Corso di Formazione

"Conversione optoelettronica nella trasmissione dei dati dai rivelatori"

Modulo 2: Componenti optoelettronici per trasmissione dati

Part II: Photodiodes

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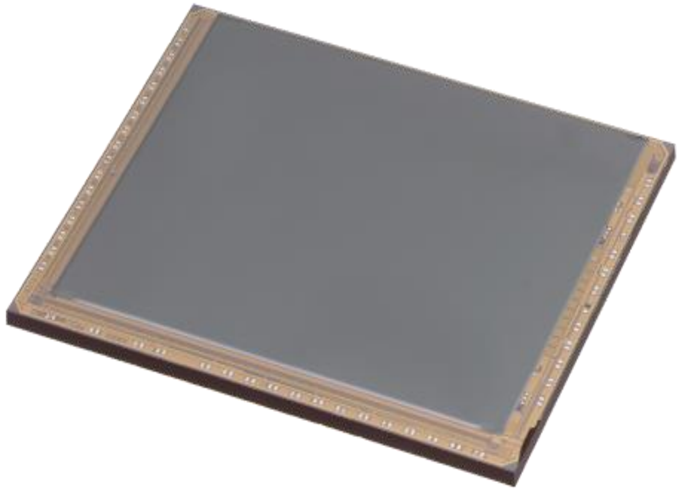
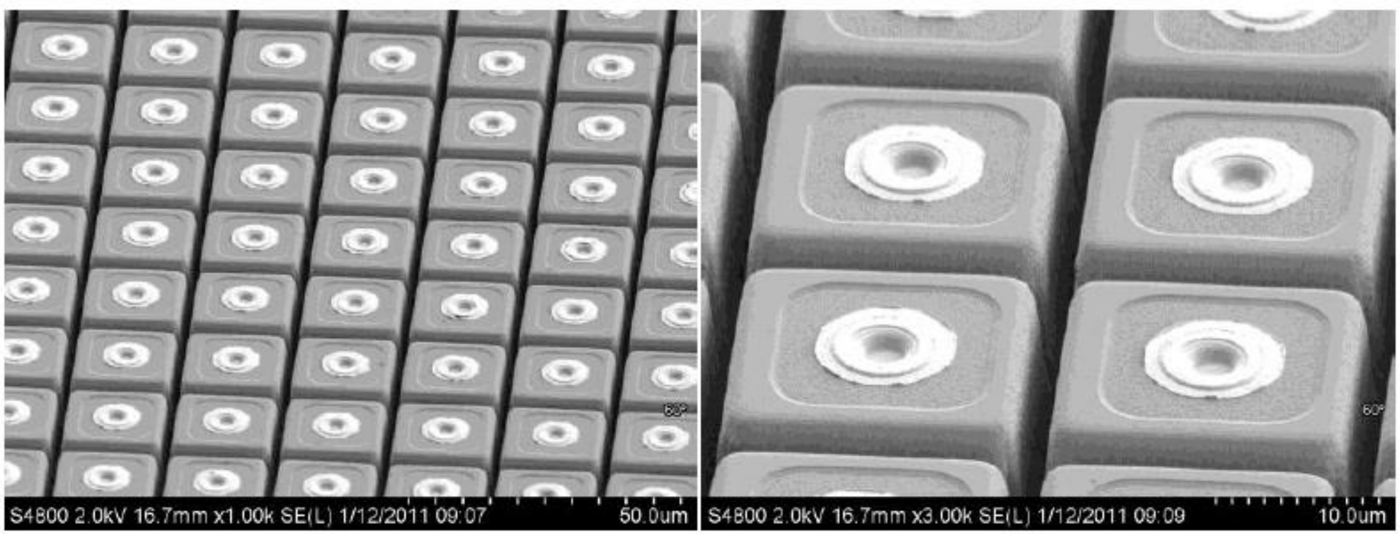
Preamble and disclaimer

- My experience and perspective on photodetectors is based on (attempts at) device-level (multi)physical simulation
- I belong to a group involved in two long-running commercial projects on photodetectors:
    1. *Imaging applications*: far-infrared focal-plane arrays based on "exotic" narrow-gap semiconductor alloys (HgCdTe)
    2. *Telecom applications*: germanium-on-silicon waveguide photodetectors

Preamble and disclaimer

1. Imaging: HgCdTe Focal Plane Array (N×N pixel matrix)





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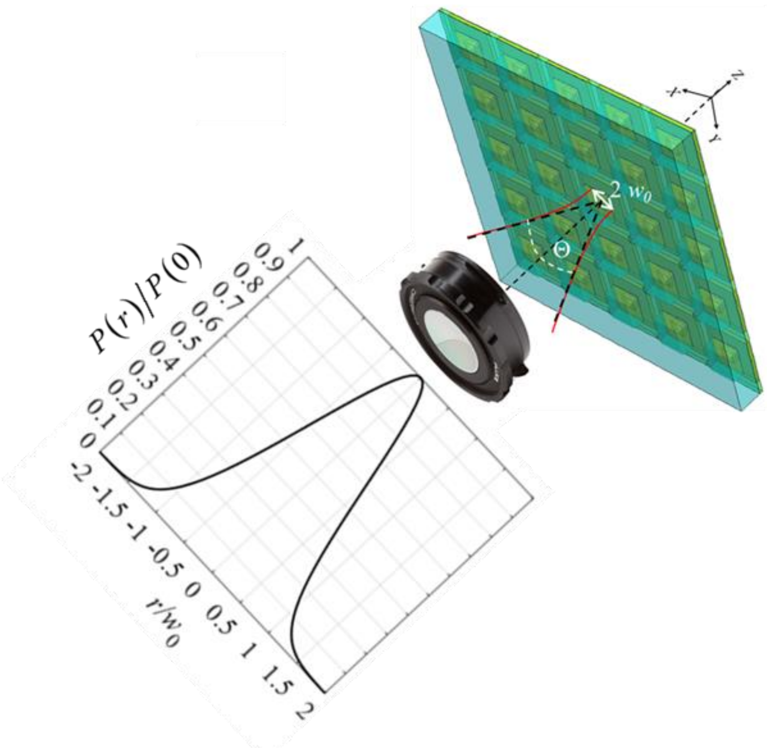
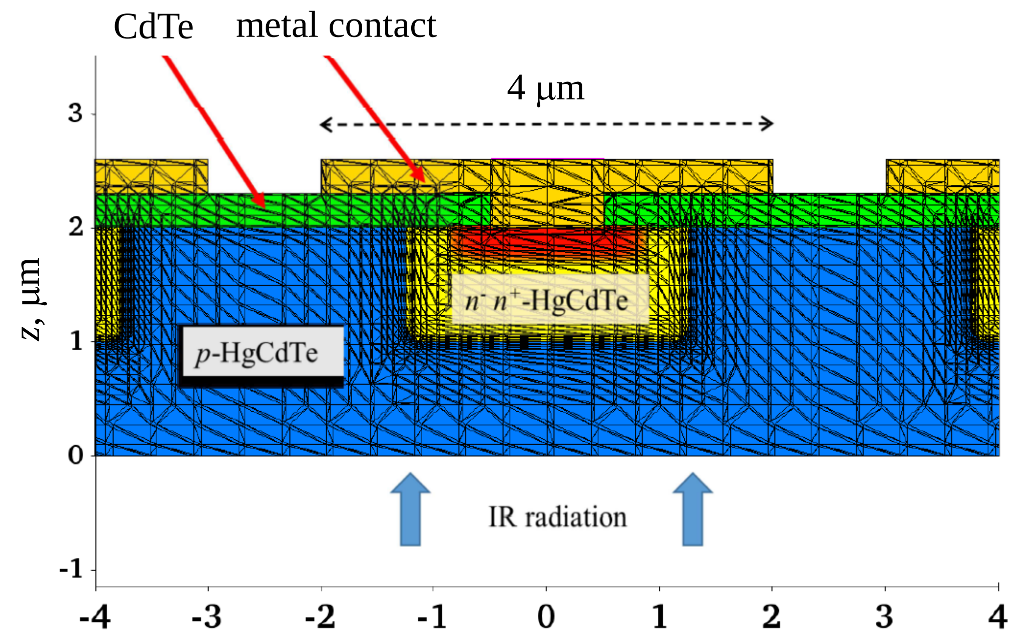
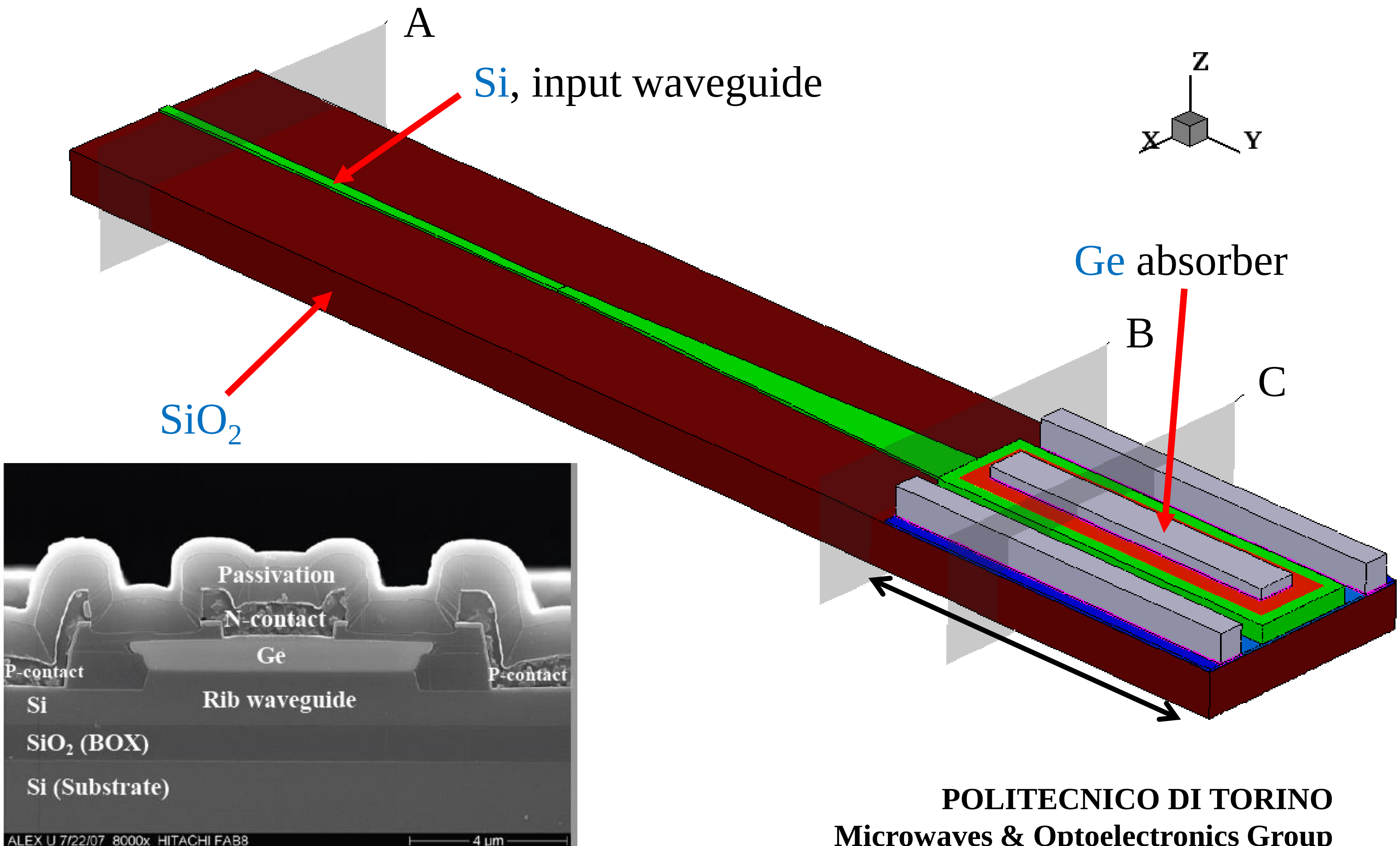




Preamble and disclaimer

2. Telecom: Ge-on-Si waveguide photodetector for silicon photonics



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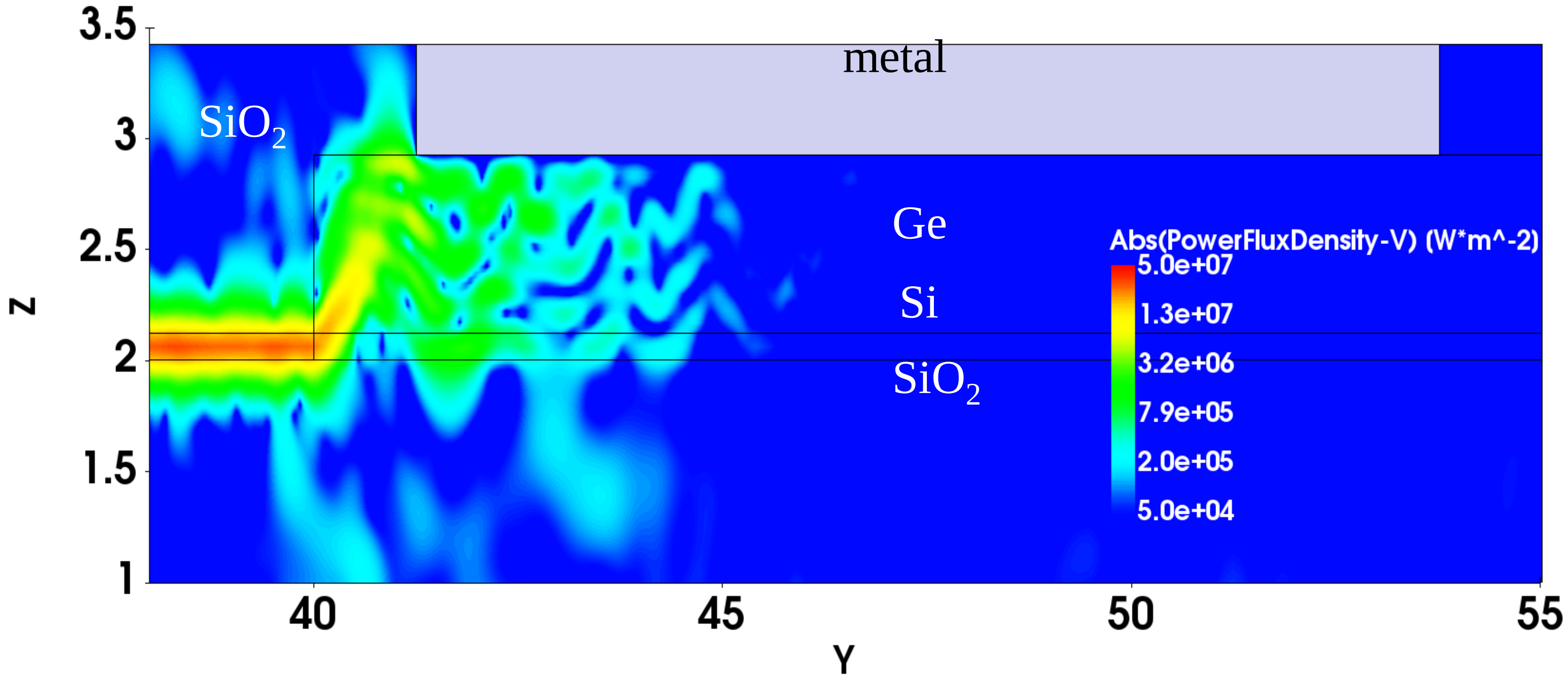
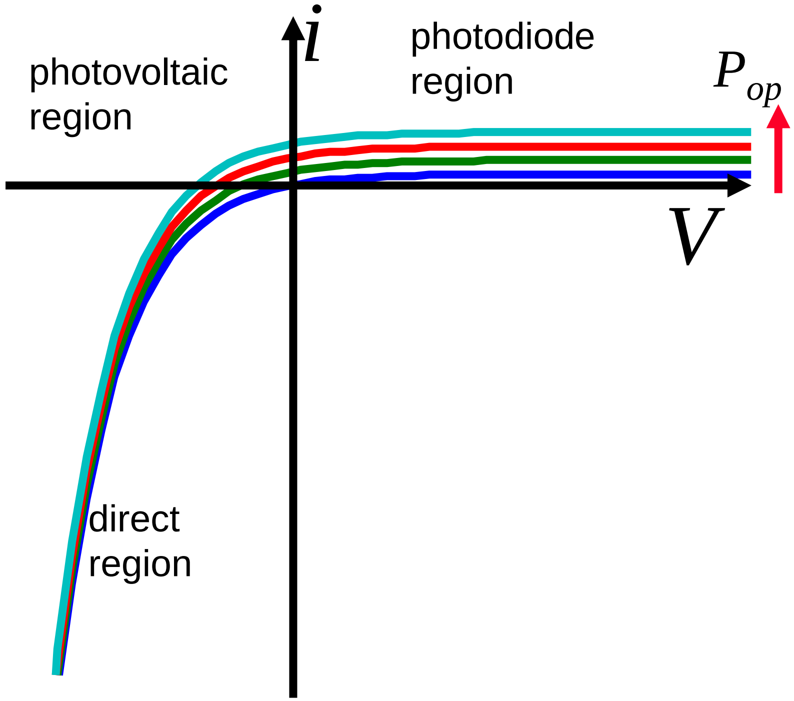
Vertical plane, at mid-waveguide, absorber detail



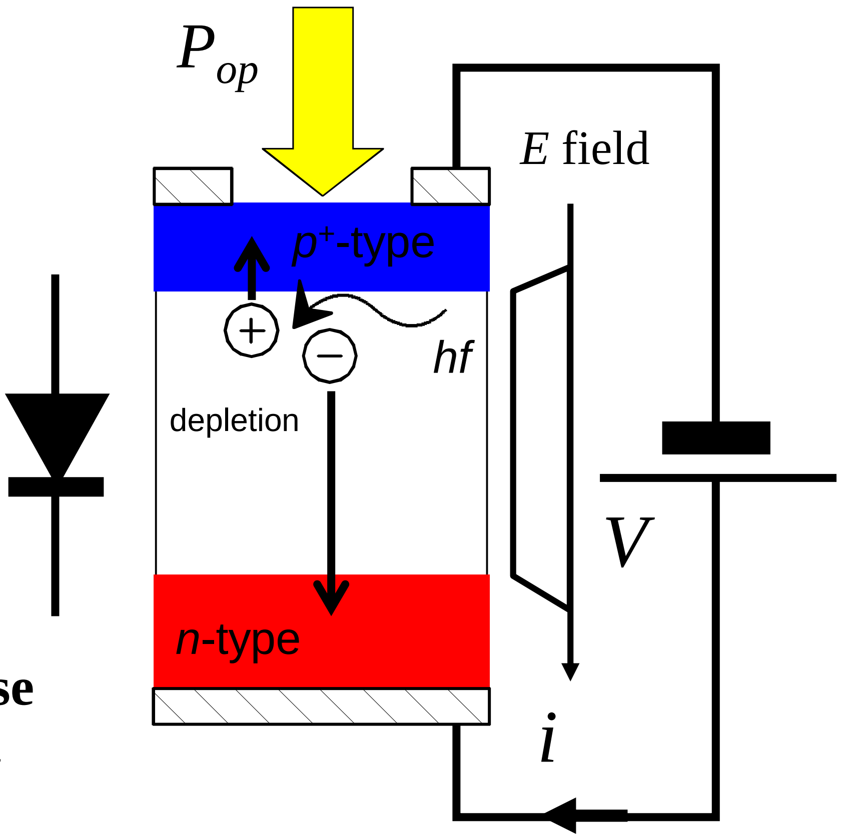
Outline

1. Photodetectors at a glance
2. Material issues affecting the optical response
3. Photodetector responsivity, quantum efficiency, optical and electrical bandwidth
4. Photodetector choices
5. Photodiodes: from pn to pin
6. Avalanche photodiodes (APD)

Photodetectors (photodiodes) at a glance



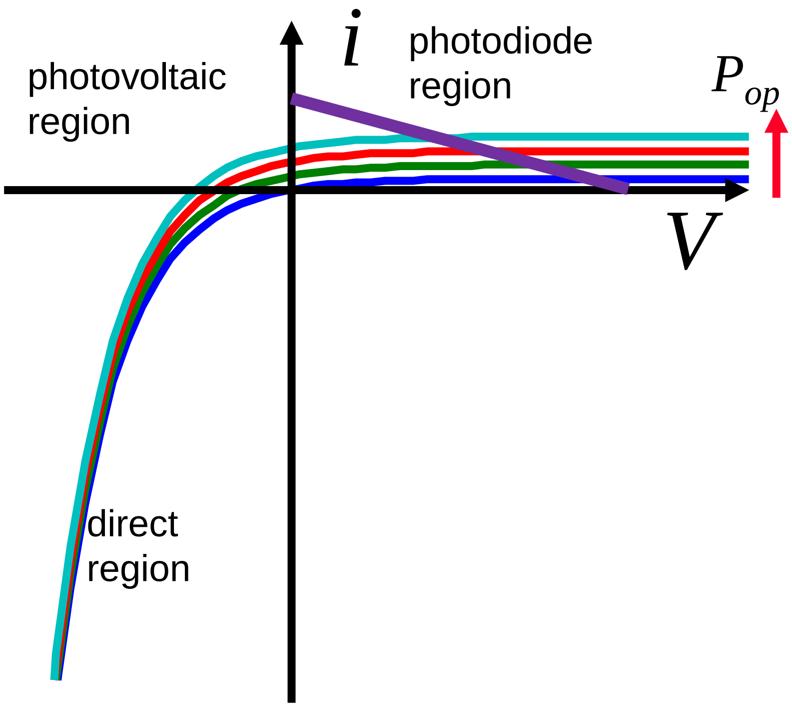
Vertical illumination (fiber coupled)



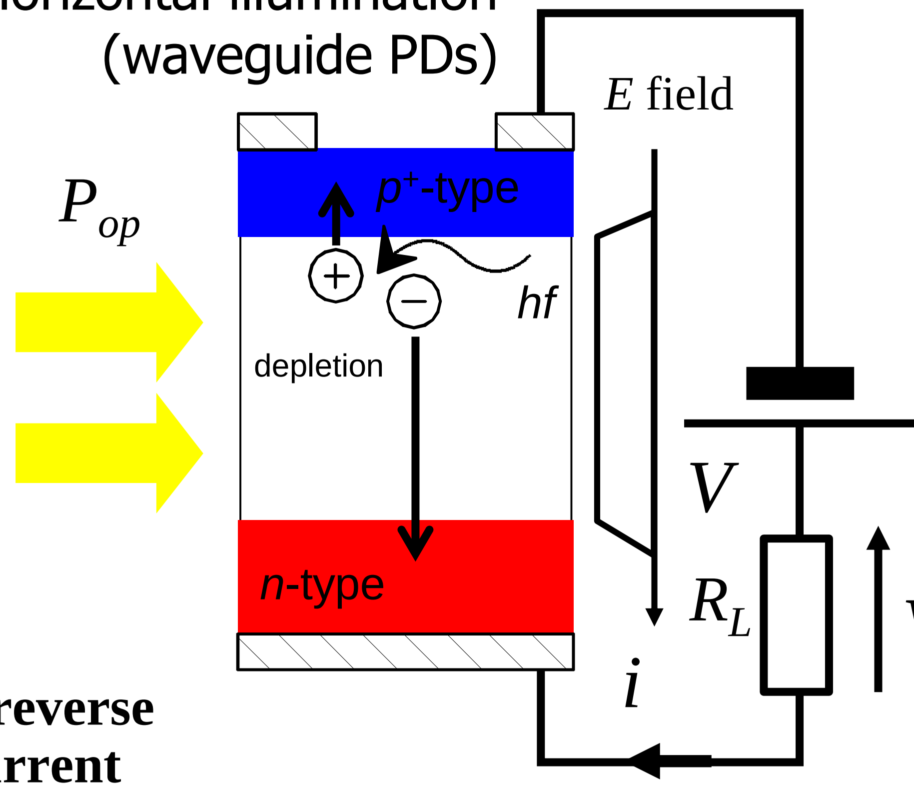
- DC VI curves like a *pn* diode whose **reverse current is enhanced by the photocurrent**
- Good linearity in photodiode region, worse in photovoltaic (the device is energetically active!), worst in direct bias

pin diode is driven by a voltage source

Photodetectors (photodiodes) at a glance



Horizontal illumination (waveguide PDs)



- DC VI curves like a *pn* diode whose **reverse current is enhanced by the photocurrent**
- Good linearity in photodiode region, worse in photovoltaic (the device is energetically active!), worst in direct bias

In real cases also a load resistor is present!

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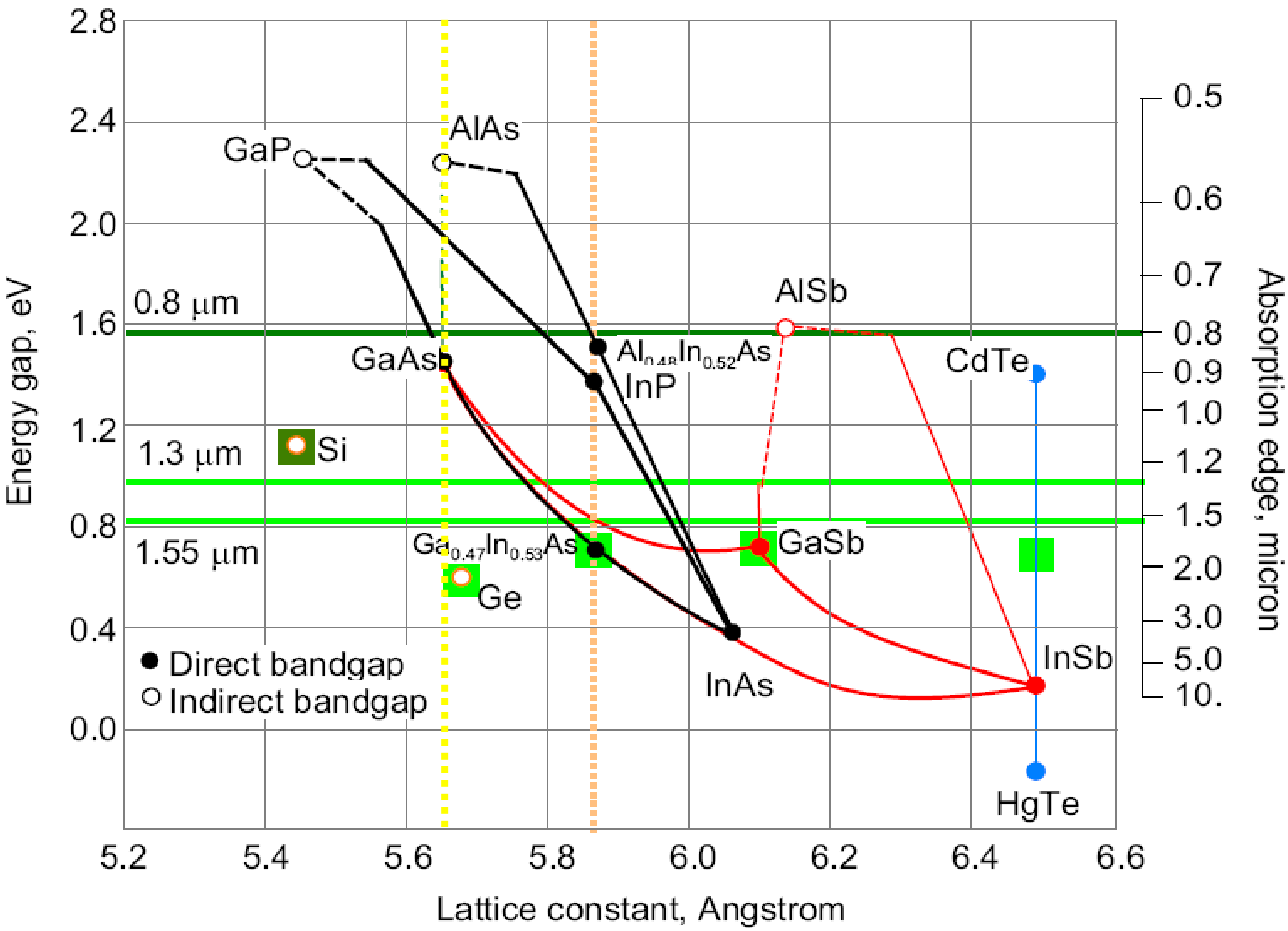
Photodetector threshold

- Generation of electron-hole pairs through light absorption and collection of generated pairs
- Absorption *threshold* (or absorption *edge*):

$$E_{ph} > E_g \rightarrow \lambda_{ph} \leq \frac{1.24\,\mu\mathrm{m}}{E_g\,\mathrm{eV}}$$

1. Impact of threshold on detector choice vs. emitter: the emitter photon energy must be larger than the detector threshold → the emitter wavelength must be smaller than the threshold wavelength
2. Both direct- (GaAs, InGaAs, InP…) and indirect-gap semiconductors (Si, Ge) can be exploited; direct materials typically have higher absorption → smaller absorption volume, higher speed.

Emitter vs. detector material choices



Detector materials – communication systems I

- **InGaAs** (tunable gap) direct bandgap, ternary alloy
  - Excellent material for long-haul communications (λ = 1.3-1.55 μm), grown (lattice-matched) on InP substrates; compatible with InGaAsP lasers
- **GaAs (AlGaAs),** direct bandgap, somewhat tunable gap, ternary alloy
  - Cannot be used for long-haul communications, only suited for applications in the first window (λ = 0.8 μm)
  - Excellent substrate availability (GaAs), mature technology, low-cost; compatible with AlGaAs/GaAs lasers

Detector materials – communication systems II

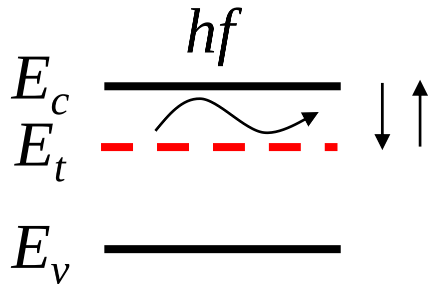
- **Si,** indirect bandgap
  - Cannot be used for long-haul communications since it cannot absorb long wavelengths (λ = 1.3-1.55 μm)
  - Excellent substrate availability (Si), mature technology, low-cost, but low electrical speed
- **Ge,** indirect bandgap
  - Can be used for long-haul communications (high secondary absorption edge due to direct processes)
  - Recently revived by the emergence of high-speed SiGe technologies → integration with Si-based photonic ICs (see later)

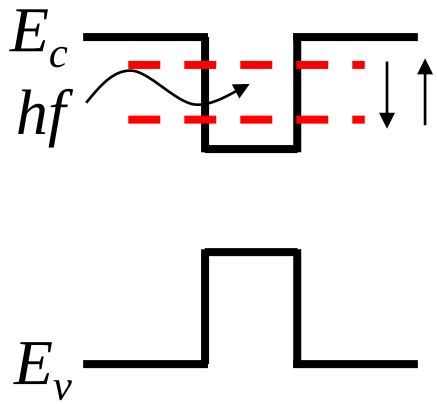
Detector materials: far infrared

- **HgCdTe** (mercury cadmium telluride), tunable (direct) gap, ternary alloy
  – Mainly used for megapixel focal plane arrays
  – The energy gap can be reduced to 0: best material for LWIR detectors (now at cryogenic temperatures, research on HOT devices)
  – Poor/expensive substrate technology → transition from CdZnTe to GaAs or Si
- **InAs (InAsSb)**, tunable (direct) gap
  – Can be grown also on mismatched substrates (GaAs)
  – Active research on InAs/GaSb type II superlattices

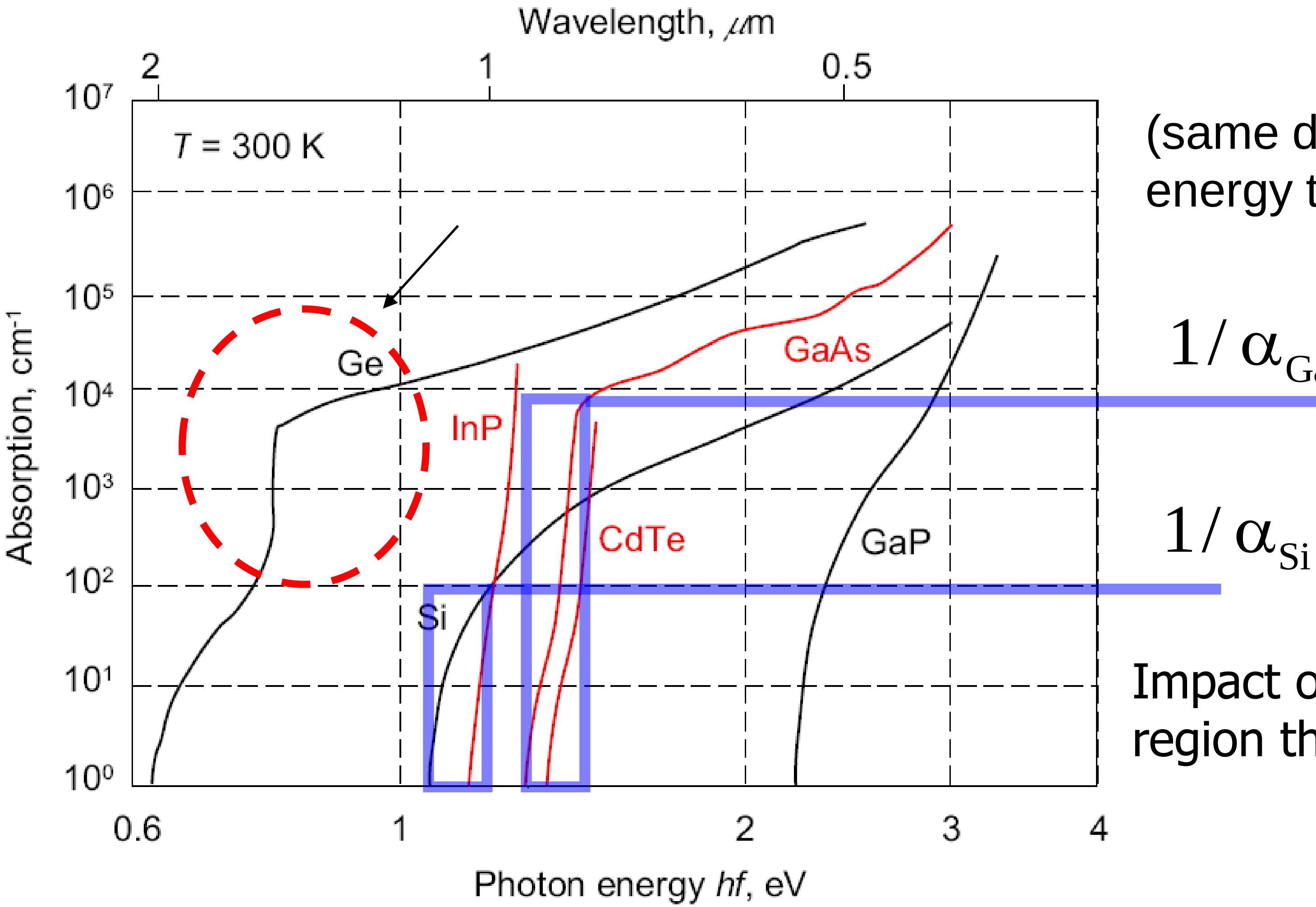
Overcoming the limit $E_{ph} > E_g$

- **Extrinsic detectors**: *transitions between bands and trap levels*; the efficiency however is low
- **QW and MQW detectors** with *subband transitions*: such transitions have energy differences much lower than the energy gap → operation in FIR (Far InfraRed), sometimes at higher than cryogenic temperatures
- Once important in FIR detectors (low gap implies high intrinsic concentration, low temperature operation)
- Poor efficiency-responsivity!





Absorption coefficients – direct vs. indirect gap semiconductors



(same distance from energy threshold)

$$1/\alpha_{GaAs} \approx 1\ \mu m$$

$$1/\alpha_{Si} \approx 100\ \mu m$$

Impact on absorption region thickness!!

Impact of α magnitude on photodetector design

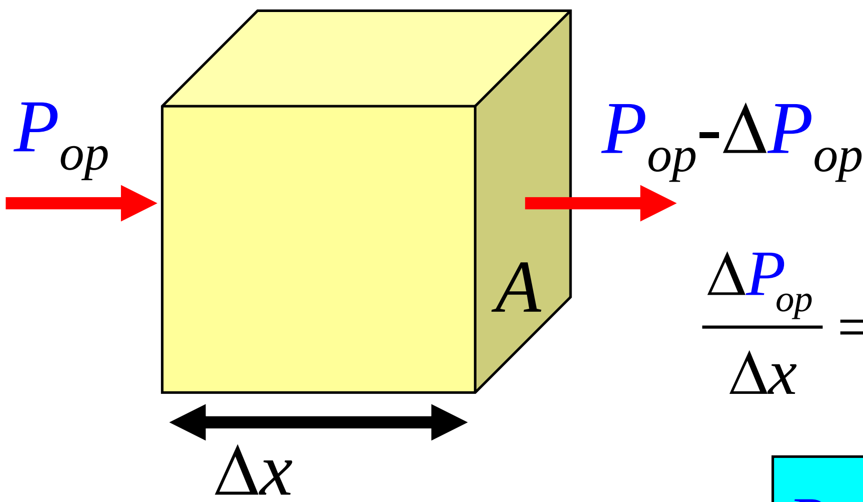
- Define $L_\alpha = 1/\alpha$ as the *absorption length*
- The optical power in the absorption region goes like:

$$P_{op}(x) = P_{op}(0)\exp(-\alpha x) = P_{op}(0)\exp(-x / L_\alpha)$$

- Therefore the **absorption region** must be somewhat longer than L_α:
  - In direct-gap materials this means a few microns (low transit time, fast device)
  - in indirect-gap materials, 10-50 microns (high transit time, slow device)
- **Transit time** limits the device speed, but so does the **device capacitance**

Absorption and optical generation rate

$$V = A\Delta x$$



$$\frac{dP_{op}}{dx} = -\alpha P_{op} \approx \frac{\Delta P_{op}}{\Delta x}$$

$$\frac{\Delta P_{op}}{\Delta x} = \frac{\text{energy lost due to absorption}}{t \cdot V} = \alpha P_{op}$$

P_{op} here optical power density (W/cm^2)

$$\frac{\dfrac{\text{Energy lost}}{t \cdot V}}{\text{Photon energy } \hbar\omega} = \boxed{\frac{\alpha P_{op}}{\hbar\omega}} = \frac{\text{Number of photons absorbed}}{t \cdot V} =$$

$$= \frac{\text{Number of carrier pairs generated}}{t \cdot V} = \boxed{G_{op}}$$

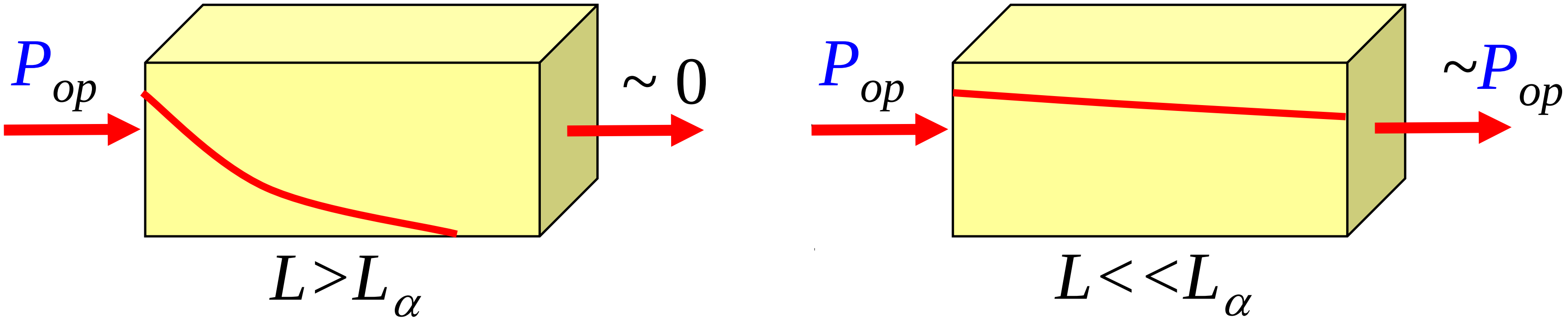
Optical Generation Rate and α

- From the variation of power *density* with *x* due to absorption:

$$\frac{\alpha P_{op}(x)}{\hbar\omega} = \alpha\,\Phi_o(x) = G_o(x) = G_o(0)\exp(-x/L_\alpha)$$

Photon flux

- If the absorption region is short vs. the absorption length, most photons escape without generating e/h pairs: low photodetector *responsivity* (current generated per unit optical power)



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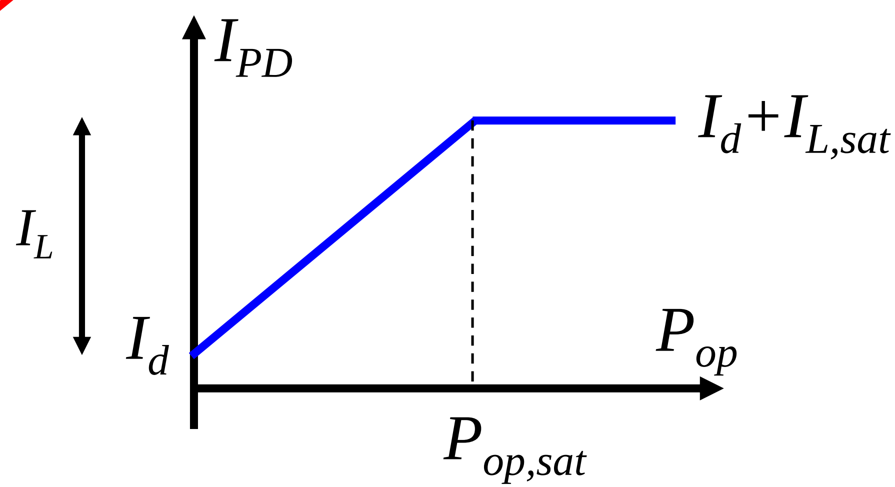
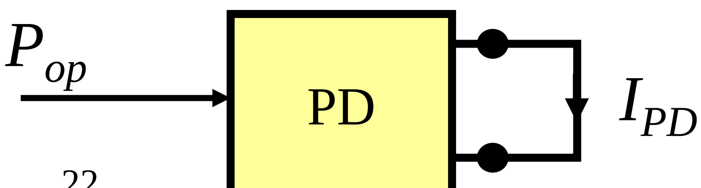
Photodetector response: DC illumination

- The photodetector converts an *input optical power* P_{op} (W) into an *output electrical current*: $I_{PD} = f(P_{op}, \lambda)$
- The relationship is typically *linear*, but saturates for high optical power; typically we refer to the <u>*short circuit current*</u>:

$$I_{PD}(t) = I_L + I_d = \mathcal{R}(\lambda) P_{op}(t) + I_d$$

- Photocurrent → I_L
- Dark current → I_d
- Responsivity → $\mathcal{R}(\lambda)$





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Photodetector responsivity

- The *responsivity* is defined as $\mathcal{R} = I_L / P_{op}$ (A/W or mA/mW) or as the ratio between the (short-circuit) photocurrent density and the optical power per unit area

$$\mathcal{R} = J_L / (P_{op}/A)$$

- For high input power, the responsivity decreases; eventually, the photocurrent saturates due to device-specific intrinsic effects (e.g. space-charge effects); in fact, the total photodetector current can also saturate due to the loading conditions
- The responsivity depends on:
  - The input wavelength → *optical bandwidth* (typically wide)
  - The modulation bandwidth of the input optical signal → *electrical bandwidth* (ex. 10 Gbps) → lowpass behaviour

Photodetector quantum efficiency

- **Internal quantum efficiency (IQE)**:

$$\eta_Q = \frac{\text{generated pairs}}{\text{photons reaching the active region}}$$

- **External** or **device quantum efficiency (EQE)**:

$$\eta_x = \frac{\text{collected pairs}}{\text{incident photons}} = \frac{I_L / q}{P_{op} / \hbar\omega} = \frac{\hbar\omega}{q}\mathcal{R} < \eta_Q$$

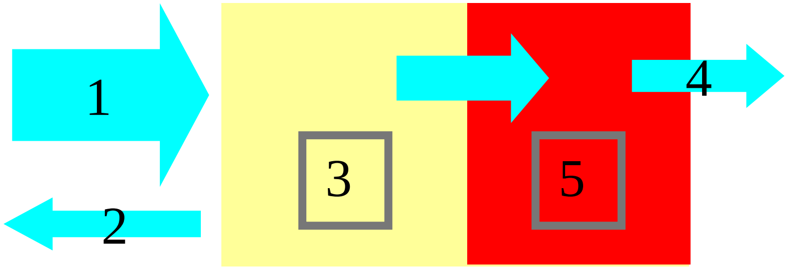
- The external quantum efficiency can be increased through **internal gain** mechanisms (→ avalanche photodiodes, phototransistors...)
- Assuming η_x~const.~1 vs. photon energy:

$$\mathcal{R} = \frac{q}{\hbar\omega}\eta_Q \approx \frac{q}{\hbar\omega}, \quad \hbar\omega > E_g$$

- Therefore, the maximum ideal value for the responsivity turns out to be $\mathcal{R}_{\max} \sim 1/E_g$ (E_g in eV) slightly above threshold

Why EQE < IQE?

1. A photon flux is incident on the photodetector
2. Some photons are reflected at the PD interface due to dielectric mismatch (power reflectivity!)
3. Some photons are absorbed but in regions of the device where they do not contribute to useful device current
4. Some photons cross the PD without being absorbed (if the absorption length is not >> than the diffusion length)
5. Finally, some photons (most of them, hopefully) are absorbed and yield a useful current component



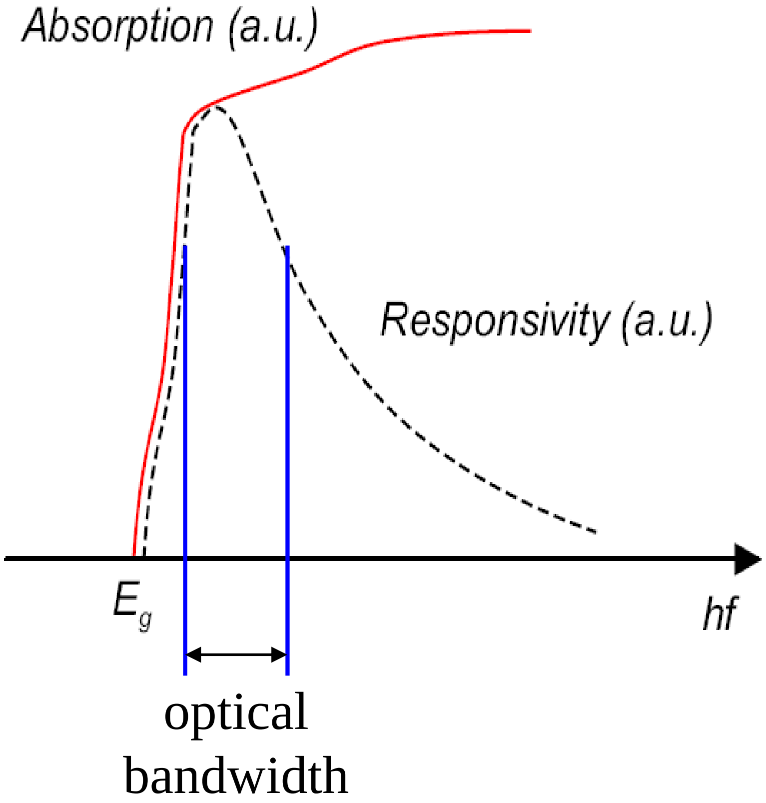
Photodetector optical bandwidth

- The responsivity follows the absorption profile and reaches a maximum for energies slightly above threshold:

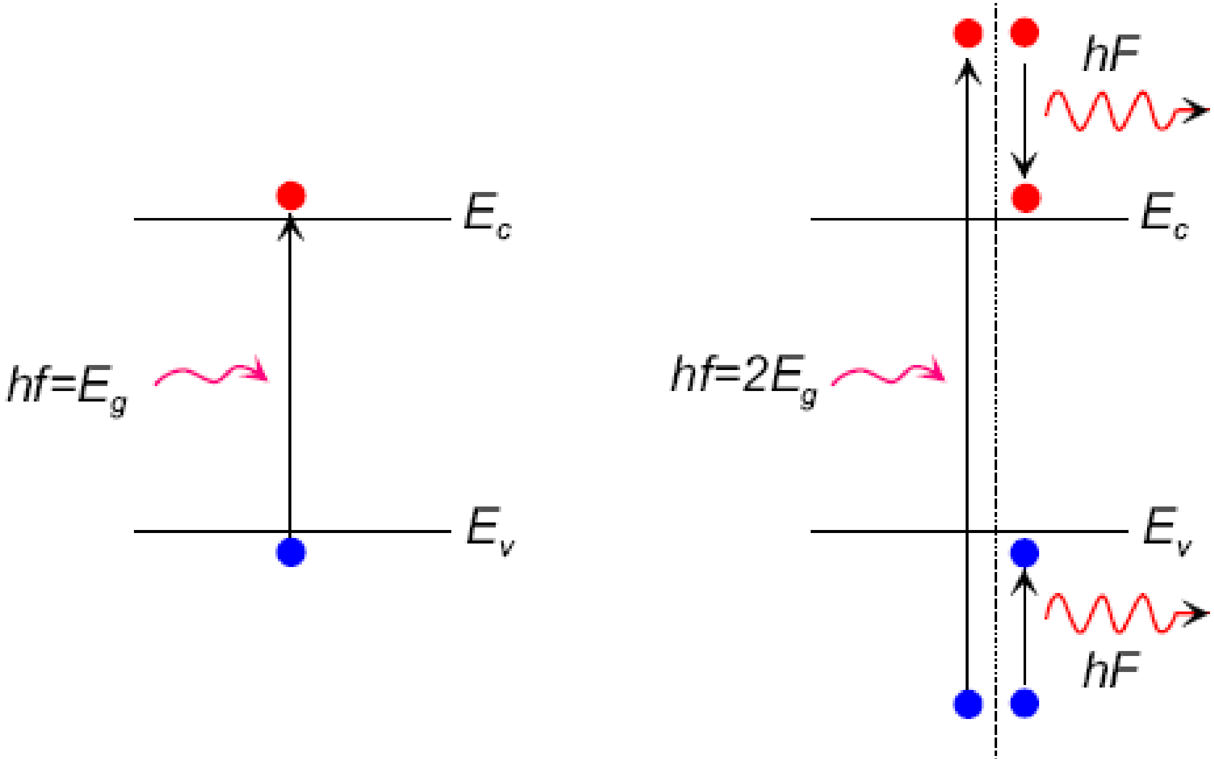
$$\mathcal{R}_{\max} \approx \frac{q}{E_g} = \frac{1}{E_g[\mathrm{eV}]}$$

- For increasing photon energies above the maximum, the responsivity drops with:

$$\mathcal{R} = \mathcal{R}_{\max} \frac{E_g}{E_{ph}} \eta_x$$



Why R decreases with energy

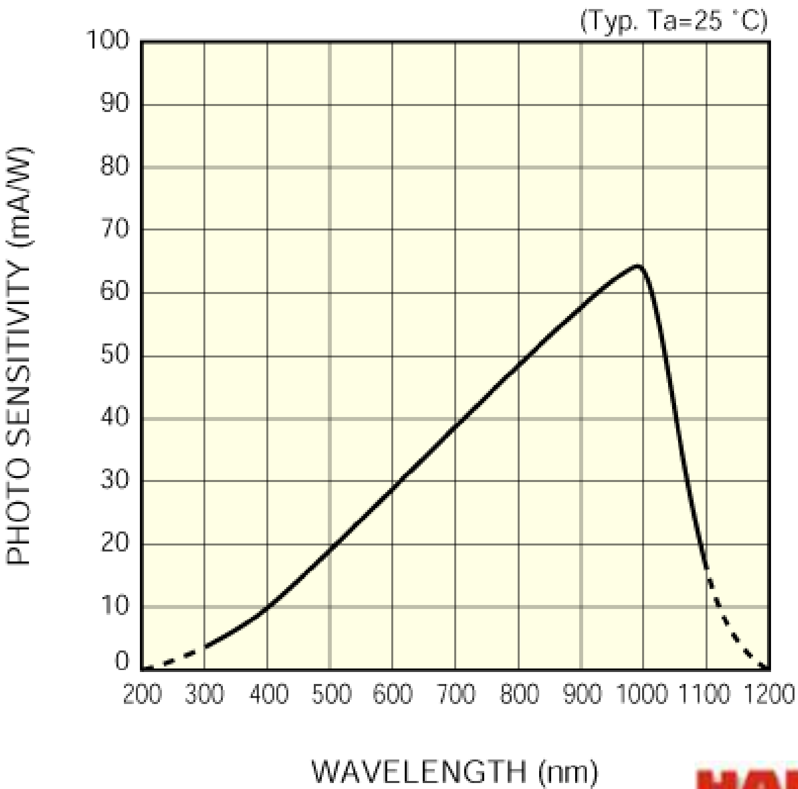


P_o @ f produces an e-h pair for each photon: R

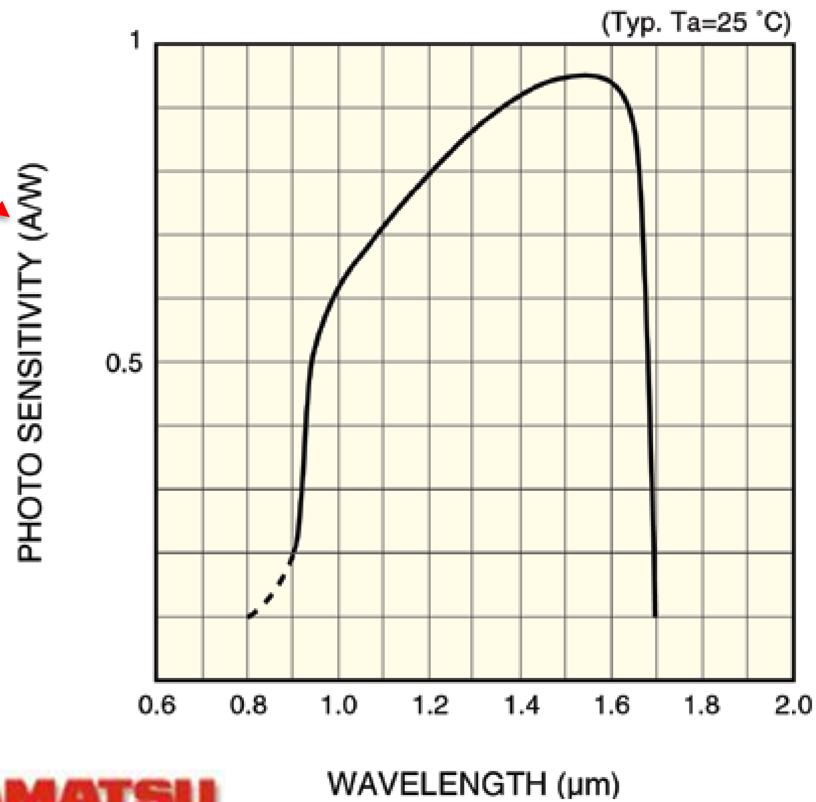
$2P_o$ @ 2f always produces an e-h pair for each photon: R/2

Example of IR PD response

Si *pin* photodiode
(photosensitivity → ℜ)



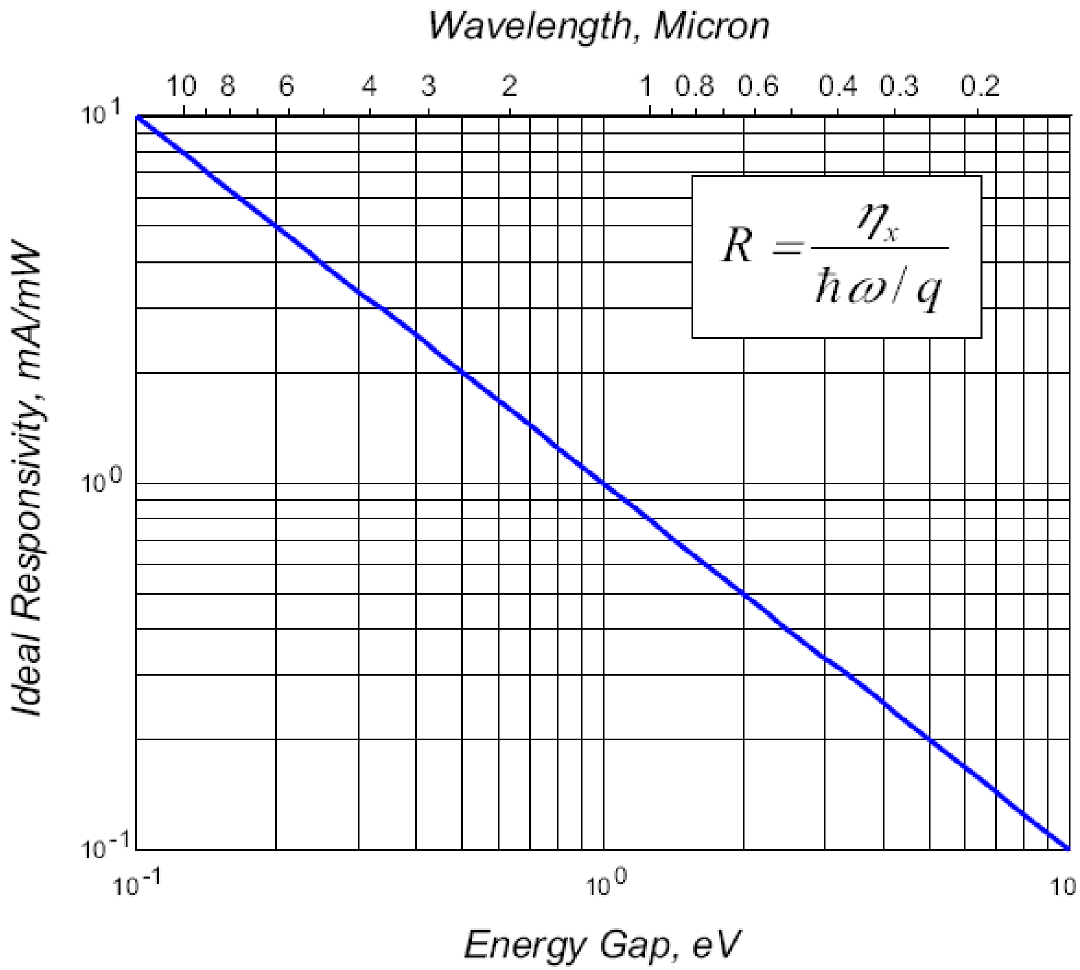
InGaAs *pin* photodiode
(photosensitivity → ℜ)



HAMAMATSU

Maximum theoretical responsivity versus semiconductor energy gap

- Assume external quantum efficiency equal to one and energy equal to gap energy
- For 1 eV gaps the ideal responsivity is 1 mA/mW !



Photodetector modulation bandwidth

- Suppose that the optical power and photocurrent have a DC + modulation component (sinusoidal at f_m):

$$P_{op} = P_{DC} + \hat{p}_{op}(t), \quad I_L = I_{DC} + \hat{i}_L(t)$$

$$\hat{p}_{op}(t) = \Re\left[\hat{P}_{op}\exp(j\omega_m t)\right], \quad \hat{i}_L(t) = \Re\left[\hat{I}_L\exp(j\omega_m t)\right]n$$

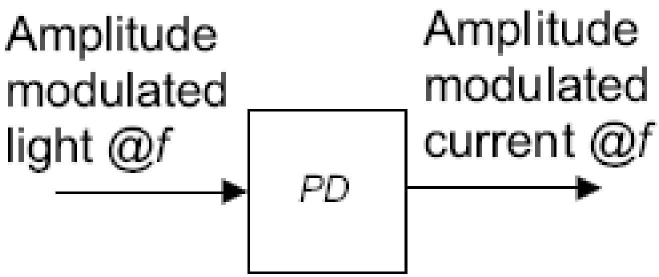
- If the photodetector is operating in linearity, the input and output modulation component are related by a complex transfer function → **complex responsivity:**

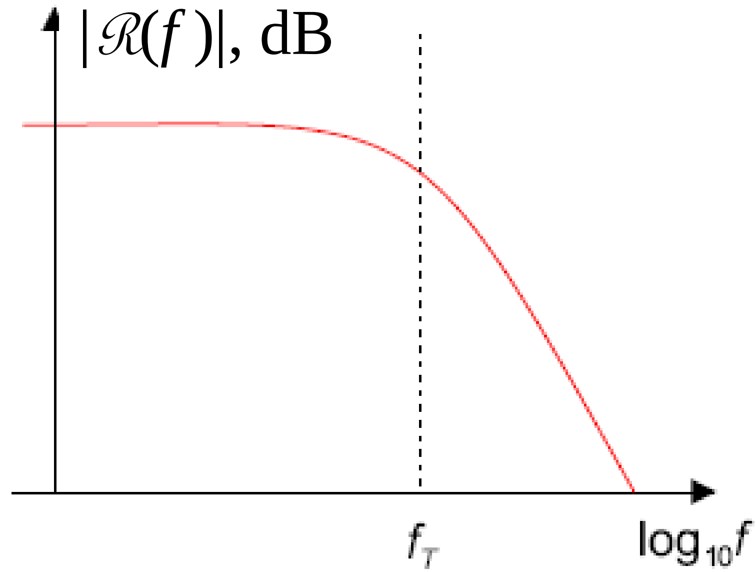
$$\hat{I}_L(f_m) = \mathscr{R}(f_m)\hat{P}_{op}(f_m)$$

- The complex responsivity is a (typically) low-pass function of the modulation frequency; usually only the **magnitude** is shown
- The DC value coincides with the responsivity.

Photodetector modulation bandwidth

- The 3dB photodetector bandwidth is often referred to as the *modulation bandwidth* (entirely different from the optical bandwidth!) or simply *speed*



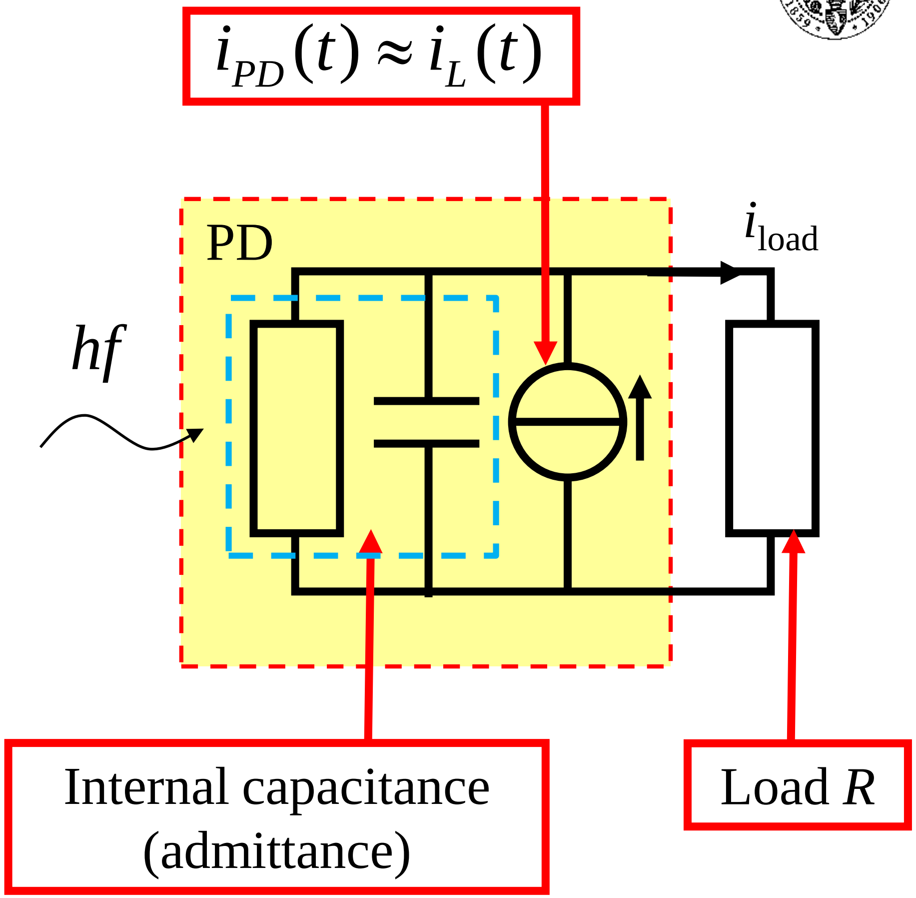


3 dB cutoff frequency

$$\mathcal{R}(f_m) = \frac{\hat{I}_L(f_m)}{\hat{P}_{op}(f_m)}$$

Factors affecting PD speed

- **Intrinsic** cutoff mechanisms:
  - Minority carrier *lifetime* (photoconductors)
  - Active region *transit time* (pin, APD)
  - Avalanche *build-up time* (APD)
  - Internal gain cutoff frequency (phototransistors)
  - Internal device capacitance (e.g. junction and/or parasitics): shorts at high frequency the photocurrent → RC cutoff with load R
- **Extrinsic** mechanisms: external parasitics, load capacitance
- [RC limitation can be removed exploiting *distributed photodetectors* → bandwidth from losses & light – RF signal velocity mismatch]



Photodetector gain

- In some PD structures, e.g. *pn* and *pin* PDs,

collected pairs = generated pairs

- ...but many PDs have *internal gain* whereby:

collected pairs >> generated pairs

- Examples:
  - phototransistors → gain due to BJT current gain (typically ~10 max.)
  - avalanche photodiodes → gain due to avalanche carrier multiplication (typically 10-100)
  - photoconductors → gain is there, even if it is difficult to tell why and where from!
- Internal gain increases $\mathscr{R}$ above the theoretical maximum value with the same IQE

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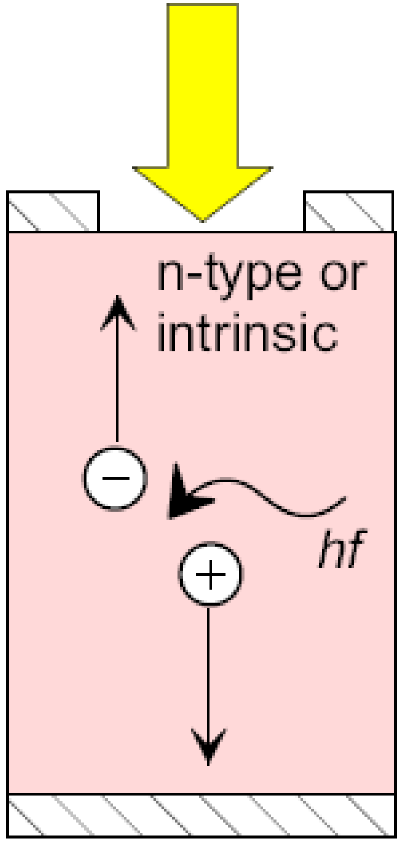
Photodetector choices

- To build a PD, carriers have to be photogenerated and then *collected* to the external circuit through an electric field → can be an E field in bulk or a junction field. Possible semiconductor choices:
  - bulk-based → photoresistors (photoconductors)
  - *pn* junction-based:
    - » *pn* photodiodes (just historical!)
    - » *pin* photodiodes
    - » avalanche photodiodes (APD)
    - » phototransistors
    - » [uni-carrier-traveling photodiodes]
  - metal-semiconductor junction based
    - » Schottky barrier photodiodes
    - » MSM photodiodes
- Non-semiconductor: vacuum detectors (phototubes and photomultiplier tubes), organic photodetectors…

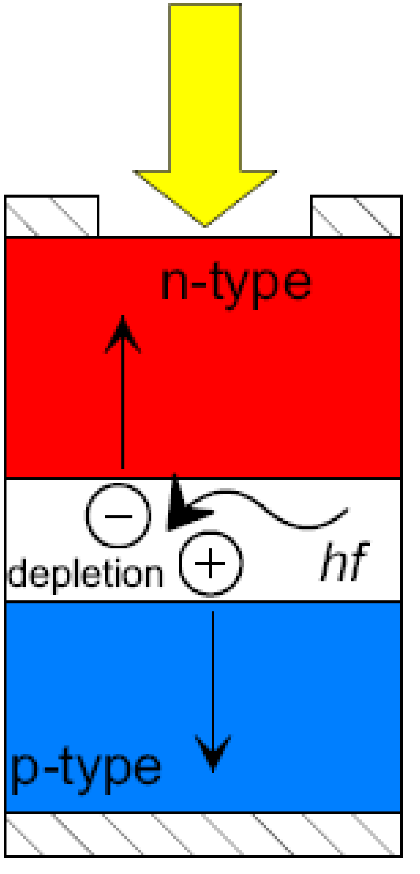
Photoconductor

- e/h generation in nearly-intrinsic or slightly doped semiconductor region
- high noise (thermal), high dark current (can be decoupled through a capacitor)
- lifetime-limited bandwidth (slow device)
- simple, low-cost device



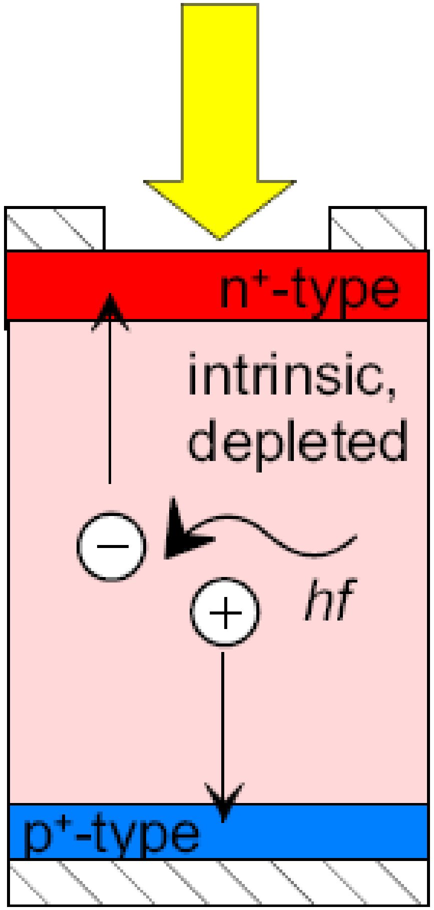
pn photodiode

- e/h generation in the depletion region of a *pn* junction
- unit gain, low noise (shot), low dark current
- bandwidth limited by *RC*, transit-time and lifetime (homojunctions)
- slower than pin diodes due to diffusion currents (homojunctions)
- poor responsivity due to small depleted region (see later)



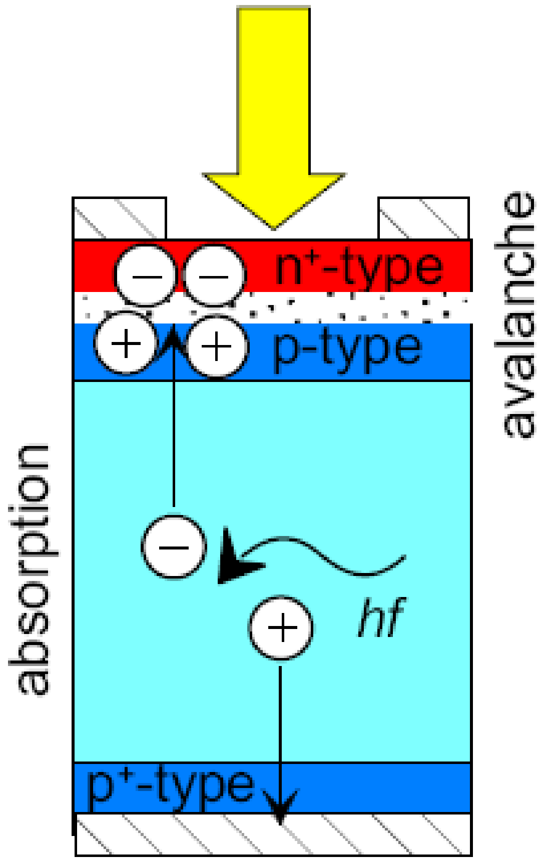
pin photodiode

- e/h generation in the intrinsic depleted region
- unit gain, low noise (shot), low dark current
- bandwidth limited by *RC* and transit time, diffusion region contribution usually negligible
- best device for speed (>40 Gbps)



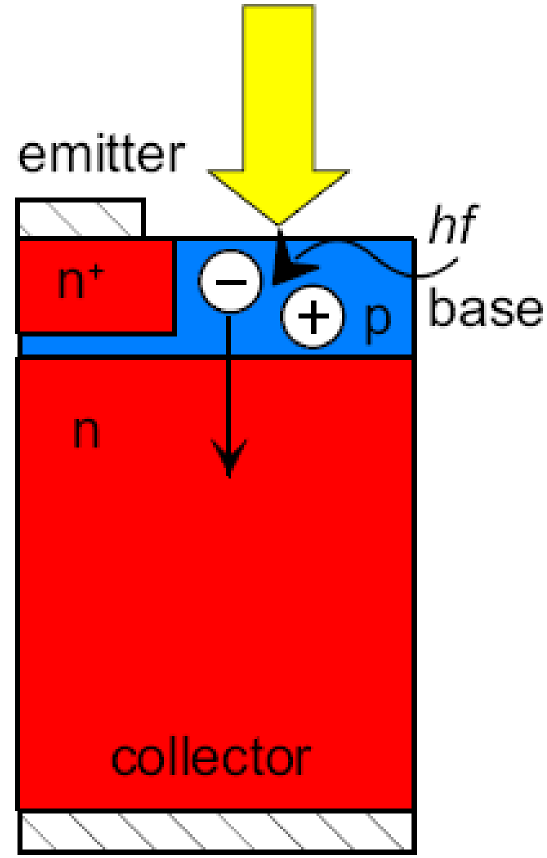
Avalanche photodiode (APD)

- e/h generation in *pn* depletion region
- moderate gain through avalanche multiplication, high noise (multiplied shot, excess)
- bandwidth limited by *RC*, transit time, avalanche buildup time
- best device for sensitivity, limited to 10 Gbps



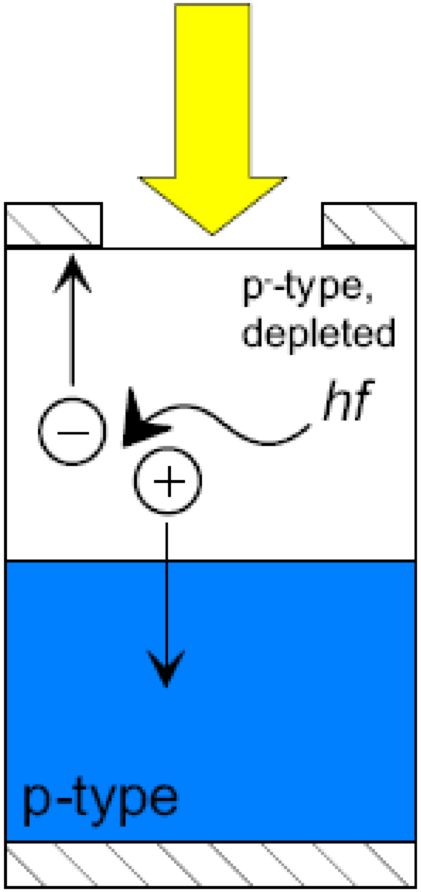
Phototransistor (PBT, PHBT)

- e/h generation in open-circuit base of bipolar transistor or heterojunction bipolar (what's this?)
- high gain, high noise (shot)
- bandwidth limited by transistor cutoff
- again popular (at least in the labs…) due to application of the concept to high-speed heterojunction bipolars



Schottky photodiode (MSM)

- e/h generation in MS depleted region and/or in metal
- unit gain, low noise, low dark current
- bandwidth limitations as in *pin* photodiodes
- simple device, high speed, poor reliability, not very popular in system applications



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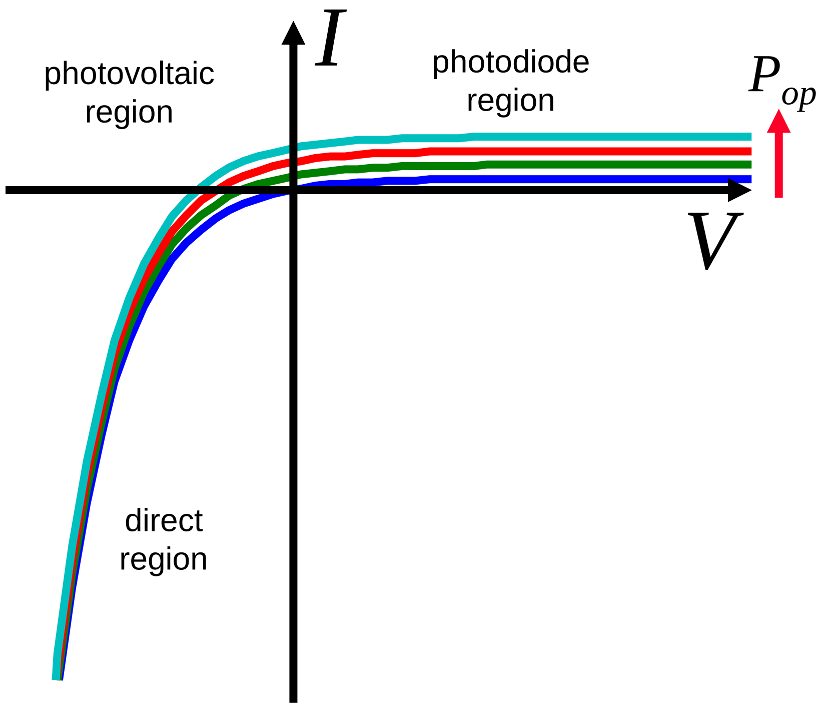
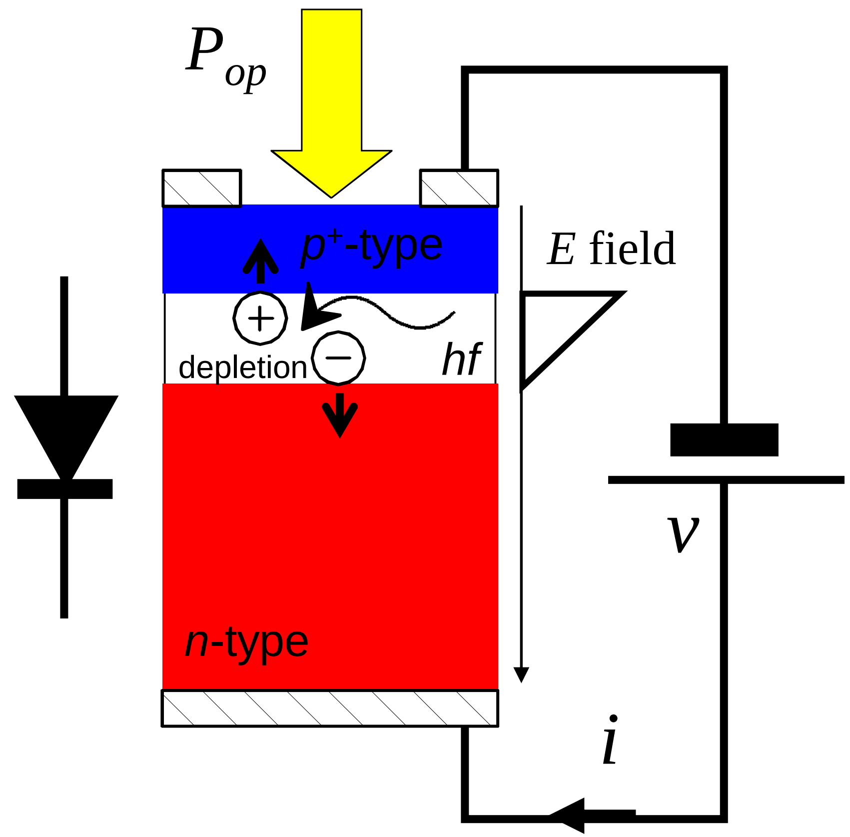
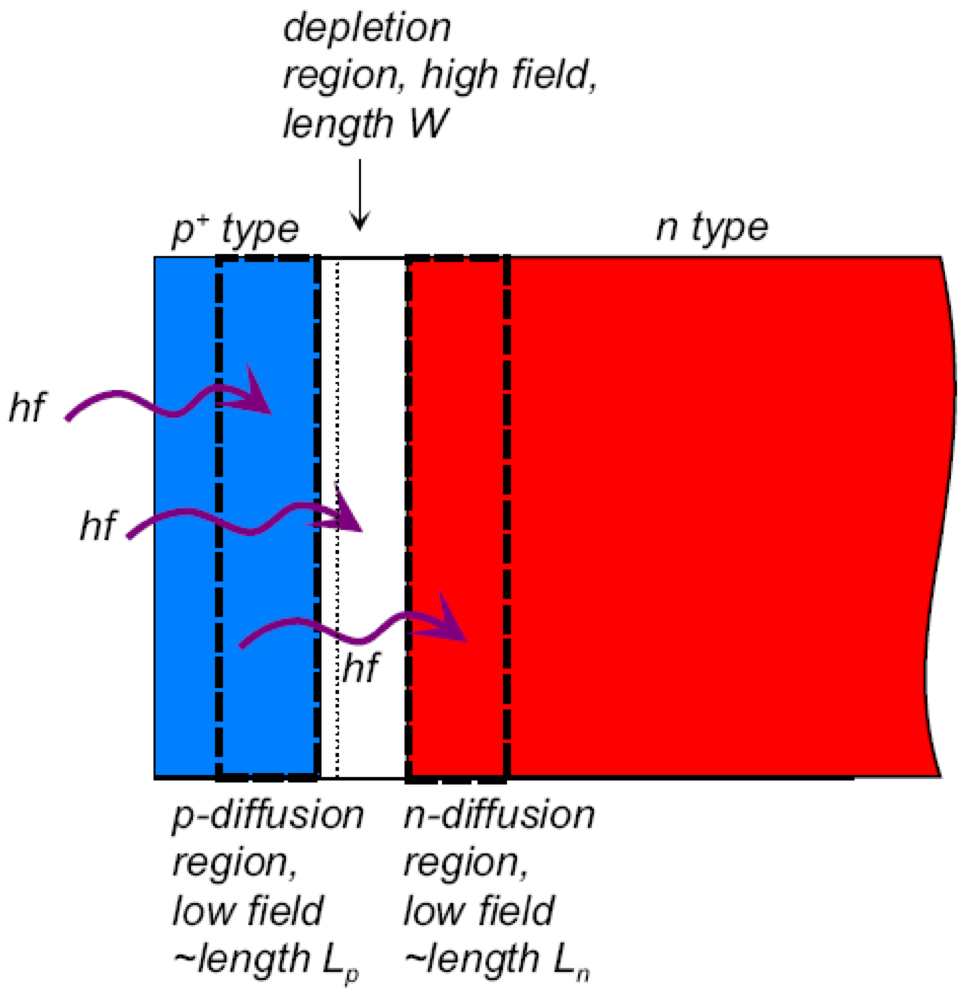
Photodiode operation





- I(V) curves are those of a *pn* diode whose reverse (dark) current is enhanced by the photocurrent
- Good linearity in the photodiode region, worse in photovoltaic (active!), worst in direct bias

pn photodiode currents



- Photons are absorbed not only in the (small) depletion region, but also in the (larger) diffusion regions, thickness:

$$L_x = \sqrt{D_x \tau_x}$$

- The total current can be shown to be (we neglect space variation of optical generation or use an average value):

$$I_L = qA\int_W G_o dx + I_{Lp} + I_{Ln}$$
$$\approx qAG_o(W + L_p + L_n)$$

Good or bad news?

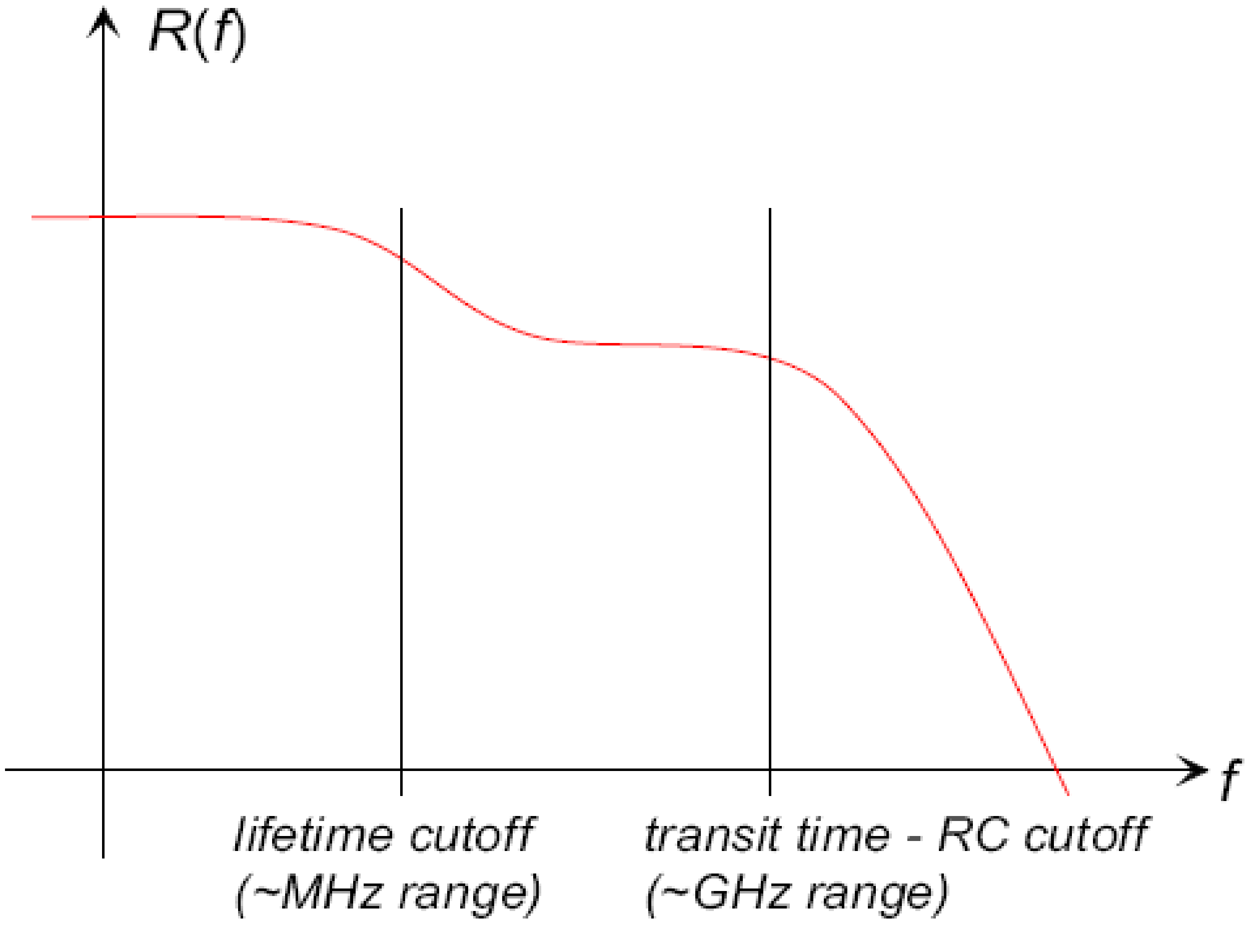
- Apparently carriers generated in the diffusion regions increase the device responsivity, but in fact a frequency-domain small-signal analysis shows that:

$$\hat{i}_L(\omega) = qAG_o(W + \mathcal{L}_p + \mathcal{L}_n)$$

$$\mathcal{L}_p = \frac{L_p}{\sqrt{1 + j\omega\tau_h}}, \mathcal{L}_n = \frac{L_n}{\sqrt{1 + j\omega\tau_n}}$$

- Thus the additional response dies out with a cutoff frequency of the order of carrier *lifetime*, and the whole response has a double cutoff (low frequency, high frequency due to transit time and capacitance effects, same in *pin* → see later).

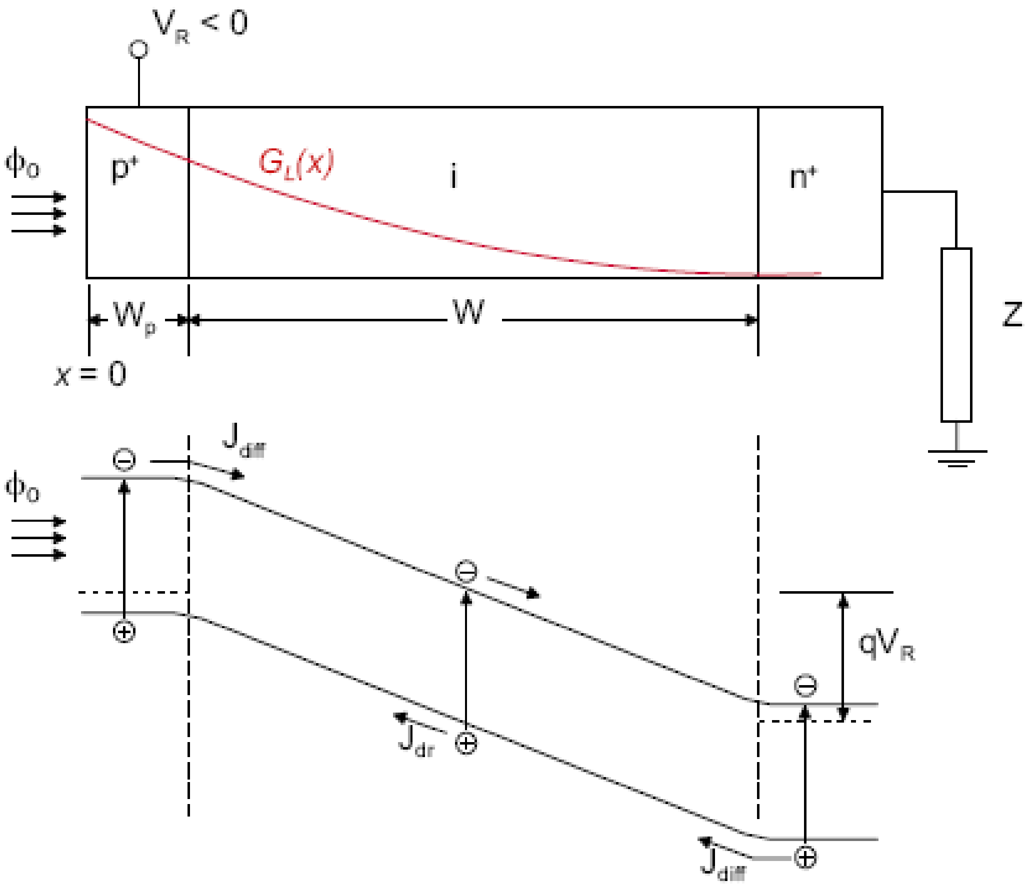
Plain *pn* frequency response – flawed!



Improving on the *pn* photodiode

- To improve frequency response and efficiency, the depletion region has to be made *larger* than the diffusion regions and the absorption length
- However, in *pn* diodes this requires extremely high reverse bias → unpractical
- To overcome the problem, the depletion region is obtained in a lightly doped (intrinsic) region → ***pin* diode**
- Additionally, in compound semiconductors the slow part of the response can be killed altogether by exploiting *NpP* or *NiP* structure, where *N* or *P* denotes widegap semicon-ductors (e.g. AlGaAs/GaAs/AlGaAs); no absorption takes place in the external regions and the related current contribution vanishes

The *pin* photodiode



- The external doped regions are usually widegap in compound semiconductors, however the upper junction is obtained by doping to avoid heterojunction carrier trapping
- Diffusion currents can be made negligible by proper design
- The modulation response is dominated by transit time and capacitance
- Tradeoff between efficiency and speed (see later)

pin photocurrent

- We neglect diffusion currents and absorption in the top *p* layer, *A* is the PD cross section:

upper face reflectivity

internal quantum efficiency

total incident power

$$I_L \approx qA\int_0^W G_L(x)dx = qA\int_0^W \left[\frac{\alpha\eta_Q(1-R)}{\hbar\omega}\frac{P_i}{A}\right]e^{-\alpha x}dx =$$

$$= q\eta_Q(1-R)\frac{P_i}{\hbar\omega}\left[-e^{-\alpha x}\right]_0^W = q\eta_Q(1-R)\frac{P_i}{\hbar\omega}\left[1-e^{-\alpha W}\right]$$

- From the current → responsivity and external efficiency

pin frequency response

- Due to the large value of the absorption region width W, the transit time of photogenerated carriers is not neglibile; it can be shown that the transit-time limited response is a sin(x)/x function of modulation frequency
- Several approximations to the 3dB transit-time limited bandwidth can be derived, e.g.:

$$f_{tr} \approx 0.44 \frac{v}{W} = 0.44 \frac{1}{\tau_{tr}}$$

- The total bandwidth is also influenced by the capacitance; assuming a load resistance R_L and a total capacitance C, the RC-limited bandwidth is

$$f_{RC} = \frac{1}{2\pi R_L C}, \quad C \approx \frac{\epsilon A}{W}$$

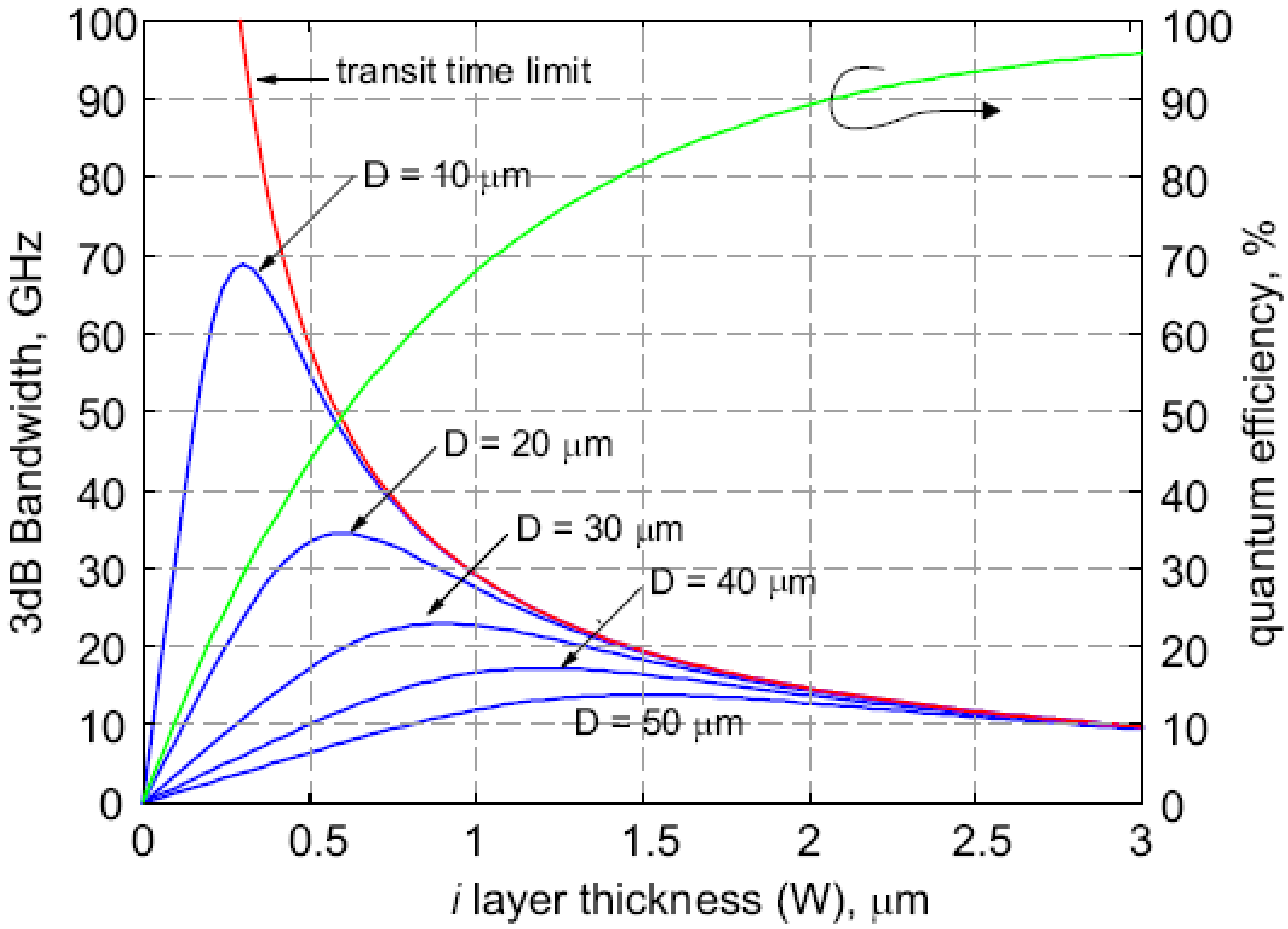
- The total bandwidth can be approximated as:

$$f_{3dB} \approx \frac{1}{\sqrt{\frac{1}{f_{RC}^2} + \frac{1}{f_{tr}^2}}},$$

$$f_{RC} \propto W, \quad f_{tr} \propto \frac{1}{W}, \quad \eta_x \propto W$$

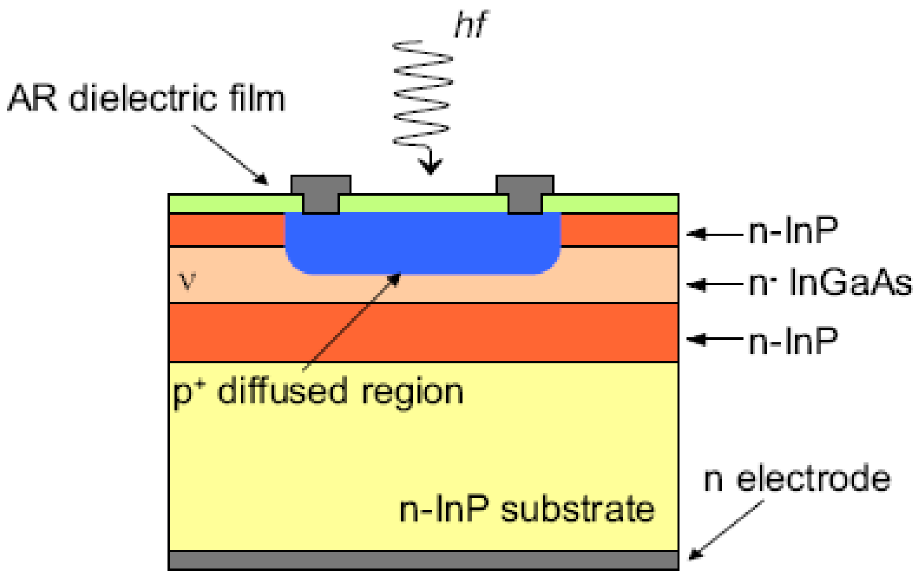
speed-efficiency tradeoff

Speed-efficiency tradeoff

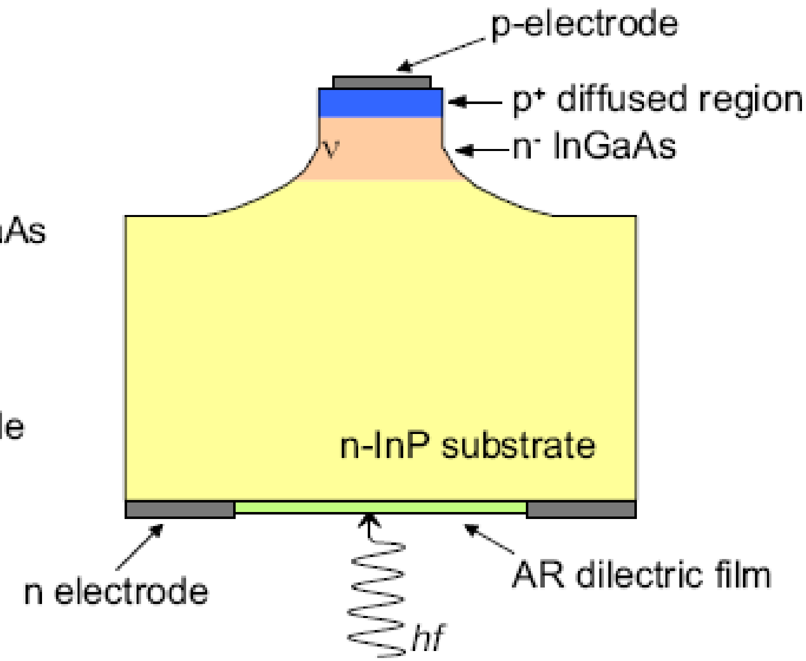


Vertical *pin* structures

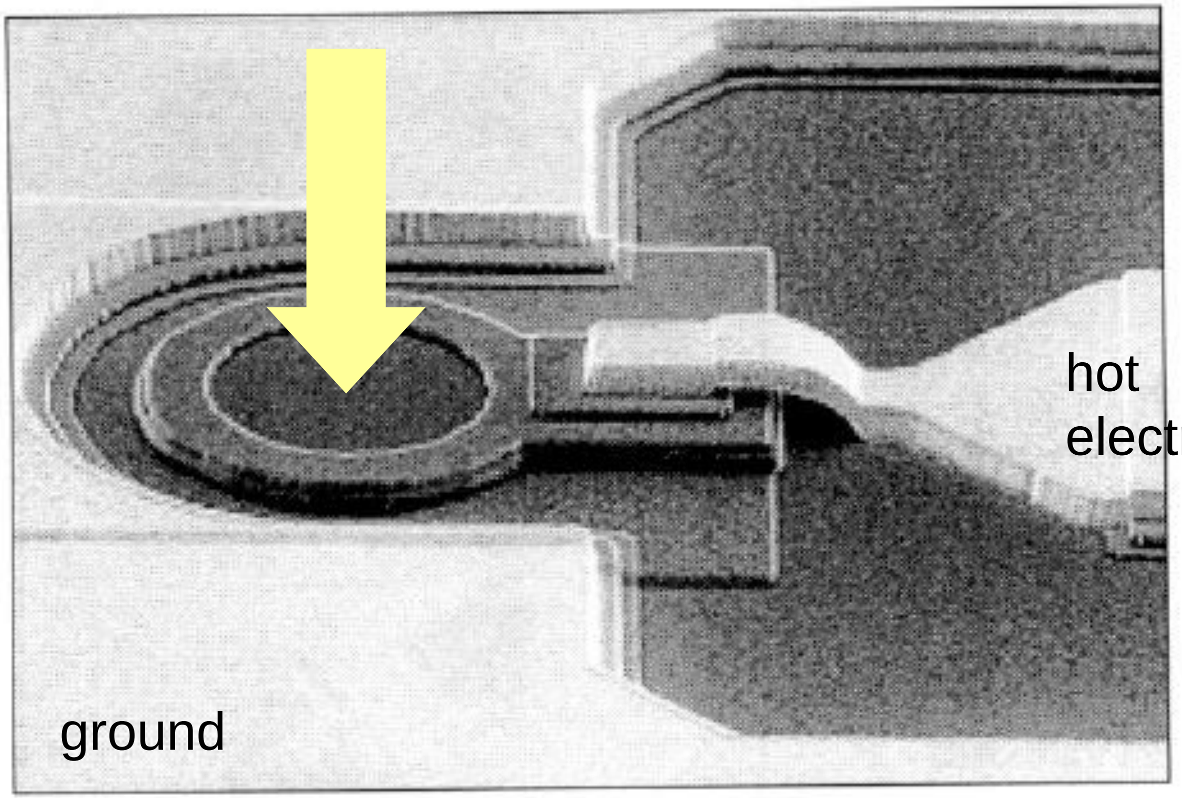
Planar pin,
double heterojunction



Mesa pin,
single heterojunction



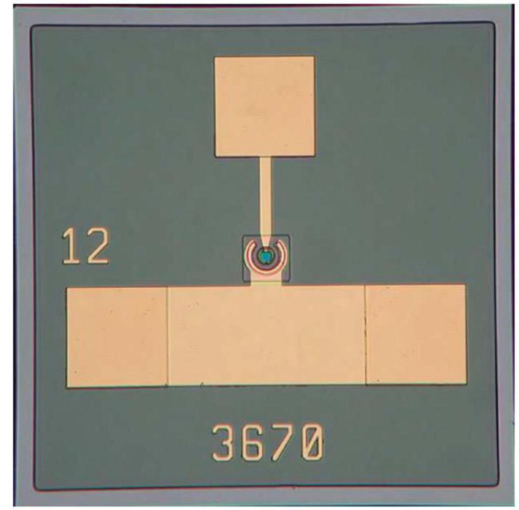
Vertical *pin* with coplanar waveguide output



Commercial High-Speed *pin* on InGaAs

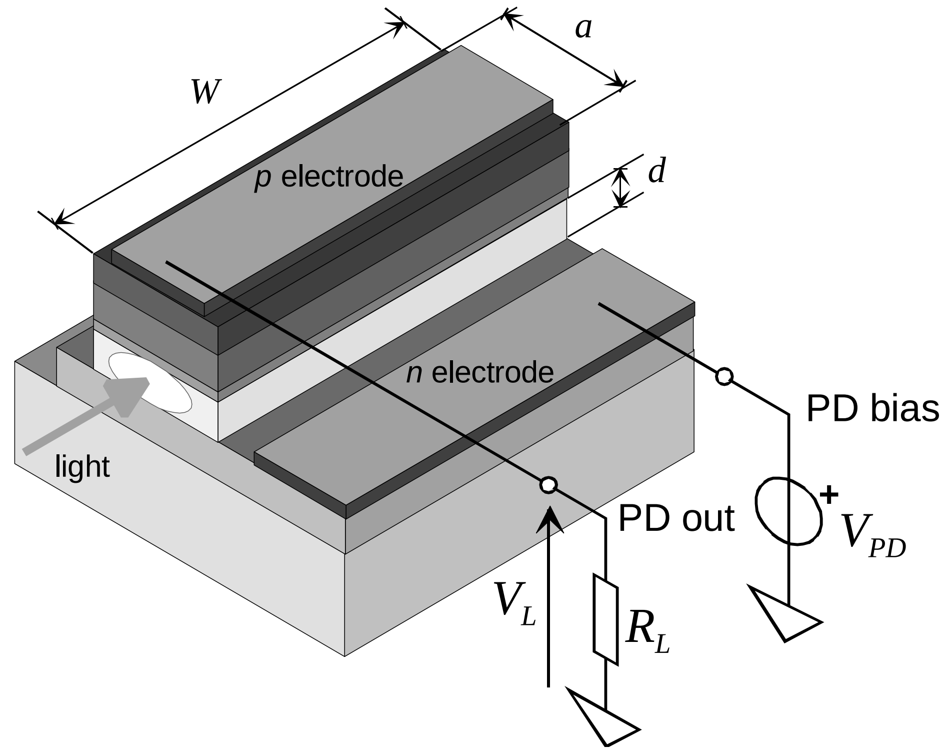
albis

- Top illuminated 40 Gb/s
- InGaAs photodiode, diameter: 12 μm
- Typical responsivity of 0.6 A/W @ 1310 nm
- Low capacitance: 70 fF
- Low dark current: 2 nA
- Low bias voltage: 2.5 V
- Operating temperature range: -40 to 85 °C
- For comparison, the 20 Gb/s photodiode has a diameter of 20 μm and responsivity 0.8 A/W
- http://www.albisopto.com/product_category/ingaas_pin/



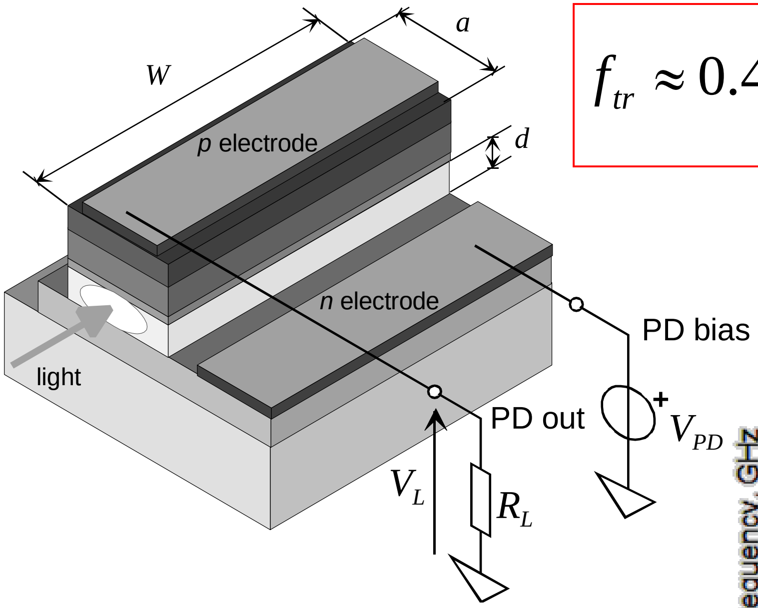
Waveguide PD – No efficiency-speed tradeoff!

- W can be made as large as needed to achieve 100% efficiency (coupling?)
- Since d is small the transit time is not a bottleneck
- The capacitance is low despite the small d because of the small a → RC limited but with large modulation bandwidth
- The **dark current** is drastically reduced due to the small Wa
- Coupling is a critical factor



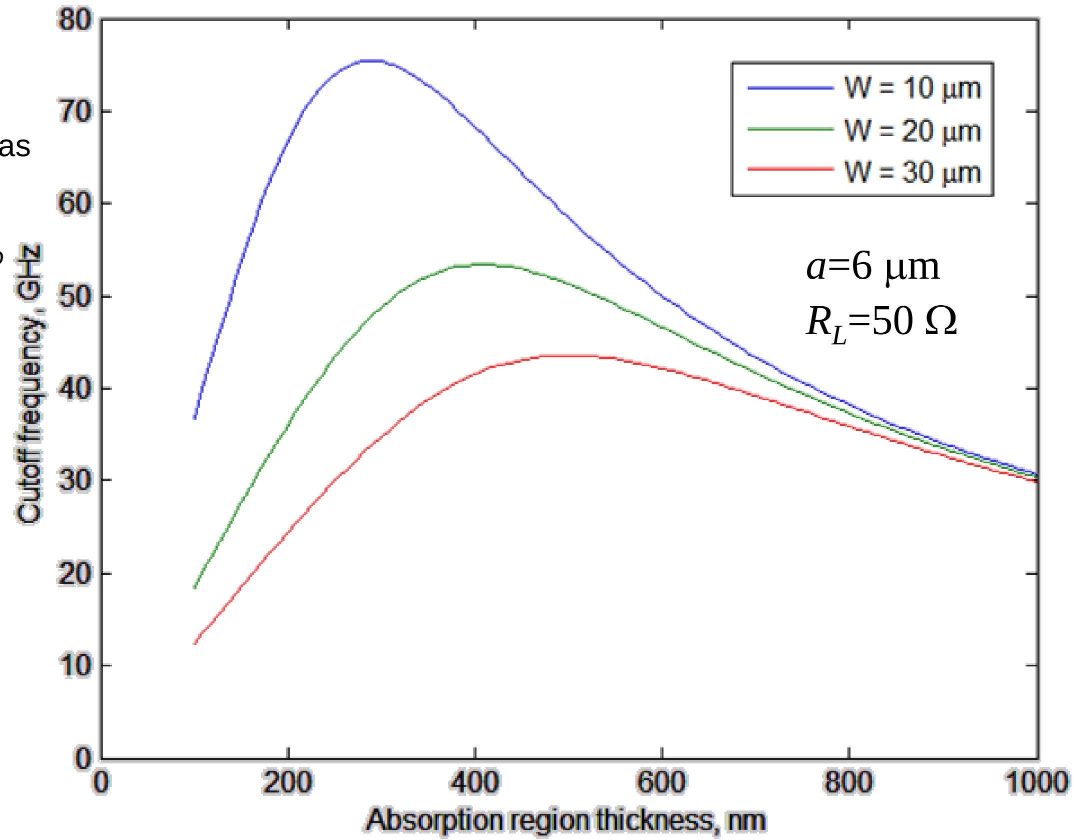
$$f_{RC} \propto \frac{d}{Wa}, \quad f_{tr} \propto \frac{1}{d}, \quad \eta_x \propto W$$

Example - Waveguide Ge - PD speed



$$f_{tr} \approx 0.44\frac{v}{d} = 0.44\frac{1}{\tau_{tr}}$$

$$f_{RC} = \frac{1}{2\pi R_L C}, \quad C \approx \frac{\epsilon_r \epsilon_0 W a}{d}$$



$$f_{3dB} \approx \frac{1}{\sqrt{\frac{1}{f_{RC}^2} + \frac{1}{f_{tr}^2}}},$$

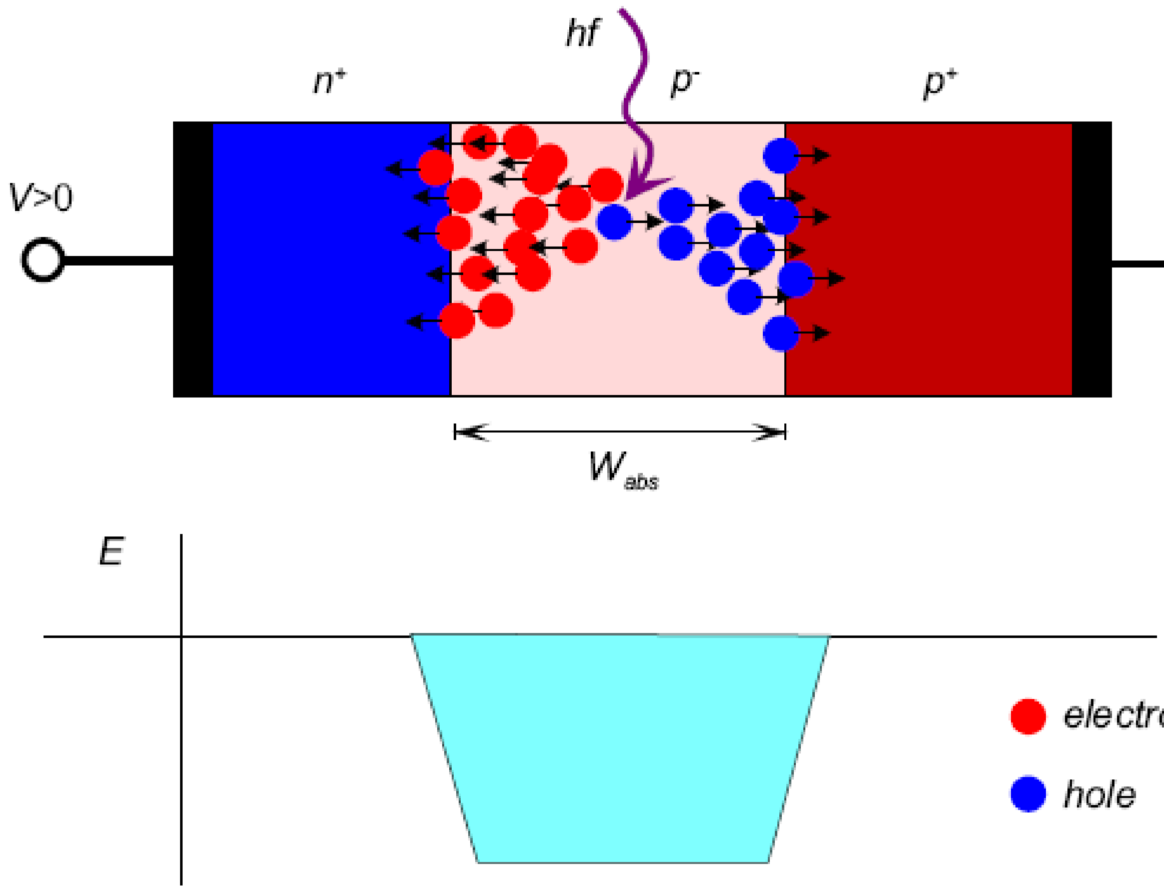
Outline

1. Photodetectors at a glance
2. Material issues affecting the optical response
3. Photodetector responsivity, quantum efficiency, optical and electrical bandwidth
4. Photodetector choices
5. Photodiodes: from pn to pin
6. Avalanche photodiodes (APD)

Increasing sensitivity through current gain: Avalanche photodiodes (APD)

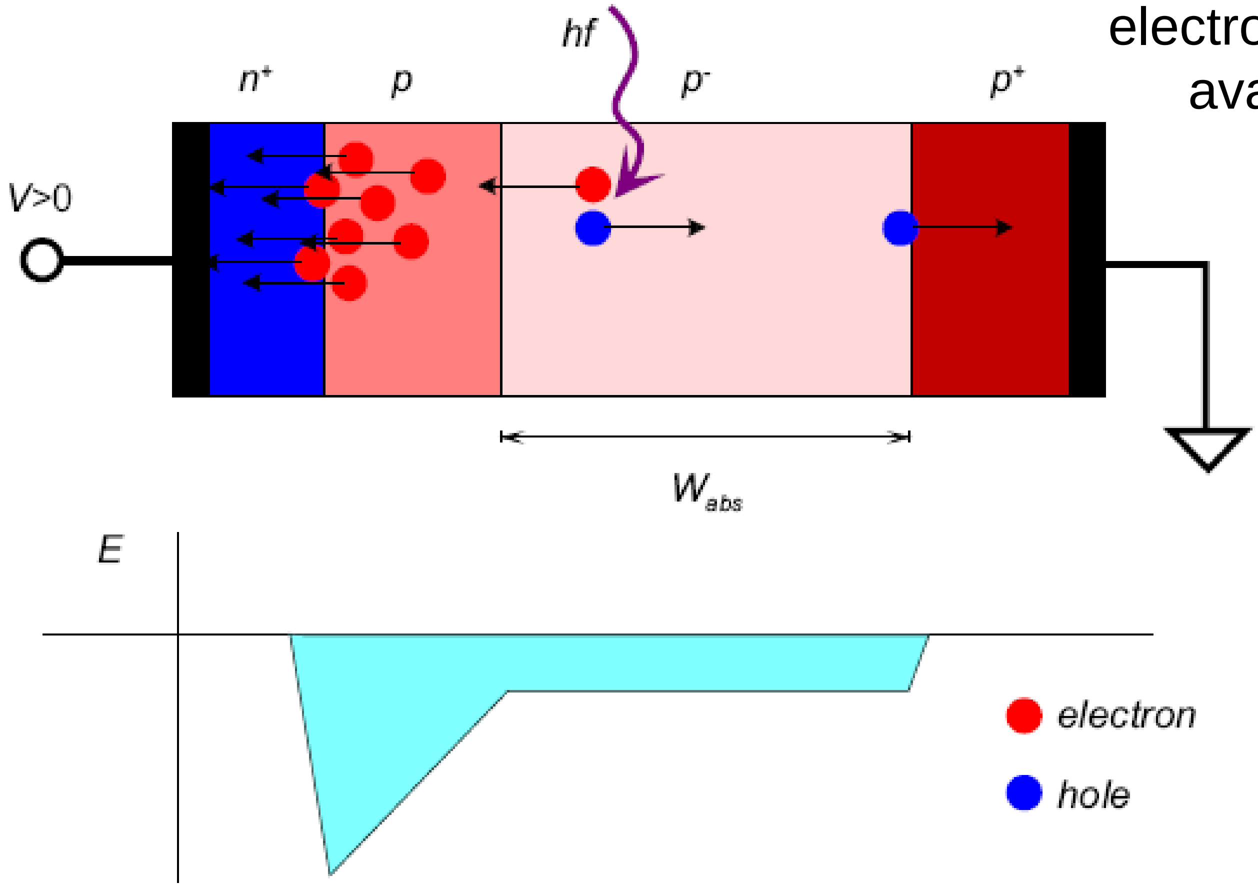
- Basic idea: multiply the number of photogenerated carriers thus increasing the device sensitivity
- Higher current than *pin* for the same illumination level but also:
  - higher noise
  - less speed
- The device includes two regions: generation and multiplication
- The two regions can be physically the same (APD) or can be separated (SAM-APD: Separate Absorption and Multiplication APD)
- The SAM-APD choice reduces noise and is the one currently implemented

APD principle



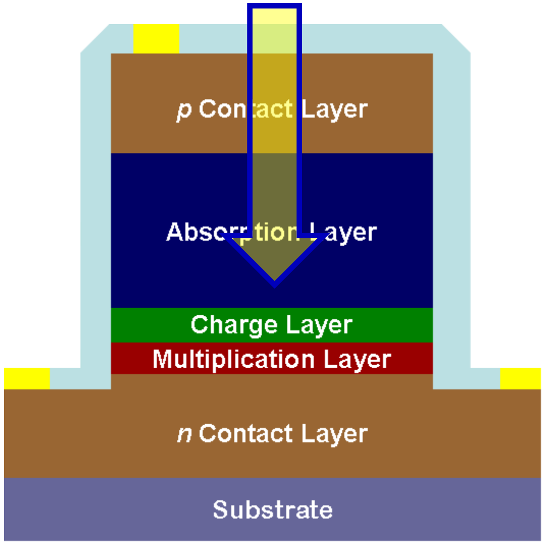
SAM-APD principle

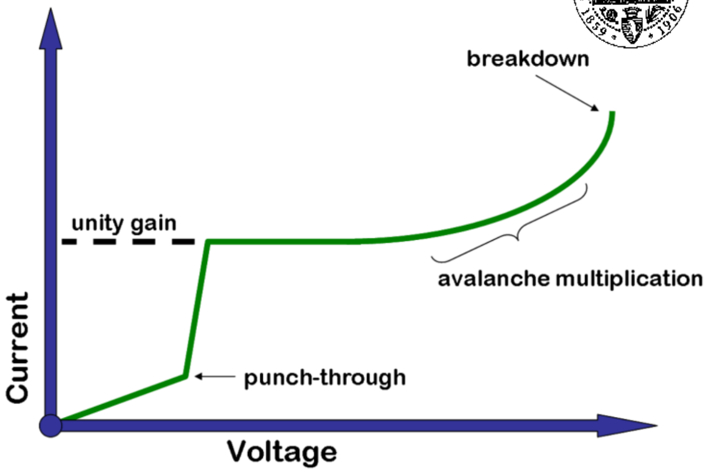
notice the electron-triggered avalanche!

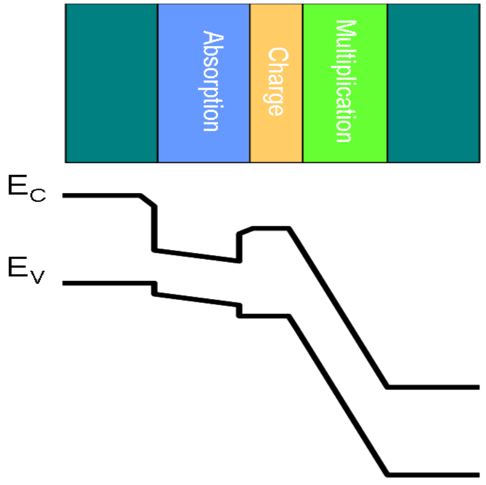


SMA-APD Charge (drift) layer

- Charge layer → control the field (through the CL **doping or dose**) in the absorption layer
- Increasing the voltage the absorption layer needs to be completely depleted before the multiplication layer gets into avalanche





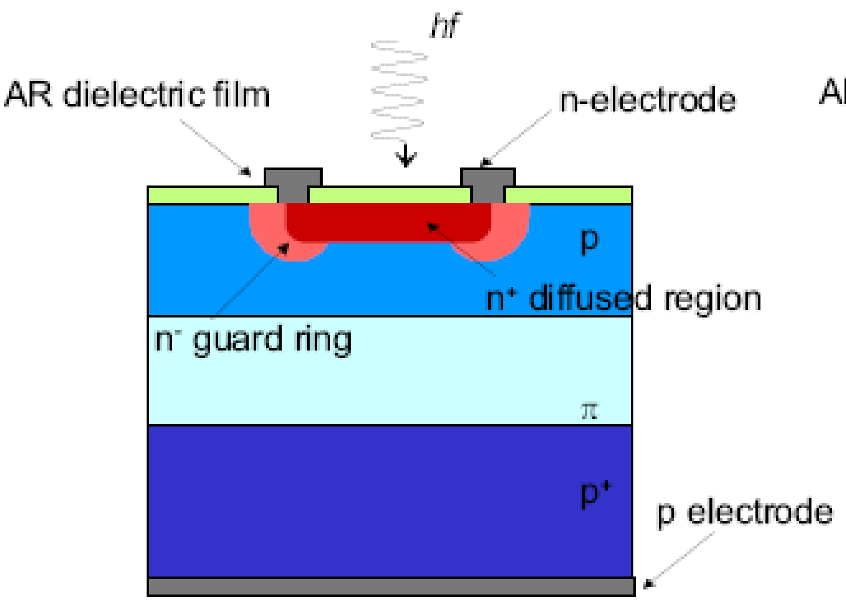


- If the absorption layer is not completely depleted the E/O dynamic response is **slow** due to low carrier velocity and carrier diffusion
- However, the absorption layer should not get into avalanche as well!

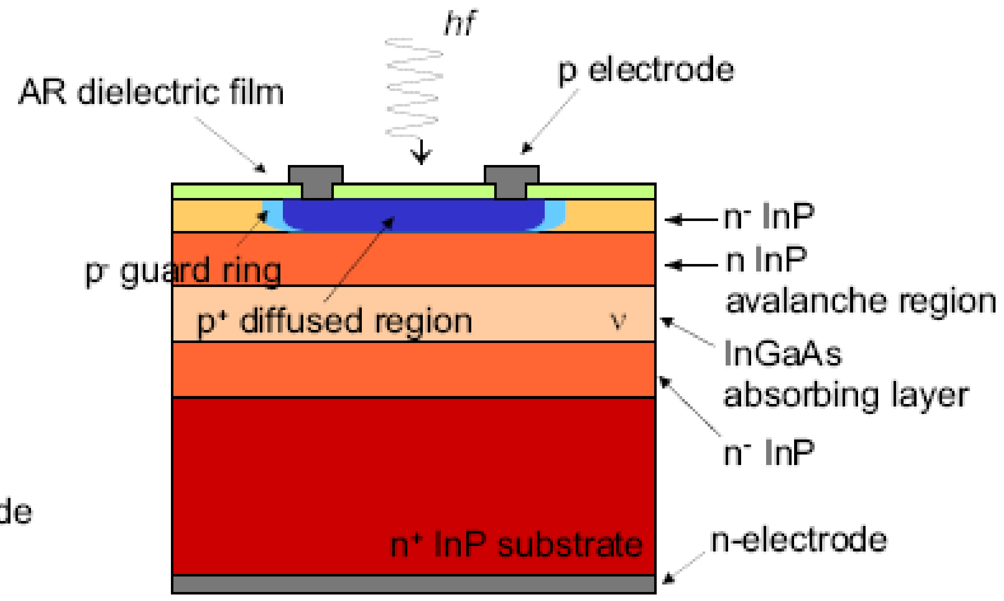
SOURCE - VOXTEL TECHNICAL NOTE: V805

APD structures

Si APD



InGaAs/InP SAM-APD



APD *I(V)* curves

- The SAM-APD current is the equivalent *pin* current by the multiplication factor:

$$I_L = M_n I_{pin} = M_n \times qAW_{abs}\,\alpha\,\frac{P_{op}}{\hbar\omega}$$

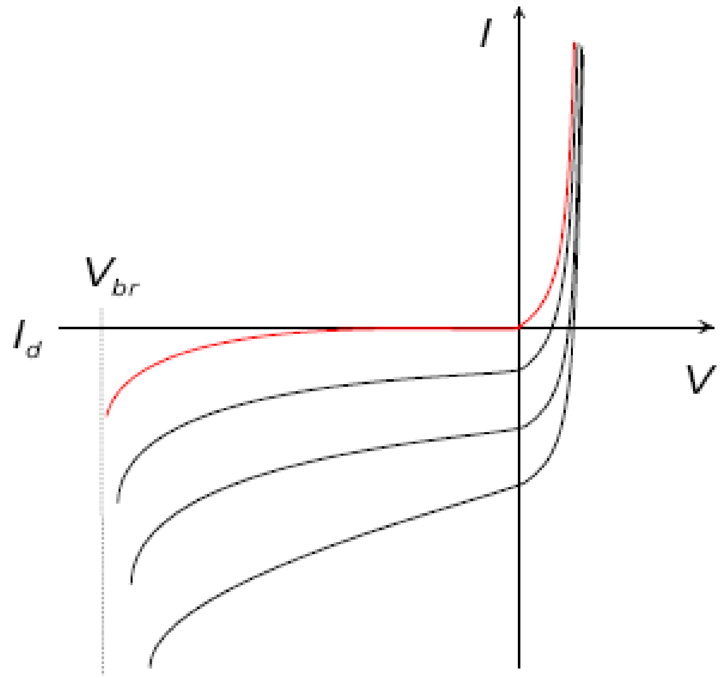
G_o

- which can be derived from the e/h avalanche ionization coefficients as:

$$M_n = \frac{1}{1-\int_0^{W_{av}} \alpha(E)\,e^{-\int_0^{x}(\alpha(E)-\beta(E))\,dx'}\,dx}$$

- Empirical expression:

$$M_n \approx \frac{1}{\left[1-\left(\frac{V-R_s I}{V_{br}}\right)\right]^n}$$

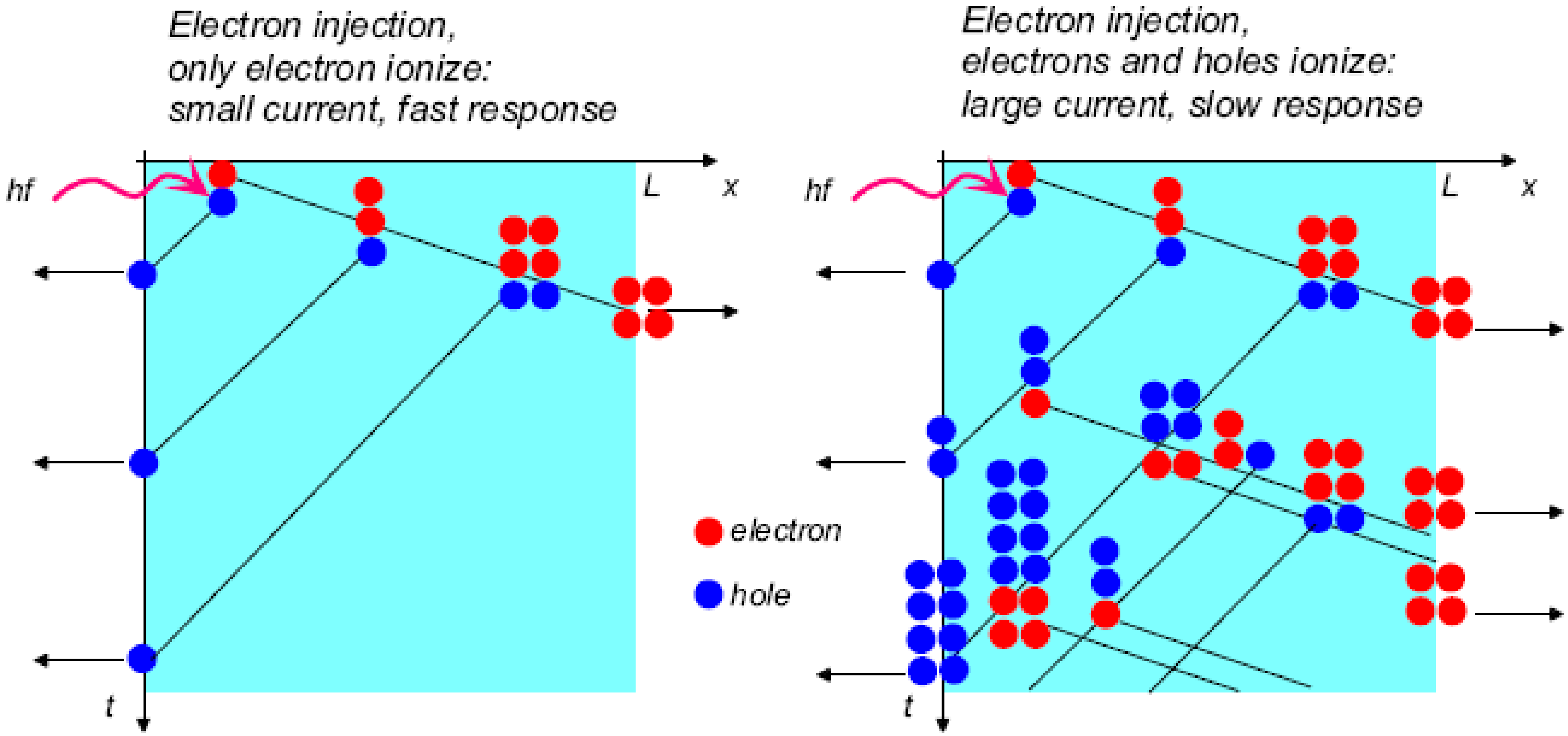


- Also the equivalent *pin* responsivity is multiplied by the bias-dependent multiplication factor!

APD speed and noise

- The APD is slower than the corresponding *pin* → to the transit time intrinsic effect we must add
  - an **additional transit time** of non-avalanche triggering carriers through the avalanche region
  - (more important) the **avalanche buildup time**
- The avalanche buildup time is minimized if avalanche coefficients are very different
- Also current fluctuation (noise) are minimized in this condition → problems for GaAs/InP (however → bandstructure engineering!), better for Si
- To make a fast and not too noisy device we have however to accept a reduction of avalanche gain → typically < 10

APD speed and ionization coefficients



APD summary

- Very popular device before the introduction of fast *pin* diodes and of fiber amplifiers (EDFAs), now popular again
- Good internal gain, high sensitivity due to higher responsivity but also high noise
- Worse speed but better sensitivity than *pin*, requires higher voltage bias, is less reliable, has a more complex structure
- Formerly very common implementation in Ge or Si, now also in InP-based compounds
- Tradeoff in systems when compared to *pin*

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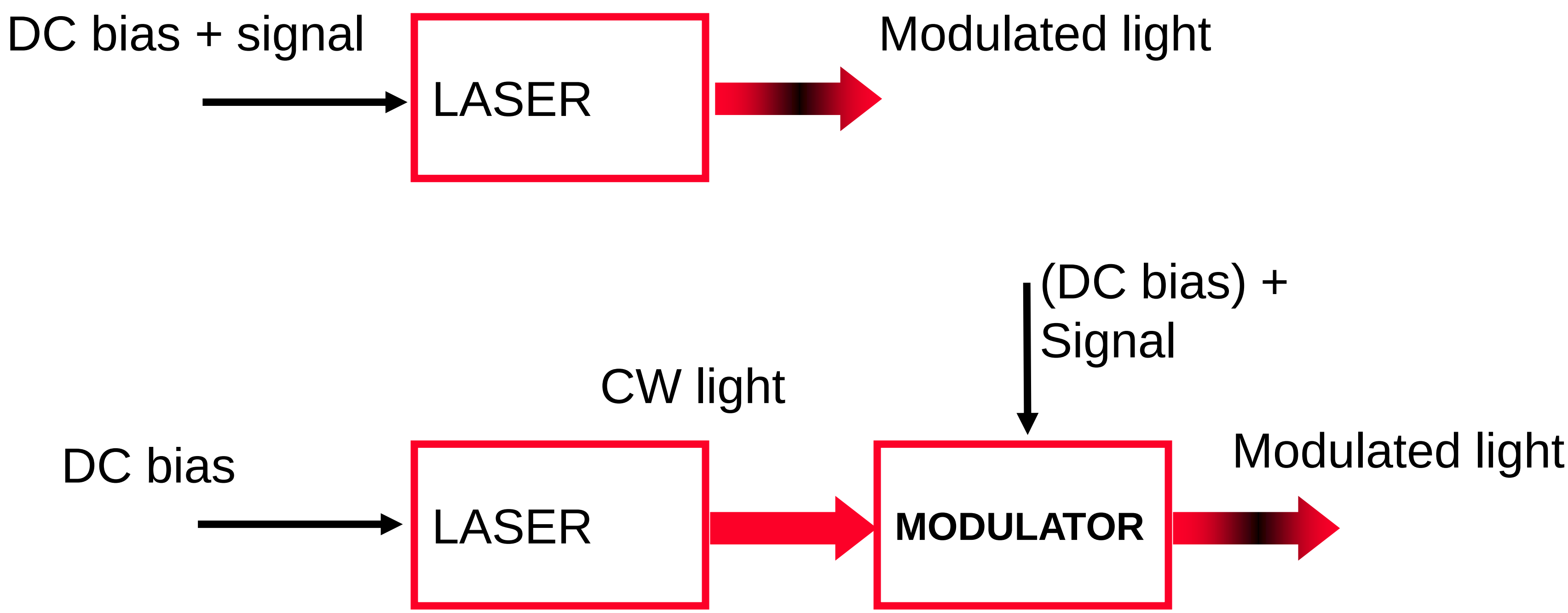
7. Free bonus: a few words on optical modulators ☺

External and internal light intensity modulation



Light modulation solutions: external vs. internal

- **Internal intensity modulation:**
  - Through modulation of the laser current
  - More compact, no additional external device required
  - Worse extinction ratio
  - Higher chirp (spurious frequency modulation of light)
  - Slower → limited to ~10 Gbps (on field)
- **External intensity modulation:**
  - Requires an external device (voltage driven), less compact
  - Higher extinction ratio
  - Lower chirp, ideally zero if required (Electro Optic solution)
  - Faster → up to 40 Gbps and beyond
  - Several solutions available

External modulator solutions

- **Electro-optic modulators (EOM):**
  - amplitude modulation through interference of two phase-modulated beams (Mach-Zehnder) or arms of a directional coupler or resonance shift of a ring resonator;
  - can be implemented in several electro-optic materials: piezoelectric (perovskites), semiconductor (GaAs, InP, SiGe, Si), polymers
  - Physical mechanism: **modulation of refractive index with applied electrical field / carrier injection**
- **Electro-absorption modulators (EAM):**
  - Direct amplitude modulation through **modulation of material absorption by an applied electric field**
  - Requires semiconductors, bulk or QW

External modulators – System level parameters I

- **Electro-optic response**: output/input light intensity vs. electrical input voltage at low frequency (DC)
- **On-off voltage**, often V_π: voltage required to turn off the input light at the output with a specific *extinction ratio*;
  - for EO modulators defined uniquely,
  - for EAM depends on the extinction ratio
- **Extinction ratio**: ratio of the ON state output light vs. the OFF state output light

External modulators – System level parameters II

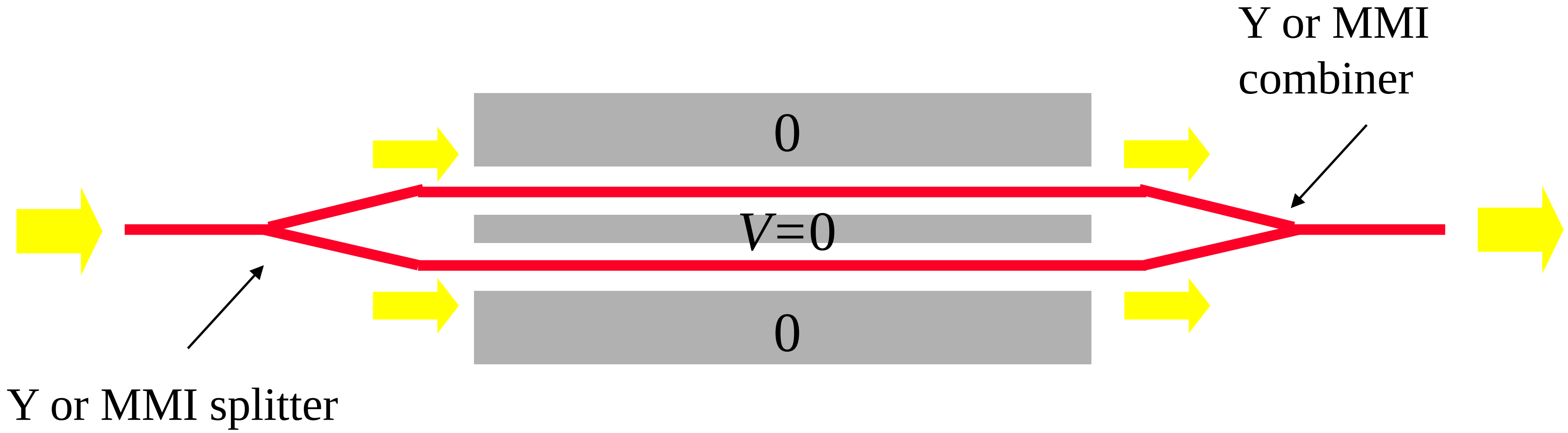
- **Frequency response**: modulated light amplitude for harmonic input electrical signal at frequency *f*, often relative to the low-frequency (or DC) E/O response
- **Electrical (modulation) bandwidth**, often 3 dB, see later, RF electrical input frequency at wich the f.r. decays 3 dB with respect to DC
- **Optical bandwidth**, wavelength range on which the modulator is operating
- **Chirp or instantaneous frequency deviation**: spurious frequency (wavelength) modulation of the output light with respect to unmodulated light
- **Optical insertion loss**: insertion loss of the modulator in the ON state
- **Electrical or RF insertion loss**: input reflection coefficient (as a function of frequency, for a harmonic modulating signal) of the modulator, seen from the electrical port.

E-field modulation of optical properties

- Application of an electric field generally causes the modulation (variation) of:
  - **Refractive index** vs. wavelength
  - **Absorption coefficient** vs. wavelength
- The two effects are related (*Kramers-Kronig*) and obey to several physical mechanisms:
  - **[semiconductors] Franz-Keldysh** (weak, optically wideband) and **Quantum-Confined Stark** (stronger, optically narrowband): modulation of *absorption* in bulk and QW semiconductors, with related modulation of *refractive index*
  - **[semiconductors] Plasma effect (Drude model)** → modulation of *refractive index* through *charge injection* (caused in turn by an applied voltage)
  - **[dielectrics] Pockels** (linear) or **Kerr** (quadratic) effect: modulation of *refractive index* in bulk crystals, modulation of *absorption* immaterial since such materials are low-loss

The Mach-Zehnder amplitude modulator I

- An optical beam is split in two beams
- Each beam undergoes electro-optic phase modulation; the two beams are combined after phase modulation
- Phase modulation is zero at zero applied signal, increases with increasing signal amplitude, at V_π is 90 degrees in each branch



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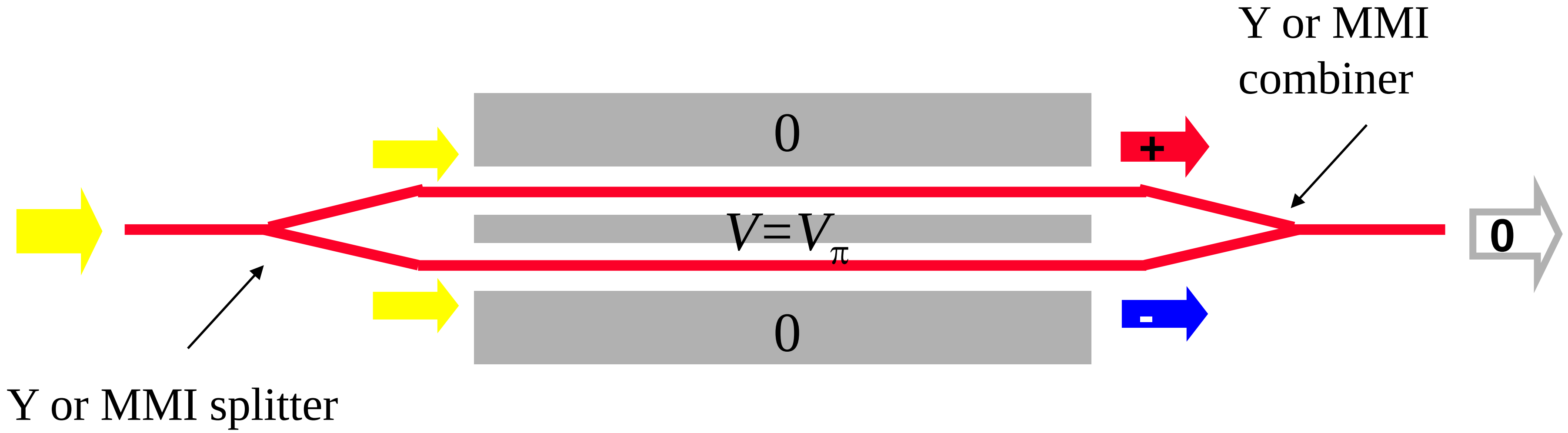

Interferometric Mach-Zehnder intensity travelling-wave (TW) modulator layout