Sensors, Signals and Noise

COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors: PhotoDetectors 3 – PD3

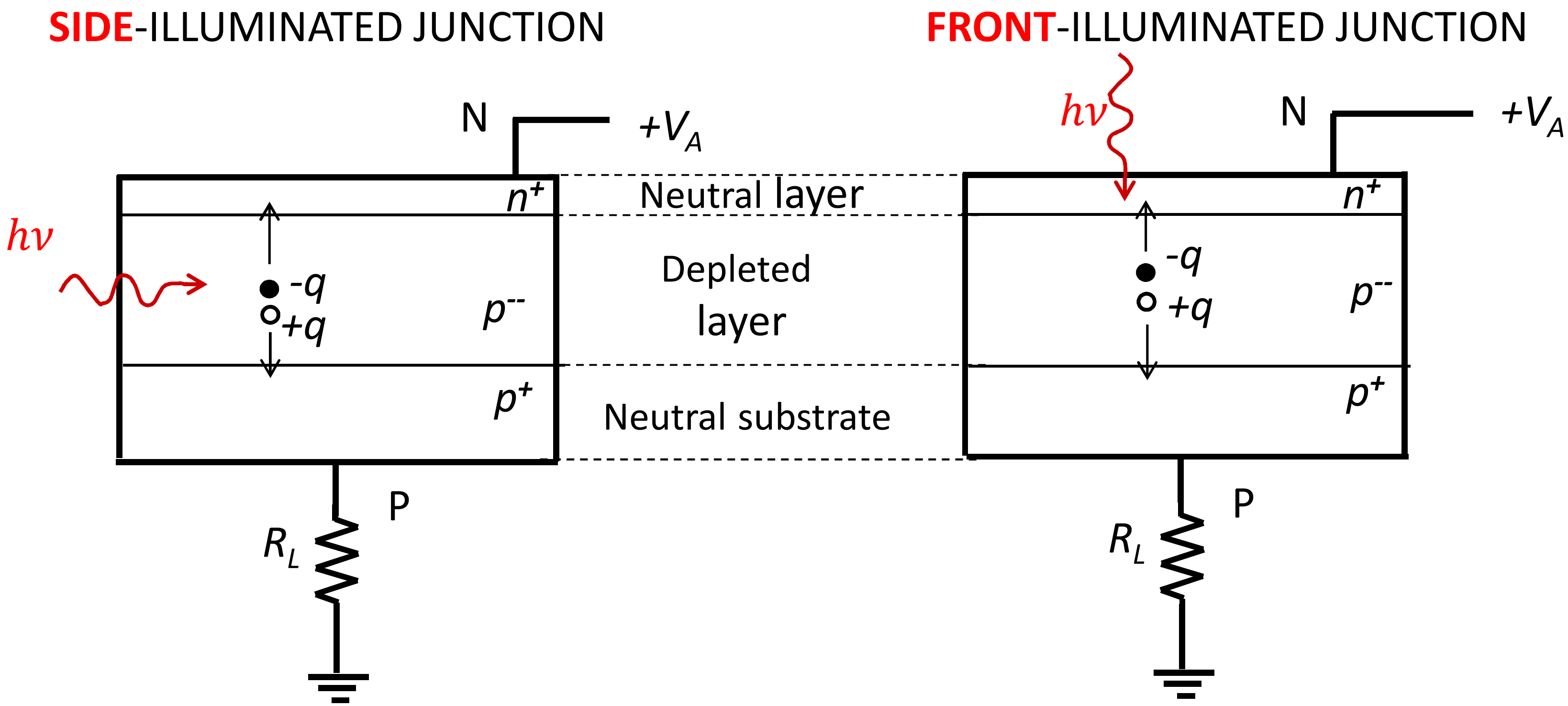
Semiconductor Photo-Diodes (PD)

- PhotoDiode (PD) devices and carrier motion
- I-V characteristics and stationary equivalent circuit of PDs
- Photo-generation of free carriers and photon detection efficiency
- Dark-Current, detector noise and sensitive area
- Current signal in PDs
- PD equivalent circuit, dynamic response and sensitive area
- Carrier diffusion effects
- Evolution of the photodiode device structure

PhotoDiode (PD) devices and carrier motion

Basic Device Structure of Photodiodes

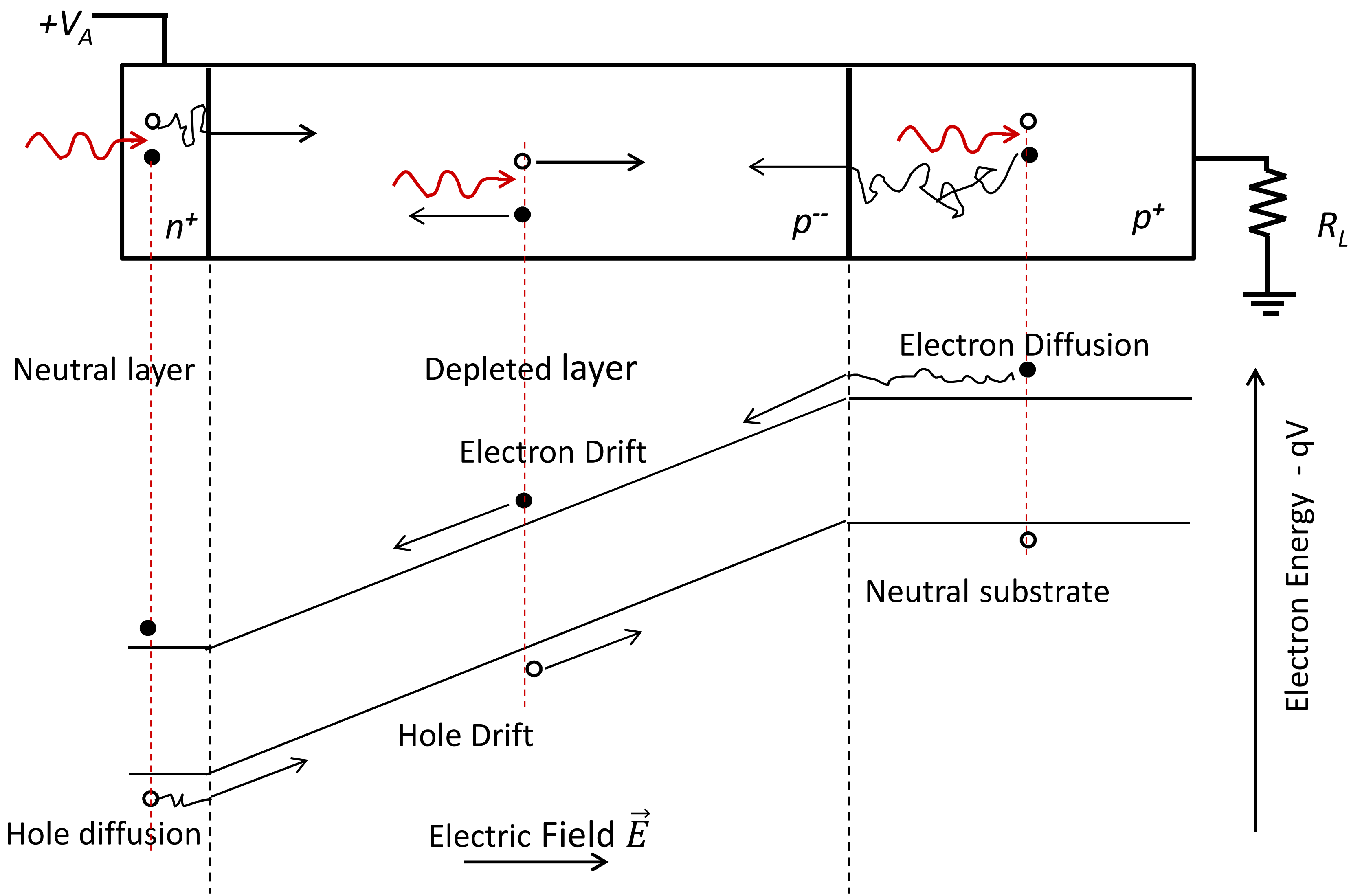
Reverse biased p-n junction: $V_A > 0$



Employed for specific purposes, e.g. microsystems with integrated waveguides for on-chip optical connections

Most widely employed; the active area (illuminated area) can be designed with flexibility and can attain wide size

Carrier motion in PD



Carrier motion and Current in PD

Carriers generated in the depleted layer:

- A carrier in the depleted layer induces opposite charges in the conductive electrodes (neutral semiconductor layer and metal contact to the external circuit)
- The value of the induced charge on a given electrode depends on the carrier distance from the electrode
- If the carrier moves the charge induced on the electrode varies, hence current flows through the contact

Conclusion: a carrier drifting in the depleted layer **causes current to flow** through the metal contact to the external circuit

Carriers generated in neutral regions:

- A carrier in a neutral region is surrounded by a huge population of other free carriers
- When the carrier moves the distribution of free carriers swifltly rearranges itself to electrically screen any effect of the carrier motion on the external circuit

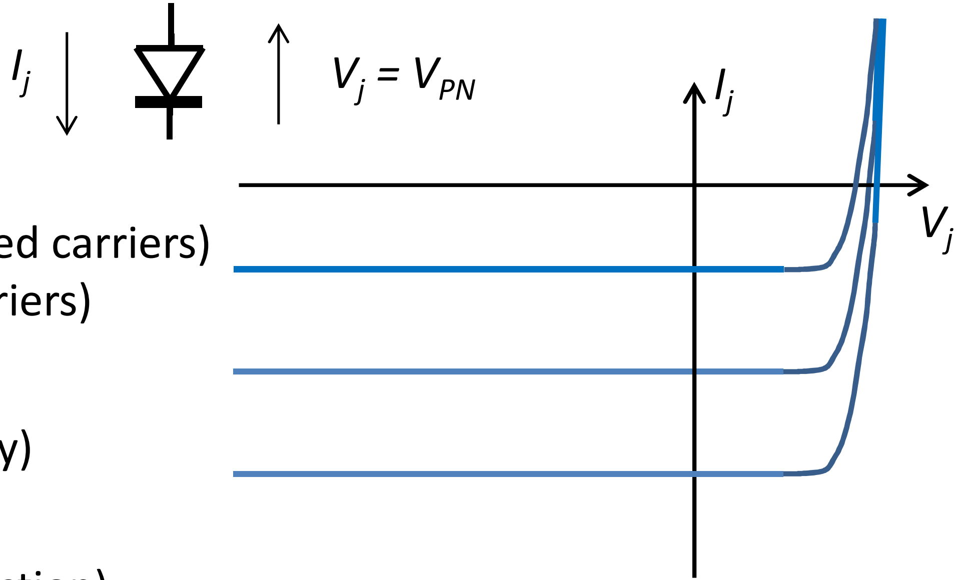
Conclusion: **as long as it diffuses** in a neutral region, a carrier **does NOT cause current** to flow through the metal contact to the external circuit.
However, **if** by diffusion it reaches the edge of depletion layer before recombining, **then** it drifts in the electric field and causes current to flow.

I-V characteristics of PhotoDiodes

I-V characteristics of PD

- I-V of illuminated p-n junction

$$\boxed{I_j = I_0 \exp\frac{qV_j}{kT} - I_0 - I_p}$$



I_0 reverse current (thermally generated carriers)
I_p photocurrent (photogenerated carriers)

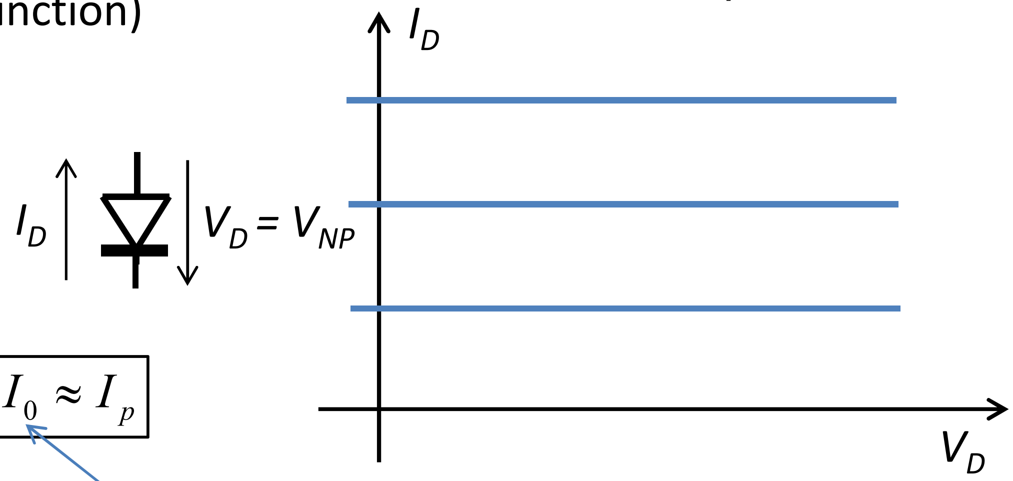
$$\boxed{I_p = S_D \cdot P_L}$$

(P_L optical power; S_d radiant sensitivity)

- Photodetector (reverse-biased junction)

I_D detector current = - I_j
V_D detector voltage = - V_j

$$I_D = I_p + I_0 - I_0 \exp\left(-\frac{qV_D}{kT}\right)$$



with $V_D \gg kT/q$

$$\boxed{I_D = I_p + I_0 \approx I_p}$$

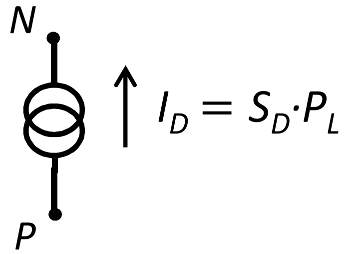
Detector photocurrent $\propto P_L$

Detector dark current

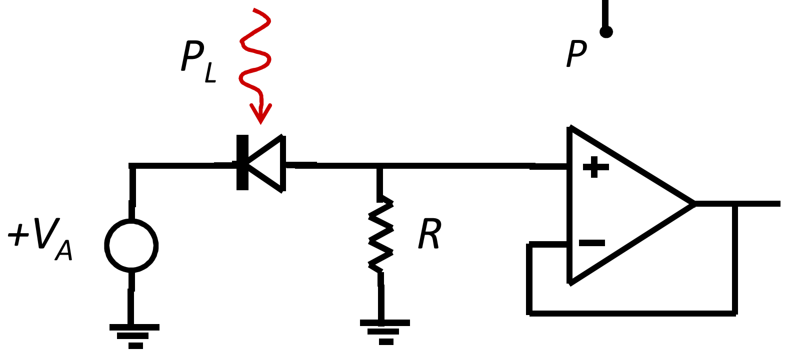
Stationary operation of PD

LINEAR PHOTOCURRENT MODE: PD with high reverse bias $V_A \gg kT/q$

stationary equivalent circuit:
photo-controlled current generator

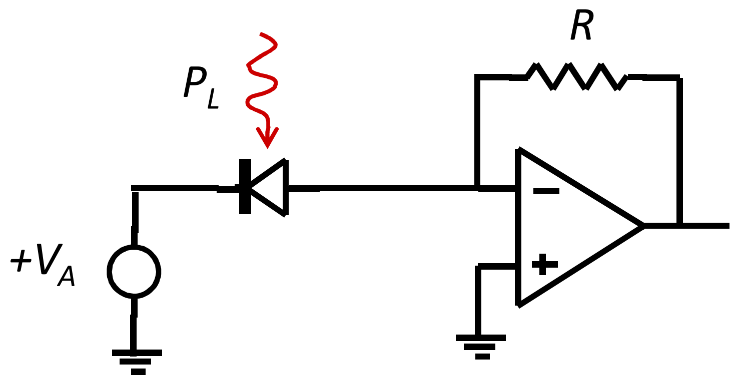


OPERATION WITH
PASSIVE LOAD



$V_O = R \cdot I_D \propto P_L$

OPERATION WITH
ACTIVE LOAD



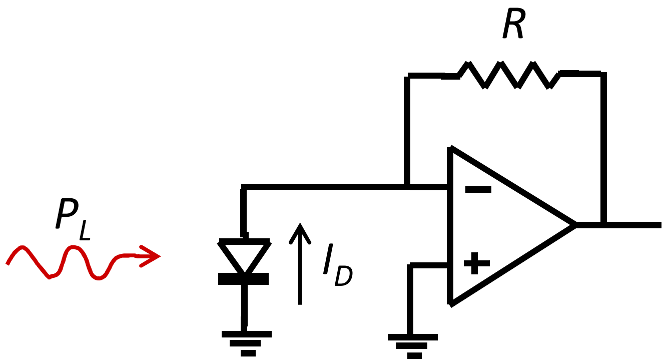
$V_O = -R \cdot I_D \propto P_L$

Operation without bias voltage on PD

Semiconductor photodiodes can be operated also without a bias voltage source. As outlined below, the short-circuit current is measured in the photoconductive mode and the open-circuit voltage in the photovoltaic mode. These configurations have modest sensitivity and slow response (see later), but their simplicity is attractive in some practical cases, e.g. for monitoring a steady light over a wide dynamic range.

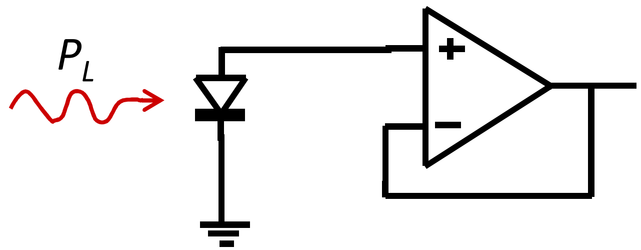
PHOTOCONDUCTIVE MODE
PD in short-circuit $V_A = 0$
Linear output scale

$$I_D = I_p + I_0 \approx I_p$$



$$V_O = -R \cdot I_D$$

PHOTOVOLTAIC MODE
PD in open-circuit $I_D = 0$
Logarithmic output scale



$$V_O = V_j$$

$$V_j = \frac{kT}{q}\ln\left(1+\frac{I_p}{I_0}\right) \approx \frac{kT}{q}\ln\left(\frac{I_p}{I_0}\right)$$

Photo-generation of free carriers and photon detection efficiency

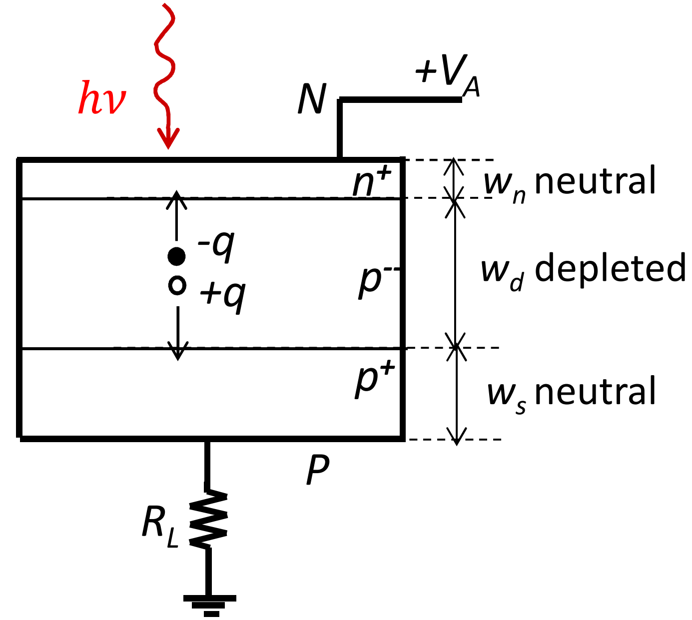
Photon Detection Efficiency η_D

P_d = probability of a photon to generate a free electron-hole pair **in the depletion layer** = product of probabilities of

1. NOT being reflected at the surface
2. NOT being absorbed in the top neutral layer w_n
3. BEING absorbed in the depletion layer w_d

Denoting by R the reflectivity (probability of reflection) and $L_a = 1/\alpha$ optical absorption depth:

$$P_d = (1-R)\cdot e^{-\alpha w_n}\cdot\left(1-e^{-\alpha w_d}\right)$$



In most PD structures the probability that carriers photogenerated in neutral regions reach by diffusion the depletion layer is negligible, hence the photon detection efficiency or quantum detection efficiency η_D is simply

$$\boxed{\eta_D = P_d = (1-R)\cdot e^{-w_n/L_a}\cdot\left(1-e^{-w_d/L_a}\right)}$$

In PD structures where carriers diffusing in neutral regions have significant probability of reaching the depletion region, additional contributions to η_D must be taken into account

Photon Detection Efficiency η_D

$$\boxed{\eta_D = P_d = (1-R)\cdot e^{-w_n/L_a}\cdot\left(1-e^{-w_d/L_a}\right)}$$

Basic sources of η_D losses are 1) surface reflection, 2) absorption in the neutral input layer and 3) incomplete absorption in the depletion layer (active volume).
The η_D value attained depends on the actual material properties and PD structure and on the light wavelength λ.

η_D loss by Reflection

- The reflection at vacuum-semiconductor surface is strong because of the high step discontinuity in refractive index n, since n is high in semiconductors. In Silicon n>3,5 over all the visible range and further rises at short λ; the reflectivity is congruently high R>30% and further rises at short λ .
- Losses can be reduced by tapering the n-transition with deposition of a multi-layer anti-reflection (AR) coating of materials with n values suitably scaled down from semiconductor to vacuum. Strong reduction can be obtained, down to R<<10%.
- In Silicon PDs a simple AR coating is obtained with a surface oxide layer (passivation layer), because SiO_2 has intermediate n≈2. Remarkable reduction can be obtained, down to R≈10%.

Photon Detection Efficiency η_D

$$\boxed{\eta_D = P_d = (1-R)\cdot e^{-w_n/L_a}\cdot\left(1-e^{-w_d/L_a}\right)}$$

η_D loss by absorption in neutral input layer

- At short λ, η_D cutoff occurs because photons are all absorbed in the neutral region at the surface. The escape probability is ruled by w_n/L_a (see 2nd term).
  In Silicon L_a is small at short λ : L_a < 1 *μm* for λ< *500nm* and L_a *<100 nm* for λ<400nm. In actual Si-PD structures w_n ranges from about *200 nm* to 2 *μm;* the cutoff λ congruently ranges from about *300 nm* to *400 nm*.

η_D loss by incomplete absorption in the depletion layer

- At long λ , η_D cutoff occurs because the absorption falls down. Absorption is ruled by w_d/L_a (see 3d term); with w_d/L_a << 1 we get $\left(1-e^{-w_d/L_a}\right)\approx w_d/L_a$.
  Silicon is ≈ transparent beyond *1100 nm*, since photon energy < Si energy gap. In actual Si-PD structures the depth w_d can range from one to various tens of *μm*; given the λ-dependance of L_a , the cutoff λ ranges from about *900 nm* to *1100 nm*.

Current Si-PDs provide high efficiency (η_D *> 30%)* in the visible 400nm < λ < 800nm.

The operation range can be extended to longer λ with PDs in other semiconductors:
up to 1500nm with Germanium devices and up to 2000nm with InGaAs devices

Dark-Current, detector noise and sensitive area

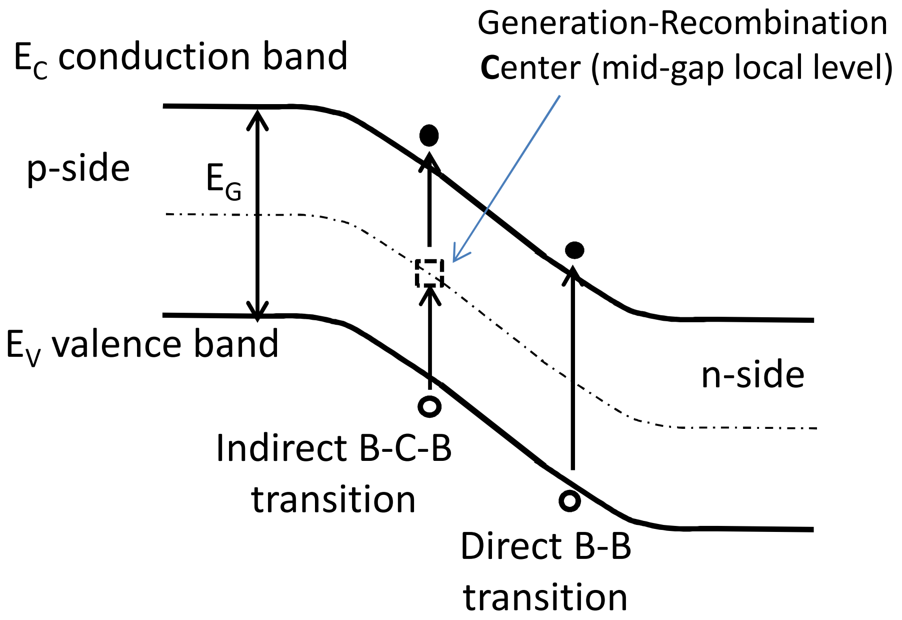
Dark Current and Noise

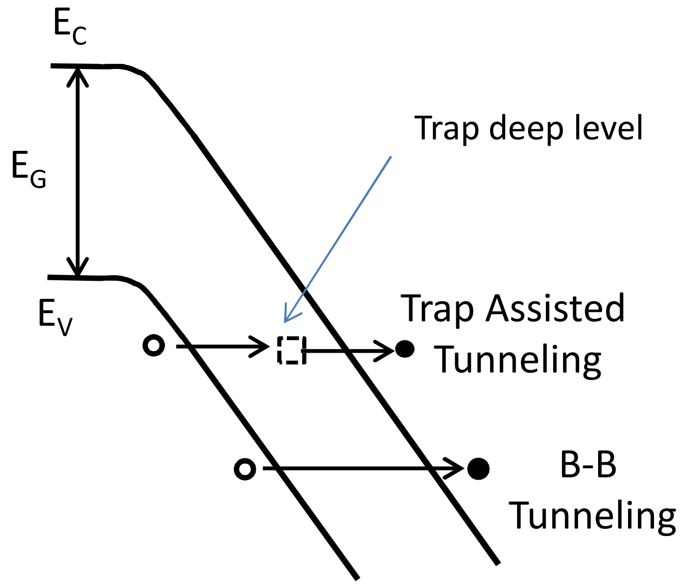
- Even without light falling on it, a finite current I_B flows in a reverse-biased p-n junction. It is called **Dark Current** in PDs and reverse current in ordinary circuit component diodes.
- I_B is due to spontaneous generation of free cariers by thermal effects (and also by tunnel effects in device structures with high electric field).
- Just like in Phototubes, the shot noise of I_B is the photodiode internal noise, with effective power density (unilateral)

$$\sqrt{S_B} = \sqrt{2qI_B}$$

- The internal noise of PD devices with **microelectronic-size** (sensitive area <1mm^2) is much lower than the input noise of even the best high-impedance preamplifiers. In the applications of microelectronic PDs the circuit noise is dominant, just like for vacuum phototubes.
- However, semiconductor PDs have **dark current density j_B much higher than vacuum phototubes**; this fact significantly limits the active area size of semiconductor detectors that can be employed for very low-noise operation.

Carrier Generation (and Recombination)





THERMAL TRANSITIONS

TRANSITIONS ASSISTED BY HIGH ELECTRIC-FIELD

- Various physical phenomena take part in carrier generation-recombination, with varying relative relevance in the various cases, with different materials, device structures and operating conditions (bias voltage, temperature, etc.).
- Silicon has very favourable properties for achieving low generation rate.
- Materials for IR detectors (Ge, InGaAs) have smaller energy gap and therefore inherently higher noise, since all generation processes are favoured by a smaller E_G

Dark Current of Si-PD

In Silicon device physics and technology it is ascertained that in reverse-biased junctions with moderate electric field intensity:

a) the dark current is mainly due to thermal generation of carriers in the depletion layer. Contribution by diffusion of minority carriers from neighbouring neutral regions are much lower and negligible in comparison.

b) The thermal generation rate in the depletion has volume density n_G given by

$$\boxed{n_G = \frac{n_i}{2\tau}}$$

n_i = intrinsic carrier density; $n_i = 1{,}45 \text{ x } 10^{10}\ \mathrm{cm}^{-3}$ @ Room Temperature

τ = minority carrier lifetime, strongly dependent on the device technology i.e on the starting material and on the fabrication process. Typical values:

$\tau \approx \mu s$	ordinary Si technology for integrated circuits
$\tau \approx ms$	ordinary Si technology for detector devices
$\tau \approx 1 \div 10s$	best available Si technology for detector devices

Dark Current and active area of Si-PD

A Si-PD with circular active area of diameter *D* (area $A = \pi D^2/4$) and depletion layer thickness w_d has dark generation rate $n_B = n_G A w$. For setting a limit $n_B < n_{Bmax}$ the diameter *D* must be limited

$$A < A_{\max} = n_{B\max} / n_G w_d = 2\tau n_{B\max} / n_i w_d$$

$$D \le D_{\max} = \sqrt{8\tau n_{B\max} / \pi n_i w_d}$$

<u>Example</u>: Si-PD with w_d =10µ in good Si detector technology (τ ≈10ms), intended to have the widest possible area with noise lower than a preamplifier with $\sqrt{S_i} = \approx 0{,}01 pA/\sqrt{Hz}$. For keeping the shot noise so low, the generation rate must be limited to $n_{B\max} < 10^9 s^{-1}$ which implies

$$D < D_{\max} = 1{,}3\ cm$$

As we will see, the area limitation is more severe for avalanche photodiodes (APD). The APD internal gain makes negligible the role of circuit noise, hence the APD detector noise that limits the sensitivity and it is worth to reduce it more drastically.

<u>Example</u>: Si-APD with *w =10µm,* fabricated in very good Si detector technology (say *τ≈1s*) intended to have low dark rate, comparable to that of a good vacuum tube photocathode, say $n_{B\max} < 10^3 s^{-1}$ like a S20 photocathode with diameter 3cm. The limit is

$$D < D_{\max} = 130\,\mu m$$

Current signal in PDs

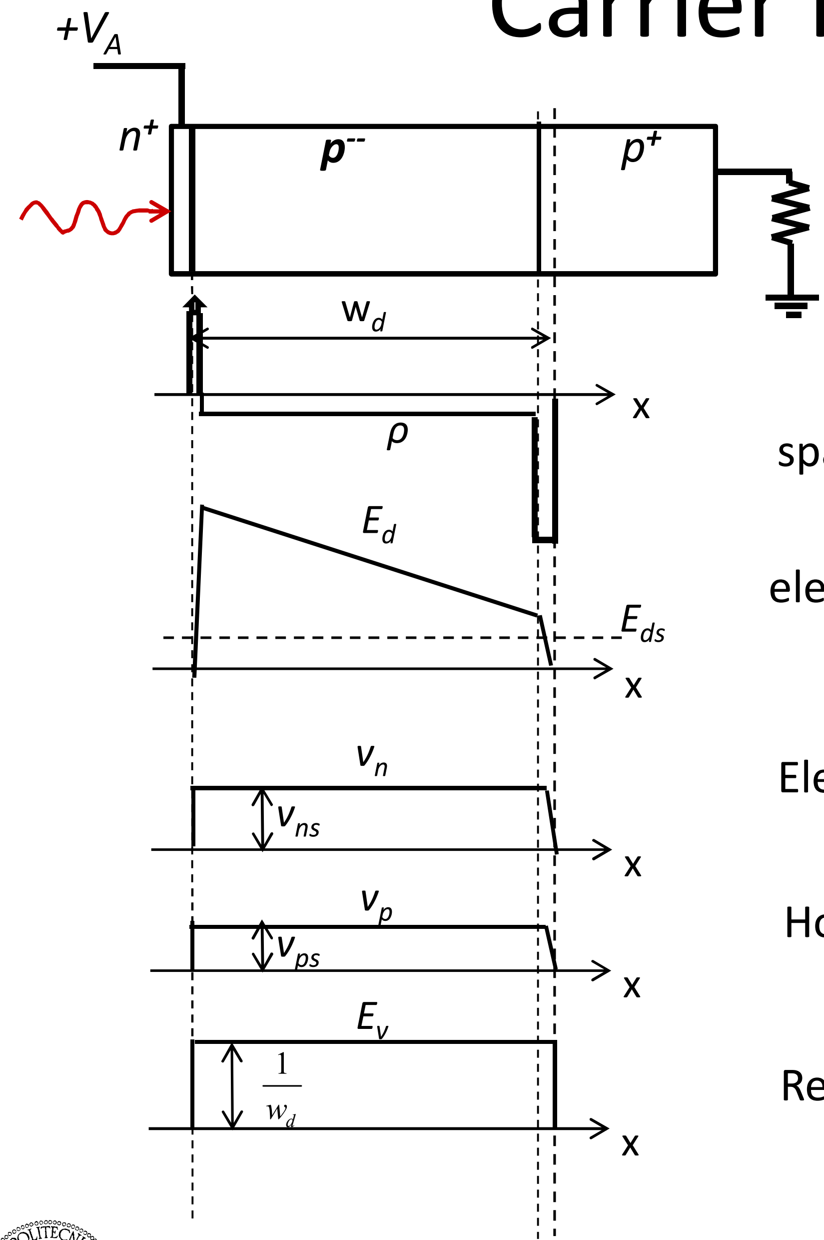
Carrier motion and detector current

- Carriers drifting in depleted regions induce current at PD terminals, whereas carriers diffusing in neutral regions do NOT
- The Shockley-Ramo (S-R) theorem is still valid in presence of space charge
- Knowing the actual velocity v_c of a drifting carrier, the current induced at the PD terminals can be computed by the S-R theorem
- The motion of carriers in a semiconductor with electric field E_d is different from that in vacuum with equal E_d : carriers suffer scattering on the lattice and dissipate in the collisions most of the energy received from the field.
  No more the acceleration, but the drift velocity v_c is a function of the field E_d .
- In Silicon (and other materials) the motion of electrons is different from holes:
  - at **low field E_d <2 kV/cm** *= 0,2 V/µm* the regime is **Ohmic**: $v_c = \mu_c E_d$
    (electron mobility $\mu_n \approx 1500\ cm^2V^{-1}s^{-1}$; holes $\mu_p \approx 450\ cm^2V$)
  - as E_d increases above *2kV/cm* the velocity rises progressively slower
  - at **$E_{ds} \approx$ 20kV/cm** *= 2V/µm* the **velocity saturates** at the scattering-limited values

for electrons $\boxed{v_{ns} \approx 10^7\ cm/s}$ for holes $\boxed{v_{ps} \approx 8 \cdot 10^6\ cm/s}$

which are almost equal to the thermal scattering velocity $v_{th} \approx 10^7\ cm/s$

Carrier motion in PD



cross-section of typical PD structure

space charge density ρ in the depleted region

electric field E_d > saturation E_{ds} over almost all w_d

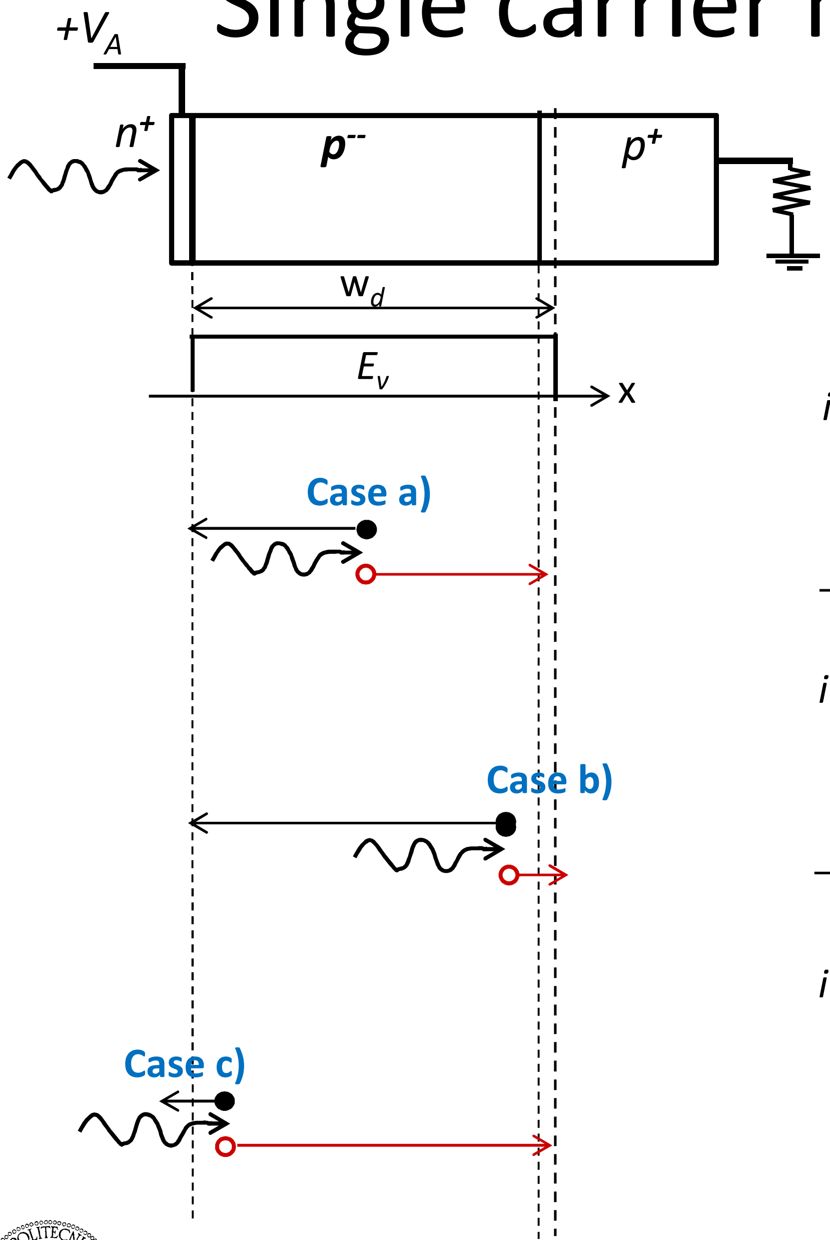
Electron drift velocity $v_n \approx v_{ns}$ over almost all w_d

Hole drift velocity $v_p \approx v_{ps}$ over almost all w_d

Reference Field E_v for S-R theorem

$$E_v = \frac{1}{w_d}$$

Single carrier motion and current

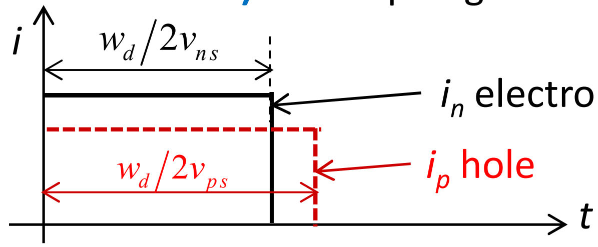


Current of a single-carrier

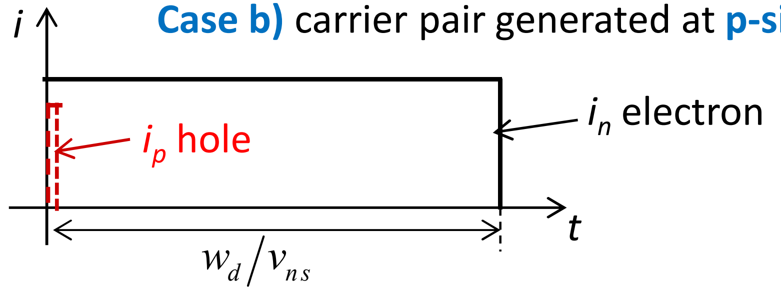
$$\boxed{i_c = q_c v_c E_v}$$

S-R theorem:
E_v reference field
q_c and v_c carrier charge and velocity

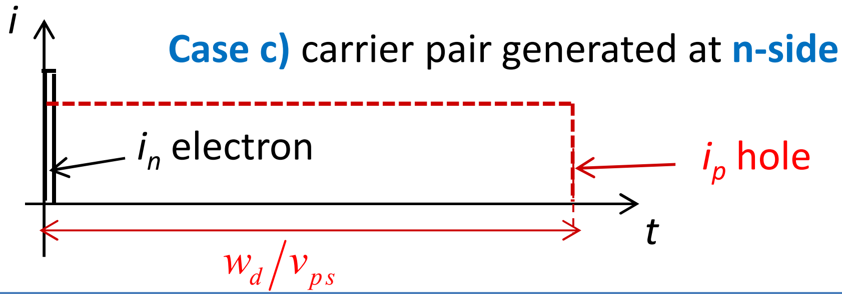
Case a) carrier pair generated at **mid-way**



Case b) carrier pair generated at **p-side**



Case c) carrier pair generated at **n-side**



Single carrier motion and current

- The duration of a single-carrier pulse is given by the transit time T_t of the carrier in the depleted region. At saturated velocity it is quite short: in Silicon the carrier travel takes ≈10ps/µm, that is, with $w_d = 1 \div 100\mu m$ it is $T_t = 10ps \div 1ns$.
- The single-carrier pulse duration thus depends on the position of carrier generation. Rigorously, the waveform of the current due to a fast multi-photon pulse is not the convolution of the optical pulse with a standard carrier response: it is a more complex computation that depends on the spatial distribution of absorbed photons.
- However, convolution with a suitable standard single-carrier response gives the waveform with approximation adequate for most cases, at least for times longer than the carrier transit time.
- A simplifying and conservative approximation currently employed for Silicon PDs assumes as standard the response to an electron that crosses all the depletion layer.

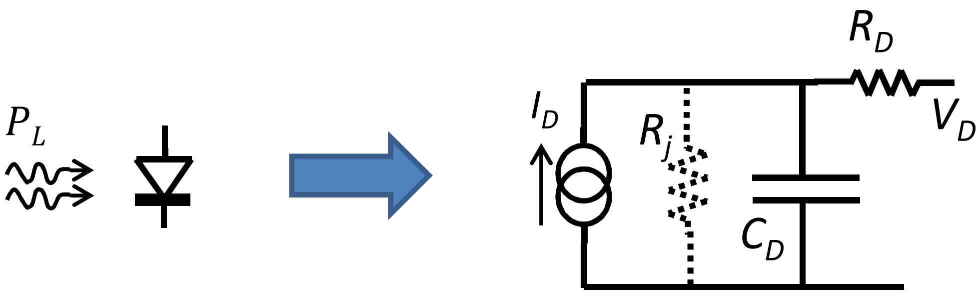
Finite width of response implies <u>low-pass filtering in light-to-current transduction</u>: it's a mobile-mean over time $T_t = w_d/v_{sn}$, with upper band-limit $1/2T_t = v_{sn}/2w_d$.

Note the w_d trade-off: long w_d is required for high quantum efficiency at long wavelength λ, short w_d for ultrafast time response. Remark, however, that this is valid for front-illuminated junction and not with side illuminated junction

PD equivalent circuit,

dynamic response and sensitive area

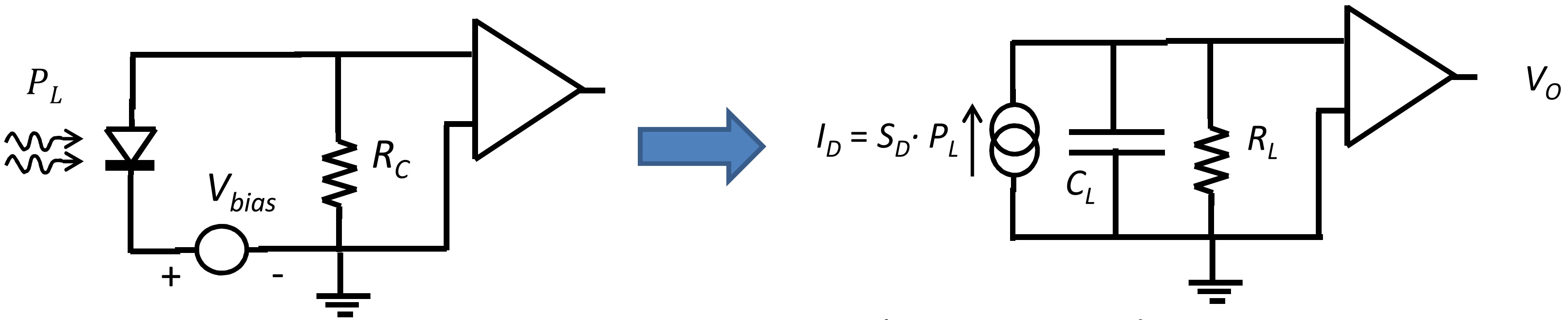
Photodiode Equivalent Circuit



- $I_D = S_D \cdot P_L$ photo-controlled generator (S_D radiant sensitivity or responsivity)
- C_D diode capacitance (p-n junction)
- R_D diode **series** resistance (of the input layer and substrate)
- R_j parallel resistance of the reverse biased junction is considered → ∞

REAL CIRCUIT

EQUIVALENT CIRCUIT



R_C circuit input resistance

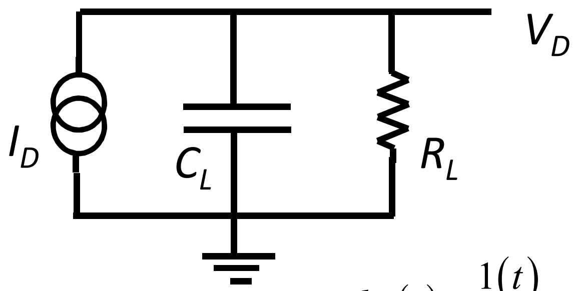
R_L total Resistance Load ≈ $R_C + R_D$
C_L total Capacitive Load = $C_D + C_S$ (stray) + C_A (amplifier)

the load circuit is a low-pass filter with time constant $R_L C_L$ in the transfer from detector current I_D to output voltage V_O

Photodiode Dynamic Response

In summary, the PD dynamic response is limited:

1. By the light-to-current transduction, with pulse response $h_D(t)$ of finite-width T_t , well approximated by a rectangular pulse.
2. By the load circuit, with δ-response $h_L(t)$ of finite-width $T_L \approx 2R_LC_L$



$$h_L(t) = \frac{1(t)}{C_L}\exp\left(-t/R_LC_L\right)$$

The δ-response $h_P(t)$ in the transfer from light power to detector voltage results from the convolution of the two

$$h_P(t) = h_D(t) * h_L(t)$$

Hence the width T_P is the quadratic addition of the two

$$T_P = \sqrt{T_t^2 + T_L^2} = \sqrt{T_t^2 + 4R_L^2C_L^2}$$

For exploiting well the fast response $h_D(t)$ of the PD current, the load circuit does not need to have much faster response, but just comparable or slightly better

$$\boxed{T_L = 2R_LC_L \le T_t}$$

Photodiode Dynamic Response

For a PD in planar Silicon with depletion layer w_d and circular area A of diameter D

$$C_D = \varepsilon_{Si} \frac{A}{w_d} \qquad\qquad T_t = \frac{w_d}{v_{sn}} \approx w_d \cdot 10\ ps/\mu m$$

Assuming (quite optimistically) that the load capacitance be given only the junction $C_L \approx C_D$ and applying the condition $2R_L C_L \leq T_t$ we get

$$A \leq \frac{w_d^2}{v_{sn}} \frac{1}{2R_L \varepsilon_{Si}} \qquad \text{that is} \qquad D \leq w_d \sqrt{\frac{2}{\pi v_{sn} R_L \varepsilon_{Si}}}$$

In wide-band operation the load resistance R_L is small, but is not much less than 100 Ω (diode resistance ≈ some ten Ohm and characterisic resistance of wide-band circuits 50÷75Ω). For exploiting well the fast response limited by the transit time, with R_L = 100 Ω, ε_{Si}≈1,06pf/cm, $v_{ns} \approx 10^7$ cm/s , the limit to the size of sensitive area is

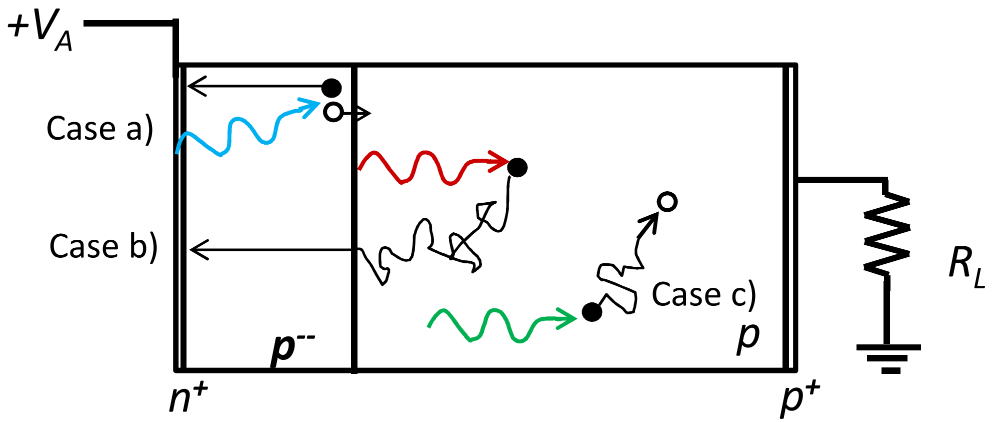
$$D \leq 25 \cdot w_d$$

In the design of detector devices, the selected depletion layer depth w_d depends on the wavelength of interest and on the photon detection efficiency sought; it actually ranges from 1μm to about 100μm.

The area of fast semiconductor photodiodes thus is small in all cases: as w_d ranges from 1μm to 50μm the limit diameter correspondingly ranges from 25μm to 1,25mm

Carrier diffusion effects

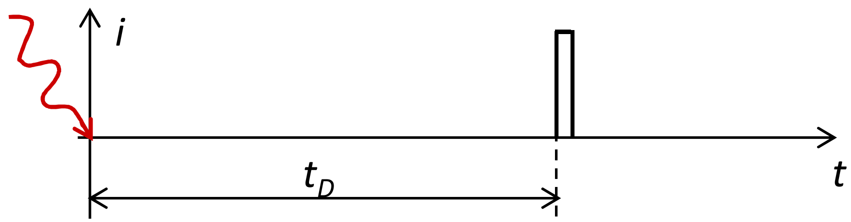
Carrier Diffusion Effects



Single-Carrier Response

a) Carrier generated in depleted region:
  short and **prompt** pulse

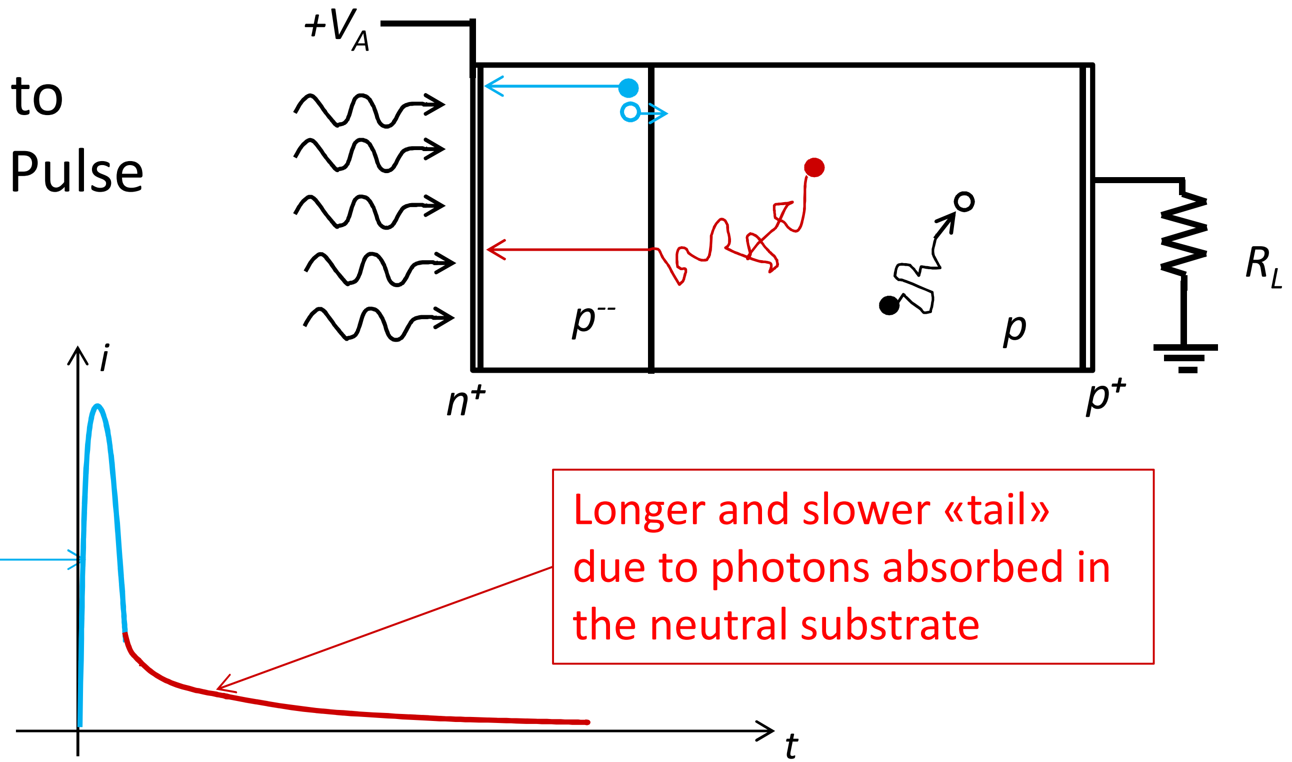
b) Minority Carrier generated in neutral region that random-walks by diffusion and attains the depleted region:
  short pulse with **random delay t_D**



c) Minority Carrier generated in neutral region that random-walks by diffusion and there recombines:
  NO current pulse

Carrier Diffusion Effects

Response to
MultiPhoton Pulse

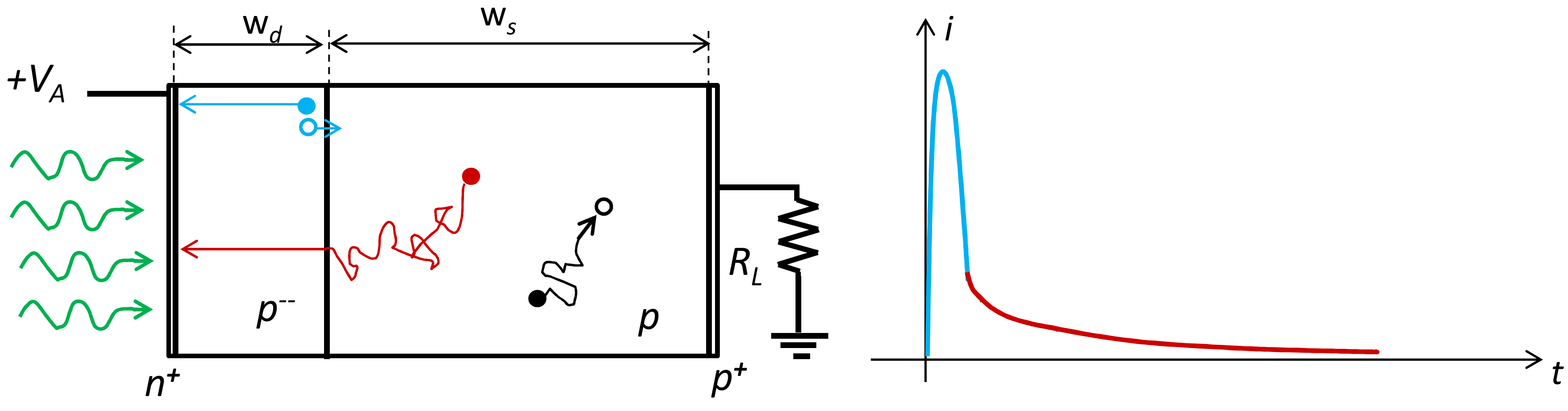


Short main pulse due to photons absorbed in the depletion region

Longer and slower «tail» due to photons absorbed in the neutral substrate

The shape and relative size of the «diffusion tail» are established by the photogeneration and by the diffusion dynamic of minority carriers in neutral regions. They strongly depend on the PD device geometry, on the material properties in the neutral regions (diffusion coefficient and minority carrier lifetime) and on the space distribution of the absorbed photons, hence on the photon wavelength.

Carrier Diffusion Effects

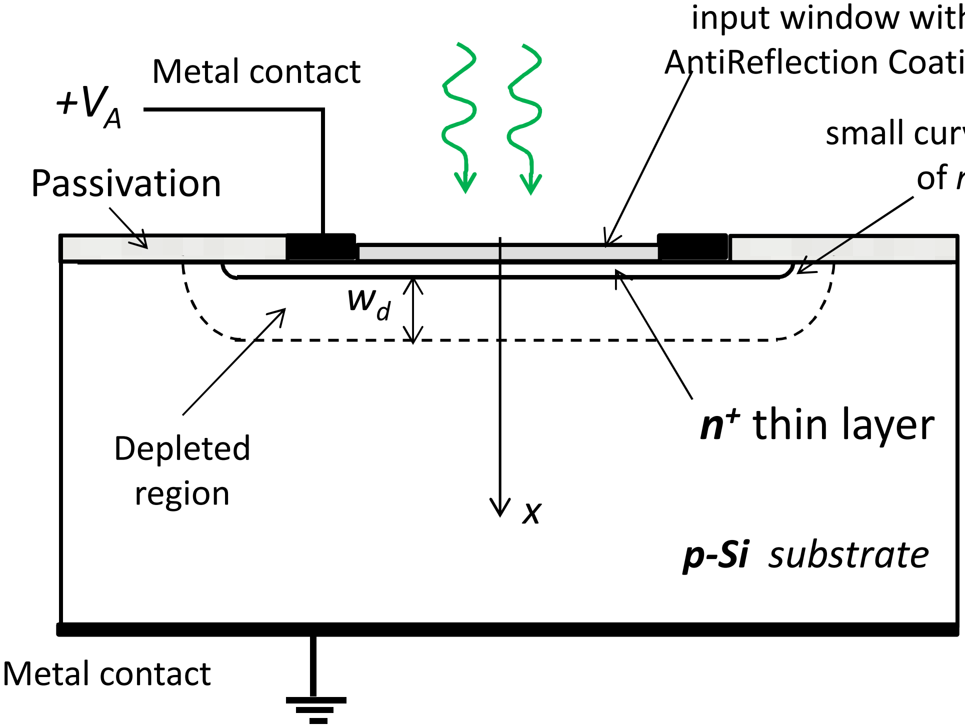


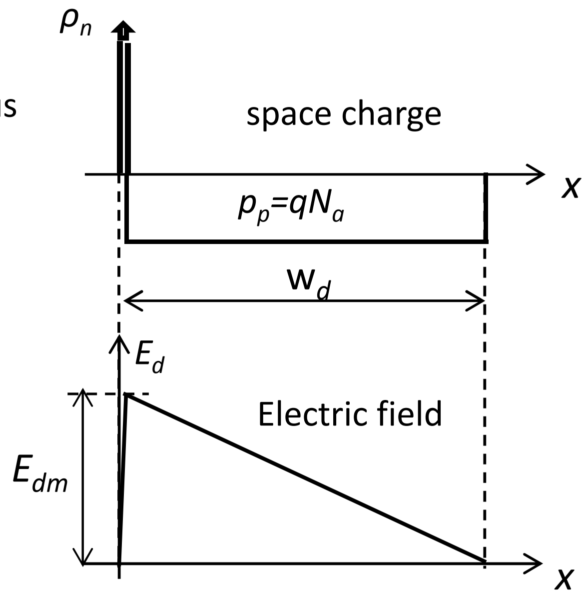
The «diffusion tail»:

- increases the photon detection efficiency, by bringing to the output a contribution from photons absorbed in a neutral region
- downgrades the detector dynamic response, since the diffusion tail is definitely longer than the prompt pulse
- The time span of the tail increases with the thickness w_s of the neutral substrate and with the minority carrier lifetime, which is longer at lower doping level.
- In Si-PD the tail can be quite significant, ranging from a few 100ns with thick layer (w_s >100µm) and low doping (≈10^{14}/cm^3) to a few 100ps with thin layer (w_s≈1÷2µm) and moderately high doping (≈10^{16}/cm^3).

Evolution of the photodiode device structure

Si-PD: primitive device structure





by Gauss theorem

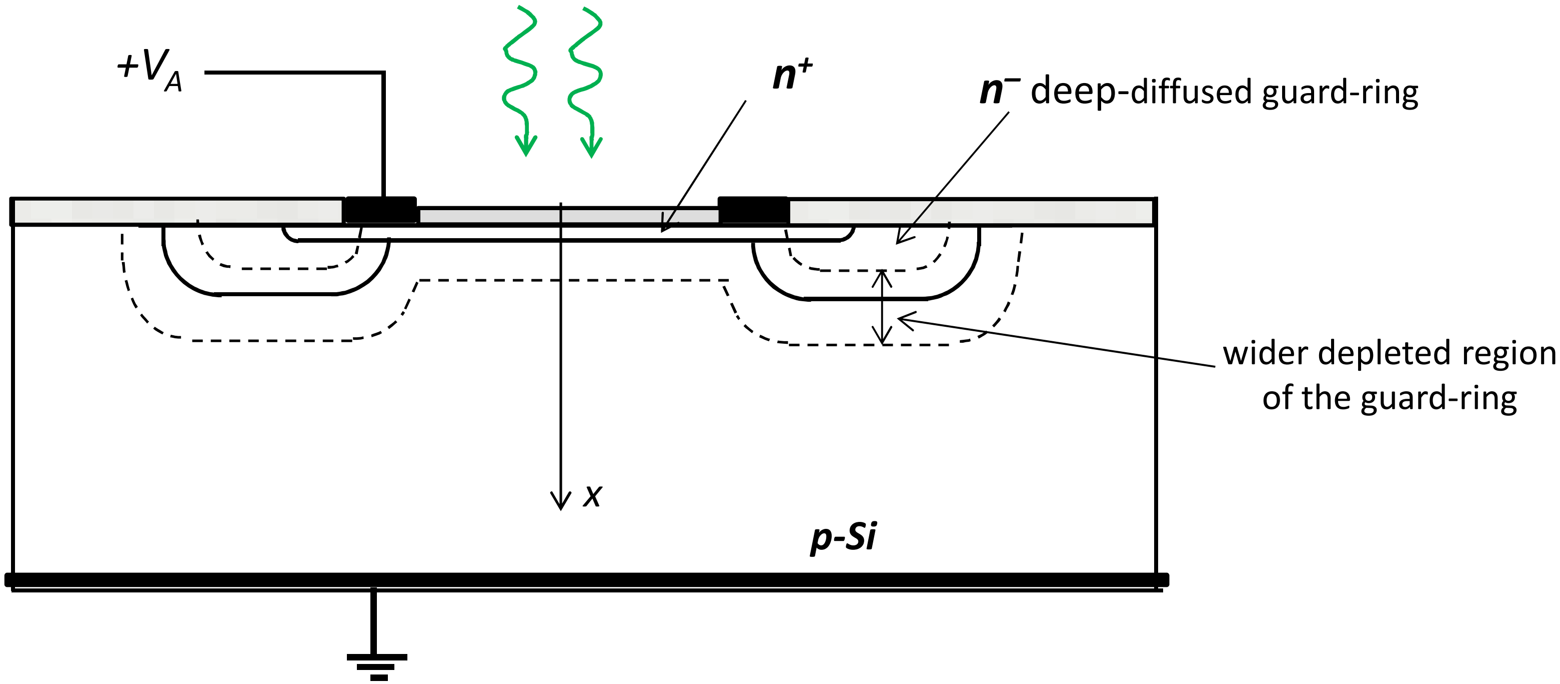
$$E_{dm} = \frac{qN_a w_d}{\varepsilon_s}$$

and by integration

$$V_A = \frac{E_{dm} w_d}{2} = \frac{qN_a w_d^2}{2\varepsilon_s}$$

- High V_A required for obtaining depth w_d adequate to long λ : e.g. $V_A \approx 80V$ for $w_d \approx 10\mu m$ with $N_a \approx 10^{15}$
- The peak electric field is fairly high and locally enhanced by **edge effects** and **local defects** (of crystal structure; of dopant concentration; etc.) which can cause local breakdown

Si-PD: simple improved structure



- Edge breakdown is avoided by a **guard-ring structure**, e.g. a deep-diffused ring with lighter n-doping, which produces wider depletion region with lower electric field
- Local breakdown is avoided by technology improvements that reduce local defects in the active area (substrate quality; thin layer technology; gettering processes; etc.)
- This device structure is free from local defects and edge effects, but has inherently high peak electric field, which causes problems and performance limitations.

Problems with the simple Si-PD Structure

The simple improved structure avoids edge effects and local breakdown effects, but has a disadvantageous electric field profile.

- At the deep boundary of the depletion, the field rises linearly from zero and remains fairly low in a significant part of the depletion layer. Low field intensity causes low carrier velocity, which slows down the PD dynamic response

- The electric field has a high peak E_{dm} (twice the average value) that must be kept below the breakdown level E_B (which in Silicon is about *200kV/cm),* in order to avoid an avalanche breakdown that generates a high spurious current.

- For increasing the depletion width w_d (in order to improve the detection efficiency at longer wavelengths) the bias voltage V_A must be increased, thereby increasing also the peak electric field E_{dm}

- Unluckily E_{dm} prematurely attains the breakdown level E_B , i.e. before producing w_d adequate for high detection efficiency in the Red and Near InfraRed (NIR) spectral range.

Problems with the simple Si-PD Structure

In Silicon:
$E_B \approx 200 kV/cm$
$\varepsilon_s = 1 pF/cm$

Maximum attainable depth w_{dm}

$$w_{dm} = E_{dm} \frac{\varepsilon_s}{qN_a} \leq E_B \frac{\varepsilon_s}{qN_a} \approx \frac{1,24 \cdot 10^{12}}{N_a \left[cm^{-3} \right]} \; cm$$

with typical lightly-doped Si-substrate $N_a \approx 10^{15}\ cm^{-3}$ we get:

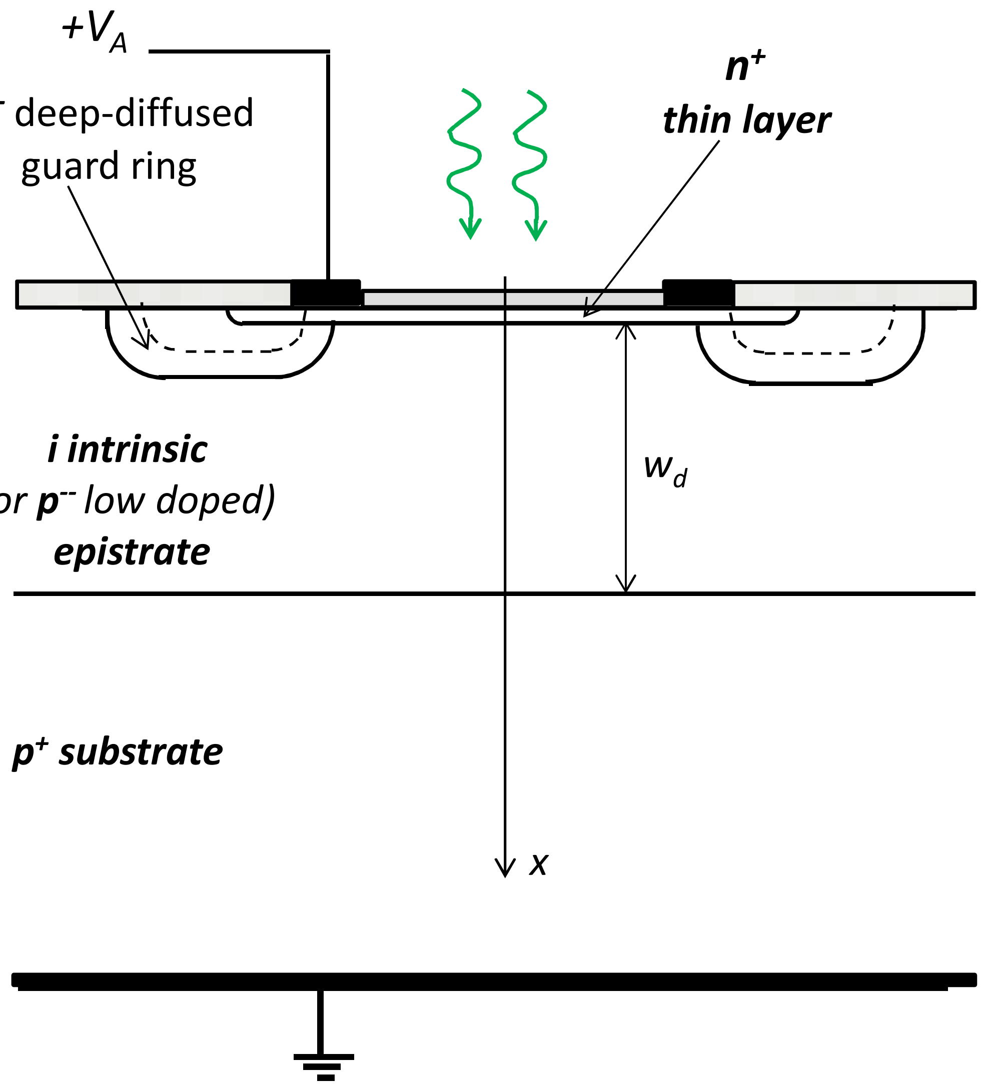
- depletion depth $w_{dm} \leq 12,4\ \mu m$ not well suitable for $\lambda > 700 nm$;
  fairly high bias voltage ; $V_A = E_B w_{dm}/2 \approx 124\,V$
- high resistivity of substrate $\rho \approx 4,5\ \Omega cm$; the current path from junction to the substrate ohmic contact has resistance $R_D \approx$ a few $k\Omega$, which is in series to the junction and impairs the PD performance (slows dynamic response, etc.)

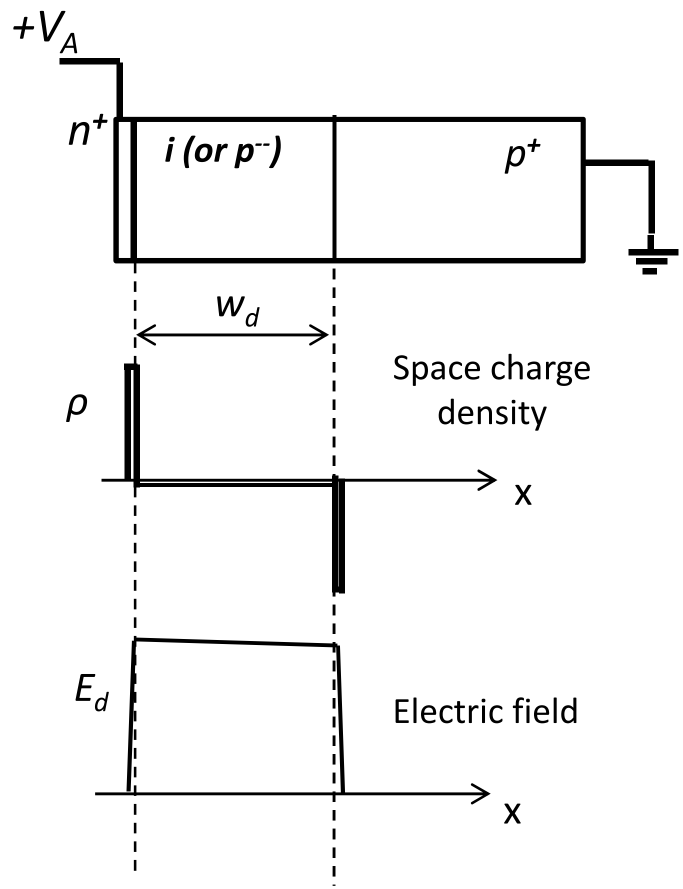
with very low-doped substrate $N_a \approx 10^{14}\ cm^{-3}$ we get wider depletion layer, but:

- higher bias voltage is required: $V_A = E_B w_{dm}/2 \approx 1.240\,V$
- higher substrate resistivity $\rho \approx 45\ \Omega cm$ and higher internal resistance $R_D \approx$ some $10 k\Omega$

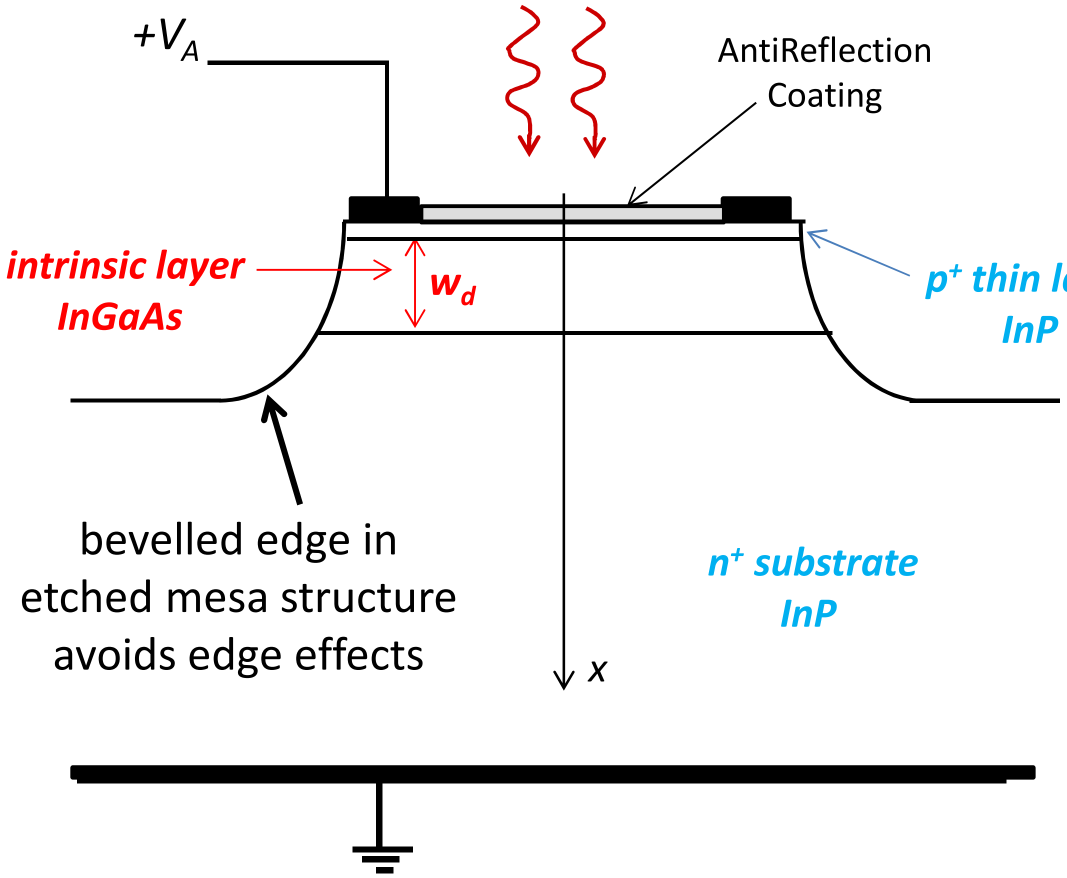
These problems of the p-n detector are overcome by the **p-i-n device structure**: detector junction built in a intrinsic (or ultra-low-doped) Si-epilayer grown onto a high-doped substrate, with thickness of the epistrate equal to the required w_d

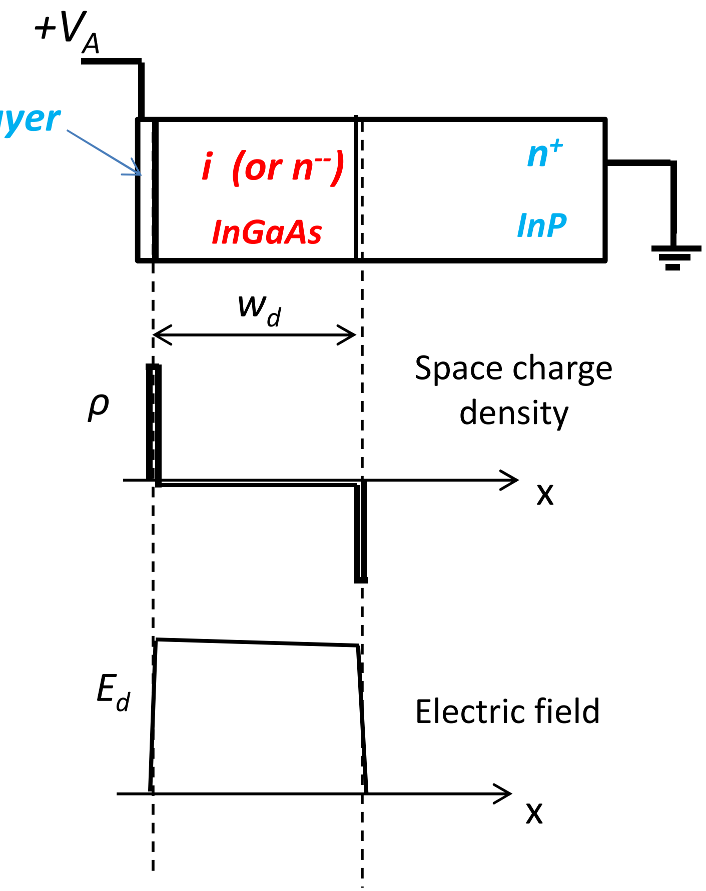
Si-PD: p-i-n epitaxial structure





InGaAs-InP infrared PD: p-i-n mesa structure





IR photons with λ ≥ 800nm are
STRONGLY absorbed in the InGaAs layer
NOT absorbed in the InP layers