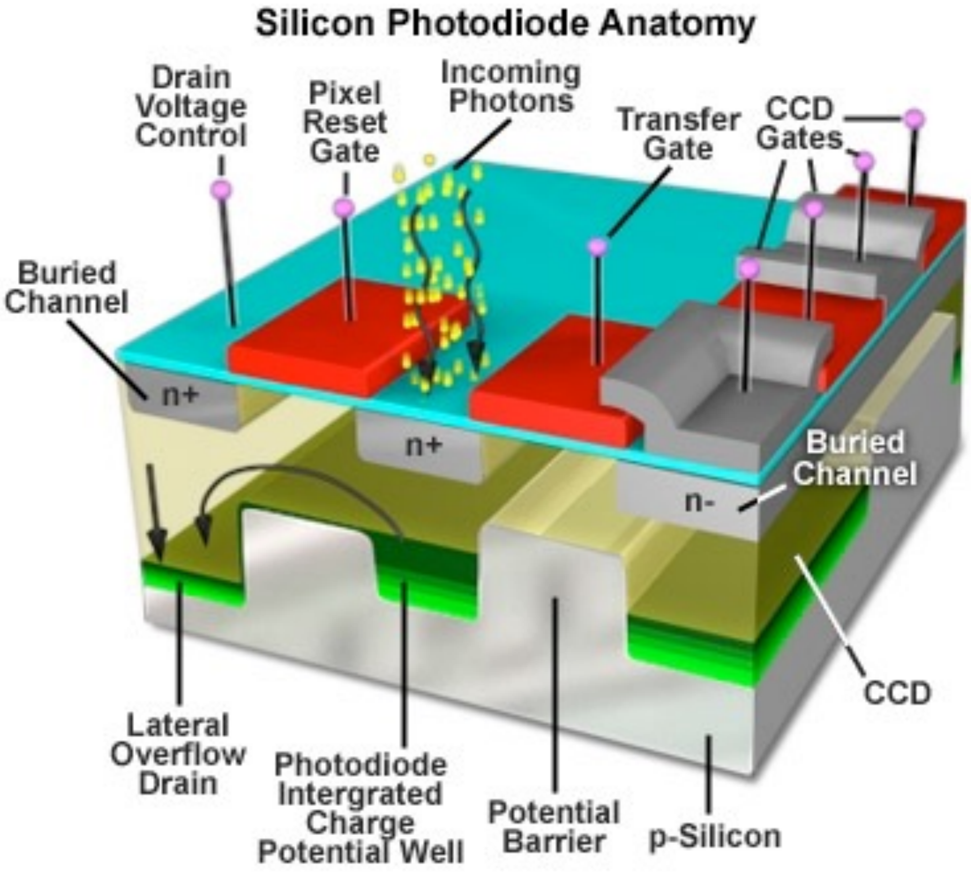
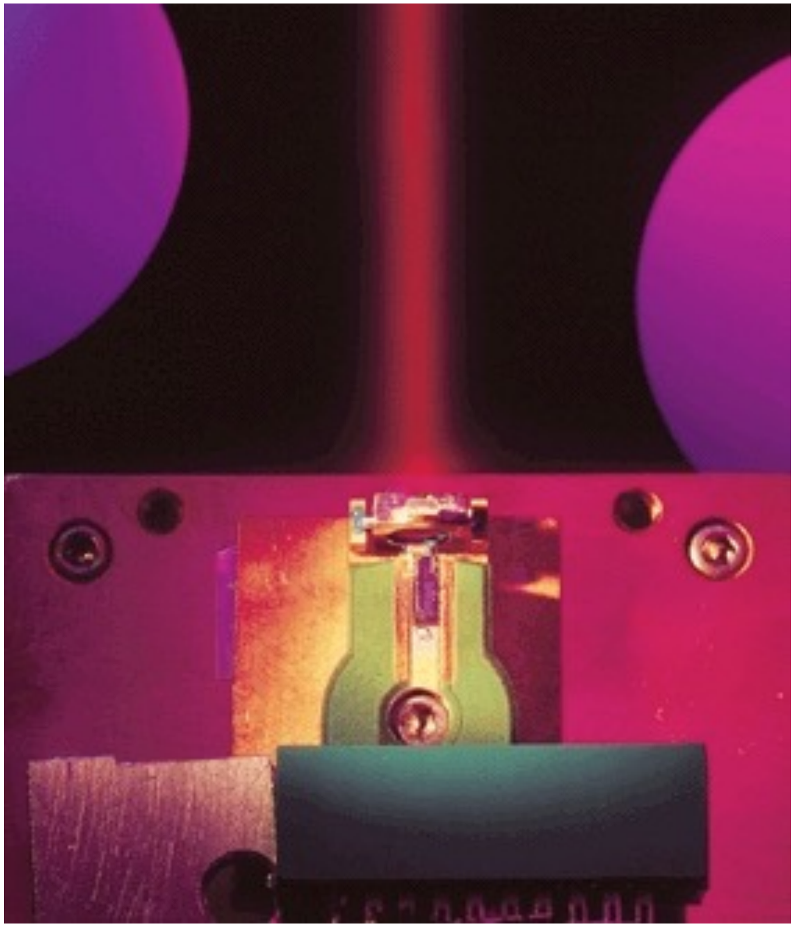
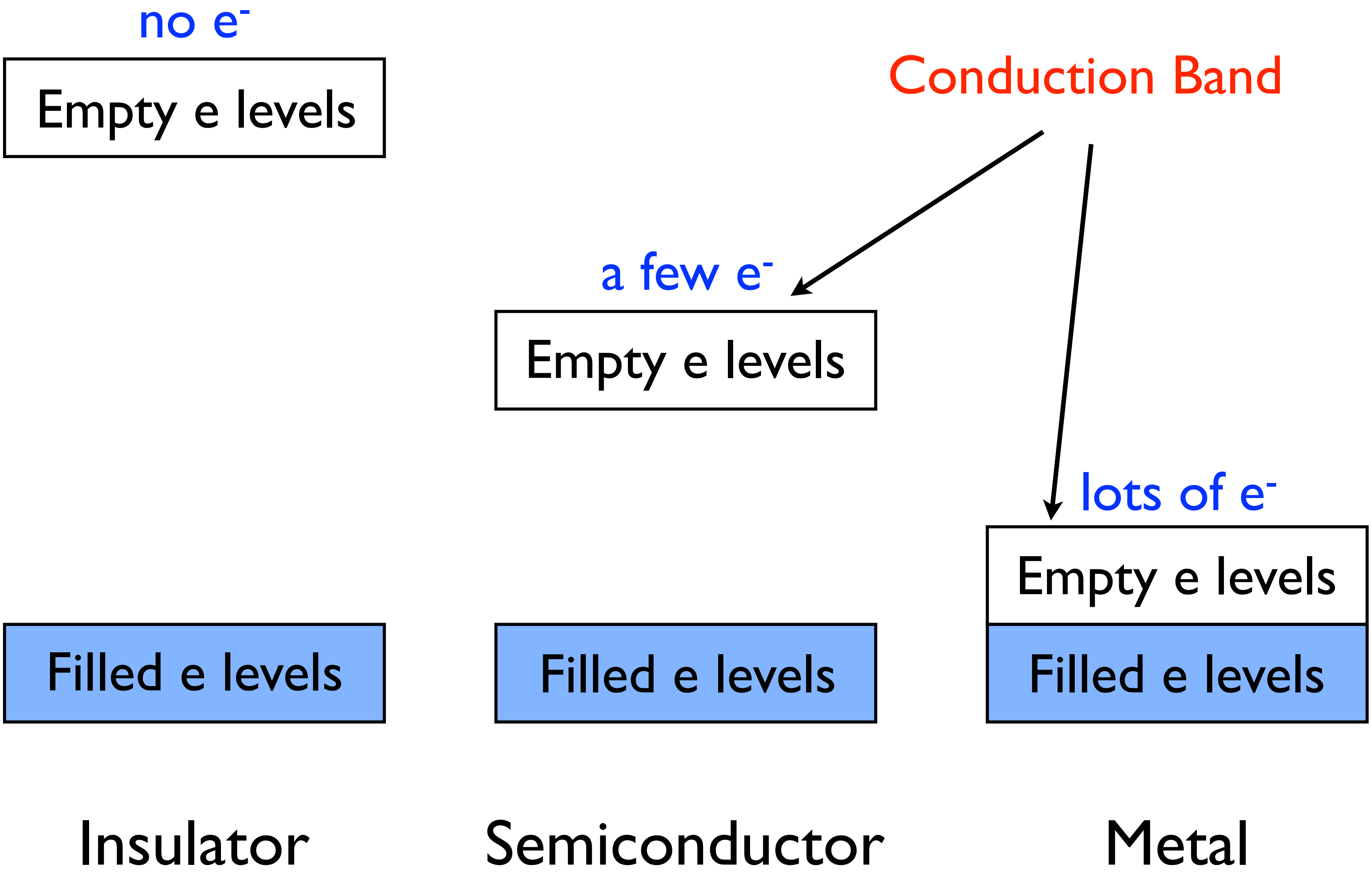
Photodiodes and other semiconductor devices





Chem 243 Winter 2017

What is a semiconductor?



no e^-

Empty e levels

Conduction Band

a few e^-

Empty e levels

lots of e^-

Empty e levels

Filled e levels

Filled e levels

Filled e levels

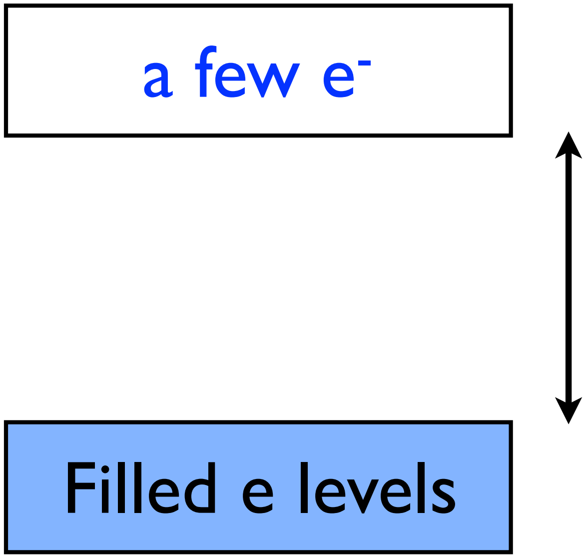
Insulator

Semiconductor

Metal

Electrons in the conduction band of semiconductors like Si can move about freely.

Energy Bandgap in Semiconductors



Conduction band

a few e^-

Valence band

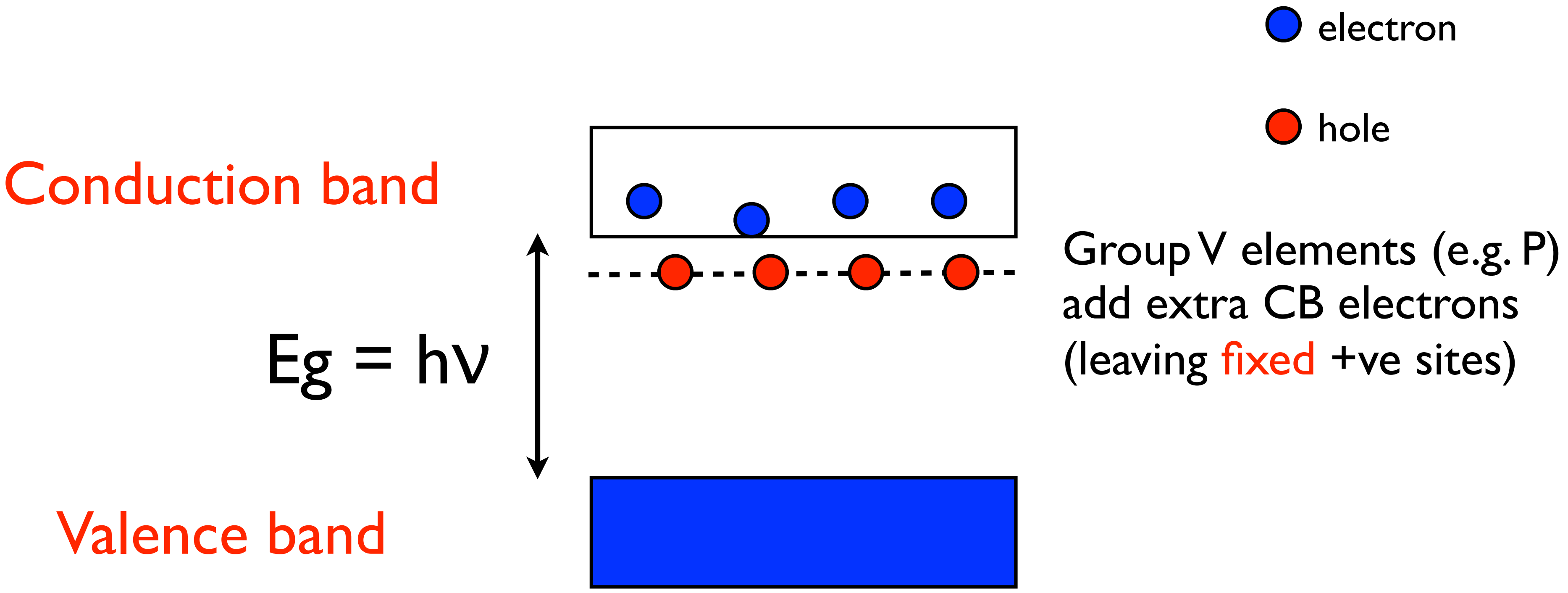
Filled e levels

$$Eg = h\nu$$

$$\lambda_{max} = 1240\ /Eg$$

We can detect photons by measuring the conduction electrons created when we shine light on a semiconductor with energy greater than the bandgap energy Eg.

n-doped semiconductor Si



🔵 electron

🔴 hole

Conduction band

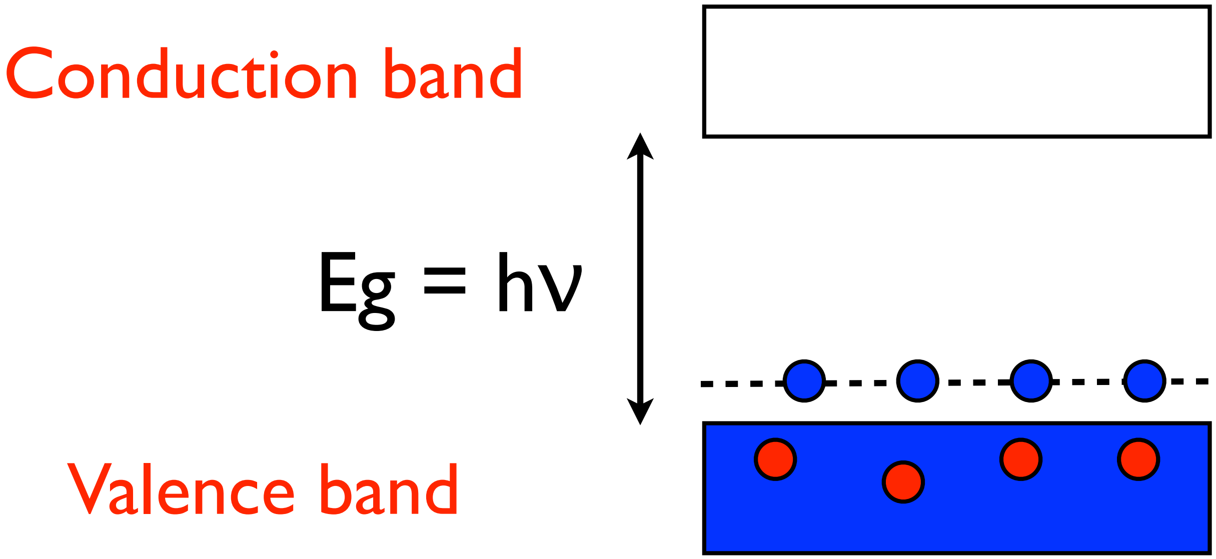
$E_g = h\nu$

Valence band

Group V elements (e.g. P)
add extra CB electrons
(leaving fixed +ve sites)

Increase in conductivity is observed due to the increase in the number of valence electrons. Primary current carrier: electrons

p-doped semiconductor Si



● electron

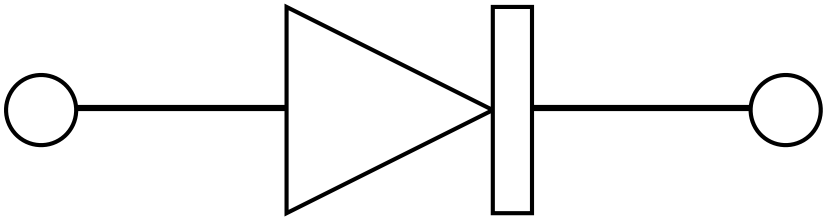
● hole

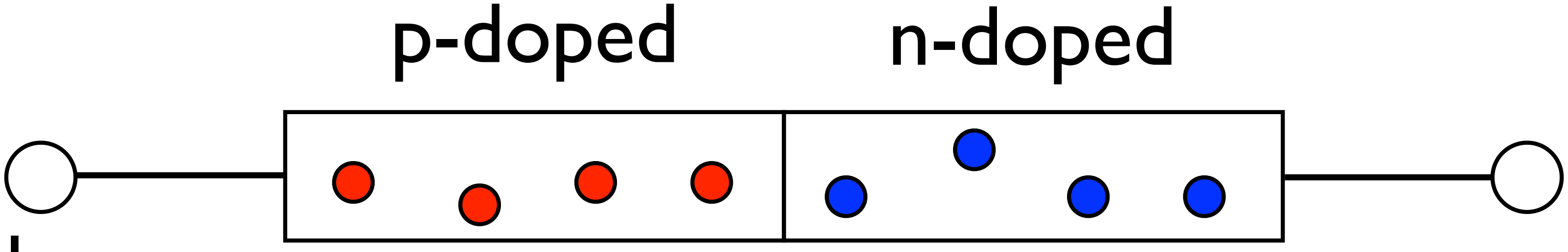
Group III elements (e.g. B) remove VB electrons and create mobile "holes" (leaving fixed -ve sites)

Increase in conductivity is observed due to the increase in the number of mobile holes.

Primary current carrier: holes

p-n junctions: diodes



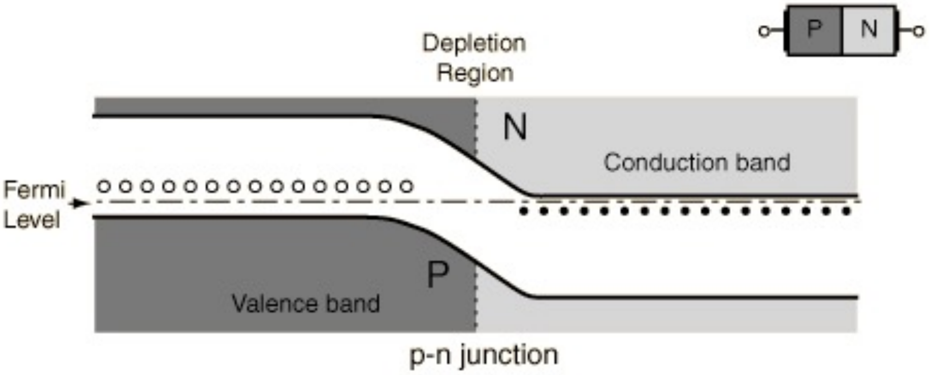


p-doped

n-doped

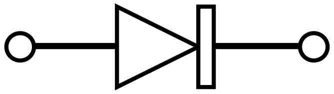
anode

cathode

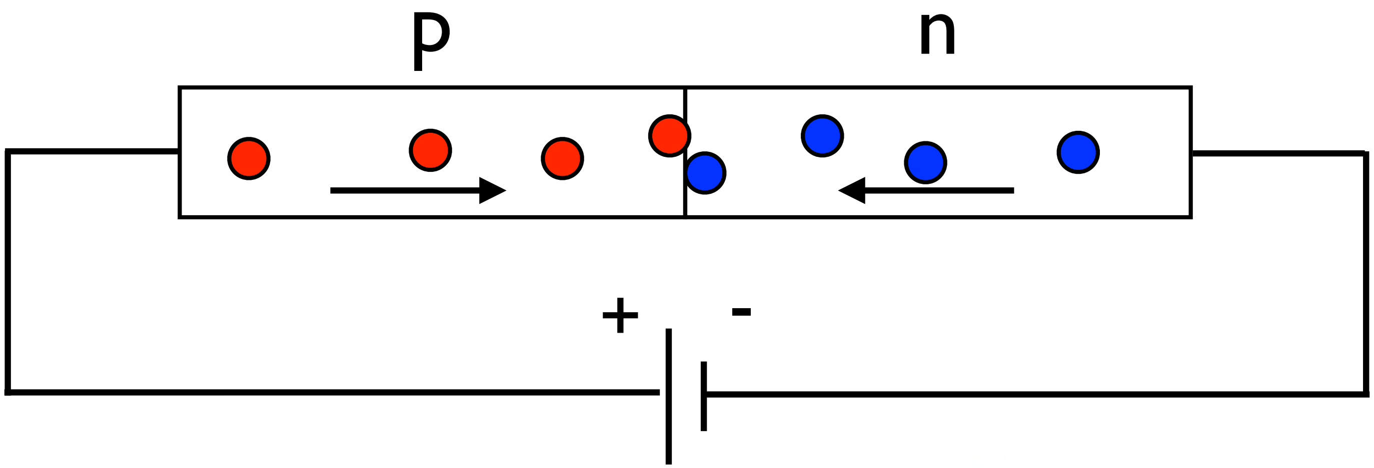


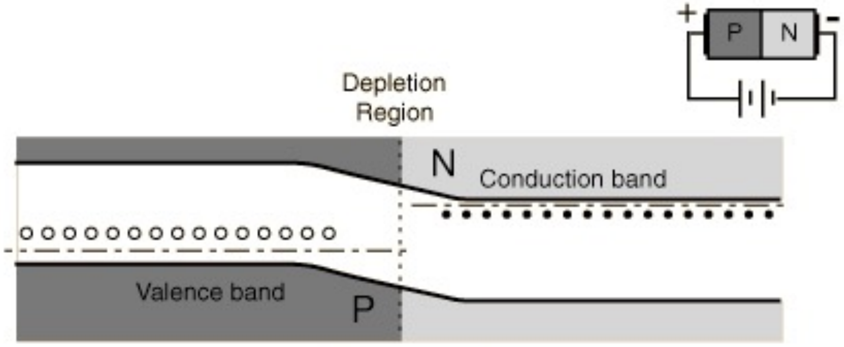
Energy levels at Equilibrium

p-n junctions: diodes



Forward bias: current flows right (electrons left)

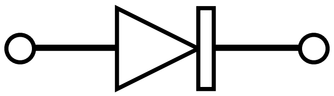




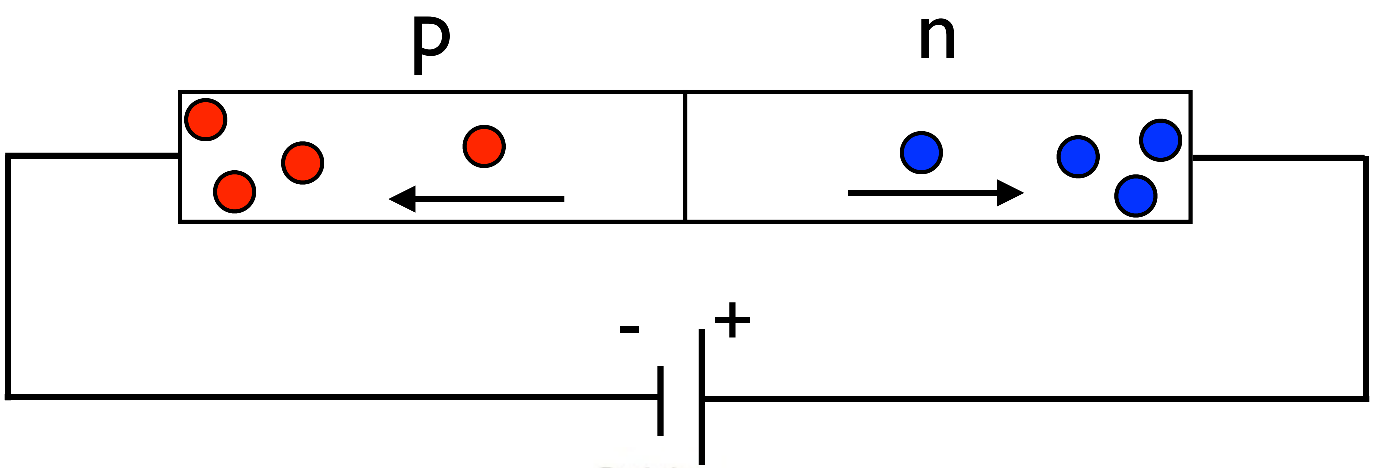
p-n junction

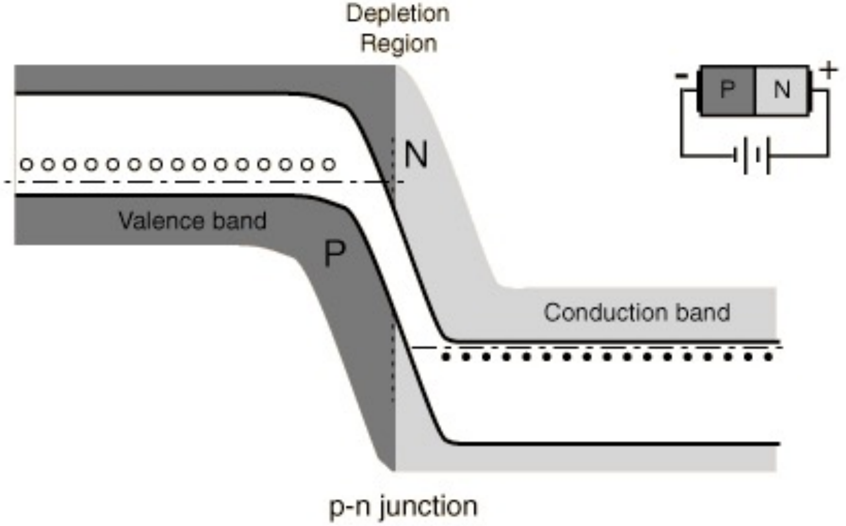
In forward bias, the p side is made more positive, so that it is "downhill" for electron motion across the junction. An electron can move across the junction and fill a vacancy or "hole" near the junction. It can then move from vacancy to vacancy leftward toward the positive terminal, which could be described as the hole moving right. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.

p-n junctions: diodes



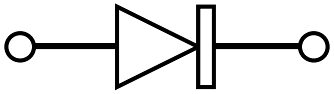
Reverse bias: no current flows (depletion layer created)

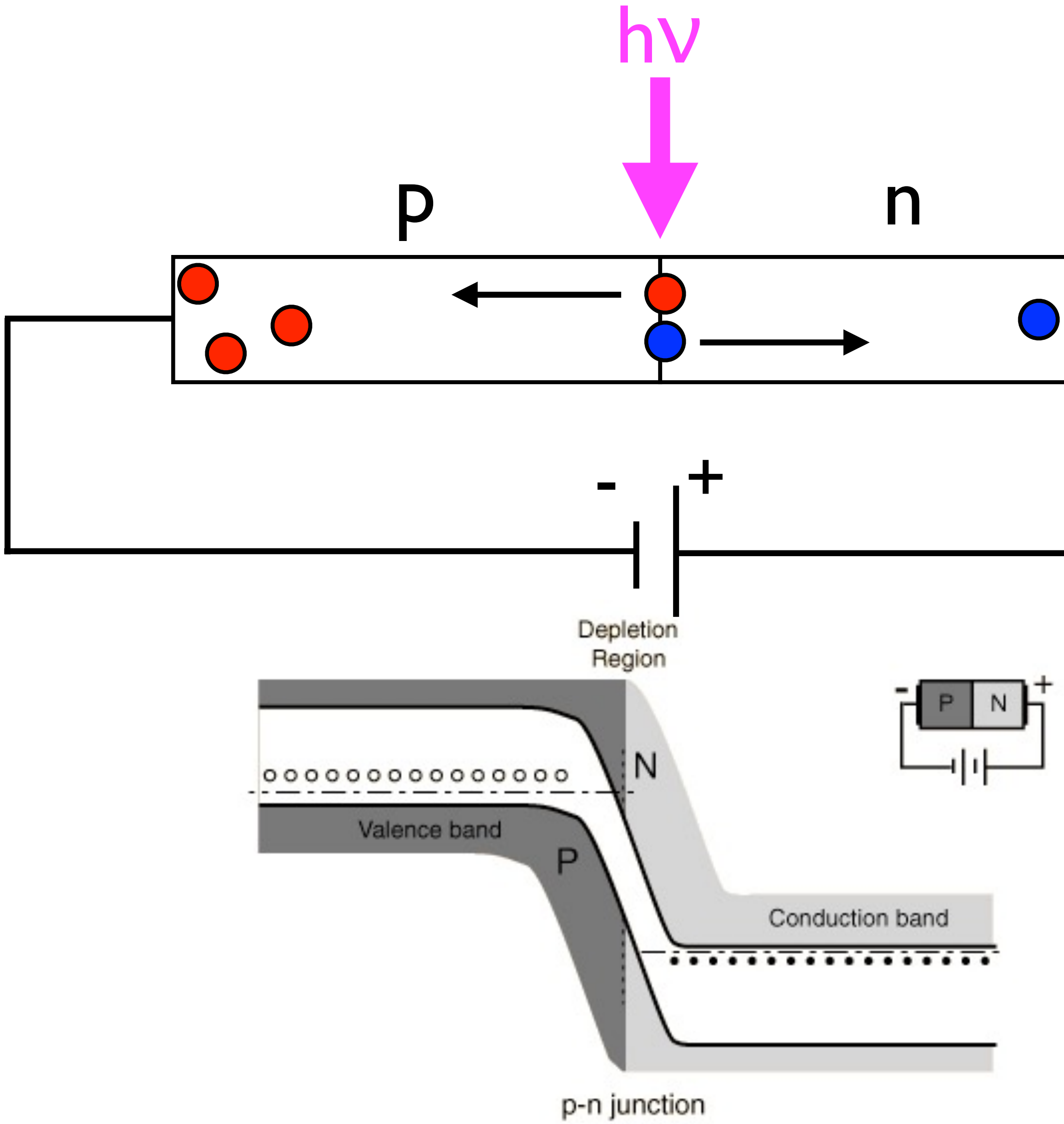




In reverse-bias, the p side is made more negative, making it "uphill" for electrons moving across the junction. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.

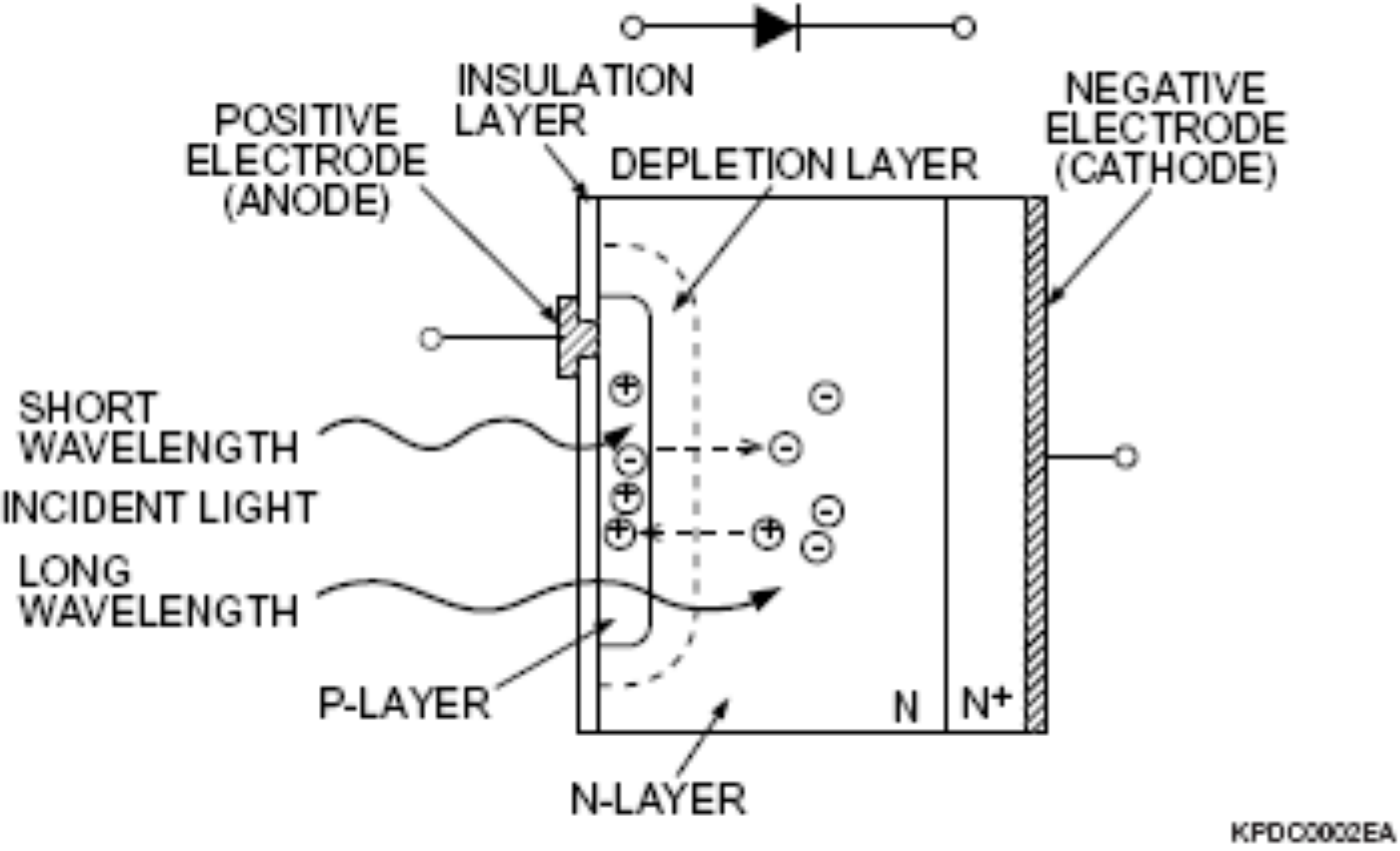
p-n junctions: photodiodes in reverse bias





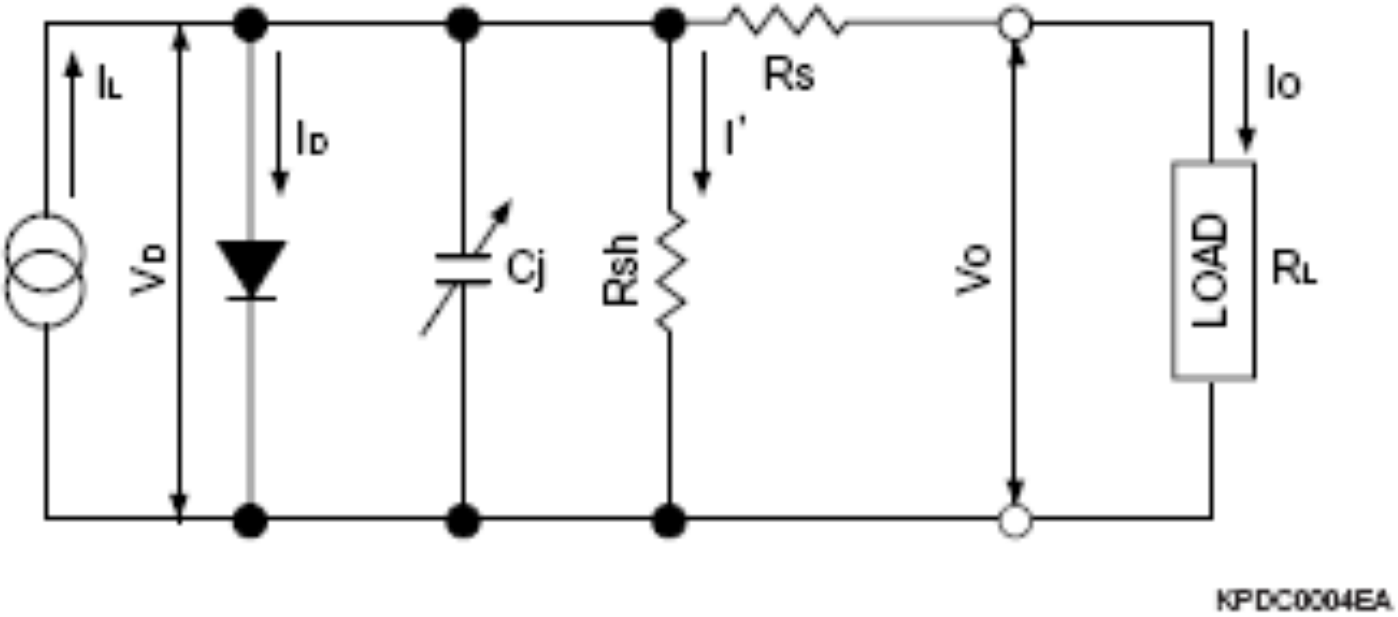
Suprabandgap photon creates an electron hole pair in the depletion region: reverse photocurrent observed

Hamamatsu photodiodes



http://sales.hamamatsu.com/assets/html/ssd/si-photodiode/index.htm

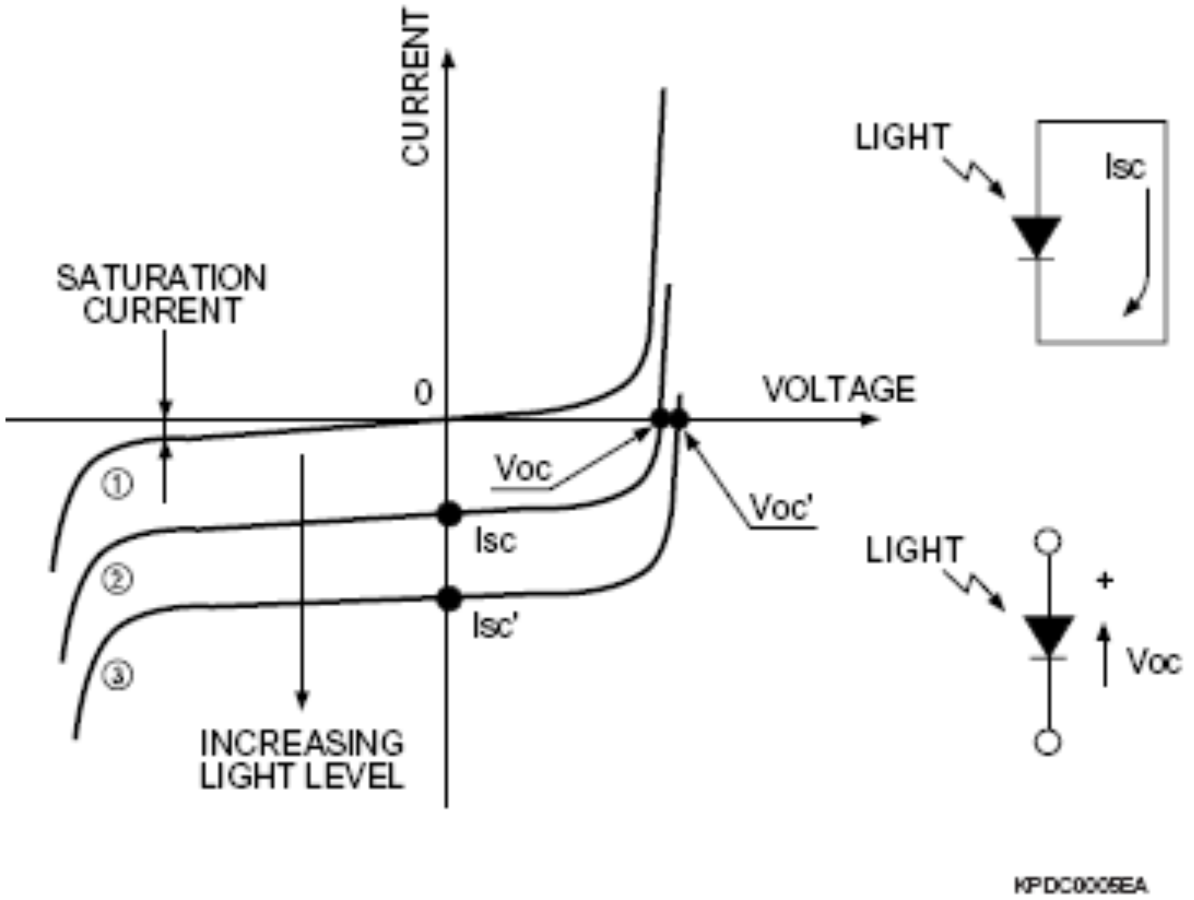
Hamamatsu photodiodes



$$I_o = I_L - I_D - I' = I_L - I_s\left(exp\,\frac{eV_D}{kT} - 1\right) - I' \;\ldots\ldots\ldots\ldots\; (2\text{-}1)$$

IL : Current generated by the incident light (proportional to the amount of light)
ID : Diode current
Cj : Junction capacitance
Rsh : Shunt resistance
Rs : Series resistance
I' : Shunt resistance current
VD : Voltage across the diode
Io : Output current
Vo : Output voltage
Is: Photodiode reverse saturation current

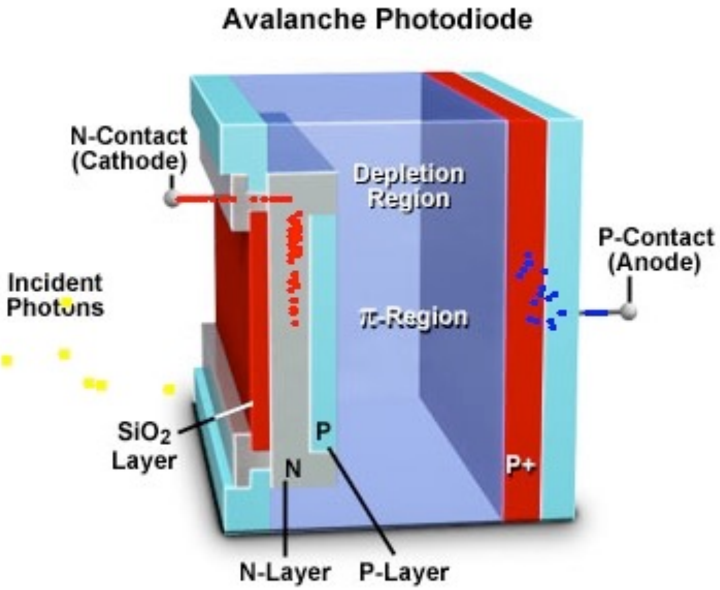
Hamamatsu photodiodes



$$\mathrm{Voc} = \frac{kT}{e}\ ln\left(\frac{I_L - I'}{I_s} + 1\right) \text{ .... } (2\text{-}2)$$

$$\mathrm{Isc} = I_L - I_s\left(exp\ \frac{e \cdot (\mathrm{Isc} \cdot \mathrm{Rs})}{kT} - 1\right) - \frac{\mathrm{Isc} \cdot \mathrm{Rs}}{\mathrm{Rsh}} \text{ ...... } (2\text{-}3)$$

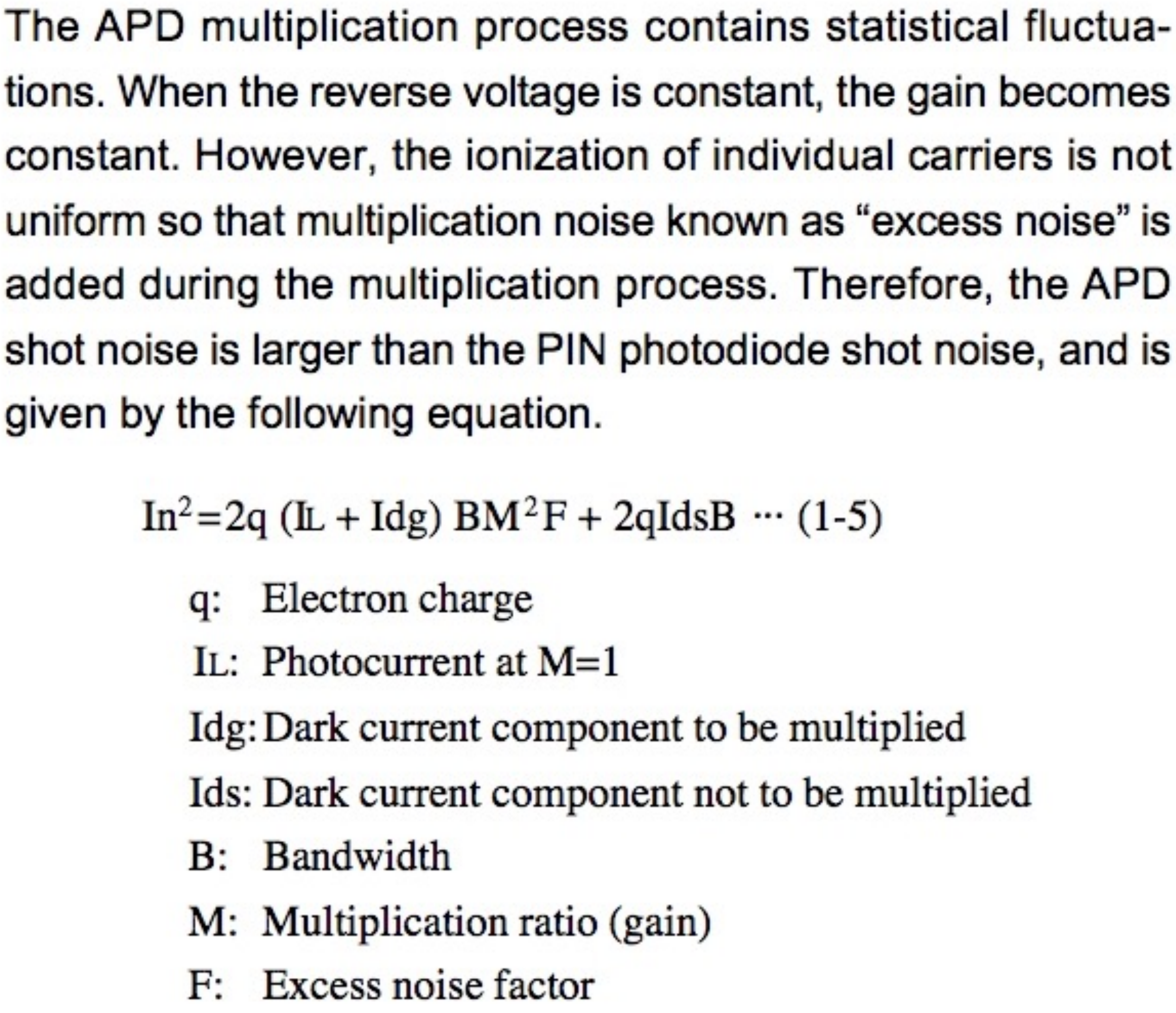
Avalanche Photodiodes: Gain = 10-1000



An avalanche photodiode is a silicon-based semiconductor containing a pn junction consisting of a positively doped p region and a negatively doped n region sandwiching an area of neutral charge termed the depletion region. These diodes provide gain by the generation of electron-hole pairs from an energetic electron that creates an "avalanche" of electrons in the substrate.

http://micro.magnet.fsu.edu/primer/java/digitalimaging/avalanche/index.html

Noise in Avalanche Photodiodes (Hamamatsu pdf)



The APD multiplication process contains statistical fluctuations. When the reverse voltage is constant, the gain becomes constant. However, the ionization of individual carriers is not uniform so that multiplication noise known as "excess noise" is added during the multiplication process. Therefore, the APD shot noise is larger than the PIN photodiode shot noise, and is given by the following equation.

$$In^2 = 2q\,(I_L + Idg)\,BM^2F + 2qIdsB \quad \cdots \; (1\text{-}5)$$

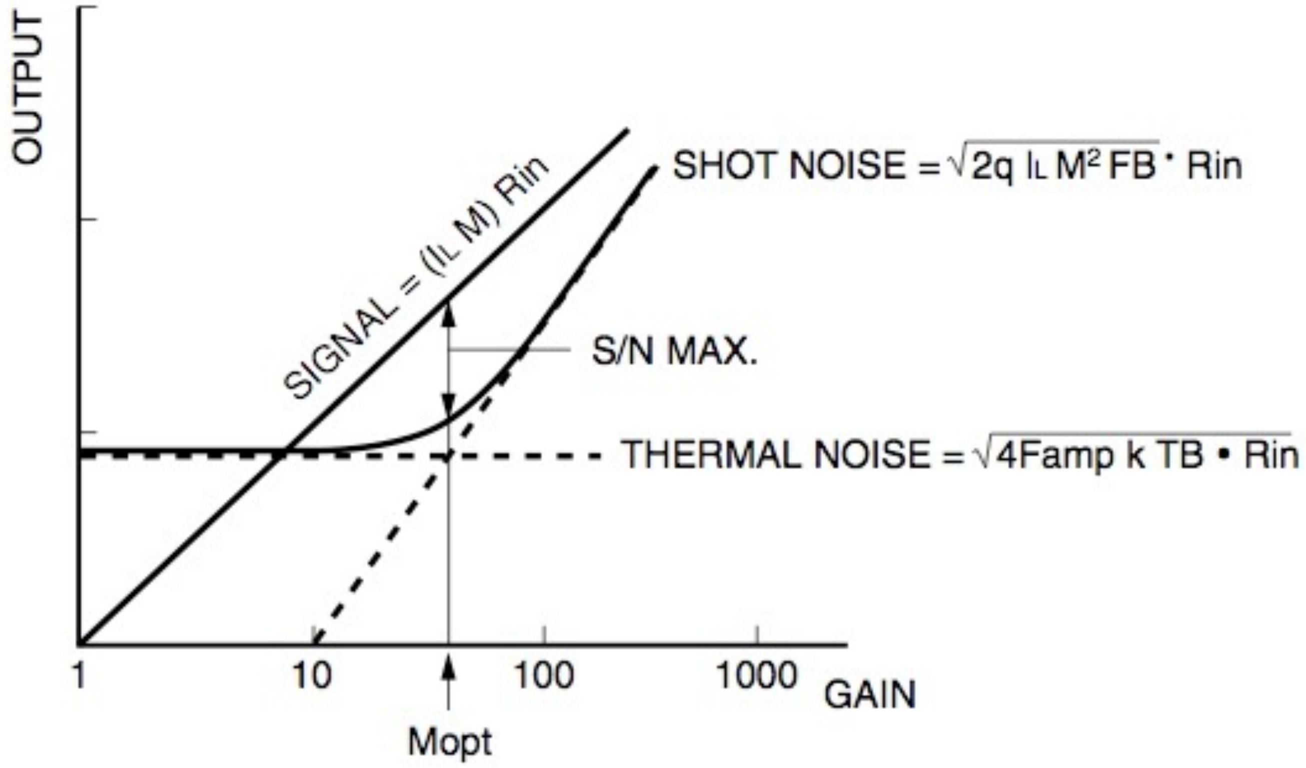
q: Electron charge
I_L: Photocurrent at $M=1$
Idg: Dark current component to be multiplied
Ids: Dark current component not to be multiplied
B: Bandwidth
M: Multiplication ratio (gain)
F: Excess noise factor

Noise in Avalanche Photodiodes (Hamamatsu pdf)

The excess noise factor F can be expressed by the multiplication ratio M and the ratio of the electron/hole ionization rate k:

$$F = Mk + (2 - \frac{1}{M})(1 - k) \cdots (1\text{-}6)$$

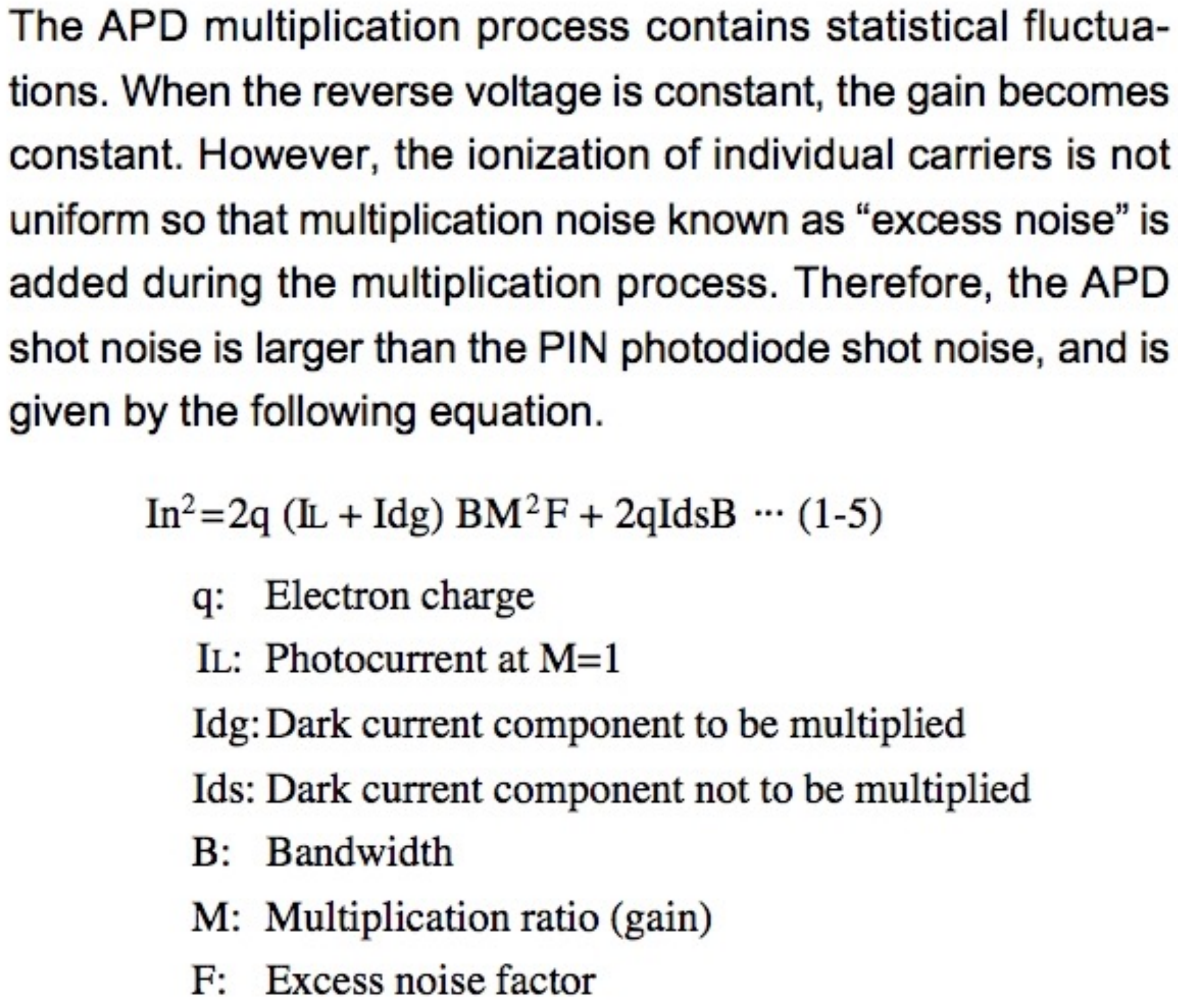
Noise in Avalanche Photodiodes (Hamamatsu pdf)



Famp: Noise figure of next-stage amplifier
Rin : Input resistance of next-stage amplifier
k : Boltzmann's constant
T : Absolute temperature

KAPDB0033EA

Noise in Avalanche Photodiodes (Hamamatsu pdf)

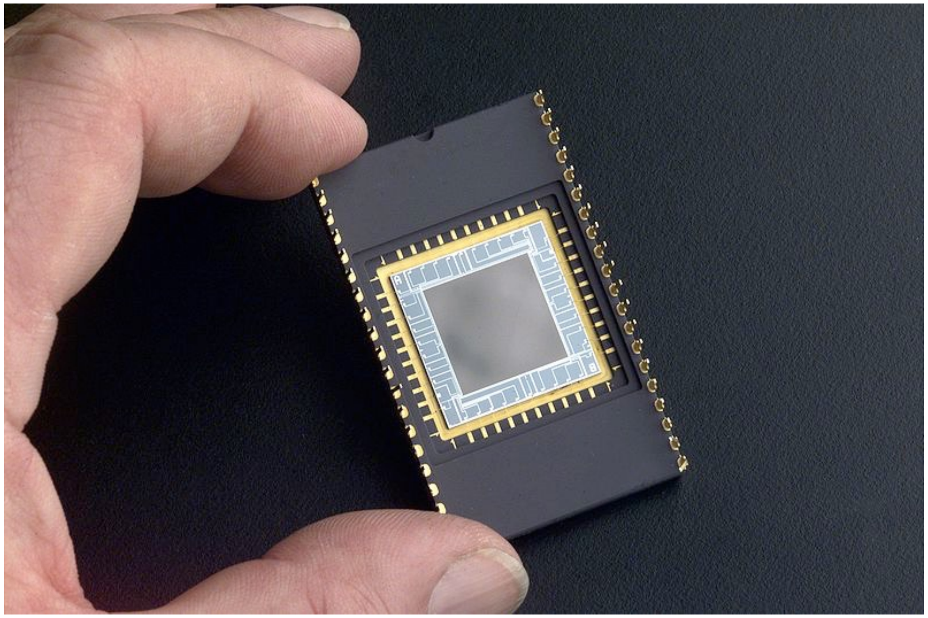


The APD multiplication process contains statistical fluctuations. When the reverse voltage is constant, the gain becomes constant. However, the ionization of individual carriers is not uniform so that multiplication noise known as “excess noise” is added during the multiplication process. Therefore, the APD shot noise is larger than the PIN photodiode shot noise, and is given by the following equation.

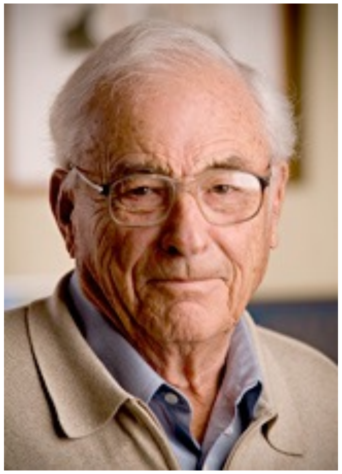
$$In^2=2q\,(I_L+Idg)\,BM^2F+2qIdsB \cdots (1\text{-}5)$$

q: Electron charge
I_L: Photocurrent at M=1
Idg: Dark current component to be multiplied
Ids: Dark current component not to be multiplied
B: Bandwidth
M: Multiplication ratio (gain)
F: Excess noise factor

2009 Nobel Prize in Physics



the CCD sensor

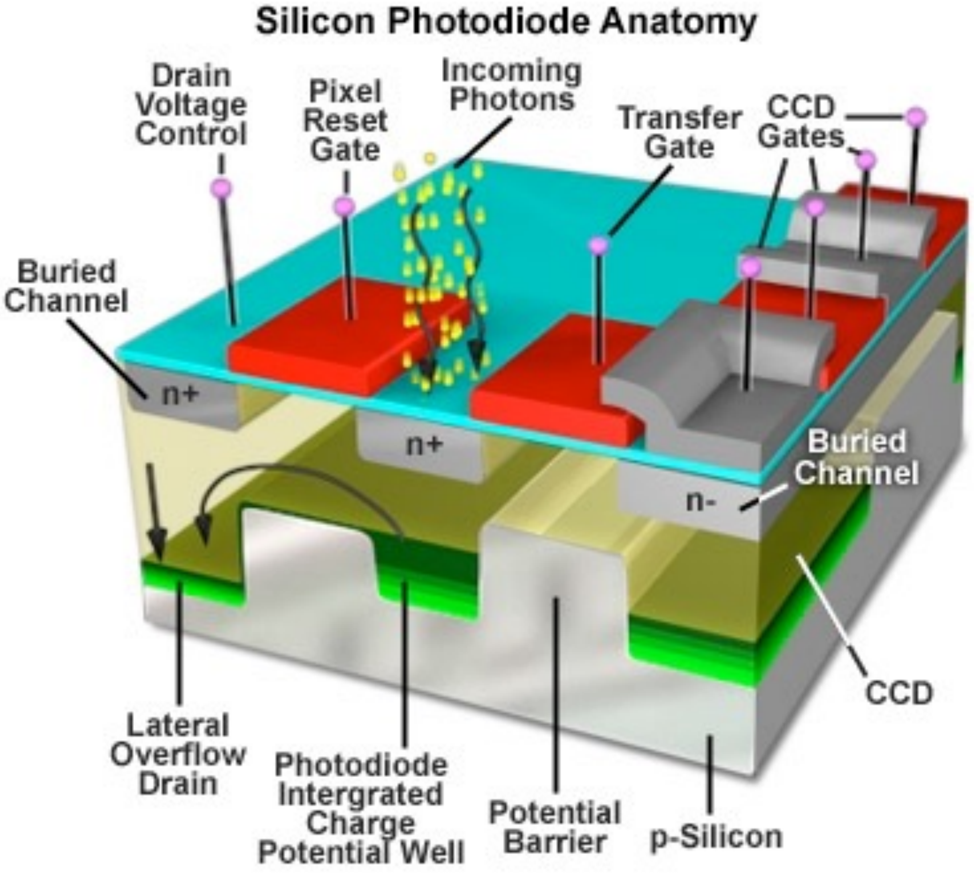


Willard S. Boyle

George E. Smith

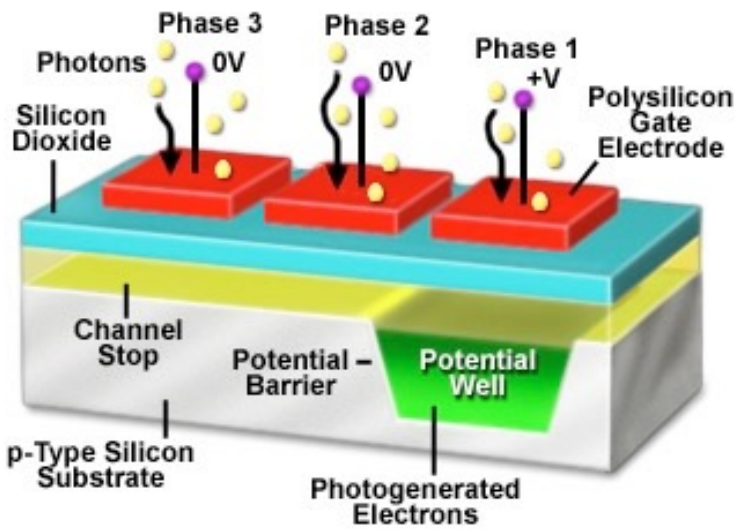
One half of the 2009 Nobel Prize in Physics went to Willard S. Boyle and George E. Smith "for the invention of an imaging semiconductor circuit – the CCD sensor" at Bell Laboratories in Murray Hill, NJ.

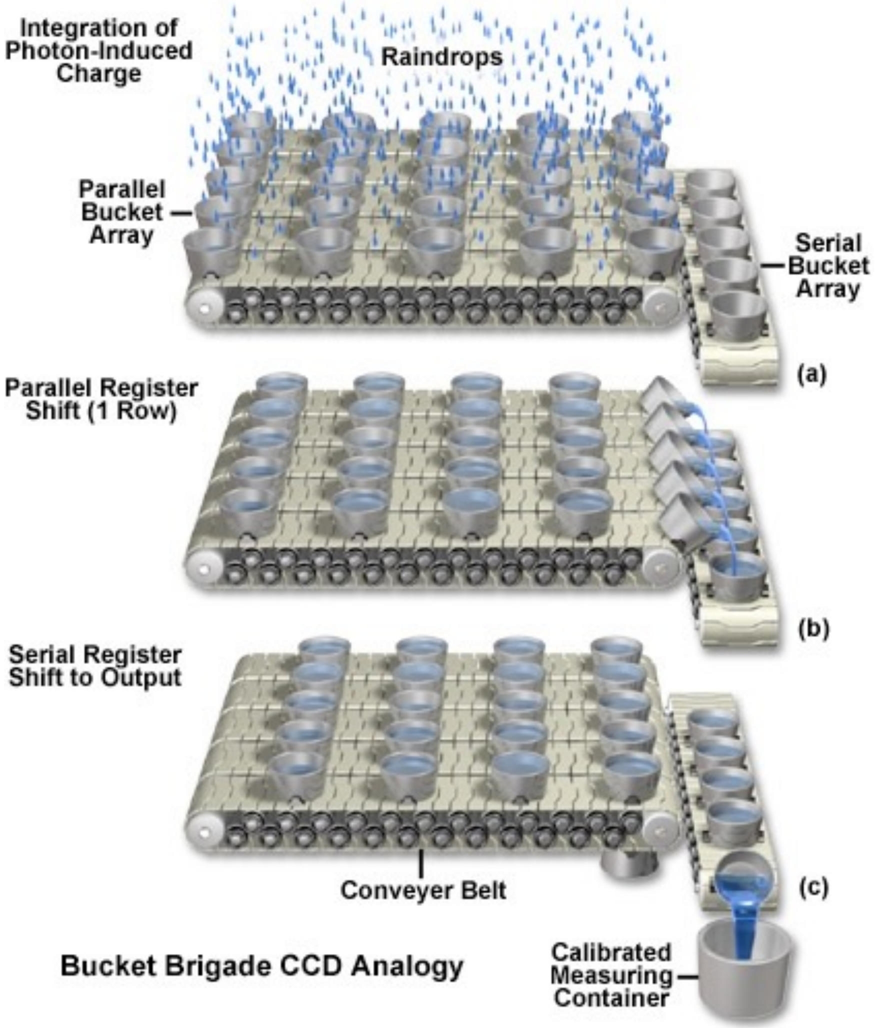
A CCD element collects the photoelectrons created by incoming light in a small potential well.



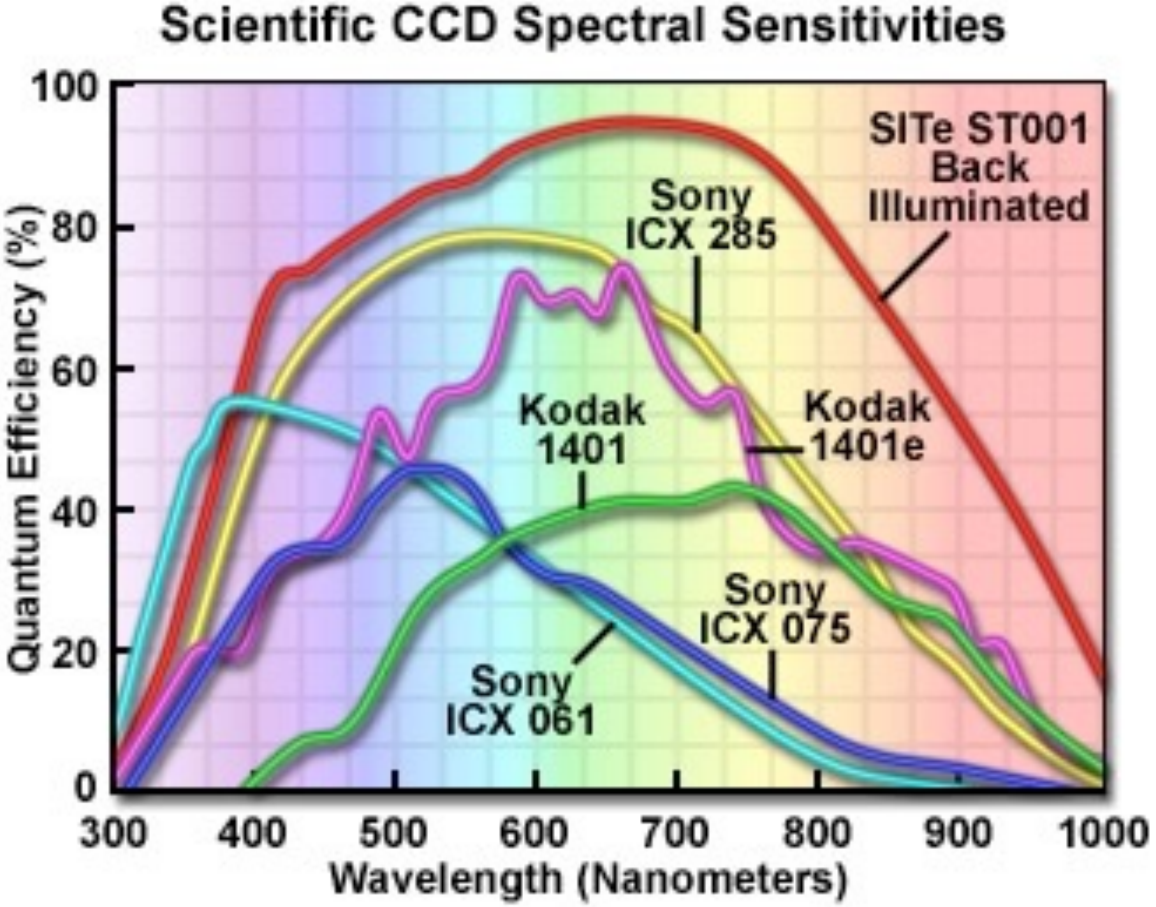
http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/concepts.html

The photoelectron pixels get pushed off the chip and are read one at a time.

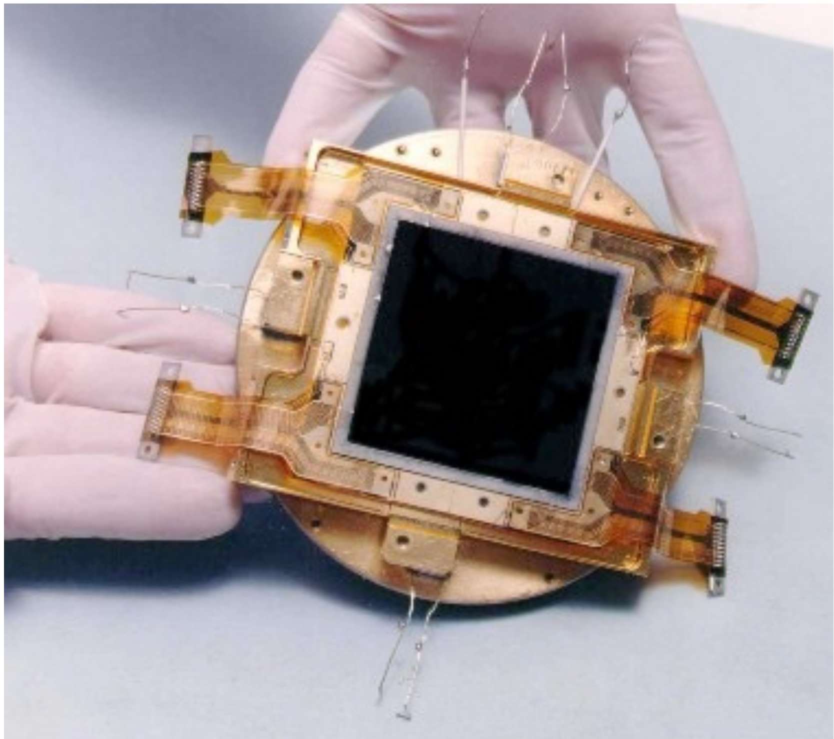

CCD Sense Element (Pixel) Structure


Bucket Brigade CCD Analogy

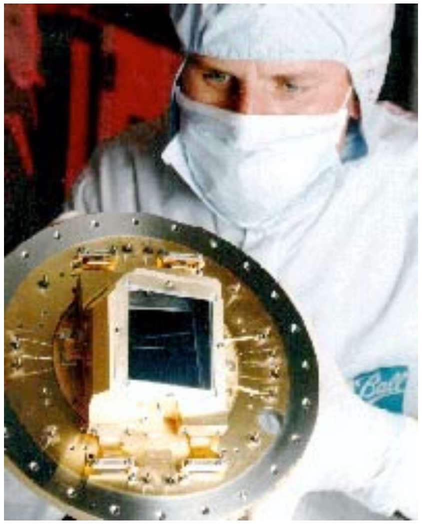
Si CCDs only measure photons with energies larger than Eg (1.1 eV or 1130 nm).



Wide field CCD Camera on the Hubble Telescope

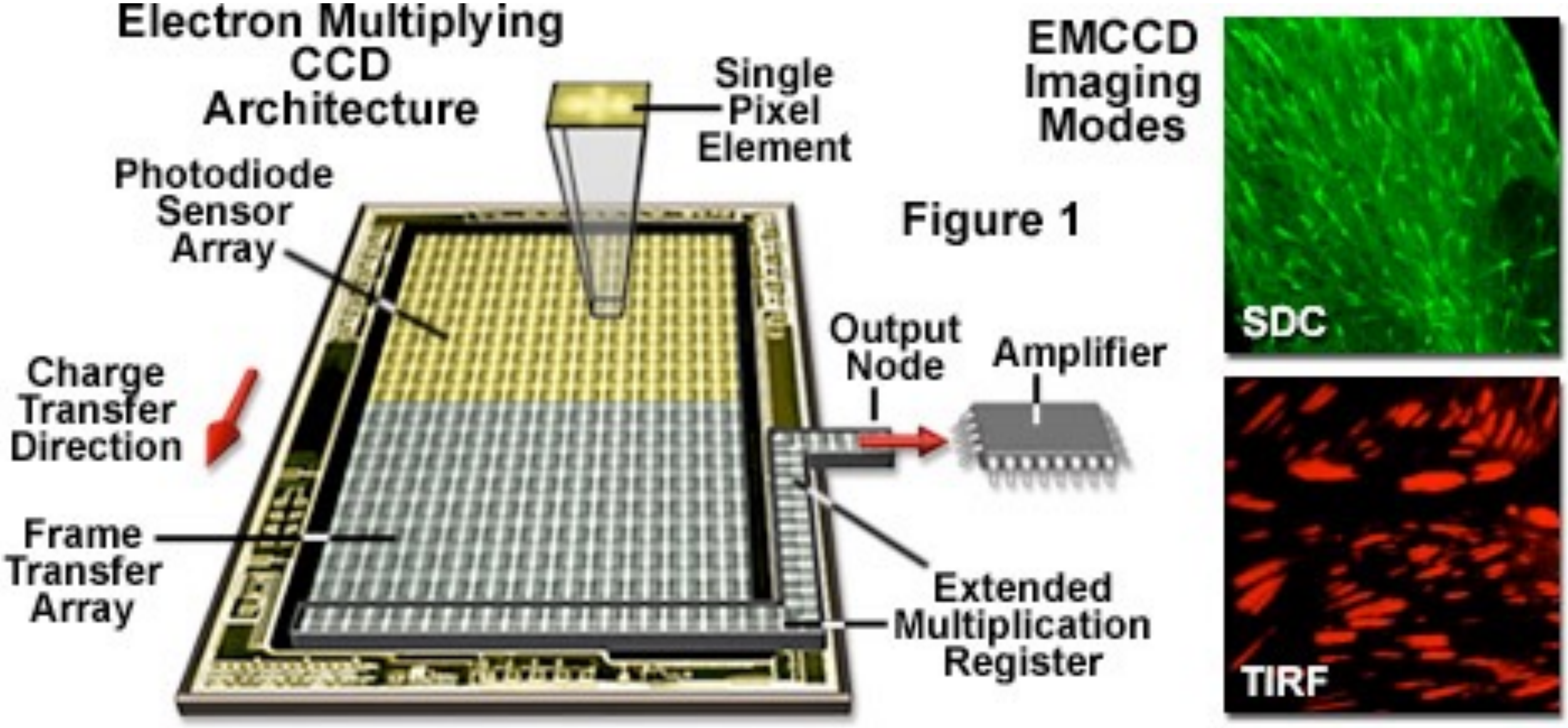


8 Megapixel Camera
(4K x 2K 15 micron pixels)



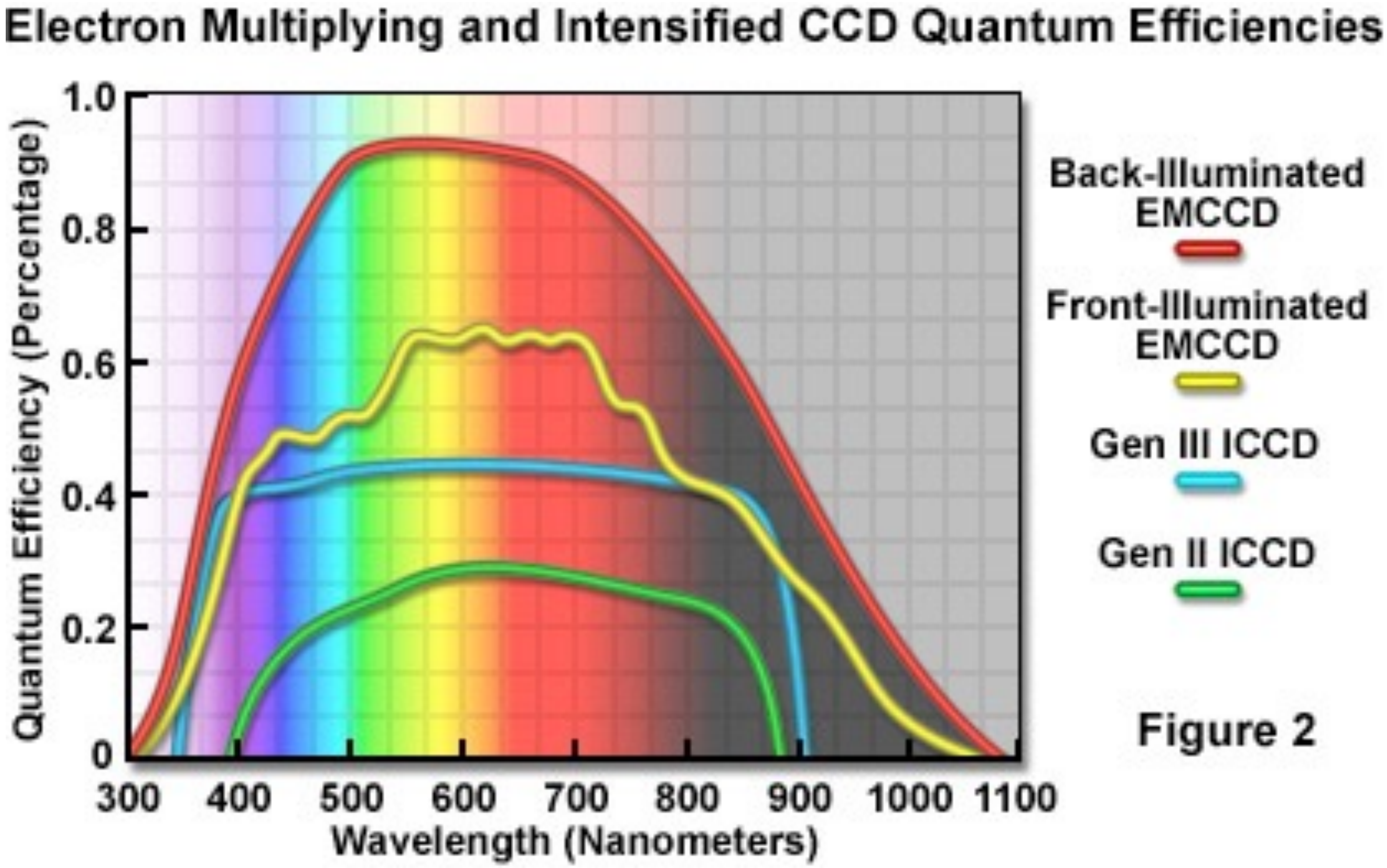
Another
8 MP camera

EMCCDs - electron multiplication



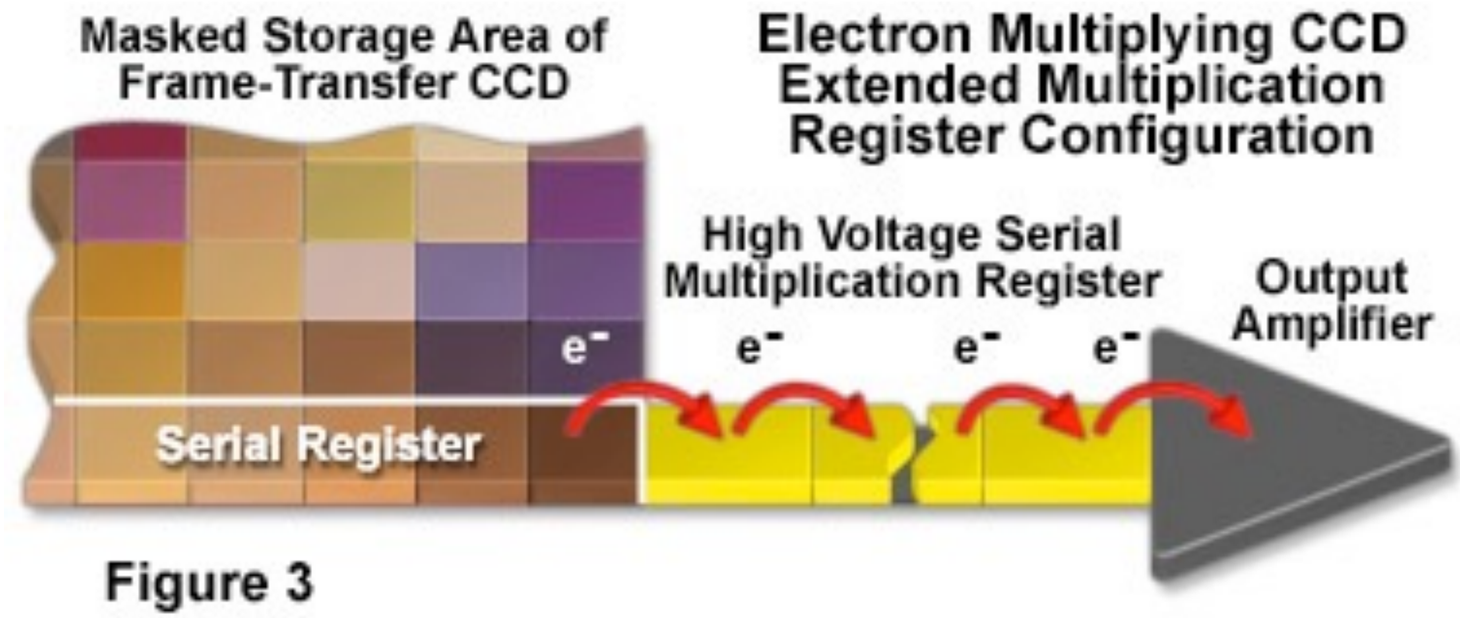
http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/emccds.html

EMCCDs - electron multiplication



http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/emccds.html

EMCCDs - electron multiplication



http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/emccds.html

EMCCDs - electron multiplication

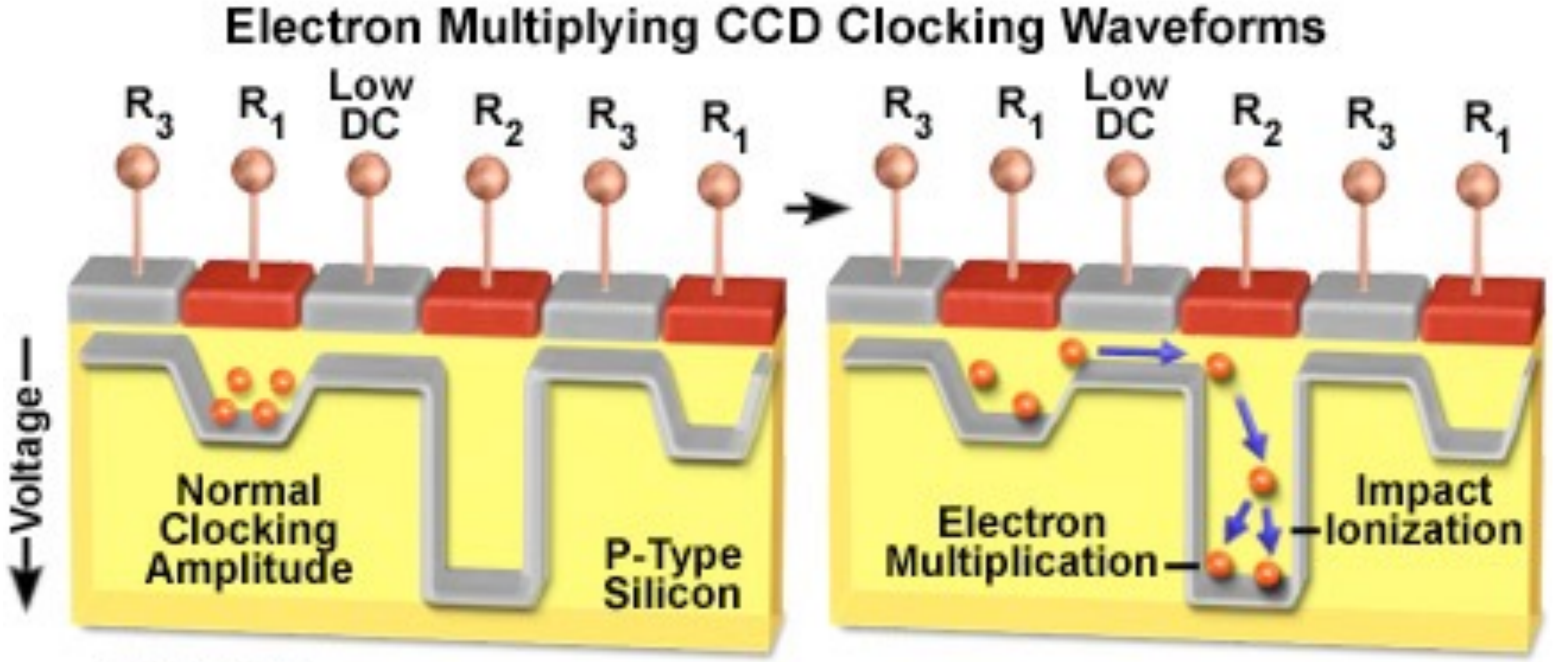
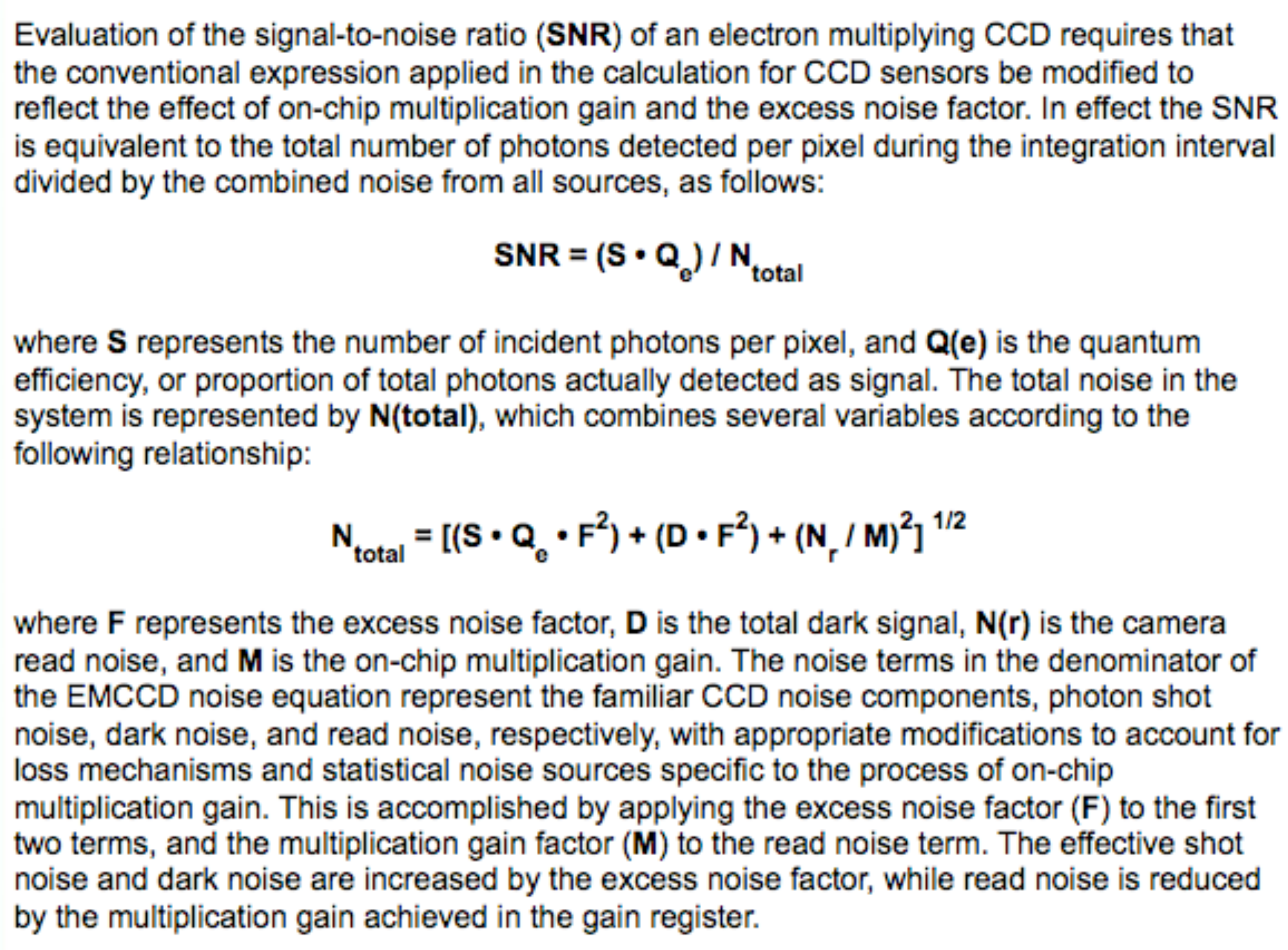


Figure 4

http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/emccds.html

EMCCDs - SNR calculations



Evaluation of the signal-to-noise ratio (**SNR**) of an electron multiplying CCD requires that the conventional expression applied in the calculation for CCD sensors be modified to reflect the effect of on-chip multiplication gain and the excess noise factor. In effect the SNR is equivalent to the total number of photons detected per pixel during the integration interval divided by the combined noise from all sources, as follows:

$$\mathbf{SNR = (S \cdot Q_e) / N_{total}}$$

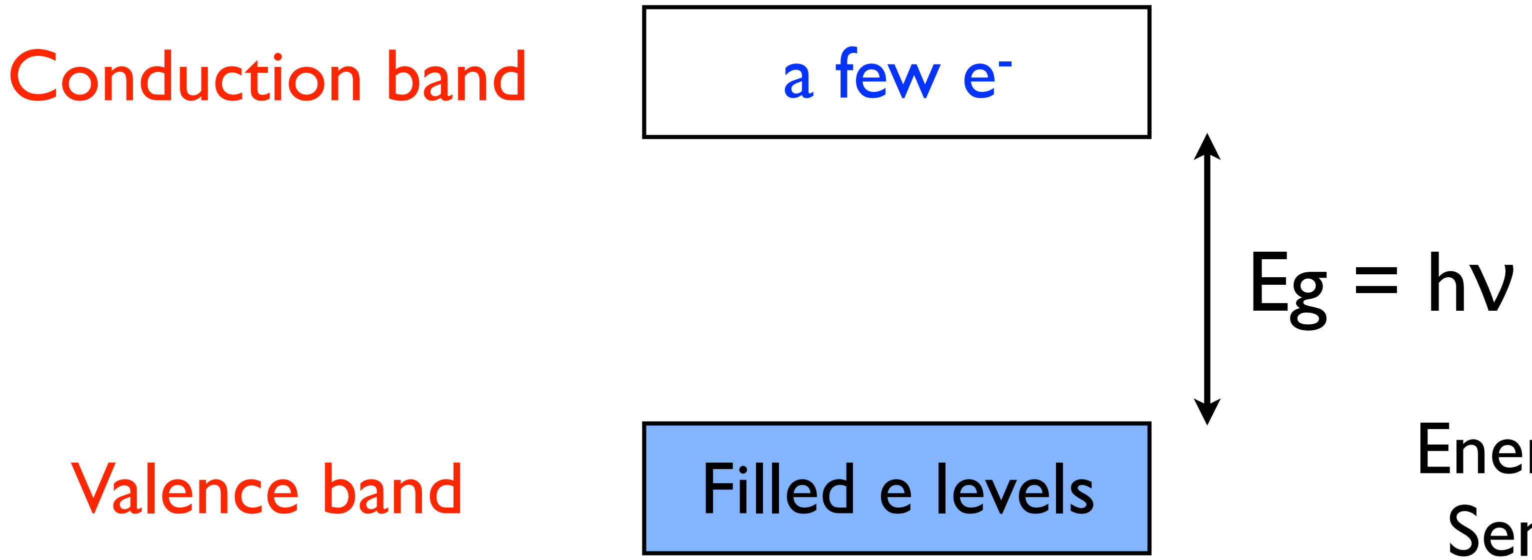
where **S** represents the number of incident photons per pixel, and **Q(e)** is the quantum efficiency, or proportion of total photons actually detected as signal. The total noise in the system is represented by **N(total)**, which combines several variables according to the following relationship:

$$\mathbf{N_{total} = [(S \cdot Q_e \cdot F^2) + (D \cdot F^2) + (N_r / M)^2]^{1/2}}$$

where **F** represents the excess noise factor, **D** is the total dark signal, **N(r)** is the camera read noise, and **M** is the on-chip multiplication gain. The noise terms in the denominator of the EMCCD noise equation represent the familiar CCD noise components, photon shot noise, dark noise, and read noise, respectively, with appropriate modifications to account for loss mechanisms and statistical noise sources specific to the process of on-chip multiplication gain. This is accomplished by applying the excess noise factor (**F**) to the first two terms, and the multiplication gain factor (**M**) to the read noise term. The effective shot noise and dark noise are increased by the excess noise factor, while read noise is reduced by the multiplication gain achieved in the gain register.

http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/emccds.html

Other semiconductor photo-applications:



Conduction band

a few e^-

$Eg = h\nu$

Valence band

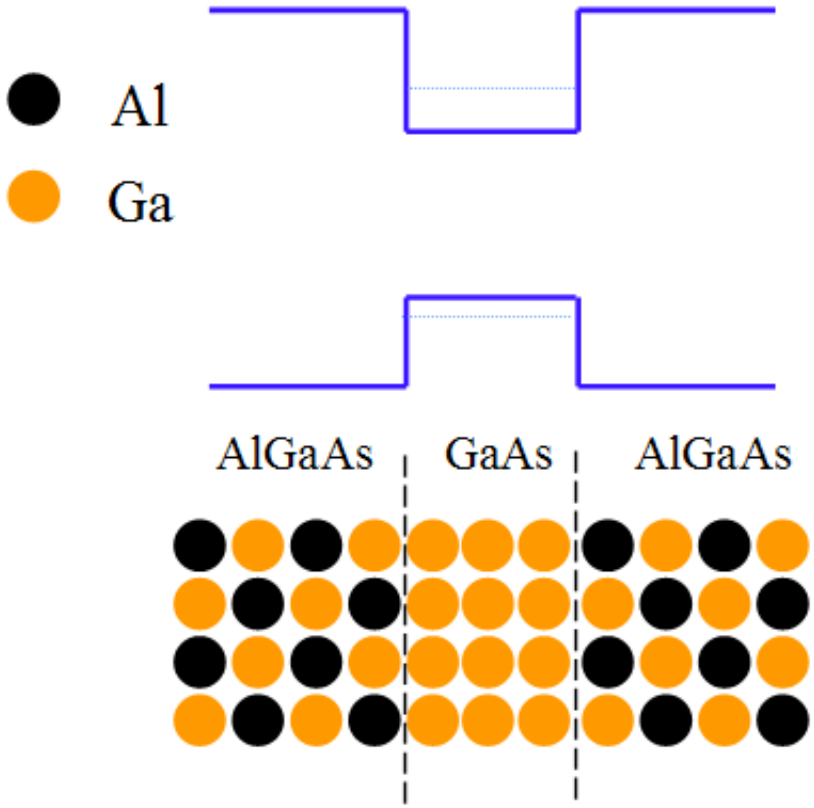
Filled e levels

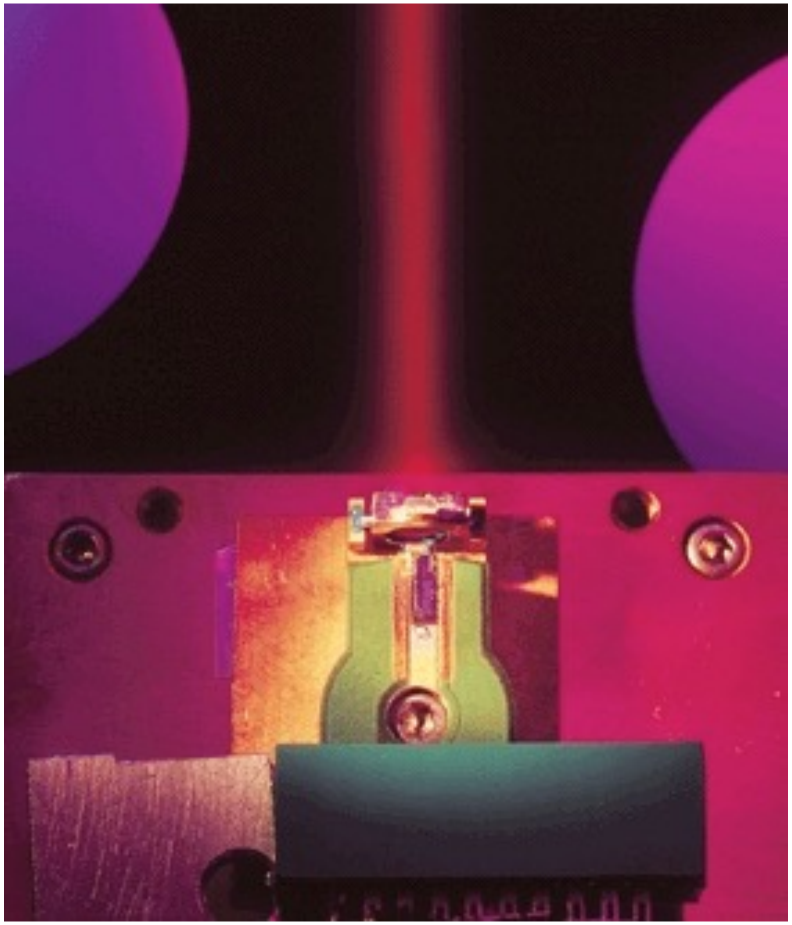
Energy Bandgap in
Semiconductors

1) Excitation of electrons into the conduction band can lead to light emission: LEDs and Laser Photodiodes.

2) Solar cells use semiconductors to convert photons to electrons for energy applications in lieu of light detection.

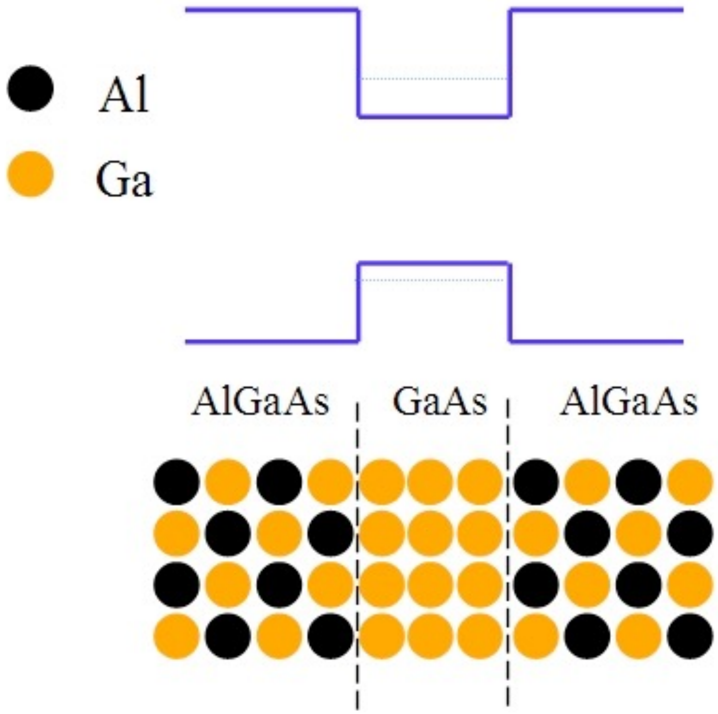
Quantum Well Devices: Applications of the PIAB.



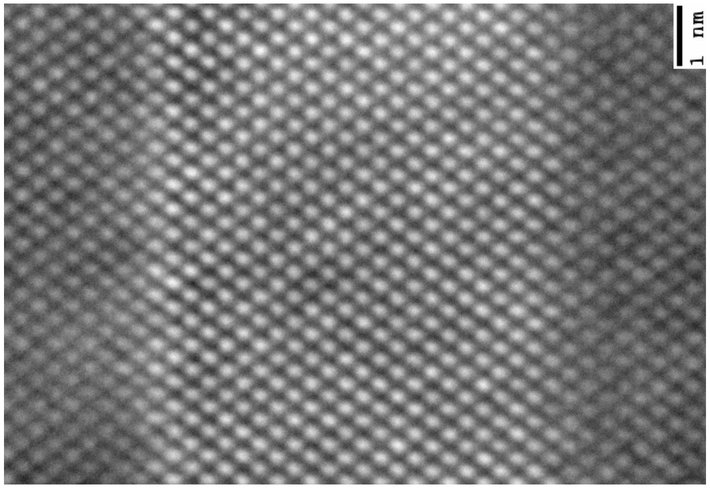


H2A Real World Friday: 2 Oct 09

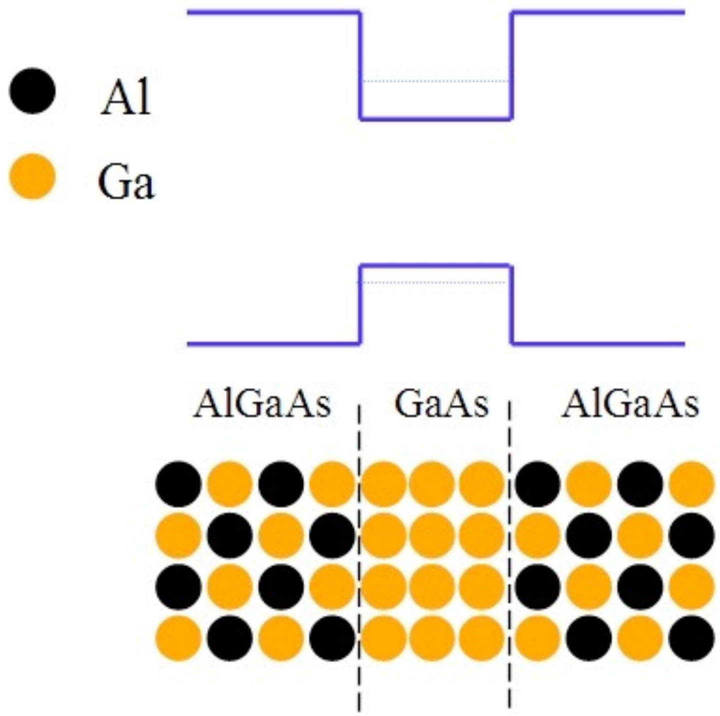
A "quantum well" structure made from AlGaAs-GaAs-AlGaAs creates a potential well for conduction electrons.

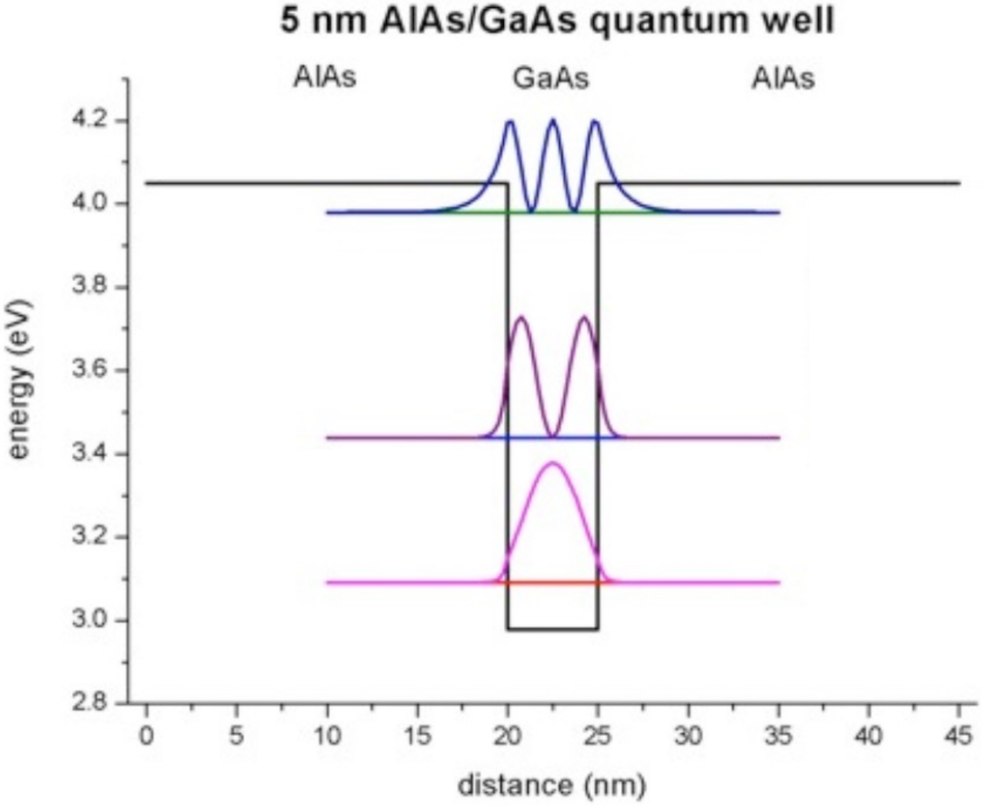


10-20 nm!

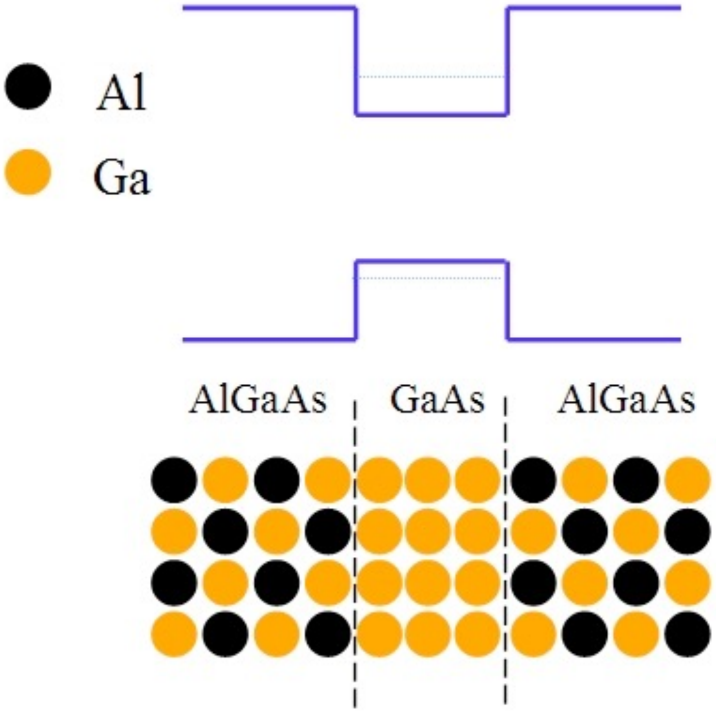


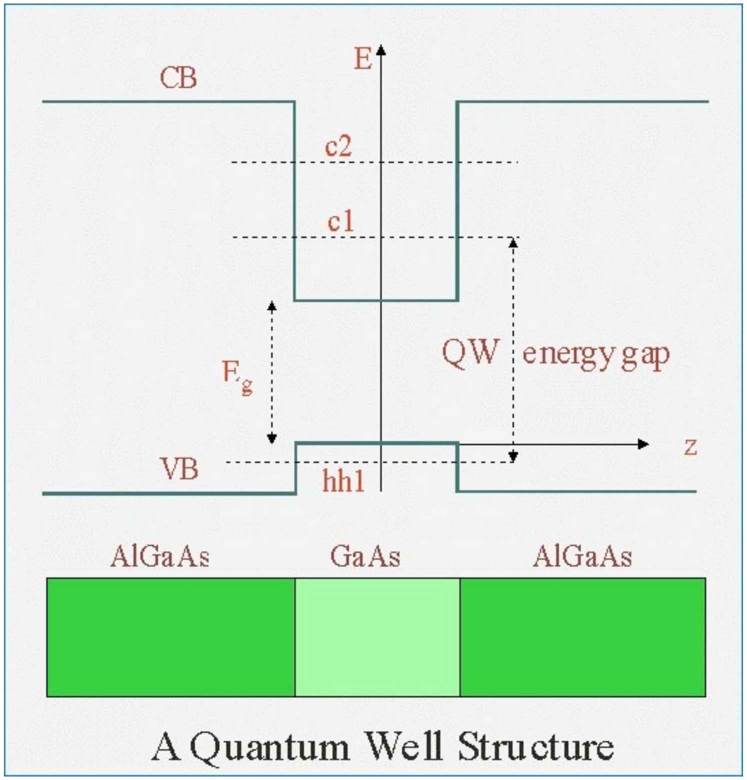
A conduction electron that get trapped in a quantum well acts like a PIAB.




5 nm AlAs/GaAs quantum well

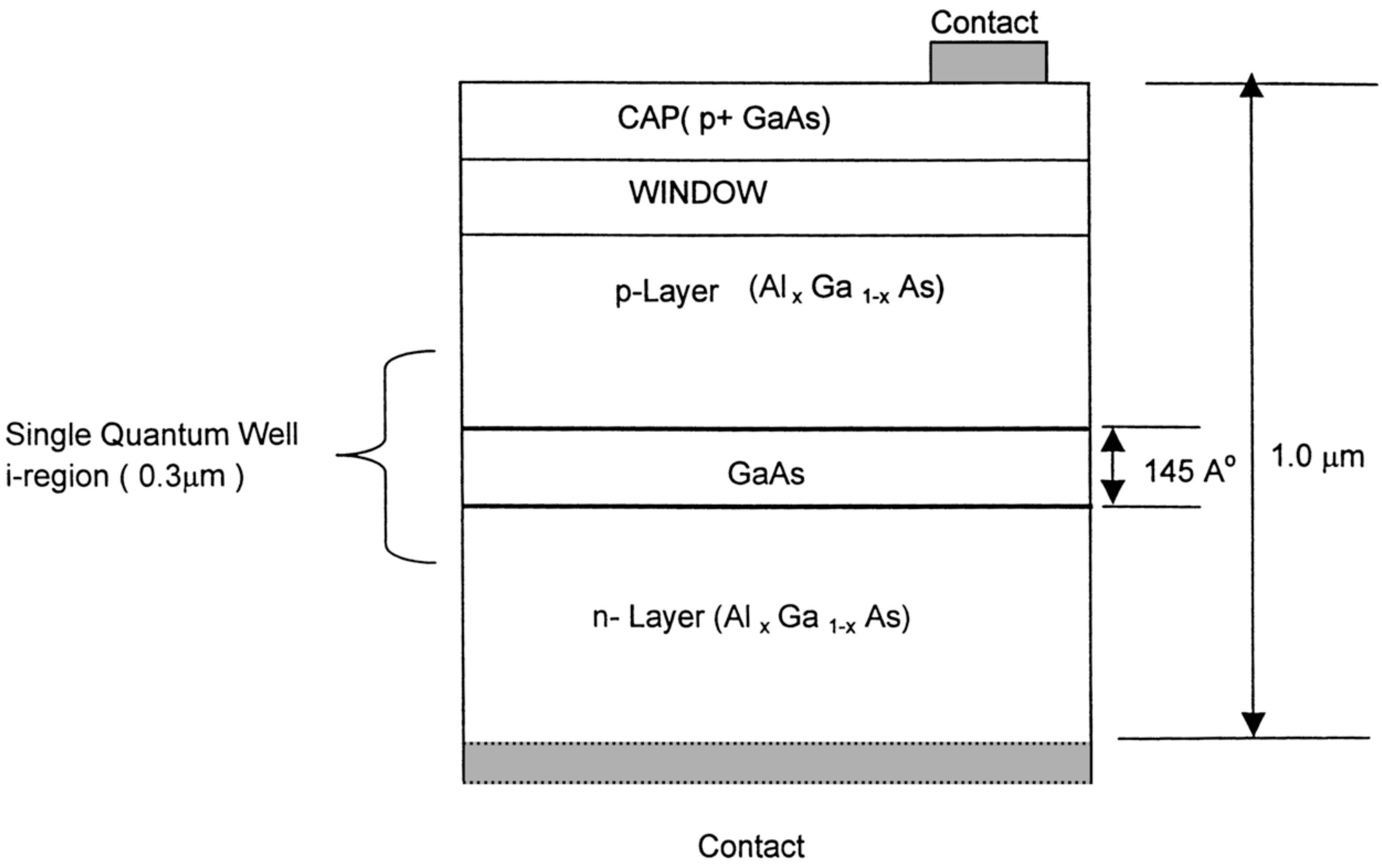
A conduction electron that get trapped in a quantum well acts like a PIAB.

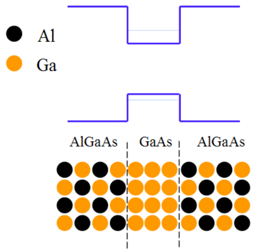




A Quantum Well Structure

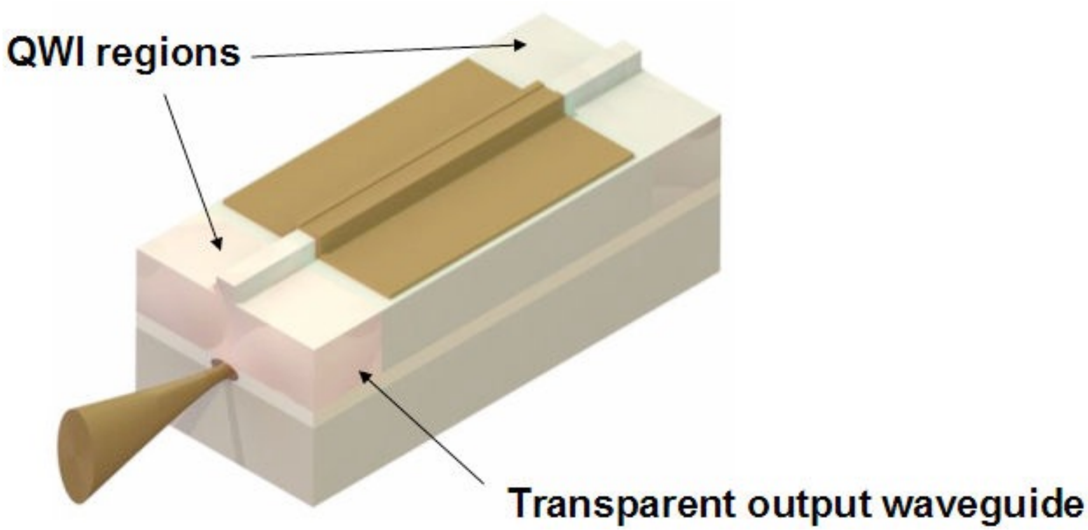
Quantum Wells are used to make Laser Diodes

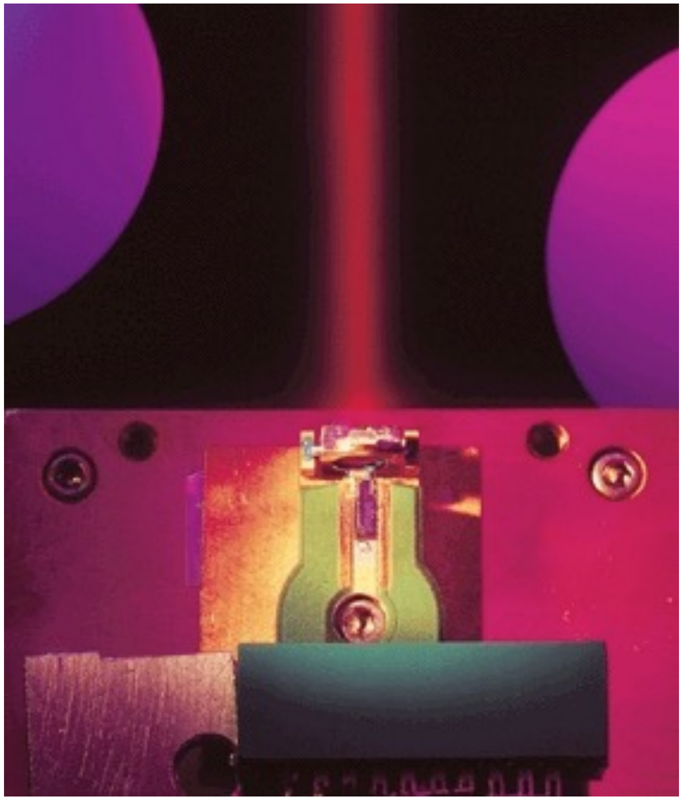


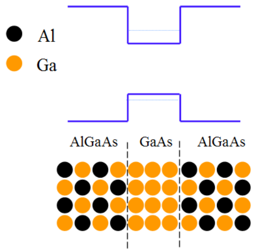


Quantum Well Laser Diodes

Quantum Wells are used to make Laser Diodes

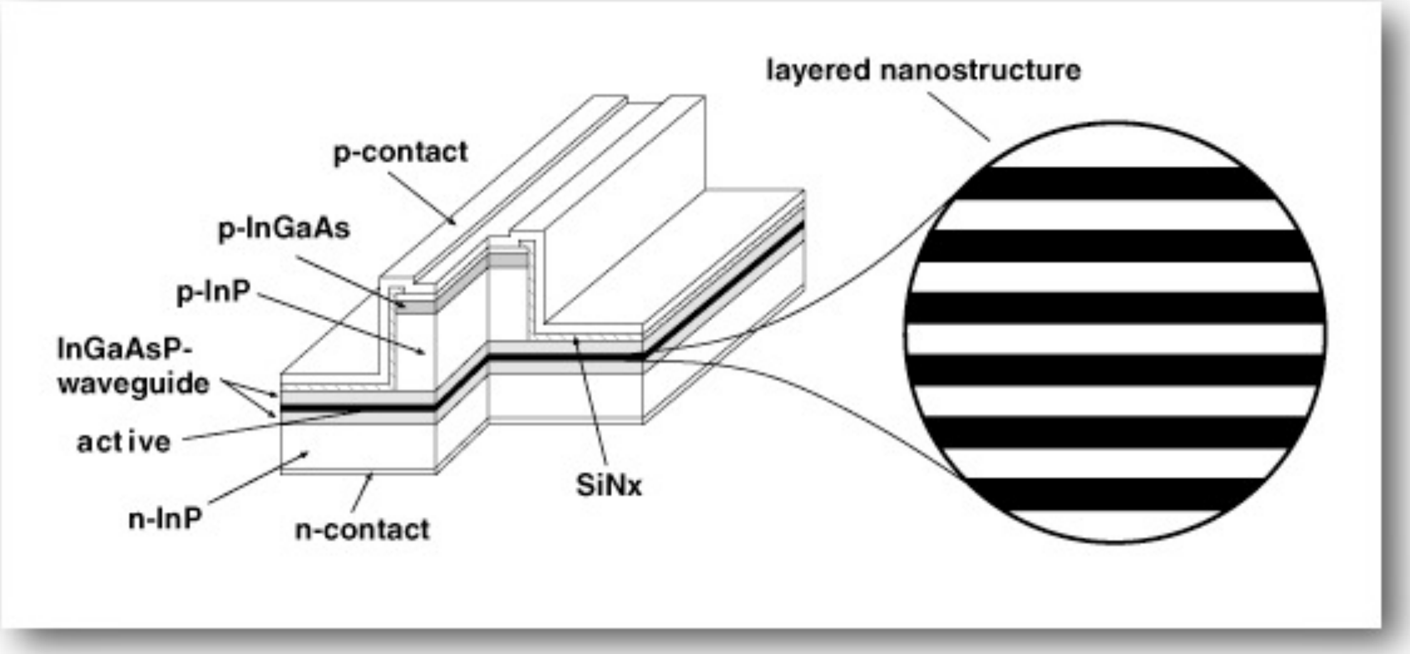


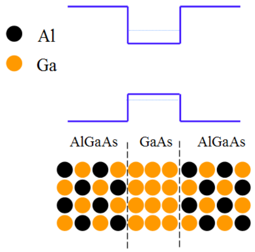




Quantum Well Laser Diodes

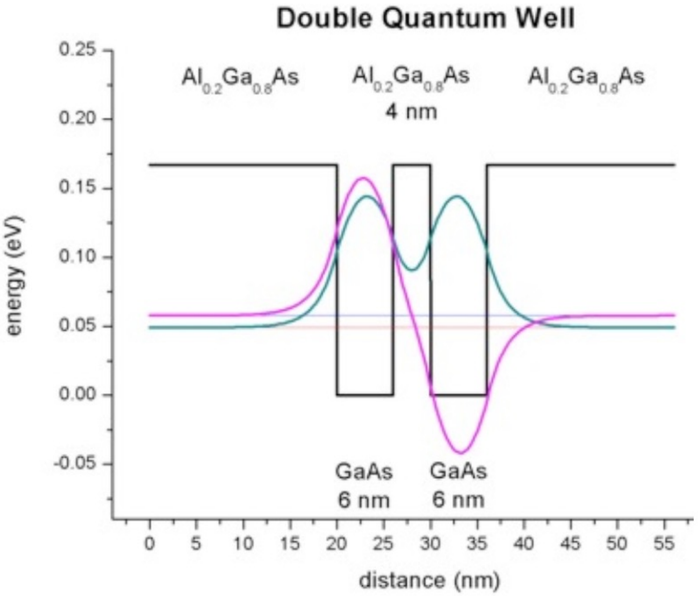
Multiple Quantum Wells work even better.

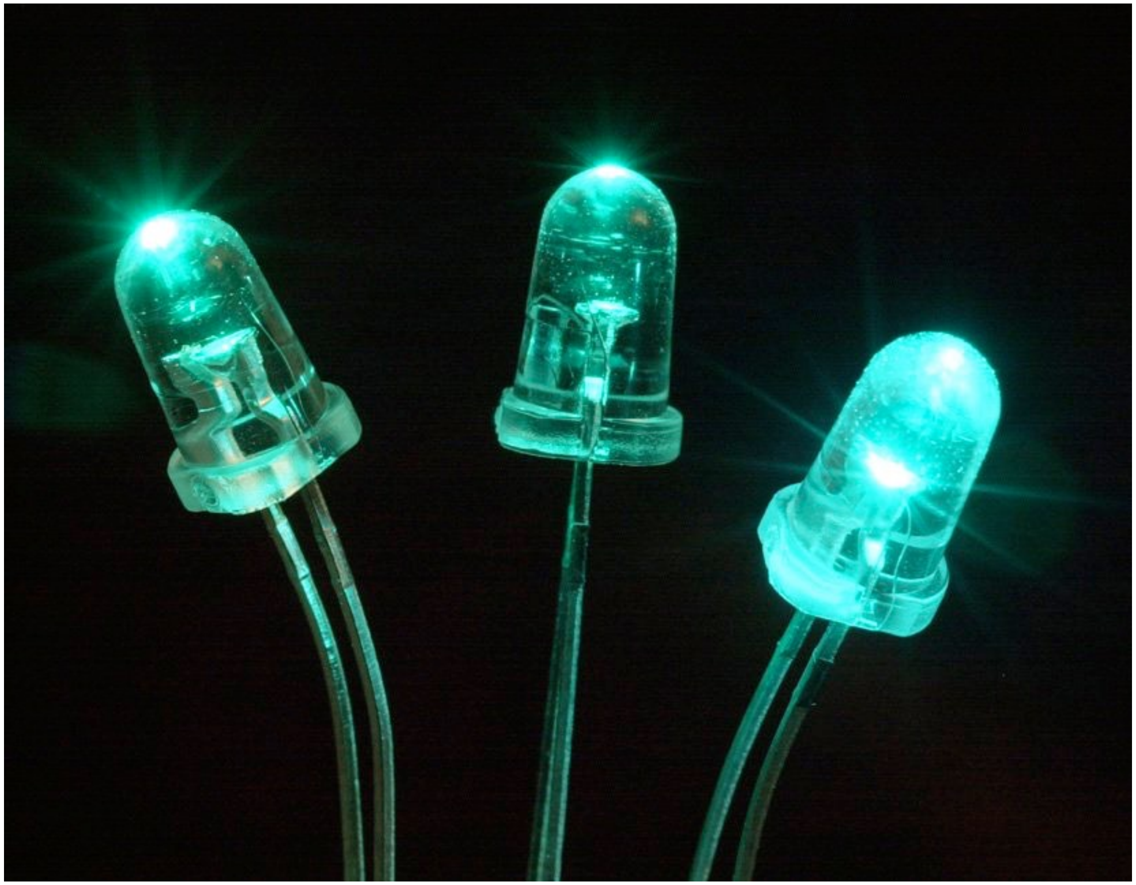




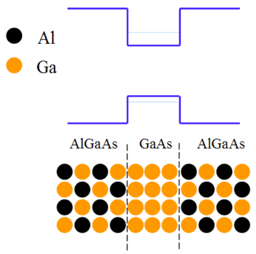
Multiple Quantum Well Laser Diodes

Multiple Quantum Wells work even better.

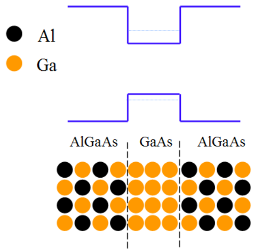




Multiple Quantum Well LEDs

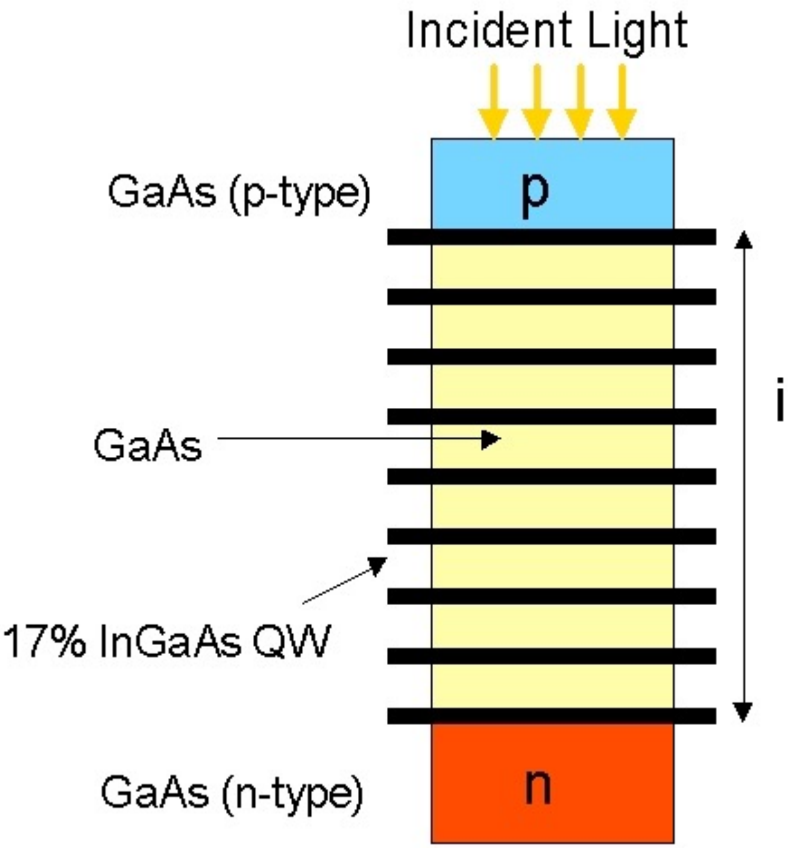


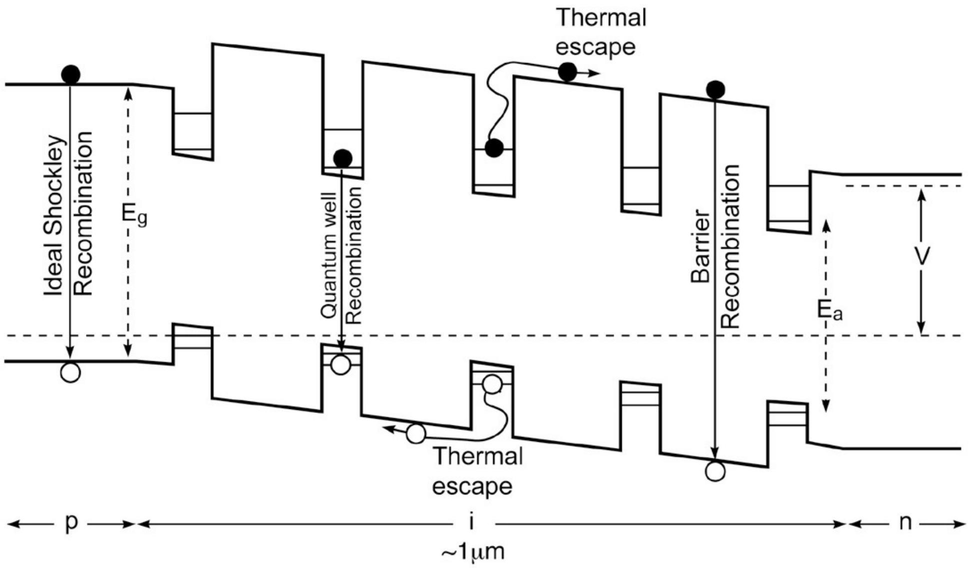
Multiple Quantum Wells work even better.



Multiple Quantum Well Laser Diodes

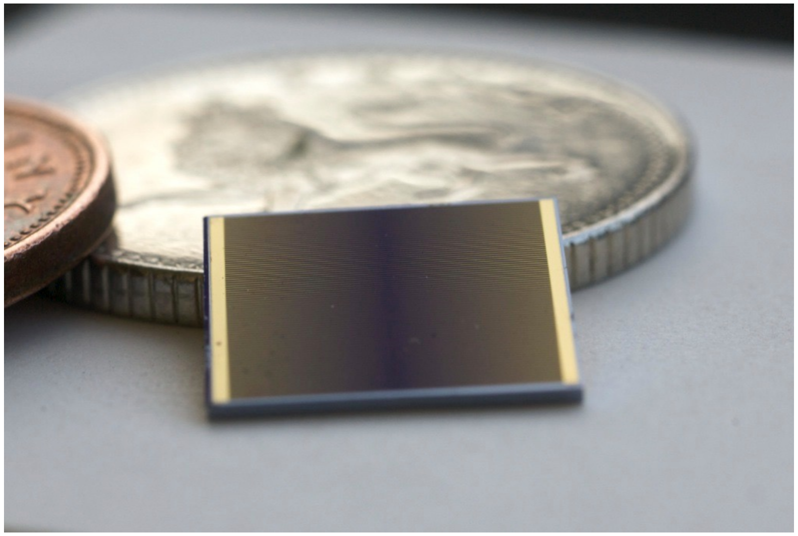
Multiple Quantum Wells also are used to make high efficiency Solar Cells.

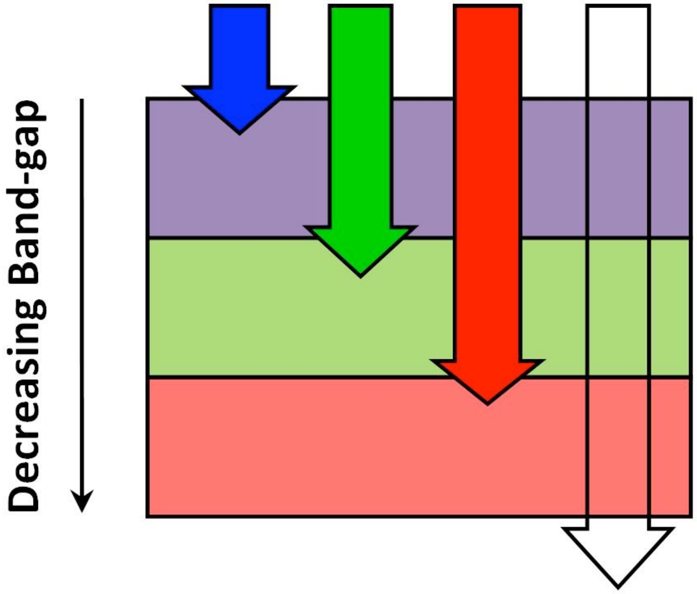




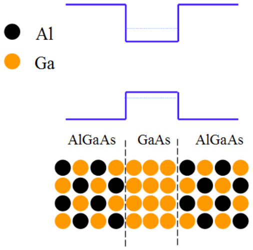
Quantum Well Solar Cells

Multiple Quantum Wells also are used to make high efficiency Solar Cells.





The most common approach to high efficiency photovoltaic power conversion is to partition the solar spectrum into separate bands and each absorbed by a cell specially tailored for that spectral band. This multi-junction approach requires careful control of the solar cell absorption bandwidth and we have pioneered an approach using quantum wells that enable us to optimally match our component junctions to the solar spectrum. The present world record efficiency using this approach is 41.1% set by the Fraunhofer Institute in Germany. Our best cell is 30.6% and we are working towards attaining 50% power conversion efficiency.



The Quantum Photovoltaic Group
Department of Physics
Imperial College London