Semiconductor Optoelectronic Devices

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Part III Photodetectors

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Lecture 22

- Photodetector basics

PD basics

- PD converts an optical signal into an electrical signal, typically a photocurrent i_L.
- The physical mechanism is the optical generation of electron-hole pairs through the absorption of incident photons.
- Photogenerated e-h pairs are then separated and collected to the external circuit by an electric field.
- This collecting field is induced by an external voltage bias in a reverse-biased junction (pn, pin, and Schottky detectors), or in bulk (photoconductor detector).
- In some cases, a third step after photogeneration and collection is that the photocurrent is amplified through external or built-in gain processes.

PD basics

- In absence of light, detectors still have an output current, which is the dark current i_d.
- The photocurrent is often linearly proportional to the input optical power as $i_L(t)=R*p_{in}(t)$, *where R is the detector responsivity 响应率 (A/W).*
- For large input optical power, the generated photocarriers ultimately screen the collecting electrical field, leading to current saturation.
- Because the absorption profile is wavelength dependent, so the responsivity is also wavelength dependent with a bandpass behavior.
- The optical bandwidth of most detectors is wide.

PD basics

- The relation $i_L(t)=R*p_{in}(t)$, holds only when the optical power varies slowly with time, with a modulation frequency lower than the device cutoff frequency.
- When the input power varies too rapidly with time, he output current does not follow its instantaneous value, because of low-pass or delay mechanisms, such as the effect of the device capacitance and the effect of the transit time that photocarriers experience before being collected.
- In the frequency domain, the responsivity R(w) is complex, relating the amplitude and phase of the small-signal photocurrent component at w. The responsivity is thus a low-pass function.

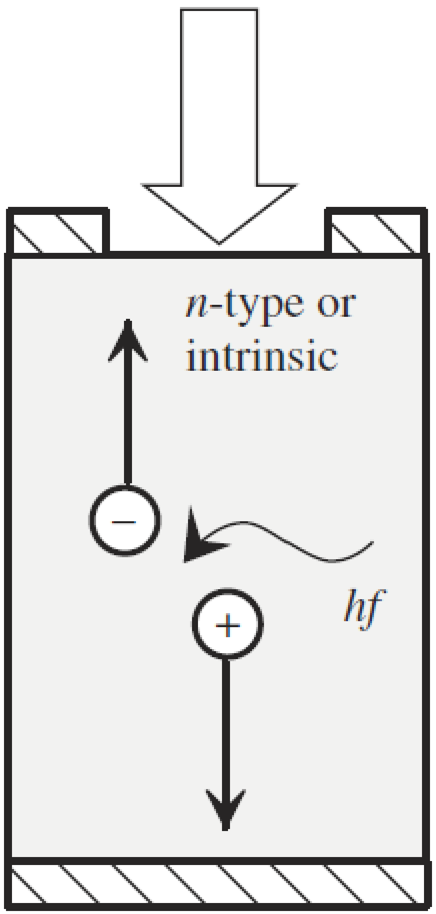
PD basics

- Besides the photocurrent and dark current, the PD also generates an output noise current, which is of shot noise type. In case the PD is composed with a front-end amplifier, whose noise is of thermal noise type. If the PD noise is dominate, the PD is operated in the shot noise limit; If the amplifier noise is dominate, the PD is operated in the thermal noise limit.

PD structures

- Photogenerated carriers are collected by an electric field, induced by an applied voltage in a bulk semiconductor or in a reverse-bias junction.
- Bulk type: photoresistors 光敏电阻 or photoconductors 光电导
- pn junction type: pn photodiode, pin photodiode, avalanche photodiodes (APD), phototransistors光电晶体管
- Metal-semiconductor junction type: Schottky barrier photodiode, metal-semiconductor-metal (MSM) photoiodes.
- Nonsemiconductor PDs: vacuum detectors and organic detectors.

Photoconductors

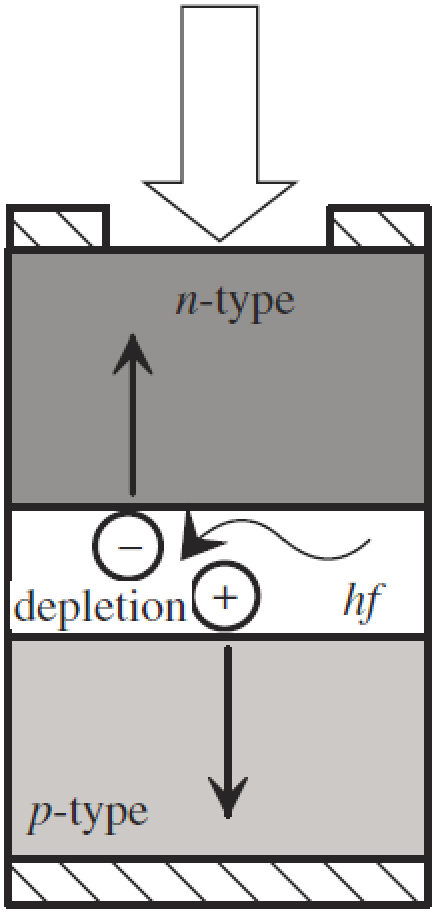


- Photoconductive effect: When light is absorbed by a semiconductor, the number of free electrons and holes increases, and raises its electrical conductivity.
- Photoconductor detectors uses the photoconductive effect, photocarrier generation takes place in a neutral or lightly doped bulk semiconductor, that is, in a resistive region. The photogenerated excess carrier density perturbs the conductivity, thus leading to current perturbation under constant bias voltage.

Photoconductors

- Carriers in photoconductors are removed to the external circuit by the almose uniform electric field induced by the voltage bias.
- Photoconductor PDs have high gain, but the bandwidth is limited by the photocarrier lifetime.
- The dark current is very high and thermal noise is typically large. Notice that the photoresistor is always working in the thermal noise limit.
- Photoconductors are simple, low-speed devices, not very well suited for high-performance telecom applications.

pn junction PDs



- In junction-based PDs, photocarriers are removed to the external curcuits by the junction reverse electric field, thus increasing the diode reverse saturation current.
- In pn photodiode, owing to the very small width of the depletion region, photons are also absorbed in the adjacent diffusion regions, leading to poor frequency response, limited by the transit time.
- The benefits of pn photodiode are the small dark current and the shot-noise limited noise.

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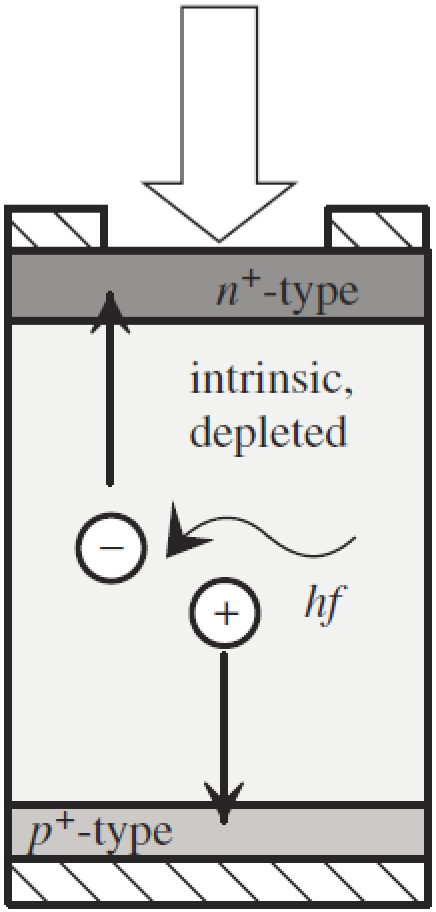
pin PDs

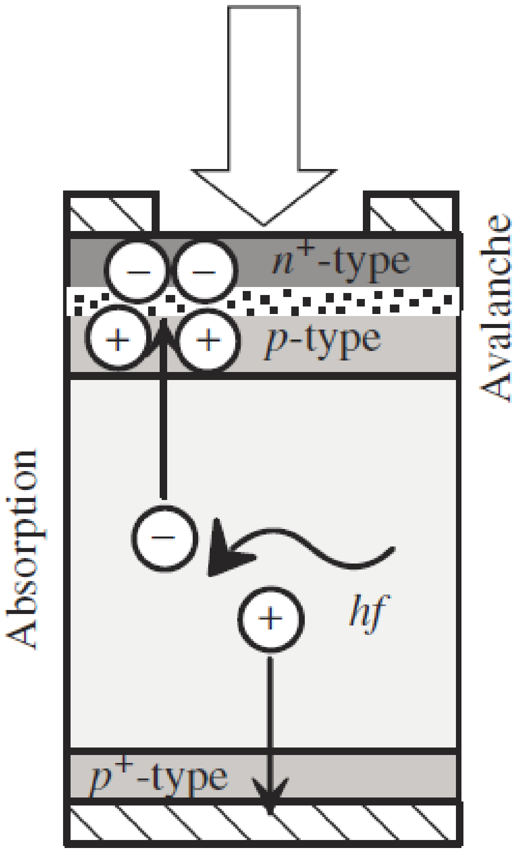


- The pn PD can be optimized by the pin structure, where the e-h generation occurs in a large intrinsic region sandwiched between high-doping layers. The width of the intrinsic layer can be made large enough with respect to the absorption length (inverse of absorption coefficient) to hinder the photocurrent from the diffusion region.
- In PiN heterostructure PDs, the photocarriers are only generated in the intrinsic region.

pin PDs

- In pin diodes, photocarriers are removed to external circuit by the almost uniform electric field induced in the intrinsic region by the applied reverse bias.
- The frequency response is limited by the transit time (and RC effects)
- Noise in pin PD is shot noise and the dark current is low.
- The pin photodiode is a high-performance device, and the achievable bandwidth is in excess of 40 GHz.
- Due to the unit gain, the sensitivity is not outstanding.

APDs

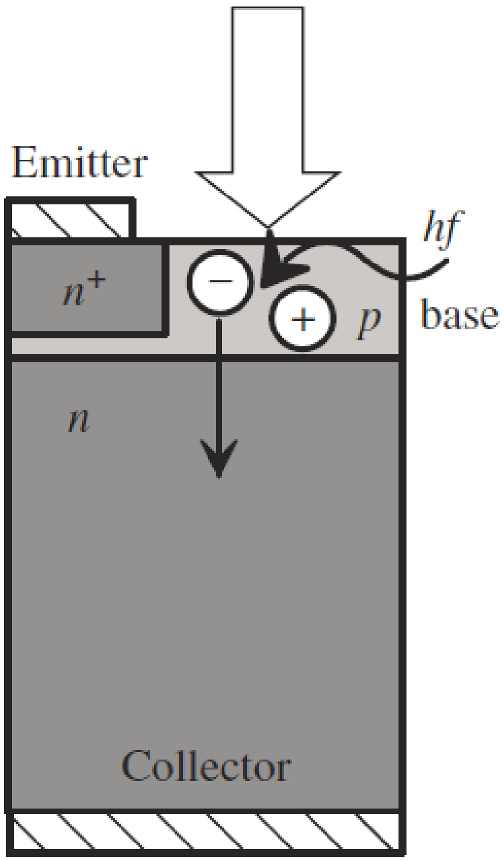


- In APDs, the structure is a *pin* diode to which an additional *pn* junction has been added with a highly doped *n* side. Photogenerated electrons in the intrinsic layer are removed to the high-field region associated with the *n*+ *p* junction depletion layer, and undergo avalanche multiplication.
- From the standpoint of responsivity, the APD can be interpreted as a *pin* device to which a photocarrier gain (multiplication) block has been added. The increase in responsivity is, however, obtained at the expense of increased noise (multiplied shot noise and excess noise) and a reduction of bandwidth (due to the additional delay introduced by the avalanche buildup).

APDs

- Despite the increase in noise, the larger responsivity typically leads, at least in a thermal noise-limited receiver, to a better (i.e., smaller) sensitivity. APDs were traditionally implemented in Si or Ge, but in recent years more advanced heterostructure devices based on InGaAs have appeared as competitors of *pin* photodiodes, at least up to 10 Gbps

Phototransistors

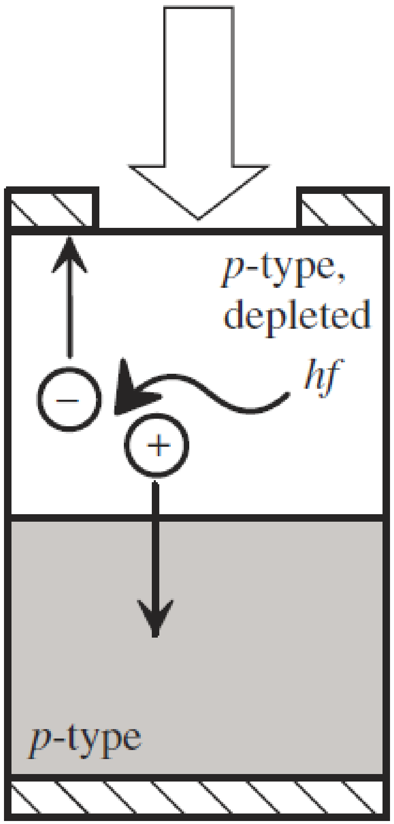


- In phototransistors, the electrons are generated by photons in the base-collector junction, and are injected into the base. This photocurrent is amplified by the emitter current gain beta.
- The output collector current is given by
  I_c=beta*R*P_{in}
  R=I_B/P_{in} is the responsivity related to the base current I_B.

Phototransistor

- The phototransistor has high gain, shot noise of the amplified collector current (but no excess noise as in APDs); the bandwidth used to be limited by the low cutoff frequency of conventional bipolar transistors but, at least in the laboratories, high-speed heterojunction phototransistors reach speeds in excess of 10 Gbps.

Schottky PDs



- Schottky or MSM detectors are based on Schottky (metal–semiconductor) junctions in reverse bias; the operation is somewhat similar to that of pn or pin diodes (although an additional photogeneration mechanism is introduced by carriers photo-excited from the metal into the semiconductor) and the device structure is simpler; however, illumination of the device area is an issue, due to metal absorption, thus requiring interdigitated electrode structures. Moreover, the frequency response is often affected by slow tails, which make the device less appealing for high-speed applications.

Photodetector material

- The photodetector relies on the photon absorption process, thus there is an absorption threshold for the minimum absorbed photon energy.

$$E_{ph} = \hbar\omega \geq E_g \quad \longrightarrow \quad \lambda\,[\mu\text{m}] \leq \frac{1.24}{E_g\,[\text{eV}]}.$$

- Direct bandgap (GaAs, InGaAs, InP) materials have higher absorption coefficients than indirect-bandgap (Si, Ge) materials. Therefore, the former has a smaller absorption volume and a higher speed.

PD material

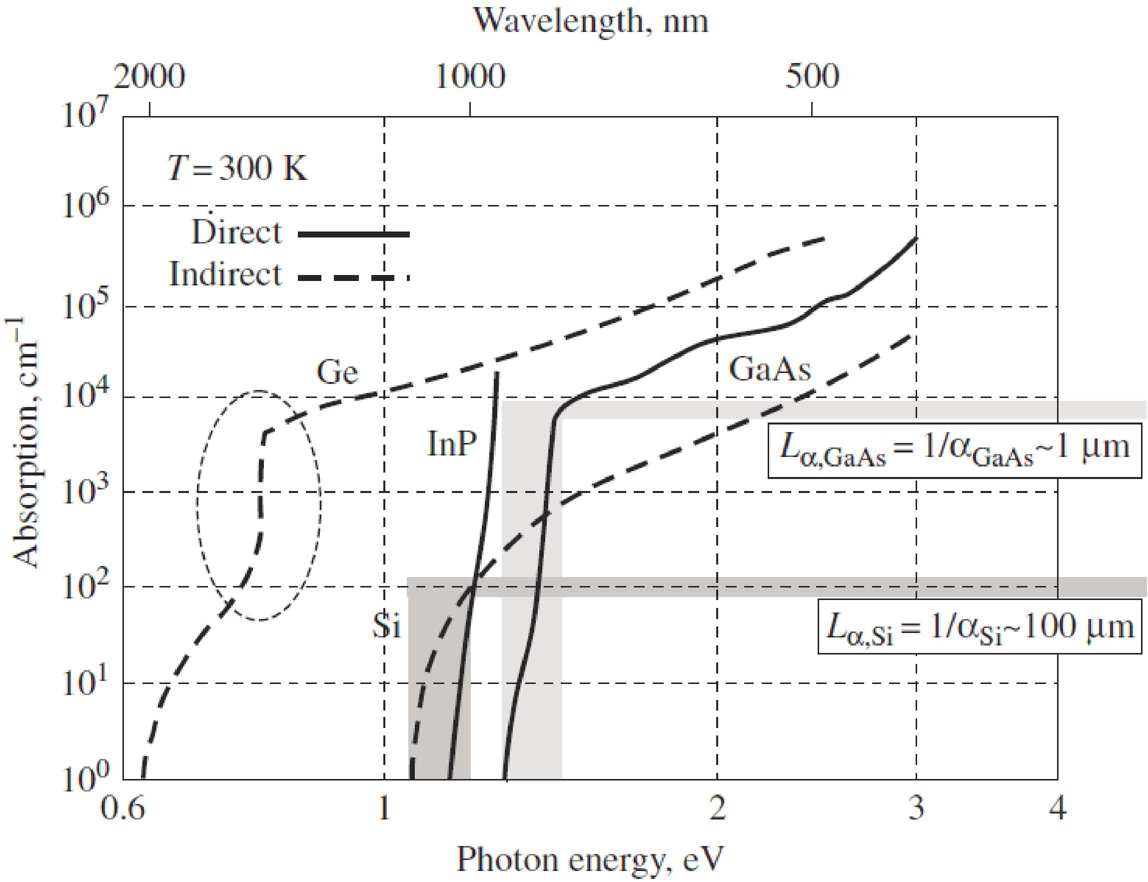
- The light experiences loss when passing through the PD material,

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

- The absorption length L_a is determined by the inverse of the absorption coefficient, when $x=L_a$, $Pin(L_a)=P_{in}(0)/e$. The thickness of the PD's active region must be suitably larger than the absorption length.
- The absorption length of indirect bandgap material is usually longer than that of direct bandgap material.

PD material

- A long absorption length means a high transit time, the delay within which photocarriers are collected, limiting the PD detection speed.



PD material

- In junction-based detectors, the depleted absorption region acts as a capacitor, and the capacitance C is inversely proportional to d, limits the detector speed, due to the RC cutoff.
- Therefore, increasing the absorption region width, the transit time-limited speed decreases, while the RC-limited speed increases, leading to the need for a design trade-off.
- The transit time-limited bandwidth is

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

- The RC-limited bandwidth is given by

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

Example 4.1

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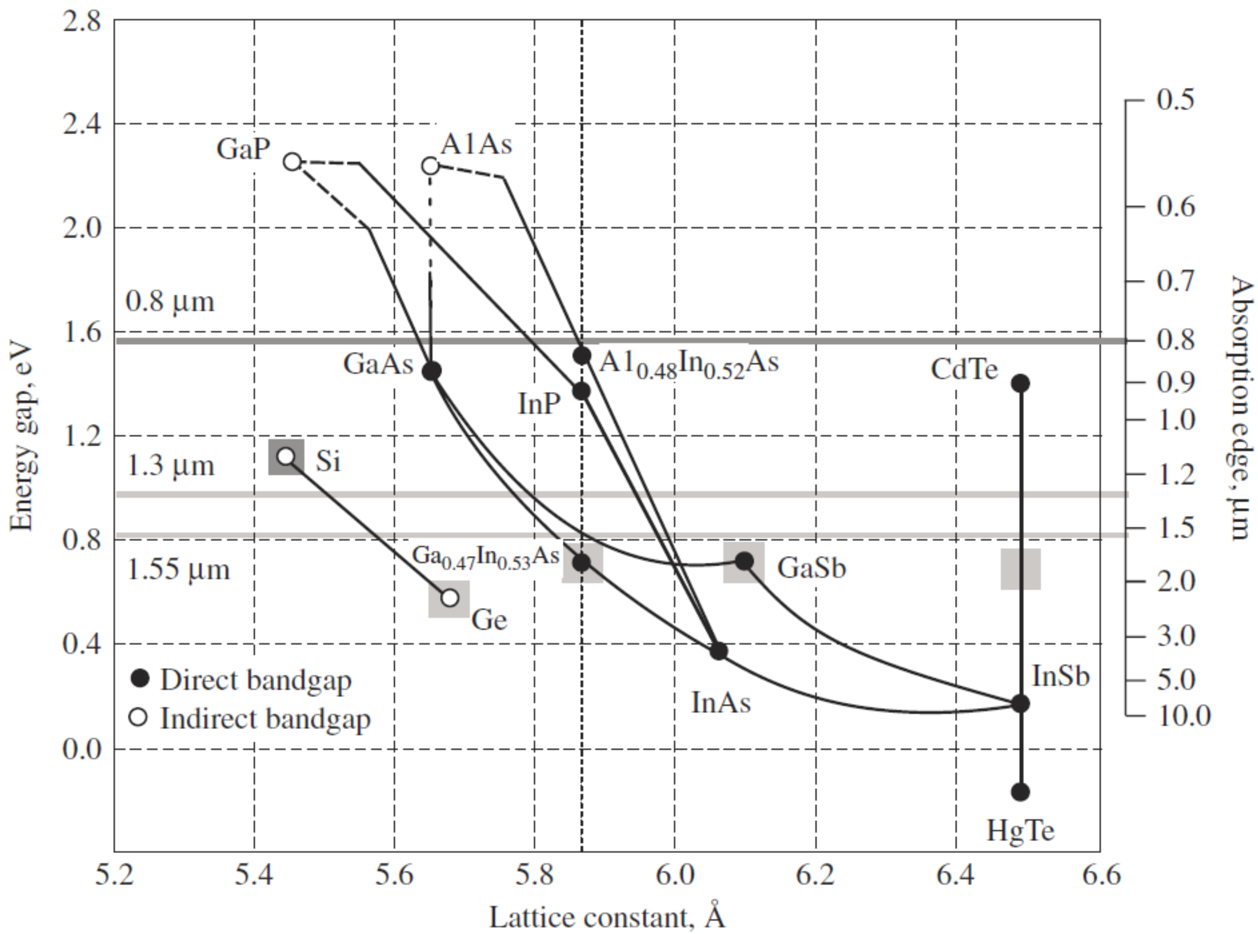
PD material

- In principle, PDs have a wide optical bandwidth, but is limited by the behavior of the responsivity versus the photon energy. Such behavior suggests that the photon energy should be suitably larger than the receiver gap, but not too large.
- For detection of 0.8 um photons, PD materials include Si, Ge, GaAs- and InP-based alloys.
- For detection of 1.3 and 1.55 um photons, PD materials include Ge, InGaAs, InGaAsP, InGaAsSb, and CdHgTe. Because Sb- and CdHgTe are not mature engouth, so Ge and InGaAs are usually used.
- Note that Si can not be used for 1.3 and 1.55 um photon detection.

PD material



Detector and source materials.

PD material

- For 1.3 and 1.55 um detection, InGaAs is more popular than Ge, owing to its higher performance of direct bandgap. It can be lattice matched to InP substrate with a fixed bandgap.

  ----In contrast, InGaAsP can be matched to InP substrate with a tunable bandgap, but InGaAs is favorable for PDs owing to the low cost.

- For 0.8 um detection, AlGaAs/GaAs is popular, owing to its maturity, low cost, direct bandgap (<45% Al), and lattice match to GaAs substrate. But it is not suitable for APDs.

  ----Si is suitable for APDs, due to the very different hole and electron avalanche ionization coefficients. However, the low absorption coefficient confines Si to low-speed applications.

PD materials

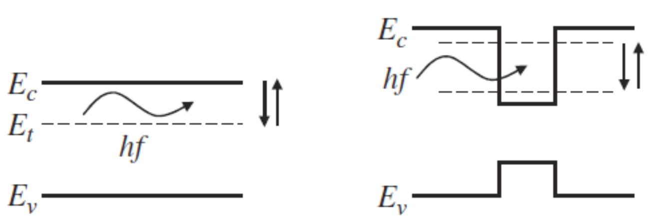
- For Si, the indirect bandgap is 1.12 eV (1.1 um);
- For Ge, the indirect bandgap is 0.66 eV (1.87 um), the direct bandgap is 0.8 eV (1.55 um).
- Ge is mature enough and the avalanche coefficients of electrons and holes are quite different (so that good quality, low noise avalanche detectors can be developed). Emerging SiGe technologies have given this material interesting perspectives for integration on a Si substrate;

PD materials

HgCdTe 碲镉汞 (mercury cadmium telluride, also called MCT) is a ternary alloy whose components are a semiconductor (CdTe) and a compound with metal bandstructure (HgTe). Assuming that a metal has negative energy gap (i.e., the valence band edge is above the conduction band edge, and the two bands overlap), the MCT gap can be tuned down to almost zero, making this material a suitable alloy for FIR detection. The substrate of choice is CdTe. Despite the complex technology, this material still is very popular for FIR detectors (much less for long-wavelength communication detectors), although the small gap and resulting large intrinsic population require low-temperature operation.

Extrinsic and QW detectors

- The bandgap limited PDs are intrinsic detectors.
- In case the trap levels are used for absorptions in PDs, this is called extrinsic detectors, which is of low responsivity.
- Intersubband absorptions in Qwells can be exploited for FIR detection, which has a larger bandgap than MCT detectors, and thus relax the constraints on low-temperature operation related to the need to lower the intrinsic carrier concentration and to suppression background noise.



Extrinsic absorption in bulk, involving a trap level (left), and in a quantum well (right), as an intersubband transition.

❑ Photodetector parameters

--- Photocurrent

--- Responsivity

--- Bandwidth

--- Gain

--- Noise

PD current

- The PD current is a function of input optical power, wavelength, and the PD voltage.

$$i_{PD}(t) = f\left(p_{in}(t), v_{PD}(t); \frac{\mathrm{d}}{\mathrm{d}t}, \lambda\right)$$

The derivative implies that the relation is memorable.

- The PD current is given by the sum of the photocurrent and the dark current.

$$i_{PD} = i_L + i_d,$$

$$i_d = f\left(0, v_{PD}(t); \frac{\mathrm{d}}{\mathrm{d}t}, \lambda\right)$$

$$i_L = f\left(p_{in}(t), v_{PD}(t); \frac{\mathrm{d}}{\mathrm{d}t}, \lambda\right) - i_d$$

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PD current

- In DC or static condition,

$$I_{PD} = f\,(P_{in}, V_{PD}; 0, \lambda) = I_L + I_d$$

where $I_d = f\,(0, V_{PD}; 0, \lambda)$ is the DC dark current, $I_L = f\,(P_{in}, V_{PD}; 0, \lambda) - I_d$ is the DC photocurrent.

- In general, the relation between the PD current and the optical power is nonlinear, but memorable or dispersive, which leads to the low-pass behavior. However, for slowly varying $p_{in}(t)$, the relation becomes memoriless,

$$i_{PD}(t) = i_L + i_d \approx \Re(\lambda, v_{PD})\,p_{in}(t) + i_d(v_{PD})$$

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PD current

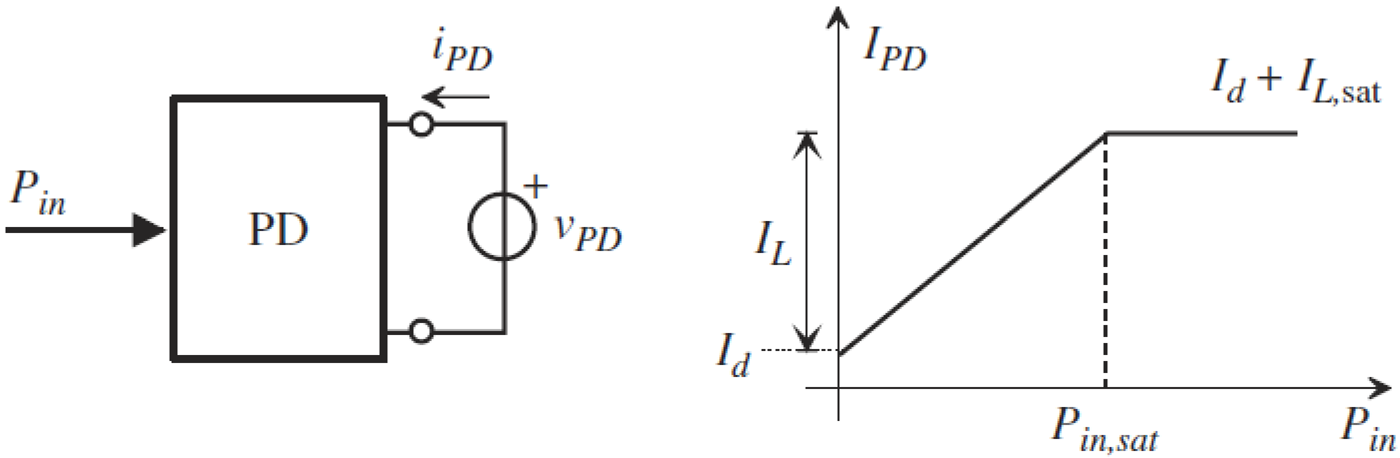
- The responsivity R is in general a function of the wavelength and the voltage (like APD). However, in reverse-biased pn or pin PDs, both the dark current and the responsivity are virtually independent of the PD voltage, while the dark current is small, therefore

$$i_{PD}(t) = \Re(\lambda) p_{in}(t) + I_d \approx \Re(\lambda) p_{in}(t)$$

- The linear dependence of PD current on the input optical power holds before the saturation optical power, which produces a saturation photocurrent.

PD current

- The saturation is due to the intrinsic space-charge screening the electrical field collecting the photocarriers, and also to the circuit loading conditions.



Responsivity

- The photocurrent I_L can be derived from the optical generation rate G_0

$$I_L = q \int_V G_o(\underline{r}, P_{in})\, \mathrm{d}\underline{r}$$

- The device responsivity is defined as

$$\Re = \frac{I_L}{P_{in}} \quad \text{or} \quad \Re_{\text{diff}} = \frac{\mathrm{d}I_L}{\mathrm{d}P_{in}}$$

The first is named incremental responsivity, and the second is the differential responsivity. Both are the same if the current-power relation is linear.

Responsivity

- The optical generation rate can be obtained from the power density change,

$$\frac{\mathrm{d}\widetilde{P}_{in}(x)}{\mathrm{d}x} = -\alpha\widetilde{P}_{in}(x) \rightarrow \frac{\text{Energy lost due to absorption}}{t \cdot V} = -\frac{\Delta\widetilde{P}_{in}}{\Delta x} = \alpha\widetilde{P}_{in}$$

- The optical generation rate is derived by

$$\frac{(\text{Energy lost}) \,/\, (t \cdot V)}{\text{Photon energy } \hbar\omega} = \frac{\alpha\widetilde{P}_{in}}{\hbar\omega} = \frac{\text{Number of photons absorbed}}{t \cdot V}$$
$$= \frac{\text{Number of e-h pairs generated}}{t \cdot V} = G_o.$$

- Finally, the optical generation rate is given by

$$G_o = \frac{\alpha\widetilde{P}_{in}}{\hbar\omega}$$

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Responsivity

- That is, the optical generation rate is given by the absorption coefficient multiplied by the photon flux.
- Therefore, the optical generation rate is dependent on the distance,

$$G_o(x) = \frac{\alpha \widetilde{P}_{in}(x)}{\hbar\omega} = \frac{\alpha \widetilde{P}_{in}(0)}{\hbar\omega} \exp(-x/L_\alpha) = G_o(0) \exp(-x/L_\alpha)$$

- Assume all the photons are absorbed, and all the generated e-h pairs are collected to the external circuit, we have

$$\frac{\text{Number of electrons in the external circuit}}{t} = \frac{I_L}{q}$$
$$= V \cdot \frac{\text{Number of e-h pairs generated}}{t \cdot V} = \frac{\text{Number of photons absorbed}}{t \cdot V}$$
$$= A \int_0^\infty G_o(x)\,\mathrm{d}x = A \int_0^\infty \frac{\alpha \widetilde{P}_{in}(x)}{\hbar\omega}\,\mathrm{d}x = -\frac{A}{\hbar\omega} \int_0^\infty \frac{\mathrm{d}\widetilde{P}_{in}(x)}{\mathrm{d}x}\,\mathrm{d}x \approx \frac{P_{in}(0)}{\hbar\omega}$$

Responsivity

- Then, we obtain the photocurrent relation with the incident light power,

$$\frac{I_L}{q} = \frac{P_{in}(0)}{\hbar\omega}$$

- So the ideal responsivity

$$I_L = \frac{q}{\hbar\omega} P_{in}(0) = \Re P_{in}(0)$$

$$\Re = \frac{q}{\hbar\omega} = \frac{q}{E_{ph}}$$

- The responsivity has maximum for photons at the bandgap,

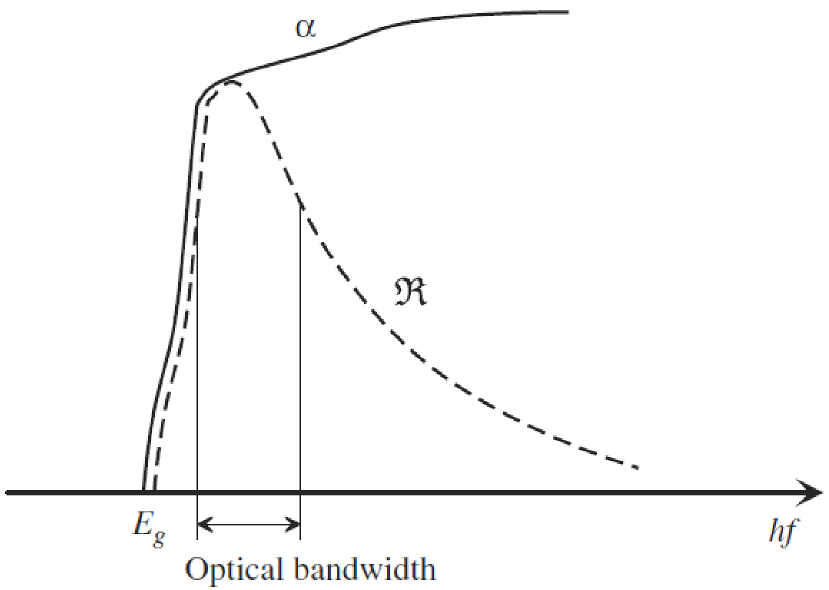
$$\Re_{\max} \approx \frac{q}{E_g} = \frac{1}{E_g\,[\mathrm{eV}]} \approx \frac{\lambda[\mu\mathrm{m}]}{1.24}$$

Responsivity

- For photon energies larger than the bandgap, the responsivity ideally decreases with increasing photon energy,

$$\Re(E_{ph}) \approx \Re_{\max}\frac{E_g}{E_{ph}}$$

- For energies close to the threshold, the responsivity approximately follows the shape of the absorption coefficient, but for higher energies, it deceases with the inverse of photon energy.



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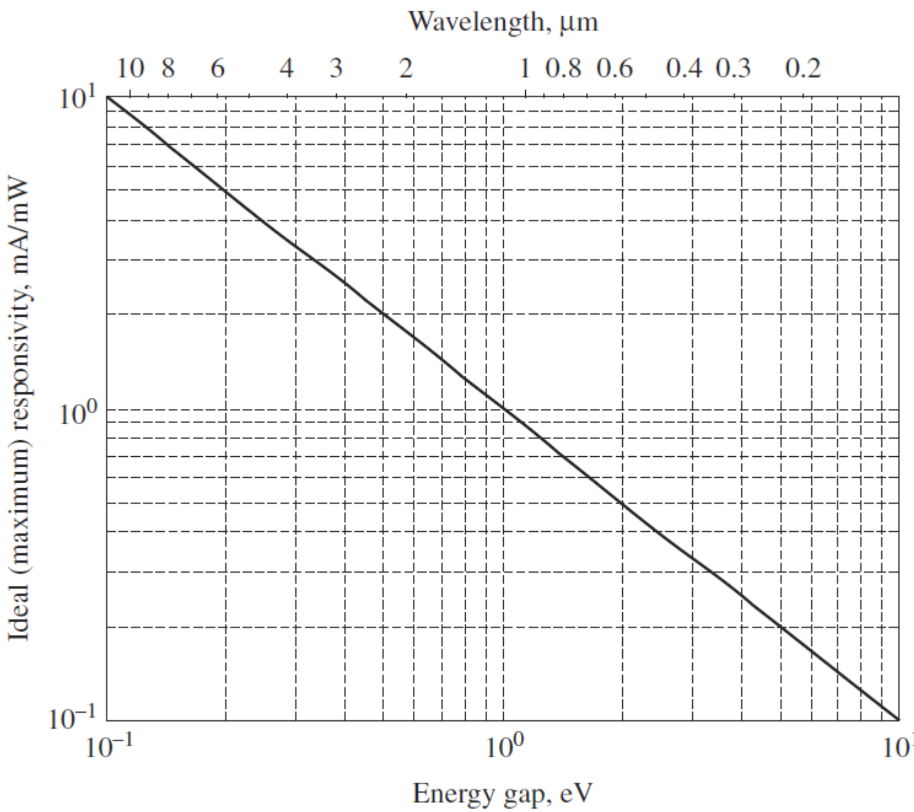
Responsivity

- The maximum responsivity increases with decreasing bandgap, so for long-wavelength infrared detectors, the maximum responsivity has an order of magnitude of 1 A/W. Responsivities larger than 1A/W can be achieved with internal gain.



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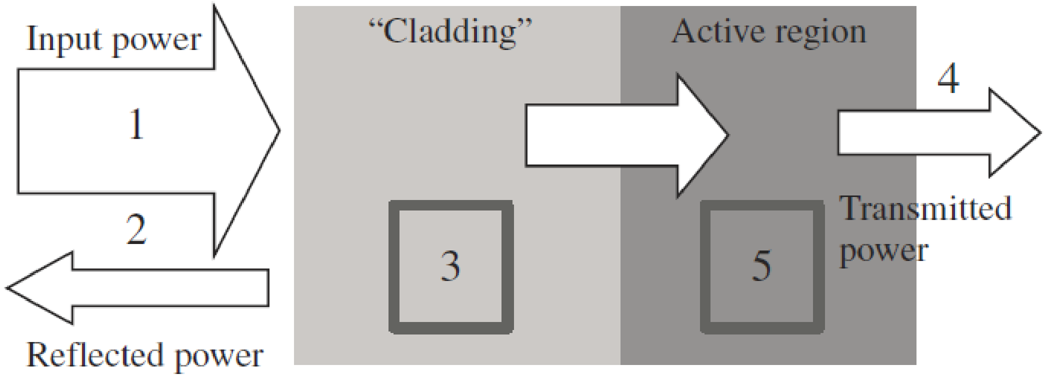
Responsivity

- In real devices, the number of electrons flowing in the external circuit can be substantially lower than the number of incident photons.



1. The optical power $P_{in}(0)$ is incident on the photodetector.
2. Part of the power is reflected at the PD interface due to dielectric mismatch.
3. Part of the power is absorbed in regions of where it does not contribute to useful output current.
4. Part of the power is transmitted through the PD without being absorbed.
5. Finally, part of the power is absorbed and yields a useful current component.

Responsivity

- Another detector figure of merit is the quantum efficiency.
- The internal quantum efficiency is defined as

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

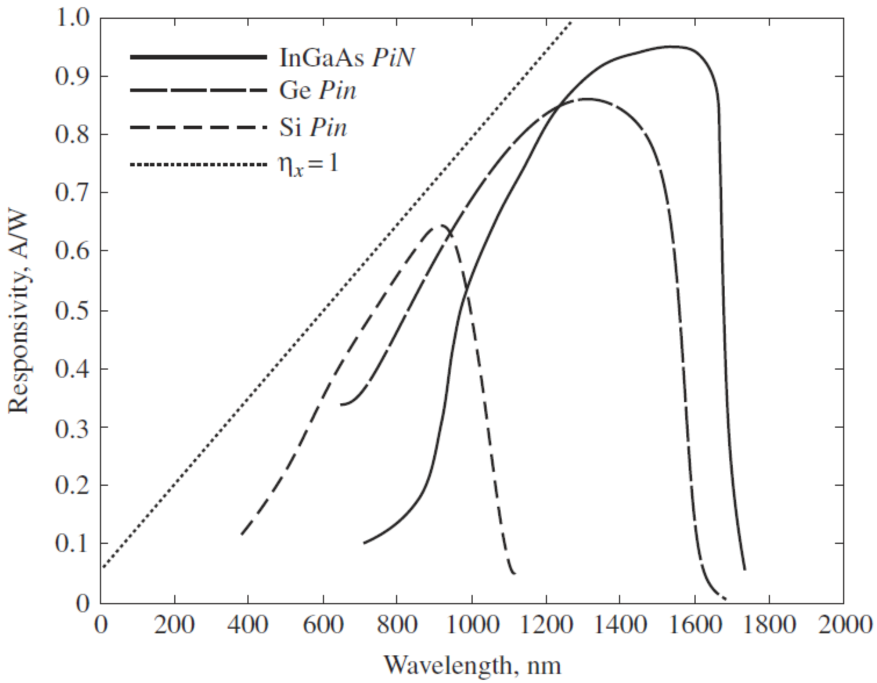
which is almost unit.

- The external quantum efficiency is directly related to the responsivity,

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

Responsivity

- The real responsivity shows an abrupt increase corresponding to the absorption edge, and hen decreases with increasing energy.
- The optical bandwidth is well in excess of 200 nm.



- For InGaAs PiN PDs, the abrupt fall at short wavelength is due to the absorption in the cladding layers.

Electrical bandwidth

- The PD current induced by modulated optical is given by

$$i_{PD}(t) = f\left(p_{in}(t), v_{PD}(t), \frac{\mathrm{d}}{\mathrm{d}t}\right)$$

$$P_{in} = P_{in,0} + \hat{p}_{in}(t), \quad V_{PD} = V_{PD,0} + \hat{v}_{PD}(t), \quad I_{PD} = I_{PD,0} + \hat{\imath}_{PD}(t)$$

$$\hat{p}_{in}(t) = \mathrm{Re}\left(\hat{P}_{in}\mathrm{e}^{\mathrm{j}\omega t}\right), \ \hat{v}_{PD}(t) = \mathrm{Re}\left(\hat{V}_{PD}\mathrm{e}^{\mathrm{j}\omega t}\right), \ \hat{\imath}_{PD}(t) = \mathrm{Re}\left(\hat{I}_{PD}\mathrm{e}^{\mathrm{j}\omega_m t}\right)$$

$$I_{PD,0} + \hat{\imath}_{PD}(t) = \underbrace{f\left(P_{in,0}, V_{PD,0}, 0\right)}_{I_{PD,0}} + \left.\frac{\partial f(\mathrm{d}/\mathrm{d}t)}{\partial p_{in}}\right|_0 \hat{p}_{in}(t) + \left.\frac{\partial f(\mathrm{d}/\mathrm{d}t)}{\partial v_{PD}}\right|_0 \hat{v}_{PD}(t)$$

The first term is DC current, the second is small-signal photocurrent, and the third is the small-signal dark current.

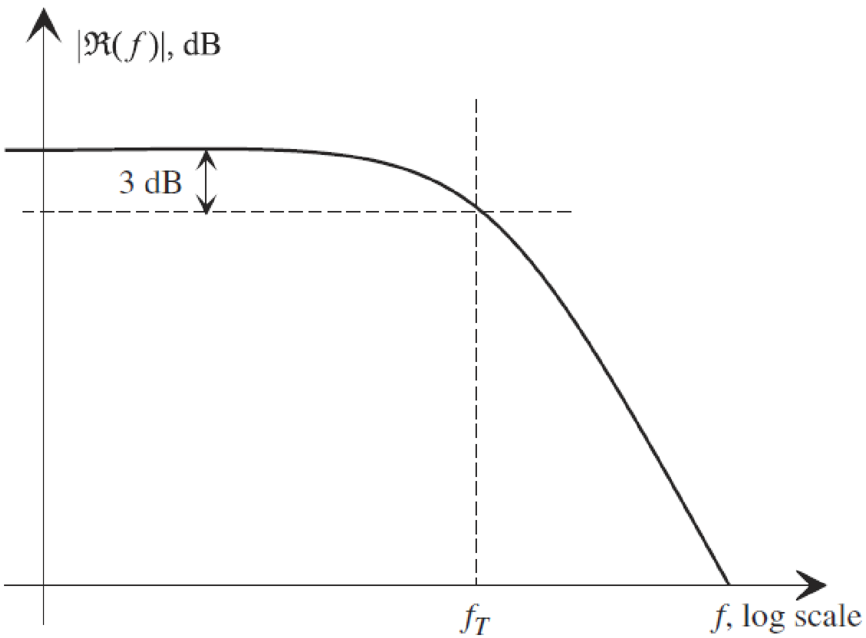
Electrical bandwidth

- The AC part of the PD current is given by

$$\hat{\imath}_{PD}(t) = \hat{\imath}_L(t) + \hat{\imath}_d(t) = \mathrm{Re}\left(\mathfrak{R}(\omega)\hat{P}_{in}e^{j\omega t}\right) + \mathrm{Re}\left(Y_{PD}(\omega)\hat{V}_{PD}e^{j\omega t}\right)$$

R(w) is the small-signal responsivity, Y(W) is the small-signal admittance.

- The complex responsivity describes the detector small-signal frequency response, which is a low-pass function of the modulation frequency.



Electrical bandwidth

- A normalized responsivity is defined as

$$\frac{\hat{I}_L(\omega)}{\hat{I}_L(0)} = \frac{\Re(\omega)}{\Re(0)} \frac{\hat{P}_{in}(\omega)}{\hat{P}_{in}(0)} = \mathfrak{r}(\omega) \frac{\hat{P}_{in}(\omega)}{\hat{P}_{in}(0)}.$$

Assuming constant $\hat{P}_{in}(\omega)$ we have

$$\mathfrak{r}(\omega) = \frac{\hat{I}_L(\omega)}{\hat{I}_L(0)} = \frac{\Re(\omega)}{\Re(0)} \rightarrow |\mathfrak{r}(\omega)|_{\mathrm{dB}} = 20 \log_{10} \left| \frac{\Re(\omega)}{\Re(0)} \right|.$$

- The 3-dB bandwidth is the frequency at which the normalized responsivity drops by 3 dB with respect to the DC value.

$$|\mathfrak{r}(\omega_{3\mathrm{dB}})|_{\mathrm{dB}} = -3 \rightarrow 20 \log_{10} \left| \frac{\Re(\omega_{3\mathrm{dB}})}{\Re(0)} \right| = -3 \rightarrow \Re(f_{3\mathrm{dB}}) = \frac{1}{\sqrt{2}} \Re(0)$$

Electrical bandwidth

- The above bandwidth is the intrinsic bandwidth, independent on the detector loading. Transit time, avalanche buildup delay, phototransistor current gain high-frequency cutoff are typically accounted for in the intrinsic cutoff frequency. On the other hand, the overall detector response is also affected by the load impedance and by parasitic (extrinsic) elements. The main loadrelated cutoff mechanism is the *RC* cutoff, caused by the combined effect of the device internal and extrinsic capacitance with the load resistance.

Electrical bandwidth

- For the loaded detector, the total responsivity becomes

$$|\mathfrak{R}_l(\omega)| = \frac{\mathfrak{R}}{\sqrt{1 + \omega^2 R_L^2 C_{PD}^2}}$$

R_L is the load resistance, and C_{PD} is the total detector capacitance.

- The total 3-Db cutoff frequency is

$$f_{3\text{dB}} = \frac{1}{2\pi R_L C_{PD}}.$$

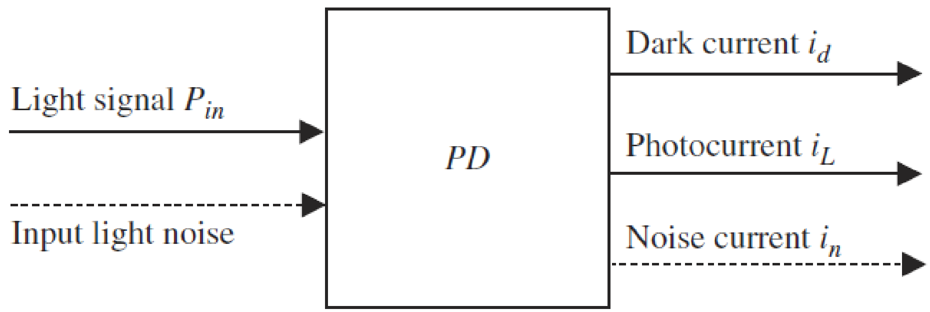
Gain

- In some detectors, the number of collected e-h pairs is much larger than the number of generated pairs, owing to the gain. This includes the phototransistor, avalanche photodiode, and photoresistor. Apart from intrinsic mechanisms, PD gain can also be obtained by integrating the detector with active blocks,

  - In front of the detector, as an optical amplifier (e.g., a semiconductor optical amplifier, SOA);
  - After the detector, as an electronic front-end amplifier, possibly integrated with the detector into an integrated receiver.

PD noise

- The PD output noise includes the light noise-converted current noise, and the noise from the PD itself.



Generation of noise from the photodetector.

- The PD current including noise reads

$$i_{PD} = \Re p_{in} + i_d + i_n$$

- The current noise has a zero average, and the mean square value is related to the power spectral density (PSD),

$$i_{n,\mathrm{rms}}^2 = \overline{i_n^2} = \int_0^\infty S_{i_n}(f)\,\mathrm{d}f.$$

PD noise

- The PSD of PD noise is usually white, so the ms value of the current noise,

$$\overline{i_n^2} = S_{i_n} B$$

where B is the system bandwidth.

- In photoresistors, thermal noise is dominated; in pn, pin photodiodes and phototransistors, shot noise is dominated; In APDs, multiplied shot noise is dominated.
- For photoresistors, the PSD of thermal noise, and the rms of the noise current is given by

$$S_{i_n} = 4k_B T G$$

$$i_{n,\mathrm{rms}} = \sqrt{\overline{i_n^2}} = \sqrt{4k_B T G B}$$

where G is the conductance

PD noise

- For pn and pin photodiode, the PSD of the shot noise, and the rms of the noise current is given by

$$S_{i_n} = 2qI_{PD} = 2qI_L + 2qI_d = 2q\Re P_{in} + 2qI_d \approx 2q\Re P_{in}$$

$$\overline{i_n^2} = 2qI_L B + 2qI_d B \approx 2q\Re P_{in} B$$

- Noise is a major concern in detectors, owing to their position as the first block in the receiver chain, and affects the receiver sensitivity *S*, which is the minimum input power needed to achieve a desired SNR at the receiver output.

PD noise

- Neglecting the dark-current shot nose, the SNR is defined as

$$\mathrm{SNR} = \frac{P_{s,av}}{P_{n,av}} = \frac{\frac{1}{2}\left(I_L^2/4G_{PD}\right)}{\frac{1}{2}\left(\overline{i_n^2}/4G_{PD}\right)} = \frac{I_L^2}{\overline{i_n^2}} = \frac{I_L^2}{2qI_LB} = \frac{I_L}{2qB} = \frac{\Re P_{in}}{2qB}$$

- Since in a loaded PD the SNR is also influenced by the (thermal) noise introduced by the front-end amplifier stage, suppose the loaded thermal noise contribution is

$$\sqrt{\overline{i_{n,L}^2}} = \sqrt{4k_BTG_nB}.$$

where G_n is the load conductance. The total SNR of the loaded PD,

$$\mathrm{SNR} = \frac{I_L^2}{\overline{i_n^2} + \overline{i_{n,L}^2}} = \frac{I_L^2}{2qI_LB + 4k_BTG_nB}$$

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PD noise

- If the loaded noise is dominate with respect to the detector shot noise,

$$\mathrm{SNR} \approx \frac{I_L^2}{4k_B T G_n B} = \frac{(\Re P_{in})^2}{4k_B T G_n B}$$

In this case, the SNR increases as the square of the optical power. This condition is the thermal noise limit of the detector.

- The sensitivity in the shot noise limit is

$$S = \frac{2qB}{\Re}\mathrm{SNR}$$

- The sensitivity in the thermal noise limit is

$$S = \sqrt{\frac{4k_B T G_n B}{R} SNR}$$

PD noise

- The SNR and sensitivity are system-level figures of merit for the receiver. Device-level noise parameters are noise equivalent power (NEP) and detectivity.
- The NEP is defined as the optical input power yielding a short-circuit SNR equal to one. The NEP defines the detector noise floor. In the short-circuit case, the load impedance is zero, and thus the PD is in shot noise limit,

$$\mathrm{SNR} = \frac{I_L^2}{2qI_LB + 2qI_dB} = \frac{\Re^2 P_{NEP}^2}{2q\Re P_{NEP}B + 2qI_dB} = 1$$

PD noise

- Depending on whether the photocurrent is larger or smaller than the dark current, we have
  - Shot-noise-limited NEP: $P_{NEP} = 2qB/\Re$;
  - Dark-current-limited NEP: $P_{NEP} = \sqrt{2qI_d B}/\Re$
- The photodetector detectivity is defined as the inverse of the NEP,

$$D = \frac{1}{\text{NEP}}$$

- In the dark current limit, the specific detectivity is defined as

$$D^* = \sqrt{AB}\,D = \frac{\sqrt{AB}}{\text{NEP}}$$