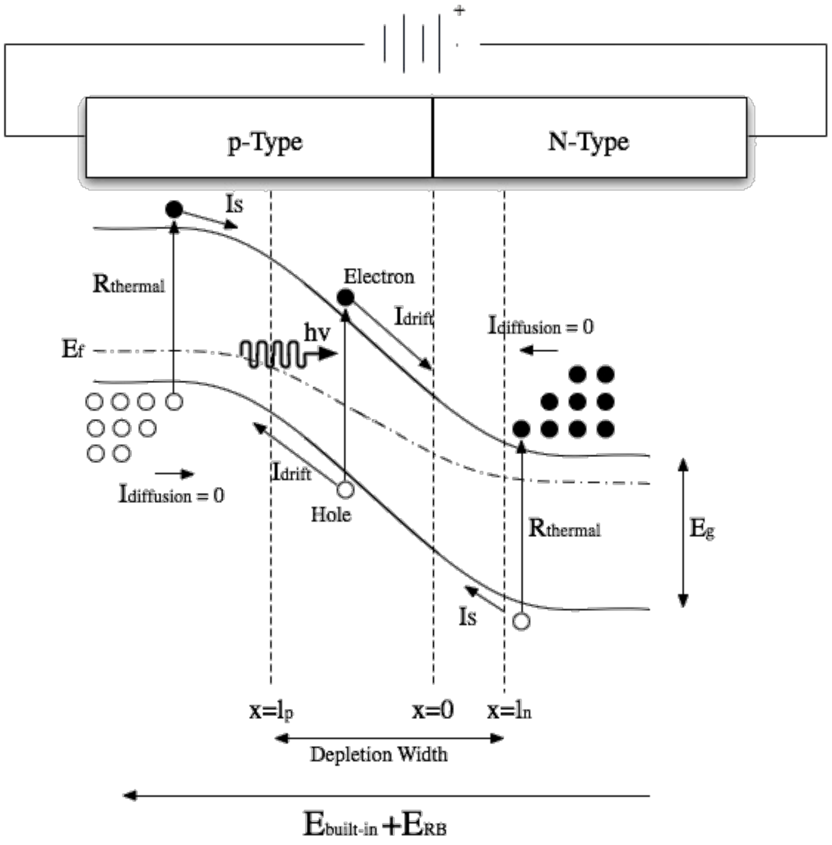
Lecture 3: Photodetectors

Photodetectors (Continued)

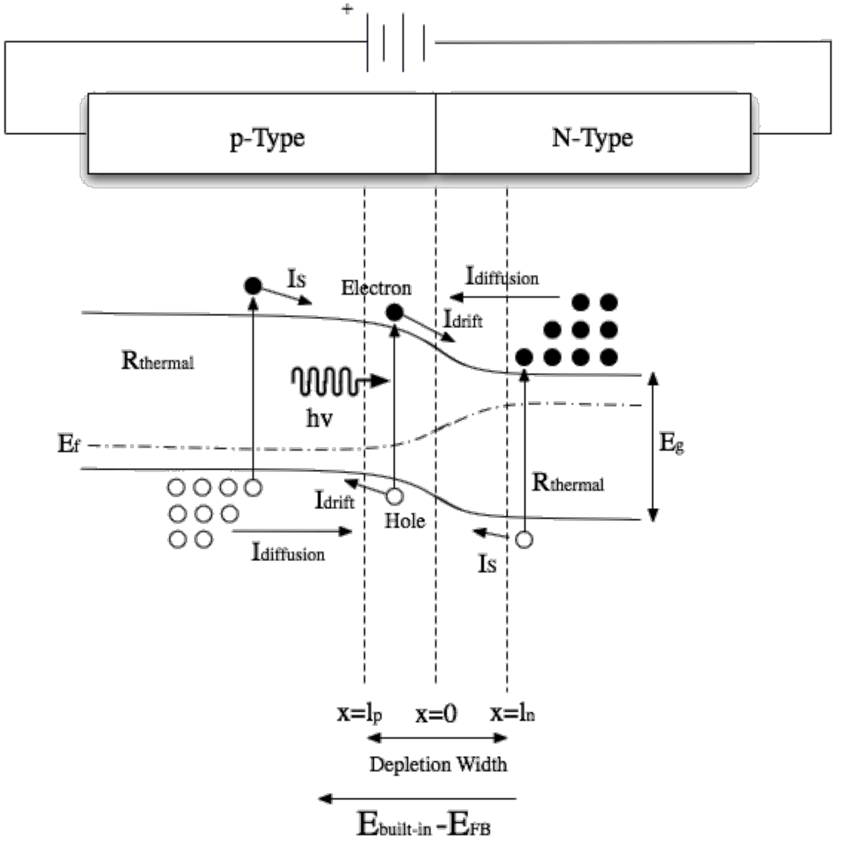
- Last lecture we covered
  - photoconductors and the dominant photon absorption mechanism: Intrinsic (Band-to-Band)
  - the power absorbed as a function of wavelength for different materials and derived the efficiency $\eta(\lambda, x)$
  - the concept of carrier lifetime and transit time and the resulting photoconductive gain (G) that results from a mismatch in electron and hole mobilities
  - Frequency response of photoconductive photodetectors

Biased p-n Junction Photodiodes

Reverse biased

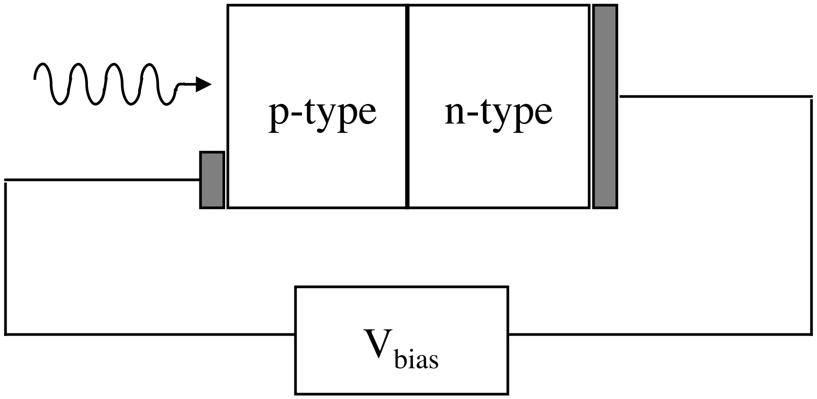


Forward biased



P-type : Semiconductor doped with acceptor atoms
N-type : Semiconductor doped with donor atoms

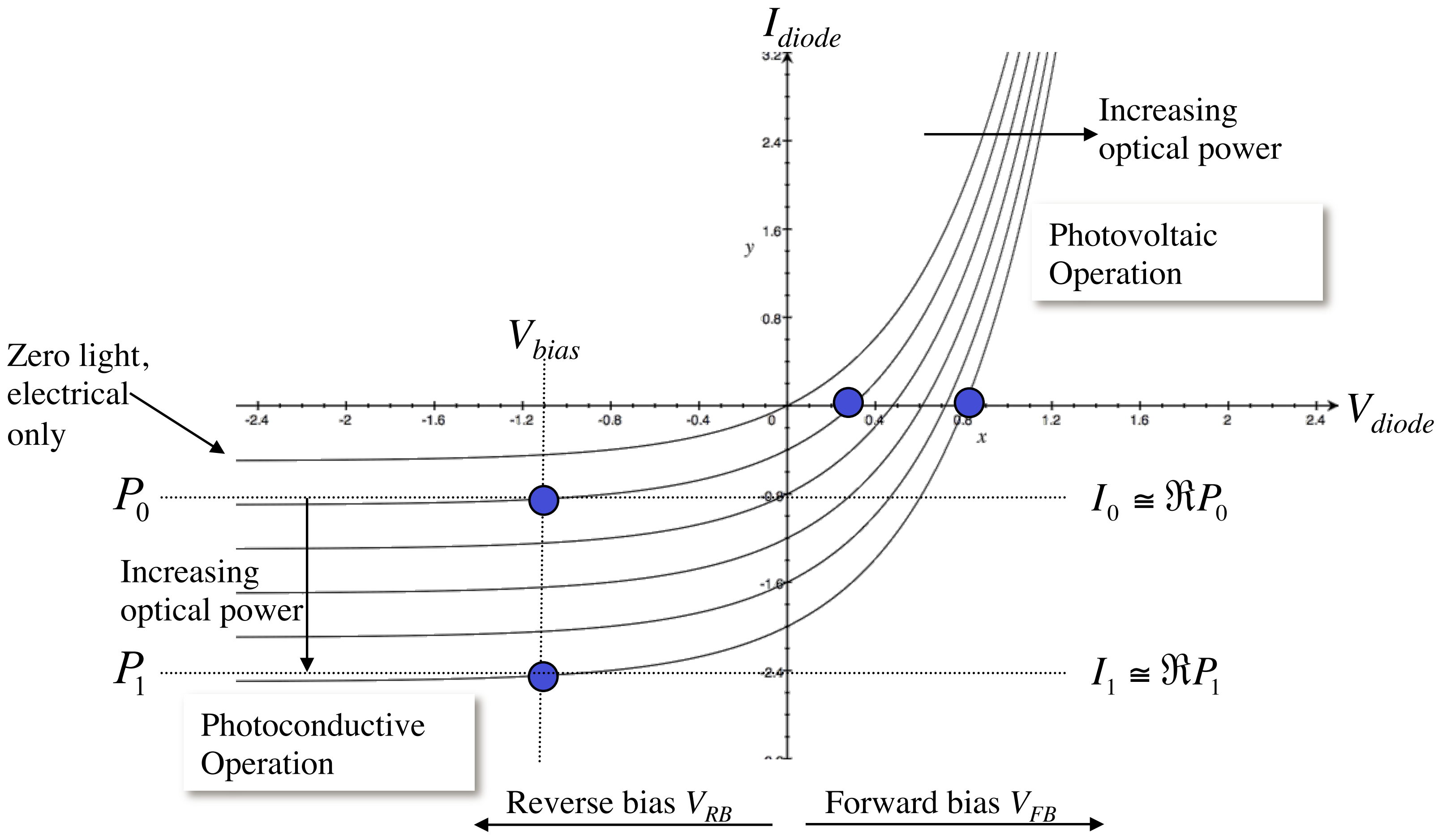
p-n Junction Photodiode Equation



$$I = (I_s)[\exp^{qV_{bias}/K_BT} - 1] - I_{photo}$$
$$= I_{dark} - I_{photo}$$

- I_{dark} = is the current that occurs with zero optical input
- $I_s = I_{th}$ is the thermal or saturation current that occurs in normal (non-illuminated) diode operating mode
- I_{photo} is photo-generated current = $\frac{\eta q}{h\nu} P_{rcvd}$
- q is the electron charge
- V_{bias} is applied bias voltage (positive = forward, negative=reverse)
- K_B is Boltzman's constant
- T is temperature (usually in Kelvin, depending on units of K_B)

p-n Junction Photodiode Regions of Operation



Increasing optical power

Photovoltaic Operation

Zero light, electrical only

$I_0 \cong \Re P_0$

Increasing optical power

$I_1 \cong \Re P_1$

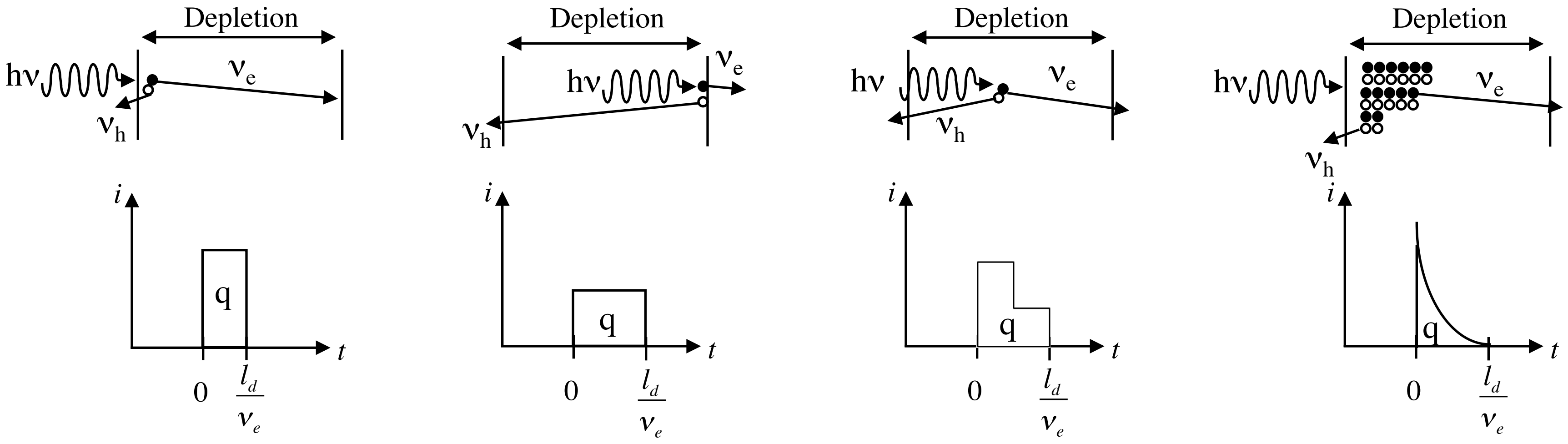
Photoconductive Operation

Reverse bias V_{RB}

Forward bias V_{FB}

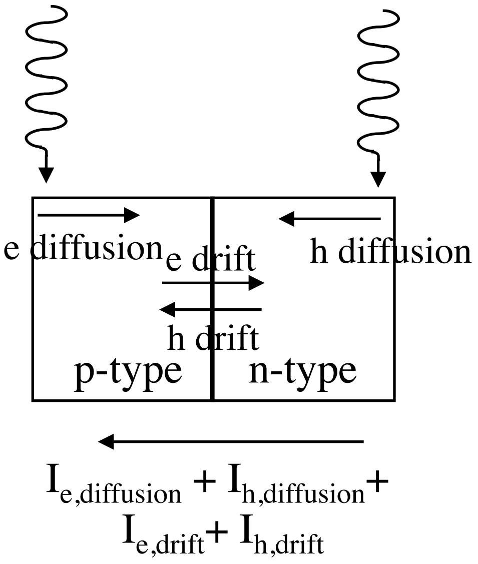
pn-Junction Carrier Dynamics (1)

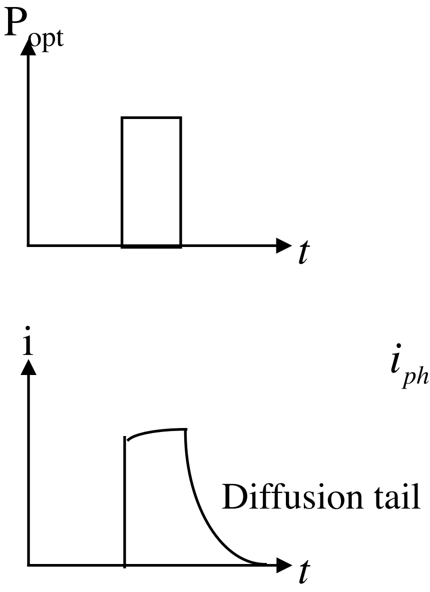
- Carrier diffusion time (~ns/µm) is typically much longer than carrier transit time (~10ps/µm)
- Electron and hole velocities saturated in depletion region due to high field strength
- Once away from depletion region carrier velocities fall below saturation
- Space charge barrier prevents carriers from entering the depletion region, therefore the multiple carrier effect seen in photoconductors does not occur when carrier velocities are mismatched

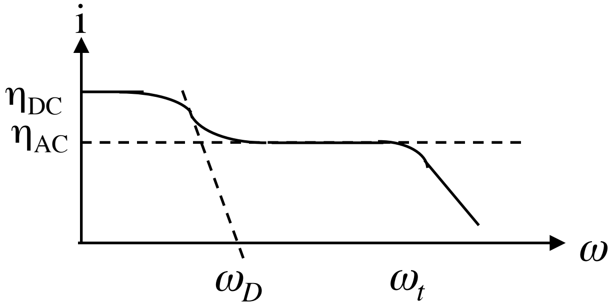


pn-Junction Carrier Dynamics (2)

- Photons absorbed within one diffusion length outside the depletion region will be absorbed and the current contributing carriers will suffer both diffusion time and transit time delays
- Effect is geometry and material dependent



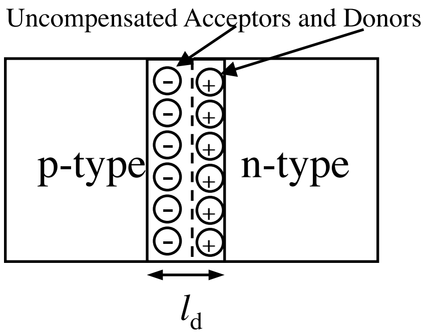




$$i_{photo}(\omega) = \frac{\eta_{DC} - \eta_{AC}}{h\nu} \frac{P_{rcvd}(\omega)}{\sqrt{1 + \left(\frac{\omega}{\omega_D}\right)^2}} + \frac{q\eta_{AC}}{h\nu} P_{rcvd}(\omega)$$

pn-Junction Carrier Dynamics (3)

- The separation of charge in the depletion region (due to uncompensated Donors and Acceptors) leads to a capacitive effect that also impacts the detector bandwidth



$$C_j = \frac{\varepsilon_0 \varepsilon_r A}{l_d}$$

ε_0 = 8.85 x 10^{-12} F/m = vacuum permitivitty
ε_r = semiconductor relative permitivitty
A = area of depletion region
l_d = depletion region length

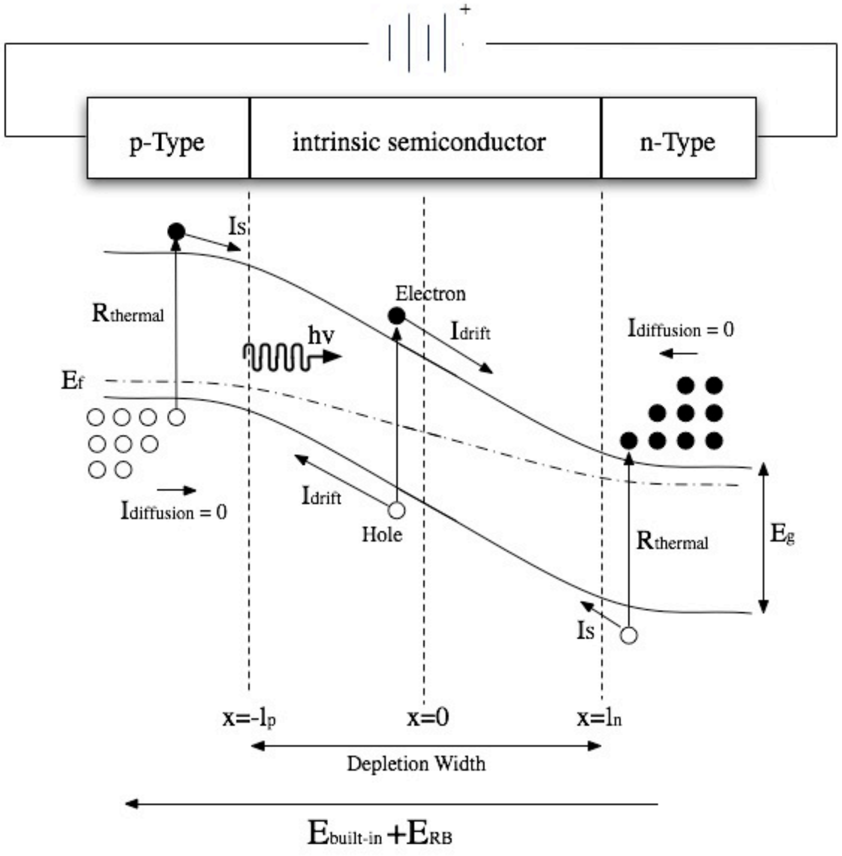
- The frequency at which the detector bandwidth rolls off by 3-dB due to the junction capacitance is

$$\omega_{RC} \frac{1}{R_S C_j}$$

Cj = area of depletion region
l_d = depletion region length

p-i-n Photodiodes

- To increase the photon absorption region, a layer of ***intrinsic*** semiconductor material can be added beteween the p and n material.
- The pin photodetector gain-bandwidth product improves of the pn-junction
  - The detector quantum efficiency can be increased over that of a simple pn junction since the depletion region is almost entirely contained in the intrinsic region and the intrinsic region can be made long.
  - Carrier diffusion effects minimized since all light absorbed in intrinsic region
  - The junction capacitance is reduced compared to a pn-junction because the distance between the effective plates is increased.
  - Carriers reach saturation velocity while traveling in intrinsic region, so even though pin depletion length $l_p + l_d$ is longer than pn-junction depletion length, lower transit time than pn-junction where carrier velocity drops below saturation not far from metallurgical junction



p-i-n Photodiodes

- As with the pn-junction, the quantum efficiency is defined by the following equation, however the distance can now be integrated over the larger intrinsic region

$$\begin{aligned} P_{abs}(x) &= P_i(1 - R)(1 - e^{-\alpha(\lambda)x}) \\ &= \eta(\lambda, x)P_i \end{aligned}$$

- As the depletion region length is increased, η increases, the junction capacitance C_j decreases, and the transit time τ_{trans} increases. The detector design must be optimized to maximize both efficiency and bandwidth. An estimate of the bandwidth is given by

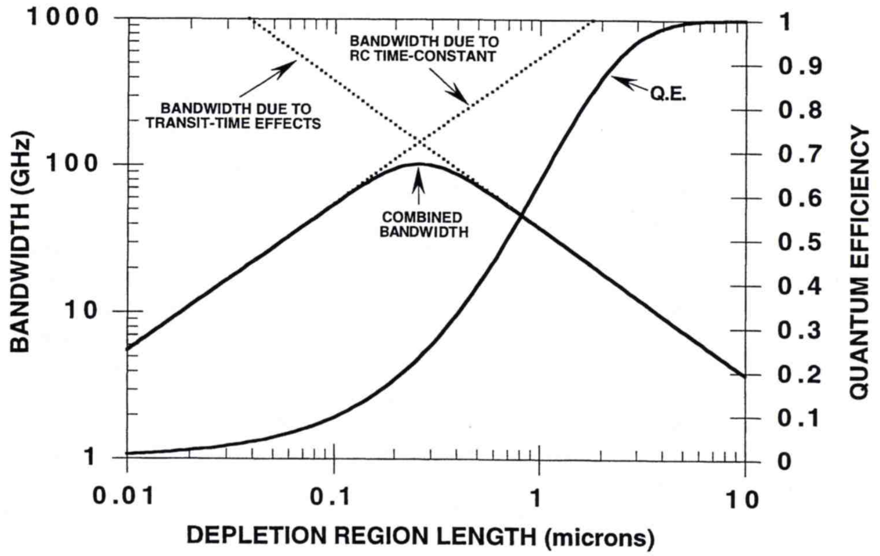
$$B_{pin} = \frac{1}{\sqrt{\left(\frac{1}{f_{RC}}\right)^2 + \left(\frac{1}{f_{trans}}\right)^2}} = \frac{1}{\sqrt{\left(2\pi R_S \varepsilon_0 \varepsilon_r \frac{A}{l_d}\right)^2 + \left(\frac{1}{0.44 v_s}\right)^2}}$$

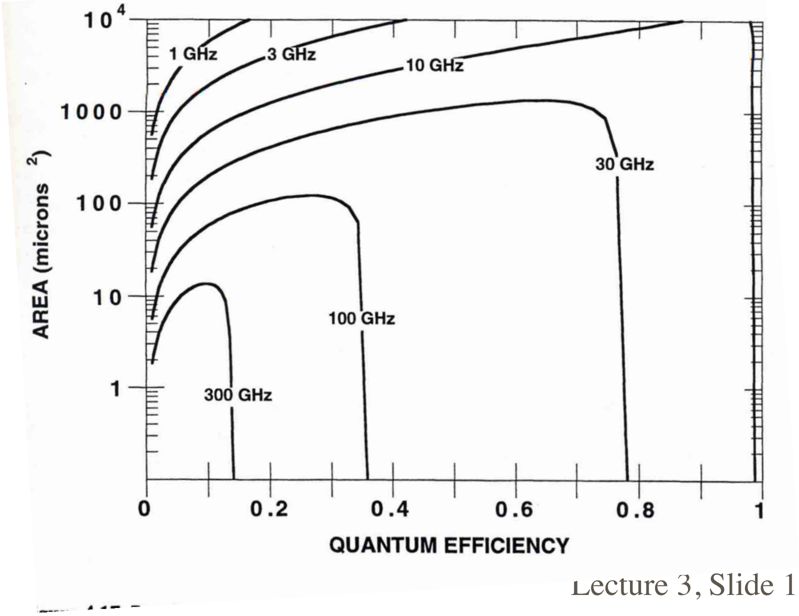
Bandwidth-Efficiency Tradeoffs in p-i-n Photodiodes

- The quantum efficiency, η, can be approximated assuming R=0 (high quality anti-reflection coating) and intrinsic region length l_d. $\eta = 1 - e^{-\alpha l_d}$
- For small l, bandwidth is transit time limited
- For large l, bandwidth it RC limited
- Optimal bandwidth length where two effects are equal
- QE keeps increasing with increased length
- If the detector area *A* and length l_d are both optimized, then bandwidth and quantum efficiency can both be maximized

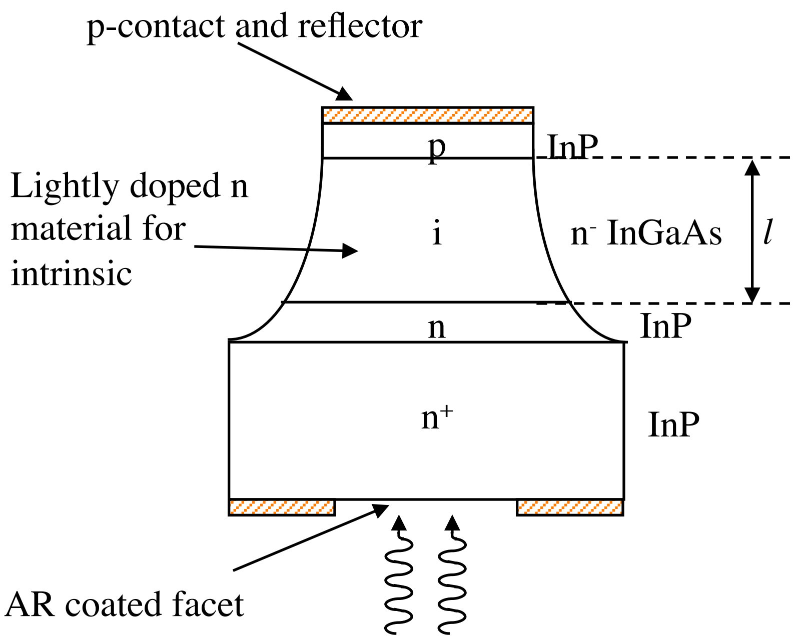
$$A = \frac{l_d}{2\pi R_l \varepsilon_0 \varepsilon_r}\sqrt{\frac{1}{B^2} - \left(\frac{l_d}{0.44 v_s}\right)^2}$$

$$l_d = -\frac{1}{\alpha}\ln(1-\eta)$$





Vertically Illuminated p-i-n Photodiodes



- ⇨ For a double pass vertically illuminated pin detector (see left figure), the quantum efficiency is

$$\eta = \left(1 + re^{-\alpha l}\right)\left(1 - e^{-\alpha l}\right)$$

- ⇨ When the carrier transit distance is approximately equal to l, and $\alpha l << 1$, the bandwidth-efficiency for a double-pass vertically illuminated pin photodiode is approximately

Uni-Traveling Carrier Photodiodes

Improving Saturation current using the high overshoot velocity of electrons to reduce the space charge effect – UTC

Photons are absorbed in the p-layer next to a wide bandgap undopedd drift layer

Holes are not transported -> become majority carriers very quickly

Electrons diffuse to depletion layer and drift rapidly

Thin depletion layer leads to electron overshoot drift velocities up to 5 times greater than saturation velocity

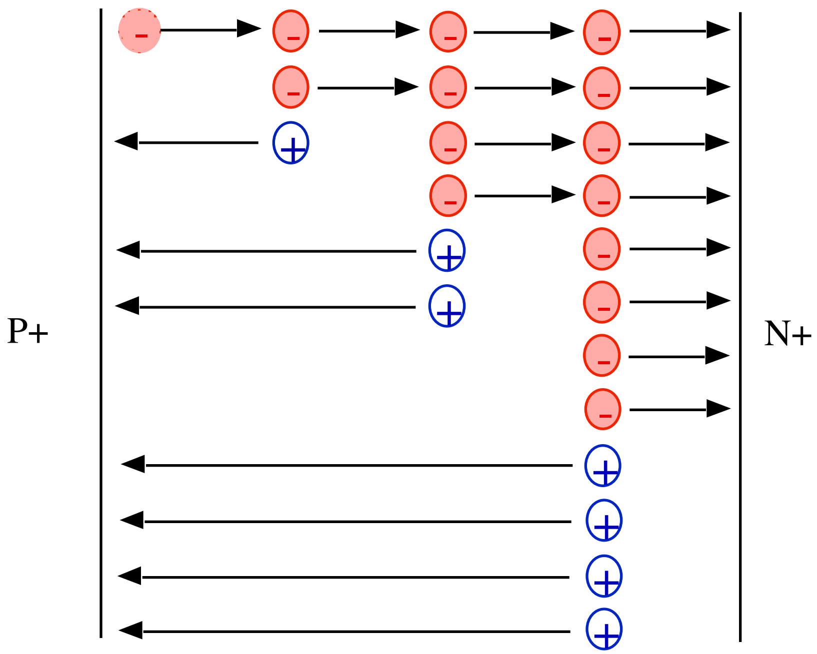
Space charge is reduced by factor of up to 5 relative to PIN, hence UTC

Avalanche Photodiodes (APDs)

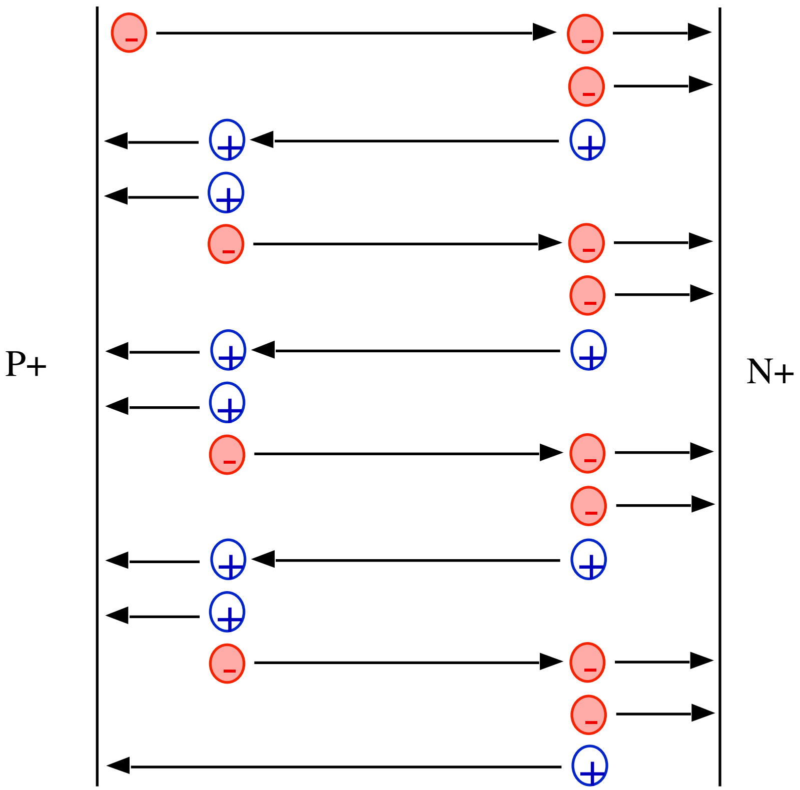
- α Rate at which electrons multiply
- β Rate at which holes multiply

- A large ratio of α/β or β/α results in a large gain bandwidth product and low noise amplification. True for Si
- Most III-Vs have a small ratio, and limited gain bandwidth product. The noise is larger, but still lower than a PIN receiver.

The Avalanche Multiplication Process

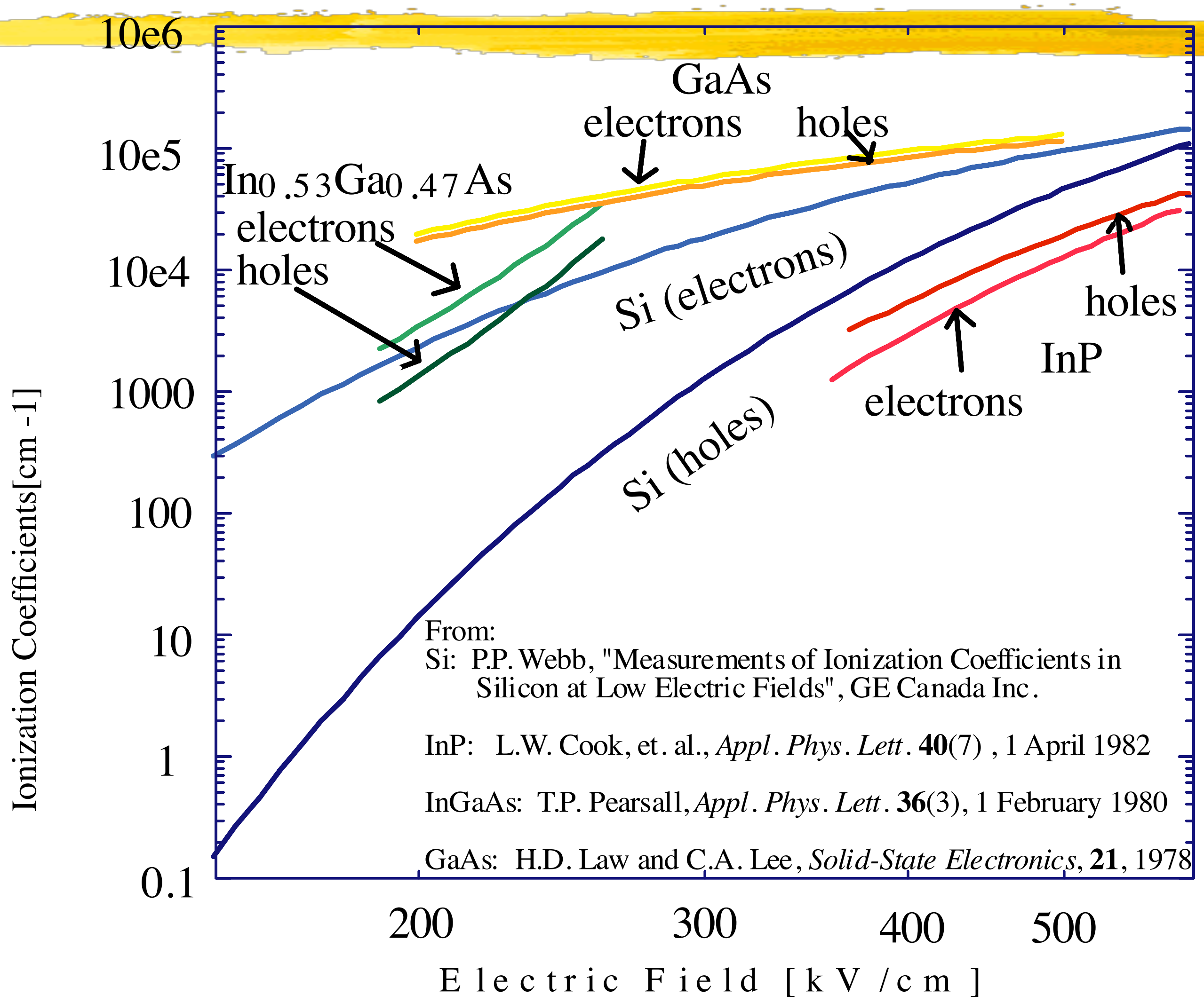


Si Multiplication Layer



InP Multiplication Layer

Ionization Coefficients for Semiconductors



From:

Si: P.P. Webb, "Measurements of Ionization Coefficients in Silicon at Low Electric Fields", GE Canada Inc.

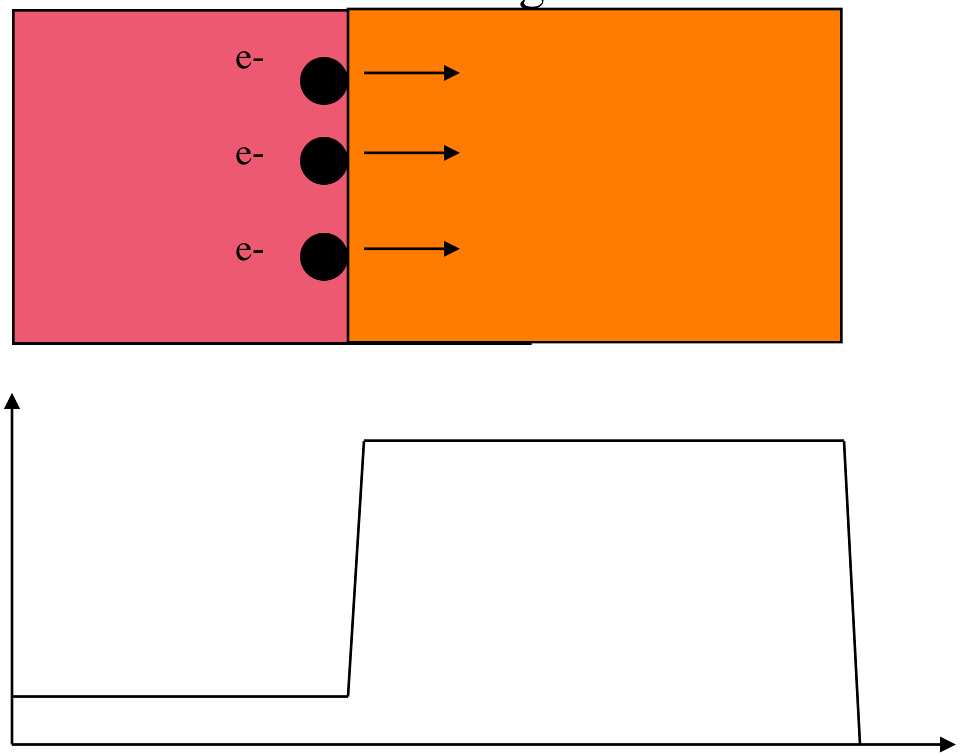
InP: L.W. Cook, et. al., *Appl. Phys. Lett.* **40**(7) , 1 April 1982

InGaAs: T.P. Pearsall, *Appl. Phys. Lett.* **36**(3), 1 February 1980

GaAs: H.D. Law and C.A. Lee, *Solid-State Electronics*, **21**, 1978

SAM APDS:
Need for Separate Absorption and Multiplication Regions

Small bandgap avalanche regions tend to have large dark current.



Absorption Region

Multiplication Region

e-

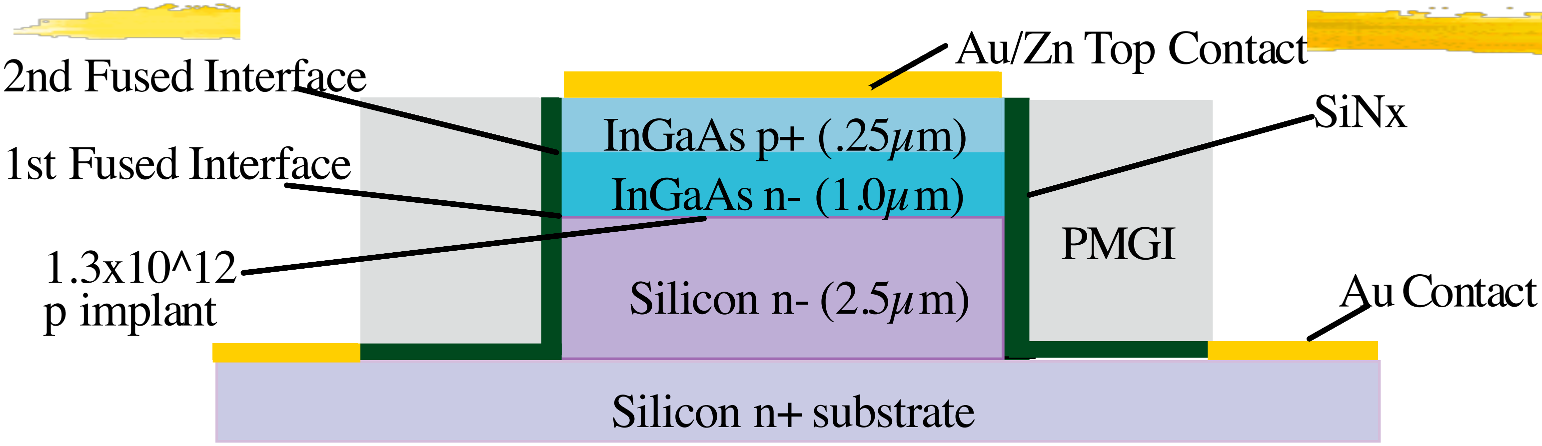
e-

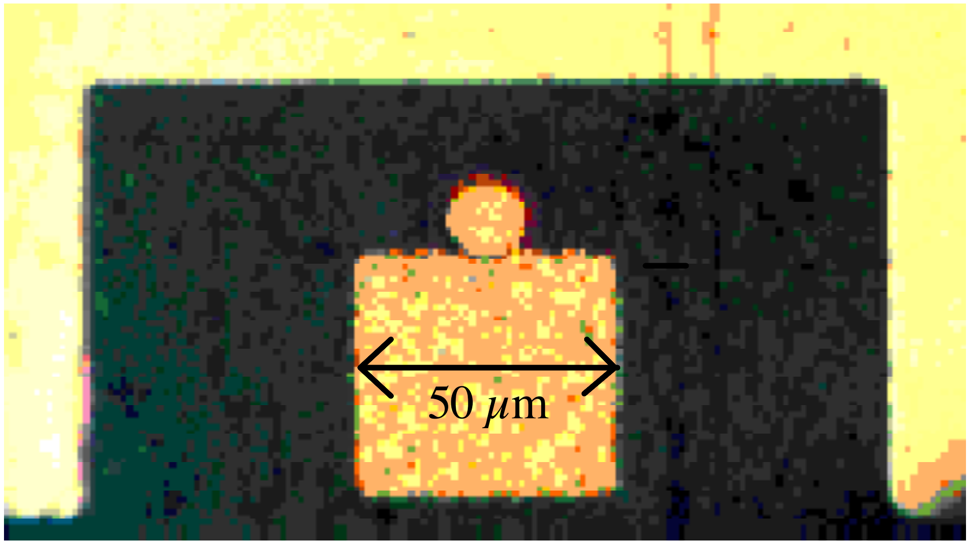
e-

Electric Field

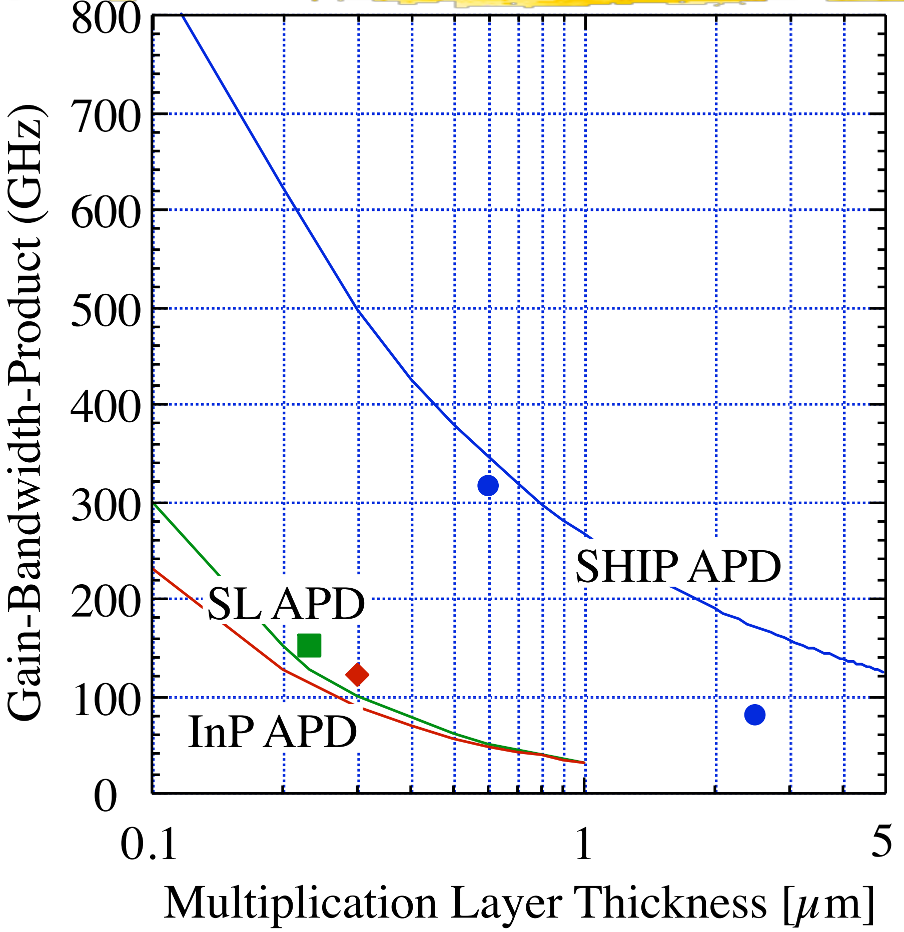
position

Cross Section and Top View of SHIP Detector





Comparison of Acheivable GB Product for SHIP, SL, and InP APDs



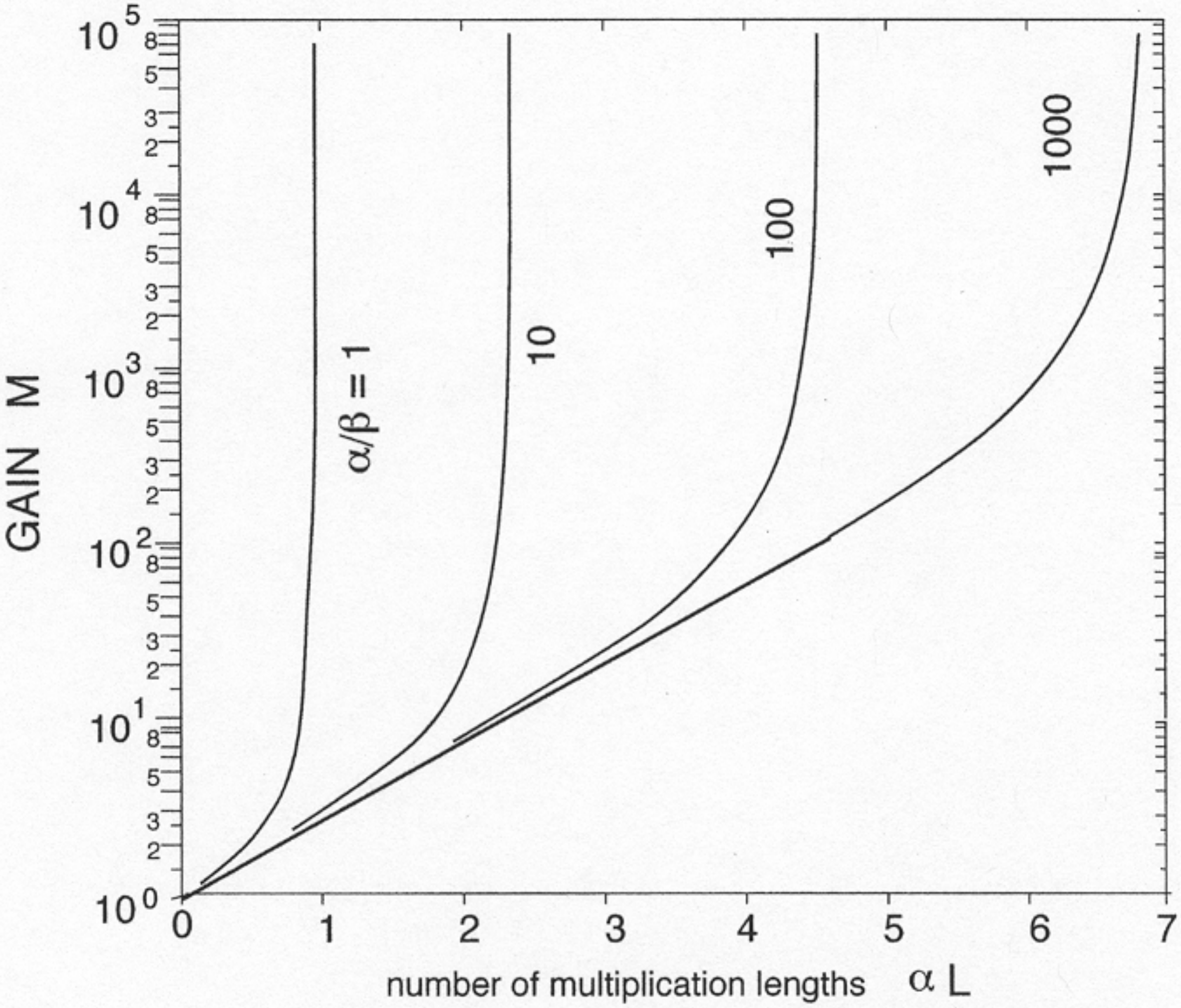


Figure 5-4.3 The dc gain M of the avalanche photodiode (for electron injection at $x=0$) as a function of the number of multiplications αL and with the ionization ratio α/β as a parameter

Staircase APD: Use of bandgap engineering to increase the ratio of ionization coefficients.

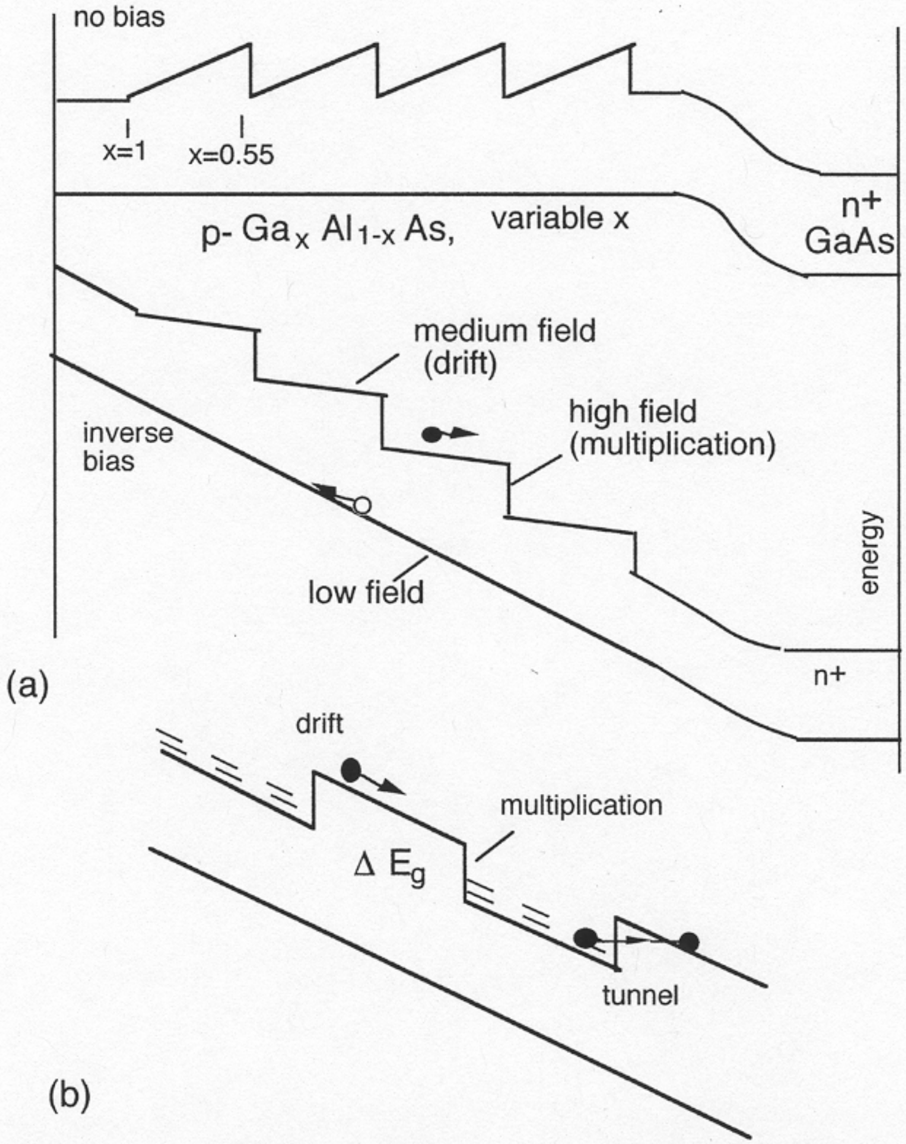


Figure 5-4.10 (a) Sawtooth APD in GaAlAs: distribution of the potential energy with no bias (above) and with reverse bias (below); **(b)** superlattice APD