EEE337 Semiconductor Electronics EEE348 Electronics and Devices (Photodetectors)

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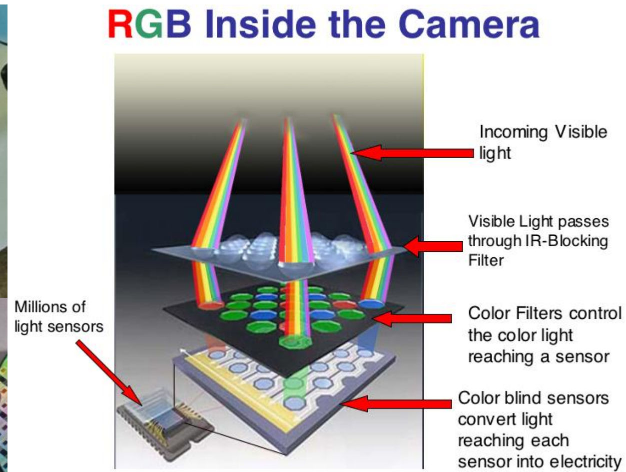
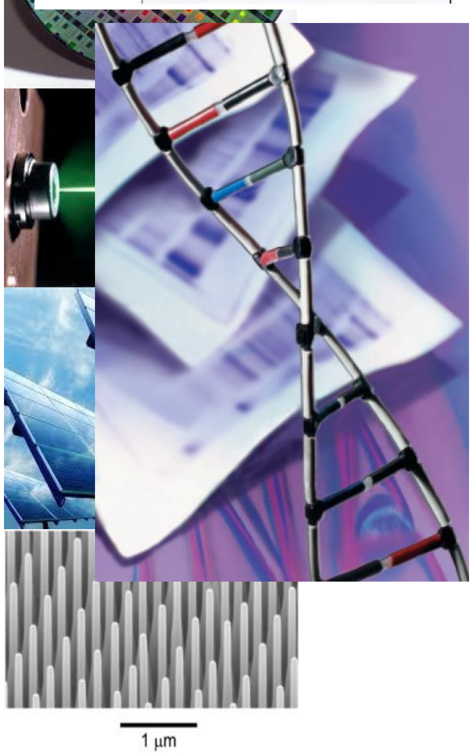
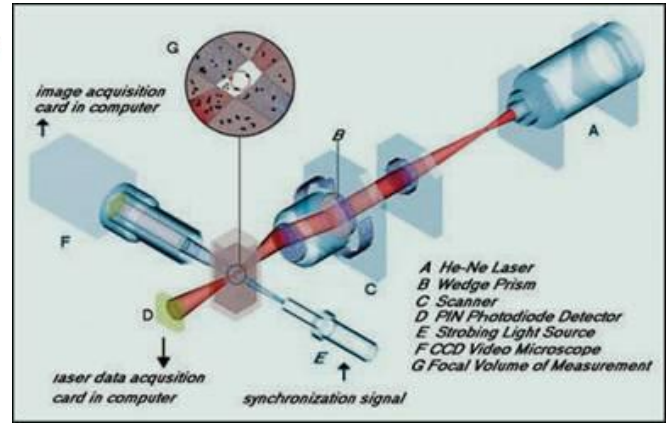
Detector applications

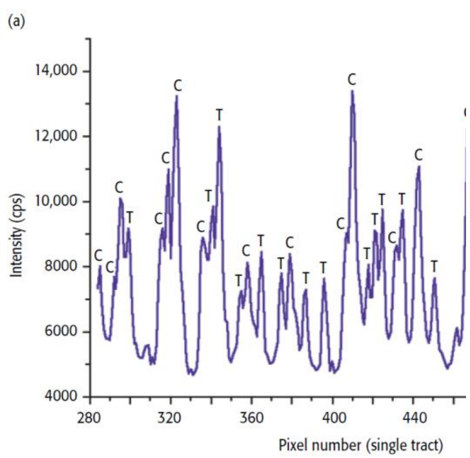


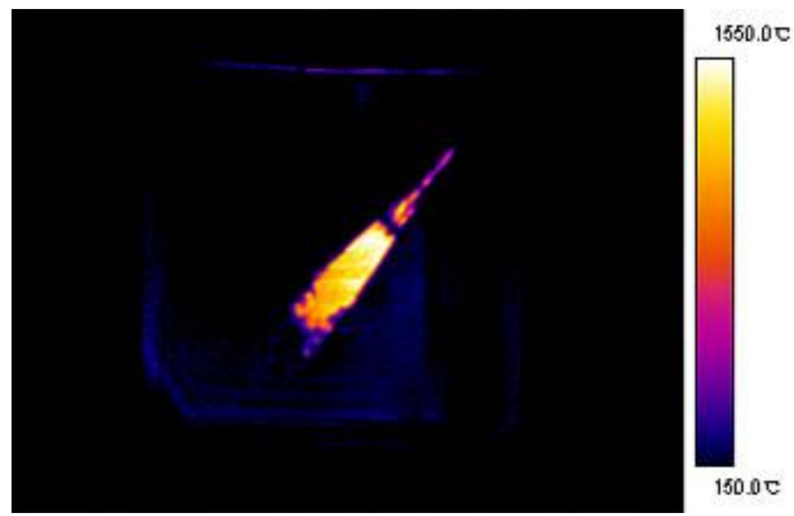


Spectroscopy

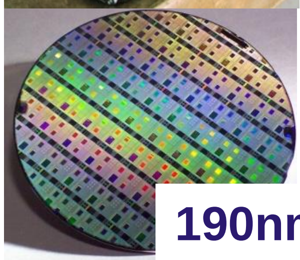


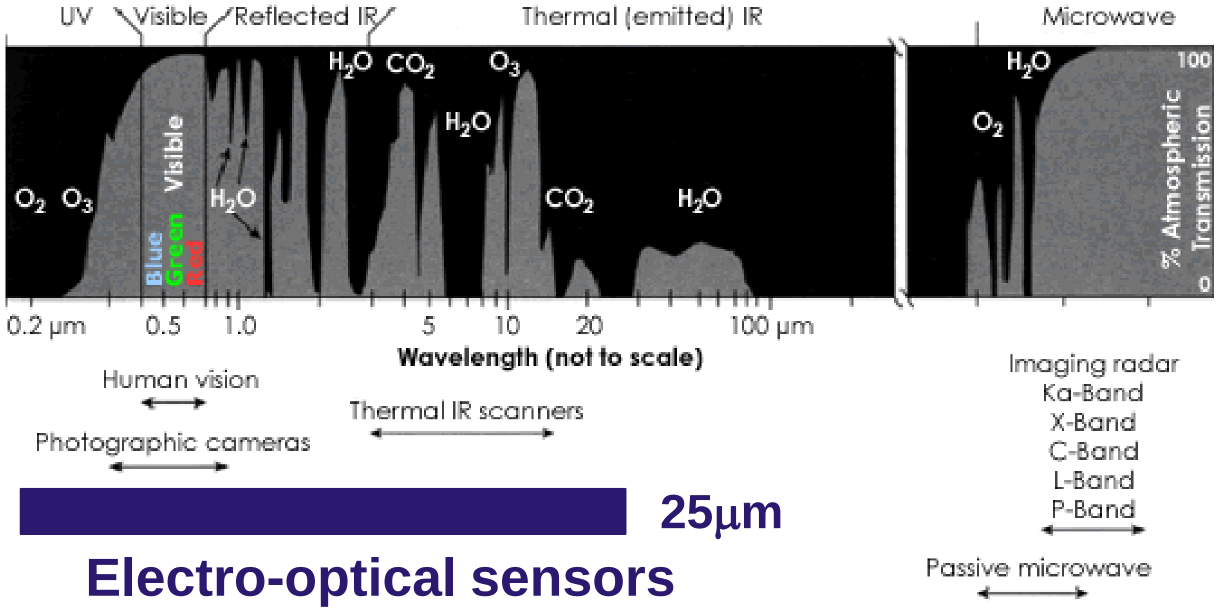
DNA analysis





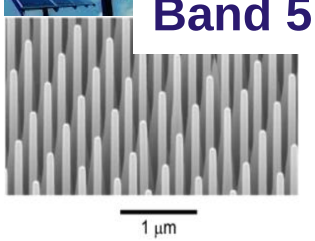
Atmospheric transmission consideration





190nm **25µm**

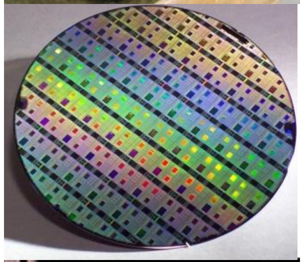
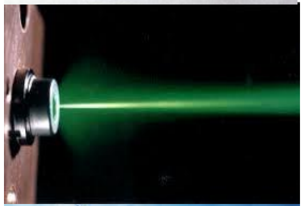
Electro-optical sensors

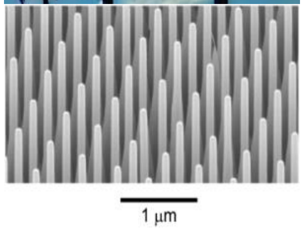


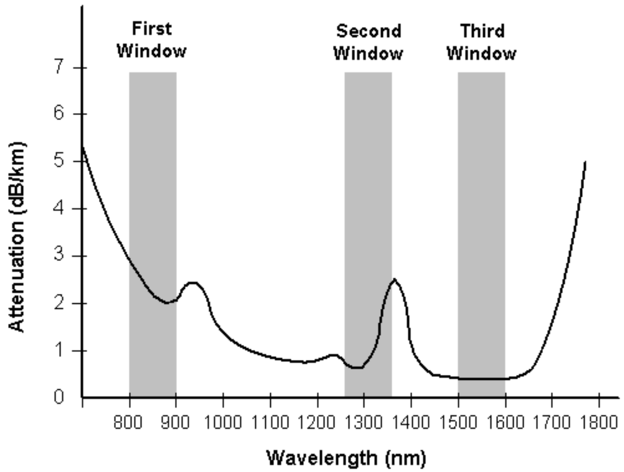
Band 1 UV-VIS-NIR	**0.19-1.0µm (reflected sunlight in VIS)**
Band 2 Short wave IR (SWIR)	**1.0-2.6µm (some reflected sunlight and some emitted radiation)**
Band 3 Mid wave IR(MWIR)	**3.0-5.0µm (emitted radiation)**
Band 4 Long wave IR (LWIR)	**8.0-14.0µm (emitted radiation)**
Band 5 Far IR (FIR)	**>15.0µm, emitted radiation**

Common wavelength bands for detectors

Detector materials

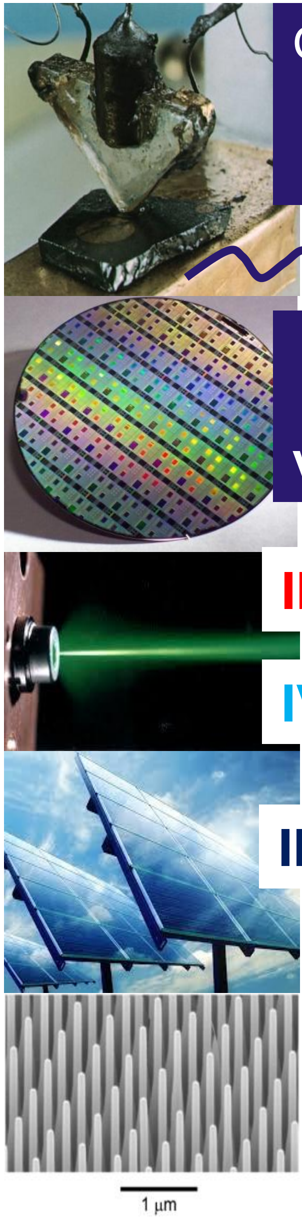


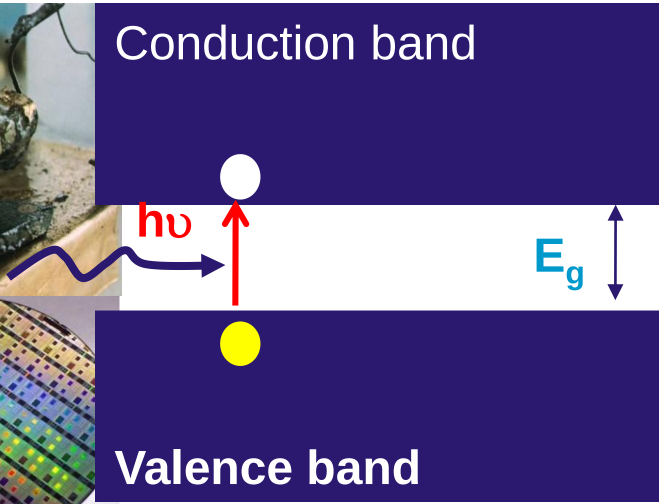


Optical communication is an important detector application. The 2nd and 3rd windows are used for high bit-rates above 2.5 Gb/s.

Material	
Si	• Covers 0.4-1.0 μm detection. First optical window for communication. • Although the absorption coefficient is not the highest, the material is high quality and low cost making them the preferred detector for visible wavelengths, CCD and solar cell too.
Ge	• Indirect bandgap material with lower absorption coefficient than InGaAs. • Covers up to 1.8μm (all 3 windows) • Used in multi-junction solar cell with GaAs and InGaP.
$In_{0.53}Ga_{0.47}As$ (lattice match to InP)	• The preferred choice for optical communication at 1300 and 1550nm. • Used for night vision camera.
$In_{0.53}Ga_{0.47}As_yP_{1-y}$	• Can be grown to be lattice matched to InP and InGaAs (for device engineering). • Bandgap can be adjusted $Eg = 1.35 - 0.72y + 0.12y^2$.
InSb	• Excellent detectors for 3-5μm atmospheric transmission window. Usually cooled to reduce leakage current
HgCdTe	• Excellent material for night vision and thermal imaging. Usually cooled. • Bandgap can be tuned from metal to 1.6 eV.

Semiconductor photodetector

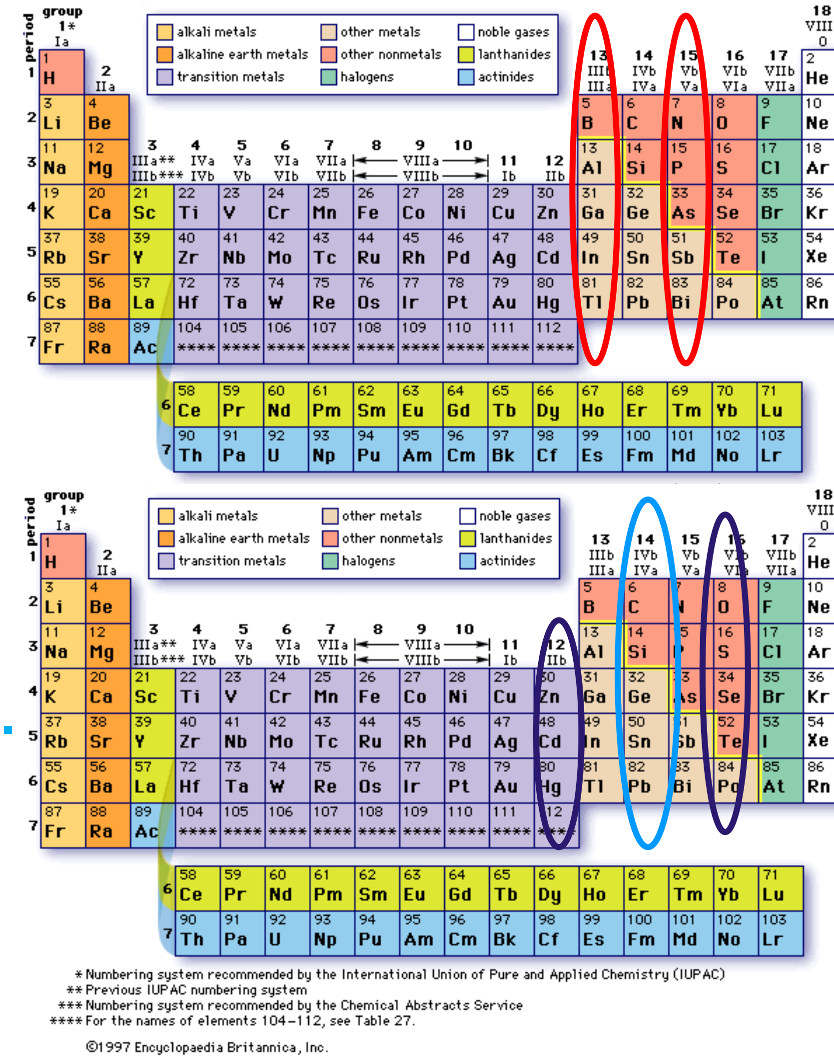




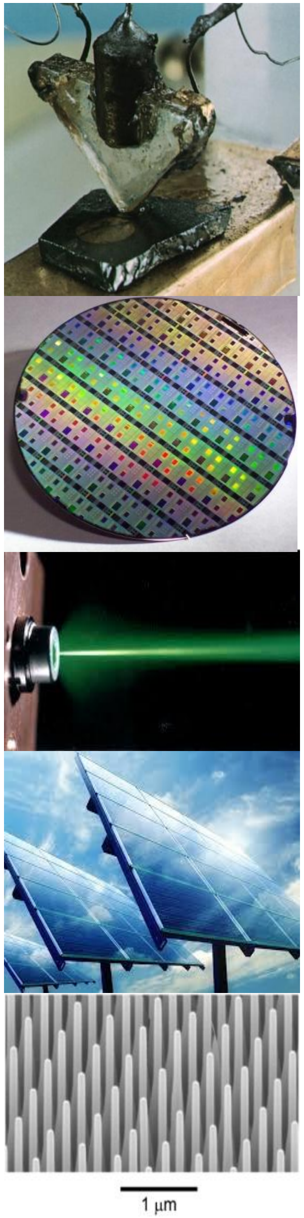
III-V: GaAs, InP, InAs, GaN etc..

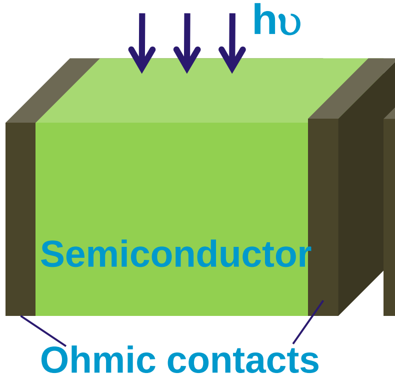
IV: Si, Ge, SiGe, SiC, SnGe etc..

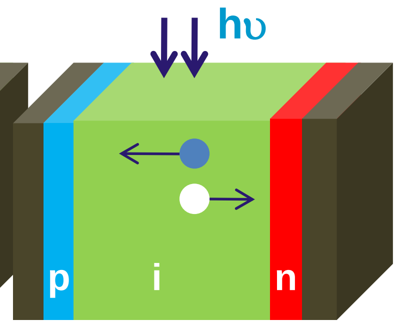
II-VI: HgCdTe, HgZnTe etc..

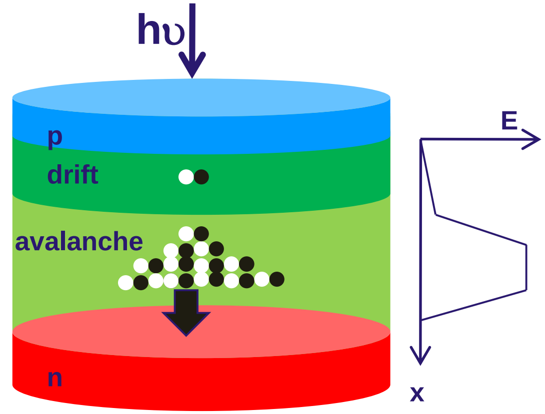


Commonly used photodetectors

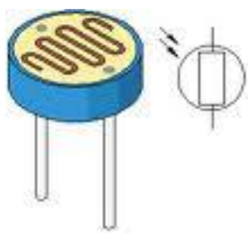






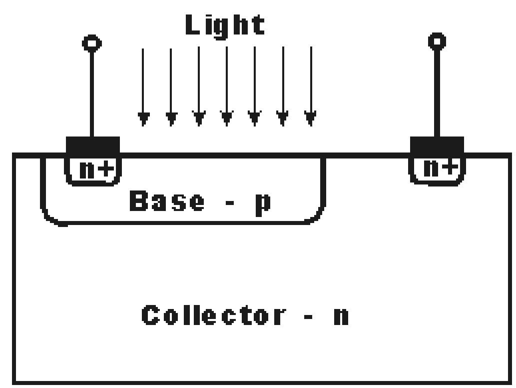


Avalanche Photodiodes (M=10-1000) and Single Photon Avalanche Diodes (M=10^5-10^6)



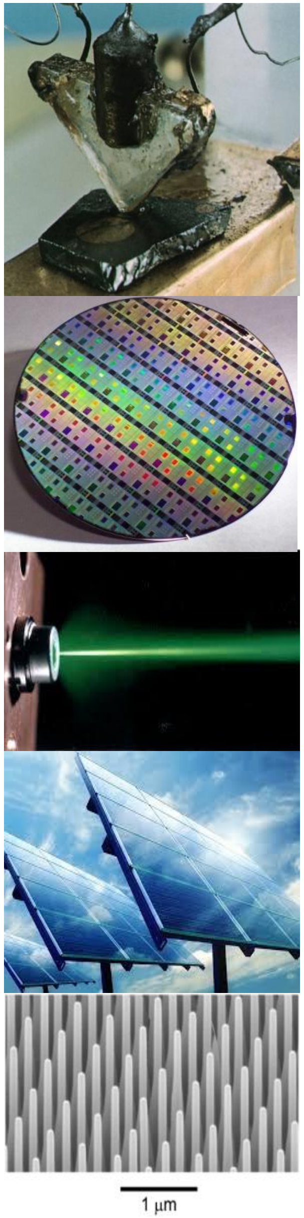
Photoconductor
Easy to fabricate
Low cost

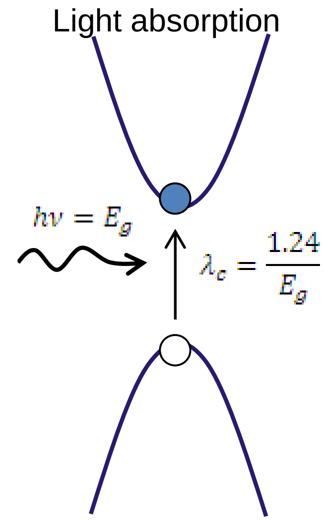
Photodiode
High quantum efficiency
High speed (controlled by the electric field)



Phototransistor
High gain, moderate speed

Quantum efficiency





When light is absorbed within the depletion region, the photogenerated electrons and holes are separated by the electric field and a photocurrent flows in the external circuit. The carriers drift within the depletion region, then diffuse in the neutral (p or n region) and eventually recombine (in the neutral region or with charges of opposite sign at the electrodes).

The number of electron-hole pairs generated per incident photon is known as the external quantum efficiency.

$$\eta = \frac{\left(\frac{I_{ph}}{q}\right)}{\left(\frac{P_{opt}}{h\nu}\right)} = \frac{\left(\frac{I_{ph}}{q}\right)}{\left(\frac{P_{opt}\lambda}{hc}\right)} = \frac{\left(\frac{I_{ph}}{P_{opt}}\right)}{\left(\frac{\lambda}{1.24}\right)}$$

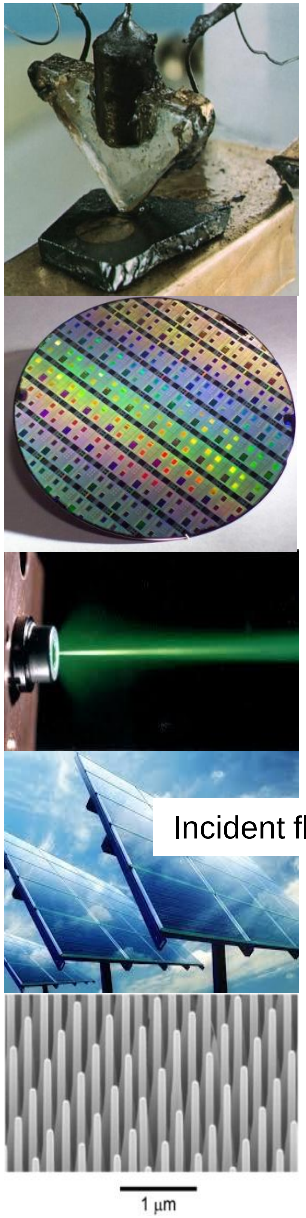
$$R_{measured} = \frac{I_{ph}}{P_{opt}}$$

$$R_{\max} = \frac{\lambda}{1.24}$$

I_{ph} is the measured photocurrent, P_{opt} is the incident optical power, $h\nu$ is the photon energy.

Therefore to maximise the quantum efficiency it is important to minimise carrier loss through recombination in the photodetector. We can achieve this by confining the absorption within the depletion region using wide bandgap materials in a p and n layers of a p-i-n structure.

Absorption coefficient and quantum efficiency



As mentioned before the intensity of light is given by $I = I_o \exp(-\alpha x)$

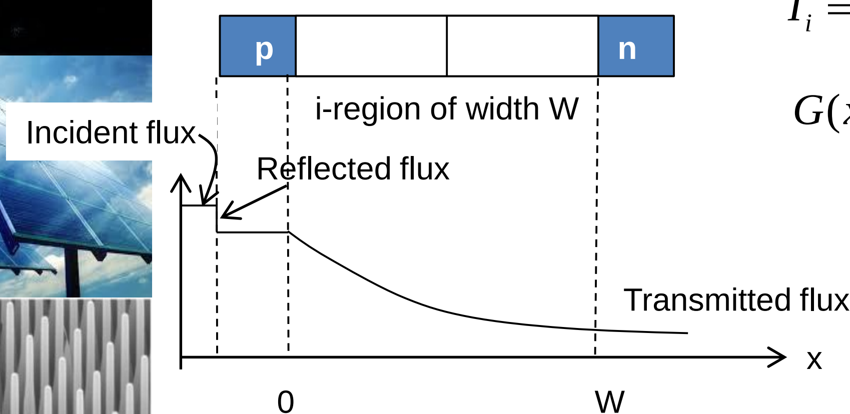
where α is the absorption coefficient which is a strong function of wavelength.

Within the depletion width, the generation rate is $G(x) = \alpha \Phi_o \exp(-\alpha x)$
where Φ_o is the photon flux per unit area. Including light reflected at the air-semiconductor interface we have $\Phi_o = P_{opt}(1-R)/Ahv$

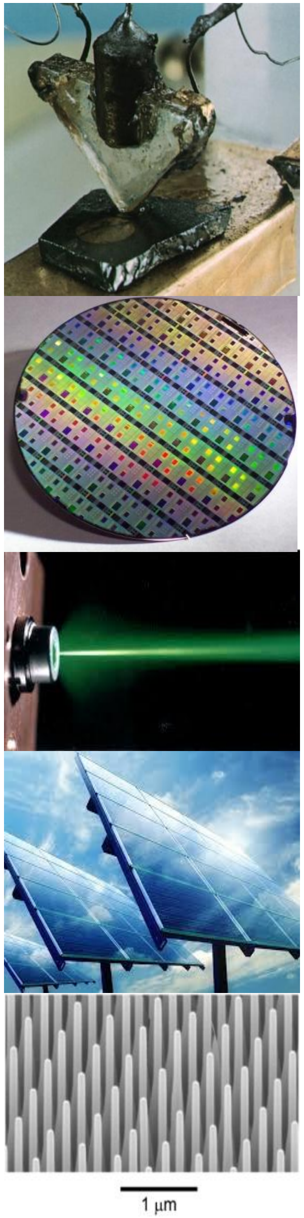
Assuming that light is absorbed in the i-region only (for instance in p-i-n diode with wide bandgap transparent p and n regions) the photocurrent generated within the depletion region is

$$I_i = qA\int_0^W \alpha \Phi_o \exp(-\alpha x)dx = qA\Phi_o[1-\exp(-\alpha W)]$$

$$G(x) = \alpha \Phi_o \exp(-\alpha x)$$



Effect of depletion width on



The quantum efficiency is

$$\eta = \left(\frac{I_i}{q}\right)\left(\frac{P_{opt}}{h\nu}\right)^{-1} = \frac{qA\Phi_o[1-\exp(-\alpha W)]}{q}\left(\frac{P_{opt}}{h\nu}\right)^{-1}$$

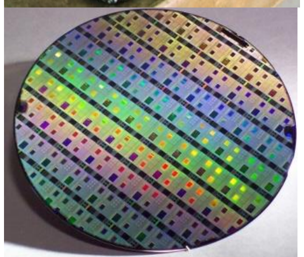
$$\eta = \frac{AP_{opt}(1-R)[1-\exp(-\alpha W)]}{Ah\nu}\left(\frac{P_{opt}}{h\nu}\right)^{-1} = (1-R)[1-\exp(-\alpha W)]$$

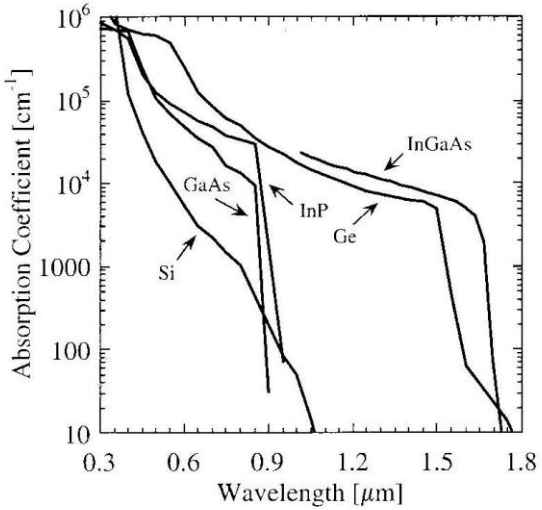
$$\boxed{\eta = (1-R)[1-\exp(-\alpha W)]}$$

The larger the depletion width, the higher the quantum efficiency. However the quantum efficiency is always less than unity. In practice the absorption region thickness should be at least 1/α (i.e 63% of light is absorbed) for acceptable quantum efficiency.

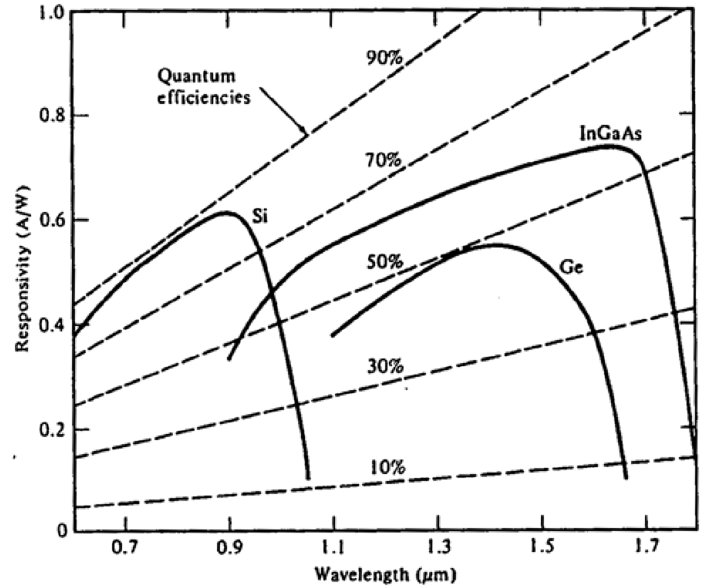
In most photodetectors, the upper limit of the absorption layer thickness is likely to be controlled by the response speed requirement. In other cases (e.g quantum well and superlattice) the growth of very thick absorption layer is costly.

Absorption coefficient and quantum efficiency





Handbook of Optical Constants of Solids, edited by Edward D. Palik, (1985), Academic Press NY.



The absorption coefficient at wavelengths << λ_c is usually very large (10^5 cm^{-1}). Light is therefore absorbed very close to the surface and majority of the photogenerated carriers recombine due to high density of surface states. At wavelengths >> λ_c no appreciable carriers are generated. Therefore the photocurrent contributed by very long and very short wavelengths are negligible, leading to a well defined response wavelength band. Light should be absorbed within the depletion region to maximise the responsivity.

Responsivity is defined as

$$R_{res} = \frac{I_{ph}}{P_{opt}} = \frac{\eta q}{h\nu} = \frac{\eta q \lambda}{hc} = \frac{\eta \lambda}{1.24}$$

The maximum theoretical responsivity is therefore

$$\boxed{R_{res\_\max} = \frac{\lambda}{1.24} \quad \text{A/W}}$$

Detectivity

A wide range of IR detectors is available. HgCdTe is an important IR detector covering a wide wavelength range.

Bulk semiconductors

InSb, InAs, HgCdTe, PbSe

Conduction band

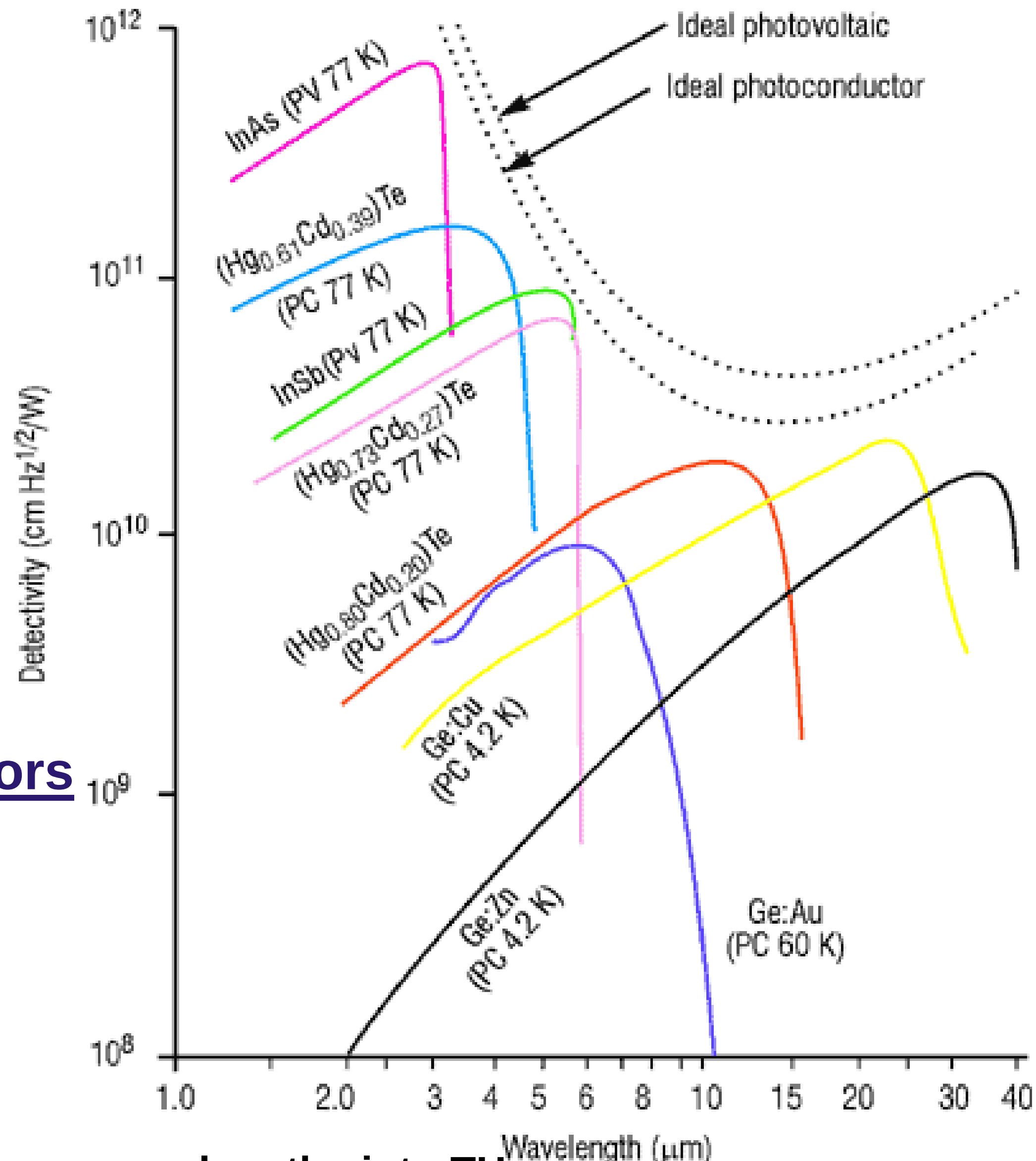
Valence band

Detectivity = Responsivity x Area$^{0.5}$ / Noise current

Impurity doped semiconductors

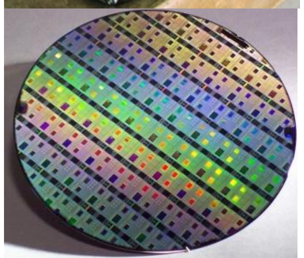
Ge:Zn, Si:As

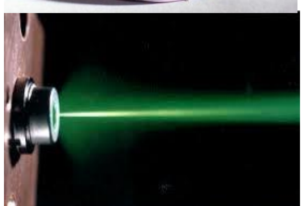
Conduction band	Conduction band
Impurity band	Impurity band
Valence band	Valence band

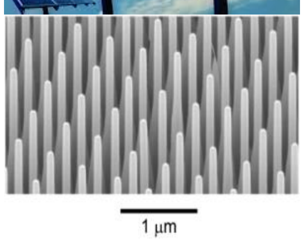


Impurity doped semiconductors can cover wavelengths into THz.

Response speed







The response speed depends on (1) time for carriers to diffuse, (2) time to transit the depletion region and (3) RC time constant.

Carriers generated outside the depletion region must diffuse. The time taken to diffuse a distance *x* is known to be

$$t_{diff} = \frac{4x^2}{\pi^2 D_p}$$

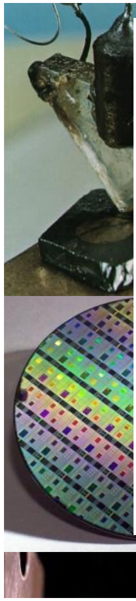
In Si, electron diffusion constant is 36 cm^2/s. What is the diffusion time over a 1μm ? Compare this to the transit time across a depletion region of the same width assuming a drift velocity of 10^7 cm/s.

The transit time limited bandwidth is given by $$f_{3dB\_tr} = \frac{0.4}{t_r} = \frac{0.4 v_s}{W}$$

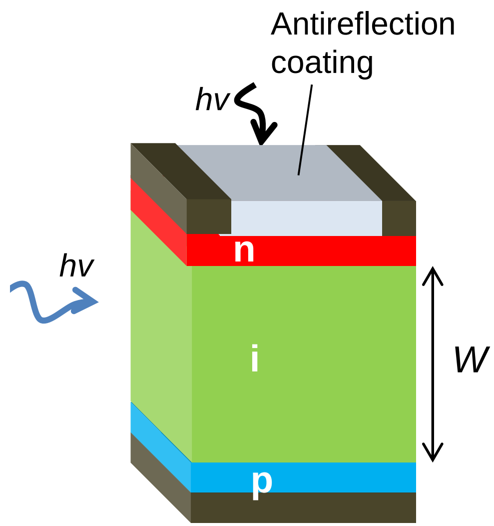
Since $t_r = W/v_s$ the depletion width W sets a trade-off between response speed and quantum efficiency. $\eta = (1-R)[1-\exp(-\alpha W)]$

See Sze and Ng, p.676 -679 for derivation.

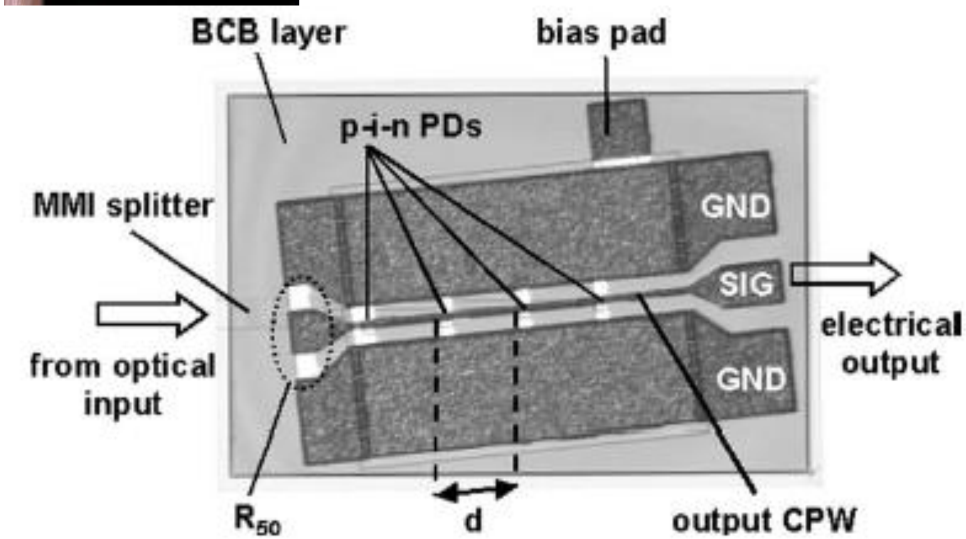
Top and side injection

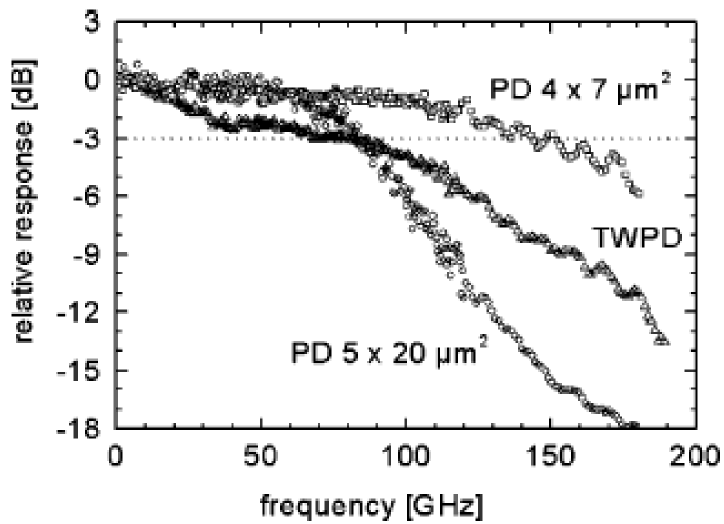


Side injection can be used when *W* is reduced. The lateral length of the diode can be easily fabricate to ensure sufficient light absorption. This is the preferred approach for very high speed photodiode working > 10 GHz.
This "waveguide photodiode" has much smaller RC and transit times. Waveguide photodetectors can achieve responses >100 GHz.



When injecting light from the top, *W* presents a trade-off between speed and quantum efficiency. In most cases the cross sectional area is also quite large (to ensure good optical signal coupling). Consequently in vertically illuminated diode RC time constant is also limiting the speed response.





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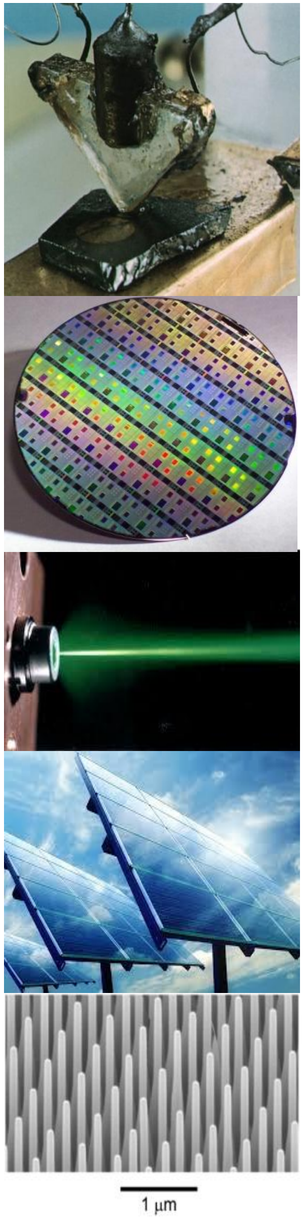
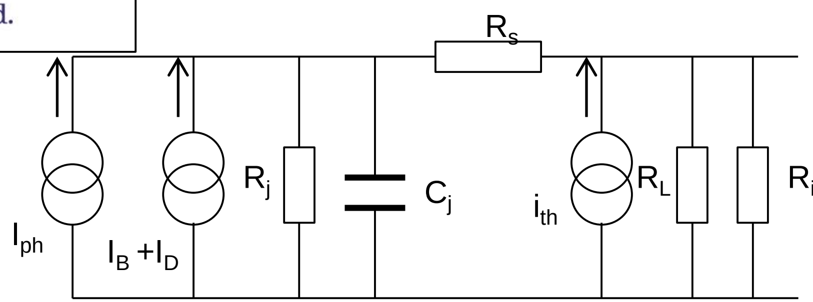
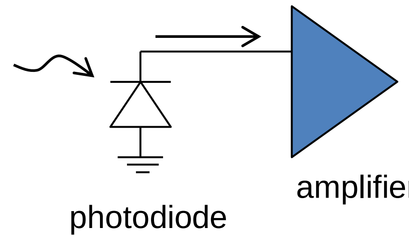
Noise





$I_T = I_{ph} + I_B + I_D$



I_{ph} = photocurrent, I_B = background induced current, I_D = dark current.

In semiconductors such as Si and GaAs, the SRH recombination is the dominant recombination process that contributes to dark current.

Since carriers are generated randomly, these current components contributed shot noise. $<i_s^2> = 2qI_T B$

where B is the system bandwidth. The thermal noise is given by

$$<i_{th}^2> = \frac{4kTB}{R_{eq}}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_j} + \frac{1}{R_L} + \frac{1}{R_i}$$

R_j = diode junction resistance

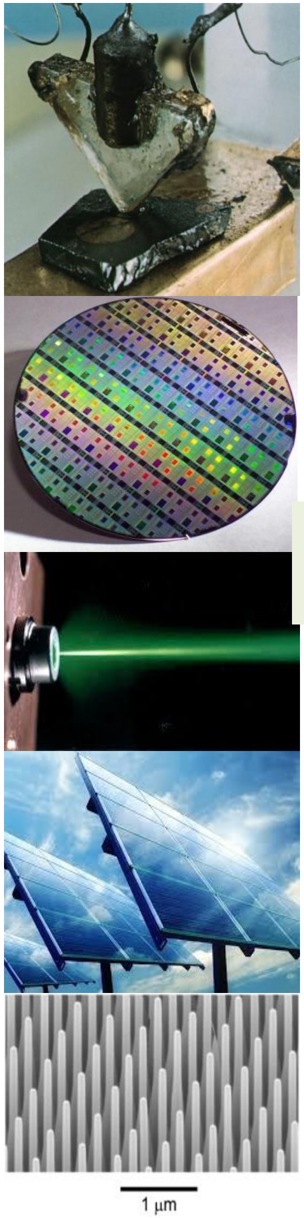
R_L= load resistance

R_i= input resistance of the following amplifier

The series resistance is usually much smaller and is ignored. The signal to noise ratio can be written as

$$SNR = \frac{I_{ph}^2}{<i_s^2> + <i_{th}^2>} = \frac{(q\eta P_{opt}/h\nu)^2}{2qI_T B + 4kTB/R_{eq}}$$

Noise



For B = 1 Hz, the noise equivalent power (NEP) can be derived by setting SNR =1 $(q\eta P_{opt}/h\nu)^2 = 2qI_T + 4kT/R_{eq}$

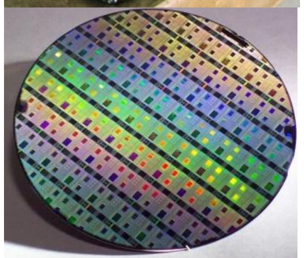
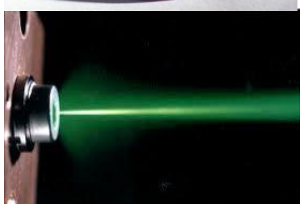
$$P_{opt,\min} = \frac{h\nu}{q\eta}\sqrt{2q\left(I_D + I_B + 2kT/qR_{eq}\right)} = \frac{h\nu}{\eta}\sqrt{\frac{2I_{eq}}{q}}$$

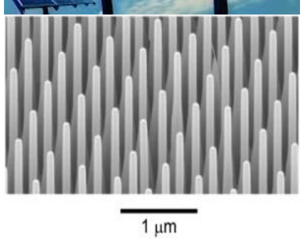
I_{ph} omitted from shot noise to derive the minimum optical power required to produce SNR =1

$$I_{eq} = \underbrace{I_D + I_B}_{\text{photodiode noise}} + \underbrace{2kT/qR_{eq}}_{\text{amplifier noise}}$$

To improve the sensitivity of the photodiode, we should increase η and R_{eq} (if amplifier noise is larger than the photodiode noise) but minimise I_D and I_B.

PIN diode SNR optimisation



$$P_{opt,\min} = \frac{h\nu}{\eta}\sqrt{\frac{2I_{eq}}{q}}$$

$$I_{eq} = I_D + I_B + 2kT/qR_{eq}$$

To maximise η we need to

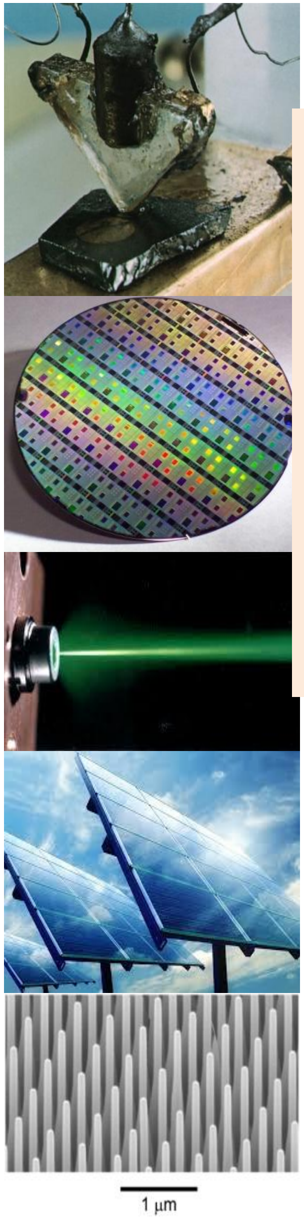
1) Minimise light reflection at the surface. Use antireflection coating and light scattering structure (such as those in solar cell).
2) Use thick absorption layer when possible
3) Reduce carrier loss through recombination. Surface should be passivated to reduce surface recombination. Wide bandgap p and n "window" layers should also be used when available.

To maximise I_{eq} we need to

1) Make sure R_{eq} is large.
2) Use the widest bandgap available to detect the wavelength of interest to reduce dark current I_D. It is also important to minimise defects and hence lattice matched materials should be used.
3) The background induced signal can be removed by using optical filters.
4) If acceptable, cool the diode as cooling will reduce the dark current generated and the thermal noise.

The University Of Sheffield.

PN and PIN diodes



PN

- Simple growth, such as a single implantation step.
- Depletion width is controlled by doping in the p and n regions.
- Usually a homojunction design.
- Electric field is not uniform such that carriers may not drift at the saturated velocity throughout the depletion region.
- Capacitance depends on bias voltage

PIN

- An additional growth required to define the epilayer.
- Depletion width is controlled by i-region thickness and doping.
- Can include wide bandgap transparent p and n layers to reduce dark current.
- Electric field is almost constant across the high field region such that carriers drift at their saturated velocities.
- Capacitance is virtually constant independent of bias voltage.

Avalanche photodiodes (APDs)

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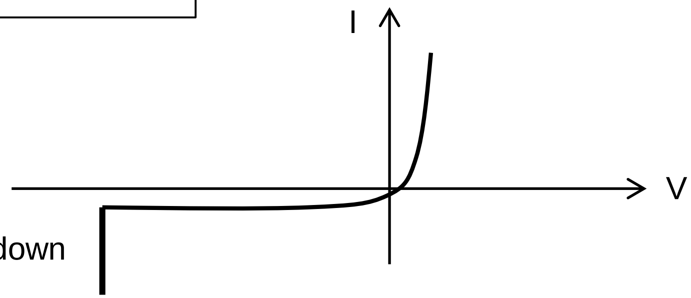
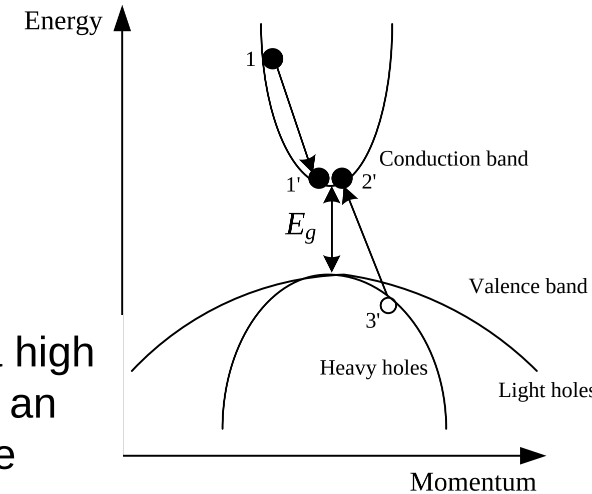
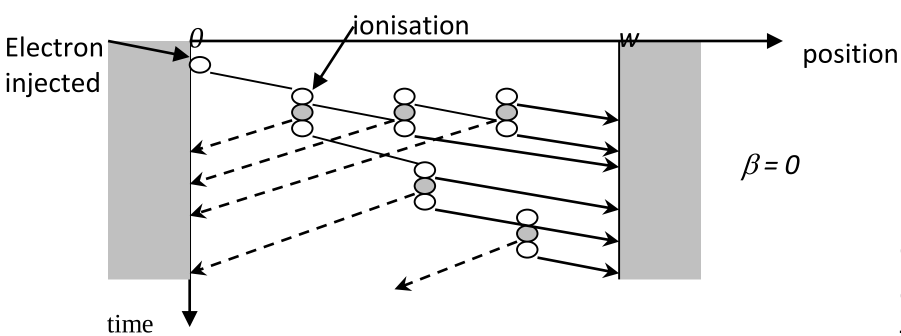
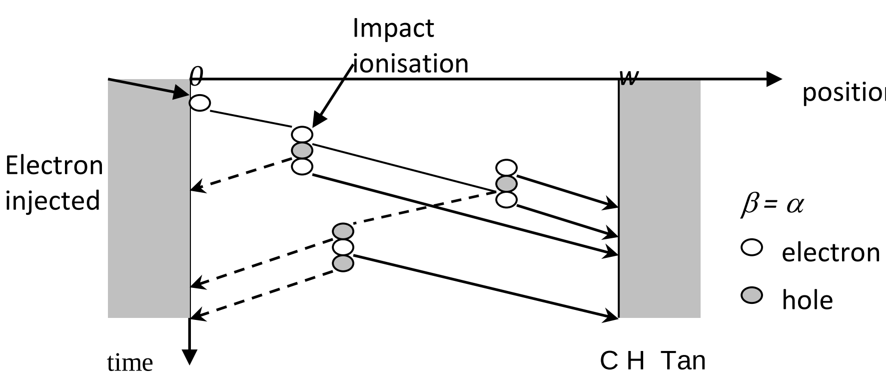




When operated close to the reverse breakdown voltage a high energy electron can collide with a lattice atom to promote an electron from VB to CB. Since a hole is also produced, we have a new electron-hole pair.





C H Tan

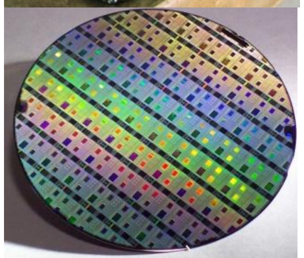
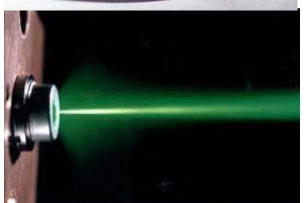
β and α are the hole and electron ionisation coefficients, respectively.

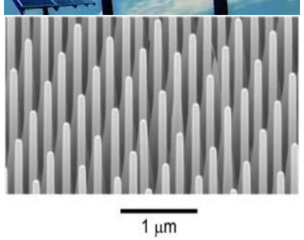
For k = 0 there is large number of electrons present at a given time. If one of the electrons does not impact ionise, the effect on gain is small.

When k =1, there are much fewer electrons in the high field region. Hence if one of them does not ionise, the gain is significantly reduced.

The randomness in impact ionisation is minimum when k = 0.

Multiplication factor



α (or β), the electron (or hole) ionisation coefficient, represents the inverse of the mean distance between successive impact ionisation events. The ratio k = β / α is normally used to characterise the breakdown characteristics. Lets consider two special cases for a diode with a constant electric field in the avalanche region of width W.

1) Assuming that we have $\alpha = \beta$, we have **k = 1**. The multiplication factor is given by

$$M = \frac{1}{1-\alpha W}$$

The diode breakdown condition is defined by αW=1 that leads to M=∞.

2) If hole ionisation, β = 0, we have **k = 0** the so-called single carrier ionisation since only electron can produce new carriers via impact ionisation. In this case the multiplication factor is given by

$$M = \exp(\alpha W)$$

Here the diode does not have a well defined breakdown. The multiplication factor increases exponentially with α.

For other values of k, we have

$$M(x) = \frac{\exp[-(\alpha-\beta)x]}{1-\frac{\alpha}{(\alpha-\beta)}[1-\exp(-(\alpha-\beta)w)]}$$

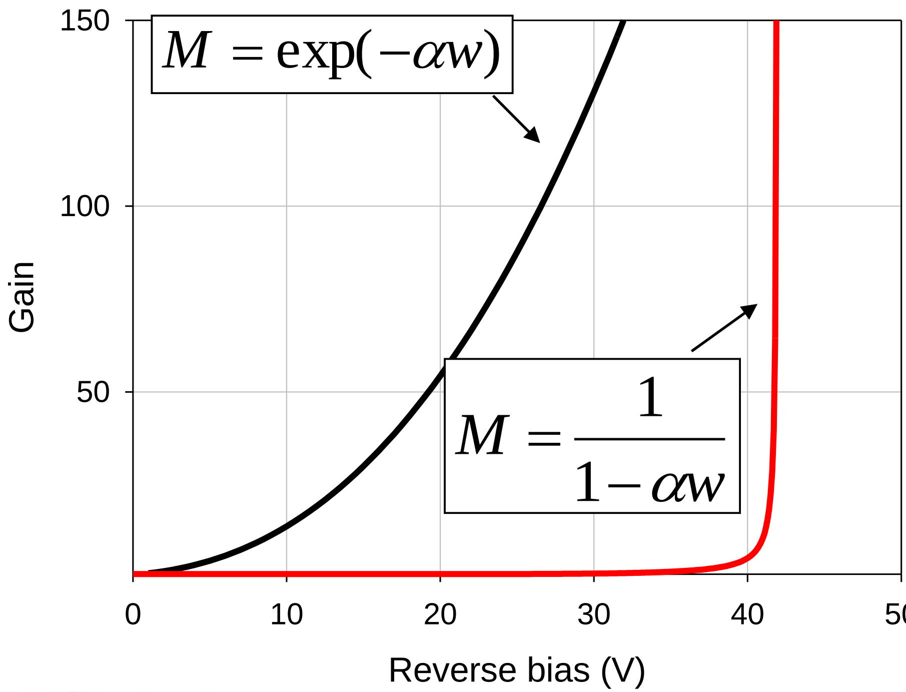
Where x is the carrier injection position. For example x=0, when electron is injected to initiate the multiplication process in the previous slide. It is also possible to express the multiplication factor as a function of voltage.

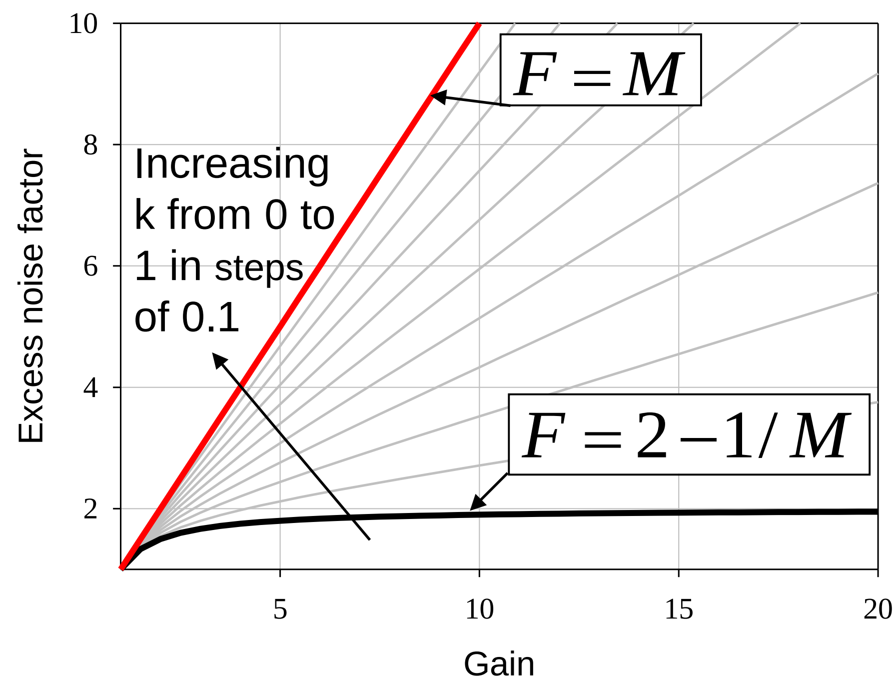
$$M = \frac{1}{1-\left(\frac{V-IR}{V_b}\right)^{n_m}}$$

Gain and excess noise for k=0 and k=1

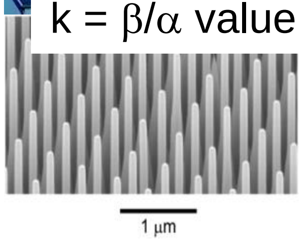
Although impact ionisation can provide internal gain in the APD, the multiplication process has statistical fluctuation that introduce noise. The noise factor in an APD with a constant electric field is given by

$$F = kM + (2 - 1/M)(1 - k)$$





Gain vs. Reverse bias is a reasonable indicator of
k = β/α value



The excess noise is minimised when k = 0.

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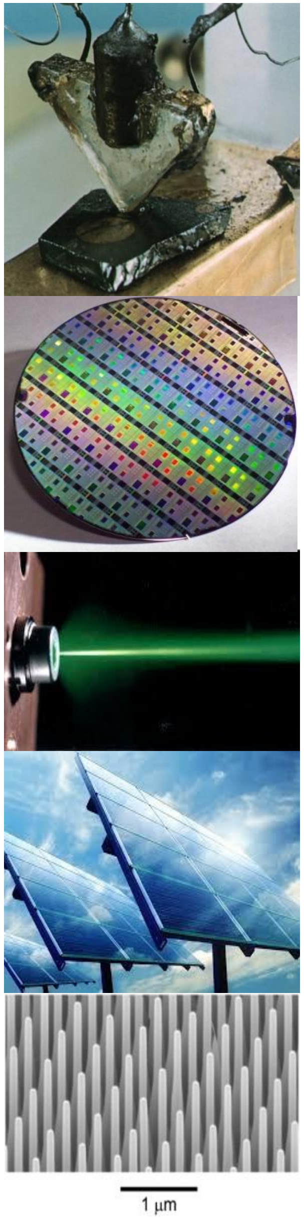
Excess noise



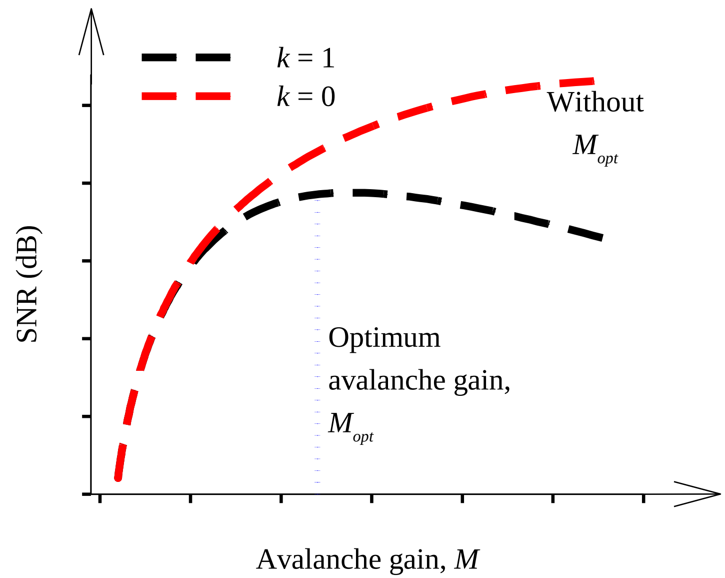
To understand the advantages of APDs, we need to revisit the SNR. Consider a gain or multiplication factor of M is provided by the APD.

$$SNR = \frac{(MI_{ph})^2}{M^2 < i_s{}^2 > + < i_{th}{}^2 >} = \frac{(q\eta P_{opt} M / h\nu)^2}{\underbrace{2qI_T M^2 FB}_{\text{Diode noise}} + \underbrace{4kTB / R_{eq}}_{\text{Amplifier noise}}}$$

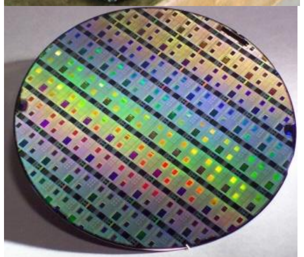
$$SNR = \frac{(q\eta P_{opt} / h\nu)^2}{2qI_T FB + 4kTB/(M^2 R_{eq})}$$

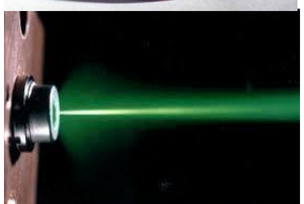
Amplifier noise is reduced by a factor of M^2. APDs are advantages as long as the excess noise factor F is low so that the diode noise is lower than the amplifier noise.

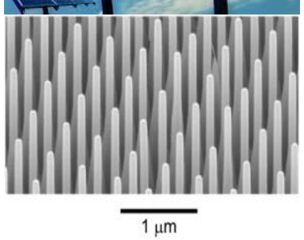
When k ≠ 0 there is an optimum multiplication factor (avalanche gain), M_{opt}. If the APD is operated at $M > M_{opt}$, the excess noise from the APD becomes the dominant noise source and SNR degrades.



Avalanche photodiodes







$$SNR = \frac{(MI_{ph})^2}{M^2 < i_s{}^2 > + < i_{th}{}^2 >} = \frac{(q\eta P_{opt} M / hv)^2}{2qI_T M^2 FB + 4kTB / R_{eq}}$$

$$SNR = \frac{(q\eta P_{opt} / hv)^2}{2qI_T FB + 4kTB/(M^2 R_{eq})}$$

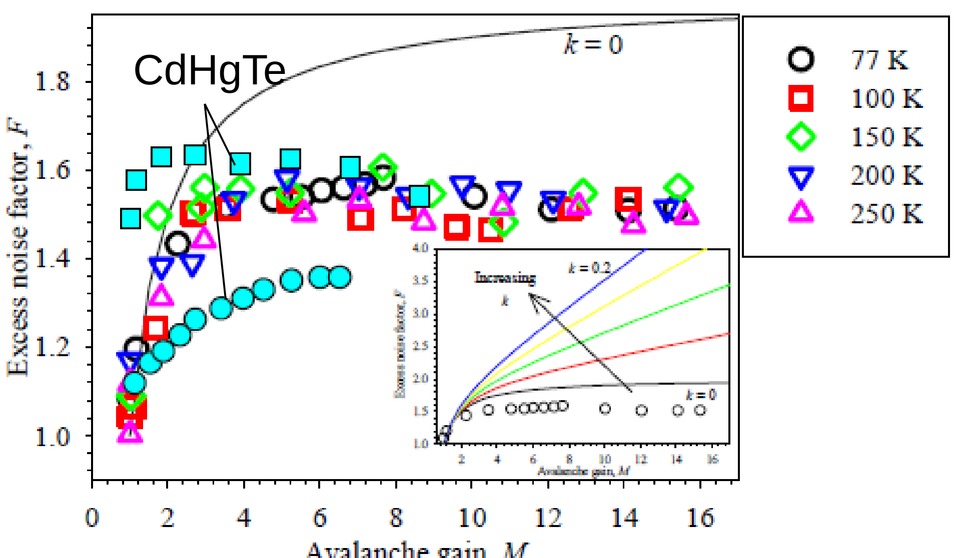
APD offers improved SNR over a pin diode only when the noise is dominated by the amplifier. The amplifier noise is usually dominant when

Very high bandwidth and high gain is required. An important example of this situation is the high speed optical fiber communication above 2.5 Gb/s. Therefore one of the most important applications of APD is in high speed optical communication.

Extremely high gain > 10^8 is required for detection of very low optical signal. Such as in fluorescence measurement in DNA analysis, and in ranging application called LIDAR (http://www.youtube.com/watch?v=WJoaksSKaOo).

Low noise APDs

Material	k = β/α value	Application
Si	0-0.1	Low light detection within 400-1000 nm, Widely available at affordable cost.
InP	0.2-0.4	Used with an InGaAs absorption region in the 1300 and 1550 nm optical fiber communication.
CdHgTe	0	Can cover all low light detection from Near IR to Longwave IR (10μm). Need to be cooled to 77 K and hence it is expensive.
InAs	0	Currently developed at Sheffield for imaging and gas sensing applications at 1000 to 3600 nm.



InAs APDs developed at Sheffield has excess noise factor below k = 0.

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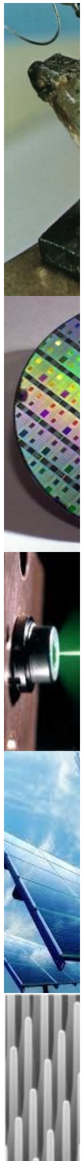
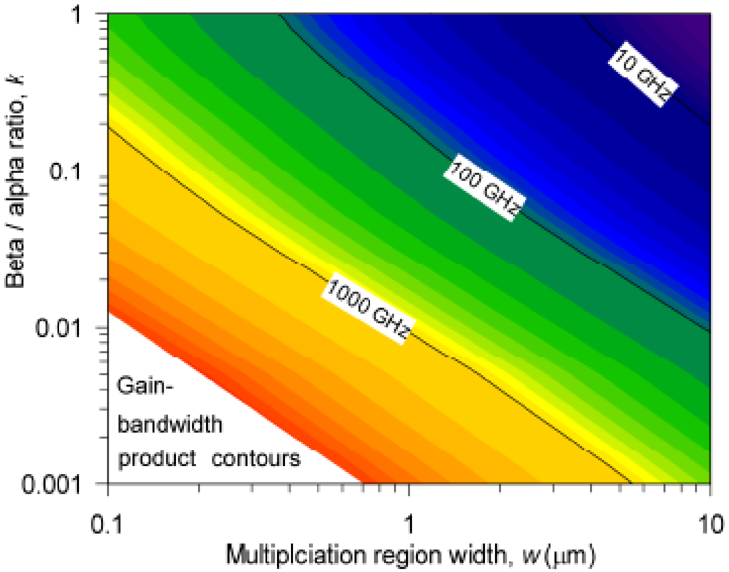
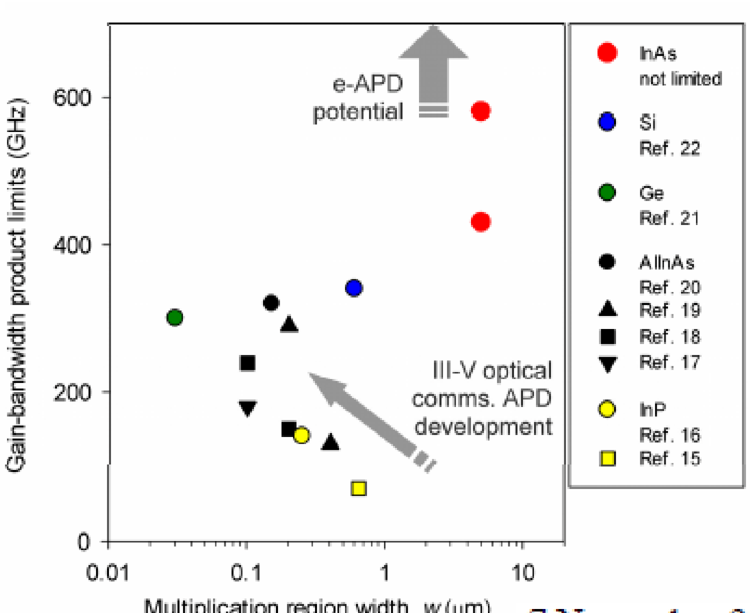
APD gain-bandwidth products







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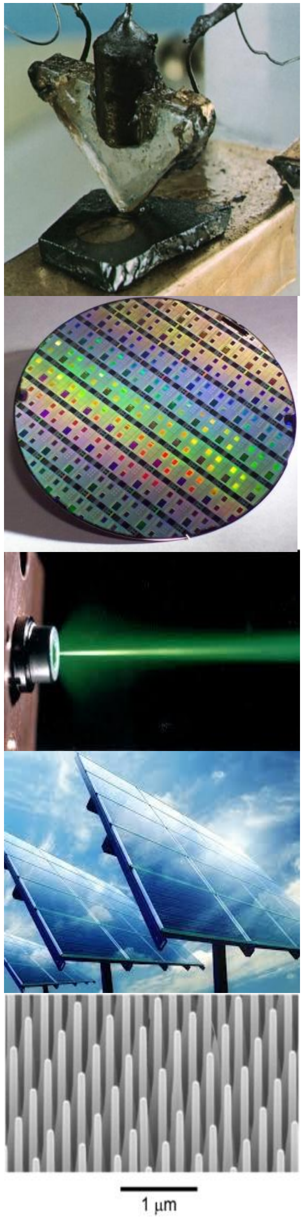
For k ≠ 0, the multiplication process requires several transit times to build up the charge concentration required for high gain. Therefore the avalanche material is not instantaneous in most semiconductors. Consequently the bandwidth reduces as the gain increases leading to an approximately constant gain-bandwidth product.

Low multiplication region width and low value of k provide the highest gain-bandwidth product.

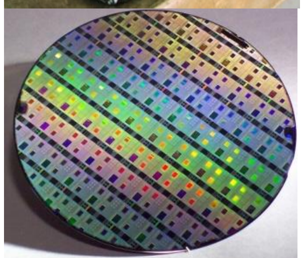
Consider an InGaAs/InP APD with a gain-bandwidth product of 140 GHz. Estimate the maximum gain that it can provide when used to detect signal at a bit rate of 10 Gb/s.

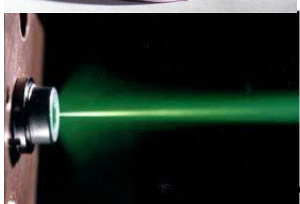
APD Design Issues

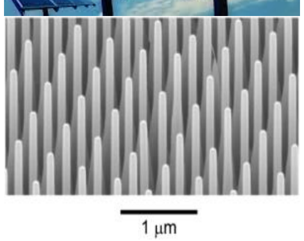


- SAMAPD design, need to keep the electric field low in absorption region.
- Gain is sensitive to bias and temperature.
- For high speed APD with thin multiplication region, it is limited by onset of tunnelling current.
- For infrared APDs, narrow bandgap materials such as CdHgTe and InAs are limited by tunnelling current and high dark current. They require cooling mechanisms.

Bipolar Junction Transistor (BJT)







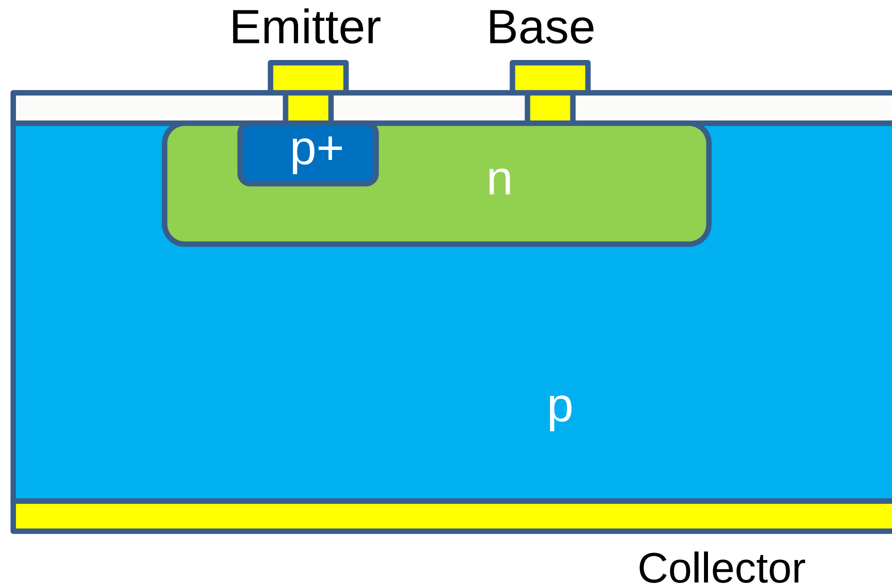
Fabrication steps:

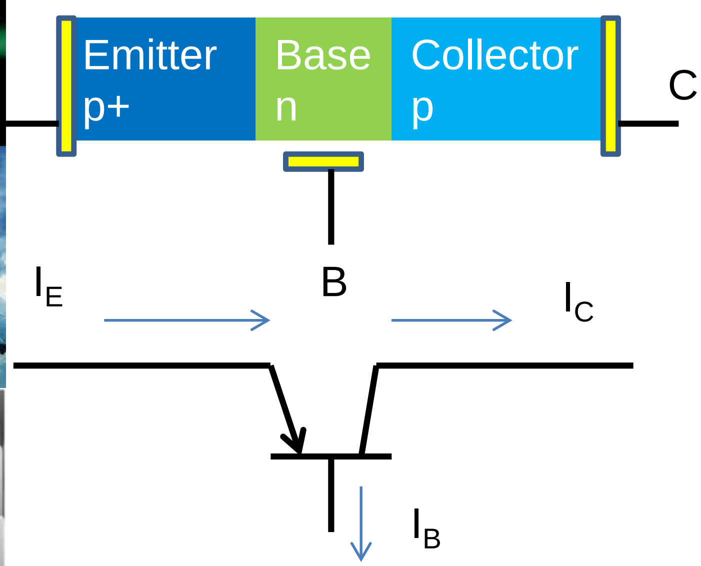
Start with a p-substrate

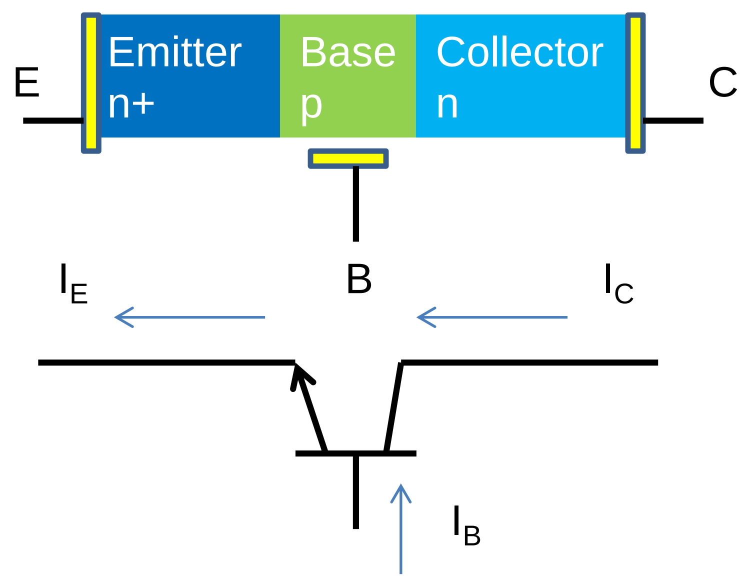
Diffuse n dopant to form base

Diffuse p+ dopant to form emitter

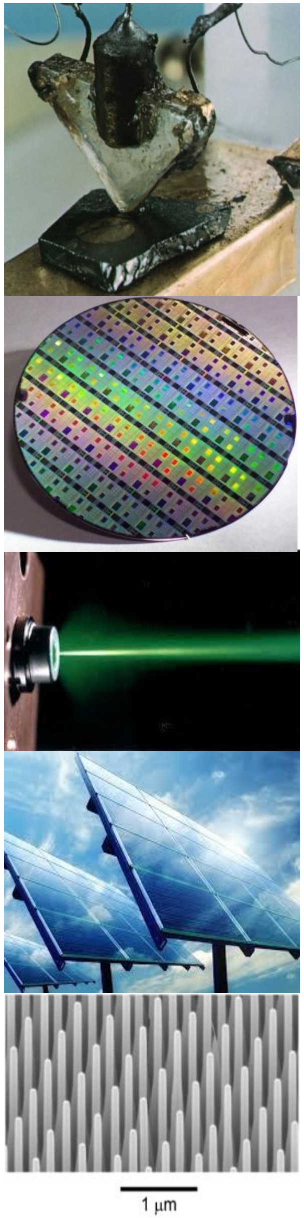
Deposit metal contacts

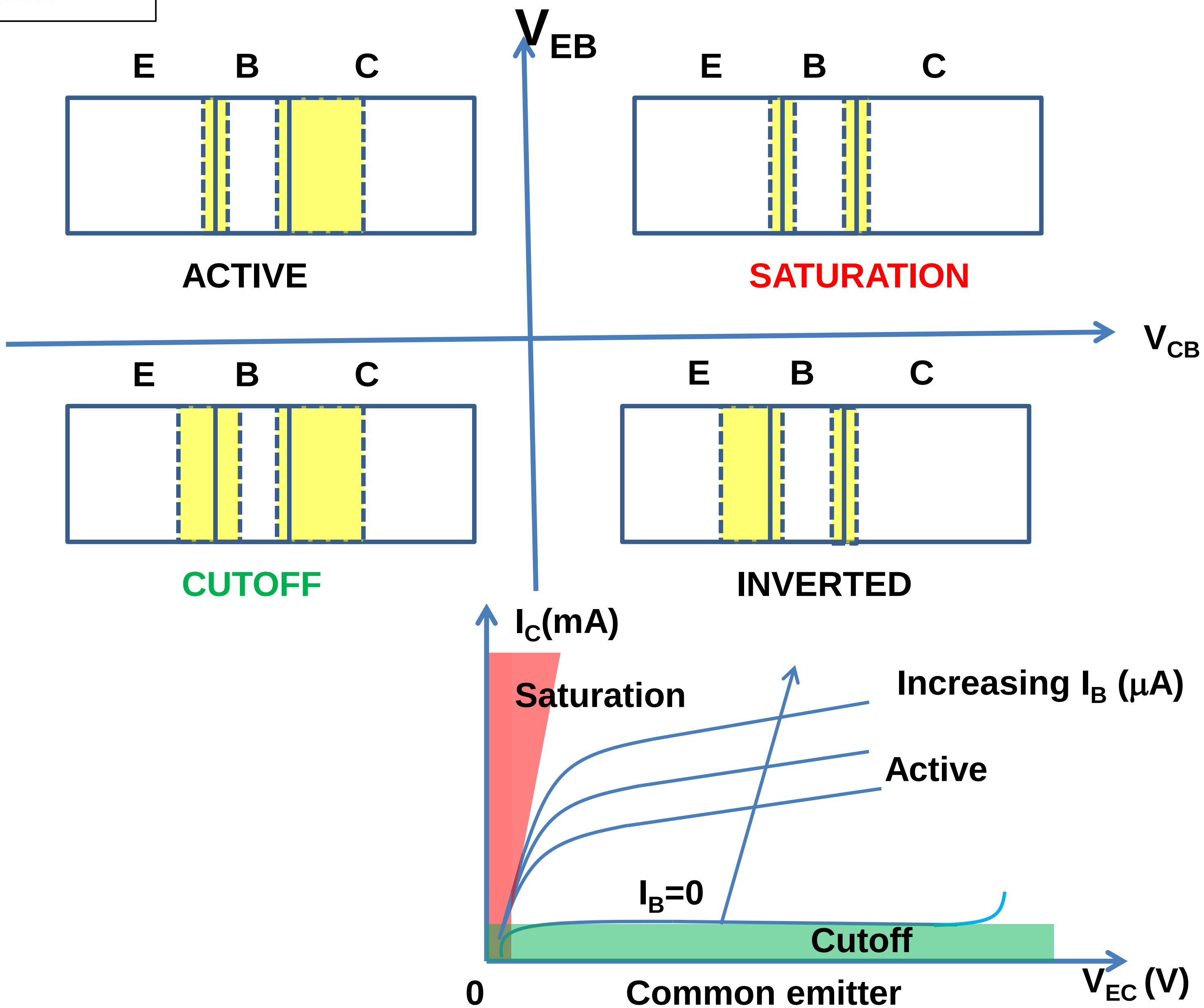




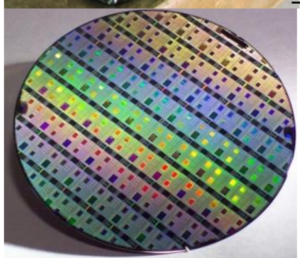


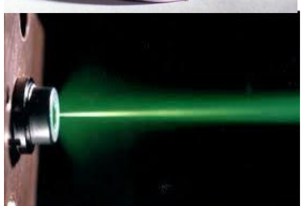
Modes of operation

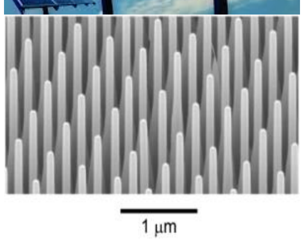


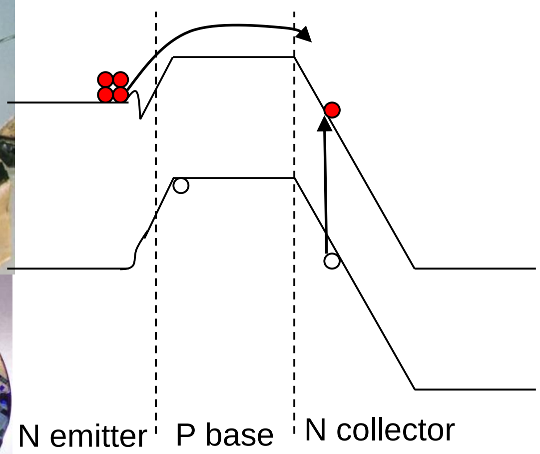


Phototransistor







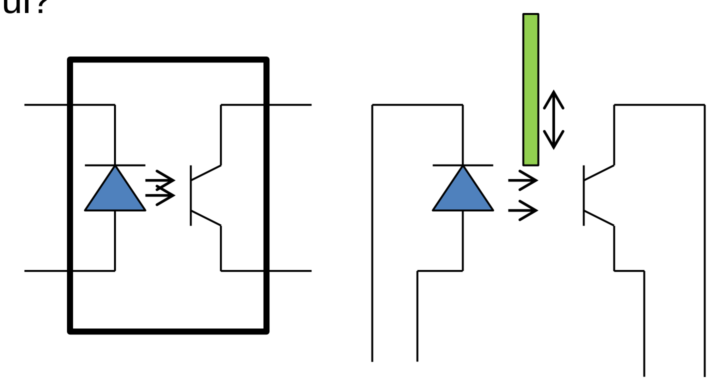


In a phototransistor the base is not electrically connected. Light is absorbed in the base-collector depletion region and the undepleted base region (if emitter is a wide bandgap material). Photogenerated holes are trapped at the base and raises the potential that allows more electrons to be injected from emitter to collector. Provided that the electron transit time is much smaller than the minority electron lifetime, a high amplification factor or gain is achieved.

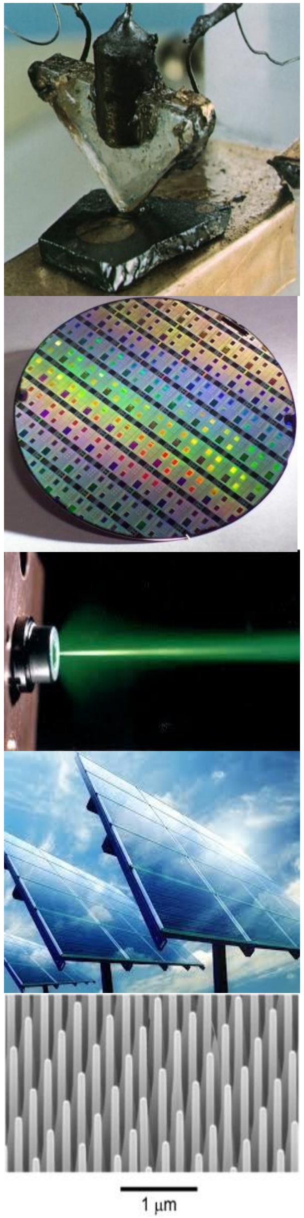
Gain of up to 10^3 can be obtained. Unfortunately the dark current is also amplified by the same factor. The response speed of phototransistor is also lower than PINs and APDs.

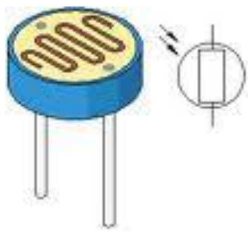
Phototransistors are used in optical isolator because of its high output to input current ratio, known as the current-transfer ratio. A value of 50% is typical which is much high than that achieved using a photodiode (0.2%). Phototransistors are cheaper than APDs. Can you list applications where optical isolator is particularly useful?

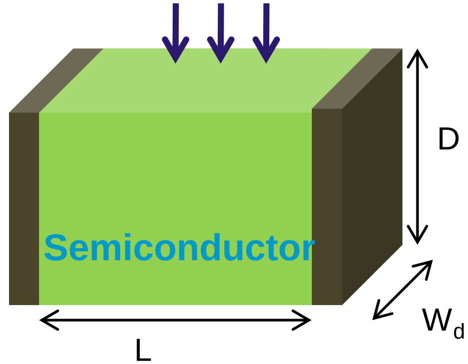
To protect an expensive equipment or circuit.
To isolate two circuits with very different bias range.
To data communication.
To minimise interference between circuits and antenna.
To detect object/particle counting



Photoconductor







This is simply a slab of semiconductor sandwiched between two metals. When light is absorbed the photogenerated electron-hole pairs modify the conductivity of the semiconductor.

$$\sigma = q(\mu_e n + \mu_h p)$$

Consider a steady flow of photon flux illuminated on the area $W_d L$ *and* $D >> 1/\alpha$. The generation rate is therefore

$$G = \frac{\eta(P_{opt}/h\nu)}{W_d LD} = \frac{n}{\tau}$$

$$I_{ph} = \sigma E W_d D = q\mu_e n E W_d D$$

$$I_{ph} = q\frac{\eta P_{opt}}{h\nu}\left(\frac{\mu_e \tau E}{L}\right)$$

For high gain, the lifetime should be long, while the spacing between electrodes should be short and mobility should be high.

Gain: 1-10^6

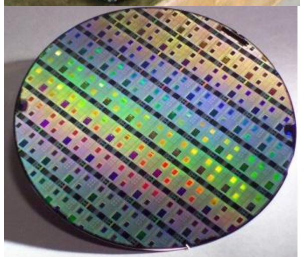
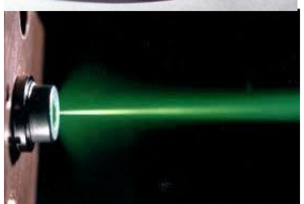
Response time: 10^{-8} -10^{-3} s

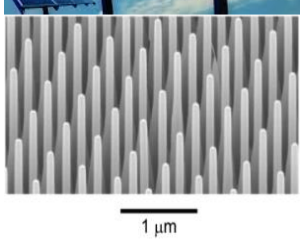
$$I_{pr} = q\frac{\eta P_{opt}}{h\nu}$$

$$Gain = \frac{\mu_e \tau E}{L} = \frac{\tau}{t_r}$$

Recombination lifetime

Transit time

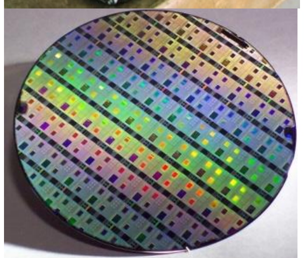
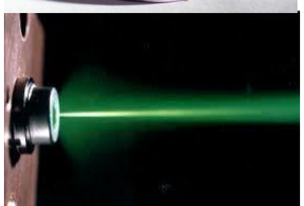




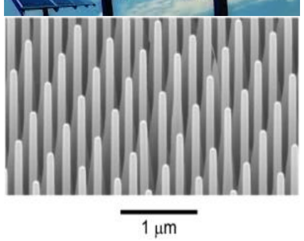


Infrared photodetectors

C H Tan

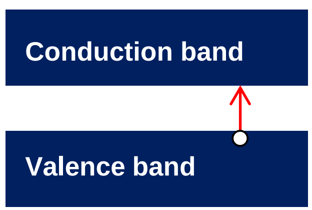
Photoconductor

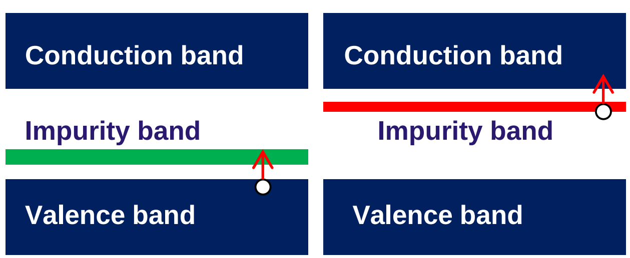


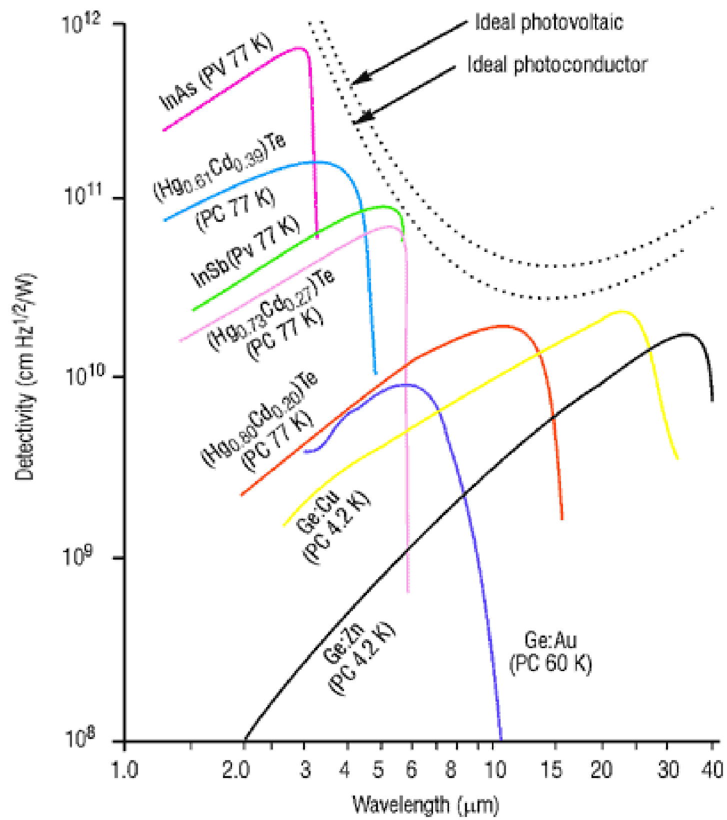
Photoconductor (PC) can be separated into intrinsic (band to band transition) and extrinsic (impurity band to CB or VB) PCs. They are used as low cost infrared detectors. For example in non-contact temperature measurement of steel plate.

Intrinsic PC

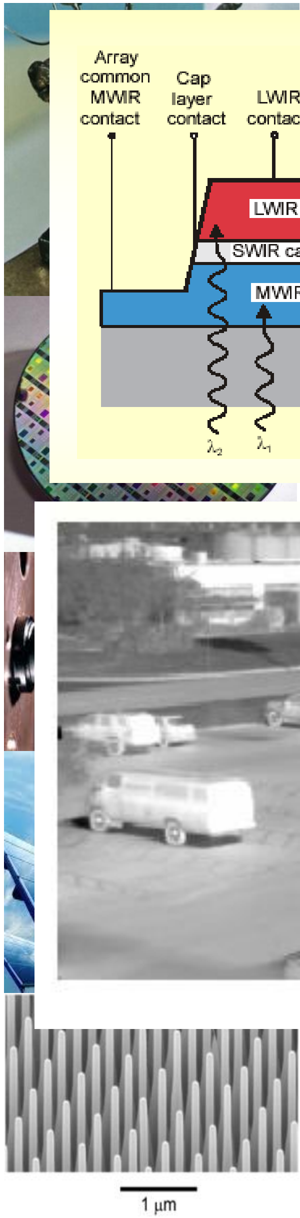


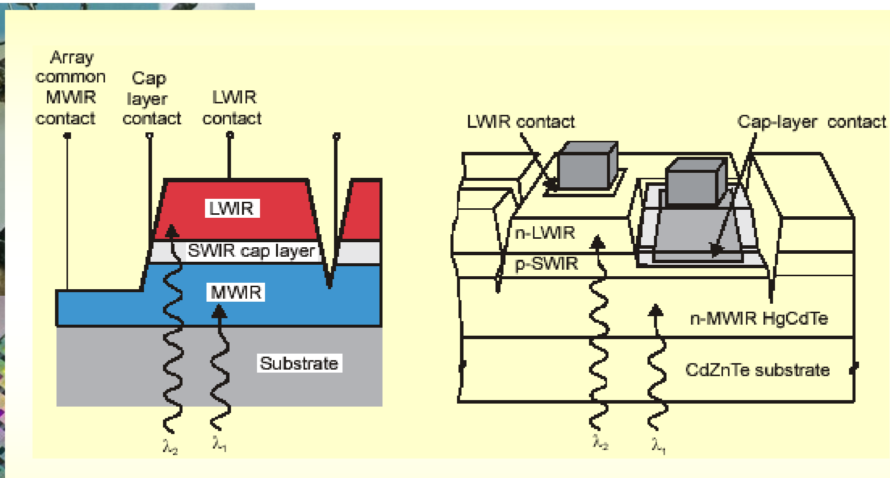
Extrinsic PC





CdHgTe Dual band detection





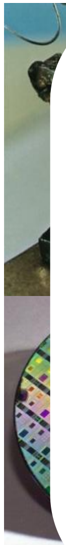
Lattice match system enables MWIR/LWIR dual band detection.

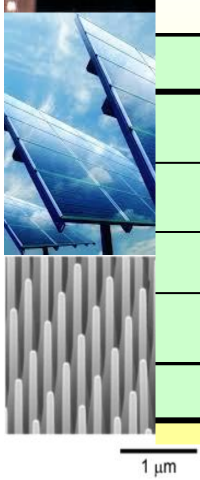
(a) LWIR (b) MWIR

Image is sharper in MWIR due to lower leakage current but LWIR detects lower temperature objects.

Smith et al., Proc. SPIE 6127

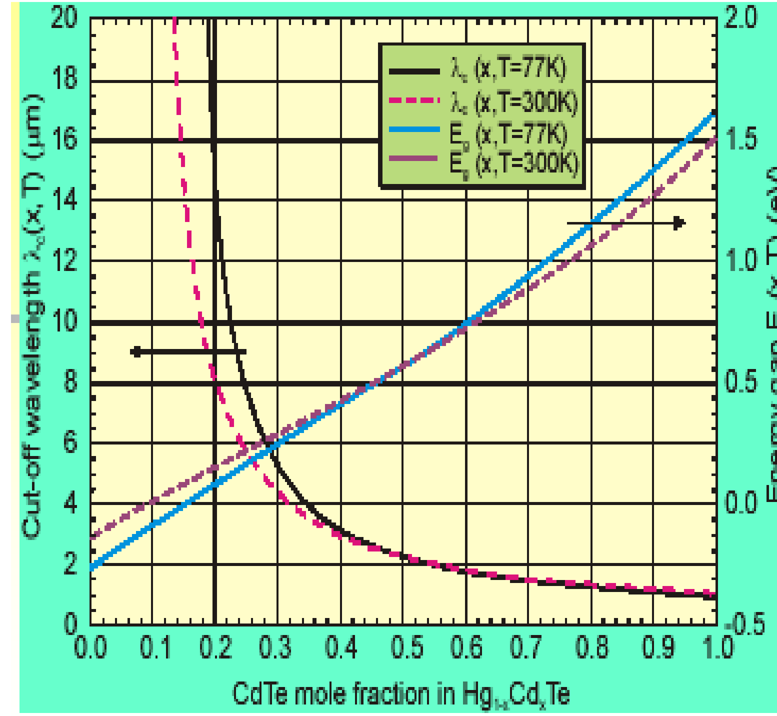
CMT : High performance IR detectors





$Cd_xHg_{1-x}Te$ (CMT)

- **Difficult growth**
- **Low temperature operation to avoid Auger recombination**
- **Fabrication is complicated**
- **Smaller array**
- **Poor stability due to weak Hg-Te bond**
- **Not bias tuneable**



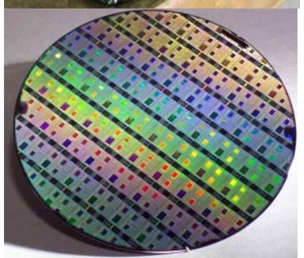
Cutoff wavelength for *x* variations of 0.1%, and the corresponding cutoff wavelength shift for $Hg_{1-x}Cd_xTe$

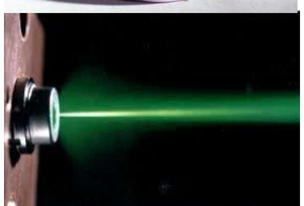
x-value	Cutoff wavelength (µm)	Temperature (K)	Uncertainty (µm)
0.395	3	77	0.012
0.295	5	77	0.032
0.210	10	77	0.131
0.196	14	77	0.257
0.187	20	77	0.527

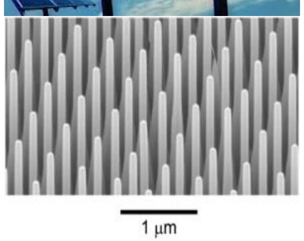
Rogalski et al. Narrow-Gap Semiconductor Photodiodes

The University Of Sheffield.

Quantum well Photodetector





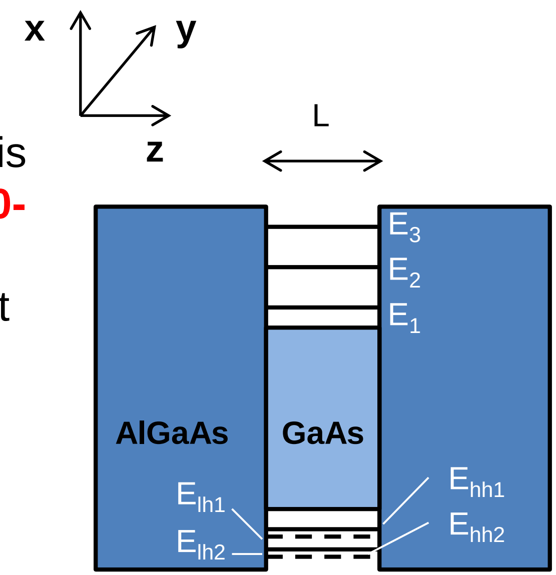


When a bulk narrow bandgap material is not available, nanostructures can be used. Quantum well and superlattice are important heterostructrures that provide further energy band engineering.

What is a quantum well?

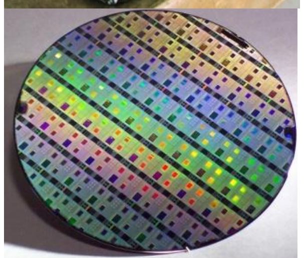
Consider a GaAs/AlGaAs system. The quantum well is formed when the width of GaAs layer is reduced to **10-20 nm**. This width is comparable to the de Broglie wavelength $\lambda_{Broglie}=h/p$ where h is the Planck constant and p is the carrier momentum.
Assuming an infinite barrier height, the quantised energy level is constant and is given by

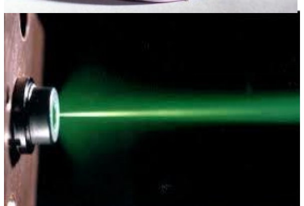
$$E_n = \frac{1}{2m^*}\left(\frac{\pi\hbar n}{L}\right)^2$$

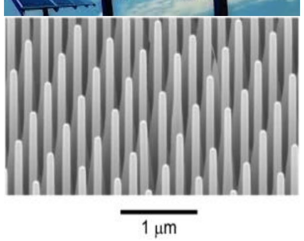


Electrons and holes are confined in the z-direction. This leads sub-bands (E_1,E_2, E_3) in a 2-D system. Since the energy levels are very similar in each sub-band, it is usually represented as individual discrete levels. We can see that the width of the well is very important in controlling the energy levels. A larger value of L produces a lower E_n. The number of allowed energy levels will depend on the barrier height.

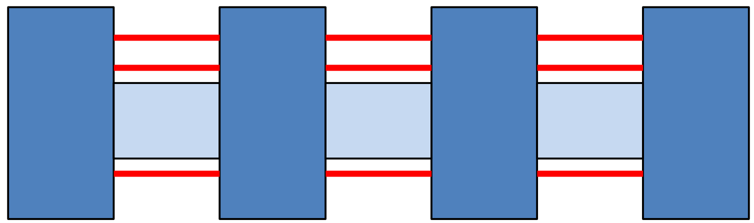
Quantum well IR Photodetector (QWIP)



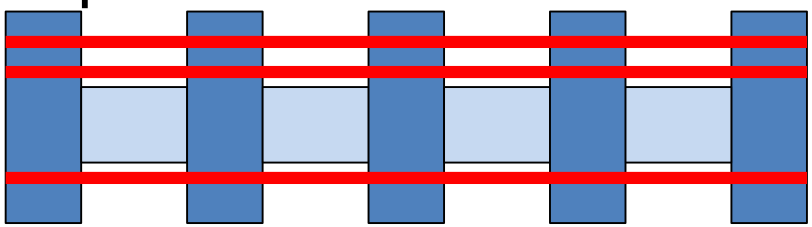




Quantum well



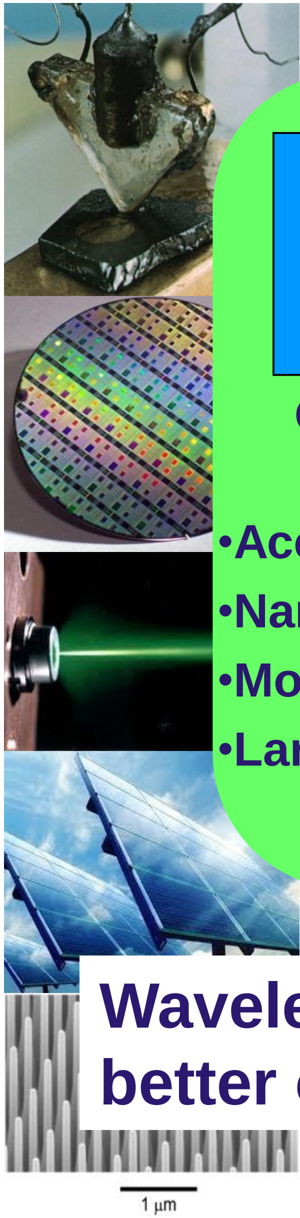
Superlattice

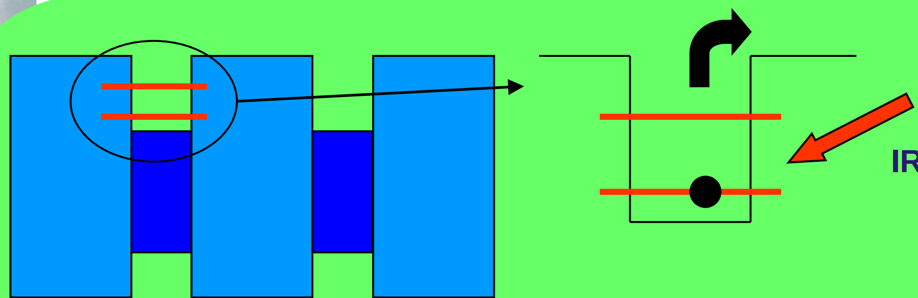


When the wells are separated by thick barriers, the electron wavefunctions are decoupled. However if the barrier thickness is reduced, the wavefunctions start to overlap in the superlattice. Due to the wavefunction overlap, the energy is now continuous in space and energy minibands are formed.

Since the energy levels are easily adjusted by changing the quantum well design, it offers the freedom to “ENGINEER” the energy separation to match the energy of photon, $E_2 – E_1 = E_{photon}$. The quantum well infrared photodetector (QWIP) is an important technology for detection of wavelengths in the LWIR. GaAs/AlGaAs and InGaAs/InAlAs are two important material systems for QWIP technology that offers high resolution thermal imaging.

Large 2D QWIPs array

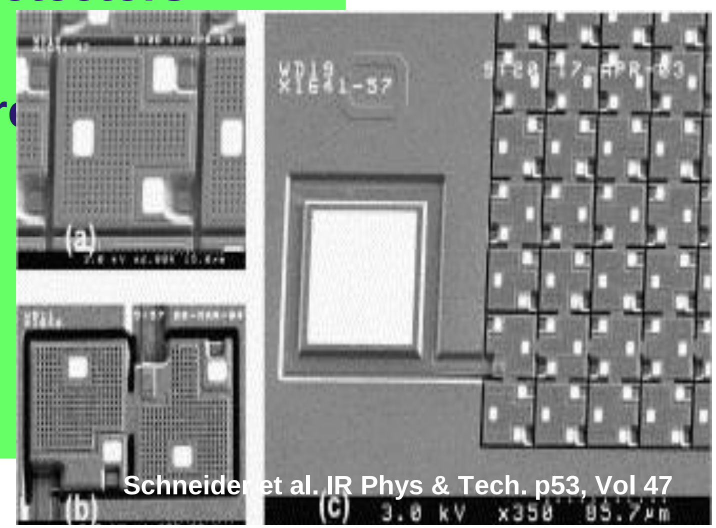




Quantum Well Infrared Photodetectors (QWIPs)

- Accurate cutoff wavelength contr
- Narrower spectral response
- More flexible fabrication
- Larger array size

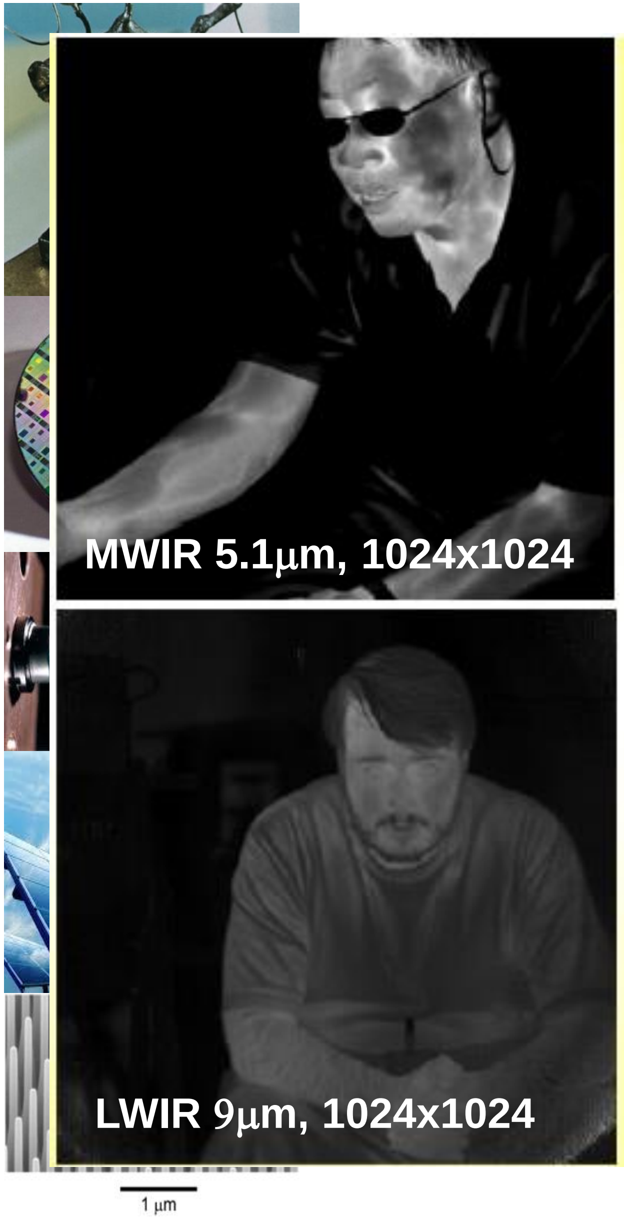
GaAs/AlGaAs
InGaAs/InP

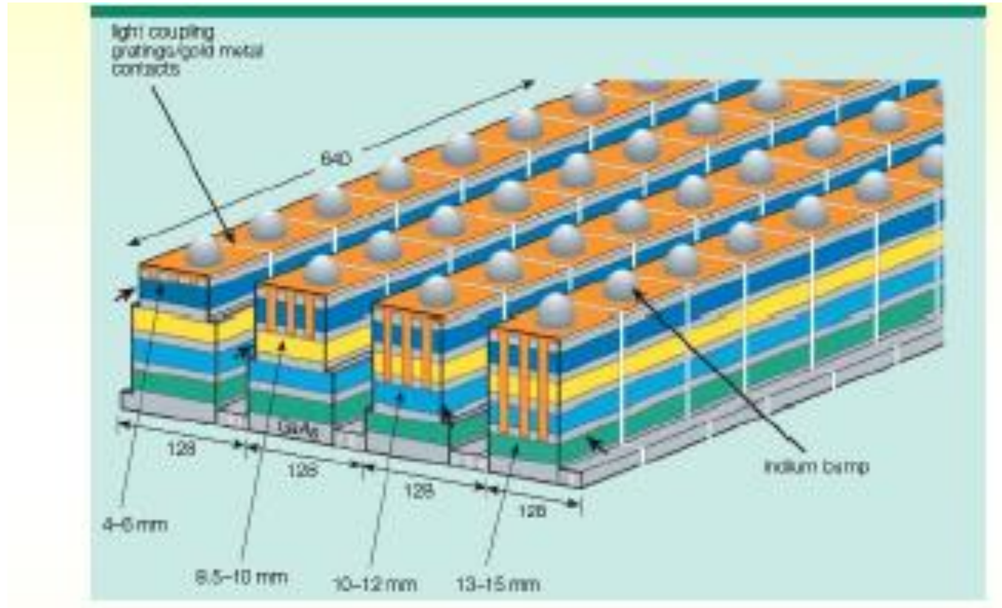


Schneider et al. IR Phys & Tech. p53, Vol 47

Wavelength tuned by adjusting layer thicknesses and hence better control of uniformity than CMT

QWIPs



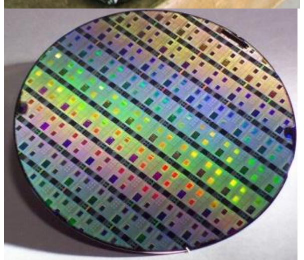
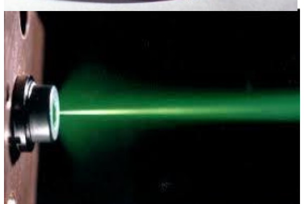


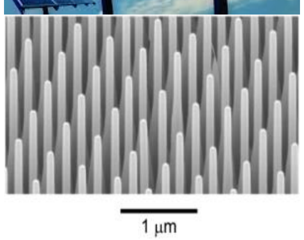
4 colour QWIPs, Gunapala et al., IEEE TED, 50, 2353, 2004

Detection wavelength can be easily adjusted by the well width and hence multi-band detection can be realised for gas sensing, imaging and material characterisation applications.

[after S.D. Gunapala *at el.*, *Semicond. Sci. Technol.* **20**, 473–480 (2005)]

Photodetector comparison



Photodetector	Gain	Response Time (s)
Photoconductor	$1\text{-}10^{6}$	$10^{-8}\text{-}10^{-3}$
Photodiodes (pn)	1	10^{-11}
Photodiodes (pin)	1	$10^{-10}\text{-}10^{-8}$
Phototransistors	$10^{2}\text{-}10^{3}$	10^{-6}
Avalanche Photodiodes	$10^{2}\text{-}10^{4}$	10^{-10}

Photodetector selection

Wavelength	Response time	Signal intensity	Photodetector	Material
Visible	µs	Low		
Visible	≤µs	Very Low		
SWIR	<ns	Very low		
MWIR	ms-µs	Moderate		
MWIR	≤µs	Low/moderate		
LWIR	ms-µs	Low/moderate		
VLWIR	ms-µs	Low/moderate		