Lecture Series

Wireless Communications - Part III - OWC - VLC – Optical Rx - Photodetectors

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OWC - Visible Light Communication – The Use of Photodetectors

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Seamless integration with lighting [1]

Sensing + Communication

Sensing + Positioning

Integrated technology

Positioning + Communication

Control + Communication

Indoor & outdoor applications:

- Last meter access network
- Underground
- In-chip communications
- Farming
- Industry
- Data centres
- AR, VR
- ITS
- IoT
- IoE

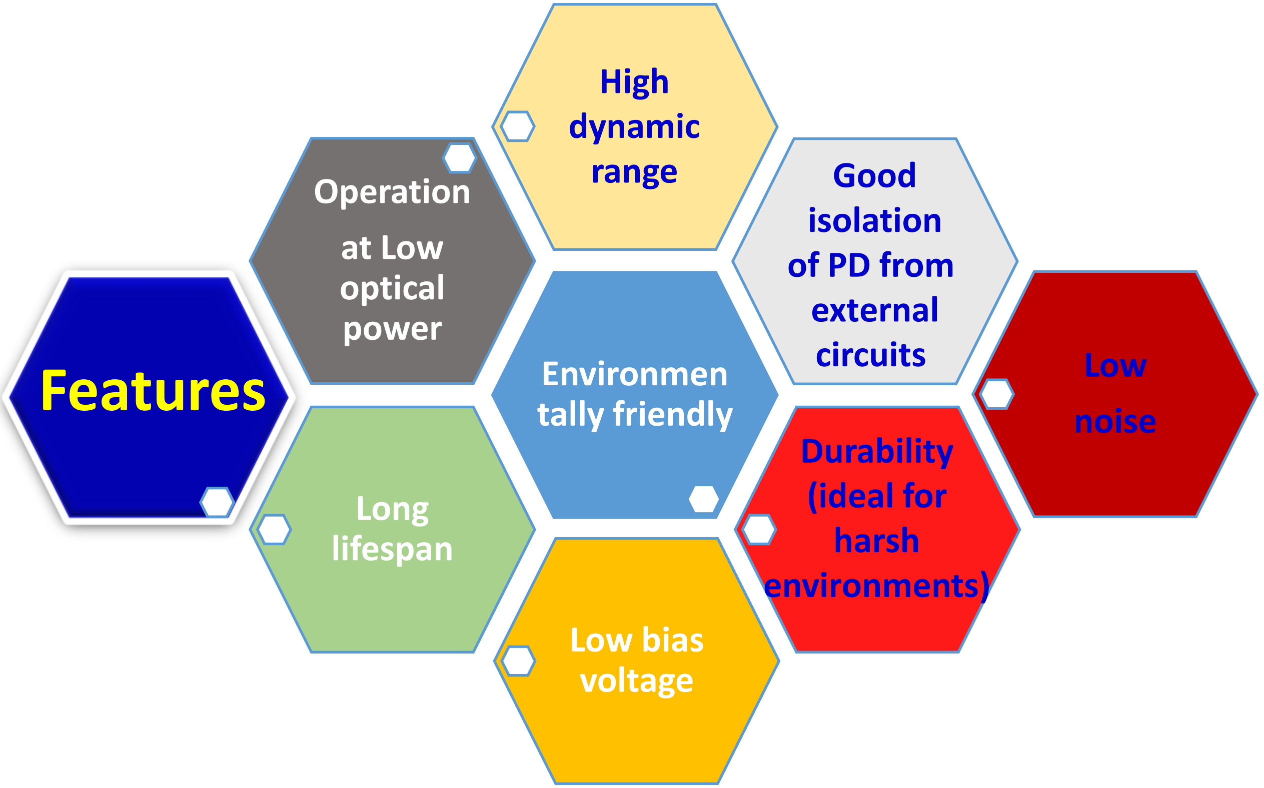
Underwater communications

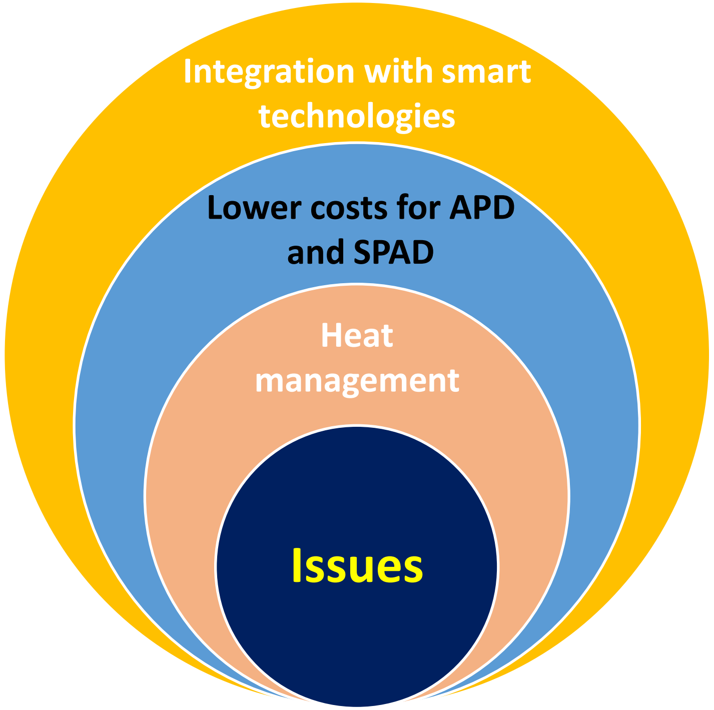
1- M. H. Memon et al., “Micro-Trench Deep-Ultraviolet LEDs With Boosted Efficiency for High-Speed Solar-Blind Optical Communication,” J. Lightwave Technol., vol. 43, no. 5, pp. 2248– 2254, Mar. 2025, doi: 10.1109/JLT.2024.3486102.

OWC - Visible Light Communication

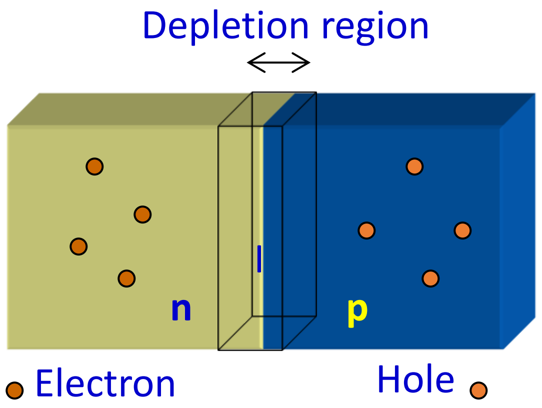
Photodetector + Optical Rx

- Both use a photodiode to convert an optical signal to an electrical signal
- Optical Rx – is composed of a PD followed by a low noise, linear and high-bandwidth amplifier



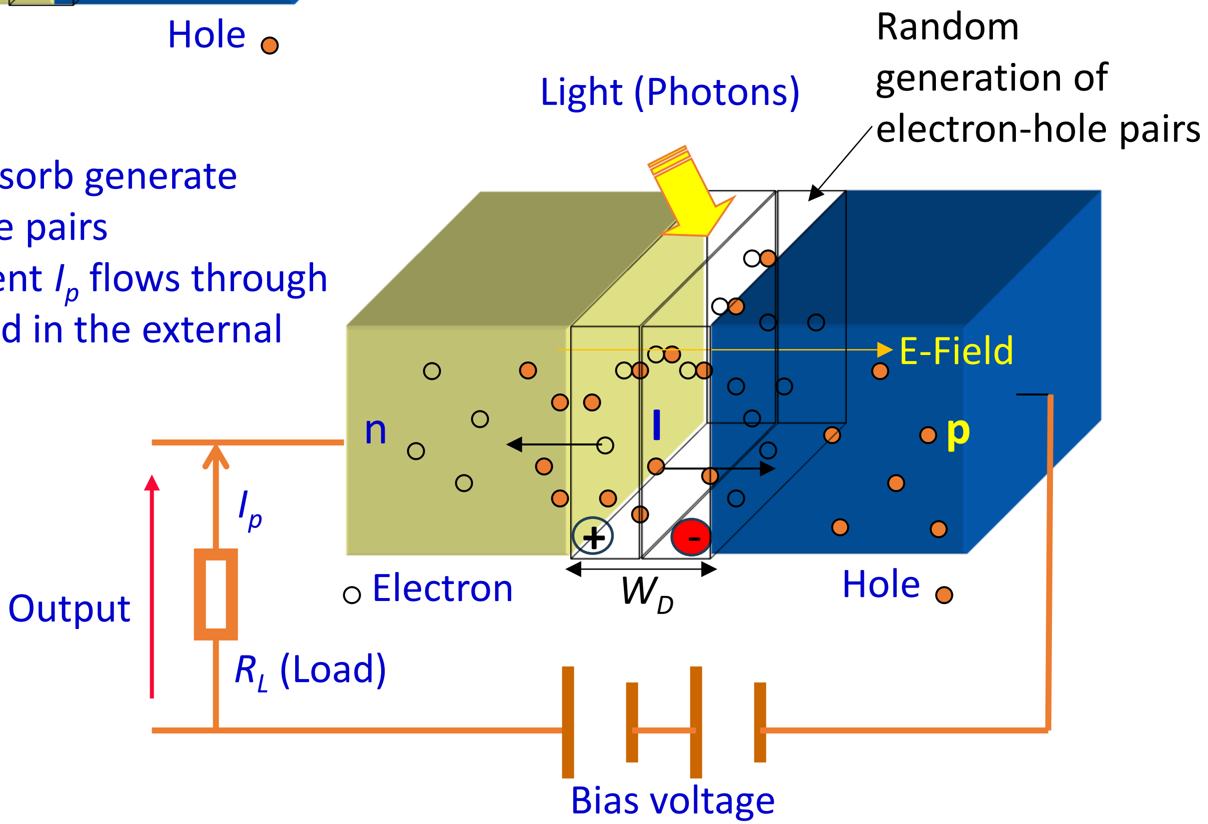


OWC - PDs - Structure



- No carriers in the *I* region
- No current flow

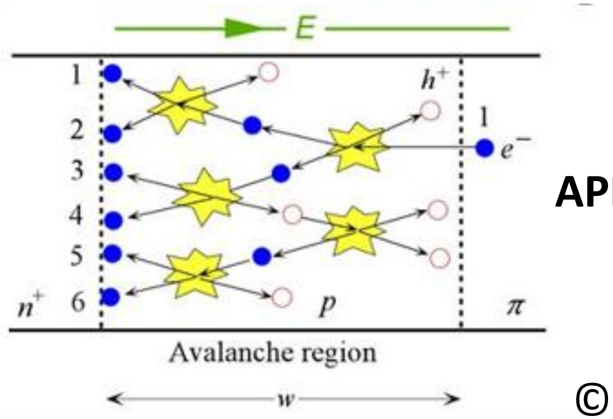
- Photons absorb generate electron-hole pairs
- Photocurrent I_p flows through the diode and in the external circuitry



Power level at a distance *x* from the surface of the depletion region is given by the Beer-Lambert Law:

$$P(x) = P_o e^{-\alpha x}$$

α is the photon absorption coefficient



APD with gain

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OWC - PDs

Performance characterisation

Responsivity
$\mathcal{R}$

External quantum efficiency
$$\text{EQE} = \mathcal{R}\frac{hf}{q}$$

Noise equivalent Power (NEP)

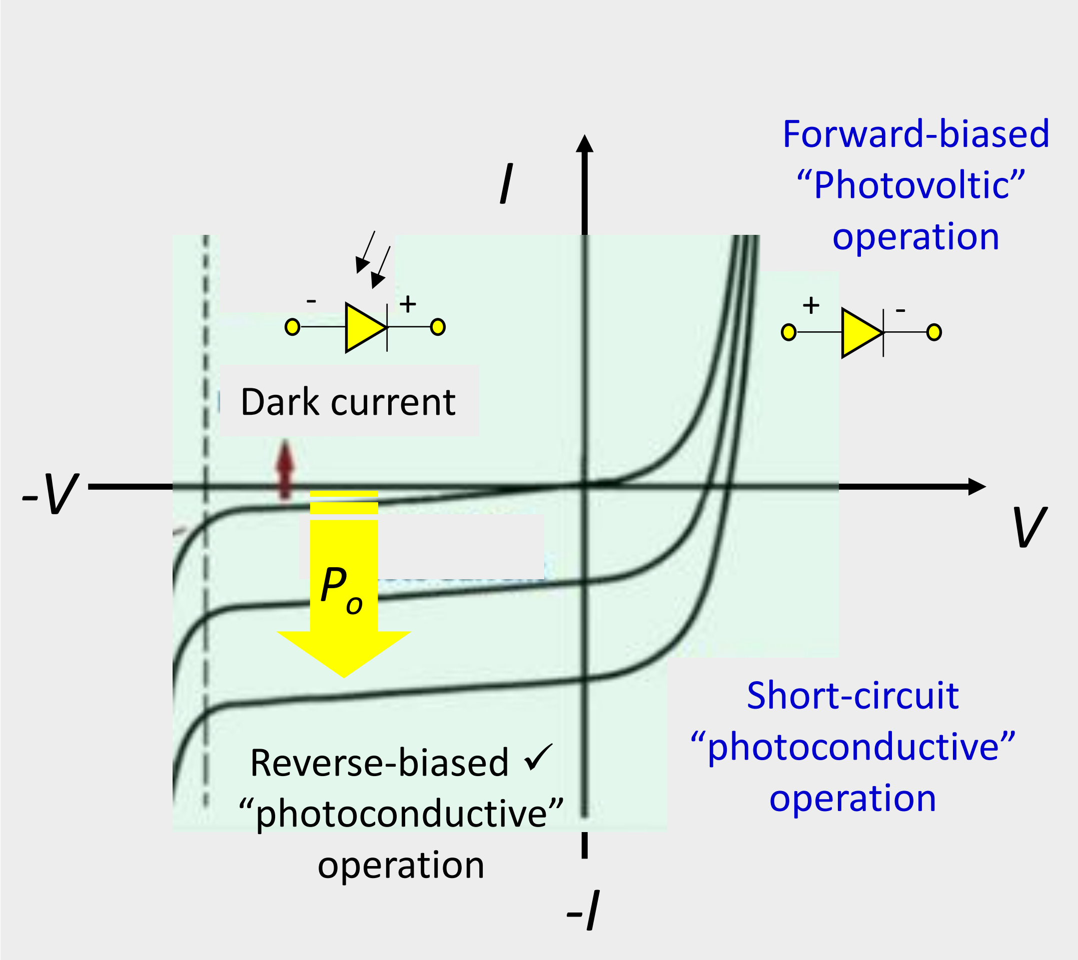
Detectivity
$$D = \mathcal{R}\sqrt{\frac{A}{2qI_d}}$$
A – PD surface area

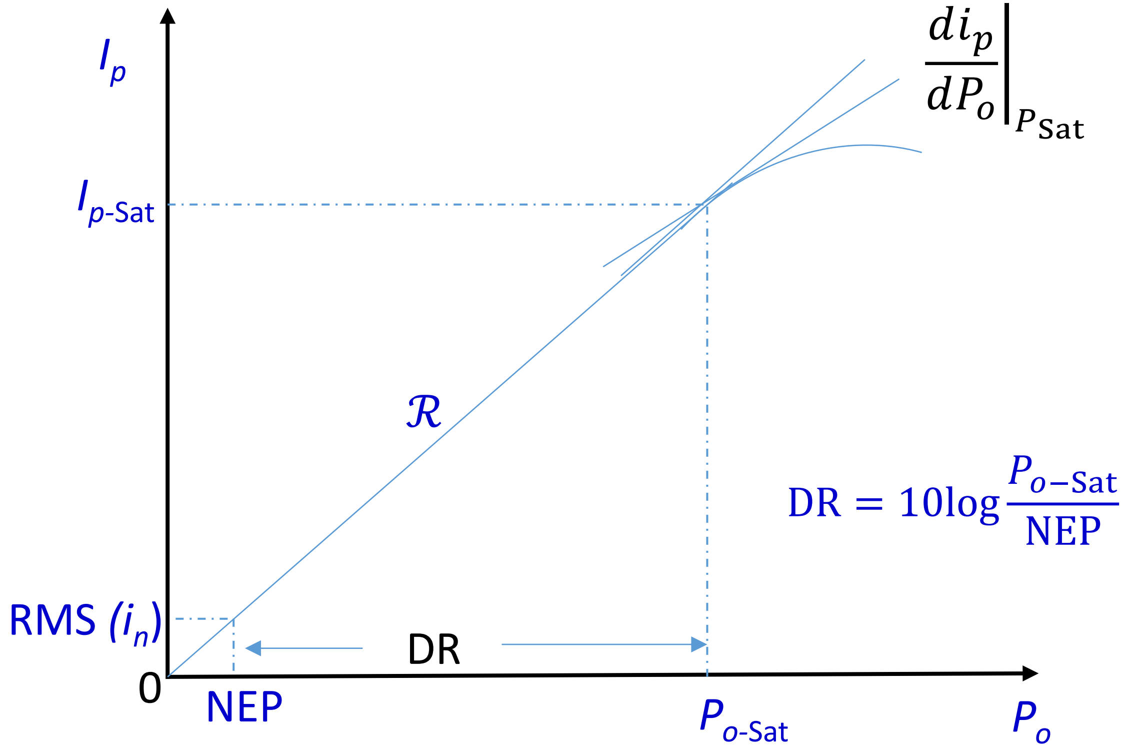
Response time (Rise and fall times)

Gain
G

1- https://pubs.rsc.org/en/content/articlehtml/2024/ma/d4ma00934g
2- https://pubs.rsc.org/en/content/articlehtml/2024/tc/d3tc04206e

OWC - PD – V-I-P Characteristics





One could also show *V* vs. *P*, which could be more relevant to photovoltaic devices.

OWC - PDs - Photocurrent

Cross sectional area

The capacitance of the depletion layer i.e., junction capacitance

$$C_j = \frac{\varepsilon\varepsilon_0 A_D}{W_D}$$

Depletion region width $\propto$ Is proportional to the bias voltage

Electron charge

Incident optical power

Photocurrent
$$I_p = \eta_q \frac{qP_o}{hf}(1 - e^{-\alpha W_D}) = \mathcal{R}P_o$$

Quantum efficiency

Plank's constant

Frequency = c/λ

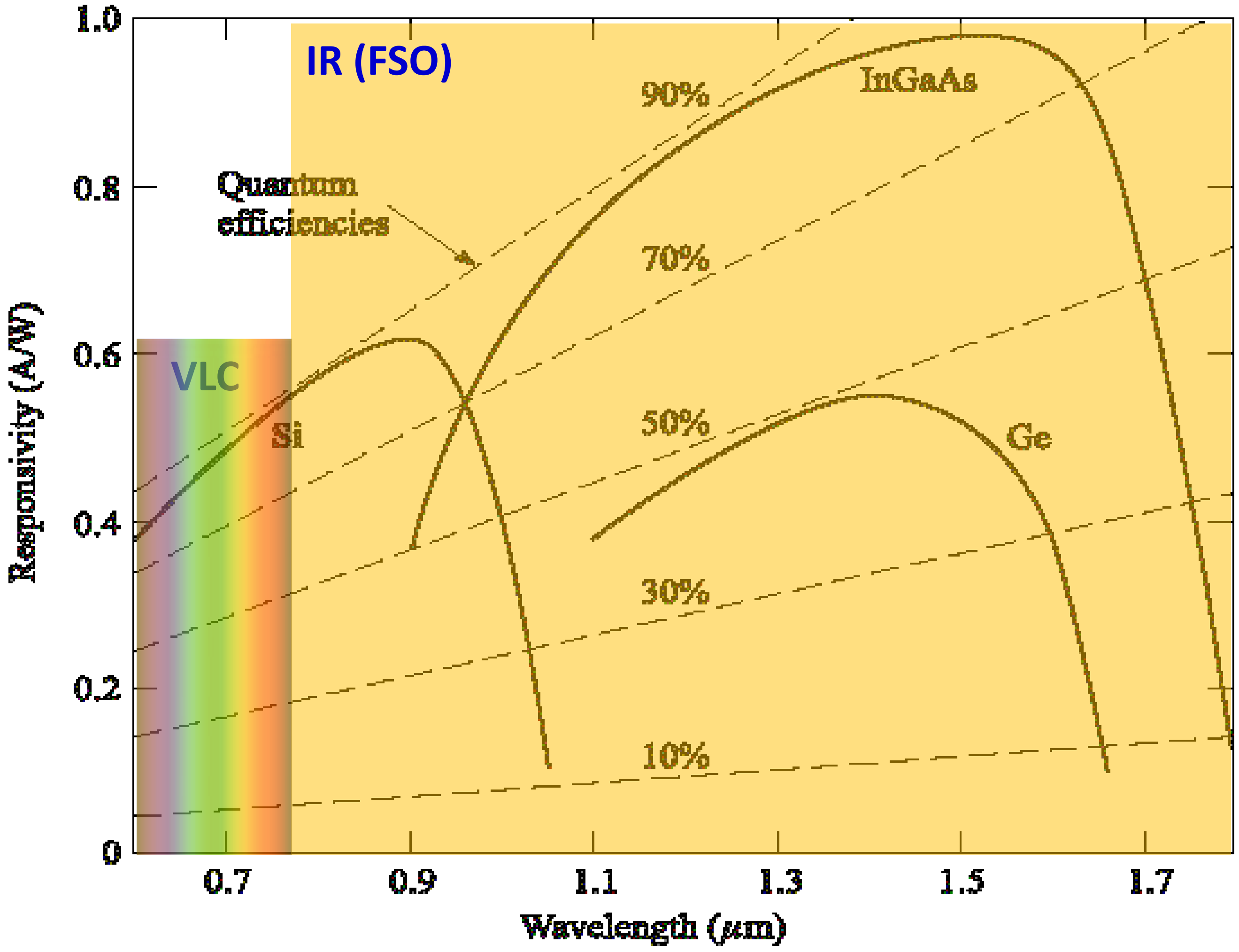
PD Responsivity – Measures how efficiently a PD converts light into electrical current

Responsivity for PIN PD $\mathcal{R} = \frac{I_p}{P_o} = \eta_q \frac{q}{hf} = \eta_q \frac{\lambda}{1.24}$ A/W

Responsivity for APD $\mathcal{R}_{APD} = G_{APD}\mathcal{R}$ A/W

Note: Current $I_p \propto P_o$

OWC - PDs - Responsivity



G Keiser , 2000

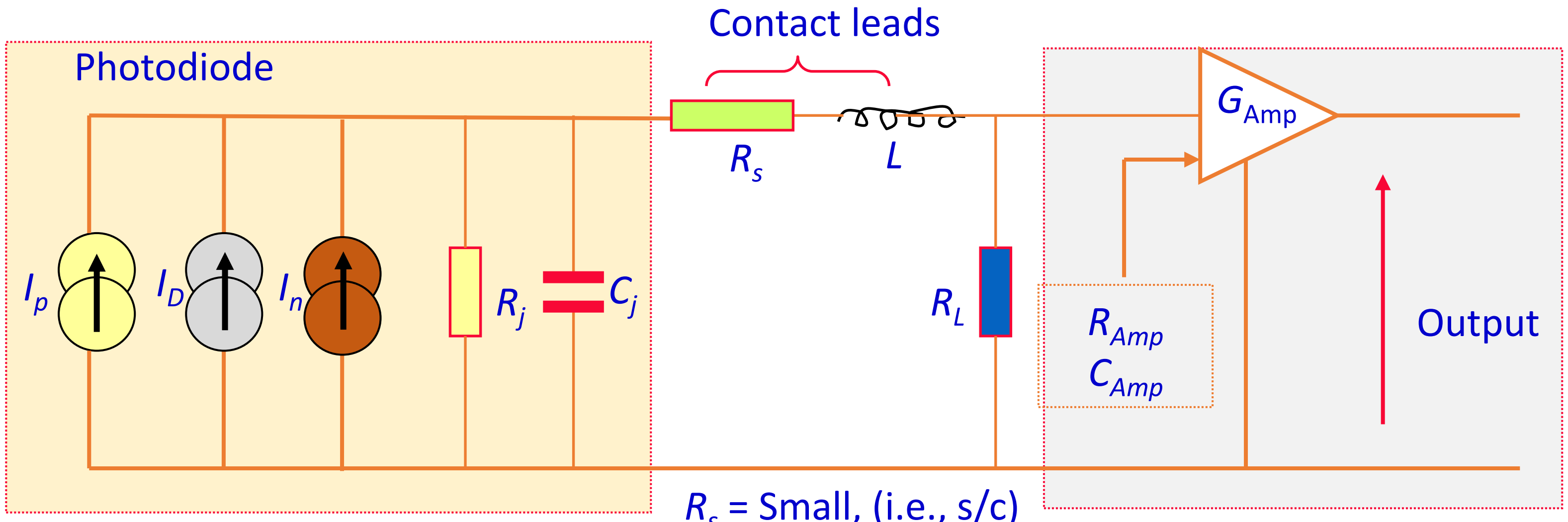
Key features				
Type	Peak ℜ mA/W	Bandwidth (GHz)	Dark current (nA)	Bias voltage (v)
Si	635 @900 nm	0.3-0.6	1-10	50-100 (APD)
Ge	500 @1400 nm	0.5-3	50-500	6-10
InGaAs	A broader response @ around 1550 nm	1-10	1-20	5-6

OWC - PDs – Equivalent Circuit

I_p: Photocurrent

I_D: Dark current

I_n: Photocurrent



R_s = Small, (i.e., s/c)

L = Large, (i.e., o/c)

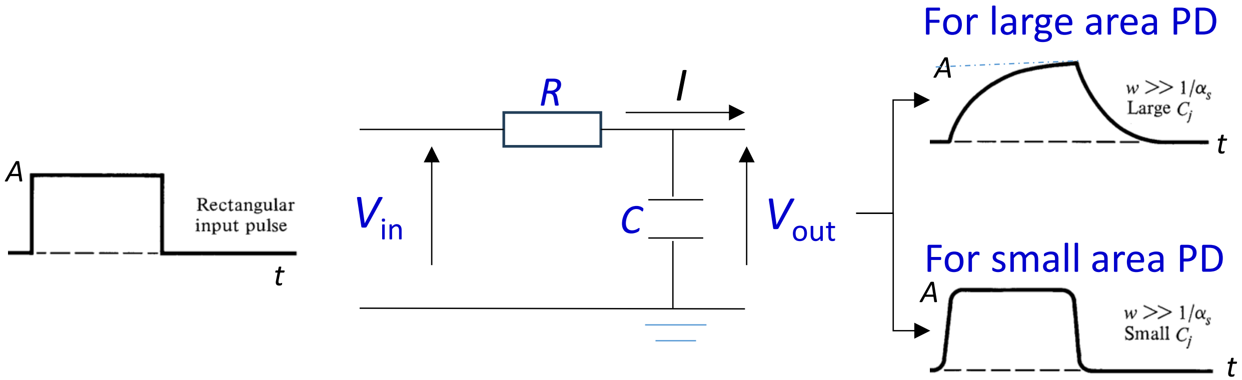
$R_T = R_j \,||\, R_L \,||\, R_{Amp}$

$C_T = C_j + C_{Amp}$

The transfer function $H(s) = \frac{X_c}{R + X_c} = \frac{1/C_T s}{R_T + 1/C_T s} = \frac{1}{1 + R_T C_T s}$

Where $s = j\omega = i2\pi f$

OWC - PDs – EC – Simplified RC Model



w = Depletion layer

α_s = Absorption coefficient

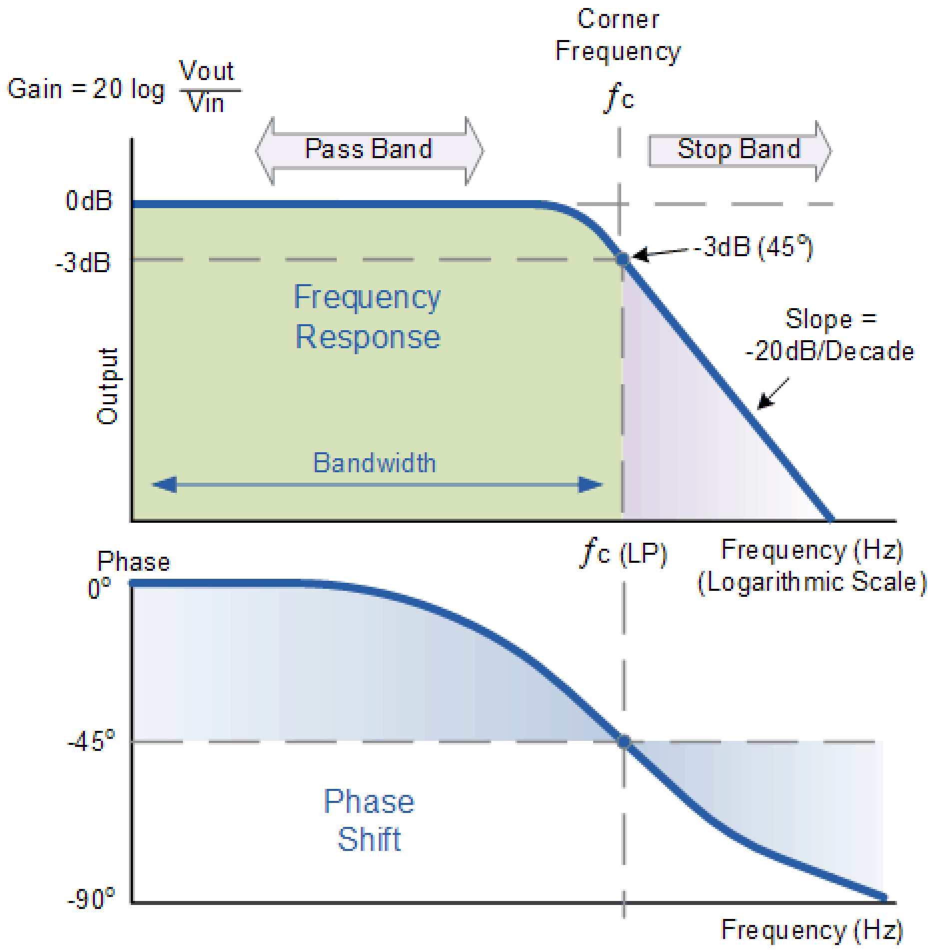
$$H(\omega) = \frac{1}{1 + j2\pi fRC}$$

$$f_{3dB} = B = \frac{1}{2\pi RC}$$

The phase $\emptyset = -\arctan(2\pi RC)$

The relation between the rise or fall time of the PD and 3-dB frequency is:

$$t_r = \frac{0.35}{B}$$



https://www.electronics-tutorials.ws/filter/filter_2.html

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OWC - Photodetectors

Types:

- PN/PIN (400-1700 nm)
- APD (800-1700 nm)
- SPAD / SiPM (100-1600 nm)
- IS - CMOS CCD
- Photo-voltaic
- Others

APD, SPAD / SiPM – With gain

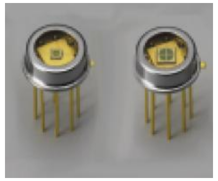
PN/PIN, APD, SPAD / SiPM – Solid-state Junction PDs

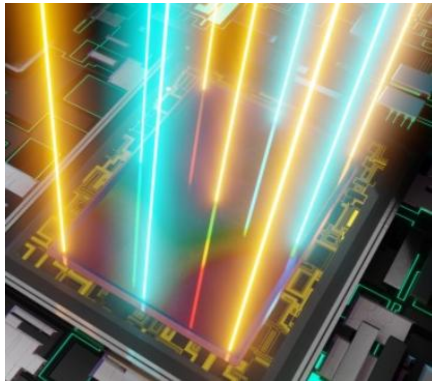
+ Organic PDs: Flexible, Low bandwidth, Ultra-thin

IS - CMOS CCD – Solid-state array PDs with high gain

Photo-voltaic – Solid-state PDs with very low bandwidth

All → For OWC





PM – Photomultiplier
CCD - Charge-coupled devices

SPAD – Single photon avalanche diode
CMOS - Complementary metal-oxide-semiconductor

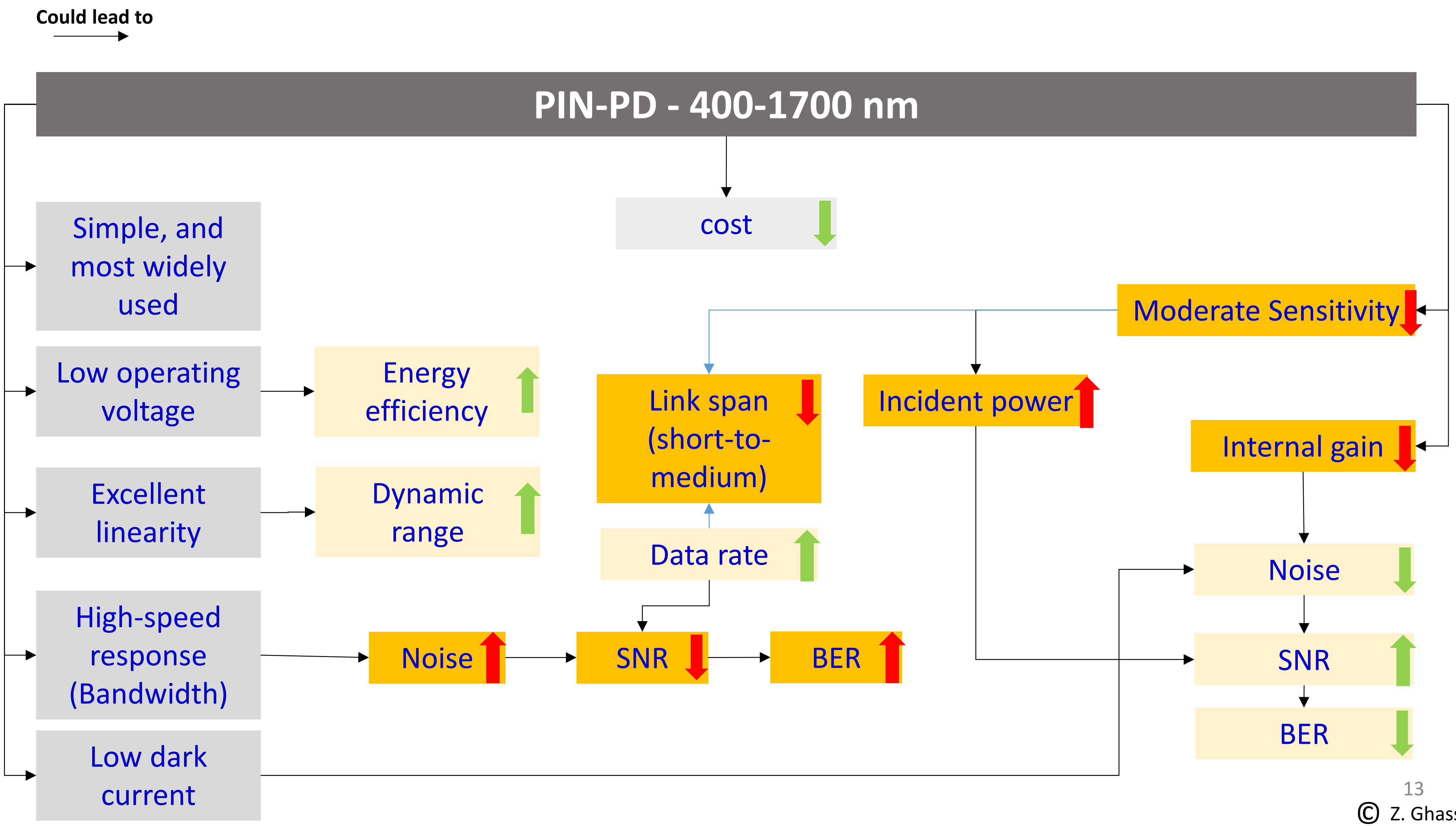
OWC - VLC – PD

Selection criteria

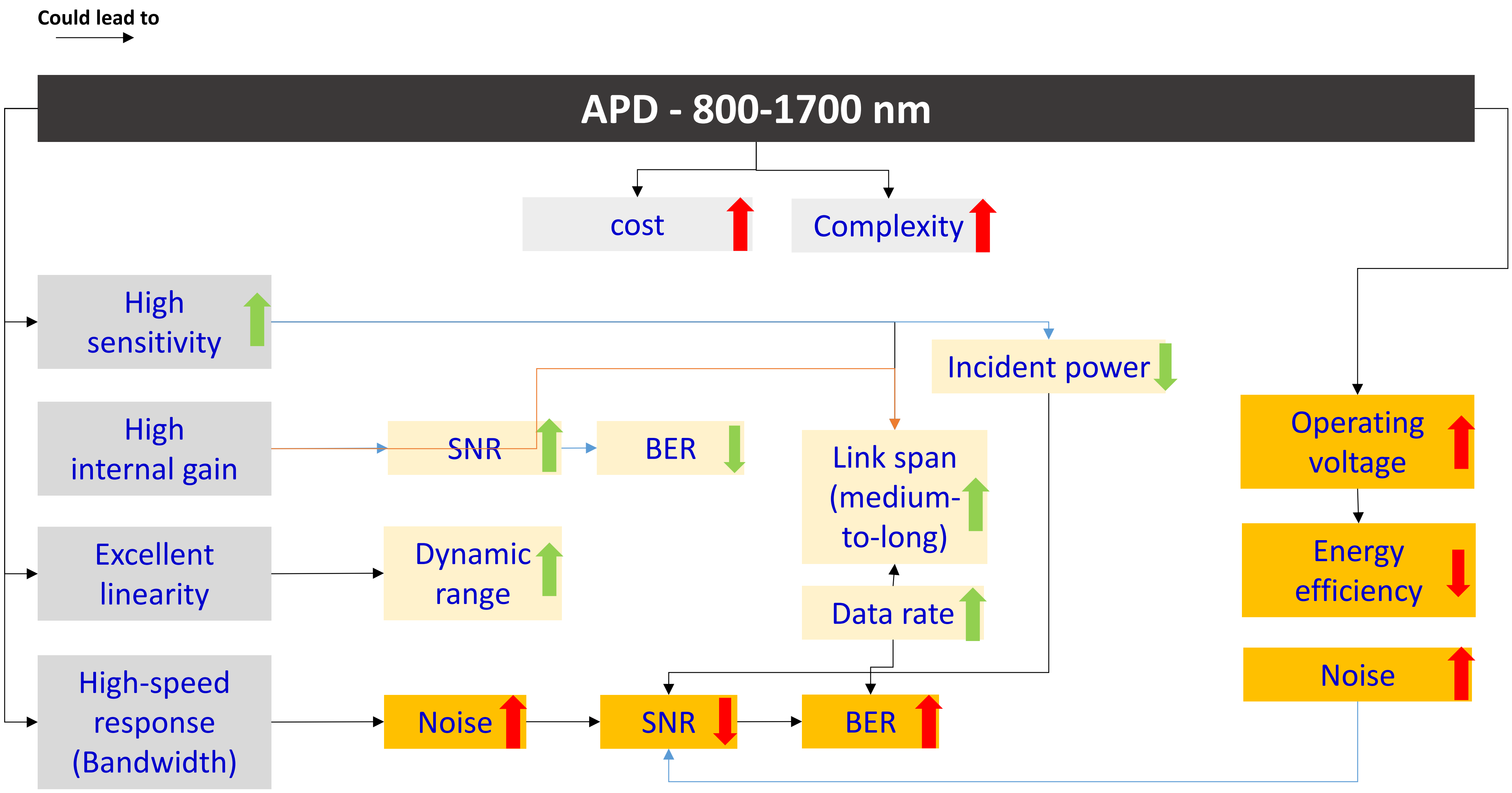
- Quantum efficiency
- Responsivity for a given BER and SNR
- Spectral response range
- Power consumption
- Bandwidth
- Gain
- Cost
- Dark current noise
- Integration
- Dynamic rang
- Complexity
- Reliability & stability

Different trade-offs for given applications.

OWC - VLC – PDs - Features



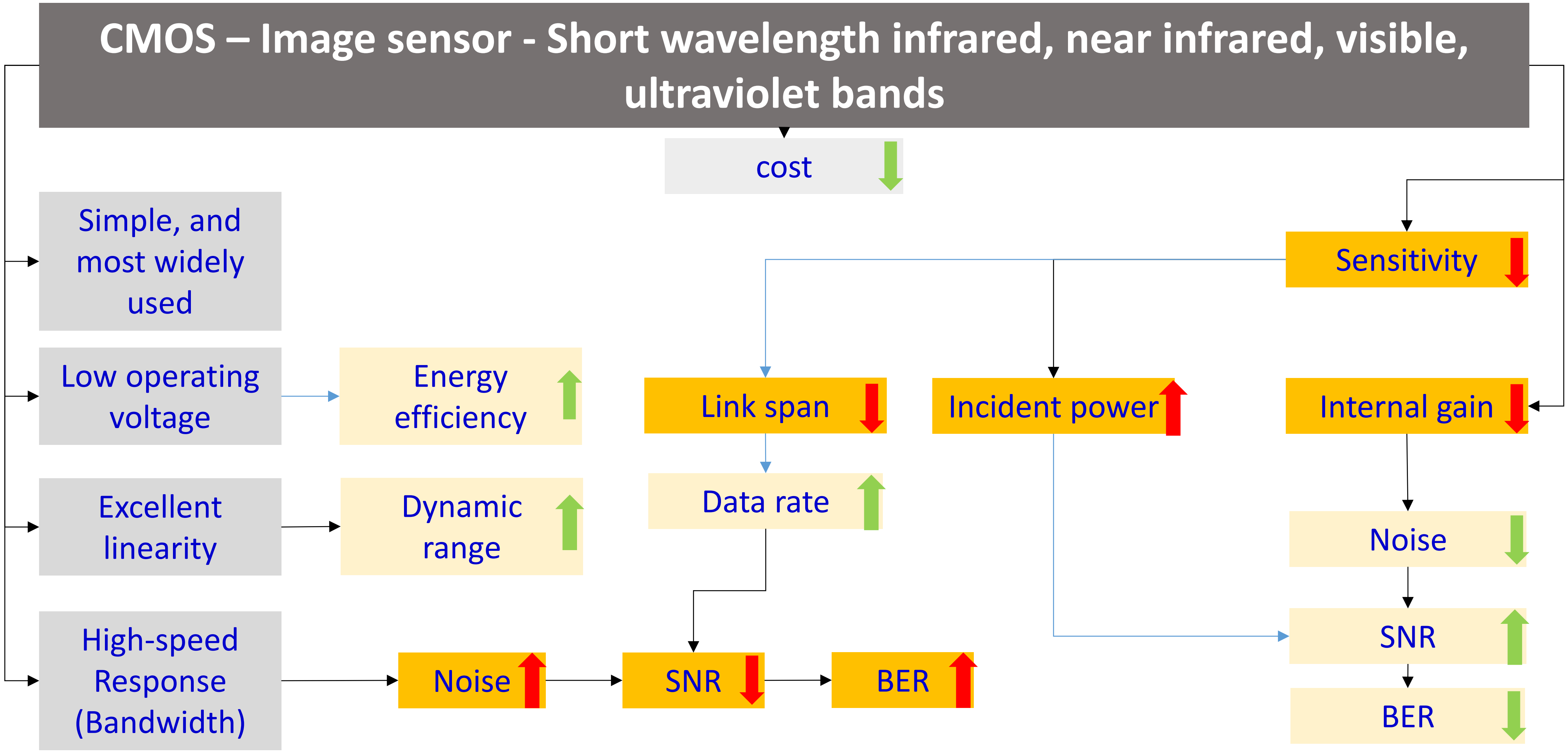
OWC - VLC – PDs



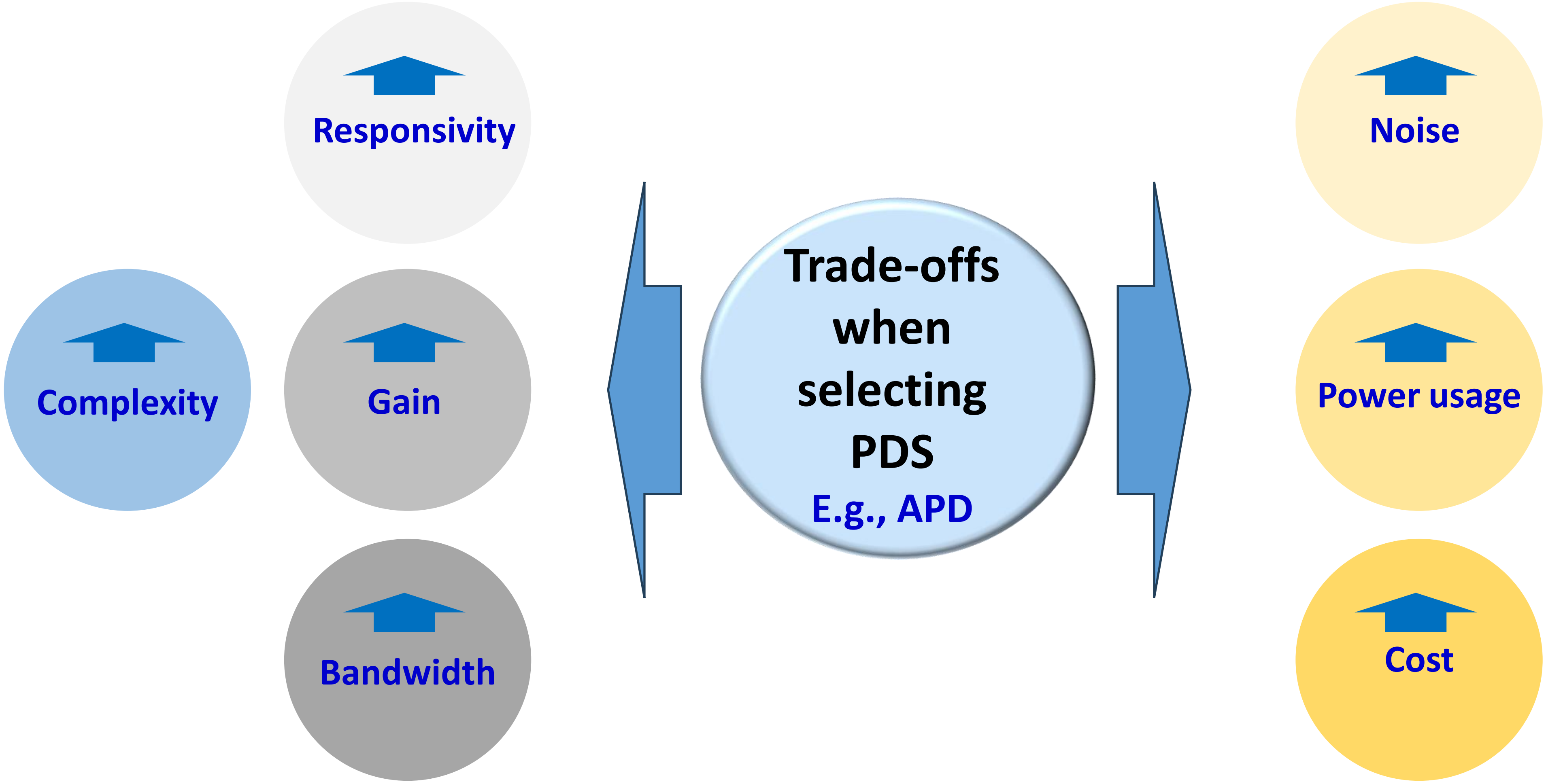
Could lead to
APD - 800-1700 nm
cost
Complexity
High sensitivity
Incident power
High internal gain
SNR
BER
Link span (medium-to-long)
Operating voltage
Excellent linearity
Dynamic range
Energy efficiency
Data rate
Noise
High-speed response (Bandwidth)
Noise
SNR
BER

OWC – VLC – PDs

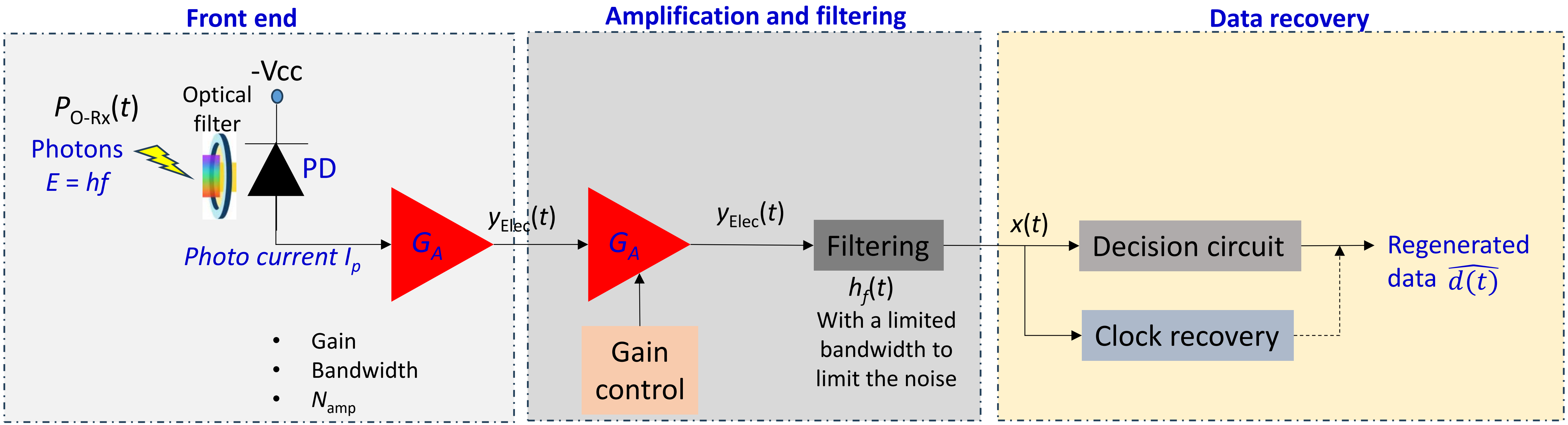
Could lead to →



OWC - VLC – PDs


Responsivity
Complexity
Gain
Bandwidth
Trade-offs when selecting PDS
E.g., APD
Noise
Power usage
Cost

OWC - Receiver



$P_{\text{O-Rx}}(t) = \sum_{n=-\infty}^{\infty} A_n \, p_{o-Rx}(t - nT_b)$

Pulse shape (p_{o-Rx}) — Bit duration (T_b)

Photocurrent for:

- PIN PD $\quad i_p(t) = \mathcal{R} \cdot P_{o-Rx}(t)$
- APD $\quad i_p(t) = \mathcal{R} \cdot G_{\text{APD}} \cdot P_{o-Rx}(t)$

The average optical power $P_{ave} = \dfrac{\text{SNR} \cdot i_n}{\mathcal{R}}$ (SNR: For a desired BER)

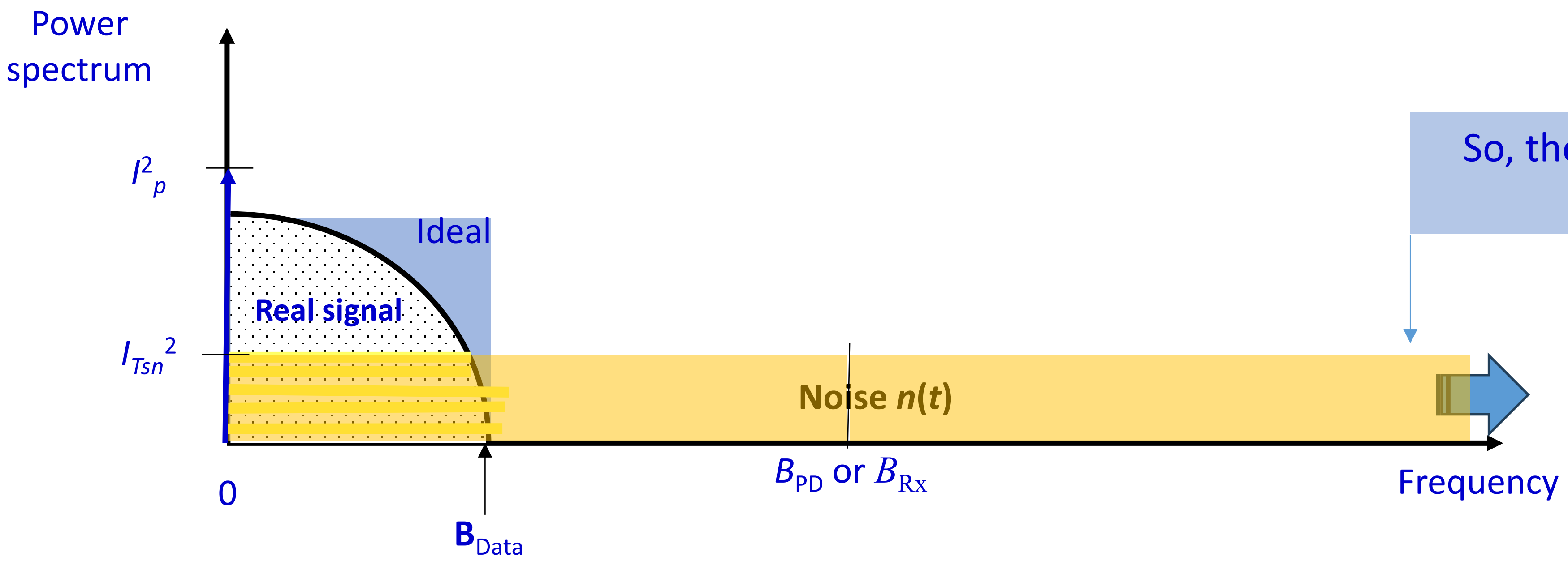
Photocurrent I_p = Average photocurrent (DC current) $I_{p\text{-DC}}$ + Signal current $i_{p\text{-AC}}(t)$

OWC – Rx - Noise

A random process:

- Not described in an explicit function of time. In the time domain is characterized in terms of Mean and Variance (standard deviation)
- Can also be characterized in terms of the Root Mean Square (RMS) value:

$$n_{rms} = \sqrt{\overline{n^2(t)}} \quad \Rightarrow \quad n_{rms} = \lim_{T\to\infty} \sqrt{\frac{1}{2T}\int_{T_1}^{T_2} |n(t)|^2 dt}$$



So, the use of **Power Spectral Density (W/Hz)**

OWC – Rx – Noise - Types

- **Quantum shot noise (QSN) – Signal dependent due to random arrival of photons → Random generation of electron-hole pairs per bit**

The mean square QSN $\overline{i_{sh}}^2 = 2qI_pB_{PD} \quad (A^2)$

- **Dark current shot noise** $\overline{i_{ds}}^2 = 2qI_dB_{PD} \quad (A^2)$

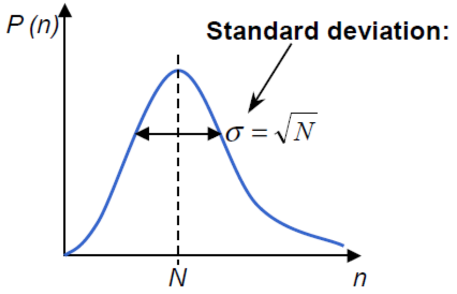
Total shot noise current
I_{Ts} = QSN + DCSN

$$\overline{i_{tsn-PIN}}^2 = 2q\left(I_p + I_d\right)B_{PD} \quad (A^2)$$

$$\overline{i_{tsn-APD}}^2 = 2q\left[\left(I_p + I_d\right)\right]G^2{}_{APD}FB_{PD} \quad (A^2)$$

Noise figure $F = G^x$ for $0 < x < 1$

$$N_{e-h} = \frac{\mathcal{R}}{hf}\int_0^{\tau} P(t) = \frac{\mathcal{R}P_o\tau}{hf}$$



Poisson distribution:
i.e., probability of n-photon in τ

- **Thermal noise** $\overline{i_{th}}^2 = \frac{4KTB_{PD}}{R_L}$

B may be treated as a post-detection bandwidth, amplifier or Rx bandwidth

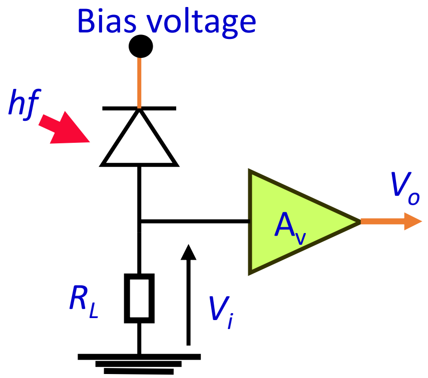
OWC – Rx – Noise - Types

- **Thermal noise** $\overline{i_{\mathrm{th}}^{\,2}} = \frac{4KTB_{\mathrm{PD}}}{R_L}$

For PIN PD - At lower optical power level, thermal noise the dominant.
For APD – The shot noise could be at the same level as the thermal noise due to the internal gain → improved SNR

- **Amplifier noise = Voltage noise + current noise**

$$\overline{i_{\mathrm{amp}}^{\,2}} = \overline{v_a^{\,2}} = 2\frac{qI_c}{g_m^{\,2}}B_{\mathrm{PD}} + \overline{i_a^{\,2}} = 2qI_bB_{\mathrm{PD}}$$



Total noise I_{nT}

$$\overline{i_{\mathrm{Total-PIN}}^{\,2}} = \overline{i_{\mathrm{tsn-PIN}}^{\,2}} + \overline{i_{\mathrm{th}}^{\,2}} + \overline{i_{\mathrm{amp}}^{\,2}}$$

$$\overline{i_{\mathrm{Total-APD}}^{\,2}} = \overline{i_{\mathrm{tsn-APD}}^{\,2}} + \overline{i_{\mathrm{th}}^{\,2}} + \overline{i_{\mathrm{amp}}^{\,2}}$$

When using a laser diode as a source, relative intensity noise should be added to the total noise.

OWC – Rx - Noise

Noise equivalent power of a PIN PD

$$A = \pi r^2 NEP = \frac{\left[2q\left(\bar{i_p} + \bar{i_d}\right) + 4kT/R_L\right]^{0.5}}{\mathcal{R}} B^{0.5}$$

Note:

$$\overline{i_n^2} \propto B$$

$$NEP \propto B^{0.5}$$

- For most PDs operating at λ < 3 µm, the dominated noise is the dark current or the thermal noise, or both.
  - The intrinsic NEP is defined by the dark current, assuming that R_L is sufficiently large.
- A high-speed PD has a small area, thus a small dark current, but requires a small R_L → a large thermal noise.
  - NEP is usually limited by the thermal noise.

Next series on Performance of Optical Receiver Part II.

Thank you!

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