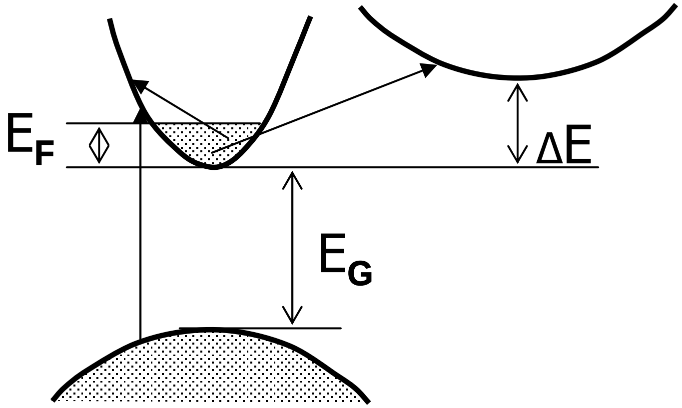


Radiative efficiency 99% with *response time*: τ_{rad}

Free-carrier absorption

InP (at 0.92 μm)





- Room temperature optimum ≈ 1mm with re-emission several mm (explained on next viewgraph)
- Standard GaAs or InP wafer thickness 0.5 mm
- Stack up layered systems

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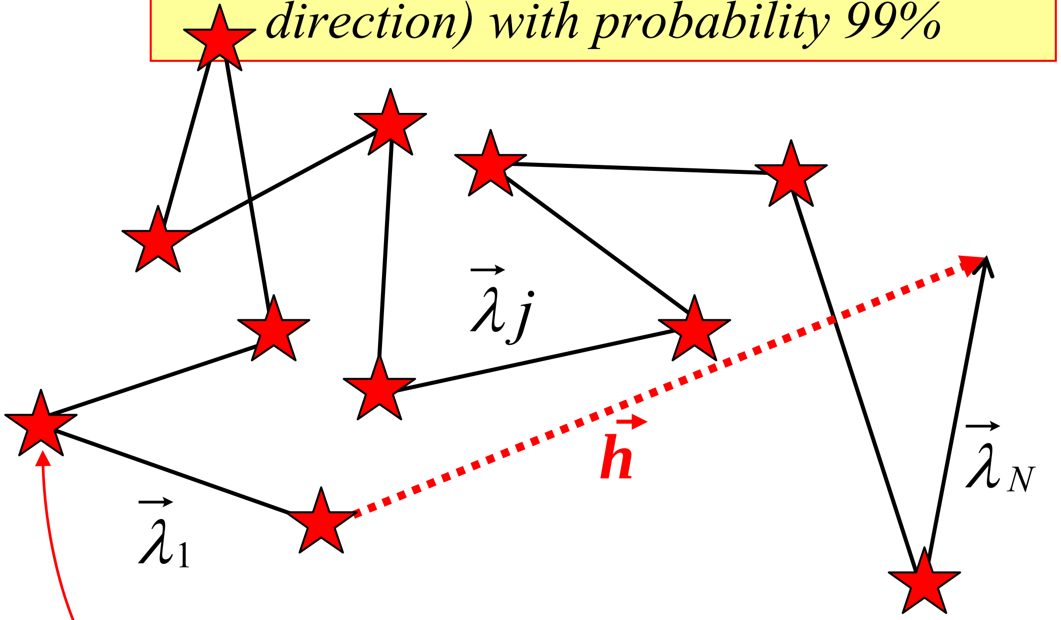
Diffusive propagation of light

after every interband absorption event the photon is regenerated (in a random direction) with probability 99%



$$\vec{h} = \sum_{j=1}^{N} \vec{\lambda}_j$$

$$h^2 = \sum_j \lambda_j^2 + \sum_{i \neq j} \vec{\lambda}_j \cdot \vec{\lambda}_i$$

$$\langle h^2 \rangle = N \langle \lambda^2 \rangle$$

$$\bar{h} = \sqrt{N}\,\lambda$$

We can take 1 cm thick slab and still collect over 80%

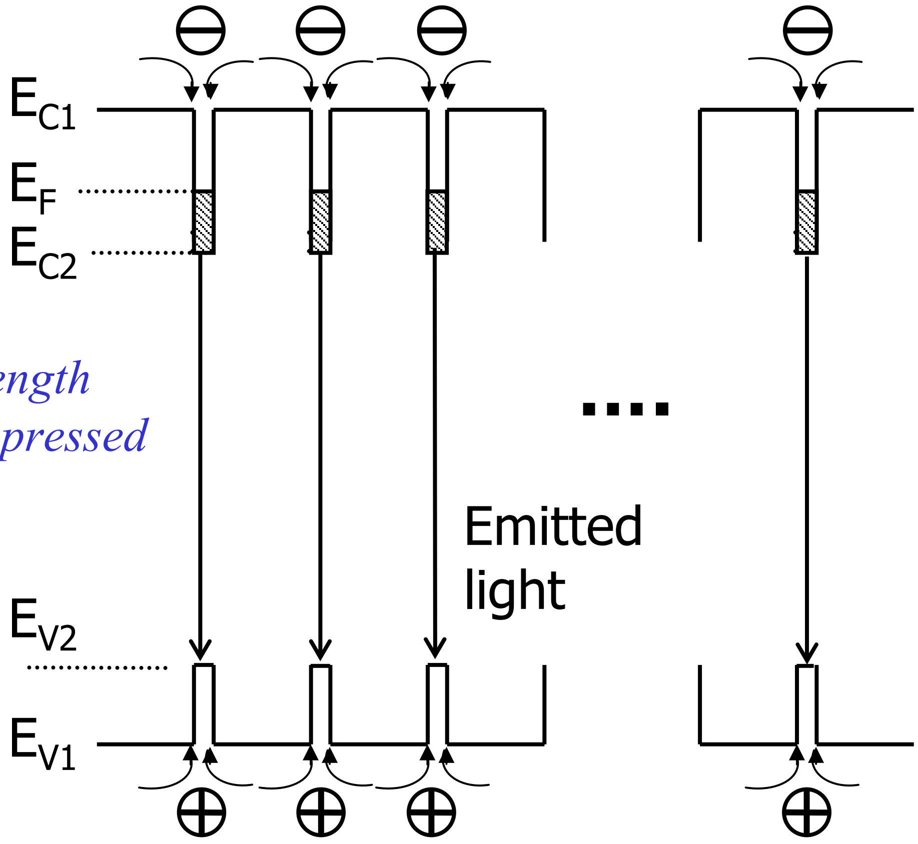
each re-emission introduces delay $\tau_{\text{rad}} \approx 1$ nS

Heterostructures

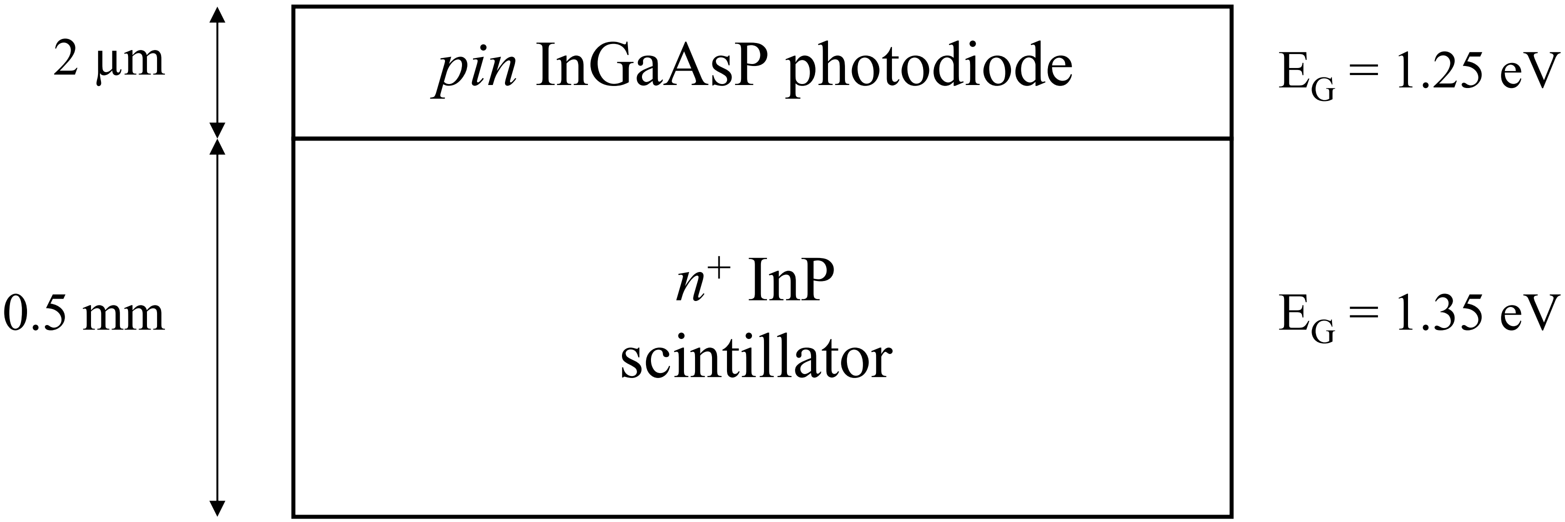
$$\tilde{\lambda} = D \times \lambda$$

$$D \approx 100 \text{ (Duty cycle)}$$

- *virtually unlimited absorption length*
- *free-carrier absorption also suppressed*
- *tough to make, however !*



Epitaxial detector
enables 3D integration



2 μm

pin InGaAsP photodiode

$E_G = 1.25$ eV

0.5 mm

n^+ InP
scintillator

$E_G = 1.35$ eV

back to DHS applications

- Scintillator with a “semiconductor” resolution: excellent isotope discrimination
  high spectroscopic resolution results from 240,000 photons per MeV
  and nearly 100% photoelectric conversion at epitaxial photodetector
  expected Fano factor $F=0.1$
- Exceptional sensitivity results from virtually unlimited
  detector thickness by 3D integration:
  increased stand-off distance
- Room temperature operation: moderate cost
- Ultrafast response (1 ns): rapidly moving targets
- Pixellated and layered photodetector system: **directional capability**
  the technique provides *both* angular resolution and isotope identification

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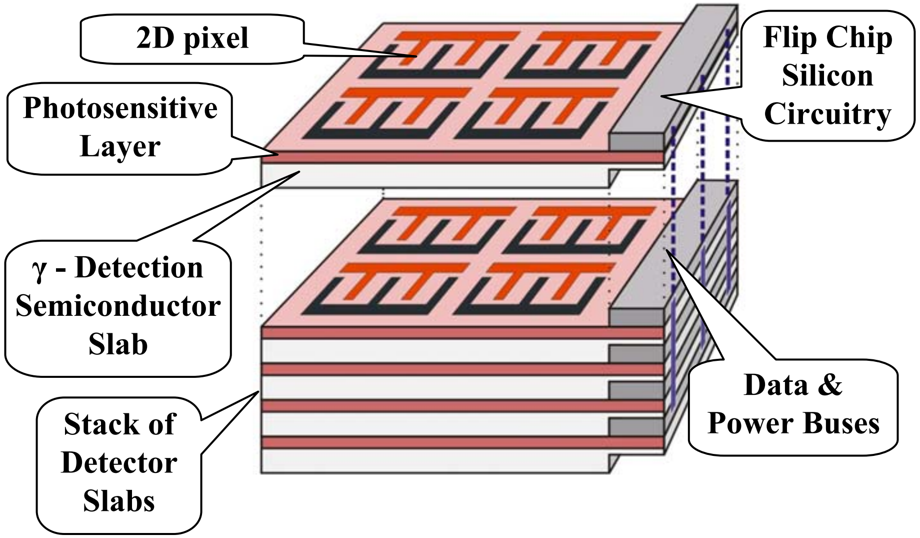
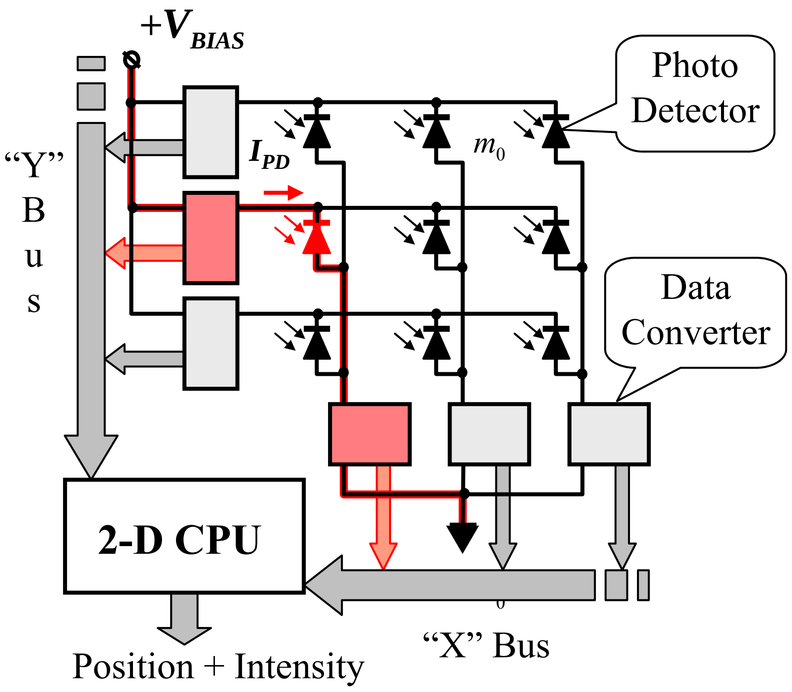
3D Pixellation



Upon analog-to-digital conversion each unit reports not a 1 ns pulse but an information-carrying signal:

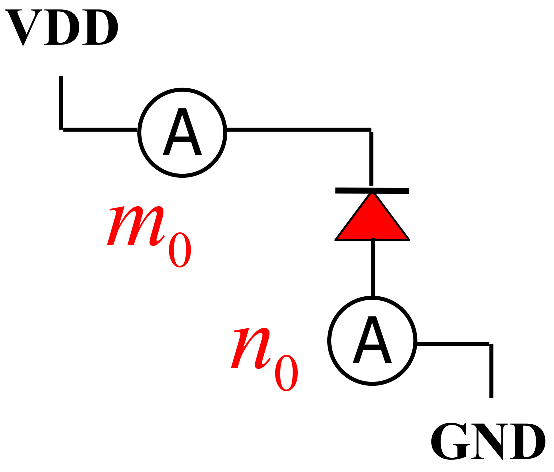
- where ionization occurred
- time of the event
- amplitude of the event

Photodetection Matrix

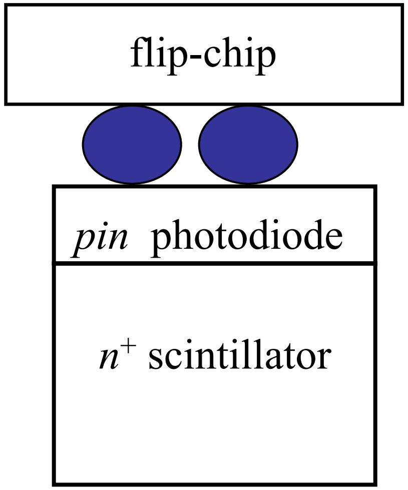


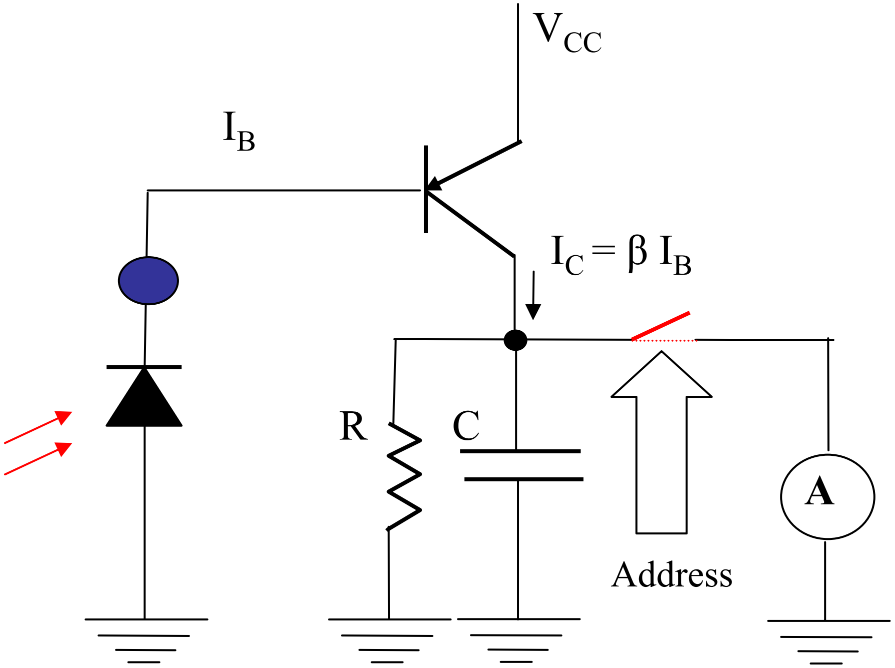
$m \times n$ detector array

$m + n$ # of data lines and converters



Partition between InP and Si



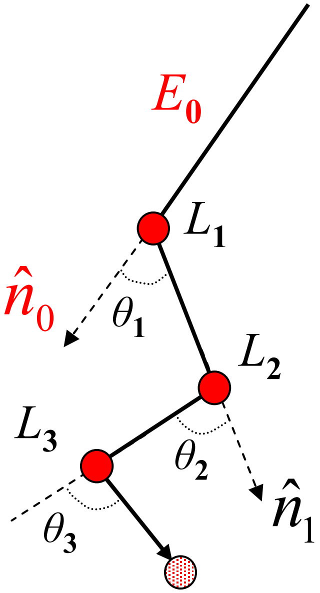


Compton "telescope"

kinematics:

$$\boxed{\begin{aligned} \cos\theta_i &= 1 + E_{i-1}^{-1} - E_i^{-1} \\ L_i &= E_{i-1} - E_i \end{aligned}}$$

(in units of $m_e c^2 = 511\,\mathrm{keV}$)

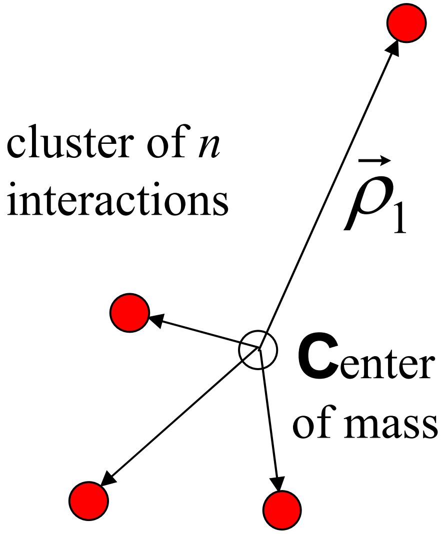


Having identified first three interactions (in the correct order) we find the energy of the incident photon:

$$\boxed{E_0 = L_1 + \frac{L_2}{2} + \frac{1}{2}\left(L_2^2 + \frac{4L_2}{1-\cos\theta_2}\right)}$$

Also the directional cosine $\hat{n}_0 \cdot \hat{n}_1$
about the measured direction $\mathbf{n}_1$
i.e., the object is placed on a cone

Direction to source



cluster of *n* interactions

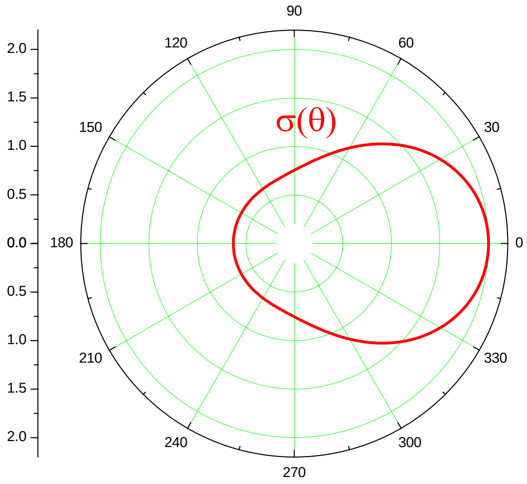
Center of mass

dynamics (Klein-Nishina formula):

$$\boxed{\sigma(\theta_i) = \sigma_0 \left(\frac{E_i}{E_{i-1}}\right)^2 \left(\frac{E_i}{E_{i-1}} + \frac{E_{i-1}}{E_i} - \sin^2(\theta_i)\right)}$$

anisotropic scattering cross-section

662 keV:



$$\left\langle \vec{\rho}_1 \right\rangle_n \equiv \frac{1}{N_n} \sum_{j=1}^{N_n} \vec{\rho}_1^{\,(j)} = \left(np_n - 1\right) \vec{\rho} + \frac{\vec{\delta}}{\sqrt{N_n}}$$

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GaAs *versus* InP

- **GaAs pros**
  - Higher radiative recombination coefficient, while nonradiative similar

$$\boxed{B_{\text{GaAs}} \approx 7B_{\text{InP}}} \qquad \boxed{C_{\text{GaAs}} \approx C_{\text{InP}}}$$

  - Higher bandgap (good for low-noise photodetection at room temperature)
  - Lower cost, mature electronics
- **GaAs cons**
  - Lighter weight elements
  - Epitaxial detector questionable

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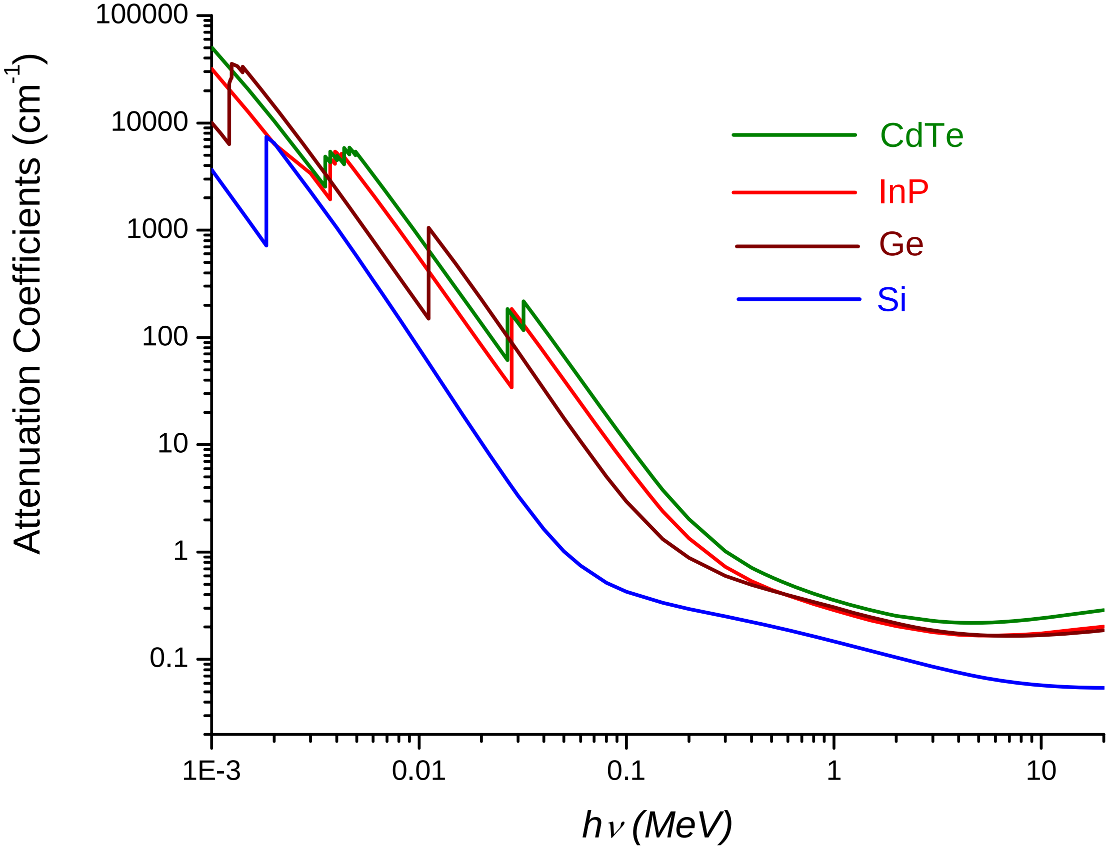
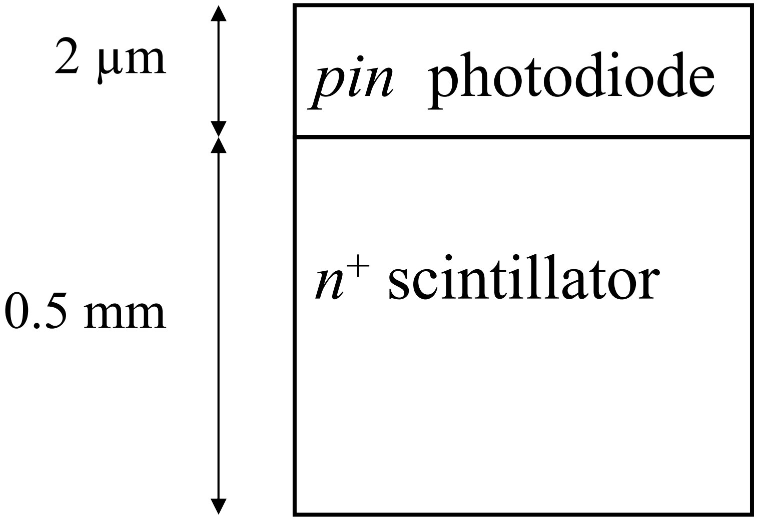
X-ray (γ-ray) attenuation



Element	Z
Si	14×2
Ga/As	31/33
Ge	32×2
In/P	49/15
Cd/Te	48/52

GaAs *versus* InP

epitaxial photodetector issues



$E_G = 1.25$ eV	$E_G = 1.35$ eV
InGaAsP	(In)GaAs-N
$E_G = 1.35$ eV	$E_G = 1.45$ eV
InP	GaAs

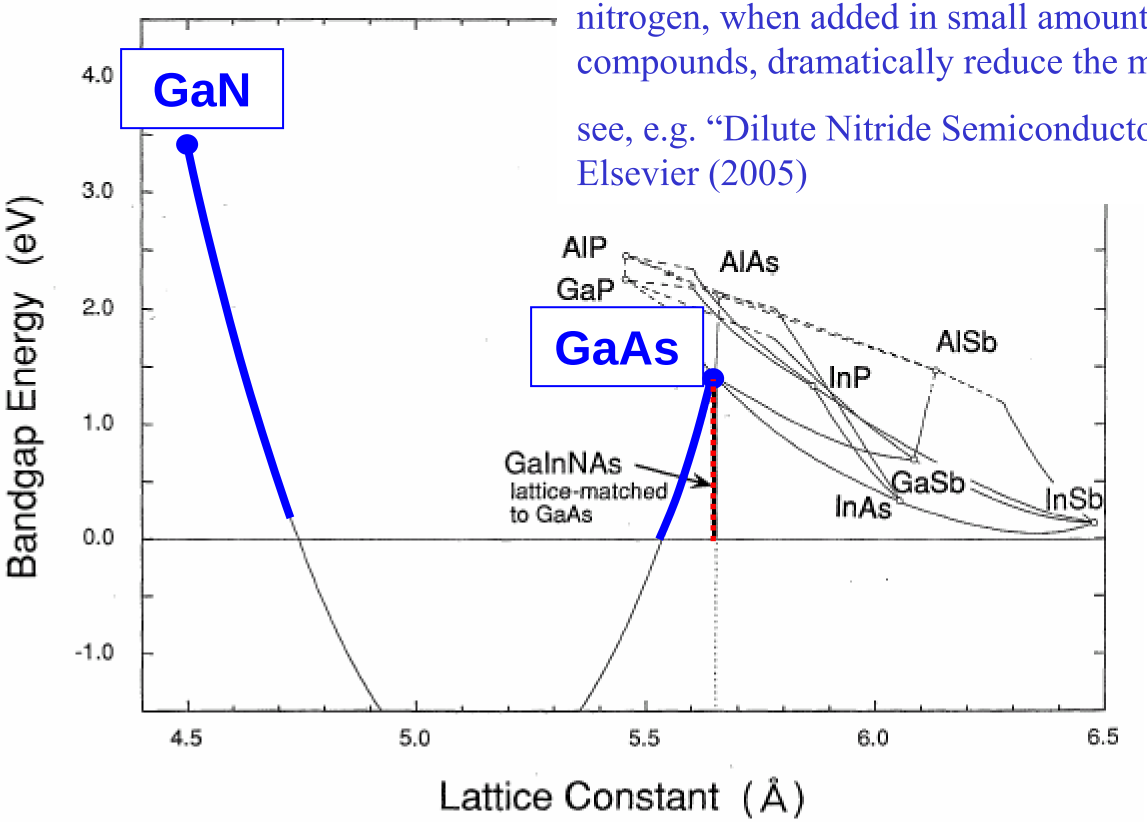
U. Michigan (Rachel Goldman) collaboration:

dilute nitride epitaxial photodiodes on GaAs

Dilute Nitride

Due to their high electronegativity and small size, atoms of nitrogen, when added in small amount (atomic %) to III-V compounds, dramatically reduce the material bandgap.

see, e.g. "Dilute Nitride Semiconductors", ed. by M. Henini, Elsevier (2005)



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Summary

- The basic issue for any semiconductor scintillator

  semiconductor is *not transparent to the radiation it produces*

- We have resolved this issue

  Moss-Burstein shift in a direct-gap, low-effective-mass semiconductor, such as InP or GaAs, makes it transparent to its own radiation, *permits extracting photons from as deep as several millimeters from the detector surface*

- New type of scintillator is proposed, advantageous for:

  multiple applications, including 3D pixellation for:

  radiation spectrometry and SNM identification

  rapid determination of direction to source

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Cooperative Agreement 2007-DN-077-ER0005 (started March 1, 2007)

U.S. Department of Homeland Security

“Semiconductor high-energy radiation detector with excellent isotope identification and directional capability”

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