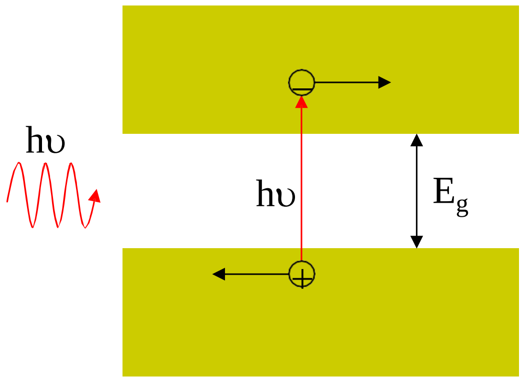
Photodiode detectors

- Background concepts
- p-n photodiodes
- Photoconductive/photovoltaic modes
- p-i-n photodiodes
- Responsivity and bandwidth

Electron-hole photogeneration

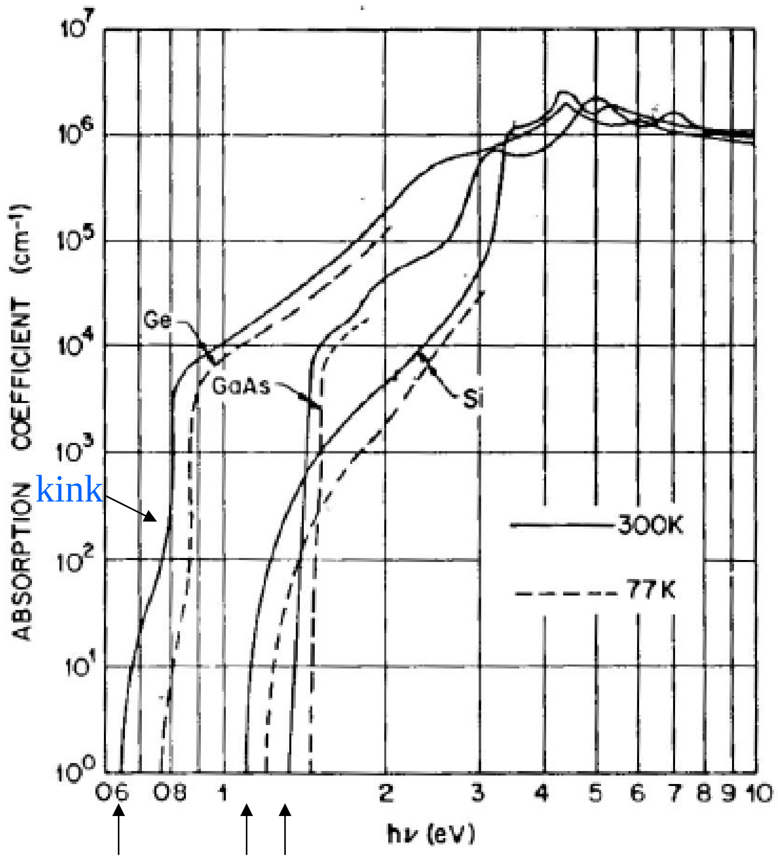
- Most modern photodetectors operate on the basis of the *internal photoelectric effect* – the photoexcited electrons and holes remain within the material, increasing the electrical conductivity of the material
- *Electron-hole photogeneration* in a semiconductor



- absorbed photons *generate* free electron-hole pairs

•*Transport* of the free electrons and holes upon an electric field results in a *current*

Absorption coefficient



Bandgaps for some *semiconductor photodiode materials* at 300 K

	Bandgap (eV) at 300 K	
	Indirect	Direct
Si	1.14	4.10
Ge	0.67	0.81
GaAs	-	1.43
InAs	-	0.35
InP	-	1.35
GaSb	-	0.73
$In_{0.53}Ga_{0.47}As$	-	0.75
$In_{0.14}Ga_{0.86}As$	-	1.15
$GaAs_{0.88}Sb_{0.12}$	-	1.15

Absorption coefficient

- E.g. absorption coefficient $\alpha = 10^3$ cm^{-1}
- Means an 1/e optical power absorption length of

$$1/\alpha = 10^{-3}\ \text{cm} = 10\ \mu\text{m}$$

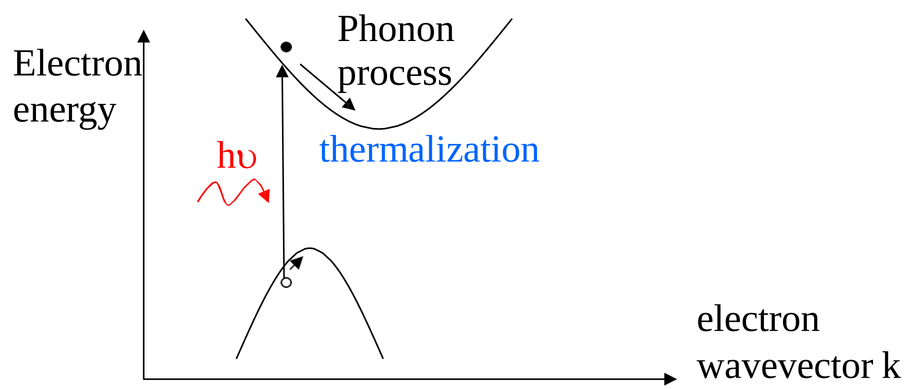
- Likewise, $\alpha = 10^4$ cm^{-1} => 1/e optical power absorption length of 1 μm.

$\alpha = 10^5$ cm^{-1} => 1/e optical power absorption length of 100 nm.

$\alpha = 10^6$ cm^{-1} => 1/e optical power absorption length of 10 nm.

Indirect absorption

- *Silicon* and *germanium* absorb light by both indirect and direct optical transitions.
- ***Indirect*** absorption requires the assistance of a *phonon* so that momentum and energy are conserved.
- *Unlike the emission process, the absorption process can be sequential, with the excited electron-hole pair thermalize within their respective energy bands by releasing energy/momentum via phonons.*
- This makes the *indirect absorption less efficient than direct absorption* where no phonon is involved.



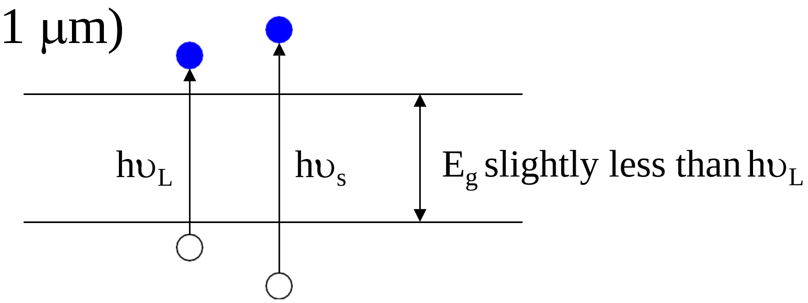
Indirect vs. direct absorption in silicon and germanium

- ***Silicon*** is *only weakly* absorbing over the wavelength band 0.8 – 0.9 μm. This is because transitions over this wavelength band in silicon are due only to the indirect absorption mechanism. The *threshold* for indirect absorption (*long wavelength cutoff*) occurs at 1.09 μm.
- The bandgap for direct absorption in silicon is 4.10 eV, corresponding to a threshold of 0.3 μm.

- ***Germanium*** is another semiconductor material for which the lowest energy absorption takes place by indirect optical transitions. Indirect absorption will occur up to a threshold of 1.85 μm.
- However, the *threshold for direct absorption* occurs at 1.53 μm, for shorter wavelengths germanium becomes strongly absorbing (*see the kink in the absorption coefficient curve*).

Choice of photodiode materials

- A photodiode material should be chosen with a *bandgap energy slightly less than the photon energy* corresponding to the *longest* operating wavelength of the system.
- This gives a *sufficiently high absorption coefficient* to ensure a good response, and yet limits the number of *thermally generated* carriers in order to attain a low "*dark current*" (i.e. current generated with no incident light).
- *Germanium photodiodes have relatively large dark currents* due to their *narrow bandgaps* in comparison to other semiconductor materials. This is a major shortcoming with the use of germanium photodiodes, *especially at shorter wavelengths* (below 1.1 μm)



III-V compound semiconductors

- Direct-bandgap III-V compound semiconductors can be better material choices than germanium for the longer wavelength region.

- Their *bandgaps can be tailored* to the desired wavelength by changing the relative concentrations of their constituents (*resulting in lower dark currents*).

- They may also be fabricated in *heterojunction* structures (which *enhances their high-speed operations*).

e.g. $In_{0.53}Ga_{0.47}As$ lattice matched to InP substrates responds to wavelengths up to around 1.7 μm. (*most important for 1.3 and 1.55 μm*)

Junction photodiodes

- The *semiconductor photodiode detector* is a p-n junction structure that is based on the internal photoeffect.

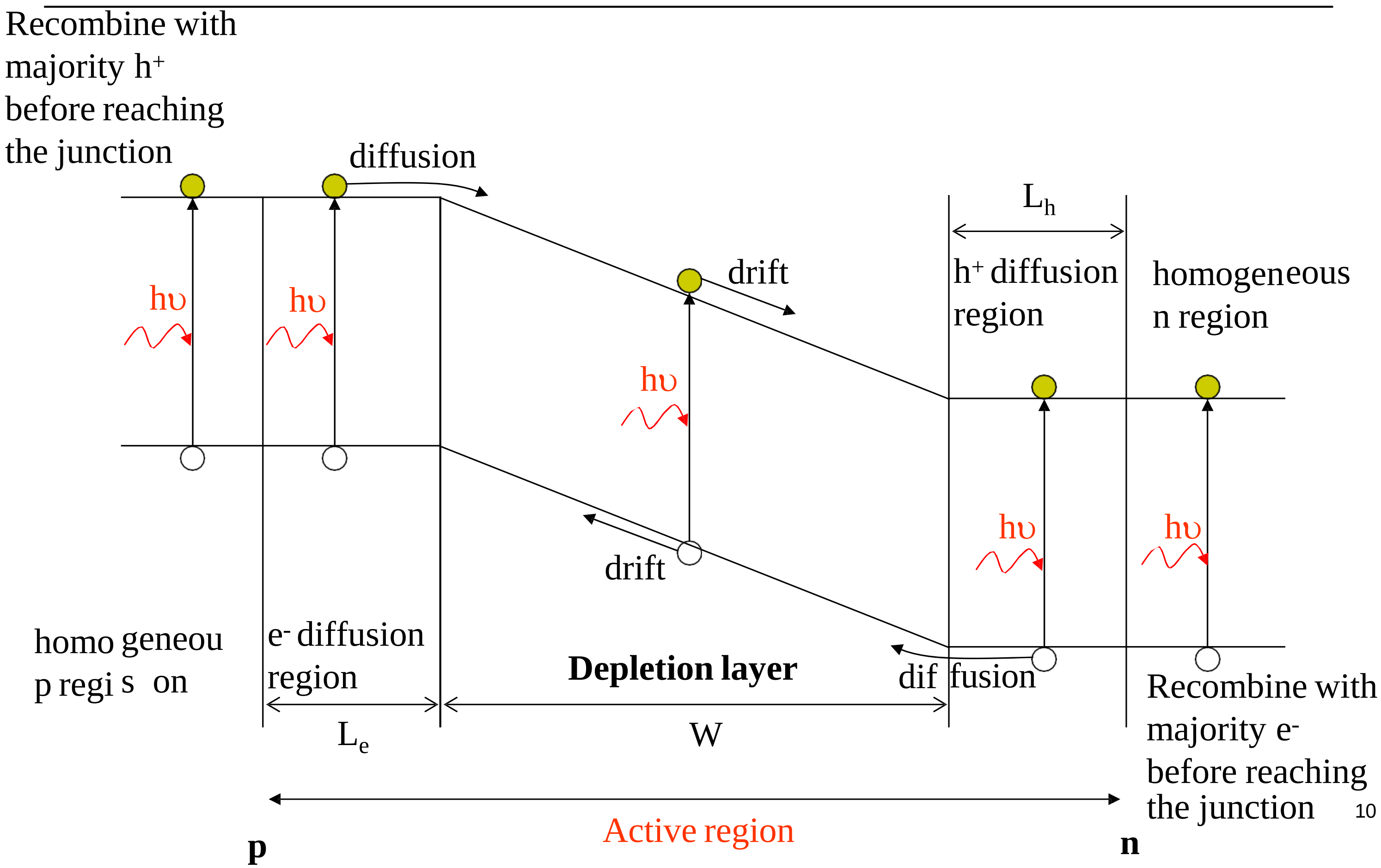
- The photoresponse of a photodiode results from the *photogeneration of electron-hole pairs through band-to-band optical absorption*.

  => The *threshold* photon energy of a semiconductor photodiode is the bandgap energy E_g of its active region.

- The *photogenerated* electrons and holes in the *depletion layer* are subject to the local electric field within that layer. The electron/hole carriers *drift* in opposite directions. This *transport* process induces an electric current in the external circuit.

- Here, we will focus on semiconductor *homojunctions*.

Photoexcitation and energy-band diagram of a p-n photodiode



- ***In the depletion layer***, *the internal electric field sweeps the photogenerated electron to the n side and the photogenerated hole to the p side*.

  => a *drift current* that flows in the *reverse* direction from the n side (cathode) to the p side (anode).

- Within one of the ***diffusion regions*** at the edges of the depletion layer, the photogenerated *minority* carrier (*hole in the n side and electron in the p side*) can reach the depletion layer by *diffusion* and then be *swept to the other side by the internal field*.

  => a *diffusion current* that also flows in the *reverse* direction.

- In the p or n ***homogeneous region***, *essentially no current is generated* because there is essentially no internal field to separate the charges and a minority carrier generated in a homogeneous region *cannot diffuse to the depletion layer before recombining with a majority carrier*.

Photocurrent in an illuminated junction

- If a junction of *cross-sectional area A* is uniformly illuminated by photons with $h\nu > E_g$, a ***photogeneration rate*** **G (EHP/cm³-s)** gives rise to a photocurrent.
- *The number of holes* created per second within a diffusion length L_h of the depletion region on the n side is $\mathbf{AL_hG}$.
- *The number of electrons* created per second within a diffusion length L_e of the depletion region on the p side is $\mathbf{AL_eG}$.
- Similarly, **A*W*G** no of carriers are generated *within the depletion region* of width W.
- The resulting *junction photocurrent from n to p*:

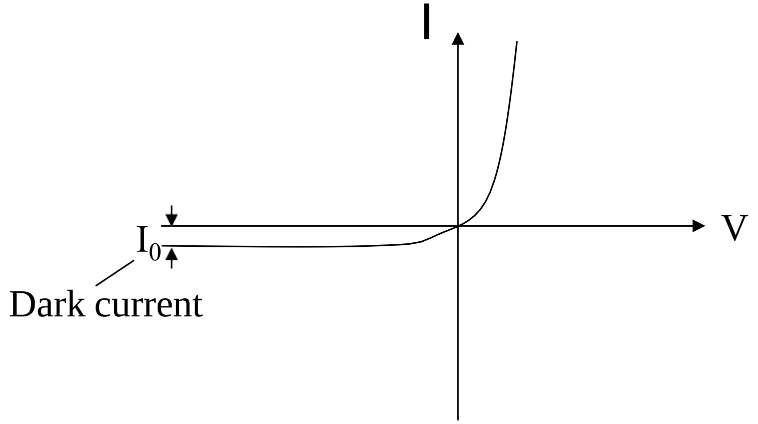
$$I_p = eA\,(L_h + L_e + W)\;G$$

Diode equation

- Recall the current-voltage (I-V) characteristic of the junction is given by the diode equation:

$$\mathbf{I = I_0(\exp(eV/k_BT) - 1)}$$

- The current I is the injection current under a *forward* bias V.
- I_0 is the "saturation current" representing *thermal-generated* free carriers which flow through the junction (*dark current*).



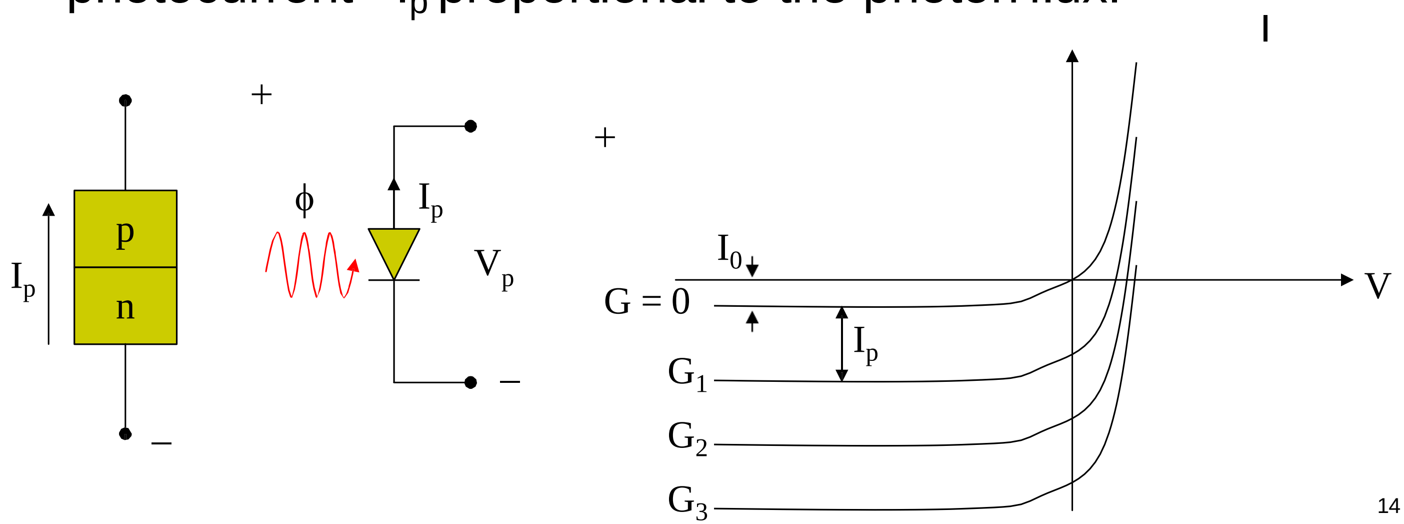
I-V characteristics of an illuminated junction

- The photodiode therefore has an I-V characteristic:

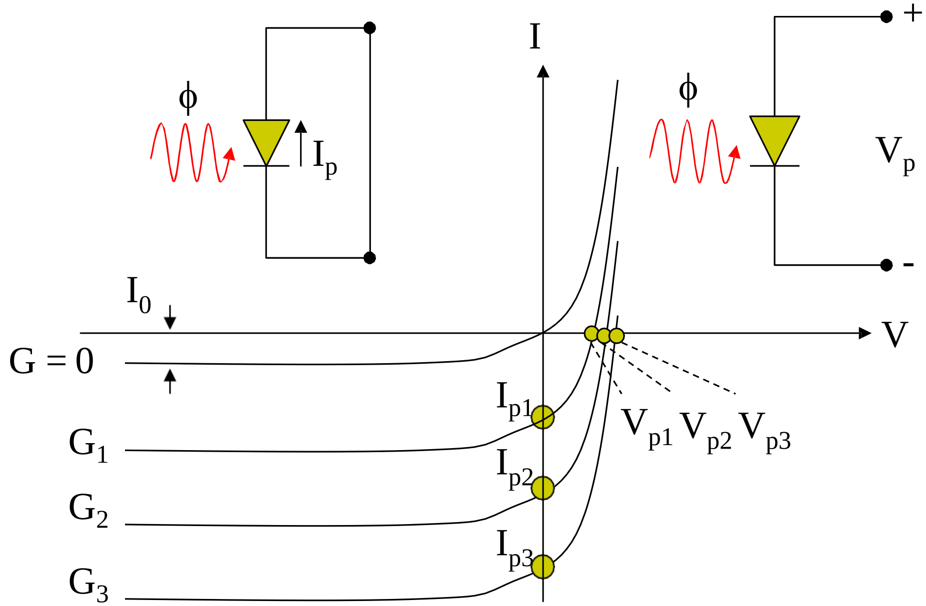
$$\mathbf{I = I_0(\exp(eV/k_BT) - 1) - I_p}$$

Where, $I_p = eA\,(L_h + L_e + W)\;\; G$

- This is the usual I-V curve of a p-n junction with an added photocurrent $-I_p$ proportional to the photon flux.



Short-circuit current and open-circuit voltage



- The *short-circuit current* (V = 0) is the *photocurrent* I_p.
- The *open-circuit voltage* (I = 0) is the *photovoltage* V_p.

(I = 0) =>

$$V_p = (k_B T/e) \ln(I_p/I_0 + 1)$$

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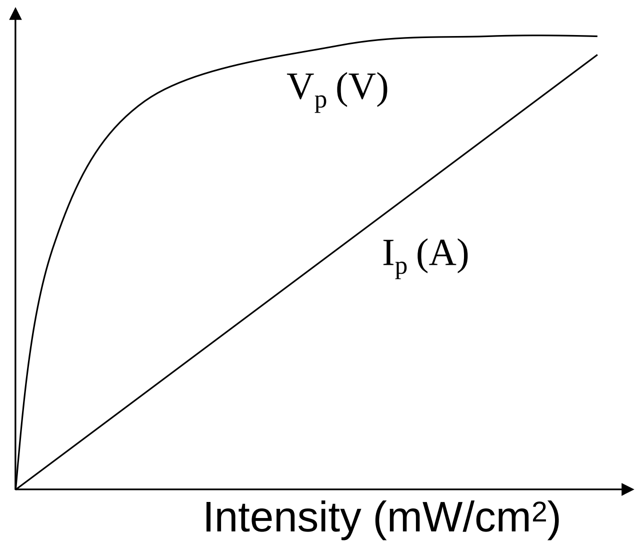
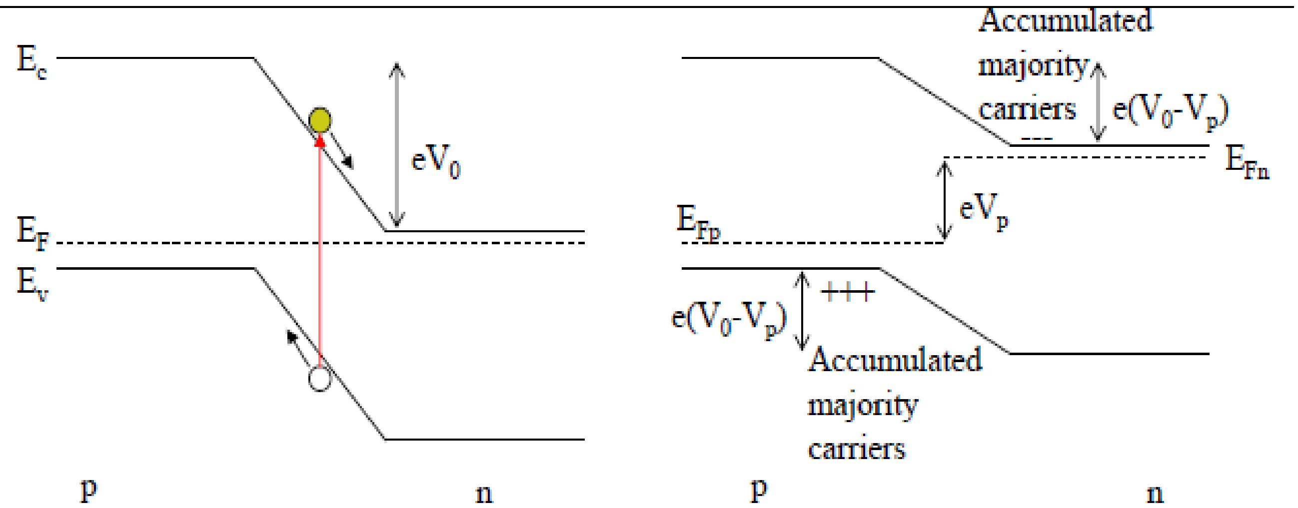
Photocurrent and photovoltage



- As the light intensity increases, the short-circuit current increases linearly ($I_p \propto G$);
- The open-circuit voltage increases *only logarithmically* ($V_p \propto \ln (I_p/I_0)$) and limited by the *equilibrium contact potential*.

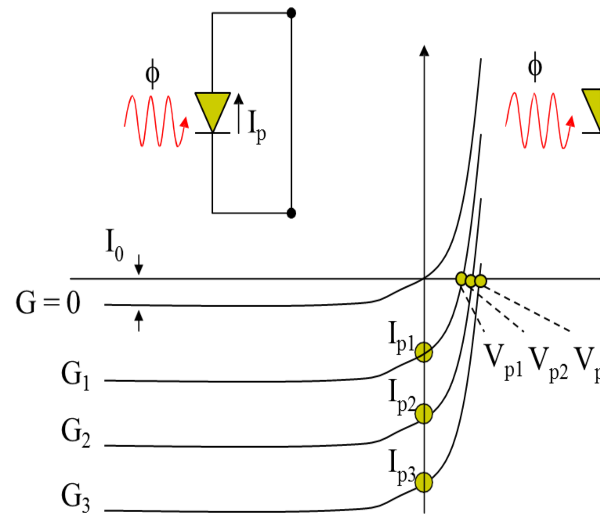
Open-circuit voltage



- The photogenerated, field-separated, majority carriers (+ve charge on the p-side, -ve charge on the n-side) forward-bias the junction.
- **The appearance of a forward voltage across an illuminated junction (photovoltage) is known as the photovoltaic effect.**
- The limit on V_p is the equilibrium contact potential V_0 as the contact potential is the maximum forward bias that can appear across a junction. (drift current vanishes with $V_p = V_0$)

Photoconductive and Photovoltaic modes

- **There are *two* modes of operation for a junction photodiode: *photoconductive* and *photovoltaic***
- The device functions in ***photoconductive*** **mode in the *third* quadrant of its current-voltage characteristics**, including the *short-circuit condition* on the vertical axis for V = 0. (*acting as a current source*)
- It functions in ***photovoltaic*** **mode in the *fourth* quadrant**, including the *open-circuit condition* on the horizontal axis for I = 0. (*acting as a voltage source with output voltage limited by the equilibrium contact potential*)



The mode of operation is determined by the *bias condition* and the *external circuitry.*

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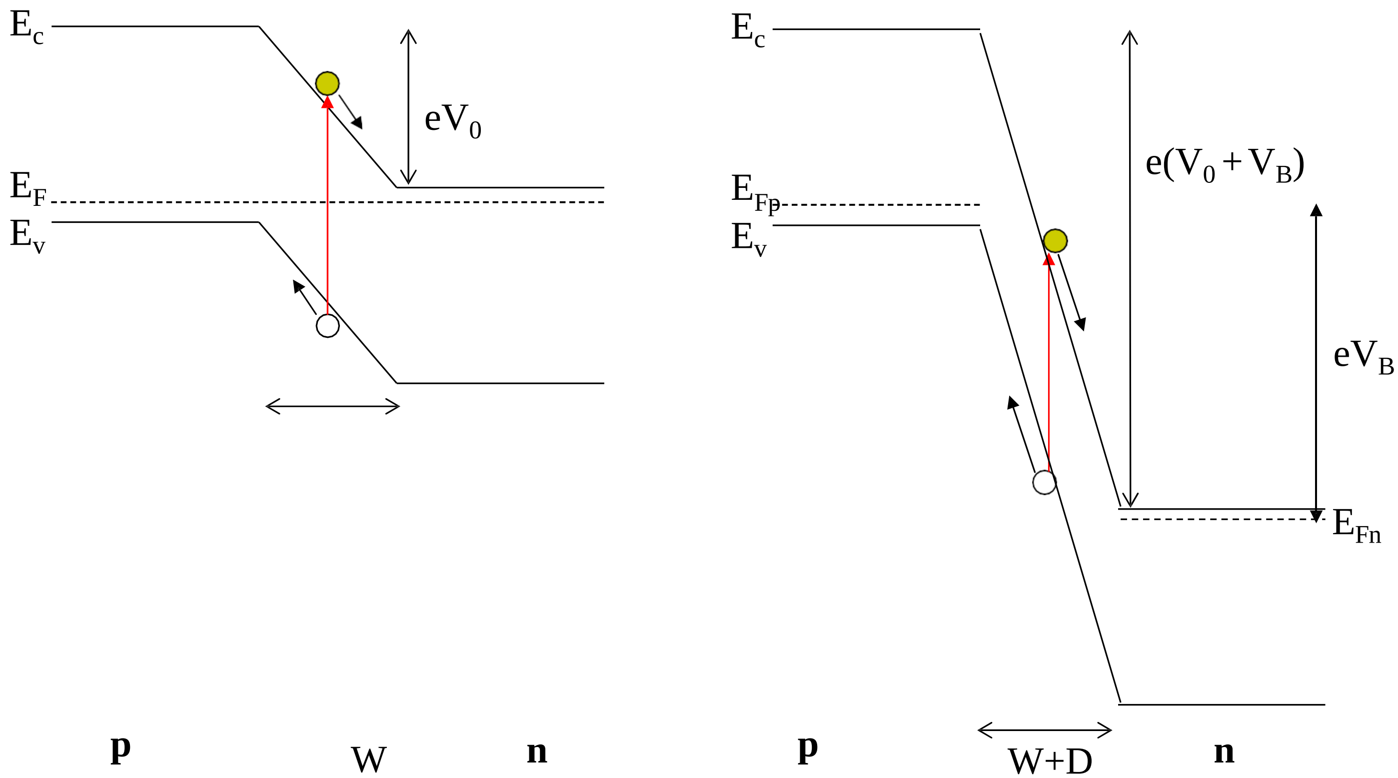
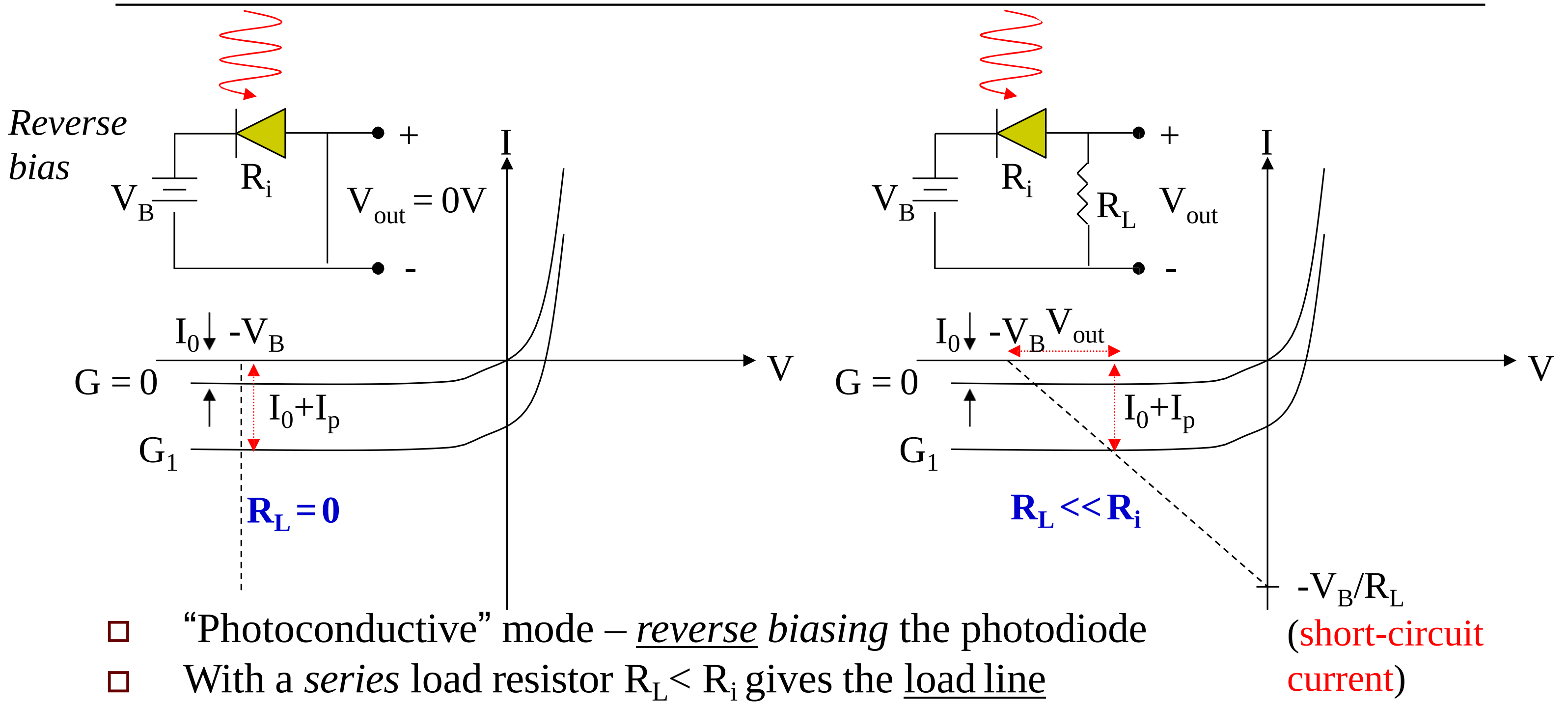
Photoconductive mode under reverse bias



(For silicon photodiodes, $V_0 \approx 0.7$ V, V_B can be up to -5 – -10 V)

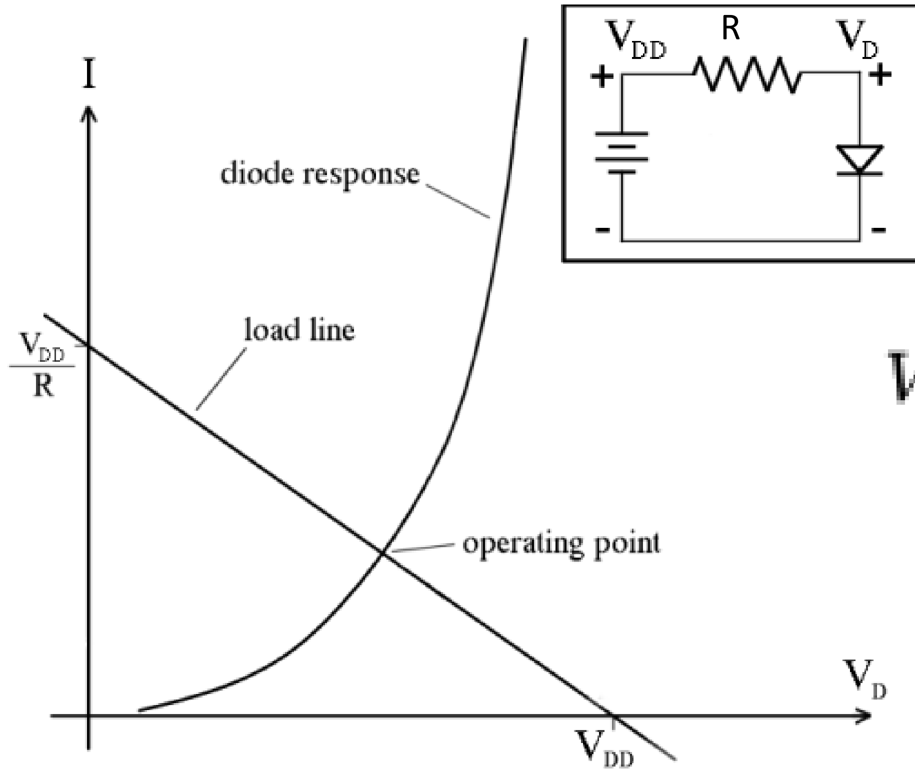
Basic circuitry and load line for the photoconductive mode



- "Photoconductive" mode – <u>*reverse*</u> *biasing* the photodiode
- With a *series* load resistor $R_L < R_i$ gives the <u>load line</u>
- Keep $V_{out} < V_B$ so that the photodiode is <u>*reverse*</u> biased (V_B *is sufficiently large*)
- Under these conditions and before it saturates, a photodiode has the following *linear response*: $V_{out} = (I_0 + I_p)R_L$

A **load line** curve represents the constraint put on the voltage and current in the nonlinear device by the external circuit.

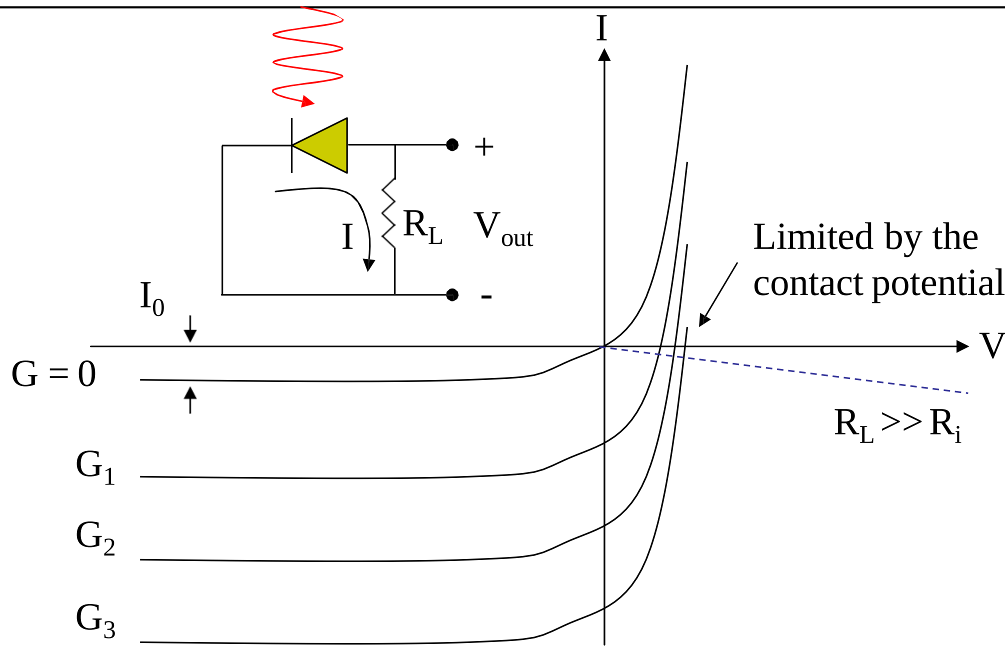
Load line (electronics)



$$V_D = V_{DD} - IR$$

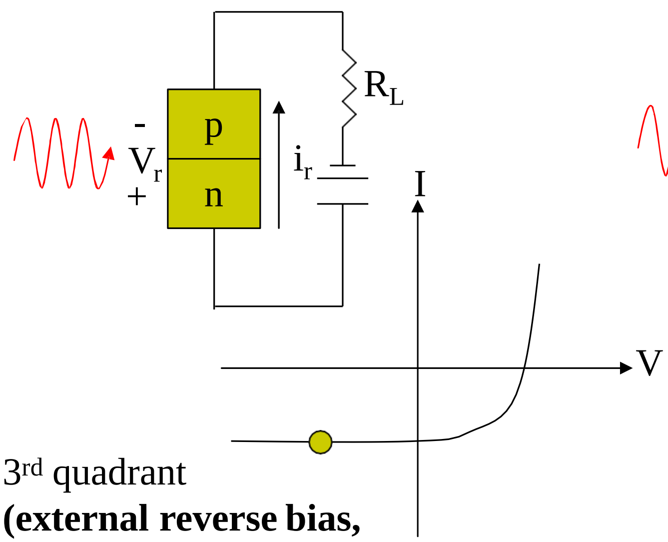
The **operating point** of the circuit will be at the **intersection of the curve with the load line**.

Basic circuitry and load line for the photovoltaic mode

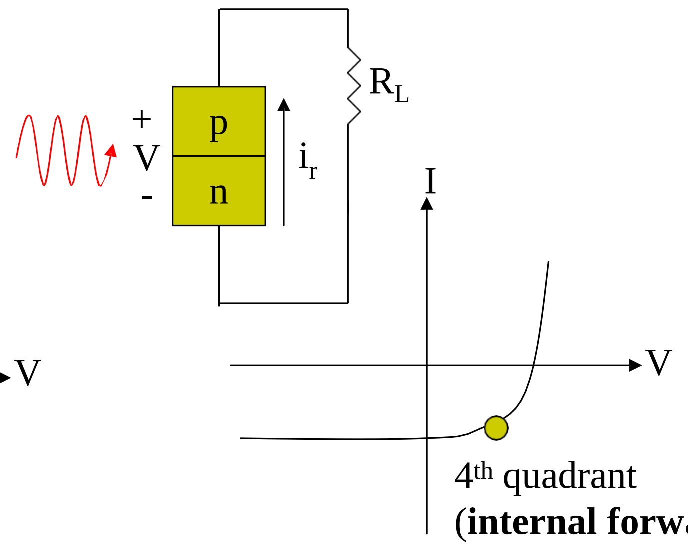


- *Does not require a bias voltage* but requires a ***large load resistance***.
- $R_L >> R_i$, so that the current I flowing through the diode, the internal resistance is negligibly small.

Operation regimes of an illuminated junction



3rd quadrant
(external reverse bias, reverse current)



4th quadrant
(**internal forward bias, reverse current**)

Photoconductive:

Power (+ve) is delivered *to the device by the external circuit* (photodetector)

Photovoltaic:

Power (-ve) is delivered *to the load by the device*
(solar cell/ energy harvesting)

Solar cell Parameters

Conversion of optical energy → electrical energy. (current and voltage)

For calculation of **important parameters**,

Open circuit mode , I= 0.

V_{oc} → open circuit voltage.

$$I = 0 = I_L - I_0[\exp\left(\frac{eV_{oc}}{mkT}\right) - 1]$$

$$V_{oc} = \frac{mkT}{e}\ln\left(1 + \frac{I_L}{I_0}\right)$$

V_{oc} ≈ 0.7 eV for Si solar cell.

Short circuit mode , R= 0 , V = 0.

Short circuit current, I = I_{sc} = I_L

Electrical power delivered to the load

$$P = IxV = I_L V - I_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]V$$

P is maximum for (V_m, I_m).

The conversion efficiency,

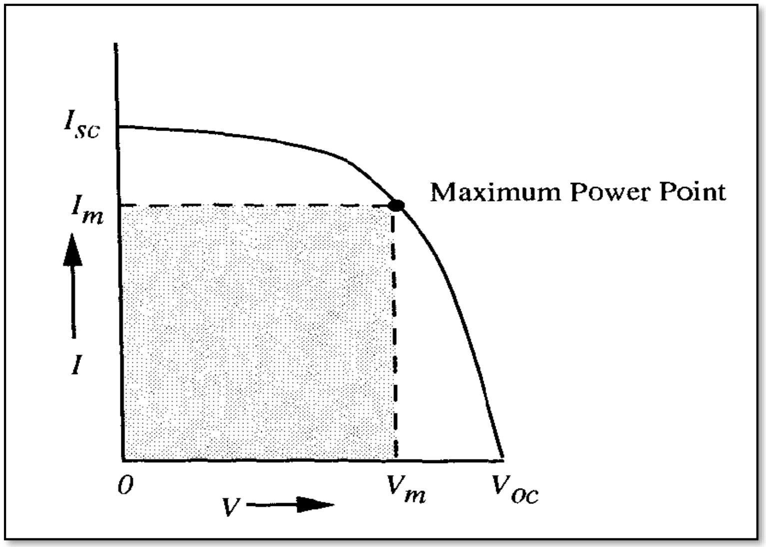


Fig. 45: The relationship between the current and voltage delivered by a solar cell. The open circuit voltage is Voc and the short circuit current is Isc. The maximum power is delivered at the point shown.

$$\eta_{conv} = \frac{\text{output electrical power}}{\text{input optical power}} = \frac{P_m}{P_{in}} x100\%$$

$$= \frac{I_m V_m}{P_{in}} x100\%$$

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Fill factor

$$F_f = \frac{I_m V_m}{I_{sc} V_{oc}} \approx 0.7 \text{ for most solar cell.}$$

Photons with $E > \hbar\omega$ will produce e-h pairs. $(\hbar\omega - E_g)$ excess is dissipated as heat.

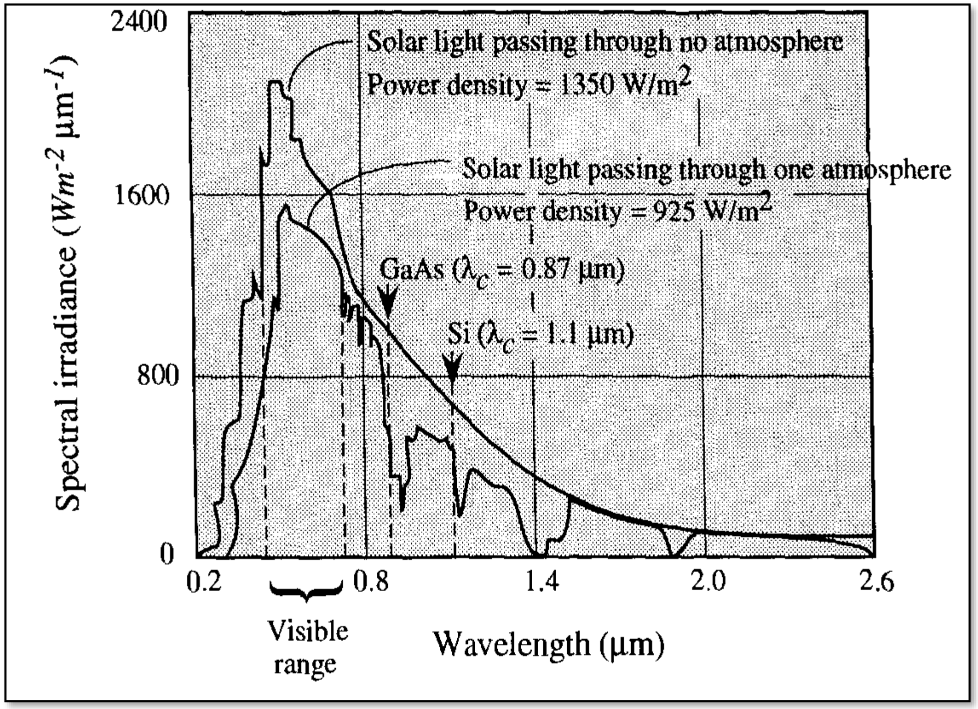

Fig. 46: The spectral irradiance of the solar energy. The spectra are shown for no absorption in the atmosphere and for the sea level spectra. Also shown are the cutoff wavelengths for GaAs and Si.

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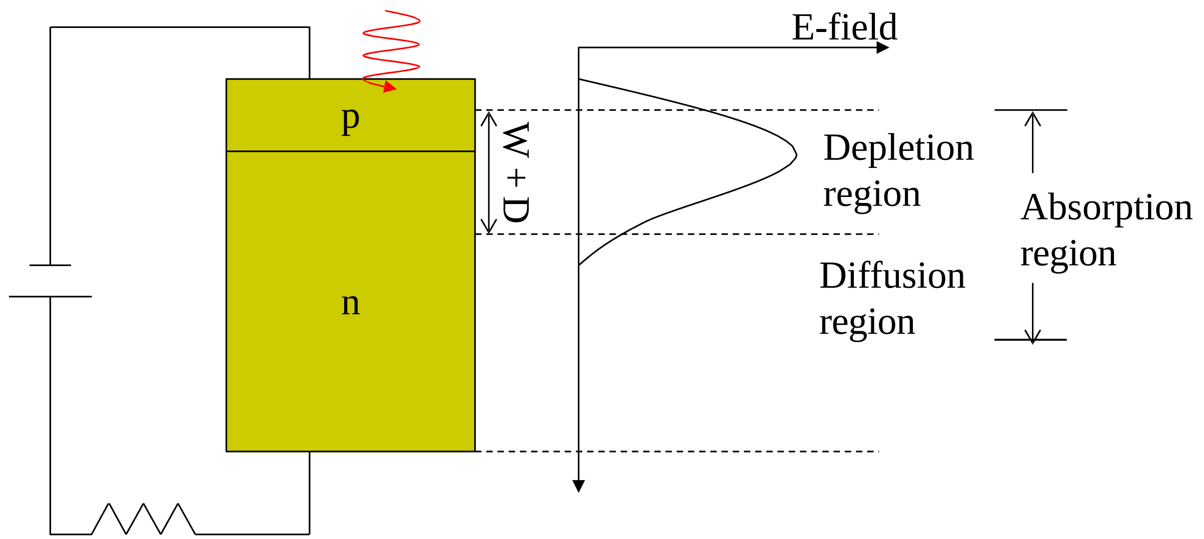
A reverse-biased p-n photodiode



- It is important that the photons are absorbed in the **depletion region.** Thus, it is made **as long as possible** (say by decreasing the doping in the n type material). The depletion region width in a p-n photodiode is normally 1 – 3 μm.
- The *depletion-layer width widens* and the *junction capacitance drops* with reverse voltage across the junction.

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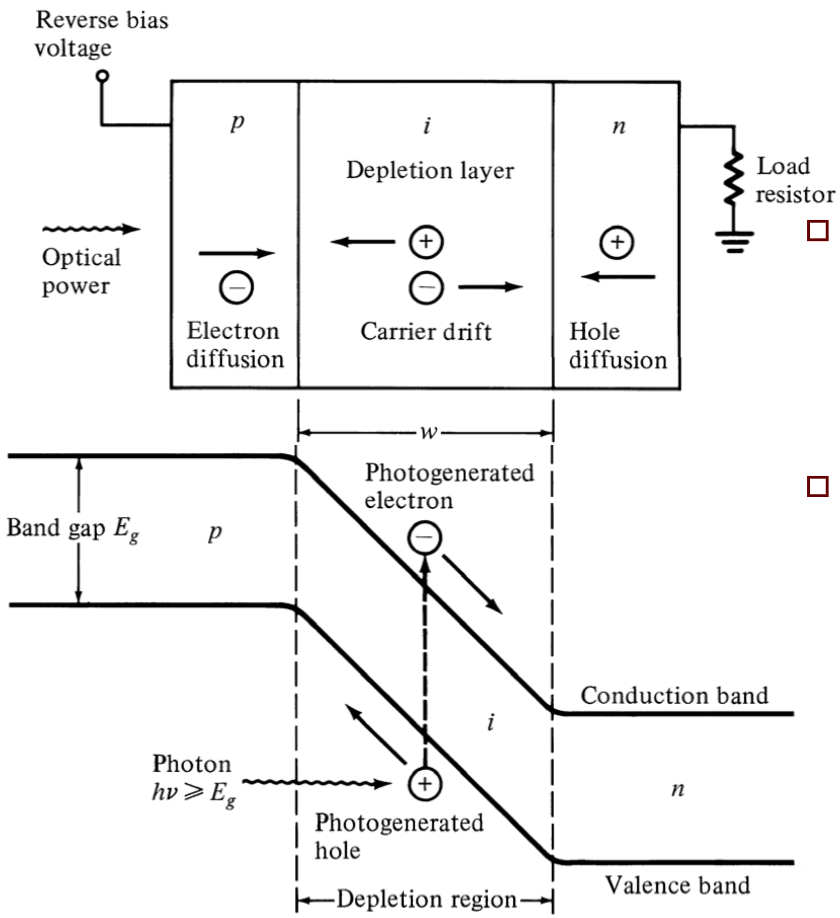
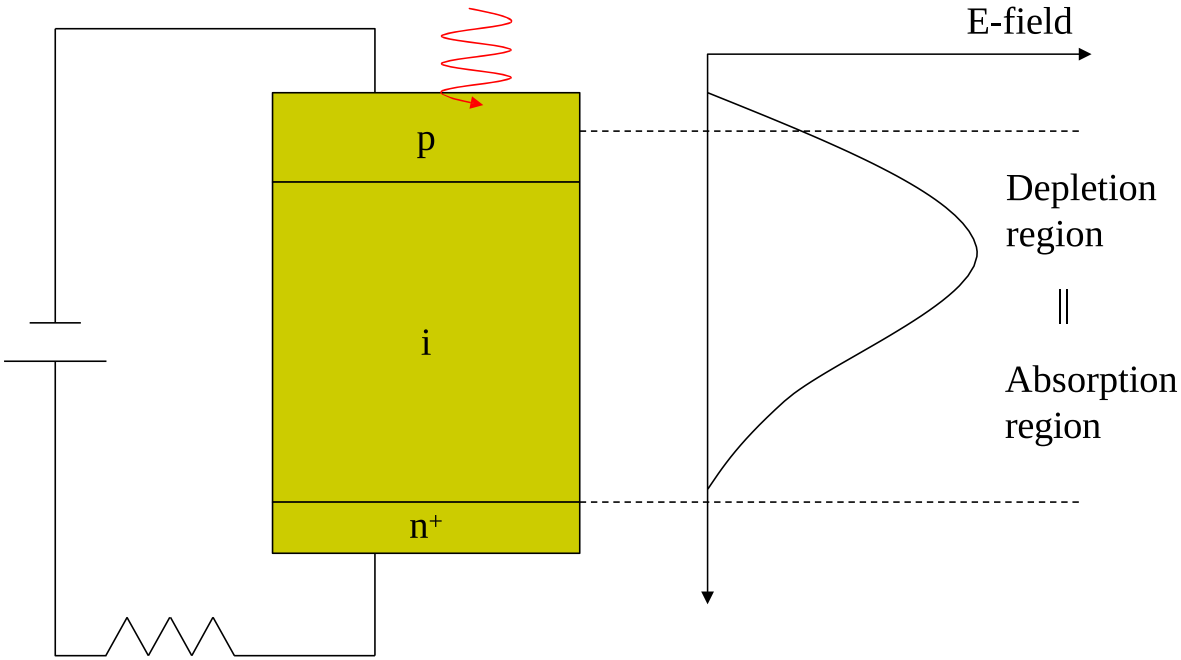
p-i-n photodiodes



- A p-i-n photodiode consists of an *intrinsic* region sandwiched between heavily doped p^+ and n^+ regions. The *depletion layer* is almost completely defined by the intrinsic region.
- In practice, the intrinsic region does not have to be truly intrinsic but only has to be highly resistive (lightly doped p or n region).

A reverse-biased p-i-n photodiode

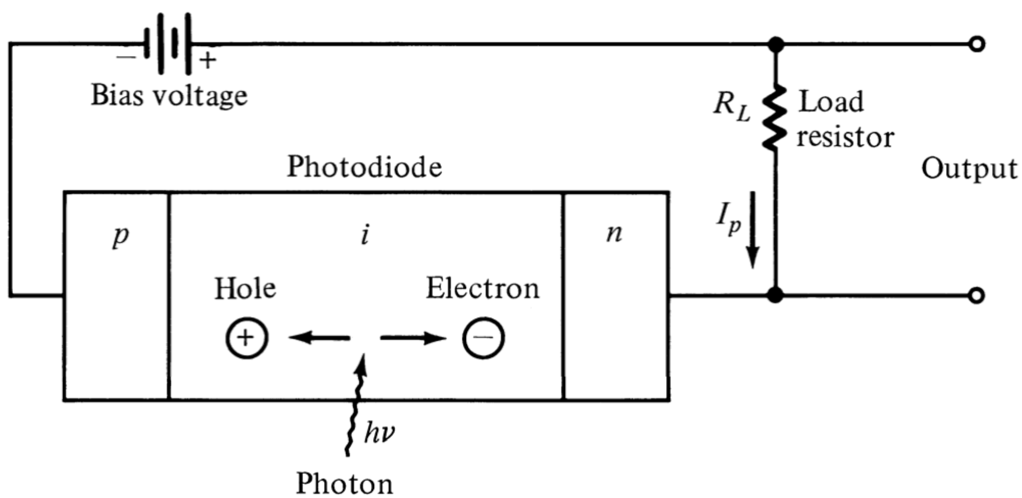


- All the absorption takes place in the depletion region. The intrinsic region can be an n-type material that is lightly doped, and to make a low-resistance contact a highly doped n-type (n^+) layer is added.

- The depletion-layer width W in a p-i-n diode does *not* vary significantly with bias voltage but is essentially fixed by the thickness, d_i, of the intrinsic region so that $W \approx d_i$.
- The internal capacitance of a p-i-n diode can be designed:

$$C_i = C_j = \varepsilon A/W \approx \varepsilon A/d_i$$

This capacitance is essentially independent of the bias voltage, remaining constant in operation.



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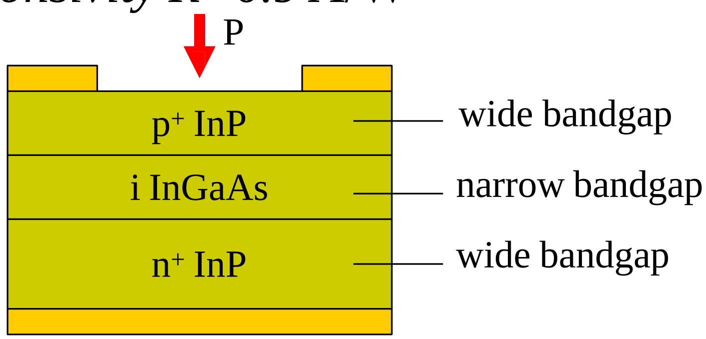
- p-i-n photodiodes offer the following advantages:
  - *Increasing the width of the depletion layer* (where the generated carriers can be transported by drift) *increases the area available for capturing light*
  - Increasing the width of the depletion layer *reduces the junction capacitance* and *thereby the RC time constant*. Yet, the transit time increases with the width of the depletion layer.
  - Reducing the ratio between the diffusion length and the drift length of the device results in *a greater proportion of the generated current being carried by the faster drift process*.

Heterojunction photodiodes

- ***Many III-V p-i-n photodiodes have heterojunction structures***.
- Examples: p^+-AlGaAs/GaAs/n^+-AlGaAs, p^+-InP/InGaAs/n^+-InP, or p^+-AlGaAs/GaAs/n^+-GaAs, p^+-InGaAs/InGaAs/n^+-InP.
- AlGaAs/GaAs (0.7 – 0.87 μm)
- InGaAs/InP (1300 – 1600 nm). A typical InGaAs p-i-n photodetector operating at 1550 nm has a *quantum efficiency* $\eta \approx 0.75$ and a *responsivity* $R \approx 0.9$ A/W



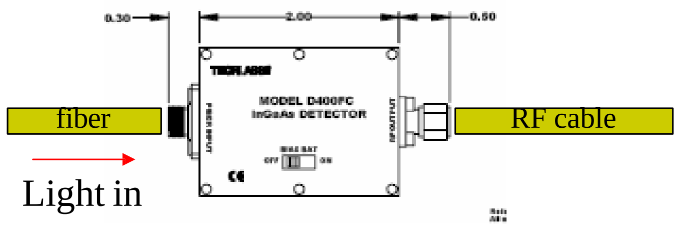
Heterojunction photodiodes

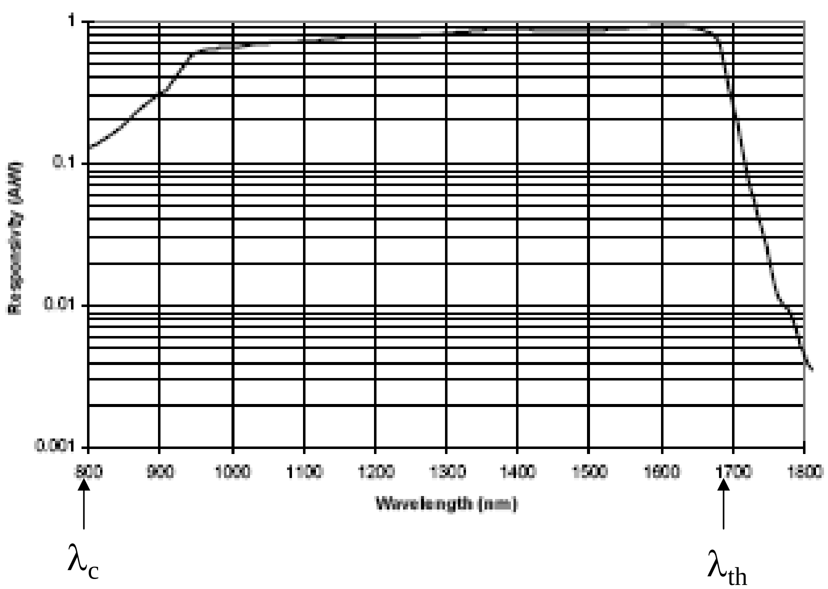
- Heterojunction structures offer additional flexibility in optimizing the performance of a photodiode.
- In a heterojunction photodiode, the active region normally has a bandgap that is *smaller* than one or both of the homogeneous regions.
- A *wide-bandgap homogeneous region*, which can be either the top p^+ region or the substrate n region, serves as a *window* for the optical signal to enter.
- The *small bandgap of the active region* determines the *long-wavelength cutoff* of the photoresponse, λ_{th}.
- The *large bandgap of the homogeneous window region* sets the short-wavelength cutoff of the photoresponse, λ_c.

=> For an optical signal that has a wavelength λ_s in the range $\lambda_{th} > \lambda_s > \lambda_c$, the *quantum efficiency* and the *responsivity* can be optimized.

InGaAs fiber-optic pin photodetector

(Thorlabs D400FC)





Spectral response	800 – 1700 nm
Peak response	0.95 A/W @ 1550 nm
Rise/fall time	0.1 ns
Diode capacitance	0.7 pF (typ)
NEP @ 1550 nm	1.0 x 10^{-15} W/√Hz
Dark current	0.7nA (typ), 1.0nA (max)
PD Active diameter	0.1 mm
Bandwidth	1 GHz (min)
Damage threshold	100 mW CW
Bias (reverse)	12V battery
Coupling lens	0.8” dia. Ball lens
Coupling efficiency	92% (typ) from both single- and multi-mode fibers over full spectral response

Application notes – output voltage

- The RF output signal (suitable for both pulsed and CW light sources) is the direct photocurrent out of the photodiode anode and is a function of the incident light power and wavelength.
- The *responsivity* $R(\lambda)$ can be used to estimate the amount of photocurrent.
- *To convert this photocurrent to a voltage* (say for viewing on an oscilloscope), add an external *load resistance*, R_L.
- The *output voltage* is given as:

$$V_0 = P\, R(\lambda)\, R_L$$

Responsivity

- The *responsivity* of a photodetector relates the electric current I_p flowing in the device circuit to the optical power P incident on it.

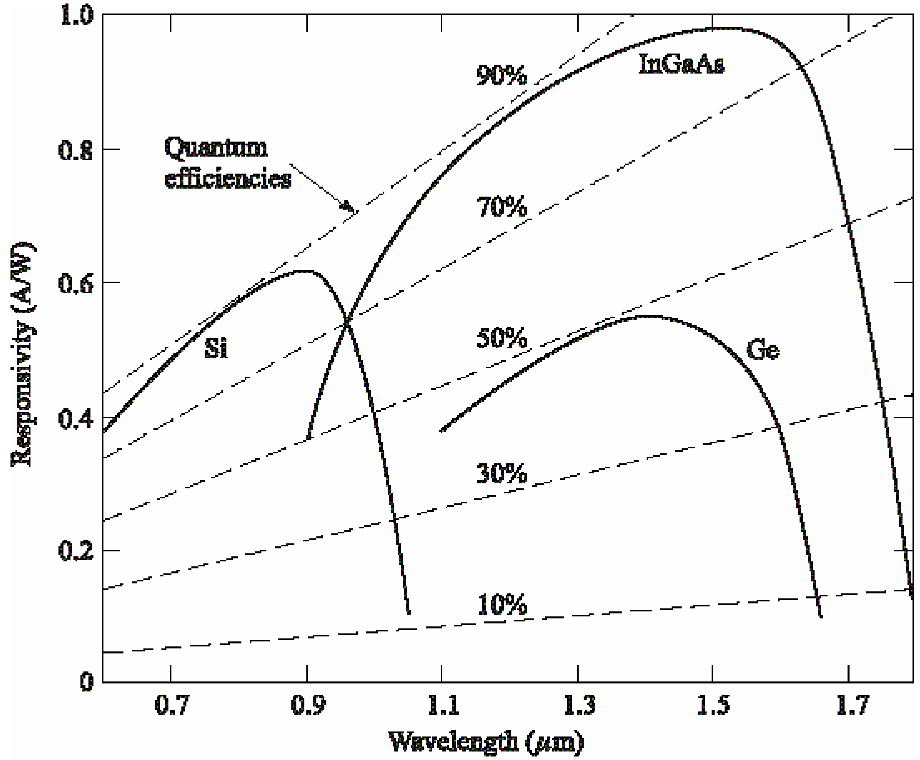
$$I_p = \eta\, e\Phi = \eta\, eP/h\upsilon \equiv R\,P \qquad \eta\text{: quantum efficiency}$$

$$\textbf{Responsivity } \mathbf{R = I_p/P} = \eta e/h\upsilon = \eta\, \lambda/1.24 \text{ [A/W]}$$

- The responsivity is *linearly proportional* to both the *quantum efficiency* η and the free-space wavelength λ.

  (e.g. for $\eta = 1$, $\lambda = 1.24$ μm, R = 1 A/W)

Responsivity vs. wavelength



- Responsivity R (A/W) vs. wavelength with the quantum efficiency η shown on various dashed lines

Quantum efficiency

- The ***quantum efficiency*** (***external quantum efficiency***) η of a photodetector is the probability that a single photon incident on the device generates a photocarrier pair that contributes to the detector current.

$$\eta(\lambda) = \zeta\,(1\text{-}R)\,[1 - \exp(-\alpha(\lambda)d)]$$

R is the optical power reflectance at the surface, ζ is the fraction of electron-hole pairs that contribute to the detector current, $\alpha(\lambda)$ the absorption coefficient of the material, and **d** the photodetector depth.

ζ is the fraction of electron-hole pairs that *avoid recombination (often dominated at the material surface)* and contribute to the useful photocurrent. *Surface recombination* can be reduced by careful material growth and device design/fabrication.

$[1 - \exp(-\alpha(\lambda)d)]$ represents the fraction of the photon flux absorbed in the bulk of the material. The device should have a value of d that is *sufficiently large*. ($d > 1/\alpha$, $\alpha = 10^4\ cm^{-1}$, $d > 1\ \mu m$)

Dependence of quantum efficiency on wavelengths

- The characteristics of the semiconductor material determines the spectral window for large η.
- The bandgap wavelength $\lambda_g = hc/E_g$ is the *long-wavelength limit* of the semiconductor material.

- ***For sufficiently short λ*, η also *decreases* because most photons are absorbed *near the surface* of the device** (e.g. for $\alpha = 10^4$ cm^{-1}, most of the light is absorbed within a distance $1/\alpha = 1$ μm; for $\alpha = 10^5 – 10^6$ cm^{-1}, most of the light is absorbed within a distance $1/\alpha = 0.1 – 0.01$ μm).
- ***The recombination lifetime is quite short near the surface*, so that the *photocarriers recombine before being collected*.** (*short-wavelength limit*)
- In the near-infrared region, silicon photodiodes with *antireflection coating* can reach 100% quantum efficiency near 0.8 – 0.9 μm.
- **In the 1.0 – 1.6 μm region, Ge photodiodes, InGaAs photodiodes, and InGaAsP photodiodes have shown high quantum efficiencies**.

Speed-limiting factors of a photodiode

- ***High-speed photodiodes*** are by far the most widely used photodetectors in applications requiring high-speed or broadband photodetection.

- **The speed of a photodiode is determined by *two* factors:**
  - **The *response time of the photocurrent***
  - **The RC *time constant of its equivalent circuit***

- Because a photodiode operating in *photovoltaic* mode has a large RC time constant due to the large internal *diffusion capacitance upon internal forward bias* in this mode of operation

  => ***only photodiodes operating in a photoconductive mode are suitable for high-speed or broadband applications*.**

Response time of the photocurrent (photoconductive mode)

- The response time is determined by two factors:
  - ***Drift*** of the electrons and holes that are photogenerated in the *depletion layer*
  - ***Diffusion*** of the electrons and holes that are photogenerated in the *diffusion regions*
- ***Drift*** of the carriers across the depletion layer is a *fast* process - given by the *transit times* of the photogenerated electrons and holes across the depletion layer.
- ***Diffusion*** of the carriers is a *slow* process – caused by the optical absorption in the diffusion regions outside of the high-field depletion region.

  (***diffusion current can last as long as the carrier lifetime***)

  => *a long tail in the impulse response of the photodiode*

  => a *low-frequency falloff* in the device frequency response

Photodiode capacitance

- ***Time constant incurred by the capacitance of the photodiode with its load*** – the *junction capacitance*

$$C_j = \varepsilon A/W$$

where ε is the permittivity of the semiconductor material and A is the diode junction area.

- A small depletion layer width W increases the junction capacitance.

(The *capacitance of the photodiode* C_{pd} is that of the junction *together with the capacitance of the leads and packaging*.

This capacitance must be *minimized* in order to reduce the RC time constant. In ideal cases, $C_{pd} \approx C_j$.)

Remarks on junction capacitance

- ***For pn junctions***, because the width of the depletion layer decreases with forward bias but increases with reverse bias, the junction capacitance increases when the junction is subject to a forward bias voltage but *decreases when it is subject to a reverse bias voltage*.
- ***For p-i-n diodes***, the width of the depletion (*intrinsic*) layer is fixed => the junction capacitance is *not* affected by biasing conditions.
- **e.g.** A GaAs p-n homojunction has a 100 μm x 100 μm cross section and a width of the depletion layer W = 440 nm. Consider the junction in thermal equilibrium *without* bias at 300 K. Find the *junction* capacitance.

$$\varepsilon = 13.18\varepsilon_0 \text{ for GaAs, } \varepsilon_0 = 8.854 \times 10^{-12}\,\text{Fm}^{-1}$$

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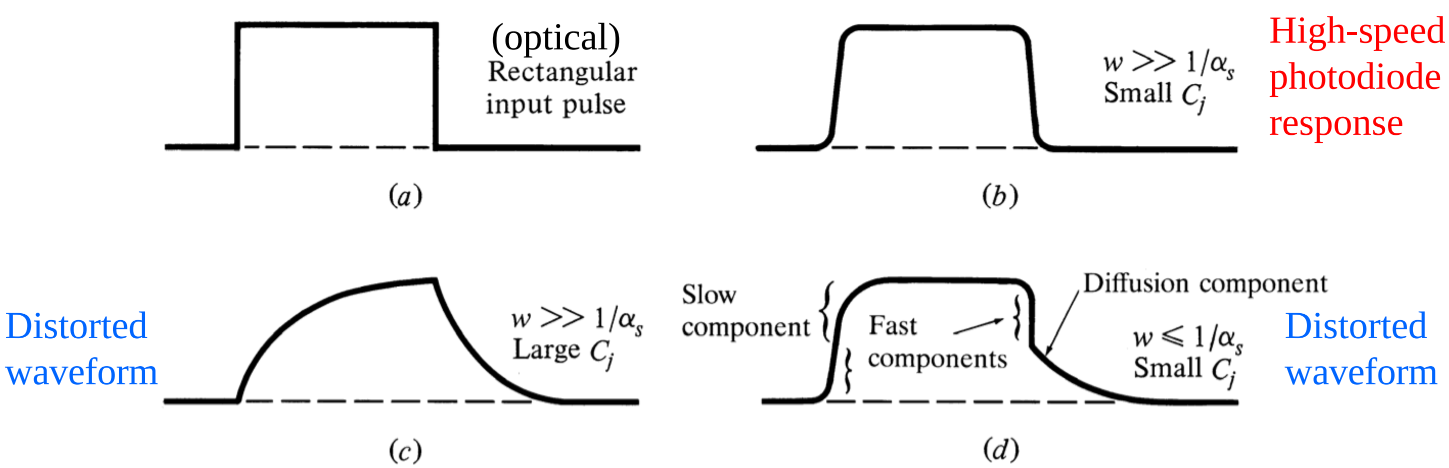
$$\Rightarrow C_j = 13.18 \times 8.854 \times 10^{-12} \times 1 \times 10^{-8}/(440 \times 10^{-9}) = 2.65\text{ pF}$$

Photodiode response to rectangular optical input pulses for various detector parameters



- W >> 1/α (all photons are absorbed in the depletion layer) and small C_j. High speed response.
- W >> 1/α, *large photodiode capacitance*, RC time limited
- W ≤ 1/α, (some photons are absorbed in the diffusion region) *diffusion component limited*

Transit-time-limited

- Thus, *for a high-speed photodiode, diffusion mechanism has to be eliminated* (by reducing the photogeneration of carriers outside the depletion layer through design of the device structure).
- *When the diffusion mechanism is eliminated*, the frequency response of the photocurrent is *only limited by the transit times of electrons and holes*.
- In a semiconductor, electrons normally have a higher mobility (*smaller electron effective mass*), thus a smaller transit time, than holes.
- *For a good estimate* of the detector frequency response, we use the *average* of electron and hole transit times:

$$\tau_{tr} = \tfrac{1}{2}(\tau_{tr}{}^{e} + \tau_{tr}{}^{h})$$

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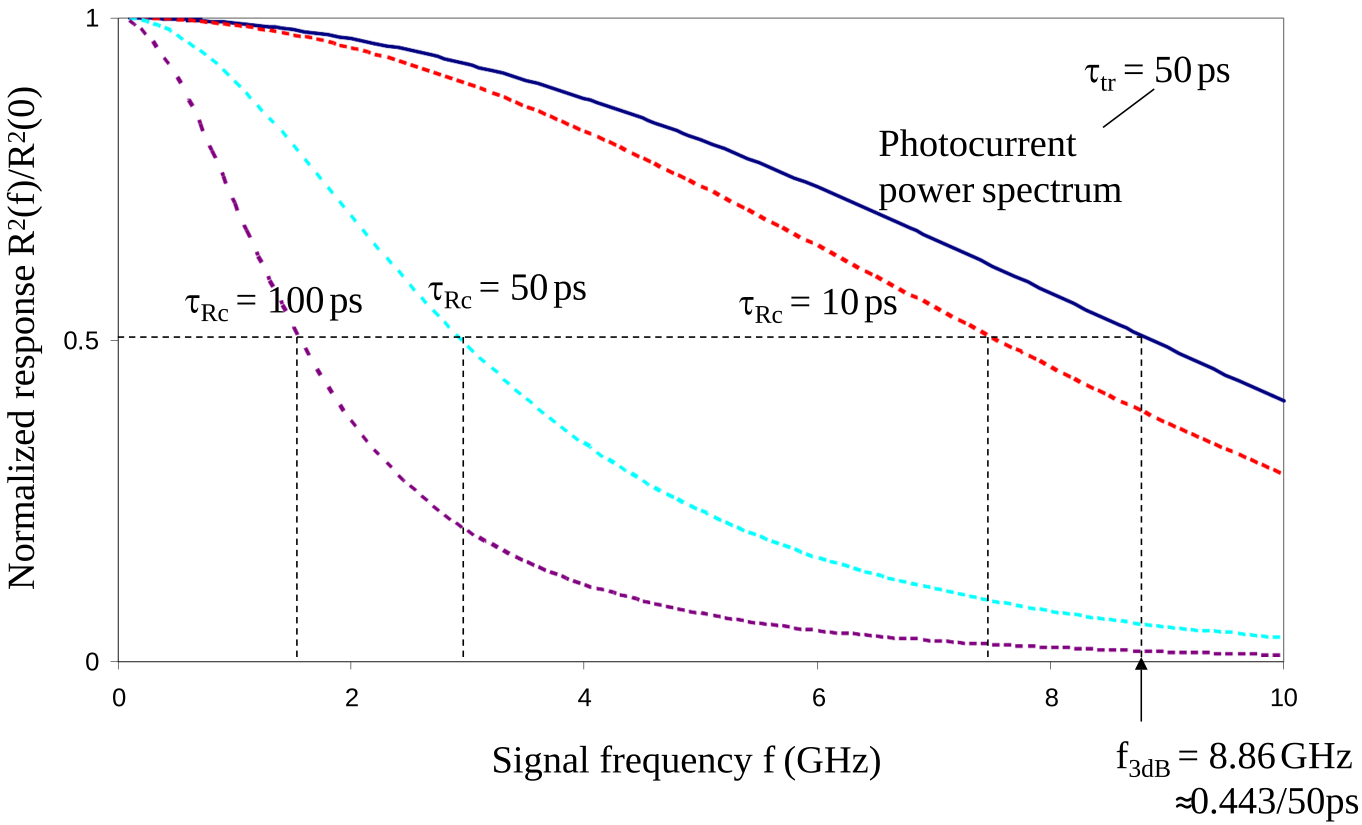
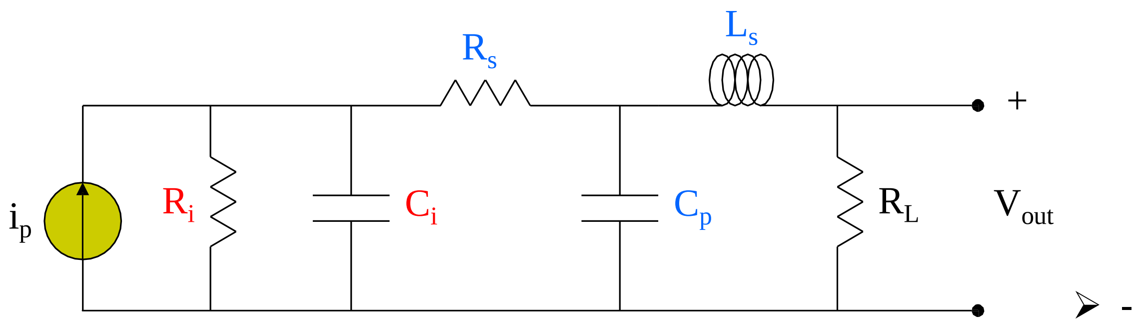
Total frequency response



Small-signal equivalent circuits



- A photodiode has an *internal resistance* R_i and an *internal capacitance* C_i *across its junction*.
- The ***series resistance*** $\mathbf{R_s}$ takes into account both resistance in the *homogeneous regions* of the diode and *parasitic resistance* from the contacts.
- The *external parallel* ***capacitance*** $\mathbf{C_p}$ **is the *parasitic capacitance*** from the contacts and the package.
- **The series inductance $\mathbf{L_s}$ is the parasitic inductance** from the wire or transmission-line connections.
- The **values of $\mathbf{R_s}$, $\mathbf{C_p}$, and $\mathbf{L_s}$ can be minimized** with careful design, processing, and packaging of the device.

- Both R_i and C_i depend on the *size* and the *structure* of the photodiode and *vary with the voltage across the junction*.

- In ***photoconductive*** mode under a *reverse* voltage, the diode has a *large* R_i normally on the order of 1 – 100 MΩ for a typical photodiode, and a *small* C_i dominated by the junction capacitance C_j.
- As the reverse voltage increases in magnitude, R_i increases but C_i decreases *because the depletion-layer width increases with reverse voltage*.

- In ***photovoltaic*** mode with a *forward* voltage across the junction, the diode has a *large* C_i dominated by the diffusion capacitance C_d.
- It still has a large R_i, *though smaller than that in the photoconductive mode*.

Frequency response of the equivalent circuit

- The **frequency response** of the equivalent circuit is determined by
  - The *internal* resistance R_i and capacitance C_i of the photodiode
  - The *parasitic* effects characterized by R_s, C_p, and L_S
  - The *load* resistance R_L
- The *parasitic effects must be eliminated* as much as possible.

- **A high-speed photodiode normally operates under the condition that $R_i >> R_L, R_s$.**
  => *equivalent resistance* $\approx R_L$

- *In the simple case, when the parasitic inductance/capacitance are negligible*, the speed of the circuit is dictated by the RC time constant $\tau_{RC} = R_L C_i$.

RC-time-limited bandwidth

e.g. In a silicon photodiode with W = 1 μm driven at *saturation drift velocity*,

$$\tau_{tr} \approx 10^{-4}\ \text{cm}/10^{7}\ \text{cm s}^{-1} \approx 10\ \text{ps}$$

Suppose, the diode capacitance = 1 pF and a load resistance of 50 Ω,

$$\tau_{RC} \approx 50\ \text{ps}$$

$$\Rightarrow f_{3dB} \approx 1/2\pi\tau_{RC} \approx 3.2\ \text{GHz}$$