Camera Sensors

Livio Fent
Metro Continuing Education

Course outline

1. Sensor size
    i. Wafer dimensions
    ii. Pixel dimensions
    iii. Optical considerations
2. Sensor types
    i. CCD
    ii. CMOS
    iii. AgBr
3. Sensor Materials
    i. Silicon
    ii. AgBr

Course outline

4. Photo Conductance
    i. Excitation energy
    ii. Electron – hole mobility
5. p-n junctions
    i. Potential well, Capacitance well
6. The CCD
    i. Structure
    ii. Charge Transference
7. The CMOS
    i. Structure
    ii. Charge transference
8. Silver Halide
    i. Structure
    ii. Latent Image

Course outline

8. Sensor Performance – Silicon and AgBr

i. Pixel size, Fill factor

ii. Quantum efficiency

iii. Full well capacity

iv. Noise

v. Dynamic Range

vi. Analogue to Digital Conversion

vii. ISO

viii. Linearity

ix. Resolution

x. Color

xi. Infrared

Course outline

9. Frame rates
10. Categories of sensors
11. Wrap-up

Introduction

- The image sensor in your camera is the true 'heart' of your imaging system and often, the most expensive component.
- How does it convert light to driving the digital technology of today's camera systems?
- What are some of the constraints that manufacturers need to address in this process?
- How does the digital technology differ from film? How is it similar?
- How can we use this knowledge to aid us in our evaluations, in our picture taking?

Sensor Manufacturers

One may assume that individual camera manufacturers make their own sensors for their cameras, right? Not quite!

Camera Companies	Sensor manufacturer
Canon	Canon
Nikon	Sony
Pentax	Samsung, Sony, Kodak
Fujifilm	Sony, Toshiba
Olympus	Various
Samsung	Samsung
Sony	Sony
Sigma	Foveon

Sensor Manufacturers

Some sensor manufacturers and the 'state of the art' in sensor size.

Company	Sensor Type	Sensor size	Pixel size	Typical Applications
Gpixel Inc. - GMAX3005	CMOS	150MP	5um	Medical, scientific
e2v - CCD 290-99	CCD	85.1MP	10um	Aerial photography
Toshiba Corporation - T4KA7	CMOS	20MP	1.12um	Phone cameras
Teledyne DALSA Inc. - FTF9168C	CCD	60MP	6um	DSC, Aerial

Film manufacturers

Film is making a comeback as a 'retro' product (similar to vinyl records). In fact Kodak recently announced they would be ramping up manufacture of Ektachrome once again. They are also considering bringing back “other” film stocks. Only color infrared is missing from the film lineup on the right.

Film Company	Film size	ISO	Spectral sensitivity	Type
Fujifilm	35mm – 8X10	50 – 1600	Pan	B&W, color
Rollei	35mm – 8X10	25 – 400	Pan, ortho, ext-red, infrared	B&W, color
Ilford	35mm – 11X14	50 – 3200	Pan, ext-red	B&W
Kodak	35mm – 8X10	100 – 800	Pan	B&W,color
Arista	4X5 – 11X14	N/A	Ortho	B&W
Foma	35mm – 8X10	100 – 400	Pan	B&W
Adox	35mm – 8X10	100 – 160	Pan	B&W,color

Sensor Size

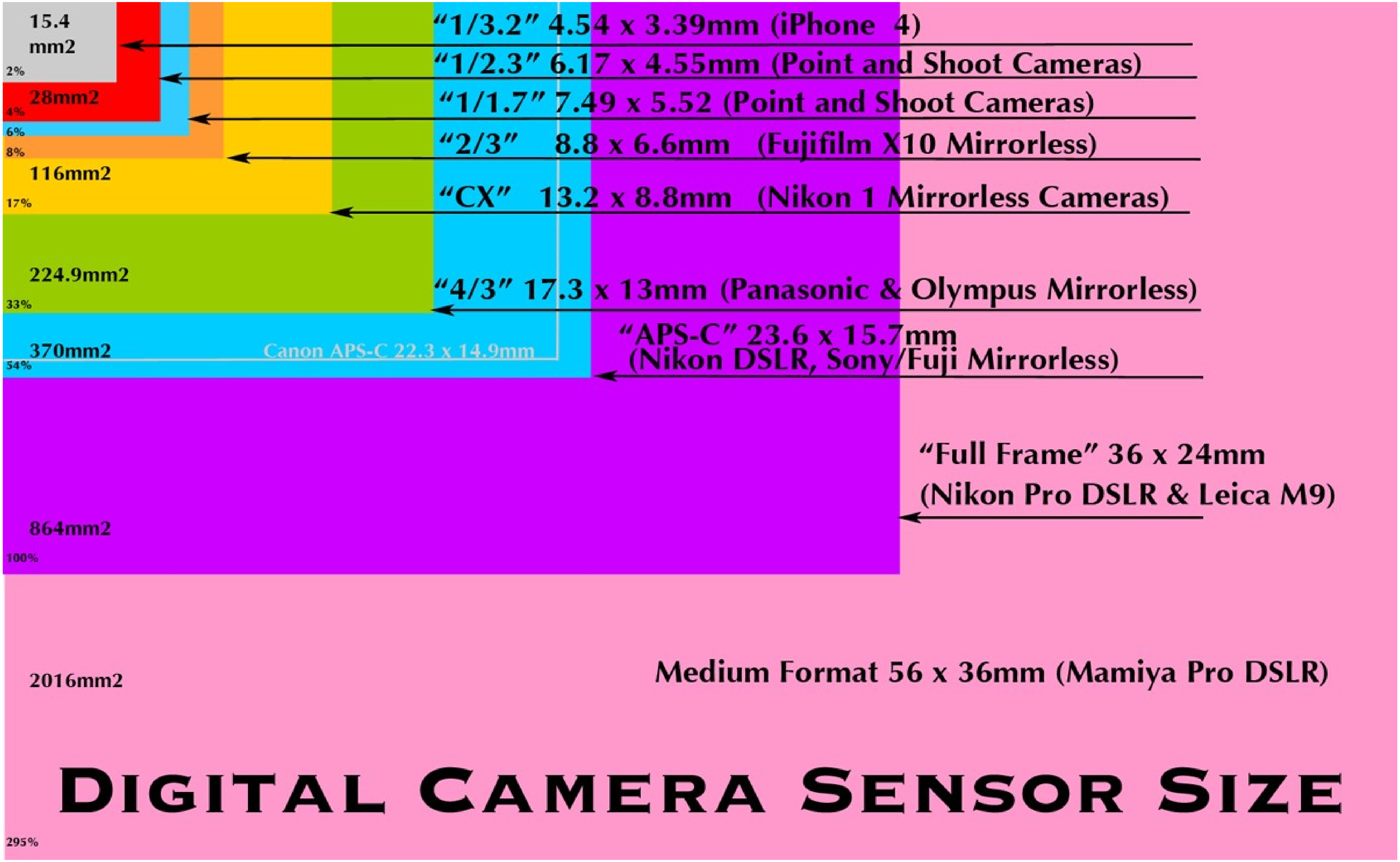
- The public and sometimes even camera sellers emphasize only quantity in camera sensors.
- Typically the megapixel number is the first, and often, the only inquiry as to the performance of the camera.
- The more the pixels, the 'better' the camera.
- Generally physical dimensions and pixel size are often either not reported or glossed over.
- Let's start our investigation with size....

Sensor Size

Digital commercial sensors range from the smallest usually found in cell phones to the largest as used in aerial photography cameras.

- iPhone 4 = 5MP-15.4mm^2
- iPhone 7 = 12MP-32.3mm^2
- Ultracam Eagle 2 = 340MP-7208mm^2

Sensor Size

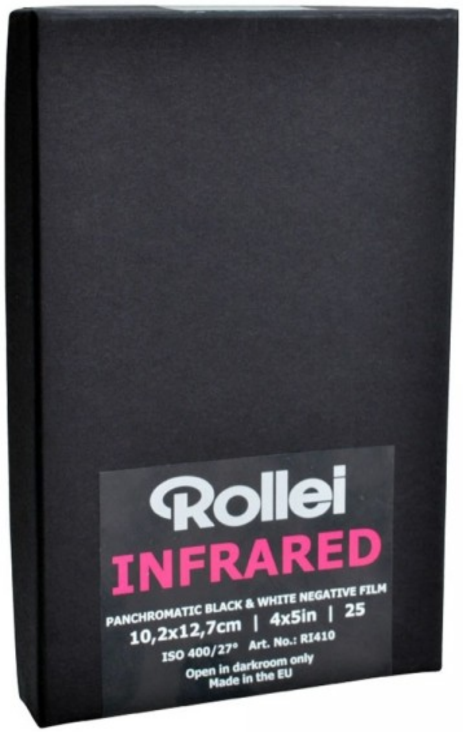


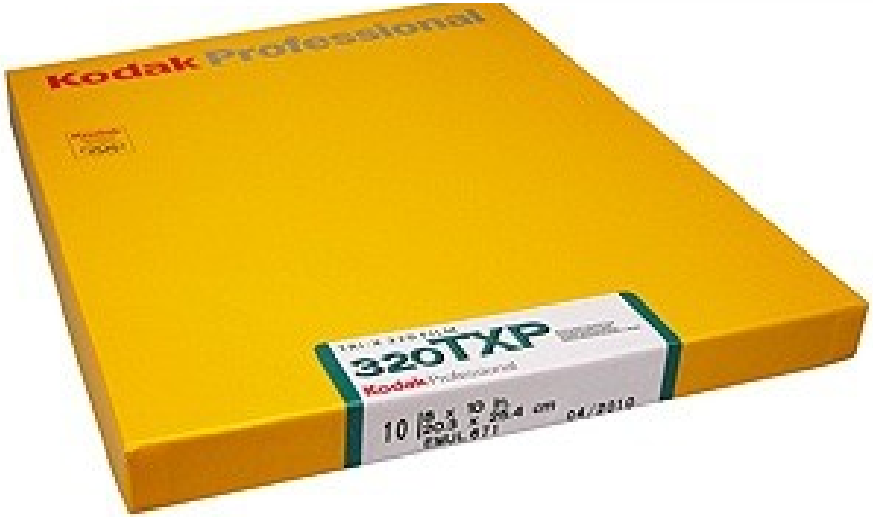
15.4 mm2
2%
28mm2
4%
6%
8%
116mm2
17%
224.9mm2
33%
370mm2
54%
Canon APS-C 22.3 x 14.9mm
864mm2
100%
2016mm2
295%
"1/3.2" 4.54 x 3.39mm (iPhone 4)
"1/2.3" 6.17 x 4.55mm (Point and Shoot Cameras)
"1/1.7" 7.49 x 5.52 (Point and Shoot Cameras)
"2/3" 8.8 x 6.6mm (Fujifilm X10 Mirrorless)
"CX" 13.2 x 8.8mm (Nikon 1 Mirrorless Cameras)
"4/3" 17.3 x 13mm (Panasonic & Olympus Mirrorless)
"APS-C" 23.6 x 15.7mm
(Nikon DSLR, Sony/Fuji Mirrorless)
"Full Frame" 36 x 24mm
(Nikon Pro DSLR & Leica M9)
Medium Format 56 x 36mm (Mamiya Pro DSLR)
DIGITAL CAMERA SENSOR SIZE

Sensor Size
Film

Film (silver halide) as noted, is still a sensor of choice for some. It is, in fact, the largest sensor material commercially available:

- 4 X 5 sheet film 12827 mm2
- 8 X 10 sheet film 51612 mm2





Sensor size
Megapixels

Consider these two camera types:

Camera	Type	Megapixels	Sensor size (mm2)	Pixel size (microns)
IPhone 7	Phone camera	12	32.3mm2	1.55
Nikon D90	DSLR	12.3	371mm2	5.5

Same megapixels but sensor size/pixel size are quite different.

- How will the images produced from these two cameras differ?
- How are they alike?

Sensor size: optics

- As sensor size increases, a lens needs to produce a larger image to encompass a set field of view.
- Tyically referred to as the 'crop factor'.
- A full frame sensor (36X24mm) has a crop factor of 1, an APS-C sensor is 1.6, a point and shoot is around 4 to 6.

A 50mm lens on a full frame DSLR or 35mm produces a field of view of about 47°

- On a APS-C sensor the equivalent FoV would be attained with a 31 mm lens,
- On a point-and-shoot camera sensor the same FoV would be obtained with a 8.3 mm lens.

Sensor size: optics
(supplementary)

The following is the formula to calculate the field of view (FoV) for any size sensor:

Field of View = 2 * arctan (sensor diagonal / (2 * focal length))

Example

For a full frame sensor diagonal (d) = 43mm (36X24mm) and f = 50mm,

$$FoV = 2*arctan\ (43/(2*50) = 46.5°$$

And, for a APS-C sensor with a diagonal (d) of 28.4mm (23.6X15.7mm) and f = 31mm

$$FoV = 2*arctan\ (28.4/2*31) = 49.2°$$

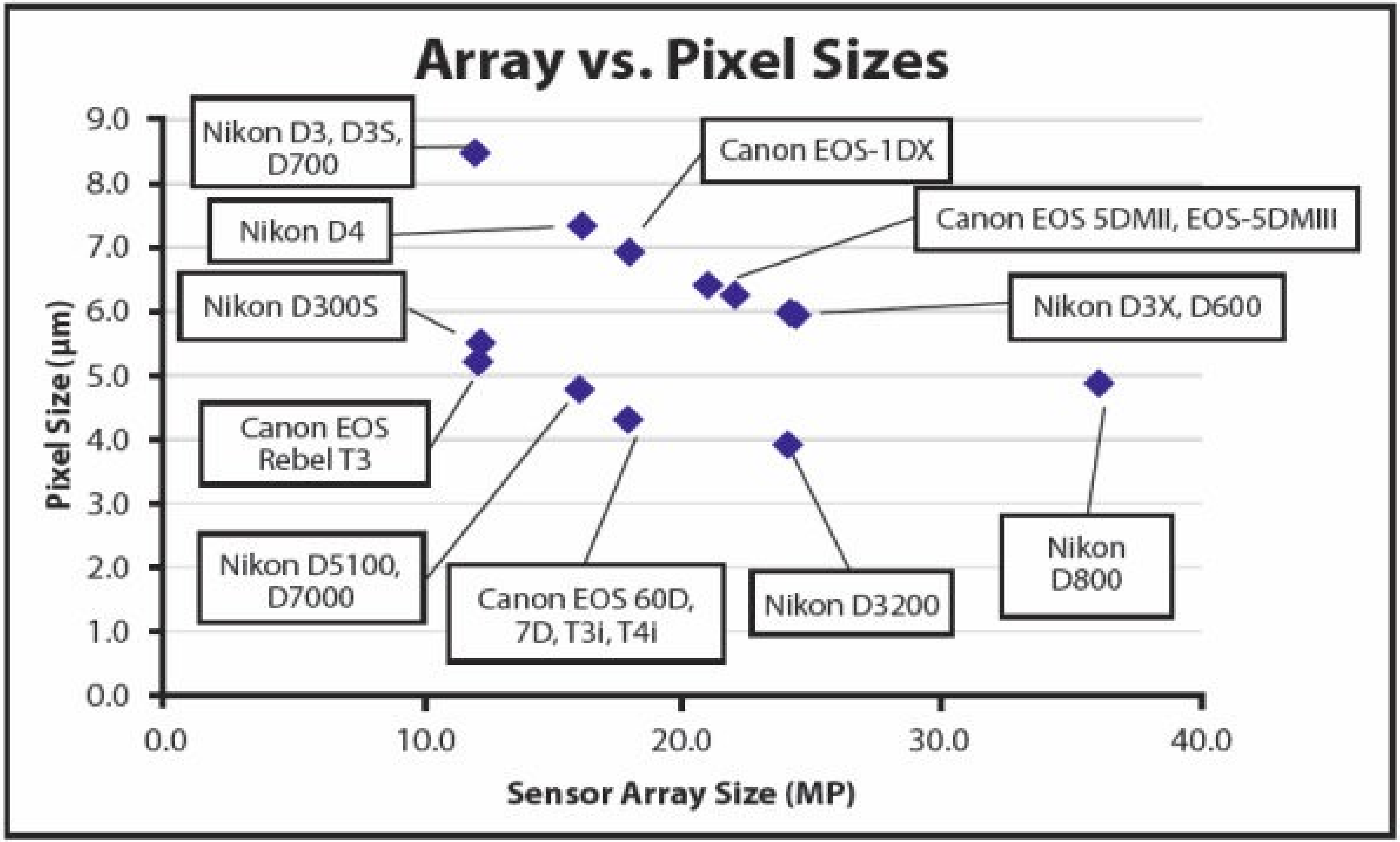
Sensor Pixel Size

- Pixel sizes are not often mentioned when camera image sensors are described (you have to dig for the information).

  http://www.digicamdb.com/specs/

- The pixel sizes range from relatively large pixel sizes of older cameras (over 10 microns) to the relatively small pixel sizes found in cell phones sensors of about 1 micron.
- Very small pixels are prone to higher noise levels and are less sensitive but can, potentially, resolve more detail. We'll investigate these tradoffs in detail later.

Sensor Pixel Size

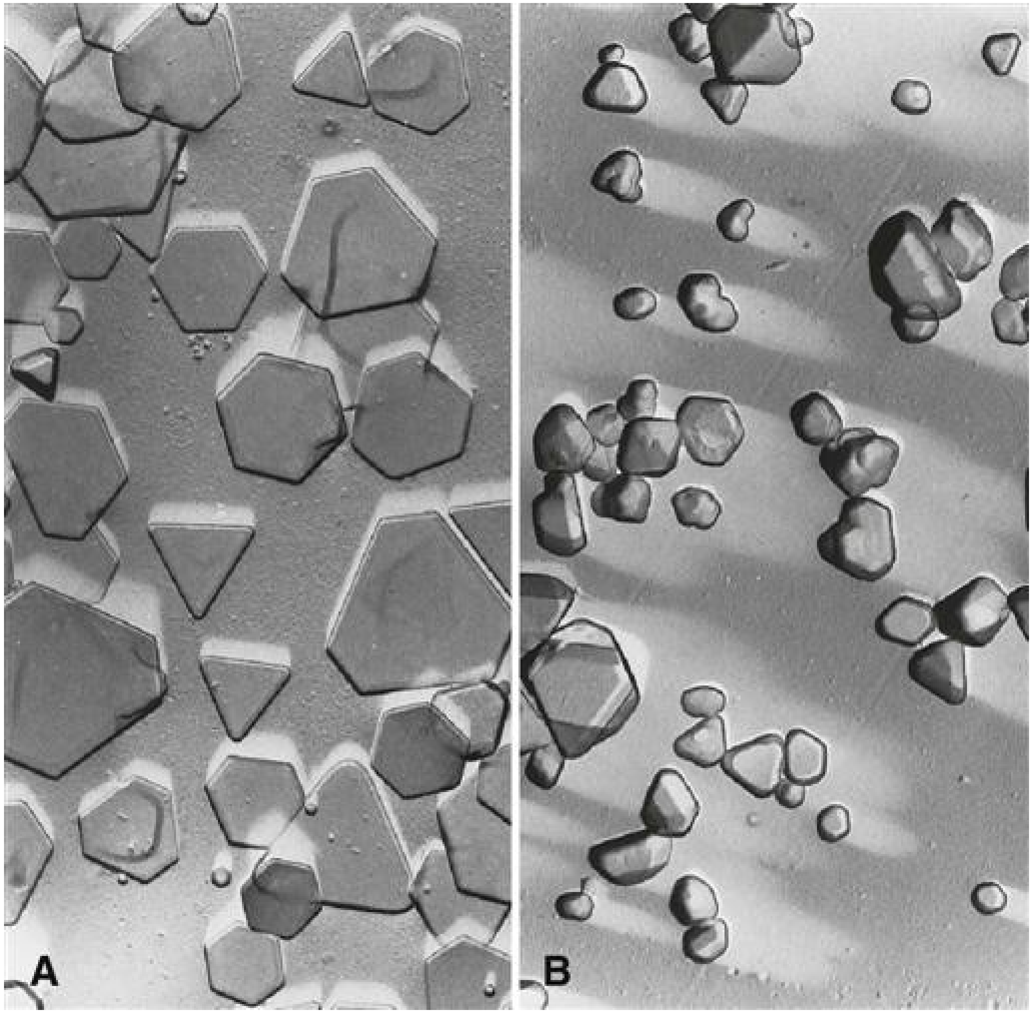


Sensor Pixel Size

Film

Film's sensor pixel unit is the silver halide crystal. These crystals are about about 1 micron or less.

Because they are 'stacked' in the emulsion they provide a tonal richness unique to this type of sensor.



Sensor types
CCD, CMOS, AgBr

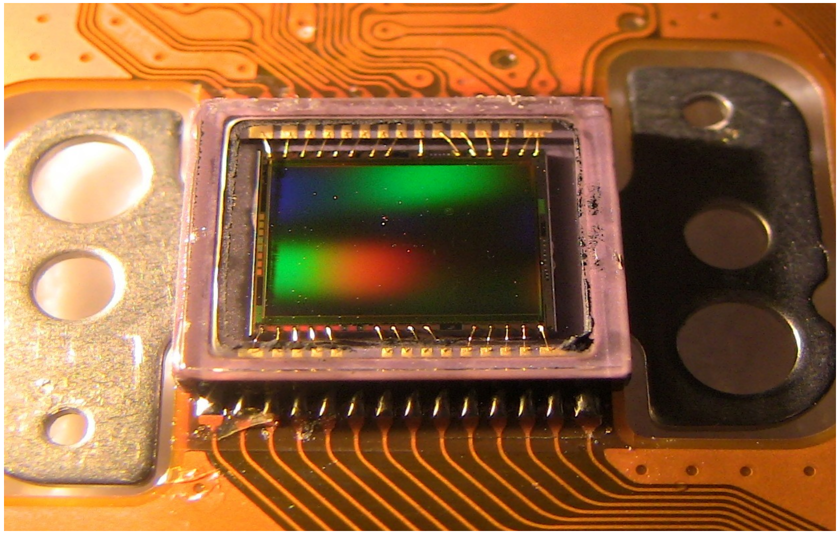
- Three types of sensors are manufactured:
- Two are silicon based
  - CCD, Charged Coupled Device
  - CMOS, Complementary Metal Oxide Semiconductor
- The third is silver halide based
  - AgBr crystals found in film emulsions
- All three are classed as semiconductor materials, converting photonic energy to electronic energy. We'll investigate this later in the course.

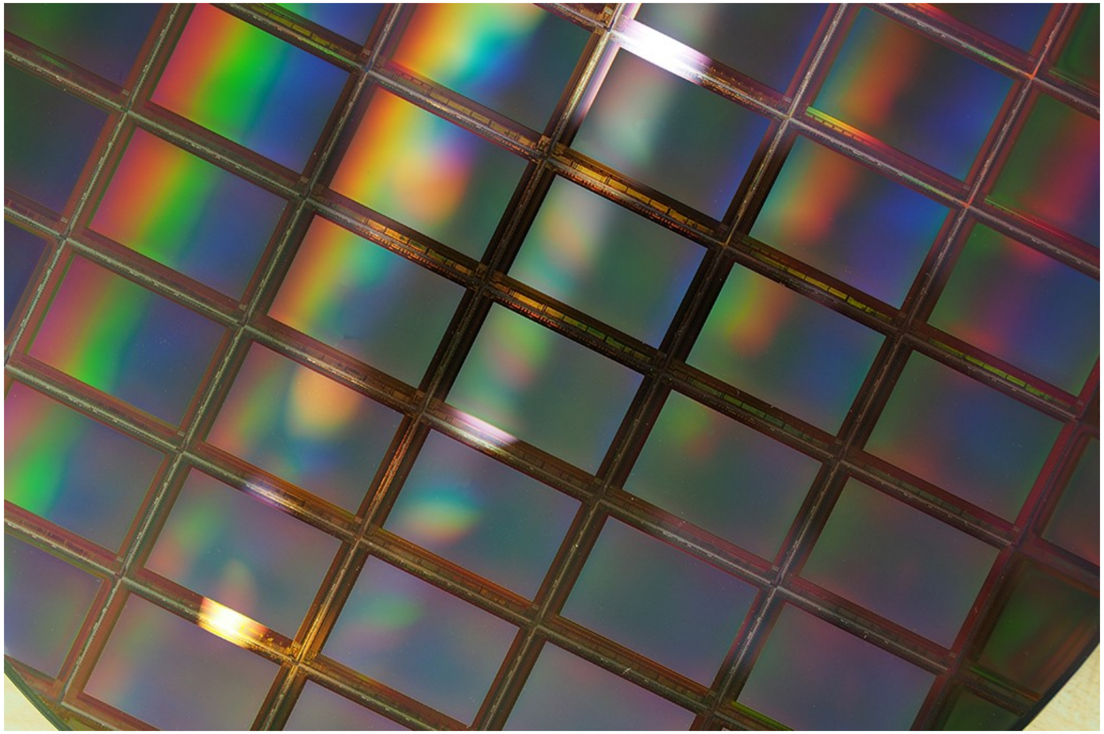
Sensor types
CCD, CMOS, AgBr

- Silver halide is the oldest image forming sensor as found in film
- The CCD is the original digital image foming architecture.
- The CMOS has also been around a long time but was used only in low-end optical systems.
- The CMOS has come into its own over the past 10-15 years. Most camera systems now use the CMOS architecture.
- Which one is 'better'? We'll investigate later...

Sensor Basics

- Exactly how does light register onto the sensor to create an image?
- Does all light register the same? Is there a difference between colors?
- What determines the sensitivity of the sensor, What's too little light? What's too much?





Sensor basics

- Both silicon and silver halides are ***sensitive*** to light particles or photons.
- Photons ***transfer*** their energy to the molecular structure of the silicon or silver halide.
- The transferred energy ***excites*** valence (outer) electrons dislodging them from their molecular fixed position.
- The excited (or energized) electrons are transferred to a higher energy level: a conductance band. Here they are able to move around and produce a ***current*** (or electricity).
- These photo-generated electrons represent the units of image formation and information.

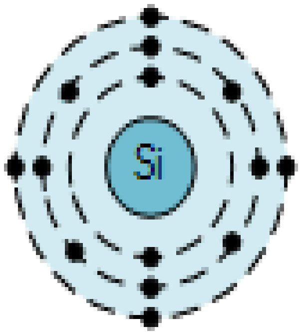
Sensor materials
Silicon

Silicon, atomic # 14:

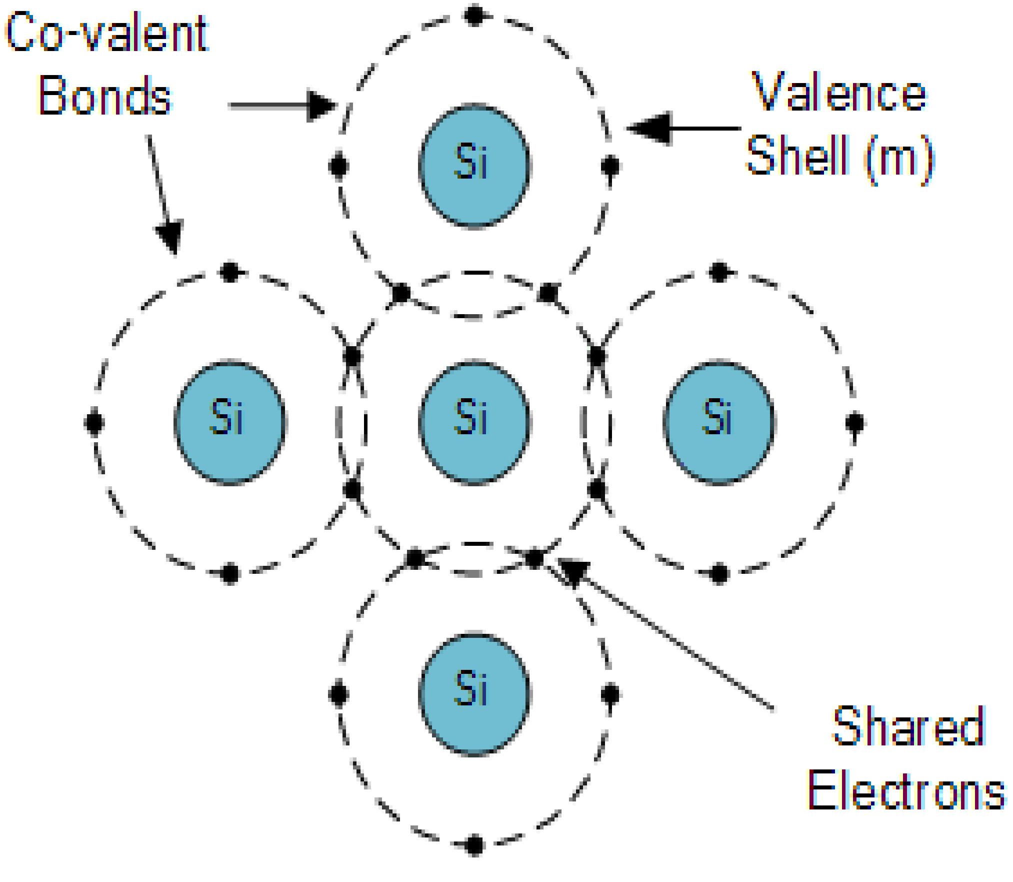
Quantum levels:

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$

A Silicon Atom,
Atomic number = "14"



Silicon atom showing 4 electrons in its outer valence shell (m)



Silicon Crystal Lattice

Sensor Materials

Silver Bromide - AgBr

Silver, Ag, atomic# 47

Quantum levels:

$1s^2$

$2s^2$, $2p^6$

$3s^2$, $3p^6$, $3d^{10}$

$4s^2$, $4p^6$, $4d^{10}$, $5s^1$

Bromine, Br, atomic# 35

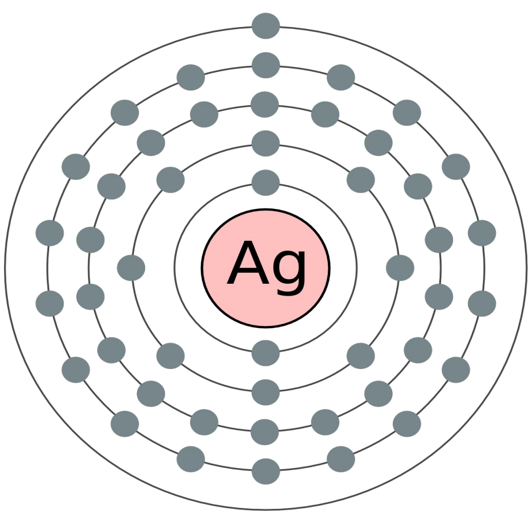
Quantum Levels:

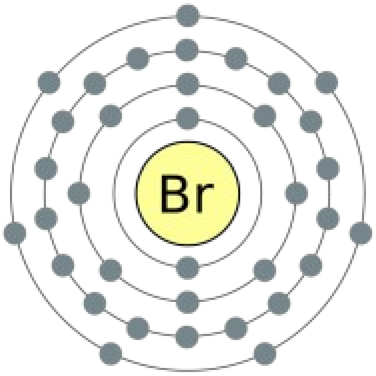
$1s^2$

$2s^2$, $2p^6$

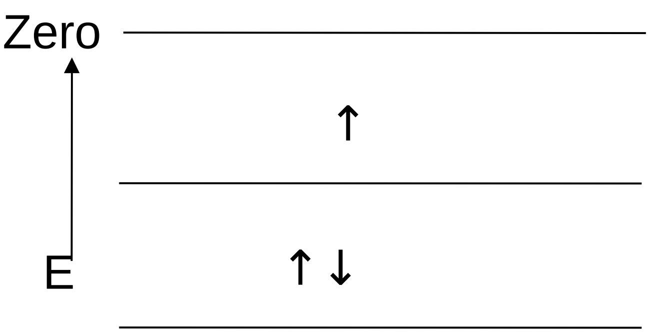
$3s^2$, $3p^6$, $3d^{10}$

$4s^2$, $4p^5$





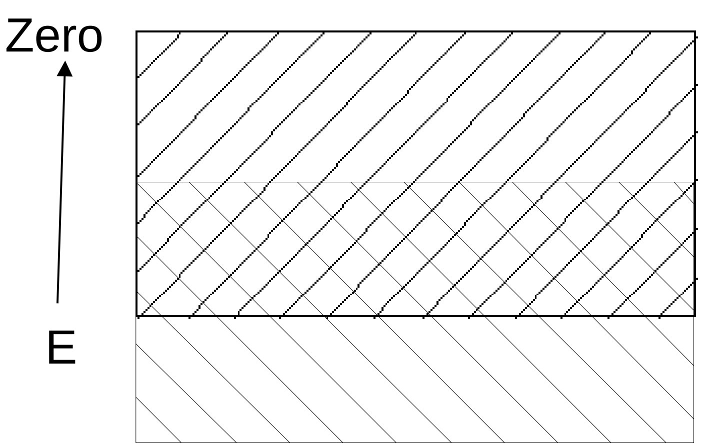
Sensor Materials
Semi-conductor band concepts



Motion possible in conductance band (uppermost level)
(one electron in valence band)

Full band

1. Conductance when only one electron fills the valence shell, eg. Copper, iron..



Conductance band

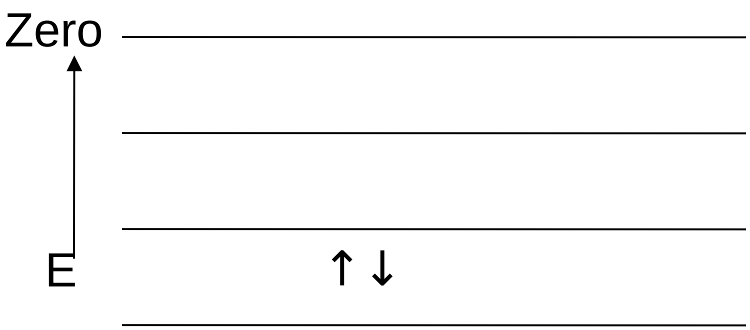
Region of overlap -------> electron movement

Full band

2. Conductance when two electrons occupy the valence shell, valence shell is full , however, Conductance is still possible due to the overlap of the conductance and filled bands eg. Mg, Ca

Sensor Materials

Semi-conductor band concepts



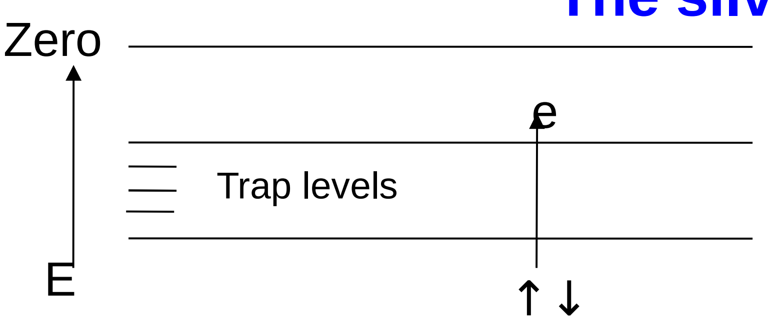
Conductance Band, no electrons

Energy Gap is large, width (or E) varies

Filled Valence Band

3. Situation in which the valence shell is full and no electrons are in the conductance band. This Material would be an **Insulator**.

The silver bromide and silicon crystal band structure



Conductance Band, no electrons

Energy Gap = 2.5eV for AgBr and 1.1 eV for Si

Filled Valence Band

4. AgBr and Si are normally insulators but when at least 2.5 and 1.1 eV Energy are absorbed say, through a quanta of light, then they become a conductors ie. The valence electron is excited and moves to the conductance band. These are **semi-conductors**

What does the 1.1eV and 2.5eV energy gap mean photographically?

Two equations in optical physics are needed to resolve the question:

$\Phi = h\nu$ and $\lambda = c/\nu$, where Φ = quantum energy (eV)

h = Planck's constant

ν = frequency

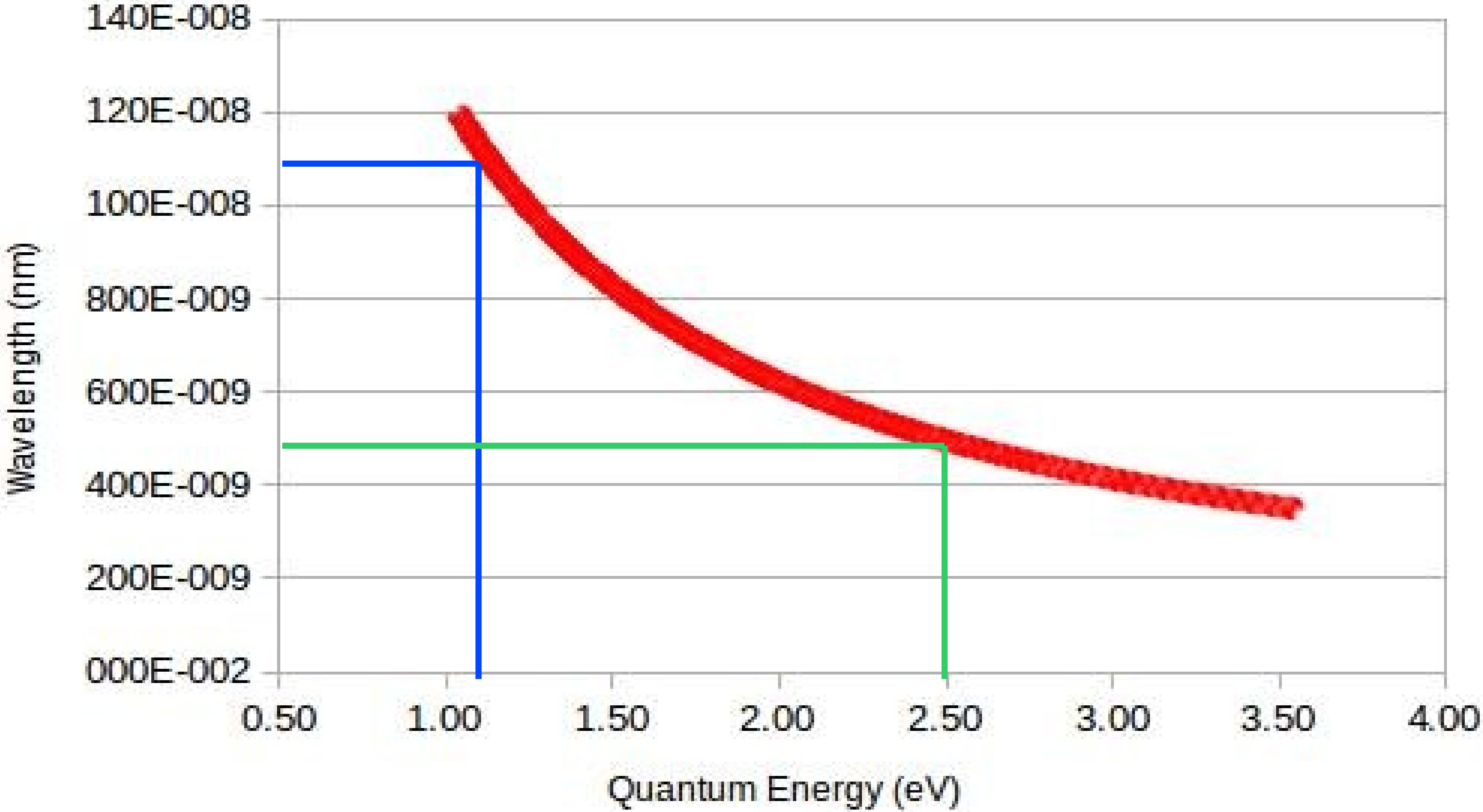
c = speed of light

λ = wavelength

Combine the two equation and solve for Φ, the quantum energy:

$\boldsymbol{\Phi = hc / \lambda}$ since h and c are constants the quantum energy varies with wavelength

What does 1.1eV and 2.5eV mean photographically?



How are the electrons accounted?

Silicon

Generally, one electron is produced for every photon ie. The quantum efficiency = 1. In real life the efficiency is closer to 0.4 or 0.5. For film, it is 0.1.

1. Next, need to 'gather' the photo-generated electrons in some place (pixel): *p-n junctions and potential wells*

2. Then, we need to move them to a place to be counted: *CCD's = bucket brigade, CMOS = pixel capacitor,*

3. Finally, the electrons are coverted to voltages, amplified, and then converted to digital values (say, 0-255). *AD converters*

How are the electrons accounted?

Silver Bromide

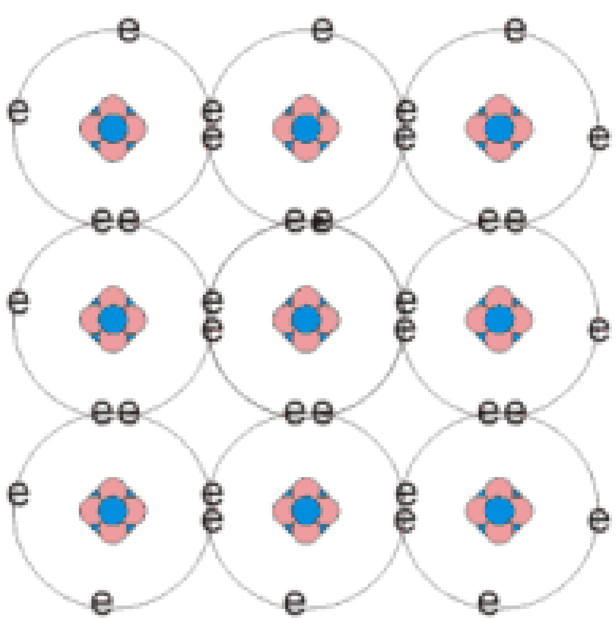
As noted the quantum efficiency for film is about 0.1.

1. First, 'gather' the photo-generated electrons at some place in the crystal: *create the latent image with trap levels associated with impurities in the AgBr crystal*

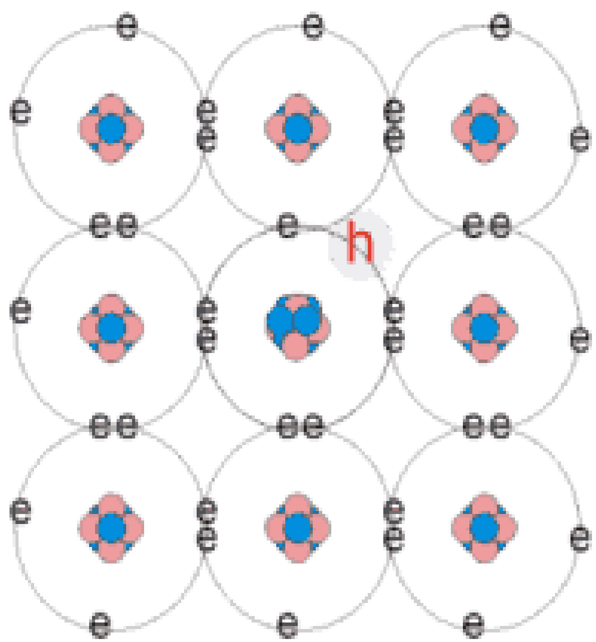
2. Then, we need to amplify the latent image so we can see it: *Chemical development and image fixation.*

Creating a 'container' for the photo-generated electrons

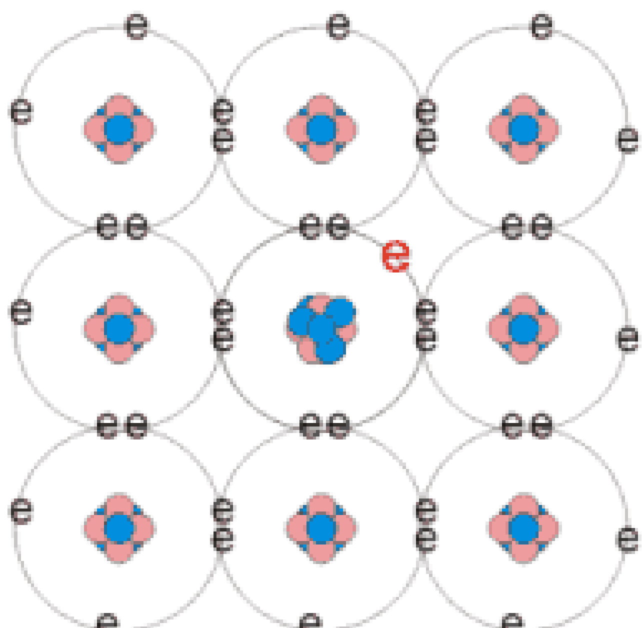
Using a manufacturing process called *doping,* a small amount of Boron or Phosphorous are typically added to pure Silicon to produce electrons and positive holes (the absence of an electron). The Boron or Phosphorous ions are fixed in their lattice location but their valence electrons and holes are mobile. These are called p-type and n-type semiconductors, respectively. <u>Remember, these are manufactured materials</u>. No light has yet to hit the materials.



The intrinsic semiconductor



p-type extrinsic



n-type extrinsic

p-type and n-type layers in contact
the p-n junction

<u>When p-type silicon is placed in contact n- type silicon some very remarkable properties are created and form the basis of most semiconducting devices.</u>

At the contact zone:

1. The n-type electrons move to the p-type silicon while the p-type holes move to the n-type silicon.

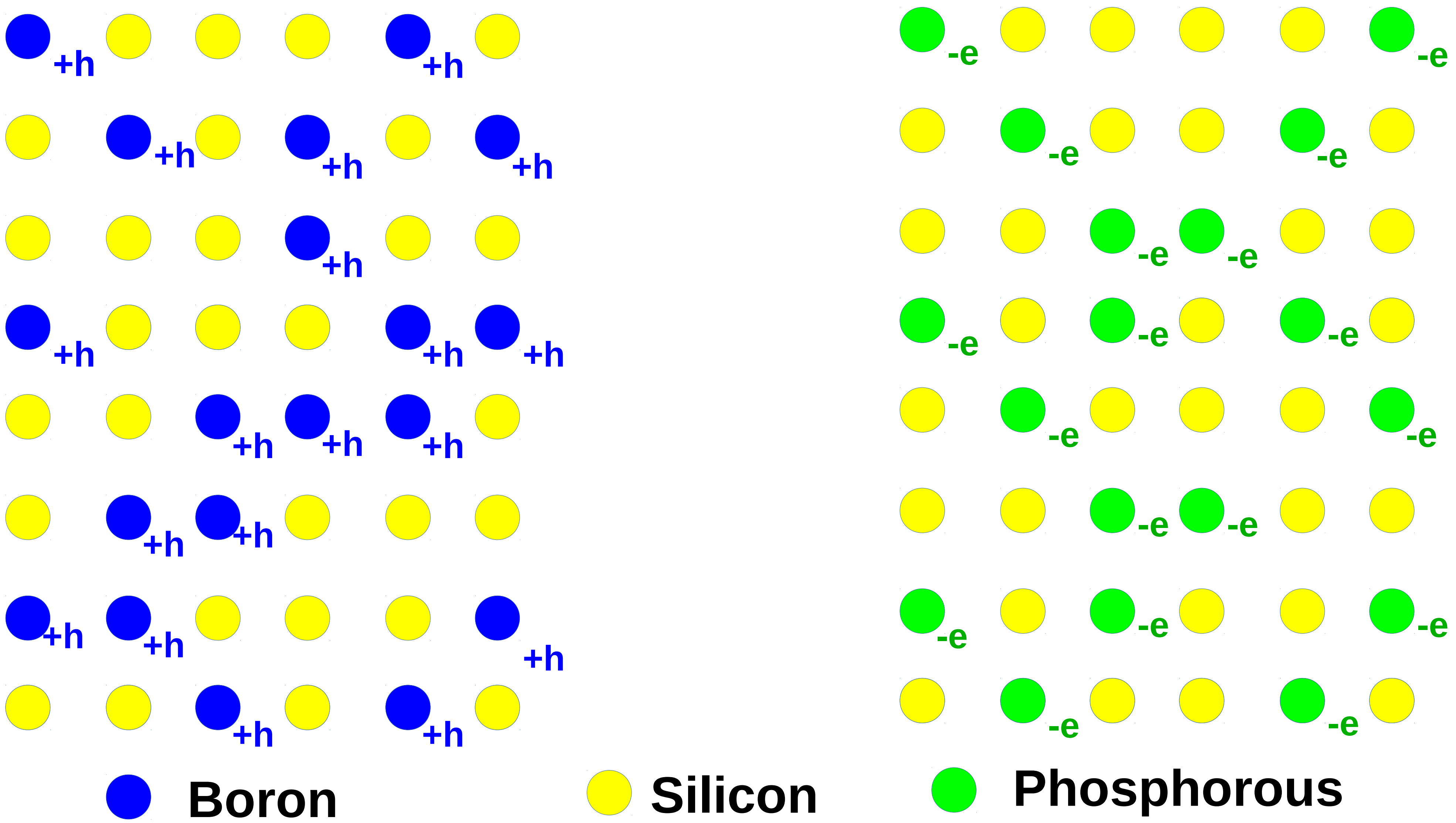
2. At the contact zone the doped negative and positive ions (the ions are Boron and Phosphorus) stay fixed and create an electric field. This area is called the depletion zone (because there are no electrons or holes); in sensor terminology it is also sometimes called a potential well.

3. It is in this well that our photo-generated electrons accumulate.

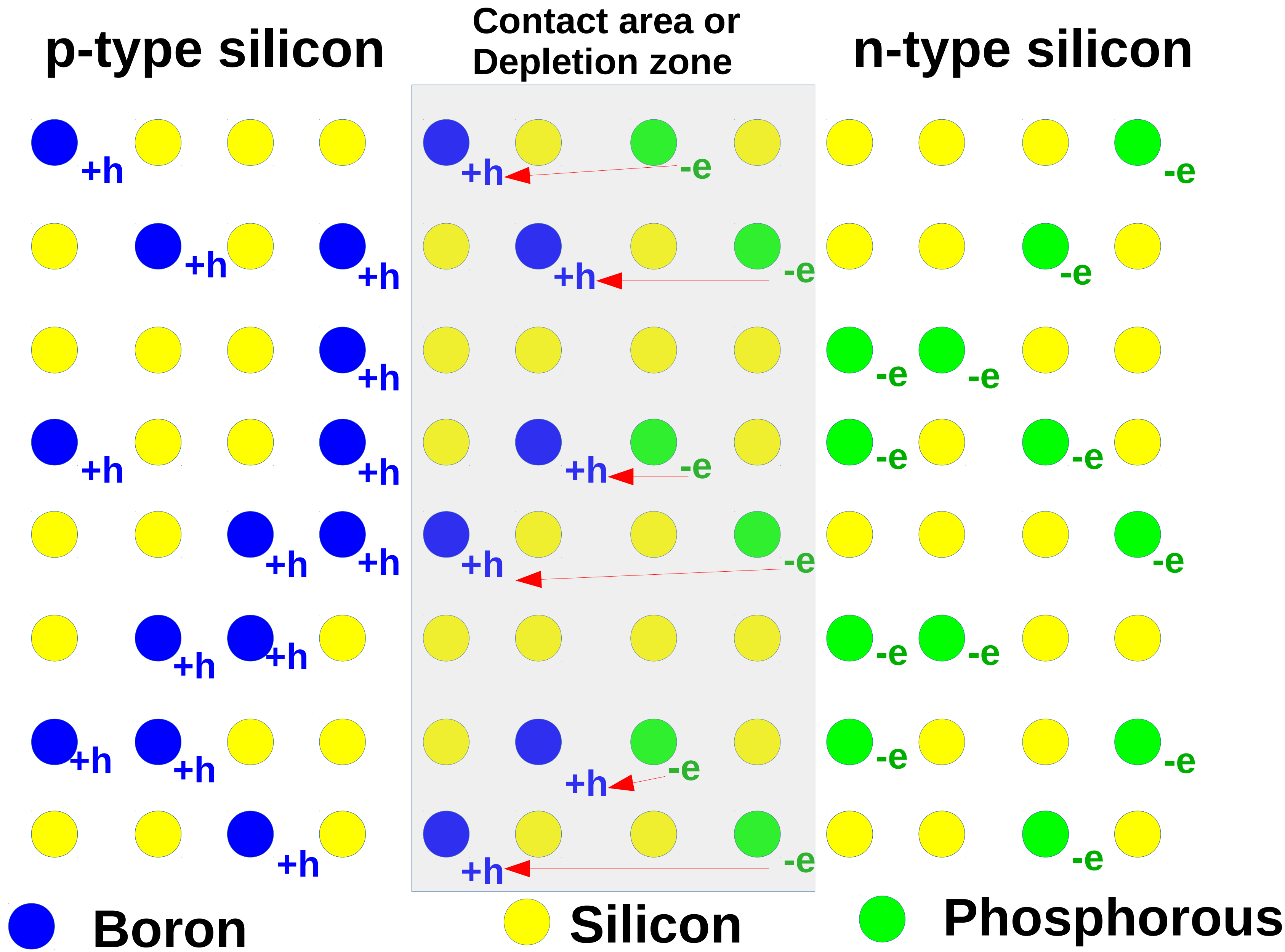
p-n junctions in action: the doped silicon

p-type silicon

n-type silicon

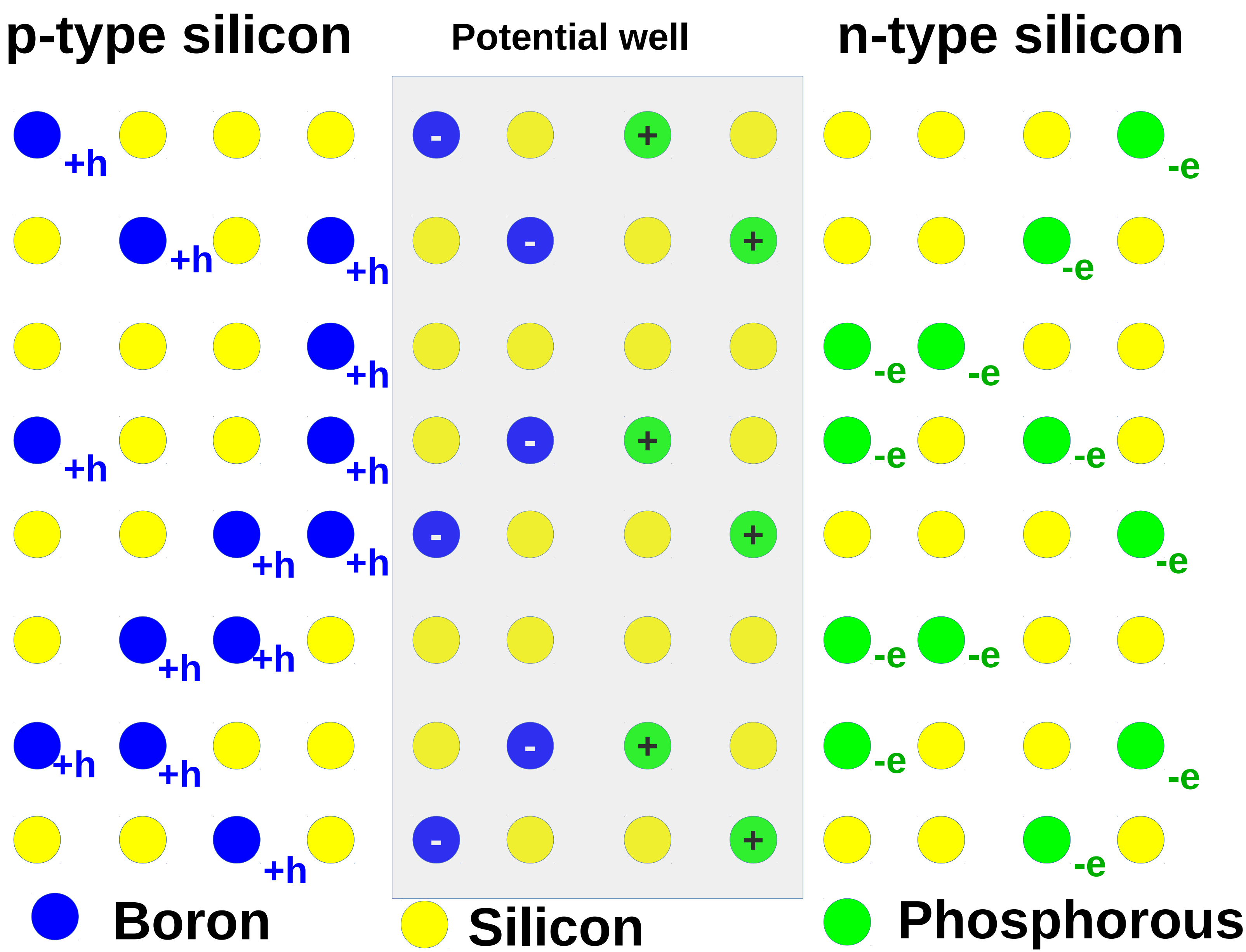


p-n junctions in action: contact and electron diffusion

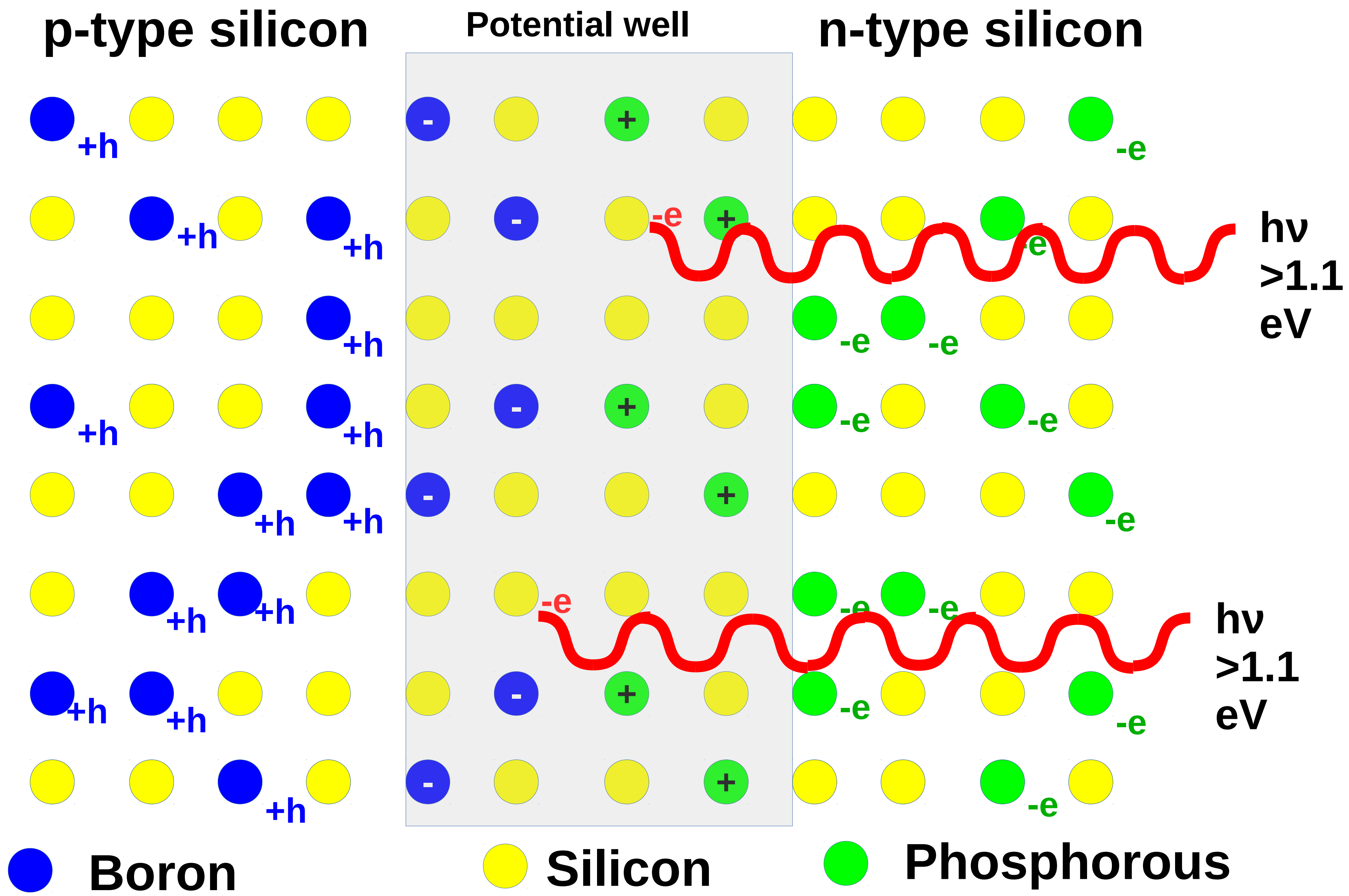


p-n junctions in action: capacitance well

The 'depletion' zone means that it is deplete of charge carriers ie electrons. It acts like a storage area, much like a capacitor stores a charge.



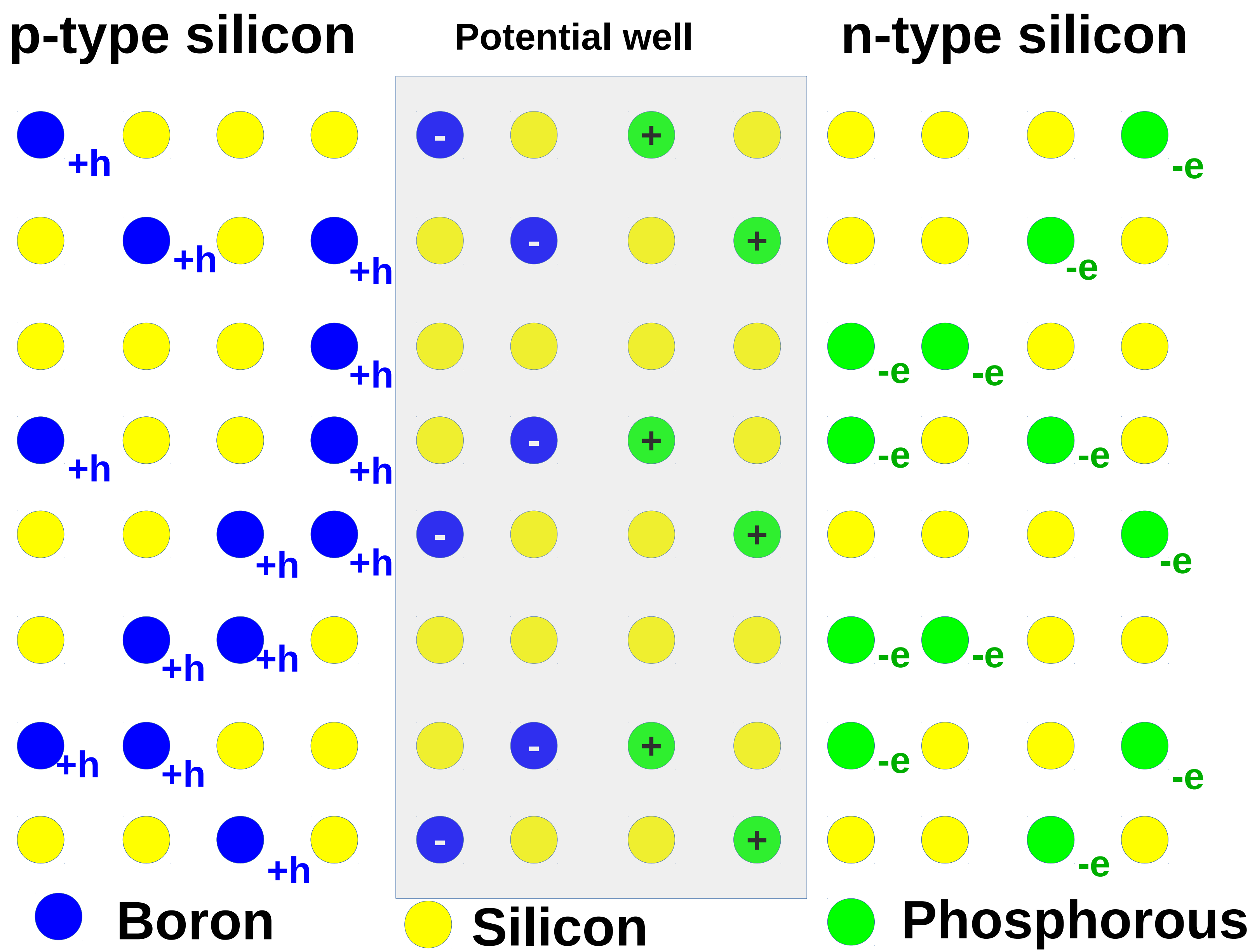
p-n junctions in action: photo-generated electrons



p-n junctions in action: Increasing the capacitance well

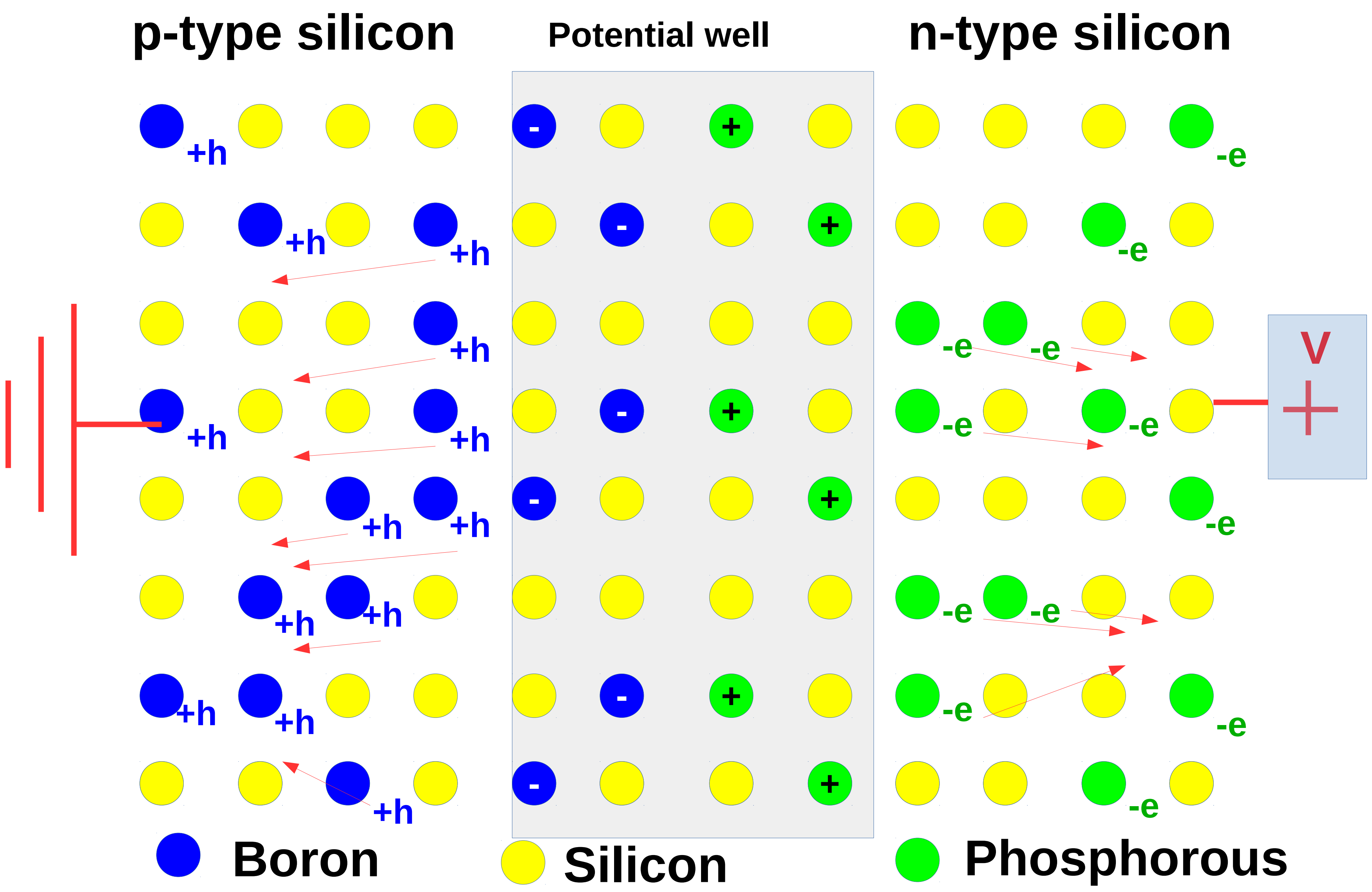
Since the potential well is of key importance in holding photo-generated electrons, can we modify it?

How can we increase its capacity?

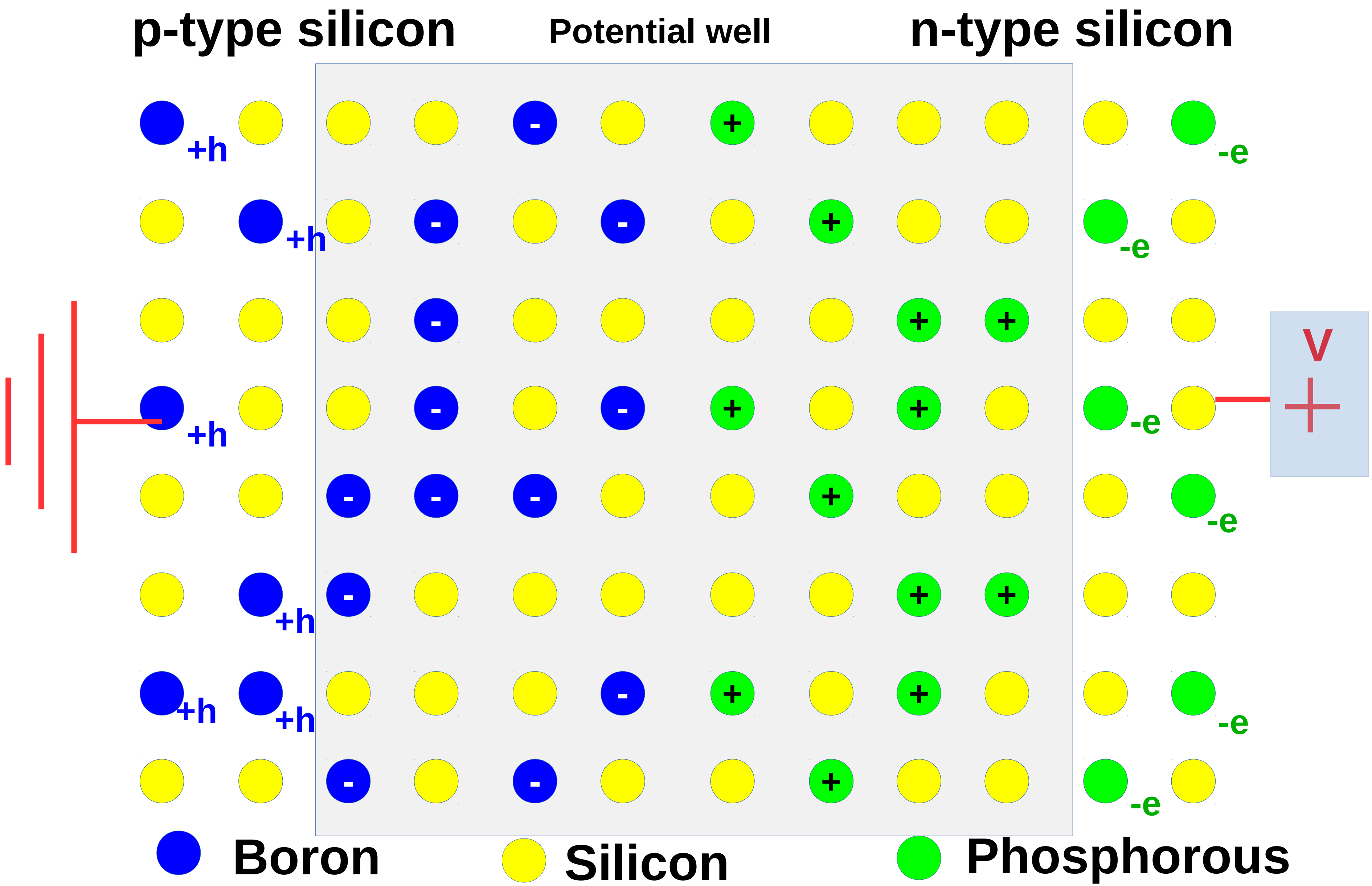


p-n junctions in action:

Positive voltage on the n-type: reverse bias



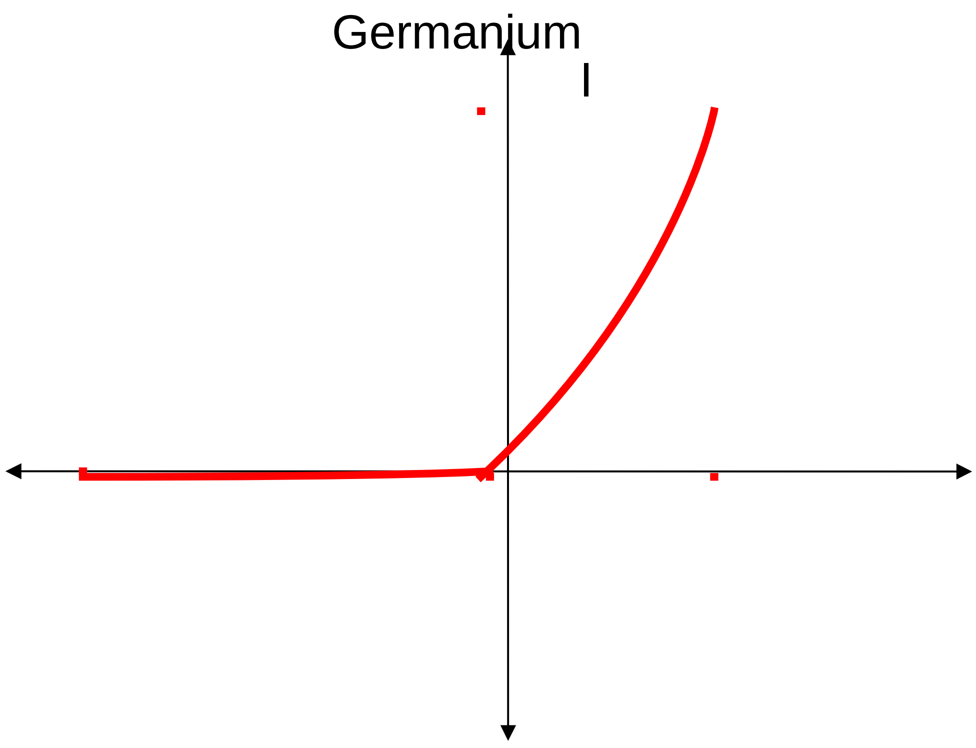
p-n junctions in action: Well capacitance increases

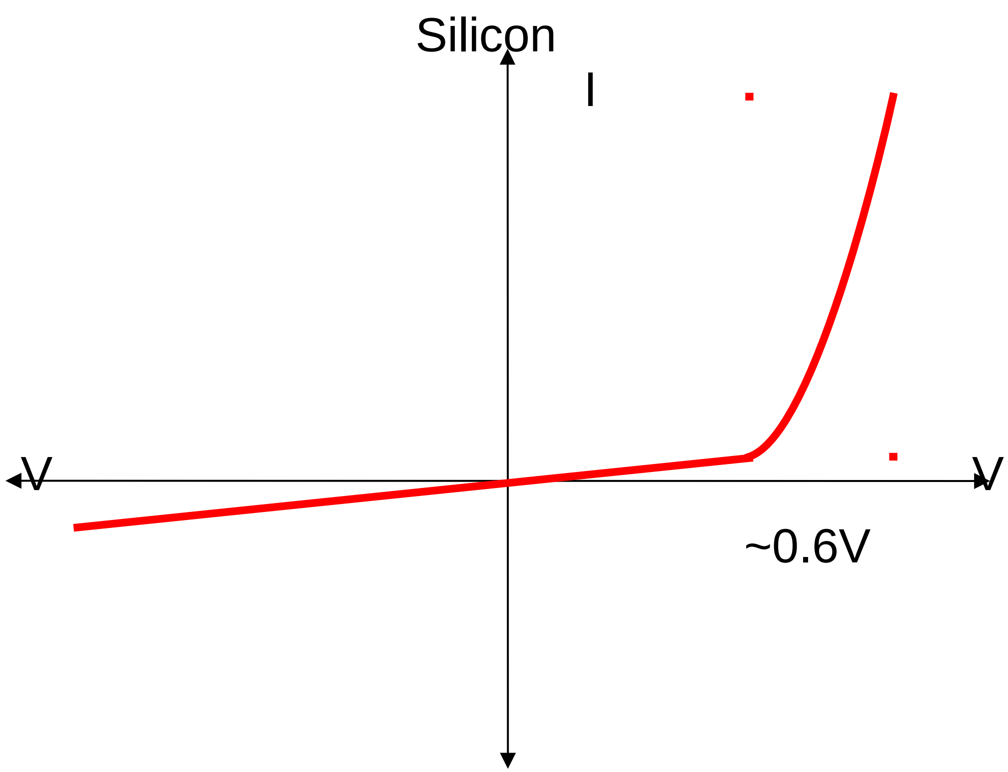


Semi-conducting physics

The p-n junction: current characteristic summary

The p-n junction exerts a remarkable control on the current and this depends on the direction of the applied potential. If the p-side of the junction is made positive the current flows easily and increases rapidly as V is increased. Conversely if V is negative very little current flows and, for large negative values of V, it flattens off to a constant value.





Significance of the potential well

- Where measured electrons due to light action are initially stored.
- Well size affects how many electrons can be stored. Effects such as saturation and blooming are caused by well capacity.
- Extraneous electrons (not created by light) cause issues such as noise and is one of the contributors to signal-to-noise ratios.
- Quantum efficiency is indirectly affected by well size.

Basic structure of the CCD: the Charge Coupled Device

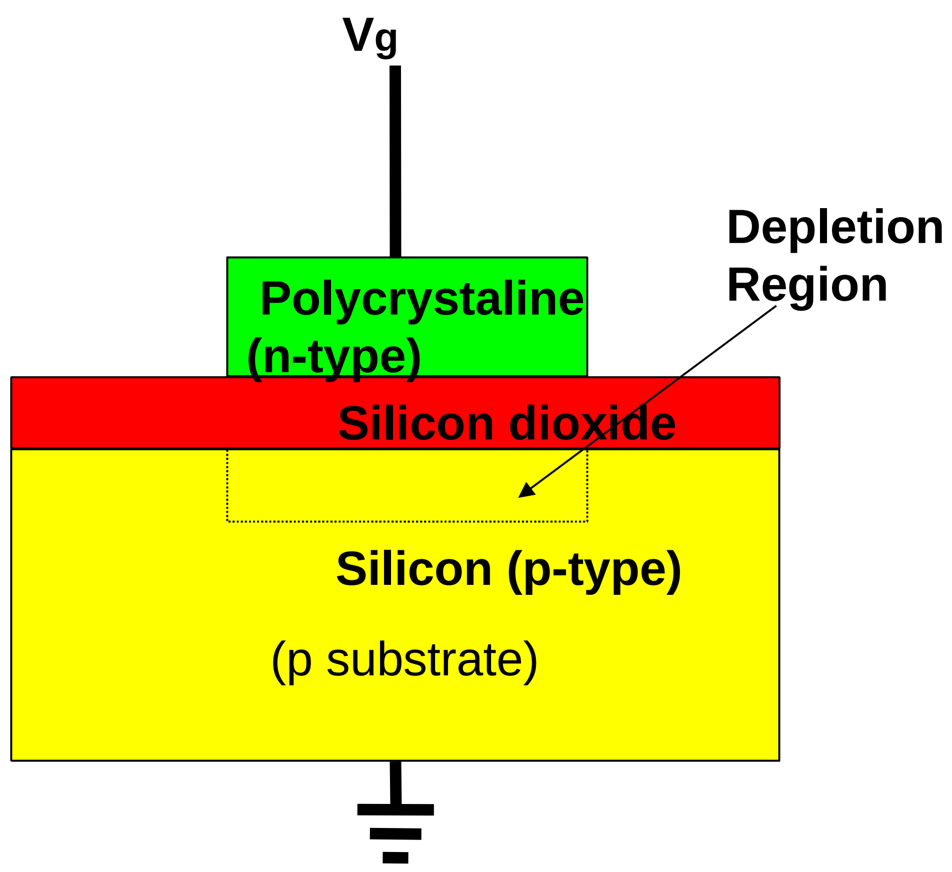
The CCD is based on a device called a Metal Oxide Semiconductor (MOS). This semi-conductor is known as a 'pin' type.

The polycrystaline is the n-type silicon

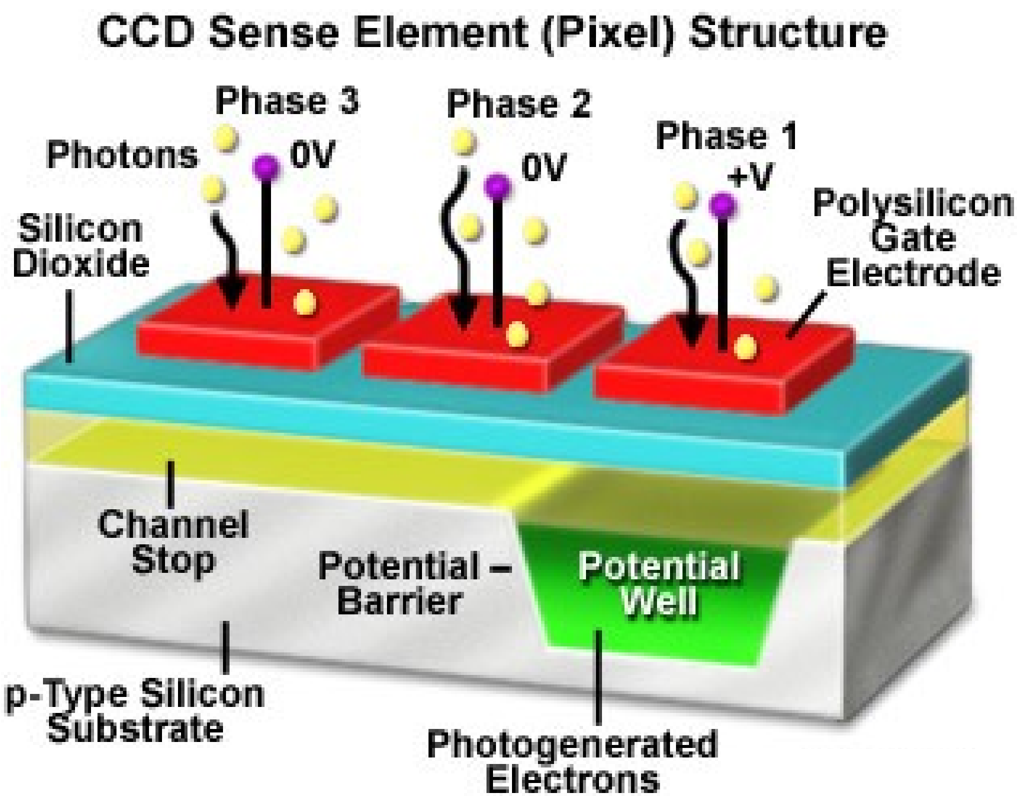
The silicon dioxide (oxide) is an effective insulator (8eV band gap)
It is the 'i' in 'pin'

The potential well forms in the p-type silicon, below the n-type polycrystaline.

A voltage (reverse bias) enhances the potential well and also enables well 'movement'



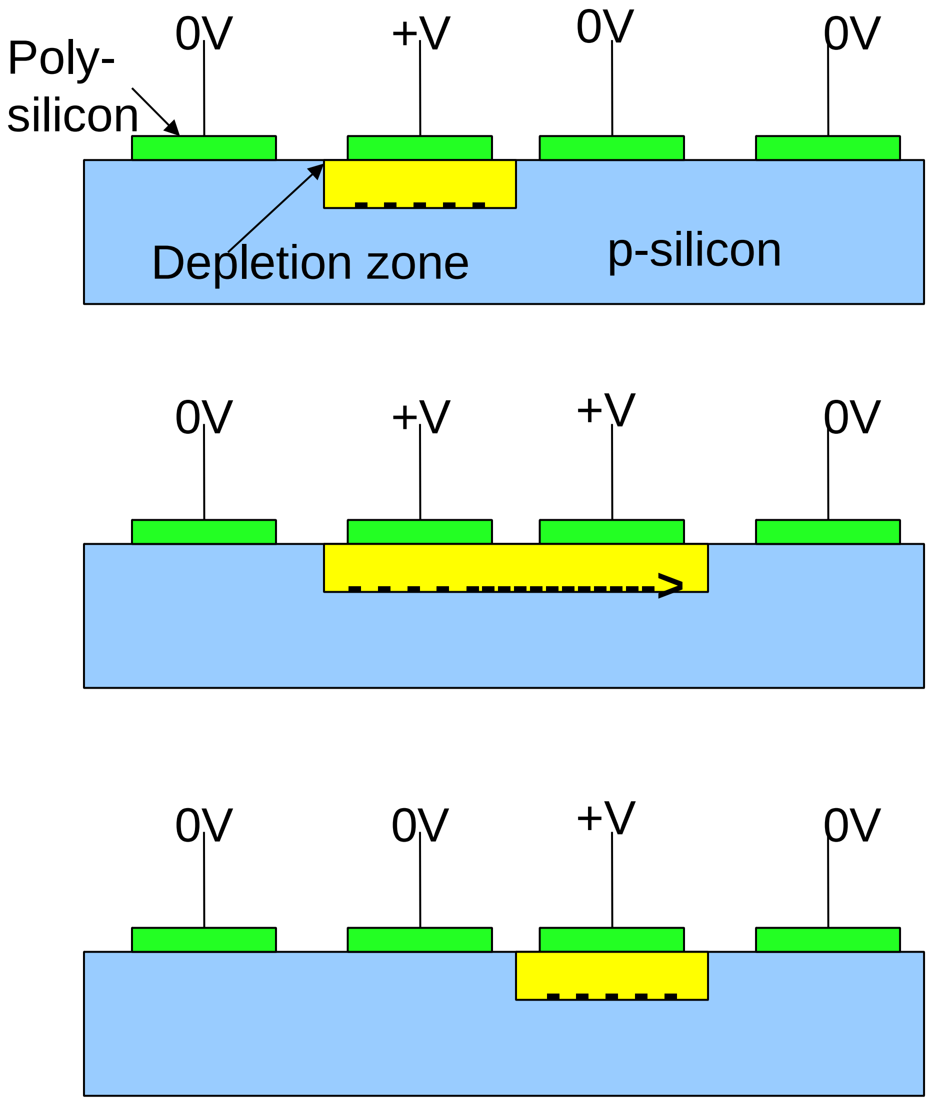
Applying the MOS diode basics to the charge coupled device



A three phase CCD pixel. The potential well
Is another term for the depletion zone. The
Channel stop is typically an n-type silicon
Designed to prevent photo generated electrons
From 'leaking' from the depletion zone

The CCD is a series of MOS units designed to accomplish the task of collecting and storing electrons generated by photons (the MOS device does this on its own) and transferring those electrons to a point for measurement.The MOS array, or CCD, performs this action via a phased applied voltage. Charge coupling refers to the method by which the photo-electrons are transferred by each MOS unit and applied positive voltage.

Photo-electron signal transfer by charge coupling

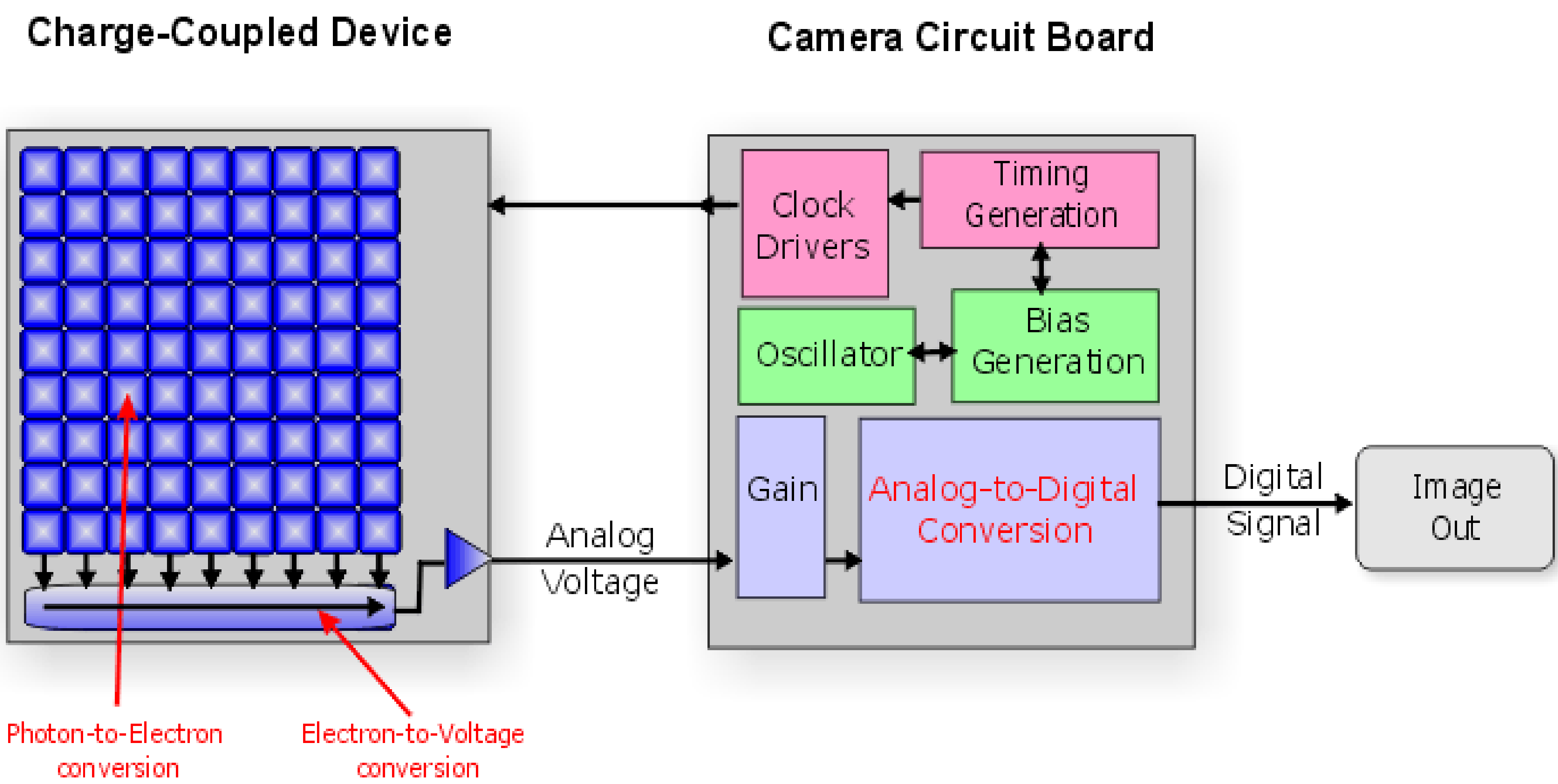


1. The charge is localised under the gate with the highest applied potentials because the positive bias (Vg) causes the underlying silicon to be in depletion state ie holes are created and electrons fill the depletion zone.

2. As the voltage of the adjacent gate is positively biased another depletion zone is formed and the electrons 'spill' into the adjacent potential well.

3. With a series of alternating voltage pulses, the electrons can be transferred down the array to a final output measurement device (bucket brigade type of movement).

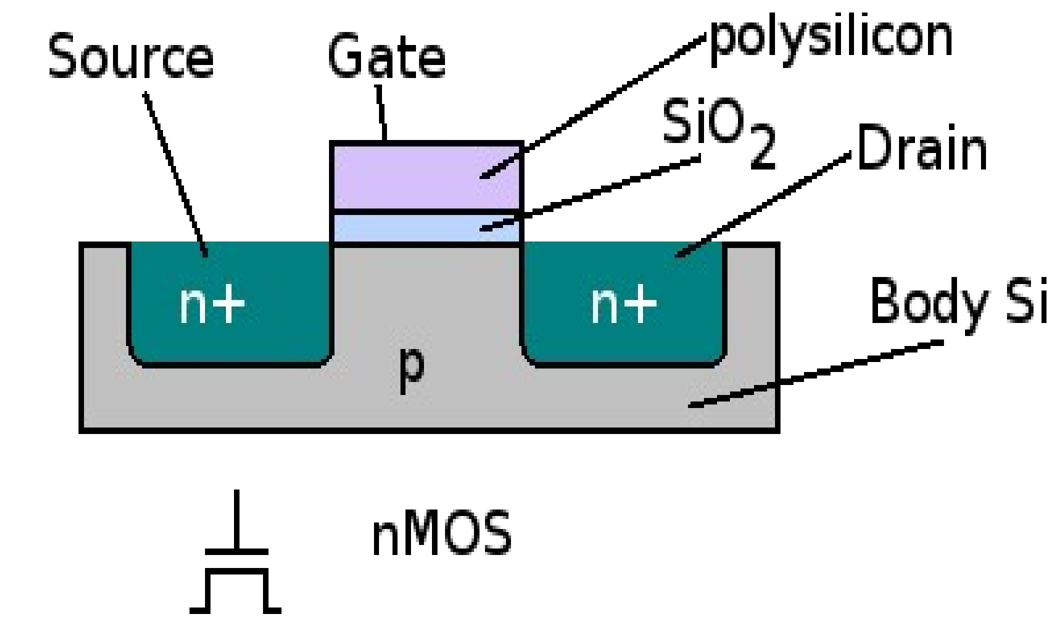
CCD: supporting circuit functions

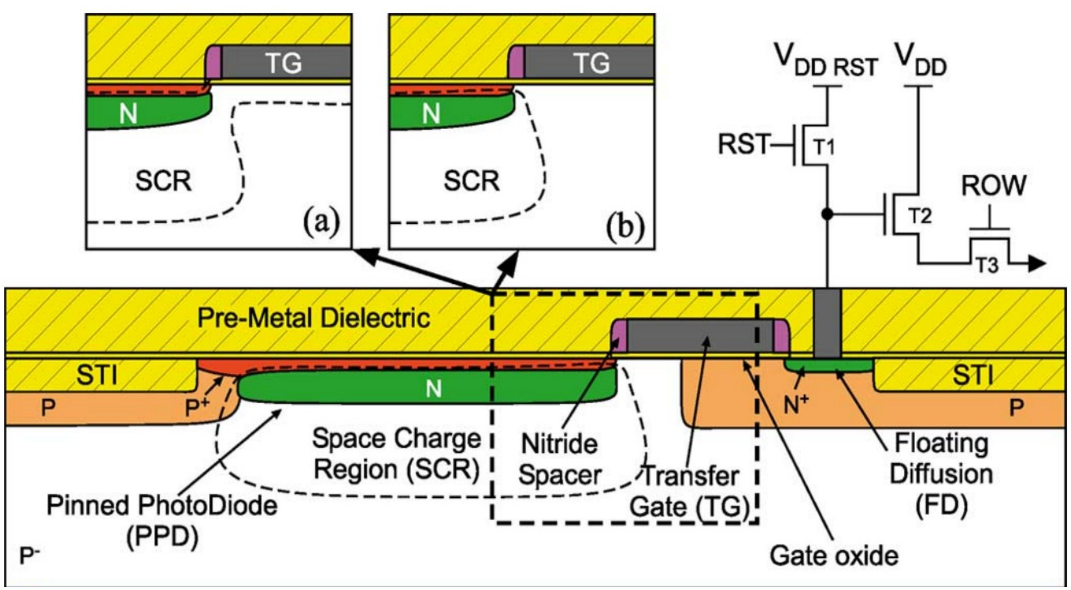


Basic structure of the CMOS: Complementary MOS

- Since the CMOS is basically a 'MOS' type of device, it functions essentially in the same manner as a CCD in converting photons to electrons.
- The key difference is that it does not transfer the electrons from pixel to pixel to be converted to voltage but it transfers electrons from <u>within</u> the pixel to a voltage-converting device.
- The term 'complementary' refers to the *on-off switching* action of two MOSFET devices <u>**on**</u> the pixel (a nMOS (+V,on) and/or a pMOS (+V, off)); they work in complement in the CMOS
- In a CMOS there is more hardware on the pixel than a CCD and there are consequences to this..more later.

CMOS structure





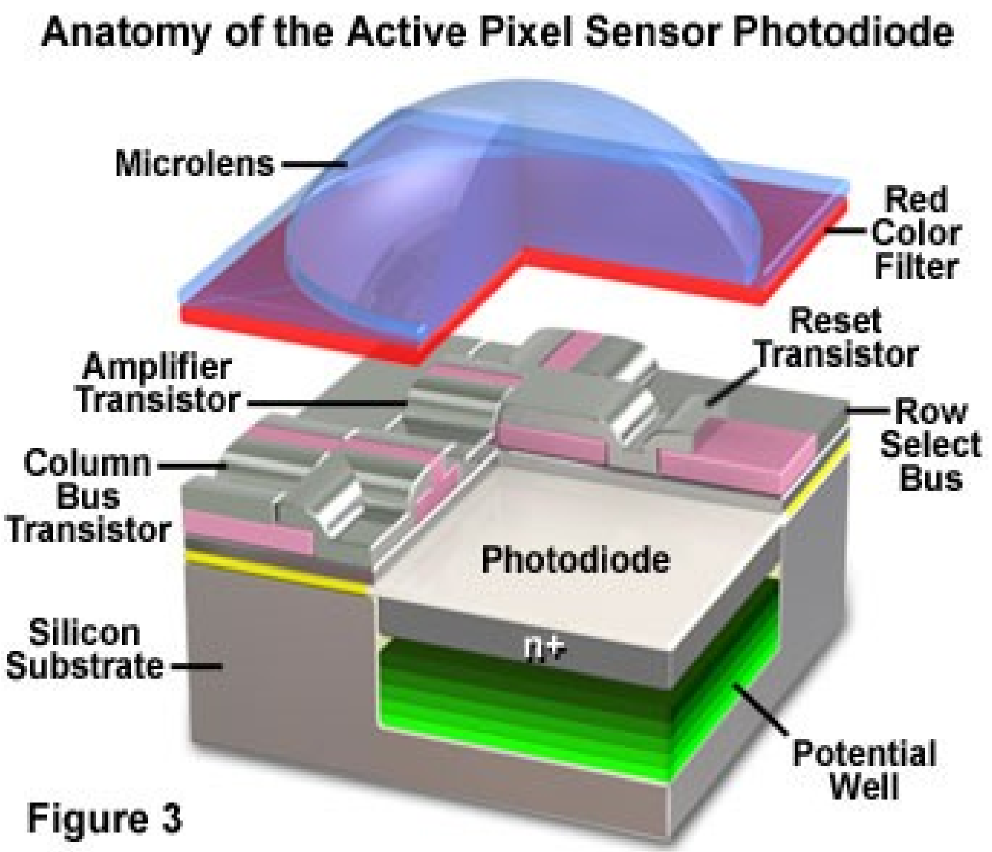
- Key components of a CMOS device are:
  - Source, also the photodiode area (PD). This is the potential well zone (SCR) and where electrons are formed from photons.
  - Transfer Gate (TG), under positive voltage a transfer channel is created under the gate to move electrons from the source to..
  - Drain, or Floating Diffusion (FD) area for next level processing.

Next level processing

- The electrons representing the amount of light that hit the sensor (now in the 'Drain' or Floating Diffusion area) need to be converted to voltage for measurement.
- The typically low voltage reading is then amplified to provide a better signal.
- Upto this point all processes are analogue
- The amplified voltage signal is then put through an analogue to digital coverter (ADC) to create the familiar 'bits' that a computer can process.

A few details on CMOS sensors

- CMOS have a significant amount of transitor hardware right on the pixel.
- This lowers the amount of area available for actual light sensing.
- Micro lenses are added to gather light.
- CMOSs range from 3T upto 6T types.

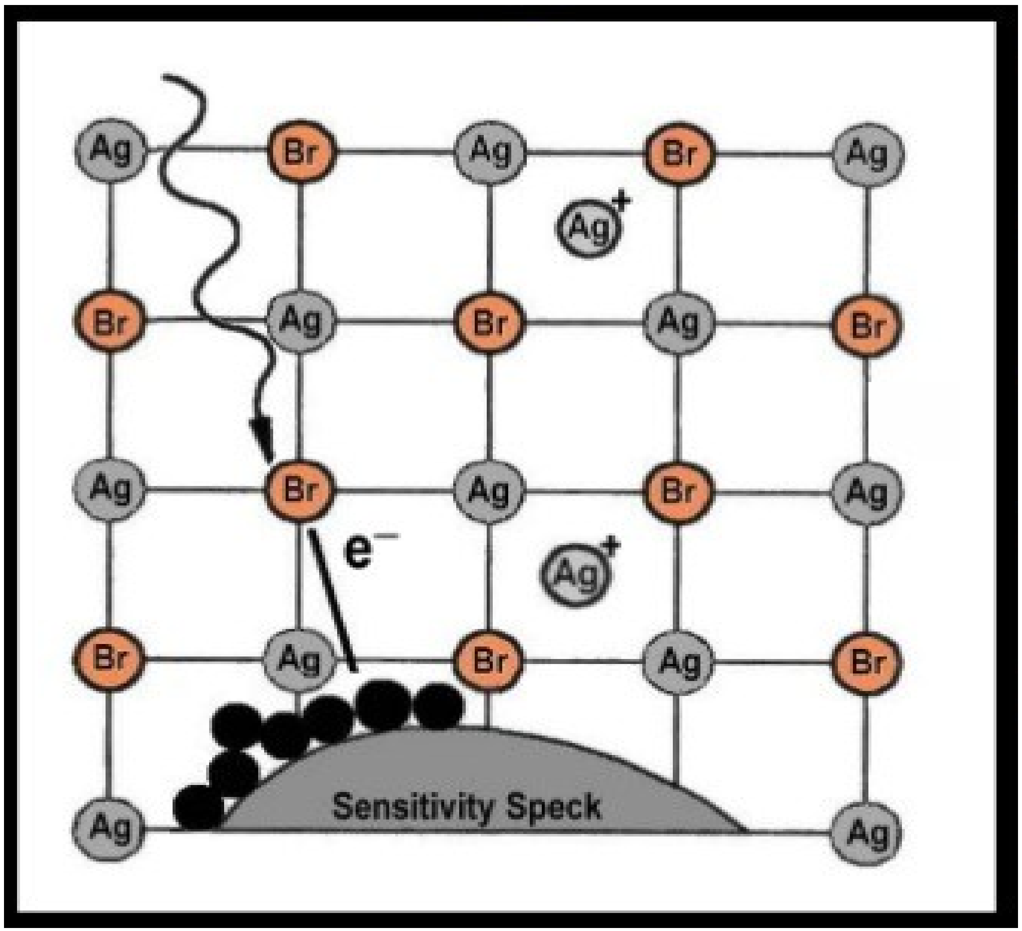


A 4T (four transitor) type CMOS pixel

Silver halide sensors

- Silver halides, like silicon, also use the photoelectric effect to convert photons to electrons.
- Thus film photography, at its core, is essentially an electronic process.
- As noted, 2.5 eV energy is needed to excite the electron into the conduction band. This is typically blue light.
- Therefore, the basis of film photography is based on the semi-conductor properties of silver halide.

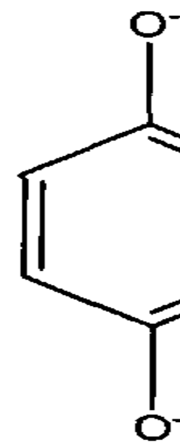
The silver halide exposure process: G-M Theory



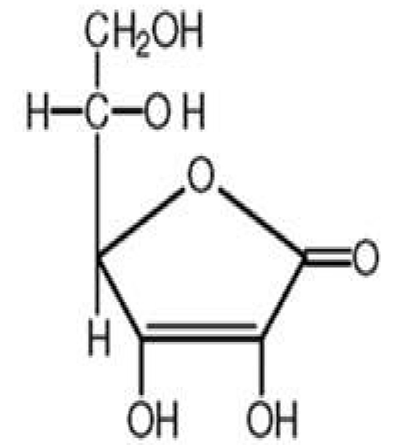
- A photon is absorbed by the Br- ion (2.5eV)
- The electron enters the conduction band and is trapped elsewhere at a ***sensitivity speck*** (usually silver sulfide).
- Interstitial Ag+ ions (due to lattice imperfections) are attracted to the negative speck.
- Ag+ and the electron produce silver metal (Ag) and a latent image centre is created.

Image Development

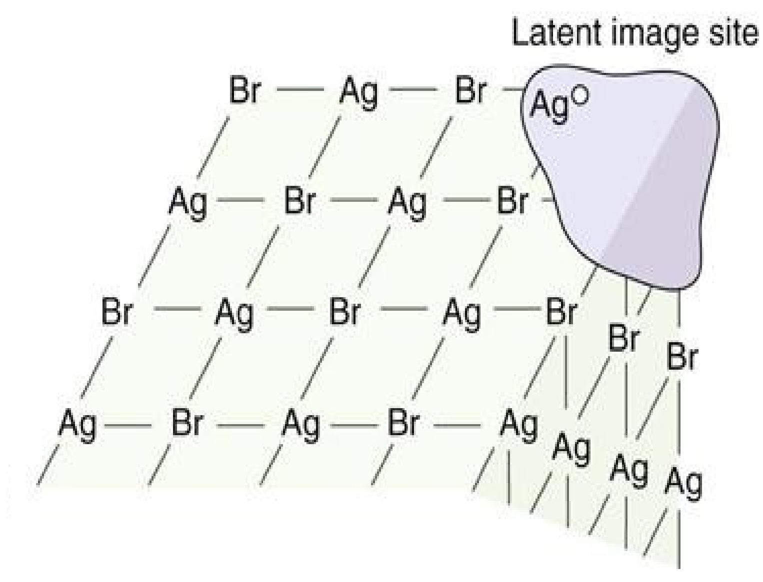
- In silicon the electrons are amplified via transistors.
- In AgBr the electrons that create the latent image are amplified *chemically via an electron donor..*
- The developer molecule is attracted to the silver speck and proceeds to reduce (convert Ag+ to Ag) the complete crystal.
- A AgBr grain is never partially developed.



Hydroquinone



Ascorbic Acid



Recapping the important concepts in sensor functions

1. Two types of sensors are generally available:
   a) Digital sensors (silicon based), of which two types are commercially used:
      i. CCD
      ii. CMOS
   b) Analogue sensors (silver halide based)
2. Both sensors are primarly electronic in that photons produce electrons that are then processed to create the image signal.
3. The surface area of the sensor is important since the number of photons captured is a function of that area, which is a determinant of sensitivity.

Recapping the important concepts in sensor functions

4. Both silicon and silver based sensors are 'activated' by the use of chemical dopants in the pure silicon and silver halide crystals.

5. The well capacity of a silicon sensor limits how many photo-generated electrons can be converted by light.

6. Noise, which we can define as electrons **NOT** generated by photons is present in both silicon and silver based sensors.

7. Silicon or silver halide sensors simply reproduce light quantity or intensity, color generation is a secondary process.

Understanding sensor performance

Now that we know the basic science and technology of how a sensor works we can investigate and evaluate a number of performance parameters of sensors.

- Pixel sizes and resolution
- Sensor sizes
- Sensitivity/saturation
- Noise
- Linearity
- Dynamic range
- QE
- Color/spectral rendition

Pixel size

- We started the course with the simplistic observation that 'more pixels is better'.
- We now look at this statement through the understanding we've gained of sensor functioning.
- We also noted that the statement needs to be qualified by, at least, knowing the pixel size of the sensor in question.
- So, let's look at pixel and sensor size and identify the advantages and disadvantages inherent in the 'large' and the 'small'.

Pixel size – Fill Factor

- The area (fill factor) of the larger pixel is 4X the smaller pixel.
- It can capture 4X the number of photons.
- It would have, at least, 4X the light sensitivity.

  Larger pixels are generally more sensitive, as expressed by ISO, than smaller pixels.

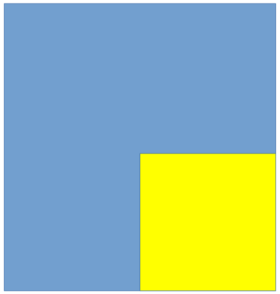
4 micron pixel = 16 microns^2

8 micron pixel = 64 microns^2

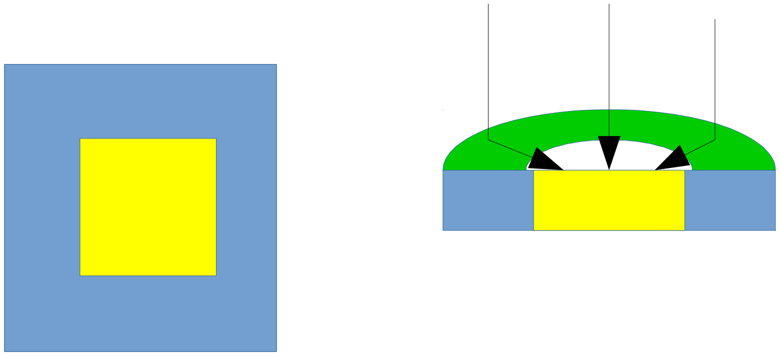
Pixel Fill Factor – CCDs vs CMOS

- The full surface of a CCD is available for incoming electrons
- With CMOS part of the surface area is occupied by voltage converters and reset transistors. Fill factor decreases.
- Centering the photodiode and adding a lens increases efficiency again.

CCD 5 micron pixel fill factor =100%



CMOS 5 micron pixel fill factor =75%



CMOS 5 micron pixel fill factor = close to 100%

Sensor size

- As noted at the beginning of the course sensor size does need to be assessed along side of pixel pitch.

  For example:

  Let's say we had to compare:

  – A 10 Megapixel sensor with a 5um pixel pitch vs.
  – A 15 Megapixel sensor with a 10um pixel pitch
  – A 20 Megapixel sensor with a 10um pixel pitch

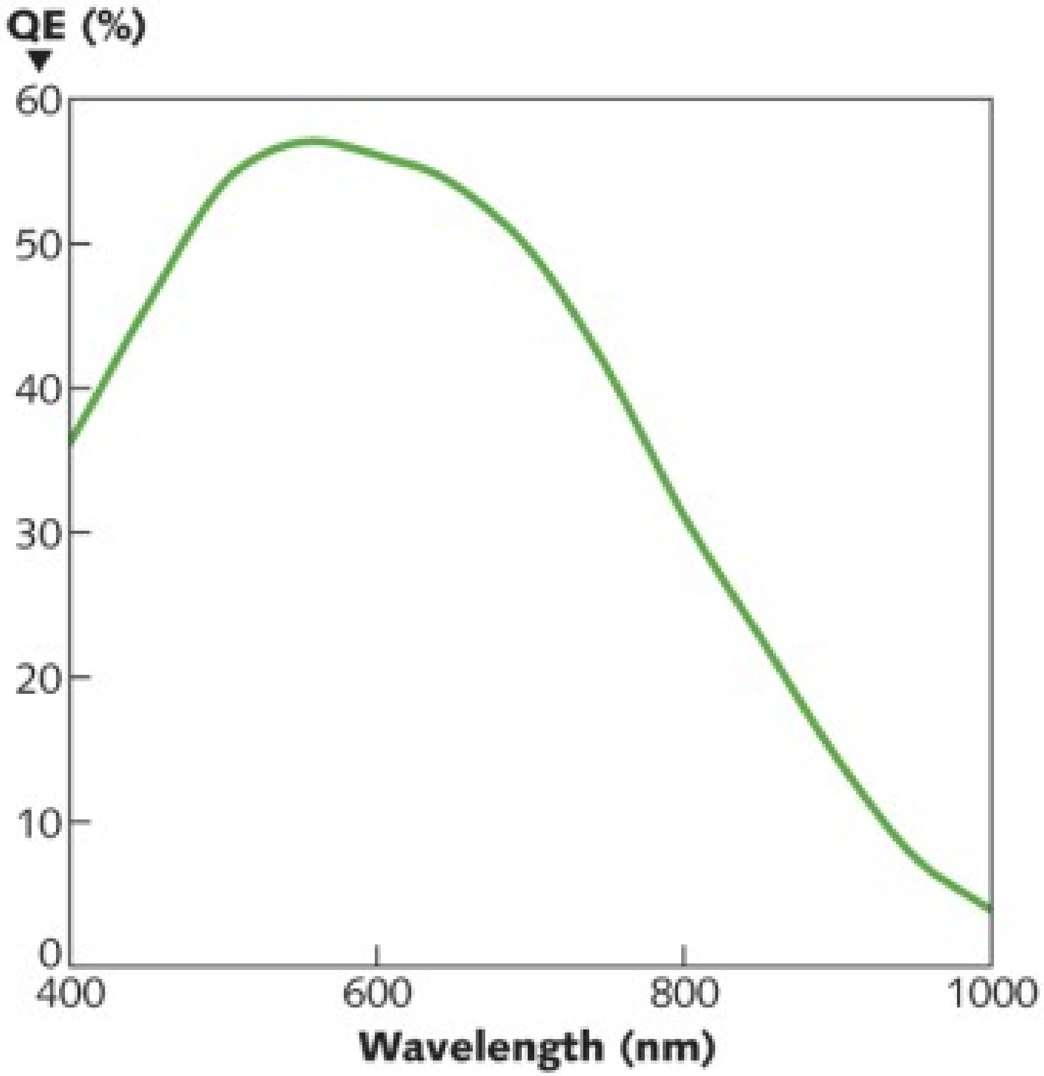
  Can you rank these sensor sizes from best to worse?

Quantum Efficiency

Quantum efficiency (QE) is simply a ratio of the number of photons required to produce one electron. It is expressed as a percentage. The higher the QE, the more sensitive the sensor.

QE is wavelength dependent with maximum efficiency around 500nm to 700nm.

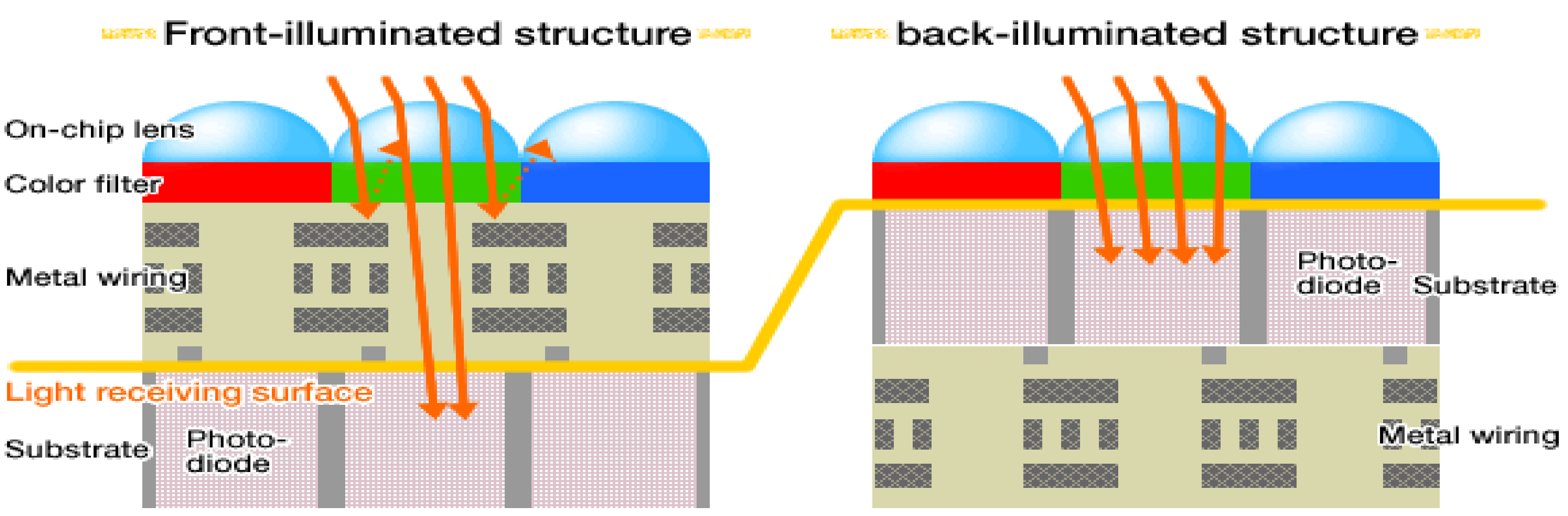
The challenge for manufacturers is how to get more area available to the incoming photons..



A typical CCD QE curve

QE and design factors

We've already looked at how small lenses are used to collect more photons (and increase QE). Another fabrication technique is to 'back light' the pixels ie. Place the transistor hardware under the photosensitive surface. This design is especially important for CMOS types.



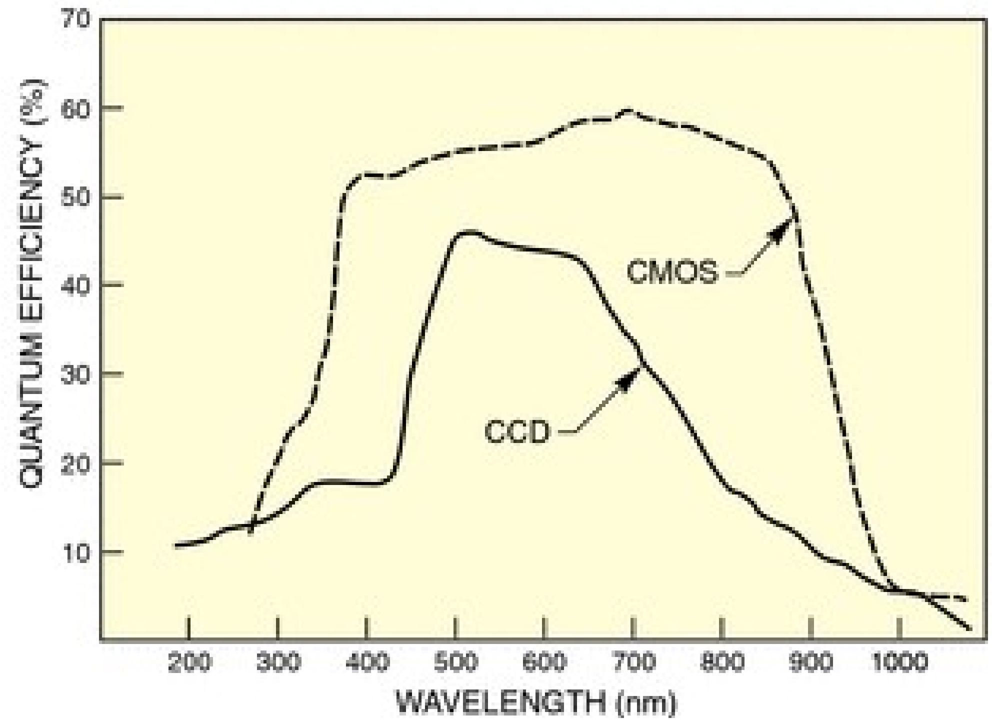
QE = ~50% **QE = ~80%**

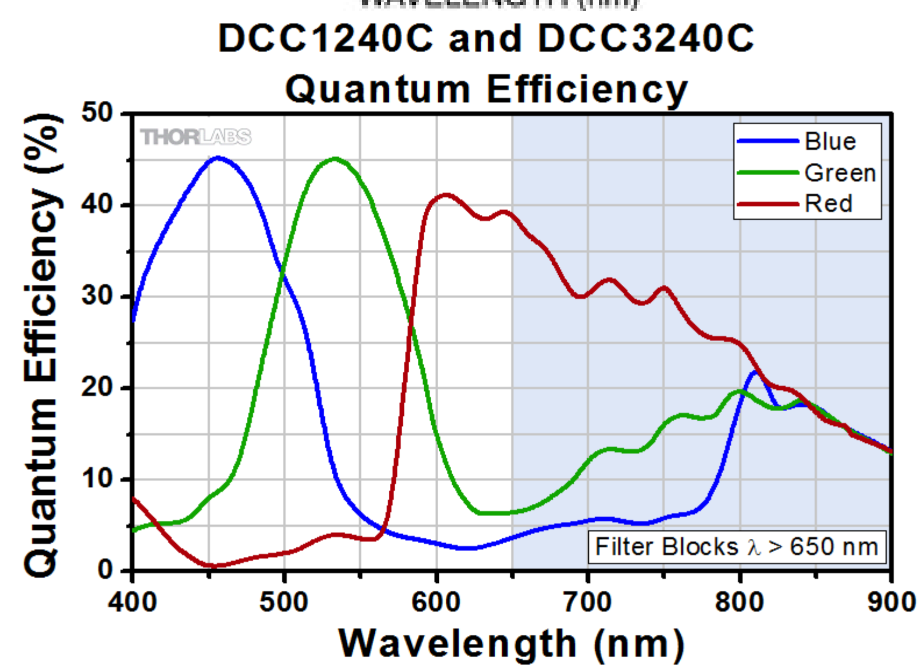
QE: CCD vs CMOS

A CMOS generally has a higher QE than a CCD, all else being equal.

A CMOS has also a higher QE in the NIR portion of the spectrum making it better for NIR imaging.

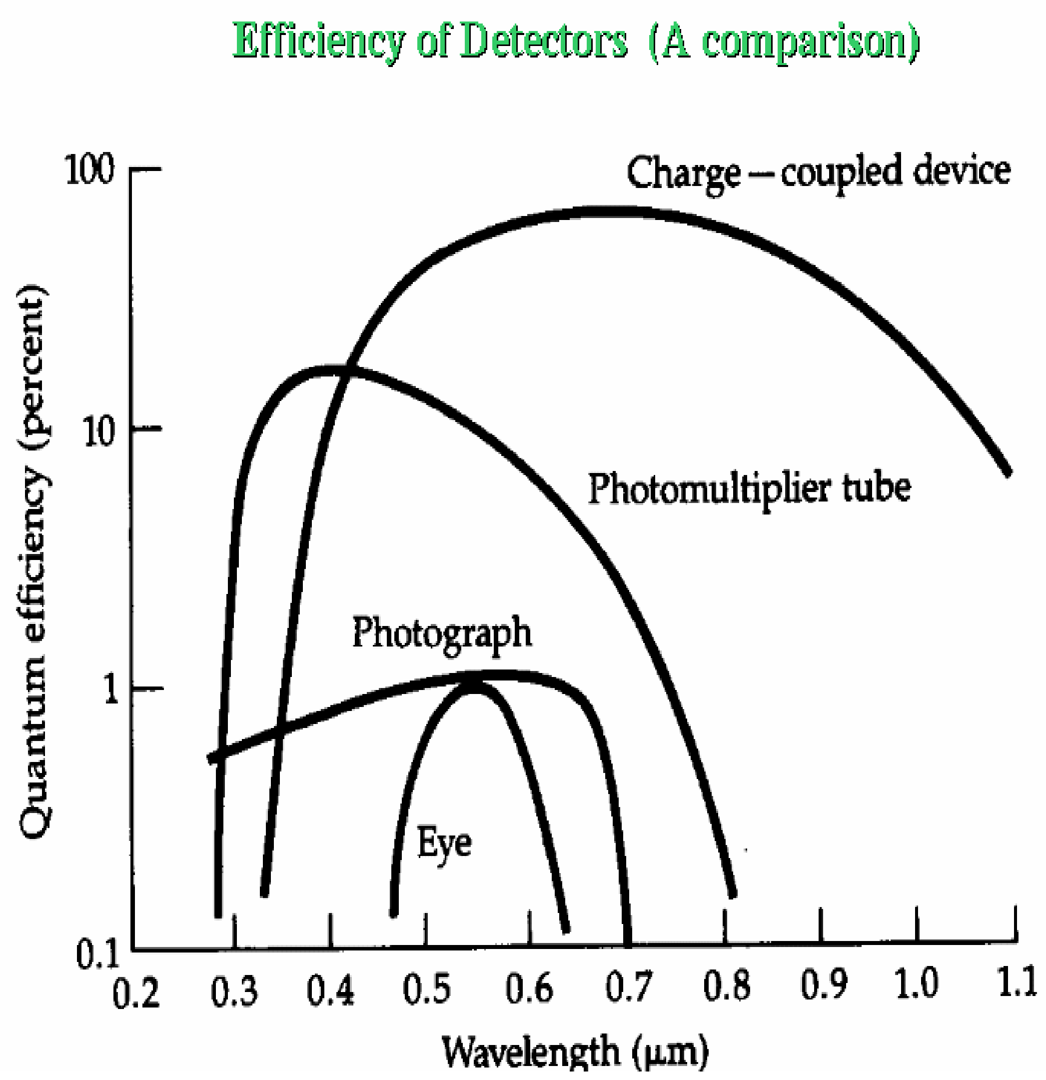
Since most image sensors have a color filter array on the pixels, the QE is further modified as per the example in the diagram----------------->





QE: silver halide

- QE of film emulsions usually stated to be less than 10%, ie. 10 photons to produce one latent image AgBr.
- Current (past 10 years) advances have raised the QE to 50%, however the advances have not made it to market due to the low film demand.



Full Well Capacity

The well potential (deletion zone of the p-n junction) and its *capacity* to hold electrons determines the characteristics of some key imaging parameters:

- Sensor sensitivity – a larger well = more electrons
- Saturation limits – a larger well provides better detail in highlights
- Dynamic range - a larger well can reproduce more tones from shadows to highlights
- Noise – larger wells reduce the Signal-to-Noise ratio (SNR), more later..

Well capacity is generally measured in number of electrons, tens of thousands is typical.

Large Well Capacity factors

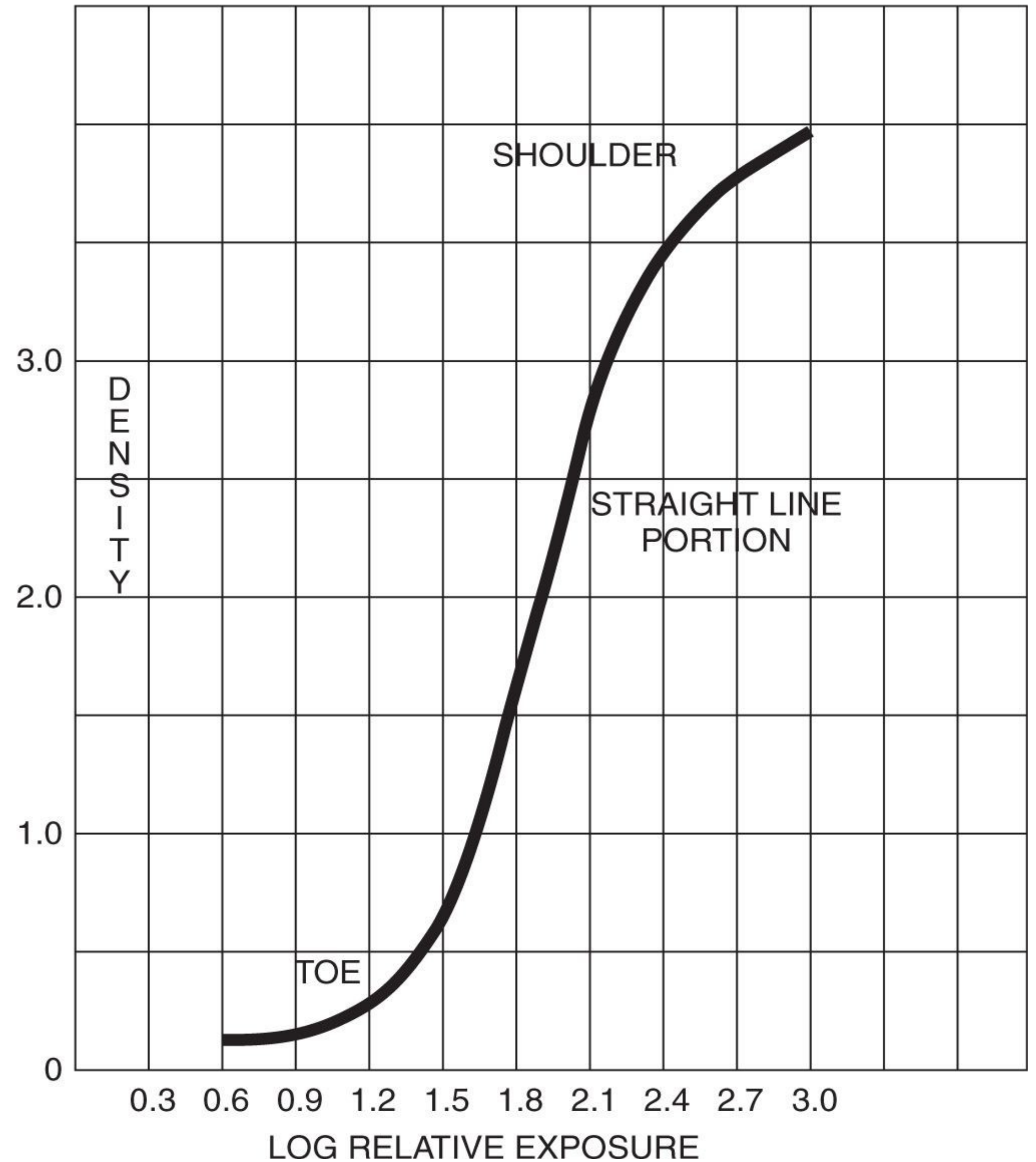
- Pixel size. A larger pixel size (depth is important) will have a larger capacity which means a wider dynamic range, less prone to saturation effects (blooming) and, as seen previously, will be more sensitive.
- Voltage. Usually referred as *reverse bias (positive at the gate).* A positive potential on the gate repels positive holes and attracts electron which increases the depth of the potential well.
- Pixel Architecture. Was generally higher with CCDs but with today's technology CMOS wells are equivalent.

Well Capacity – some cameras

Camera	Sensor type	MegaPixels	Pixel size	Well Capacity
Canon S70	CCD	7.1	2.3	8200
Canon 7D	CMOS	17.9	4.3	24800
Nikon D300	CMOS	12.3	5.5	45000
Canon 300D	CMOS	6.3	7.4	45500
Nikon D3	CMOS	12.1	8.5	65600

Does the concept of well capacity apply to film?

- The short answer is 'no' but..
- Exposure saturation is common in film (blown highlights) but this occurs as an agregate of AgBr crystals, not as as individual crystals like with pixels.
- AgBr crystals are either completely developable or not.



Saturation controls Silicon & AgBr

Si	AgBr
• B and Ph doping	• Film emulsions rely on silver sulfide (AgS) doping to produce sensitivity centres
• Reverse bias (depth)	• Volume is produced by amount of latent image developable grains
• QE = 30%-60%	• Most photo-electrons recombine with holes (90%) 10% - 50%

Sensor Noise

Sensor noise hampers sensor performance. It is most often noted in sub-optimal ISO quality and compromised dynamic range.

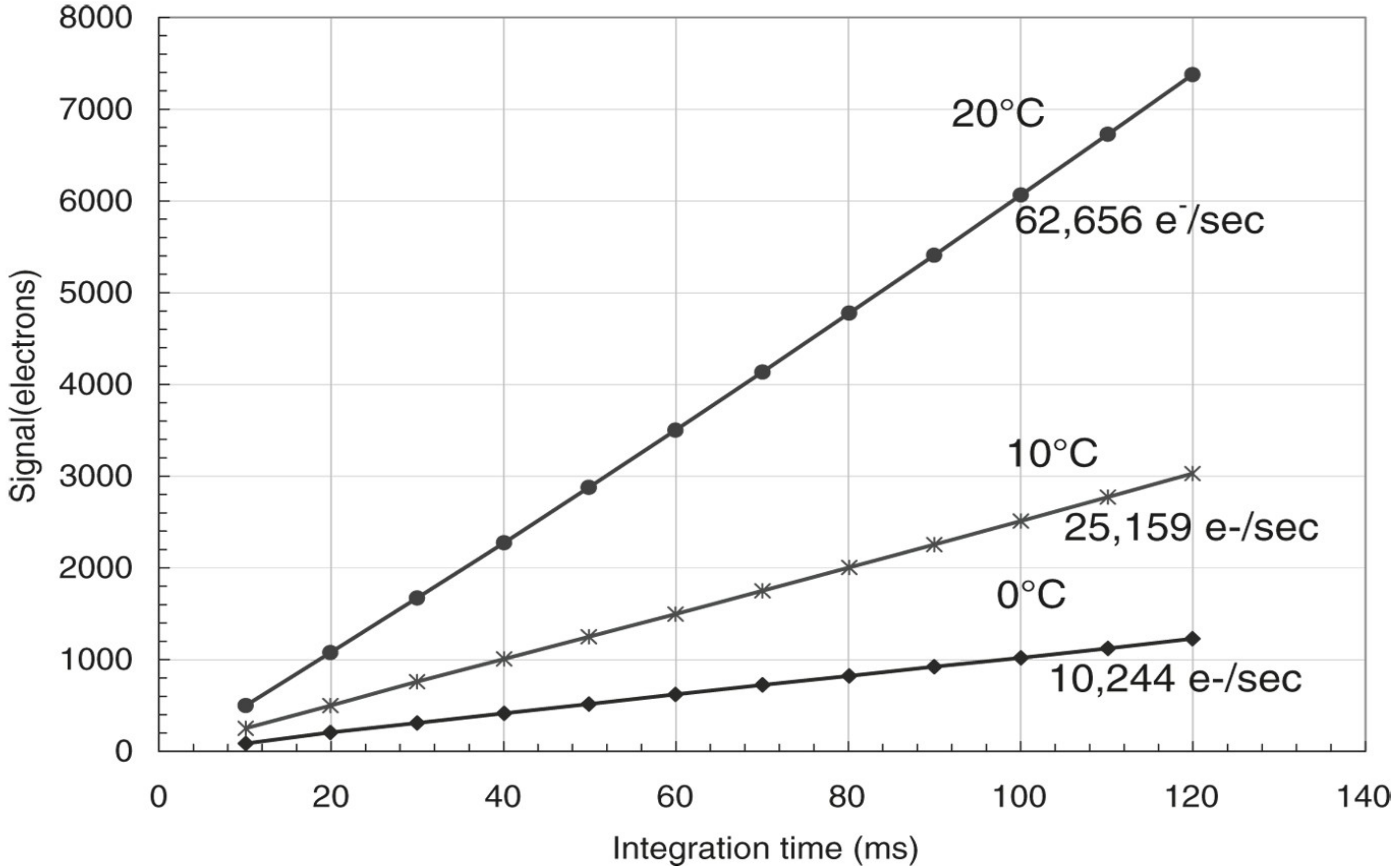
- Noise is simply electrons in the imaging system <u>not</u> produced by image-forming photons.
- Noise in the silver halide world is referred to as 'fog'; it is also a result of silver halide crystals not activated by photo-generated electrons.
- The variable that defines noise performance is called the signal-to-noise ratio or SNR (also S/N ratio). A higher SNR is better than a lower SNR (altough not always), let's look closer..

Sensor Noise – Sources

1. **Dark Current.** This is thermally induced noise produced simply because of the p-n junction; it is the outcome of a n-type silicon in contact with a p-type silicon. A field is created even if no light is present.
2. **Fixed Pattern Noise.** Caused by inconsistencies in the sensitivity of the pixel, which in turn is due to the variations in the film thickness and aperture area.
3. **Shot Noise.** Generated by the statistical variations in the number of photons striking the pixel.
4. **Readout Noise.** This is thermally dependent noise caused by the electronic hardware used to process the photo-electrons (amplifier, switching devices..)

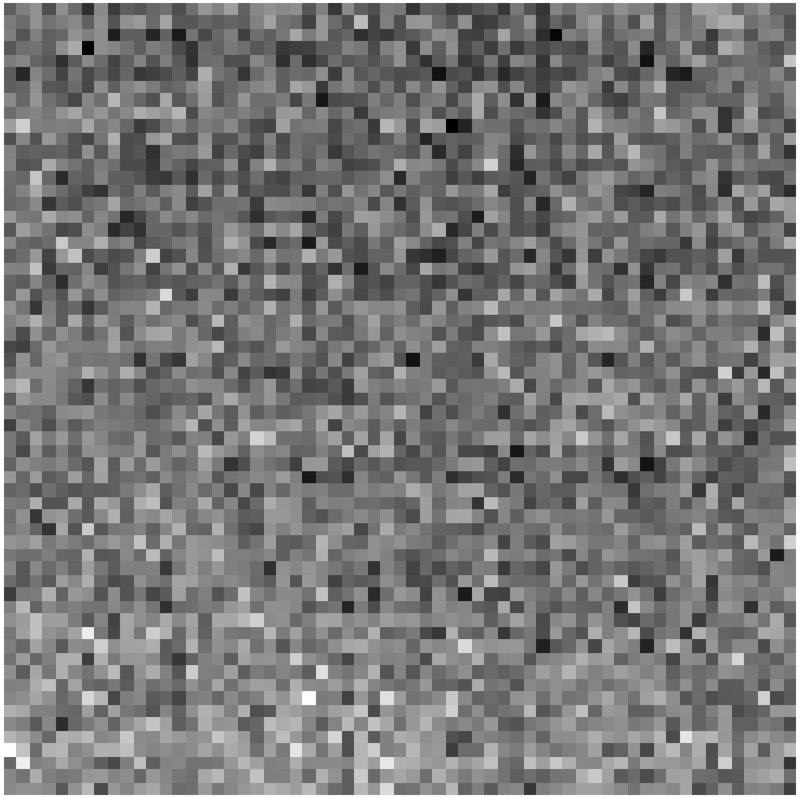
Sensor noise: dark current

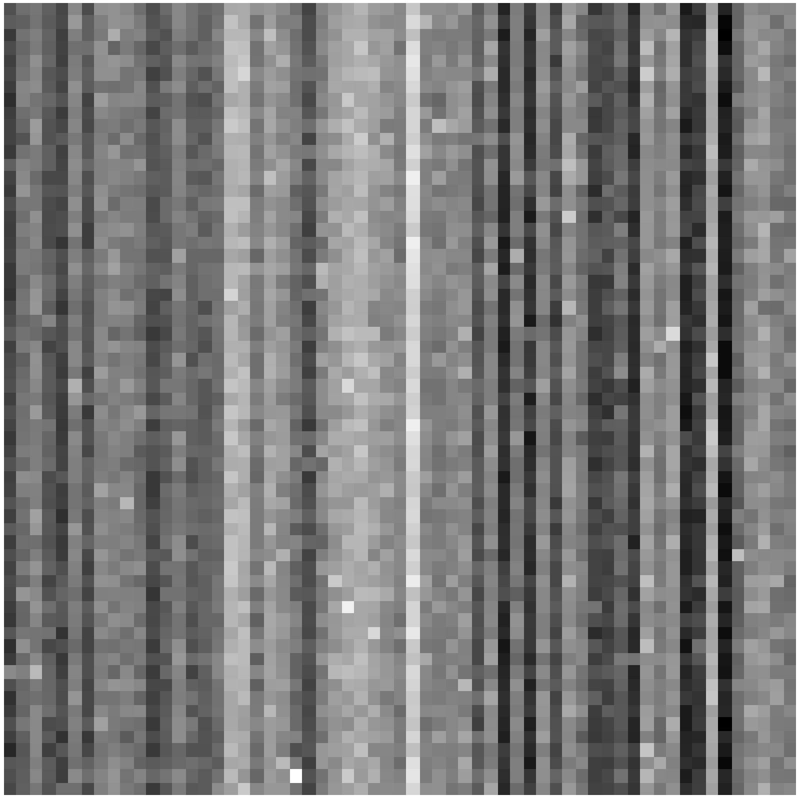
Dark current is electrons excited in the silicon lattice by thermal energy.



Sensor Noise: Fixed Pattern Noise

FPN tends to be discernable when longer exposures are used and is different on CCDs and CMOSs. Ideally, the images should be a uniform tone.



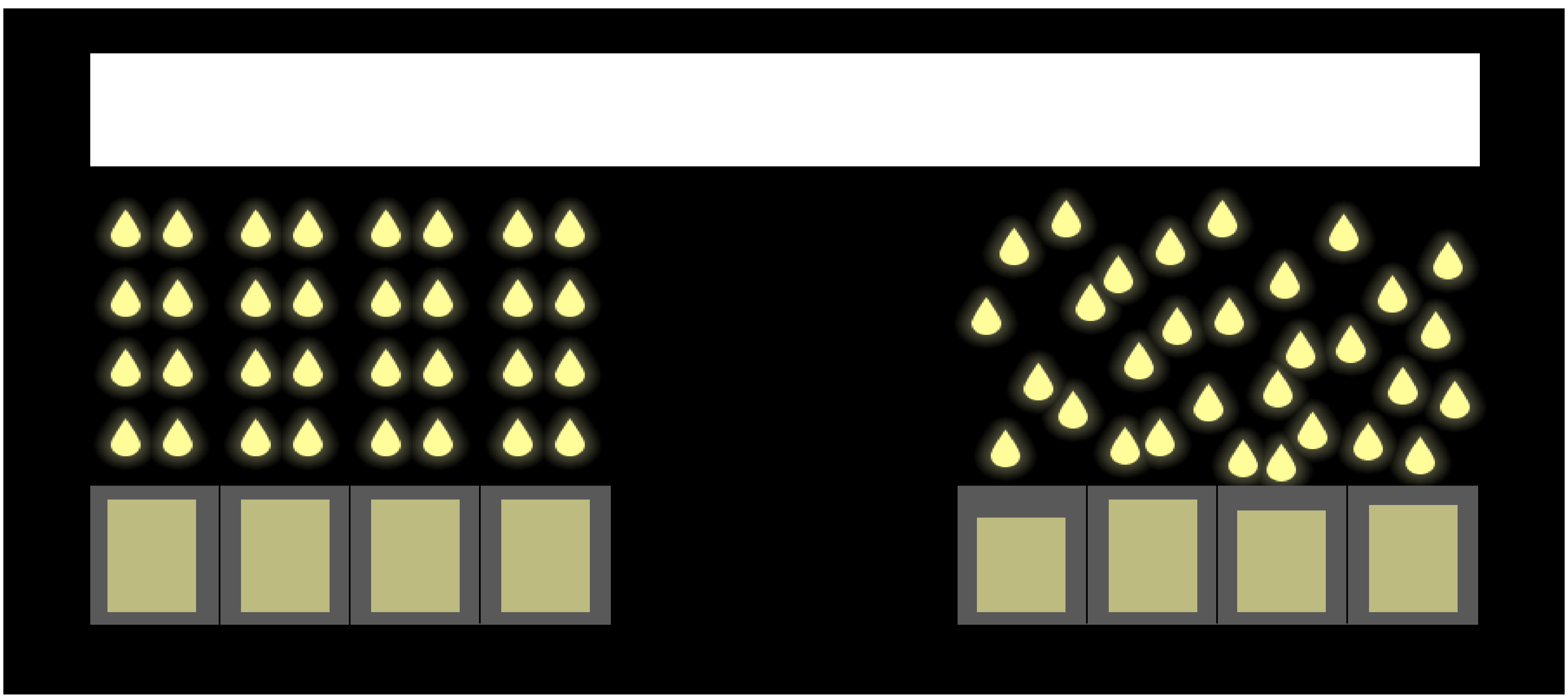


Source: A Novel Fixed Pattern Noise Reduction Technique in Image Sensors for Satellite Applications

Shahram Mohammadnejad, Mehdi Nasiri sarvi, Sobhan Roshani, Saeed Roshani

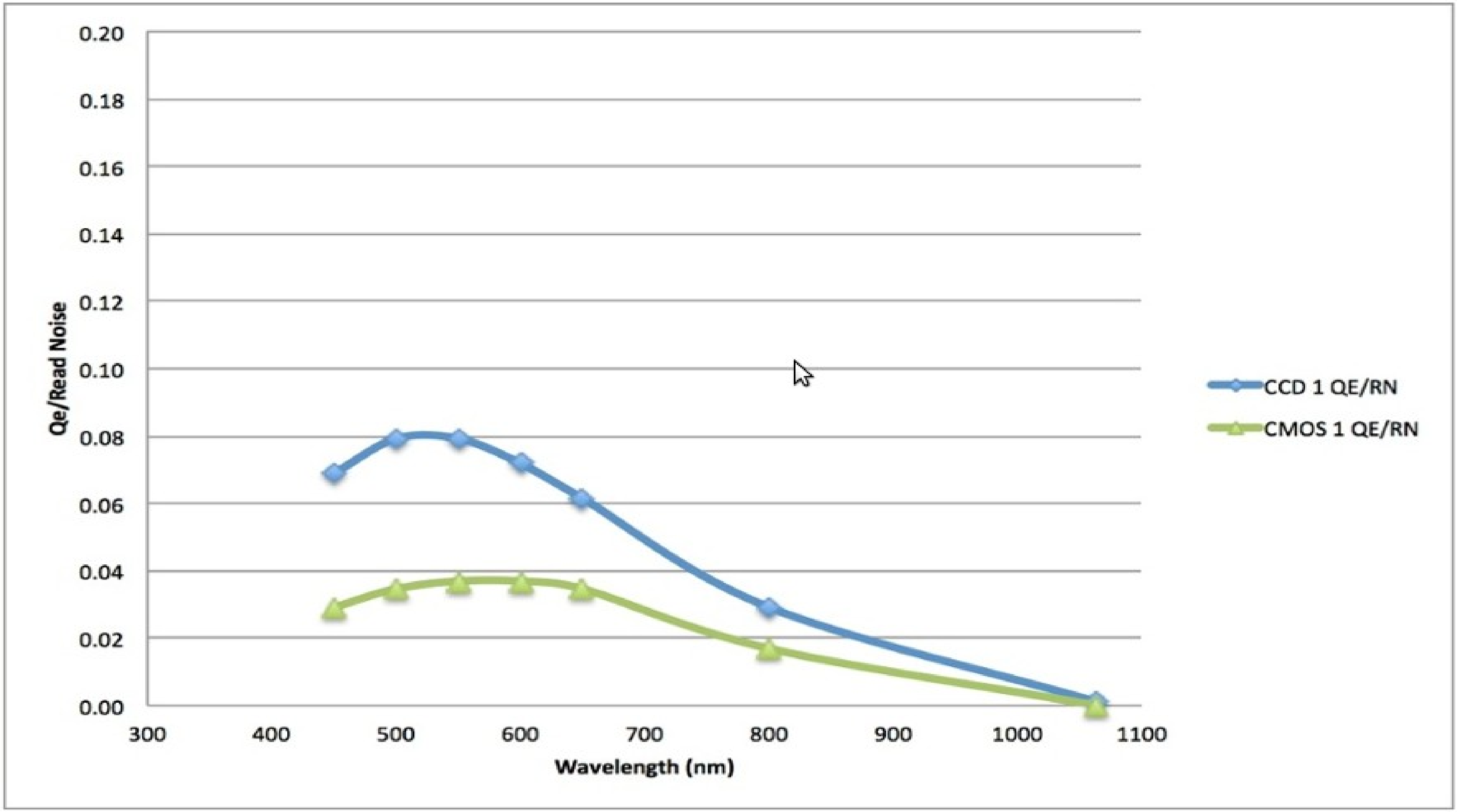
Sensor Noise: Shot Noise

A Poisson distributed occurence of random electrons produced by photons and current. It is temperature and frequency dependent and defined as N = SQRT(e), e is the total electrons



Readout Noise

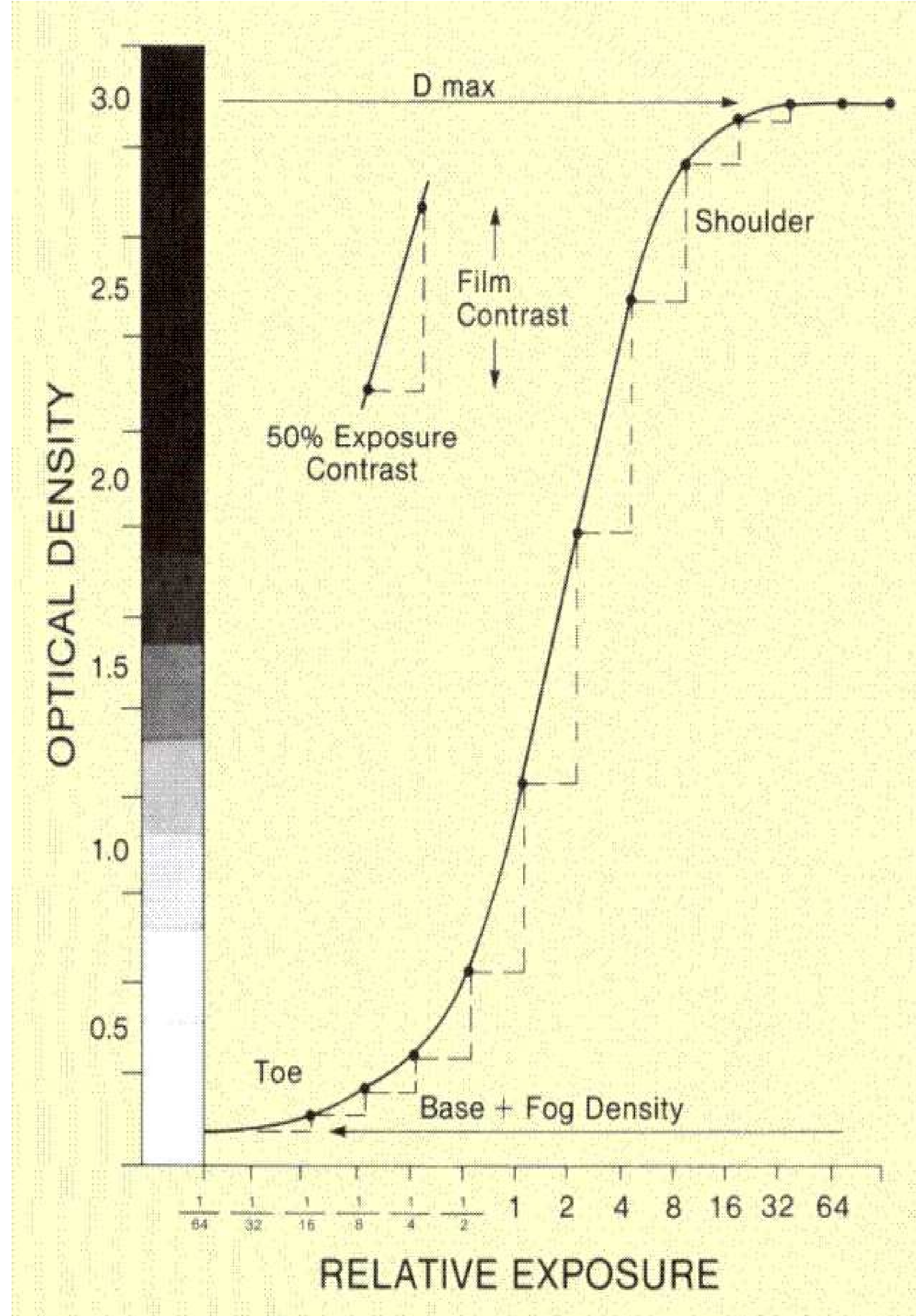
Noise attributed to the hardware on a pixel or sensor, such as the switches, amplifiers, and converters. CCDs will generally have lower readout noise than CMOSs because their on-pixel circuitry is less.



Noise in film

The term 'fog' is used to used to describe noise in unexposed film, it is the result of thermally generated electrons that create random developable silver grains.

The main effect of fog noise is to reduce the exposure range of a fillm emulsion.



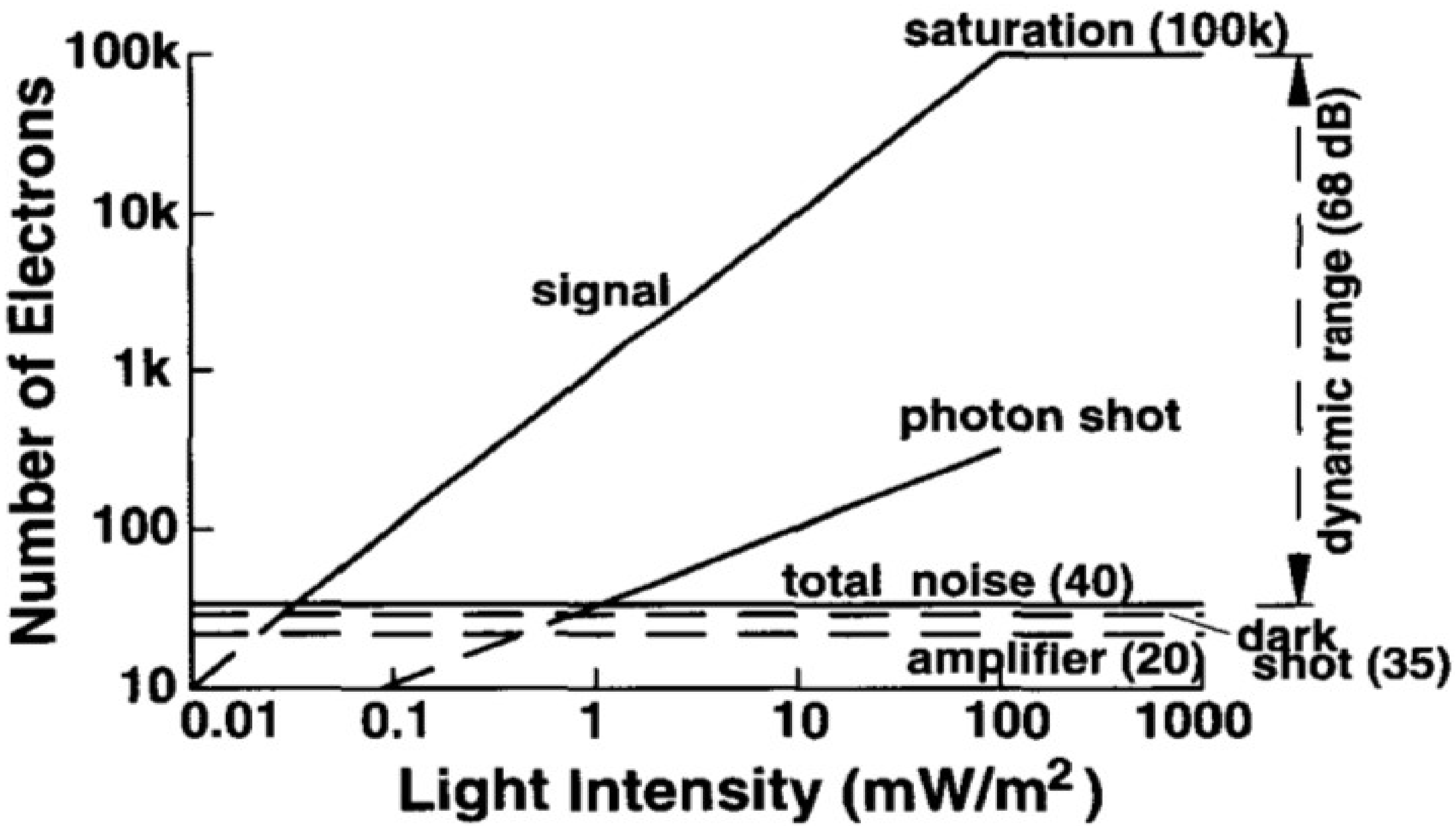
Signal-to-Noise Ratio

- The signal-to-noise ratio (SNR) is the metric that sensor manufacturers describe system noise.
- It is calculated by taking the image source electrons (S) and dividing by the summing all the noise source electrons (N); *S/N*
- It is typically described in decibels and therefore expressed as $SNR = 10\log(S/N)$. The measurement usually involves exposure of an 18% reflectance target at a specified ISO.
- Here is the SNR for the Canon 7D; 40dB @ 100 ISO, 22dB @ 6400 ISO.
- As can be seen a larger SNR is more desirable.

Dynamic Range

It is a function of a couple of the variables we have investigated: Saturated well capacity and noise.

It defines the range of exposure or, as we've seen, the range of image generated electrons that the sensor and the associated circuitry can encompass.



Dynamic Range

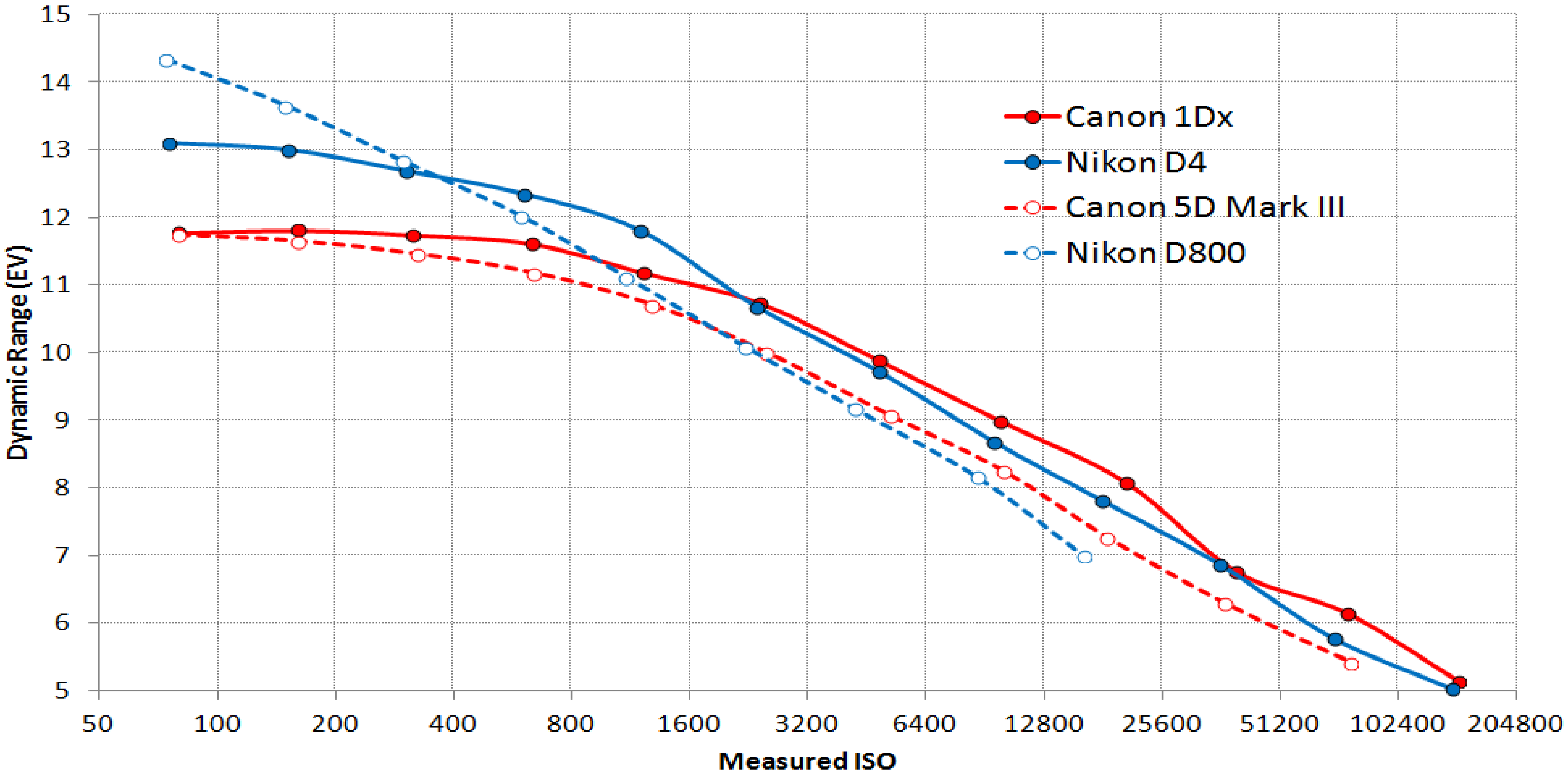
- Dynamic Range (DR) is defined as the ratio between the saturated signal (electrons or voltage) and the Noise level based on the previous discussion.
- Expressed in decibels: DR = $20\log(e_S/e_N)$
- Some typical values include:

Full Frame Canon 5D	20,000	86dB
APS-C Nikon D300	9,130	79dB
Point and shoot Canon S70	8200	78dB

Dynamic Range

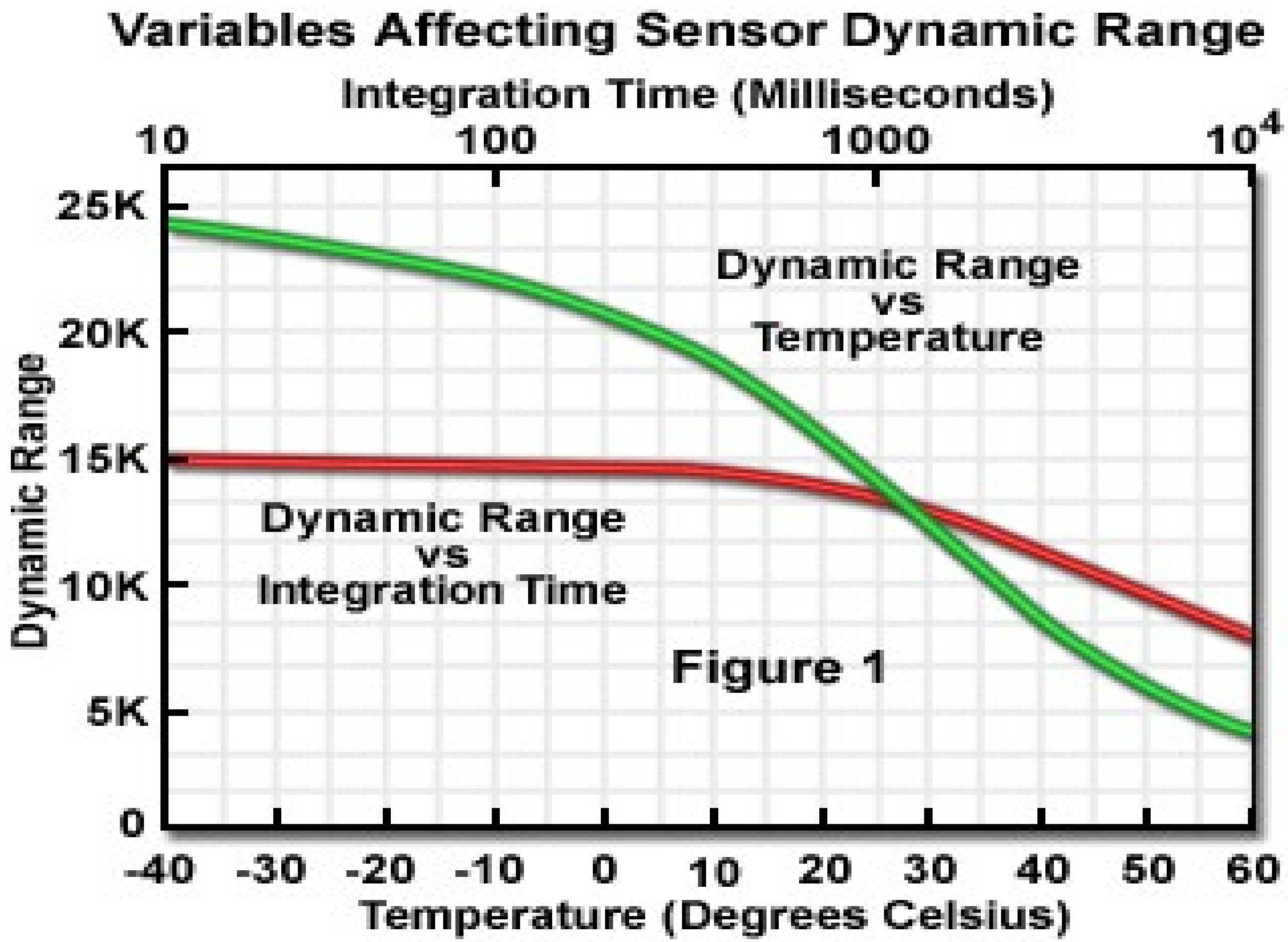
Exposure Latitude

Probably the best way to visualize dynamic range is by expressing it in aperture stops or as an Exposure Value (which is a stop). Here, it's variation is plotted against ISO.



Dynamic Range
temperature

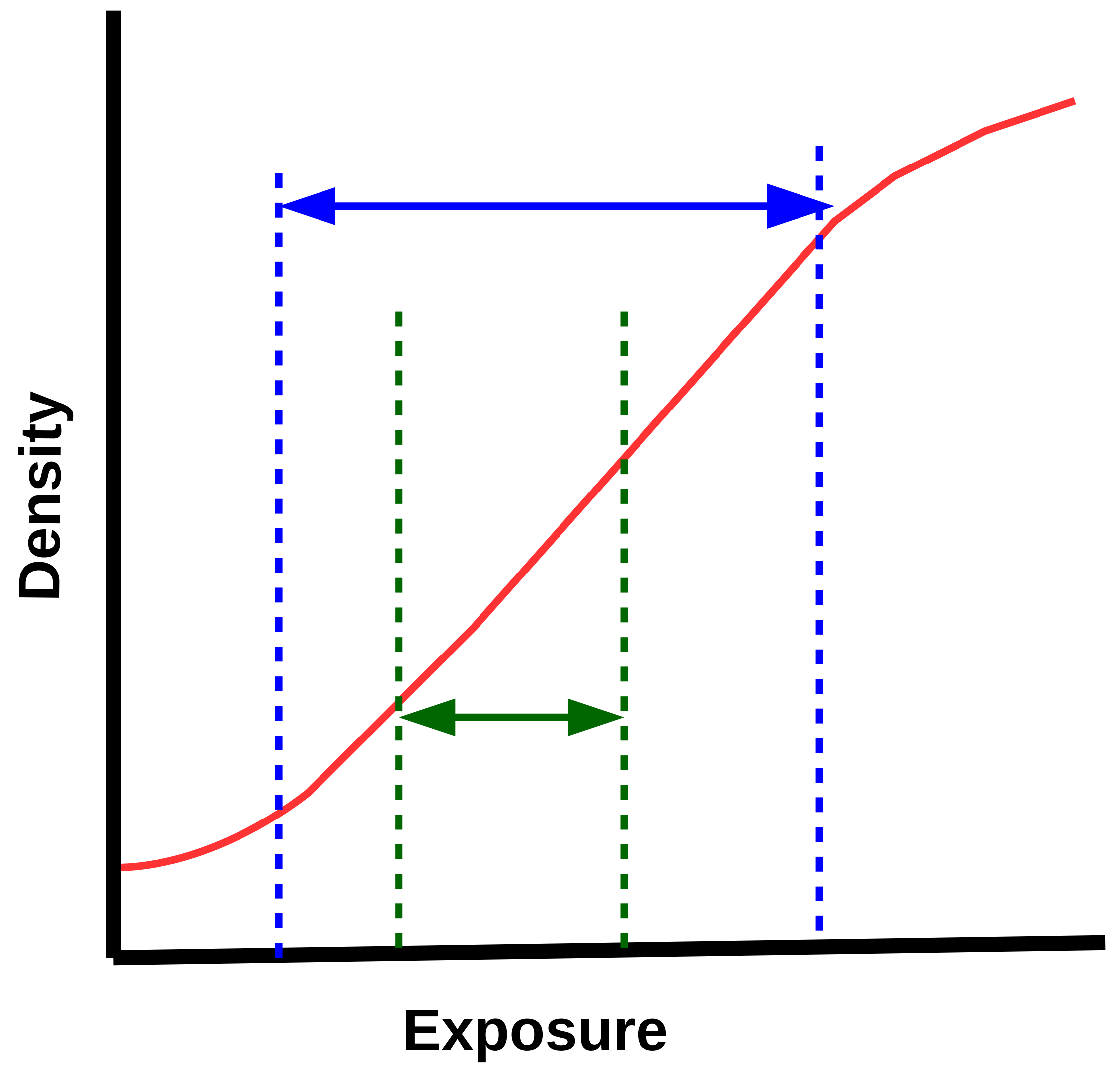
A significant portion of noise is thermal, temperature therefore, will affect the DR in a major way:



Film Dynamic Range

Exposure Latitude

- Stipulates how much an exposure can vary before there is loss of information in either the shadows or highlights.
- Measured as the straightline potion of the density vs exposure curve.
- Will vary depending on the processing 'gamma' (contrast)



Analogue to digital conversion
based on noise and DR

The Digital Number (DN) is the parameter most people relate to regarding the signal and range from the photodiode and is the resulting value from the analogue-to-digital operation.

As seen many artifacts are introduced in the photon-to-electron-to-voltage-to-amplification-to-digital conversion, mostly related to types and levels of noise.

These artifacts affect Dynamic Range (DR) and are important in the specifications and choice of Analogue-to-Digital-Converter (ADC).

The choice of the ADC is dependent on the *effective* image information delivered to the converter.

Analogue to digital conversion

what is an appropriate ADC converter?

- We have 7micron pixel, with a well capacity of 49000 electrons (rule of thumb is about 1000X the pixel dimension).
- Noise is about 10 electrons giving a dynamic range of 49000/10 = 4900 electrons.
- A 12-bit converter (2^{12}=4096 levels) would almost match the required conversion of the electrons. A 14 bit converter (2^{14}=16384) would create levels with no information (oversampling).

  An 8 bit converter (2^8=256) would undersample the signal.

ISO settings

For digital cameras the ISO pertains to the sensitivity of the sensor, except, as we've seen the sensitivity of the sensor is a physical variable dependent on:

- Quantum efficiency
- Sensor size
- Well capacity
- Noise level

These are all variables that are generally, fixed. So, does sensor sensitivity really change when you change the ISO setting?

ISO settings

It is important to note that digital ISO is not an exposure variable as it is in film. In the digital world only the shutter and/or the aperture settings affect light quantities. A setting of ISO 200 does not mean the sensor is twice as sensitive as a setting of ISO 100. So, why can we reduce/increase exposure with ISO, what does it do?

- ISO is an amplification process that magnifies <u>ALL</u> the electrons produced by the pixel, noise included.
- The end effects of an increase in ISO is an increase in relative noise and a decrease in dynamic range.

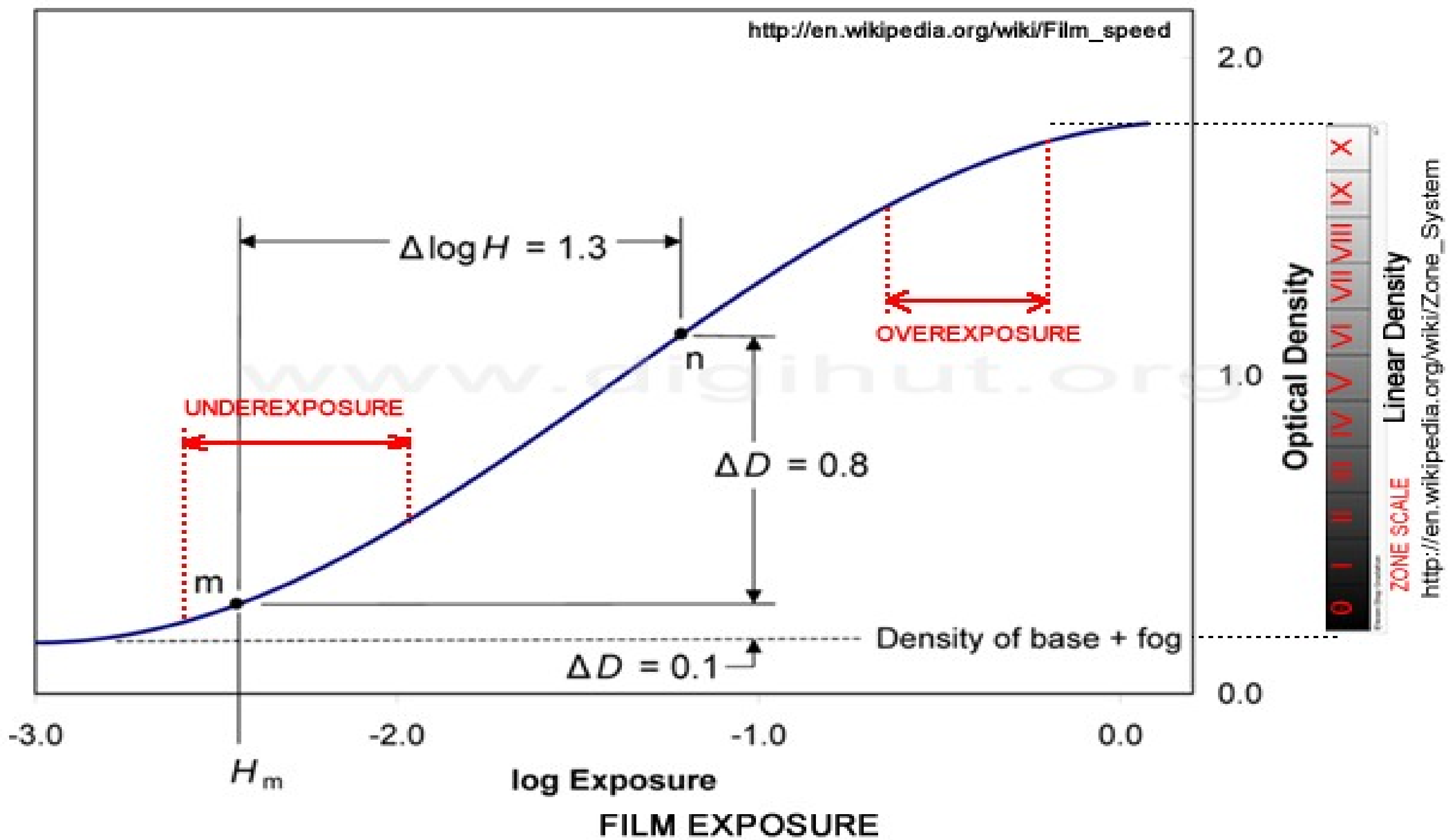
ISO, Dynamic Range, Noise
A general pixel example

ISO	100	200	400	800
Shutter	'1/250	1/250	1/250	1/250
Aperture	'f/5.6	'f/8	'f/11	'f/16
Electrons	50000	25000	12500	6250
Read Noise	10	10	10	10
Dynamic Range	5000	2500	1250	625
Amplified Electrons	0	50000	50000	50000
Amplified Noise	0	20	40	80

Film ISO

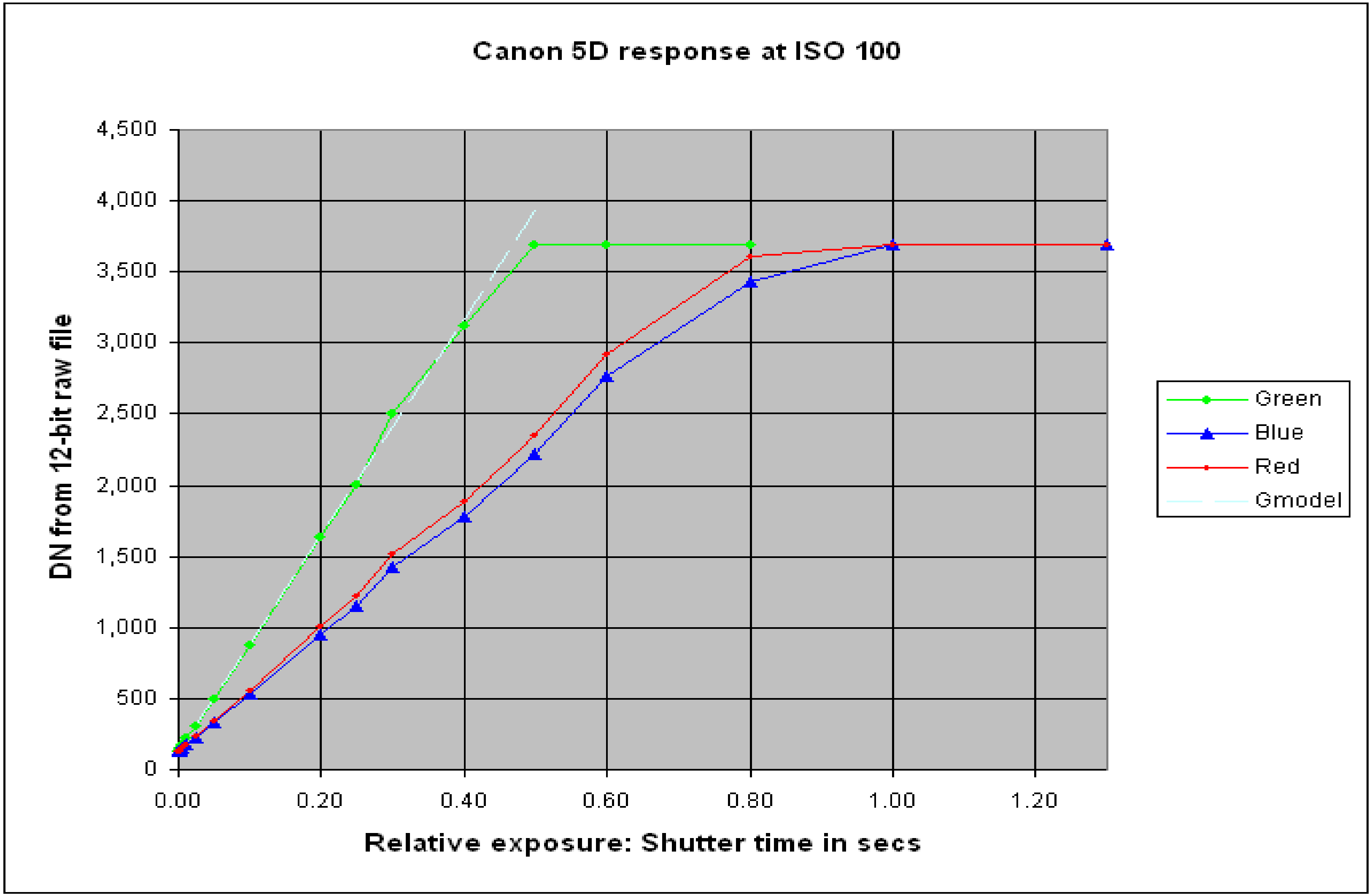
Unlike digital systems, higher ISO films are more sensitive to light (more electrons can be produced by photons). This is typically a function of larger grain size.

But like digital systems higher ISO films have more 'noise' as measured by the RMS Granularity.



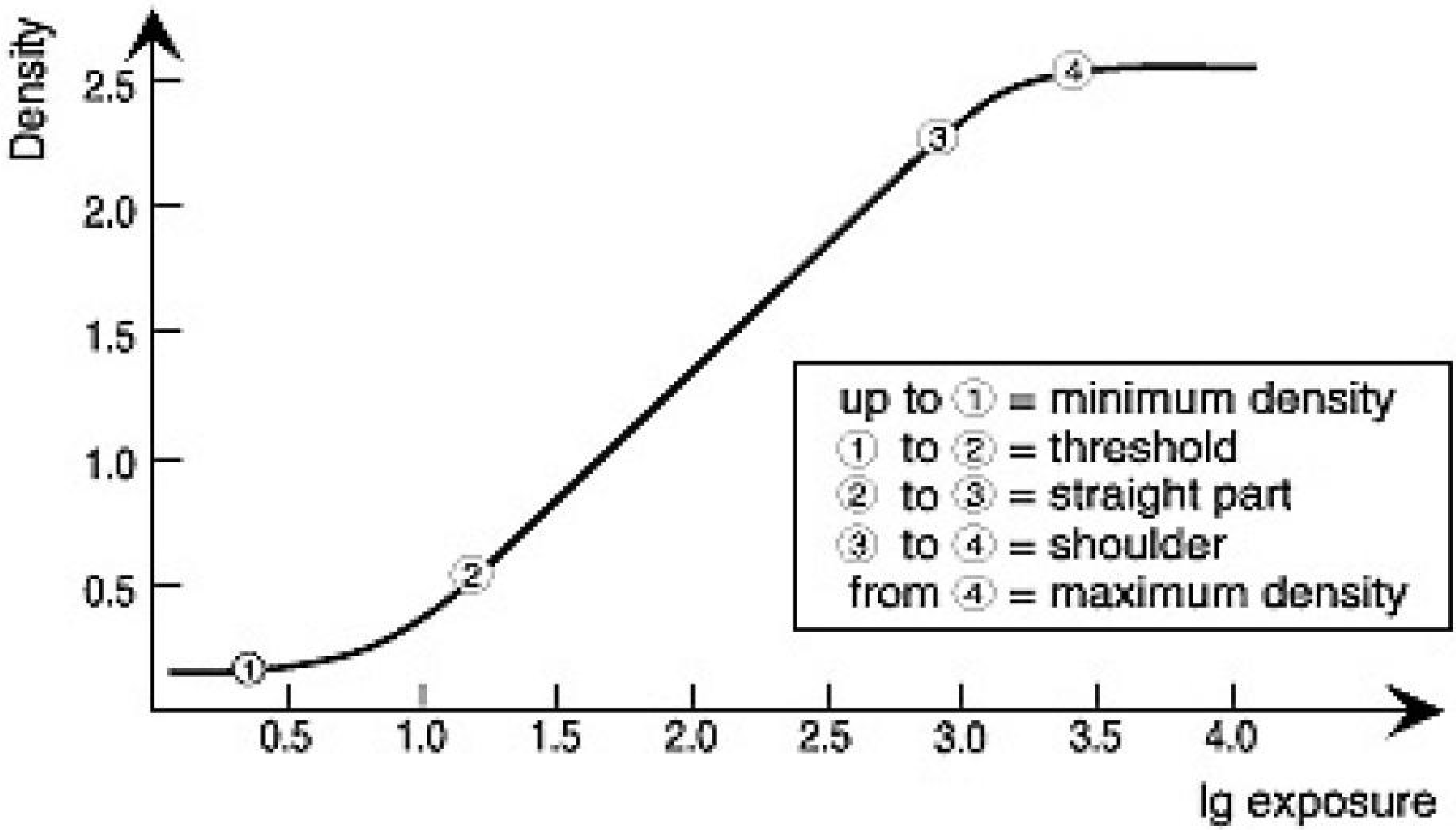
Linearity

Linearity is the sensor's capability to reproduce tones in a constant fashion, for example as exposure doubles photo-generated electrons also double. Linearity enhances a sensor's dynamic range. It is typically expressed as a %



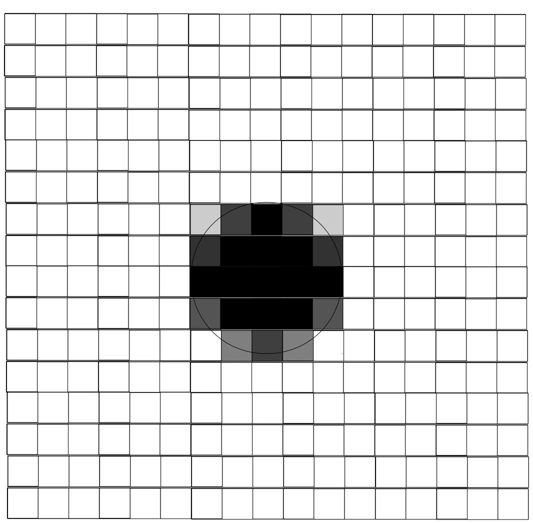
Linearity - film

Linearity in film is also compromised at low and high exposures, we can see this in the familiar characteristic curve of film.



Pixel size - Resolution

- In simple terms, the smaller the pixel the more it will resolve an object.
- The Nyquist sampling rate (~twice the size of the pixel) determines the resolution limit for the pixel size.
- How many pixels are needed to resolve the *circle?*



Pixel pitch is 2 um

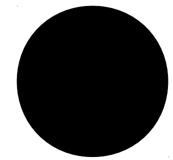
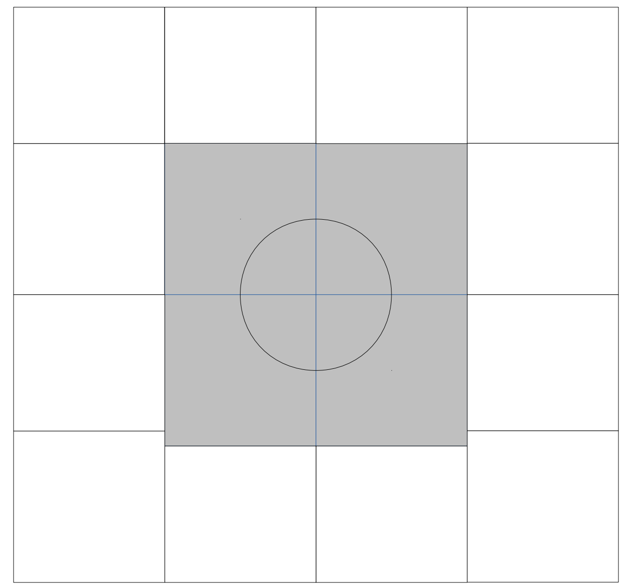
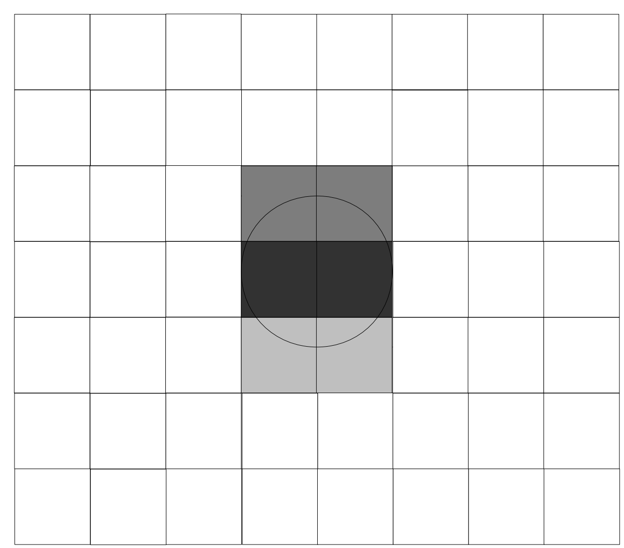


Image diameter is 10um



Pixel pitch is 10um



Pixel pitch is 5um

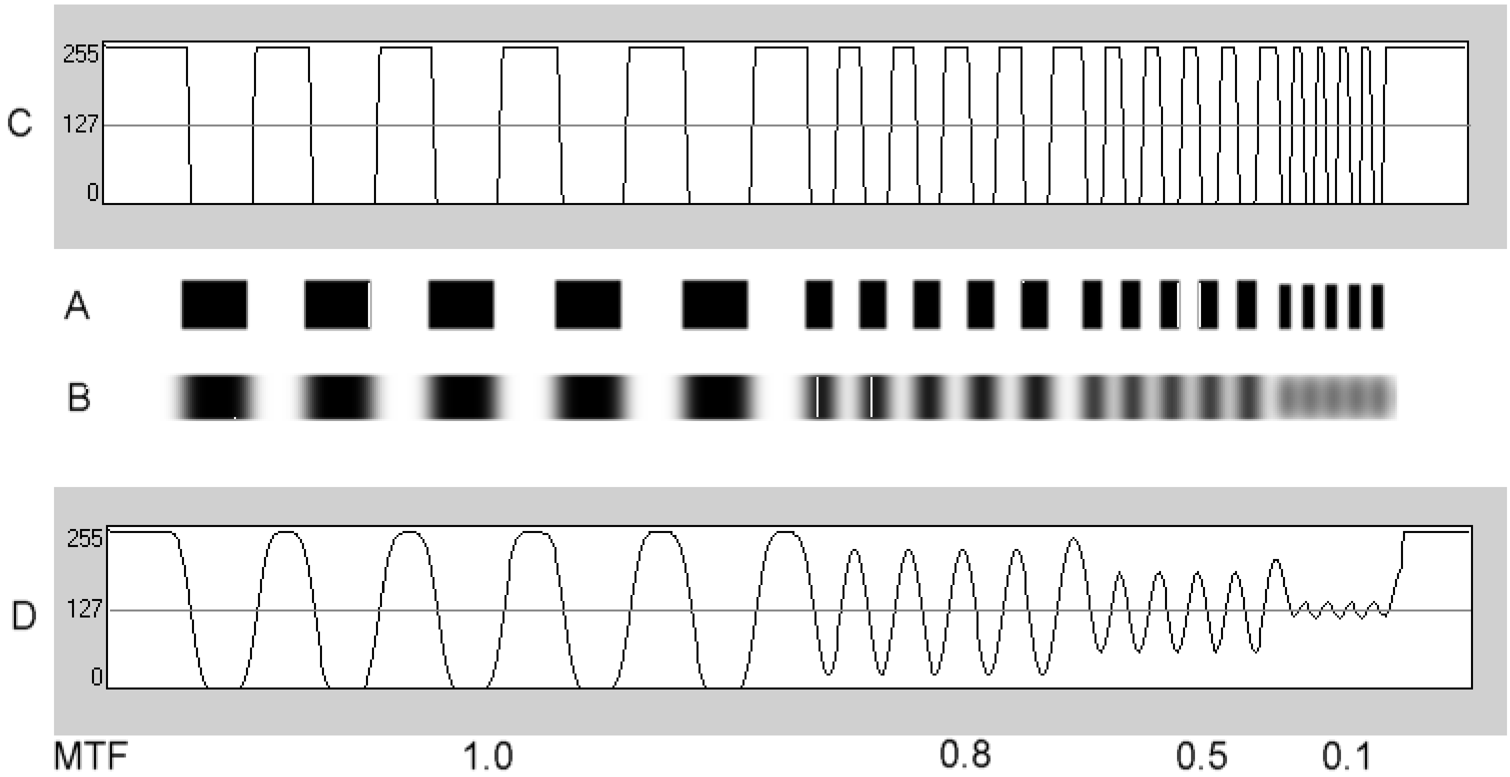
Pixel size and resolution

- Pixel size is only one of the factors that determines resolution.
- Lens quality is another essential component (if the image is blurred, even the smallest pixel pitch won't resolve the object).
- Noise also interferes with resolution. We'll look at this variable later..
- Image blur, as with slow shutter speeds deteriorate the image formed on the sensor.

Resolution – MTF

The Modulation Transfer Function

- The MTF allows for a scientific comparison of sensors, including film sensors.
- Since the MTF is a *system* variable, the full resolution effects of a sensor + lens + signal processing can be analysed.



Object response

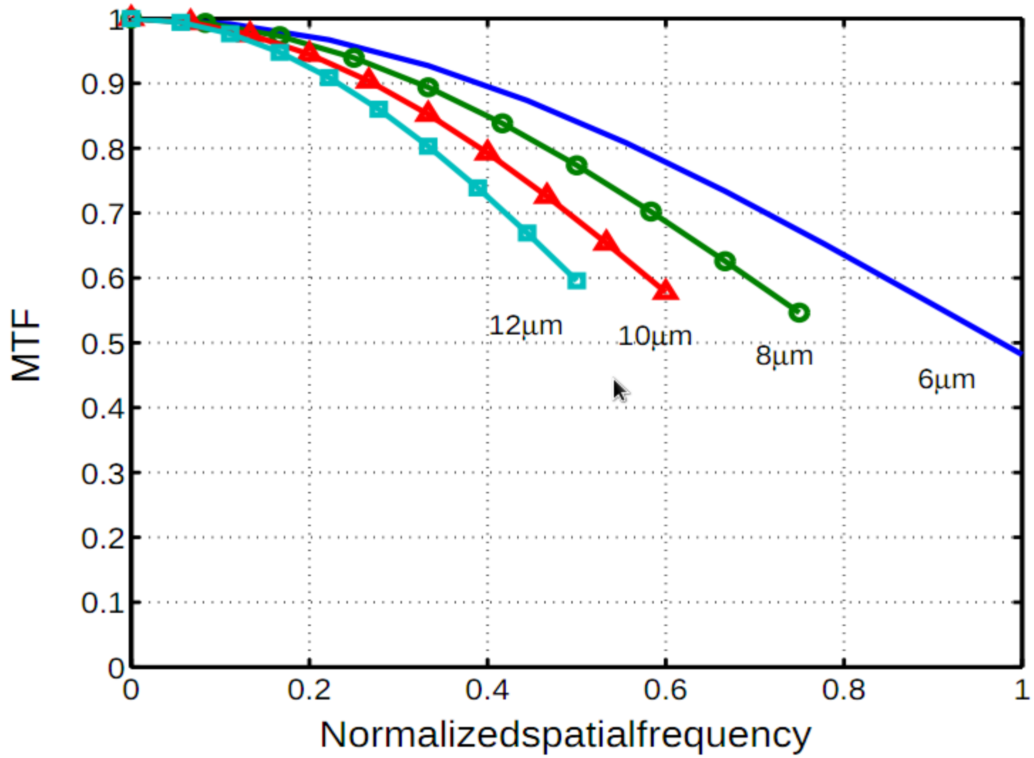
Object

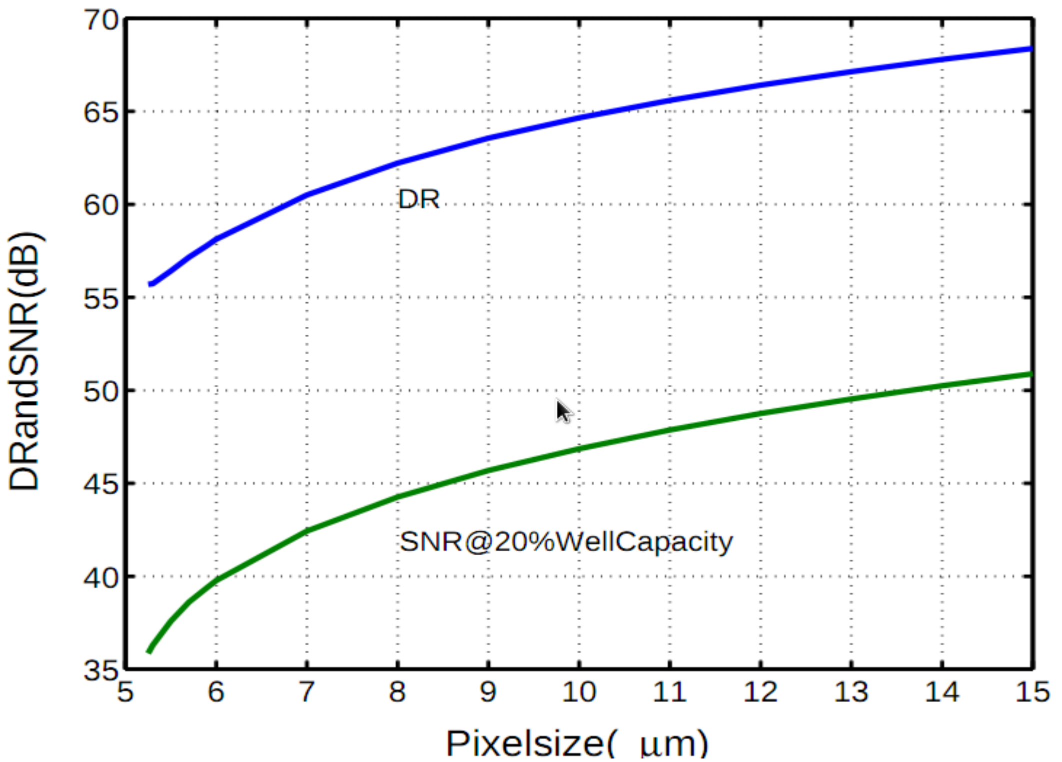
Image

Image response

CCD/CMOS MTF, DR and SNR

As expected the MTF performance improves as the the size of the photodiode decreases but it should be noted that this occurs at the expense of both the Dynamic Range and the Signal-to-Noise Ratio. The implication is then that the larger pixel imager, although not as highly resolving as the smaller pixel, is better at rendering image information in shadows (lower SNR) and highlights (higher well capacity).

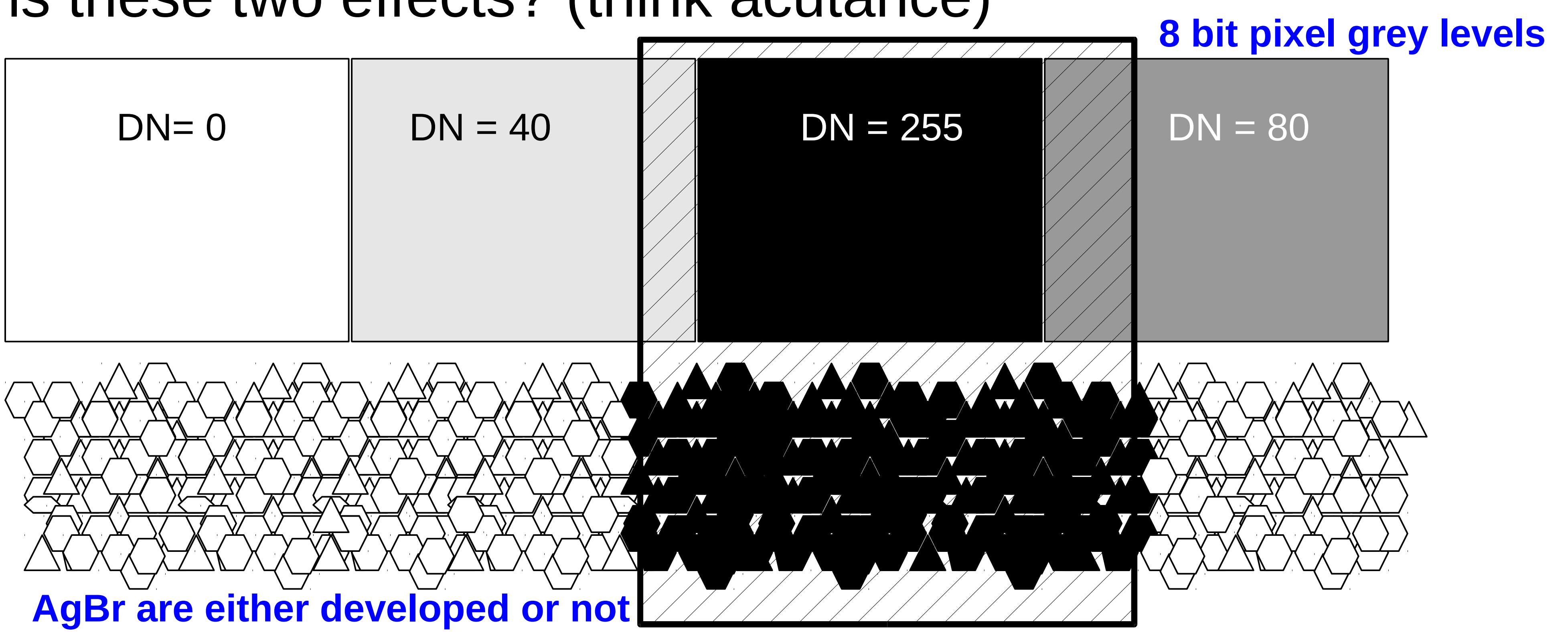




Pixel and film grain resolution

Differences at the pixel-grain level

As noted the measurement of the MTF is dependent on a bar target, its sinusoidal imaging response provides the metric for the MTF variable. Consider the representation of a black line (hatched) 7 um wide on a 4 X 5um^2 pixel array and a film composed of 0.5um grains,what are the pros and cons these two effects? (think acutance)



A comparison of two CCD manufacturers', 6μm^2 sensors

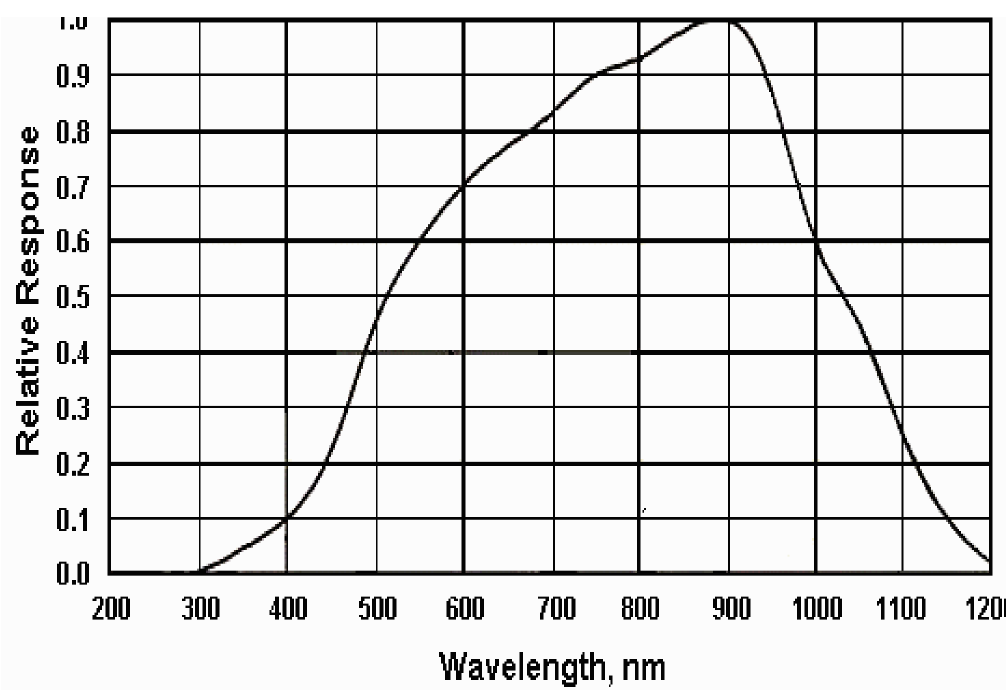
Parameter	TeledyneDalsa	Kodak
Sensor	FTF6080C	KAF-50100
Array (pixels)	6000 X 8000	8176 X 6172
QE (R,G,B)	37,31,20	22,22,16
Dyn.Rge (dB)	72.4 dB	70.2
Dark Current @60° pA/cm2	120	42
Charge Transfer Eff.	.999999	.999999
Full-well capacity (e)	50000	40300
Read Noise	--------	12.5 e
Non-Linearity	3%	5%
MTF @ 83 lp/mm	65%	----------

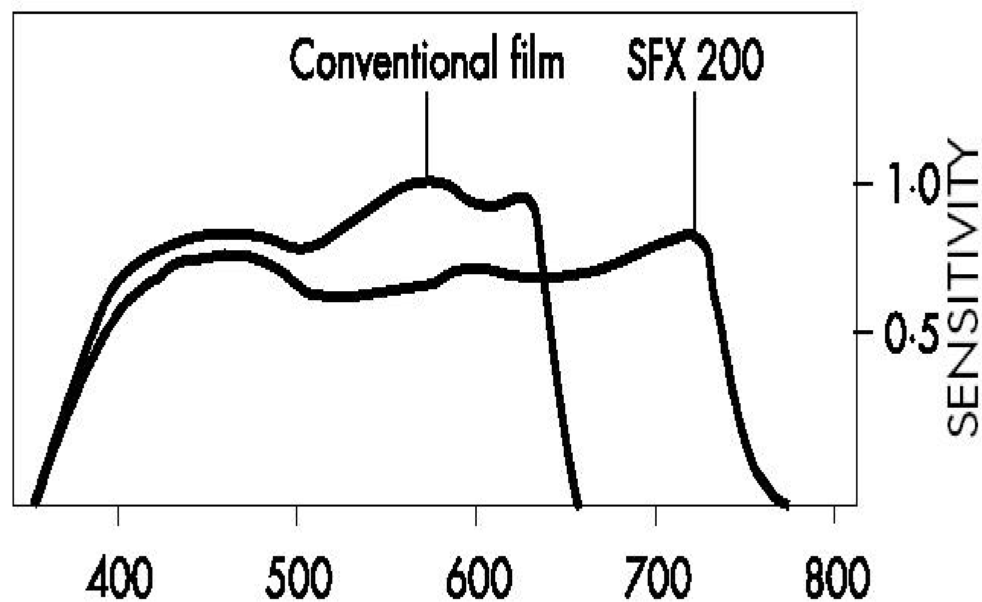
Sensor Color Rendition

The Basics

By definition a CCD (a MOS) cannot represent 'color' as humans perceive color. Although silicon has inherent sensitivities from about 300nm to about 1100nm, as a sensor it can only represent the *number* of photons creating electrons ie. quantity not quality. The same holds true for silver halide sensors, the process is strictly quantitative-electronic.

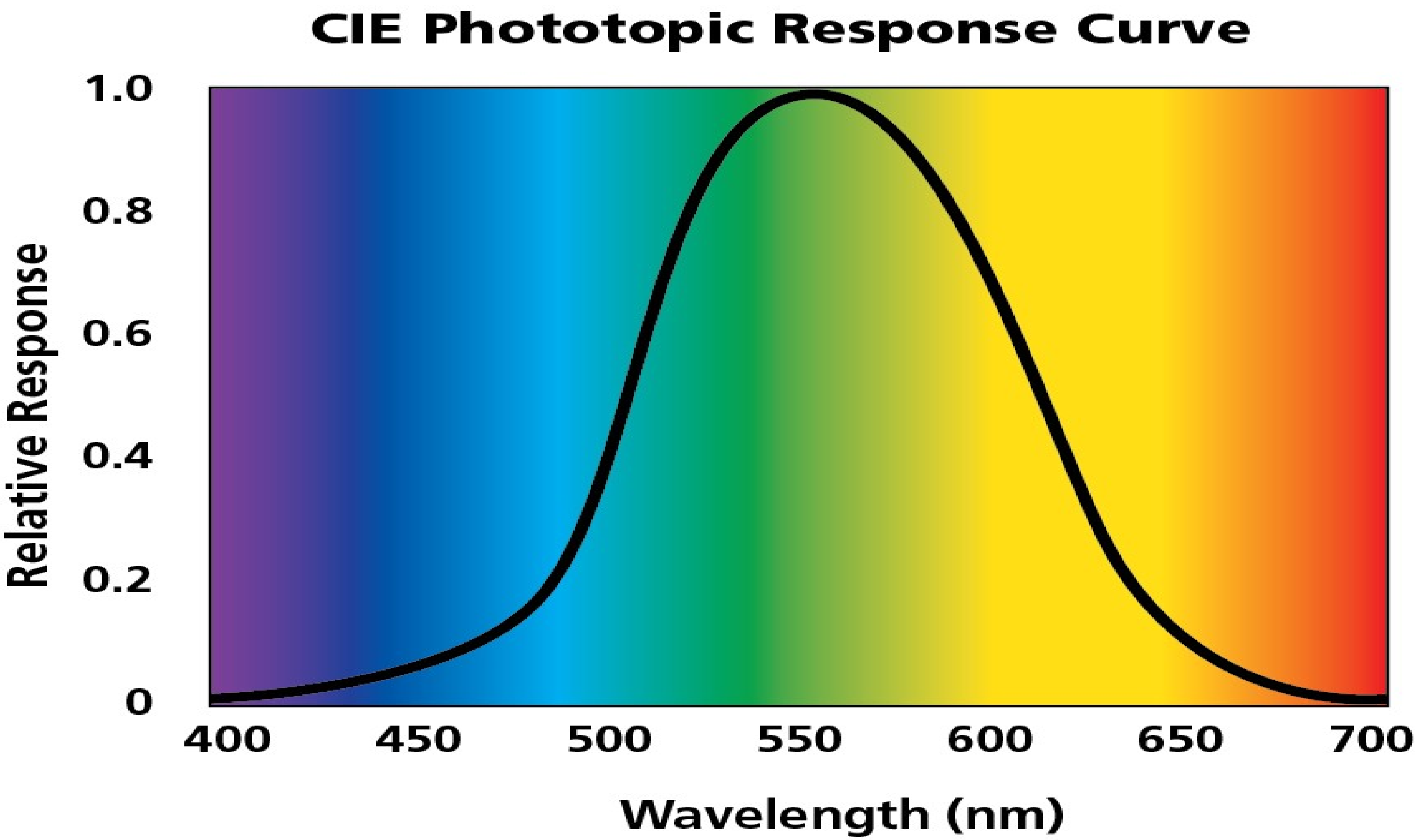
Silicon spectral sensitivity





Creating Color Perception

Color perception is created by separating out the Blue (400-470nm), Green (470-570), and Red (570-690) components of the visible spectrum. Approximating the eye's spectral sensitivity is a general goal (the photoic curve).

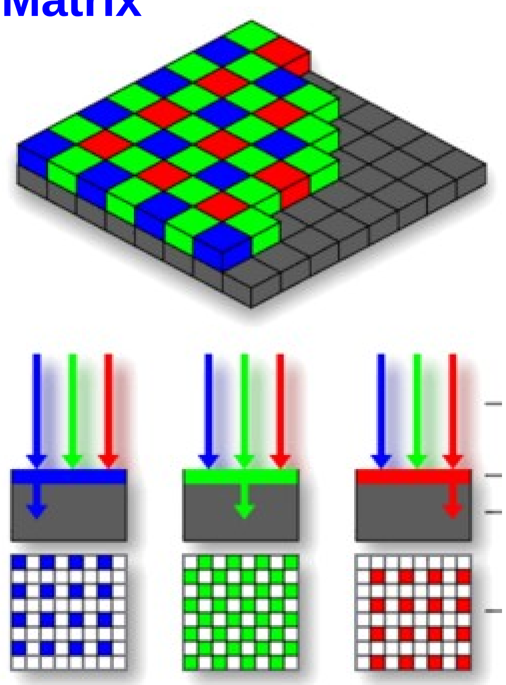


Creating Color Perception

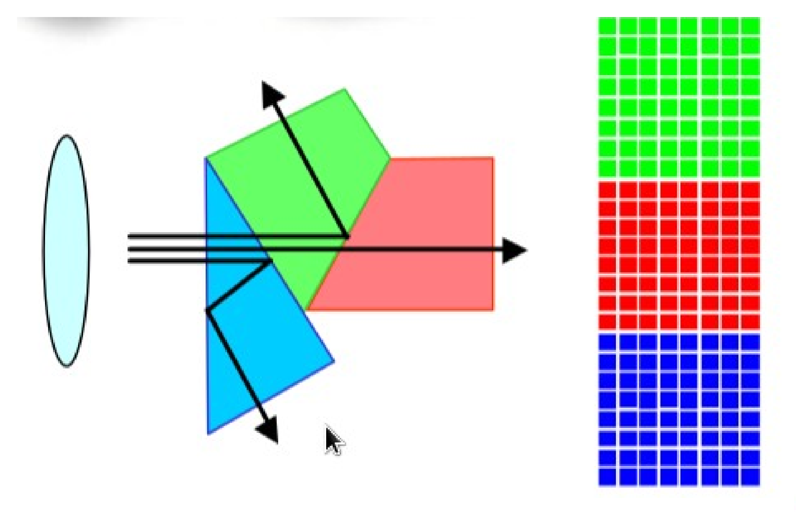
Three techniques have been devised to separate photons into their blue, green and red components:

- The Color Filter Array or matrix
- Prisimatic/tri-tetrachroidseparation/filter stacking
- Silicon depth separation

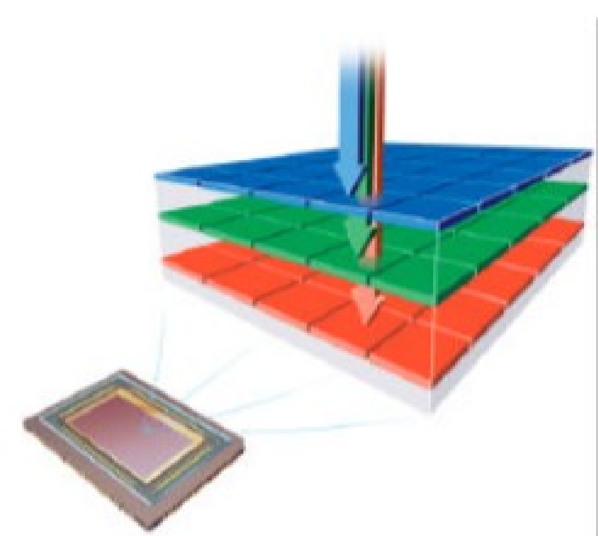
Matrix



Prismatic or tri/tetrachroic separation

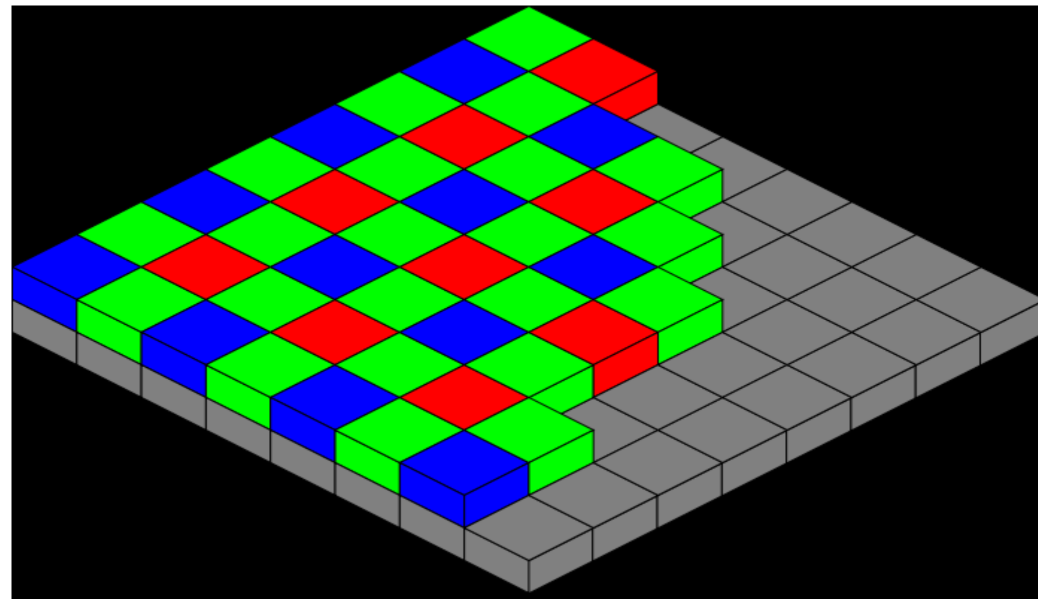


Silicon depth separation



The Color Filter Array (CFA)

- Represents the most common means of producing color in commercial cameras
- Was created by Bryce Bayer of Kodak in the late 60's and therefore often called the Bayer filter.
- The filter has 2X the # of green pixels



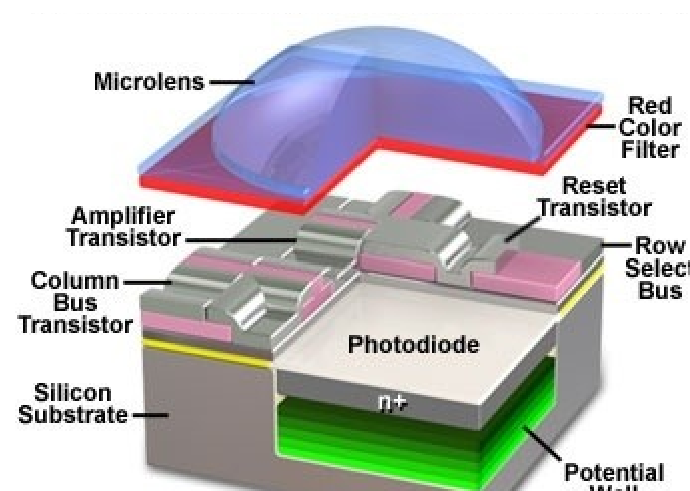


Figure 3

Adjustments in CFA sensors

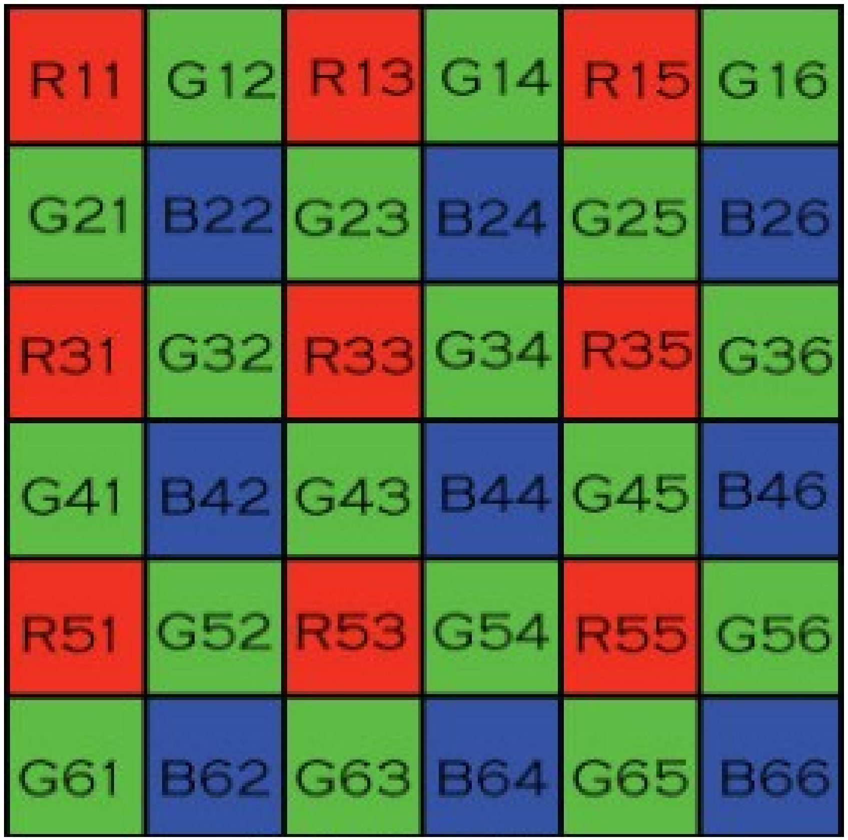
Demosaicing

Since only one color is captured by each pixel the other two need to be interpolated for that pixel. The process is called demosaicing. A number of 'demosaicing' algorithims are used:

- **Pixel Doubling**
- **Bilinear and Bicubic Interpolations**
- **Gradient Based Interpolation**
- **High Quality Linear Interpolation**
- **Adaptive Homogeneity Directed Interpolation**

Although the algorithms are quite reliable it can be argued that true color is never really represented at each pixel.

Reconstructing pixel RGB using a simple bilinear method



Pixel R33 (red pixel):
Red = R33
Green = (G23+G34+G32+G43) / 4
Blue = (B22+B24+B42+B44) / 4

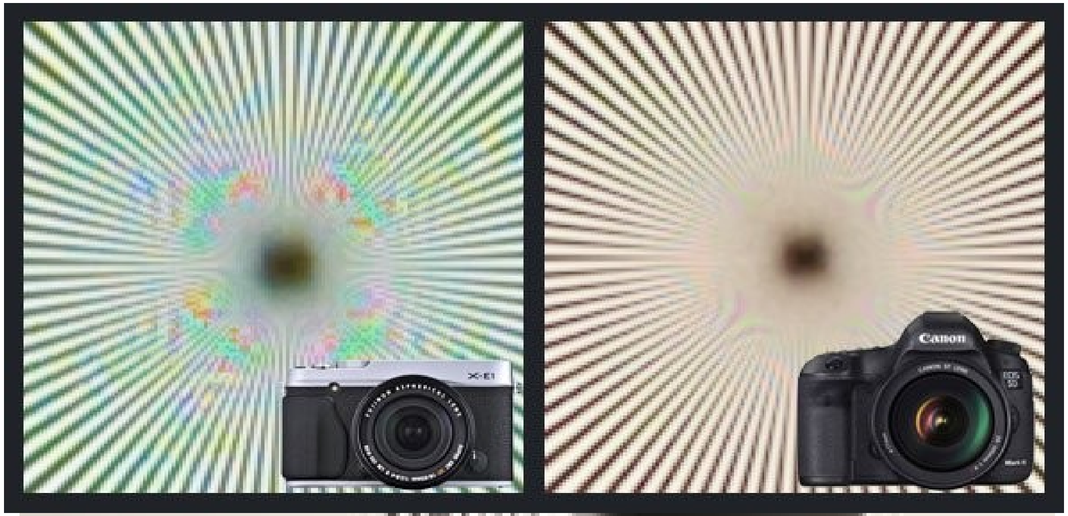
Pixel B44 (blue pixel):
Blue = B44
Green =(G34+G43+G45+G54) / 4
Red = (R33+R35+R53+R55) / 4

Pixel G43 (Green in a blue row):
Green = G43
Red = (R33+R53) / 2
Blue = (B42+B44) / 2

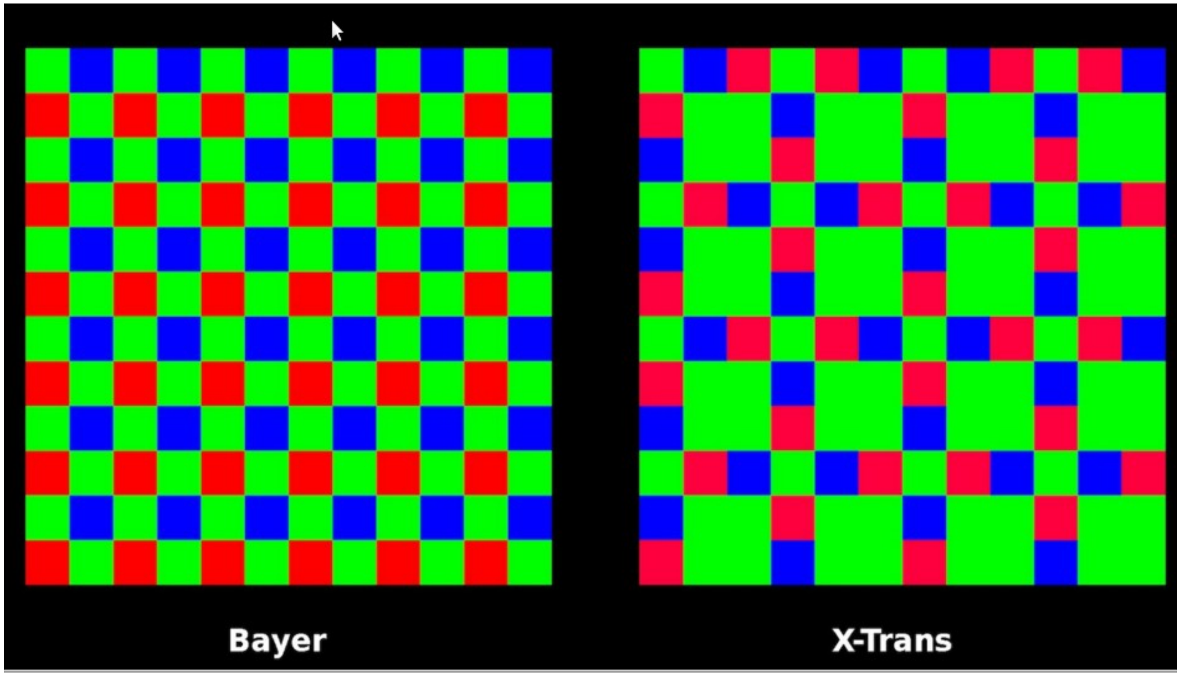
Pixel G34 (Green in a red row):
Green = G34
Red = (R33+R35) / 2
Blue = (B24+B44) / 2

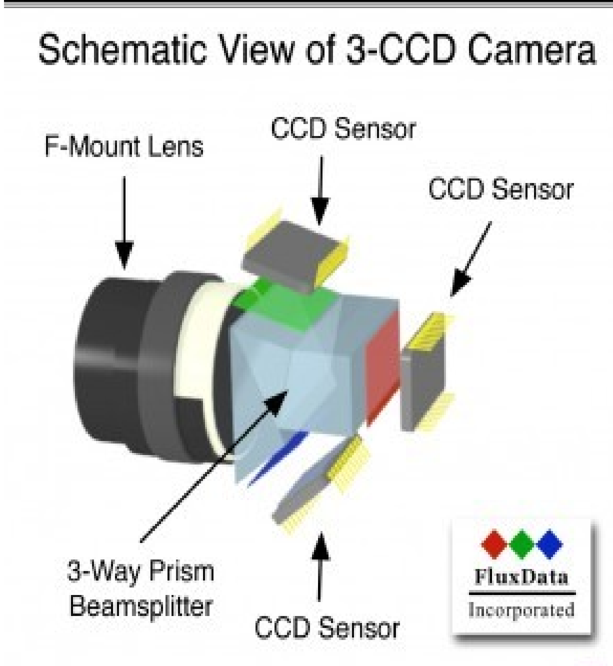
CFA sensor adjustments
Aliasing and Moire effects

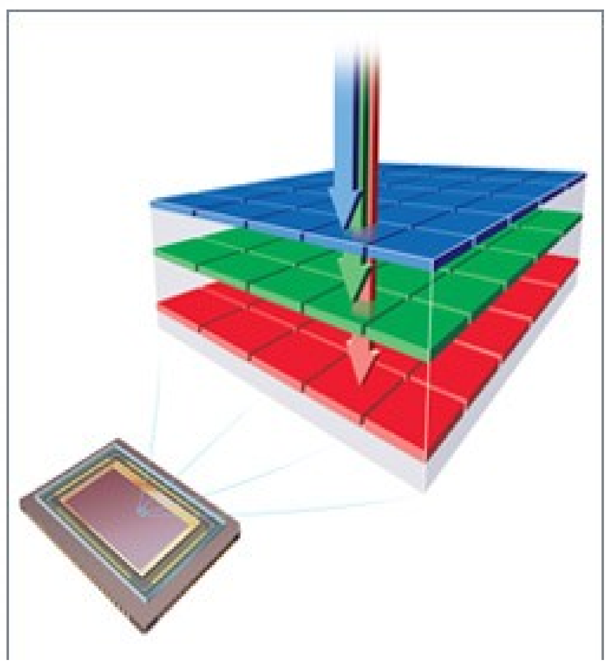
- Small-scale detail close to the resolution limit of the digital sensor can be a problem to the demosaicing algorithm.
- The effect is countered by the use of an anti-aliasing or low pass filter whcih works by blurring very fine detail.
- There is a loss of resolution by about 30%.



Demosaicing and Moire solutions







The X-trans technology from Fujifilm solves the anti-aliasing issue

Multi sensor arrays for each color solve the demosiacing issue

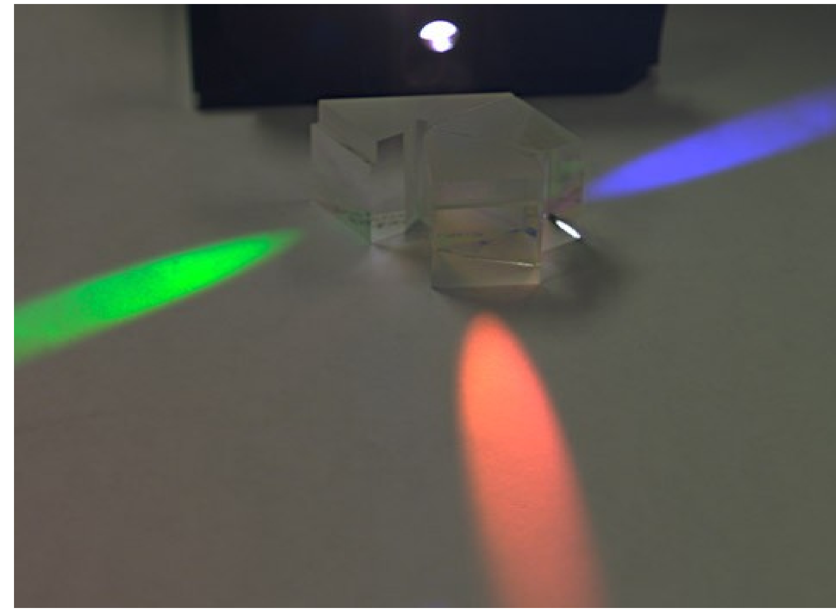
Three-color layered sensing also solve the demosaicing and anti-aliasing issue.

Prismatic/xchroid color sensors

- These type of sensors are actually three area sensors (or linear) capturing the Red, Green, and Blue spectral components separately.
- The incoming image is separated in to its RGB components by prisms or beam splitters.
- The advantage is that true RGB color is captured at every pixel; no demosaicing is needed and results in sharper images
- Some disadvantages are expense (three sensors), registration of the three R, G, and B images, bulk – not practical for small cameras.

Prismatic/xchroid beam splitters color sensors examples

Panavision Genesis
(cinematography)

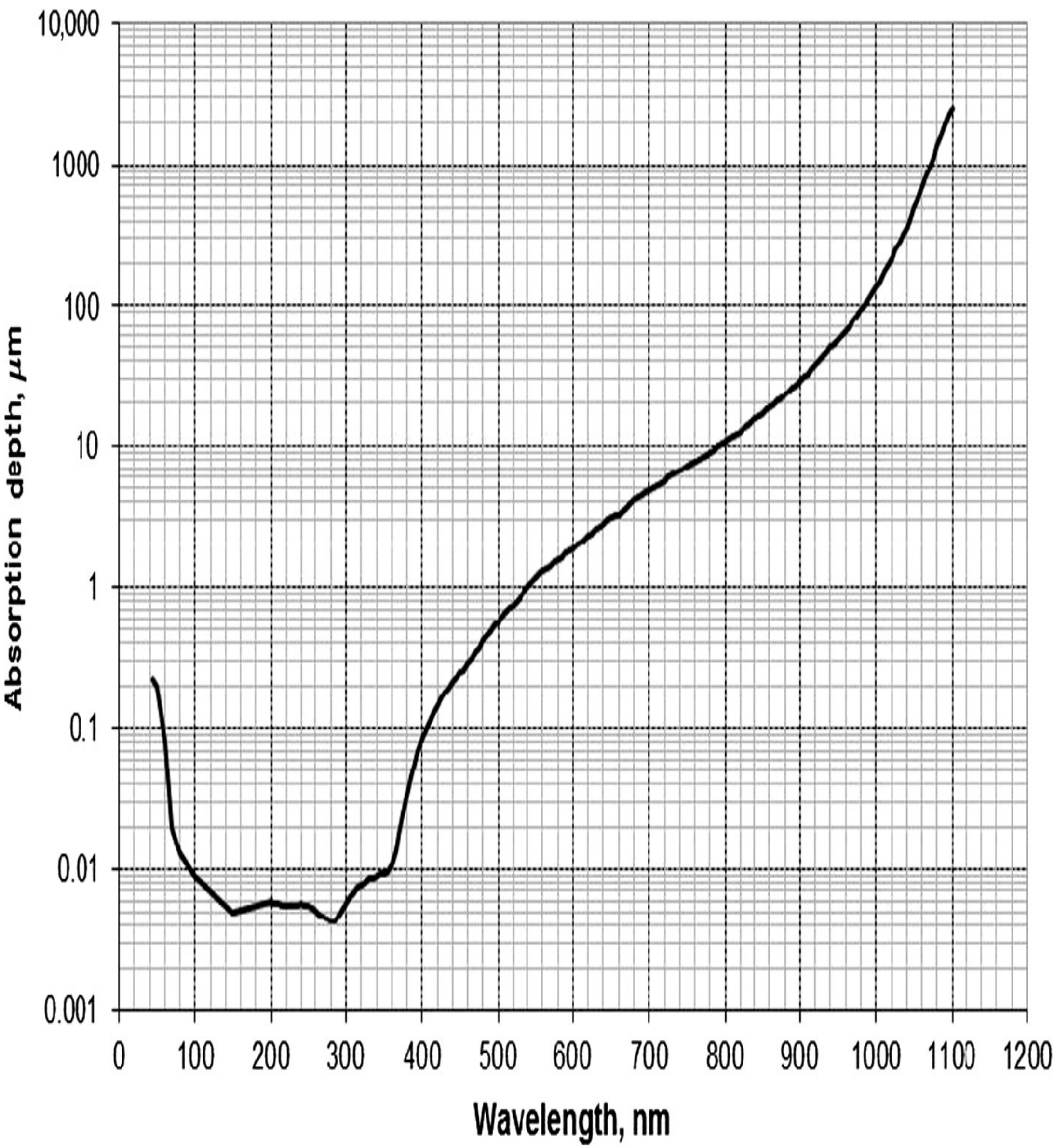


Leica ADS 100
tetrachroid beam
splitter
(aerial photography)

Layered filtration in silicon

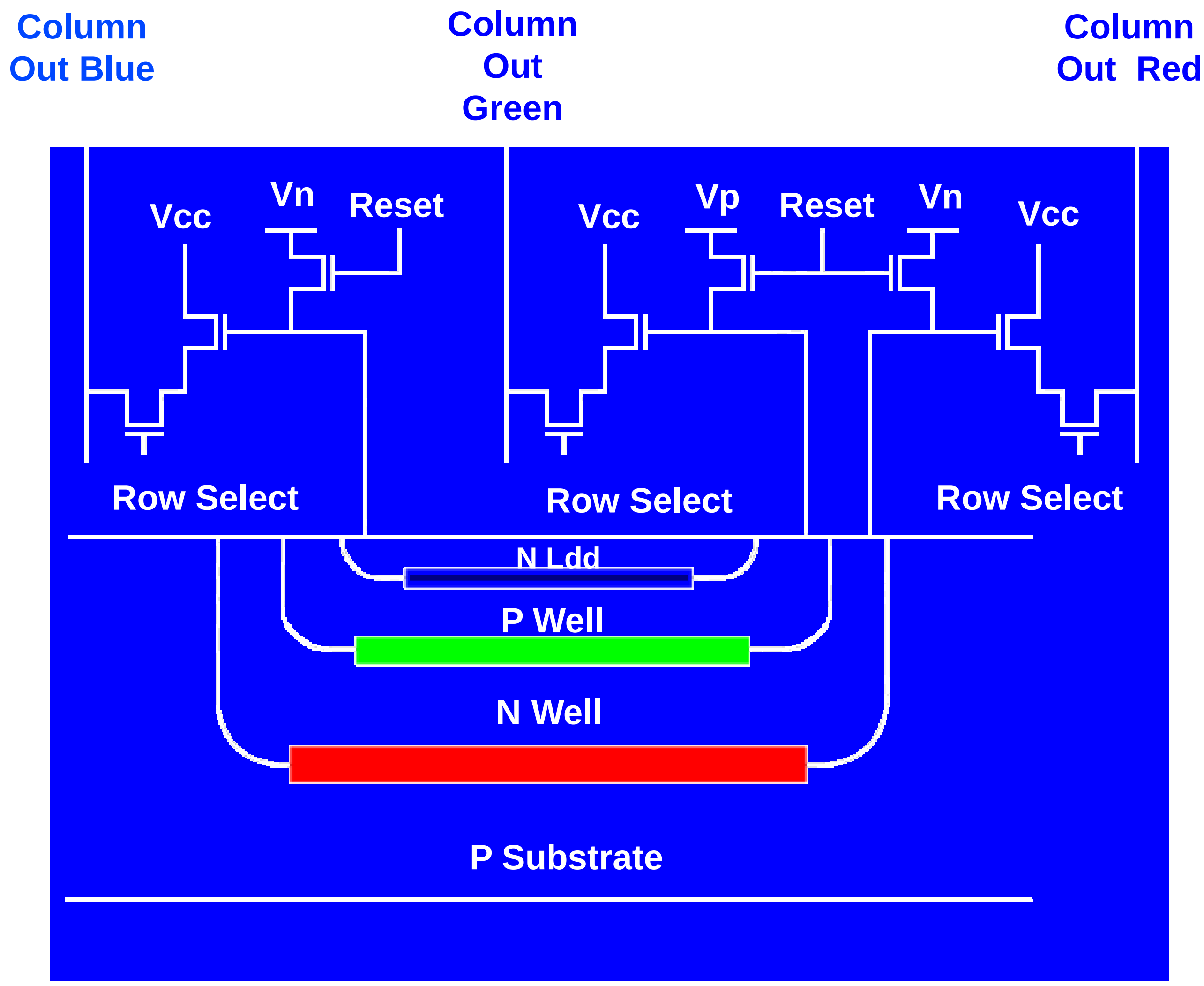
Layered filtration (as with film) uses the inherent differential depth sensitivity of silicon to partition out photons of different energies and wavelengths.

As noted earlier silicon has an effective light sensitivity between 300 and 1100 nanometers but electrons and holes are produced at different depths in the silicon. Blue is absorbed at shallow depths, red deeper in the silicon.



The triple well sensor: Foveon X3

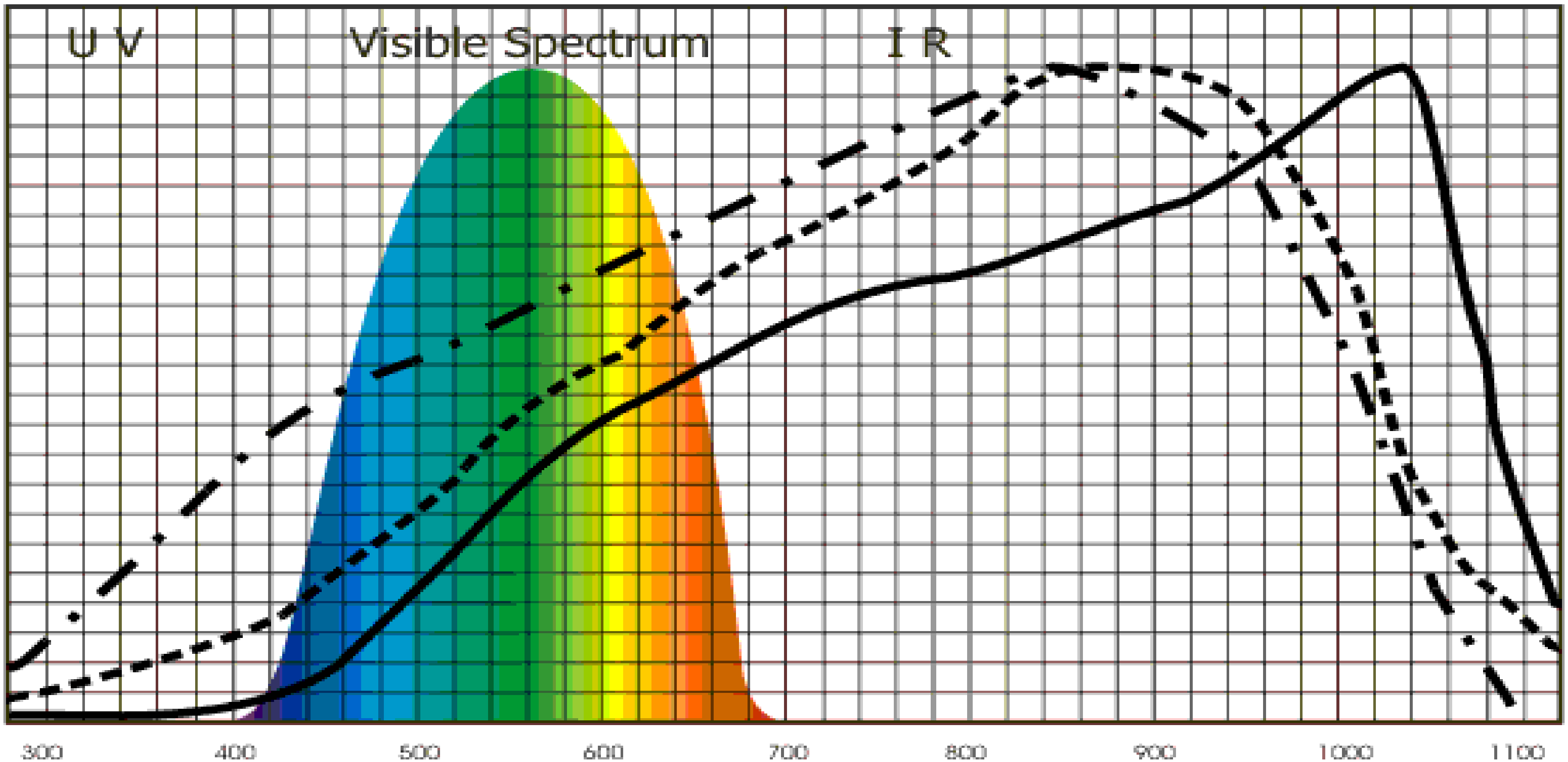
The Foveon X3 sensor employs a triple-well strategy to capture and segregate the blue, green and red photons and their electrons. **Based on the differential wavelength depth dependent absorption of silicon**, the blue photons are absorbed and 'welled' at the shallowest junction, the green at middle junction and the red at the deepest junction.



Silicon sensors and the infrared

As already noted silicon is inherently sensitive to near-infrared wavelengths

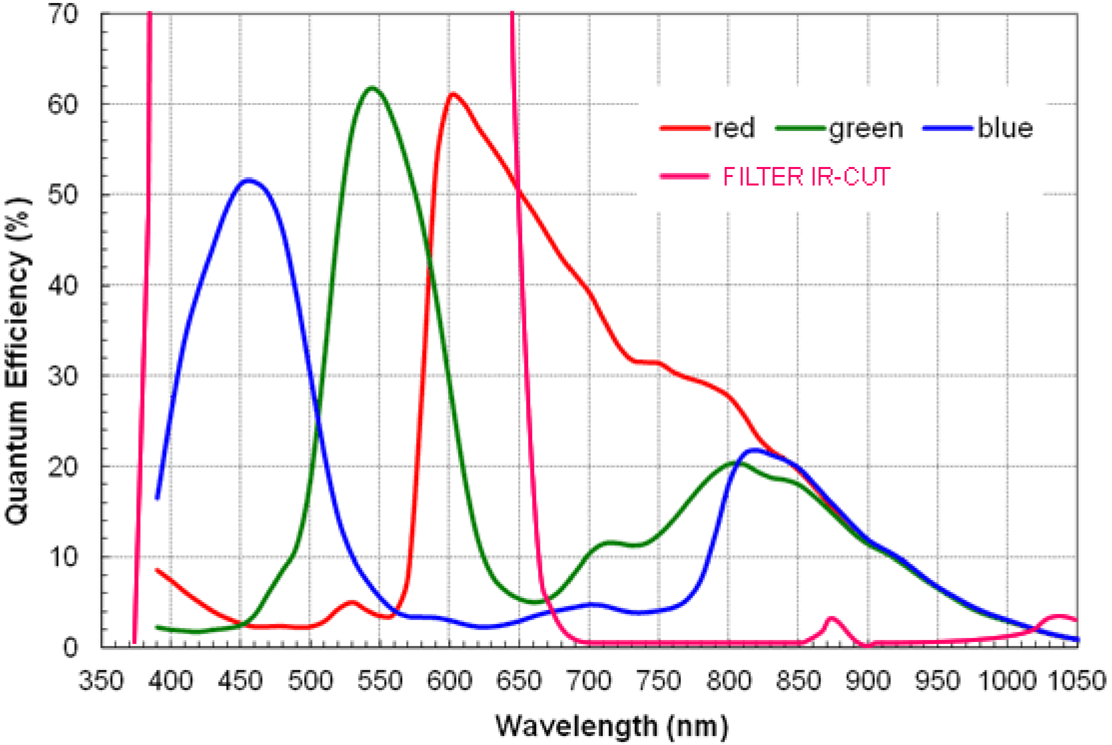
Unfiltered Silicon Sensitivity

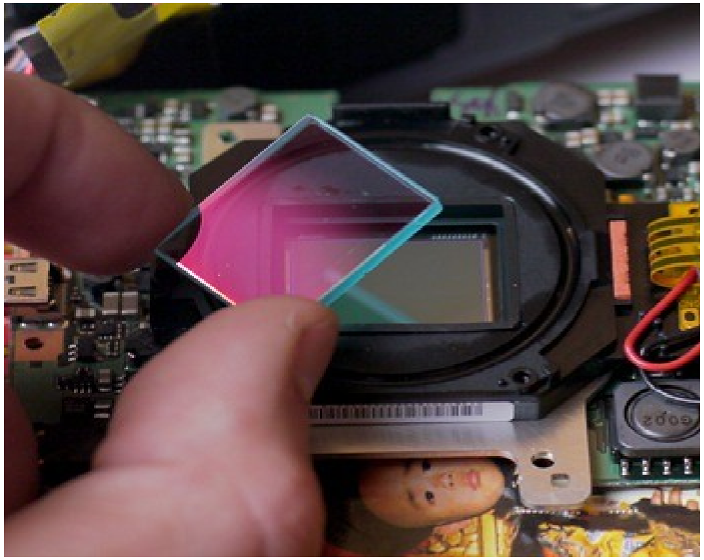


Silicon sensors and the infrared

The infrared portion is filtered out by manufacturers with the use of a infrared blocking filter or 'hot-mirror'. This done for a few reasons:

- Bayer CFA 'leaks' IR
- Improved autofocus
- Resolution (chromatic aberration)

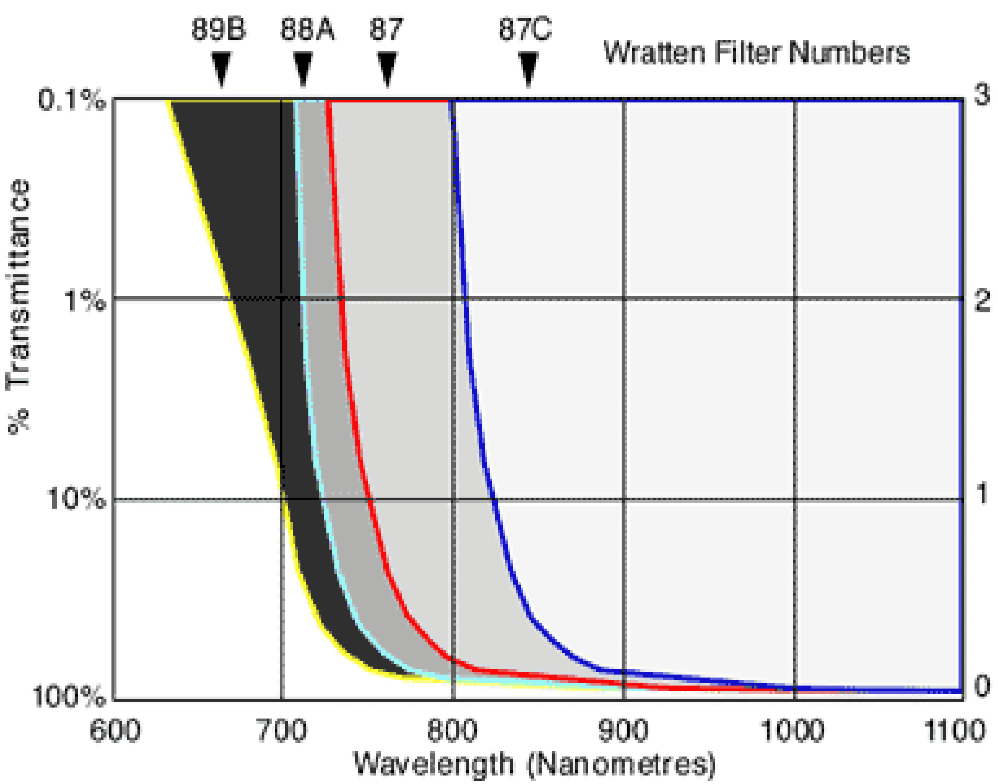




Silicon sensors and the infrared

Removal of the Hot mirror

Most digital camera sensors can be transformed into infrared cameras (Lifepixel, Kolari Vision) by removing the hot mirror and adding an infrared filter. Keep in mind that infrared light is basically monochrome.

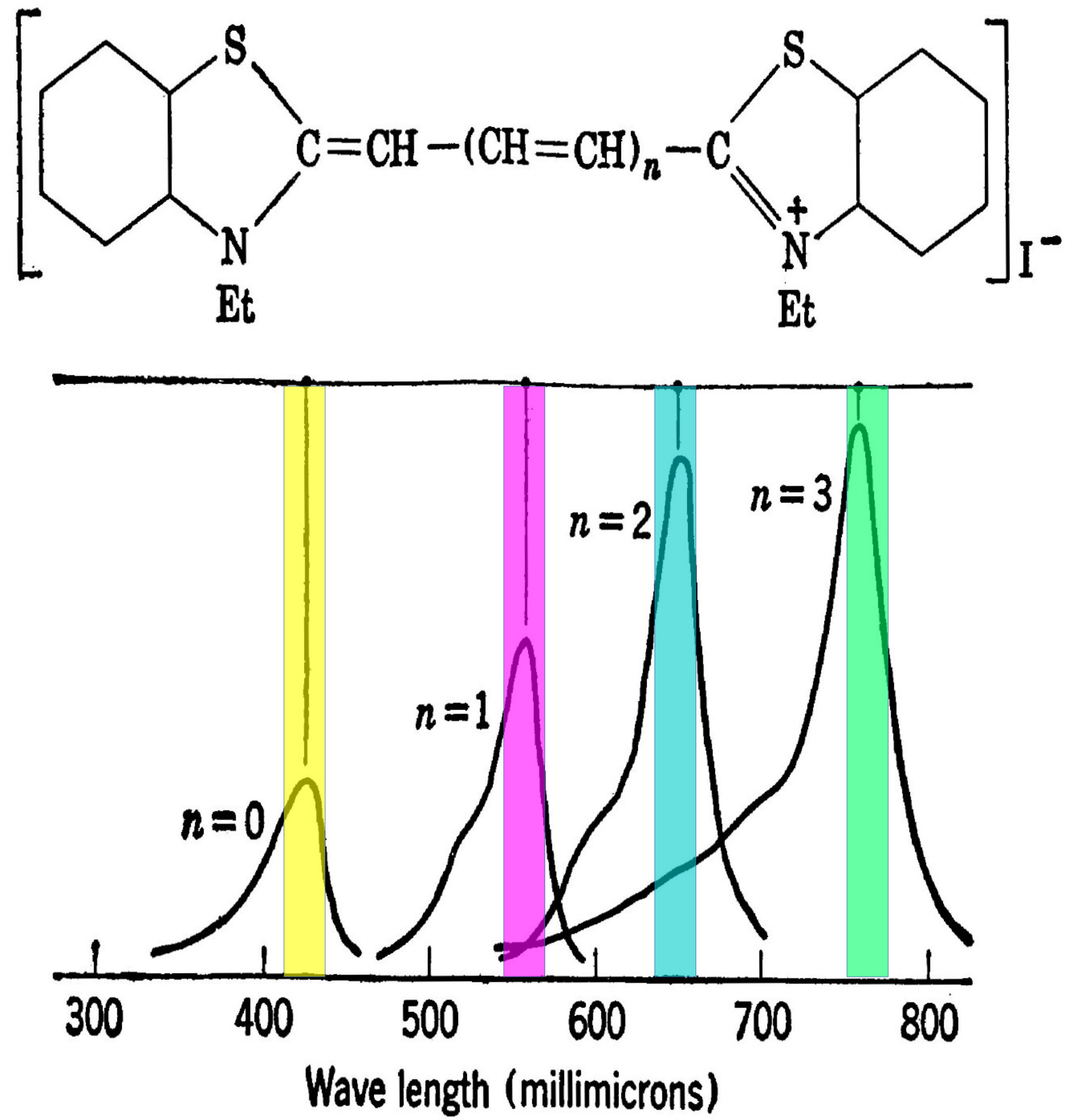


Infrared Cameras

- Only one truely commercial infrared camera (full spectrum) is being marketed at present, the Fujifilm XT1 IR.
- The Sigma SD1 is normal spectrum camera that converts to full by the easy removal (and replacement) of the hot mirror, however, it is not marketed by Sigma as a full spectrum camera.

Film and color

Thiacyanine dye series

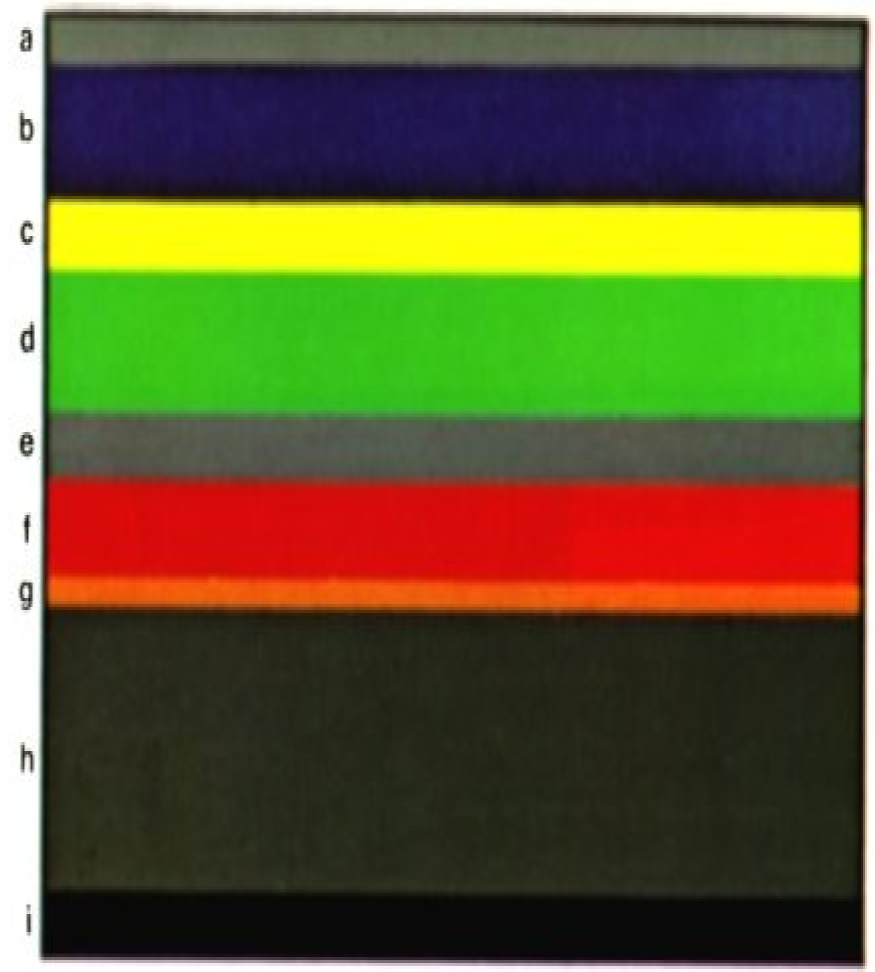


Silver halide sensors are only sensitive in the blue (upto 500nm). Spectral sensitizers (dyes) are used to extend sensitivity to other colors and the infrared.

n=0 thiacyanine
n=1 thiacarbocyanine
n=2 thiadicarbocyanine
n=3 thiatricarbocyanine

Film and color

- Color film is actually three emulsions, each sensitive (via the dyes) to Blue, Green, and Red respectively, stacked on top of each other. The Foveon sensor design mimics this approach. With film, as with the Foveon and prisim/trichroic approaches, three separate images are formed.
- Yellow filtering is used to contain the blue wavelengths only to the top blue layer.



Sensor frame rates

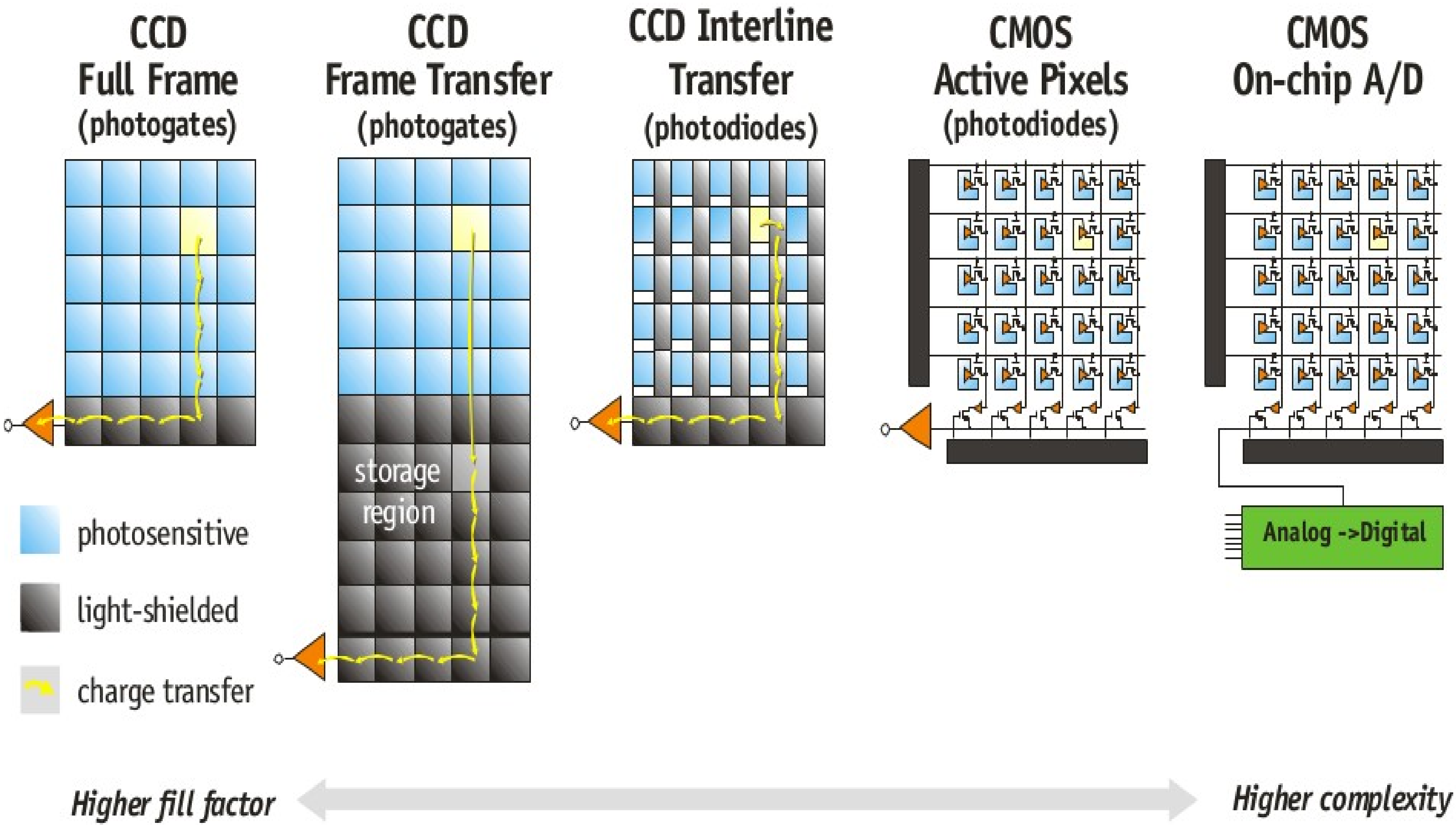
The frame rate of an image sensor is the measure of how many times the full pixel array can be read in a second (fps). It is mostly a function of pixel density and sensor architecture.

- CCDs are inherently slower because the full frame has to be read before it is converted (electrons to voltage) <u>off</u> chip. This type of shuttering is known as a ***Global Shutter.***
- CMOSs are faster because each pixel has a voltage converter on the pixel. As each row is read and converted the row is ready for a new exposure. This type of shutter is known as a ***Rolling Shutter.***

Sensor frame rates: examples

Camera	Sensor Type	Application	MP	fps
Z/I DMC 250	CCD	Aerial Photography	250	2.3
Nikon D800	CMOS	Professional DSLR	36	6
Canon 5DS-R	CMOS	Professional DSLR	53	5
Canon EOS C300 Mark II EF	CMOS	Cinema/video	9	24-60

Sensor Architectures



Sensor Architectures

Sensor description	Type	Fill Factor	Noise	Dynamic Range
Full Frame	CCD	High	Low	Higher
Frame transfer	CCD	High	Low	Higher
Interline	CCD	Medium	Medium	Lower
3T	CMOS	Lower	High	Lower
4T/5T	CMOS	Lower	Lower	Higher

The Future of Camera Sensors

Materials

Silver halides and silicon have been the cornerstones of imaging sensors. Will these materials simply continue to get refined in terms of performance, or, will there be another 'revolution' in imaging such as the change from silver based to silicon based?

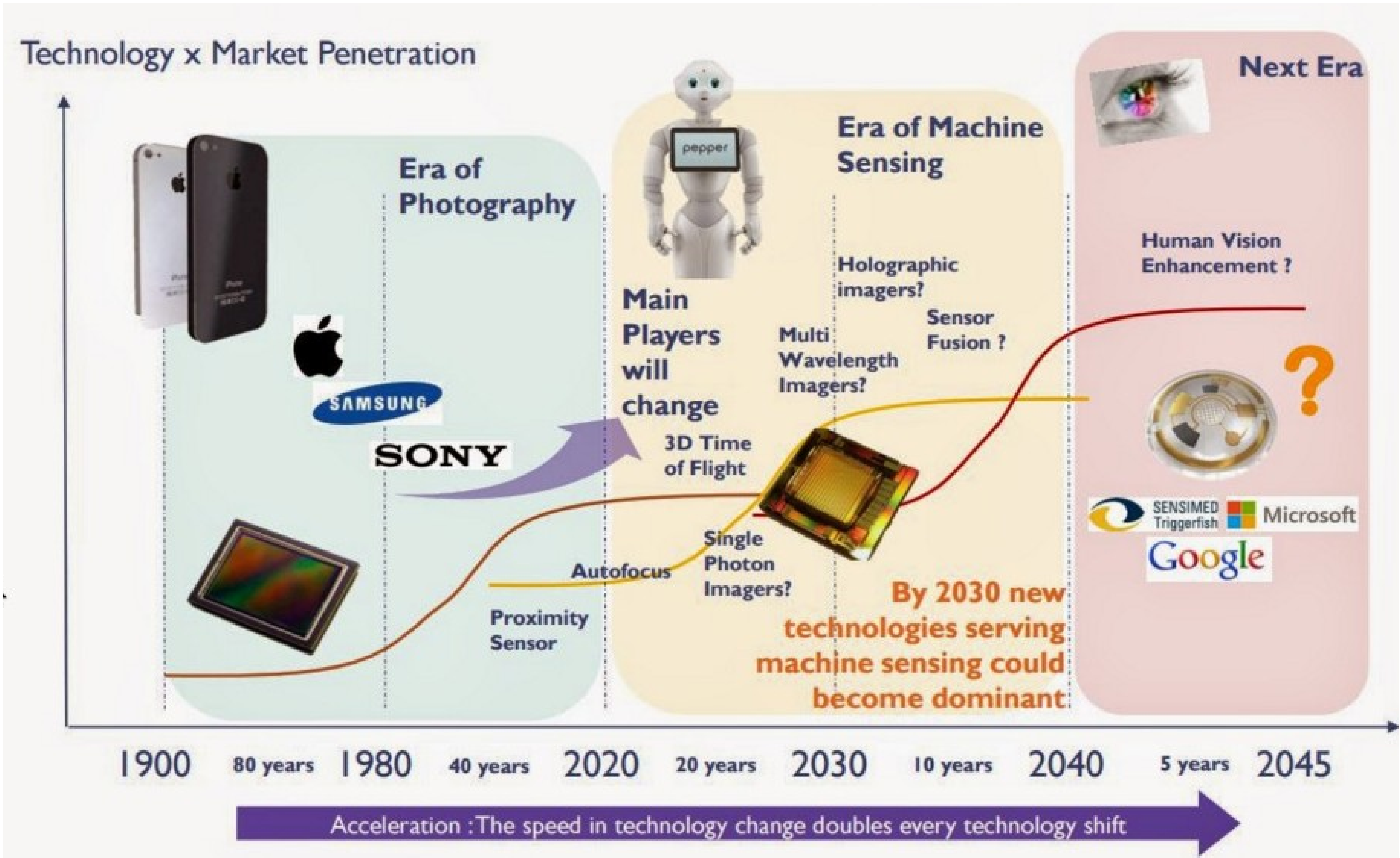
- The answer is probably some of both, with the near future leaning on refinement and the longer future edging towards new materials and methods.

The Future of Camera Sensors

What is on the near-future horizon for imaging sensors?

- The CCD eventually replaced by the CMOS
- CCD and CMOS performance approaching cooled quality parameters but at room temp (high ISO).
- Film actually making a comeback in a niched market.

The Future of Camera Sensors



Wrap-up – Key Learnings

1. **Size.** Always assess pixel dimensions in conjuction with sensor size. A 10MP point and shoot camera with an APS-C sized sensor will not perform the same as a 10MP phone camera with a smaller sensor.
2. **Quantum Efficiency.** Converting photons to electrons ***is*** the primary job of the sensor, the better the QE the better is this primary job. The QE of different sensors will vary depending on the design of the sensor: Back-lit/front-lit sensors, Foveon sensors, temperature..

Wrap-up – Key Learnings

3. **Noise**. The more complex a sensor gets the greater are the sources for noise and the lower is its dynamic range. Look for low readout noise since this is the hardware noise of the sensor. Remember, larger pixels allow lower noise and more sensitivity; this is how you get relatively 'clean exposures at high ISOs

4. **Dynamic Range.** Possibly the next most important variable after QE since it reflects charcateristics of the well potential and noise. Aim for DRs of close to or above 70db. This value means that your camera should encomapss some 15 EVs or stops.

Wrap-up – Key Learnings

5. Is film analogue? Although silicon is often considered the digital system and film analogue, at the fundamental exposure level the opposite is true.

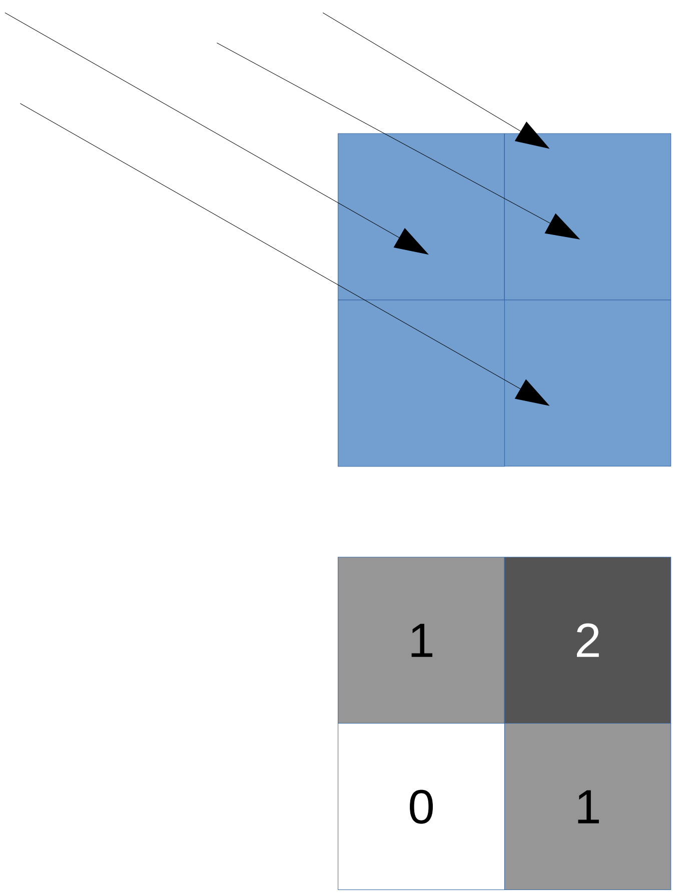
Electrons captured in potential wells are a continuous representation of photons striking the pixel; they are converted to a digital representation only after the the ADC process.

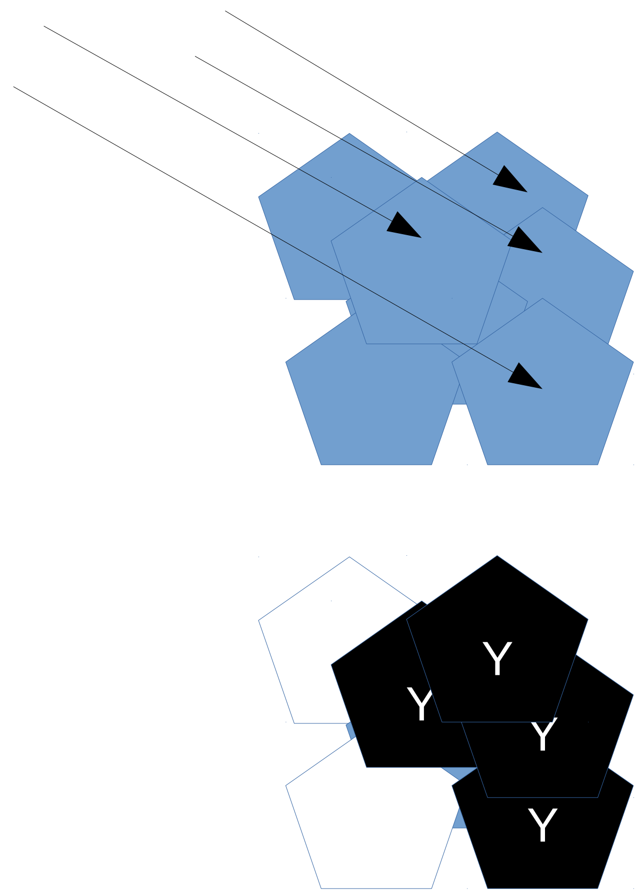
AgBr crystals on the other hand, are either activated by a photon or not. If activated, the whole grain turns black (silver) upon development, if not, it is removed in image fixation: a true binary system.

Wrap-up – Key Learnings

Emulsions

Consider 4 photons striking a 2X2 1micron pixel array and a similar sized emulsion with 1micron AgBr grains:





Wrap-up – Key Learnings

6. All sensors are monochrome. A sensor (silicon or AgBr) only senses the *quantity* of photons striking it, not their wavelength.

To produce color, the photons have to be filtered (Bayer CFAs, trichroic filters) or stratified by absorption depth in silicon (Foveon). With film, wavelength dependent absorption dyes are used to associate photon wavelength with emulsion layers.

7. All silicon sensors (digital cameras) are infrared sensitive. Manufacturers block the near IR sensitivity with a hot mirror placed on top of the sensor.