Photodetectors
Read: Kasip, Chapter 5
Yariv, Chapter 11
Class Handout

ECE 162C

Lecture #16

Prof. John Bowers

Final: Thursday, June 12 12-3

Final

- Final: Tuesday, June 10 12-3
- 1 two sided 8.5 x 11” crib sheet
- Material:
  - Kasip, chapters 1-6
  - Lecture notes
- Problems:
  - Photodetectors+ Photovoltaics
  - VCSEL
  - Lasers
  - Optical fibers
- Review session: Friday, June 6 at 10-12 at ESB 1001

Types of Photodetectors

- Photoelectric detectors
  - Photovoltaic (PIN)
  - Photoconductive
  - Avalanche photodetector (APD)
  - Phototransistor
- Photoemission detectors
  - Vacuum photodiode
  - Photomultiplier
- Thermal detectors
  - Bolometer
  - Thermocouple
  - Pyroelectric
- Weak interaction Detectors
  - Photon drag

Definitions

- Quantum efficiency η: Ratio of the number of electrons collected to the number of photons incident.
- Responsivity: current out divided by optical power incident

$$R_d = \eta \frac{e}{h\nu} = \eta\lambda \frac{e}{hc} = \frac{\eta\lambda}{1.24W / A}$$

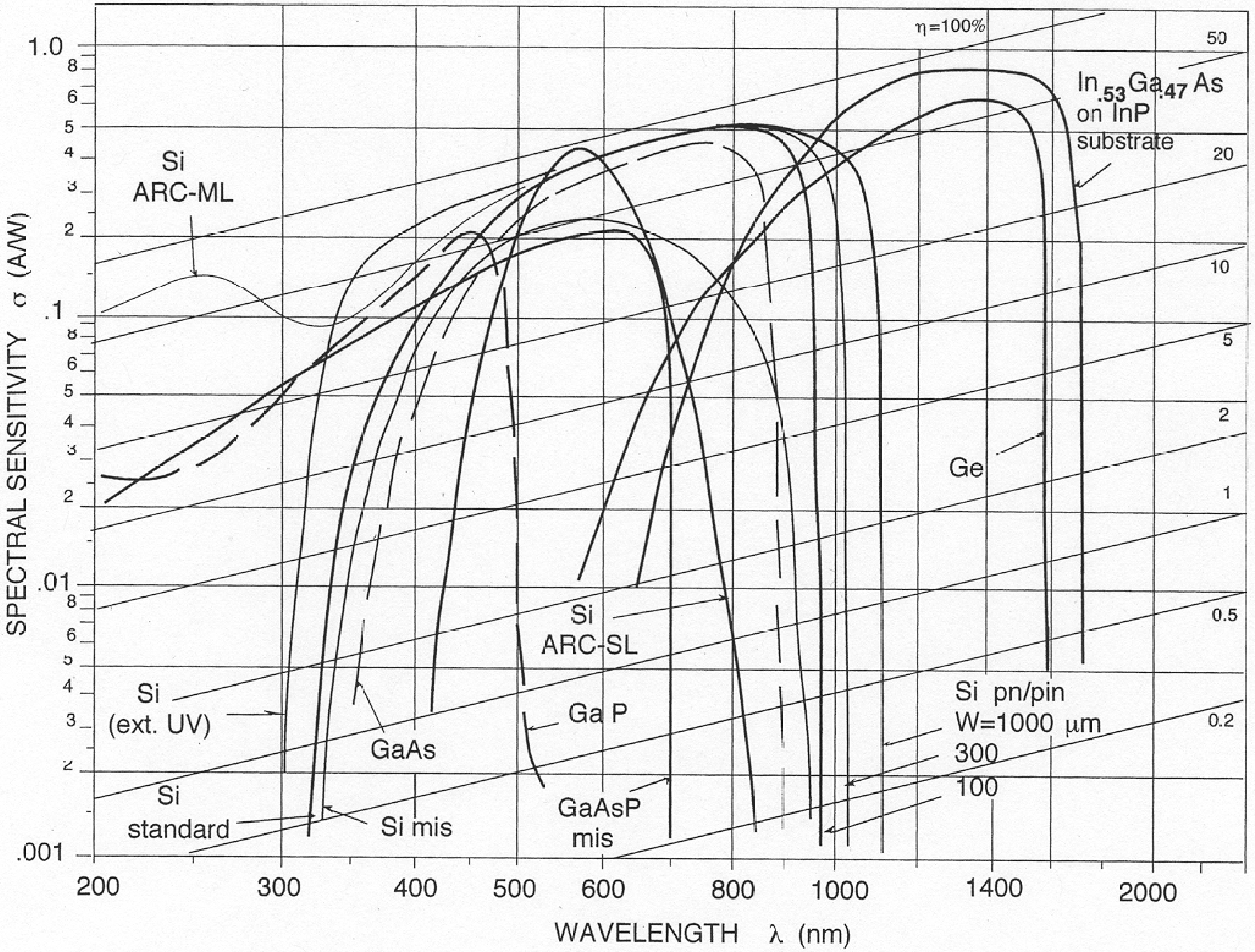


Fig. 5.2.5 Spectral sensitivity σ(λ) of typical semiconductor photodiodes in several materials and structures from UV to NIR (T=300 K). The lines of equal quantum efficiency η are also indicated.

Absorption

Direct gap in semiconductors: α~1/μm
Indirect gap in semiconductors a~0.01/μm

$$I(z) = I_0 e^{-\alpha z}$$

$$\alpha(\lambda) = K\lambda^2 \sqrt{\frac{hc}{\lambda} - E_G}$$

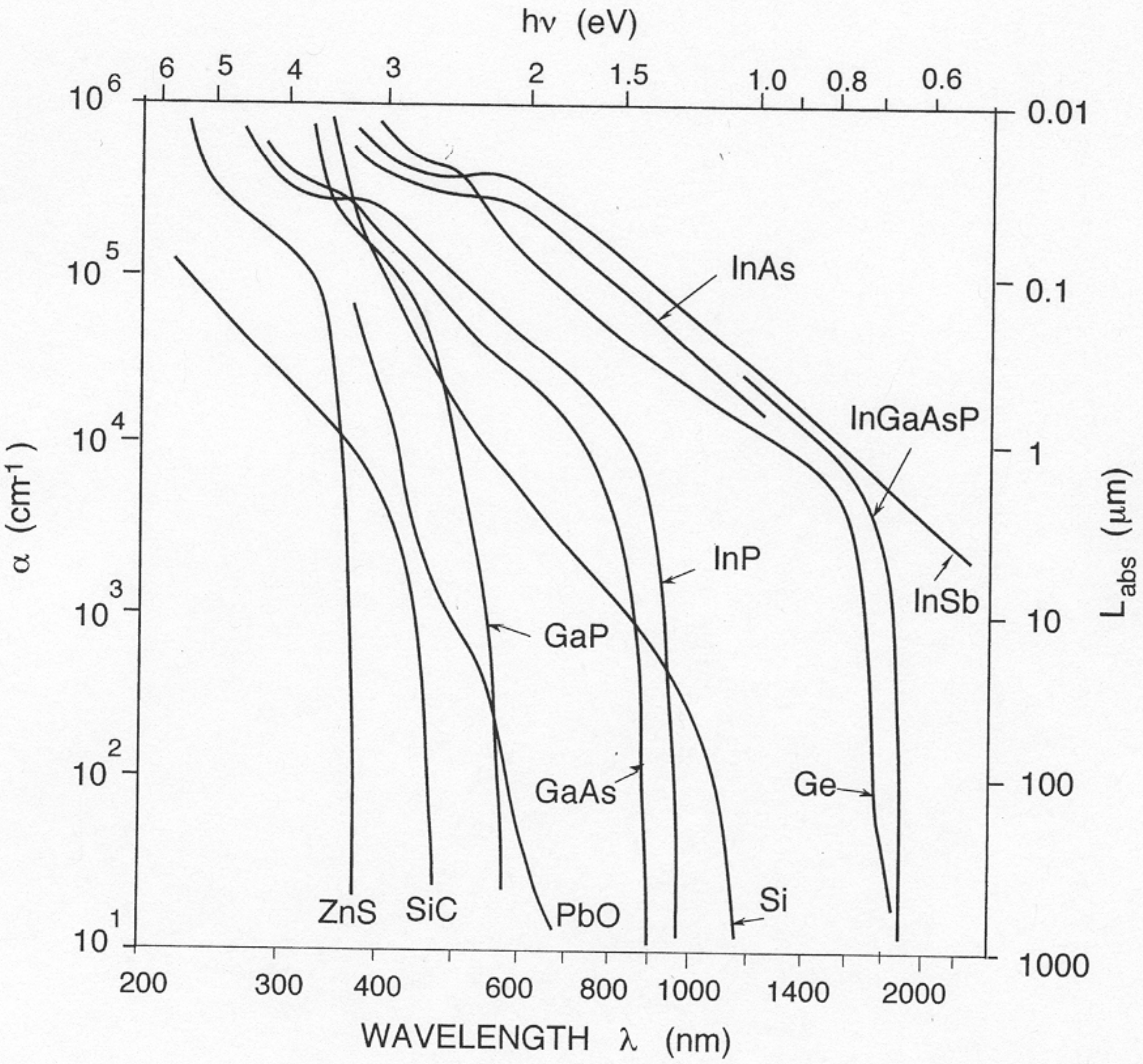


Figure 5-2.2 Wavelength dependence of the absorption coefficient α and of the absorption length L_{abs} for several semiconductors (data for T=300 K)

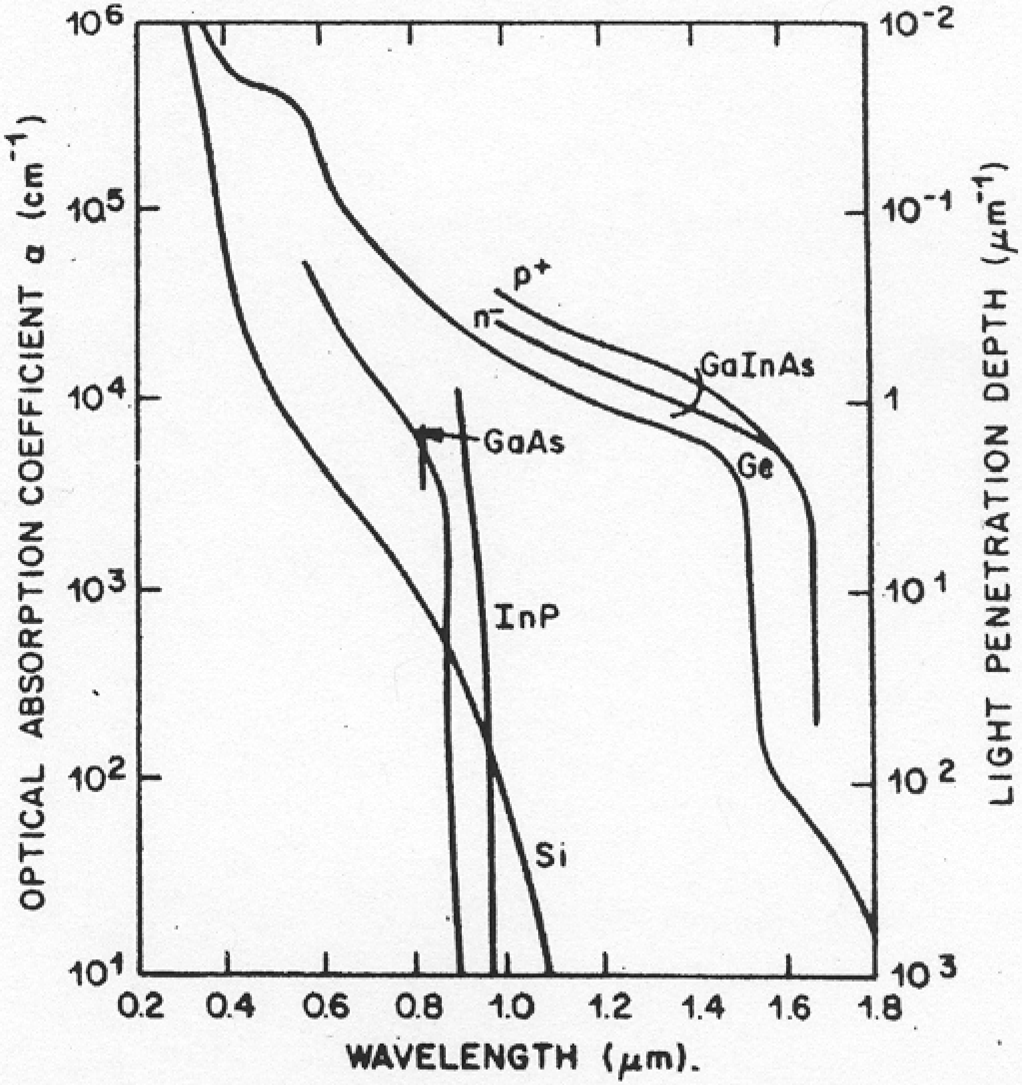
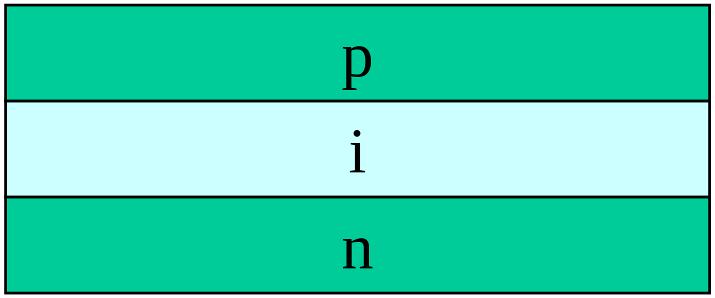


Fig. 6. Dependence of absorption coefficient on wavelength for several materials [18]–[20].

Photoelectric detectors	Gain?
– Photovoltaic (PIN)	No
– Photoconductive	Yes
– Avalanche photodetector (APD)	Yes
– Phototransistor	Yes



Photodetector Classifications

- Illumination
  - Surface normal
    - Top illuminated
    - Substrate illuminated
  - Surface perpendicular
    - Edge absorbing detectors
    - Waveguide detectors
    - Traveling wave photodetectors
- Contacts
  - Metal (MSM photodetectors)
  - Semiconductor

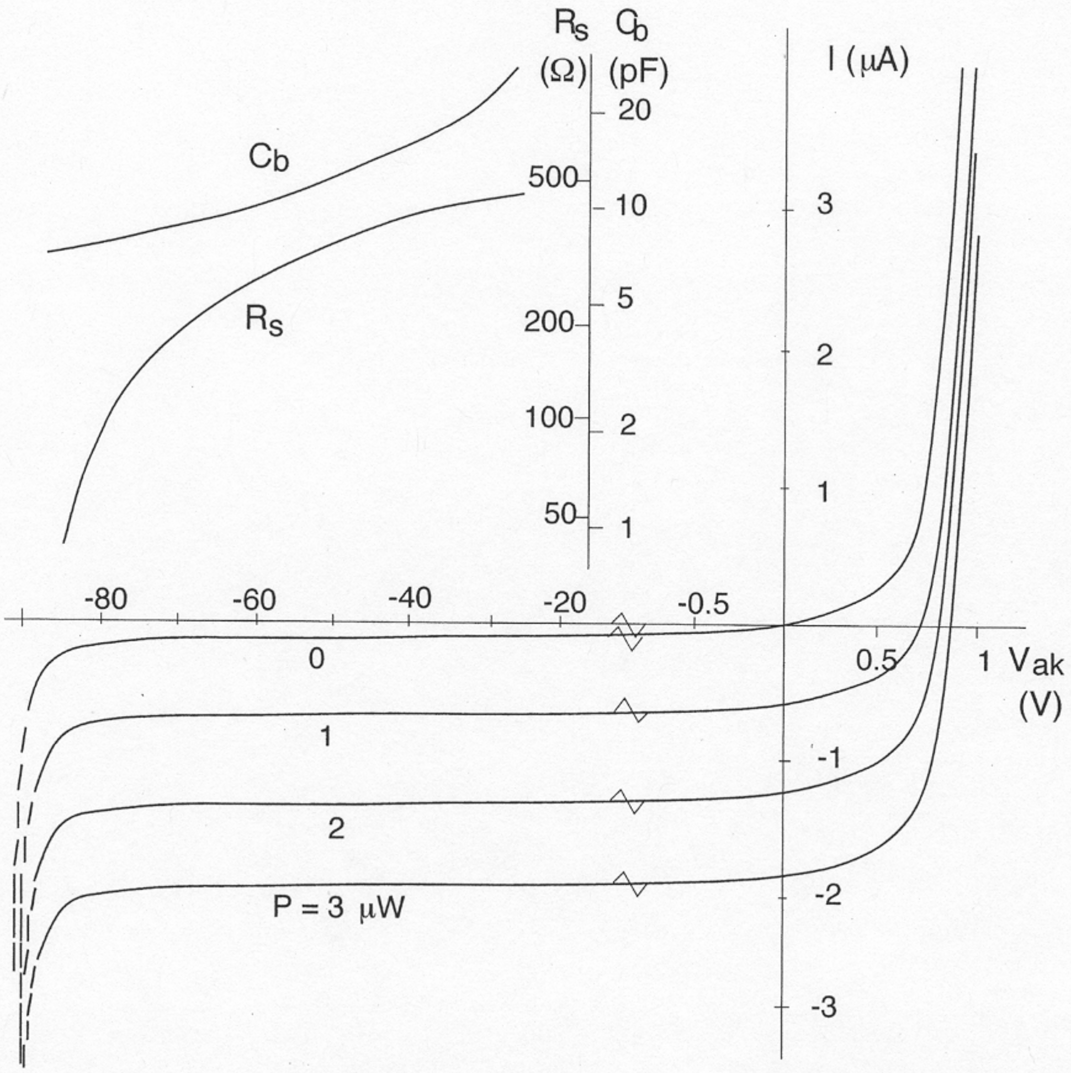


Figure 5-2.7 Current/voltage characteristics of a silicon photodiode (for small signals and λ=900nm). Insert shows the dependence of junction capacitance and series resistance upon V (note the scale change for V<0).

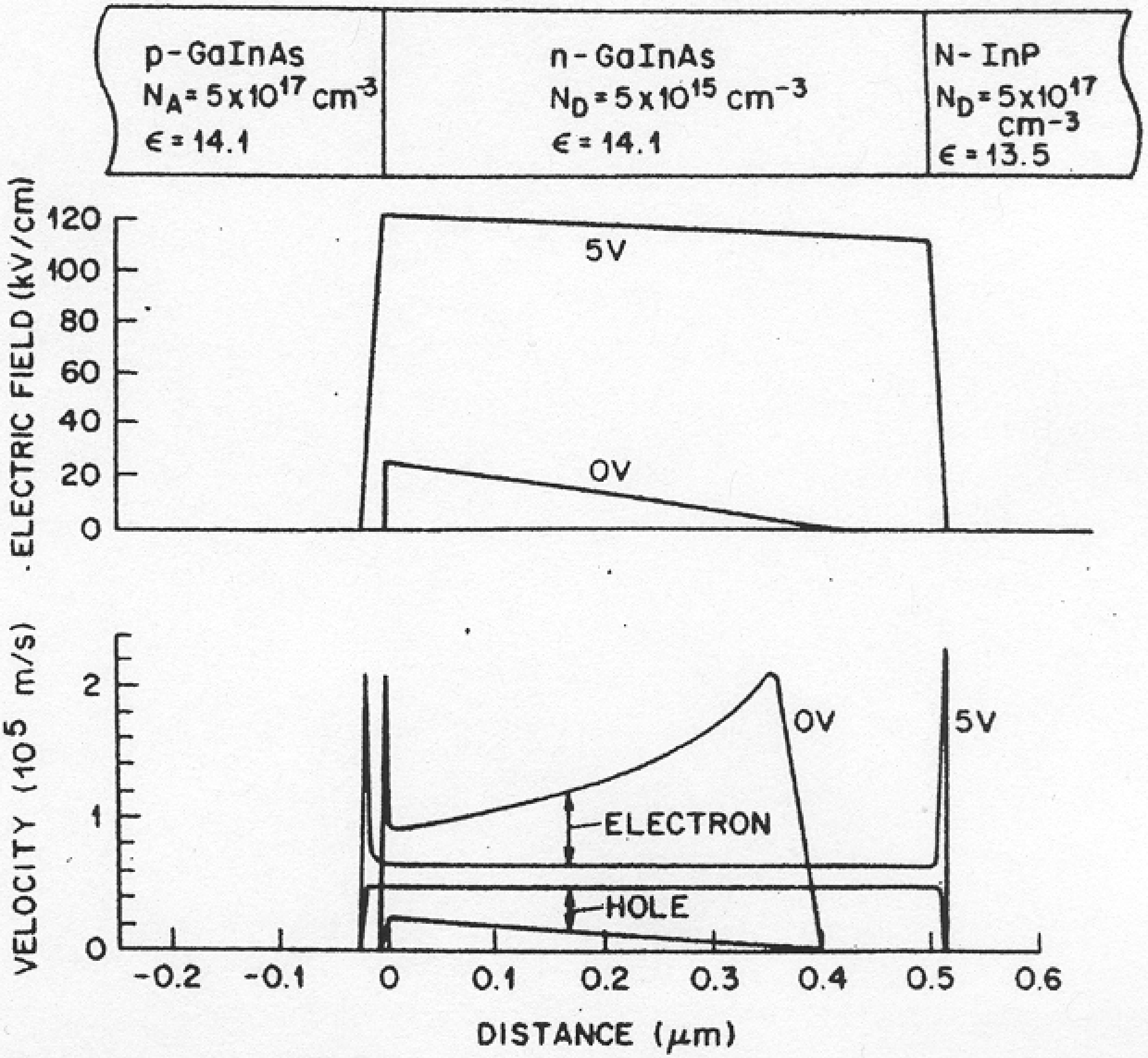


Fig. 2. Schematic diagram of a p-i-n detector and the electric field and electron and hole velocities as a function of position in a p-i-n detector.

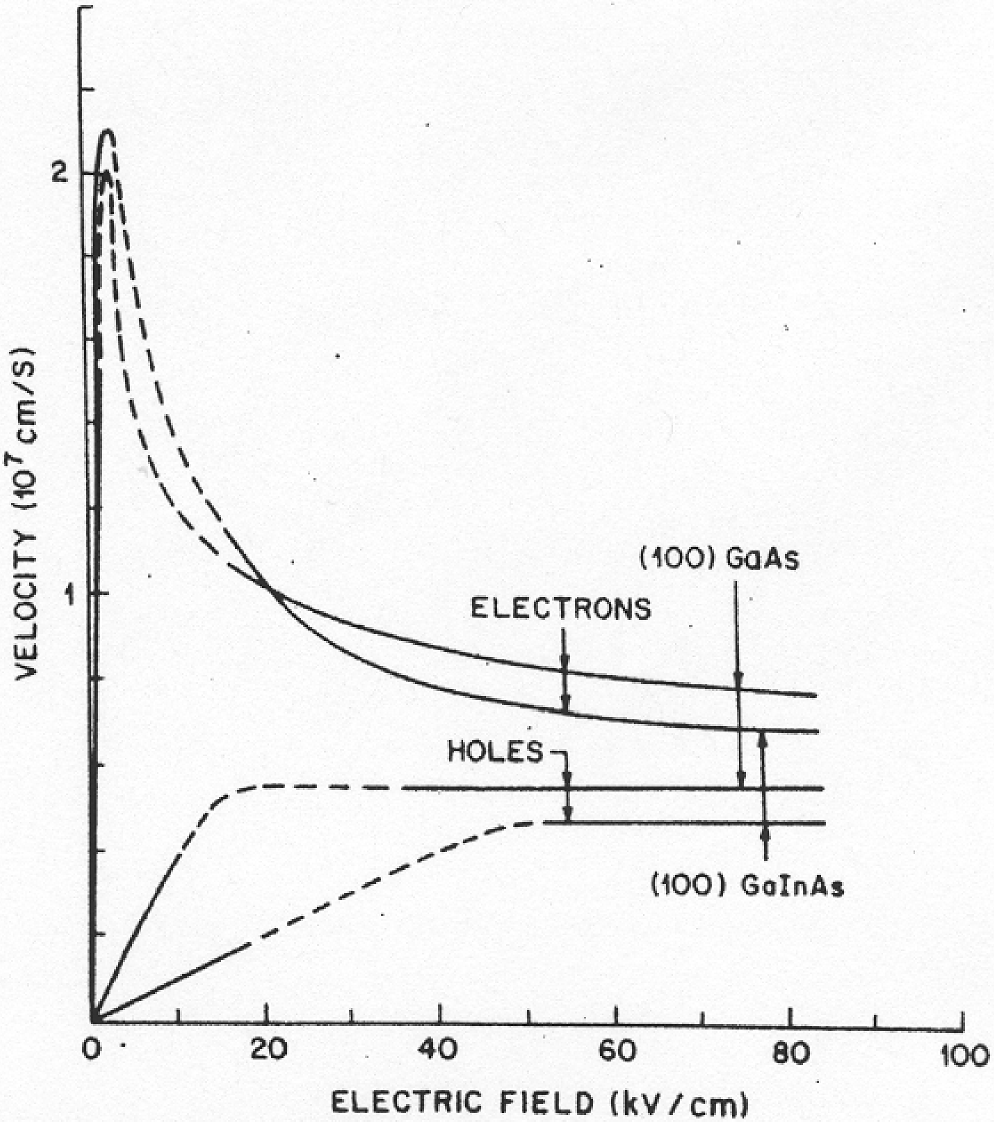


Fig. 1. Dependence of carrier velocity on electric field for GaInAs [11]–[13] and GaAs [14], [15].

PIN Impulse Response?

PIN Impulse Response?

$$j = \frac{v_e e\sigma_e + v_h e\sigma_h}{L}$$

Displacement current flows. That is what is measured in an external circuit, not conduction current.

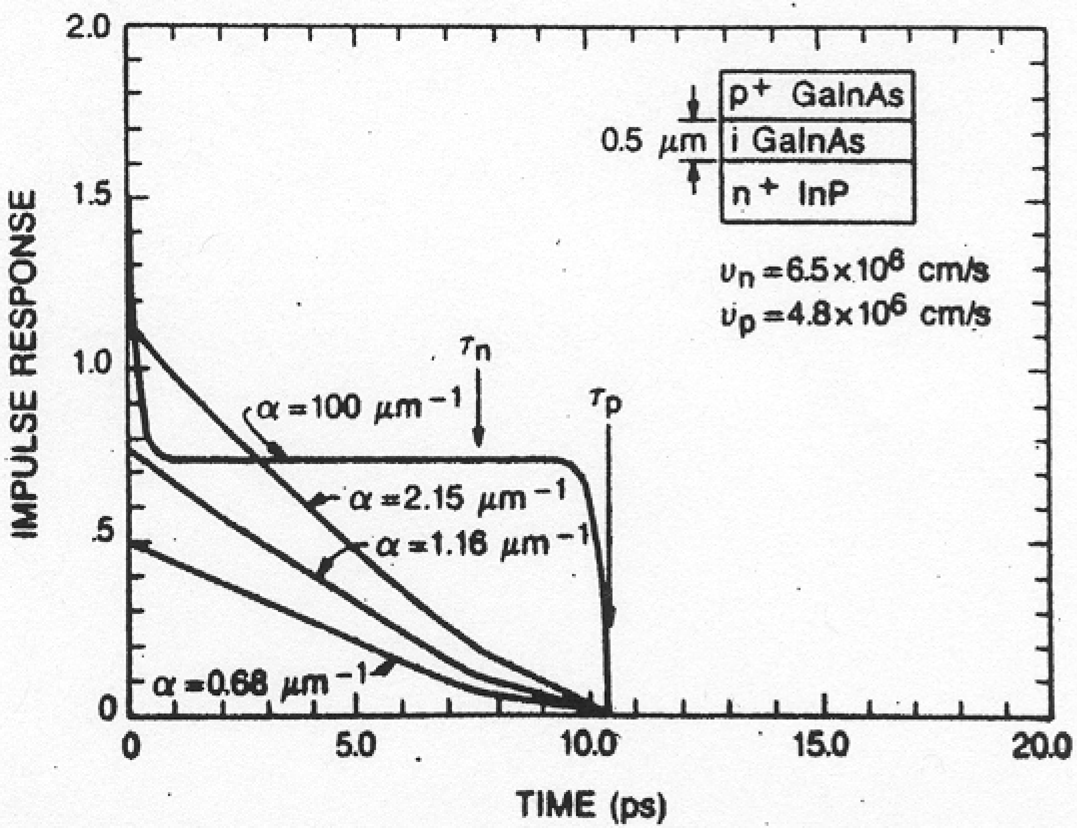


Fig. 3. Impulse response of a p-i-n detector for different values of α: $\alpha = 0.68\ \mu m^{-1}$ ($\lambda = 1.55\ \mu m$), $\alpha = 1.16\ \mu m^{-1}$ ($\lambda = 1.36\ \mu m$), $\alpha = 2.15\ \mu m^{-1}$ ($\lambda = 1.06\ \mu m$), ($v_p = 4.8 \times 10^6$ m/s, $v_n = 6.5 \times 10^6$ m/s, corresponding to GaInAs.

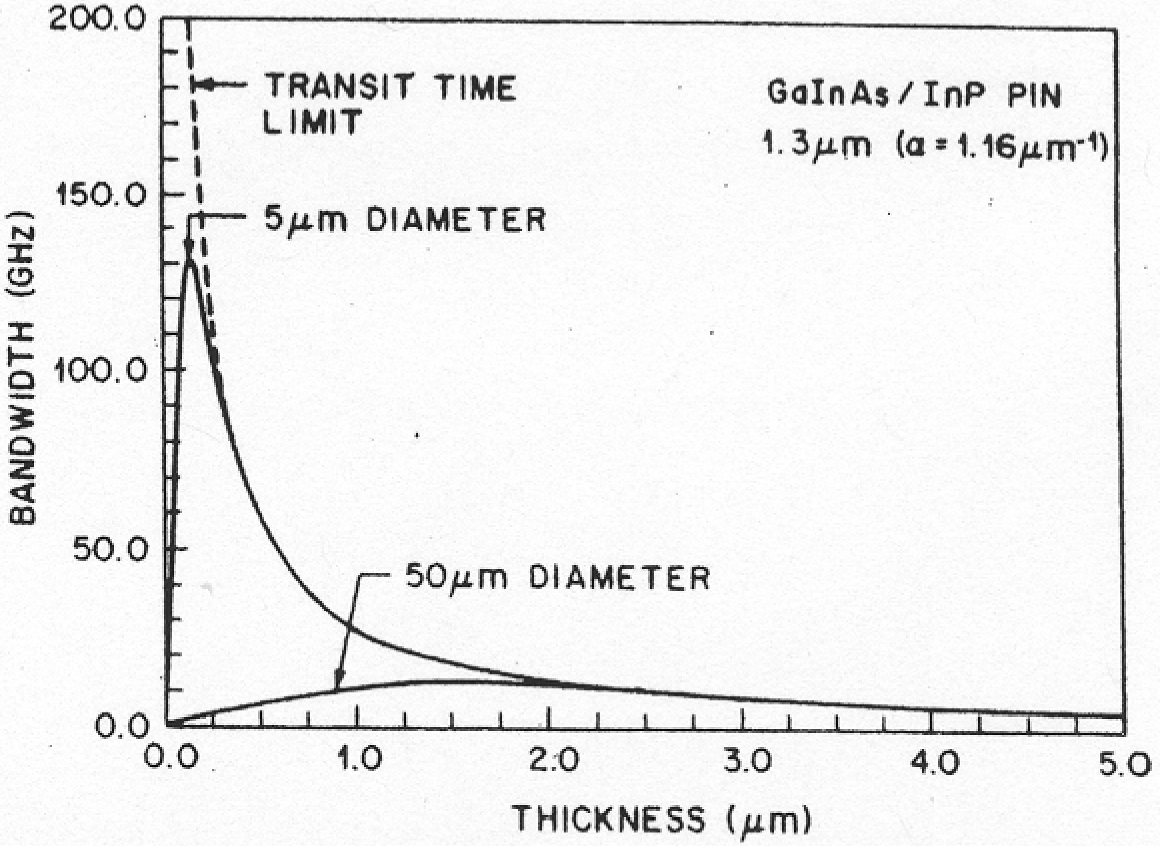


Fig. 4. GaInAs p-i-n detector bandwidth dependence on depletion-layer thickness for 5 and 50 μm diameters. (α = 1.16 μm (1.3-μm wavelength) $v_n = 6.5 \times 10^6$ cm/s, $v_p = 4.8 \times 10^6$ cm/s.)

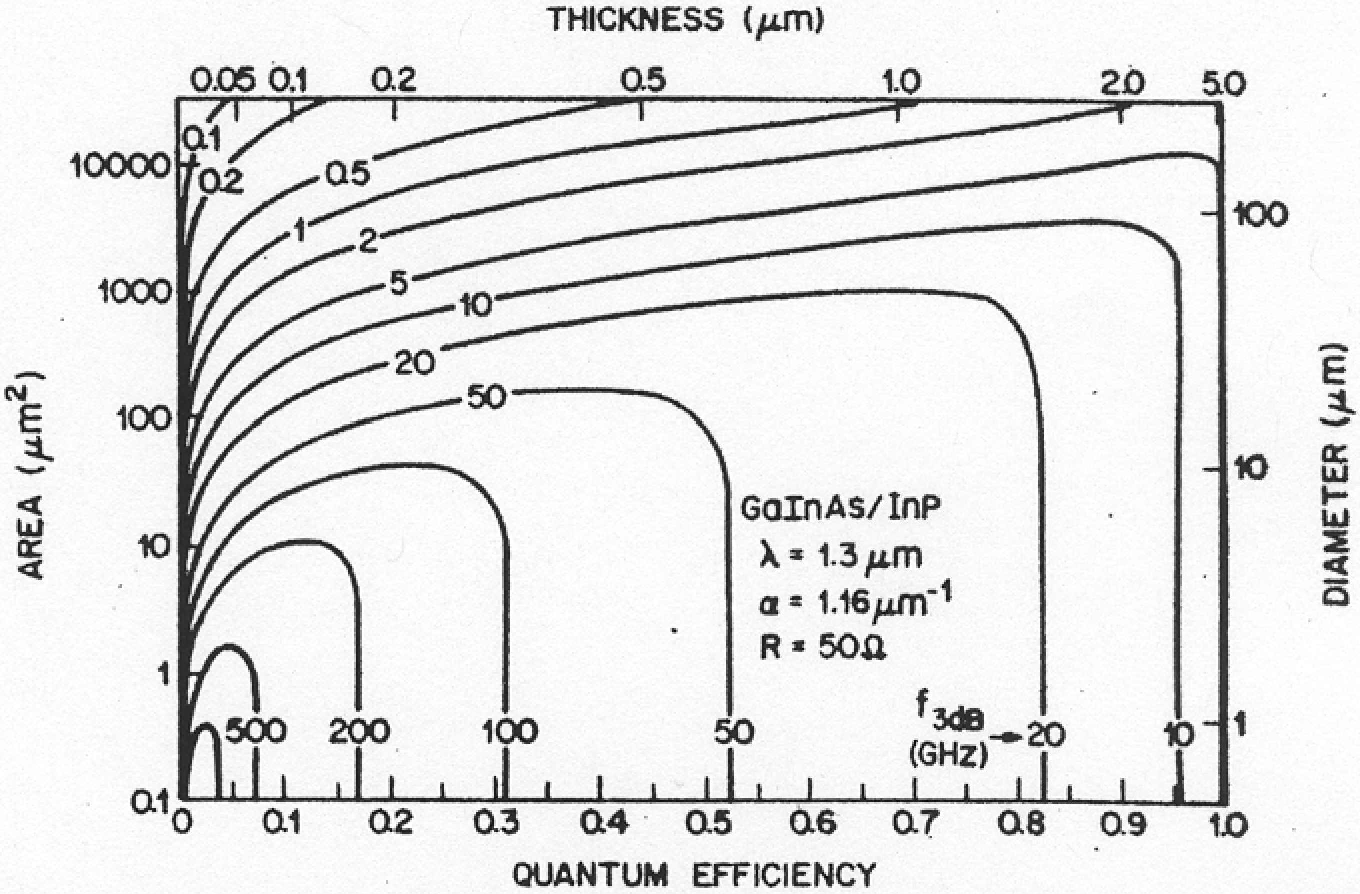


Fig. 5. Contours of constant 3-dB bandwidth in the detector-area, depletion-layer-thickness plane. ($\alpha = 1.16\ \mu m^{-1}$, (1.3-μm wavelength), $v_n = 6.5 \times 10^6$ cm/s, $v_p = 4.8 \times 10^6$ cm/s, $\epsilon = 14.1$.)

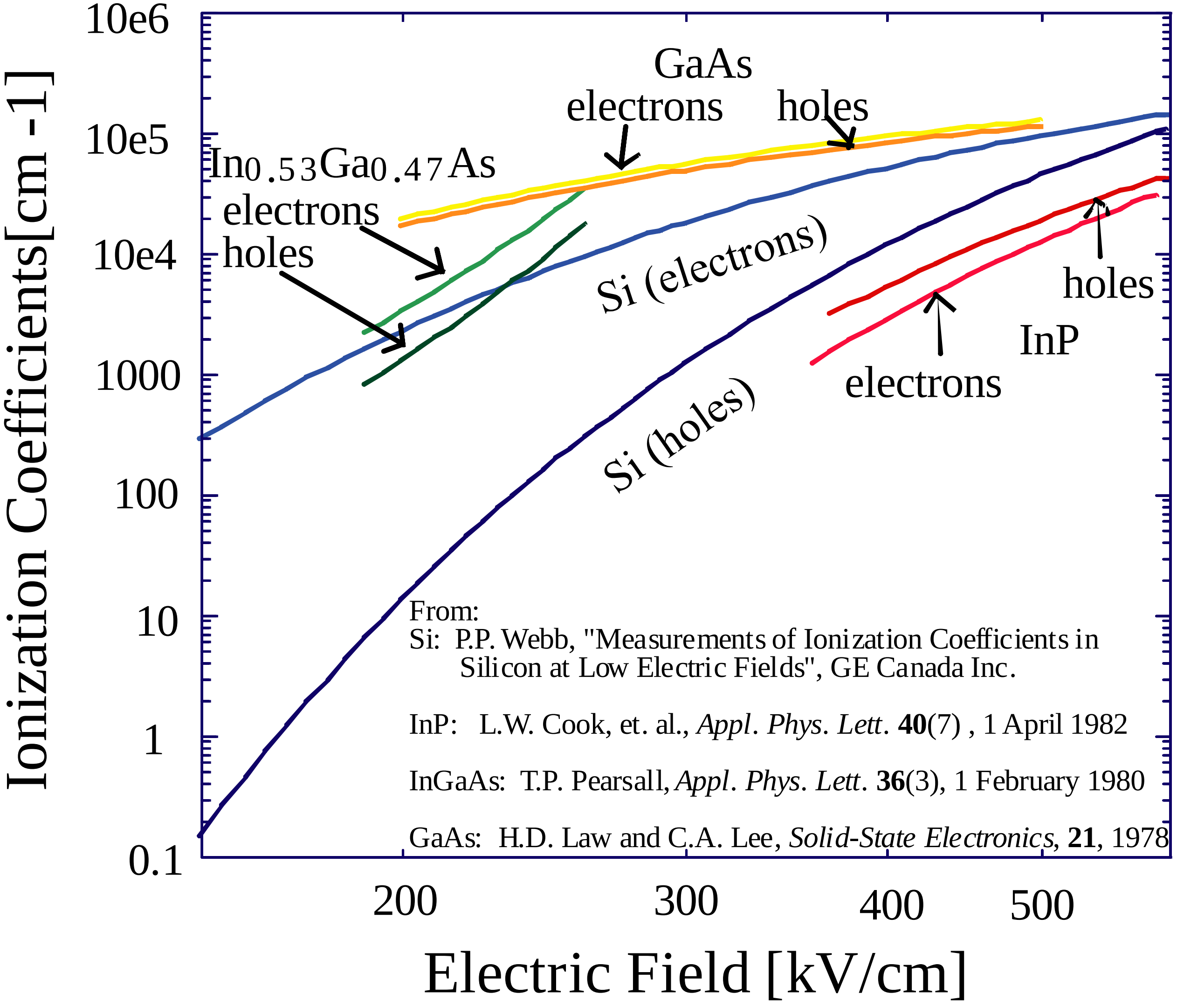
Avalanche Photodiodes (APDs)

□ 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.

Ionization Coefficients for Semiconductors



From:

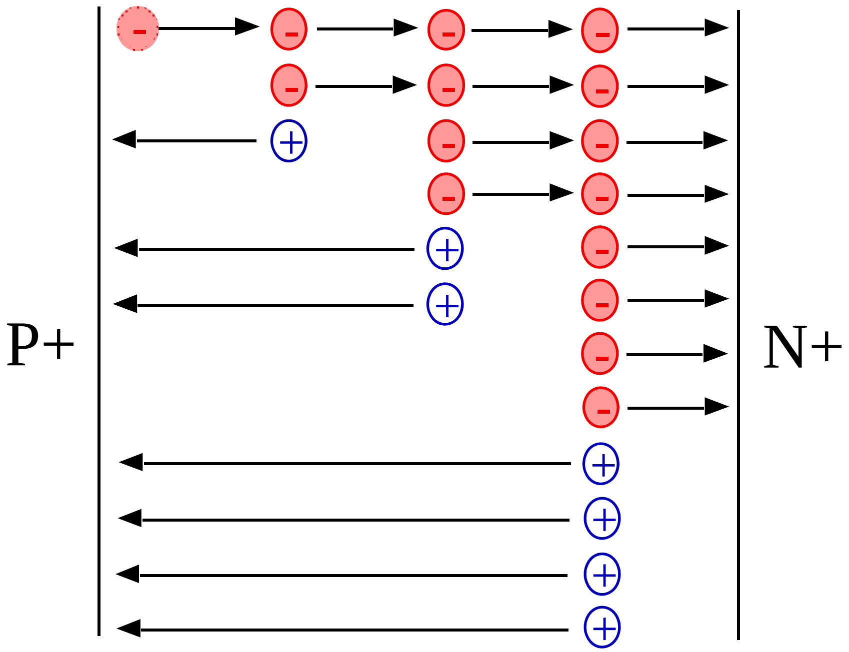
Si: P.P. Webb, "Measurements of Ionization Coefficients in Silicon at Low Electric Fields", GE Canada Inc.

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

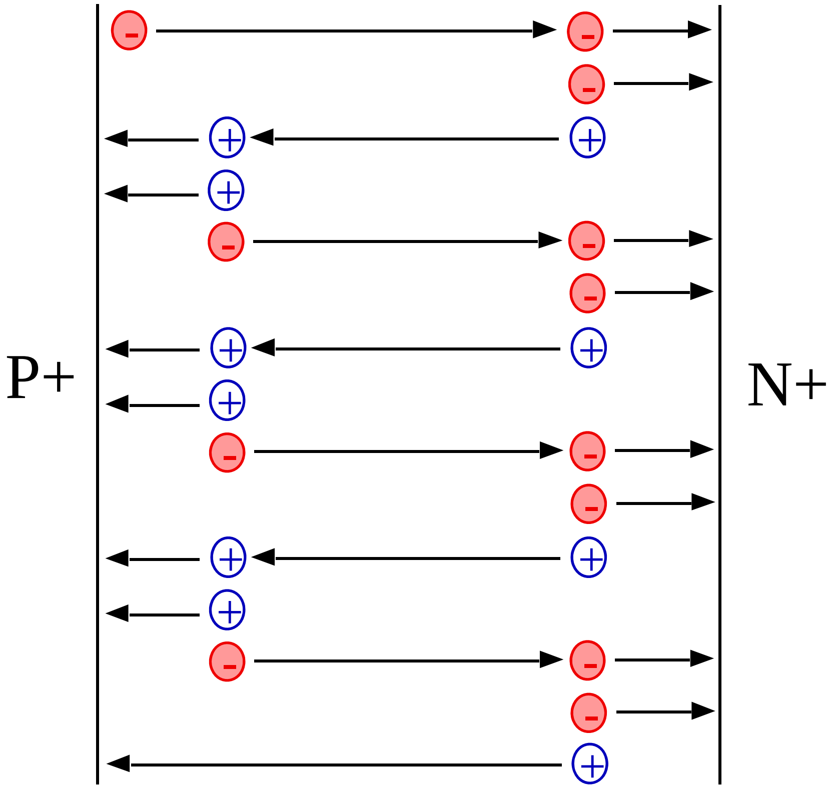
InGaAs: T.P. Pearsall, *Appl. Phys. Lett.* **36**(3), 1 February 1980

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

The Avalanche Multiplication Process



Si Multiplication Layer



InP Multiplication Layer

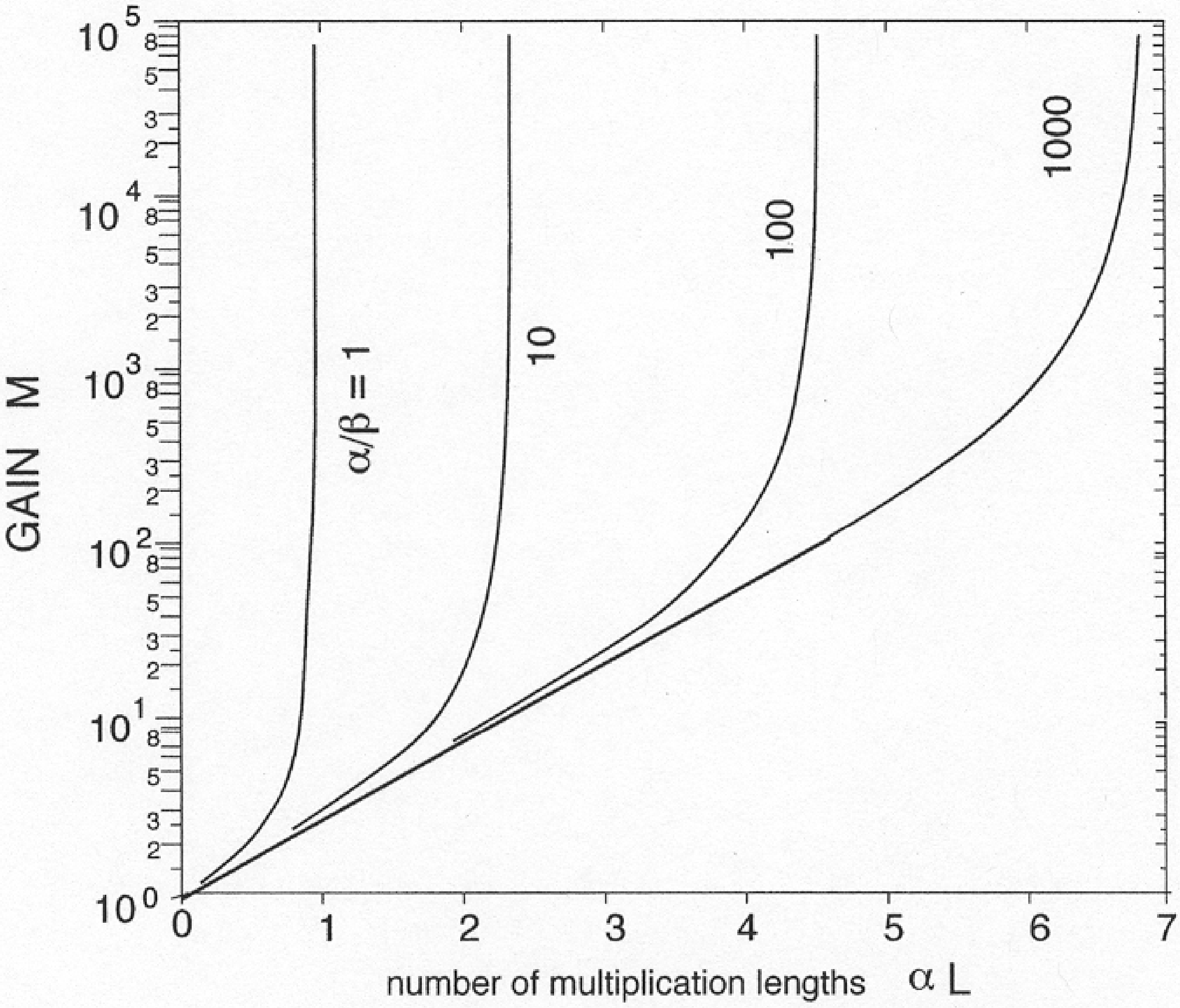


Figure 5-4.3 The dc gain M of the avalanche photodiode (for electron injection at x=0) as a function of the number of multiplications αL and with the ionization ratio α/β as a parameter

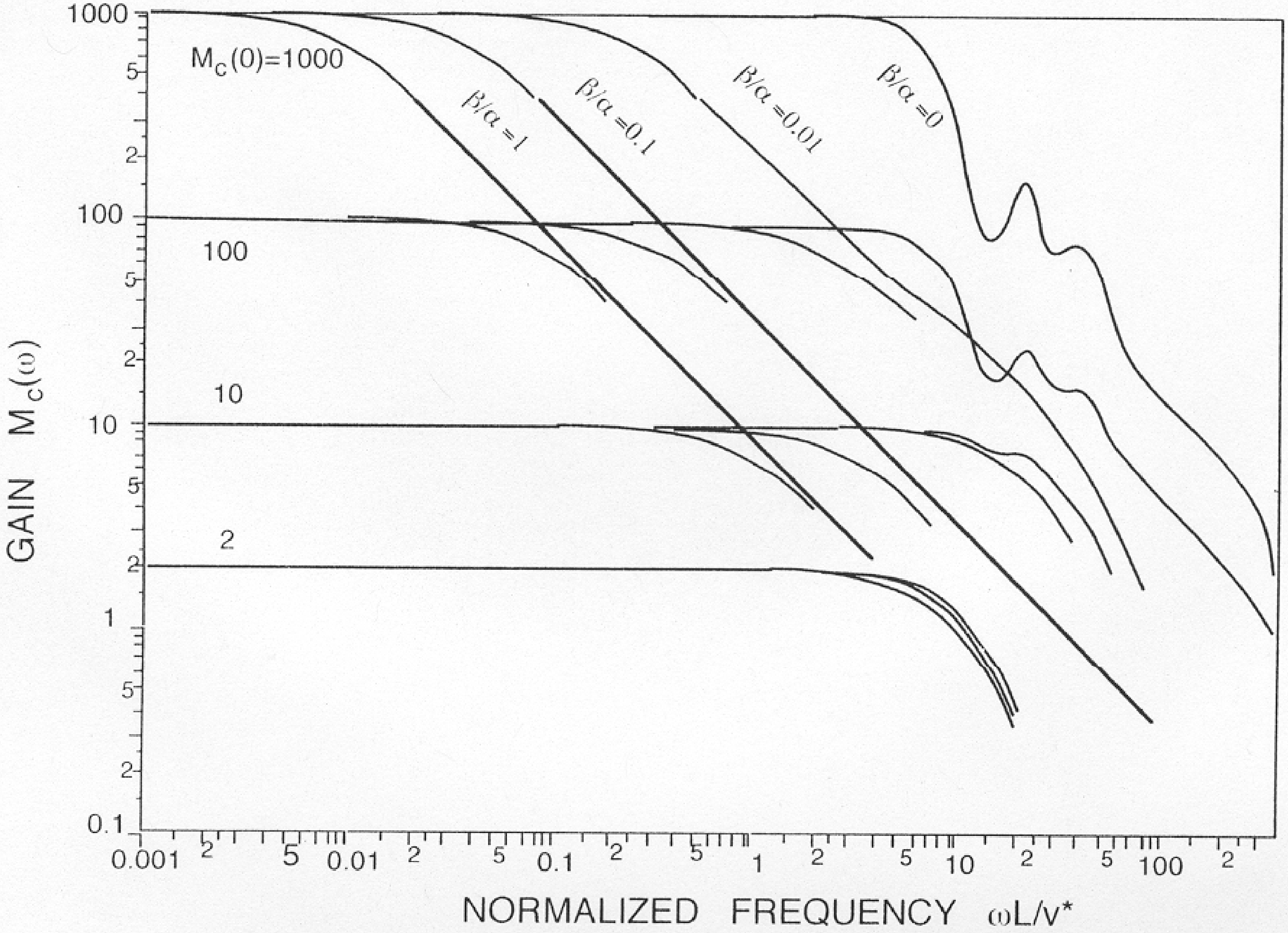
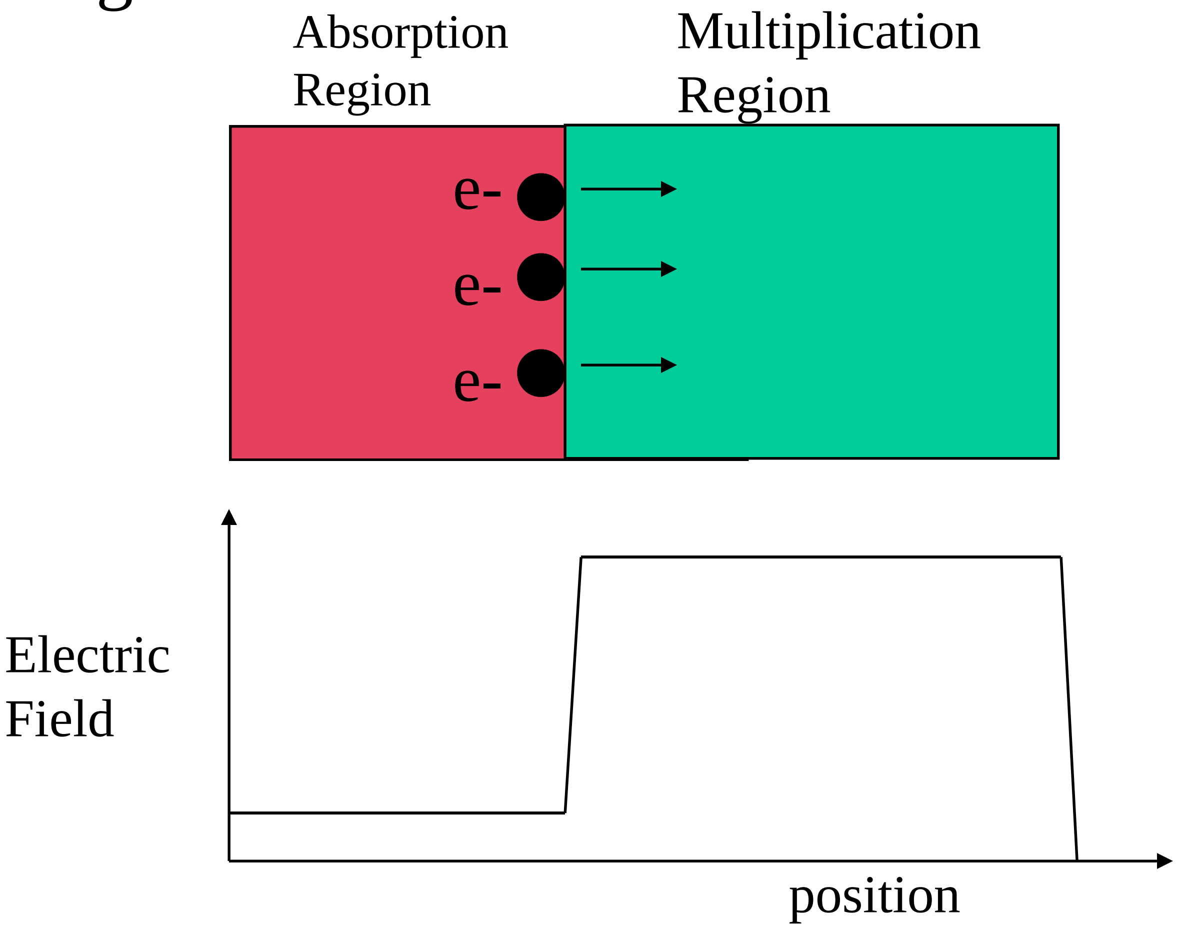


Figure 5-4.4 Frequency response of the avalanche photodiode gain $M_c(\omega)$ as a function of the normalized frequency $\omega L/v^*$ and with the ionization ratio β/α as a parameter (case for electron injection at $x=0$ and equal carrier velocities, $v_e=v_h$)

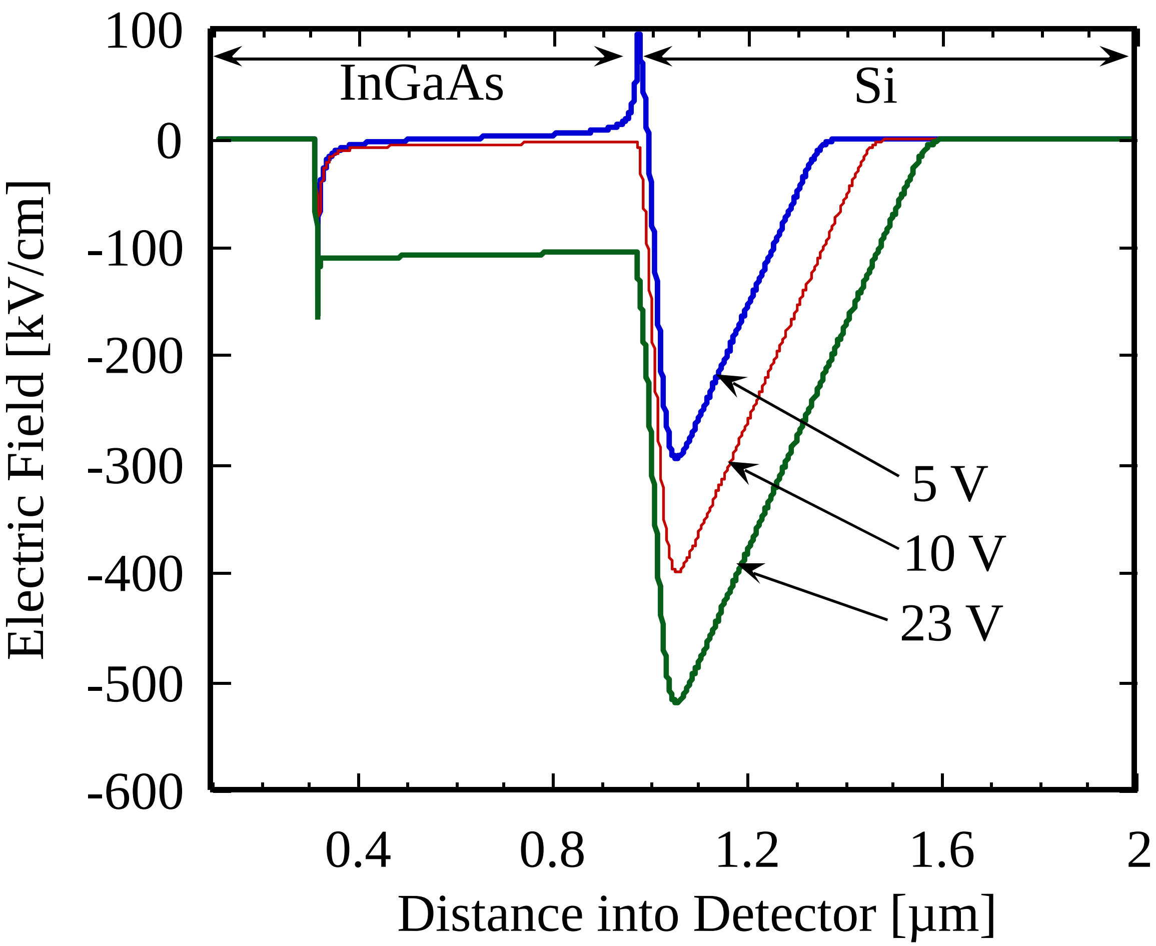
SAM APDS:

Need for Separate Absorption and Multiplication Regions

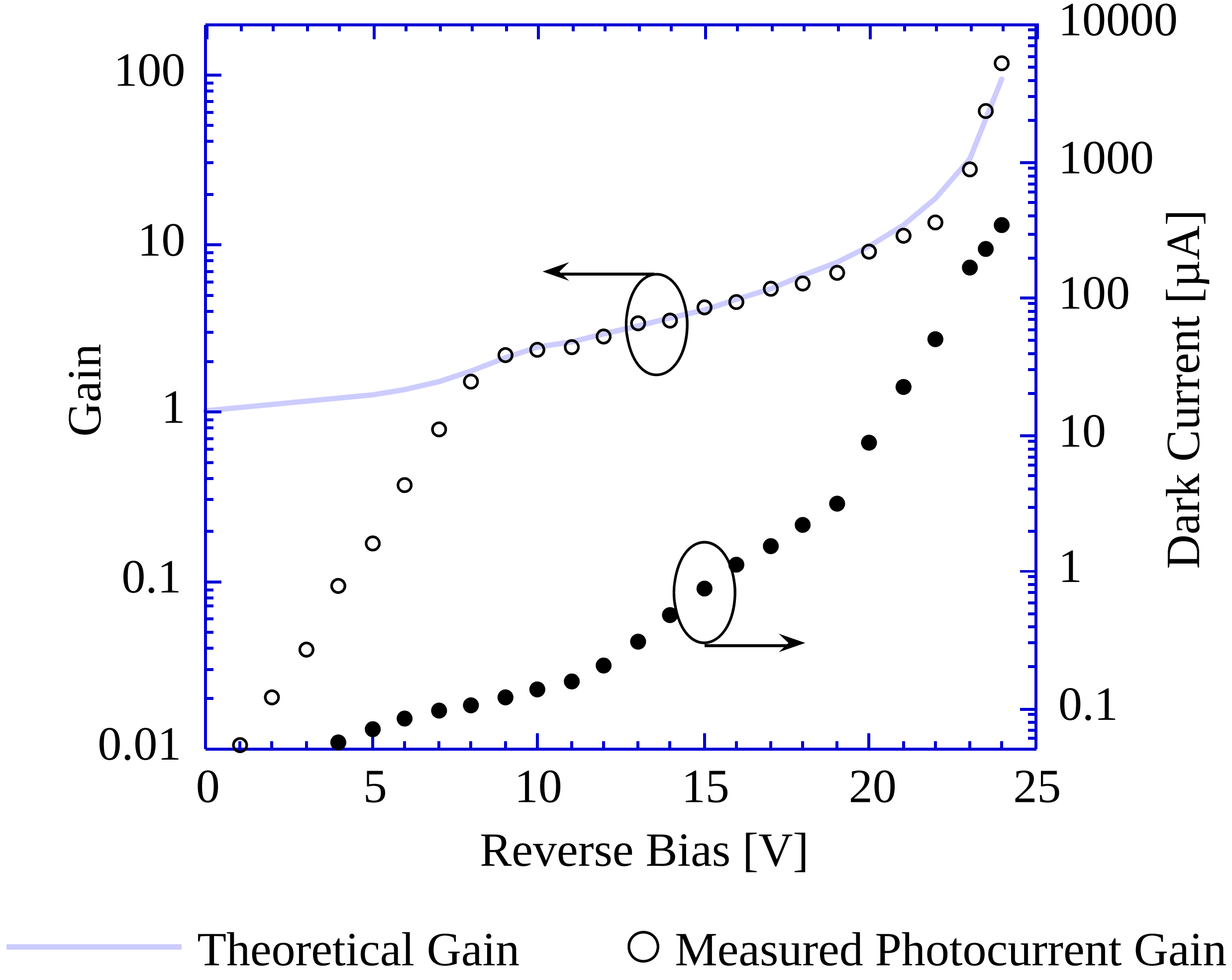
Small bandgap avalanche regions tend to have large dark current.



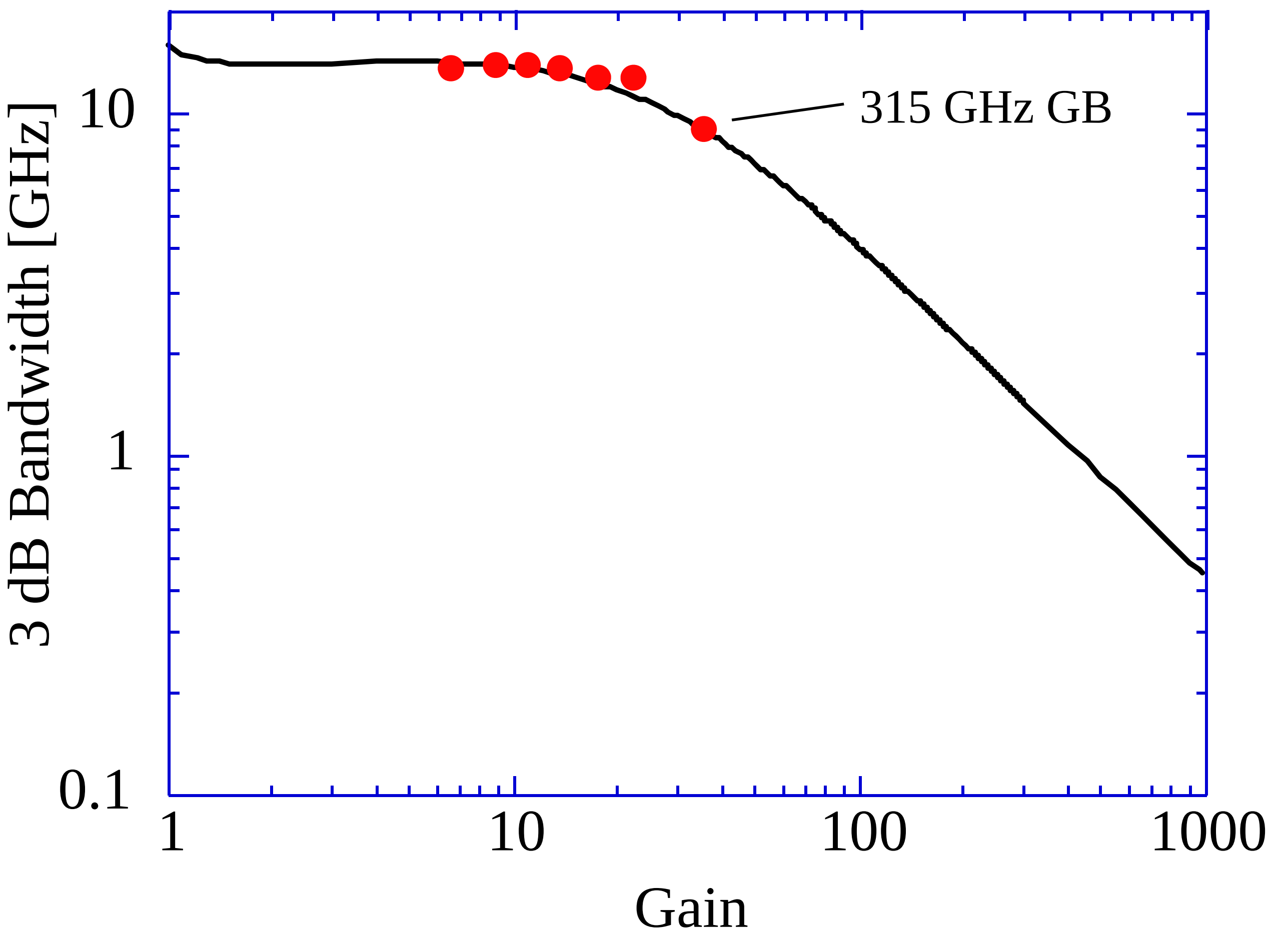
Electric Field Simulation for SHIP



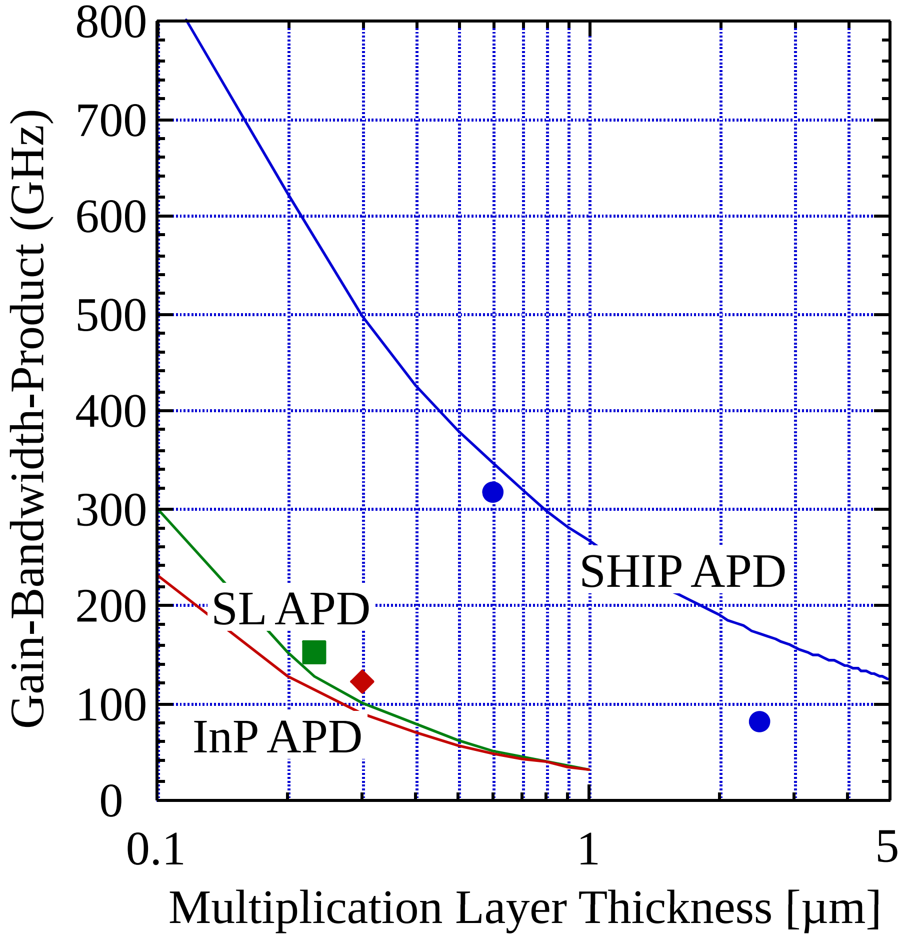
Gain and Dark Current vs. Bias. 23 μm diameter SHIP



SHIP Detector 3-dB Bandwidth versus gain



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



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

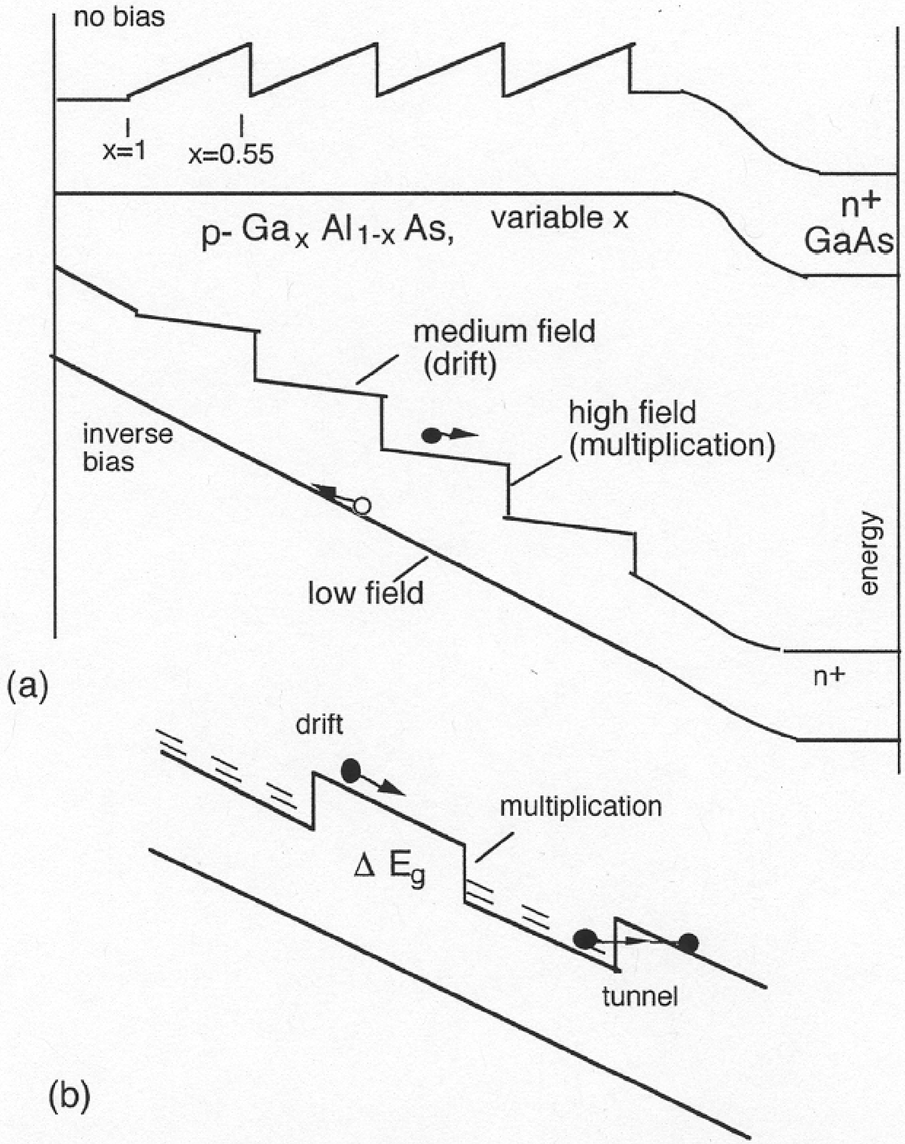


Figure 5-4.10 (a) Sawtooth APD in GaAlAs: distribution of the potential energy with no bias (above) and with reverse bias (below); **(b)** superlattice APD

Sensitivity and Noise

- Responsivity: R=I/P (current/input power)
- NEP (noise equivalent power)
  - NEP=g/R
  - NEP is the input power that gives unity signal to noise ratio
  - Smaller NEP is better

Detectivity

- Detectivity: D=1/NEP
- Larger detectivity is better
- Noise is proportional to bandwidth and detector area.
- A better metric is to normalize out bandwidth and area: D*
- Analysis below is for a dark current limited noise current.

$$I_n^2 = 2eI_d B = 2eJ_d AB$$

$$NEP = \frac{I_n}{R} = \frac{\sqrt{2eJ_d AB}}{R}$$

$$D^* = D\sqrt{AB} = \frac{\sqrt{AB}}{NEP} = \frac{R}{\sqrt{2eJ_d}}$$

D**

- Detectors with a narrower field of view have lower noise.
- Define field of view by the numerical aperature NA
- A better metric compensates for this
- D** (D double star)

$$D^{**} = D^{*}NA = \frac{NA\sqrt{AB}}{NEP}$$