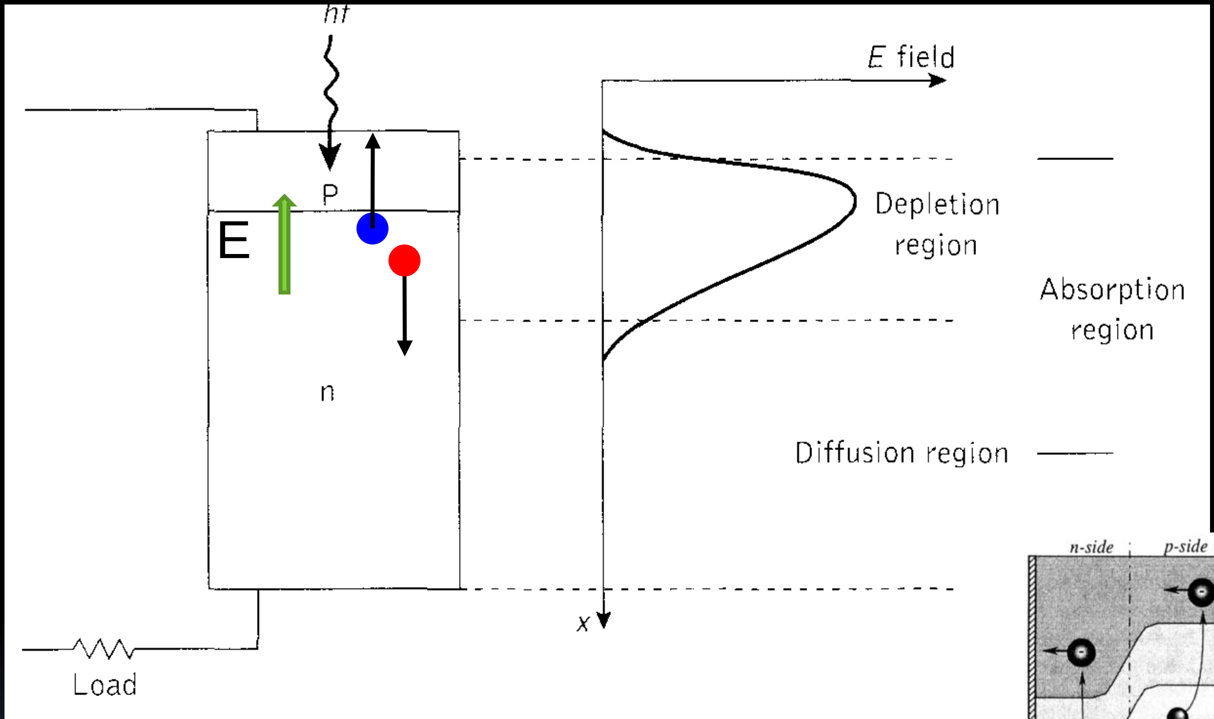
ECE 6323

DETECTORS AND SIGNAL DETECTION
P.2

Detectors, Detection and Signals

- (Part 1) Introduction
  - Concept
  - Detection mechanism and types of detectors
- (Part 1) Photoelectric detectors
  - Detection mechanism
  - Key features
- Types of photodiodes
  - p-n and p-i-n
  - Advanced p-i-n structures
  - Phototransistors
  - Avalanche photodiodes
  - Others: MSM
- Signal and noise, detection theory

Basic *p-n* Photodiode



The *p–n* photodiode showing depletion and diffusion region

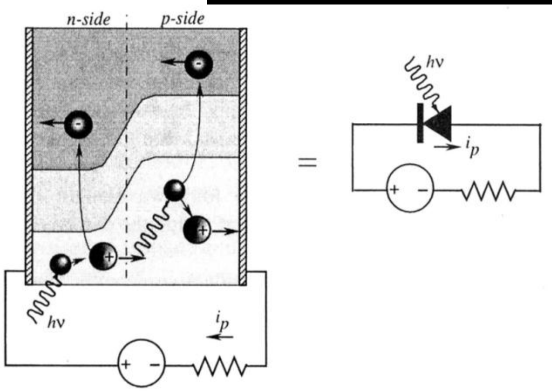
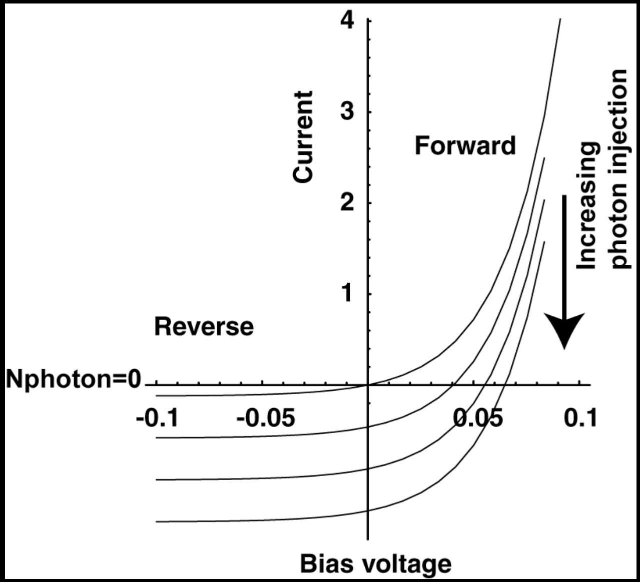
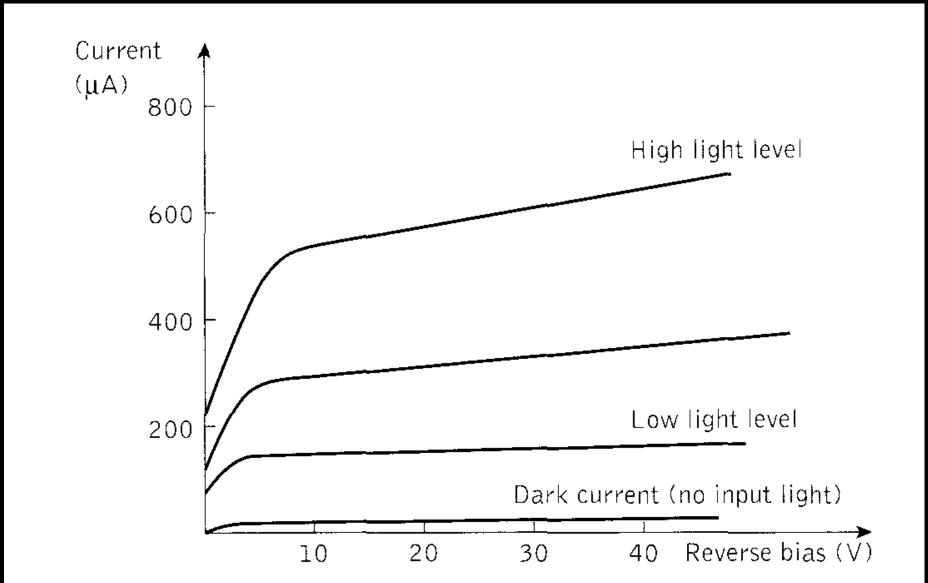


FIGURE 13.3. Structure of a photodiode.

I-V Characteristics of *p-n* Diode

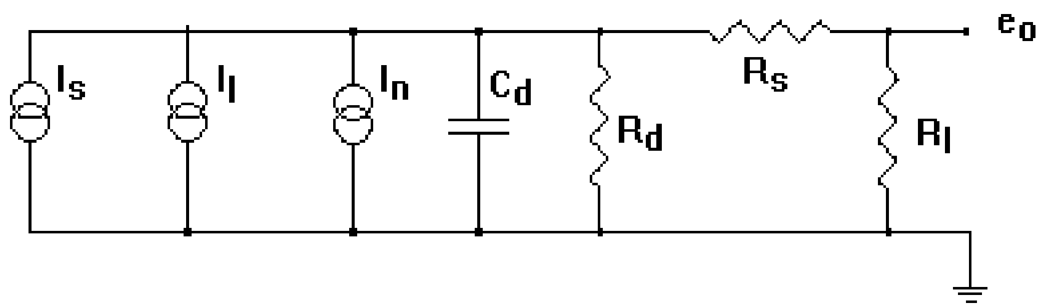




Typical *p–n* photodiode output characteristics

- Reverse bias voltage: trade off between high dark current vs. higher responsivity and speed
- Must stay below breakdown voltage

Equivalent Circuit



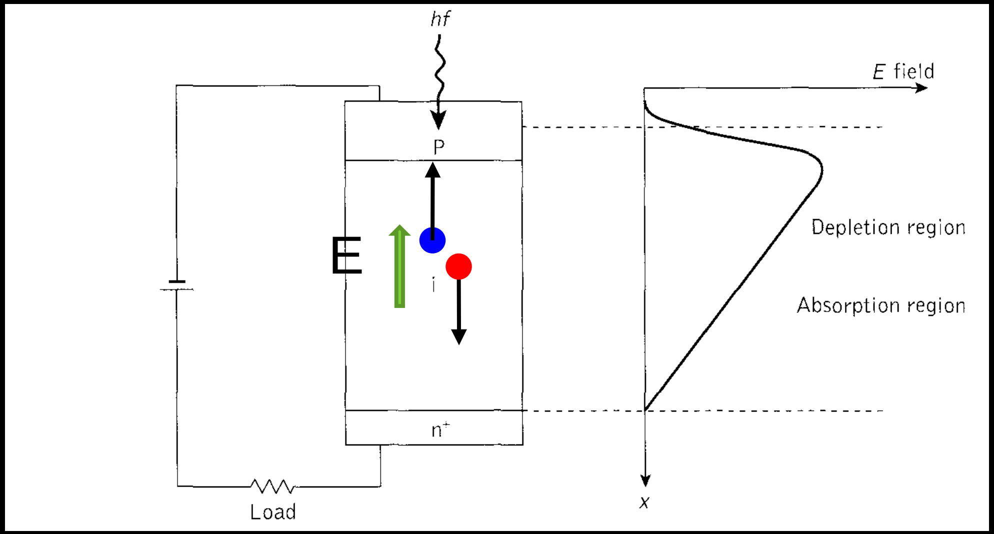
I_s = signal current
I_l = leakage current
I_n = noise current
C_d = diode junction capacity

R_d = diode parallel shunt resistance
R_s = diode series resistance
R_l = load resistance

$$e_o = [I_s + I_l + I_n][R_l R_d][R_l + R_d + R_s]$$

p-i-n Photodiode

- A separate absorption region (*i*) that is devoid of carriers to reduce recombination and enhance QE
- Can be designed for any absorbance (large depletion) and bandgap independently from the *p* or *n (which are for ohmic contact only)*

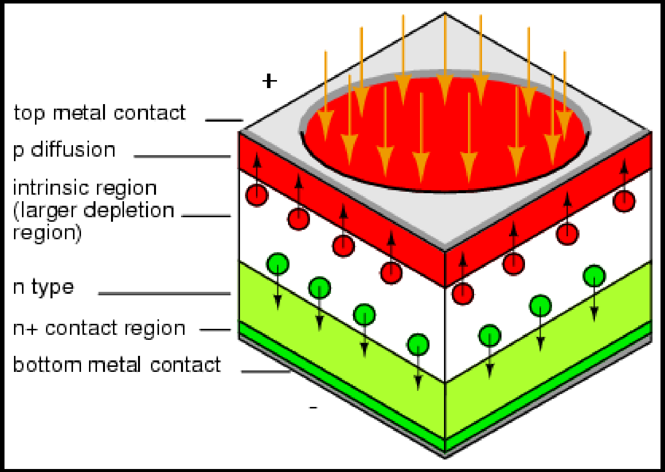


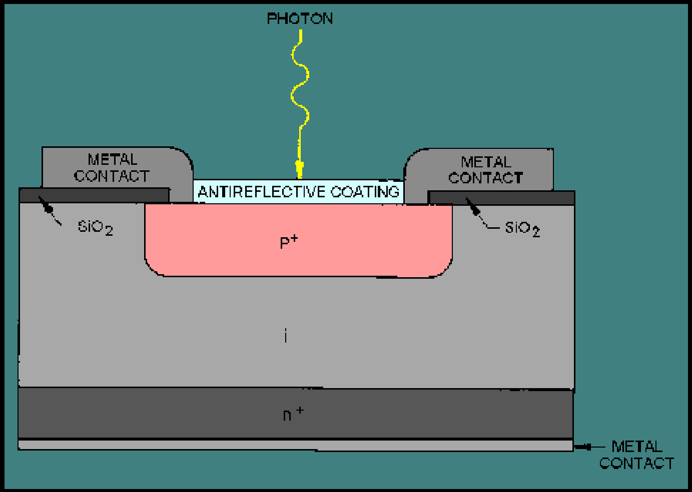
- Similar to laser design, bandgap engineering can be applied to produce heterostructures that are optimized for the PD performance.
- Undoped, high crystal quality of the *i*-region offers long carrier lifetime (see 1st item above) and mobility for high QE and high speed.

See the avalanche photodiode project example

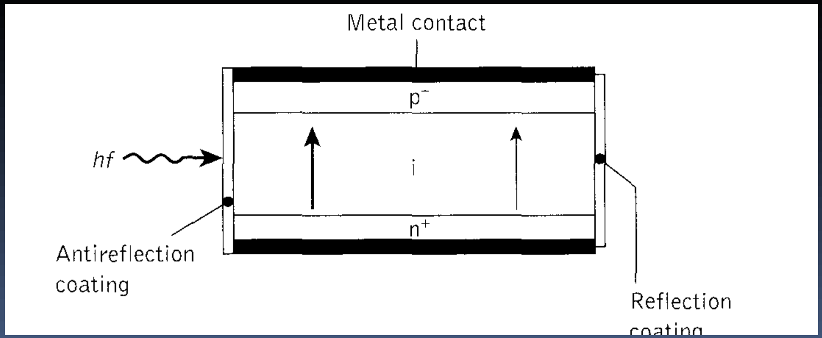
Structure of Planar *p-i-n* Photodiode

Top illumination (most PD)



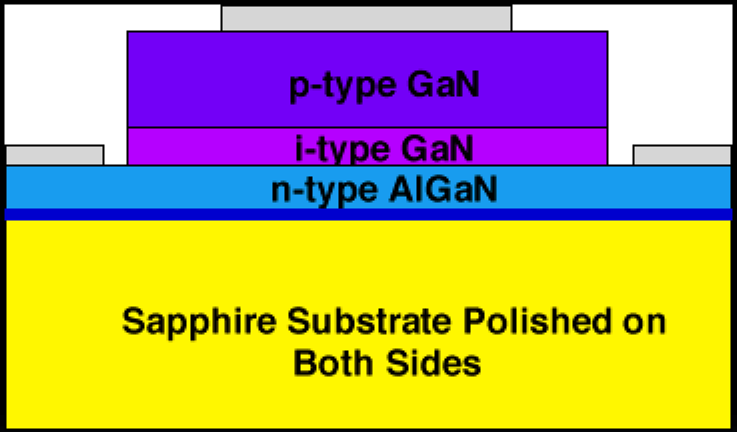


Edge illumination (rare)

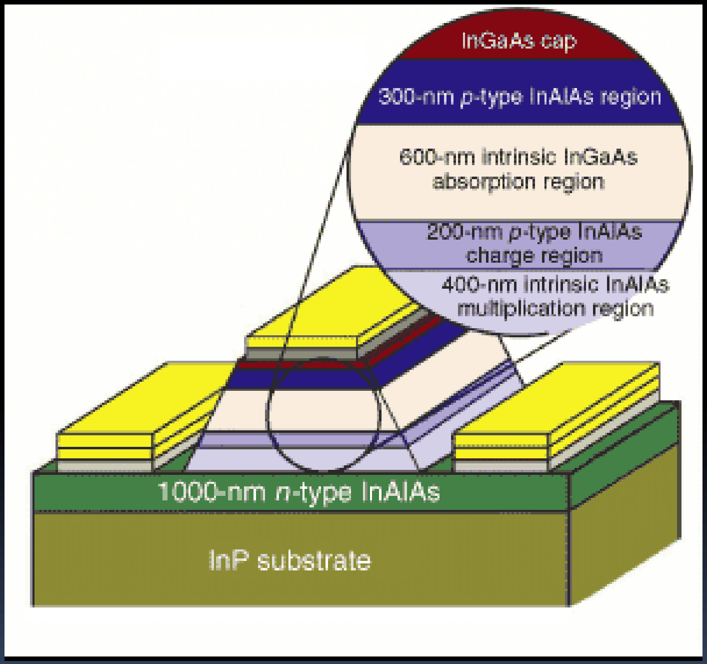


Some Example of *p-i-n* PD Structure

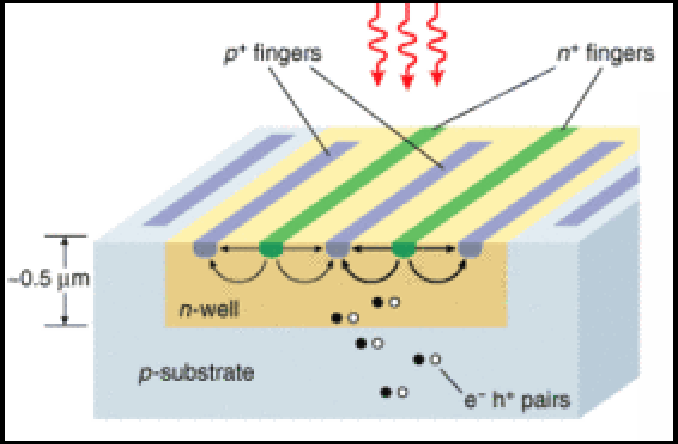
GaN PD for UV-blue applications

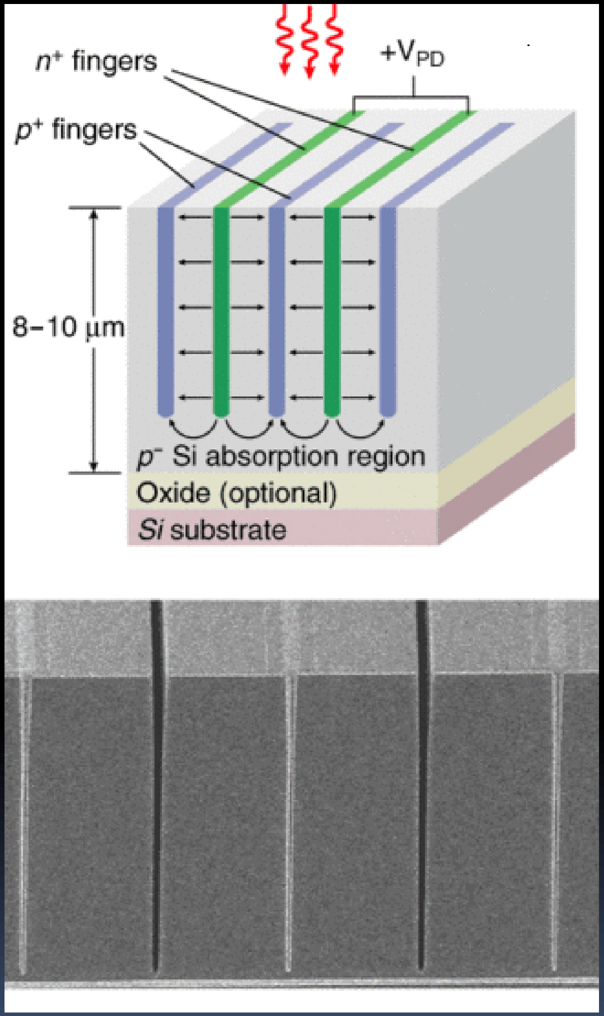


InGaAs avalanche PD (example with heterostructure)



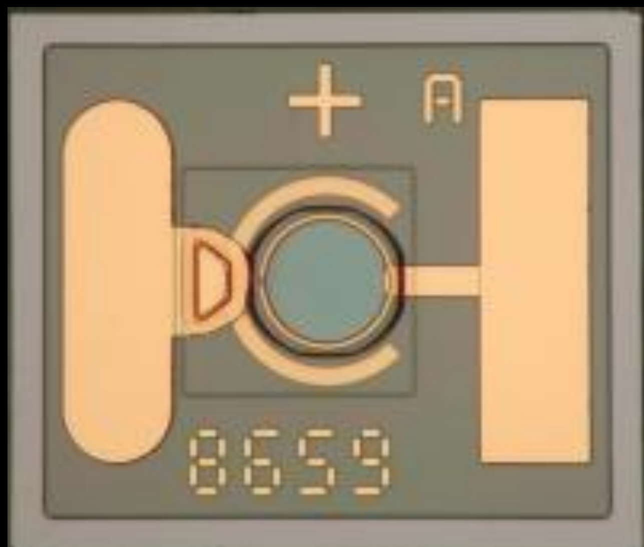
Structure of Lateral *p-i-n* Photodiode

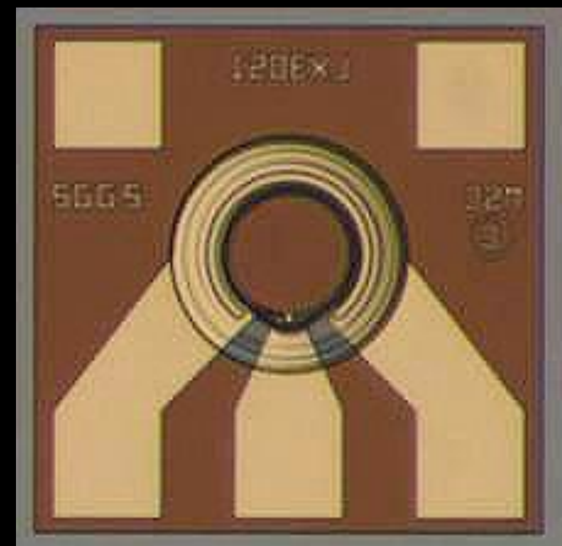


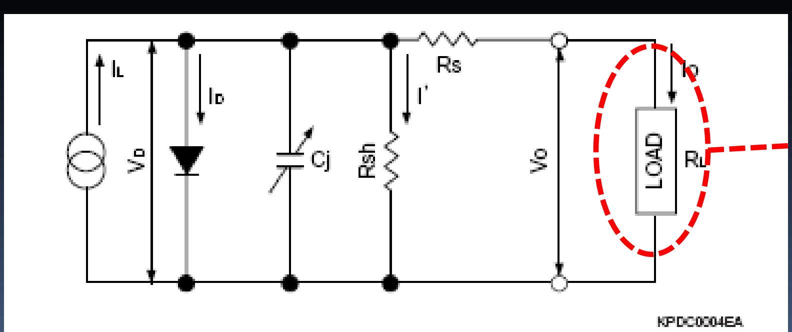


- The field is parallel with surface instead of perpendicular.
- Can greatly enhance speed with large active area (without losing responsivity) if multiple junctions are used with narrow gap for fast transit time.
- However more complex fabrication and cost.

Planar *p-i-n* Photodiode







Device output are coupled to microwave waveguide for high-speed application

Advanced Structure Photodiodes

- Engineering for speed:
  - Traveling wave photodiode
  - Unitraveling carrier photodiode
- Engineering for large responsivity
  - Avalanche photodiode
- Engineering for integrated amplification (special applications)
  - Phototransistor

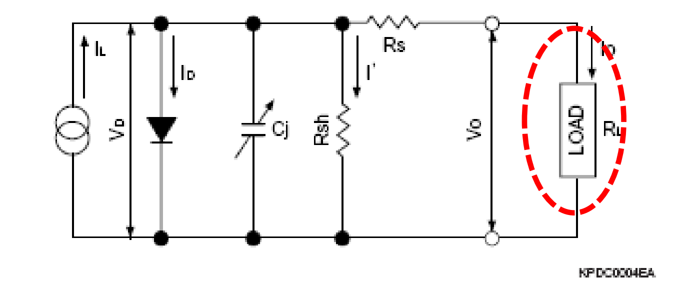
Factors on the Speed of PD

- Intrinsic carrier lifetime τ
  - Example: semiconductors with excessive defects (trade-off speed for quantum efficiency)
- Carrier transit time
  - Drift time in active region (depletion)
  - Diffusion time in collector regions

$$t_d = \frac{w}{v_{\mathrm{drift}}} = \frac{w}{\mu E}$$

$$t_{\mathrm{Diff}} = \frac{d^2}{2D_{\mathrm{e\,or\,h}}}$$

- Capacitance (RC time)



$$t_C = RC$$

High Speed PD considerations

- Dominated by transit time (or designed to be so)

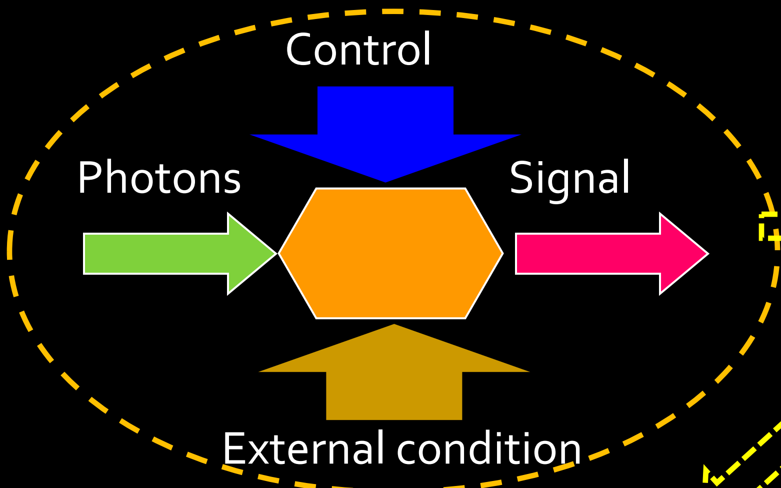
$$f_{3\mathrm{dB}} \cong \frac{1}{2\pi\, t_d} = \frac{\mu E}{2\pi\, w}$$

- High mobility
- Narrow transit region (but high absorbance)
- High bias (usually at the near saturated drift velocity)
- Low capacitance:
  - Very small active area A
  - Very thin depletion layer width w

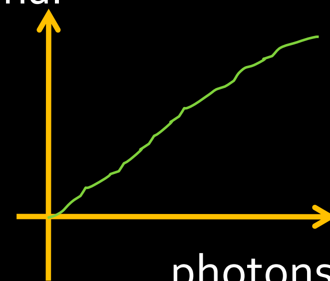
$$t_C = RC$$

$$C = \frac{\varepsilon A}{w}$$

Basic Operational Concepts



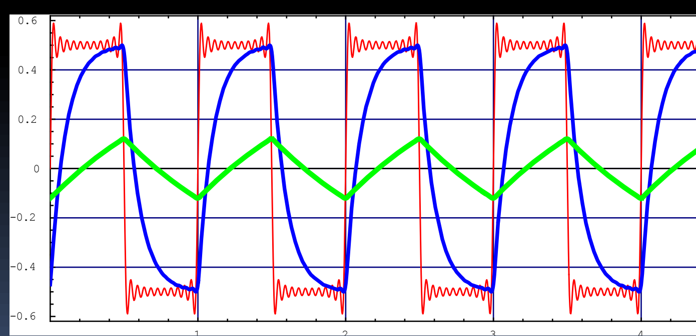
Response curve



$$R = \frac{I(A)}{P(W)}$$

$$\eta_{QE} = \frac{\text{electron}}{\text{photon}}$$

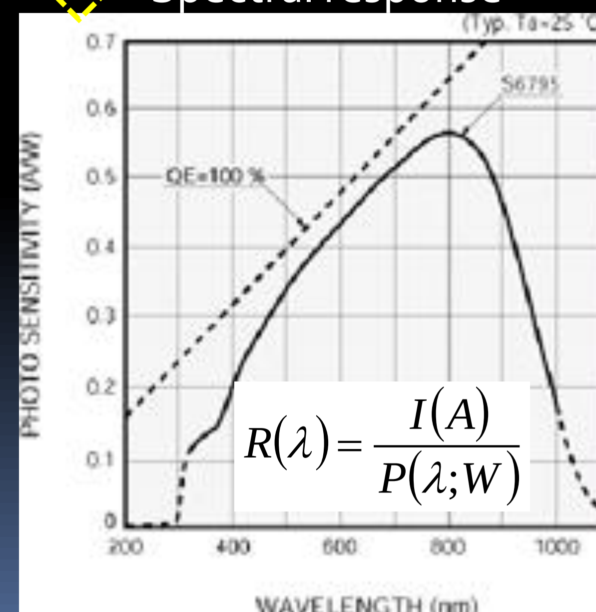
Temporal (frequency) response



$$S(f) = H[f]P(f)$$

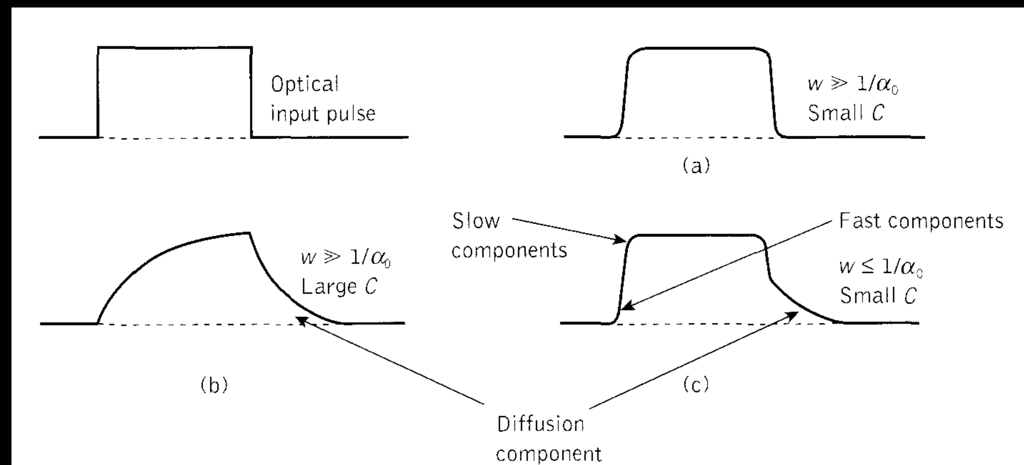
$$S(t) = \int h[t-\tau]P(\tau)d\tau$$

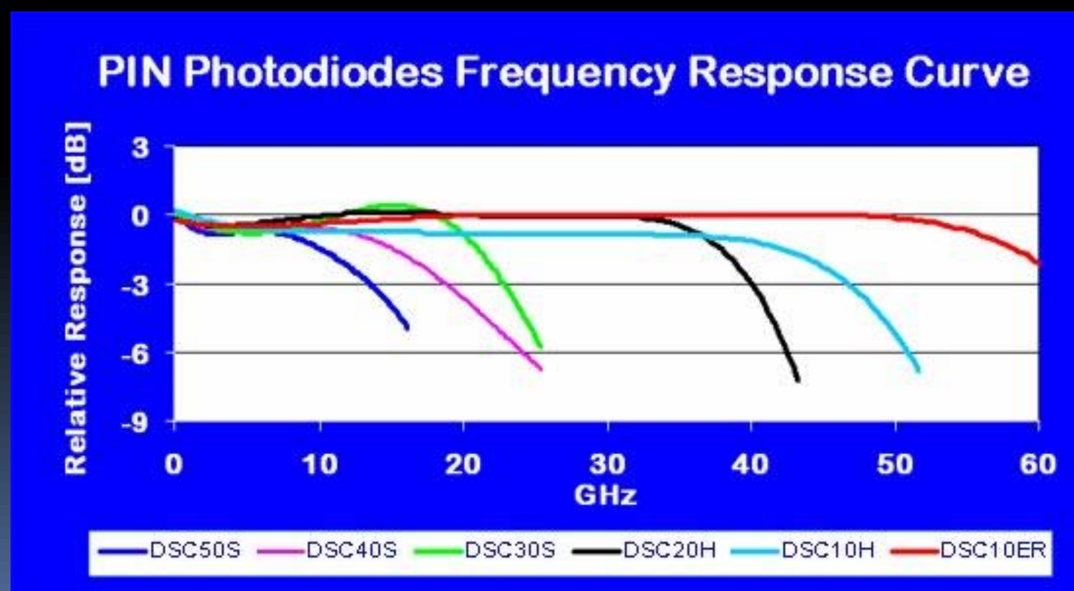
Spectral response



$$R(\lambda) = \frac{I(A)}{P(\lambda;W)}$$

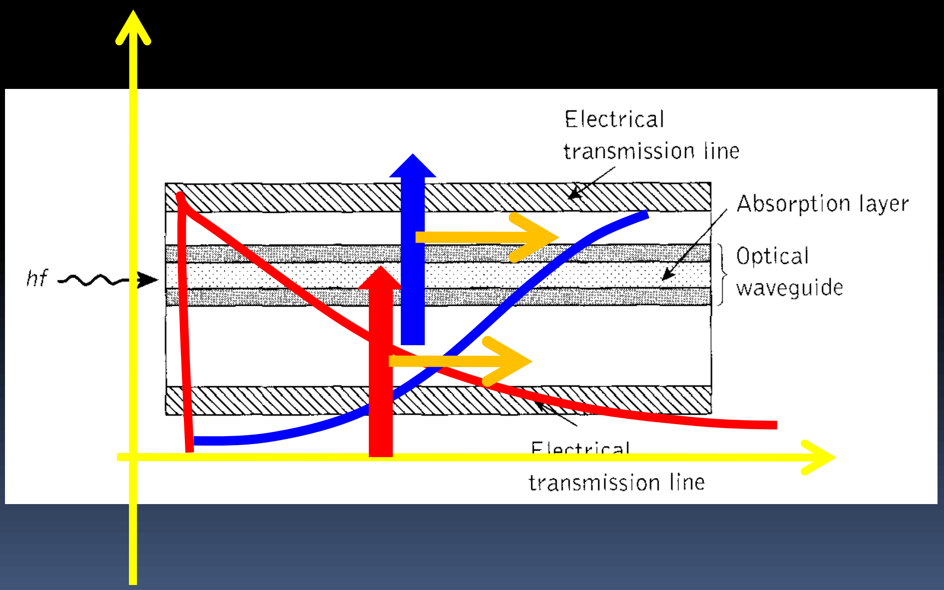
Example of PD Temporal and Frequency Response





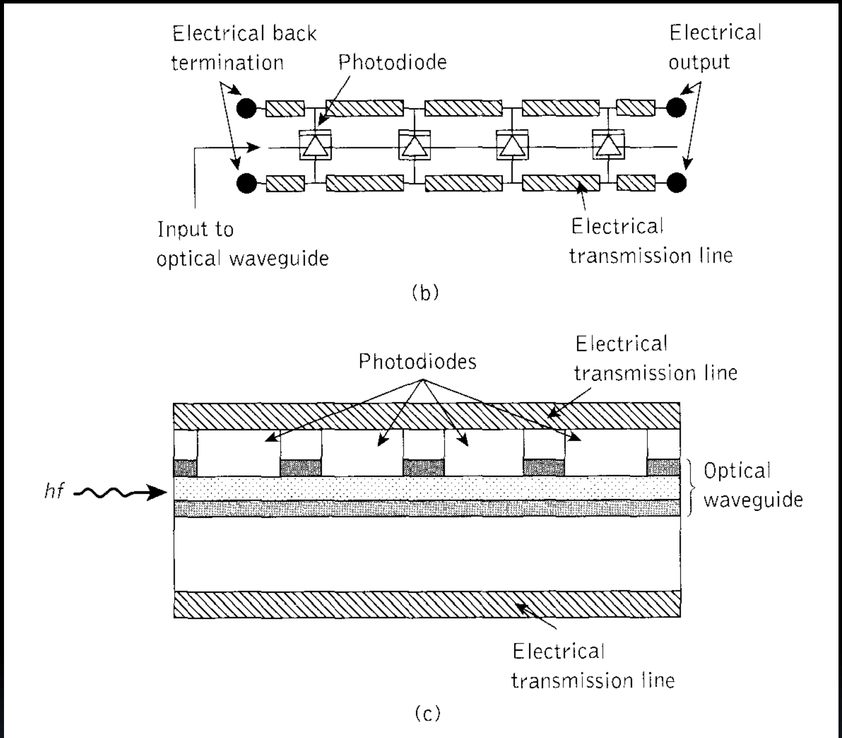
Traveling Wave Photodiode

- Capacitance is not a problem, if the microwave signal is traveling (distributed circuit element)
- This is the concept of traveling wave photodiode: the signal is generated within a transmission line
- Requirement: phase match between optical wave and microwave: difficult



Traveling Wave Photodiode

- Alternative design: separate optical waveguide design from microwave transmission line (Design for tuning the uwave transmission to match optical waveguide)
- Distributed detector area
- High speed achieved, but complex to be manufactured

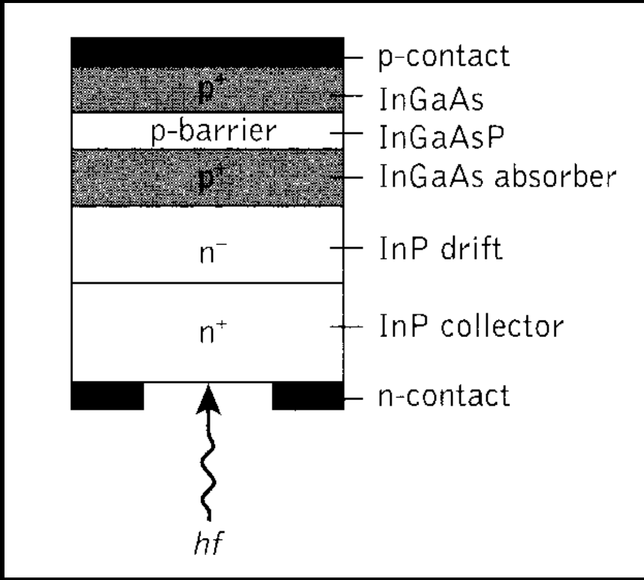


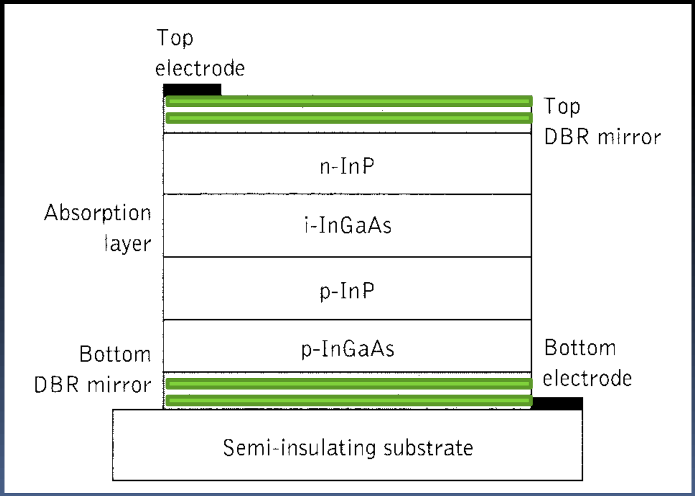
Unitraveling carrier photodiode

- Fundamental concept is to use only one type of carrier with high mobility: usually electrons because

$$\mu_e >> \mu_h$$

- A region to catch (stop the slow carriers), allowing the fast carriers to conduct the photo signal
- Trade-off speed for poor absorption (low QE)
- To increase absorption, resonance cavity can be made
- Complex to be manufactured





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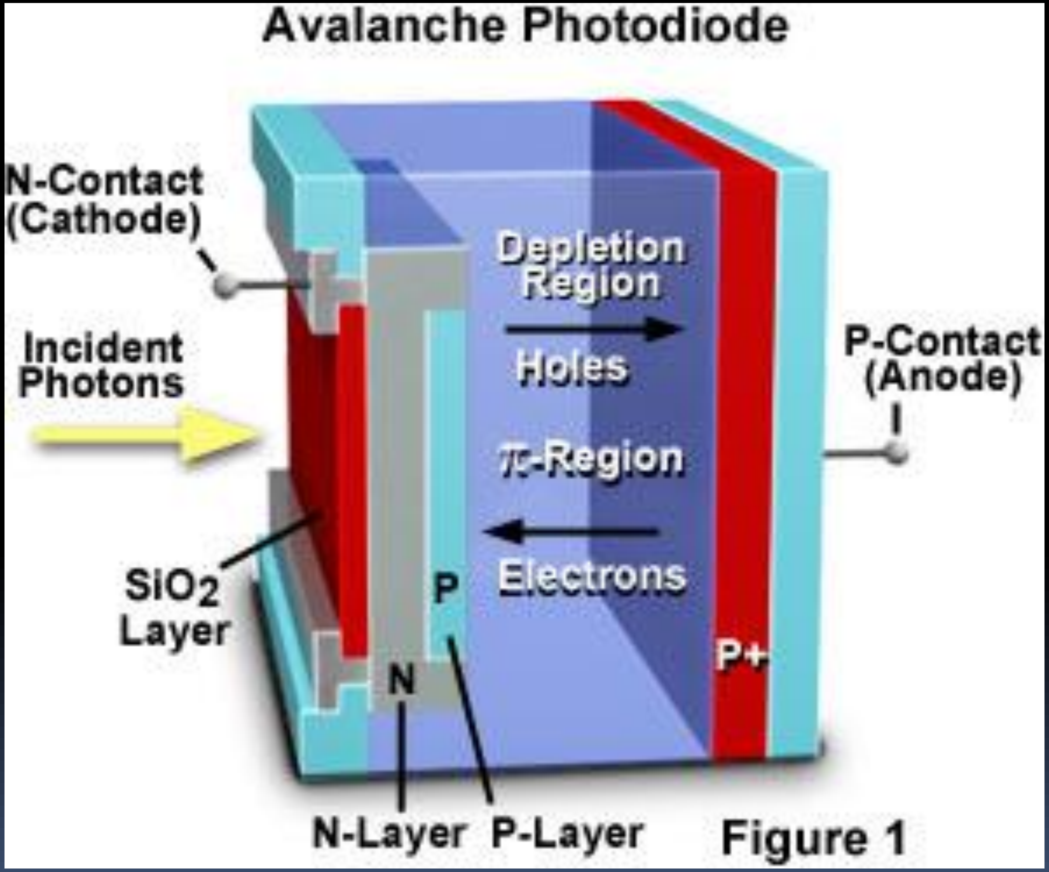
Avalanche Photodiode

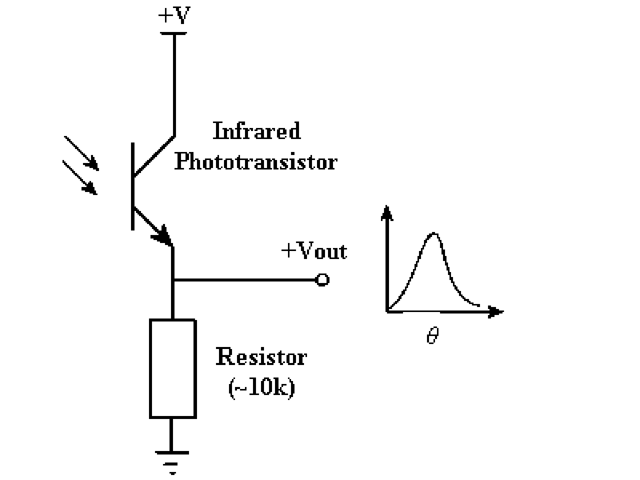


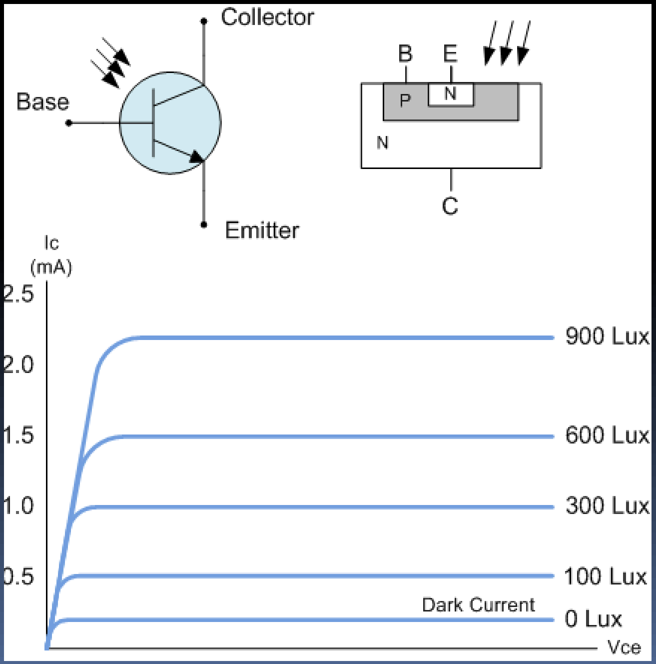
Phototransistor

- Used primarily as a light sensor with preamp
- Photocurrent input acts like current to a base: high gain

$$G = \eta h_{FE}$$

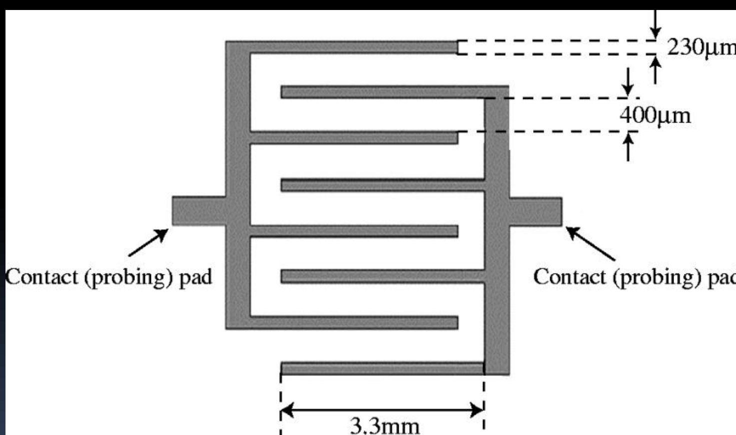
- Can be design for high speed like waveguide phototransistor
- However, most common not for speed, but for convenience to eliminate preamp.

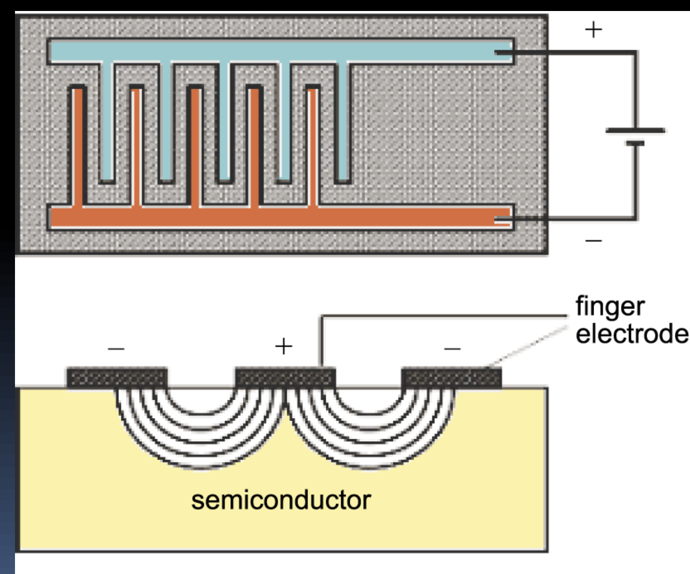




Metal-Semiconductor-Metal (MSM) Detector

- It is a photoconductive detector
- Can be designed for high speed, with trade-off with sensitivity
- Application as a switch





Source: Laval (2000)

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SIGNAL AND NOISE