Topic 20

20. Avalanche Photodiode

20.1 Introduction

20.2 Operation Mechanism

20.2.1 Impact Ionization

20.2.2 Multiplication Factor

20.3 Design Consideration

20.4 Noise Performance

Introduction (i)

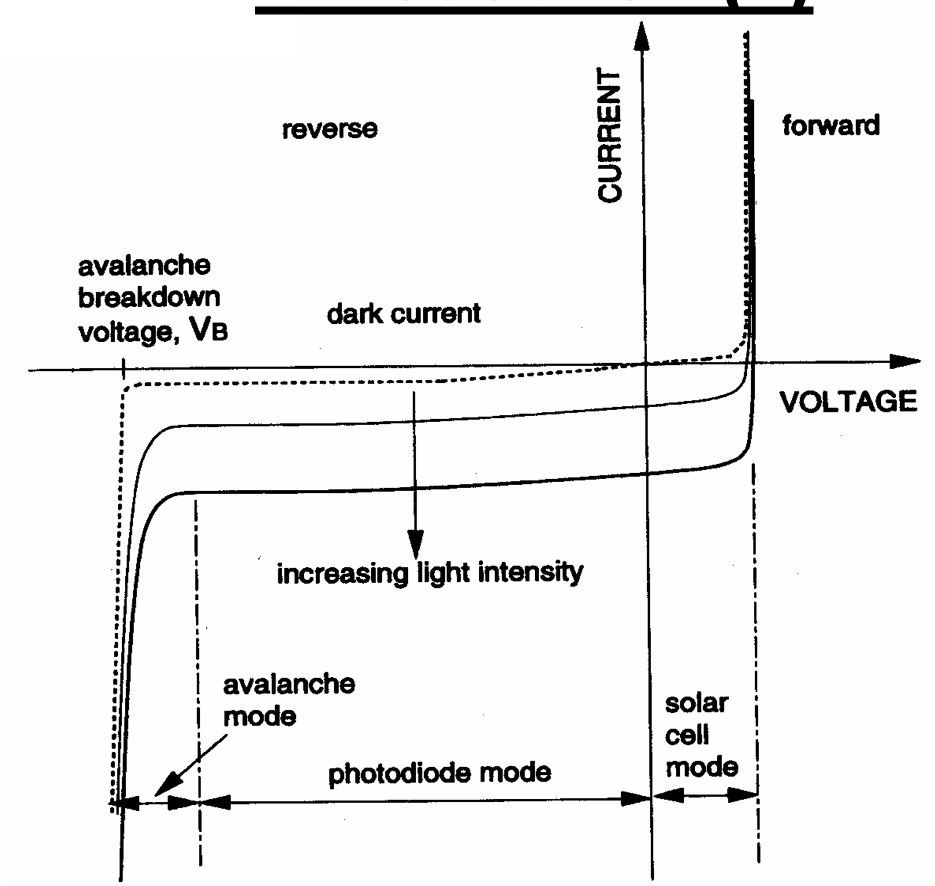
- **Very high sensitivity**: to detect very low signal (need a sort of "magnified" function

Therefore, a few concepts are involved:

1. Impact ionization: carrier multiplication

2. Operation voltage is close to $V_{breakdown}$

Introduction (ii)

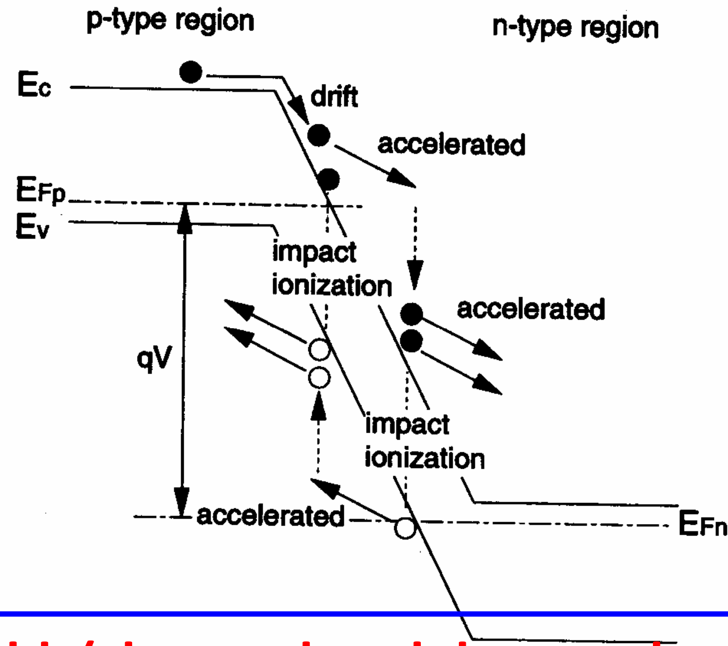


p-i-n photodiode and breakdown

- LED suffers “breakdown” at large reverse bias

- What are the processes at play?

Impact Ionization



- **Under high E-field (close to breakdown voltage):**
  Photo-generated carriers (primary photocurrent from the photo generate carriers due to incident signal) acquire **sufficient energy** from the field, and thus collide with lattice occurs, exciting an electron from valence band to conduction band. This is **carrier multiplication.**
  This leads to a very high output current

- It leads to **two concepts**:

1. Threshold ionization energy
2. Impact ionization coefficients

Threshold Ionization Energy

This is a collision process involving 3 carriers

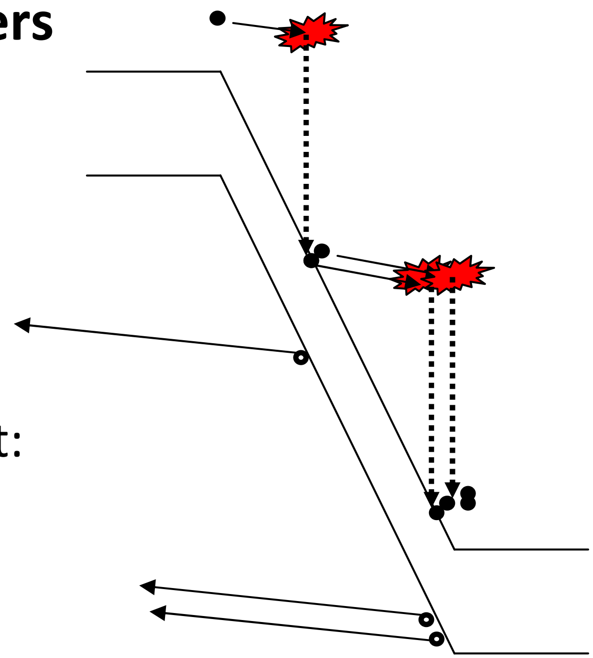
1. Before collision:

energy of a single carrier: $\boxed{\frac{1}{2}mv_s^2}$

momentum: $\boxed{mv_s}$

2. Energy required for impact ionization at least:

$$\boxed{E = E_{gap} + \frac{3}{2}m\ v_f^2}$$



Due to the conversation of energy and momentum before and after collision:

$$\frac{1}{2}m\ v_s^2 = E_{gap} + \frac{3}{2}mv_f^2$$

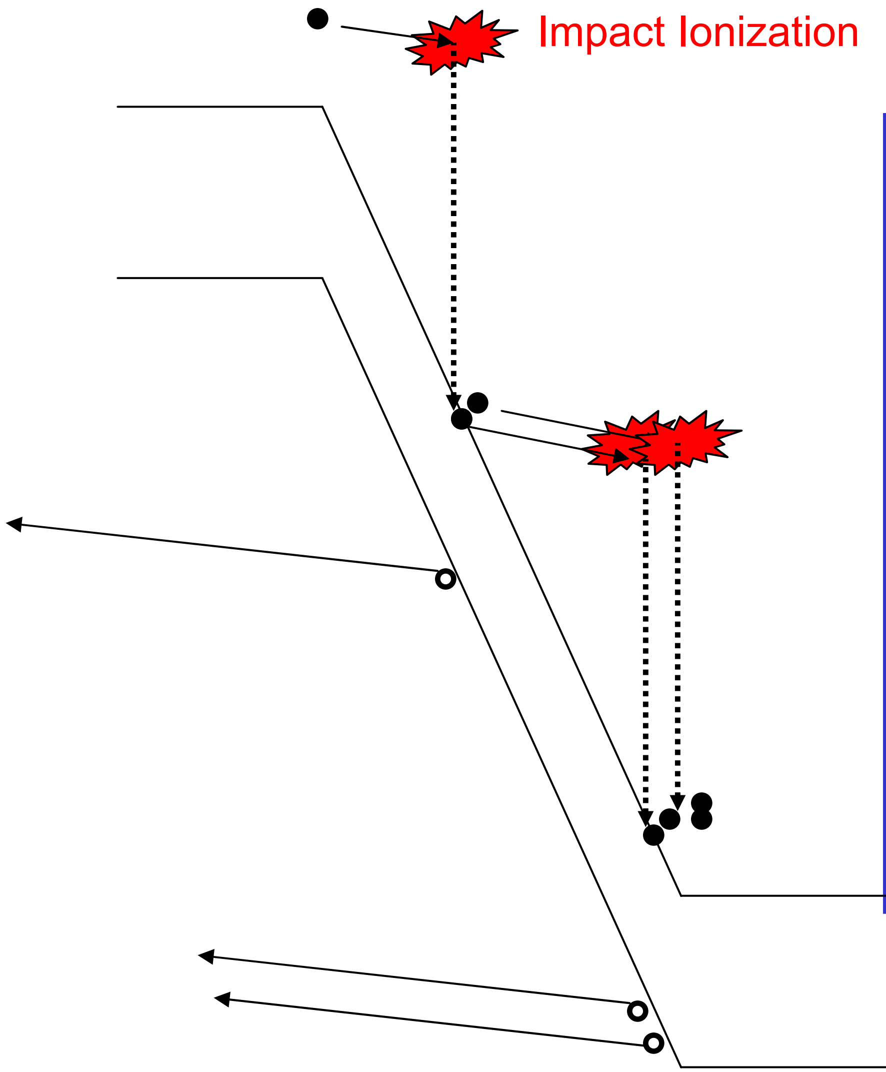
$$m\ v_s = 3mv_f$$

- Minimal Requirements for impact ionization: carriers with energy of at least :

1.5 E_{gap}

- This energy is provided by reverse bias

Multiplication



- Define impact ionization coefficients for electrons and holes, α & β, respectively
- α, β: describe probabilities that a given carrier will excite an e-h pair in unit distance
- $1/\alpha$, $1/\beta$: distance between ionization events
- Unfortunately, α, β, cannot be directly measured

Multiplication Factor

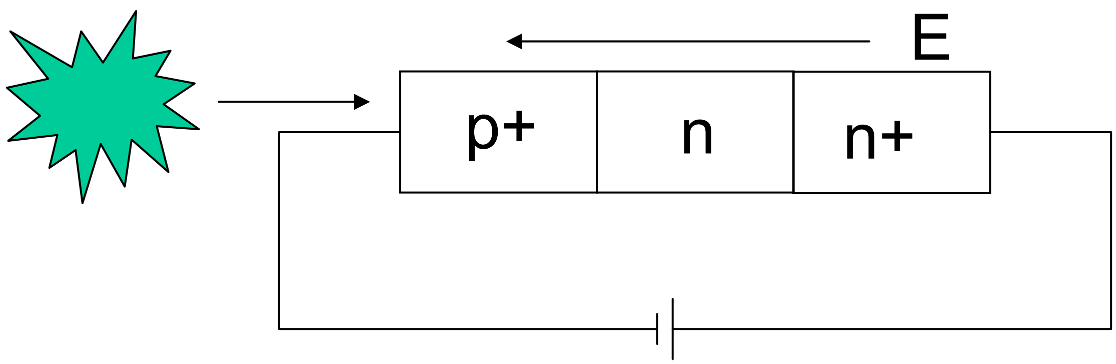
1. α and β cannot be directly measured

2. What we can measure is the current (electrons drifting toward n^+ and holes drifting toward p^+) $J_T = J_e + J_h$

3. Measurable parameter: multiplication factor

$$M_e(E) = \frac{J_{eo}}{J_{ei}}$$

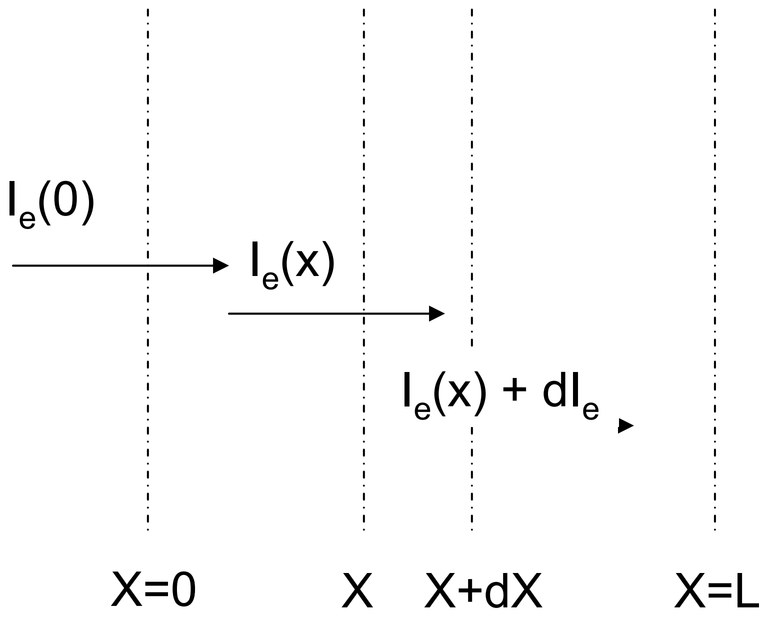
$$M_h(E) = \frac{J_{ho}}{J_{hi}}$$



• Ratio of multiplied output current to the primary photocurrent

It needs to establish a relationship between α, β and M_e, M_h

Multiplication - Electrons Only



- Ignore the hole impact ionization ($\beta = 0$)

- Create photo-electrons in the left-hand p-doped region – inject electron at x = 0

$dI_e = I_e(x)\alpha dx$

$dI_e/dx = \alpha\ I_e(x)$

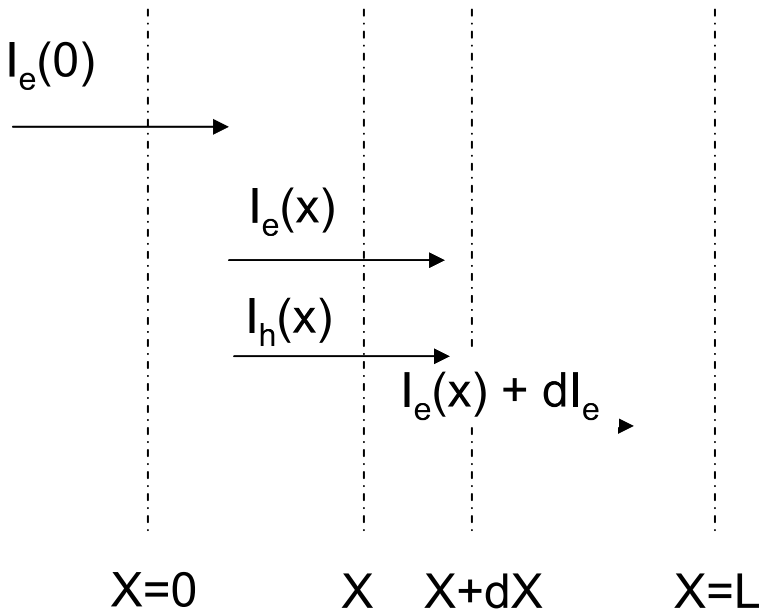
$I_e(x) = I_e(0)\exp(\alpha x)$

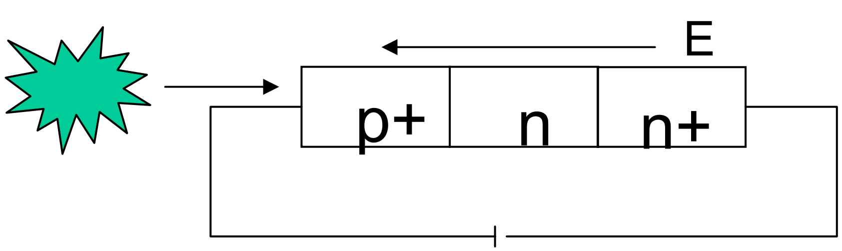
- **Multiplication factor, M (avalanche gain)**

 $M = I_e(L)/\ I_e(0) =$ **exp (αL)**

Get the avalanche of electrons arriving together – the response time given by the transit time of electrons *plus* transit time of holes.

Multiplication - electrons and holes (ii)





- Assume ($\alpha=\beta$)
- Create photo-electrons in left hand p-doped region – inject electron at x = 0

$dI_e = I_e(x)\alpha dx + I_h(x)\ \beta\ dx$

But $I_e(x) + I_h(x) = \text{constant} = I$

$dI_e = I_e(x)\alpha dx + \{I - I_e(x)\}\ \beta dx$

As ($\alpha = \beta$); $dI_e = I\beta dx$ so $dI_e/dx = \beta I = \alpha I$
and $I_e(x)=I_e(0) + \alpha Ix$

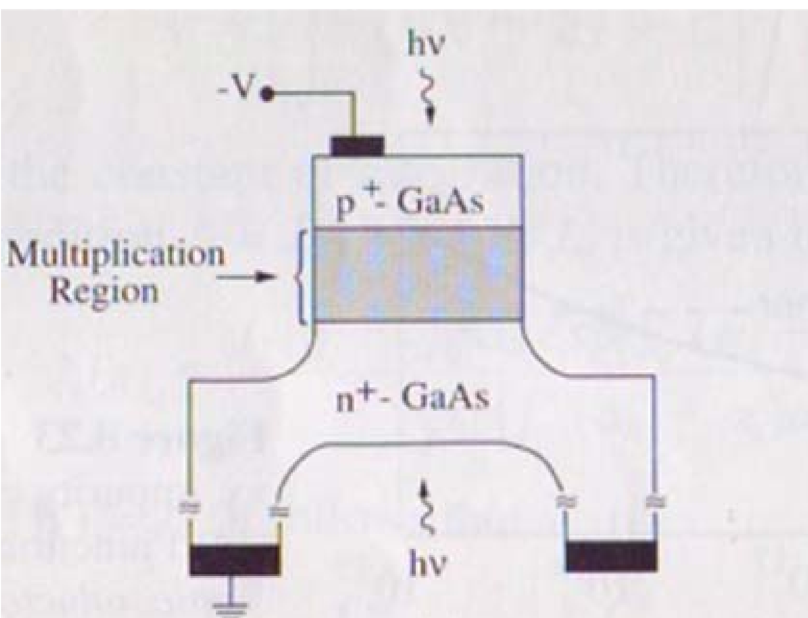
At x=L, $I_e(L)= I_e(0) + \alpha IL = I$ as $I_h(L) = 0$

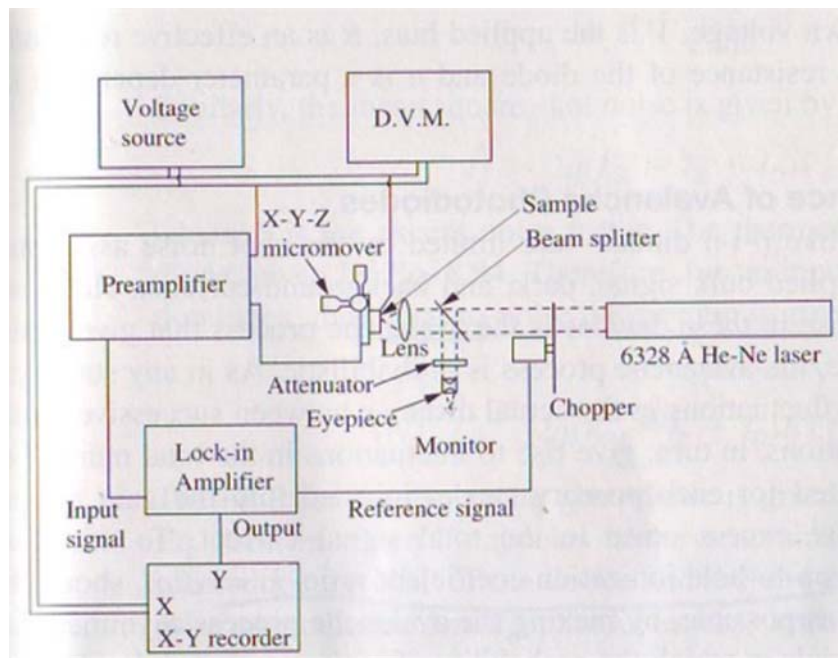
- Multiplication factor , M_e
  $M_e = I_e(L)/ I_e(0) = I/(I-\alpha IL) =$ **$1/(1- \alpha L)$**

Multiplication Factor

$$\alpha(E) = \frac{1}{L}\left[\frac{M_e(E)-1}{M_e(E)-M_h(E)}\right]\ln\left[\frac{M_e(E)}{M_h(E)}\right]$$

$$\beta(E) = \frac{1}{L}\left[\frac{M_h(E)-1}{M_h(E)-M_e(E)}\right]\ln\left[\frac{M_h(E)}{M_e(E)}\right]$$





Multiplication Factor

An example to calculate multiplication fact of an APD:

(1) λ= 1.5 um; (ii) Quantum efficiency η=70%, (iii) signal P_0=2.0 μW; (iV) output current I_m=40 μA

Responsivity:

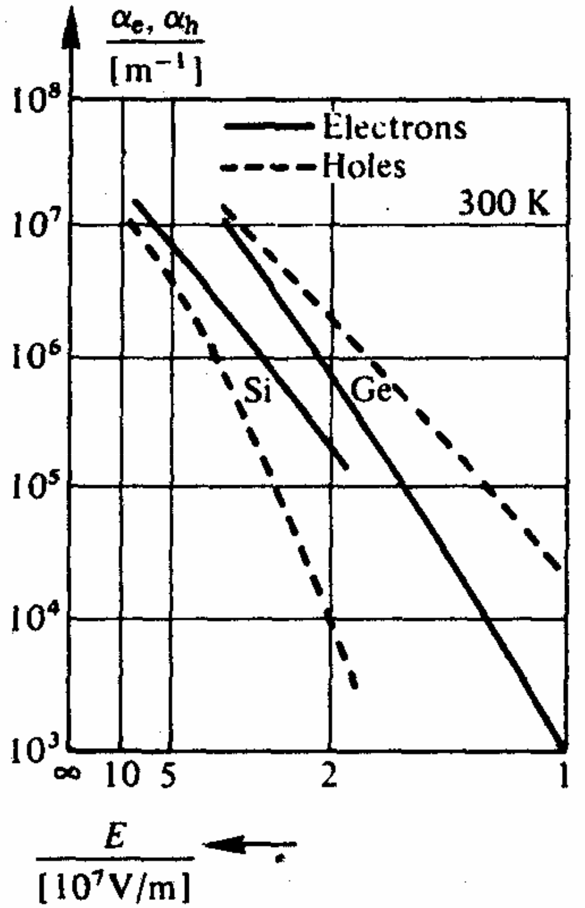
$R=\eta q\lambda/(hc)=0.8x1.60x10^{-19}x1.3x10^{-6}/(6.63x10^{-34}x3x10^{8})=0.965$

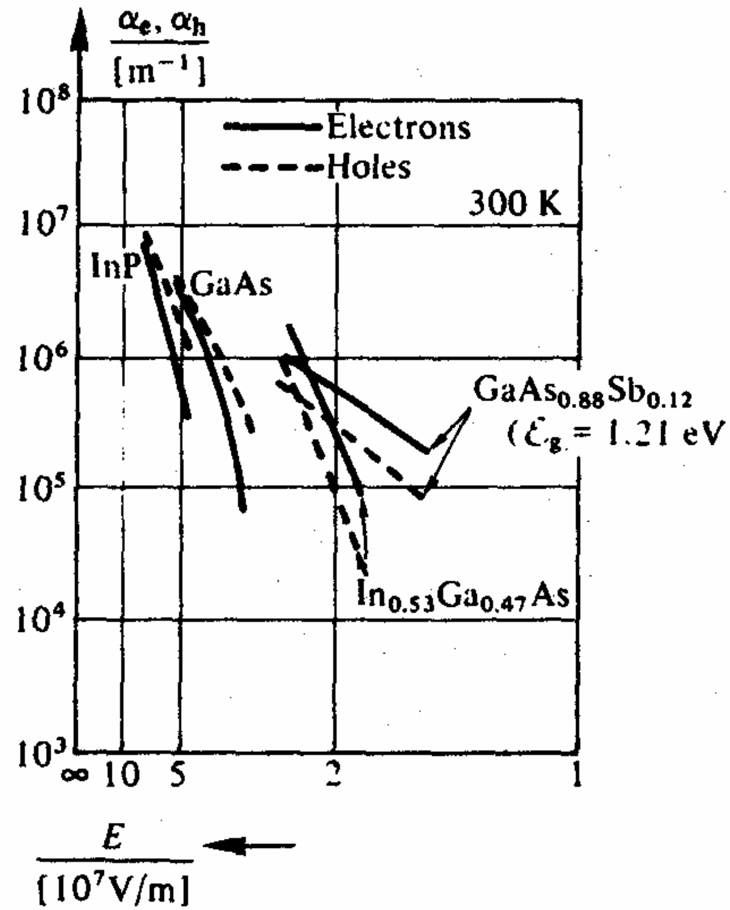
Primary current: $I_p=P_0R=2.0x10^{-6}x0.965=1.9x10^{-6}$

Multiplication factor: $M=I/I_p=40x10^{-6}/(1.9x10^{-6})=21$

Comparison of α and β

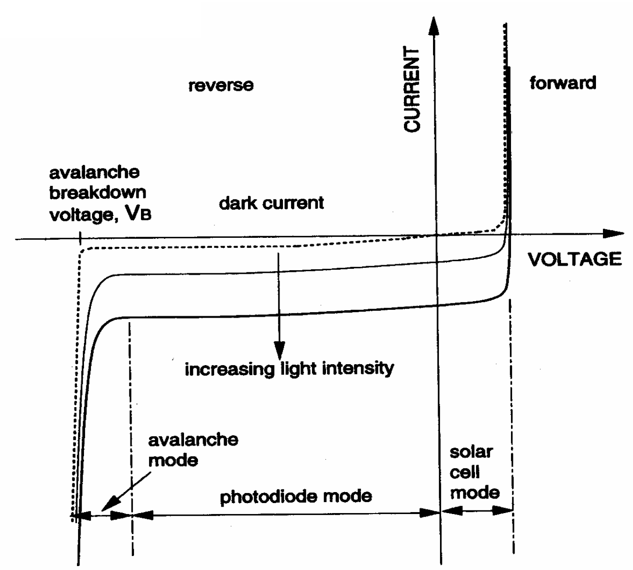
Si:	$\alpha/\beta > 1$
Ge:	$\alpha/\beta < 1$
InP:	$\alpha/\beta < 1$
InGaAs:	$\alpha/\beta > 1$

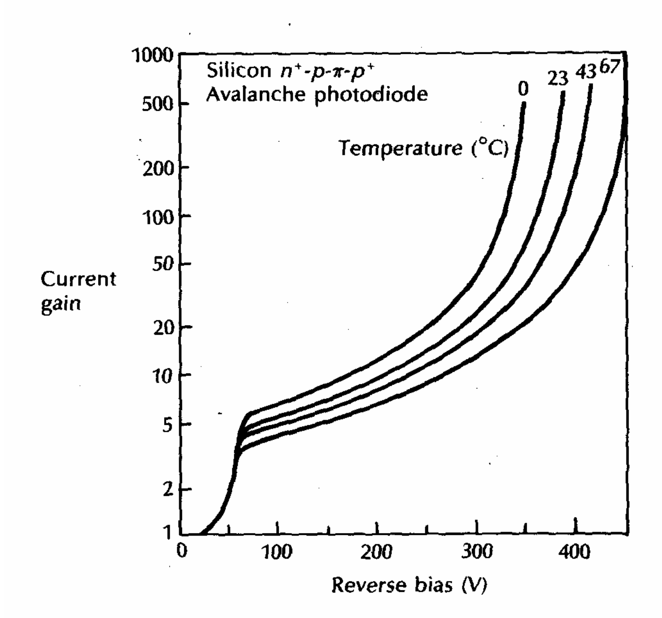




- α and β depend in complex ways on the band-structure
- Increase E-field – more high-energy carriers – **higher α and β**
- Increase temperature – enhanced scattering – **decreases α and β**

Operating Conditions



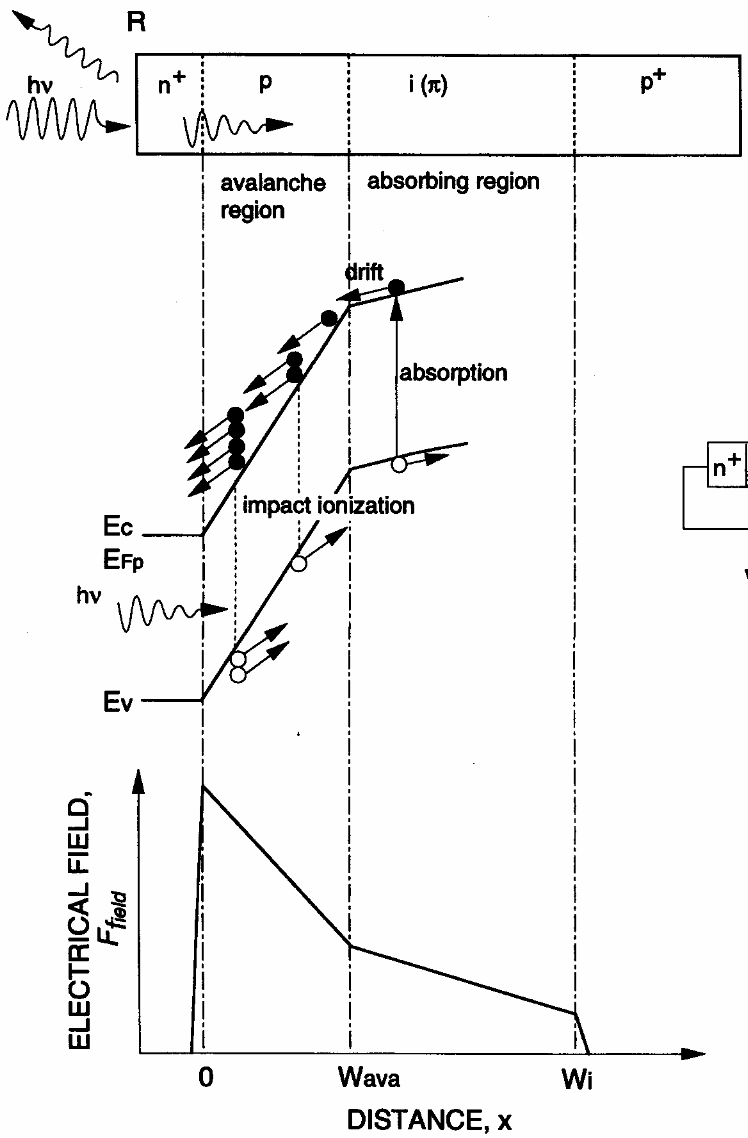


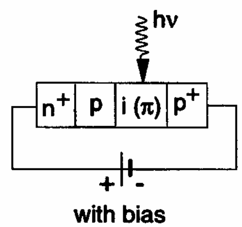
•E = V/L so M increases rapidly with $V_{reverse}$ Therefore, the operating voltages are high (10s to 100s of volts) in order to generate a very high multiplication factor, **allowing to detect a very weak signal**

Avalanche photodiode is used for the application of a low signal

•M is sensitive to temperature – **need a cooling or smart biasing method**

APD design





For Silicon or InGaAs – $\alpha/\beta > 1$

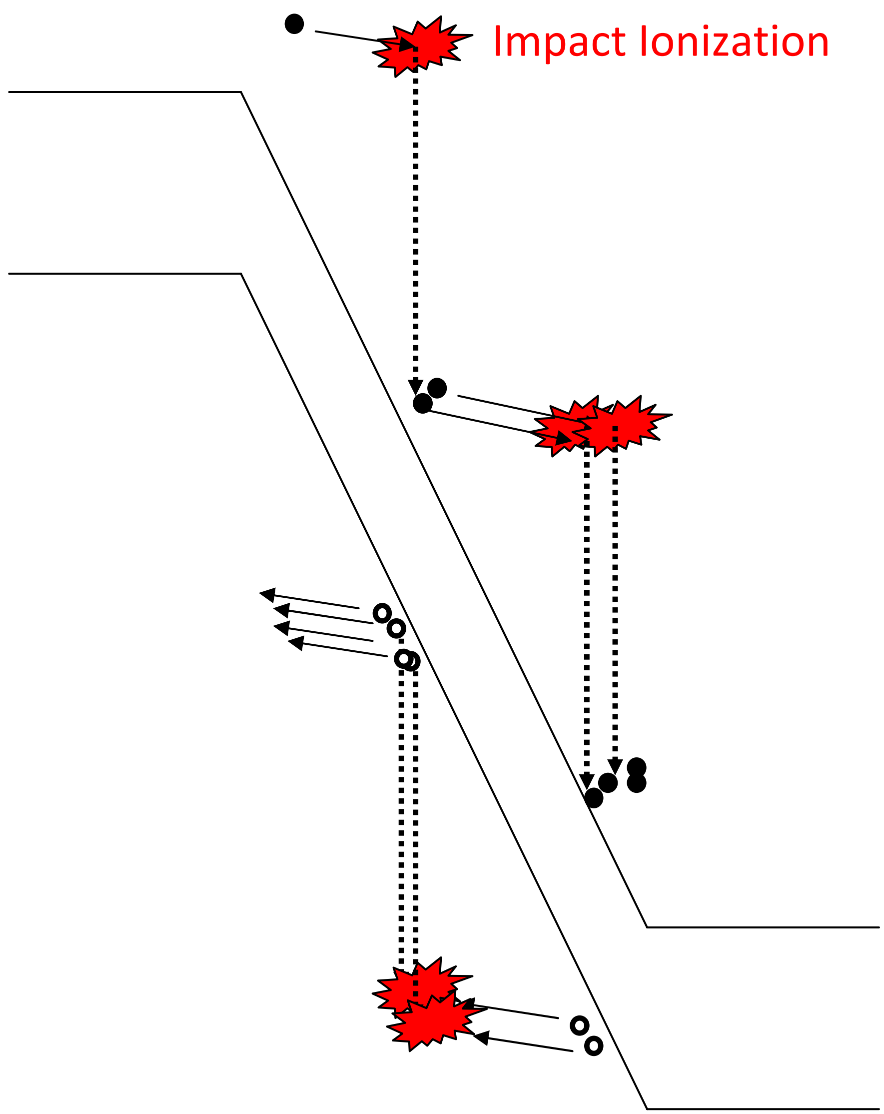
•Thin avalanche region (E = V/L)

•Thicker biased absorbing region

•Careful and clever use of different doping concentrations

•Avalanche and absorbing region in a different layer

Noise Performance (i)



- Limited by the shot noise associated with the primary, un-multiplied signal and background current. This is the same as that if in p-i-n diodes:

- Principal source of the noise: due to multiplication (**different from p-i-n diodes**)
- Random fluctuation in the actual distance between successive ionising collisions $\Rightarrow$ **Fluctuation in the total number of secondary carriers**

Excess noise in the total signal current

- Solution: high α/β or β/α ratio in order to minimise avalanche noise

Noise Performance (ii)

•**Shot noise**

$$\overline{i_{sn}^2} = 2q\bar{I}\Gamma_G F B_{bw}$$

$$\overline{i_{sn}^2} = 2q(I_{ph} + I_d + I_{bg})\Gamma_G F B_{bw}$$

Compared p-i-n diode, extra item:
noise due to multiplication ($\Gamma_G F$), where F = excess noise factor

•**Thermal Noise (Johnson Noise)**

Random motion of carriers with a distribution of thermal energy produces a noise in the current and hence a noise voltage over a resistor:

$$\overline{i_{jn}^2} = \frac{4k_B T B_{bw}}{R_{eq}}$$

Which is the same as that for a p-i-n diode.

Signal to Noise (Power) Ratio

For an amplitude modulated bit, rms signal current:

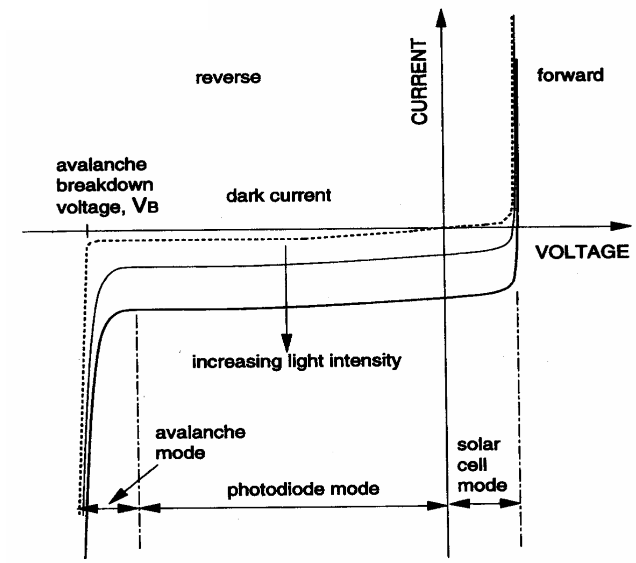
$$\overline{i_{ph}^2} = I_{ph}^2 = \left(\frac{\eta q P_{peak}}{h\nu}\right)^2$$

Signal Power $= R_{eq}\,\overline{i_{ph}^2}$

Noise Power $= R_{eq}\left(\overline{i_{sn}^2} + \overline{i_{jn}^2}\right)$

Signal/Noise Ratio $= \dfrac{S_{rms}^{pp}}{N_{rms}} = \dfrac{\overline{i_{ph}^2}}{(\overline{i_{sn}^2} + \overline{i_{jn}^2})}$

Design Considerations



•Material – need high α/β or β/α ratio, then need to ensure preferential injection of the desired carrier

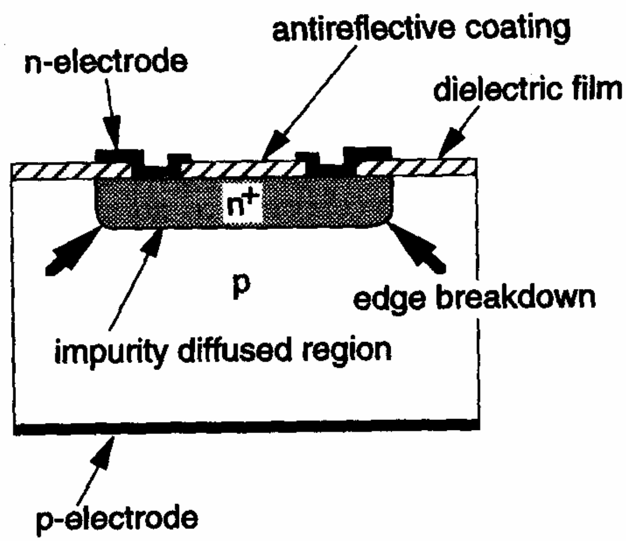
•Minimise the concentration of defects

•Operate at a high but controllable M ~10-100

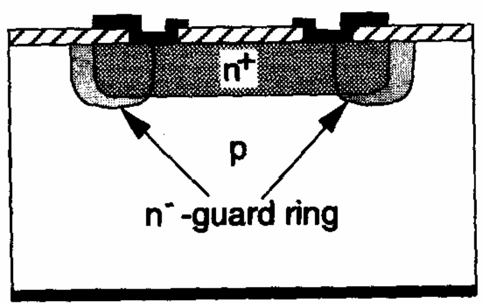
•Need to minimise any possibility of electrostatic breakdown

•E-fields high at points and edges (similar to “lightning conductor”)

Edge Breakdown and Guard Rings



(a) region of edge breakdown



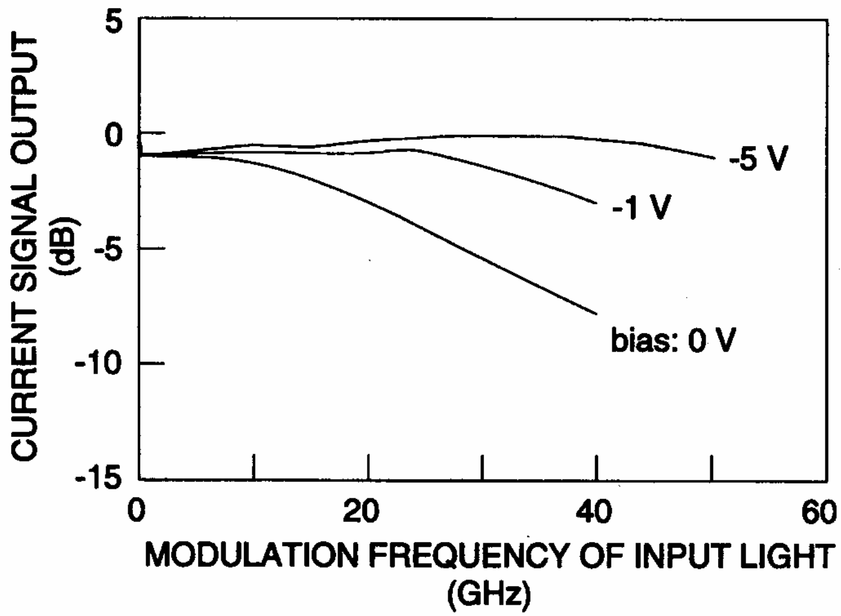
(b) guard ring

•The peripheral edge of the n^+p junction reaches avalanche breakdown before the n^+p window of illumination area.

•Solution – diffuse or implant dopants in a ring around the light absorbing region – "guard ring" (curvature effect)

•Results in breakdown in the light absorbing region – an increase in "L" for the edge region

Frequency Response



Frequency response governed by:

•RC time constant: calculating as per p-i-n diode

•Transit Time

Multiplication Time

Feedback causes re-circulation of carriers: takes additional (transit) time

Summary

- For a diode with high crystal purity a reverse breakdown is via avalanche breakdown
- At high E-fields carriers very quickly acquire large excess energies and may impact ionise with the crystal lattice to release energy in the form of an e-h pair
- Can characterize the II process by characteristic lengths / II coefficients
- Can utilise II to give gain within a photodiode – increasing the sensitivity
- For an ideal detector we want α/β>>1 or <<1 to eliminate "feedback" effects leading to self-sustaining avalanche of II events
- M (and reverse breakdown softness) is a strong function of α/β
- Coefficients are functions of band-structure, E-fields (applied bias) and temperature
- APD design non-trivial – as is manufacture – need precise control of low doping levels and thicknesses – costly
- Advantages – gain offset by disadvantages of high cost, cooling, high voltages, additional noise source

Tutorial Questions (ii)

T20.1 Describe impact ionization and how this can lead to gain in an APD.

T20.2 Discuss the requirements for the ratios of ionization coefficients for an ideal APD.

T20.3 Electrons are injected at x = 0 into one end of a high field semiconductor region of length L. Impact ionization coefficients for electrons and holes in this region are given by α and β. By considering the currents $i_e(x)$ and $i_h(x)$ carried by electrons and holes at a point x 'down stream' show that over a small distance dx the electron current increases by an amount:

$$di_e = \alpha i_e dx + \beta(I - i_e)dx,$$

where I is the total, constant current flowing, independent of x. Hence show that the electron multiplication coefficient, Me is given by,

(i) $Me = \exp(\alpha L)$, if $\beta = 0$,

(ii) $Me = 1/(1 - \alpha L)$, if $\beta = \alpha$

Tutorial Questions (ii)

T20.3 CONTINUED

As αL increases towards unity the latter expression becomes indefinitely large whereas the former expression does not. Why is this and what is this phenomenon called?

If α and β are both nonzero but unequal show that

$M_e = (\beta - \alpha)/(\beta - \alpha\exp\{(\beta - \alpha)L\})$

and check that this expression turns into (i) and (ii) in the appropriate cases.