# Semiconductor Optoelectronic Devices

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# Part III Photodetectors

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# Lecture 24

- pn photodiode

# I-V characteristics



- Based on the Shockley junction diode law, the PD current is given by

$$I_{PD} = \Re P_{in} - I_0 \left[ \exp\left( -\frac{V_{PD}}{\eta V_T} \right) - 1 \right]$$

Where the current sign is in the reverse direction (n to p). $V_{PD}$ is the reverse bias voltage, $I_0$ is the reverse saturation current (due to minority carriers). $V_T$ is the thermal voltage ($V_T=k_BT/q$, 26 mV at 300 K), eta is the ideality factor (1~2). In the reverse bias condition,

$$I_{PD} \approx \Re P_{in} + I_d$$

- When the bias voltage is large enough, the dark current

$$I_d = I_0$$

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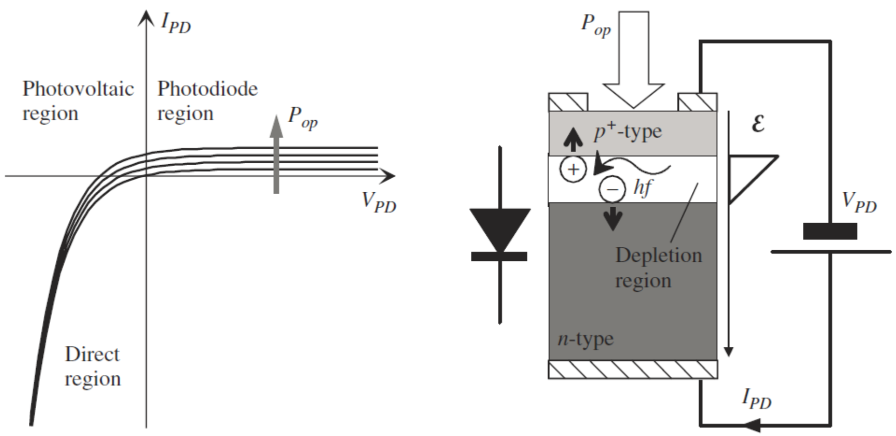
# I-V characteristics






V–I characteristics of a photodiode (left) biased by an ideal voltage source and under illumination (right).

The region in which $I_{PD} > 0$, $V_{PD} > 0$ is the *photodiode region*. If the device is under weak direct bias ($V_{PD} < 0$), the photocurrent may dominate $I_{PD} > 0$; this is the *photovoltaic region*, in which the device acts as a power source, i.e., converts the input optical power into electrical power. In this region, the applied bias is negative but the current is positive, leading to a net power flow from the photodiode to the external circuit. The photovoltaic region is the operation mode of the photodiode as a solar cell. However, the signal properties of the photodiode degrade, since the photocurrent is increasingly masked by the direct current; moreover, the responsivity will rapidly saturate for increasing input optical power. Finally, in the *direct region* the photocurrent is masked by the large direct current, and net electrical power is absorbed – an operation mode unsuited to both telecom and energy applications.

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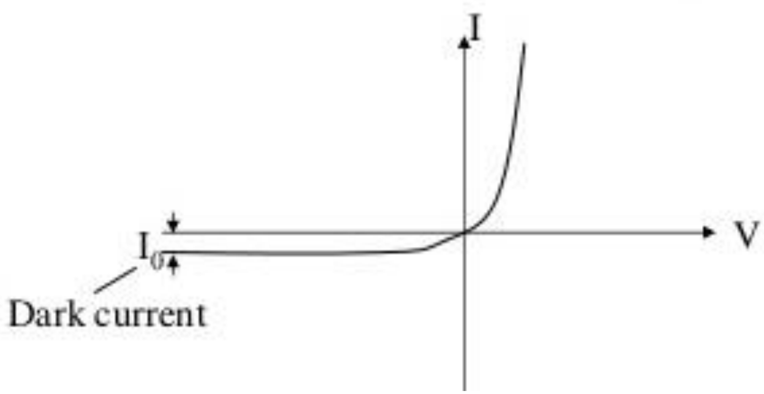
# I-V characteristics



- Without the light injection, the I-V characteristics of the pn junction (Shockley law) is

$$I = I_0(\exp(eV/k_B T) - 1)$$

- 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*).



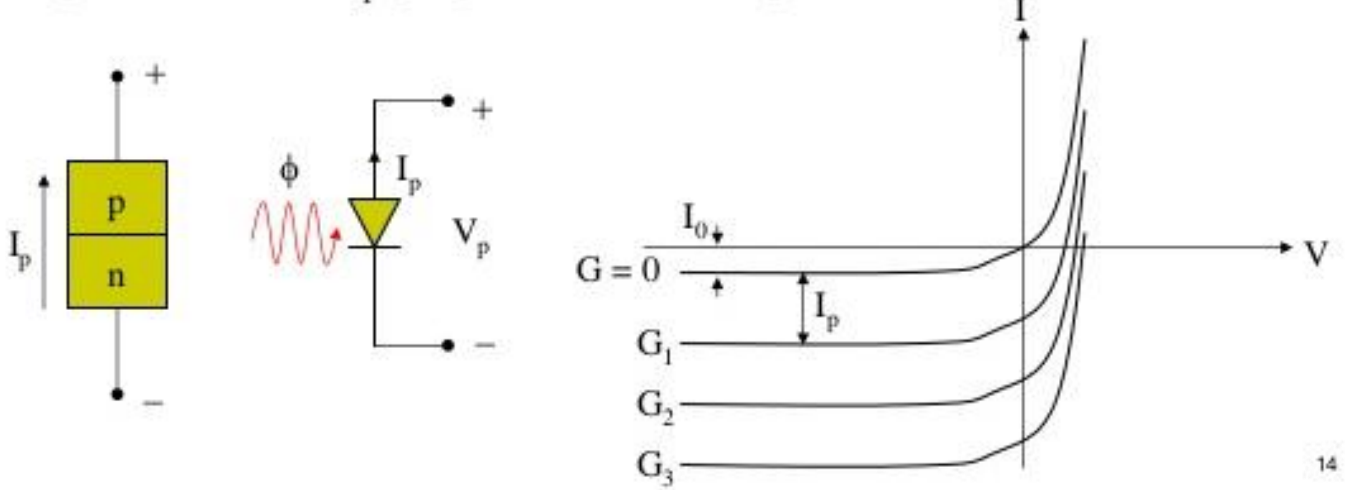
# I-V characteristics



- With the light injection, the I-V characteristics of the pn junction becomes
  - The photodiode therefore has an I-V characteristic:

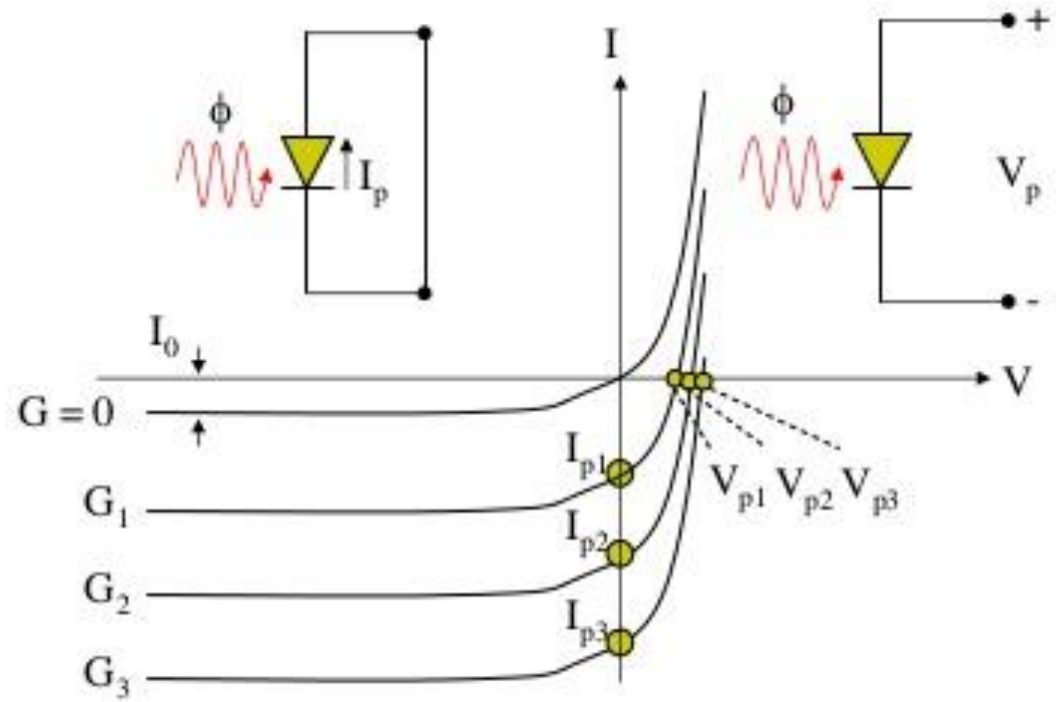
$$I = I_0(\exp(eV/k_BT) - 1) - I_p$$

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



# I-V characteristics






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

$$(I = 0) \Rightarrow \quad V_p = (k_B T/e)\ln(I_p/I_0 + 1)$$

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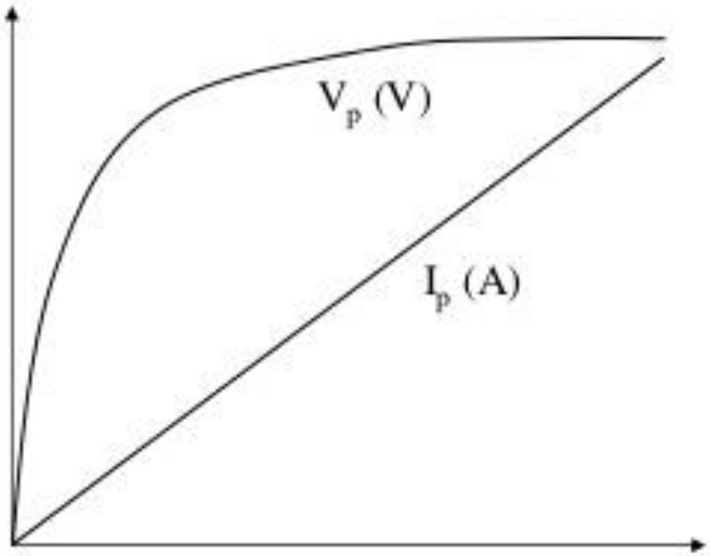
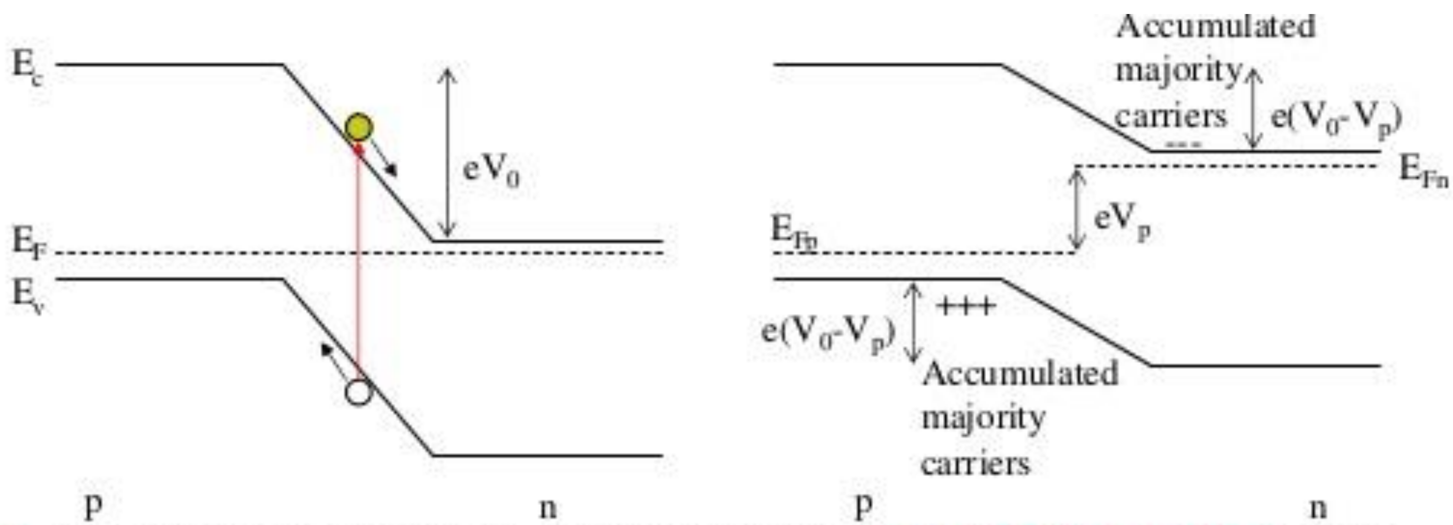
# I-V characteristics




- 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 limits by the *equilibrium contact potential*.

# I-V characteristics

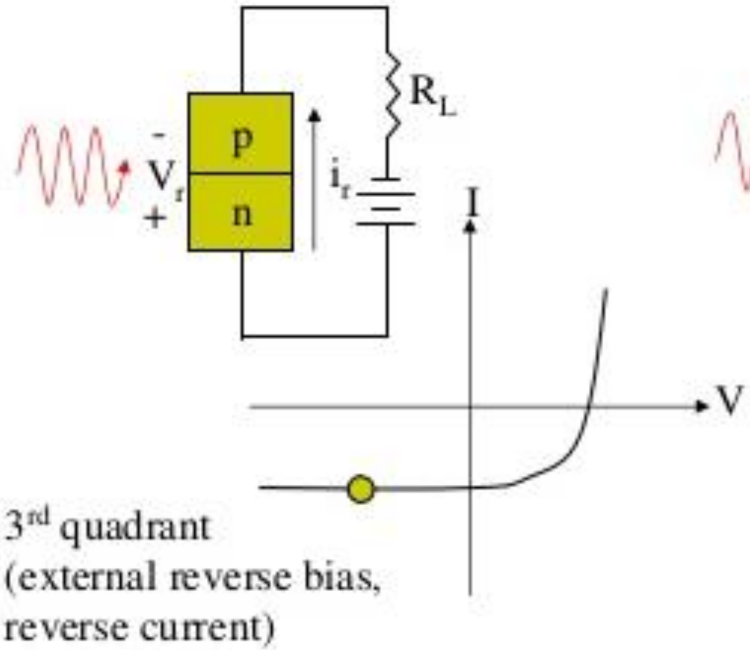


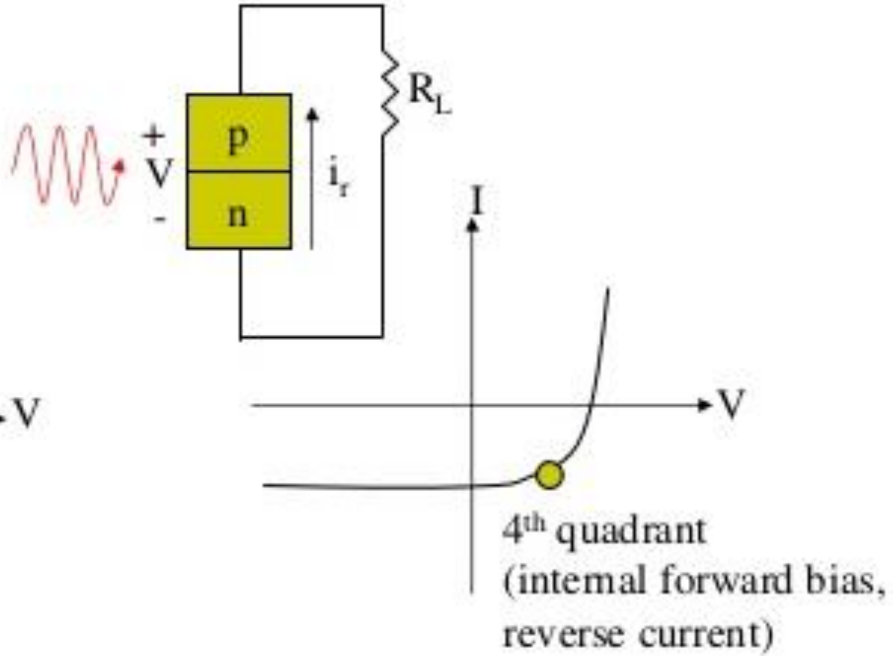

- The photogenerated, field-separated, majority carriers (+ve charge on the p-side, -ve charge on the n-side) forward-bias the junction.
- The appearance of a forward voltage across an illuminated junction (photovoltage) is known as the photovoltaic effect.
- The limit on $V_p$ is the equilibrium contact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

# I-V characteristics

- 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*.

# I-V characteristics



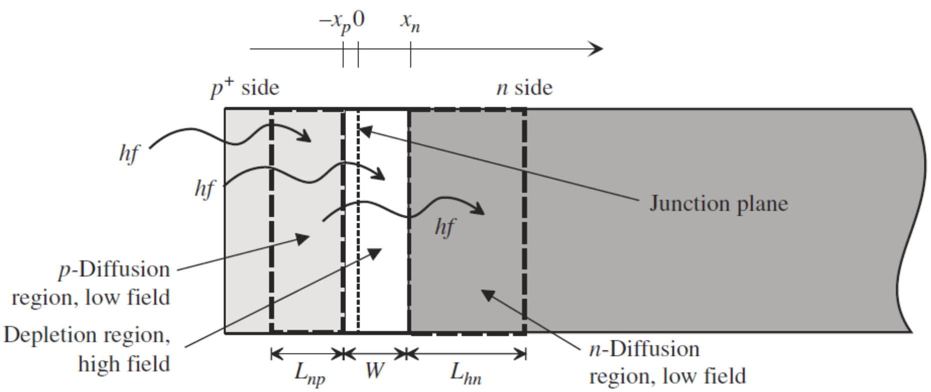

**Photoconductive**:
Power (+ve) is delivered *to the device by the external circuit* (photodetector)

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

# pn PDs



- A pn PD usually has a thin highly doped p side and a thick less doped n side.
- The photocurrent results from e-h pairs in both the depletion region and the diffusion region.




Generation of photocarriers in a *pn* photodiode: contribution of depletion and diffusion regions.

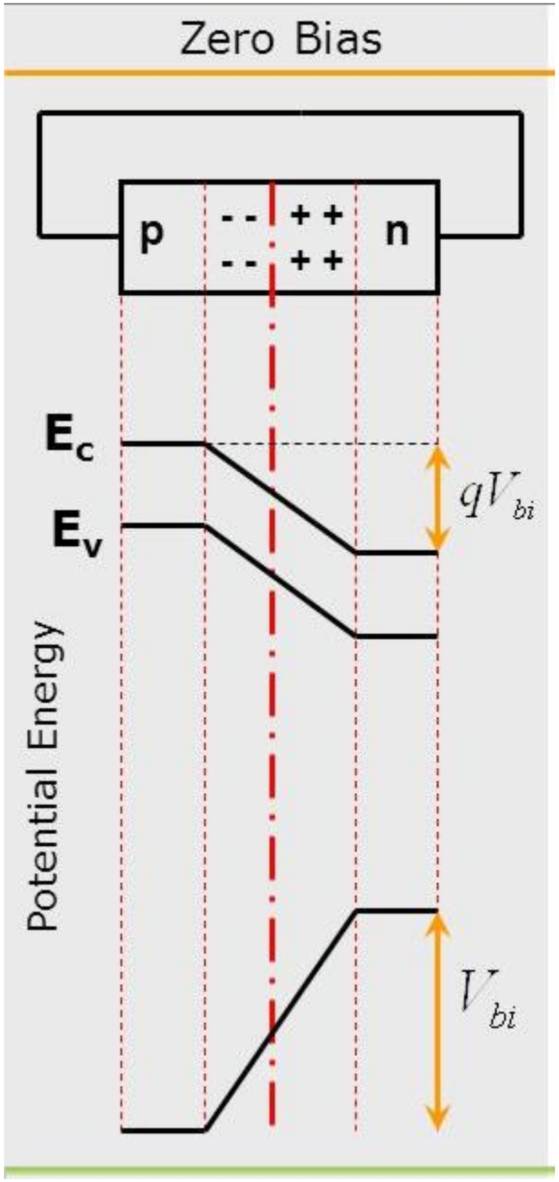
- Assume the optical generation rate is uniform $G_0$ in both regions, the total photocurrent is

$$L_{np} = \sqrt{D_{np}\tau_n}$$

$$I_L = qA\int_W G_o\,\mathrm{d}x + I_{Lp} + I_{Ln} \approx qAG_o(W + L_{np} + L_{hn})$$

$$L_{hn} = \sqrt{D_{hn}\tau_h}$$

# pn PDs



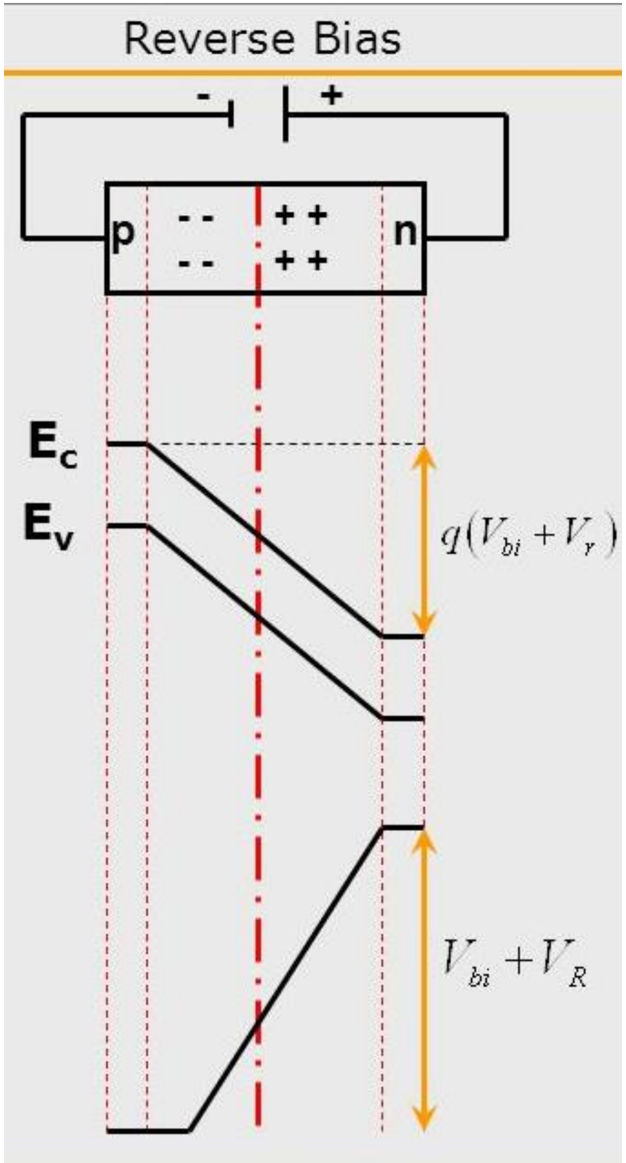

- The built-in voltage from n side to p side is

$$V_{\mathrm{bi}} = \frac{k_B T}{q} \log\left(\frac{N_D N_A}{n_i^2}\right)$$

$N_{D,A}$ is the doping density, $n_i$ is the intrinsic carrier density.

  - Therefore, the built-in voltage and the potential barrier increases with the doping level.
  - On the other hand, the depletion region width deceases with the doping level.

# Pn PDs




- In the presence of a bias $V_A$ (<0 in reverse), the depletion regions on the p side and on the n side are

$$x_n = \sqrt{\frac{2\epsilon N_{\text{eq}}\left(V_{\text{bi}} - V_A\right)}{qN_D^2}}$$

$$x_p = x_n\frac{N_D}{N_A} = \sqrt{\frac{2\epsilon N_{\text{eq}}\left(V_{\text{bi}} - V_A\right)}{qN_A^2}},$$

$$\text{where } N_{\text{eq}}^{-1} = N_D^{-1} + N_A^{-1}.$$

- The total width of the depletion region

$$W = x_n + x_p = \sqrt{\frac{2\epsilon\left(V_{\text{bi}} - V_A\right)}{qN_{\text{eq}}}},$$

- Therefore, the depletion region width and the potential barrier are enlarged by the inverse bias.

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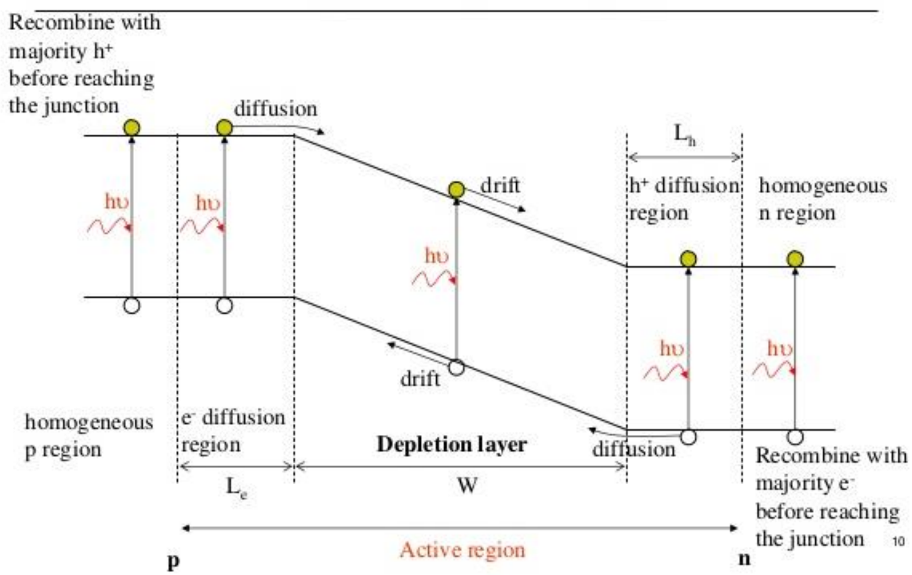
# Pn PDs



- The photocurrent is formed by both the drift current and the diffusion current.




- In the depletion region, the photogenerated carriers are drifted by the built-in electric field: electron to n side, and hole to p side.
- That is, a drift current flows in the reverse direction from n side to p side.

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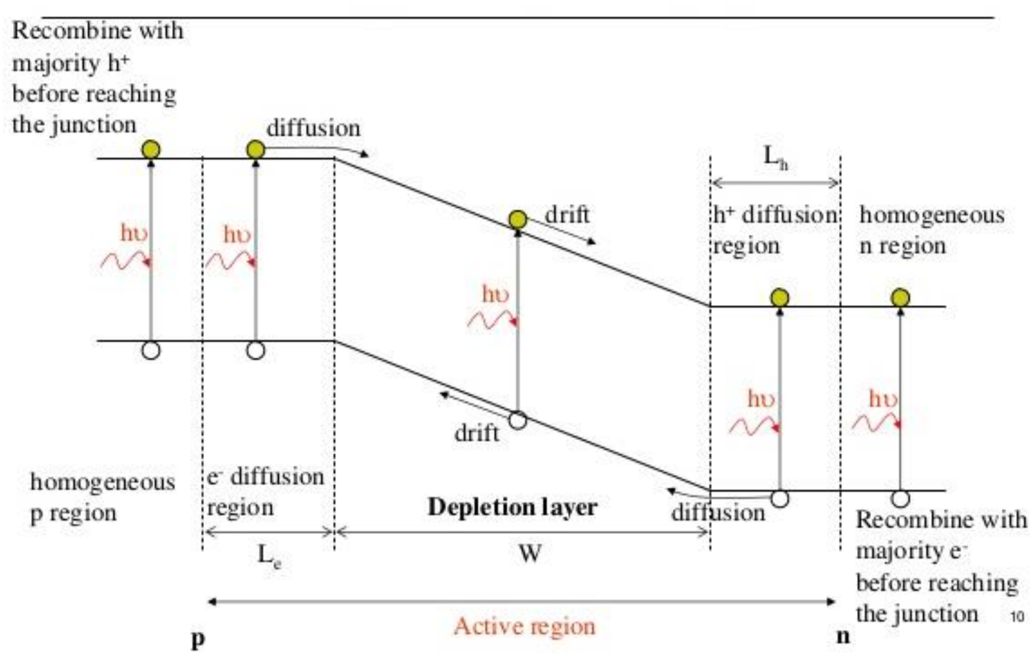
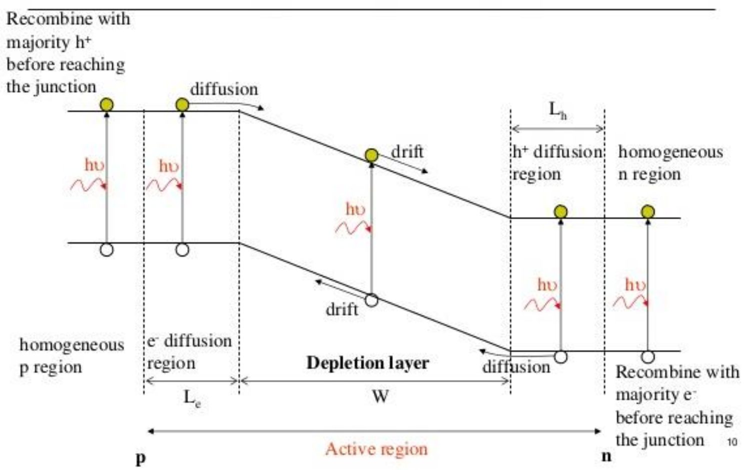
# Pn PDs

- In the diffusion region, the photogenerated minority carriers (hole in n side and electron in p side) can reach the depletion layer by diffusion and then swept to the other side by the built-in electric field.
- That is, a diffusion current also flows in the reverse direction.



# Pn PDs

- In the neutral region, no current is generated because there is no internal field to separate the charges. The photogenerated minority carriers in this region can not diffuse to the depletion region before recombining with a majority carrier.




- Therefore, the total photocurrent from n to p is

$$I_L = qA\int_W G_o\,\mathrm{d}x + I_{Lp} + I_{Ln} \approx qAG_o(W + L_{np} + L_{hn})$$

# pn PDs



- Therefore, the PD responsivity is given by

$$\Re = \frac{I_L}{P_{in}} = \frac{q}{hf}\alpha(W + L_{np} + L_{hn})$$

So the sensitivity increases with the diffusion region.

- In the frequency domain, the photocurrent is

$$I_L(\omega) = qAG_o(W + \widetilde{L}_{np} + \widetilde{L}_{hn}), \quad \widetilde{L}_{np} = \frac{L_{np}}{\sqrt{1 + \mathrm{j}\omega\tau_h}}, \quad \widetilde{L}_{hn} = \frac{L_{hn}}{\sqrt{1 + \mathrm{j}\omega\tau_n}}$$

- Therefore, the finite carrier lifetime introduces a cutoff frequency, in additional to that from the transit time and the capacitance effects.

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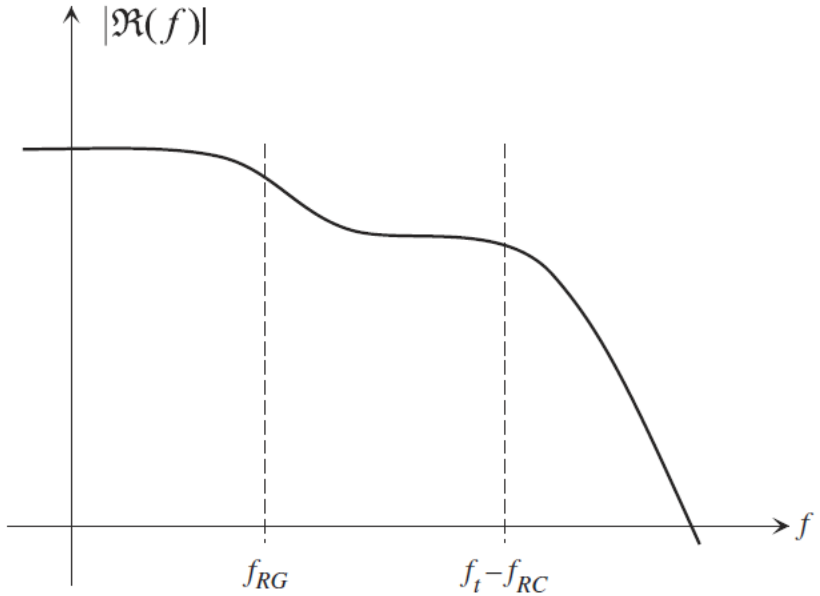
# pn PDs

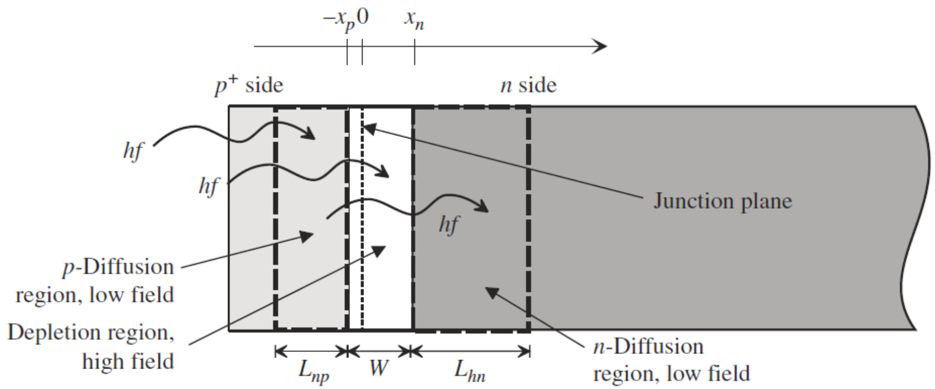


- The pn PD speed is practically limited by the carrier lifetime to 100-200 MHz.




Frequency response of a *pn* photodiode: $f_{RG}$ is the lifetime cutoff (≈MHz), $f_t$ and $f_{RC}$ are the transit time and RC cutoff, both in the GHz range (typically, the RC cutoff dominates in *pn* photodiodes).

# Pn PD current




- At a position x, the total current density is given by the sum of the drift and the diffusion currents,

$$-J_{PD} = J_{n,\mathrm{dr}} + J_{n,\mathrm{d}} + J_{h,\mathrm{dr}} + J_{h,\mathrm{d}}.$$

- Inside both diffusion regions, the excess minority carrier current density is given by the diffusion current density

$$J_n \approx J_{n,\mathrm{d}} \quad \text{for } x \leq -x_p \ (p \text{ side})$$

$$J_h \approx J_{h,\mathrm{d}} \quad \text{for } x \geq x_n \ (n \text{ side}).$$

# Pn PD current



- Inside the depletion region, the electron and hole current density change due to the photocurrent density (drift) is

$$\frac{\mathrm{d}J_n}{\mathrm{d}x} = -qG_o$$
$$\frac{\mathrm{d}J_h}{\mathrm{d}x} = -qG_o$$

- Thus, we obtain the electron current density at the depletion region edge $x_n$,

$$J_n(x_n) - J_n(-x_p) = q\int_{-x_p}^{x_n} G_o\,\mathrm{d}x \approx -qWG_o$$

$$J_n(x_n) = J_n(-x_p) - qWG_o$$

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# Pn PD current

- The total current density at the depletion region edge $x_n$,

$$
\begin{aligned}
-J_{PD} &= J_n(x_n) + J_h(x_n) = J_n(-x_p) - qWG_o + J_h(x_n) \\
&= J_{n,\mathrm{d}}(-x_p) + J_{h,\mathrm{d}}(x_n) - qWG_o,
\end{aligned}
$$

- Express the diffusion current densities as a function of the excess charge gradients, we have

$$
-J_{PD} = qD_{np}\left.\frac{\partial n'}{\partial x}\right|_{-x_p} - qD_{hn}\left.\frac{\partial p'}{\partial x}\right|_{x_n} - qWG_o = -J_d - J_L
$$

- Now, the question becomes what is the excess minority carrier density at x.

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# Pn PD current



- The excess minority carrier densities on p and n sides are described by the continuity equations,

$$\frac{\partial n'}{\partial t} = -\frac{\partial}{\partial x}\left(-D_{np}\frac{\partial n'}{\partial x}\right) - \frac{n'}{\tau_n} + G_{op}\ (p\ \text{side})$$

$$\frac{\partial p'}{\partial t} = \frac{\partial}{\partial x}\left(D_{hn}\frac{\partial p'}{\partial x}\right) - \frac{p'}{\tau_h} + G_{on}\ \ (n\ \text{side}).$$

Where D is the diffusivity, tau is the carrier lifetime, G is optical generation rate, which is assumed to be constant.

# Pn PD current

- In the frequency domain the continuity equation becomes

$$\mathrm{j}\omega n' = D_{np}\frac{\mathrm{d}^2 n'}{\mathrm{d}x^2} - \frac{n'}{\tau_n} + G_{op} \quad (p \text{ side})$$

$$\mathrm{j}\omega p' = D_{hn}\frac{\mathrm{d}^2 p'}{\mathrm{d}x^2} - \frac{p'}{\tau_h} + G_{on} \quad (n \text{ side}),$$

- Introducing the complex diffusion length,

$$\frac{1}{\widetilde{L}_{np}} = \sqrt{\frac{1+\mathrm{j}\omega\tau_n}{\tau_n D_{np}}} = \frac{\sqrt{1+\mathrm{j}\omega\tau_n}}{L_{np}}$$

$$\frac{1}{\widetilde{L}_{hn}} = \sqrt{\frac{1+\mathrm{j}\omega\tau_h}{\tau_h D_{hn}}} = \frac{\sqrt{1+\mathrm{j}\omega\tau_h}}{L_{hn}},$$

where $L_{np} = \sqrt{D_{np}\tau_n}$, $L_{hn} = \sqrt{D_{hn}\tau_h}$ are the diffusion lengths for excess electrons in the $p$ side and excess holes in the $n$ side, we finally have

# Pn PD current



- Then, the continuity equation becomes

$$\frac{\mathrm{d}^2 n'}{\mathrm{d}x^2} = \frac{n'}{\widetilde{L}_{np}^2} - \frac{G_{op}}{D_{np}} \quad (p \text{ side})$$

$$\frac{\mathrm{d}^2 p'}{\mathrm{d}x^2} = \frac{p'}{\widetilde{L}_{hn}^2} - \frac{G_{on}}{D_{hn}} \quad (n \text{ side}),$$

- The boundary conditions are

$$n'(-x_p) = \frac{n_i^2}{N_A}\left[\exp\left(\frac{V_A}{V_T}\right) - 1\right], \quad n'(-\infty) = 0 \ \ (p \text{ side})$$

$$p'(x_n) = \frac{n_i^2}{N_D}\left[\exp\left(\frac{V_A}{V_T}\right) - 1\right], \quad p'(+\infty) = 0 \ \ (n \text{ side}).$$

# Pn PD current



- The solutions of the continuity equations give the minority carrier density

$$n'(x) = \left[\frac{n_i^2}{N_A}\left(\mathrm{e}^{\frac{V_A}{V_T}} - 1\right) - \frac{\tau_n G_{op}}{1 + \mathrm{j}\omega\tau_n}\right] \exp\left(\frac{x + x_p}{\widetilde{L}_{np}}\right) + \frac{\tau_n G_{op}}{1 + \mathrm{j}\omega\tau_n} \quad (p \text{ side})$$

$$p'(x) = \left[\frac{n_i^2}{N_D}\left(\mathrm{e}^{\frac{V_A}{V_T}} - 1\right) - \frac{\tau_n G_{on}}{1 + \mathrm{j}\omega\tau_h}\right] \exp\left(-\frac{x - x_n}{\widetilde{L}_{hn}}\right) + \frac{\tau_h G_{on}}{1 + \mathrm{j}\omega\tau_h} \quad (n \text{ side}).$$

- From the above equations, we can obtain the excess minority carrier density gradients.

# Pn PD current



- Based on the minority carrier density continuity expressions, the dark current and the photocurrent are derived as

$$I_d = AJ_d = qAn_i^2\left(\frac{1}{\widetilde{L}_{np}}\frac{D_{np}}{N_A} + \frac{1}{\widetilde{L}_{hn}}\frac{D_{hn}}{N_D}\right)\left(\mathrm{e}^{\frac{V_A}{V_T}} - 1\right)$$

$$I_L = AJ_L = qA\left(\widetilde{L}_{np}G_{op} + \widetilde{L}_{hn}G_{on} + WG_o\right),$$

The dark current follows the Shockley diode law and yields a positive contribution to the total detector current $I_{PD}$ for large negative applied voltage $V_A$. The photocurrent $I_L$ is found to include three contributions, the first two referring to the diffusion regions, the last (typically much smaller) to the depletion region. Although the diffusion contribution apparently enhances the photocurrent, in fact this contribution rapidly decreases with increasing speed of the input optical signal, with a characteristic time given by the lifetime (in a direct-gap semiconductor, of the order of 1 ns, much larger in indirect-gap semiconductors). As a result, the overall device response exhibits an early cutoff (due to lifetime) plus a very high-frequency transit-time or *RC* cutoff.

- pin photodiode current

# Pin PDs

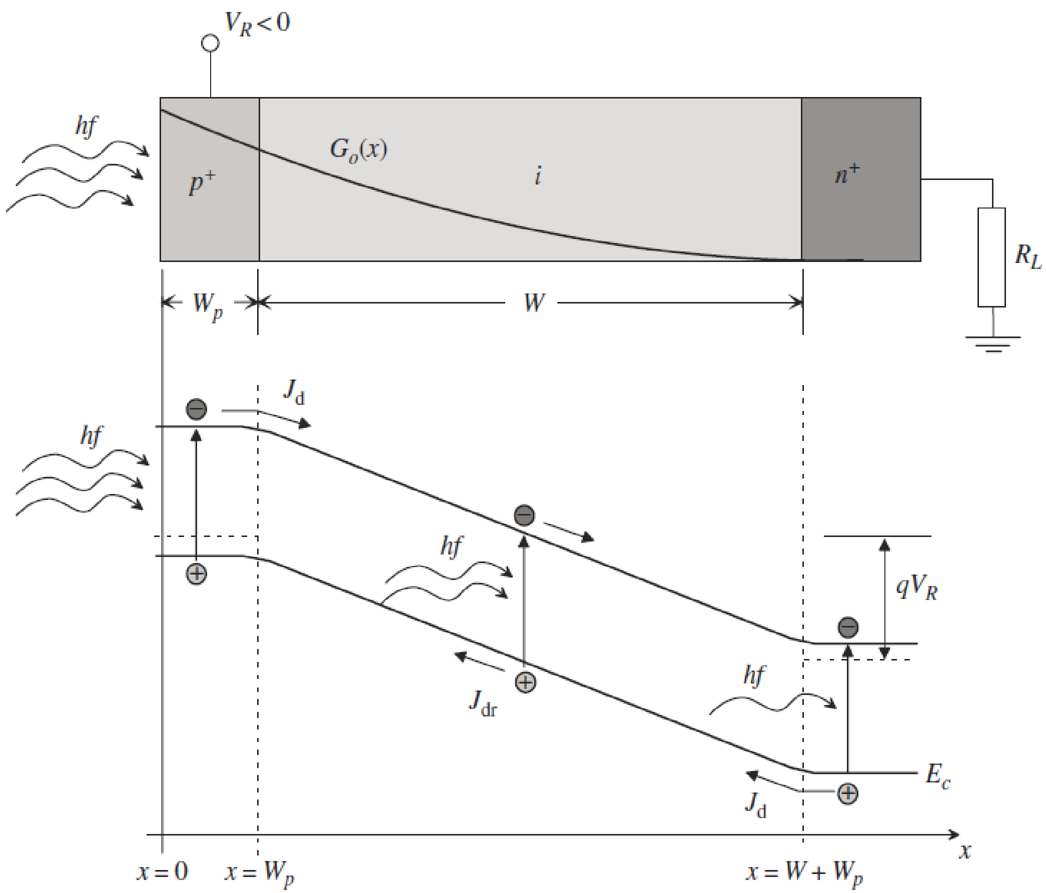


- To improve the frequency response and the high-frequency efficiency (responsivity), the depletion region width should be made much larger than the width of the diffusion region. However, in the pn diode this requires impractically large reverse voltages. An obvious solution is to interpose a lightly doped or intrinsic region between the p and the n layers that is completely depleted in reverse bias and whose electric field is almost constant. This resulting structure is the pin PDs.
- Using heterojunctions, NpP or NiP structures, no absorption at all takes place in the external regions, and the related current contribution vanishes.
- Cutoff frequencies in excess of 80 GHz have been demonstrated.
- A compromise is the speed and the responsivity.
- The device speed is dominated by the transit time and the parasitic capacitance.
- The limitation can be overcome by traveling-wave waveguide PDs.

# Pin PDs



- In pin PDs, the intrinsic region width is much larger than diffusion region, making the diffusion photocurrents negligible.



# Pin PD current



- As in PD, the pin PD current is constant in x,

$$-I_{PD} = I_n(x) + I_h(x) = I_{n,\mathrm{dr}}(x) + I_{n,\mathrm{d}}(x) + I_{h,\mathrm{dr}}(x) + I_{h,\mathrm{d}}(x)$$

- In the depletion region, the optical generation rate is nonuniform

$$G_o(x) = \eta_Q \frac{P_{in}\,(1-R)}{Ahf} \alpha \mathrm{e}^{-\alpha x} = G_o(0)\mathrm{e}^{-\alpha x}$$

- In the diffusion region, the diffusion current of minority carriers is

$$-I_{PD} = I_{n,\mathrm{d}}(W_p) + I_h(W_p) = I_n(W + W_p) + I_{h,\mathrm{d}}(W + W_p)$$

# Pin PD current



- Using the continuity equation, the electron current change in the depletion region is

$$\frac{\mathrm{d}I_n}{\mathrm{d}x} = -qAG_o,$$

- Therefore, we have

$$I_n(W + W_p) - I_n(W_p) \approx I_n(W + W_p) - I_{n,\mathrm{d}}(W_p) = I_i.$$

$$I_i = -qA \int_{W_p}^{W+W_p} G_o(x)\,\mathrm{d}x$$

# Pin PD current



- Then, the PD current becomes

$$-I_{PD} = I_{n,\mathrm{d}}(W_p) + I_i + I_{h,\mathrm{d}}(W + W_p)$$

The first contribution includes the diffusion current from the surface layer;

The second contribution, the (photogenerated) drift current from the intrinsic layer;

The third contribution, the diffusion current from the substrate. In the diffusion currents, we have both photocurrent and dark current components.

# Pin PD current



- The photogenerated drift current from the intrinsic region is

$$-I_i = q\eta_Q \frac{P_{in}(1-R)}{hf}\int_{W_p}^{W_p+W} \alpha e^{-\alpha x}\,dx = q\eta_Q \frac{P_{in}(1-R)}{hf}\left[-e^{-\alpha x}\right]_{W_p}^{W_p+W}$$
$$= q\eta_Q \frac{P_{in}(1-R)}{hf} e^{-\alpha W_p}\left(1-e^{-\alpha W}\right). \quad (4$$

- In practice, the highly dope p (light injection) side is very thin, $W_p \ll L_{alpha}$, $W_p \ll L_{np}$, then the diffusion equation can be simplified to

$$\frac{d^2 n'}{dx^2} = \frac{n'}{L_{np}^2} - \frac{G_o(0)e^{-\alpha x}}{D_{np}} \approx \frac{n'}{L_{np}^2} - \frac{G_o(0)}{D_{np}} \quad (p^+ \text{ side})$$

with boundary conditions

$$n'(0) = 0, \quad n'(W_p) = n_0'.$$

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# Pin PD current



- The solution of the minority carrier density is

$$n' = n'_0 \frac{\exp\left(-\frac{x}{L_{np}}\right) - \exp\left(\frac{x}{L_{np}}\right)}{\exp\left(-\frac{W_p}{L_{np}}\right) - \exp\left(\frac{W_p}{L_{np}}\right)} + \frac{L_{np}^2 G_o(0)}{D_{np}} \left\{ \frac{\left[\exp\left(\frac{x}{L_{np}}\right) + \exp\left(\frac{W_p - x}{L_{np}}\right)\right]\left[1 - \exp\left(-\frac{W_p}{L_{np}}\right)\right]}{\exp\left(-\frac{W_p}{L_{np}}\right) - \exp\left(\frac{W_p}{L_{np}}\right)} + 1 \right\}.$$

- Because $W_p \ll L_{np}$,

$$n' \approx n'_0 \frac{x}{W_p}$$

- Thus, the optical generation contribution is negligible.

# Pin PD current



- On the substrate n side, the minority hole diffusion equation is

$$\frac{\mathrm{d}^2 p'}{\mathrm{d}x^2} = \frac{p'}{L_{hn}^2} - \frac{G_o(0)\mathrm{e}^{-\alpha x}}{D_{hn}} \quad (n^+ \text{ side}),$$

with boundary conditions

$$p'(W_p + W) = p'_0, \quad p'(\infty) = 0,$$

- The solution is

$$p'(x) = \left[p'_0 - \frac{L_{hn}^2}{1-\alpha^2 L_{hn}^2}\frac{G_o(0)}{D_{hn}}\mathrm{e}^{-\alpha(W_p+W)}\right]\exp\left(-\frac{x-W_p-W}{L_{hn}}\right) + \frac{L_{hn}^2}{1-\alpha^2 L_{hn}^2}\frac{G_o(0)}{D_{hn}}\mathrm{e}^{-\alpha x}.$$

# Pin PD current



- Then, the diffusion electron current at $W_p$, and hole current at $W+W_p$ is

$$I_{n,\mathrm{d}}(W_p) = qAD_{np}\left.\frac{\partial n'}{\partial x}\right|_{W_p} = \frac{qAD_{np}}{W_p}n'_0$$

$$I_{h,\mathrm{d}}(W+W_p) = -qAD_{hn}\left.\frac{\partial p'}{\partial x}\right|_{W_p+W} = \frac{qAD_{hn}}{L_{hn}}p'_0 - \frac{qAG_o(0)L_{hn}}{1+\alpha L_{hn}}\mathrm{e}^{-\alpha(W_p+W)}.$$

- The total PD current becomes,

$$-I_{PD} = \underbrace{\frac{qAD_{np}}{W_p}n'_0 + \frac{qAD_{hn}}{L_{hn}}p'_0}_{-I_d} - \underbrace{\left[\frac{qAG_o(0)L_{hn}}{1+\alpha L_{hn}}\mathrm{e}^{-\alpha(W_p+W)} + I_i\right]}_{I_L},$$

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# Pin PD current

- The photocurrent can be further expressed as

$$I_L = \eta_Q \frac{q}{hf} P_{in} (1 - R)\, \mathrm{e}^{-\alpha W_p} \left(1 - \frac{\mathrm{e}^{-\alpha W}}{1 + \alpha L_{hn}}\right)$$

- The responsivity,

$$\Re = \frac{I_L}{P_{in}} = \eta_Q \frac{q}{hf} (1 - R)\, \mathrm{e}^{-\alpha W_p} \left(1 - \frac{\mathrm{e}^{-\alpha W}}{1 + \alpha L_{hn}}\right),$$

- The external quantum efficiency,

$$\eta_x = \frac{I_L / q}{P_{in} / hf} = \eta_Q (1 - R)\, \mathrm{e}^{-\alpha W_p} \left(1 - \frac{\mathrm{e}^{-\alpha W}}{1 + \alpha L_{hn}}\right)$$

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# Pin PD current



The diffusion contributions to currents are much slower than the drift contributions in dynamic operation, and should be reduced to optimize the high-speed response. This can be immediately achieved in heterojunction devices, where the substrate layer below the absorption region is widegap and therefore does not appreciably absorb light. To maximize $\eta_x$, we must also require that the thickness of the top layer be much smaller than $\alpha^{-1}$, or that the top layer again be widegap, i.e., transparent to the incoming light. For high-speed, high-efficiency photodiodes $\alpha W_p \to 0$ and $\alpha L_{hn} \to 0$, so that the external device quantum efficiency and responsivity are

$$\eta_x \approx \eta_Q (1 - R)\left(1 - \mathrm{e}^{-\alpha W}\right),$$

$$\Re \approx \frac{q}{hf}\eta_Q (1 - R)\left(1 - \mathrm{e}^{-\alpha W}\right).$$

# Saturate photocurrent



- The main mechanisms limiting the speed of pin PDs are

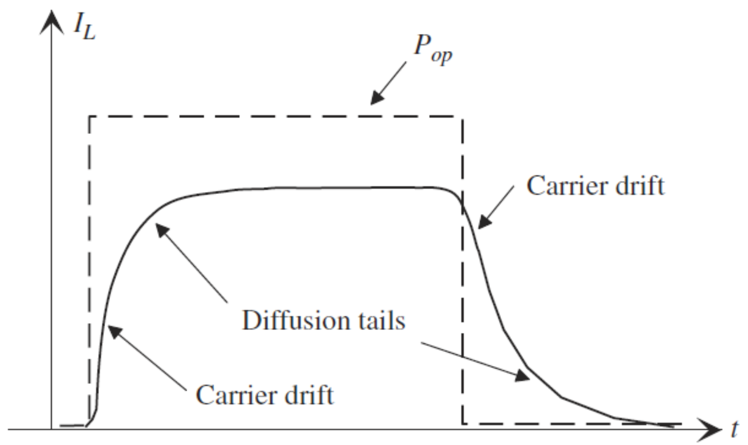
  1. the effect of the total diode capacitance, including the depleted region diode capacitance and any other external parasitic capacitance;
  2. the transit time of the carriers drifting across the depletion layer of width *W*;
  3. the diffusion time of carriers generated outside the depleted regions (mainly in homojunction devices);
  4. the charge trapping at heterojunctions (in heterojunction devices).

Transit time effects are negligible in *pn* junction photodiodes owing to the small depletion region width, but become a dominant mechanism in *pin* devices. Transit time and *RC* cutoff are thus the main limitations in practical, technology-optimized *pin* photodiodes.

# Saturate photocurrent



- In homojunction PDs, the carrier diffusion in the cladding layers introduces into the device response a slow component, this leads to a slow time constant in the time response.




Effect of diffusion currents on the *pin* dynamic response.

- This diffusion current can be minimized by using heavily doped cladding layers, which reduces the diffusivity and the carrier lifetime, and in turn the diffusion length.

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# Frequency response



- In heterojunction pin PDs, the speed can be limited by the charge trapping, related to the valance or conduction band discontinuities.

- Charge trapping can be minimized by not letting the two junctions between doped and intrinsic materials (in particular the surface junction) coincide with the heterojunctions. In this way, for example, the *Pi* junction becomes a *Ppi* junction, where the homojunction and heterojunction are very close to the top window layer. From a technological standpoint, this can be obtained by diffusion of a *p*-type dopant into the intrinsic layer.

# Saturate photocurrent



- The dynamics of photogenerated carriers in the intrinsic region can be described by the continuity equations,

$$\frac{\partial p}{\partial t} = -\frac{p - p_0}{\tau_b} + G_{op}(x,t) - \frac{1}{q}\frac{\partial J_h}{\partial x}$$
$$\frac{\partial n}{\partial t} = -\frac{n - n_0}{\tau_b} + G_{op}(x,t) + \frac{1}{q}\frac{\partial J_n}{\partial x};$$

- The electron and hole current densities are

$$J_h = q\, v_h\,(\mathcal{E})\, p - q\, D_h \frac{\partial p}{\partial x}$$
$$J_n = q\, v_n\,(\mathcal{E})\, n + q\, D_n \frac{\partial n}{\partial x},$$

v is field-dependent carrier drift velocities.

# Saturate photocurrent



- The electric field is dependent on the total charge density, following the Poisson equation,

$$\frac{\partial \mathcal{E}}{\partial x} = \frac{\rho}{\epsilon_s}$$

In the intrinsic region, photogenerated carriers, under the effect of the electric field induced by the applied bias, assume opposite drift velocities, so that electrons and holes separate. Since their drift velocities are in principle different in absolute value, some charge imbalance arises, which in turn perturbs (screens) the driving electric field.

# Saturate photocurrent

- In low-field condition, and assume the space charge effect is negligible, the hole current is given by

$$J_h = q\,v_h\left(\mathcal{E}\right)p - q\,D_h\frac{\partial p}{\partial x} \approx q\,\mu_h\mathcal{E}\,p - q\,D_h\frac{\partial p}{\partial x}$$
$$\approx q\,\mu_h\frac{|V_A|}{W}p - q\frac{k_BT}{q}\mu_h\frac{\Delta p}{W} = \frac{q\,\mu_h}{W}\left(|V_A|\,p - \frac{k_BT}{q}\Delta p\right)$$

- When $V_A \gg k_BT/q$, the diffusion current in the second term is negligible. Assume that the transit time of drifting carriers is much shorter than the carrier lifetime, thus the carriers can not recomine during the drift to the external circuit. Assume that the electric field is high enough to saturate the carrier velocity.

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# Saturate photocurrent



- The inceasing optical power inevitably leads to an increase of the space charge in the intrinsic region; which can screen the external electric field and becomes nonuniform, thus reducing the photocarrier driving force; eventually, the photocurrent saturates.
- Under assumption (low-field), the photocurrent is expressed as

$$J_L = J_h + J_n \approx q\mu_h \mathcal{E}_0 p + q\mu_n \mathcal{E}_0 n \approx 2q\mu\mathcal{E}_0 n = 2qvn,$$

- The charge density of electrons or holes is

$$|\rho| \approx \frac{J_L}{2\mu\mathcal{E}_0} = \frac{J_L}{2v}$$

# Saturate photocurrent



- This charge density induces extra field through the Poissons equation,

$$\frac{\partial \mathcal{E}}{\partial x} = \frac{\rho}{\epsilon_s} = \frac{J_L}{2\mu\epsilon_s\mathcal{E}_0} = \frac{J_L}{2\epsilon_s v},$$

- Integrating over the intrinsic region, we obtain the charge-induced field (low-field case)

$$\mathcal{E} = \frac{J_L W}{2\mu\epsilon_s\mathcal{E}_0} = \frac{J_L W}{2\epsilon_s v}$$

- In case the bias voltage is high, the carrier velocity saturates, the charge-induced field is given only by (velocity saturation case)

$$\mathcal{E} = \frac{J_L W}{2\epsilon_s v}$$

Example 4.2

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