5. PHOTODETECTORS

5.1 Principle of the pN junction photodiode

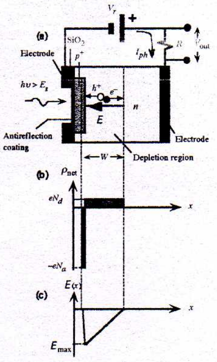
Photon Absorption

↓

e-h pair creation

↓

Photocurrent



(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the p and n sides. (c). The field in the depletion region.

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→ Absorption of photons mostly happens within depletion region to create current generating e-h pairs.

→ Photocurrent, I_{ph}, depends on # of e-h pairs photogenerated and drift velocities, while they are transiting depletion layer.

→ Created (generated) e-h pairs are separated by $\vec{E}$

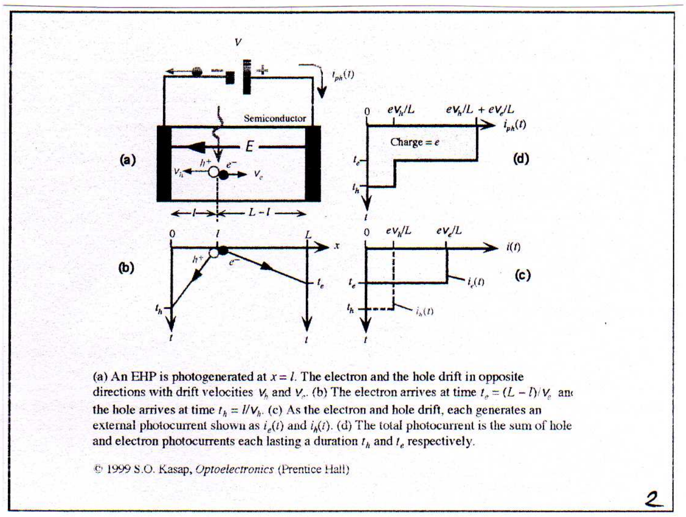
- when drifting hole reaches p^+, it recombines with an electron from battery.
- when drifting electron reaches back electrode, it leaves the diode, and goes to the battery.

5.2. Ramo's Theorem and External Photocurrent

Assume:

- The electrodes do not inject carriers.
- $|\vec{E}| = V/L$
- @ $x = l$ e-h pair is created with drift velocities:

$$v_e = \mu_e E$$
$$v_h = \mu_h E$$



(a) An EHP is photogenerated at $x = l$. The electron and the hole drift in opposite directions with drift velocities v_h and v_e. (b) The electron arrives at time $t_e = (L - l)/v_e$ and the hole arrives at time $t_h = l/v_h$. (c) As the electron and hole drift, each generates an external photocurrent shown as $i_e(t)$ and $i_h(t)$. (d) The total photocurrent is the sum of hole and electron photocurrents each lasting a duration t_h and t_e respectively.

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→ Electron and hole transit times:

$$t_e = \frac{L-l}{v_e} \quad \text{and} \quad t_h = \frac{l}{v_h}$$

The work done by dx within dt:

$$dW = \overbrace{e\underset{\substack{\downarrow \\ V/L}}{E}}^{\text{force}}\,dx = \overbrace{V \cdot i_e(t)}^{\text{power}}\,dt$$

$$e\frac{V}{L}\underbrace{\frac{dx}{dt}}_{v_e} = V\,i_e(t)$$

$$\searrow \quad \boxed{i_e(t) = \frac{e v_e}{L}}\;;\; t < t_e$$

Current lasts as long as the electron is drifting.

Similarly for holes:

$$\boxed{i_h(t) = \frac{e v_h}{L}}\;;\; t < t_h$$

- The total current will be the sum of $i_e(t)$ and $i_h(t)$
- The total charge collected:

$$Q_{\text{collected}} = \int_0^{t_e} i_e(t)\,dt + \int_0^{t_h} i_h(t)\,dt$$

$$= \int_l^L \frac{eV_e}{L}\,dt + \int_0^l \frac{eV_h}{L}\,dt$$

$$= \frac{e}{L}\left\{ \int_l^L dx + \int_0^l dx \right\} = e \;//$$

The collected charge for single photon is e, not 2e!

In general: If a charge q is being drifted with a velocity $V_d(t)$ by a field between two biased electrodes separated by L, the external current:

$$i(t) = \frac{q V_d(t)}{L} \quad ; t < t_{\text{transit}}$$

Ramo's Th.

The total external current is the sum of all currents from all drifting charges between electrodes.

5.4. Quantum Efficiency and Responsivity

- External Quantum Efficiency
- External Collection Efficiency
- Dış Toplama Verimliliği

$$\eta = \frac{\#\text{ of free e-h pairs generated and collected}}{\#\text{ of incident photons}}$$

$$\eta = \frac{I_{ph}/e}{P_o/h\nu}$$

I_{ph}/e → # of electrons collected per second

$P_o/h\nu$ → # of photons arriving per second

P_o → Optical power

→ Not all the incident photons are absorbed ($\because$ penetration depth, $1/\alpha$)

→ Not all the absorbed photons may generate free e-h pairs that can be collected.

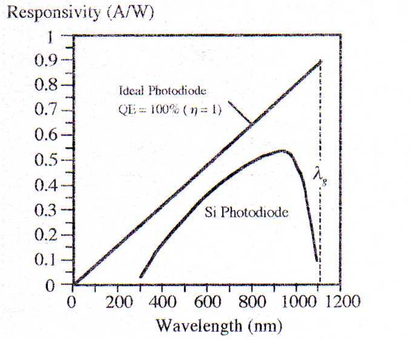
$$\therefore \eta < 1$$

Responsivity ; R (→ A/W)

- Spectral Response
- Spectral Sensitivity
- Tayfsal Duyarlılık

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_o}$$

$$\therefore \boxed{R = \eta \cdot \frac{e}{h\nu} = \eta \frac{e\lambda}{hc}}$$



Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% ($\eta = 1$) and for a typica commercial Si photodiode.

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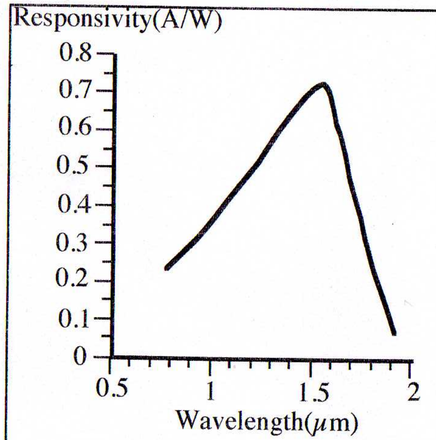
Add. 5.4



The responsivity of a commercial Ge *pn* junction photodiode

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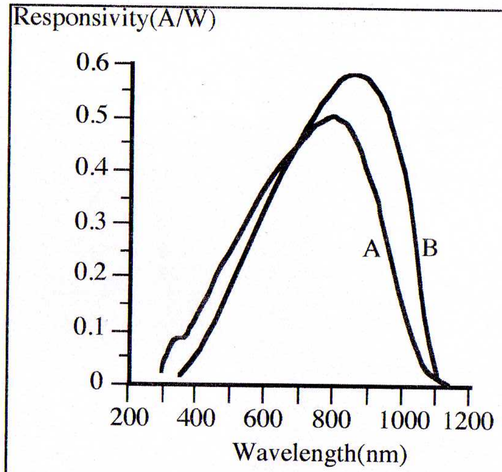

The responsivity of two commercial Si *pin* photodiodes

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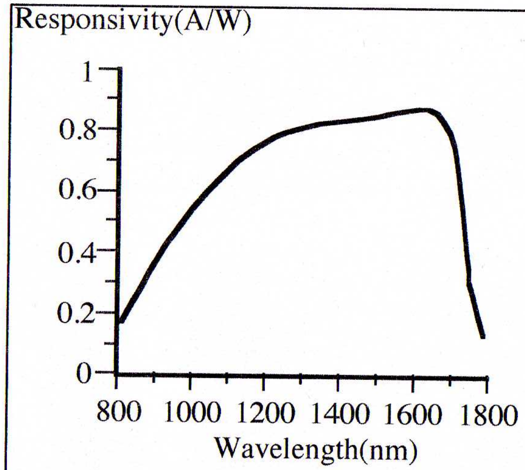

The responsivity of an InGaAs *pin* photodiode

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5.5. The pin Photodiode

pn-junction has two drawbacks

- High D.L. Capacitance (not suitable for high frequencies)
- Thin (a few microns) depletion layer (not suitable for long wavelengths)

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pin → p^+-intrinsic-n^+

W ⇒ thickness of the intrinsic layer ≈ 5 - 50 μm depending on application.

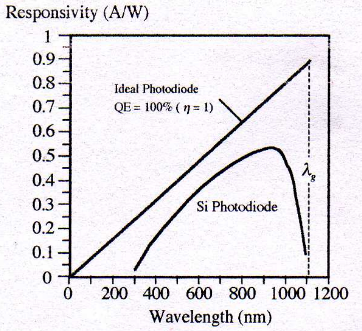
- Junction of dep. layer. capacitance

$$C_{dep} = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

- Time const. RC_{dep} ~ pseconds

- The reverse bias V_r increases the electric field.

$$E = E_0 + \frac{V_r}{W} \approx \frac{V_r}{W} \quad (V_r \gg V_0)$$



Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% (η = 1) and for a typical commercial Si photodiode.

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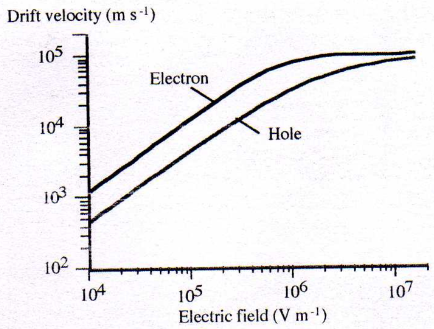

Drift velocity vs. electric field for holes and electrons in Si.

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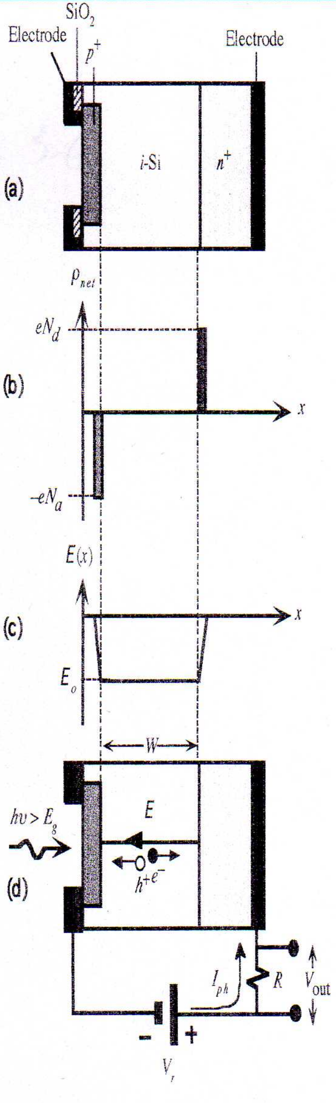

The schematic structure of an idealized *pin* photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The *pin* photodiode in photodetection is reverse biased.

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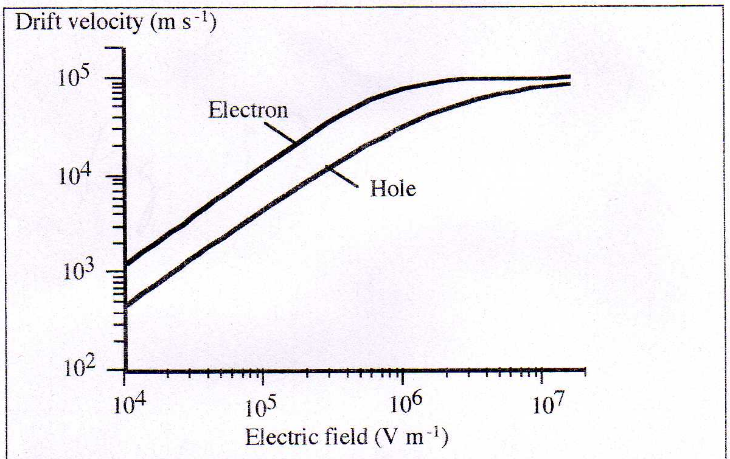
The response time of pin photodiode : Transit time

W ↑ ⇒ more photons absorbed
but longer time for carrier transit times.

$$t_{drift} = \frac{W}{v_d}$$

→ To reduce the drift time increase the applied field.

→ At high fields the dript velocity does not follow the field



Drift velocity vs. electric field for holes and electrons in Si.

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At low fields
$v_d = \mu_d E$

5.6. Avalanche Photodiode (APD)

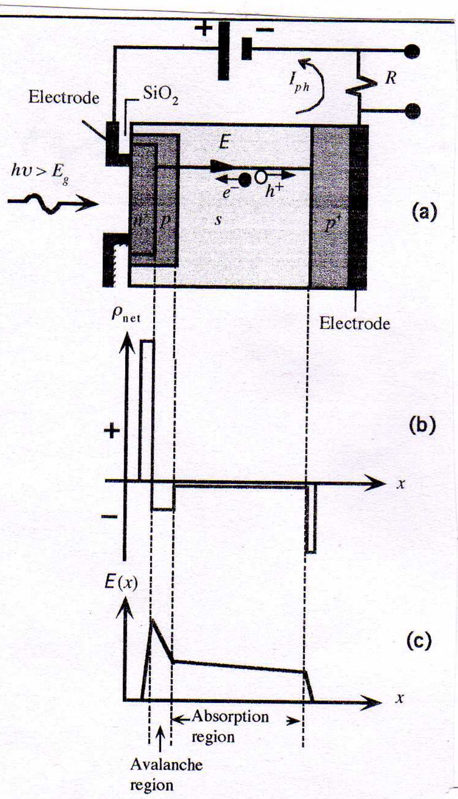
APDs → widely used in optical communications because of their high speed and internal gain.

- Photogeneration, takes place mainly in long π-layer.
- Separation, of EHP due to E-field.
- Drifting electrons experience a larger field when coming to p-layer.
- Their kinetic energies grow sufficiently large to cause impact ionization.

"AVALANCHE or Impact Ionization"

⇓

"Internal Gain mechanism"



(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

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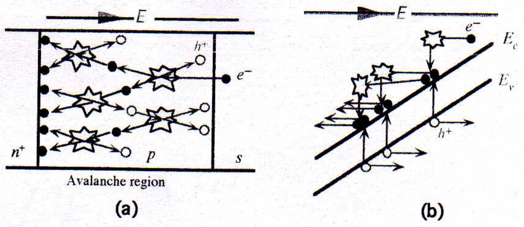

(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

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Avalanche multiplication factor, M:

$$M = \frac{\text{Multiplied Photocurrent}}{\text{Primary Unmultiplied Photocurrent}} = \frac{I_{ph}}{I_{pho}}$$

→ Measured in the absence of multiplication e.g. small V_r.

Ampirical multiplication:

$$M = \frac{1}{1-\left(\frac{V_r}{V_{br}}\right)^n}$$

V_{br} : Avalanche breakdown voltage

n : is a characteristic index

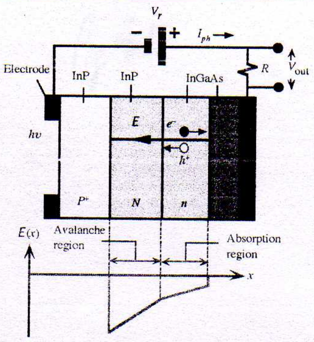
both are temp-dependent

Example 5.6.1 and 5.6.2.

5.7 Heterojunction Photodiodes

A. Seperate Absorption and Multiplication (SAM) APD

III-V compound based APDs are developed for communications at wavelengths of 1.3μm and 1.5μm.



Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. *P* and *N* refer to *p* and *n* -type wider-bandgap semiconductor.

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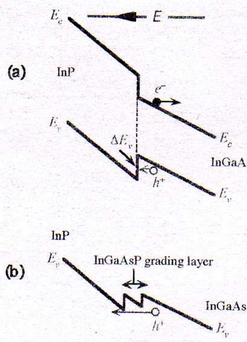
→ At the junction of N-InP and n-InGaAs photogenerated holes become absorbed, due to sharp increase in E_g and a sharp change ΔE_v.

↓

This ΔE_v is broken up into TWO steps with InGaAsP

→ • The hole, now, has sufficient energy to overcome the first step and enter InGaAsP.

• And it accelerates inside (InGaAsP) to overcome the second step to InP.



(a) Energy band diagram for a SAM heterojunction APD where there is a valence band step ΔE_v from InGaAs to InP that slows hole entry into the InP layer.

(b) An interposing grading layer (InGaAsP) with an intermediate bandgap breaks ΔE_v and makes it easier for the hole to pass to the InP layer

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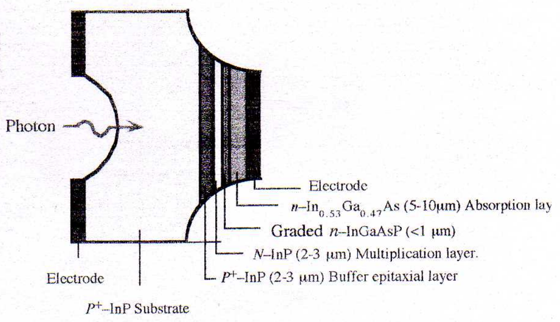
SAGM (Seperate absorption grading and multip.) APDs.



Simplified schematic diagram of a more practical mesa-etched SAGM layered APD.

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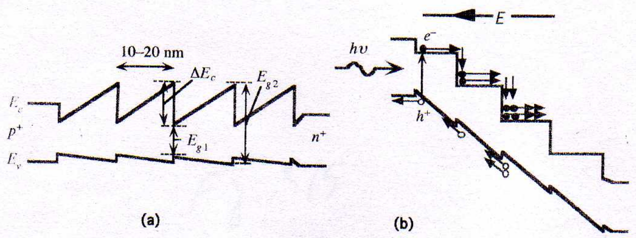
B. Super lattice APDs

APDs ⟶ excess noise in I_{ph}

To reduce excess avalanche noise, one-type multiplication.



Energy band diagram of a staircase superlattice APD (a) No bias. (b) With an applied bias.

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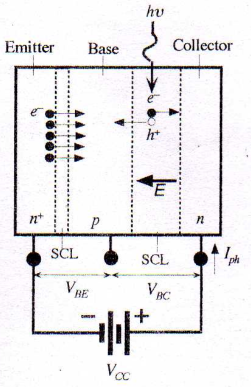
Staircase superlattice APDs. ⟷ Graded band gap ($E_{g1} \to E_{g2}$)

- → Drifting electrons (when reverse bias is applied) have kinetic en. ΔE_c, when they reach neighboring layer.
- → Impact ionization ⟶ by highly energetic electrons
- → Multiplication of photogenerated electrons
- → Impact ionized HOLES experience only small ΔE_v
- → Smaller reverse bias than typical APDs.
- → Only electrons are multiplied

∴ SOLID STATE PHOTOMULTIPLIER.

5.8 PHOTOTRANSISTORS

A phototransister is a bipoler transistor (BJT) that operates as a photodetecter with a photocurrent gain.



The principle of operation of the photodiode. SCL is the space charge layer or the depletion region. The primary photocurrent acts as a base current and gives rise to a large photocurrent in the emitter-collector circuit.

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- Base terminal is open
- Voltage applied between E and C
- Photon is absorbed in SCL and EHP is generated.
- e is collected by C and neutralized by the battery.
- h is drifted into NEUTRAL base region. It can only be neutralized by injected large number of electrons from E. into B.

(Electron recombination time in B is very longer than the time it takes for electrons to diffuse across the base.)

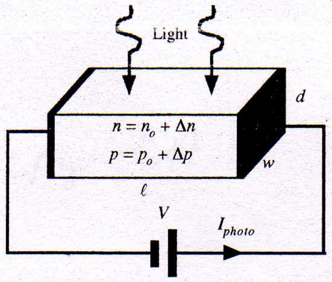
∴ E has to inject large amount of electrons to neutralize excess holes. These electrons (except one) constitute the current

$$I_{ph} \approx \beta I_{pho}$$

The photocurrent flowing in the ext. circuit

Photon generated primary photocurrent

5.9. Photoconductive Detectors and Photoconductive Gain



A semiconductor slab of length ℓ, width w and depth d is illuminated with light of wavelength λ.

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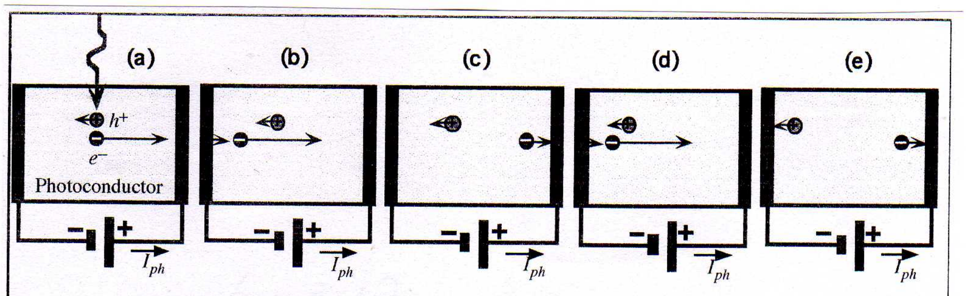
With ohmic contacts, the photoconductor exhibits photoconductive gain that is the external photocurrent is due to more than one electron per absorbed photon.

- After the absorption of a single photon EHP is created.
- The electron drifts +ve terminal → which is much faster than this
  the hole drifts −ve terminal
- Every time an electron reaches the +ve terminal, another enters in to maintain charge neutrality, until hole reaches the −ve terminal.
- The external photo current ∴ corresponds to the flow of many electrons per absorbed photon. → GAIN.



A photoconductor with ohmic contacts (contacts not limiting carrier entry) can exhibit gain. As the slow hole drifts through the photoconductors, many fast electrons enter and drift through the photoconductor because, at any instant, the photoconductor must be neutral. Electrons drift faster which means as one leaves, another must enter.

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The photogeneration rate per unit volume, g_{ph}

(# of EHPs generated per unit volume per second)

$$g_{ph} = \frac{\eta A \Gamma_{ph}}{A \cdot d} \longrightarrow \Gamma_{ph} = \frac{I}{h\nu}$$

$I \rightarrow$ intensity

Energy flowing per unit area per second.

A → Illuminated area

$$= \frac{\eta \frac{I}{h\nu}}{d} \Rightarrow \boxed{g_{ph} = \frac{\eta I \lambda}{hcd}}$$

The excess electron concentration: $\Delta n = n - n_0$

$n_0 \rightarrow n_{dark}$

photogeneration $\rightarrow \Delta n = \Delta p$

(The rate of increase in the excess electron concentration) = (Rate of photo generation of excess electrons) − (Rate of recombination of excess electrons)

$$\frac{d\Delta n}{dt} = g_{ph} - \frac{\Delta n}{\tau}$$

$\tau \longrightarrow$ mean recombination time per excess-elec

---

Δn increases exponentially until the steady state is reaches when

$$\frac{d\Delta n}{dt} = g_{ph} - \frac{\Delta n}{\tau} = 0$$

$$\Delta n = \tau g_{ph} = \frac{\tau \eta I \lambda}{hcd}$$

The photoconductivity:

$$\Delta\sigma = e\mu_e\Delta n + e\mu_h\Delta p$$
$$= e\Delta n(\mu_e+\mu_h)$$
$$= \frac{e\eta I\lambda\tau}{hcd}(\mu_e+\mu_h)$$

The photocurrent density,

$$J_{ph} = \Delta\sigma\frac{V}{\ell} = \Delta\sigma E$$

The rate of electron flow: $= \frac{I_{ph}}{e} = \frac{wd \cdot J_{ph}}{e} = \frac{\eta \cdot I w\lambda\tau}{hc}(\mu_e+\mu_h)E$ (6)

The rate of electron photogeneration: $= (\text{Volume})\,g_{ph} = (wd\ell)\,g_{ph}$

$$= w\ell\frac{\eta I\lambda}{hc}$$

The photoconductive gain:, G,

$$\boxed{G = \frac{I_{ph}/e}{(\text{Volume})(g_{ph})} = \frac{\tau(\mu_e+\mu_h)E}{\ell}}$$

The transit times: $t_e = \ell/\mu_e E$; $t_h = \ell/\mu_h E$

Using these in (6)

$$\boxed{G = \frac{\tau}{t_e} + \frac{\tau}{t_h} = \frac{\tau}{t_e}\left(1+\frac{\mu_h}{\mu_e}\right)}$$

- The transit time can be made shorter, by applying a greater field. However; increasing field intensity will increase in the dark current and more noise
- The speed of response (of device) is limited by τ.