One man's treasure another man's treasure?

- Semiconductor radiation detectors

Presenter: Chengzhu Zhang

Residency 2023~2024

Rotation Mentor: Xiao Wang

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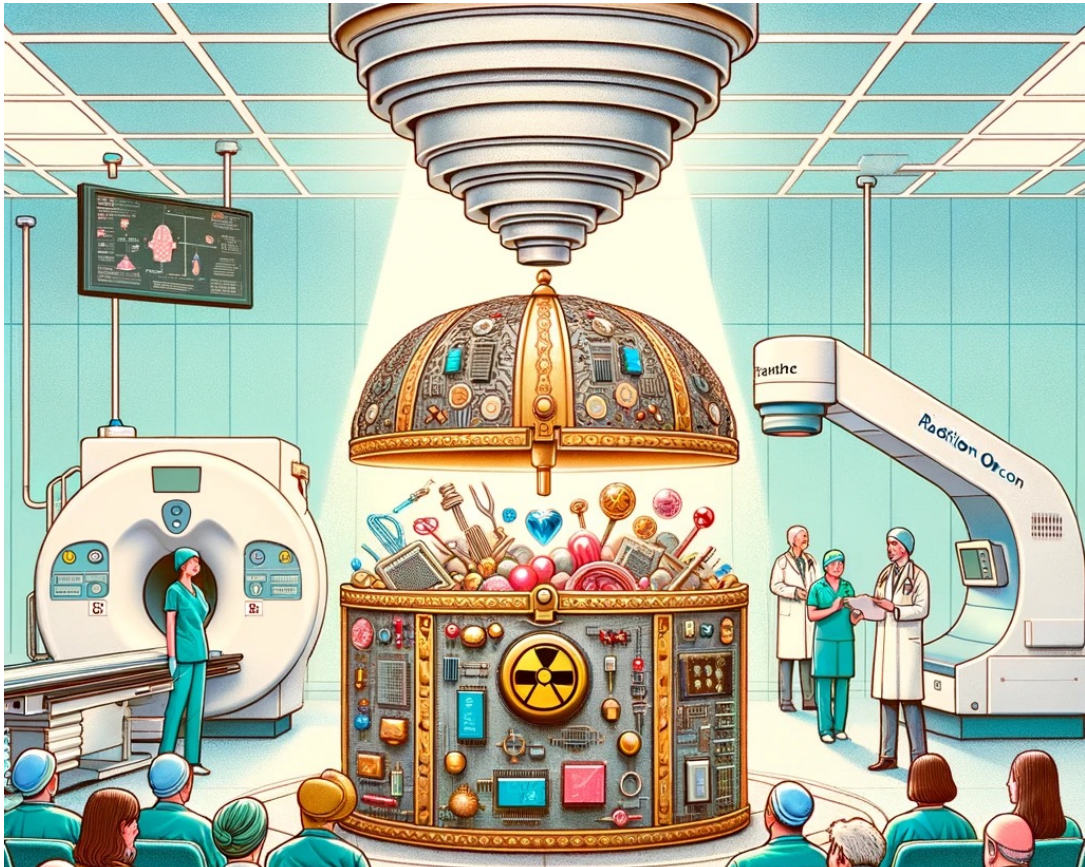
Robert Wood Johnson Medical School



Solid radiation detectors

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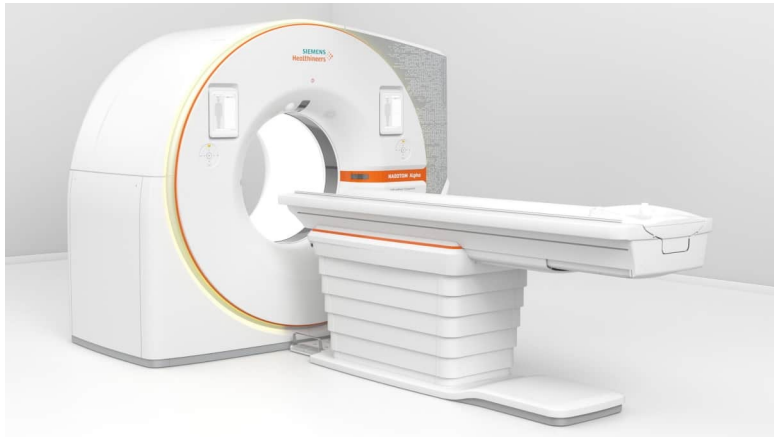
QED diode (SunNuclear)

NaI(Tl) gamma spectrometer

Photon-counting Detector (Varex)



Photon-counting CT (Siemens)

“Gas” ion chamber

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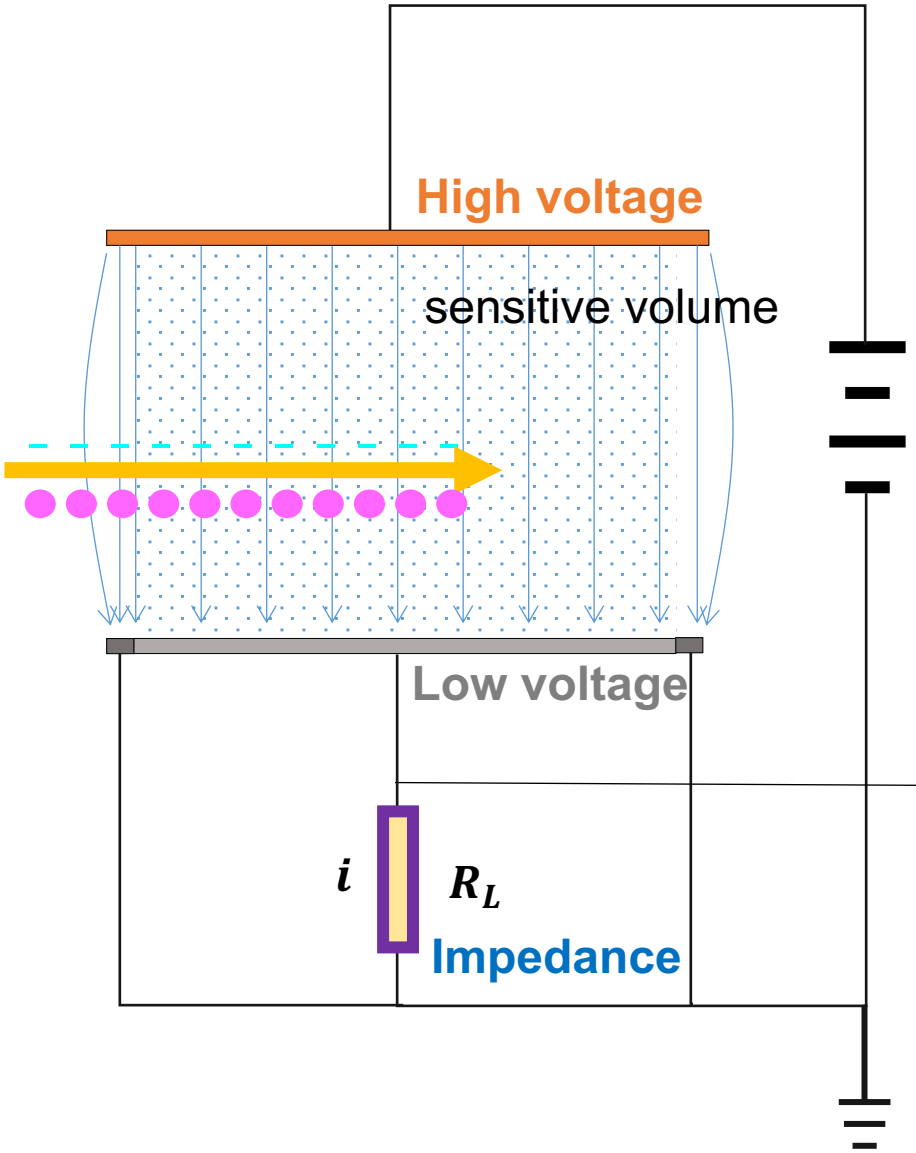
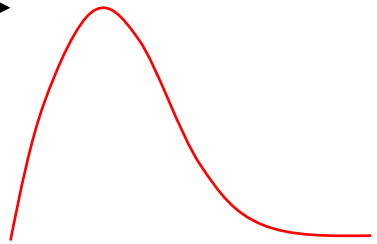


☺ Constant $\bar{W}$, ☹ but > 30 eV

☺ Low detection efficiency

☹ Large volume

☹ Slow collection



“Solid” ion chamber

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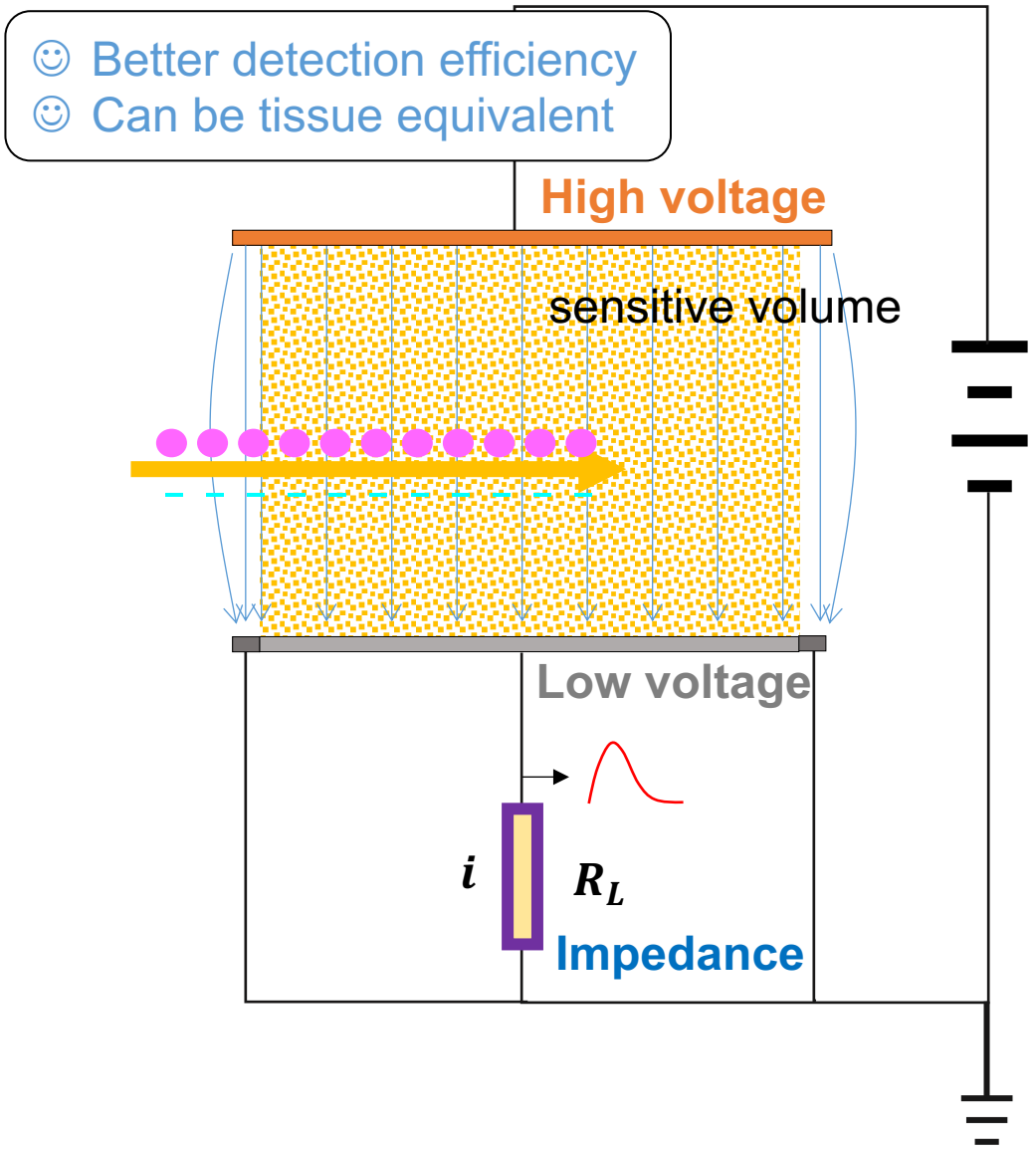
☺ Better detection efficiency
☺ Can be tissue equivalent



Insulator

☺ Smaller $\bar{W}$
☺ Low leakage current
☹ Undesired electronic property

Intrinsic Semiconductor

☺ Relatively $\bar{W}$, < 6 eV
☺ High charge carrier mobility
☹ Leakage current

Diode (p-n junc.)

☺ High impedance
☺ Goodness of semiconductor

Solid detector (I): Direct Conversion

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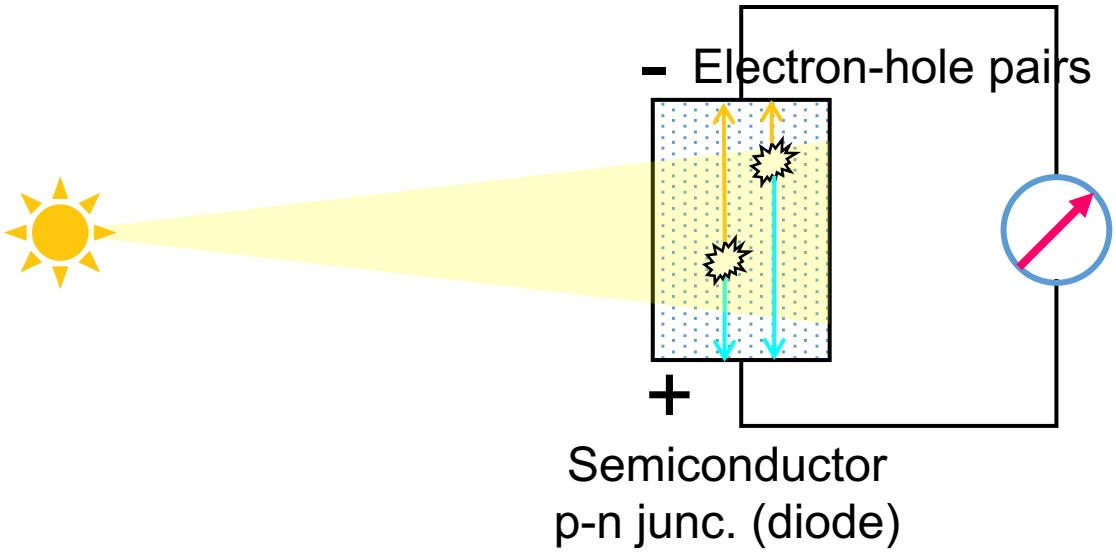

☹ Still low detection efficiency

Solid detector (II): Scintillation

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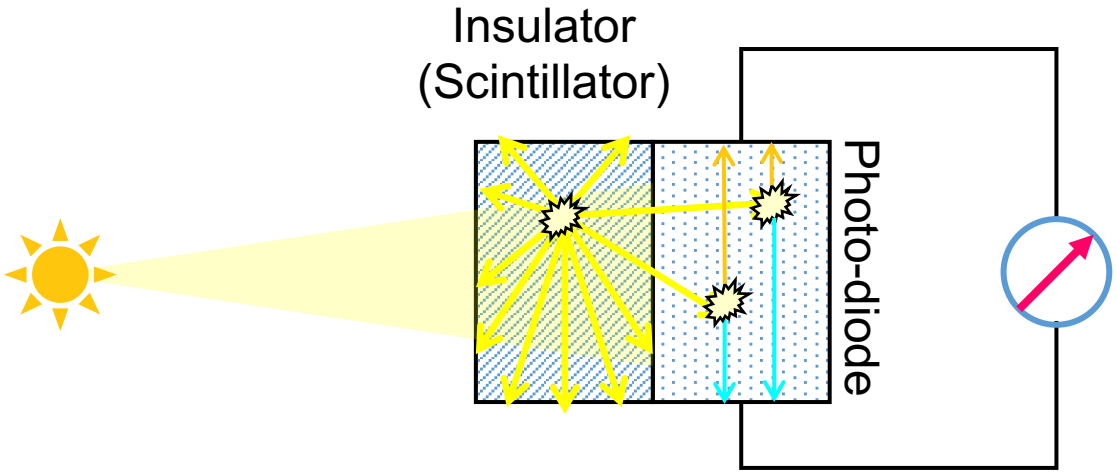
Dr. Wilhelm Röntgen 1895



☺ Good efficiency

☹ After-glow (slow collection)

☹ SNR loss

Solid detector (III): Scintillation

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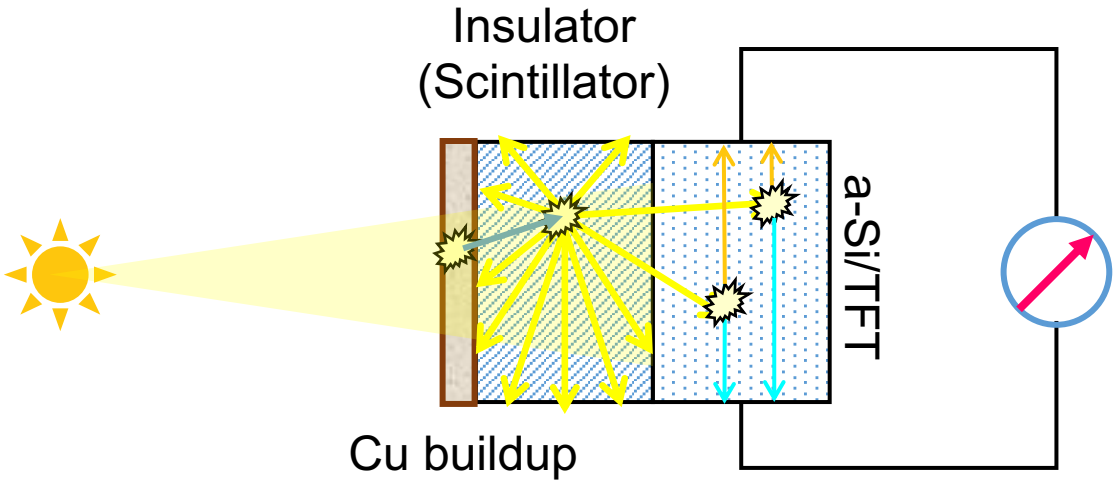

Portal Dosimetry, MV Imaging

Dose detector

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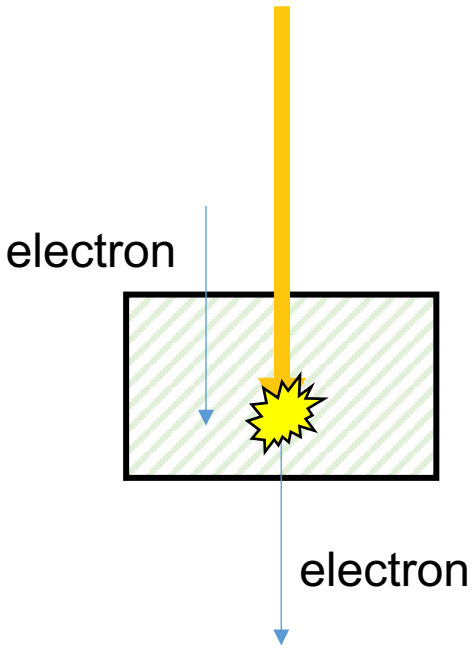
- General principle: energy transfer under CPE



$$\text{Dose} = \frac{\text{Energy}}{\text{Mass}}$$

Imaging detector

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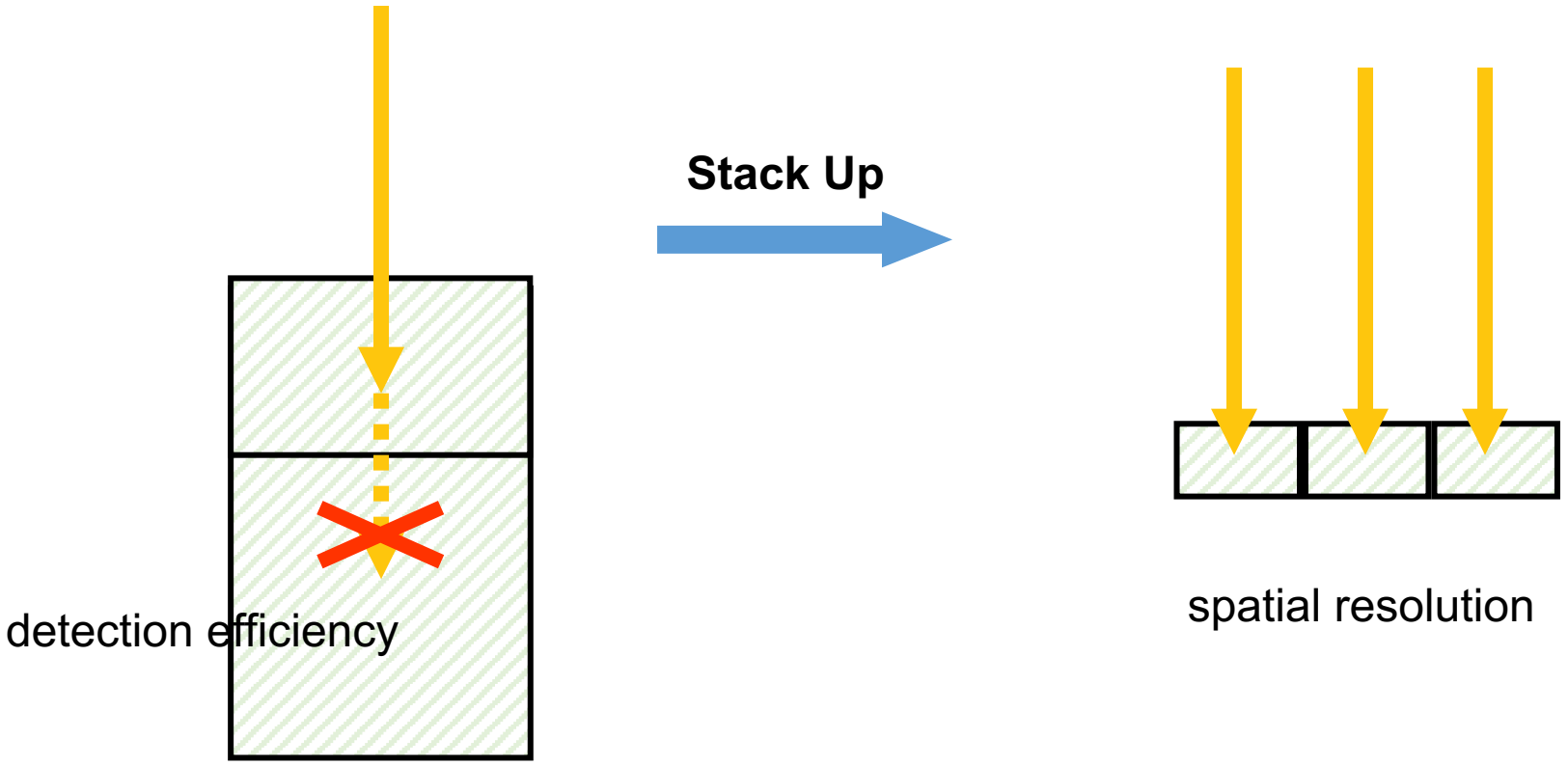
- General principle: Record photon fluence



Imaging detector

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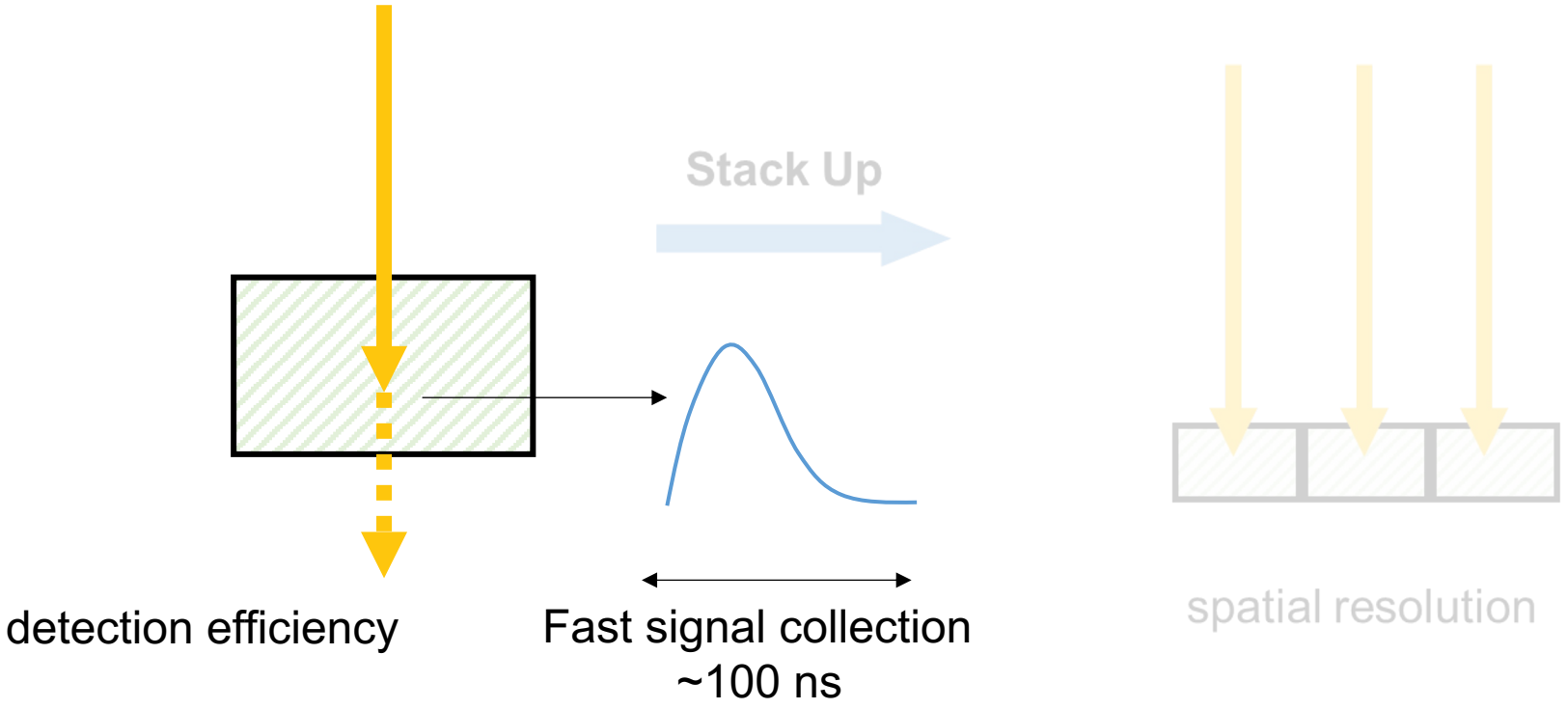
- General principle: Count the photon!



Two important x-ray imaging detectors

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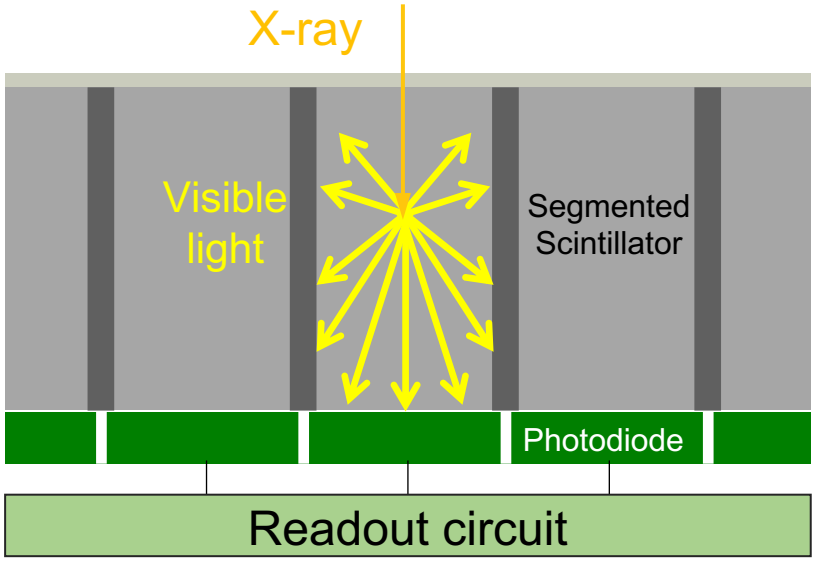
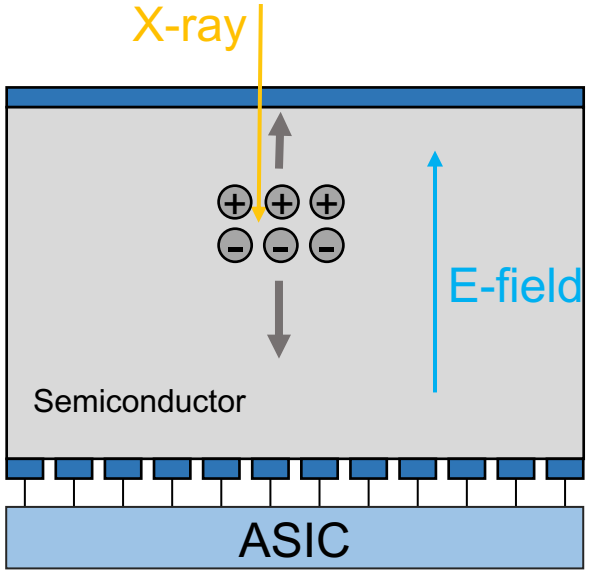


Scintillation Detector
Diagnostic/SIM CT (Gadox)
CBCT (CsI)
EPID (Gadox)



"Photon Counting" Detector
(CdTe, CdZnTe, Si)

Comparison

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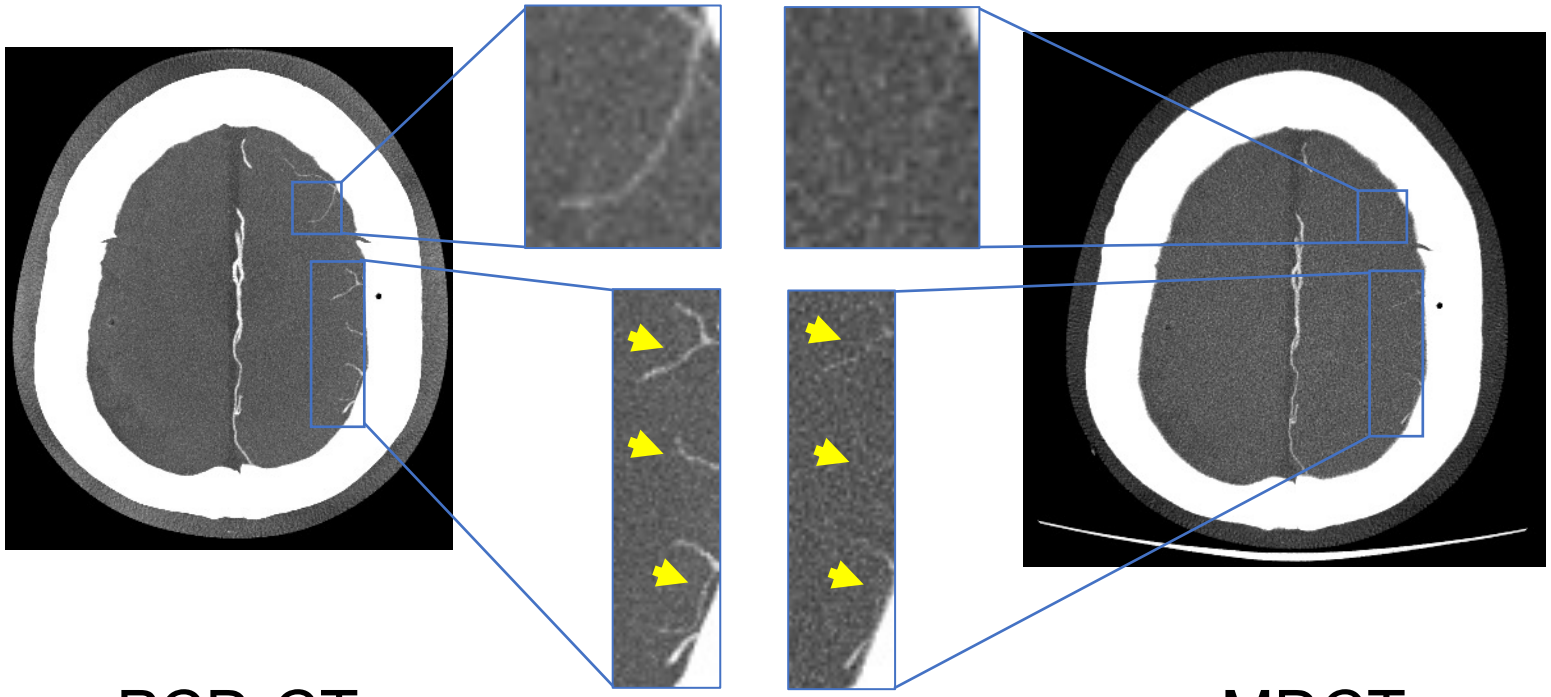

PCD-CT
(Semi-conductor)

MDCT
(Scintillation)

Courtesy of Dr Harvey

One man's treasure

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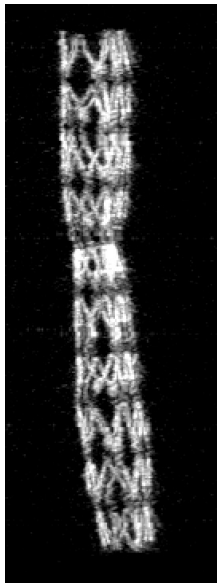
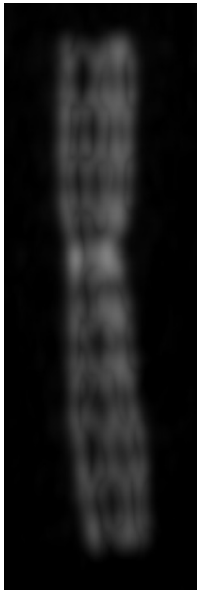
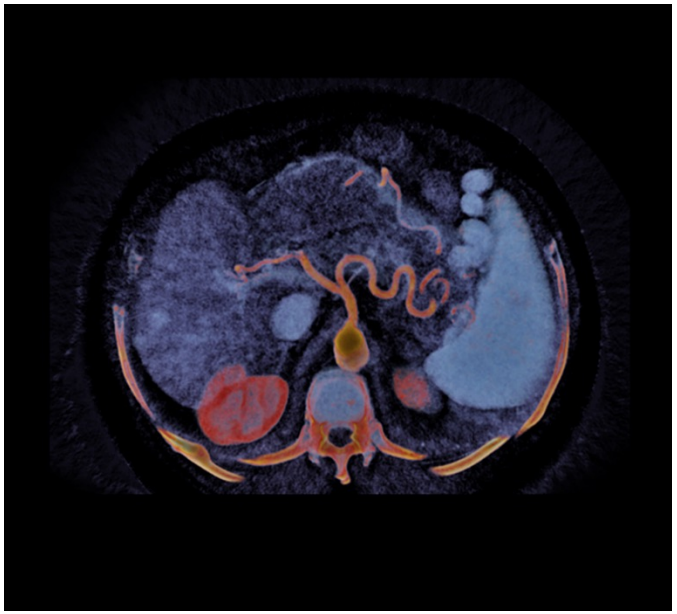


PCD-CT
Highest
resolution



CBCT
Highest
resolution



Iodine map
material decomposition

☺ High spatial resolution

☺ Better contrast

☺ Energy resolving capability

Courtesy of Dr Feng

Dosimetric member

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Our Clinic

In-vivo dosimetry (TBI, …)

Our Boy!

Major Use

Measure PDD
QA devices (Delta4, daily QA3, IC profiler)

Is it another man's treasure?

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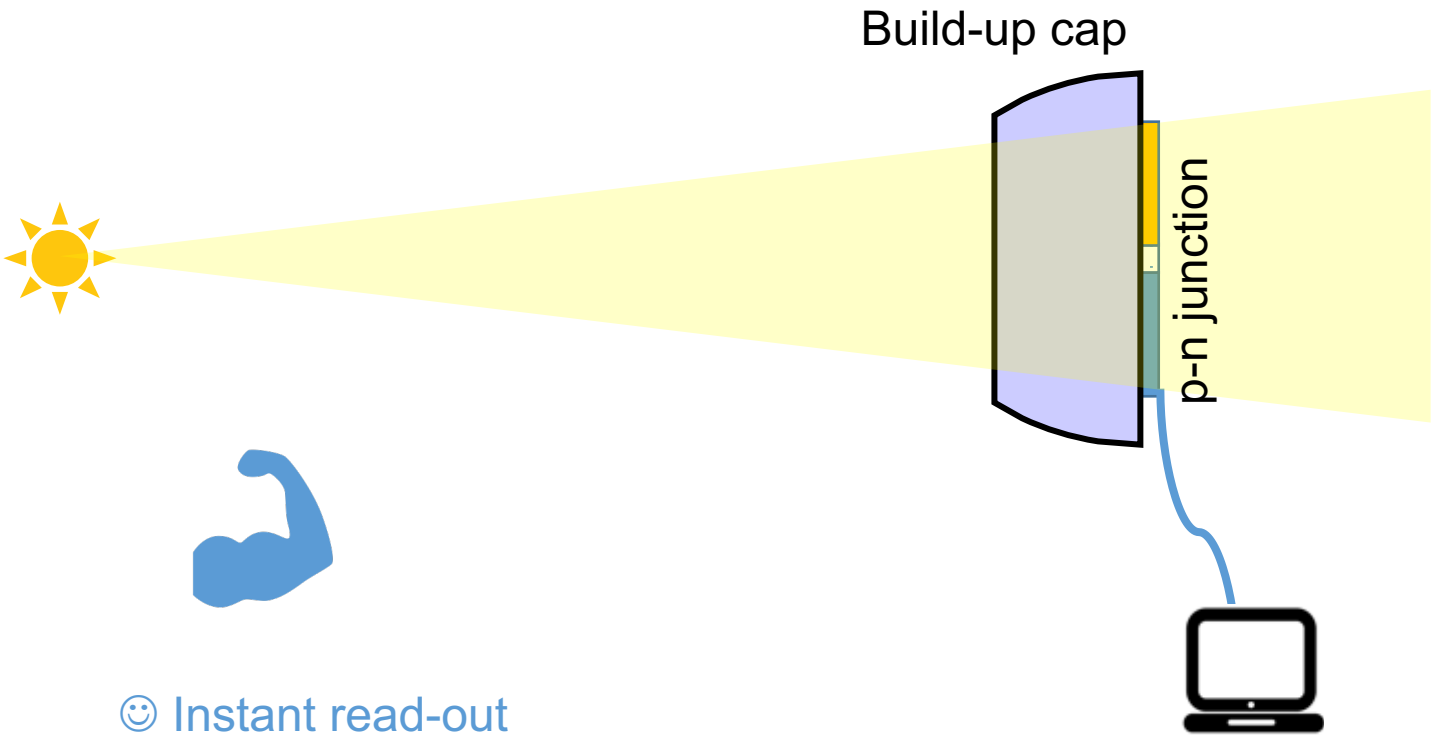

☺ Instant read-out
☺ Small volume
☺ SNR

In reality …

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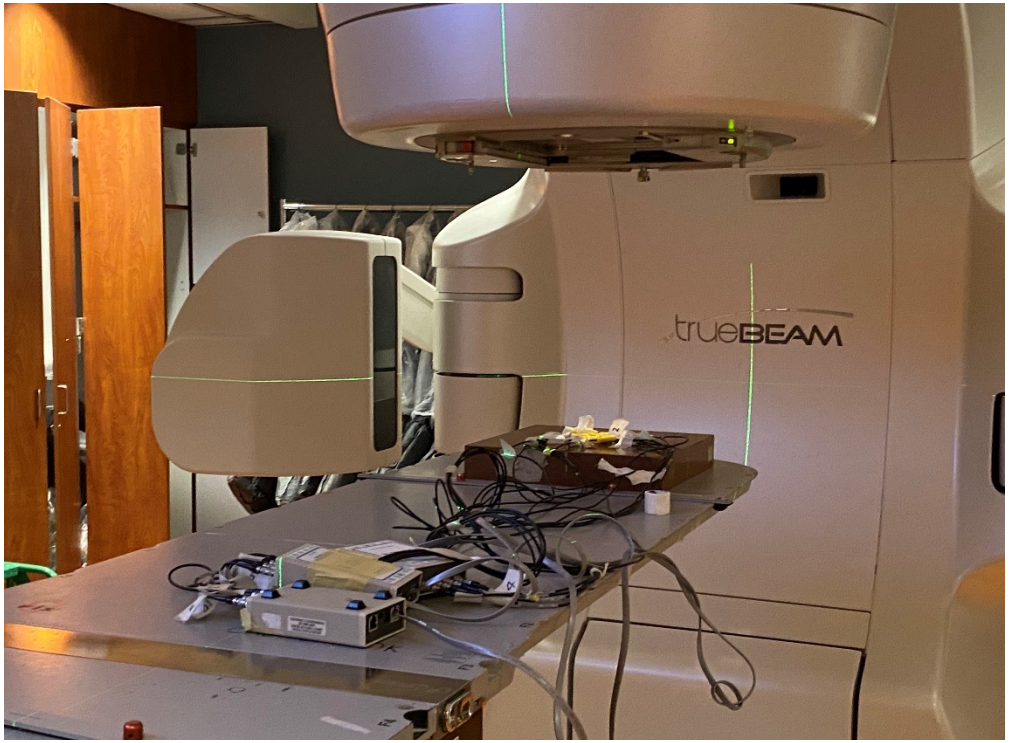

Let's be fair …

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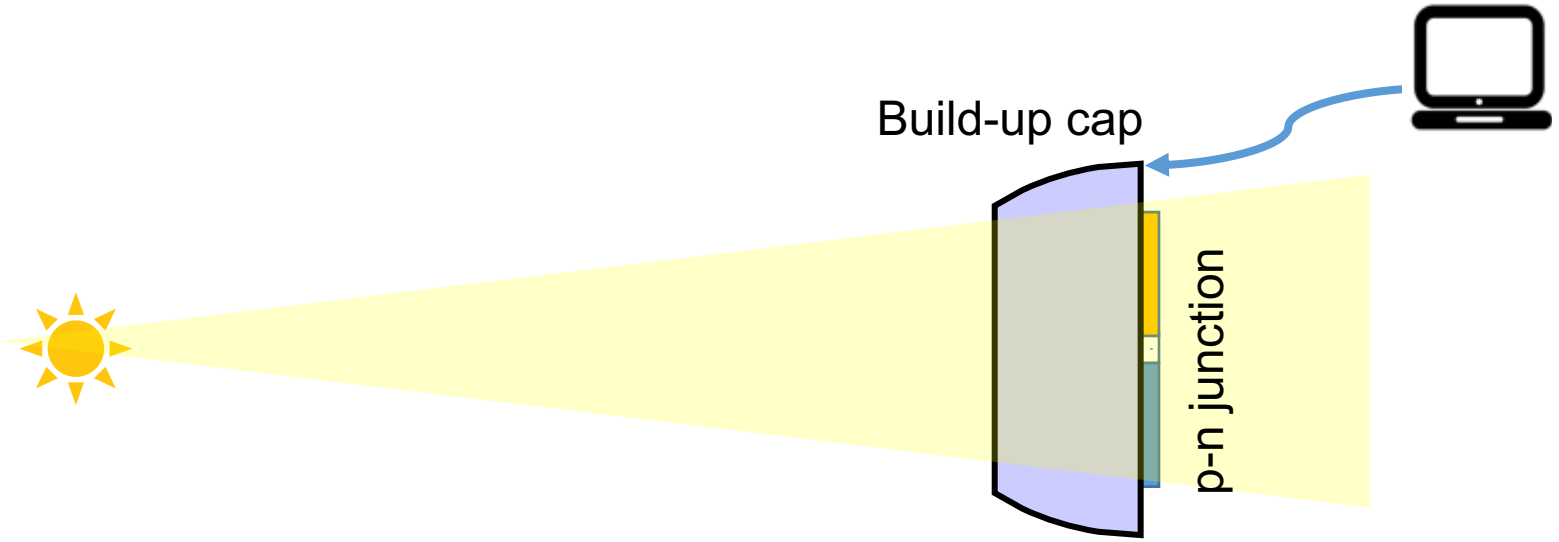

☺ SNR
☺ Small volume
☺ Instant read-out

?

☹ Temperature dependence
☹ Dose rate dependence
☹ Energy dependence
☹ Orientation dependence
☹ Radiation damage

Crystal Structure

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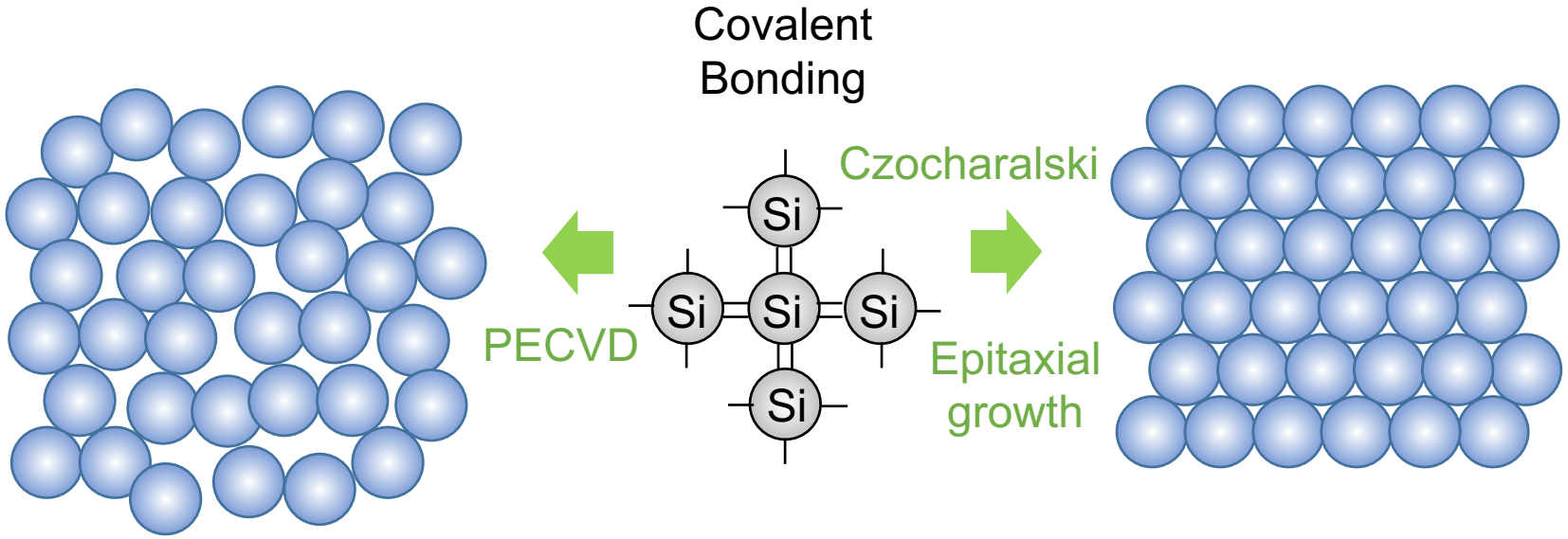

Amorphous

better electronic property

Single Crystal

EPID (large panel)

Photon-counting Detector

Expensive to fabricate

E-k diagram of an bounded electron

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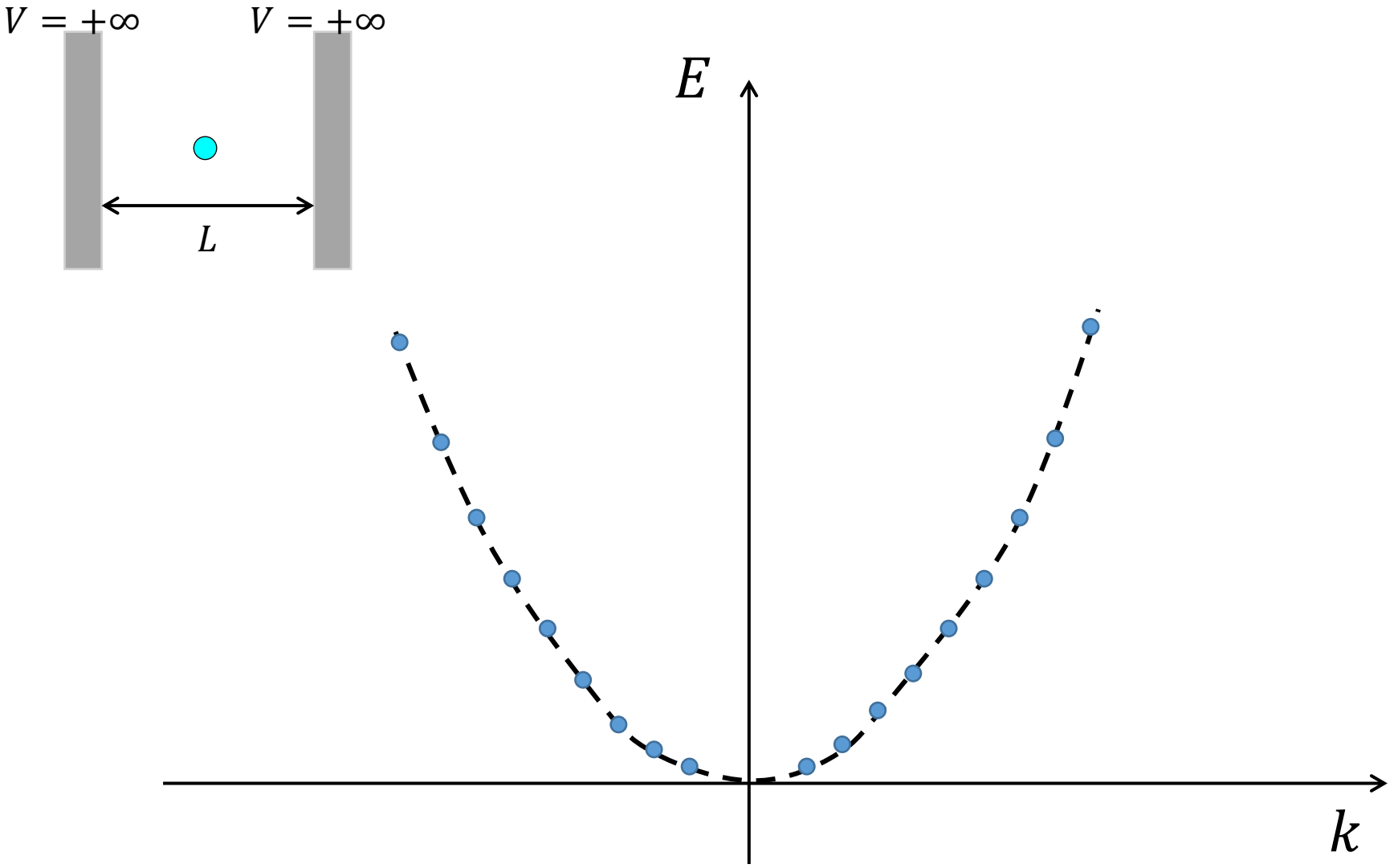

E-k diagram

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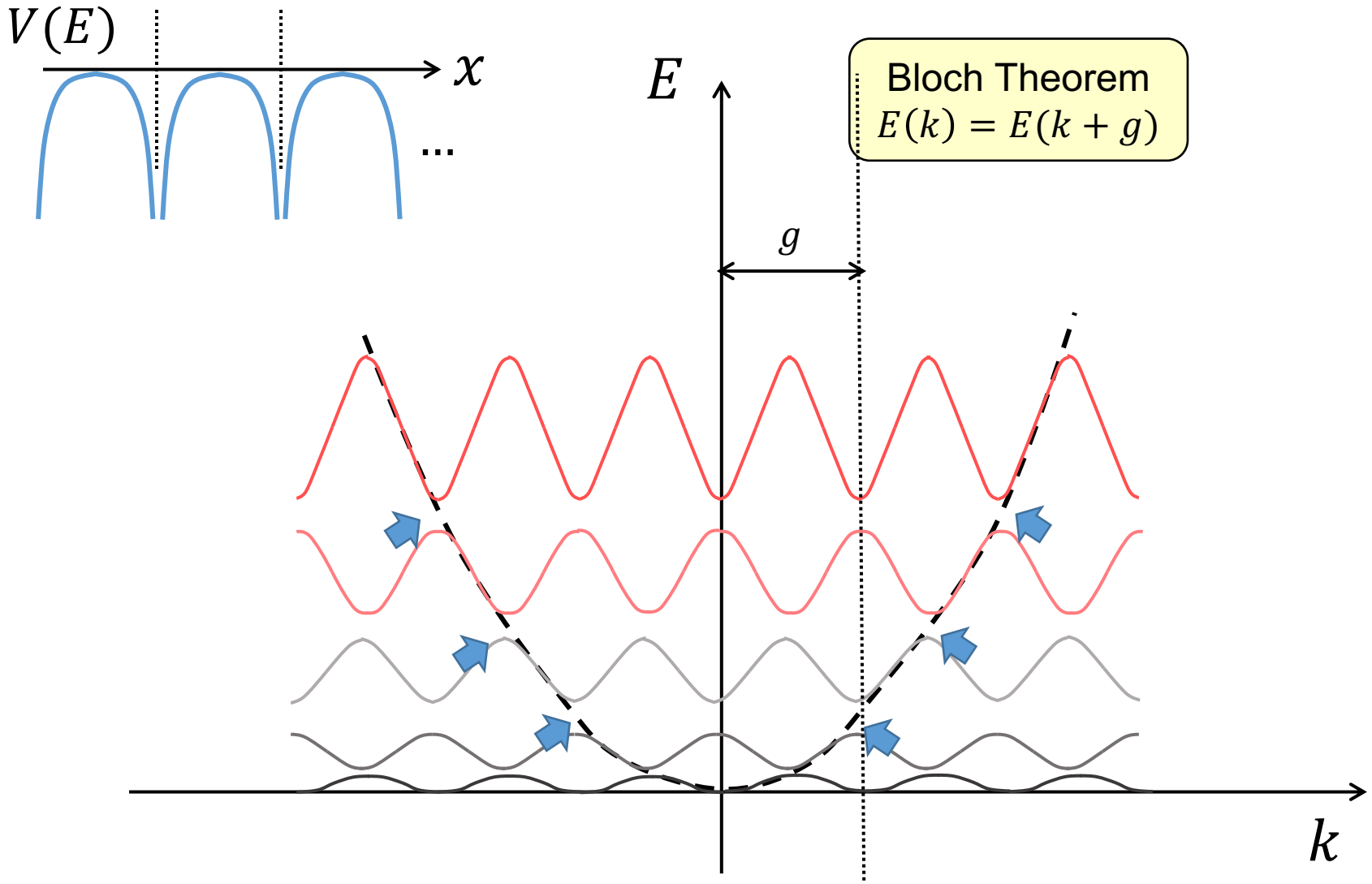

E-k diagram

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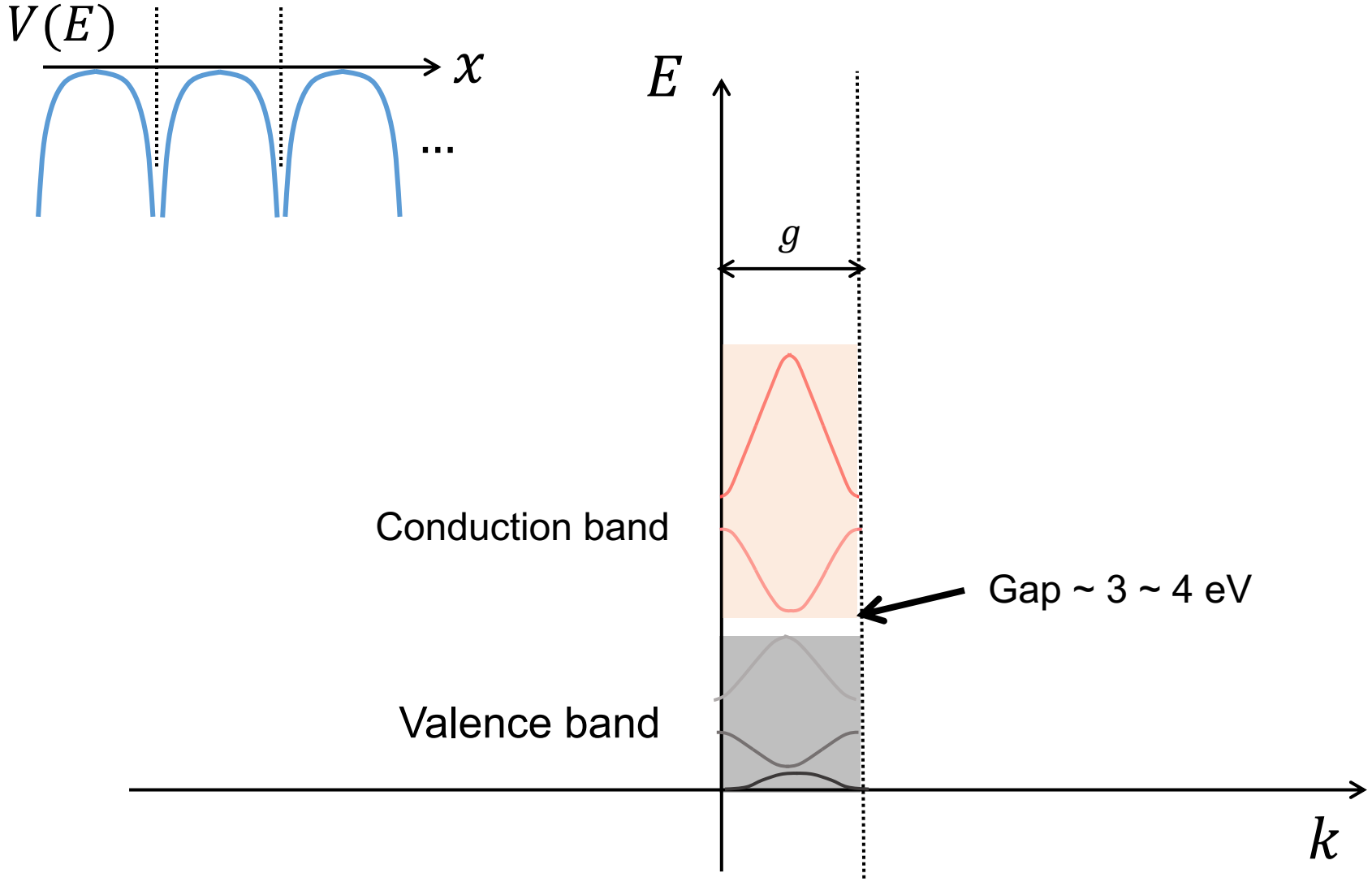

Charge carrier mobility

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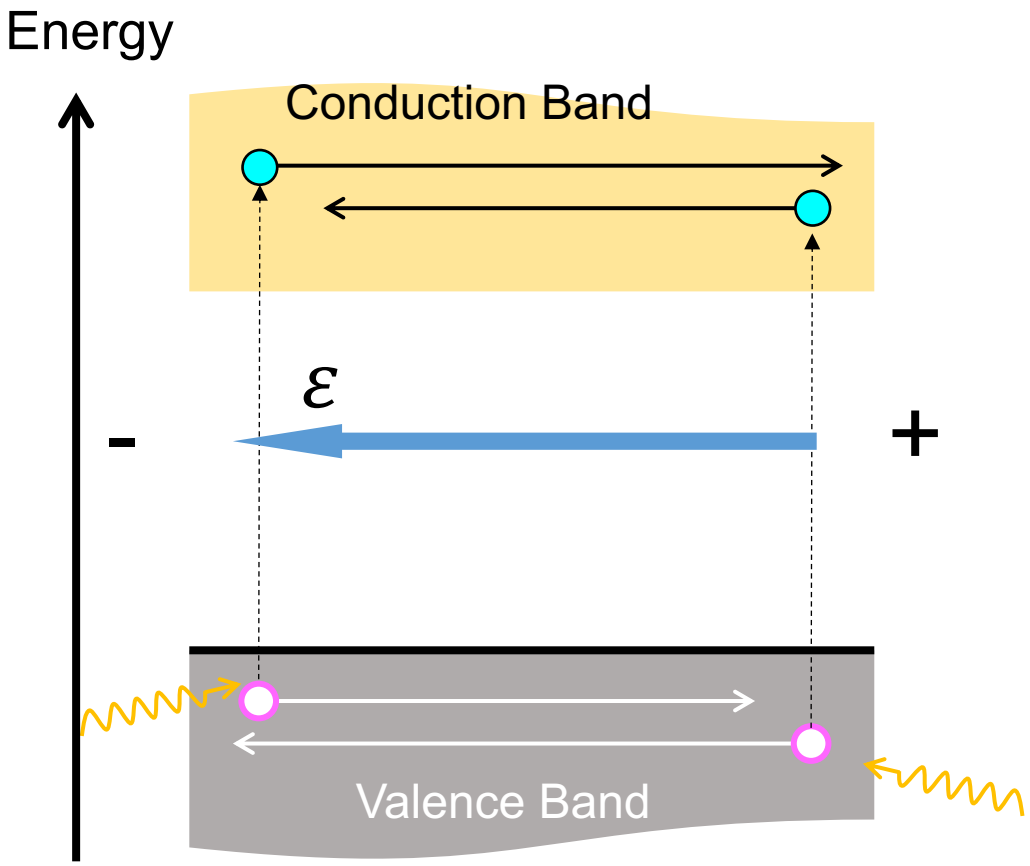
$$v = -\mu\varepsilon$$ reduced electric field

$\varepsilon\uparrow, \mu\uparrow, v\uparrow$

☺ Collection time

☺ Recombination



Material	$\mu_n[cm^2/(V \cdot s)]$	$\mu_p[cm^2/(V \cdot s)]$
c-Si	1400	480
a-Si	1	0.005
CdTe	1100	100

Doping effect

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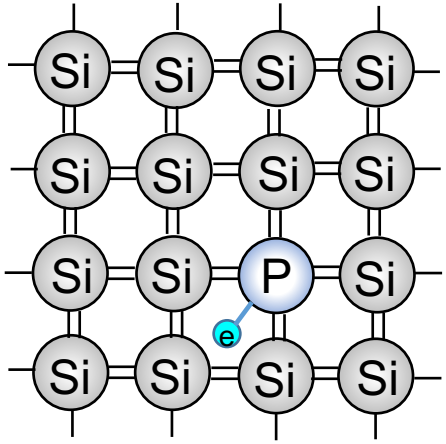
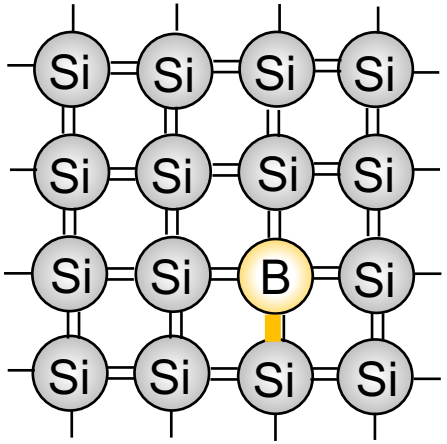
N-type

Donate electron



P-type

Receive electron



Band structure

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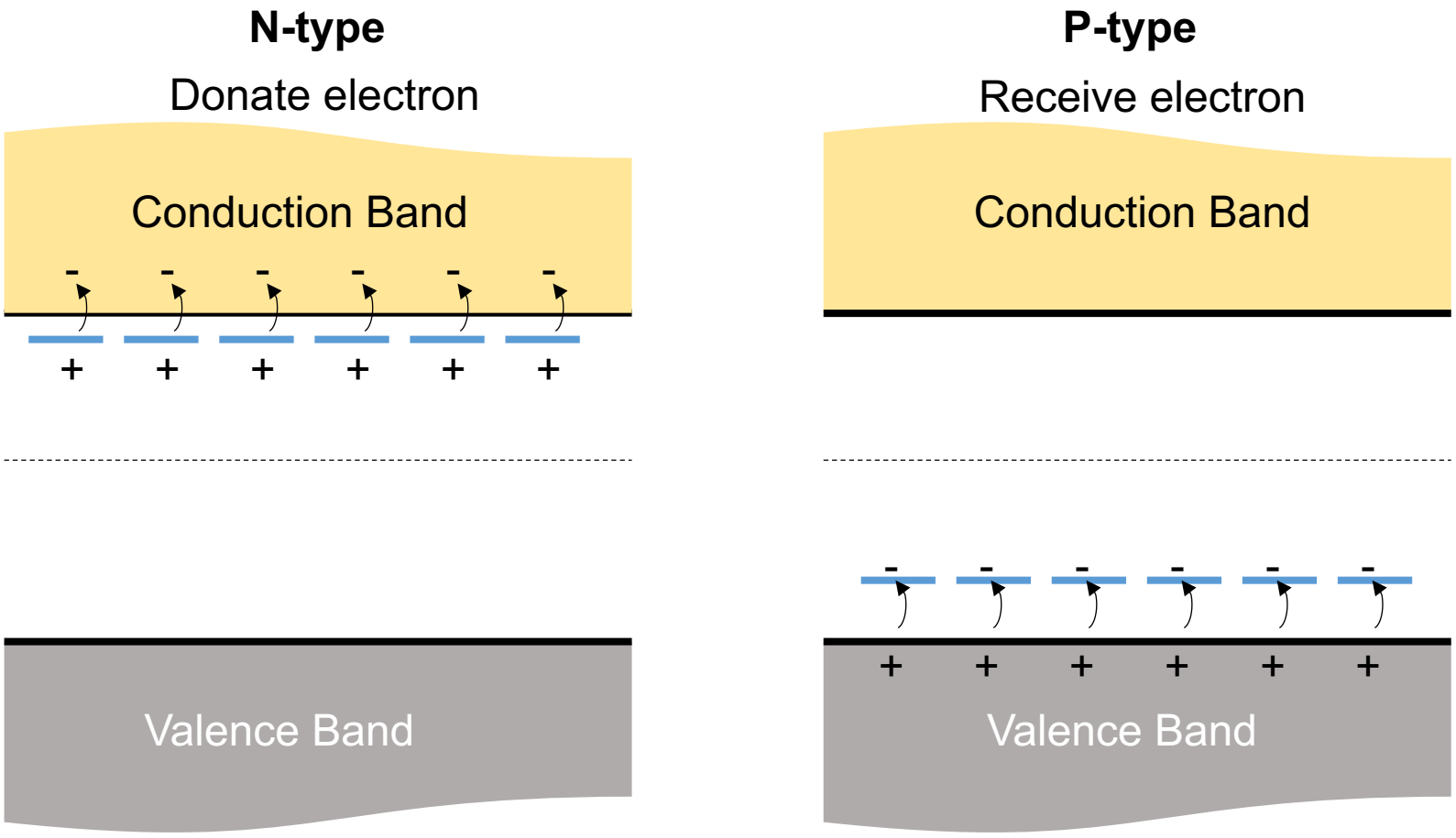

Direct conversion detector

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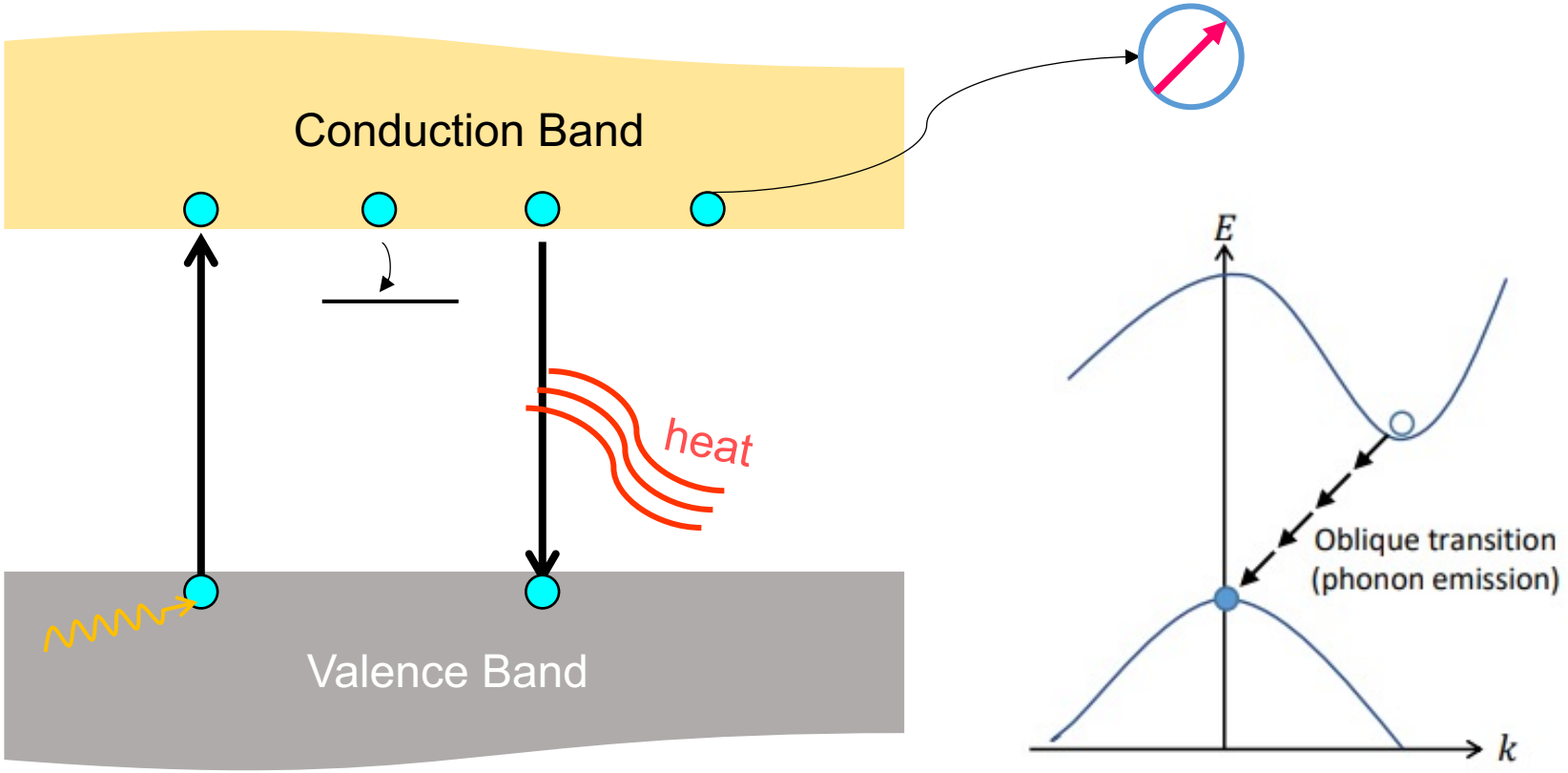

Scintillation detector

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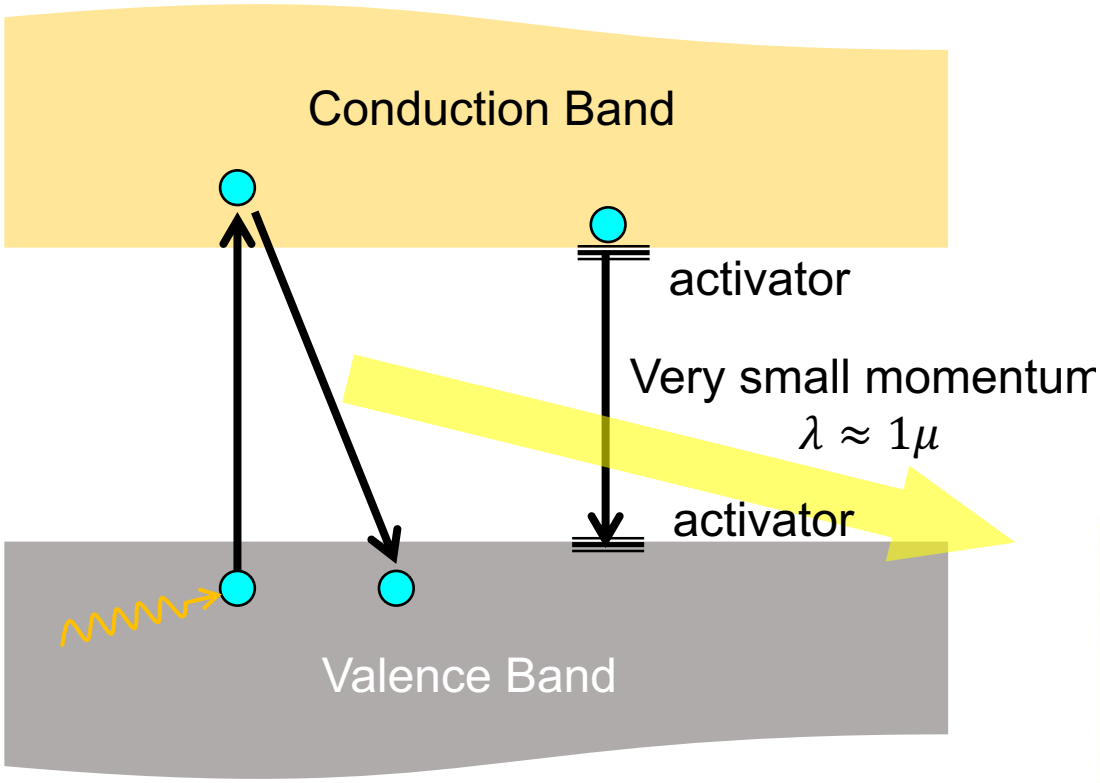

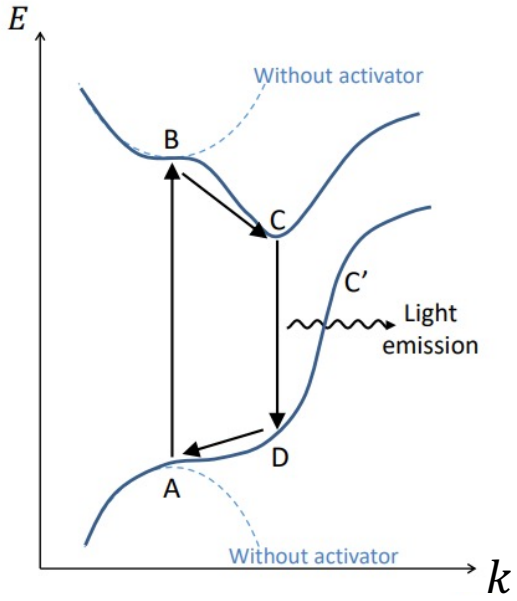

Charge carrier diffusion & drift

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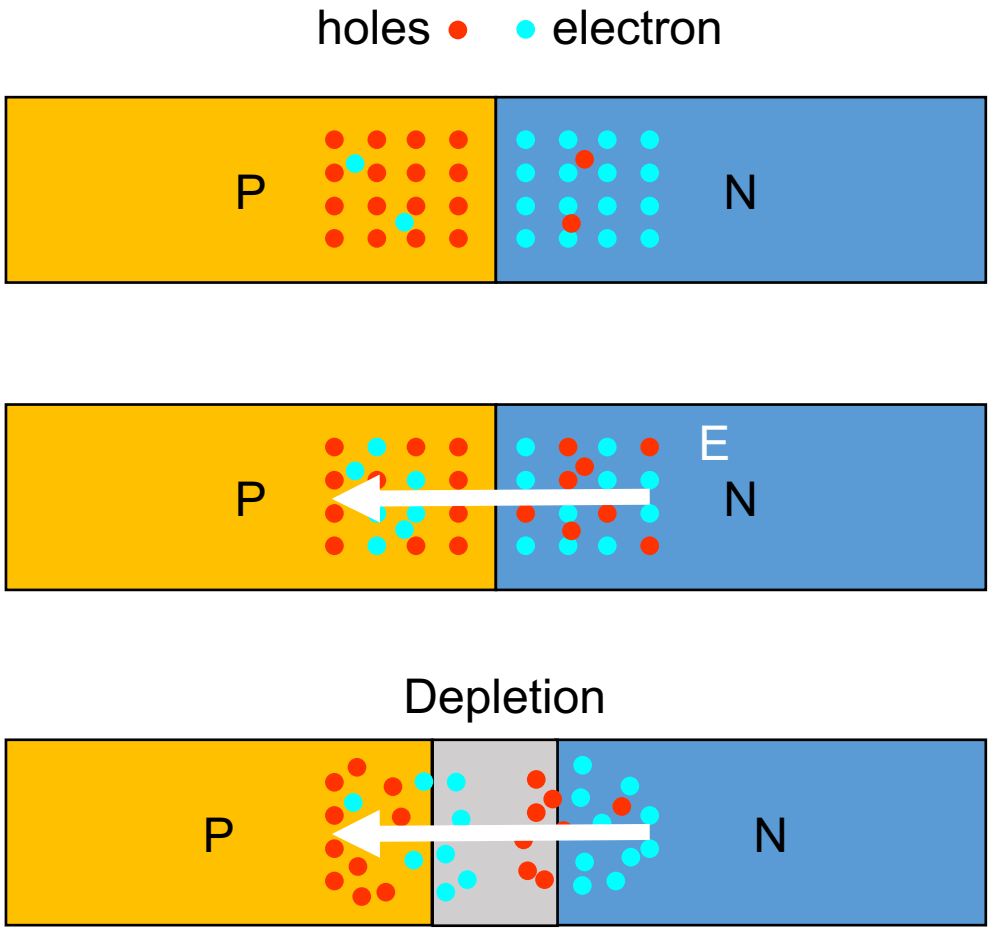
$$J = -eD\frac{\partial n}{\partial x}$$

density gradient



P-N junction

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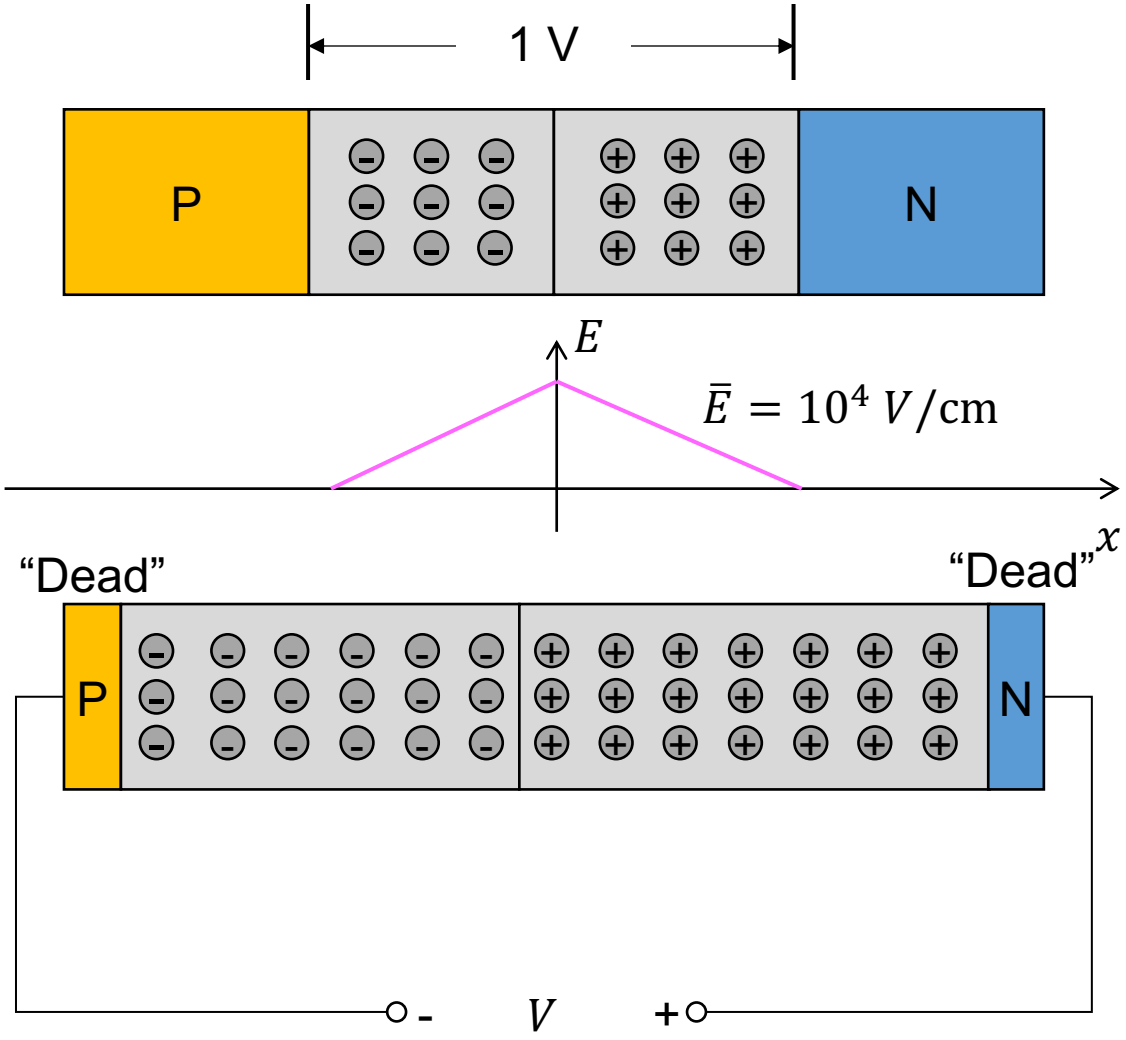

Formation of a p-n junction (I)

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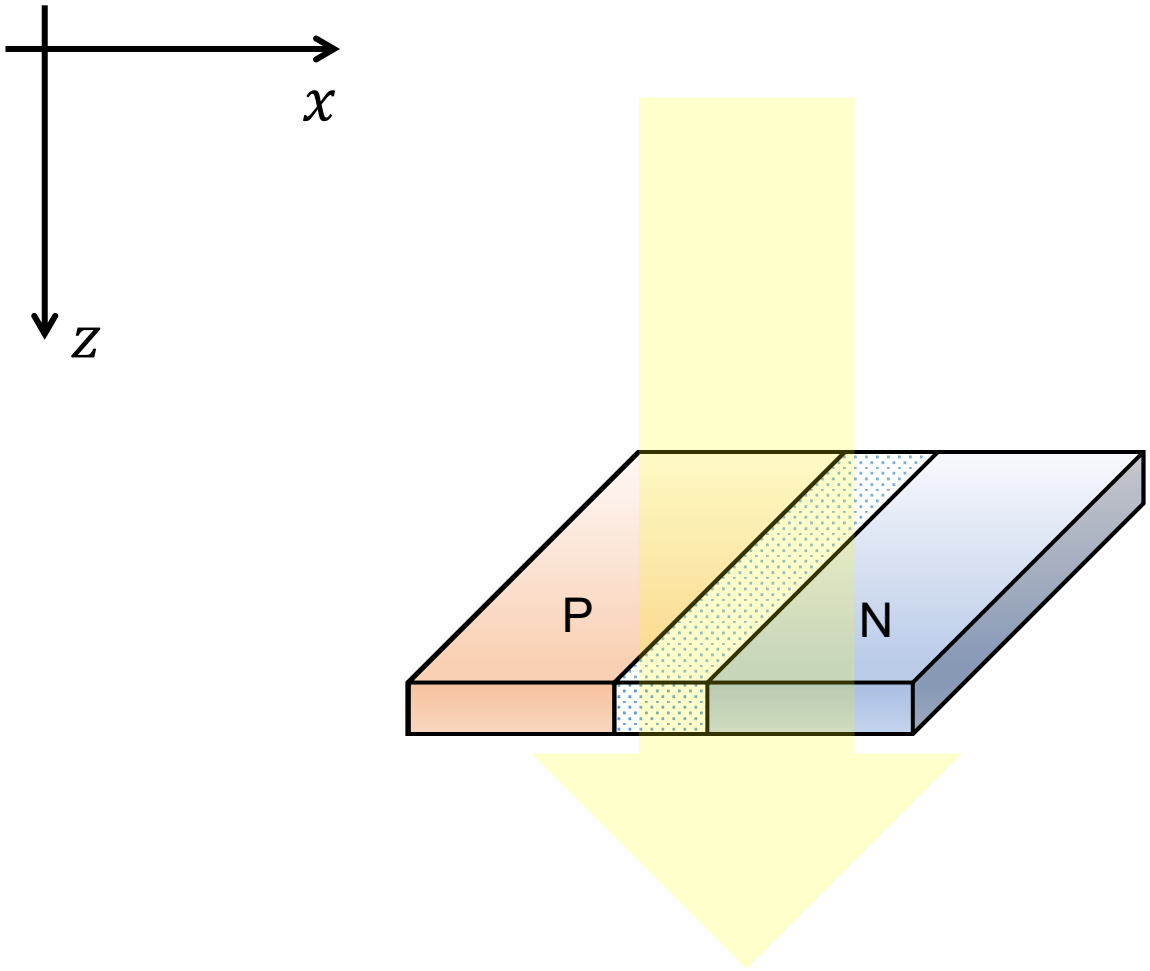

Formation of a p-n junction (II)

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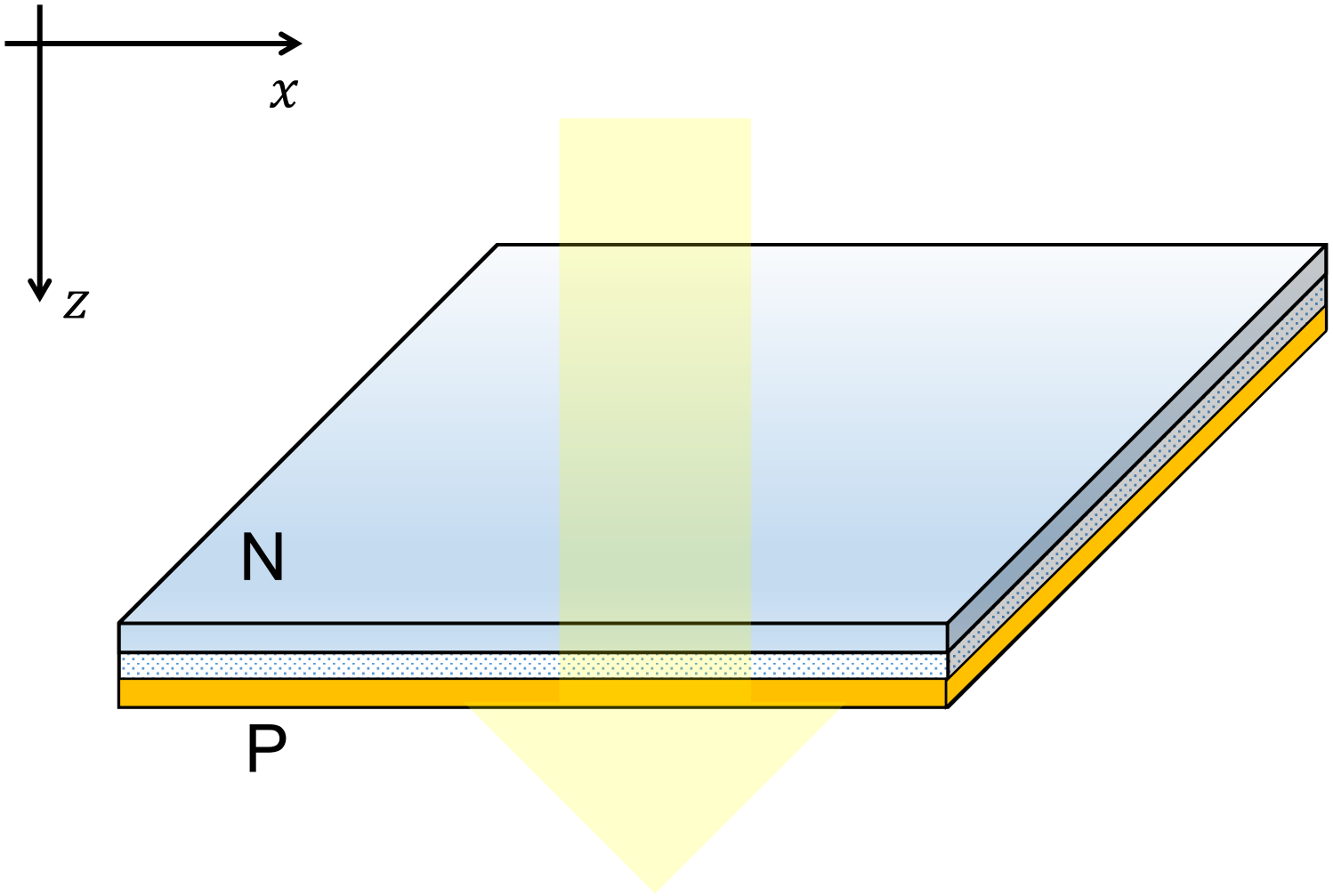

Sensitive Volume Comparison

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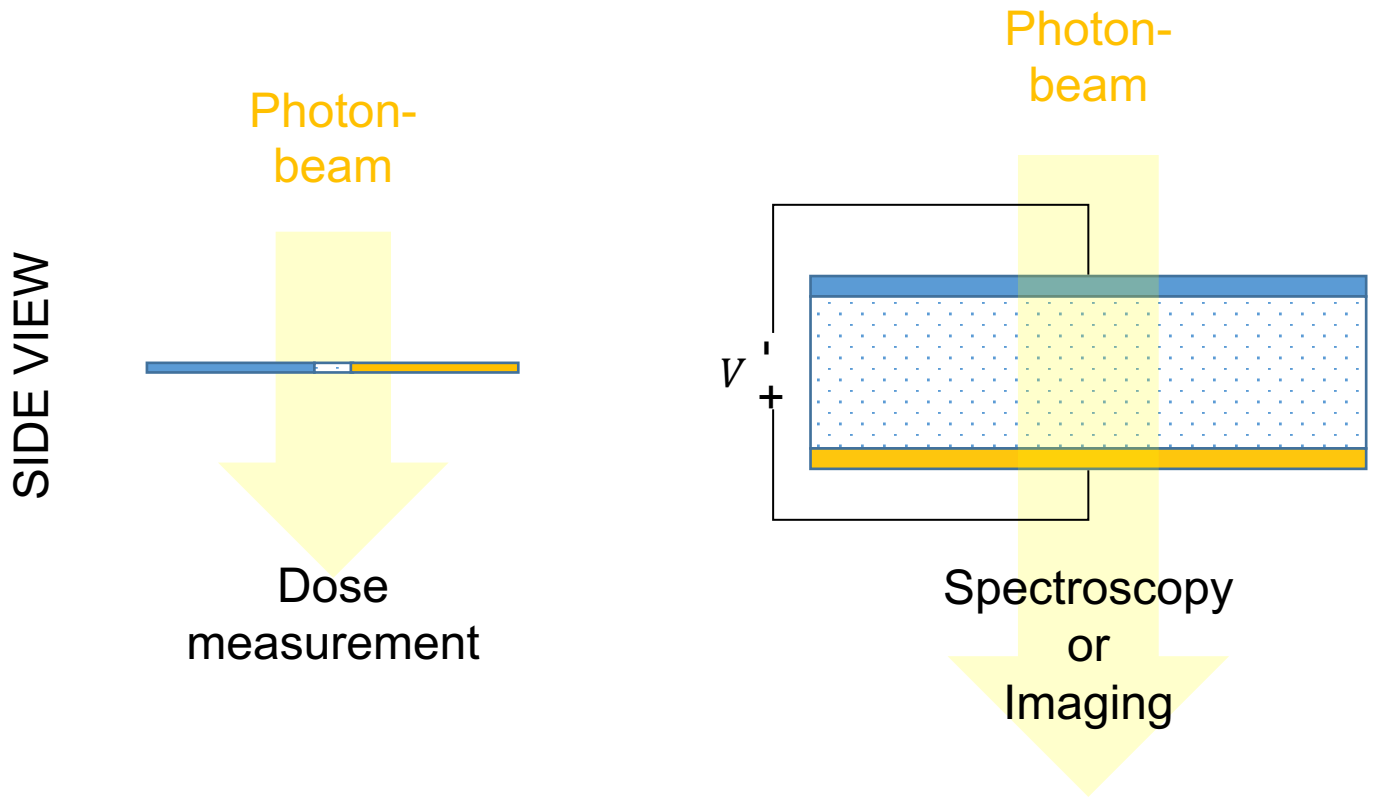

“Dose diode”

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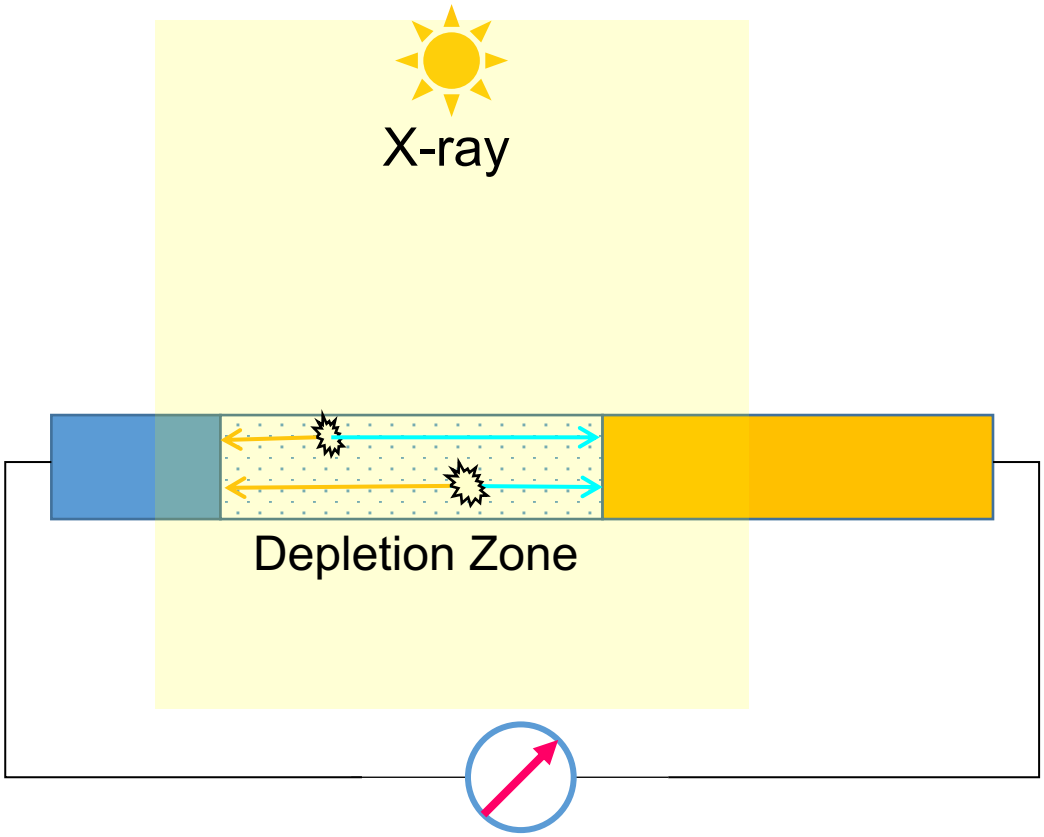

Cannot explain dose rate, temperature dependence very well

Dose Diode

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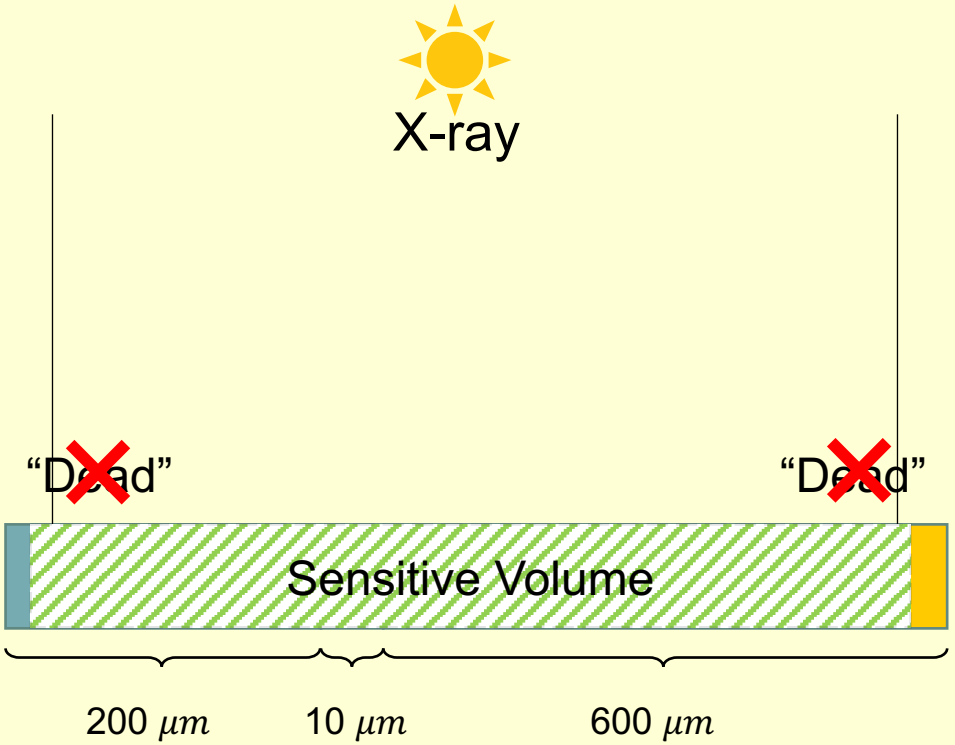

- Charge collected
  - $\propto$ Charge created (relatively constant, not all)
  - $\propto$ Sensitive volume (assume uniform dose profile)
    - Influenced by the diffusion length.

Dose Diode

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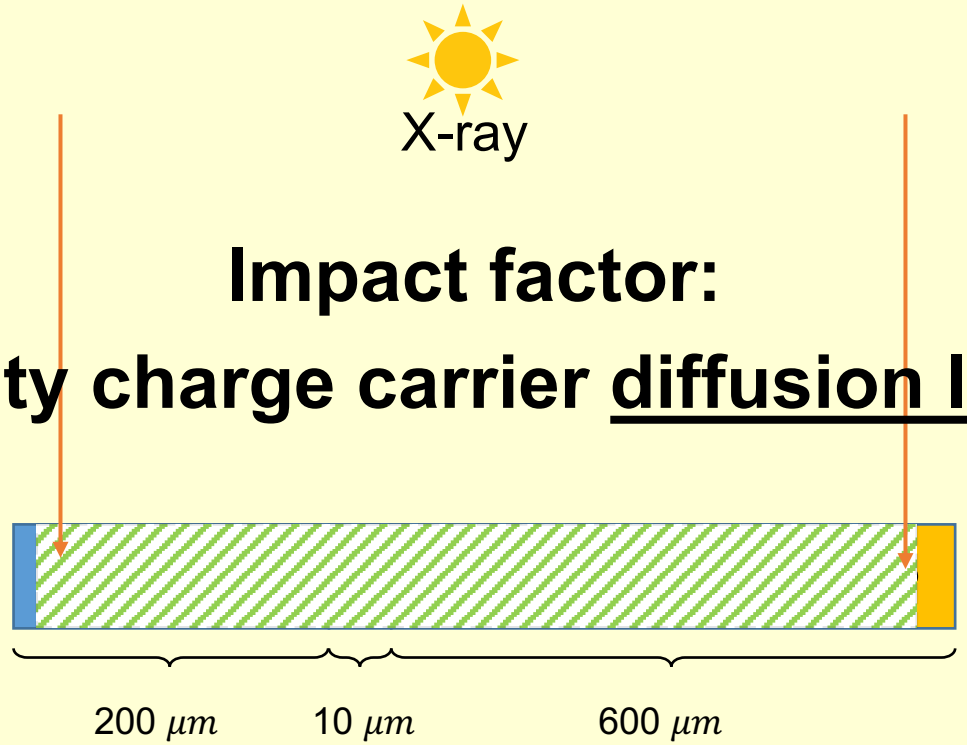

Impact factor:

Minority charge carrier diffusion length

p type has less dose rate dependence

- Dose rate↑, indirect recombination↓, charge carriers↑, SNR↑
- ~~Dose rate↑, direct recombination↑, diffusion length↓, SNR↓~~
- Temperature↑, kinetic energy↑, diffusion length↑, SNR↑

Other dependencies

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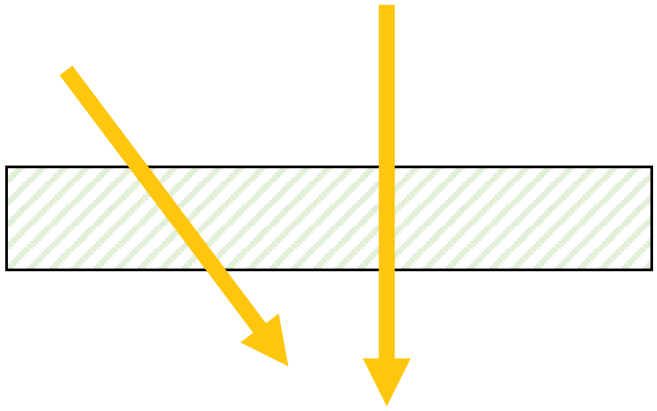
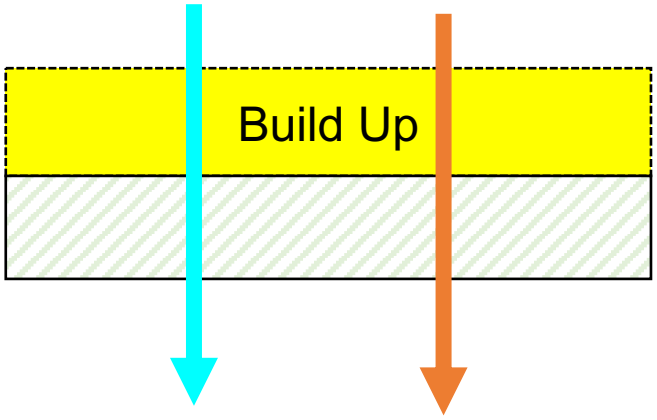


Oblique path absorption ↑



Low energy absorption > High energy

Solution

Placement

Solution

energy-specific diode

Summary for “dose diode”

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- Advantage
  - High SNR, instant readout
  - Less volume average
  - Tissue-equivalent
- Disadvantage
  - Dose rate dependence
  - Temperature dependence
  - Energy dependence (buildup)
  - Radiation Damage decreases sensitivity
  - Not so clinically versatile

“Imaging diodes”

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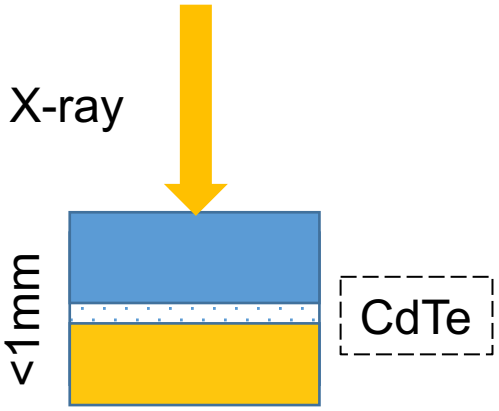
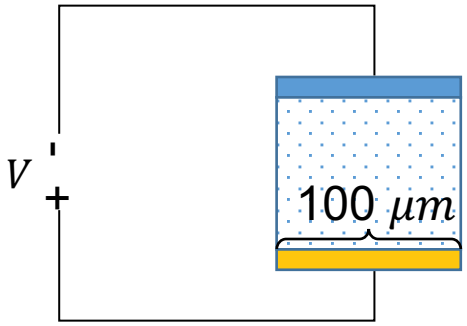
stop 95% kV x-ray

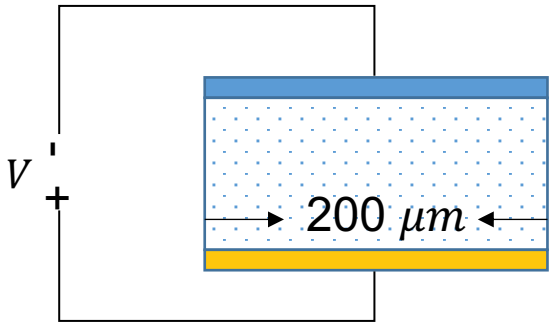
1.7 mm CdTe
55 mm Silicon



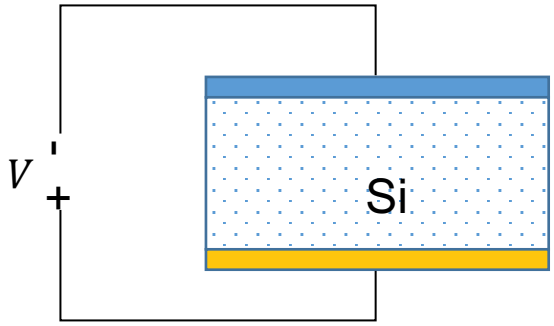
P-N junction
without bias
(face-on)



Reverse bias
Detector efficiency ↑
Thickness ↑, SNR↑



Spatial resolution tradeoff
Sensitive area↑ SNR↑



Charge mobility ↑
Collected charge ↑
Collection time ↓ ☺
Efficiency ↓ ☹

The edge on geometry

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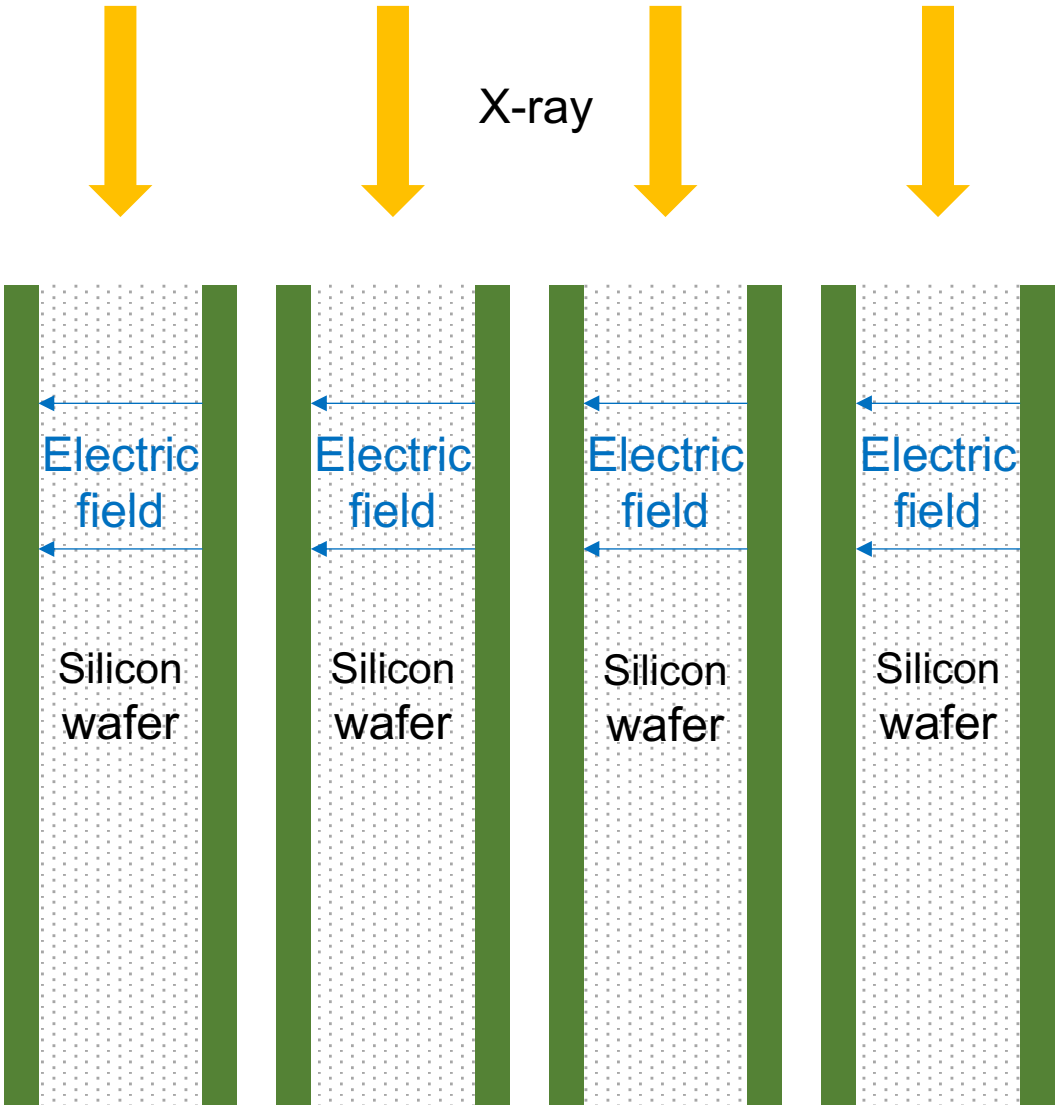

Edge-on detector

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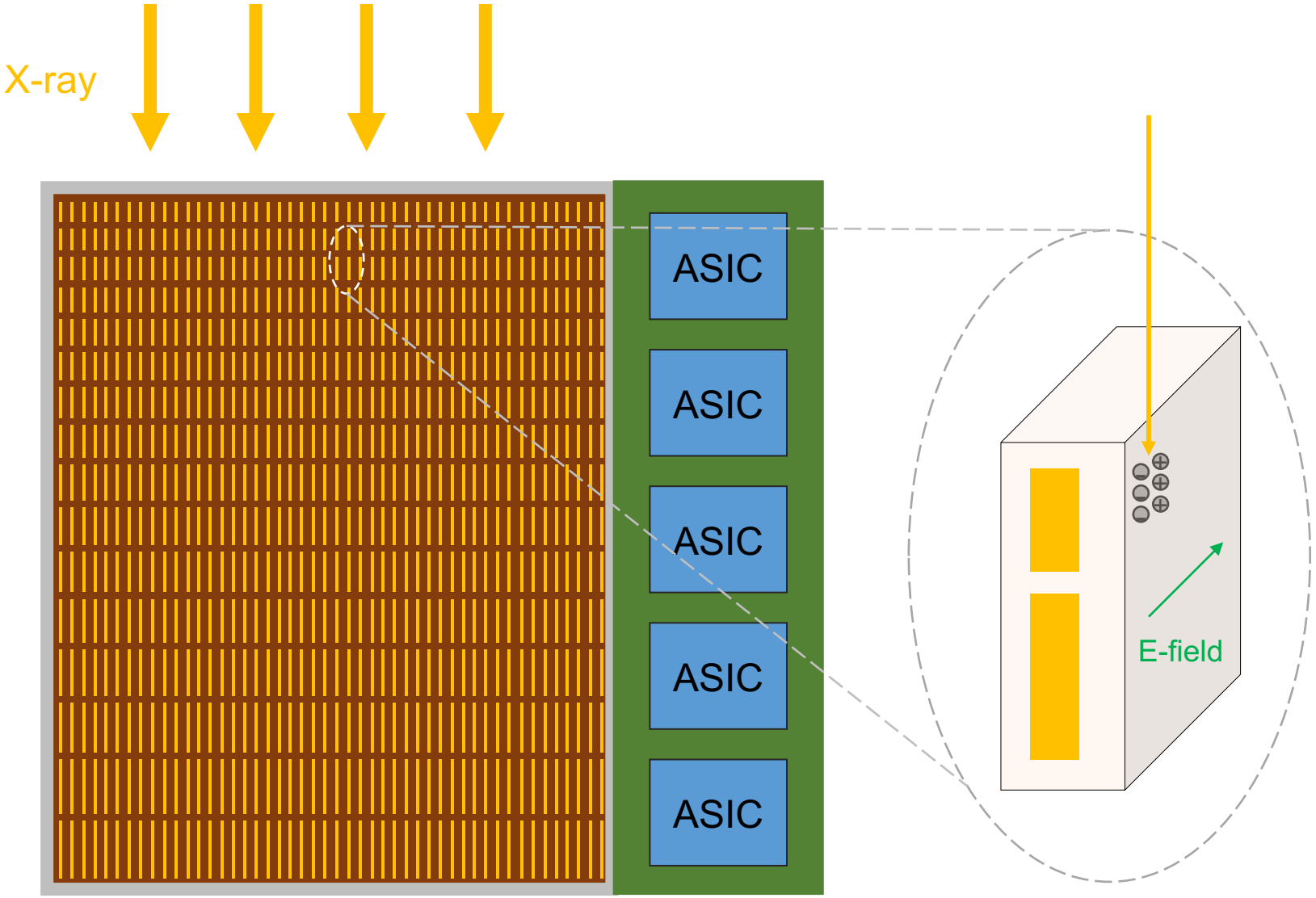

Charge Sharing

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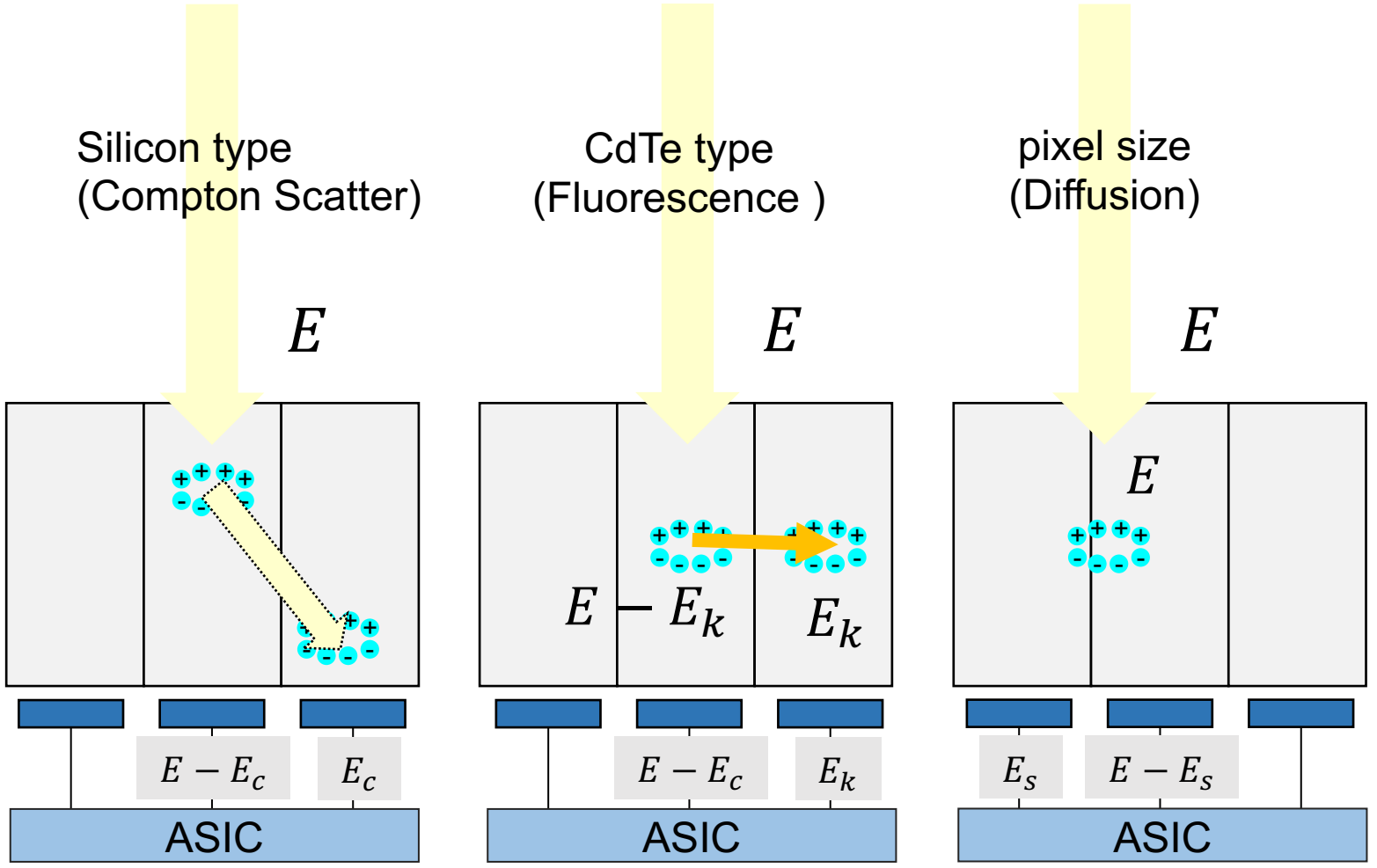

Pulse Pileup

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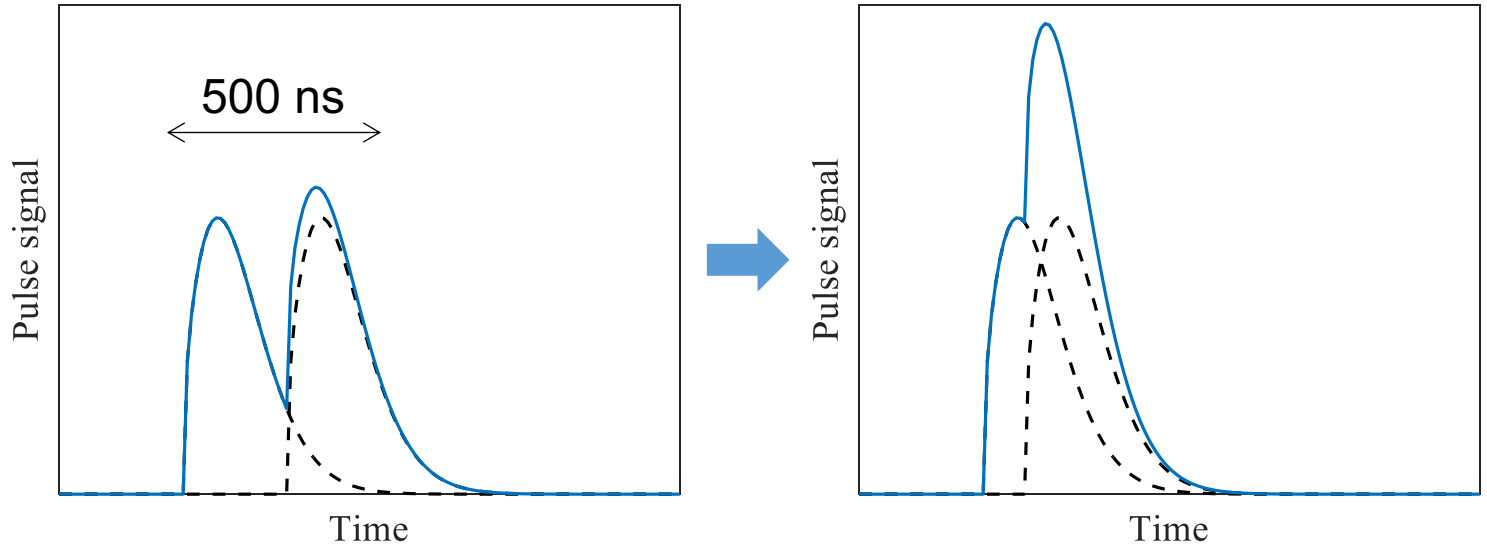
- The count rate in x-ray CT imaging is very high!
- Not a concern for dose measurement as the dosimeter works in the continuous mode.



Pulse Pileup Correction

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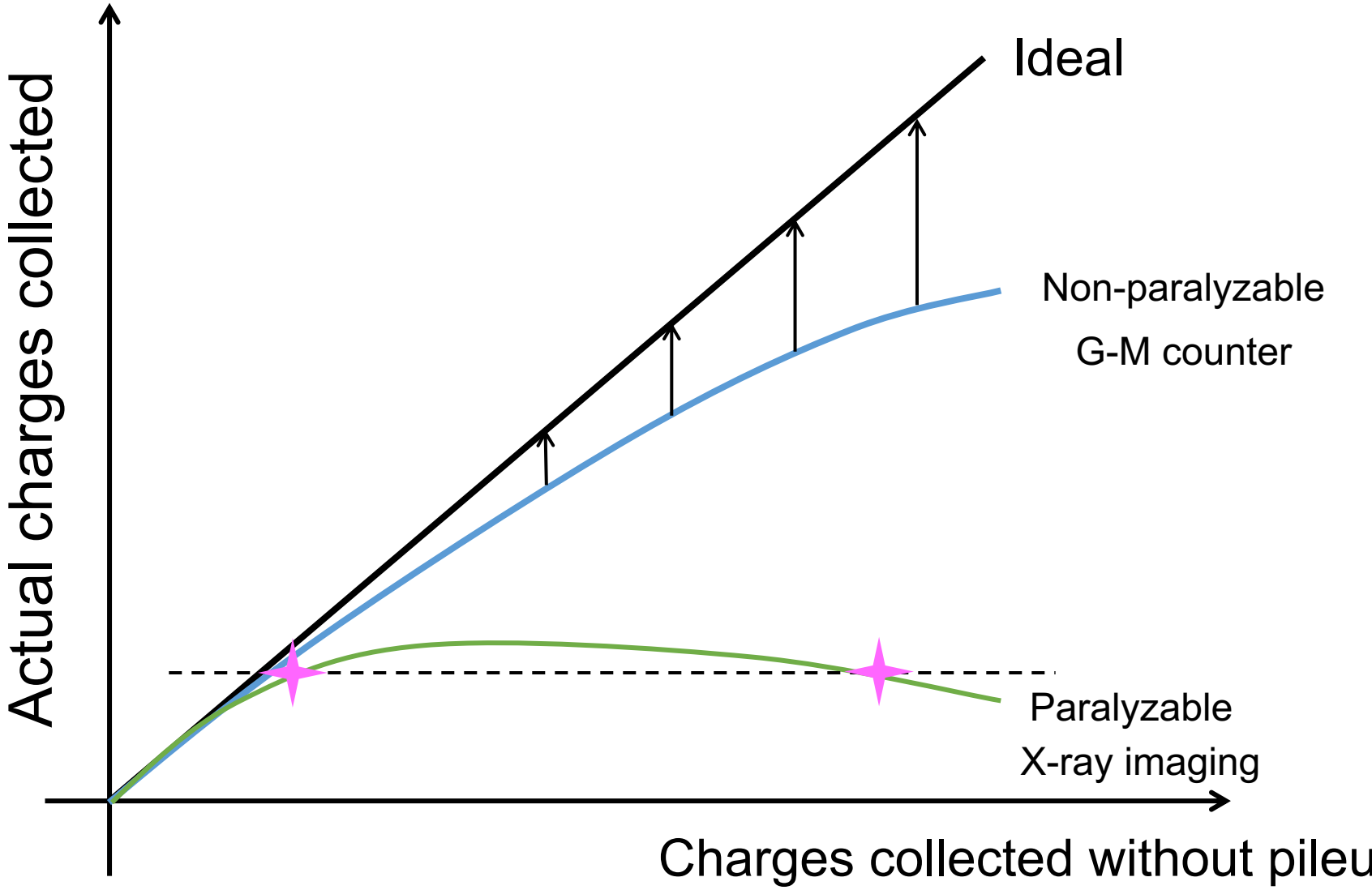

Take home message

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- Semiconductor detectors have different working conditions, which decide their characteristics specific to imaging or dosimetry purposes.

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Contact: cz453@cinj.Rutgers.edu

Shockley-Ramo theory

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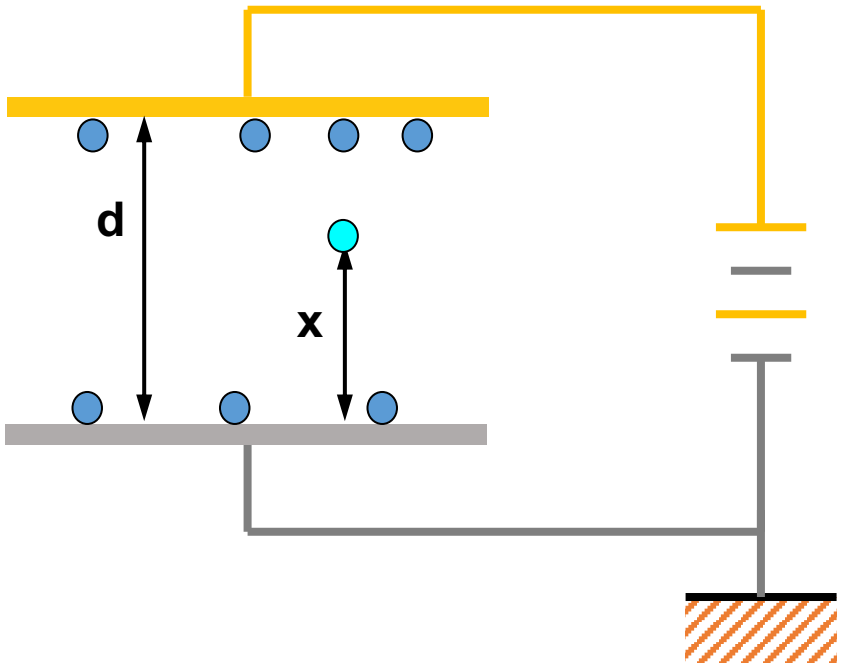

Overview of air chambers

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