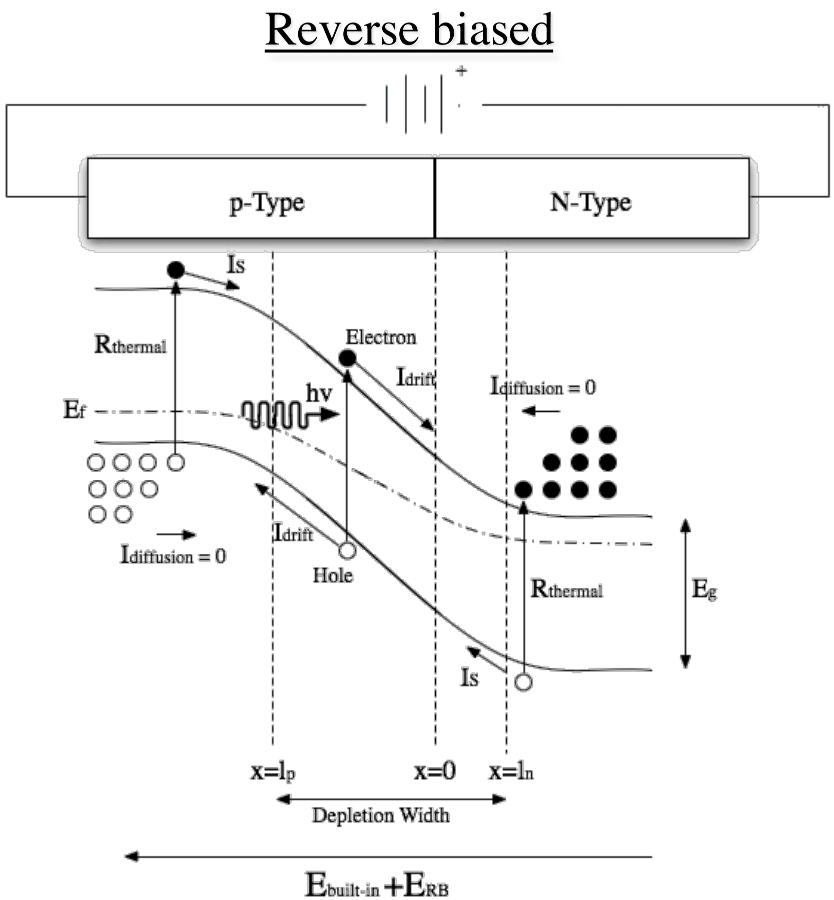
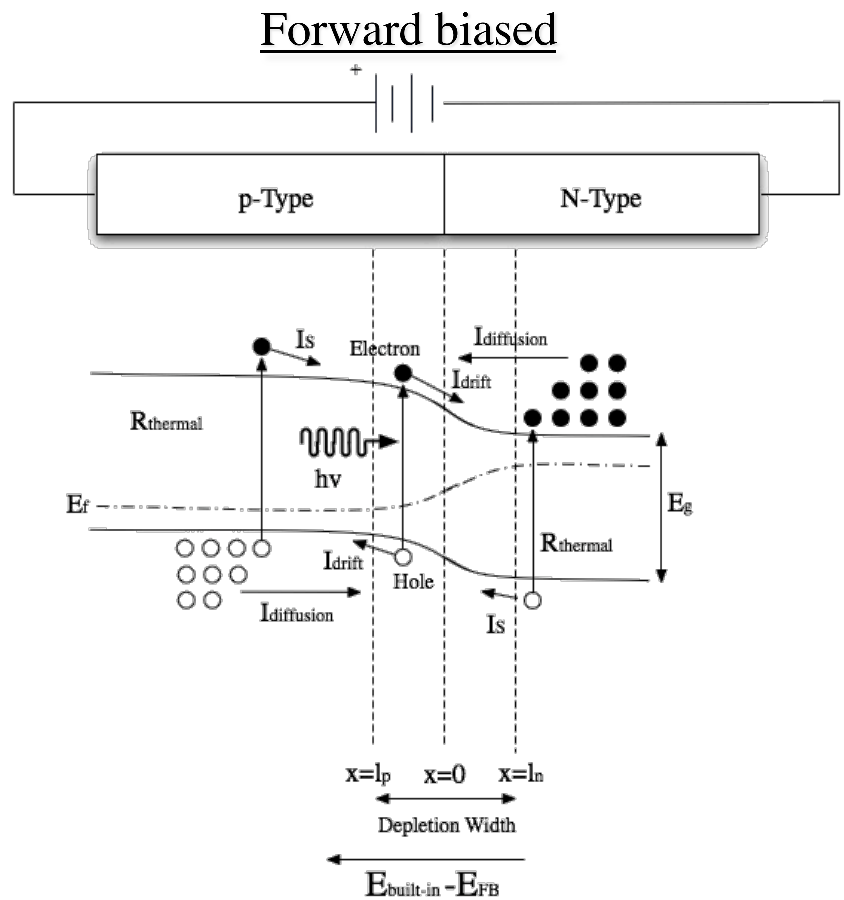
Lecture 3: Photodetectors

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

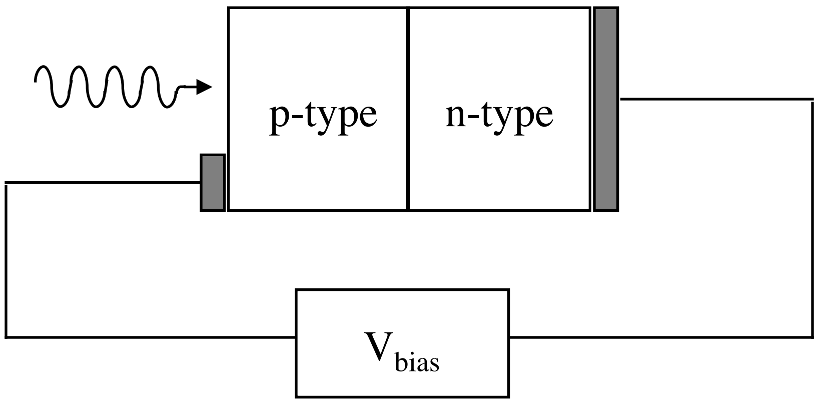
Biased p-n Junction Photodiodes





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

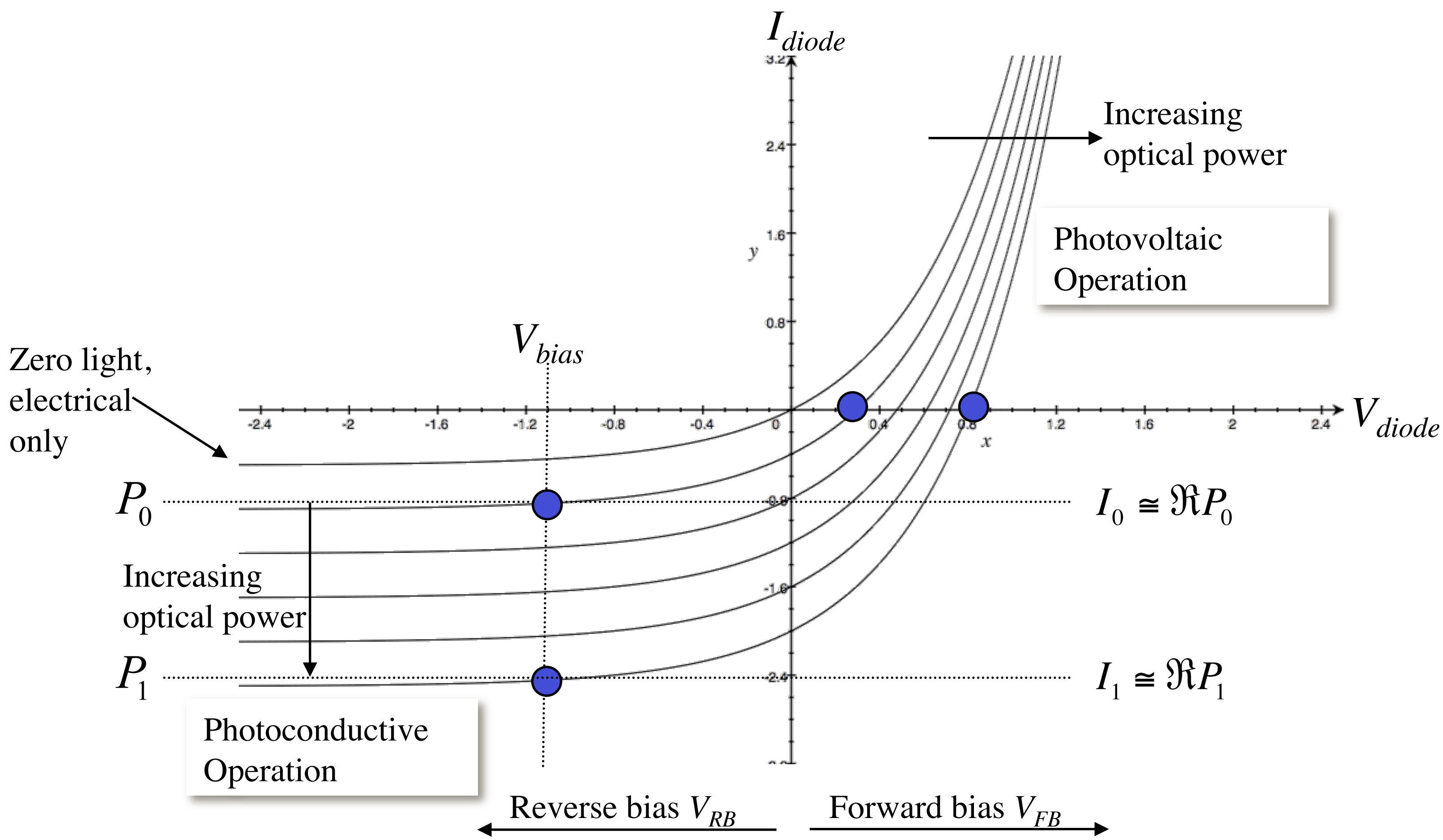
p-n Junction Photodiode Equation



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

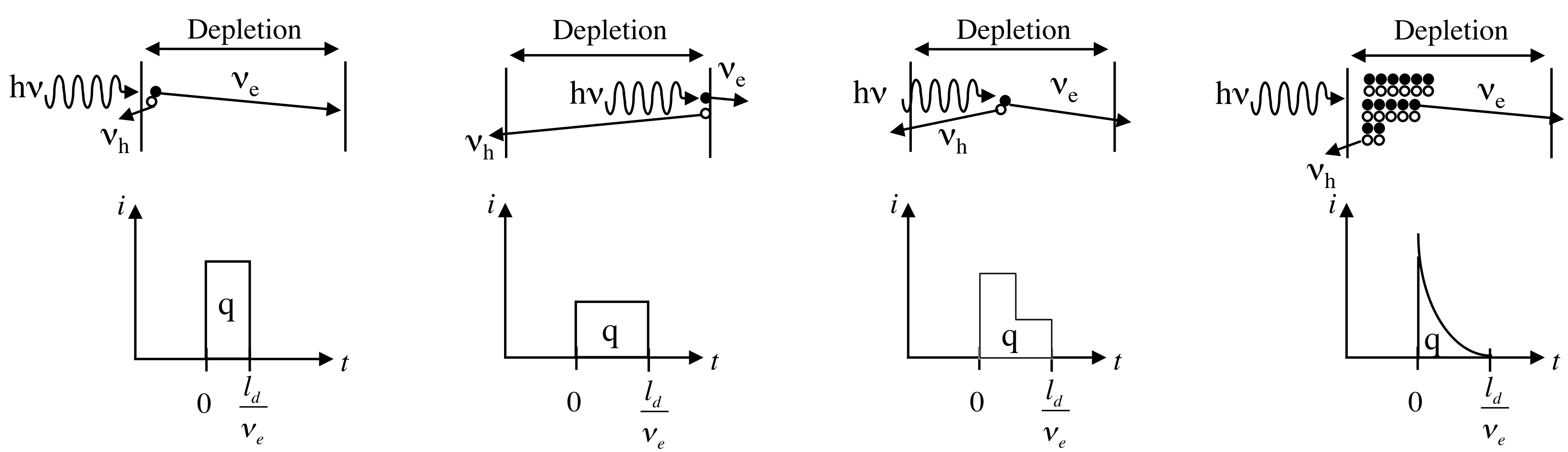
- I_{dark} = is the current that occurs with zero optical input
- $I_s = I_{th}$ is the thermal or saturation current that occurs in normal (non-illuminated) diode operating mode
- I_{photo} is photo-generated current = $\frac{\eta q}{h\nu} P_{rcvd}$
- q is the electron charge
- V_{bias} is applied bias 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



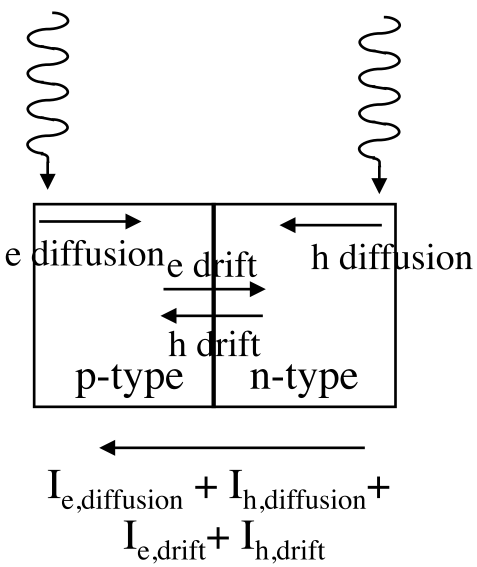
pn-Junction Carrier Dynamics (1)

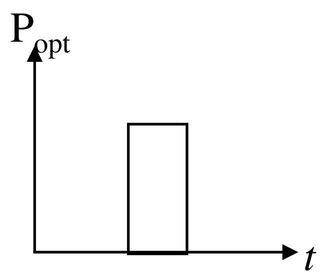
- Carrier diffusion time (~ns/μm) is typically much longer than carrier transit time (~10ps/μm)
- Electron and hole velocities saturated in depletion region due to high field strength
- Once away from depletion region carrier velocities fall below saturation
- Space charge barrier prevents carriers from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

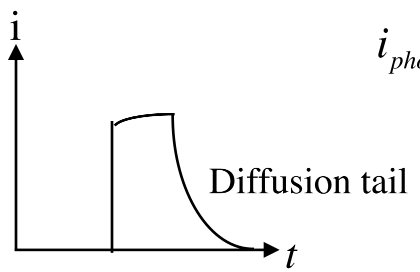


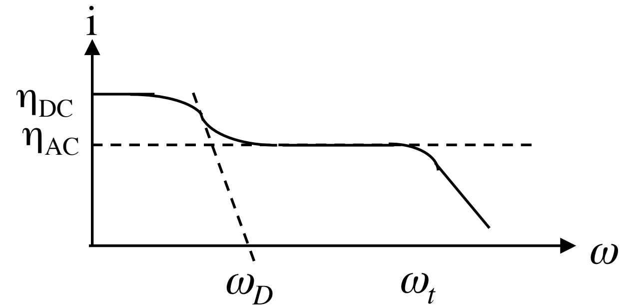
pn-Junction Carrier Dynamics (2)

- 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





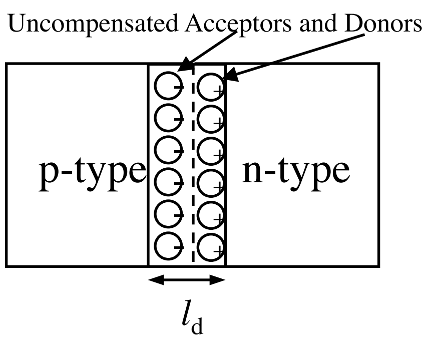




$$i_{photo}(\omega) = \frac{\eta_{DC} - \eta_{AC}}{h\nu} \frac{P_{rcvd}(\omega)}{\sqrt{1 + \left(\frac{\omega}{\omega_D}\right)^2}} + \frac{q\eta_{AC}}{h\nu} P_{rcvd}(\omega)$$

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

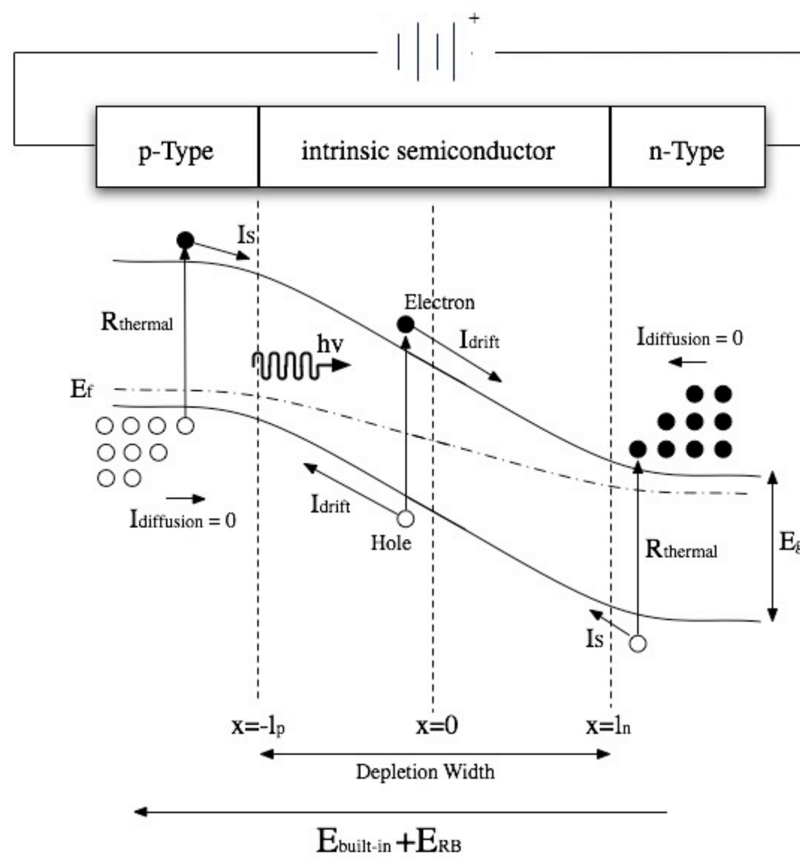
- The frequency at which the detector bandwidth rolls off by 3-dB due to the junction capacitance is

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

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

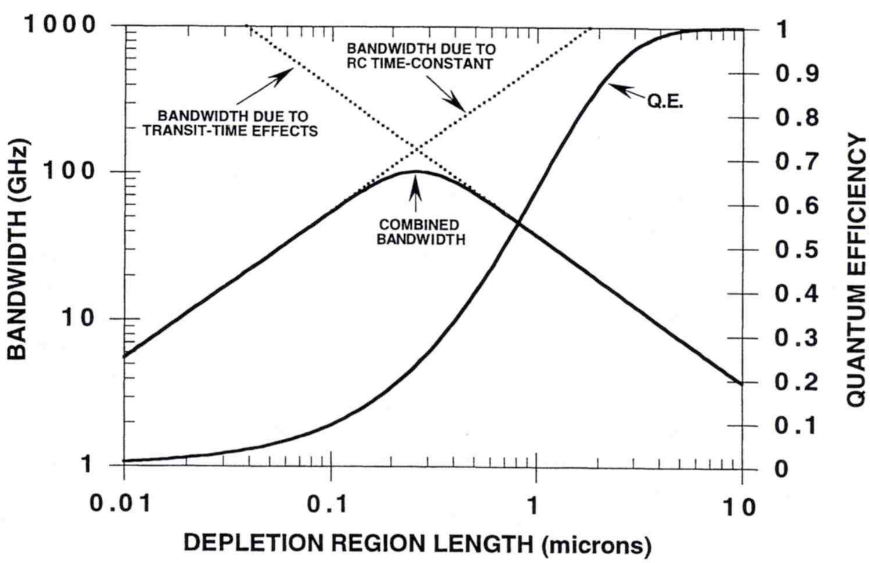
$$P_{abs}(x) = P_i(1 - R)(1 - e^{-\alpha(\lambda)x}) \\ = \eta(\lambda, x)P_i$$

- 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

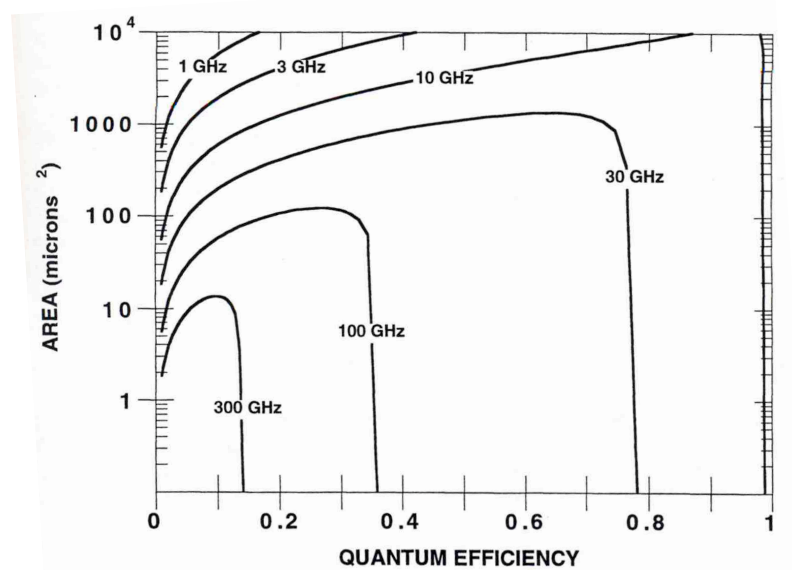
- The quantum efficiency, η, can be approximated assuming R=0 (high quality anti-reflection coating) and intrinsic region length l_d. $\eta = 1 - e^{-\alpha l_d}$
- For small l, bandwidth is transit time limited
- For large l, bandwidth it RC limited
- Optimal bandwidth length where two effects are equal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



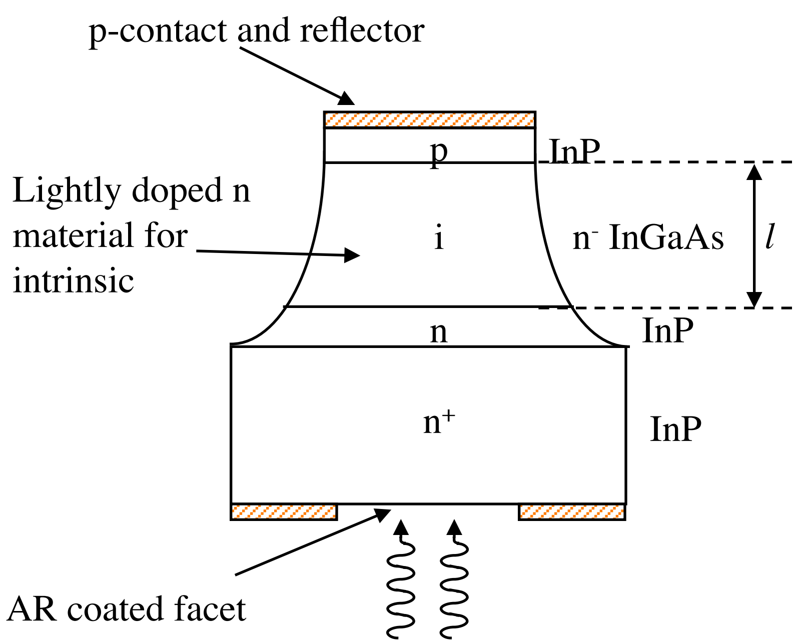
- If the detector area A and length l_d are both optimized, then bandwidth and quantum efficiency can both be maximized

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

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



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 $\alpha l \ll 1$, 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

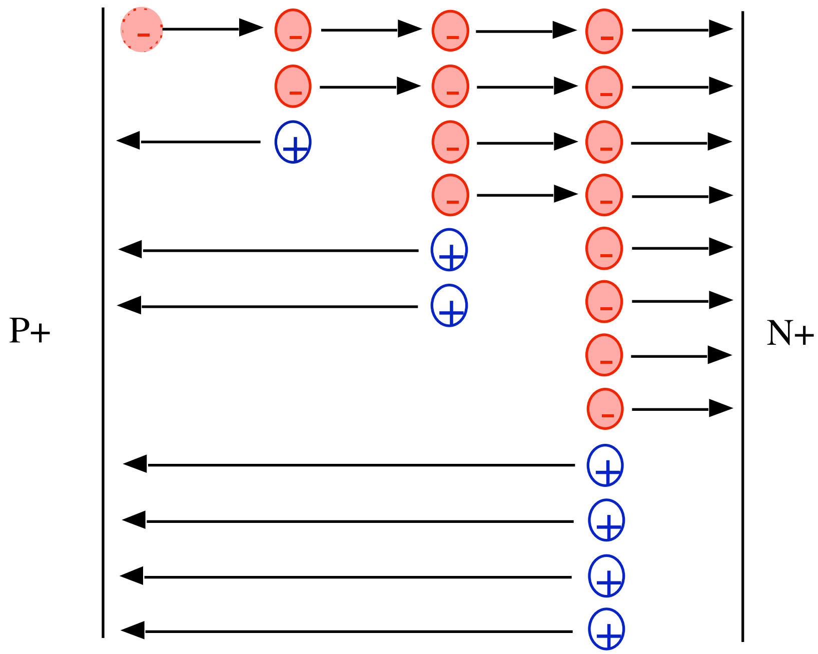
Space charge is reduced by factor of up to 5 relative to PIN, hence UTC

Avalanche Photodiodes (APDs)

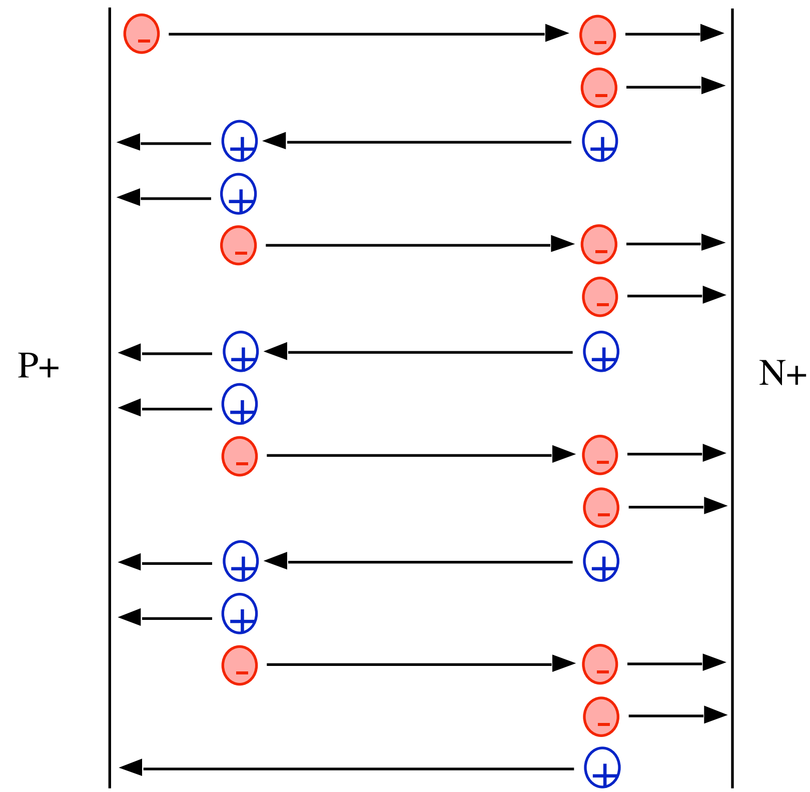
- α Rate at which electrons multiply
- β Rate at which holes multiply

- 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

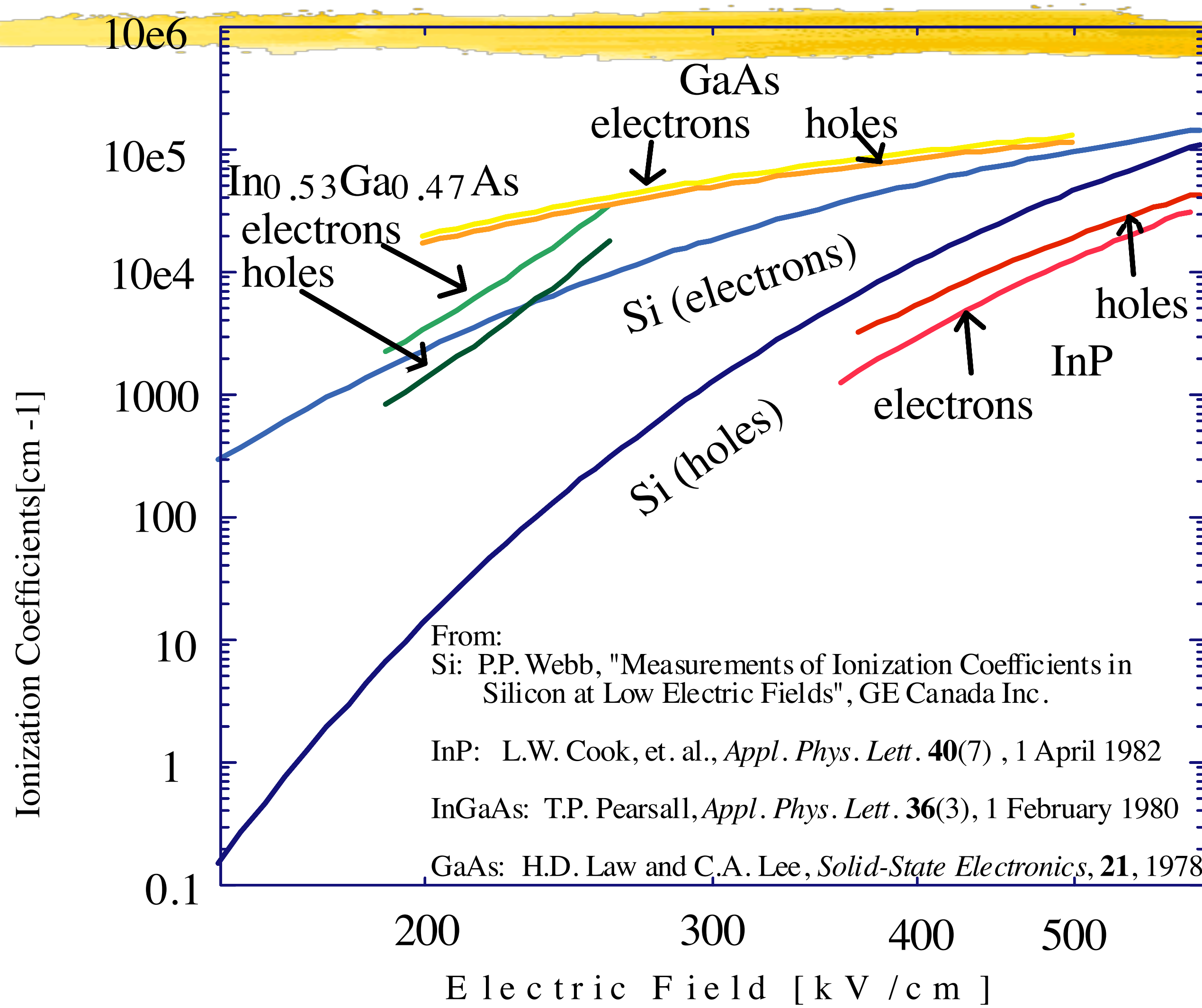


Si Multiplication Layer



InP Multiplication Layer

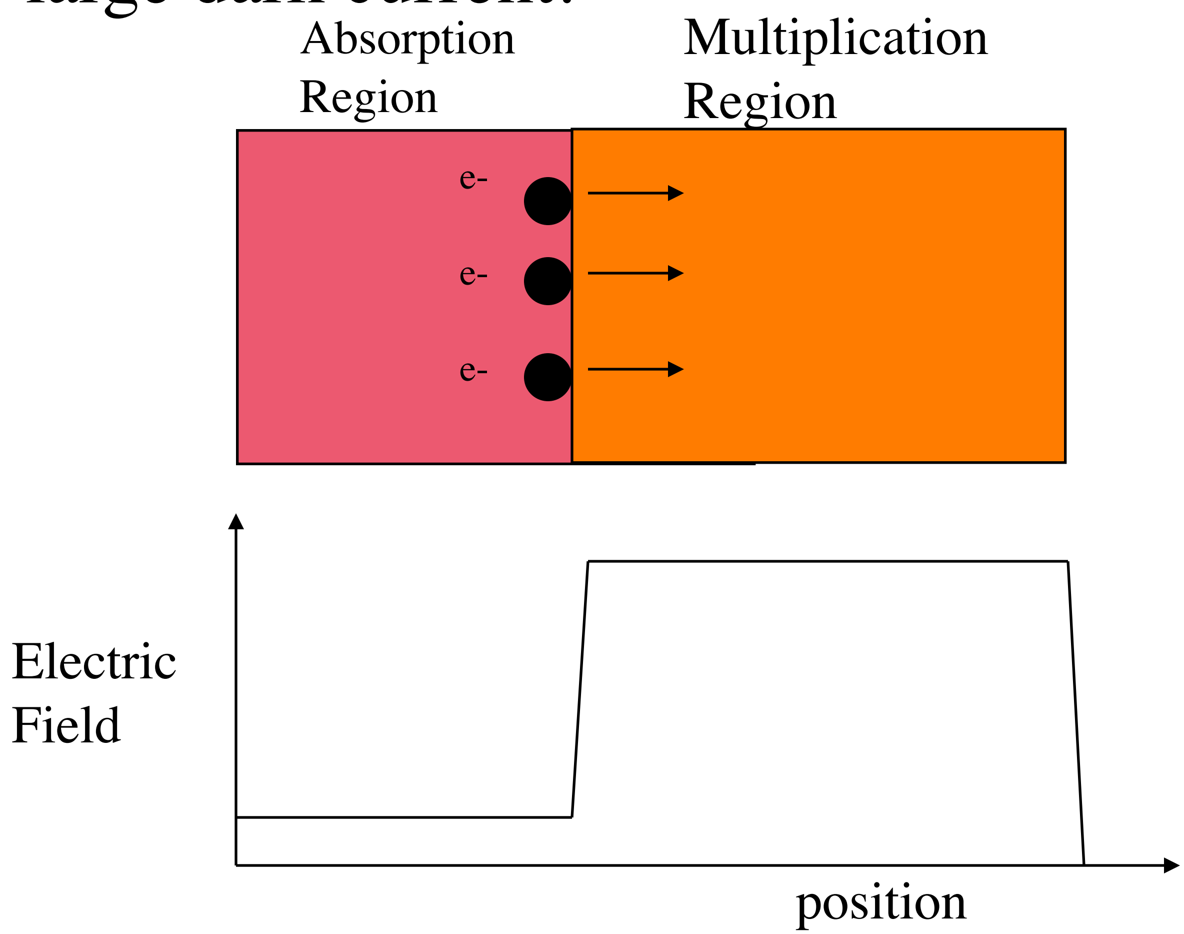
Ionization Coefficients for Semiconductors



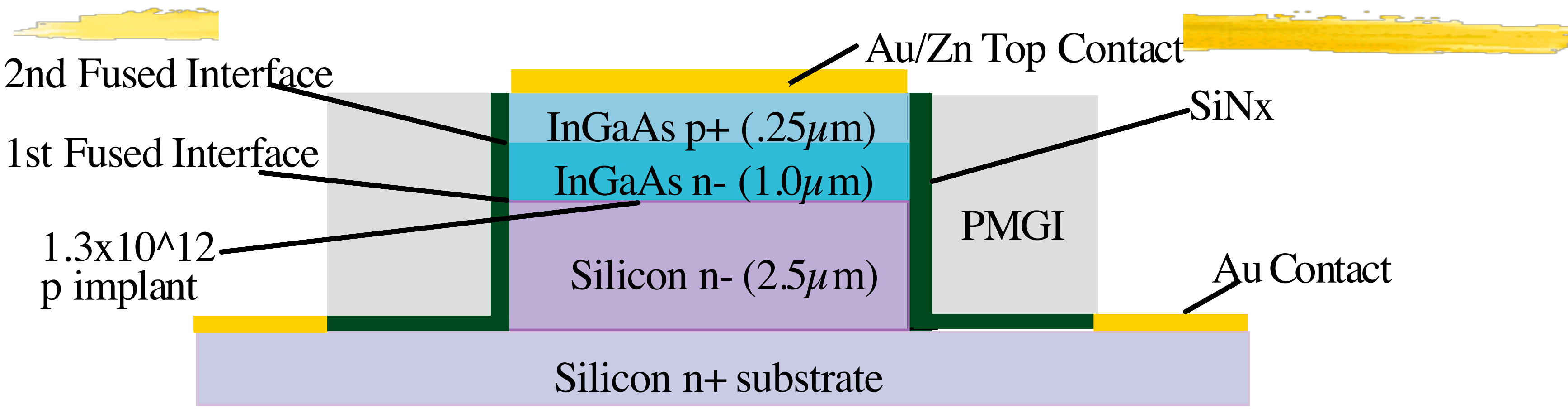
SAM APDS:

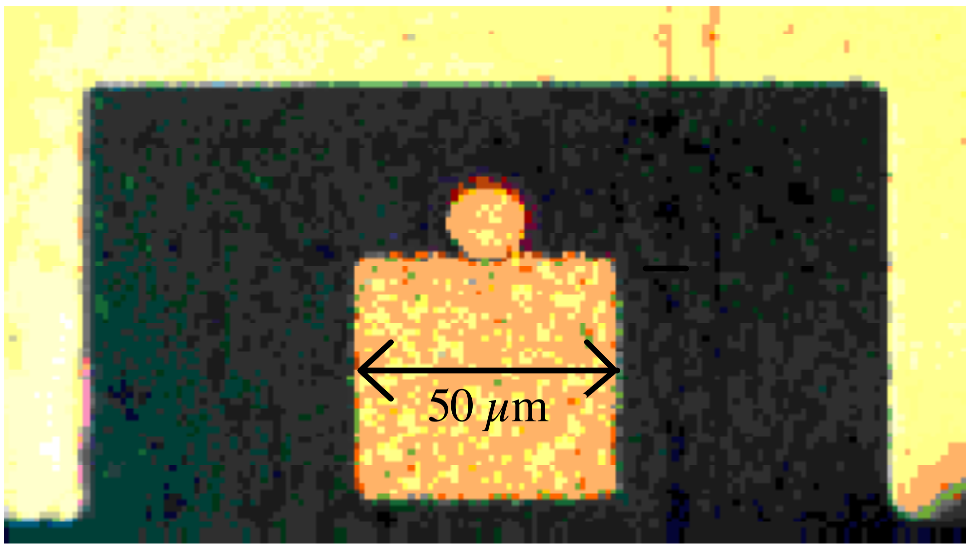
Need for Separate Absorption and Multiplication Regions

Small bandgap avalanche regions tend to have large dark current.

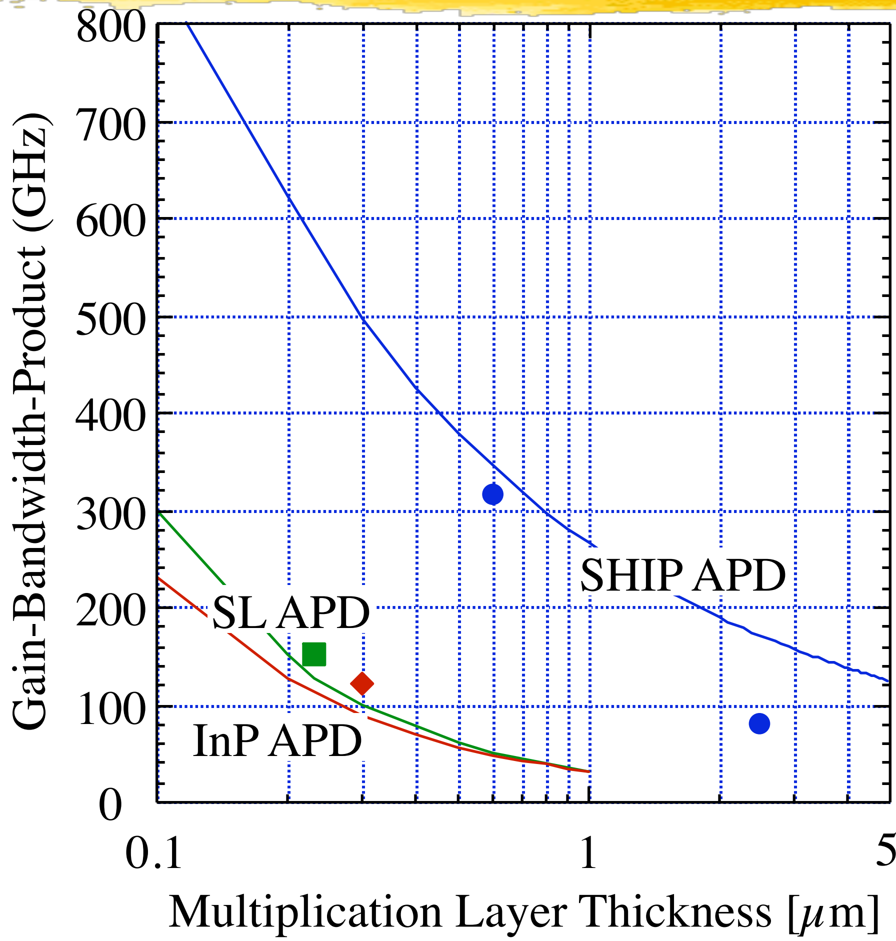


Cross Section and Top View of SHIP Detector





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



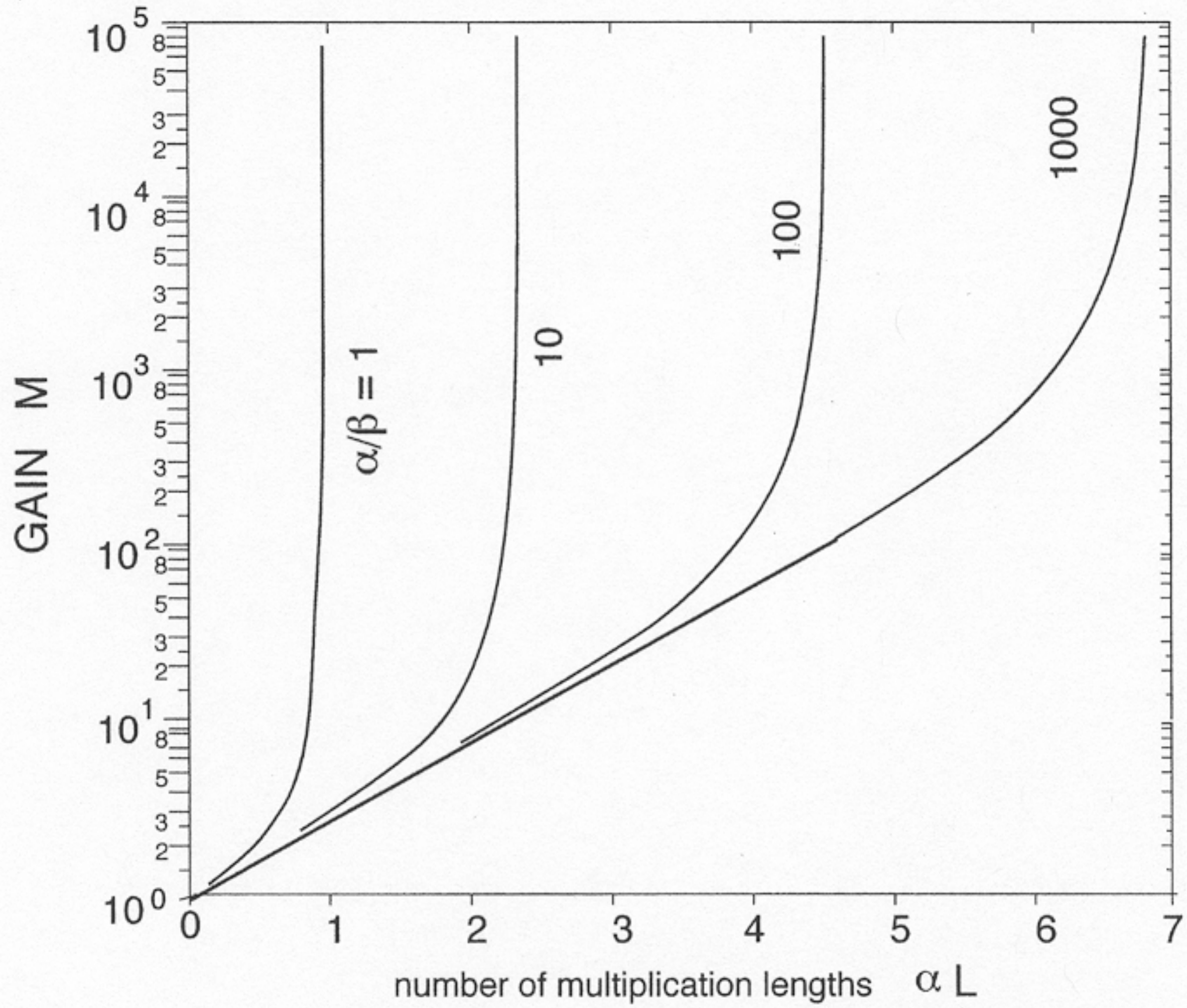


Figure 5-4.3 The dc gain M of the avalanche photodiode (for electron injection at x=0) as a function of the number of multiplications αL and with the ionization ratio α/β as a parameter

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

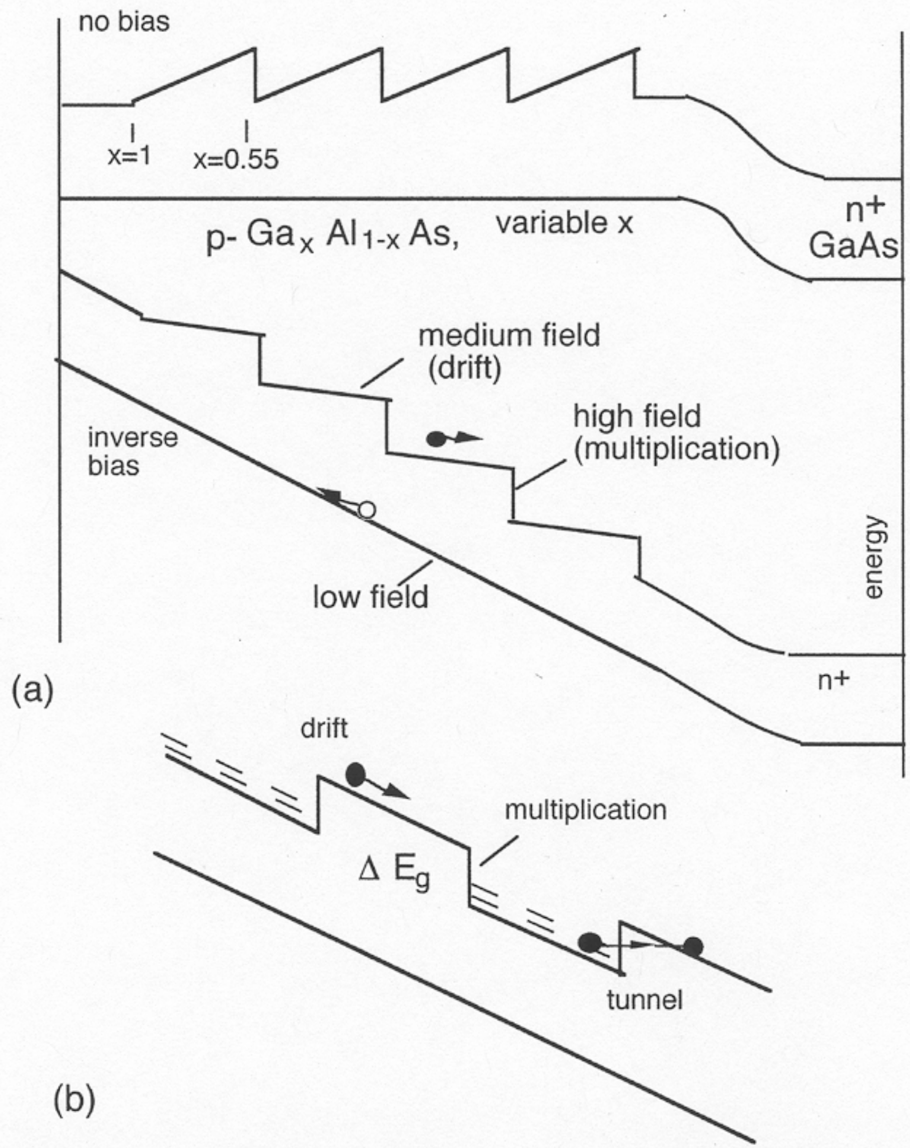


Figure 5-4.10 (a) Sawtooth APD in GaAlAs: distribution of the potential energy with no bias (above) and with reverse bias (below); **(b)** superlattice APD