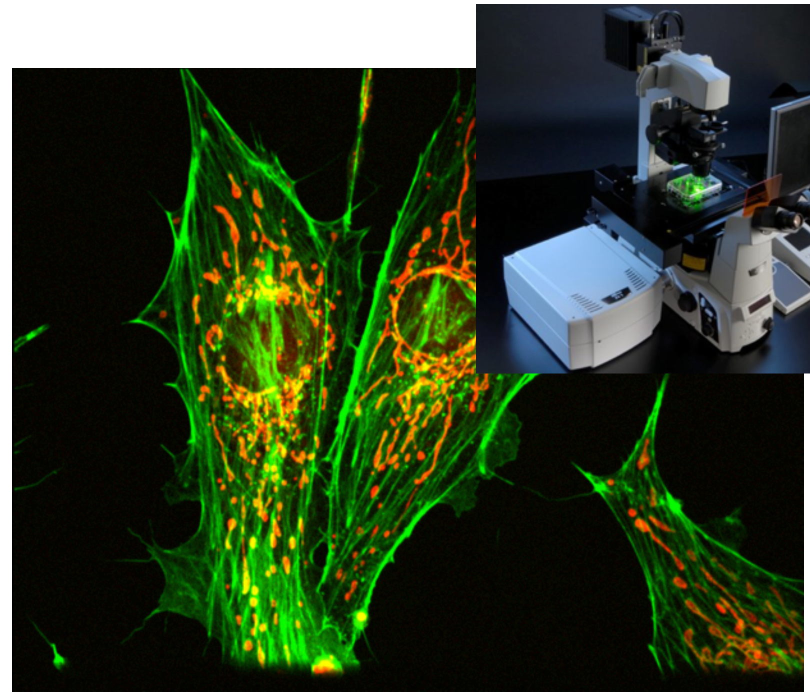
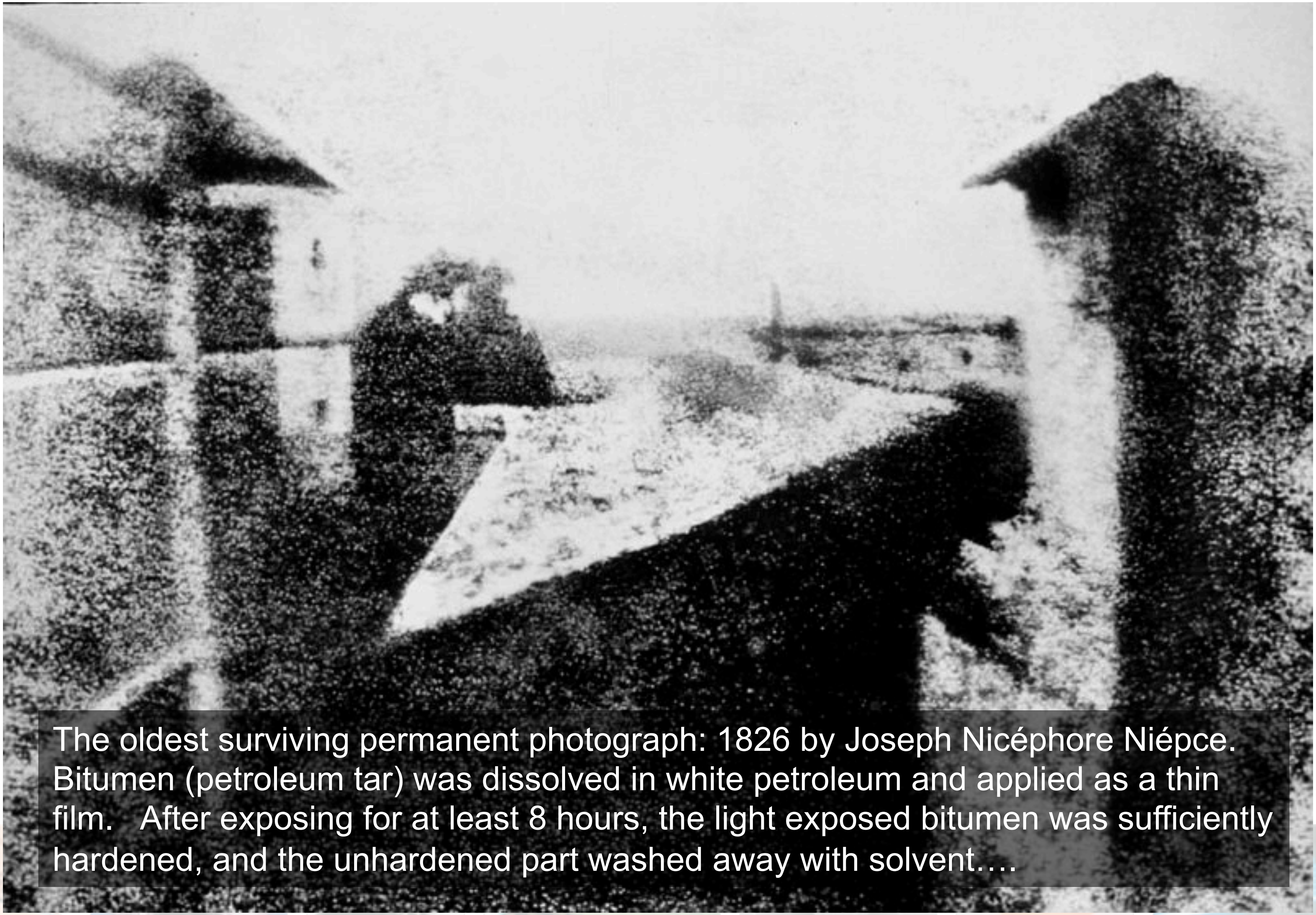
9.X – Imaging with CCDs and CMOS Arrays



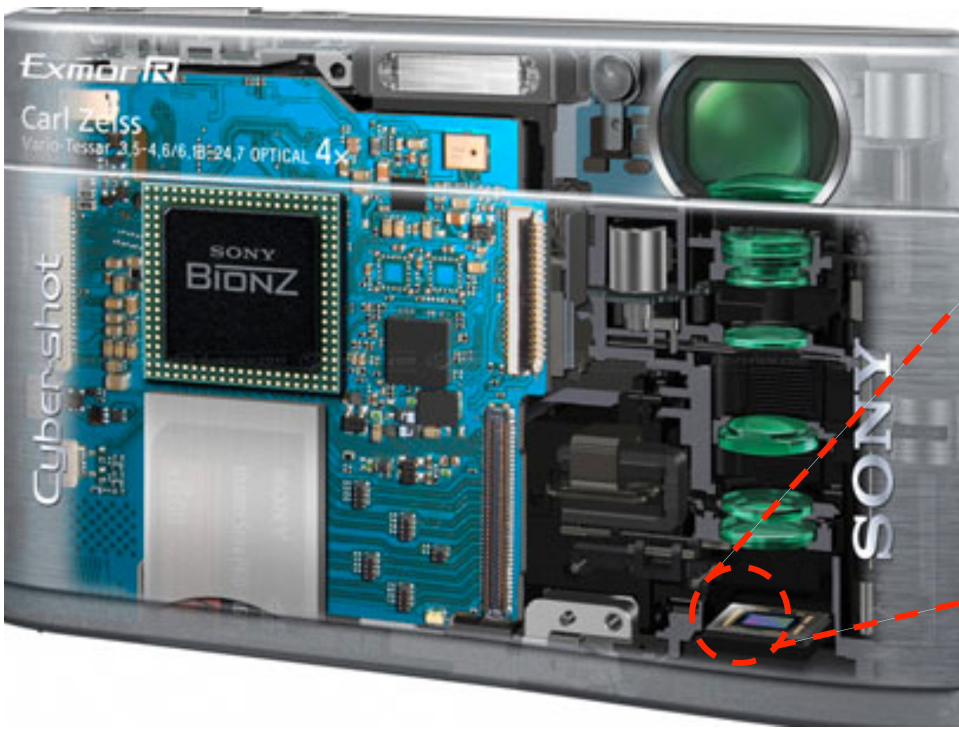
Confocal microscope image of a double labeled cell culture.

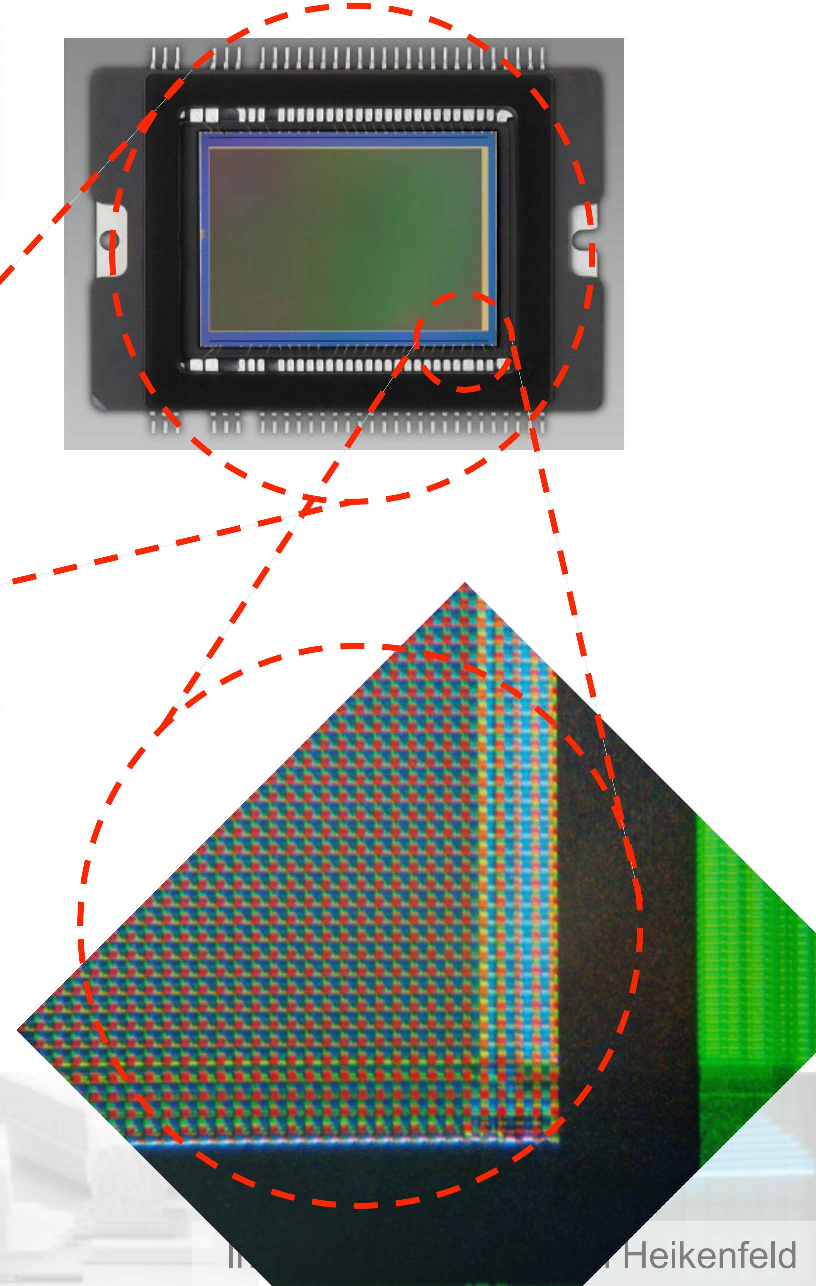


The oldest surviving permanent photograph: 1826 by Joseph Nicéphore Niépce. Bitumen (petroleum tar) was dissolved in white petroleum and applied as a thin film. After exposing for at least 8 hours, the light exposed bitumen was sufficiently hardened, and the unhardened part washed away with solvent….

Steven Sasson at Kodak invented the first digital camera in 1975. It weighed 8 pounds (3.6 kg) and had only 0.01 megapixels. The image was recorded onto a cassette tape and this process took 23 seconds. His camera took images in black and white.

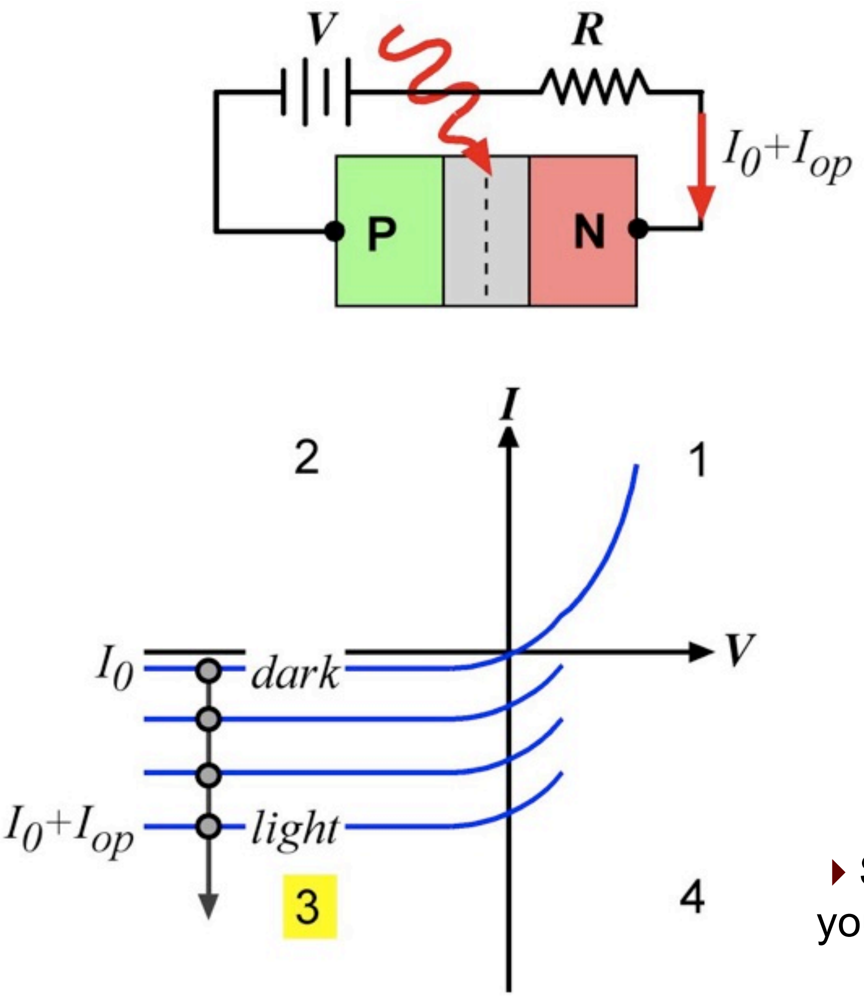
The Apple QuickTake is one of the first consumer digital camera lines, launched in 1994 and was marketed for three years before being discontinued in 1997. Three models of the product were built including the 100 and 150, both built by Kodak, 1 MB flash EPROM. The QuickTake cameras had a resolution of 640 x 480 pixels maximum (0.3 Mpx).



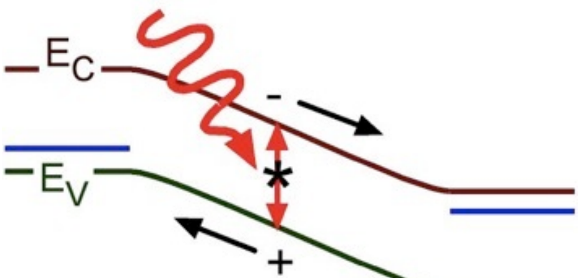


And, something a bit newer….

- Photodiode: externally powered, used as a light sensor!



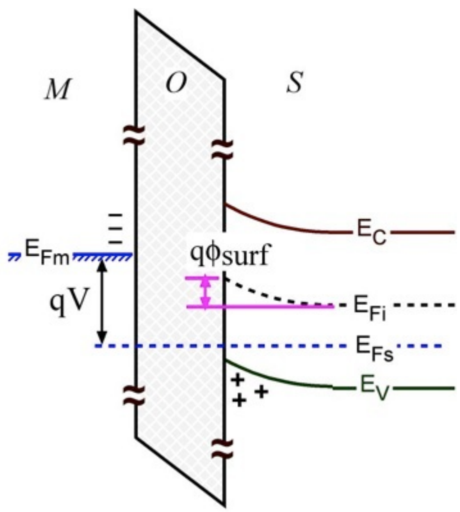
- PIN has larger A/W by increasing width of depletion region.

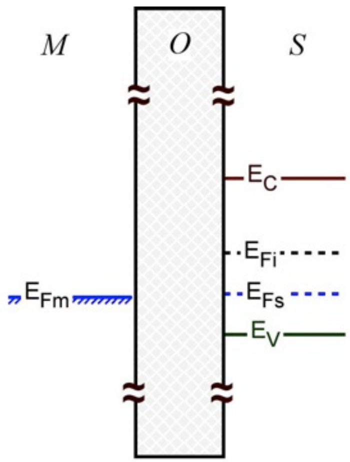


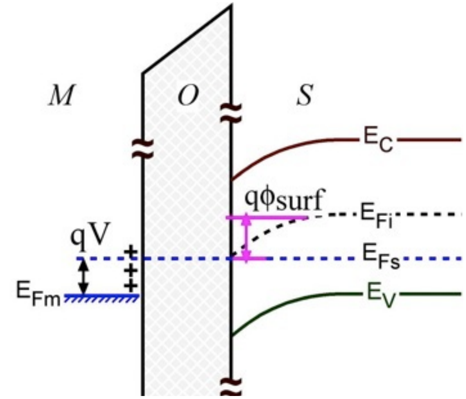
- So, make a 1M pixel camera… how would you do it? Ideas?

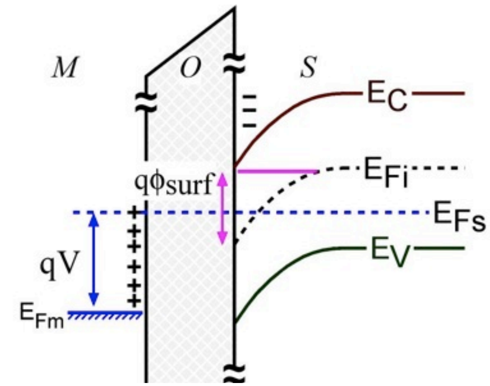
- Lets first look at the non-obvious approach (historically the 1st, because easiest to fabricate).

- Accumulation
- Flat Band
- Depletion
- Inversion

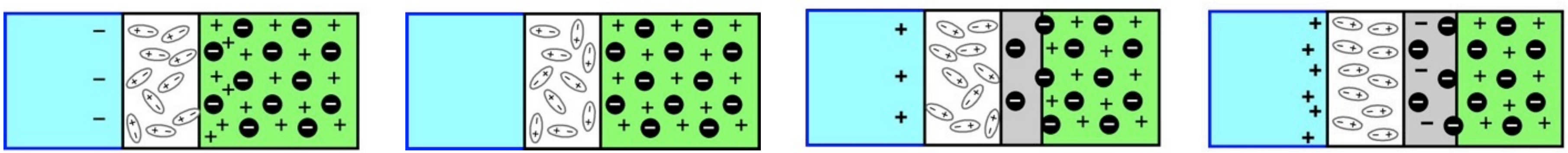






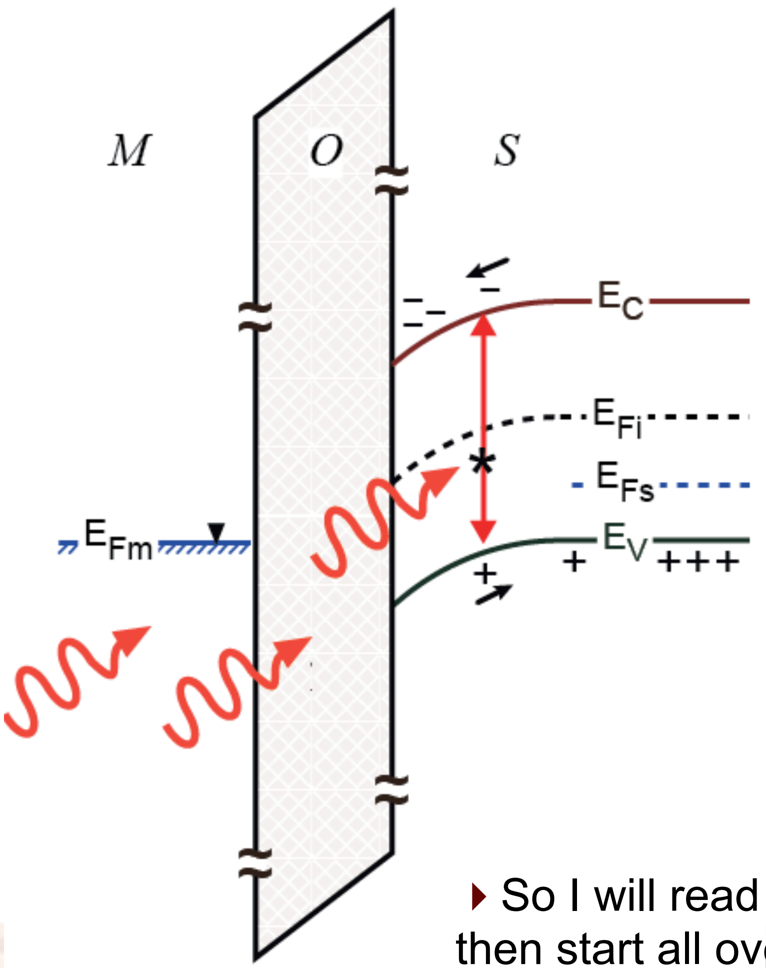


- *Note surface potential Φ, we will see it again in a moment!*



- **First question** – if I shined light on each of these, right under the oxide, which in which case would I see the largest change in photo-generated Q?
  - **Second question** – what will happen to that charge? Does it have much of anything to recombine with?
    - **Third question**, this is a very simple 'charge coupling' device structure, which could be made into a high-resolution array easily… but how get the charge out???

- I can capture photo-generated charge under the oxide… ☆



- Lets figure out how to calculate how many…

$$g_{op} = \#\ photons\ (carriers) / cc - s$$

- For a photodiode, I have the following… how modify for device at left? Hint: 2 changes…

$$I_{op} = q \times g_{op} \times A \times width$$
$$= qg_{op}A\left(L_p + L_n + W\right)$$

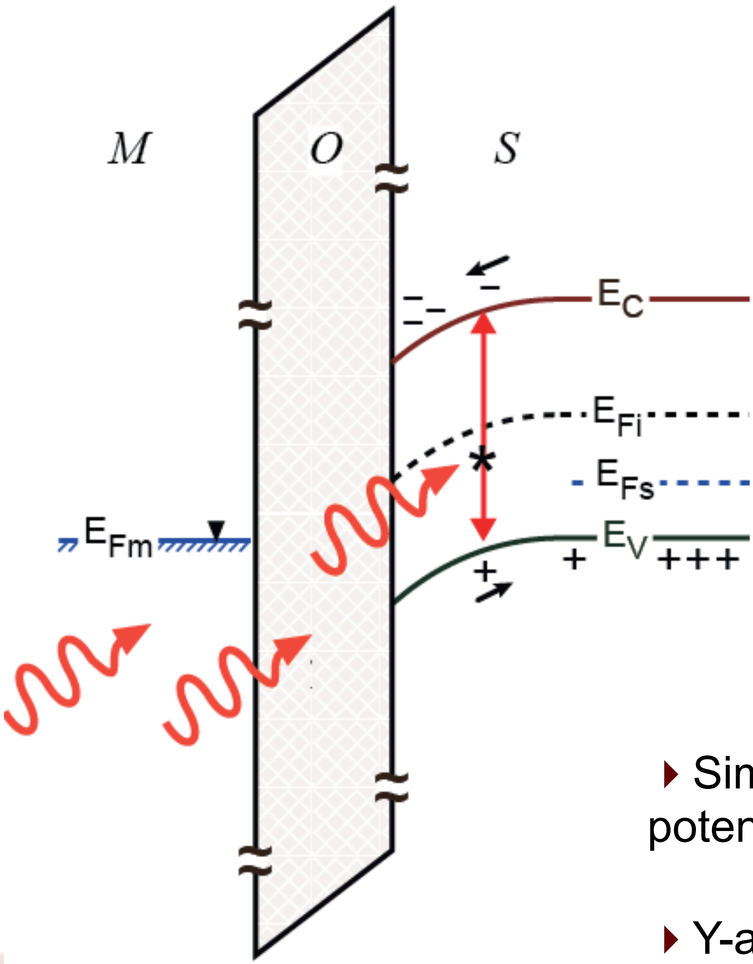
$$I_{op} = qg_{op}A\left(L_n + W_{\max}\right)$$ ☆

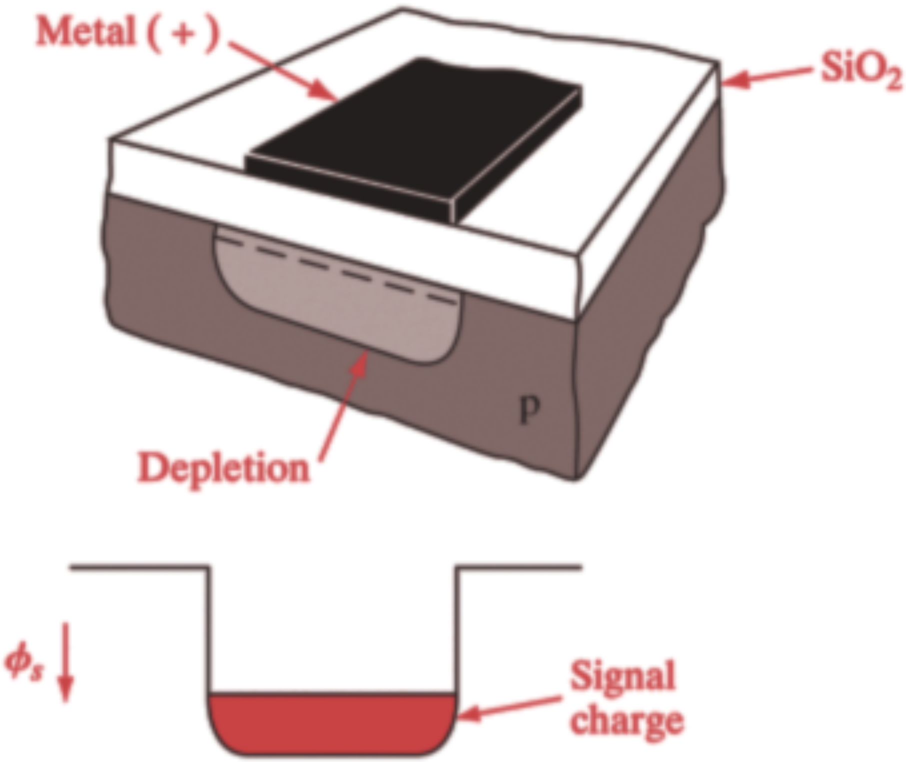
- I know I don't have current flow though, I am just building up a Q, so how calculate Q?

$$Q_{op} = I_{op} \times t_f(s) = q \times g_{op} \times A \times width \times t_f(s)$$

- So I will read this out (collect it) at a frame rate of $1/t_f$ (Hz), and then start all over again (show you how in a second)… So why are high-speed cameras more difficult and more expensive?

- Lets use some figures from the book…





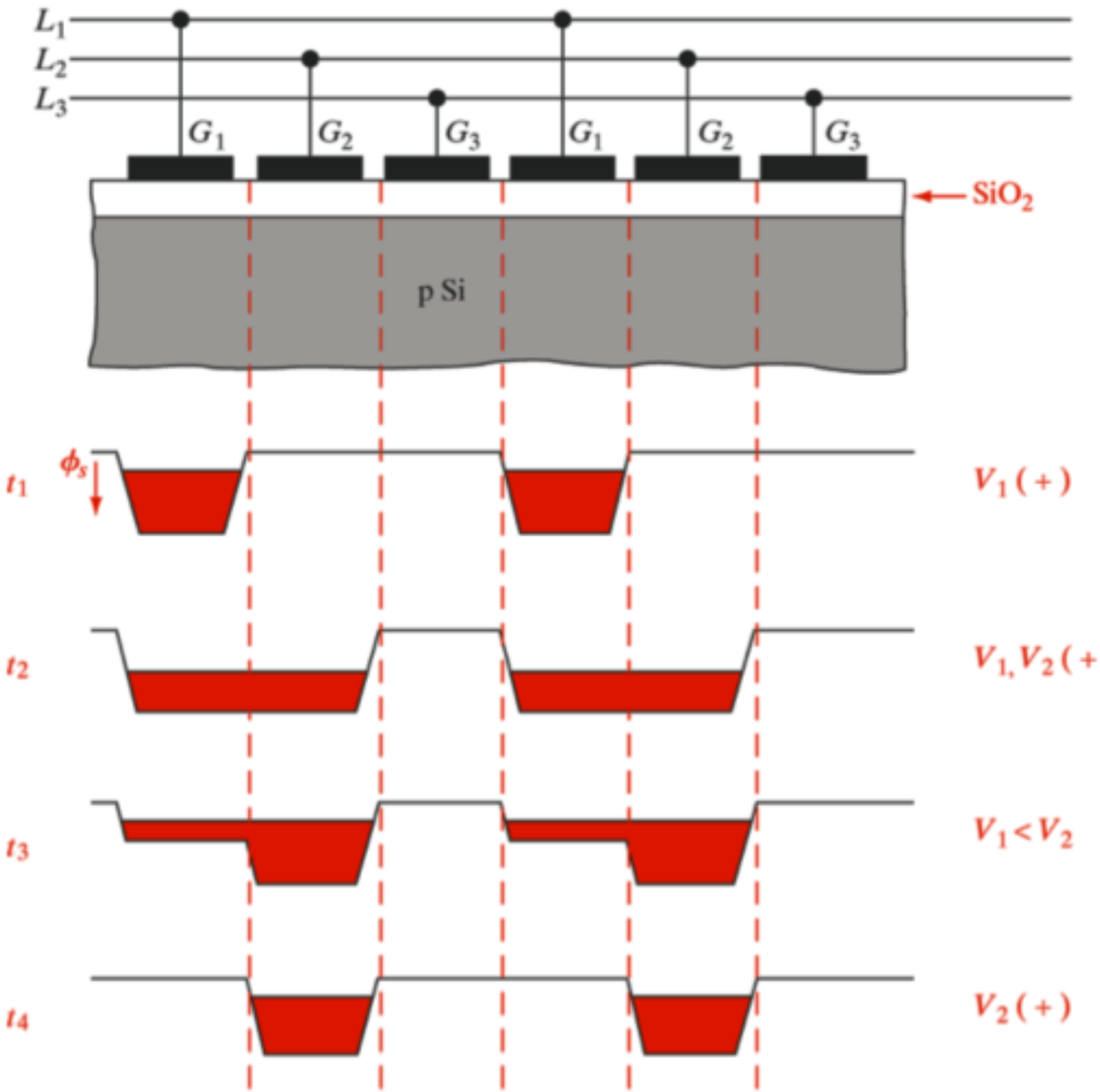
- Simply treat the ‘charge coupling’ under the gate as a potential well…
- Y-axis is surface potential Φ_s (right under the oxide), x-axis is just horizontal distance under the oxide

- Here is how I move the charge to the edge of the 'CCD' array where I can read it out at an amplifier and line-out.

- AND, the amount of charge read out is proportional to the number of photons absorbed (g_{op}) times the length of the frame before I read out the charge!

$$Q_{op} = I_{op} \times t_f(s)$$

$$= q \times g_{op} \times A \times width \times t_f(s)$$

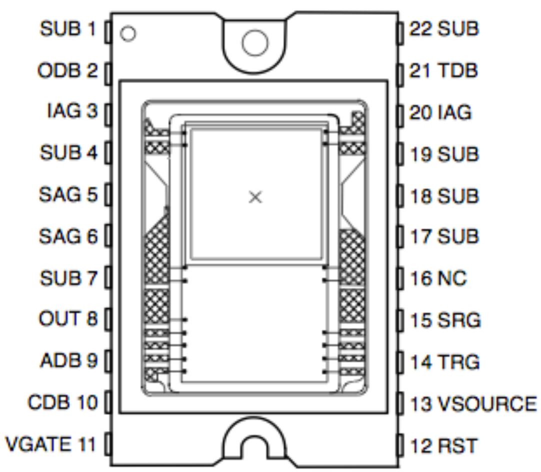


- In 2D format, read out one row at time… is a 'double' serial process, so CCDs are NOT fast!

TC281
1036- × 1010-PIXEL CCD IMAGE SENSOR

SOCS058D – JUNE 1996 – REVISED MARCH 2003

DUAL-IN-LINE PACKAGE
(TOP VIEW)



- **Up to 30 Frames per Second**
- **8-µm Square Pixels**
- **Low Dark Current**
- **Advanced Lateral Overflow Drain for Antiblooming**
- **Single-Pulse Image Area Clear Capability**
- **Dynamic Range of More Than 60 dB**

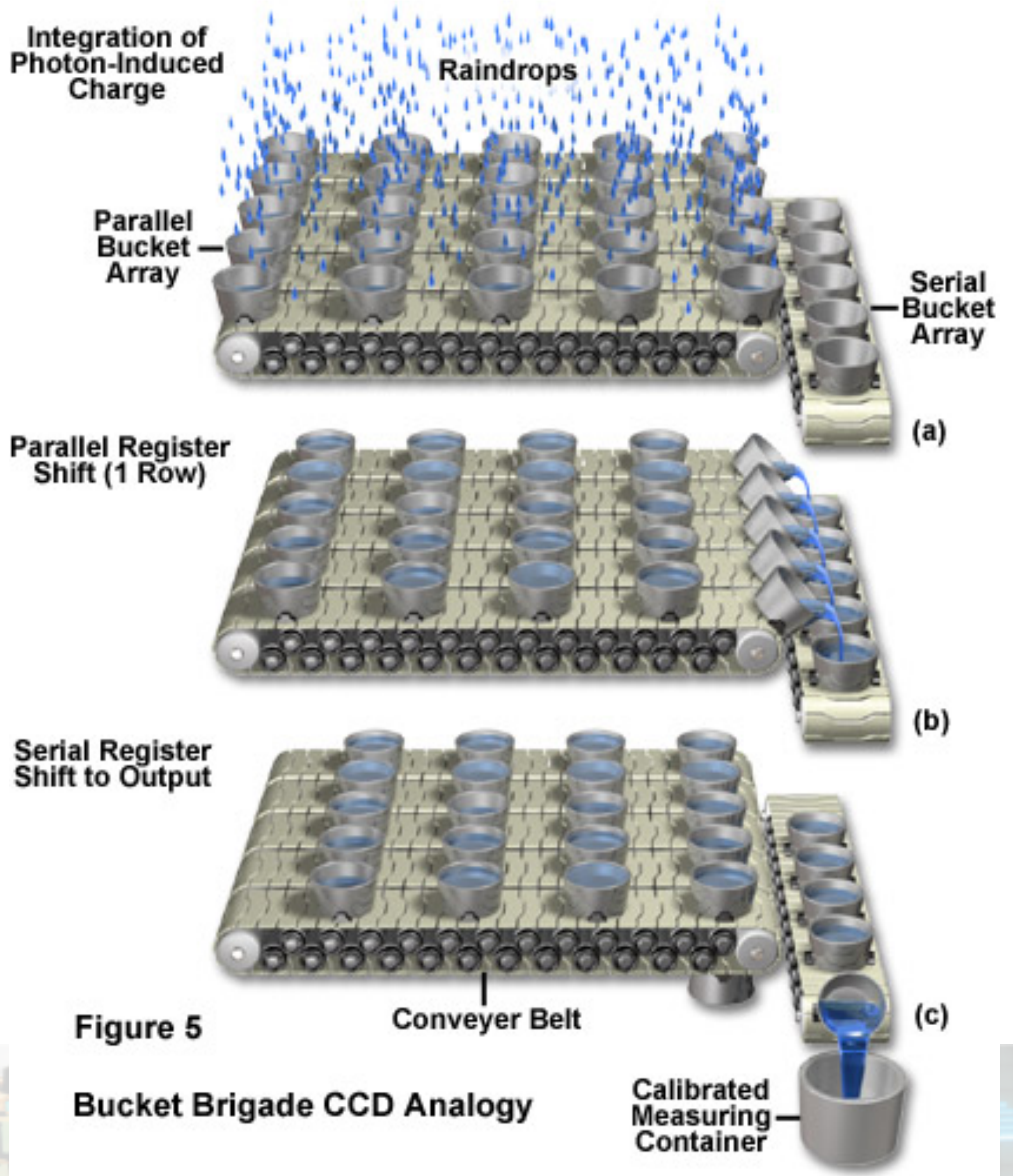
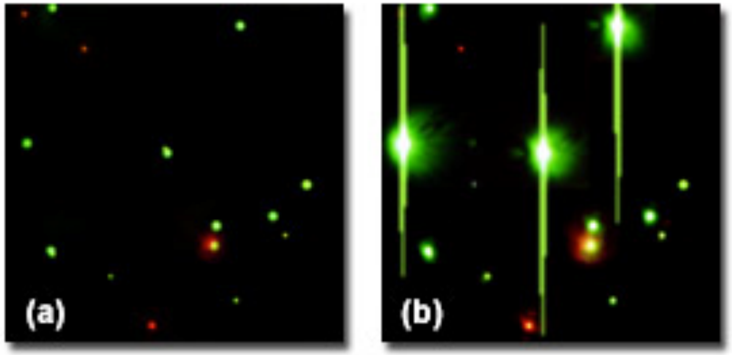
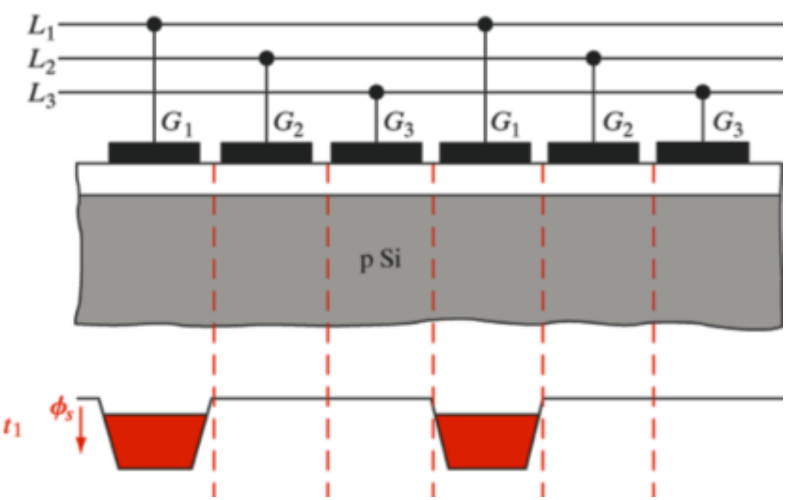


Figure 5

Bucket Brigade CCD Analogy

- Pixel Blooming… what causes it?





- One way to reduce it is by adding a lateral overflow structure next to the charge collection area, and a transfer gate to the read-out line.

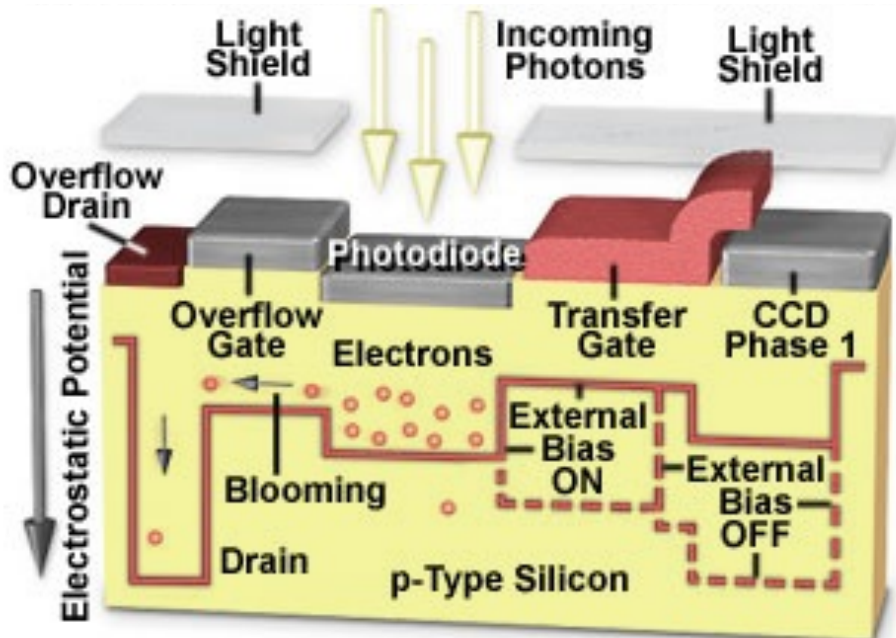
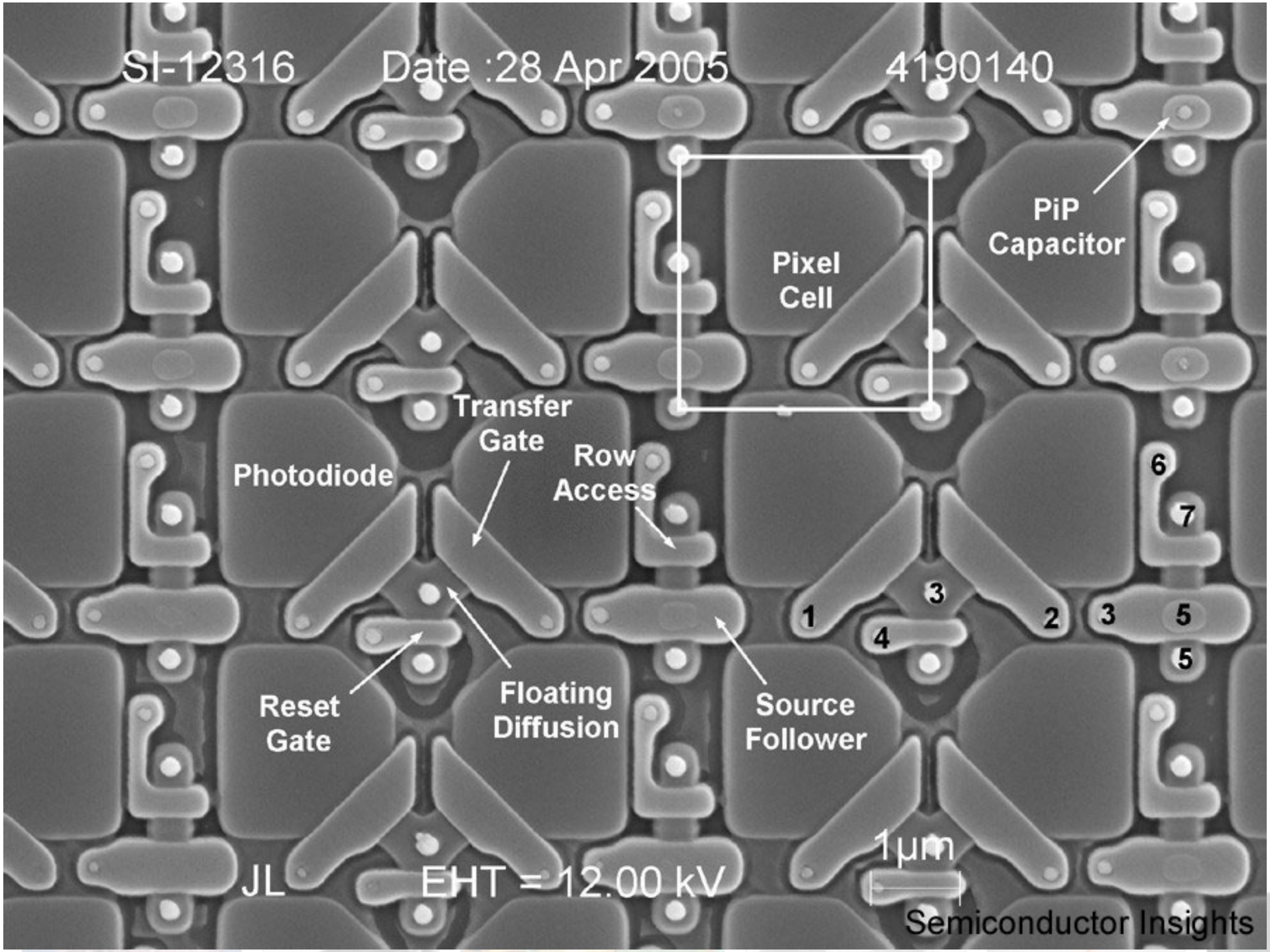
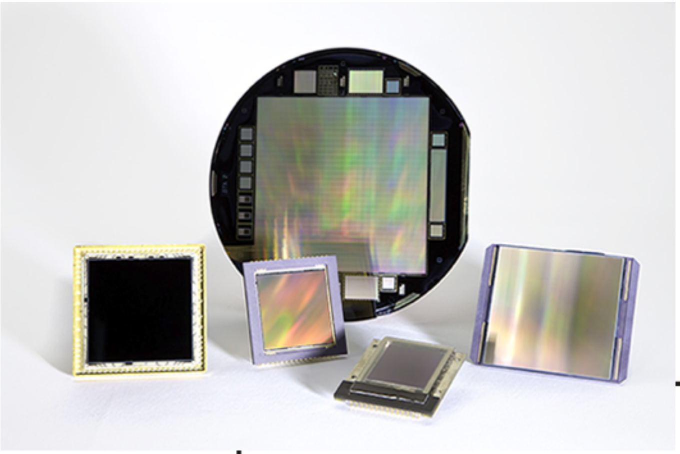


Figure 3

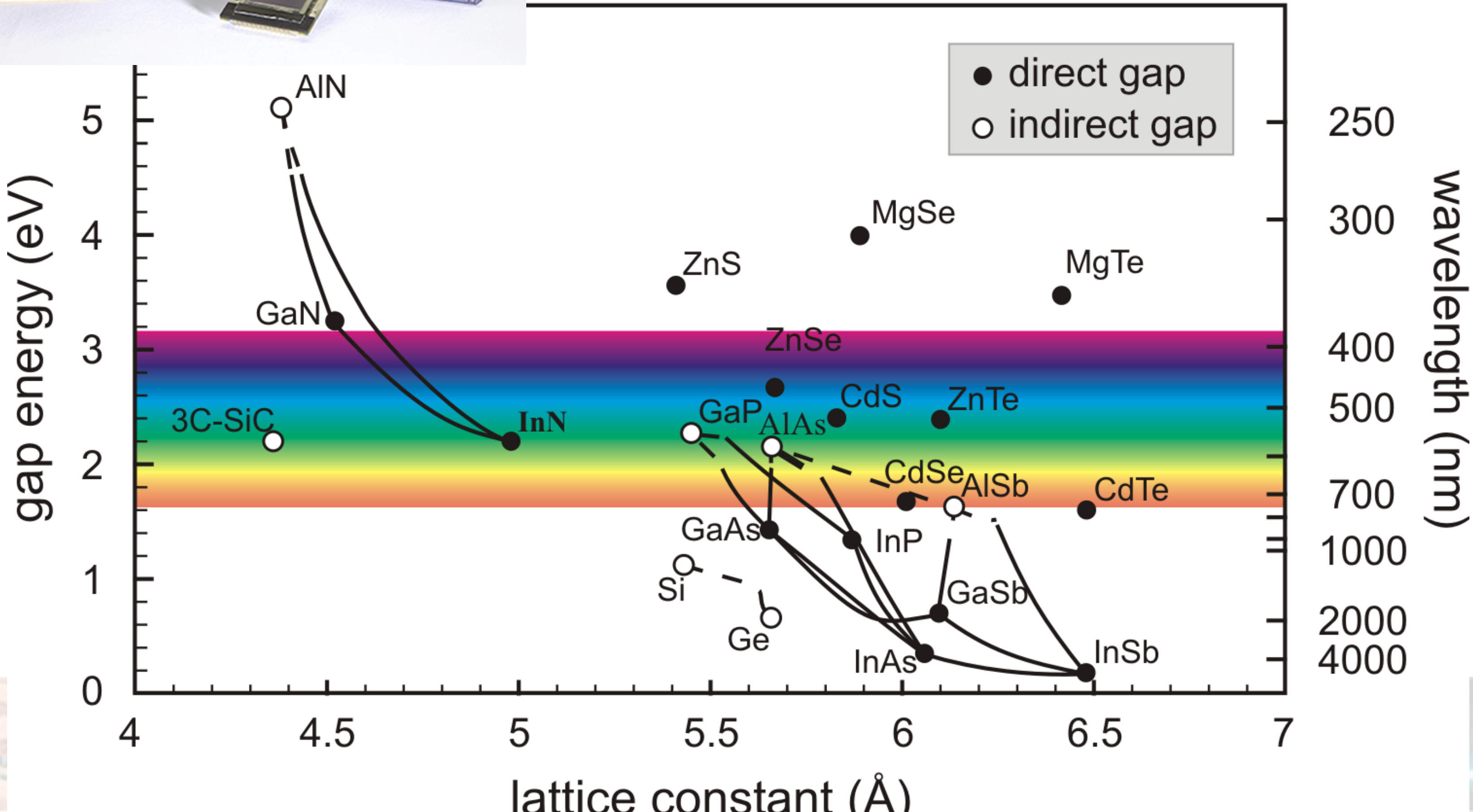

SI-12316
Date :28 Apr 2005
4190140
Pixel
Cell
PiP
Capacitor
Transfer
Gate
Row
Access
Photodiode
6
7
3
1
2
3
5
4
5
Reset
Gate
Floating
Diffusion
Source
Follower
JL
EHT = 12.00 kV
1 µm
Semiconductor Insights

- For a 'charge coupled device', what is the total depth over which we can collect charge?
- If we increase frame rate, what happens to our ability to record in low-light conditions?
- If I want to make a 'potential well', and I use positive voltage above an oxide, what type of carriers will I trap in the well?
- A camera can become 'washed out' by too much light intensity… what happens?



- CCD's used to have advantages in resolution, dynamic range (ultra-low light to ultra-bright), and low noise…

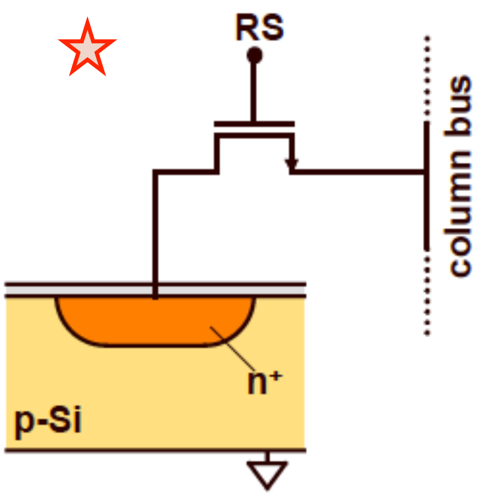
- However, CMOS imagers have eroded most of those advantages, and are utilized more often *except for long-wavelength IR… why? Long-wave CCDs are cooled, why?*

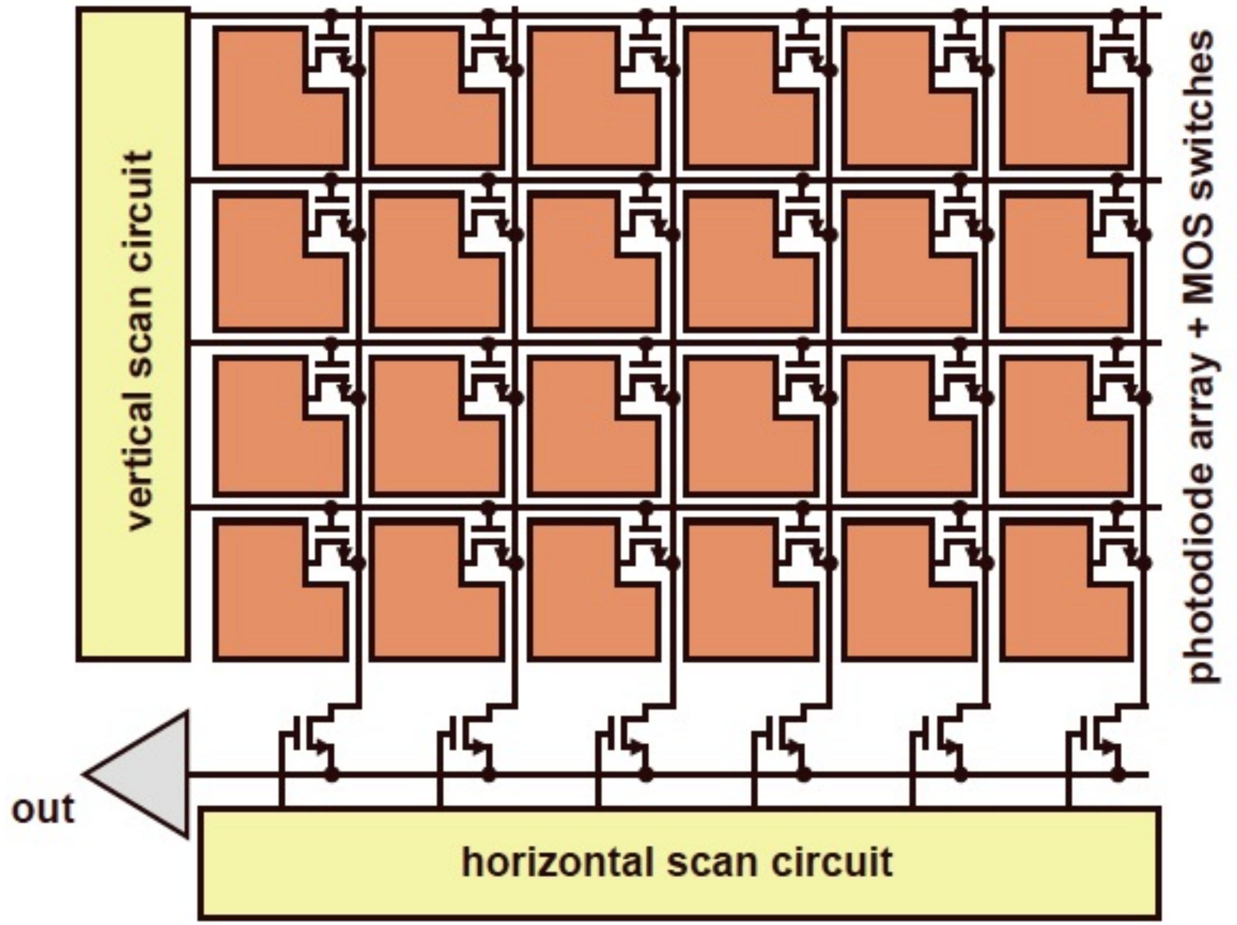


- So here is a CMOS imaging array… what is the 'orange' part?   How does it read out the pixels?

- Simple 1T cell:

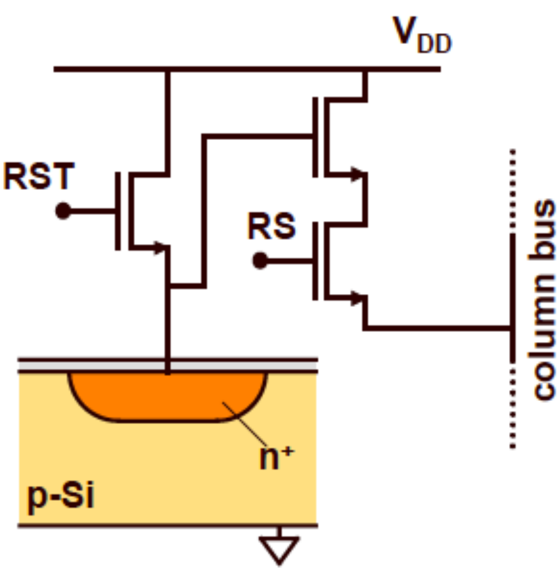
- passive pixel structure (PPS)
- high fill factor
- high noise level

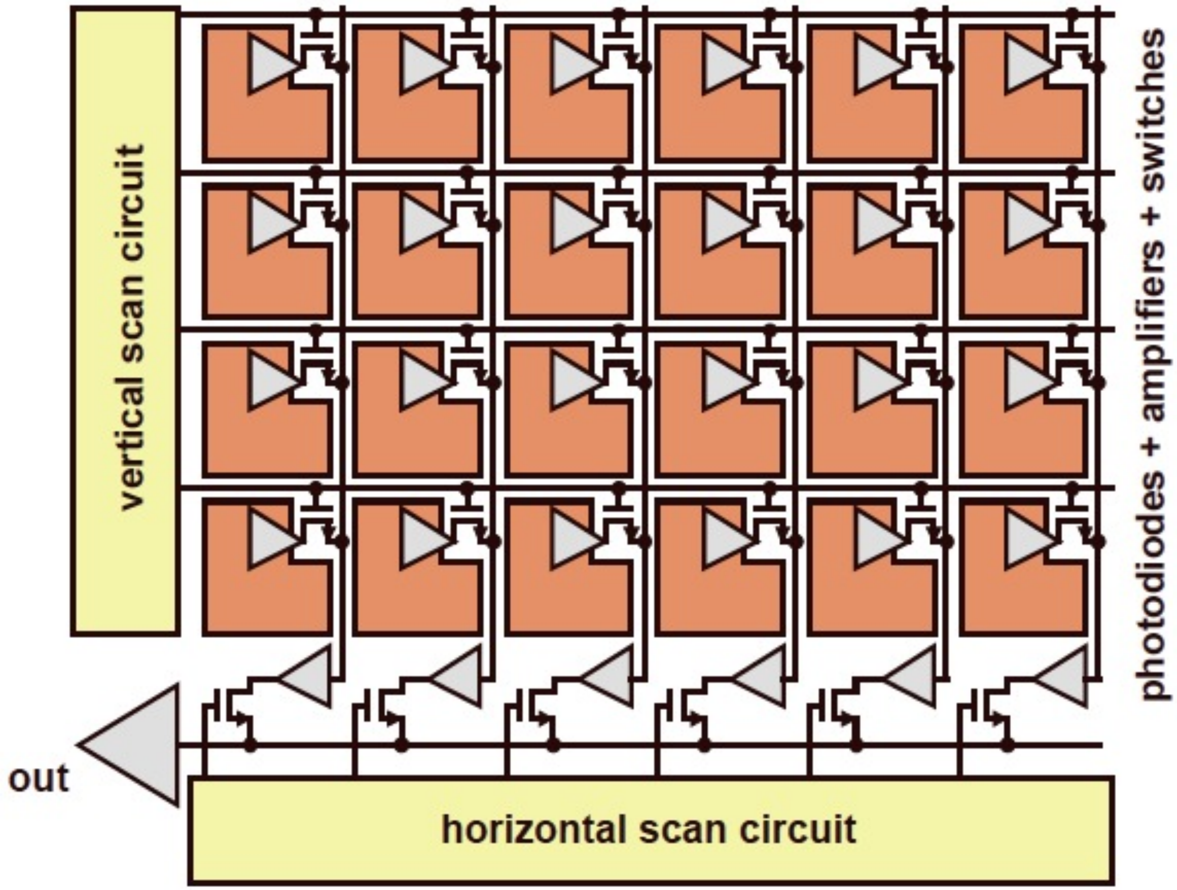




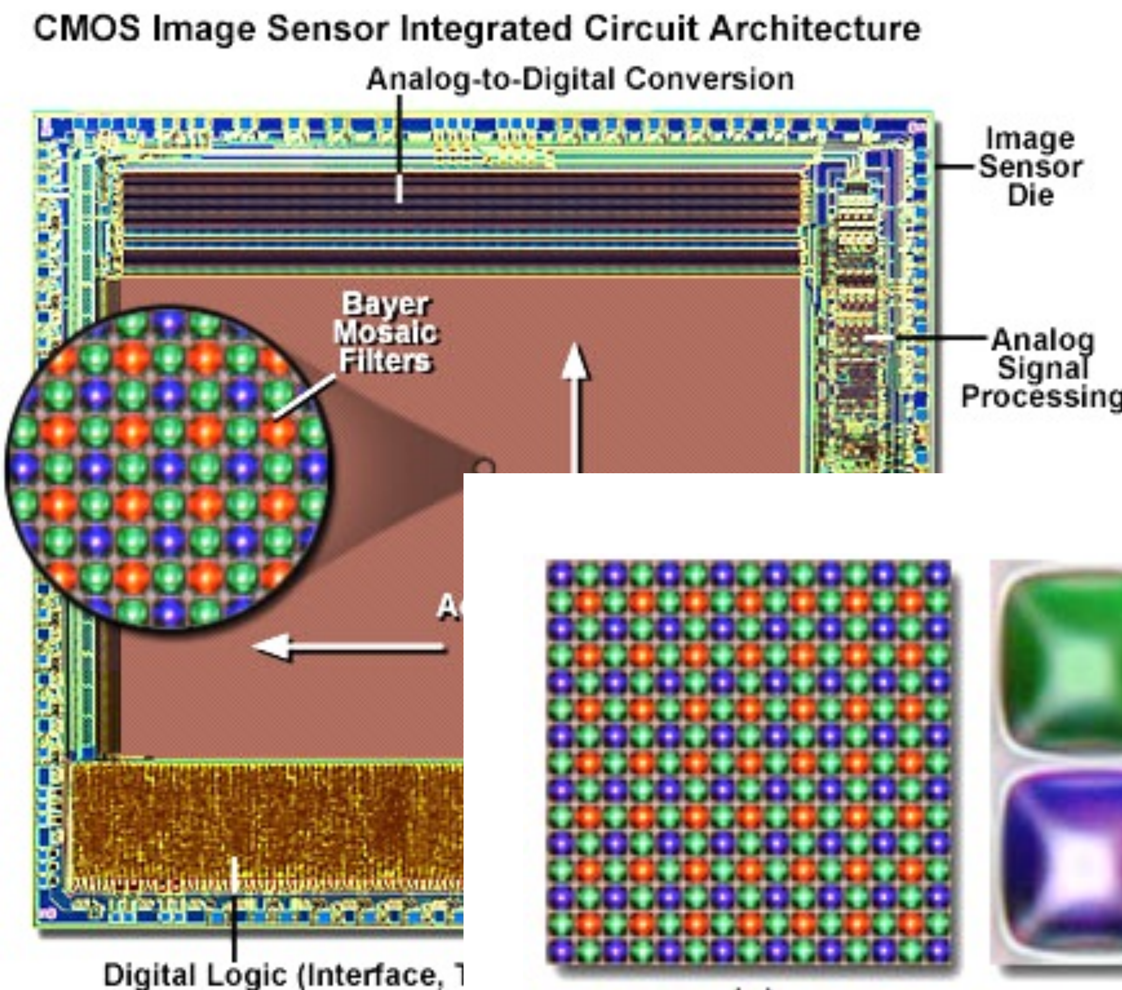
- 3T cell:

- active pixel structure (APS)
- low fill factor
- medium noise level (amplify signal before put onto noisy column line)





- Courtesy Olympus imaging:



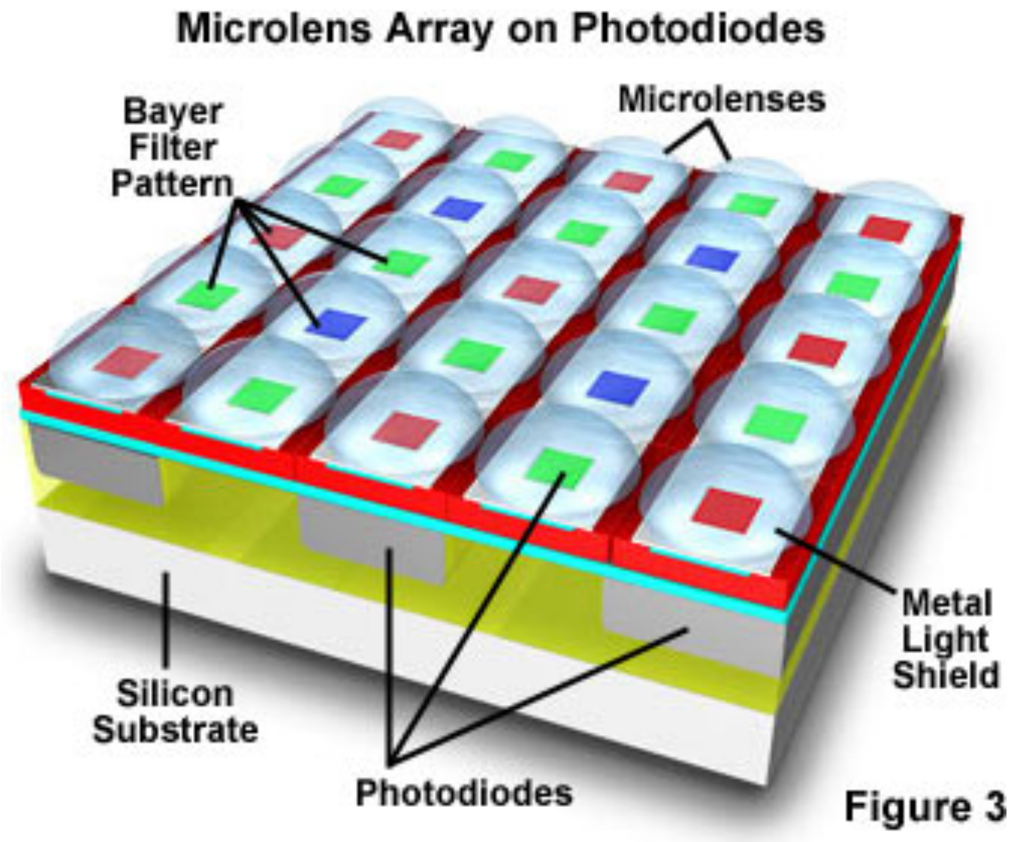
(a) (b) (c)

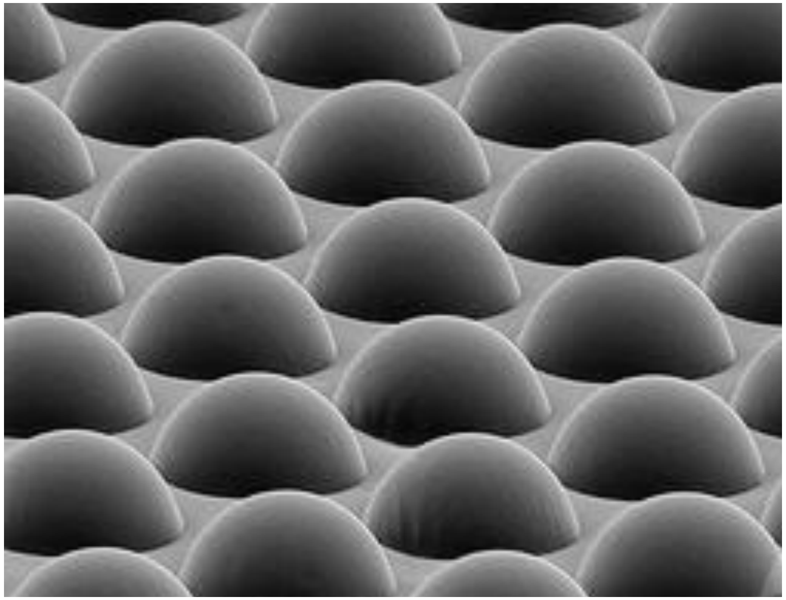
- Uses a Bayer filter array and lenses…

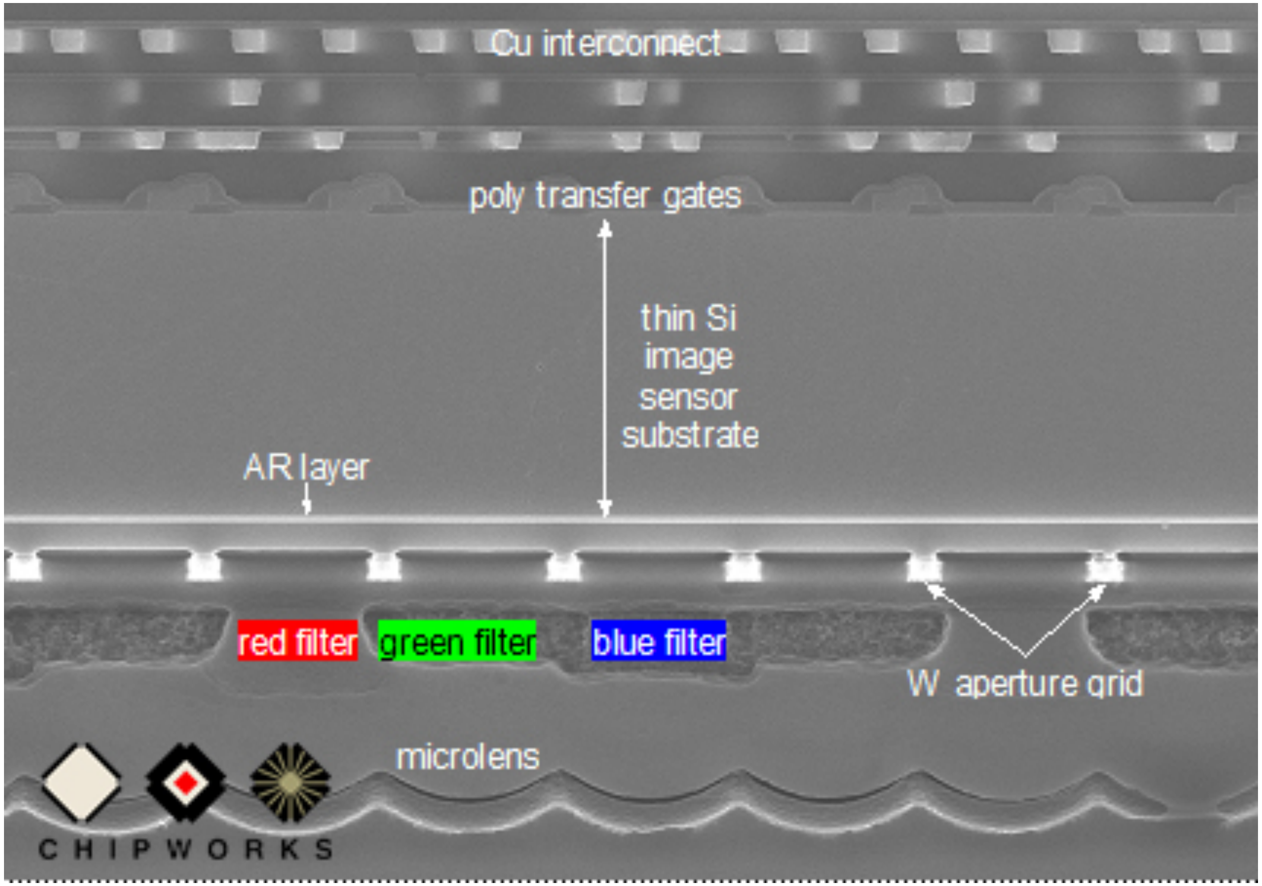
(1) Why more green subpixels than red and blue? *Think of human vision…* Blue vs. red is already also partly autocorrected, *how?*

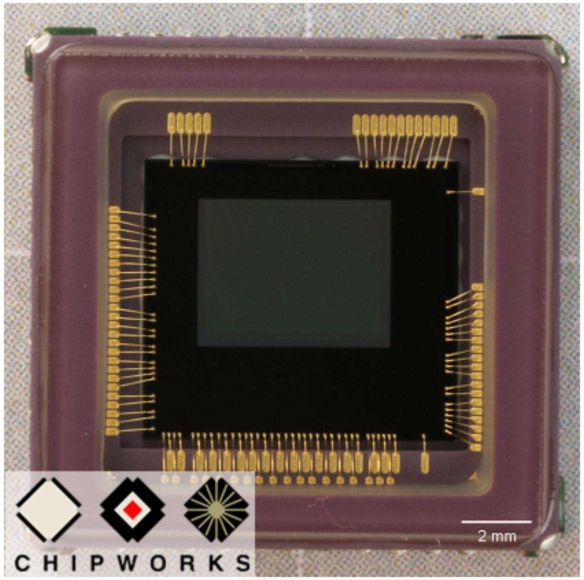
(2) What do the lenses do? *Think of optical loss at transistors and metal which can't use the light…*

- Courtesy Olympus imaging:









- Why do they work so hard to thin this substrate down (and put the electronics on the backside).

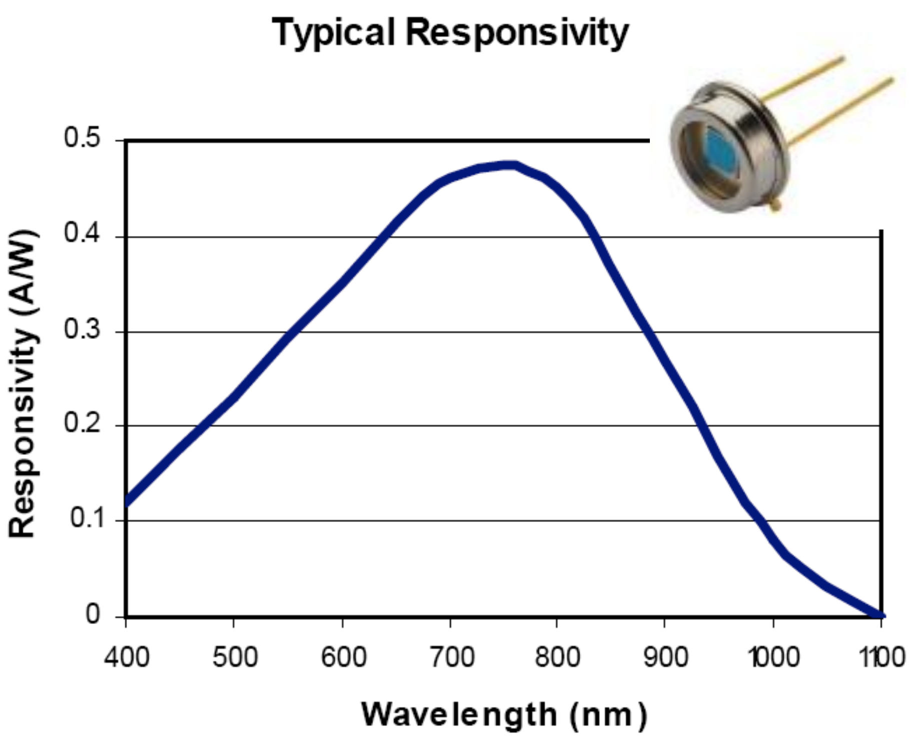
2009 - In a word, Sony's new backside illuminated image sensor process can be described as exotic.

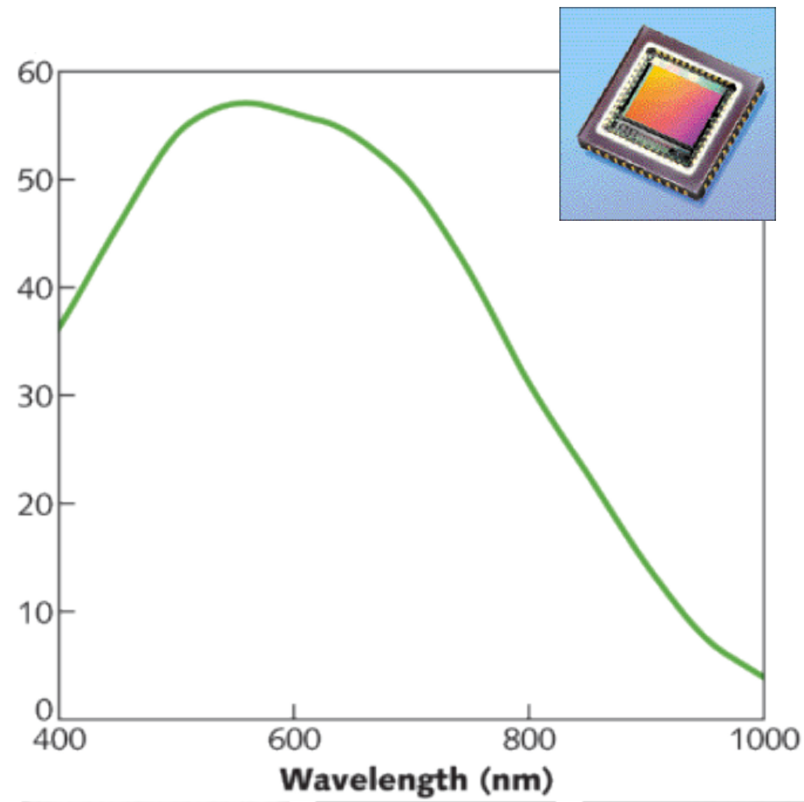
The obvious highlights are the conventional CMOS process run on a sacrificial SOI starting wafer, the wafer bonding techniques for the carrier wafer, and the backside wire bonding – but the innovation doesn't stop there. This device uses three types of isolation, unconventional liners on the copper interconnect, an unconventional pixel anti-reflection (AR) layer and extensive processing to the front and back of the thin silicon substrate (see Figure 1 and Figure 2).

Camera Quantum Efficiency

‣ Note how camera response (a.u.) vs. wavelength is similar to a simple PIN Si photodiode… Review:

(1) why do the both increase at first with wavelength?
(2) why do they both then peak out, then start to decrease down to zero?

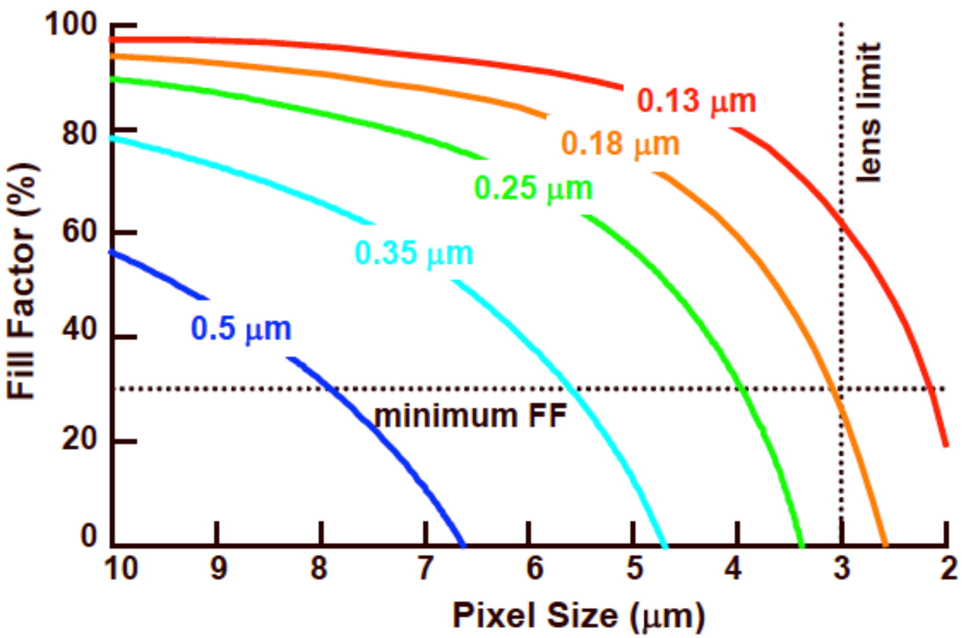


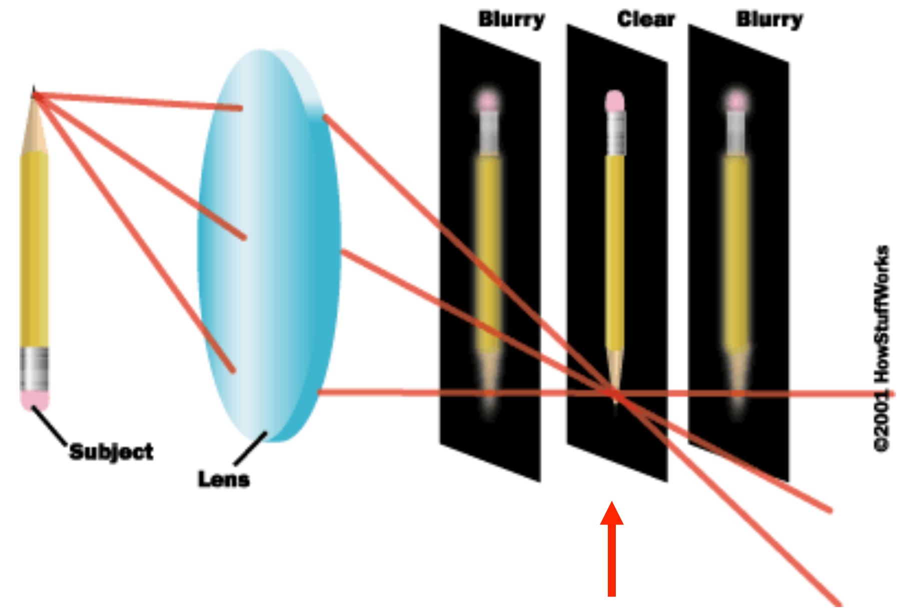


- Buyer beware… The mega-pixel count for some new camera's is now beyond which the optics can resolve (so is useless, just takes up more memory for the stored image!).

Each line is a CMOS process resolution limit.

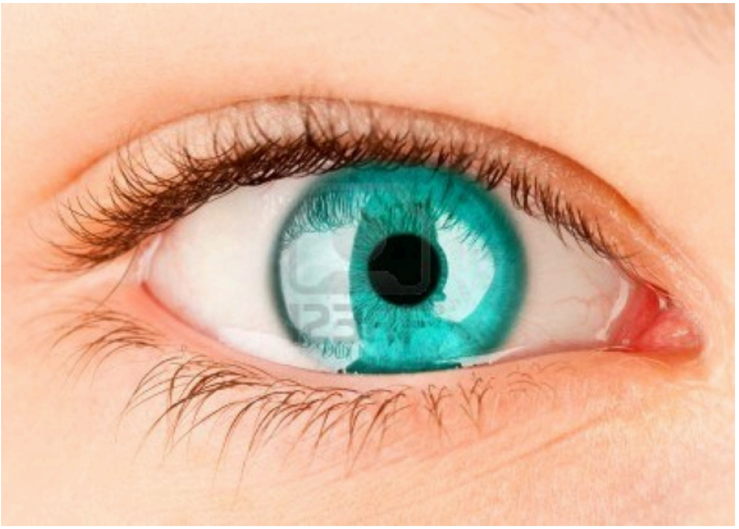
- And you need the optics! A CMOS array by itself is useless, because the array receives light from ALL objects around it! Would just see a big blur!

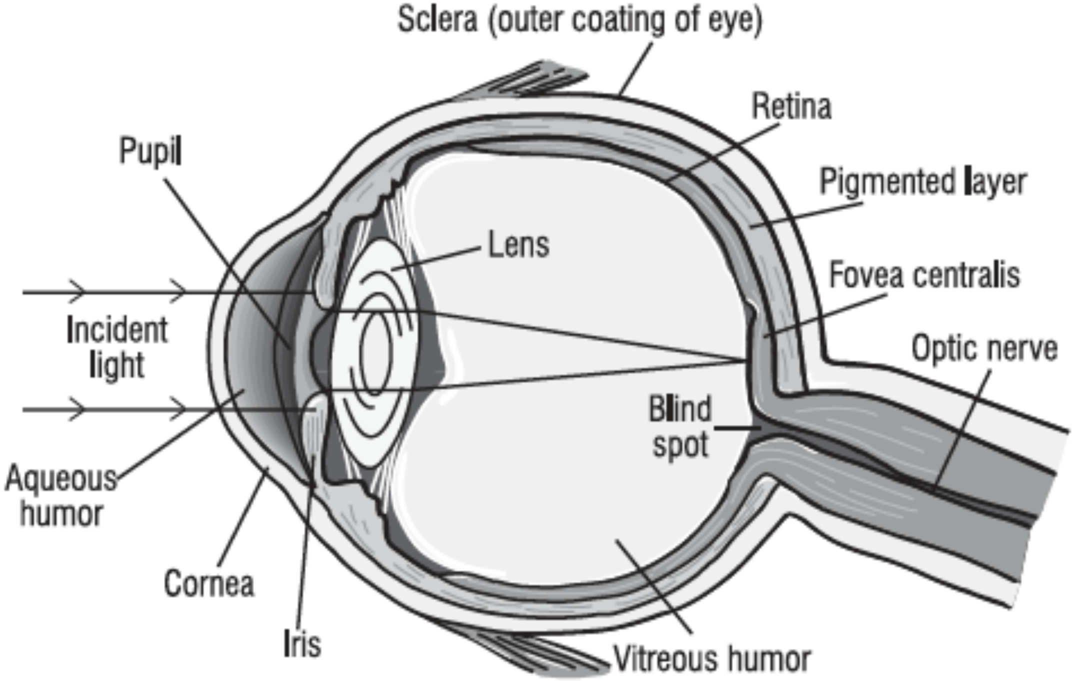




CMOS array goes here!

- The retina has a static contrast ratio of around 100:1 (about 6.5 f-stops). As soon as the eye moves (saccades) it re-adjusts its exposure both chemically and geometrically by adjusting the iris which regulates the size of the pupil. Initial dark adaptation takes place in approximately four seconds of profound, uninterrupted darkness; full adaptation through adjustments in retinal chemistry (the Purkinje effect) is mostly complete in thirty minutes. Hence, a dynamic contrast ratio of about 1,000,000:1





CHARGE-COUPLED DEVICES: CCDs lose ground to new CMOS sensors Mar 1, 2011

While enhanced CCDs still provide important niche application performance, recent advances are enabling new CMOS imagers to address scientific applications.

sCMOS performance compared to both common types of scientific CCDs

Parameter	sCMOS (Neo)	Interline CCD	EMCCD
Sensor format (Mpixels)	5.5	1.4 to 4	0.25 to 1
Pixel size (µm)	6.5	6.45 to 7.4	8 to 16
Read noise	1 e- @ 30 frames/s 1.4 e- @ 100 frames/s	4–10 e-	<1e- (with EM gain)
Readout speed (max.) (Mpixel/s)	5500	25	~30
Quantum efficiency (max.)	0.57	0.6	90% "back-illuminated" 65% "virtual phase"
Dynamic range	30,000:1 (@ 30 frames/s)	~3000:1 (@ 11 frames/s)	8500:1 (@ 30 frames/s with low EM gain)
Multiplicative noise	None	None	1.41x with EM gain (effectively halves the QE)

- The best IR cameras are typically actively ‘cooled’, why?
- For a CMOS array, I need at minimum, two devices… what are they, and what do they each provide?
- The color filters used, we double the number of green ones, why?
- We typically add small lenses on top of the pixels, why?
- We always need at LEAST one big lens in front of the whole array, why?