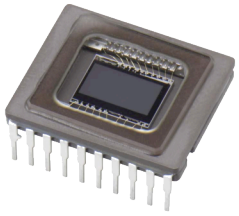
CCD and CMOS Image Sensor Technologies



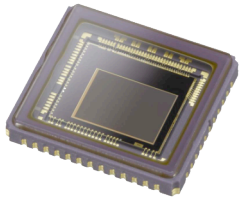


Image Sensors

- There are Two Main types of Image Sensors are available today:
- CCD and CMOS
- Both were originally developed in the late 1960's and 1970's

Defining Some Concepts

- Quantum Efficiency
  QE = Electrical Energy / Radiant Energy
- Fill Factor
  FF = Active Area in Pixel / Total Pixel Area
  - Microlenses improve the effective fill factor 2 or 3 times

Imager Types

- CCD = Charge Coupled Device
- CMOS = Complementry Metal Oxide Semi-Conductor, often called Active Pixel Sensing, or APS

- CCD = specialized production plant and process
- CMOS = standard silicon production line

Imager Types

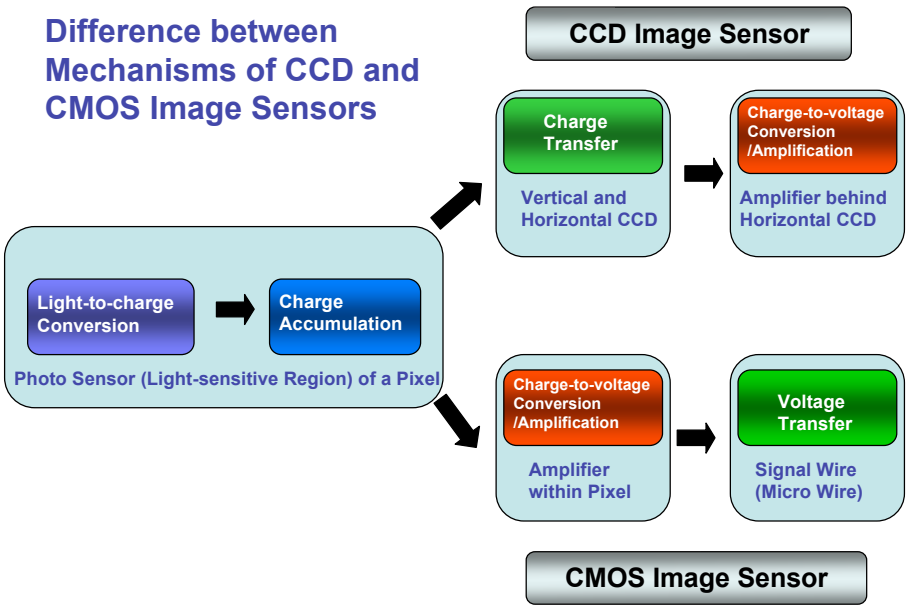
- CCD = Longer mass production period means more mature technology and better quality
- CMOS = technology to produce high image quality has proven more difficult and specialized to obtain than expected

CMOS APS Vs. CCD

- CCD
  - requires specialized expensive processes; not easily integrated with CMOS
  - has high Quantum Efficiency, high fill factor and low noise
  - lacks random access and fast readouts
  - needs multiple voltages on chip for efficient charge transfer
- APS
  - is lower voltage and lower-power
  - achieves random access and faster readout
  - can yield low noise with peripheral circuitry
  - compatible with CMOS process

Image Sensors

- Through the 80's 90's and until today CCD's became dominant primarily because they gave far superior images with the fabrication technology available.
- Not until the late 1990's could designers begin to make a case for CMOS to even be considered as a viable alternative.
- Primarily the renewed interest came from expectations of lower power requirements for CMOS.
- CMOS Designers however had to overcome the many inherent image quality deficiencies of CMOS particularly high noise, poor low sensitivity and poor dynamic range.



Basic Mechanism of CCD Image Sensors

CCD wells

- Buried “channel stops” to define columns
- Array of insulated electrodes to define pixels
- Additional array of electrodes to shift a line at a time

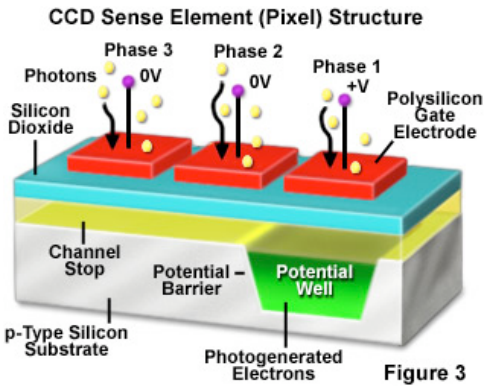
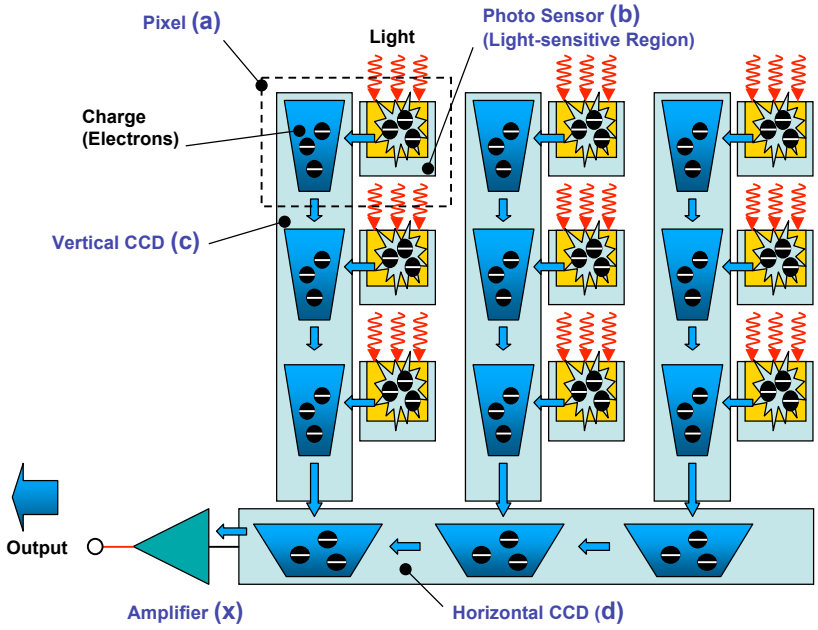
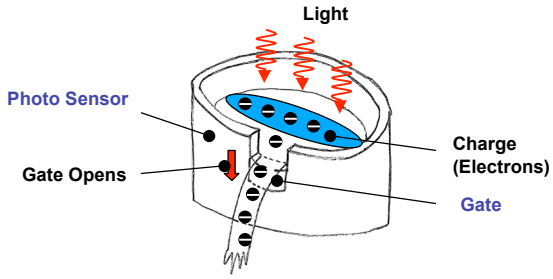


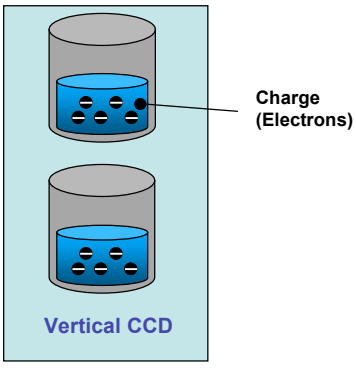
Figure 3

CCD Image Sensor

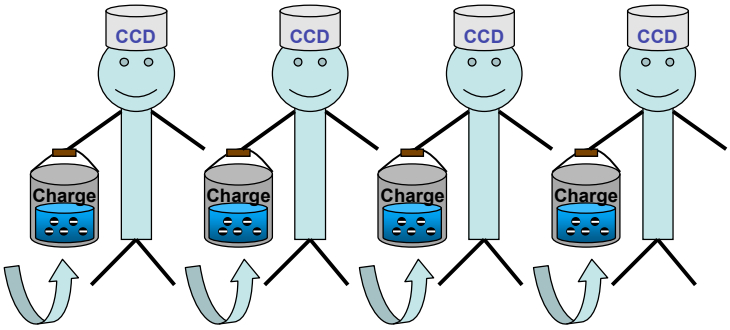




Charge Transfer from Photo Sensor to Vertical CCD – Like Water Draining from a Dam



Charge Transfer by CCD in a Bucket-brigade Fashion



Charge Transfer by CCD in a Bucket-brigade Fashion

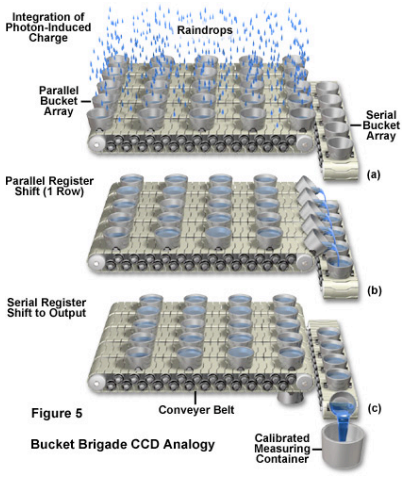
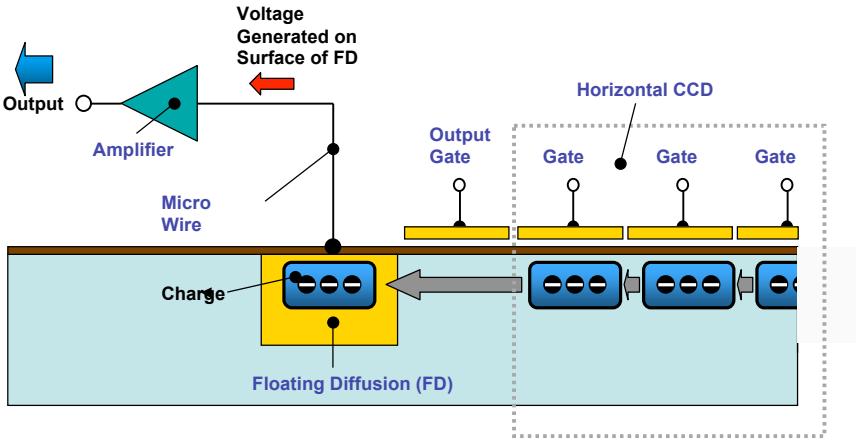


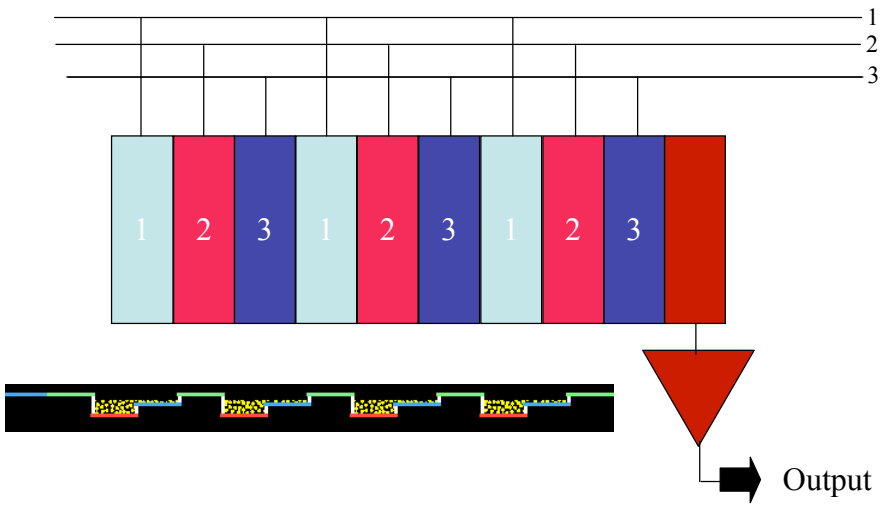
Figure 5
Bucket Brigade CCD Analogy

Amplifier of CCD Image Sensor

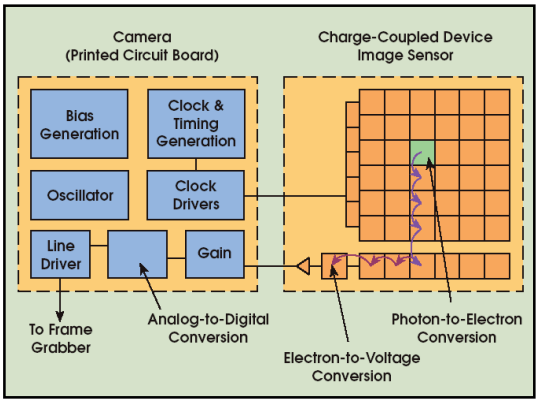


CCDs

3 Phase Serial Register



Basic CCD camera



Advantages:

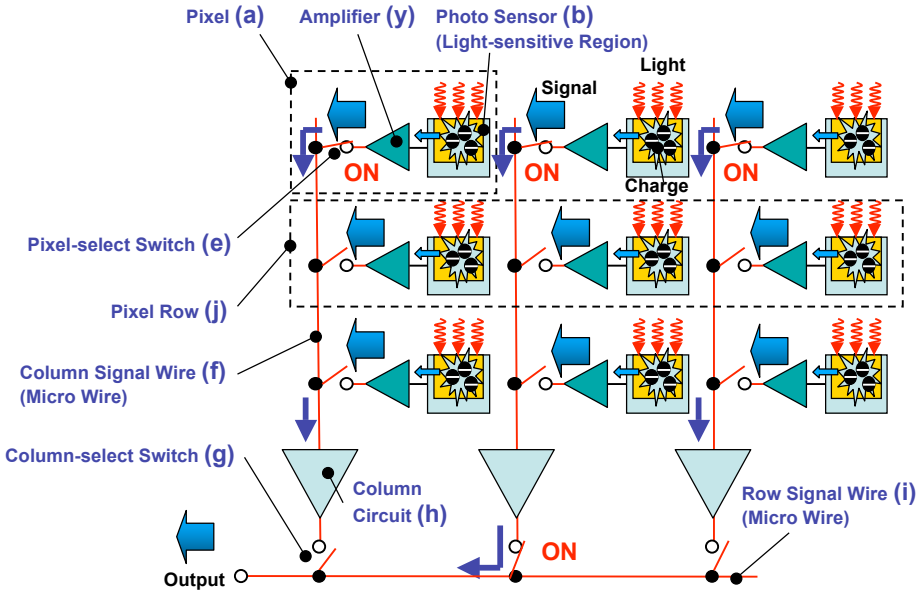
- Low noise;
- High full-well capacity;
- 100% fill factor;
- High uniformity;
- Mature technology;

Disadvantages:

- Slow readout;
- Pixel blooming;
- Specialised fabrication;
- Low functionality;

Basic Mechanism of CMOS Image Sensors

CMOS Image Sensor



Voltage Generated on Surface of Photo Sensor – Like the Rising Water Level of a Bucket

Fig. A When Charge is NOT Accumulated in Photo Sensor

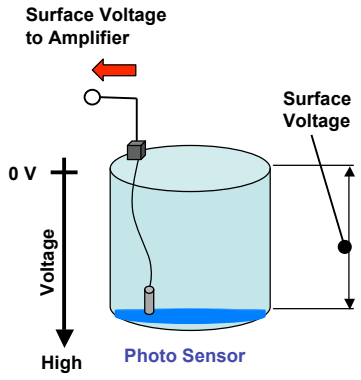
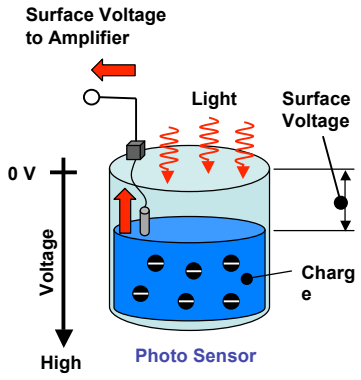
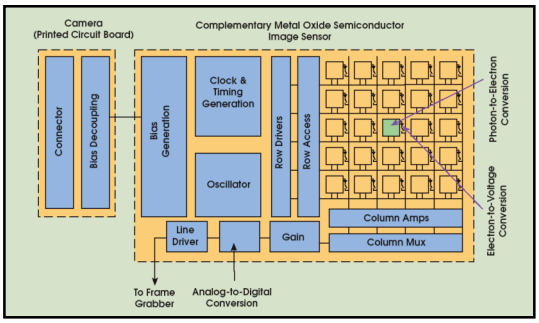


Fig. B When Charge is Accumulated in Photo Sensor



Basic CMOS camera



Advantages:

- High Speed readout;
- Random access;
- On-chip intelligence;
- Low power consumption;

Disadvantages:

- High read-out noise;
- Reduced dynamic range;
- Reduced uniformity;
- Reduced fill-factor;
- High cost;

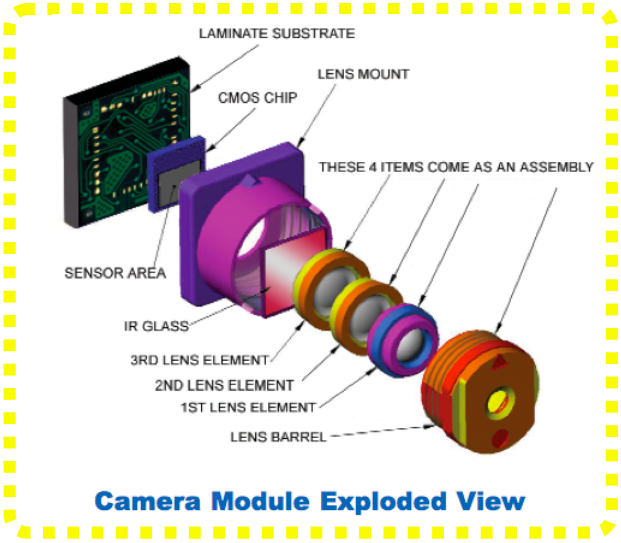
Typical camera module for the Micron MT9M111

Fixed-focus.
No "optical" zoom.

0.27 inches deep.

0.37 inch x 0.37 inch square

Source: www.asia-optical.com.tw



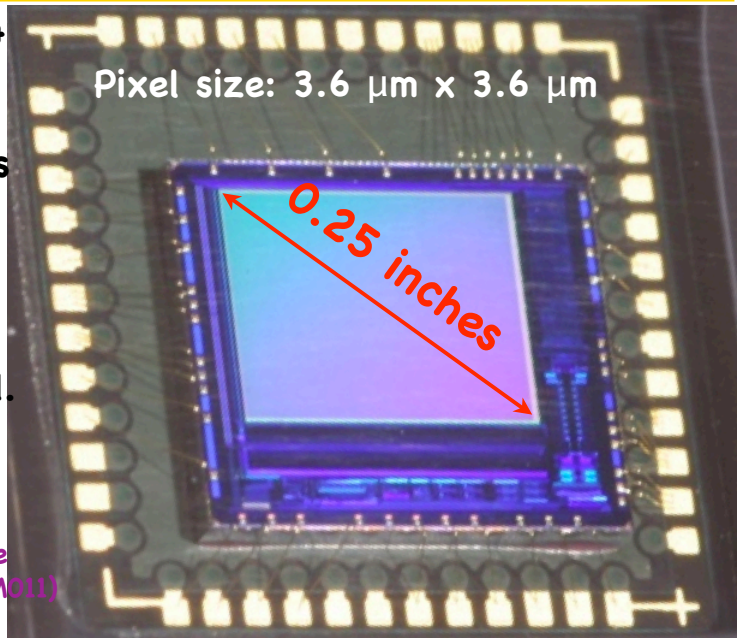
Camera Module Exploded View

Amkor Technology

Micron MT9M111* – 1.3 MPixel CMOS Imager

1280 x 1024 pixels.

Each pixel is R, G, or B. So, 2/3 of RGB image data is interpolated.



* Photo a close relative (MT9M011)

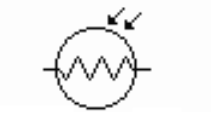
This is how "photo cells" work ...

A mainstay of 100-in-1 experimenter kits

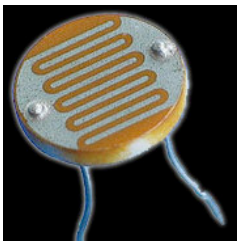
hν

Surface open to light.

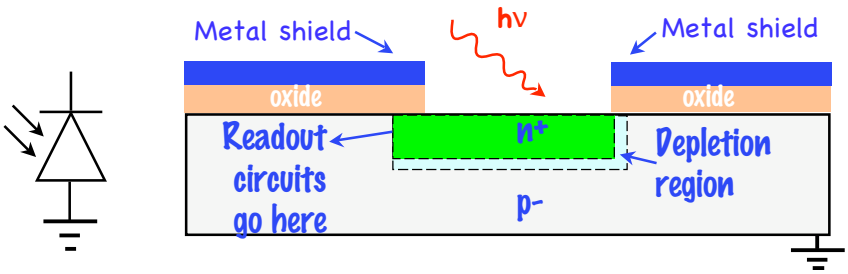
Schematic symbol

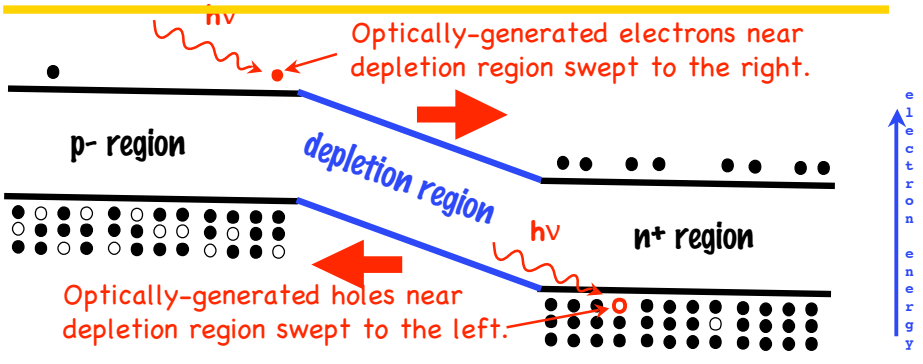


A photosensitive resistor.
The semiconductor CdS is often used, as its band gap falls in blue-green, and thus blocks infrared w/o a filter.

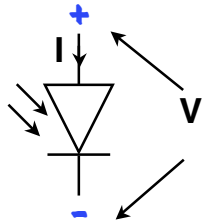


For ICs, photodiodes a better match





Photodiode I-V curves ...



$I = I_o (e^{V/V_o} - 1) - I_{ph}$

V_o : 25-60 mV

I_o : 1-20 fA

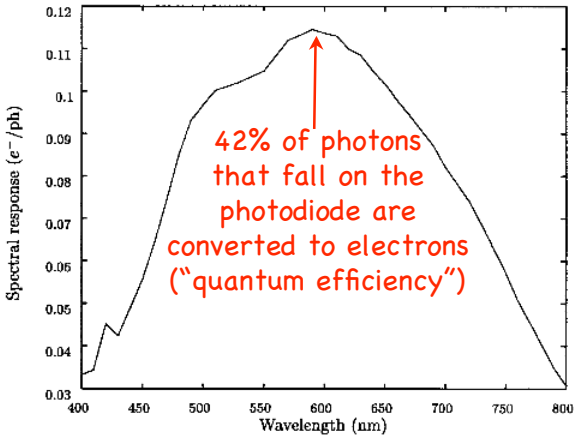
Quadrant for photosensing.

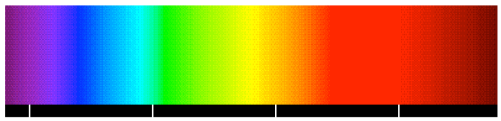
Quadrant for solar cells.

Spectral response (0.35µm n-well CMOS)

Data shown is for a standard 0.35µ CMOS logic process.

Quantum efficiency can be improved by modifying the process.



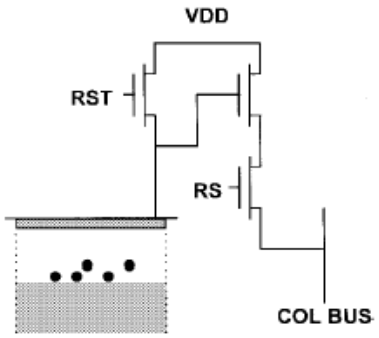


Source: "A 640 512 CMOS Image Sensor with Ultrawide Dynamic Range Floating-Point Pixel-Level ADC", David X. D. Yang, Abbas El Gamal, Boyd Fowler, and Hui Tian, JSSC, Dec 1999.

Readout Circuits

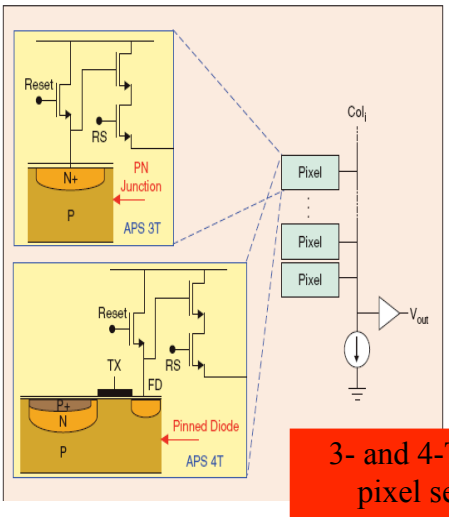
APS Design

- A Simple Photodiode APS Cell
  - Described by Noble in 1968
  - Three transistors per pixel
  - High quantum efficiency (no overlying polysilicon)

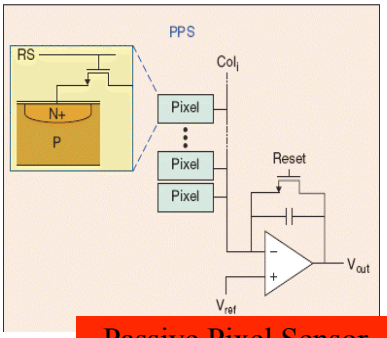


E. R. Fossum, "CMOS image sensors: Electronic camera-on-a-chip," in *IEEE IEDM Tech. Dig.*, 1995.

Pixel Circuits



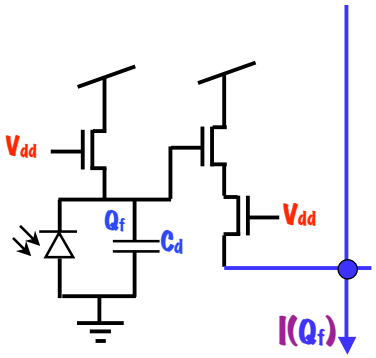
3- and 4-T active pixel sensor.



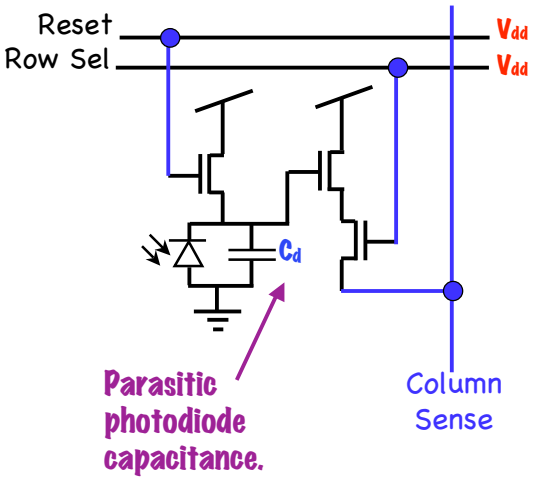
Passive Pixel Sensor.

Three-Transistor Active Pixel Cell

Step 1: Fill C_d, and sense column current.

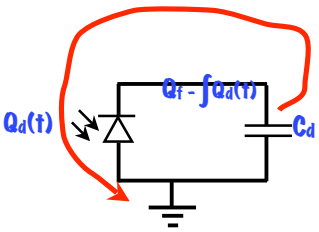


Edge circuitry samples current $I(Q_f)$ for later use.



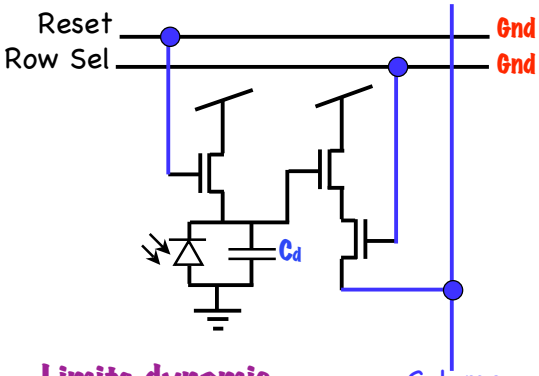
Opening the electronic shutter ...

Step 2: "Electronic shutter" is open, photodiode empties C_d.



Too much $\int Q_d(t)$, and we empty bucket before shutter closes.

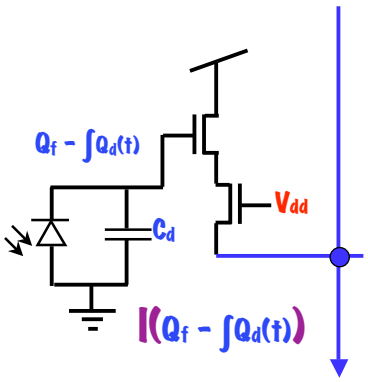
Not enough $\int Q_d(t)$, and we capture temporal noise.



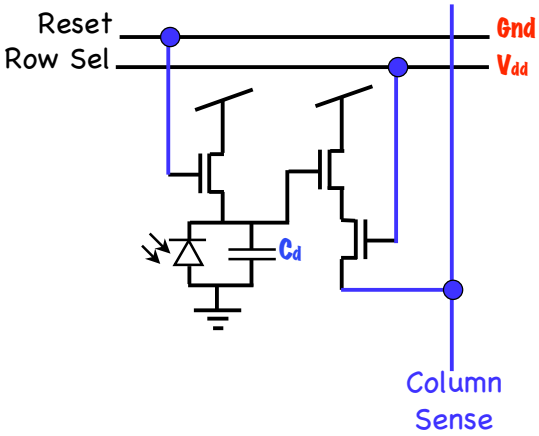
Limits dynamic range and signal-to-noise.

Close shutter, read pixel value ...

Step 3: Sense how empty C_d has become.



Use $I(Q_f)$ from start of the cycle to reduce kTC (reset) noise.



"Correlated double sampling"

Temporal noise affects Qf value.

Non-Idealities and Performance Measures

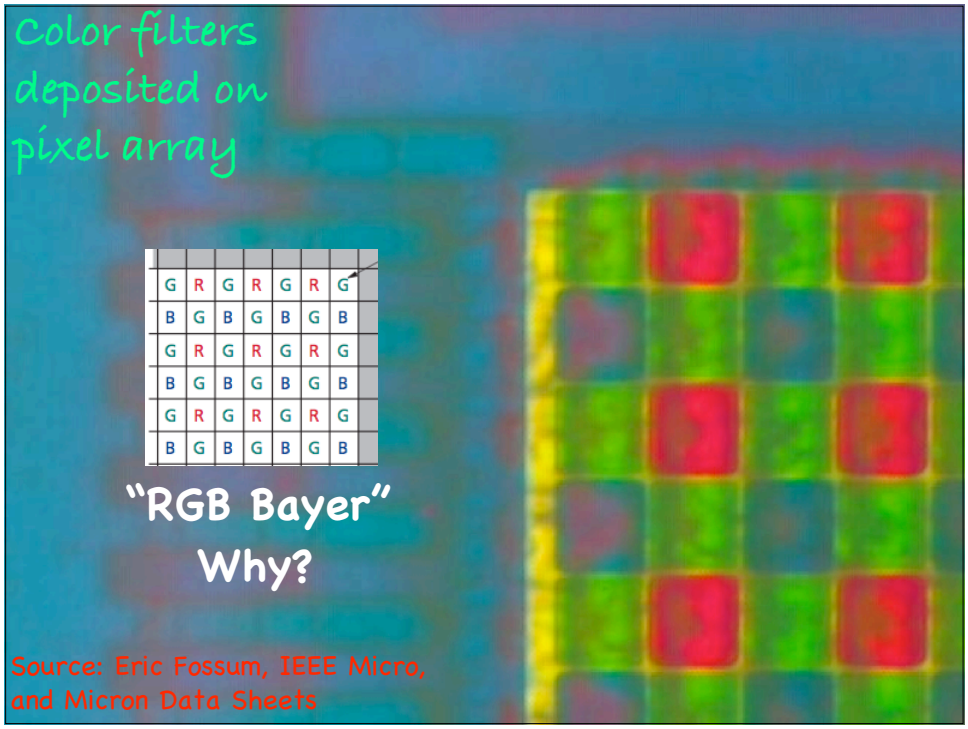
Three important aspects of image sensor performance are:

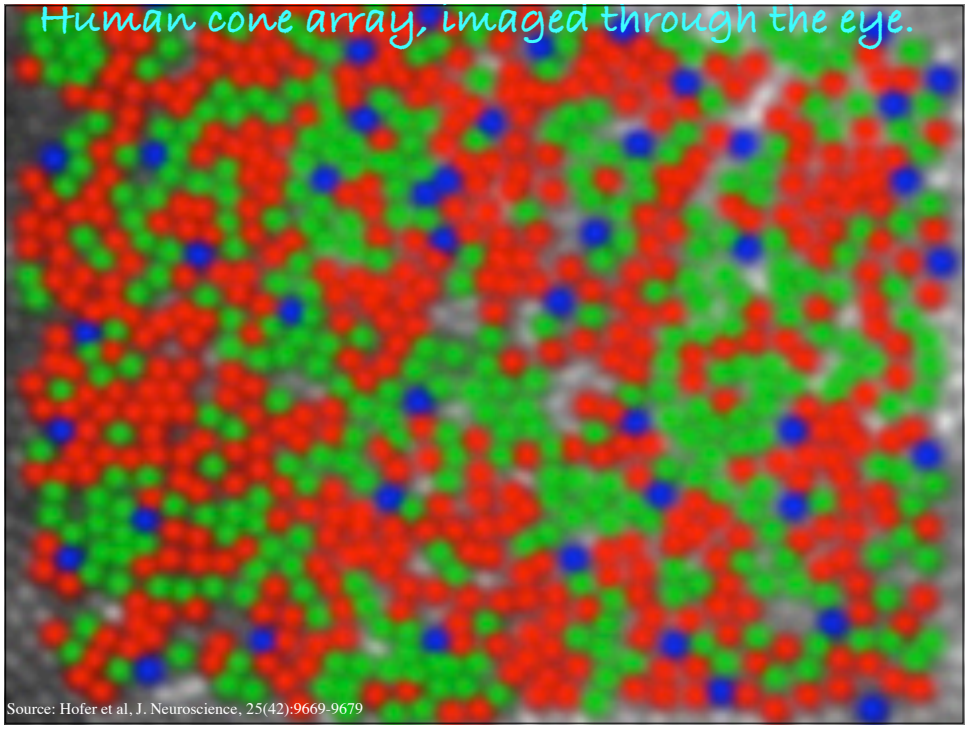
- SNR (signal to noise ratio): higher than 40 dB required
- DR (dynamic range): range of illumination that can be detected by the image sensor.
  - Standard CMOS Image sensors have a DR of 40-60 dB, While human eye exceeds 90 dB.
- Spatial Resolution: determined by the Nyquist sampling theorem.

Color

Si photodiodes "see" gray scale

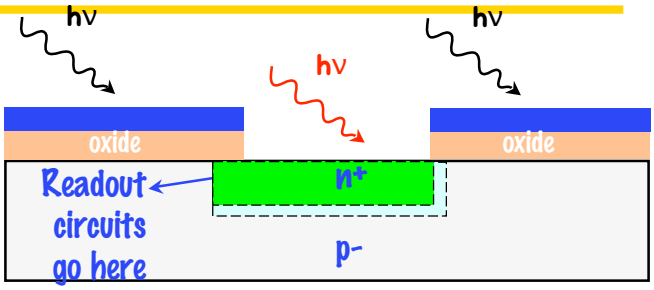
...


Color filters deposited on pixel array
G R G R G R G
B G B G B G B
G R G R G R G
B G B G B G B
G R G R G R G
B G B G B G B
"RGB Bayer"
Why?
Source: Eric Fossum, IEEE Micro, and Micron Data Sheets


Human cone array, imaged through the eye.
Source: Hofer et al, J. Neuroscience, 25(42):9669-9679

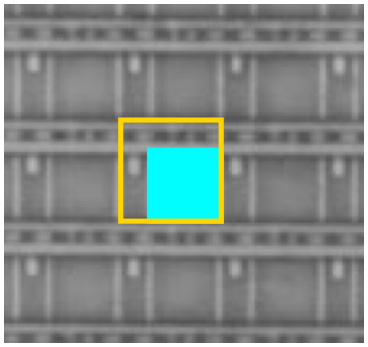
Recall: Photodiode design ...

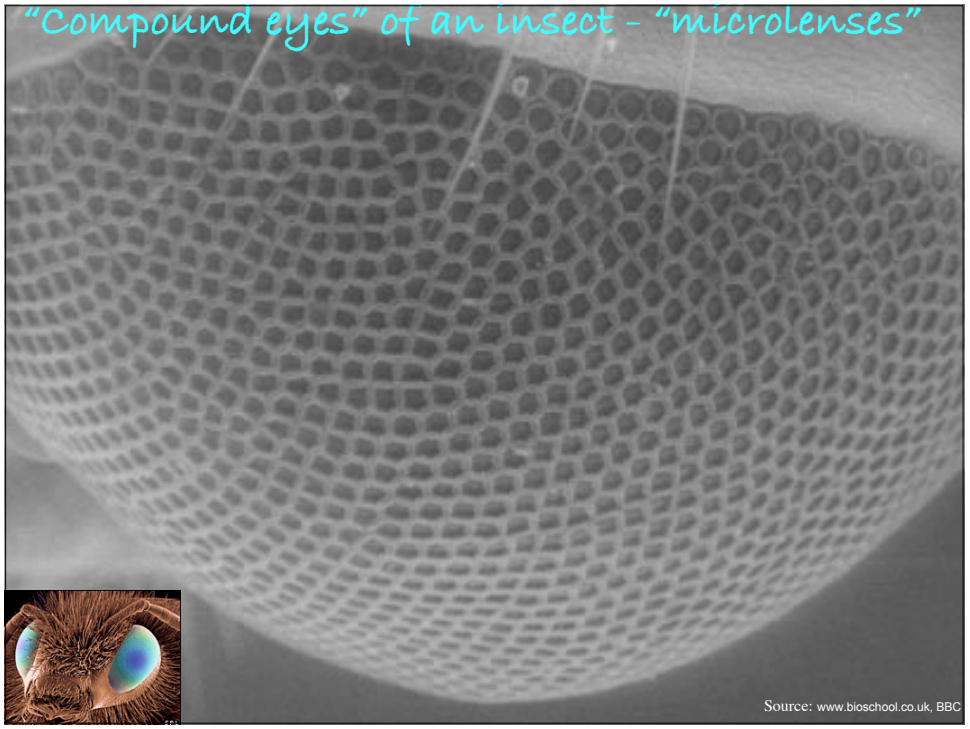
Photons that reflect off metal shielding are lost.

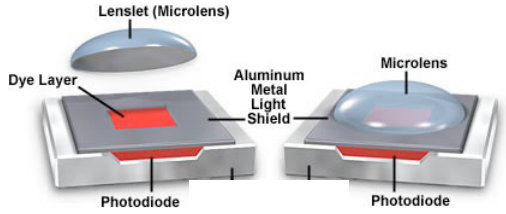


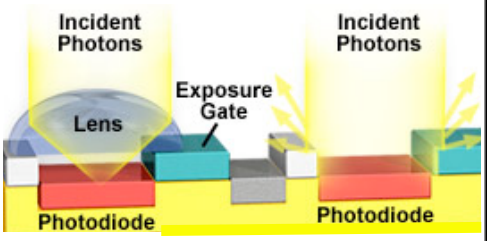
Fill factor = Photodiode area / Pixel area

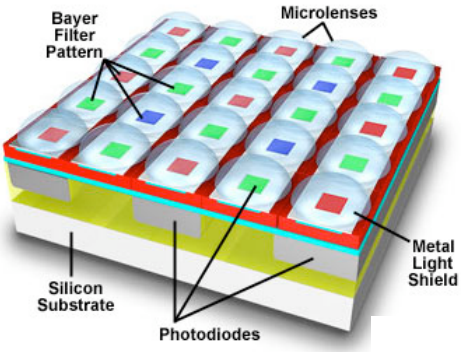
As process shrinks, readout circuits shrink and diode grows. So, fill factor increases and fewer photons lost.





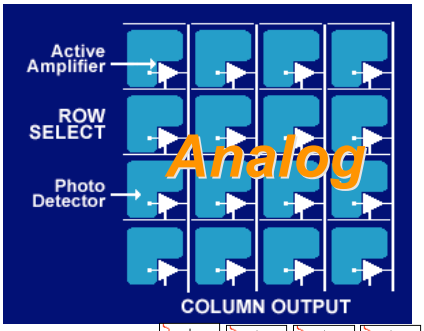




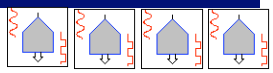


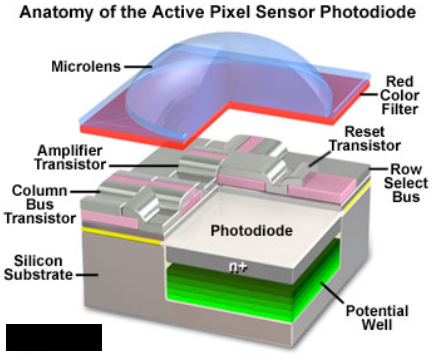
Source: http://micro.magnet.fsu.edu/

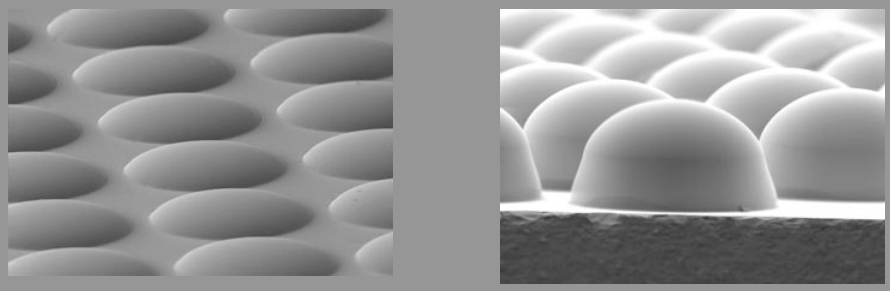
APS



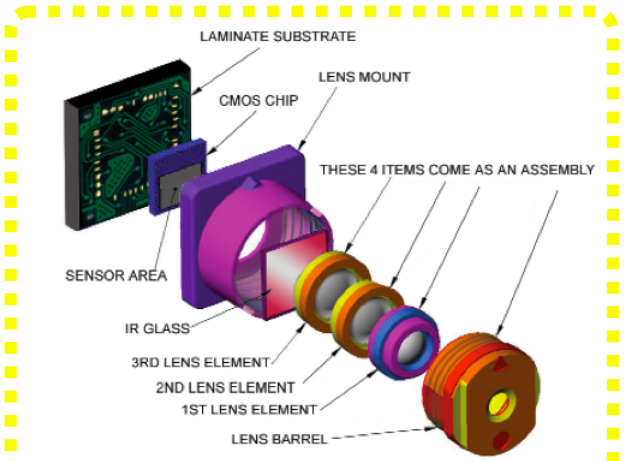
ADC's







Source: Fraunhofer ISIT



Camera Module Exploded View

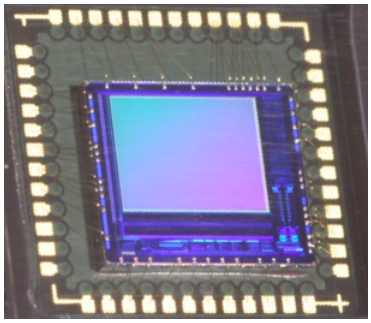
Micron

MT9M111
SOC MEGAPIXEL DIGITAL IMAGE SENSOR

1/3-INCH SOC MEGAPIXEL CMOS DIGITAL IMAGE SENSOR

MT9M111I29STC
(Micron Part Number)

Sensor Architecture



SoC interface to the outside world

Simple Power Hookup

Serial port to control the camera.

8-bit Dout Port
54 MHz Clk

1280 x 1024
@ 15 fps

640 x 512
@ 30 fps

YCrCb 4:2:2

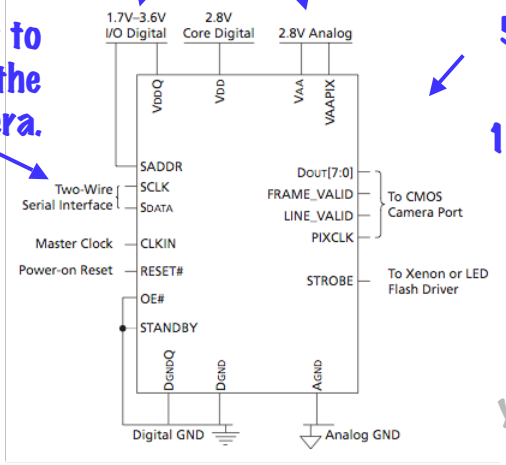
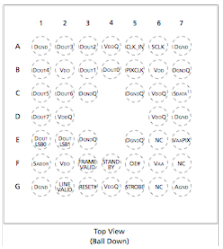
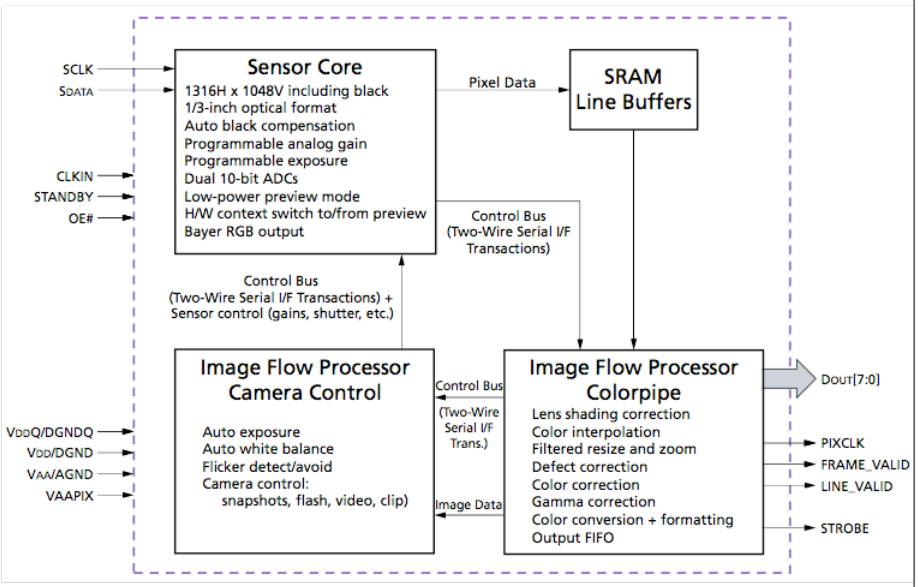


Figure 4: 44-Ball iCSP Assignment

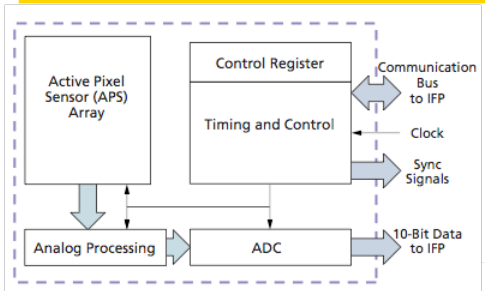


Top View
(Ball Down)

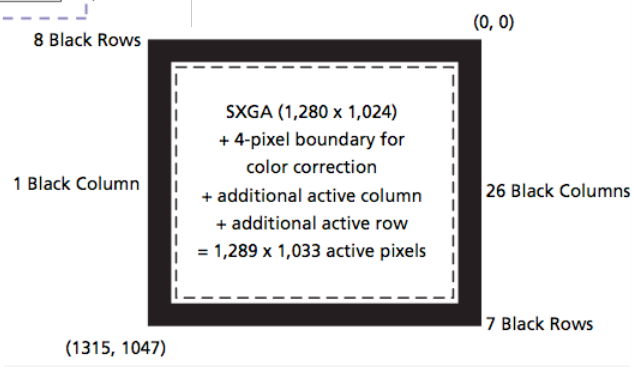
Functional Block Diagram



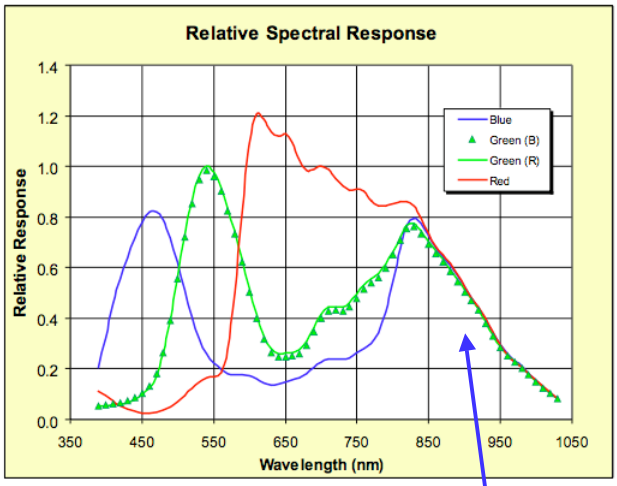
Sensor Array Details

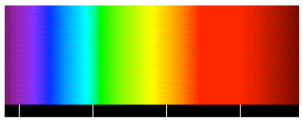


Black pixels have photodiodes covered by metal.



Spectral response ...





Note IR response. This is why camera module needs an IR filter.