Module 5 Unit 2
Electro-Optic Sensors

Dr. Suren Patwardhan

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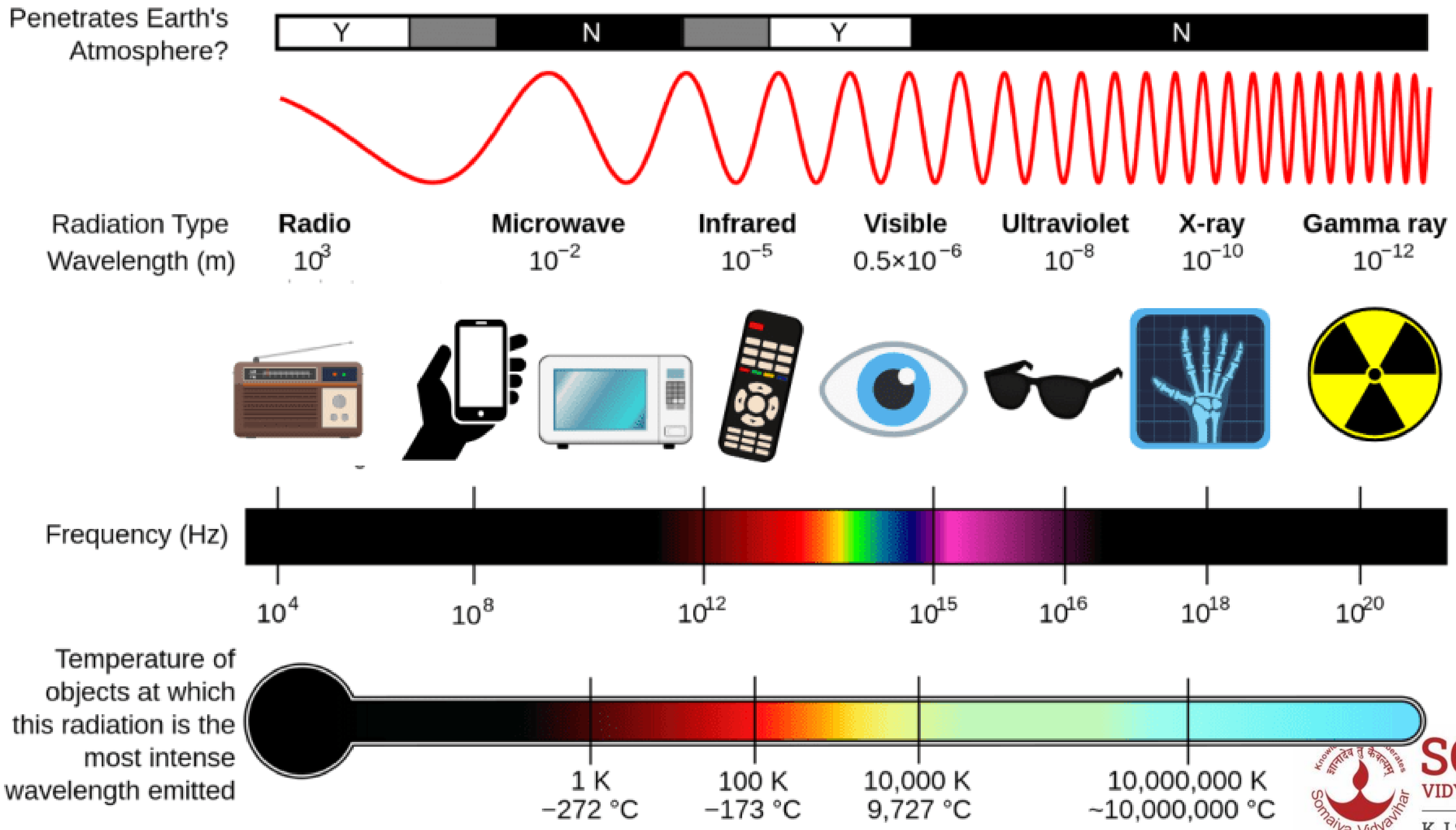
The Electromagnetic Spectrum

The electromagnetic spectrum is the range of all frequencies of electromagnetic radiation.



Types of Electro-optic Sensors

- Radiation & particle detectors (gamma rays, X-rays, alpha particles, beta particles etc.)
- UV detectors (ultraviolet radiation)
- Optical detectors (visible light)
- IR detectors (infrared radiation, optical fibre communication, thermal imaging)
- Microwave detectors (communication signals, domestic appliances)
- Radio detectors (wifi, satellite communication, TV, FM communication)

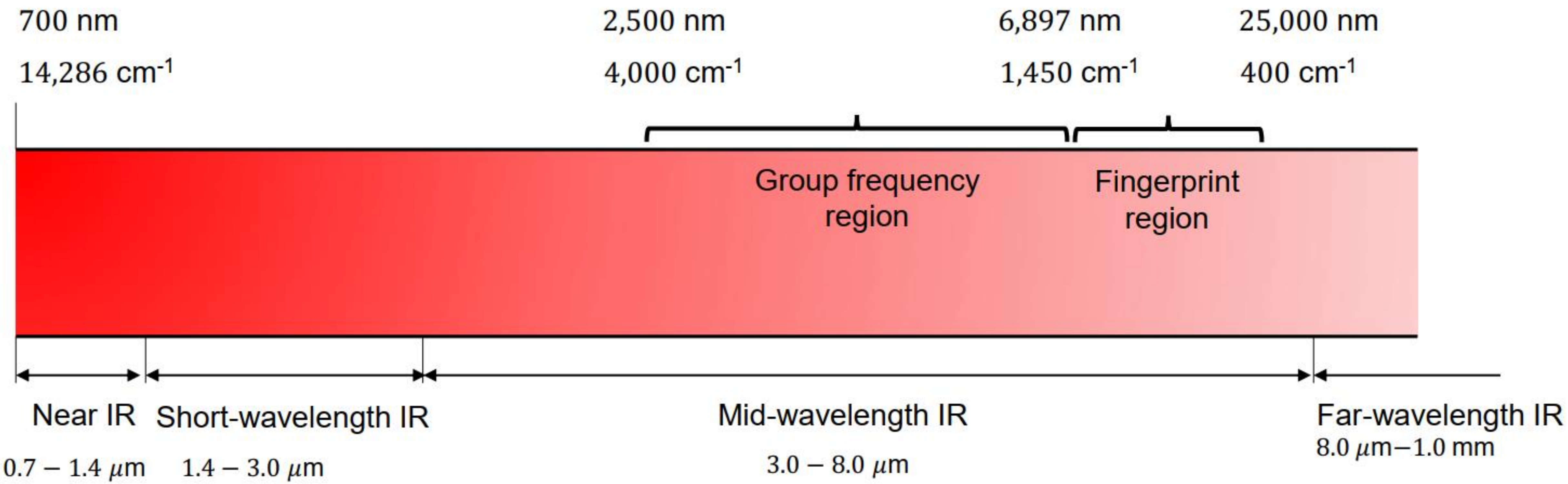
Types of detectors	Used for
Scintillation counters, ionization chamber, GM counters, PMT, solid-state detectors based on Si/Ge, SiC, Cl-tank, Mass spectrograms,	Gamma radiation, X-rays, alpha, beta radiation and elementary particles such as neutrinos, mesons etc.
Photocells, solid-state detectors based on nitrites and phosphides	X-rays, UV rays
Photodiodes, phototransistors, CCD, CMOS	Visible and IR radiation
IMPATT diode, Tunnel diode, GUNN diode, CCD	Microwaves
Antennas, RADAR, Schottky diodes	Radio waves

IR and Image Sensors: Sub-Class of Electro-optic Sensors

- IR Sensors
  - Thermal Sensors
    - Bolometer/Thermistor
    - Thermocouple/Thermopile
    - Pyroelectric
  - Photon Sensors
    - Photoconductive detectors
      - Photodiodes
      - Phototransistors
    - Photovoltaic detectors
      - Solar cells

- Image Sensors
  - CCD
  - CMOS

IR Spectrum



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Topics to be Covered

- IR Sensors
  Photodiodes (PIN photodiodes)

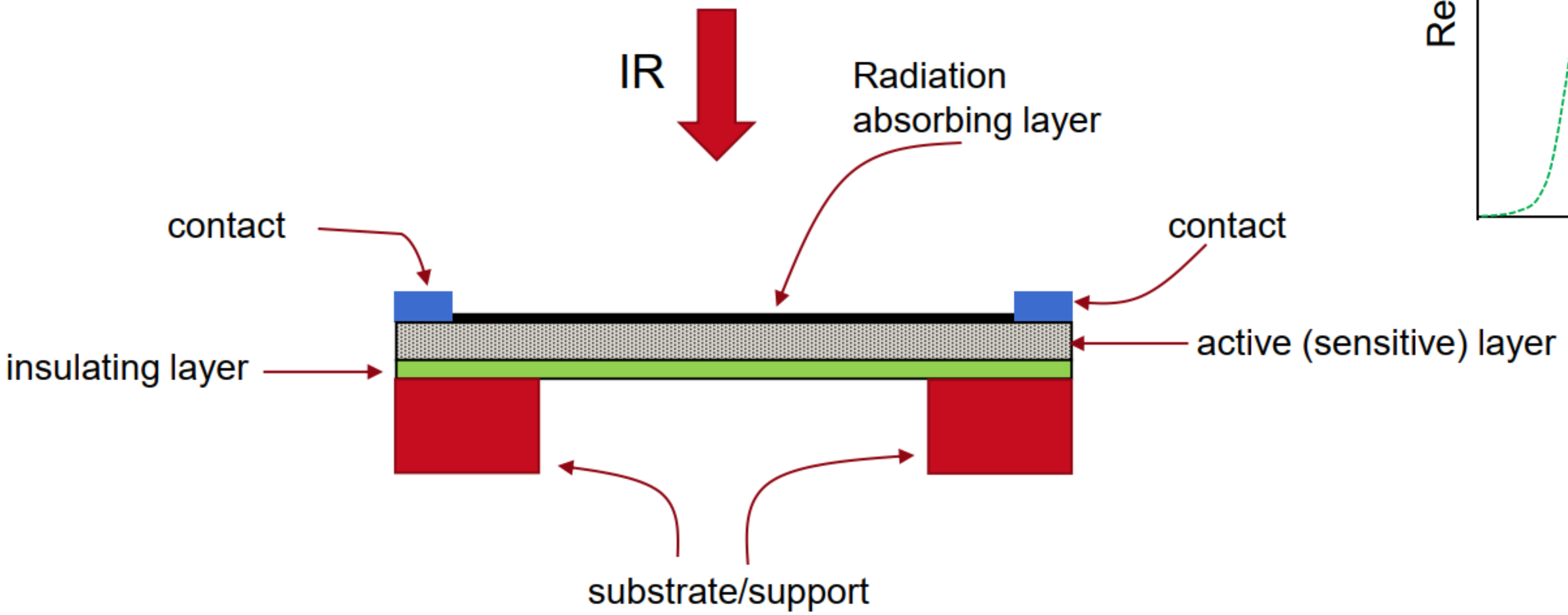
- Image Sensors
  CCD

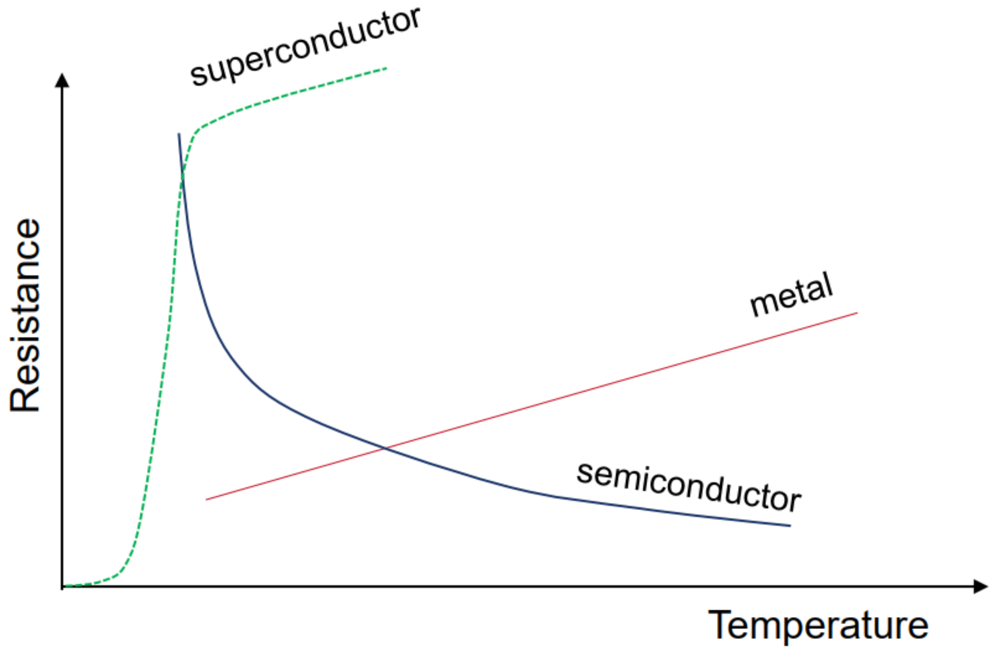
Thermal Sensors

- Thermistor
  Principle: Change of conductivity due to temperature

  Types: Metallic, Semiconductor

$$\rho(T) = \rho(T_0)(1 + \alpha \Delta T)$$



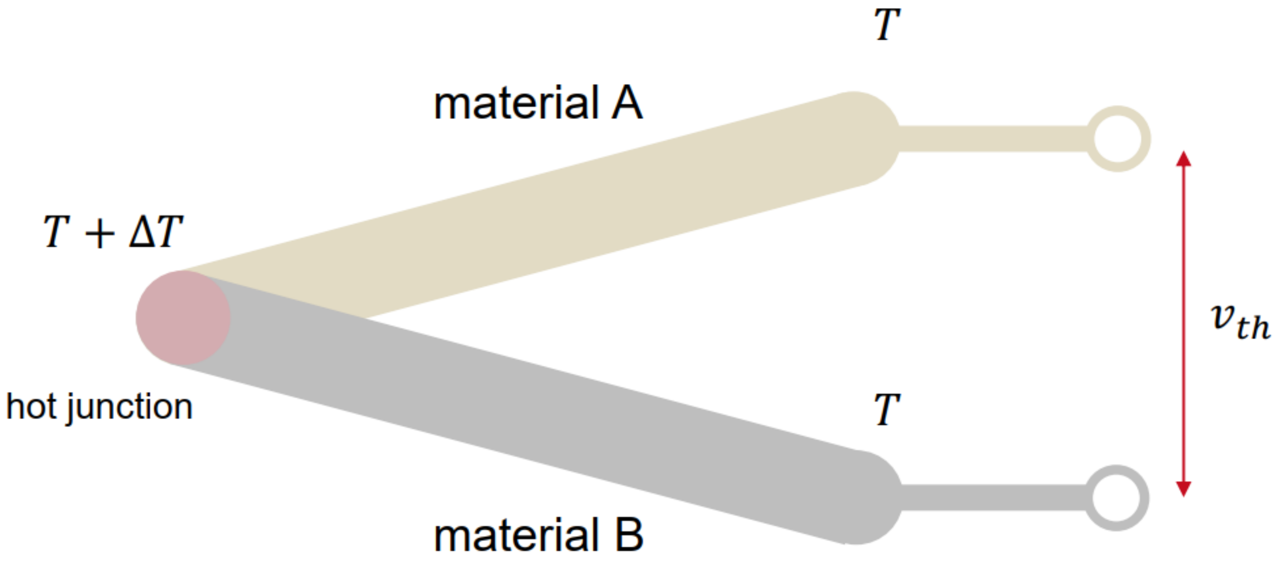


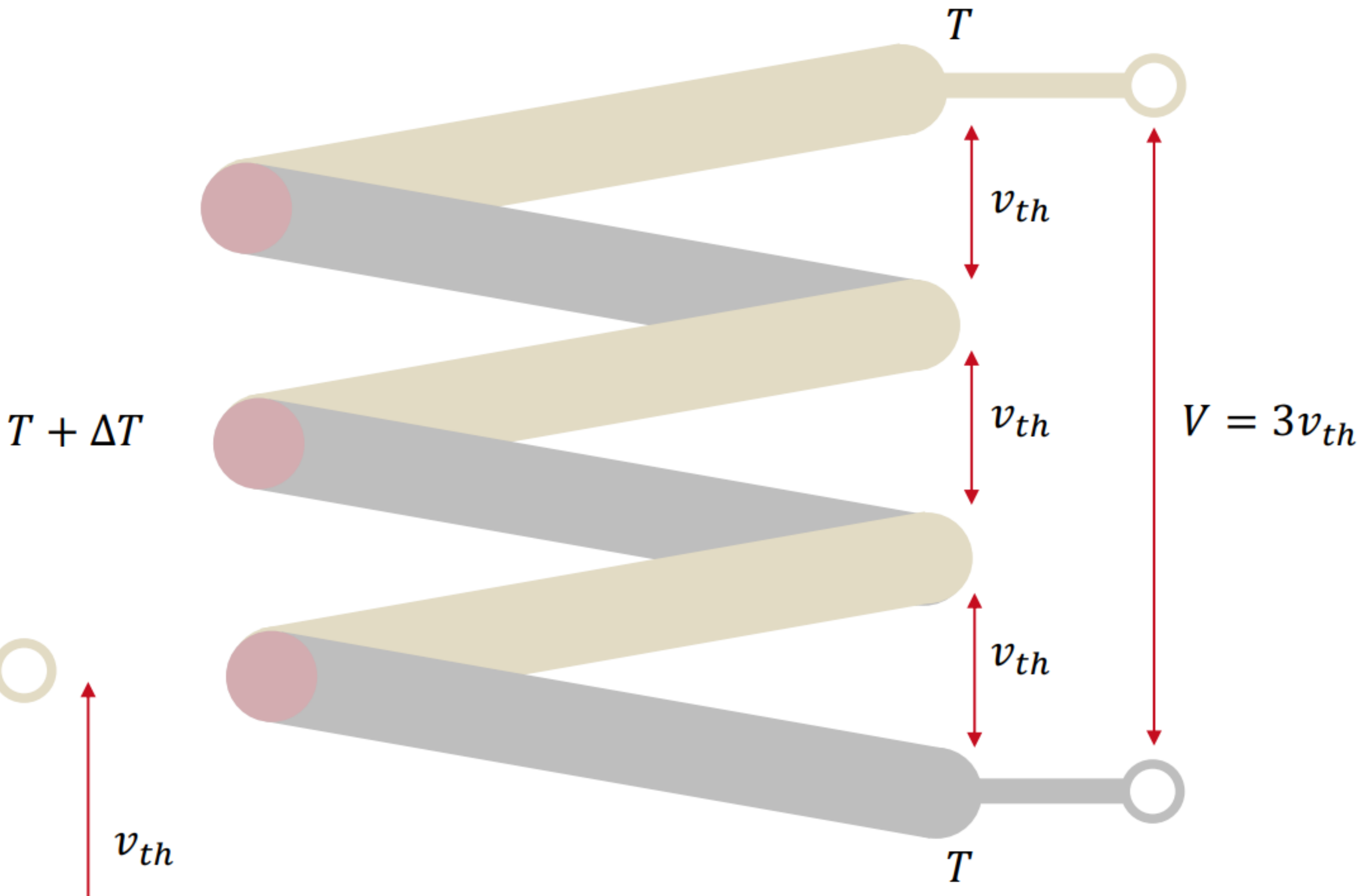
Thermal Sensors

- Thermocouple/Thermopile
  Principle: Seebeck effect

  Types: Metallic, Semiconductor

$$V_{th} = \alpha_{S,AB} \Delta T$$





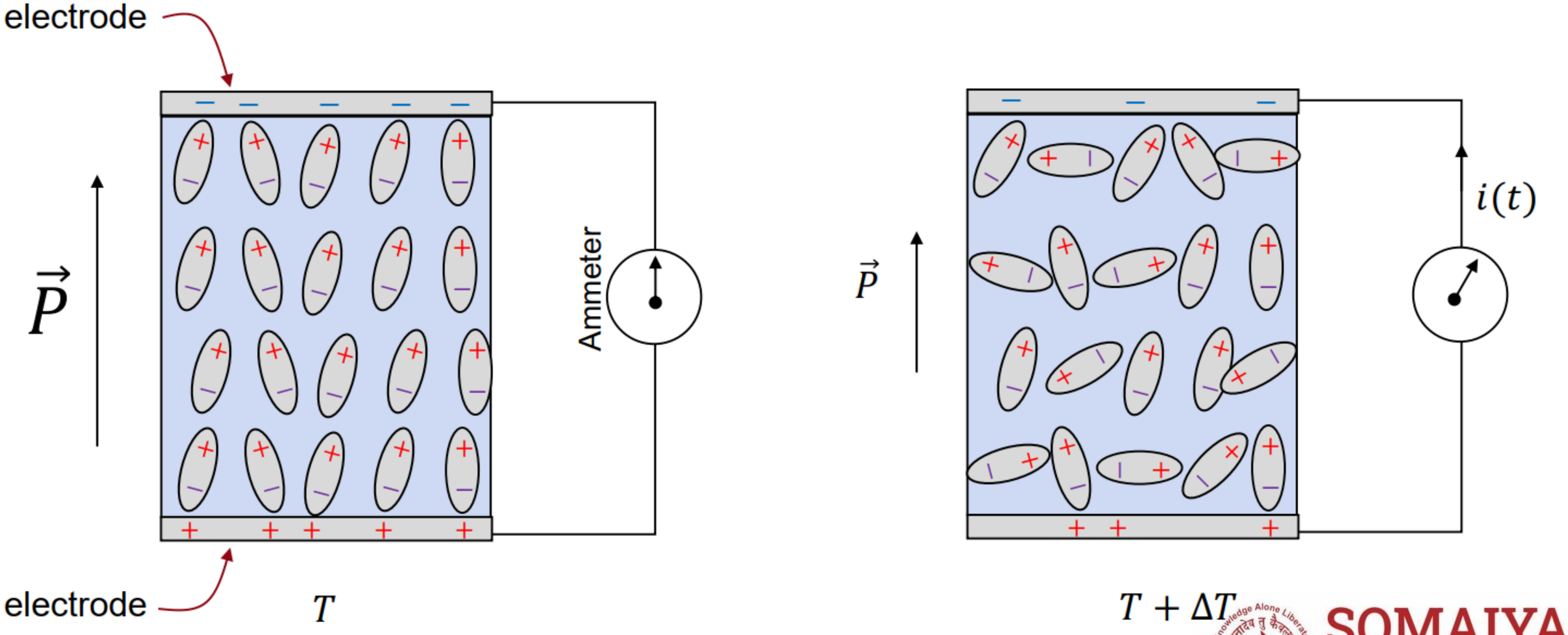
Thermal Sensors

- Pyroelectric detectors

  Principle: Pyro-electricity

  Types: Special salts e.g. Tourmaline

$$I(t) = p\frac{dT}{dt}$$

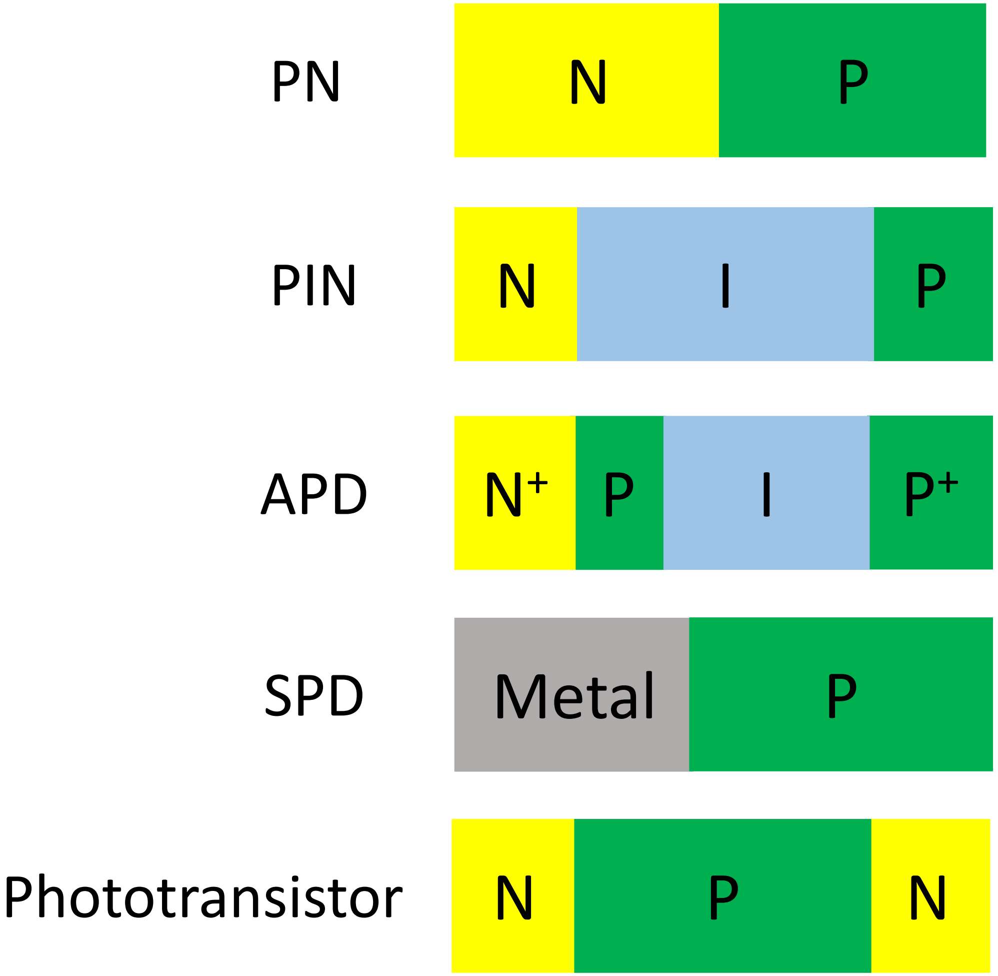


Photon Sensors

- Photoconductive detectors
  Principle: Change in current due to light
  normally used in reverse biasing mode
  Types: Photodiodes, Phototransistors

- Photovoltaic detectors
  Principle: generation of voltage due to light
  Used in zero-bias mode
  Types: Solar cells

- Photodiodes Types:
  PN normal p-n junction diode
  PIN: Broad un-doped region between P and N sides
  APD: Avalanche photodiode
  SPD: Schottky photodiode or metal-semiconductor diode



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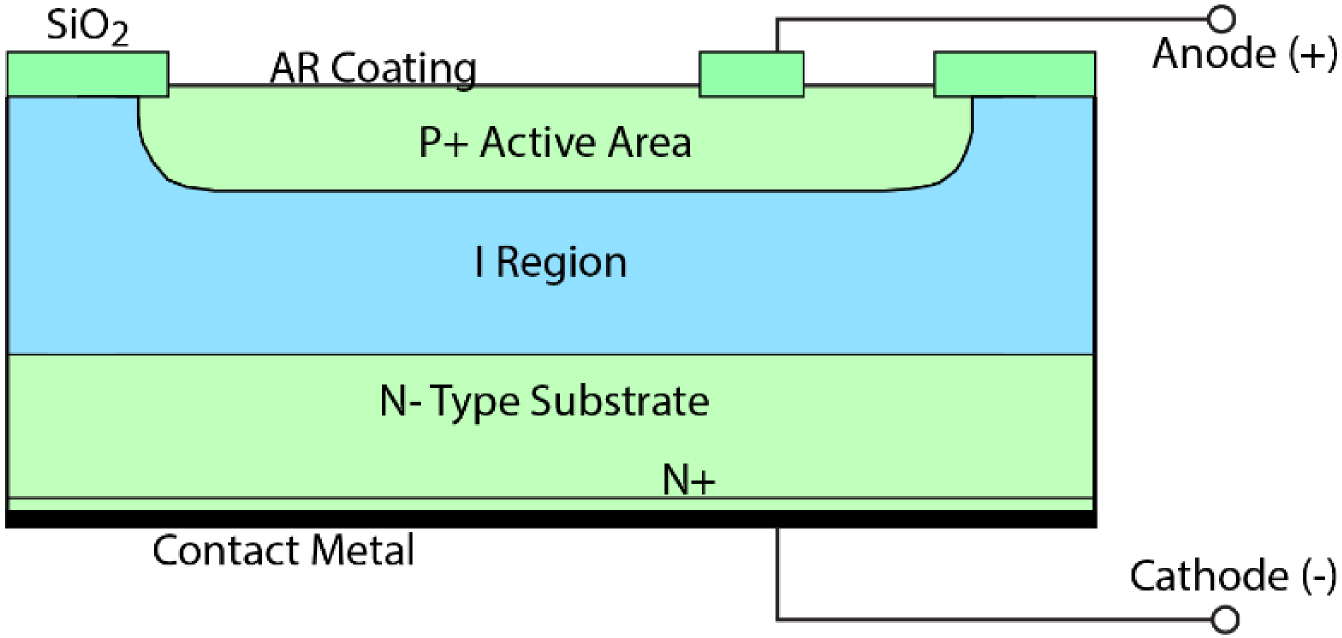
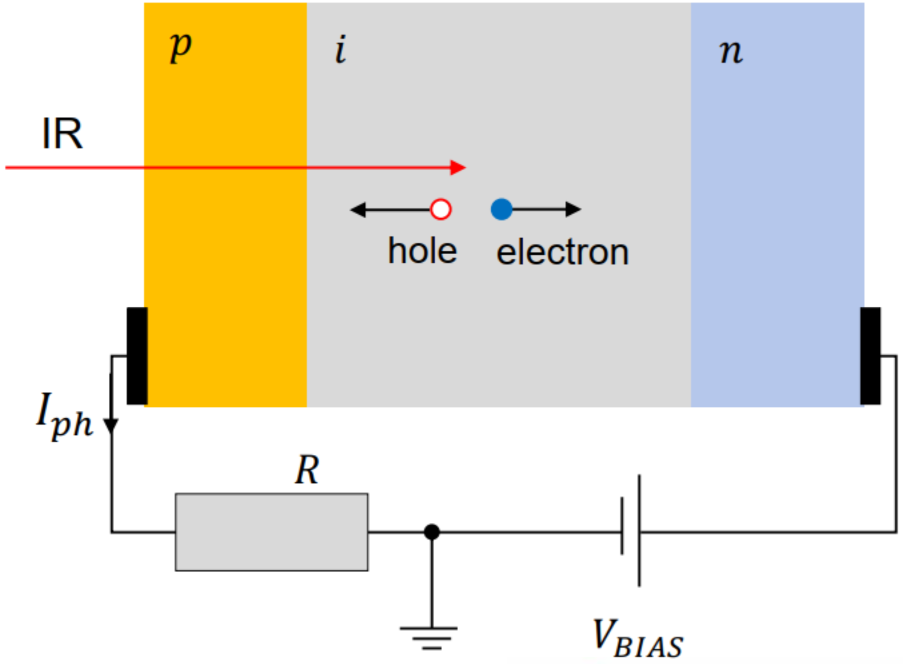
PIN Photodiode

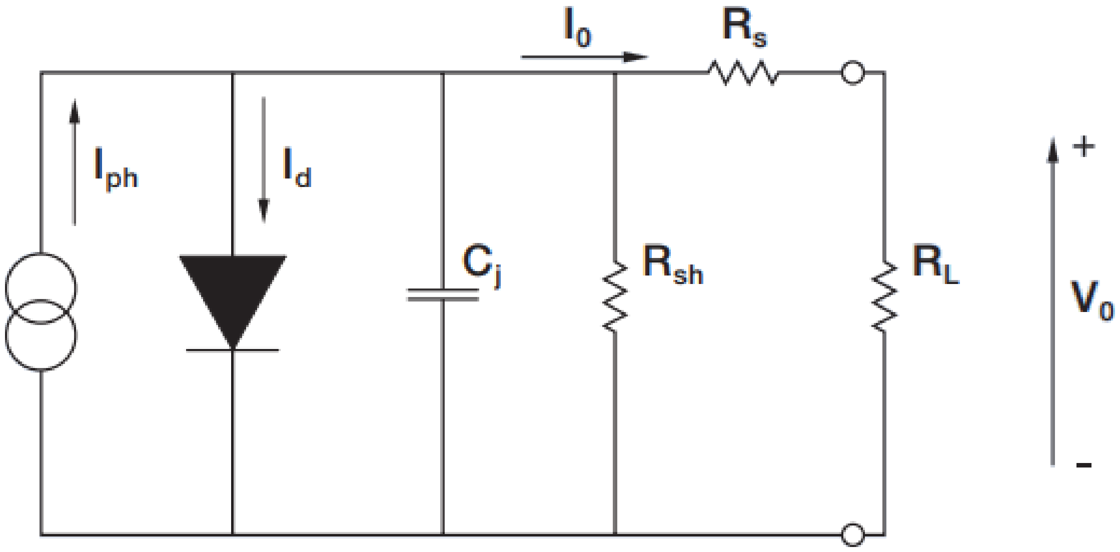
- General characteristics:
  An intrinsic layer is placed between the two doped layers
  This layer increases the electric field strength
  The larger intrinsic layer also allows for a larger amount of photons
  Response time reduces and speed of the photodiode increases
  Capacitance of the junction is decreases

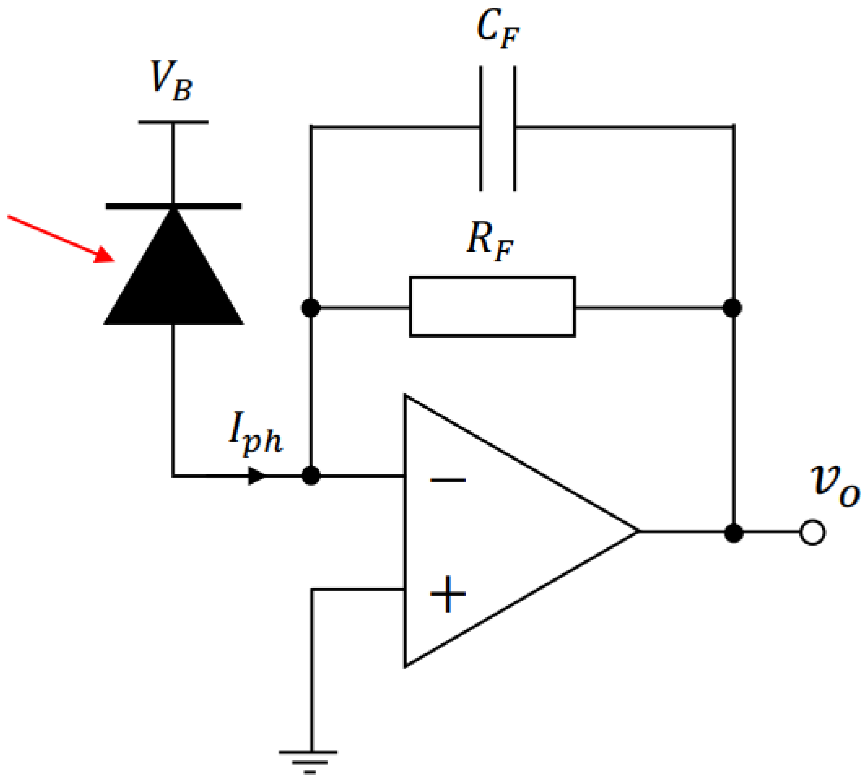




PIN Photodiode Equivalent Circuit and Biasing

Equivalent circuits gives major internal components active during its operation
PIN photodiode is best operated in reserve biased mode





PIN Photodiode Parameters

Responsivity: ratio of photocurrent generated to the incident optical power. It measures sensitivity of the photodiode

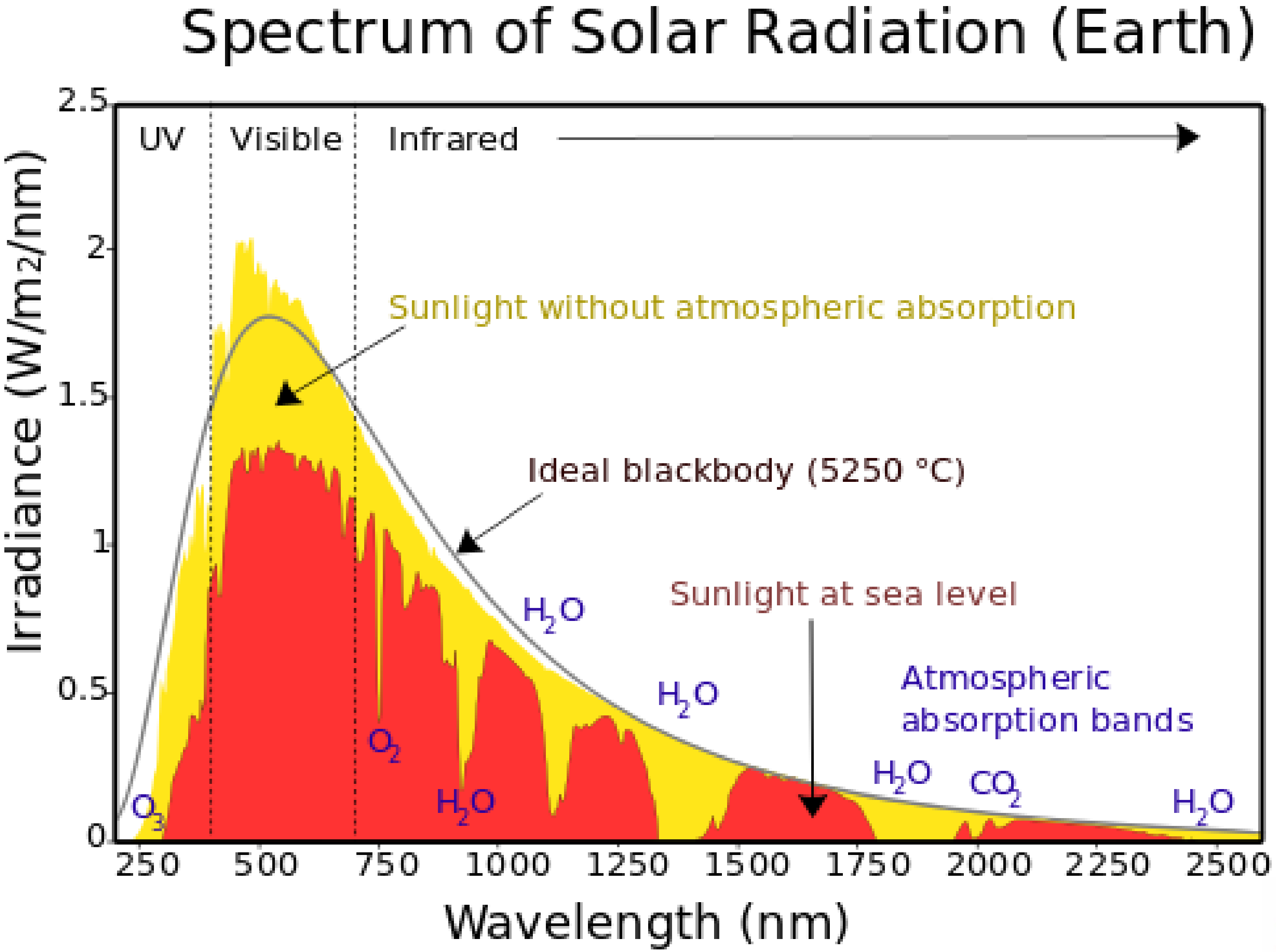
$$R_\lambda = \frac{I_P}{P}$$

Total current is given by: $I_{TOTAL} = I_{SAT}\,(e^{\frac{qV_A}{k_B T}} - 1) - I_P$

The photocurrent is given by: $I_P = \dfrac{q\eta AP}{h\upsilon}$

η: **Quantum efficiency** = number of electron-hole pairs generated per no of photons absorbed
P: **Radiation power density** (integrated)

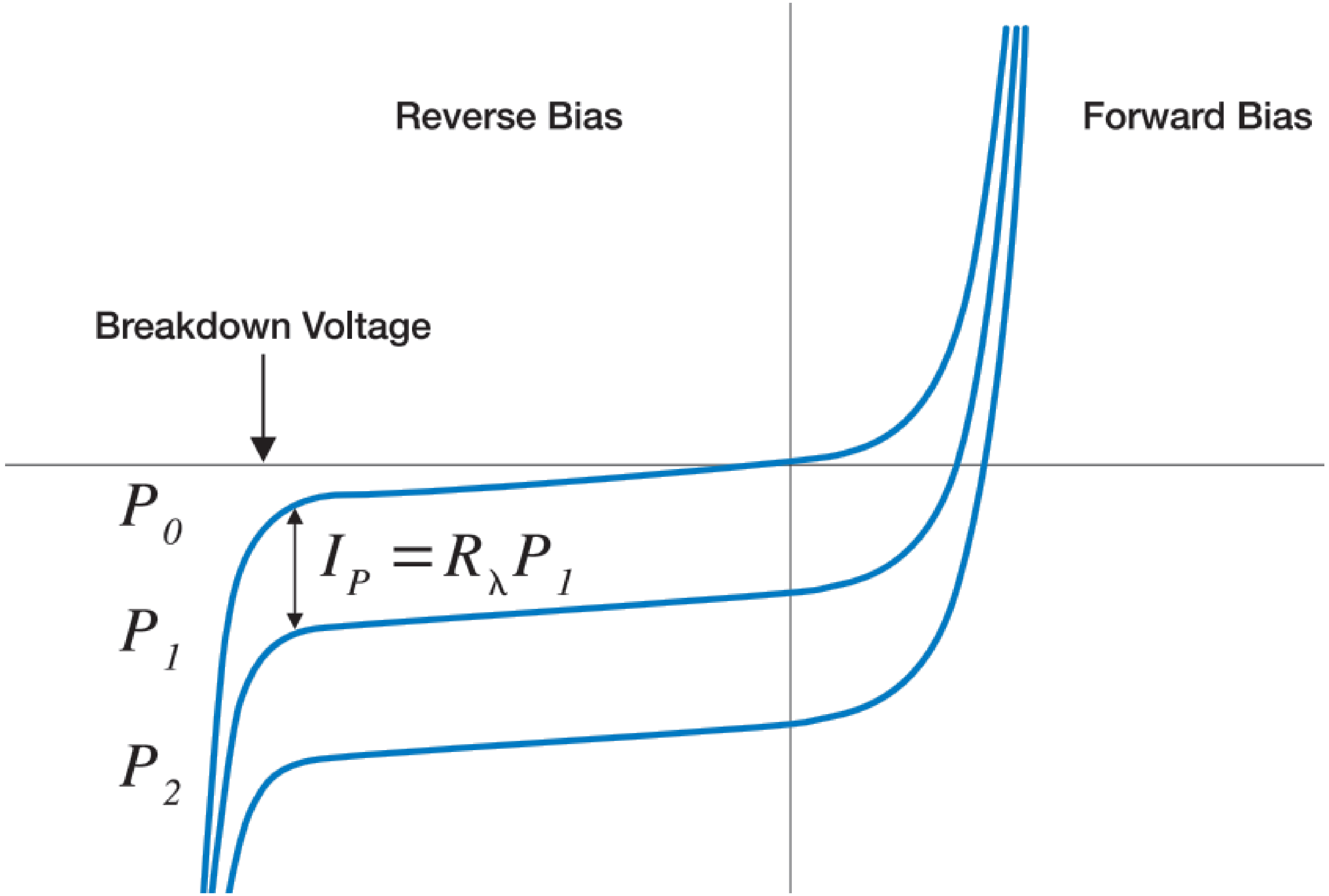
Spectral Irradiance



$$H = \int_0^\infty F(\lambda)d\lambda$$

$$= \sum_i F(\lambda)\Delta\lambda$$

PIN Photodiode I-V and light characteristics



Advantages and Disadvantages of a PIN Photodiode

- Advantages

1. High Sensitivity: they can capture weak optical signals effectively
2. Wide Spectral Response: they detect light across a broad range of wavelengths
3. Low Dark Current: Low dark current leads to higher signal-to-noise ratios
4. Fast Response Time: quickly converts light signals into electrical signals.
5. Low Noise: more accurate and reliable signal detection.
6. High Quantum Efficiency: efficiently convert incident photons into electrical current.

- Disadvantage:

1. Large Size: limits their use in applications in miniaturized designs (nanosensors)
2. Temperature Dependence: temperature affects the dark current and quantum efficiency
3. Power Consumption: a reverse bias consumes more power.

Applications of PIN Photodiode

1. Fibre optic communications: optical detectors and optical networks
2. Environmental sensing: light level detection, sensing and intensity monitoring
3. Automatic brightness control: ambient light sensors in smartphones and tablets
4. Imaging and Scanning: cameras, surveillance, and medical imaging, barcode readers
5. Automation: laser alignment, proximity detection
6. Detection of nuclear radiation

Materials for PIN Photodiodes

MATERIAL	WAVELENGTH SENSITIVITY (NM)
Silicon	190 - 1100
Germanium	800 - 1700
Indium gallium arsenide	800 - 2600
Lead sulphide	1000 - 3500

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Comparison of Different Types of Photodiodes

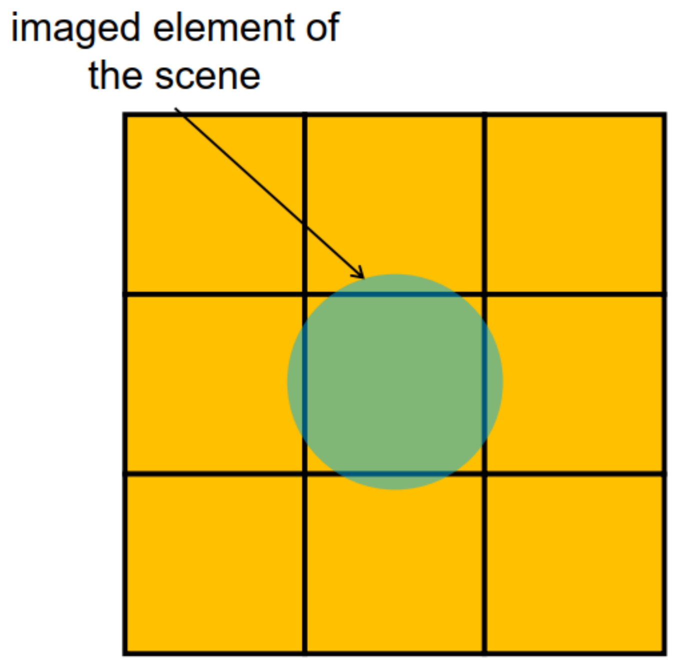
APPLICATION	CRITERION	PN	PIN	APD
Power generation	Photovoltaic	Best	Good	Poor
Fibre optic receiver	Reverse biased	Good	Best	Good
Night Surveillance	Low light	Poor	Good	Best
Commercial product e.g. remote control	Cost	Best	Good	Poor
Scientific measurements	Low noise	Good	Best	Poor

Image Sensors

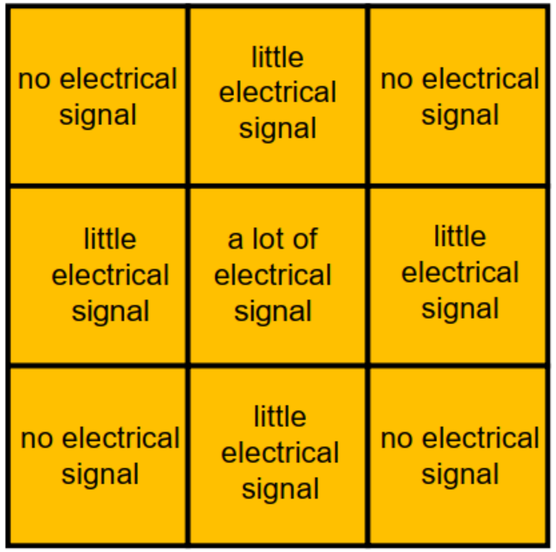
1. Image sensor converts light from an image to an electronic image
2. The light patterned and its order has to be preserved to reproduce image
3. This pattern is usually 2-D ordered matrix of intensity*
4. Unit in which conversion of patterned light to electrical signal occurs is called as pixel
5. Pixel is the smallest imaging element in an image sensor
6. Pixel density controls the quality of an image (such as HD, UHD, 4k etc.)

In some applications like holograms, 3rd dimension is recorded by capturing the phase of light waves

Basics Operation of CCD



3 × 3 array of pixels



$$S[e^-] = \eta n T_{exp} \qquad \text{(signal)}$$

η – quantum efficiency

n – photon irradiance per pixel

T_{exp} – Exposure time

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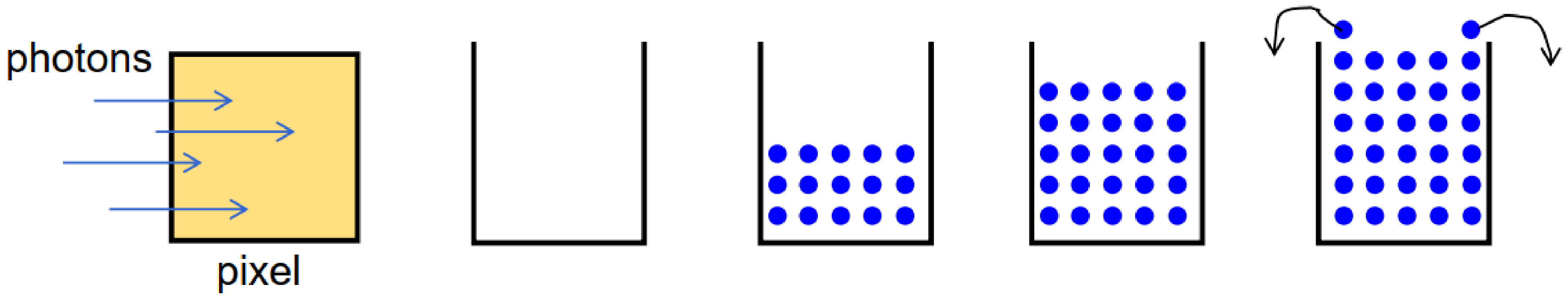
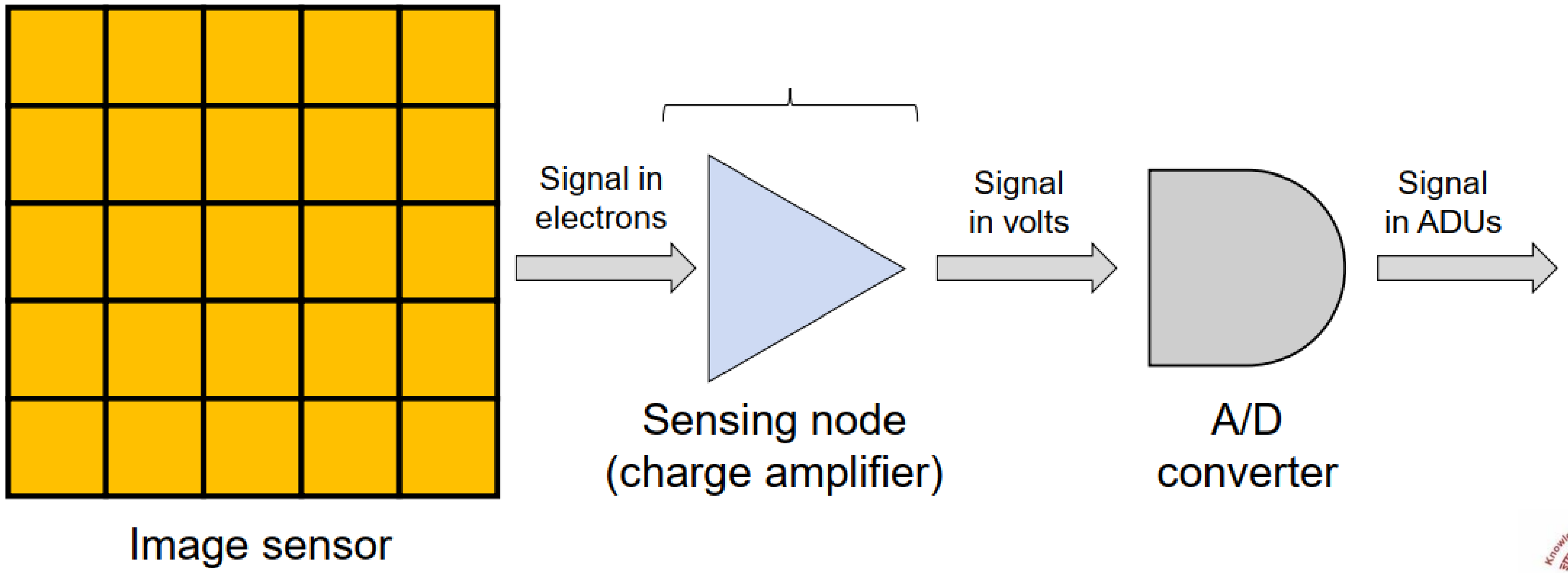
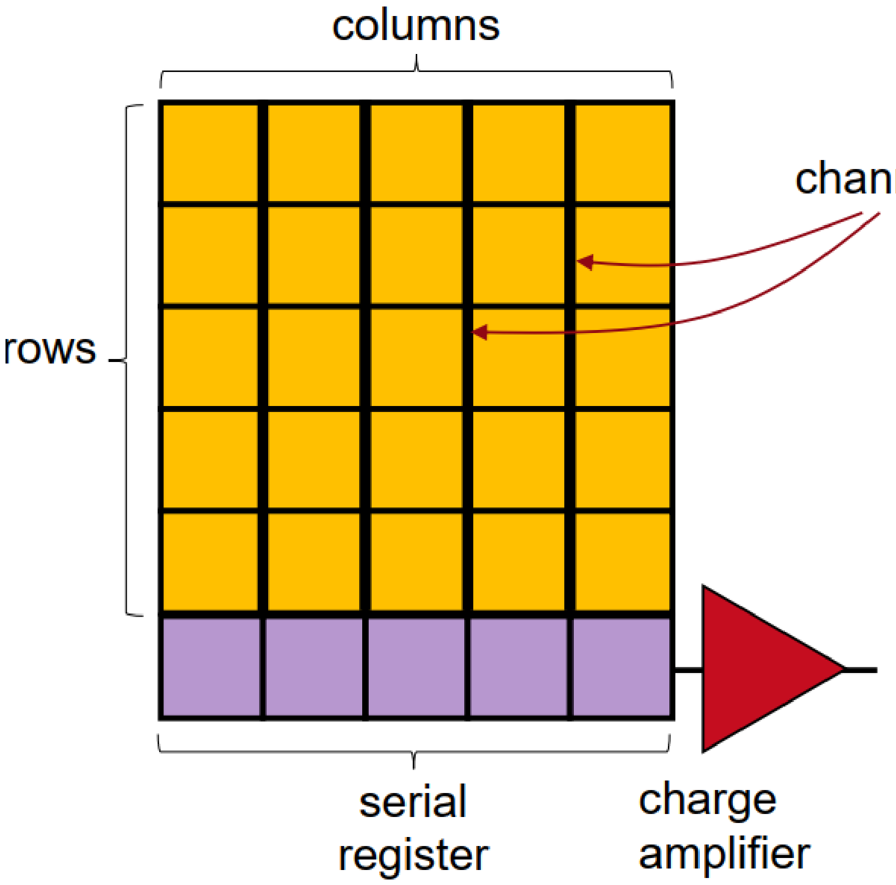
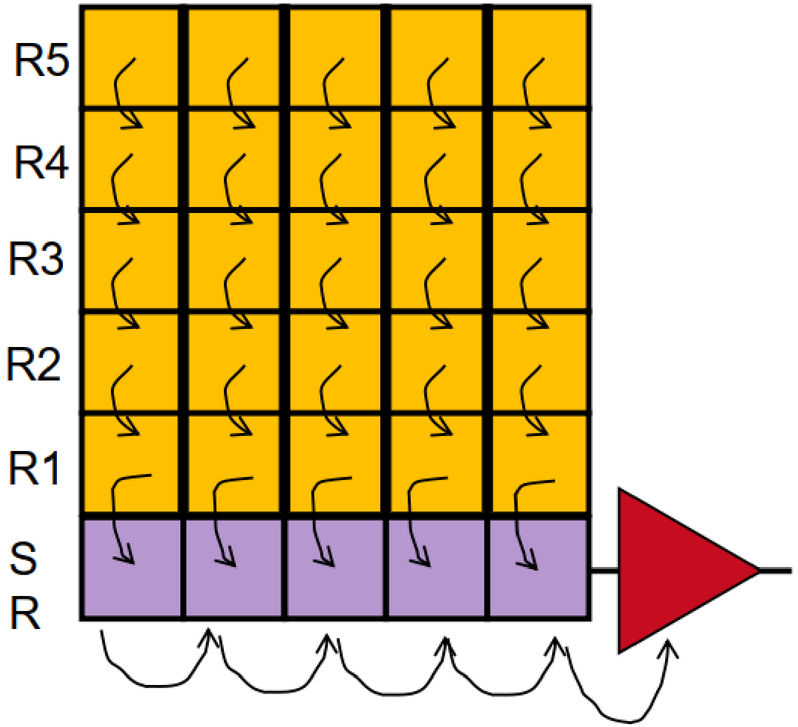
Image Sensing Process

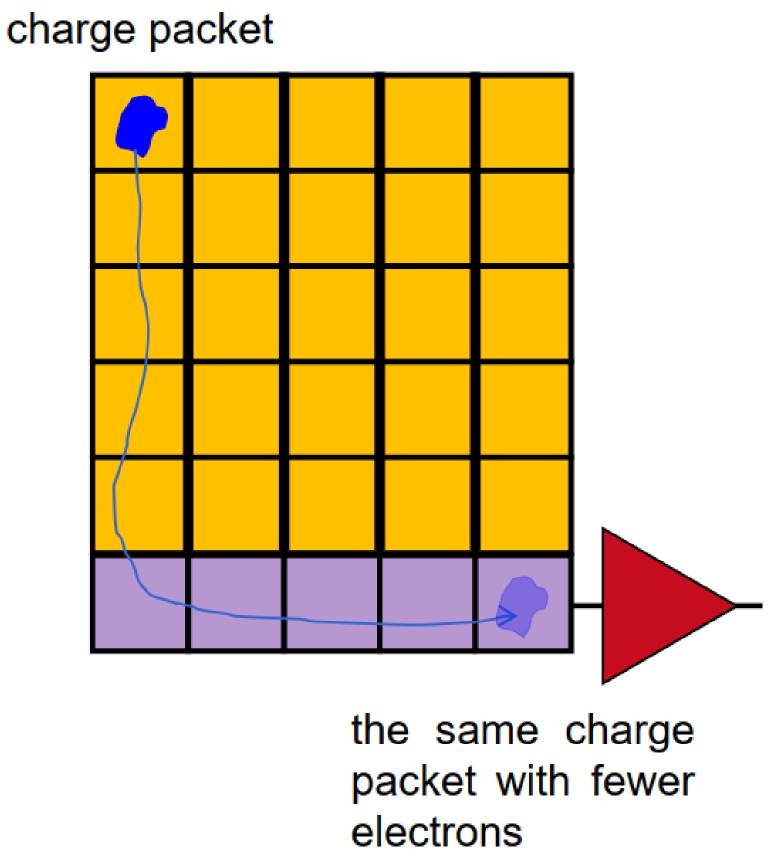




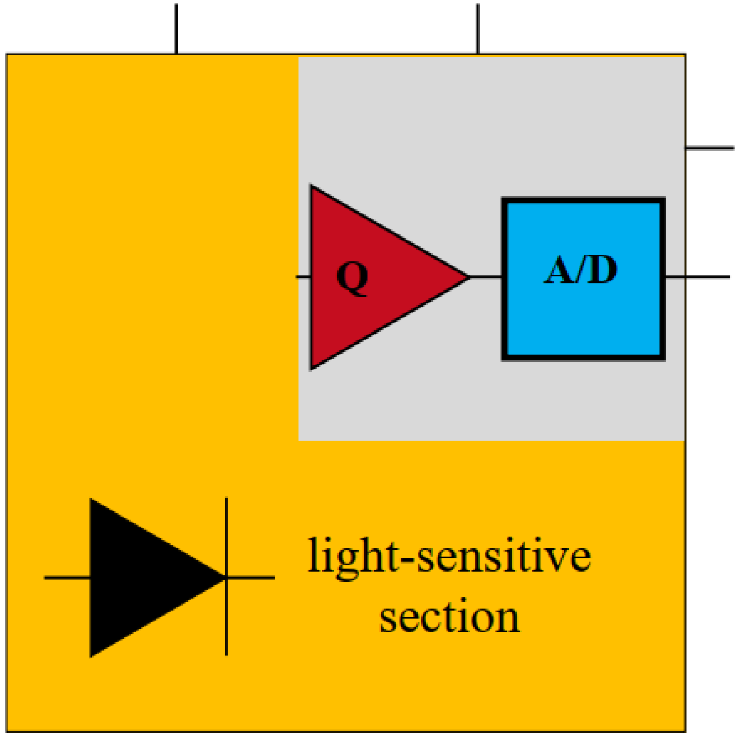
CCD Readout Process







CMOS Sensor



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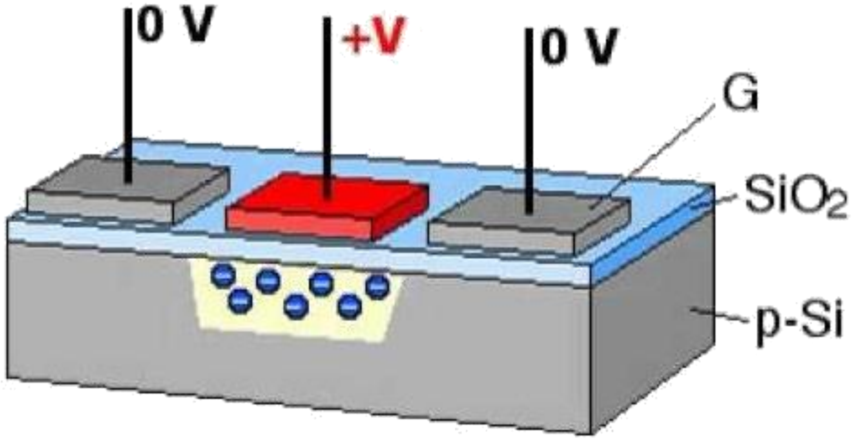
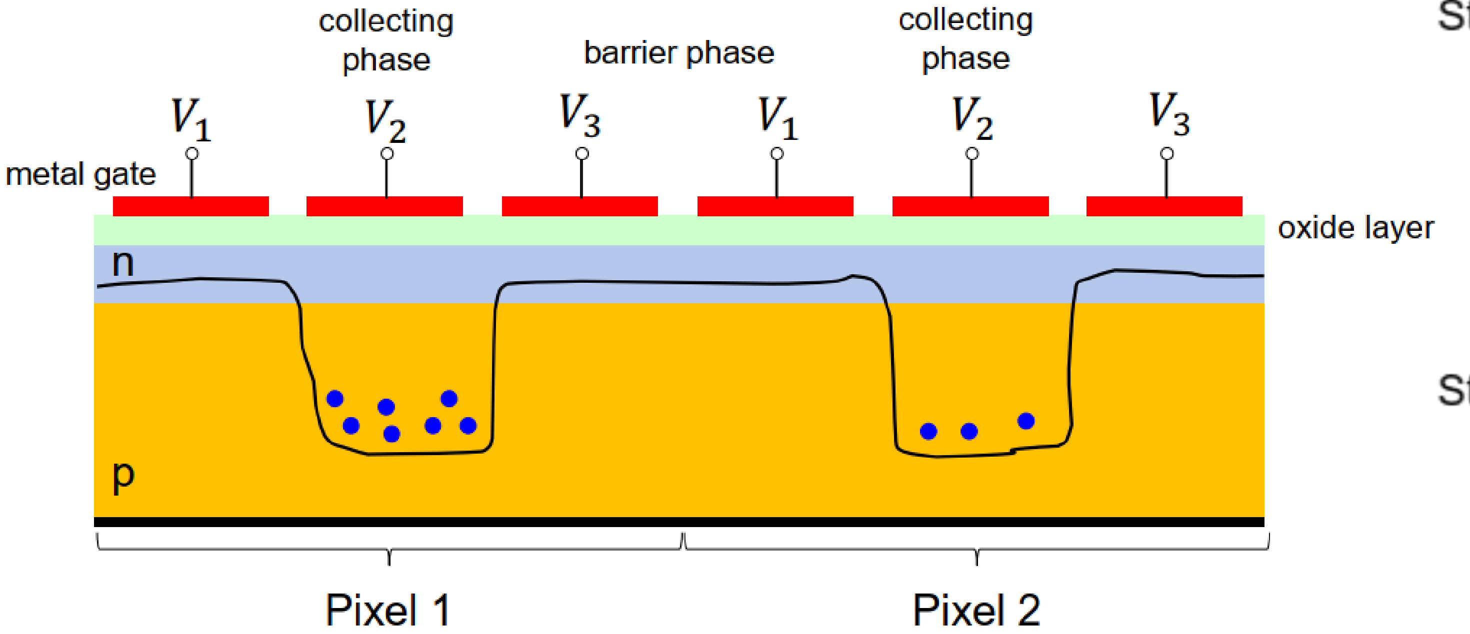
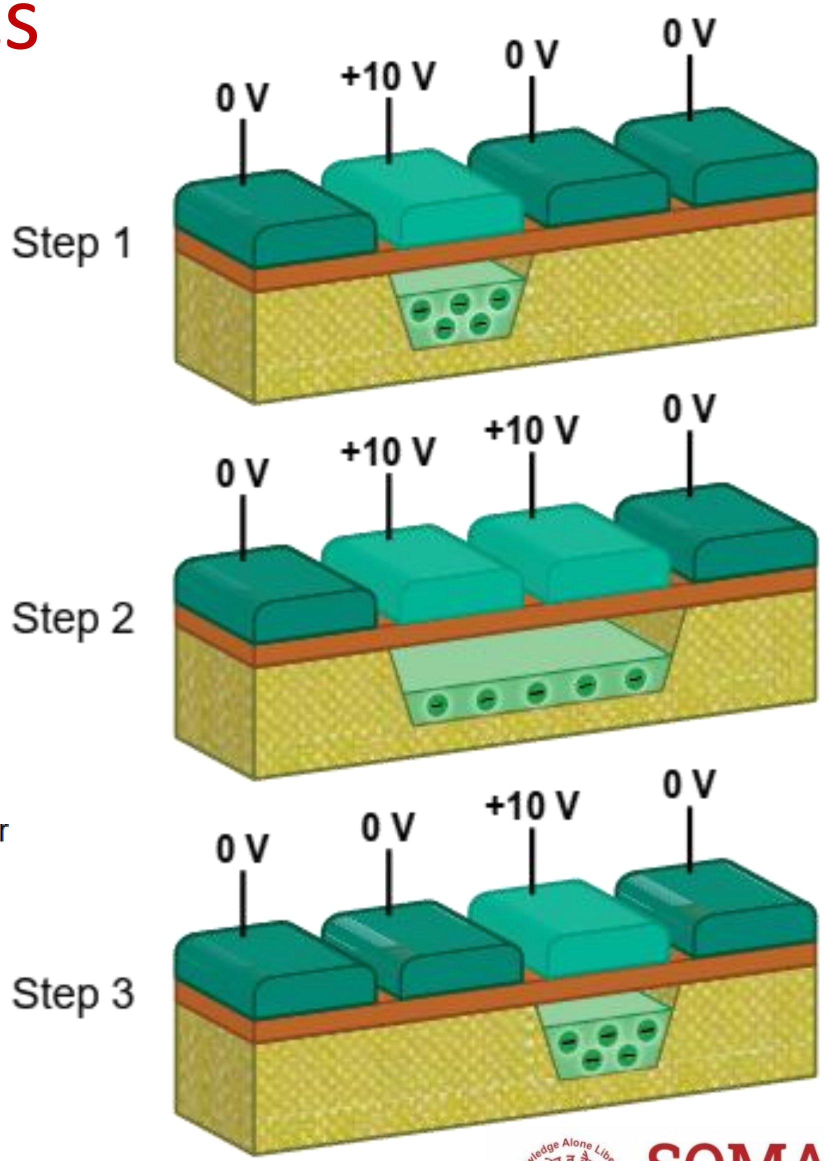
CCD Physics







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Advantages of CCD

1. Higher sensitivity
2. Lower noise
3. Simple and robust design
4. Cost-effective

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CCD Major Applications

1. Security cameras
2. Cellphone camera (CMOS CCD)
3. Raman Spectroscopy (molecular bonding)

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