Image sensors

• Sensor technologies: CMOS and CCD

• CMOS imagers dominate high-volume applications; Fabrication cost, lower power; system integration

• CCD are used in certain scientific applications (astronomy)

• CMOS sensors: viable research platform

  • Enable new experiments

  • New imaging architectures

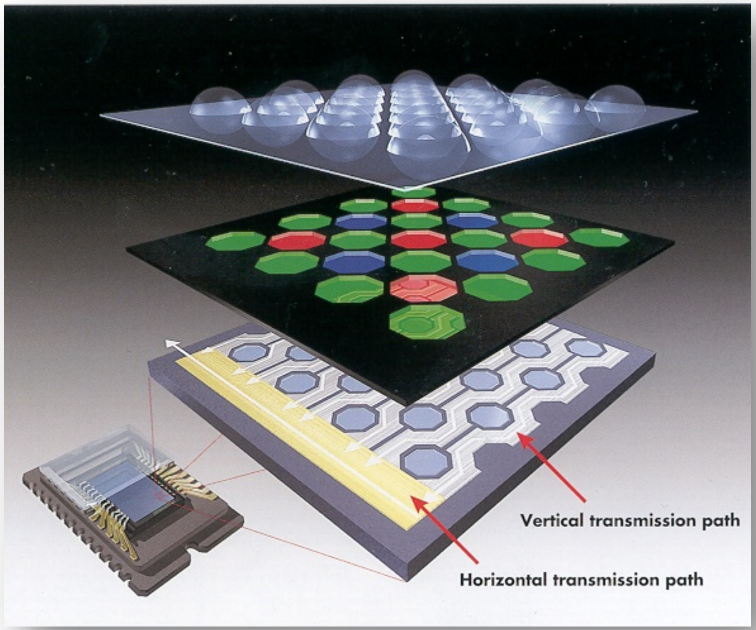
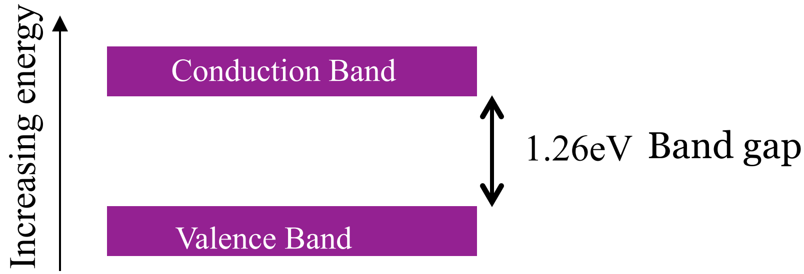


Photo detector: basic principles

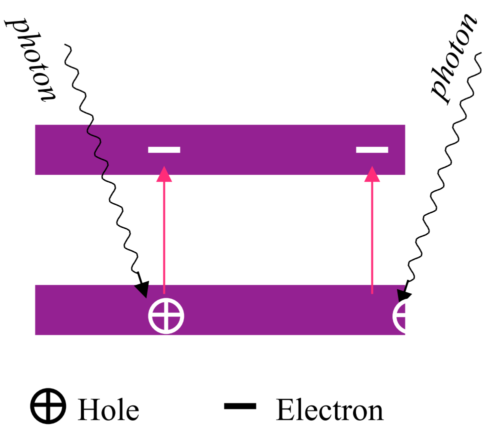
Photoelectric effect

The photoelectric effect (CMOS and CCD)

Atoms in a silicon crystal have electrons arranged in discete bands called the **Valence Band** (lower energy) and the **Conduction Band** (higher energy).

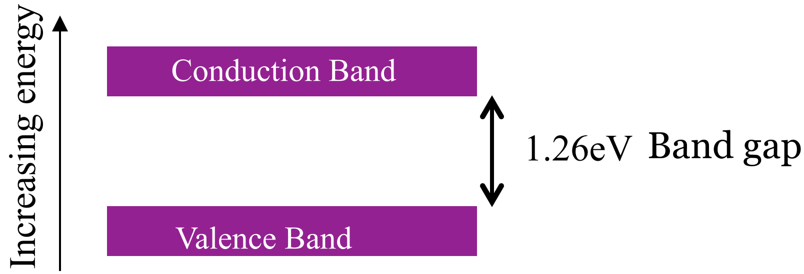


Most electrons occupy the **Valence band.** The absorption of a photon can excite electrons into the **conduction band.** The excitation requires the photon to provide at least 1.26 electron volts.

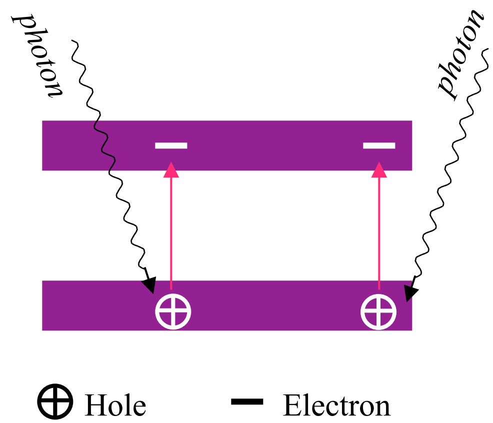


The photoelectric effect

A 1100nm photon of light has 1.26eV. Beyond this wavelength silicon is transparent; hence silicon imagers are insensitive beyond this infra-red band.



In the conduction band electrons move freely about in the lattice of the silicon crystal; this leaves a 'hole' in the valence band which acts like a positively charged carrier. In the absence of an external electric field the hole and electron will re-combine and be lost.

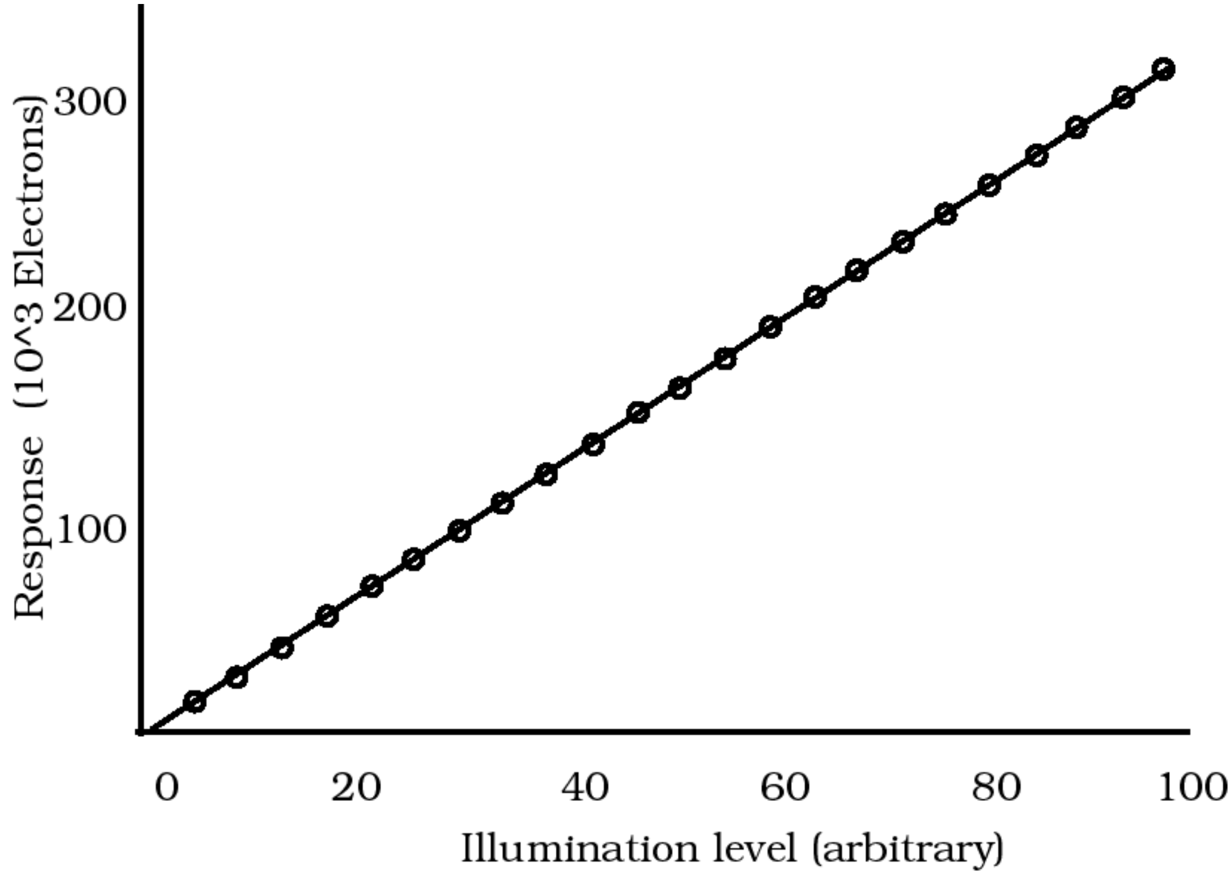


- In a CCD an electric field is introduced to prevent recombination.
- In CMOS electrons are trapped in capacitors.

CCD and CMOS transfer functions

Both are Si absorptions

Photons to electrons mapping is linear

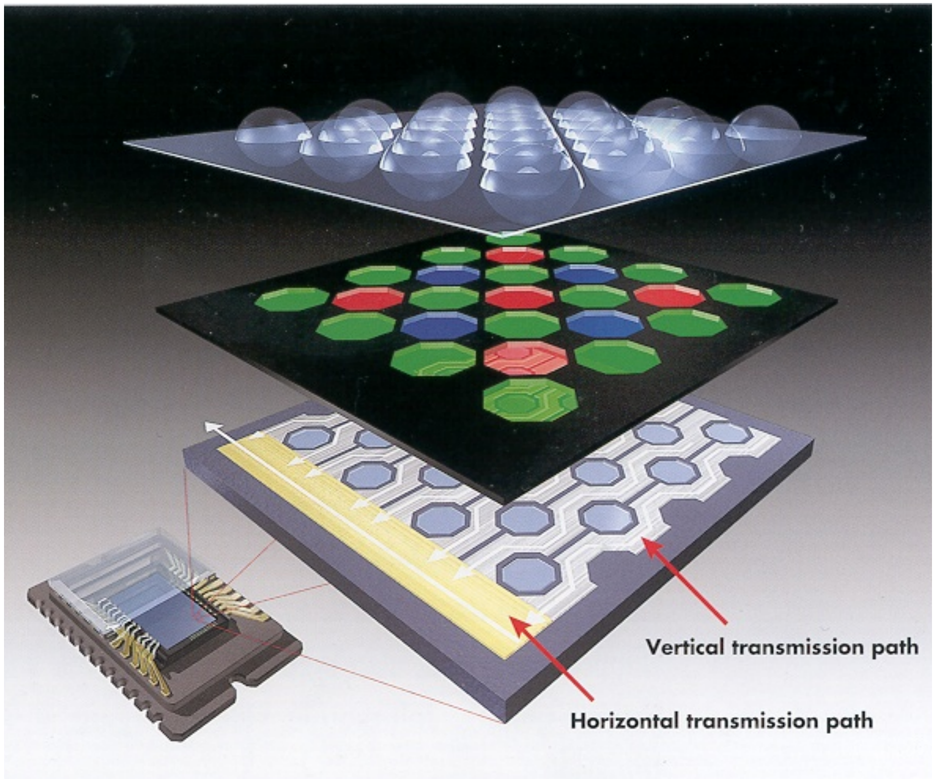


(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ...., Opt Eng., 25, 1987)

Sensors

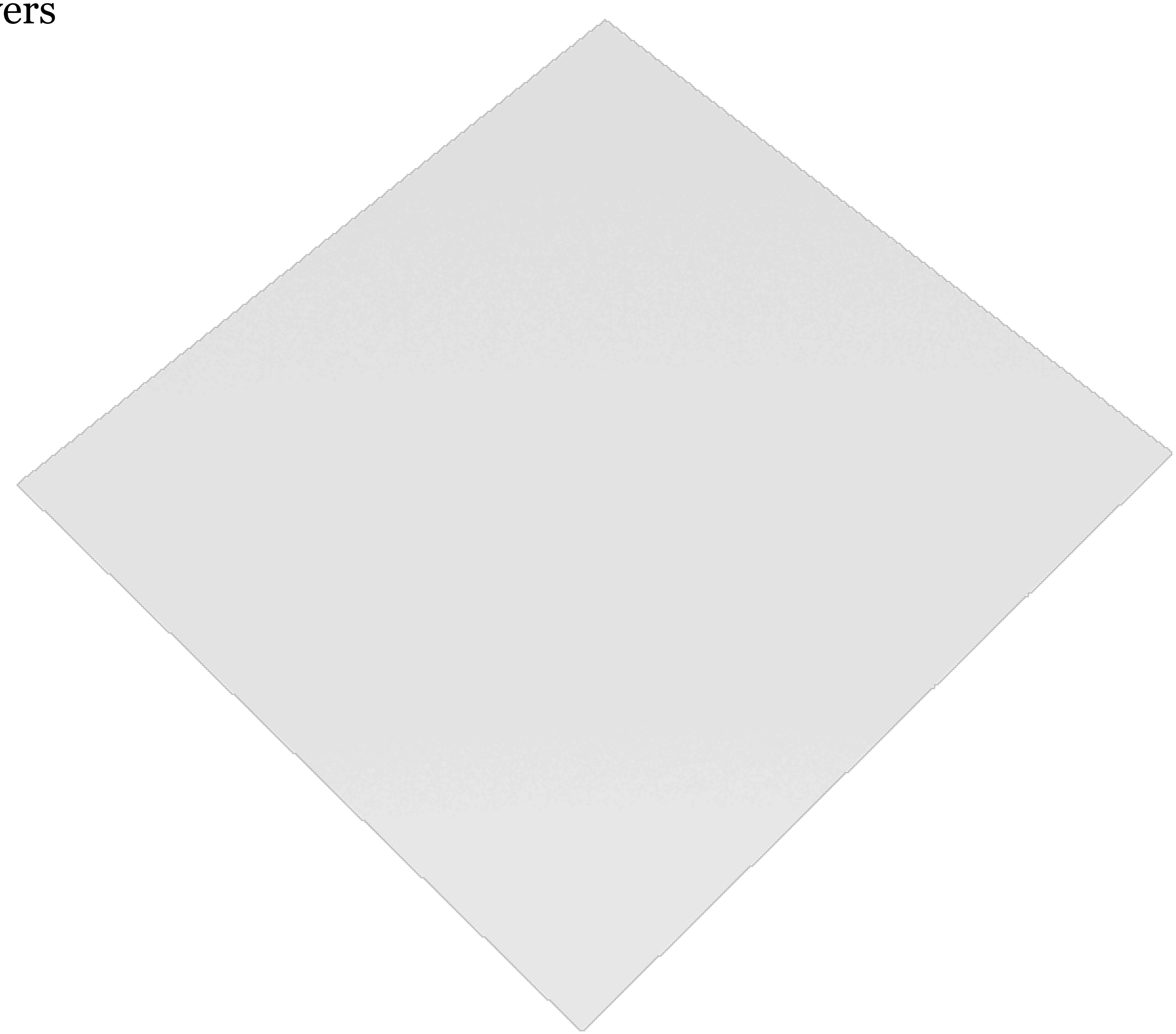
- Front-illuminated

Front-illuminated imagers



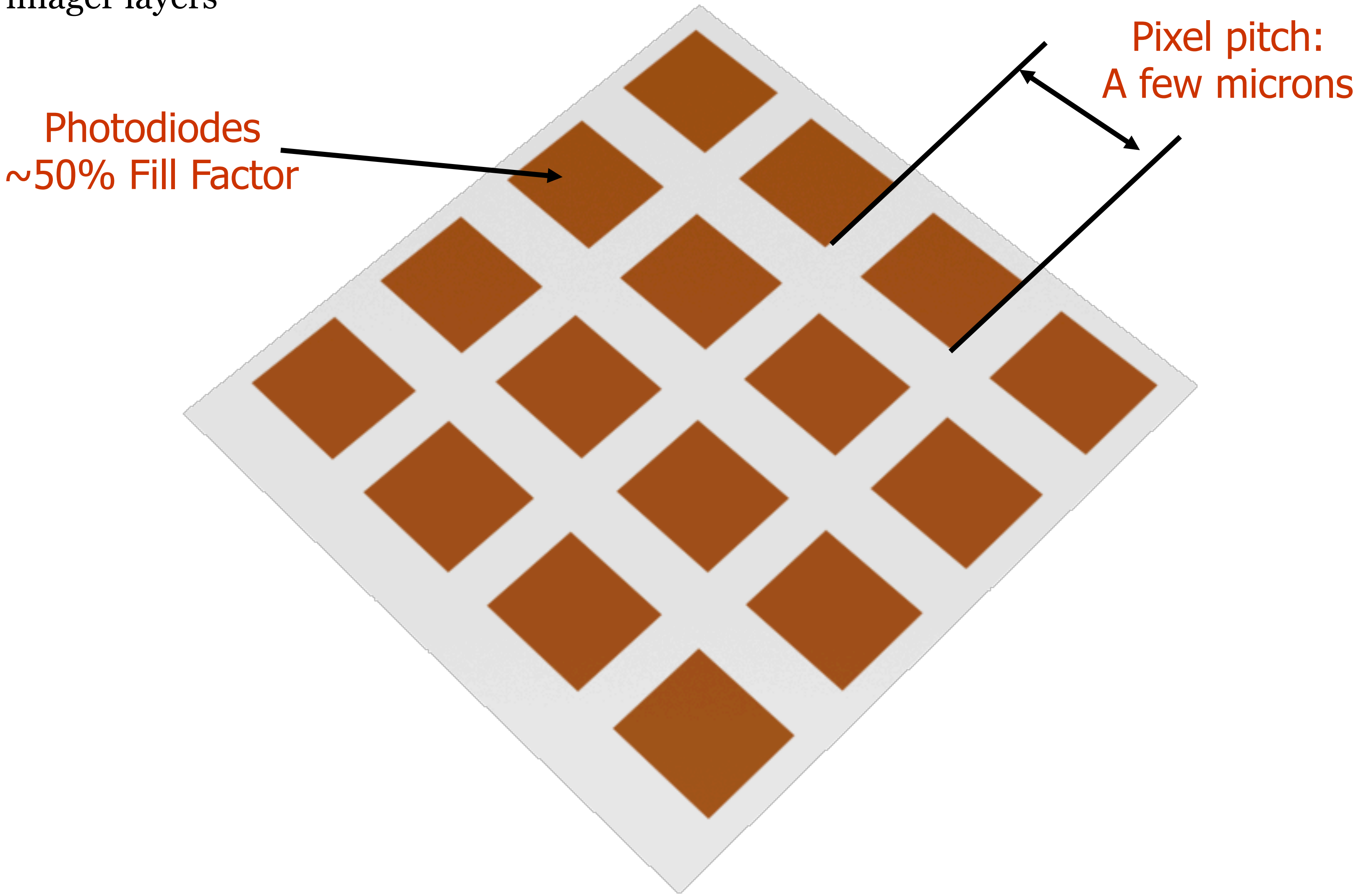
Front illuminated CMOS

Building up the
CMOS imager layers



Courtesy R. Motta

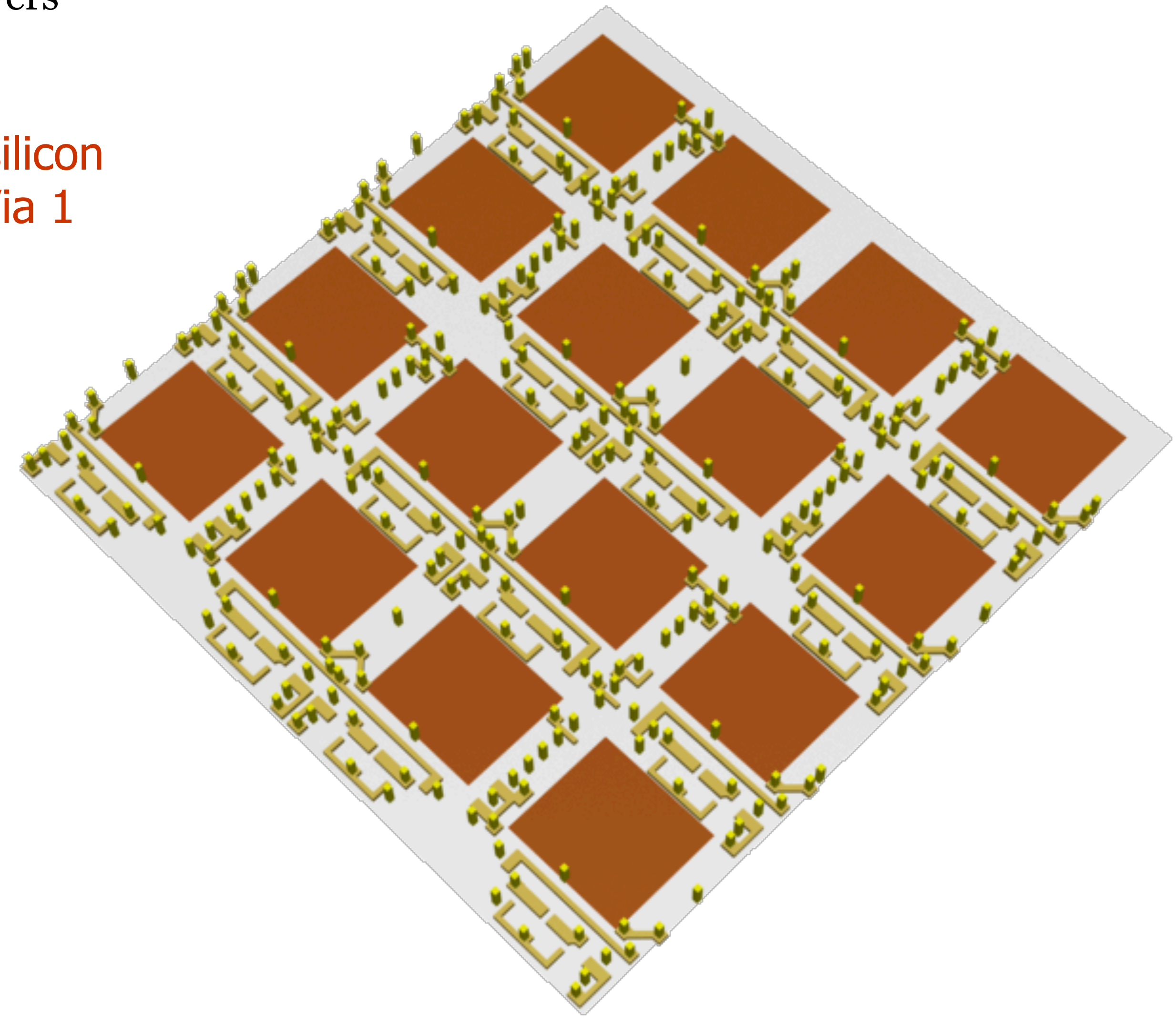
Building up the
CMOS imager layers



Courtesy R. Motta

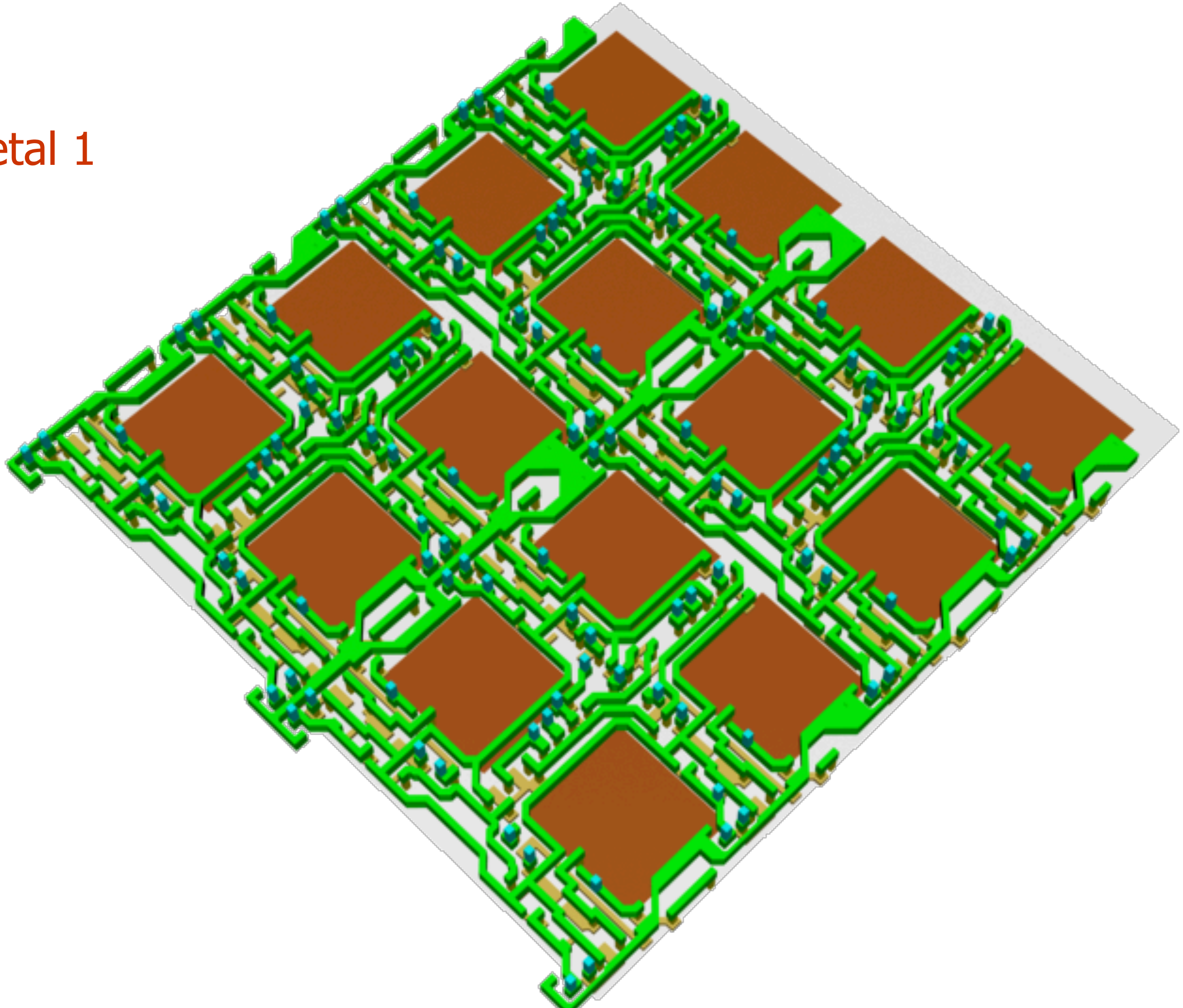
Building up the
CMOS imager layers

Polysilicon
& Via 1



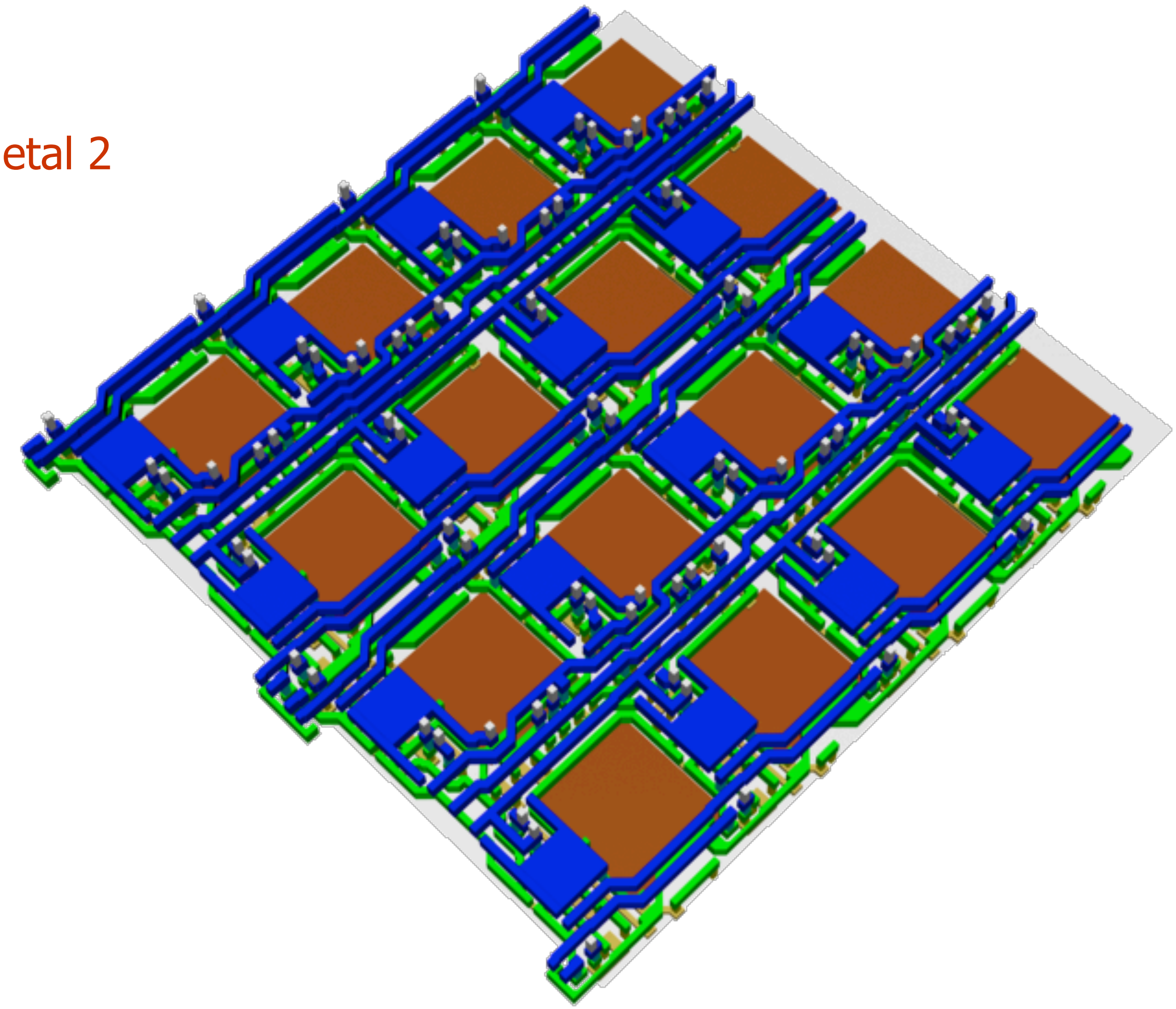
Courtesy R. Motta

Metal 1



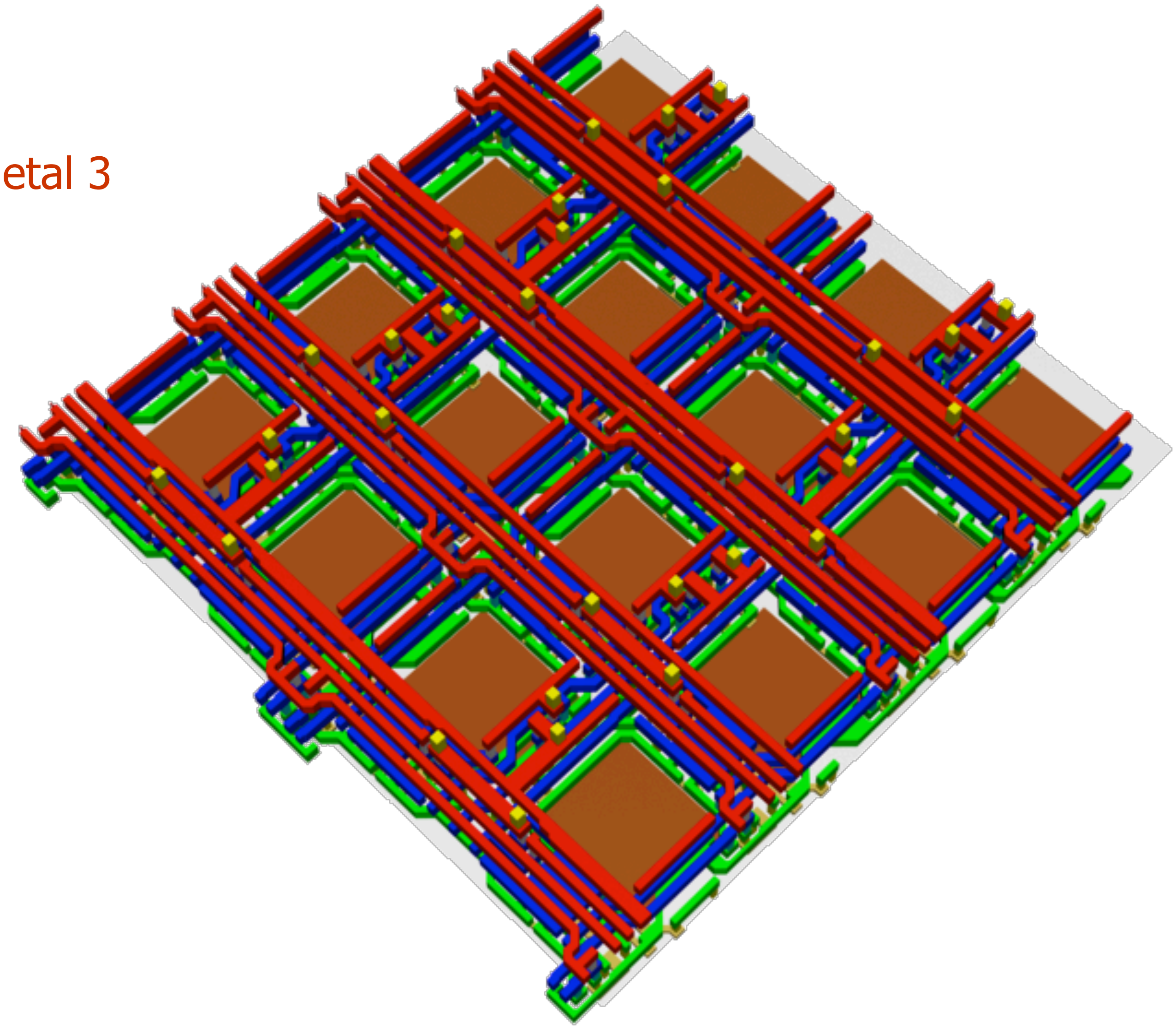
Courtesy R. Motta

Metal 2



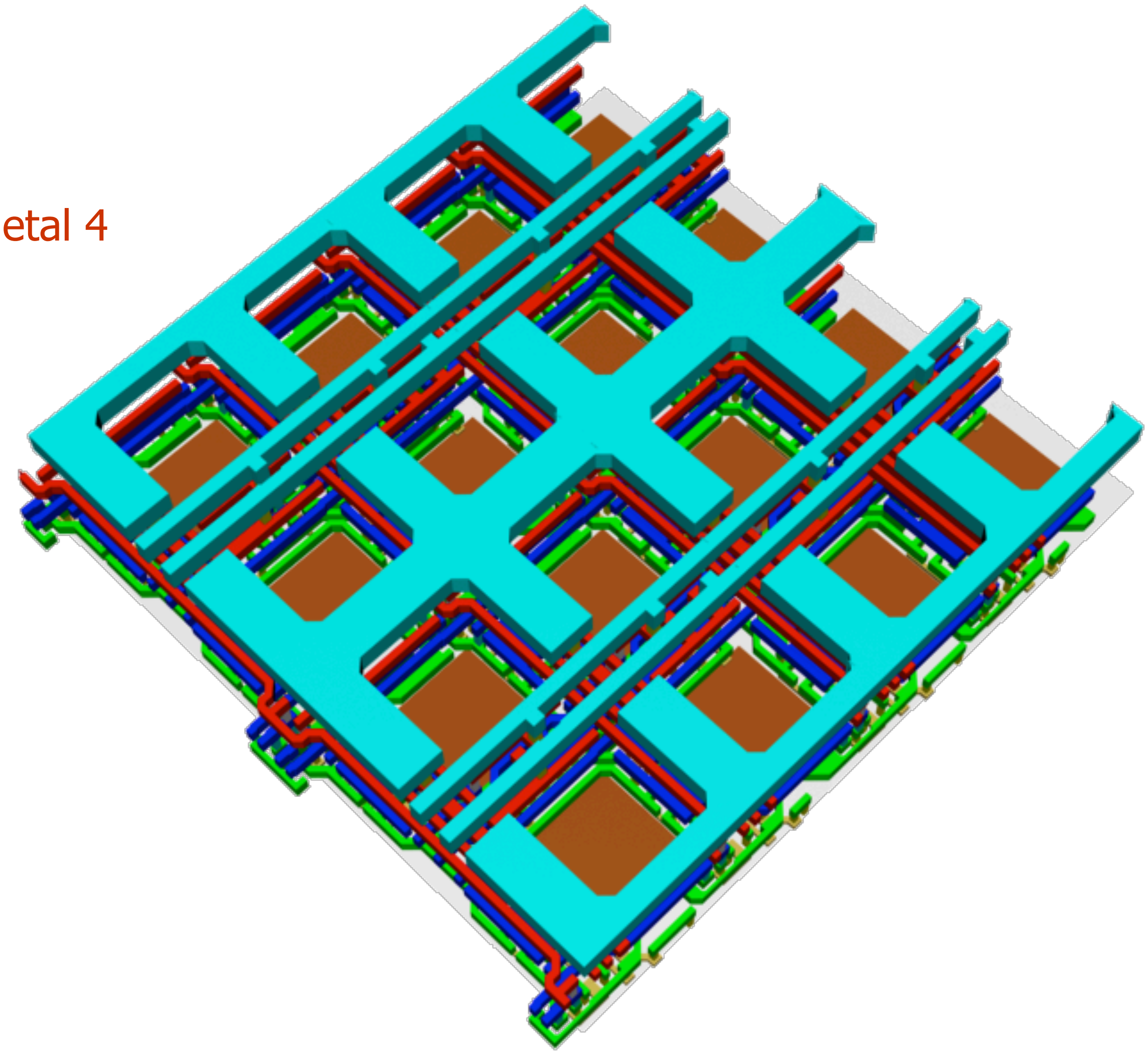
Courtesy R. Motta

Metal 3



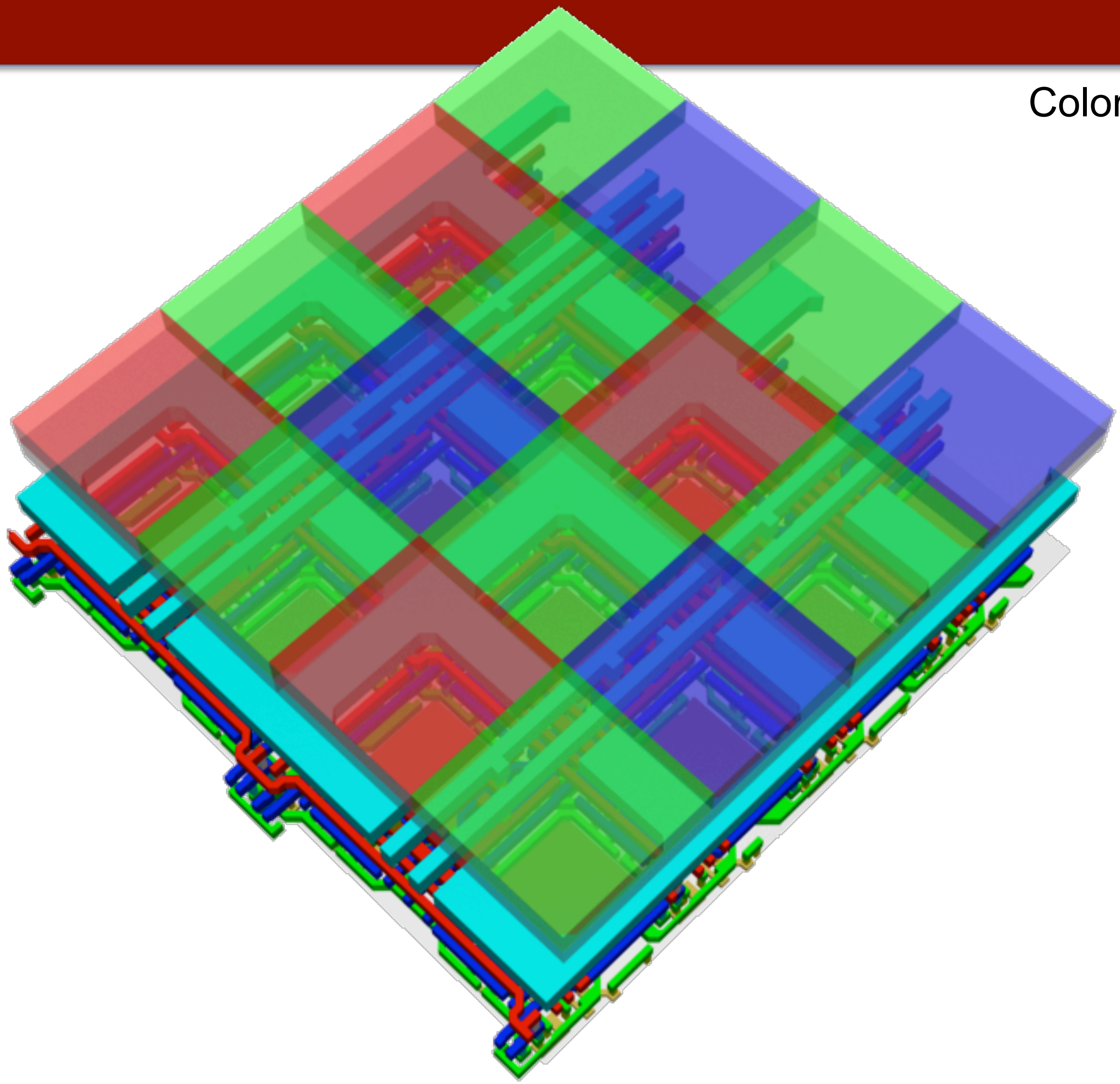
Courtesy R. Motta

Metal 4



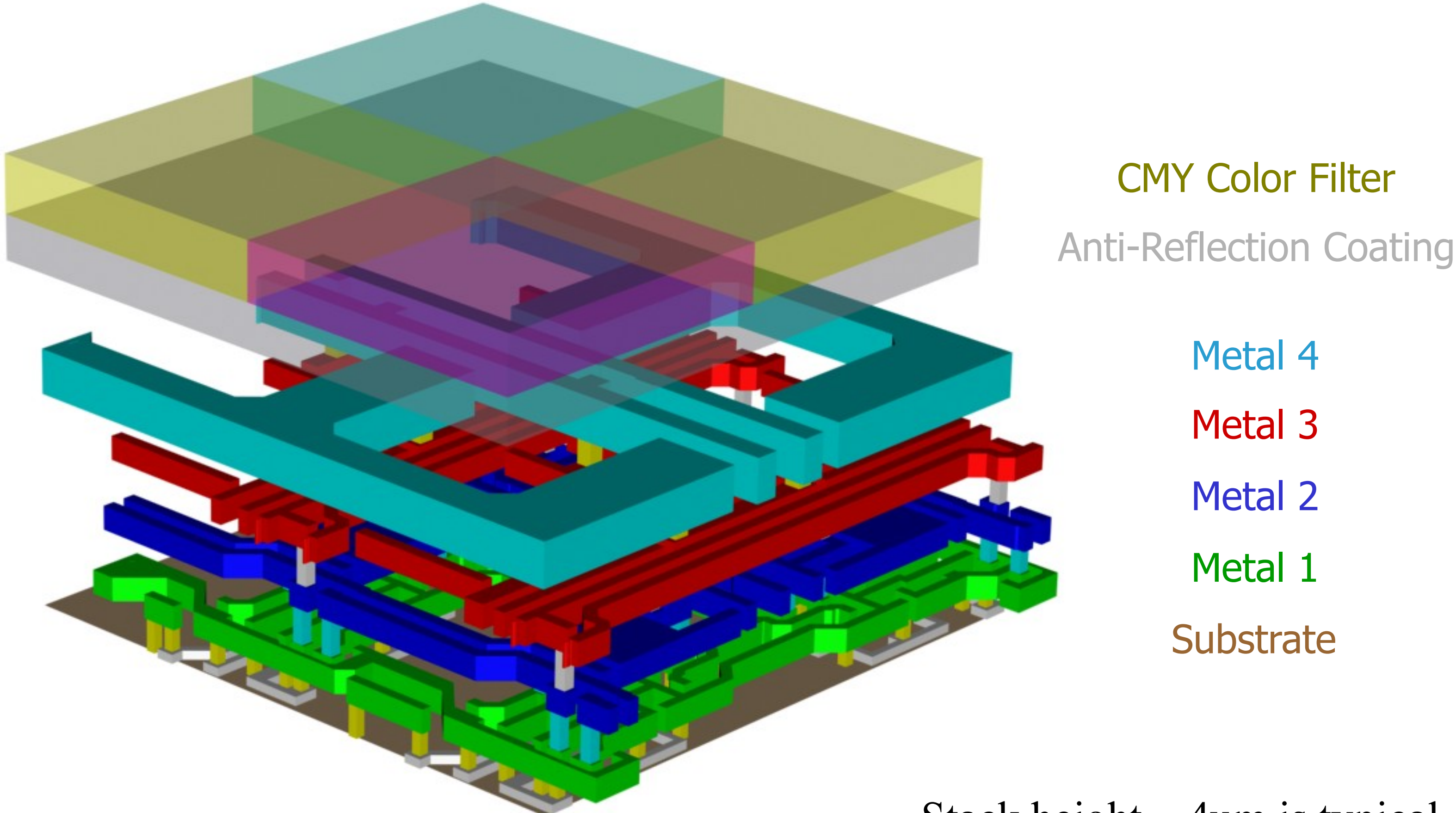
Courtesy R. Motta

Color filter array



Courtesy R. Motta

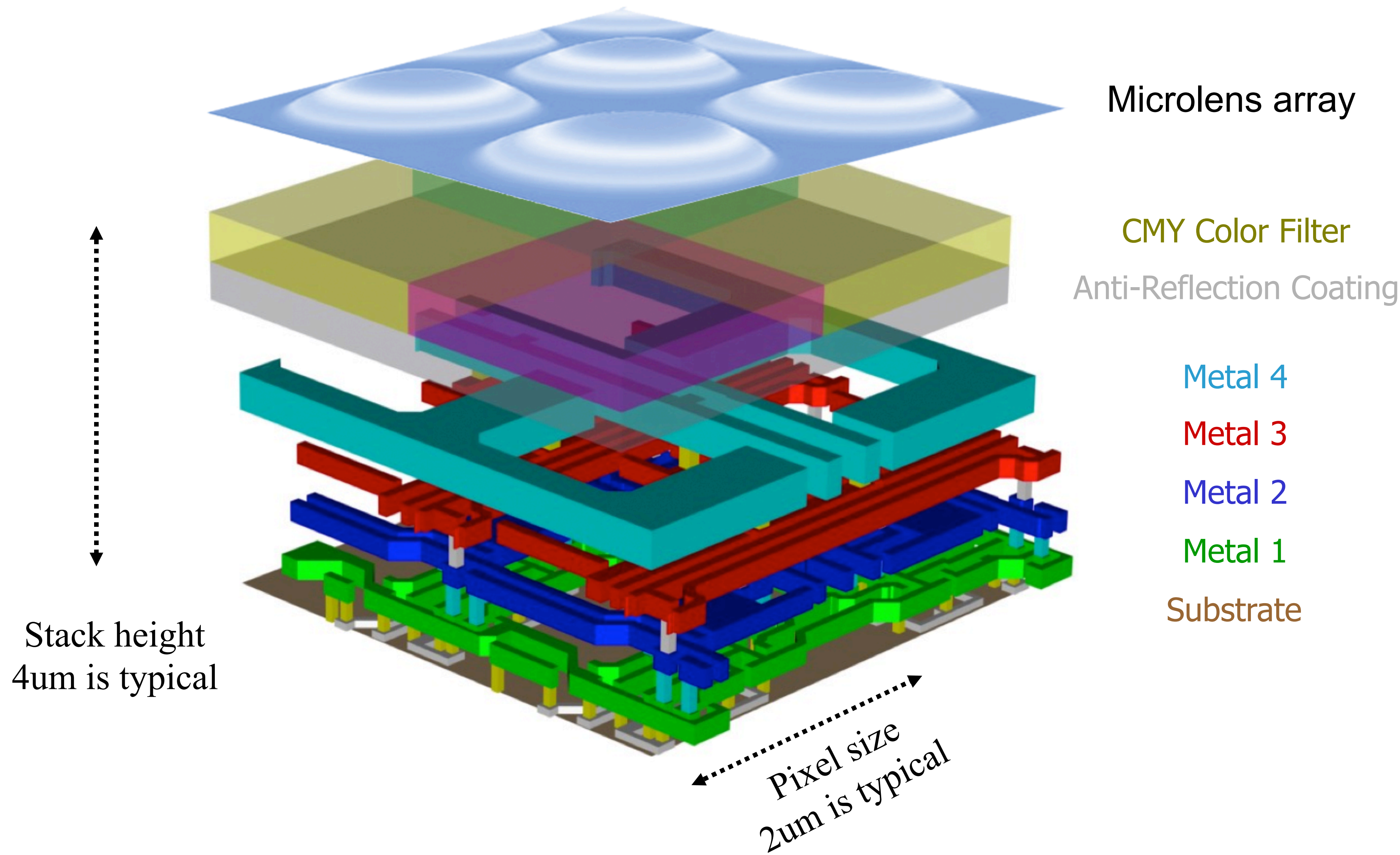
The pixel stack



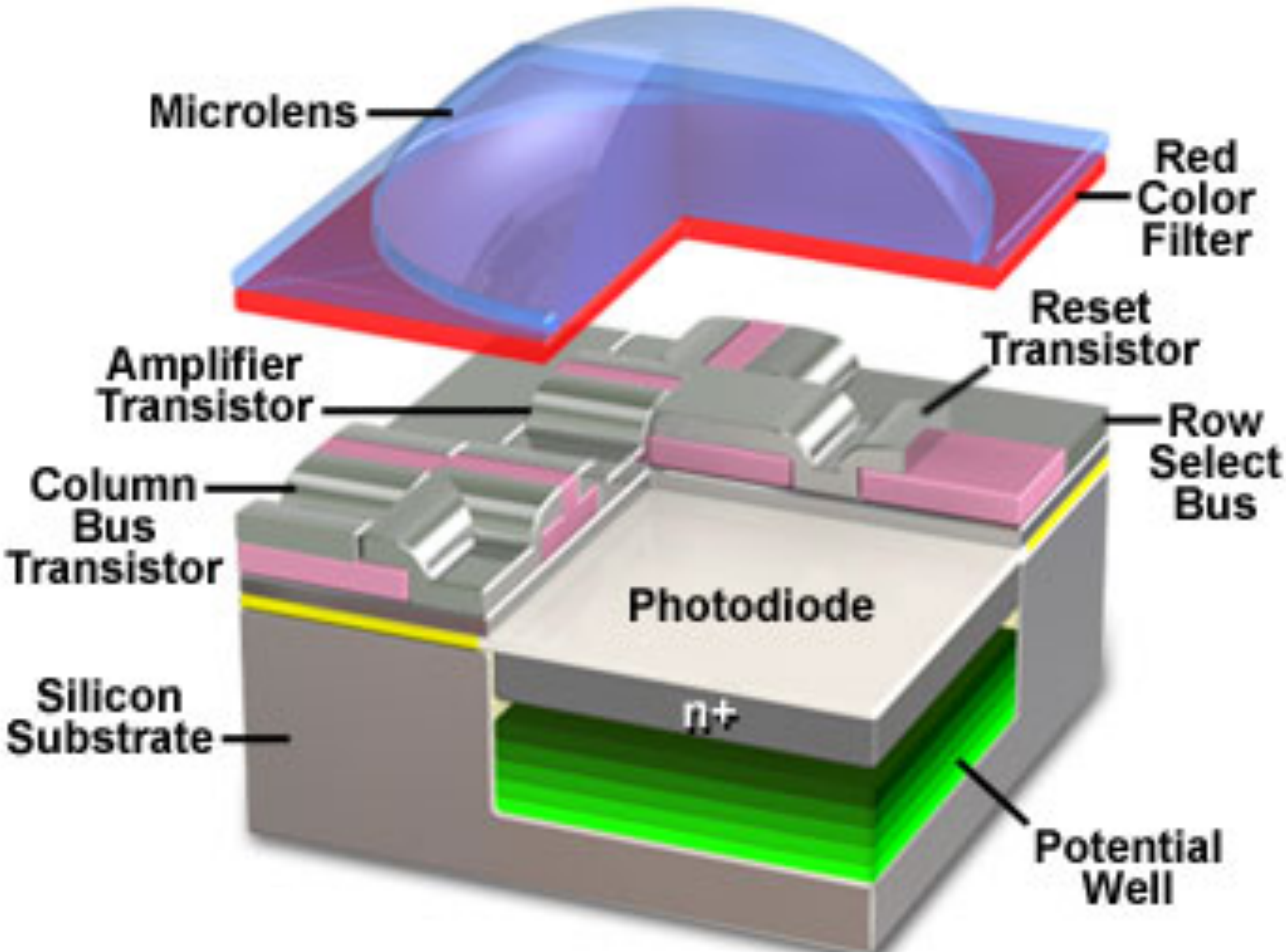
Stack height ~ 4um is typical
Pixel size ~ 2um is typical

Courtesy R. Motta

The microlens array

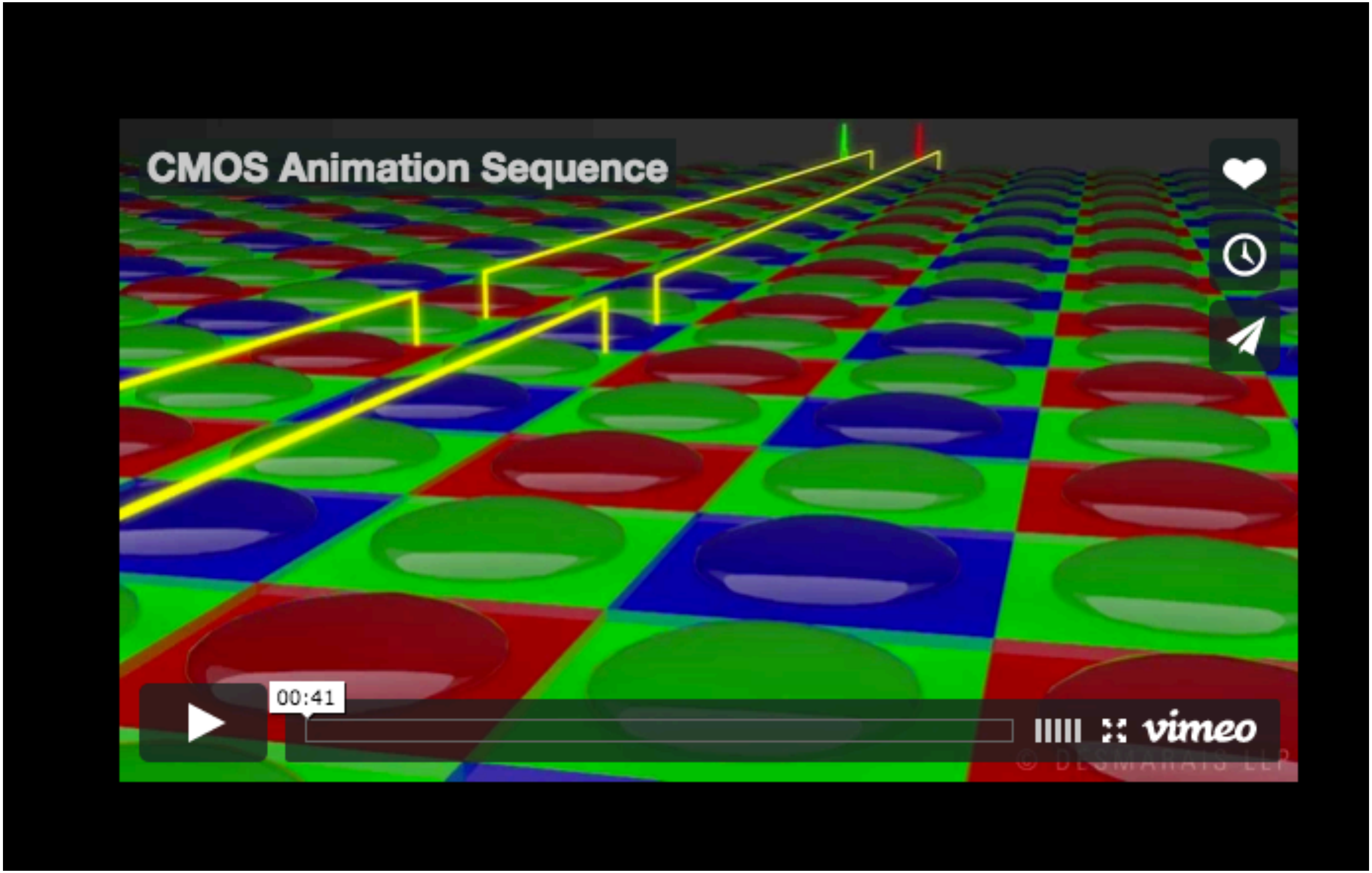


Anatomy of the Active Pixel Sensor Photodiode



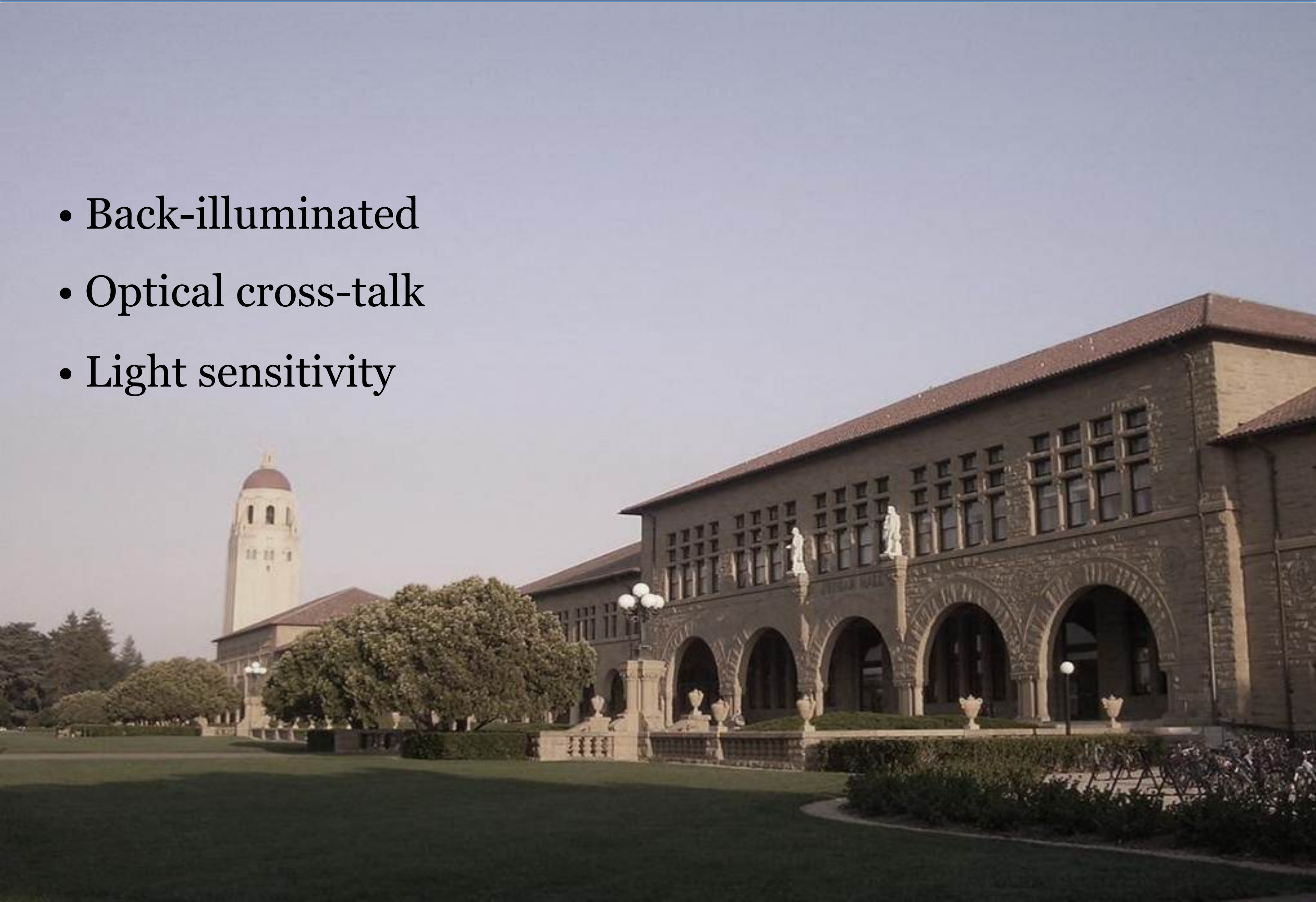
http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

CMOS graphics description



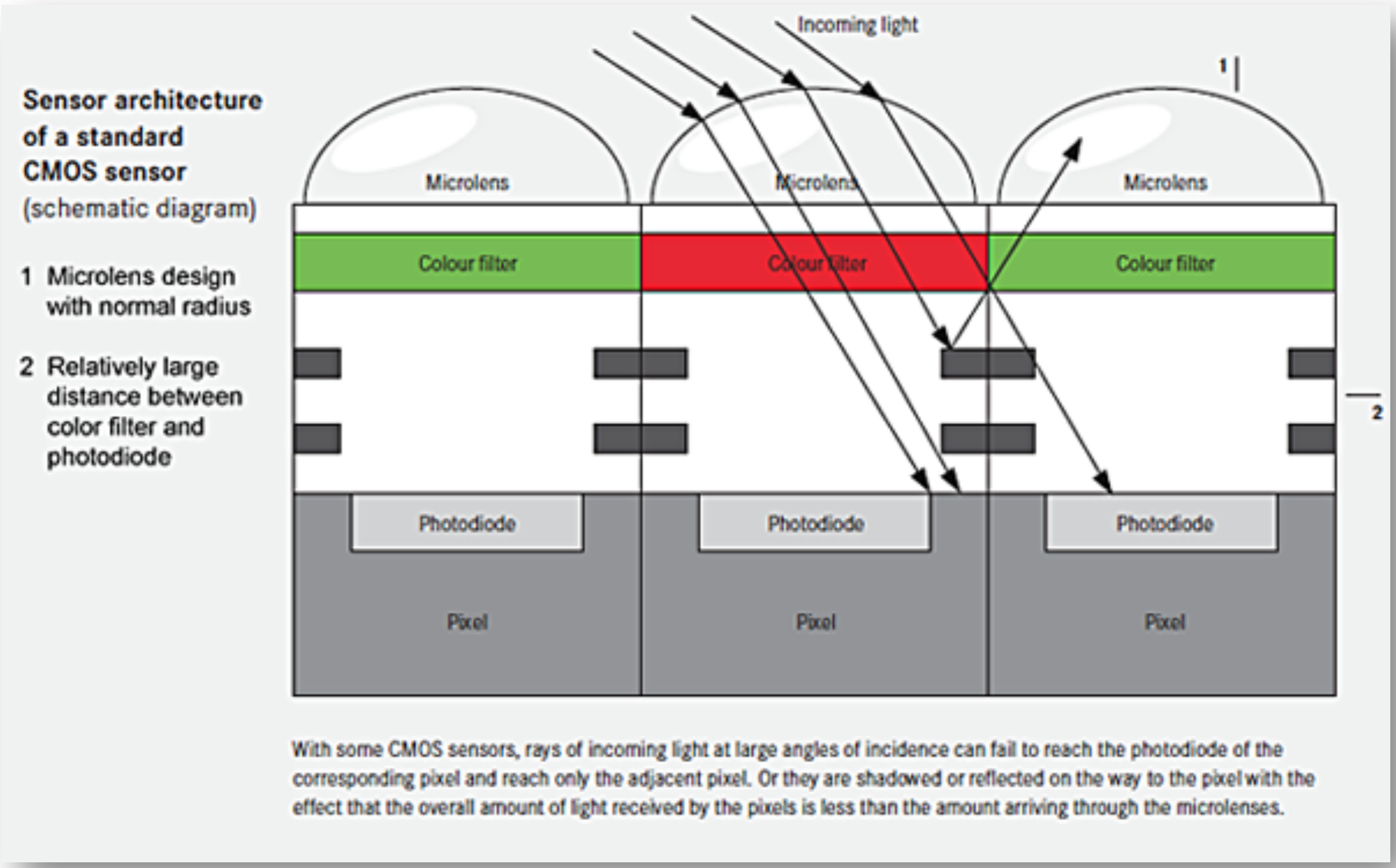
Back-illuminated sensors

- Back-illuminated
- Optical cross-talk
- Light sensitivity



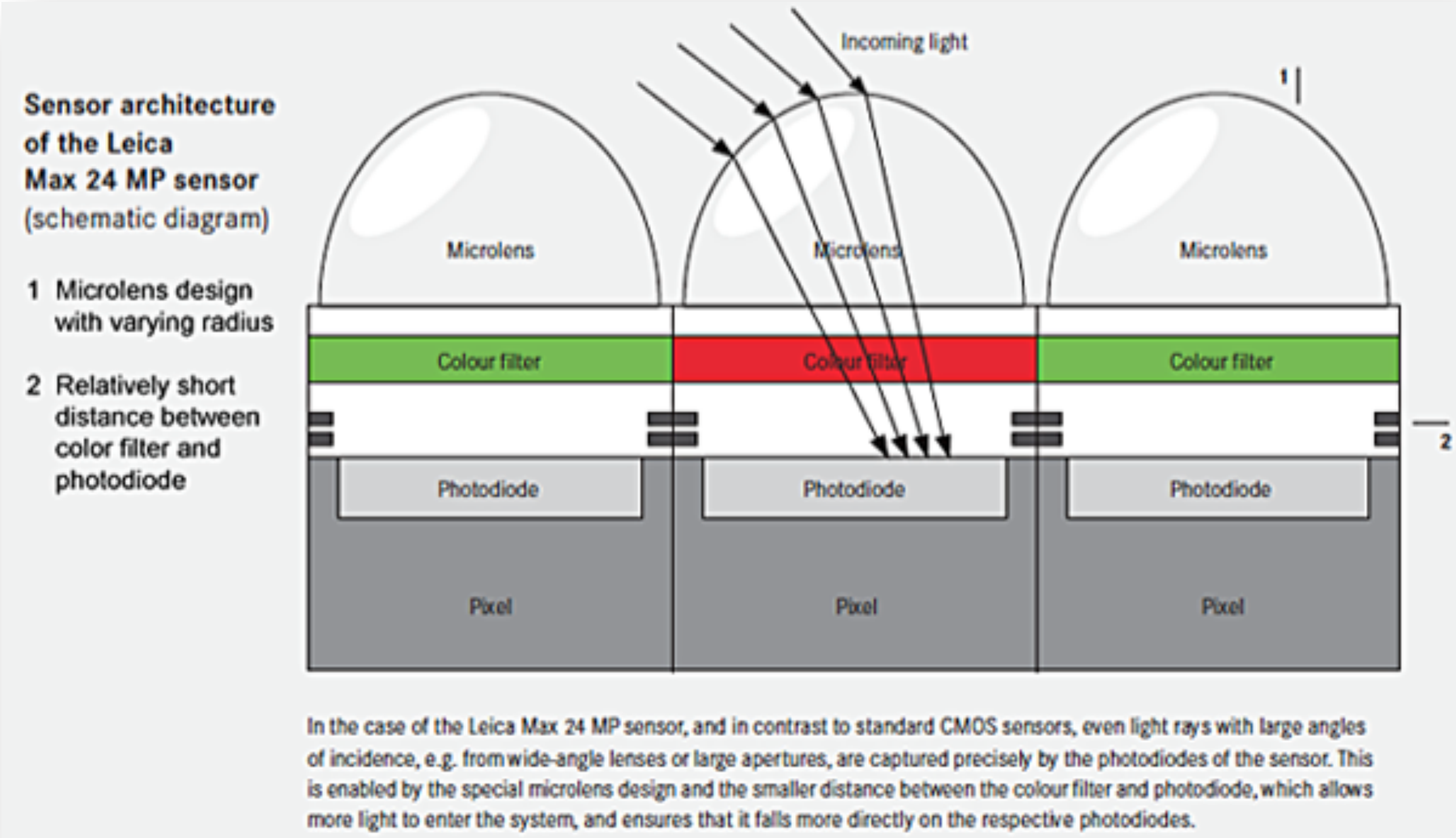
A problem with front-illuminated

Optical cross-talk



Leica

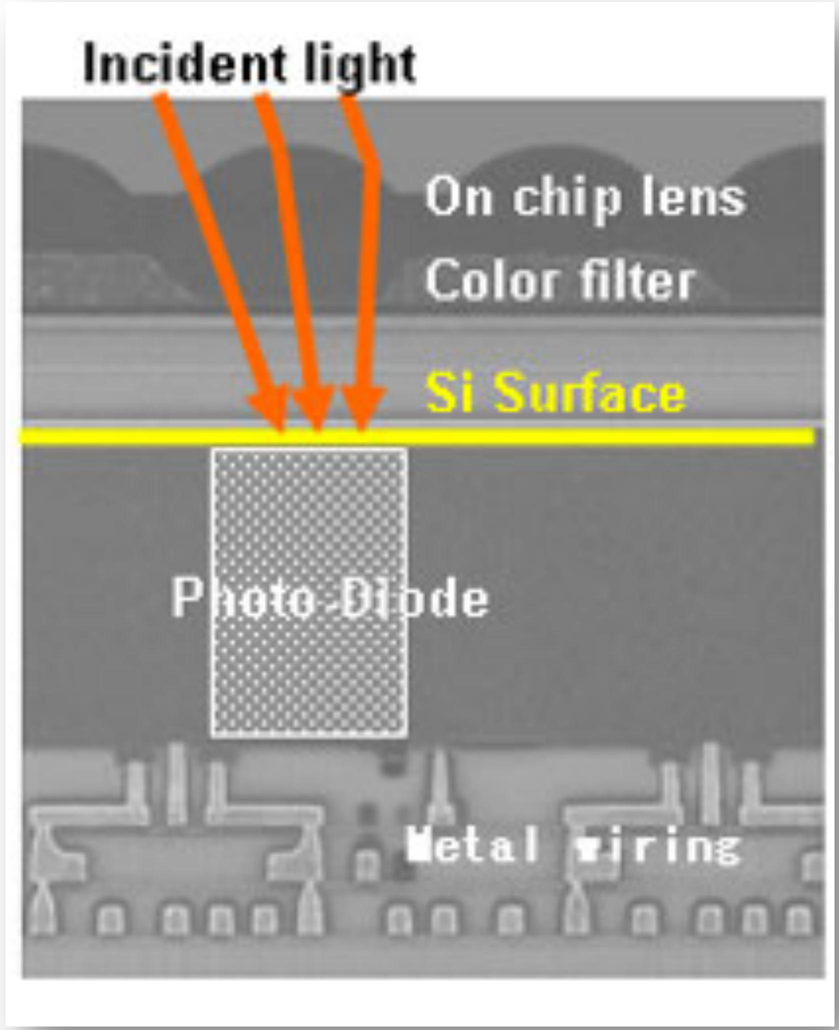
Reducing path length to correct for optical cross-talk



http://gmpphoto.blogspot.com/2012/09/the-new-leica-max-24mp-cmos-sensor.html

Back-illuminated (BI) CMOS sensor

Also called Back-side illumination (BSI)

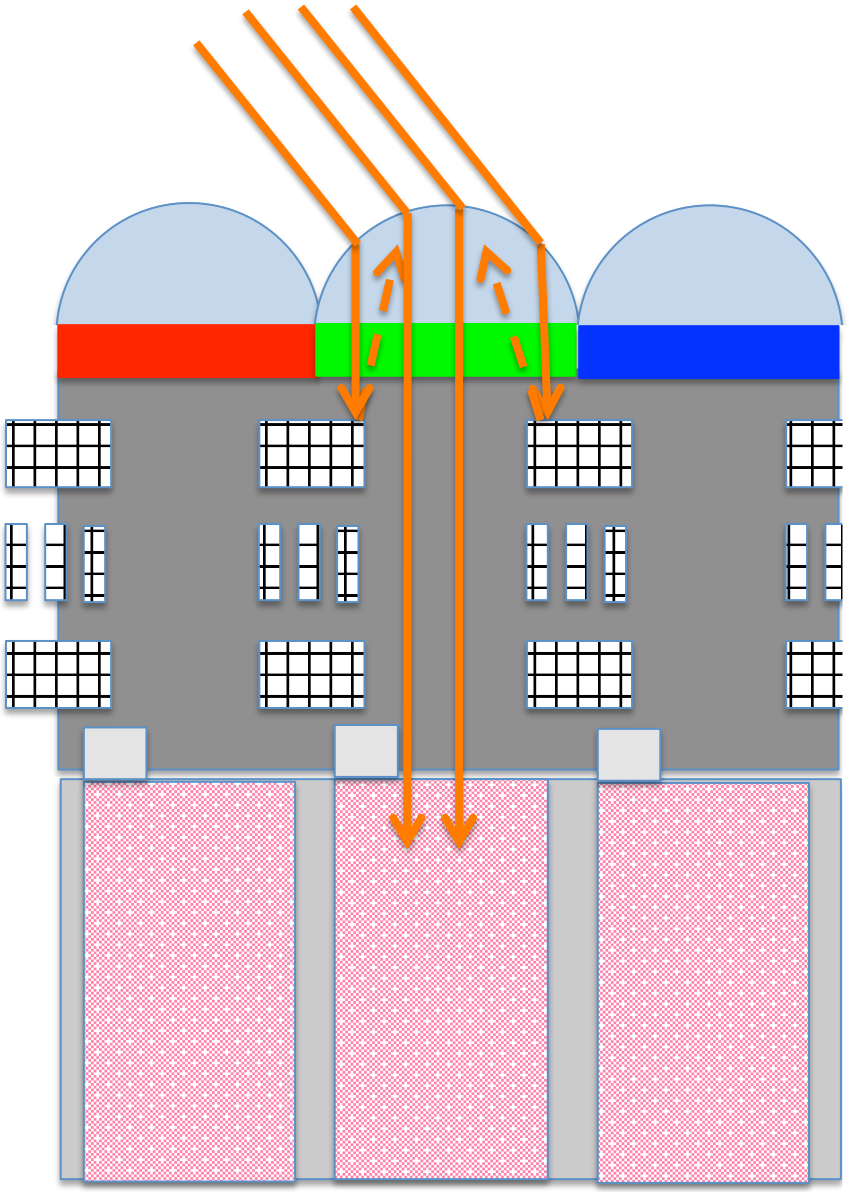


Silicon substrate

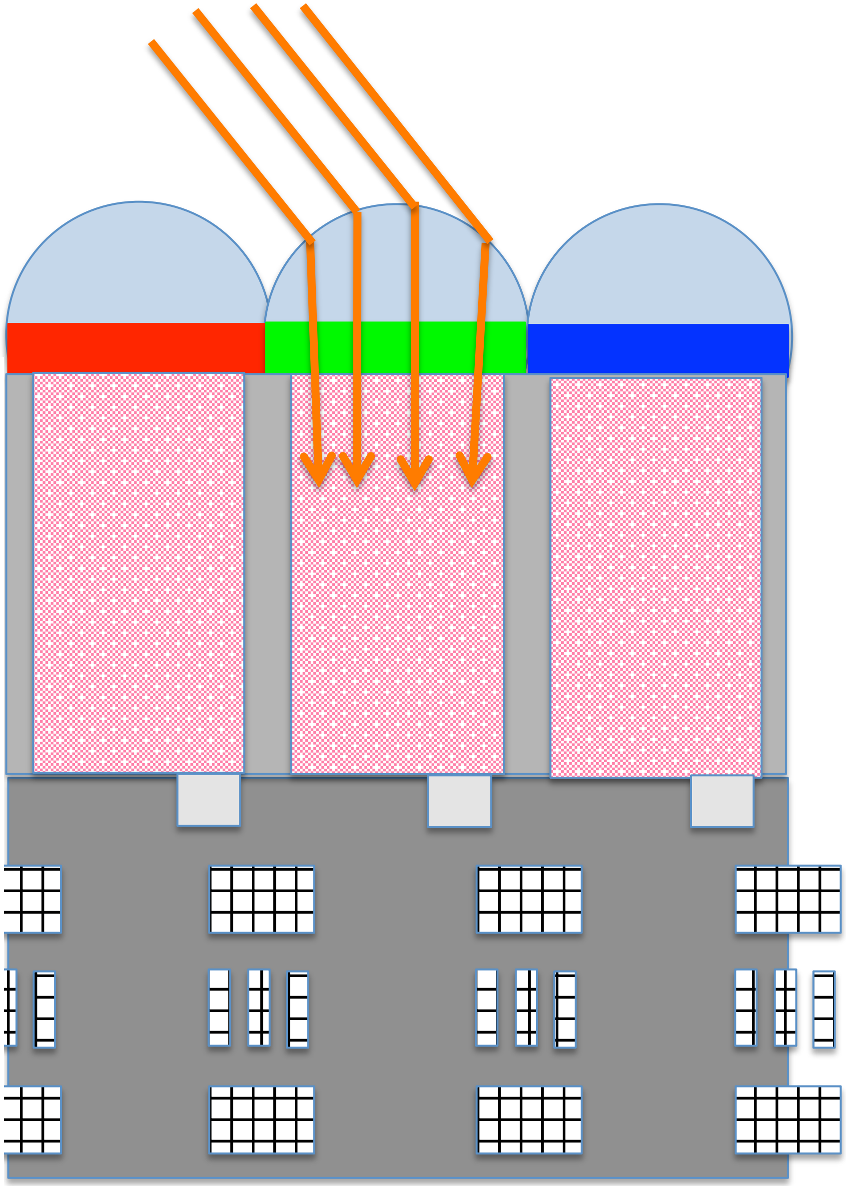
Metal layers

Adapted from http://www.sony.net/SonyInfo/News/Press/200806/08-069E/

Front vs. Back illuminated

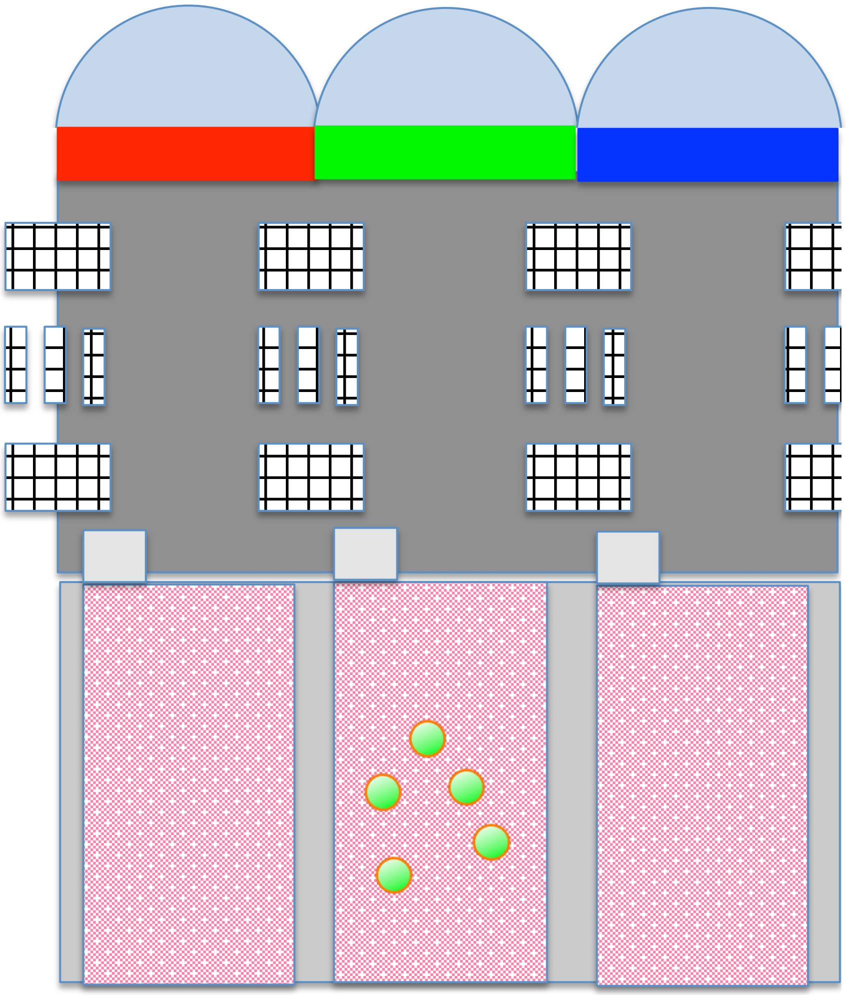


Front illuminated

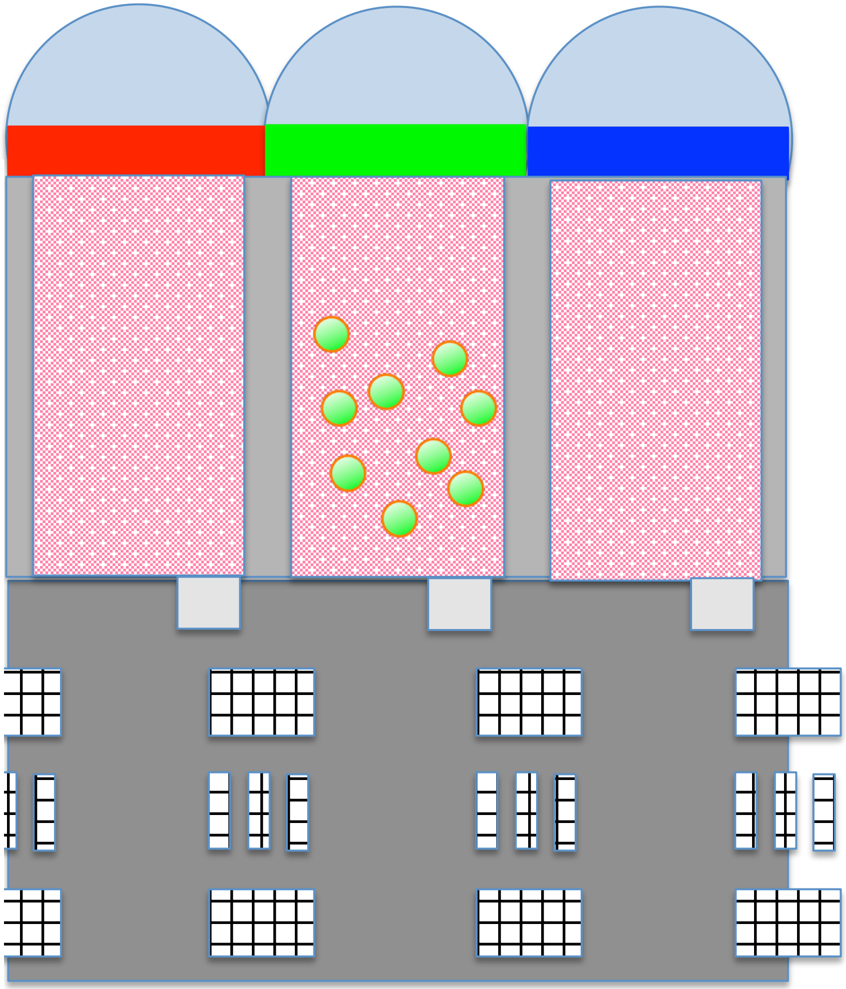


Back illuminated

Front vs. Back illuminated

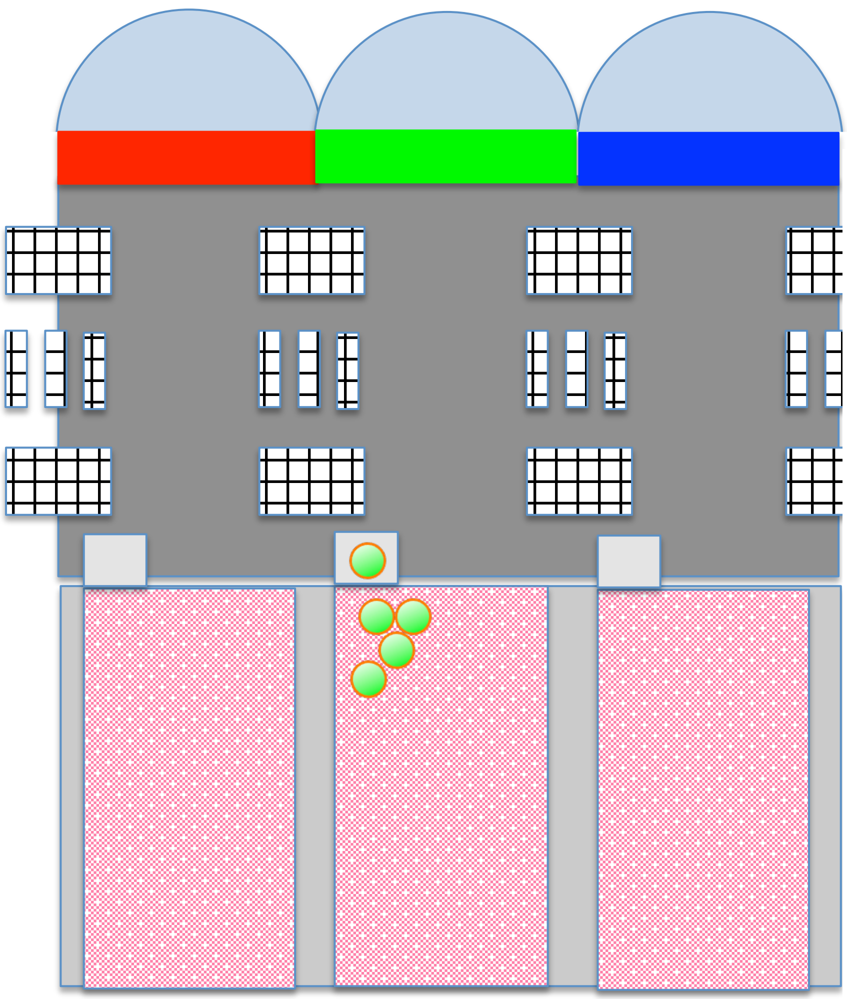


Front illuminated

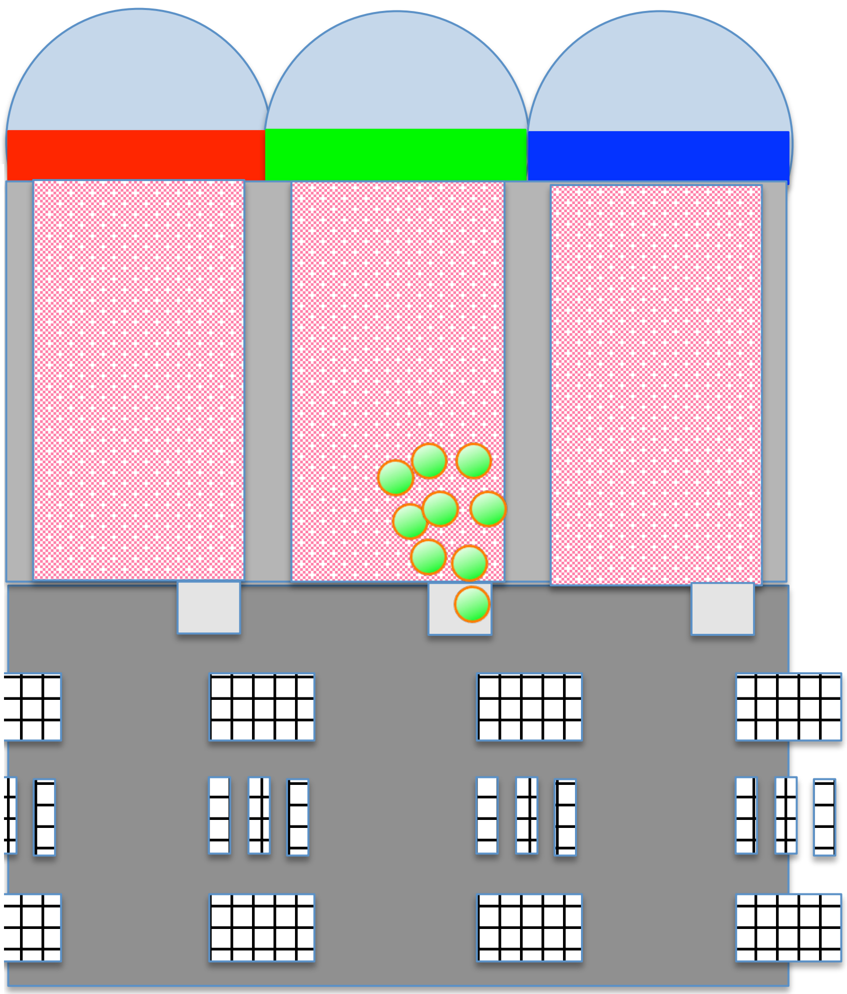


Back illuminated

Front vs. Back illuminated



Front illuminated



Back illuminated

At equal exposure durations, more photons are captured

[Sony comparison of backside illuminated CMOS]

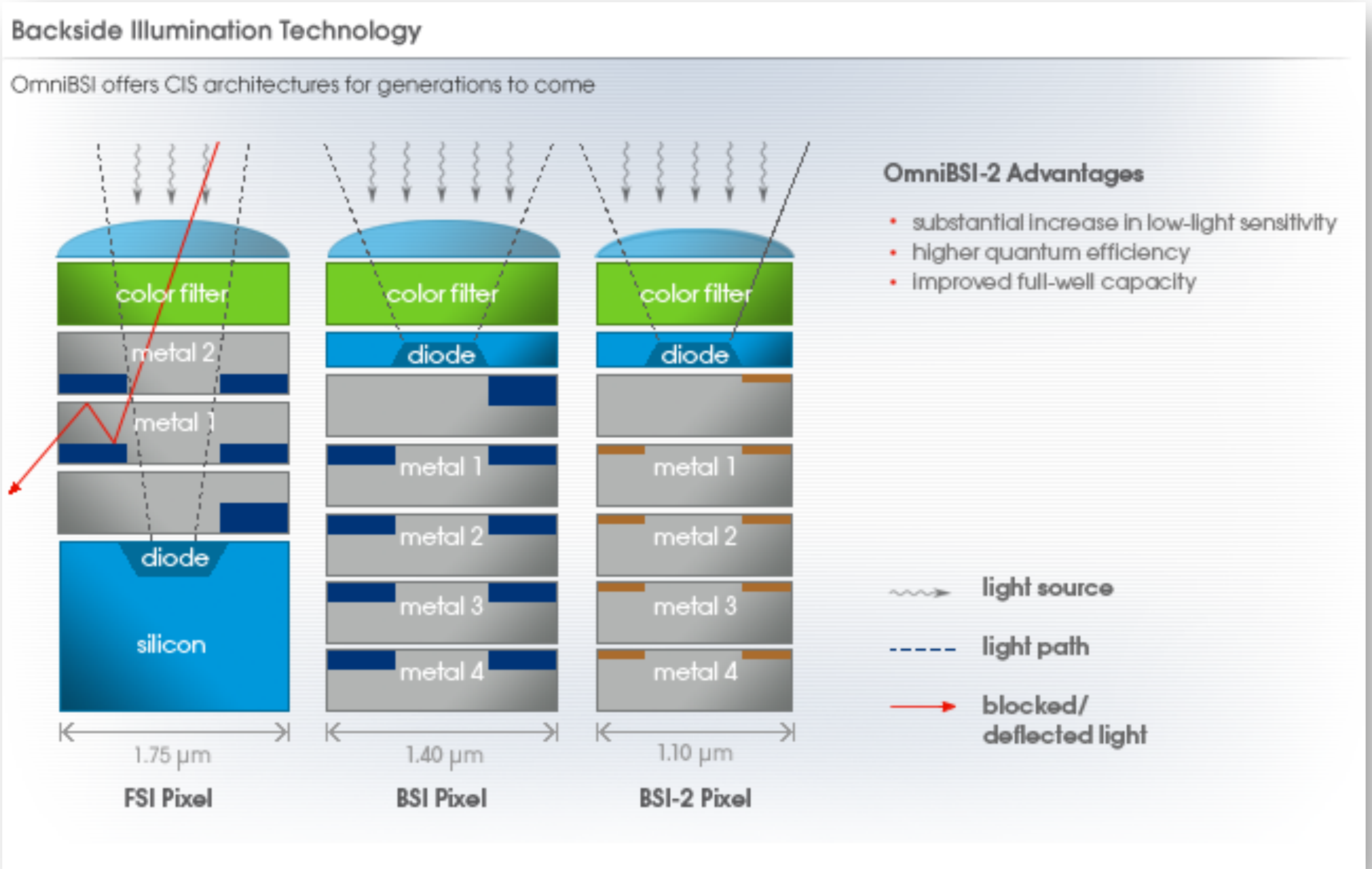
Front-illuminated structure

Back-illuminated structure

Back illuminated sensor

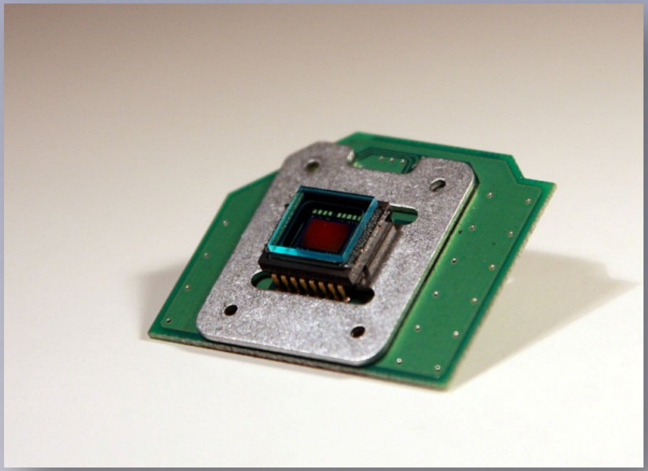
More metal layers for processing without interfering with light capture

Or, thinner form factor for mobile devices



http://www.ovt.com/technologies/technology.php?TID=7

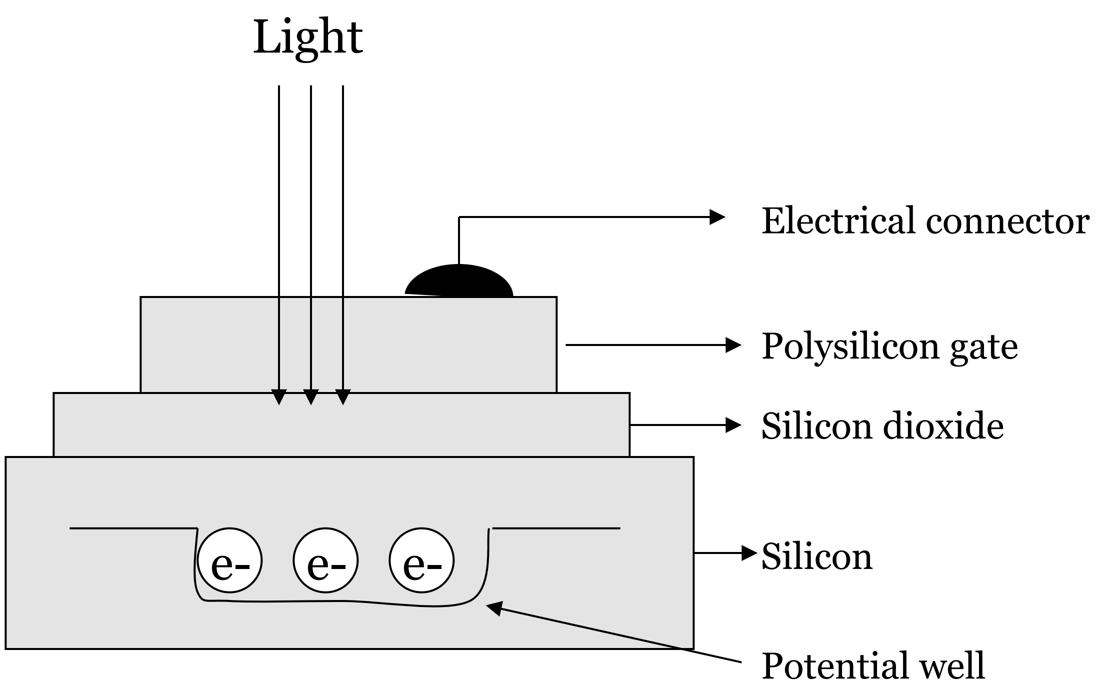
CCD imagers



- Charge transfer ideas
- Architectures
- Correlated double sampling

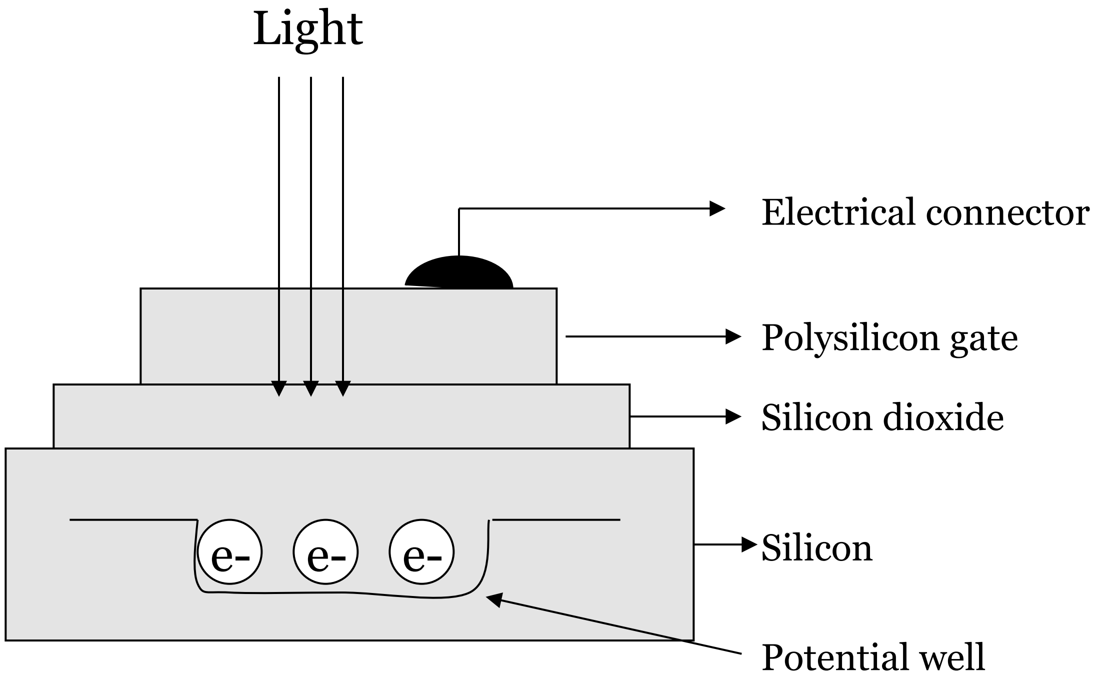
A few moments for the venerable CCD

Invented in the 1970s as memory devices; light sensitive properties were exploited for imaging applications; a major revolution in Astronomy.

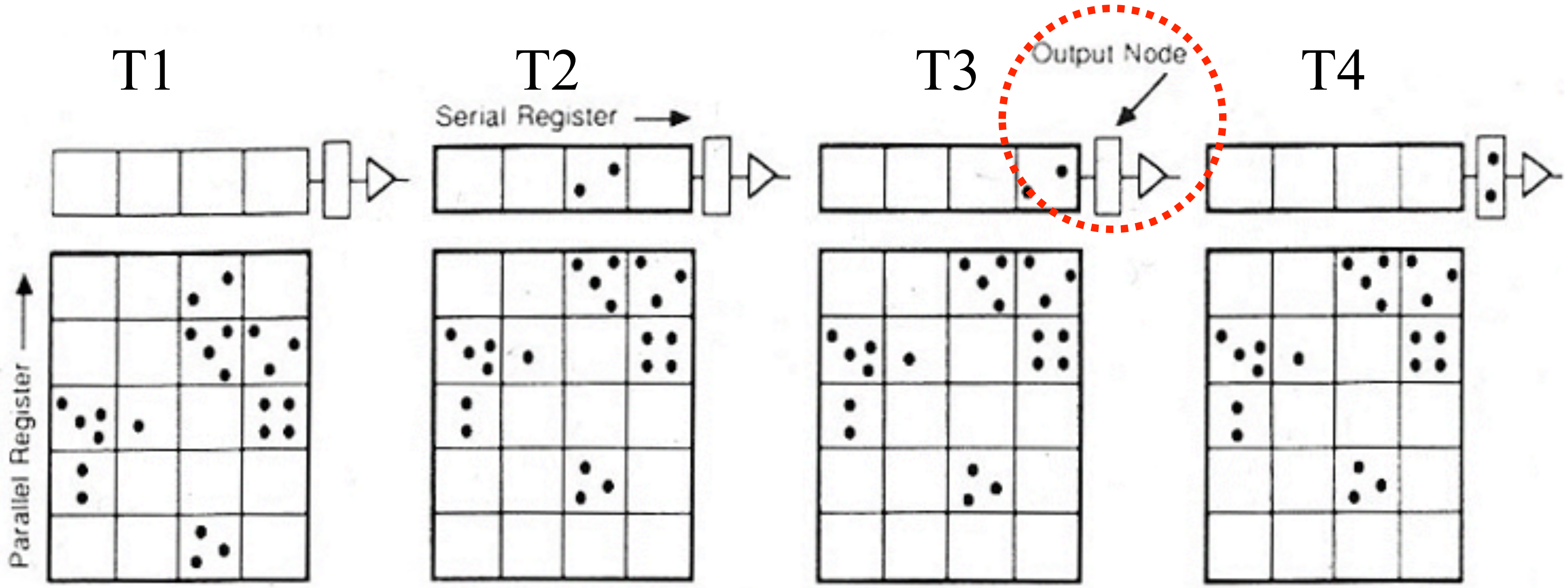


A few moments for the venerable CCD

They improved the light gathering power of telescopes by almost two orders of magnitude. In 2001 an amateur astronomer with a CCD camera and a 15 cm telescope collects as much light as an astronomer of the 1960s equipped with a photographic plate and a 1m telescope.



CCD Charge transfer

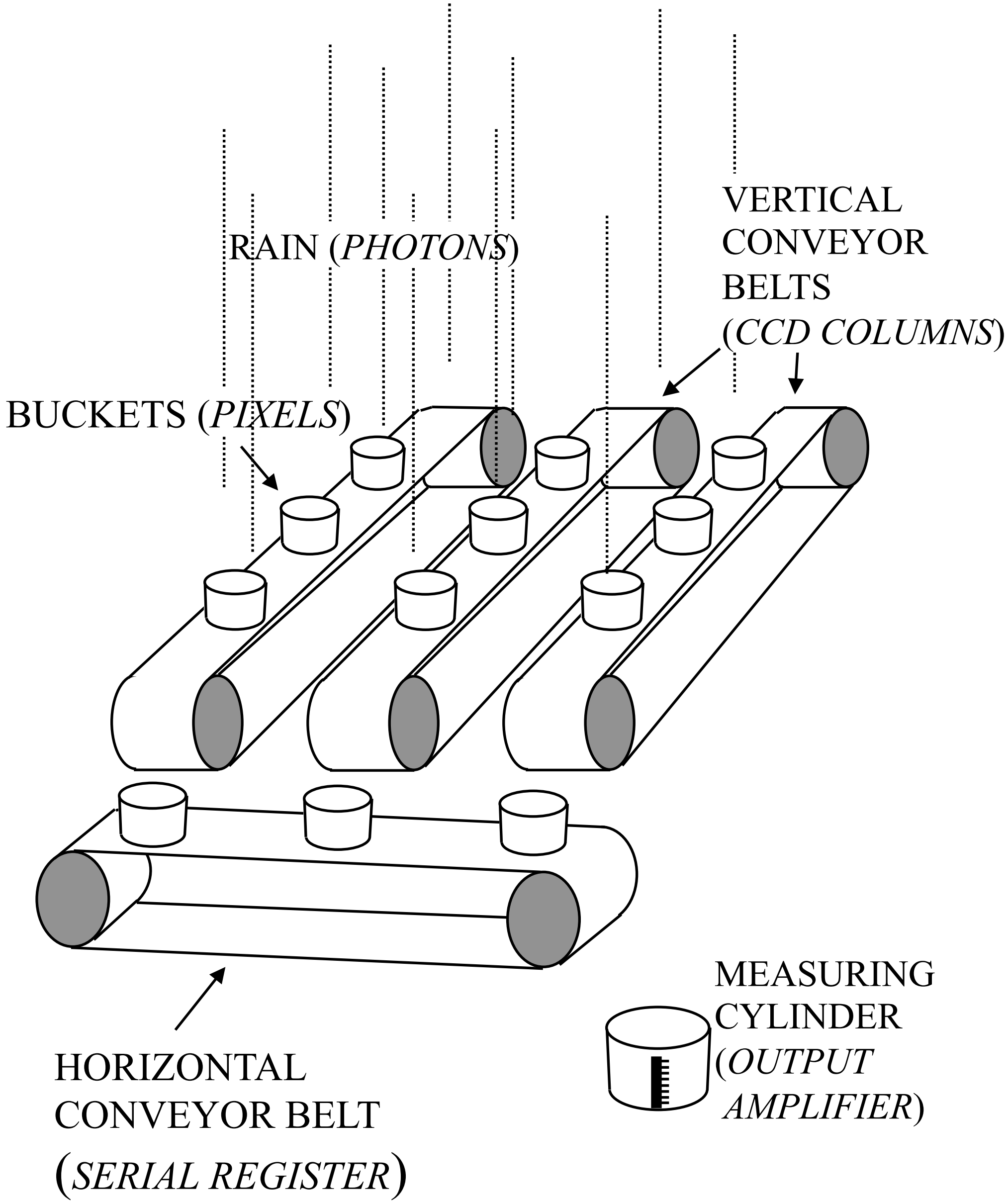


ıne CCD is exposed to light. An electronic image accumulates as a pattern of charge in the parallel register. The CCD is ready to be read out

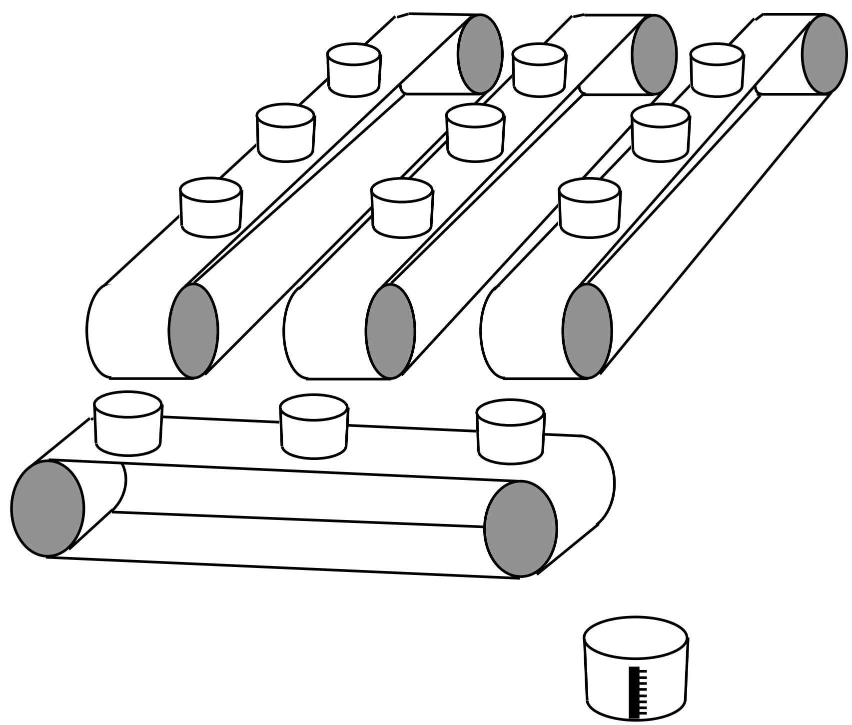
All rows are shifted in parallel. The top row is shifted into the serial register

Once in the serial register, pixels are individually shifted toward the output node

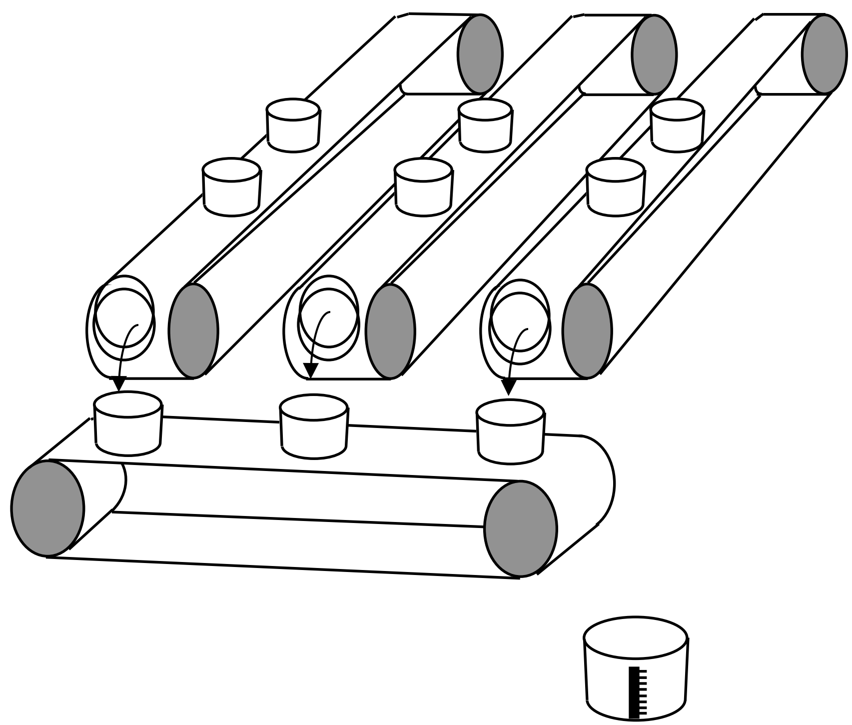
The next row can be shifted into the serial register after that register is cleared


RAIN (*PHOTONS*)
VERTICAL CONVEYOR BELTS (*CCD COLUMNS*)
BUCKETS (*PIXELS*)
MEASURING CYLINDER (*OUTPUT AMPLIFIER*)
HORIZONTAL CONVEYOR BELT (*SERIAL REGISTER*)

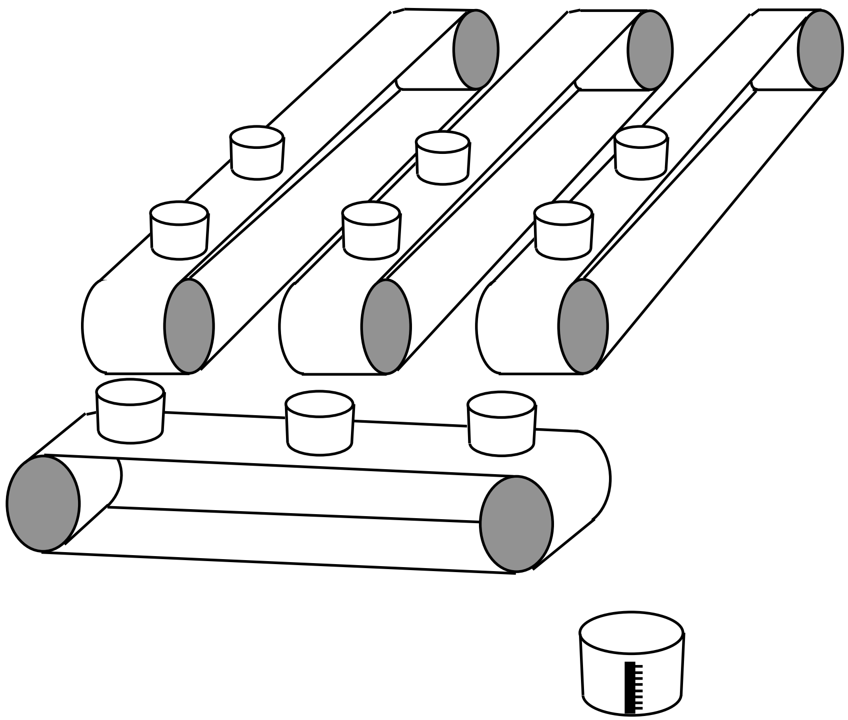
Exposure finished, buckets now contain samples of rain.



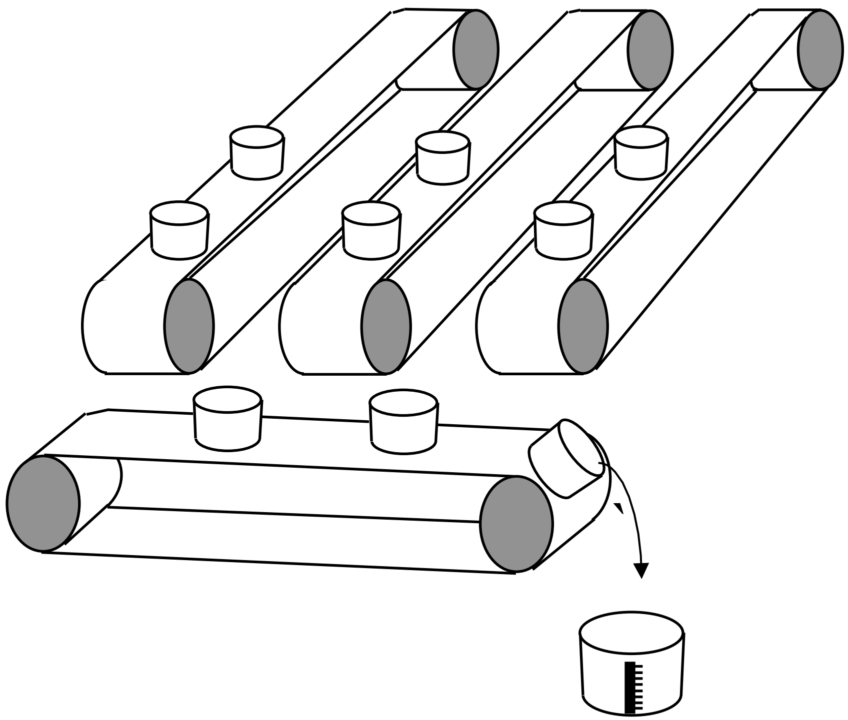
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

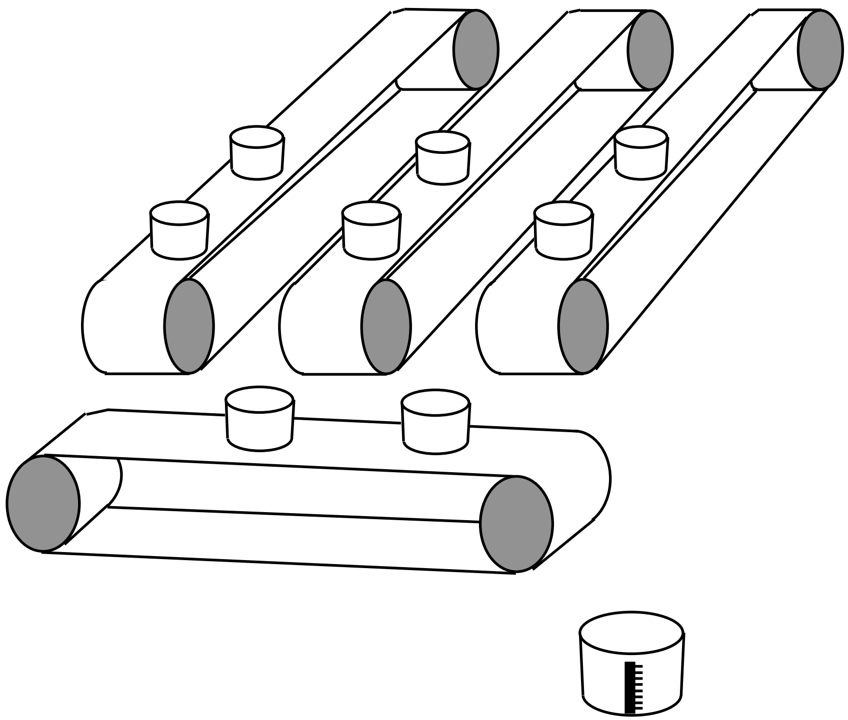


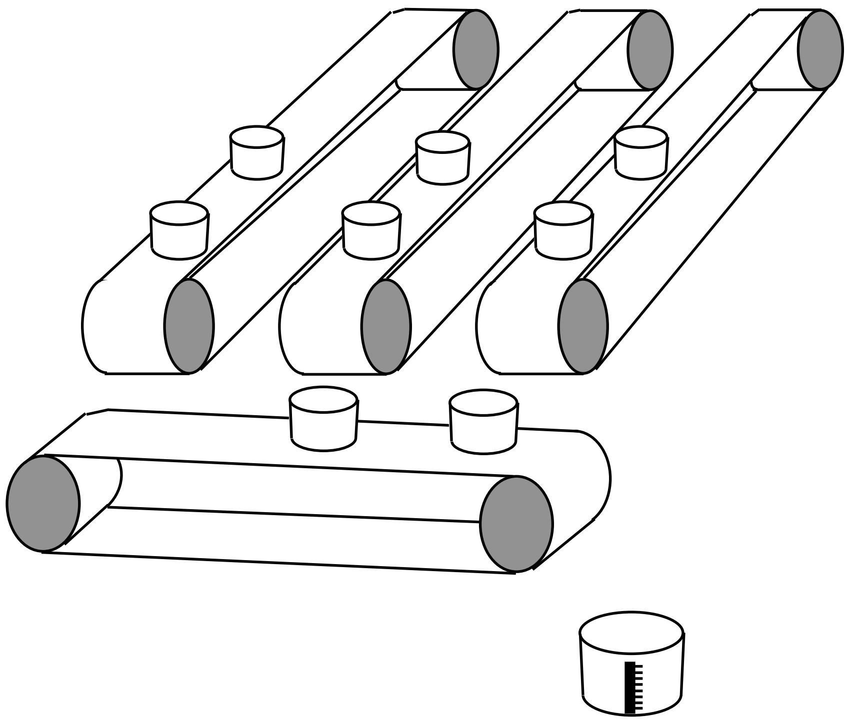
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

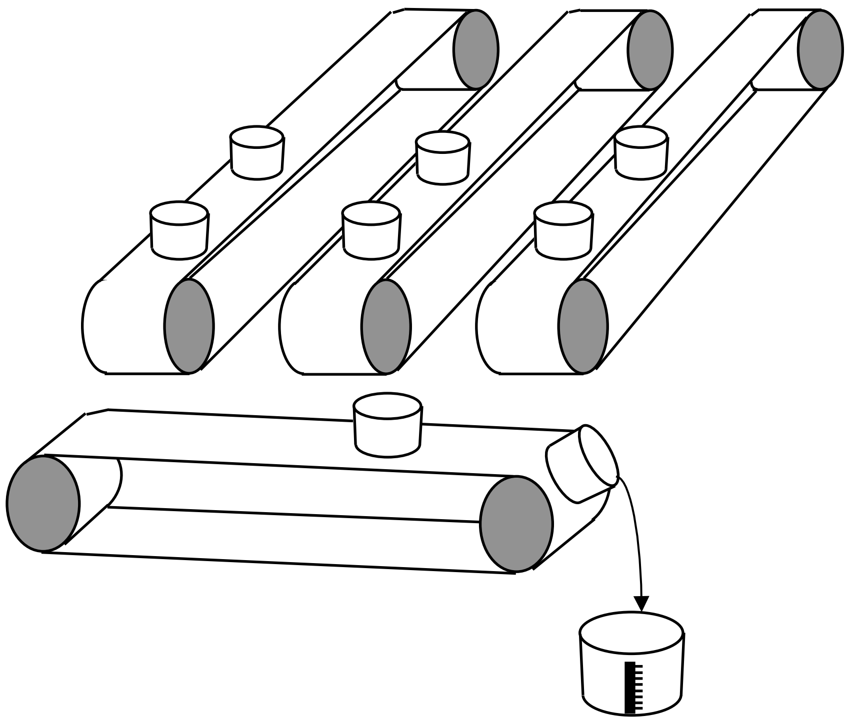


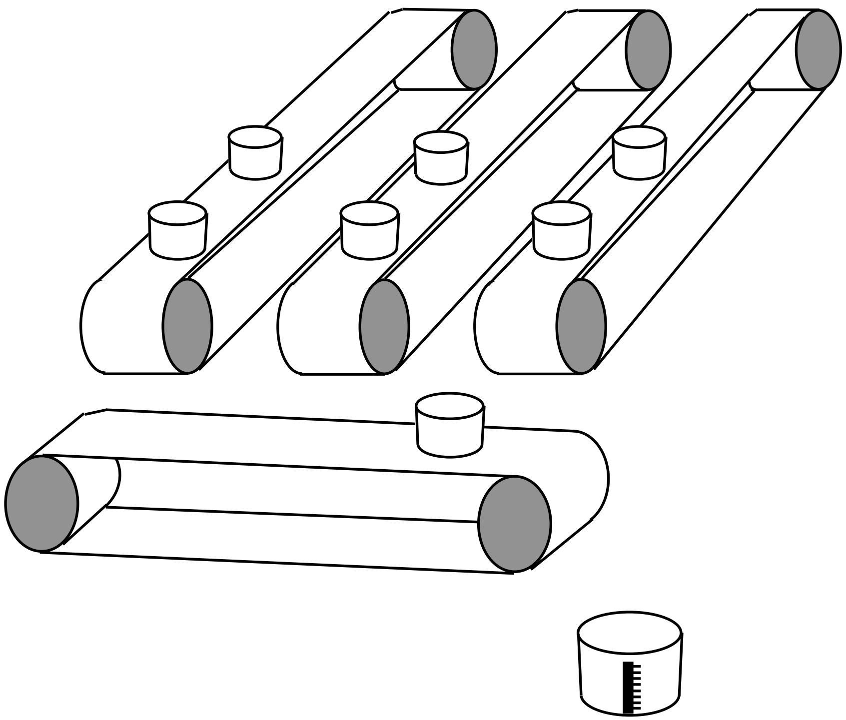
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.

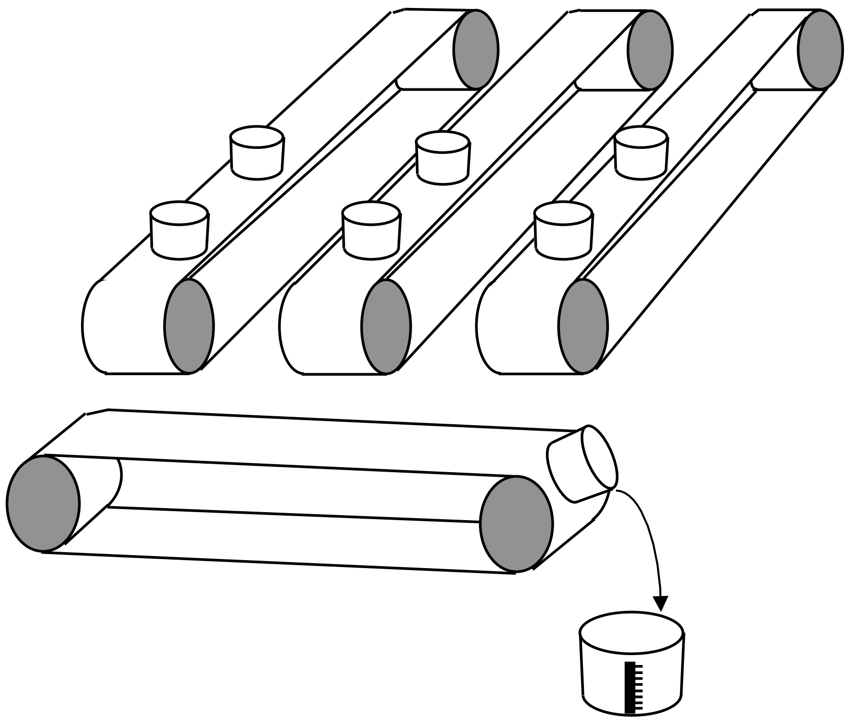


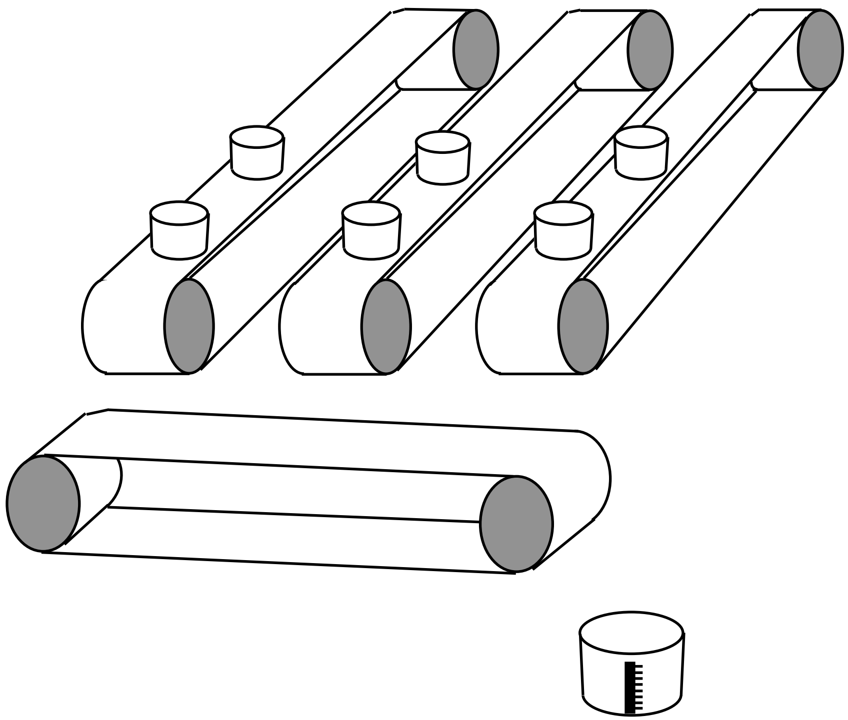




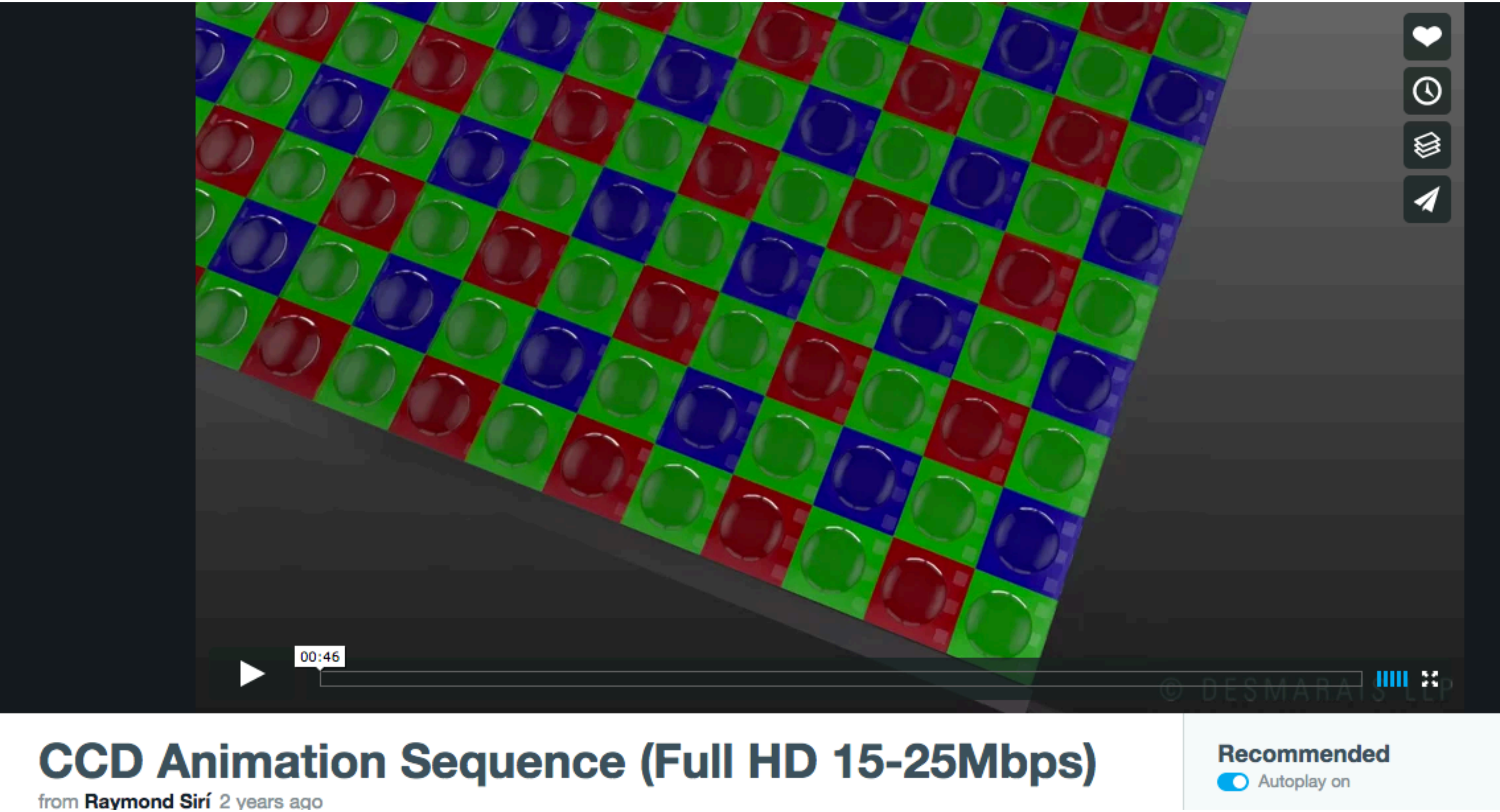




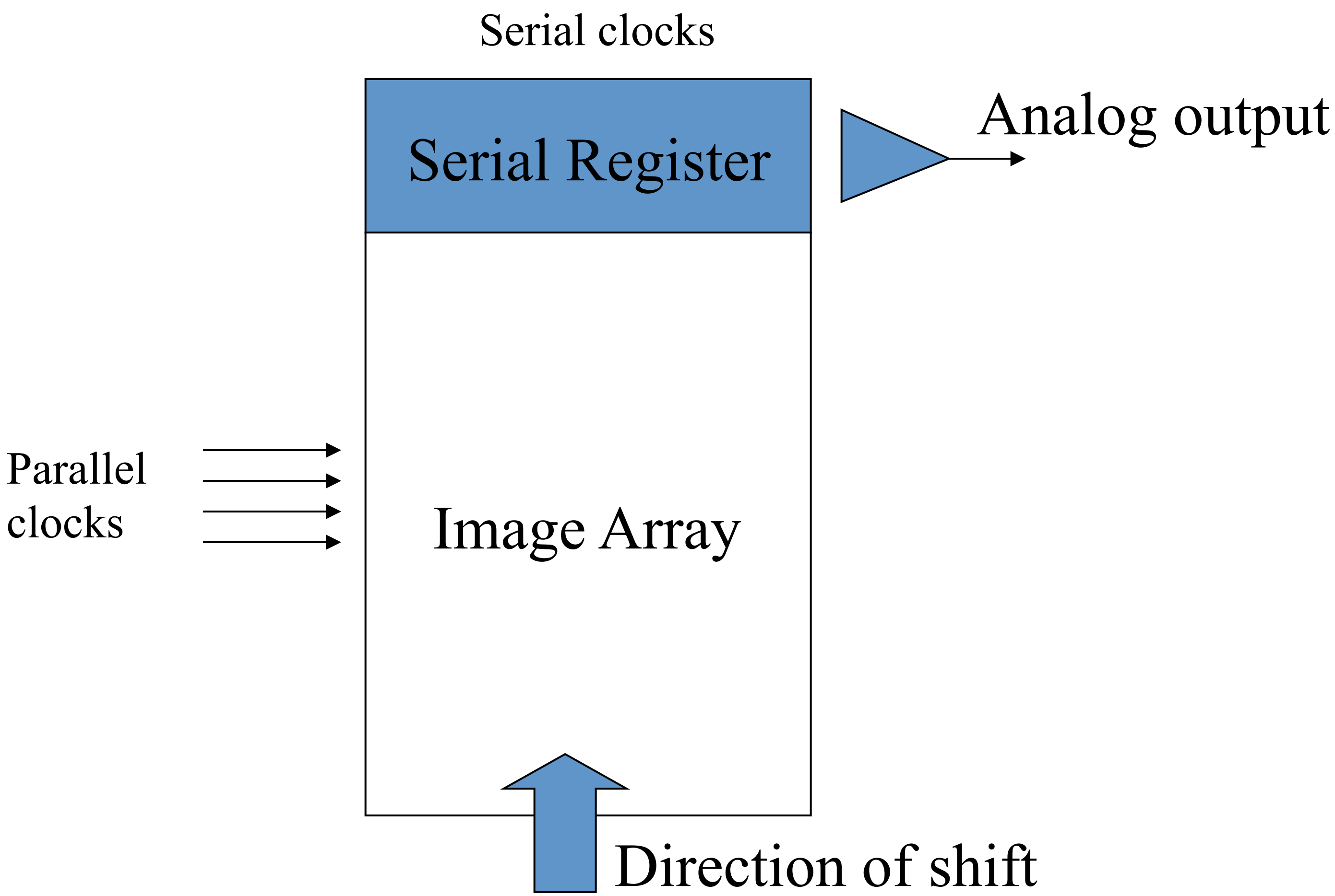




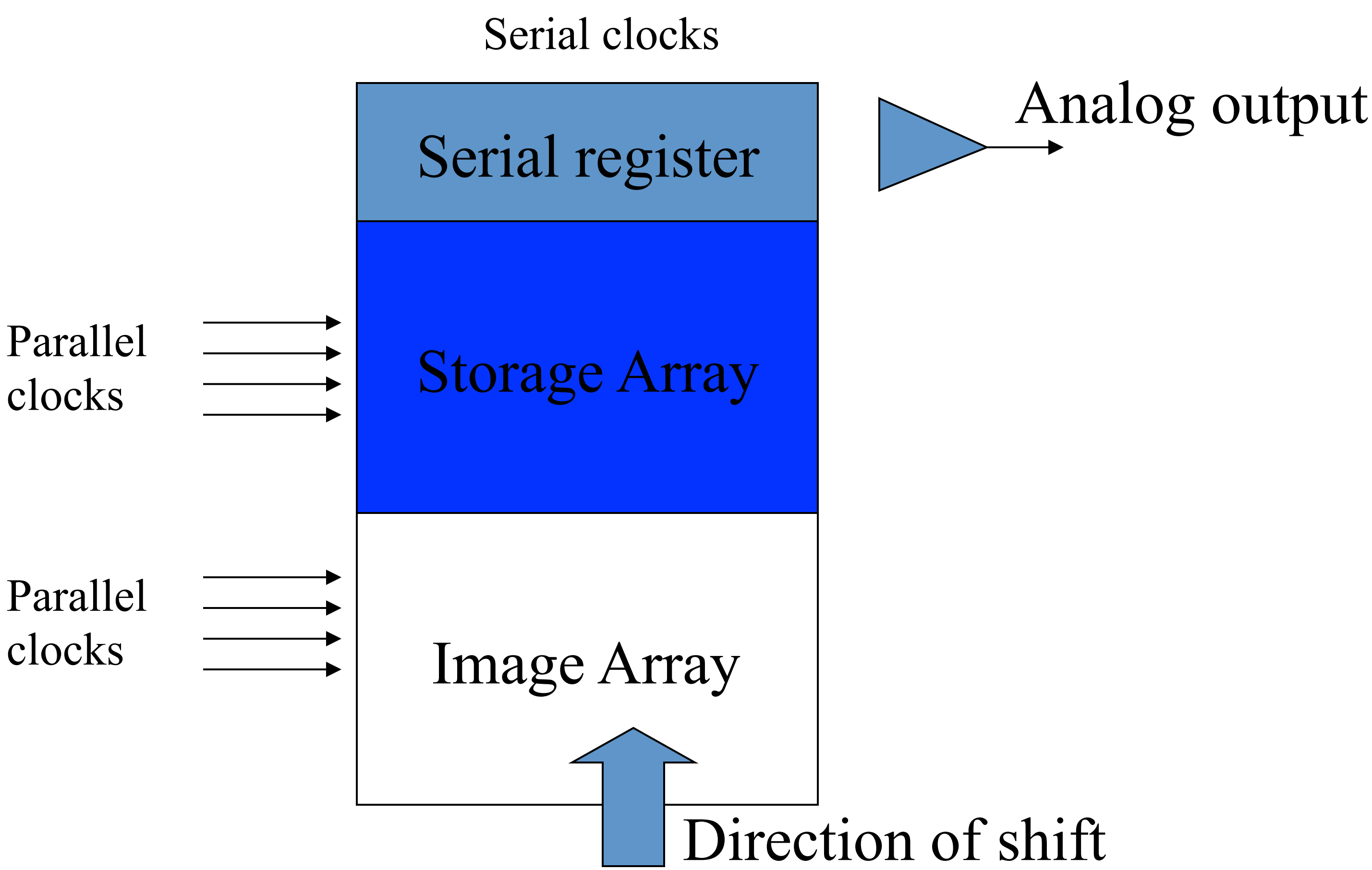
Is this better?



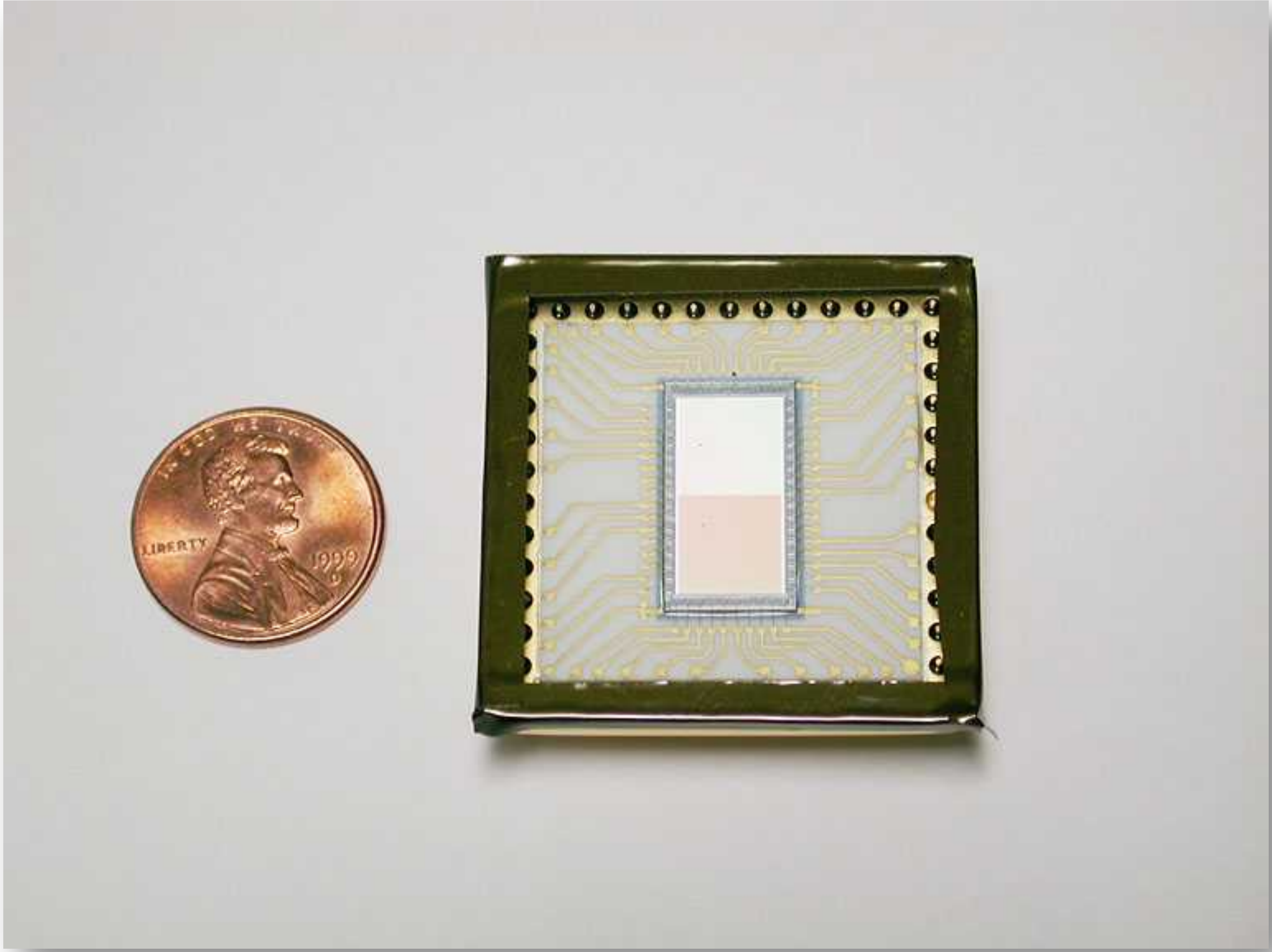
Full Frame CCD



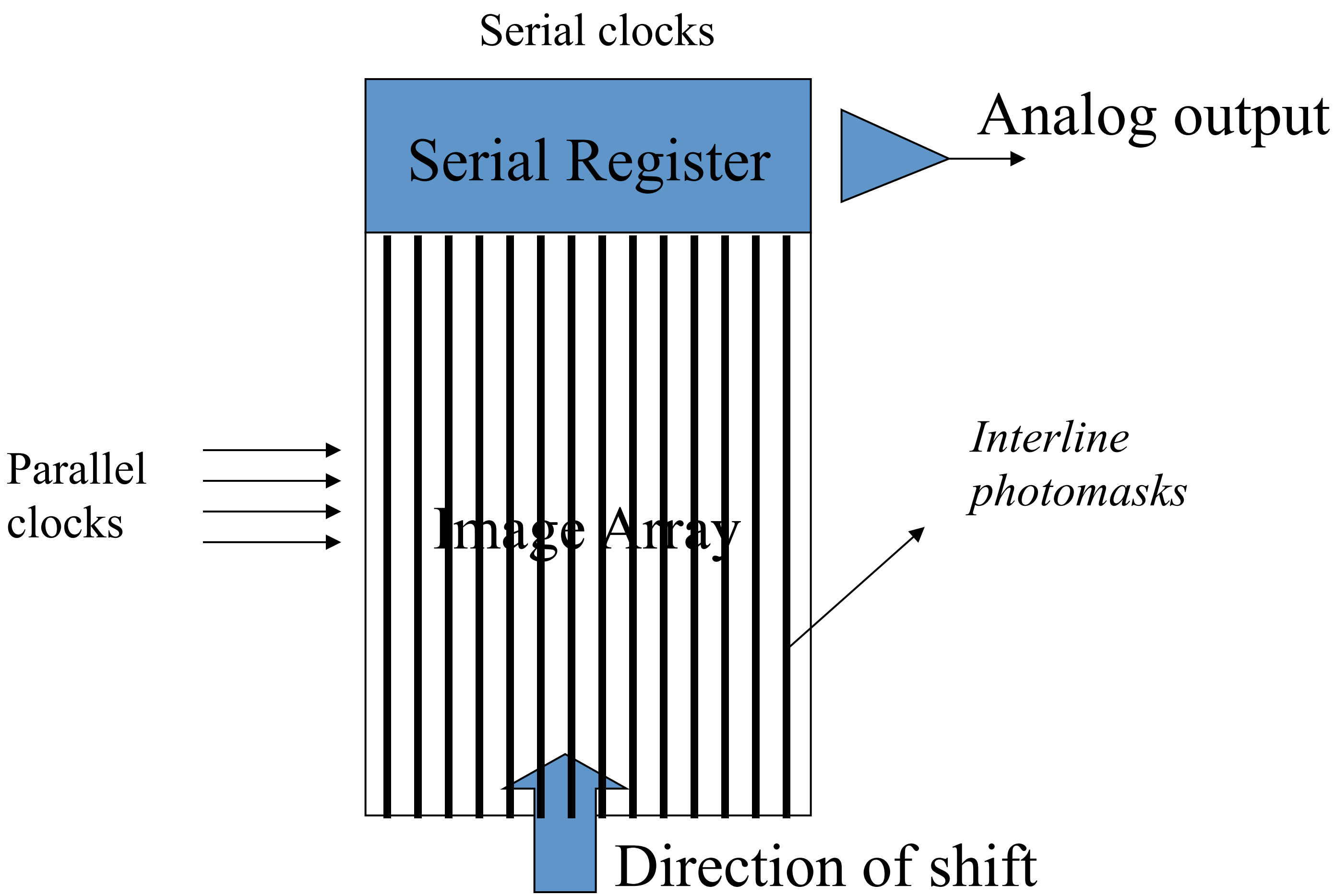
Frame Transfer CCD



Frame Transfer CCD

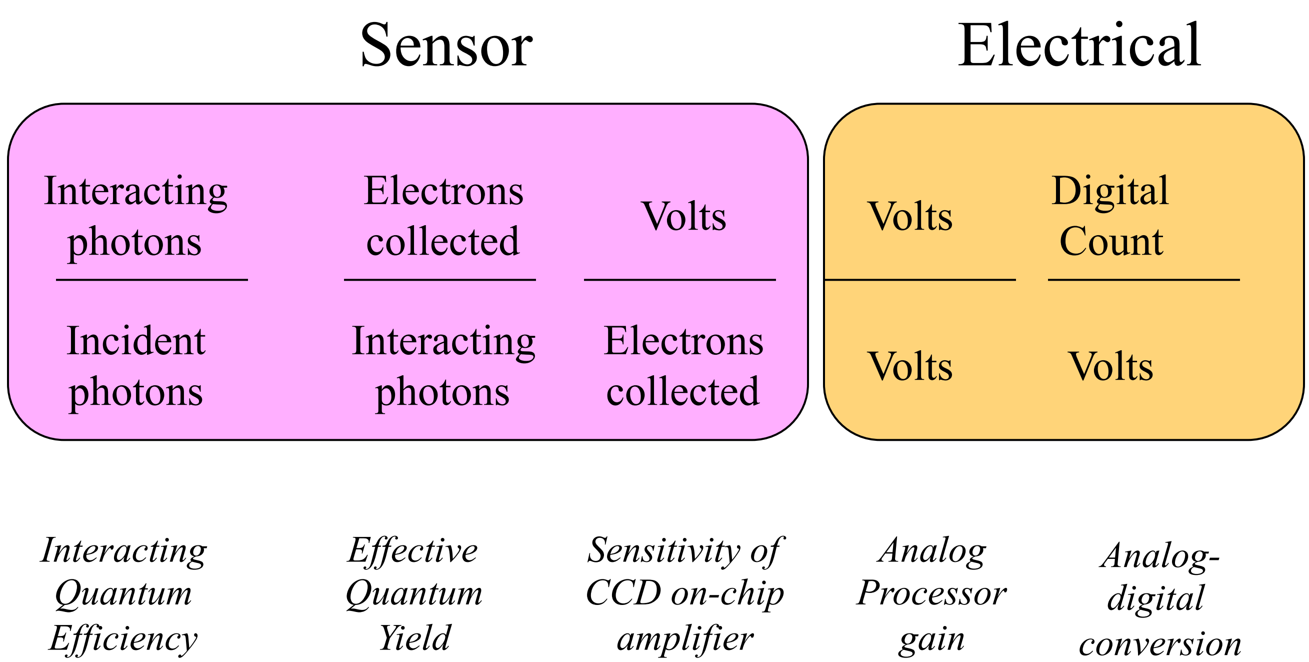


Interline Transfer CCD



Electrical Efficiency - Stages
(CCD, see Janesick's books, tutorials)

Incident photons (irradiance, in photons per square micron of the sensor per nm)



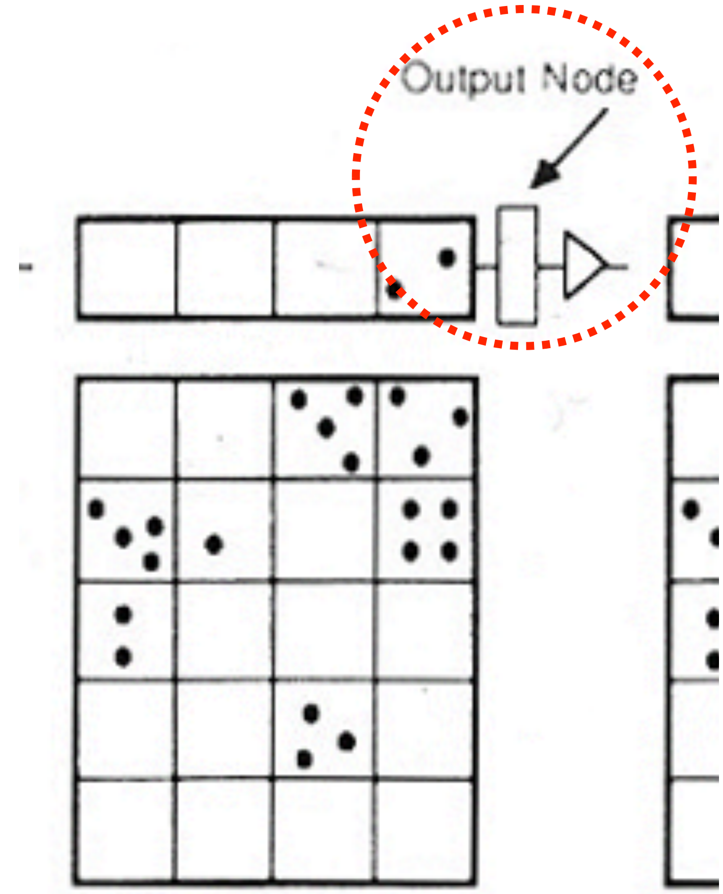
(After J. Janesick, Pixel Vision)

Engineering: Reducing 'reset' noise (CDS)

The image from a CCD is read out by transferring rows of charge into a single horizontal register, followed by transfer of individual pixel charge along the horizontal register towards a single output node.

As each pixel's charge reaches the output node, it is digitized and transferred to the computer for display.

There can be significant unwanted charge at this output stage. This unwanted signal is due to inaccurate resetting of the output.



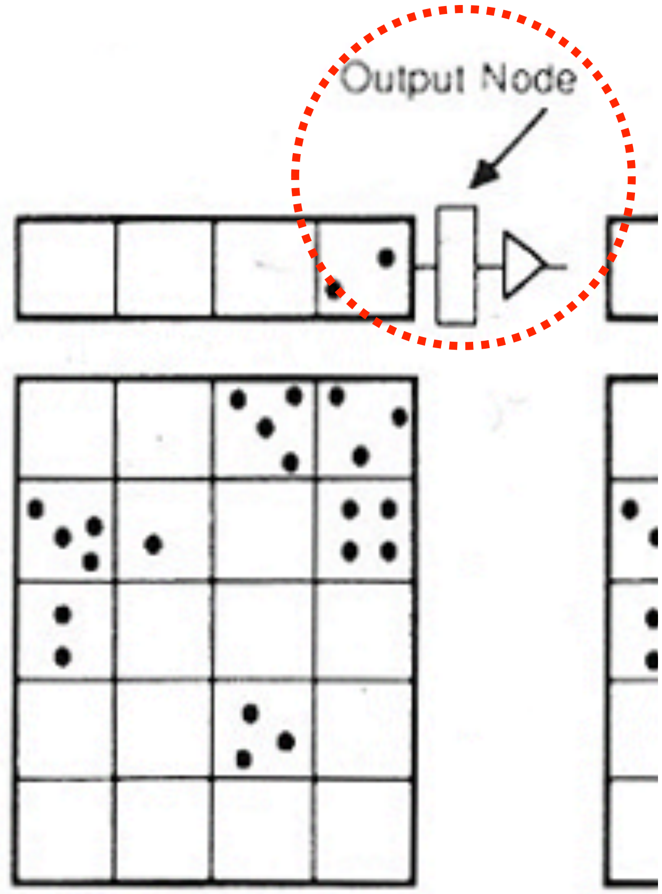
Engineering: Correlated Double Sampling (CDS)

Before the charge of each pixel is transferred to the output node, the node is reset to a fixed **reference value**. This value has Fixed and Variable Unwanted Effects.

The difference between the **reference value** and the transferred charge is measured and assigned to the pixel. This process is called Correlated Double Sampling (CDS).

Measuring the difference removes the Fixed Unwanted Effects. But reading twice causes extra noise (Variable Unwanted Effects)

It increases the Variable Unwanted Effects. When the Fixed >> Variable Unwanted, CDS is useful.

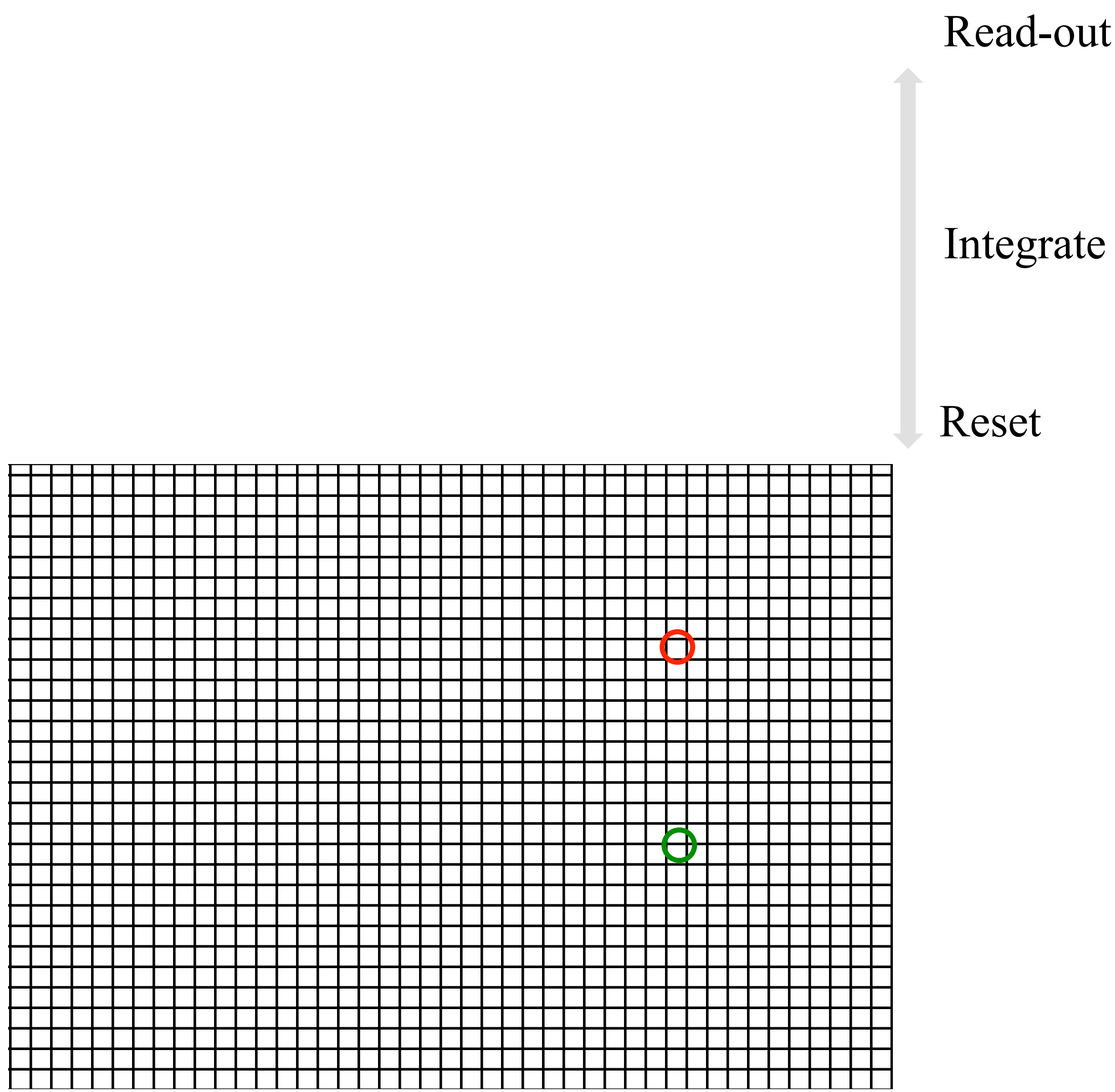


Shuttering

- Rolling
- Global

Rolling shutter

- Sensor is reset-integration-read a row (or column) at a time; this takes some time
- The scene changes during the read-out
- Temporal sampling artifacts
- These appear as spatial distortions



Movie of telephone lines

Note the power line

Rolling shutter

- Sensor is reset-integration-read a row (or column) at a time; this takes some time
- The scene changes during the read-out
- Temporal sampling artifacts
- These appear as spatial distortions

http://en.wikipedia.org/wiki/Rolling_shutter

Global shutter – single pixel

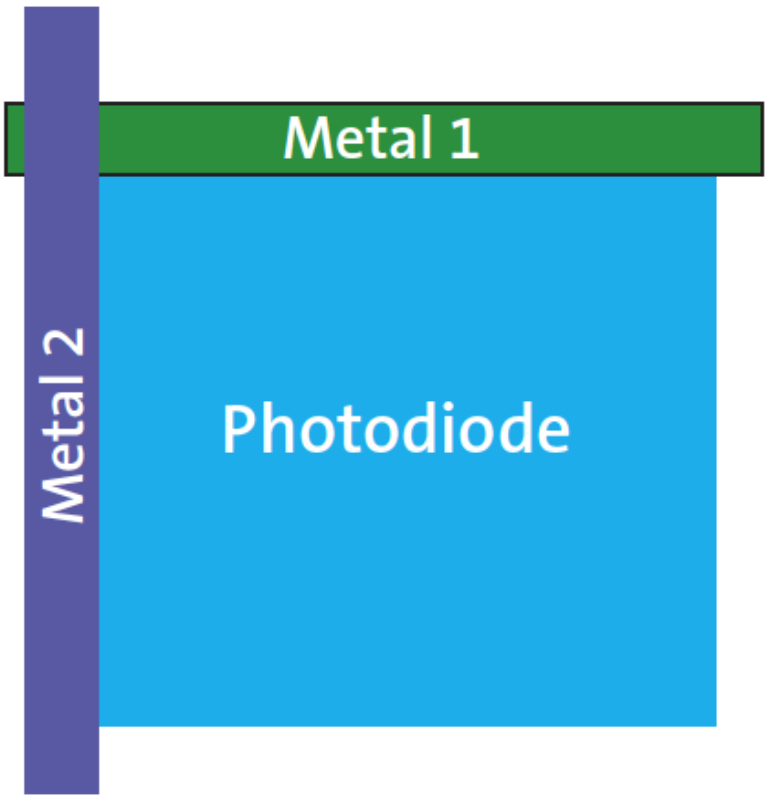


Figure 3. Rolling Shutter Pixel

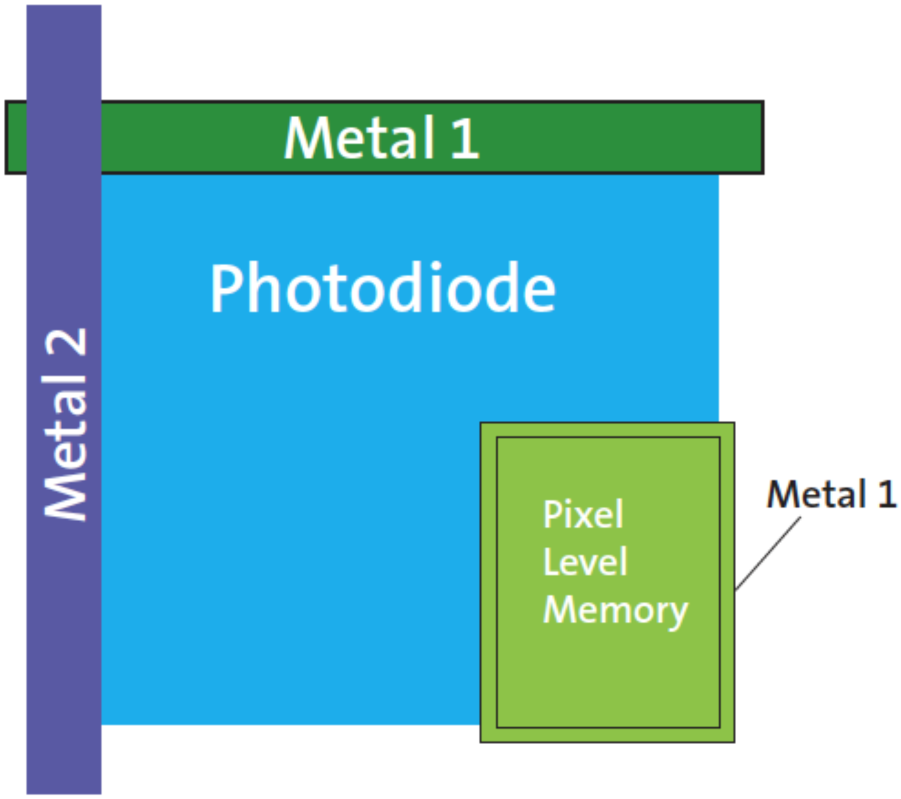
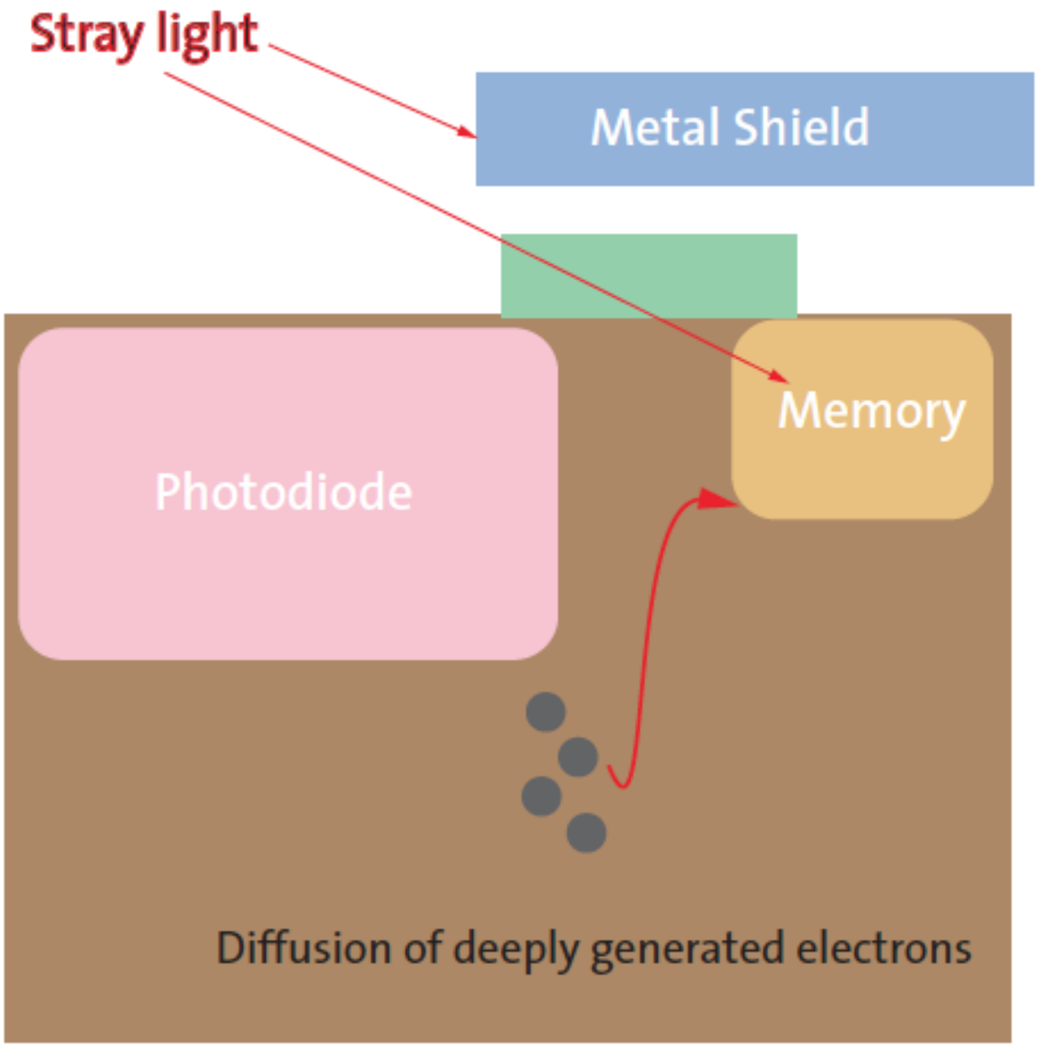


Figure 4. Global Shutter Pixel

Global shutter readout (Aptina)

- Global shutter efficiency measures how well electrons are stored in the memory without being contaminated by unwanted electrons
- This image illustrates two ways in which unwanted electrons enter the memory node



Global Shutter Pixel Technologies and CMOS Image Sensors –
A Powerful Combination – (Aptina white paper)

Global shutter readout (Aptina)

Charge from the pinned photodiode is pumped to a surface-pinned storage node.

There is an anti-reflective metal light shield in close proximity to the node to shield from stray light

The pump technology reduces the number of stray (diffusing) electrons

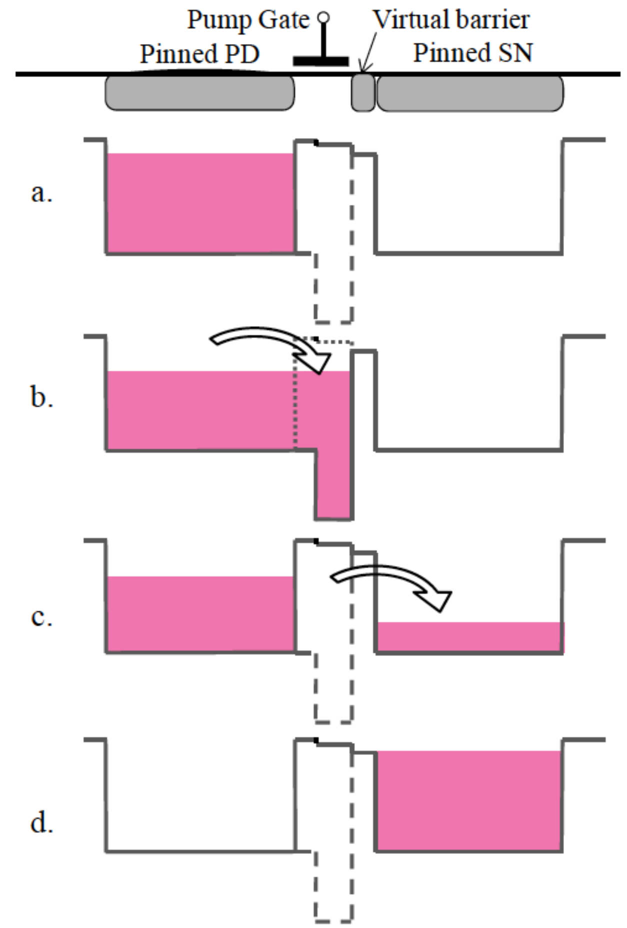
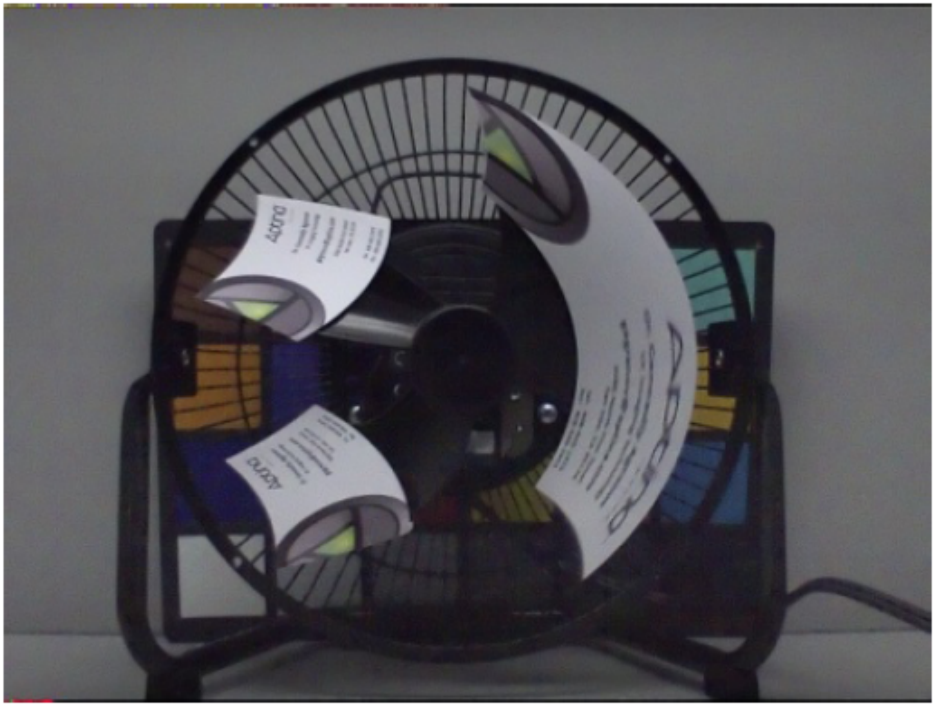


Figure 7. Transferring charge with pump gate. a.- before transferring, b.– first transfer cycle, c.– after first transfer cycle, d.- after N transfers

Global Shutter Pixel Technologies and CMOS Image Sensors – A Powerful Combination – (Aptina white paper)

Global shutter

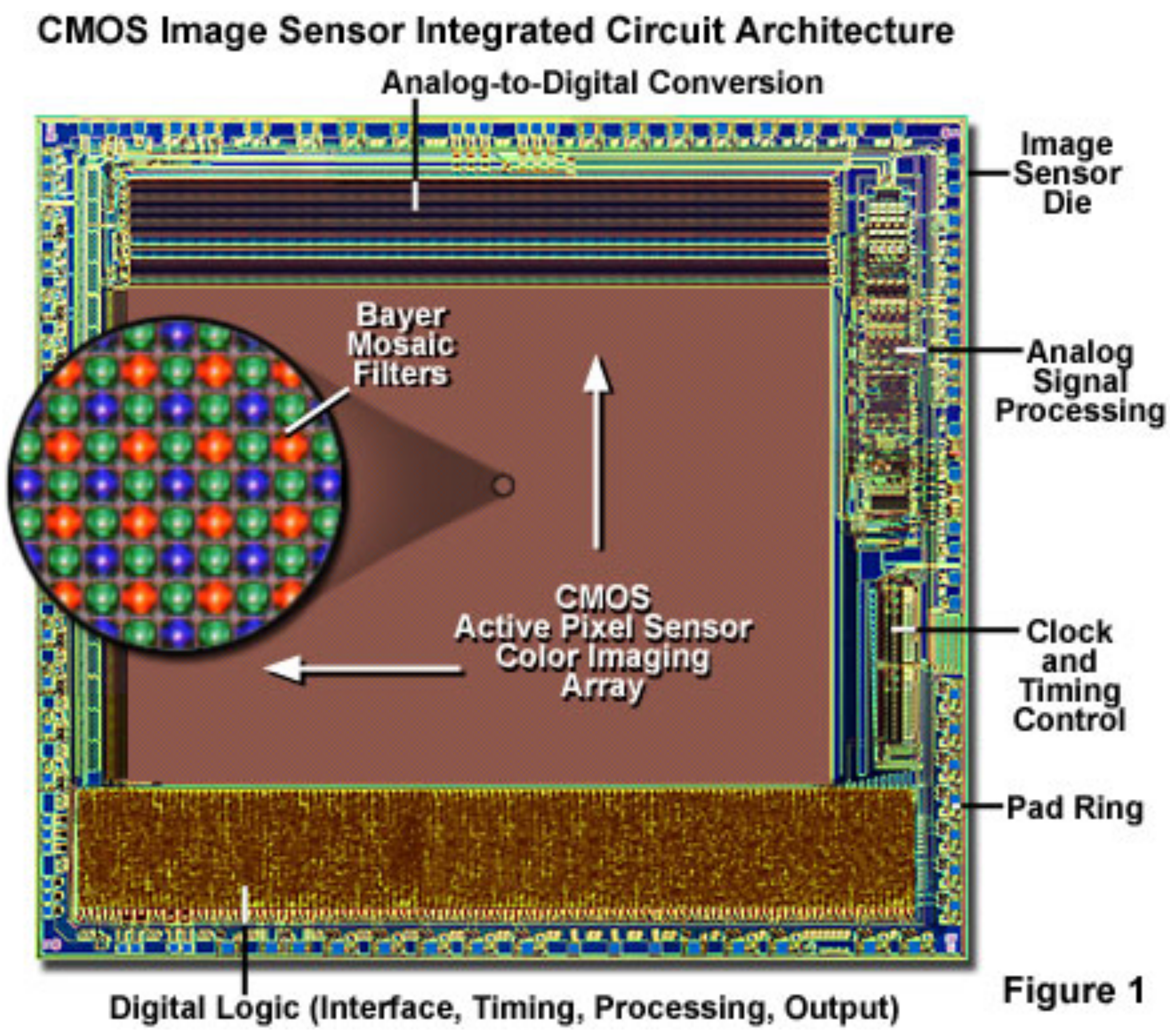
Rolling shutter



Global shutter

System on a chip

- The sensor is embedded in other circuitry
- Much of the circuitry controls the sensor read and reset
- There can be additional elements (such as masked pixels) that are used for image processing (noise)



http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

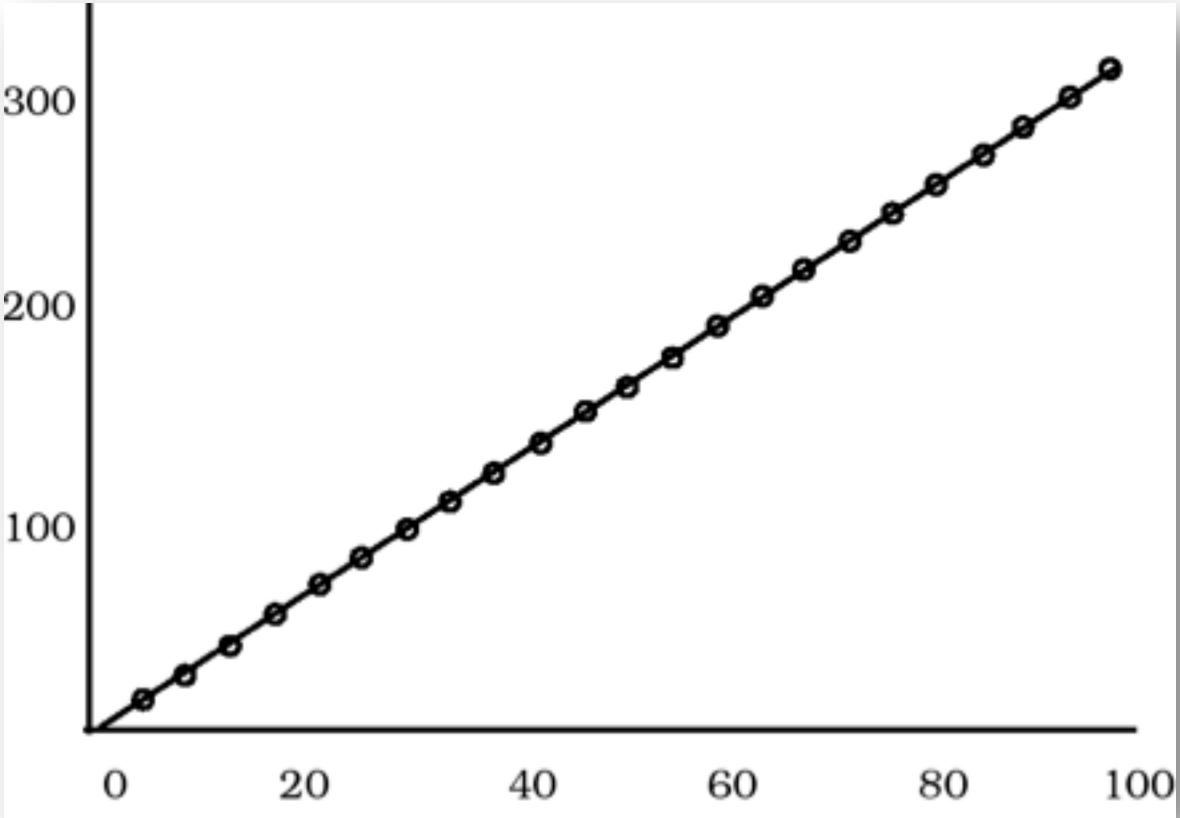
Camera equation – (No noise)

- Linear spectral responsivity
- Counting photons
- Photon noise

CCD and CMOS transfer functions

(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ...., Opt Eng., 25, 1987)

CCD and CMOS are Si absorptions



Electron absorptions

Photons at detector

Convert photons to electrons at the pixel

$$e = GT\int i(\lambda)r(\lambda)f(\lambda)d\lambda$$

G = geometric factors (pixel optical cross-section, m^2)

T = integration time (s)

i = spectral irradiance (photons/s/nm/m^2)

r = spectral responsivity of channel (electrons/photon)

f = filter and media transmissivities

e = electrons at the pixel

Check units: e = m^2 s $\int$ p/s/nm/m^2 e/p d(nm)

Camera equation (noise-free) as a matrix tableau

Electrons in each color channel

color filter transmissivity and other (e.g., lens)

photodiode quantum efficiency

Irradiance

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \cdots & f_R(\lambda)r(\lambda) & \cdots \\ \cdots & f_G(\lambda)r(\lambda) & \cdots \\ \cdots & f_B(\lambda)r(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} \\ i(\lambda) \\ \\ \end{pmatrix}$$

Wavelength samples

Camera equation (noise-free) as a matrix tableau

Electrons in each color channel

color filter transmissivity and other (e.g., lens)

photodiode quantum efficiency

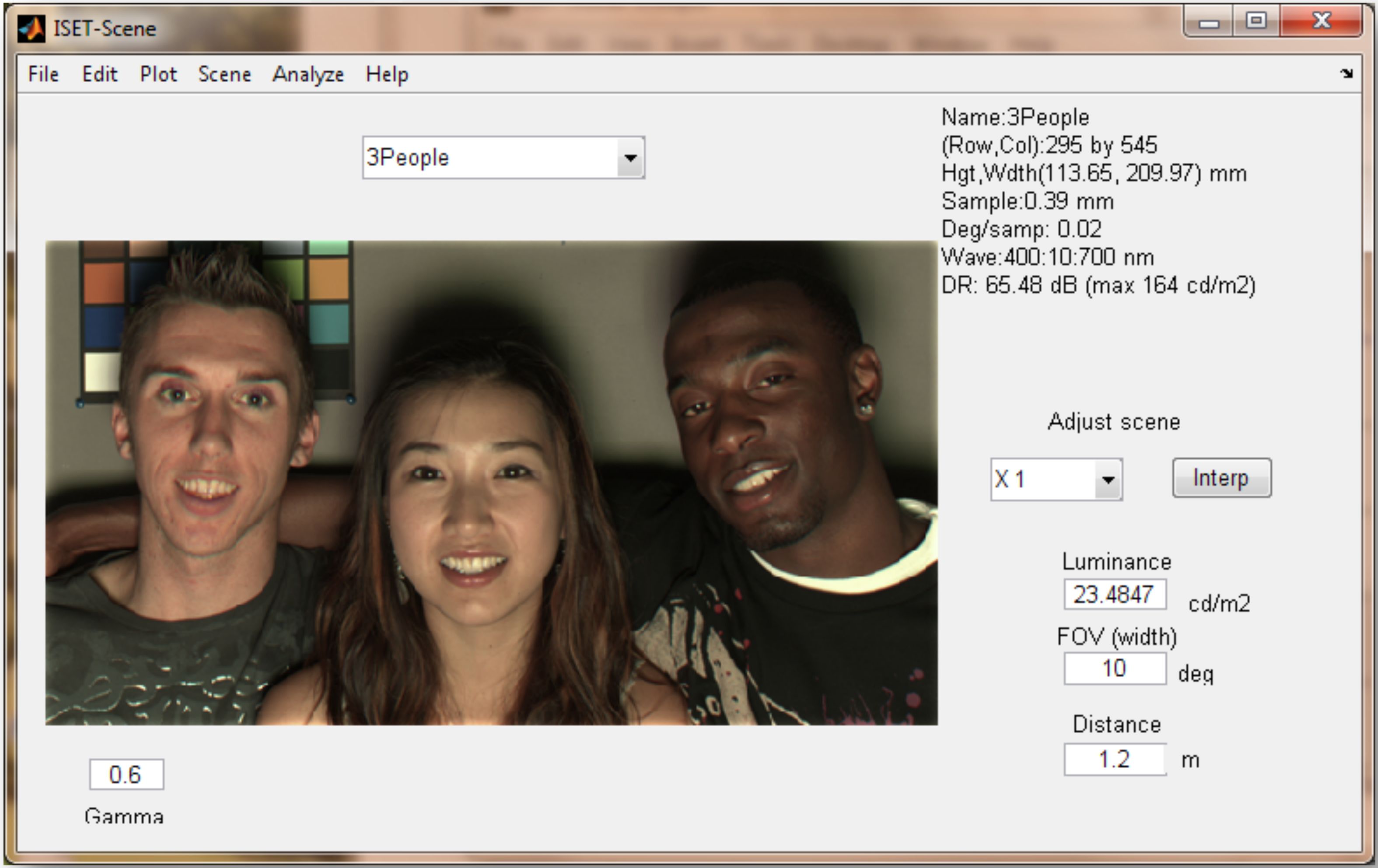
Irradiance

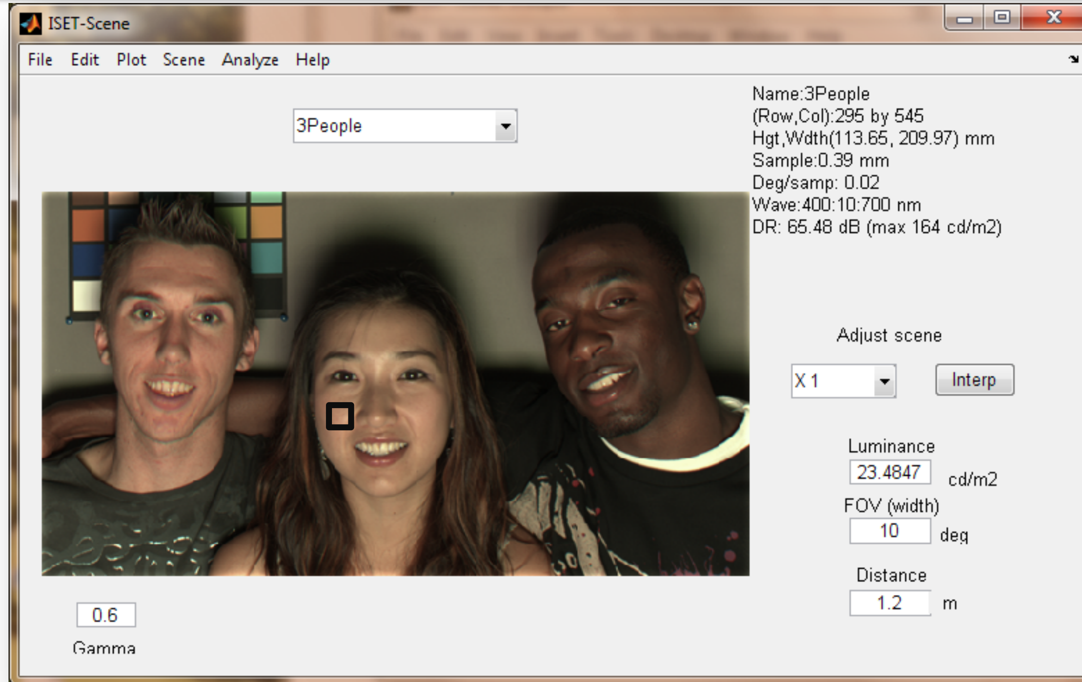
Illuminant

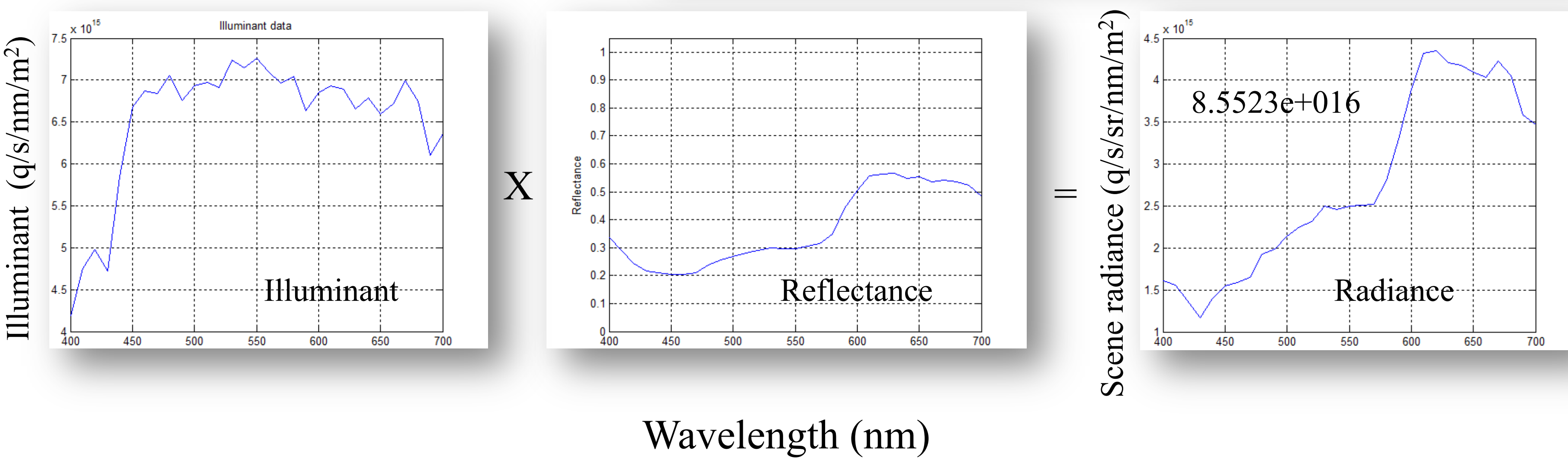
Surface

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \cdots & f_R(\lambda)r(\lambda) & \cdots \\ \cdots & f_G(\lambda)r(\lambda) & \cdots \\ \cdots & f_B(\lambda)r(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} \ddots & \cdots & 0 \\ \vdots & e(\lambda) & \vdots \\ 0 & \cdots & \ddots \end{pmatrix} \begin{pmatrix} \\ s(\lambda) \\ \\ \end{pmatrix}$$

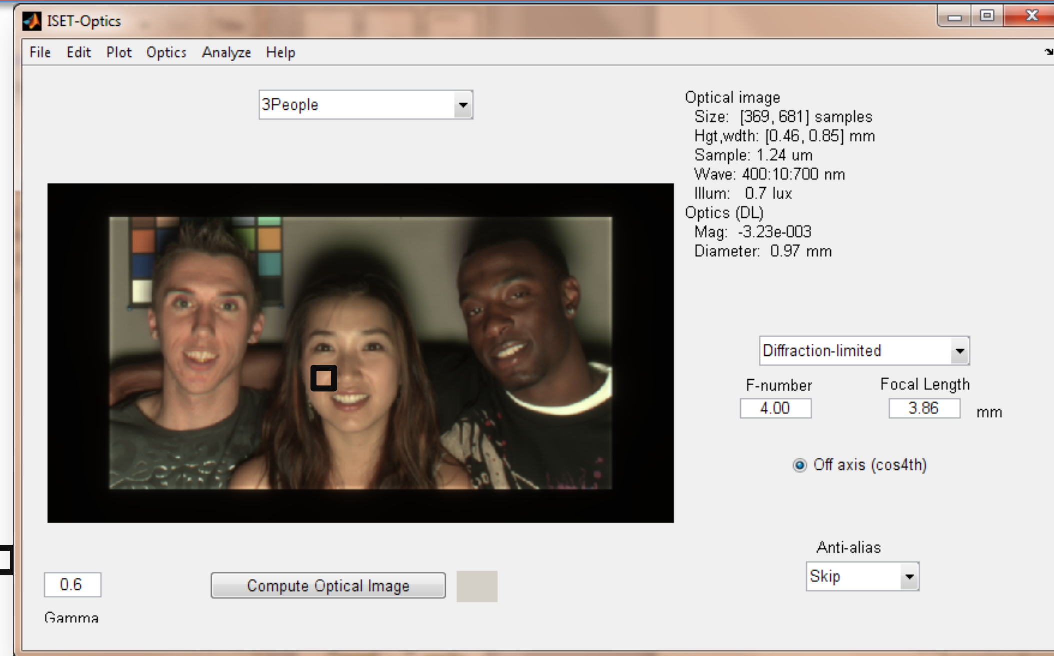
Follow the photons




ISET-Scene
File Edit Plot Scene Analyze Help
3People
Name:3People
(Row,Col):295 by 545
Hgt,Wdth(113.65, 209.97) mm
Sample:0.39 mm
Deg/samp: 0.02
Wave:400:10:700 nm
DR: 65.48 dB (max 164 cd/m2)
Adjust scene
X 1
Interp
Luminance
23.4847
cd/m2
FOV (width)
10
deg
Distance
1.2
m
0.6
Gamma


Illuminant data
Illuminant (q/s/nm/m^2)
Illuminant
X
Reflectance
Reflectance
=
Scene radiance (q/s/sr/nm/m^2)
8.5523e+016
Radiance
Wavelength (nm)

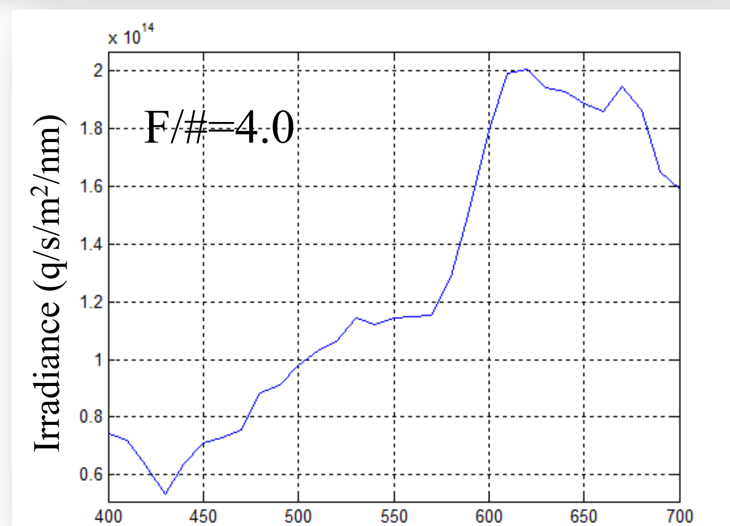
Optical image (irradiance)



If there is only loss due to the aperture, how many photons arrive at a pixel?

		Total per um² in 10 ms	CNR (dB)
F/#=2.0	1.5193e+016	152	21.8
F/#=4.0	3.9298e+015	39	16
F/#=8.0	9.7244e+014	10	10

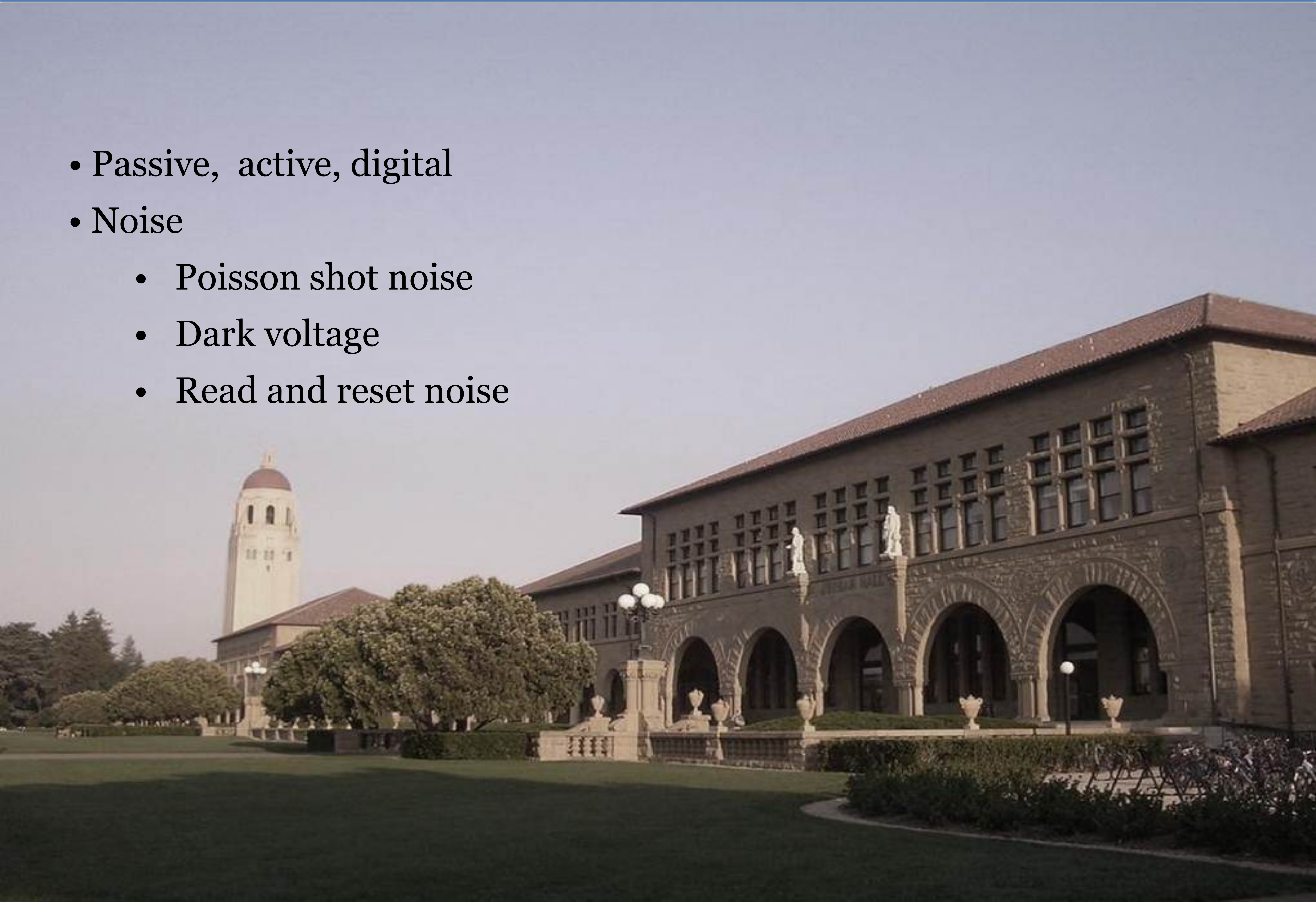
Thousand photon (30 dB) limit



Wavelength (nm)

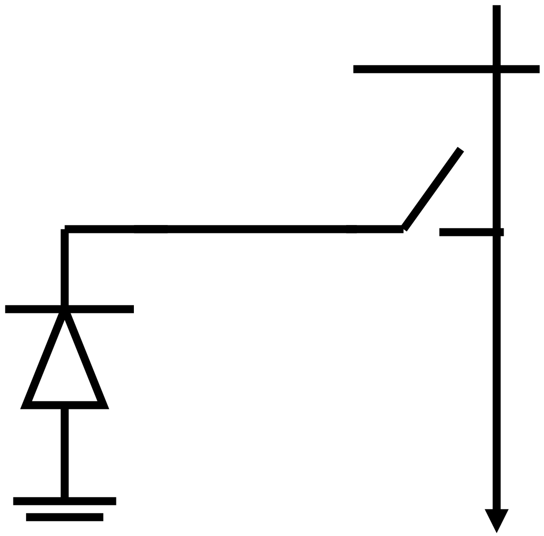
Pixels

- Passive, active, digital
- Noise
  - Poisson shot noise
  - Dark voltage
  - Read and reset noise



Hardware Development:
CMOS pixels: PPS, APS, DPS

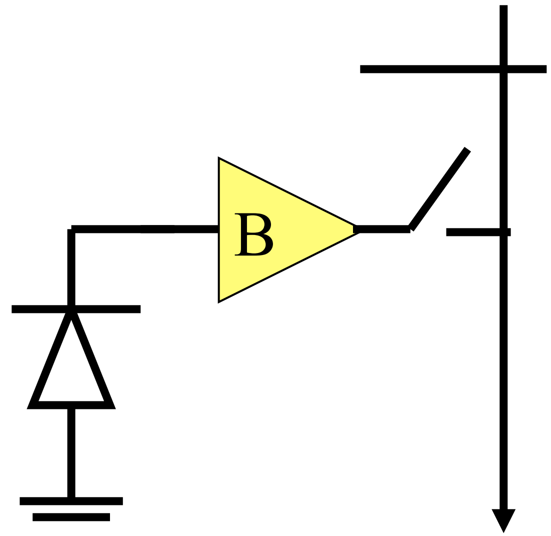
Passive pixel sensor (PPS)



Analog output

Complex, shared ADC

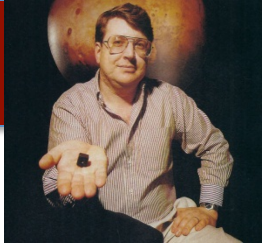
Active pixel sensor (APS)



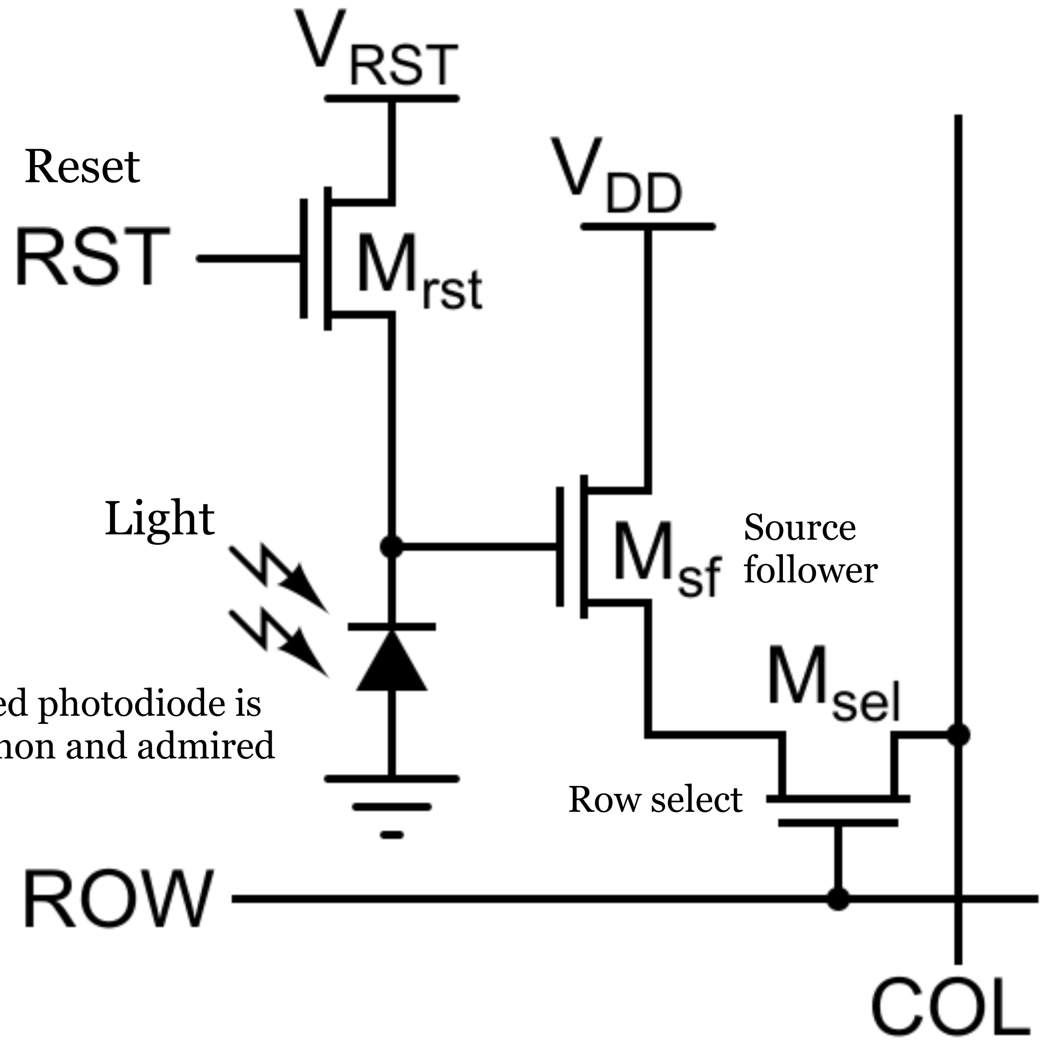
Analog output

Complex, shared ADC

CMOS pixel circuit (APS, 3T)



Eric Fossum



- Reset transistor clears the charge on the photodiode by coupling to power
- Light induces charge to accumulate at photodiode
- Source follower allows voltage to be observed without clearing the charge
- Columns tied together, one row selected at a time

Nakamura (Olympus) and Fossum (JPL/Photobit)

http://en.wikipedia.org/wiki/Active_pixel_sensor

A correction about the history

Hi Prof. Wandell,

I listened to your PSYCH 221 recording (lecture 6, 2013). I have a comment about who invented the idea of using in-pixel buffers in CMOS sensors.

Please take a look at this 1969 paper. Figure 1 and 8 show a photodiode equipped with a source follower and a reset transistor. Despite the cumbersome output mechanism, the idea of buffering each photodiode is evident.

Prof. Fossum patented this idea along with a modern readout mechanism. A heroic contribution, but the idea of buffering each pixel predates that.

Thanks,
XXX (heroic and smart young student)

Pixel-level circuit noise

t_cameraNoise.m
hwSensorFundamentals.m

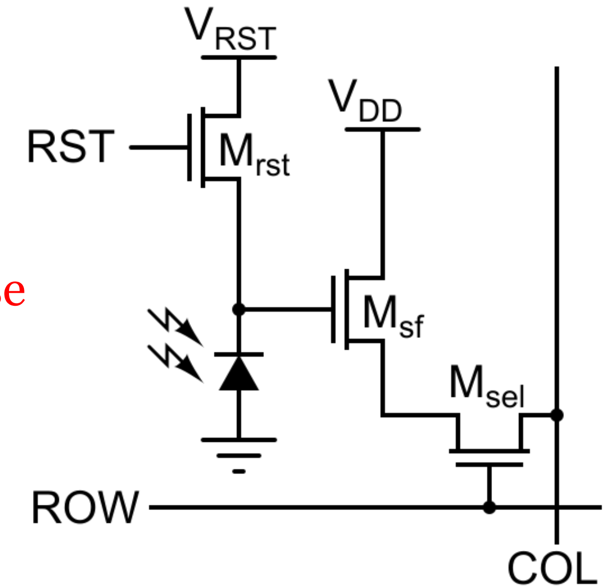
- Electrons (Poisson random variable) are converted to volts by circuit properties (conversion gain)

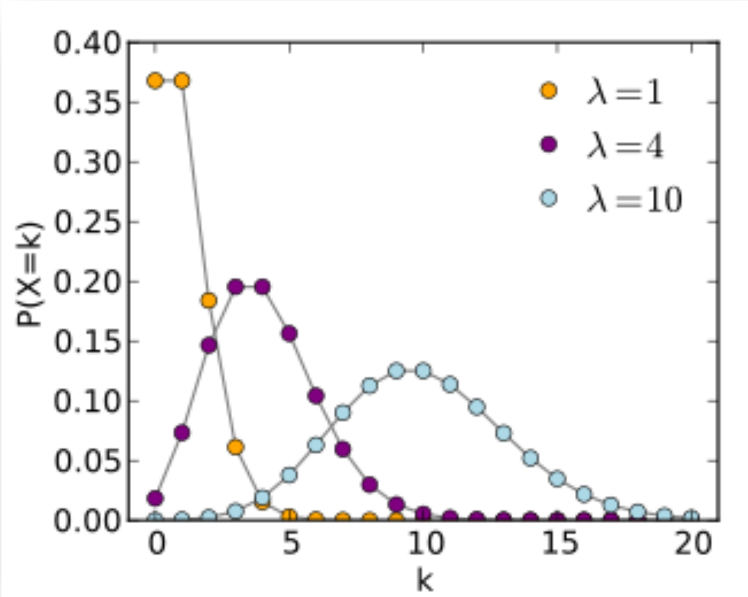
$$v_0 = c\tilde{e}$$

Poisson distribution

$$f(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!},$$

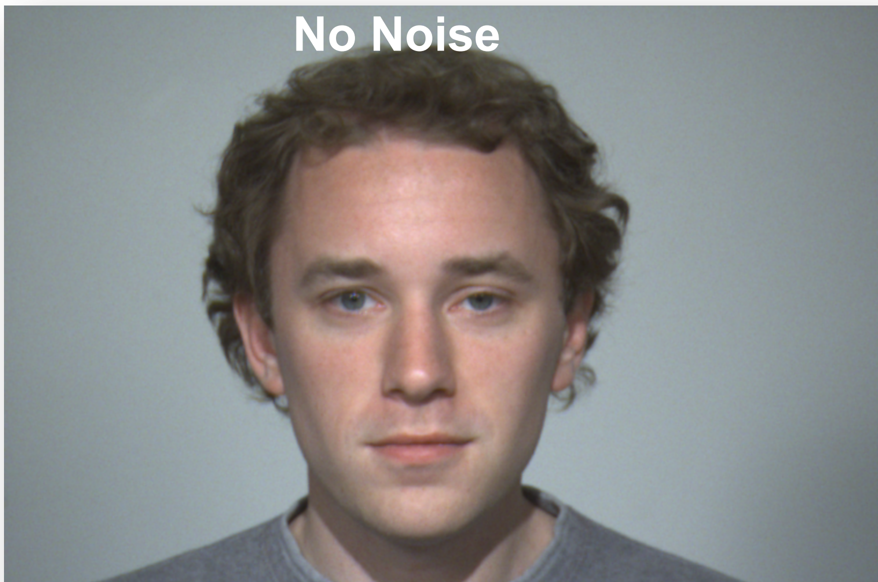
Shot noise

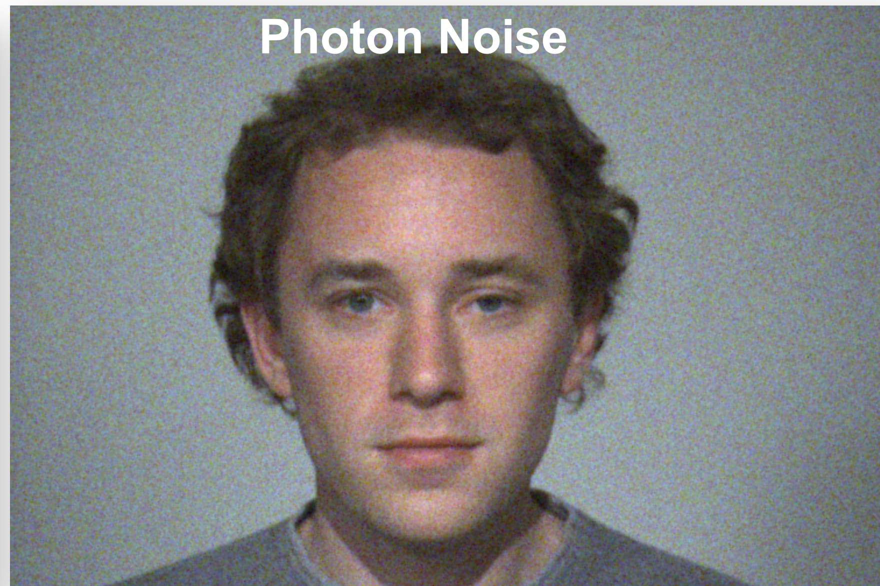




Photon noise (shot noise)

No spatial structure
Averaged away by repeated measures
Visible at an SNR of 30 dB (1000 photons, Xiao et al.)





Pixel noise

- Electrons (Poisson random variable) are converted to volts by circuit properties (conversion gain)

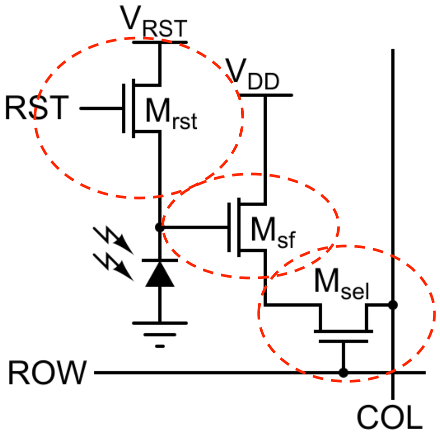
$$v_0 = c\tilde{e}$$

- Circuit imperfections introduce dark voltage that grows over time (T*V/sec)

$$v_1 = v_0 + T\tilde{d}$$

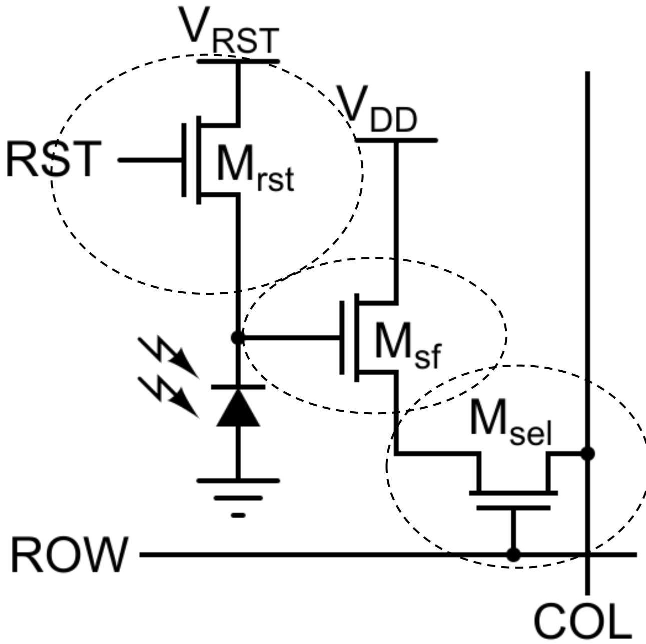
- The acts of reading and resetting the voltage are noisy (and can be grouped)

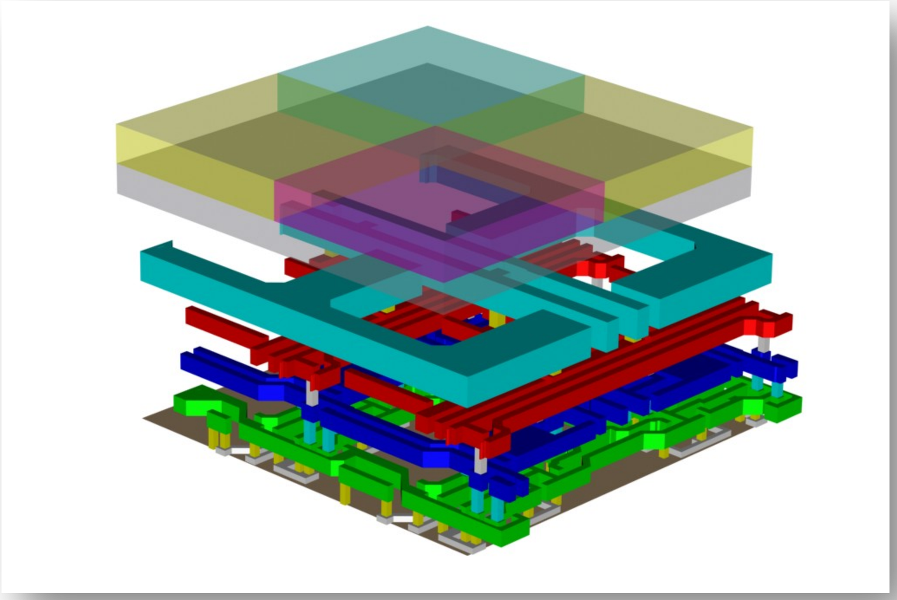
$$v_2 = v_1 + \tilde{r}_0 + \tilde{r}_1$$



Dark noise

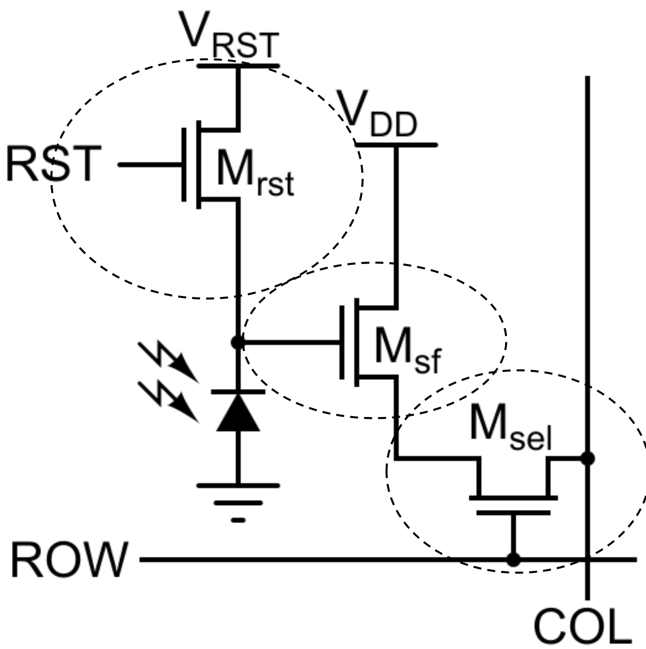
Thermally generated electrons are indistinguishable from photo-generated electrons . They constitute a noise source known as 'Dark Current.' High end CCDs are designed (e.g., by cooling or in CMOS special circuitry) to reduce the amount of dark current.

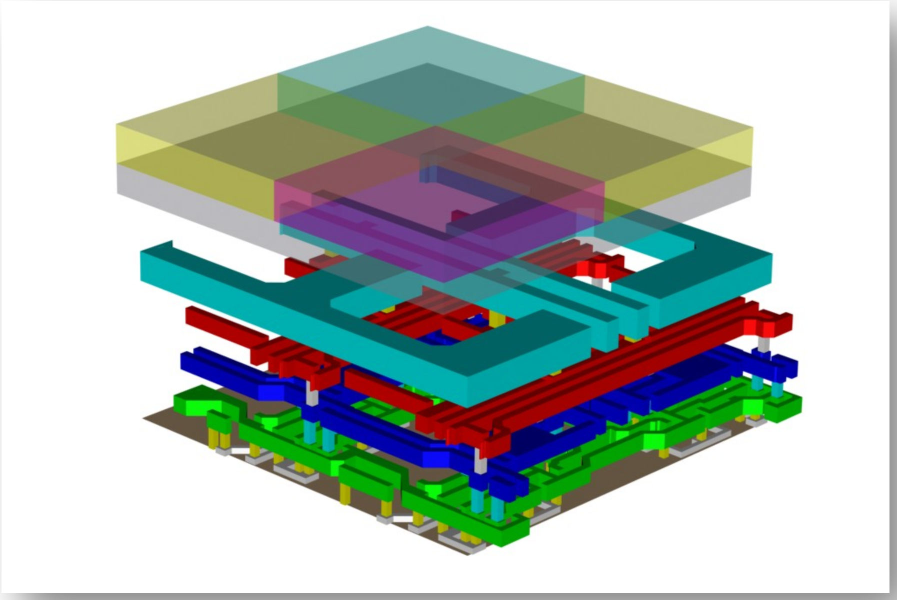




Read and reset noise

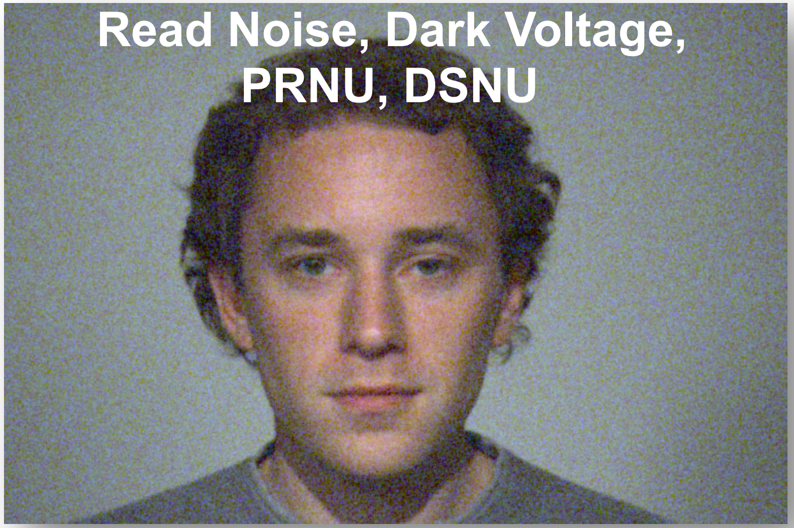
The act of reading data from a pixel and resetting the pixel level to an initialized state involve imperfect circuit events. These imperfections are sensor read and sensor reset noise. They can be separately identified, but in simulation it is convenient to group them.





Photon, read, reset, dark, prnu, dsnu

Adds to photon noise – so 1000 photons not enough for noise-free

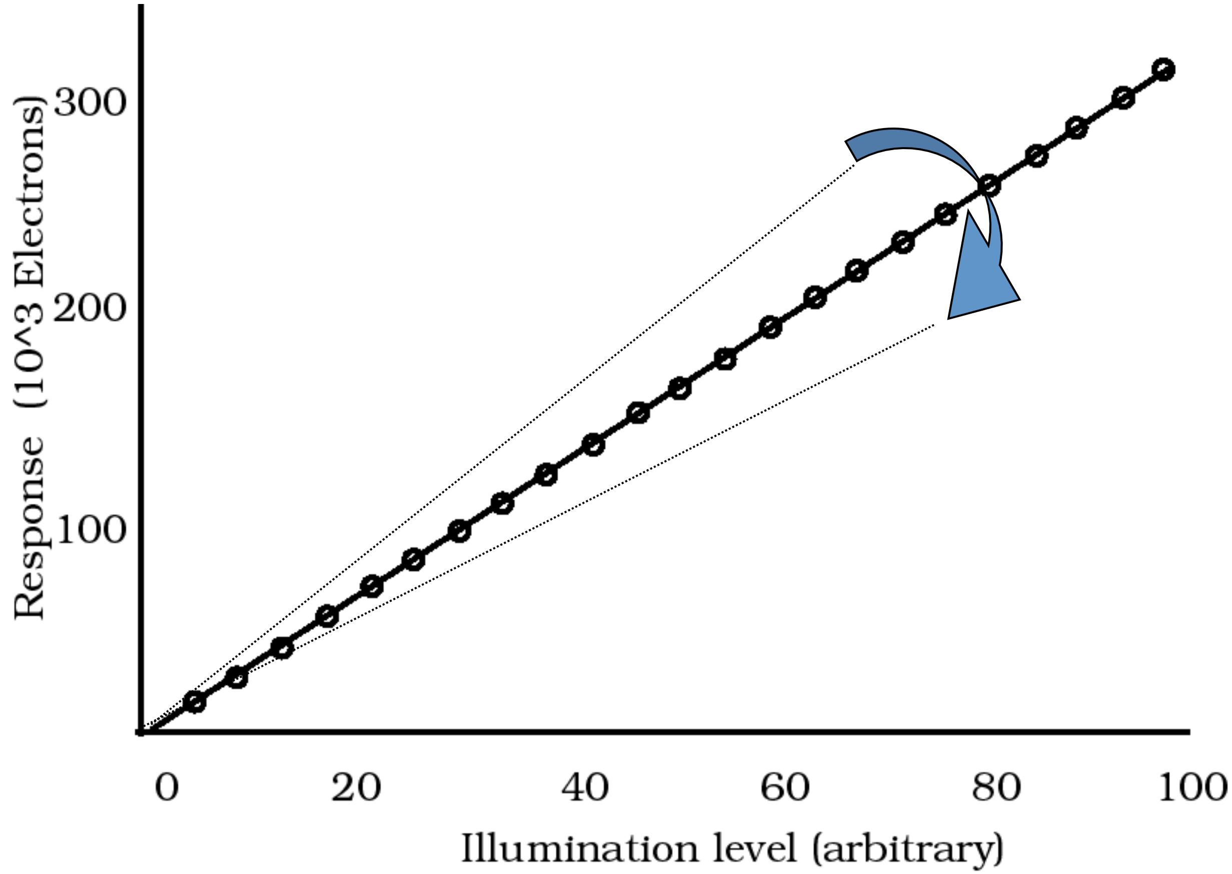


Sensor imperfections: PRNU

Photoresponse non-uniformity (**PRNU**)
Varying surface area or media transparency

Across the imager surface there are two principal imperfections:

DSNU and PRNU



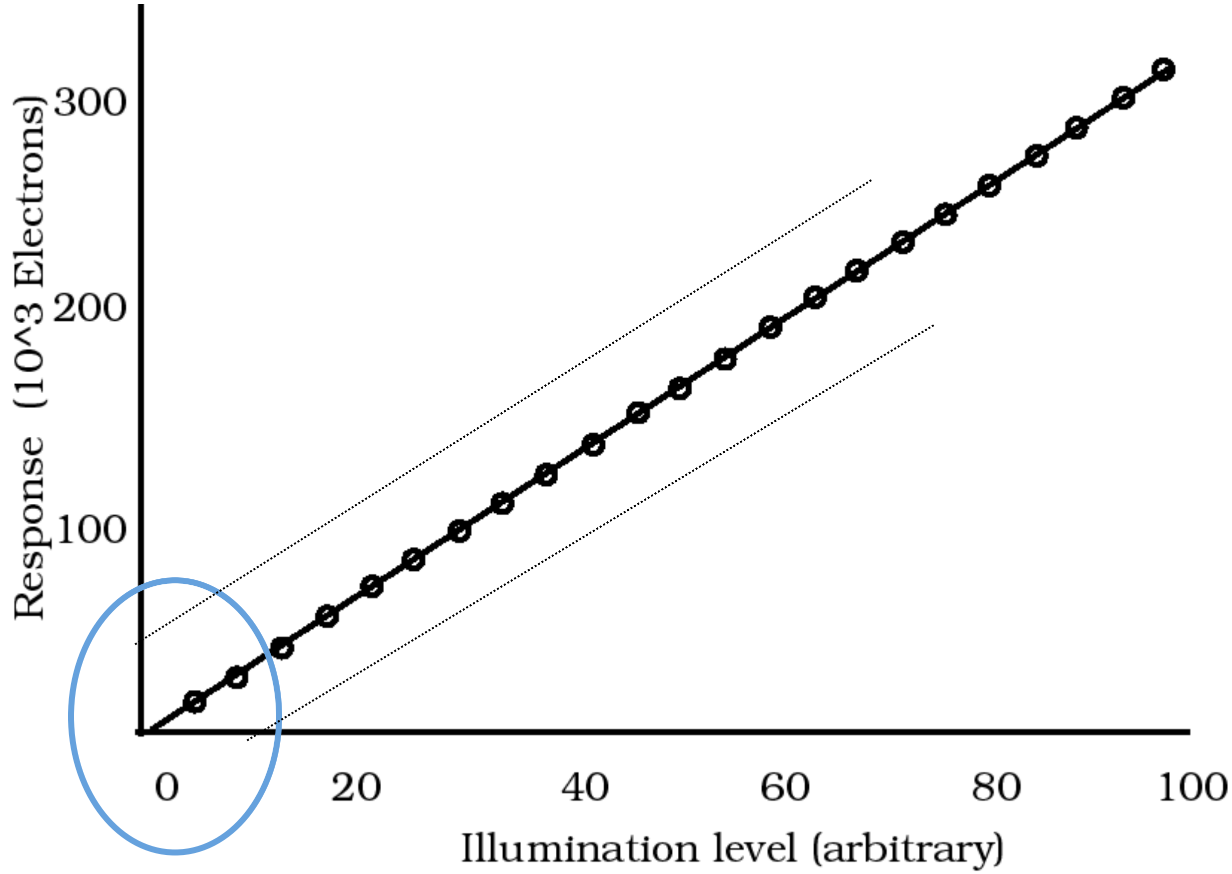
(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ..., Opt Eng., 25, 1987)

Sensor imperfections: DSNU

Photoresponse non-uniformity (**PRNU**)
Varying surface area or media transparency

Across the imager surface there are two principal imperfections:

DSNU and PRNU



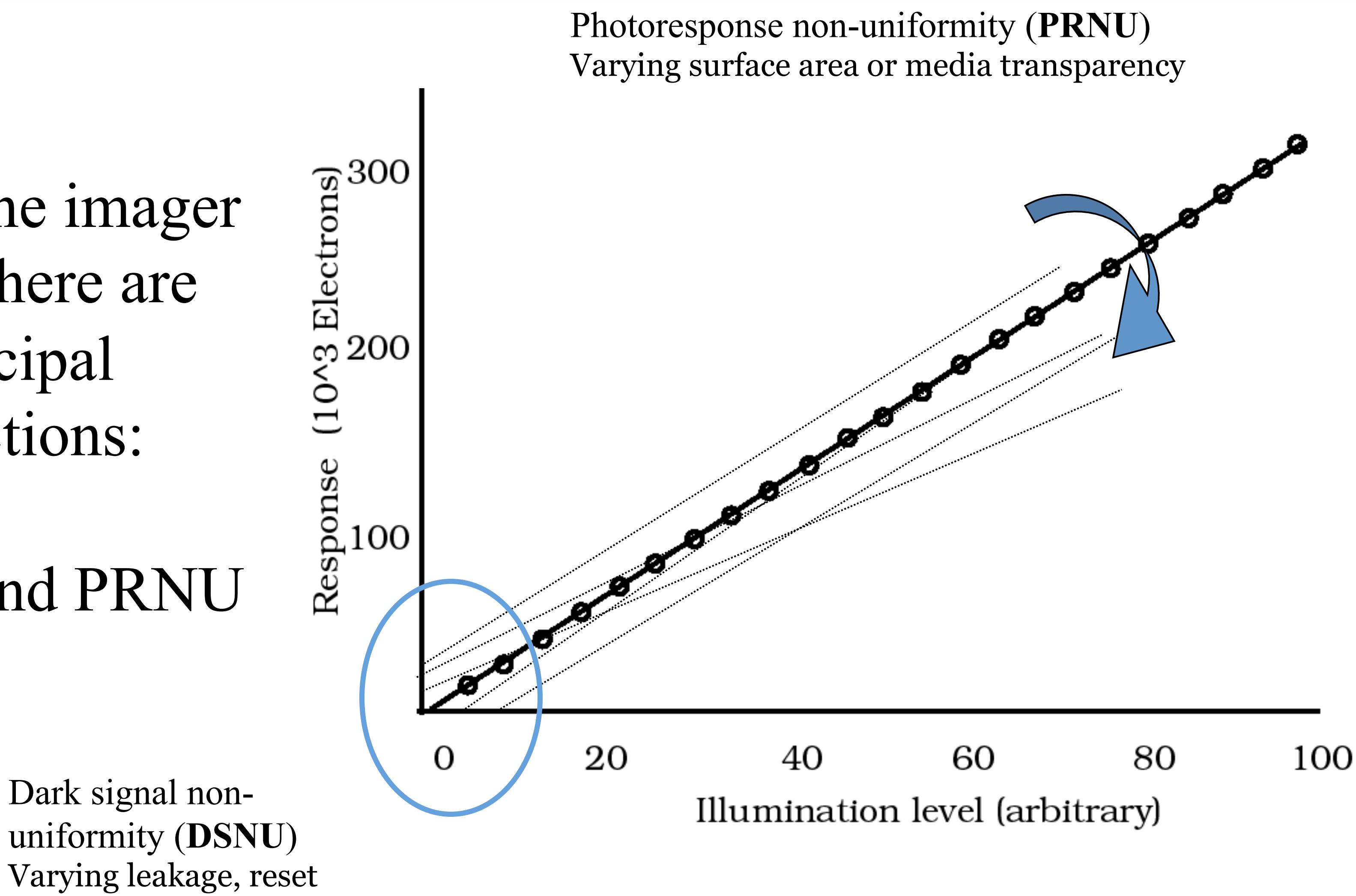
Dark signal non-uniformity (**DSNU**)
Varying leakage, reset

(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ..., Opt Eng., 25, 1987)

Combined PRNU and DSNU

Across the imager surface there are two principal imperfections:

DSNU and PRNU



(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ..., Opt Eng., 25, 1987)

Sensor imperfections

Programmable gain/offset

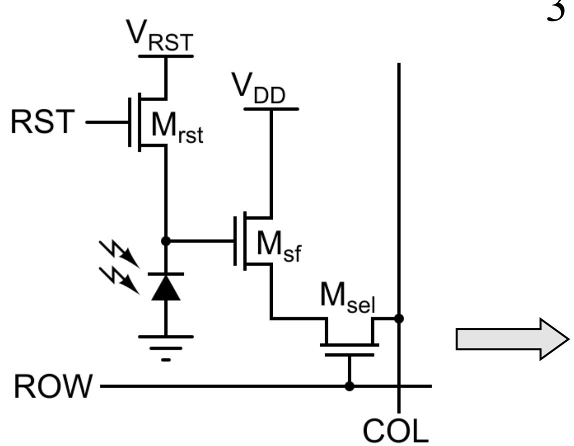
- Electrons (Poisson random variable) are converted to volts by circuit properties (conversion gain)
- Circuit imperfections introduce dark voltage (d) that grows over time (T*V/sec)
- The acts of reading and resetting the voltage are noisy (and can be grouped)
- Variations across the sensor in analog offset and gain; offset can be due to leakage and thus time-dependent

$$v_0 = c\tilde{e}$$

$$v_1 = v_0 + T\tilde{d}$$

$$v_2 = v_1 + \tilde{r}_0 + \tilde{r}_1$$

$$v_3 = \tilde{a}(v_2 + T\tilde{o})$$



Programmable gain amplifier and offset

Terminology: Temporal and fixed noise

- **Temporal noise:** Some noise terms differ across repeated reads of the pixel (e.g., read noise, reset noise, dark noise, photon noise); these can be averaged away
- **Fixed pattern:** Some noise terms are simply variations of the device properties across the array; these are fixed over time (conversion gain, DSNU, PRNU, Column gain) and are not averaged away

$$v_0 = c\tilde{e}$$

$$v_1 = v_0 + T\tilde{d}$$

$$v_2 = v_1 + \tilde{r}_0 + \tilde{r}_1$$

$$v_3 = \tilde{a}(v_2 + T\tilde{o})$$

Phenomonological model

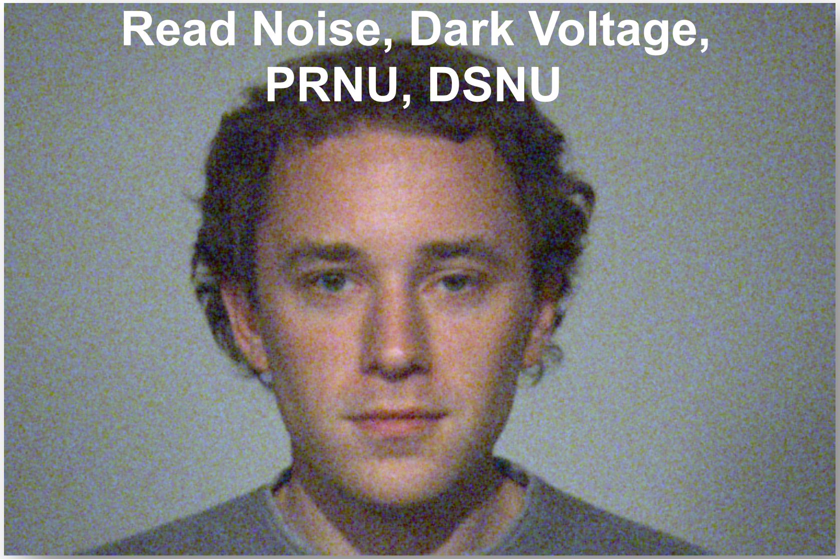
$$v = \tilde{Z}(\tilde{e} + \tilde{X} + T\tilde{Y})$$

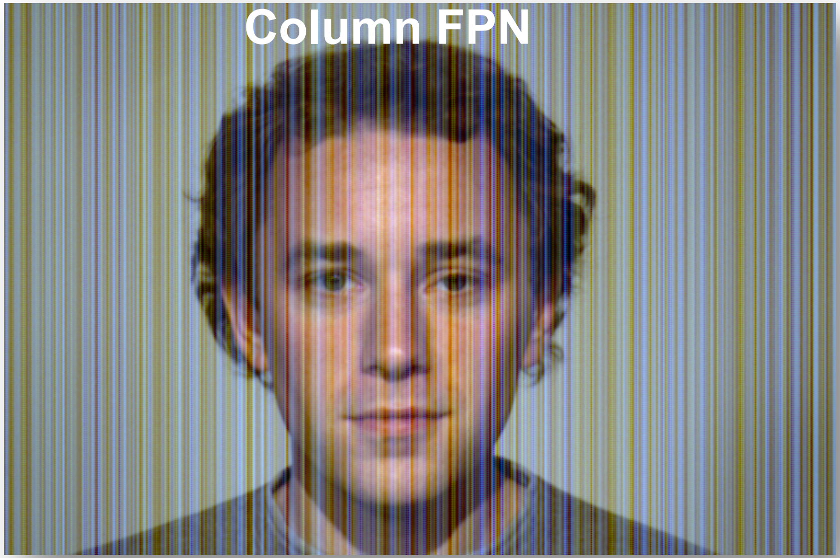
Knowledge of the noise mechanisms is important for accurate simulation because the mechanisms have different temporal and spatial characteristics; in this form the equation does not make this important issue clear.

Column amplifier variation:

A special place in imaging hell

Fixed column noise

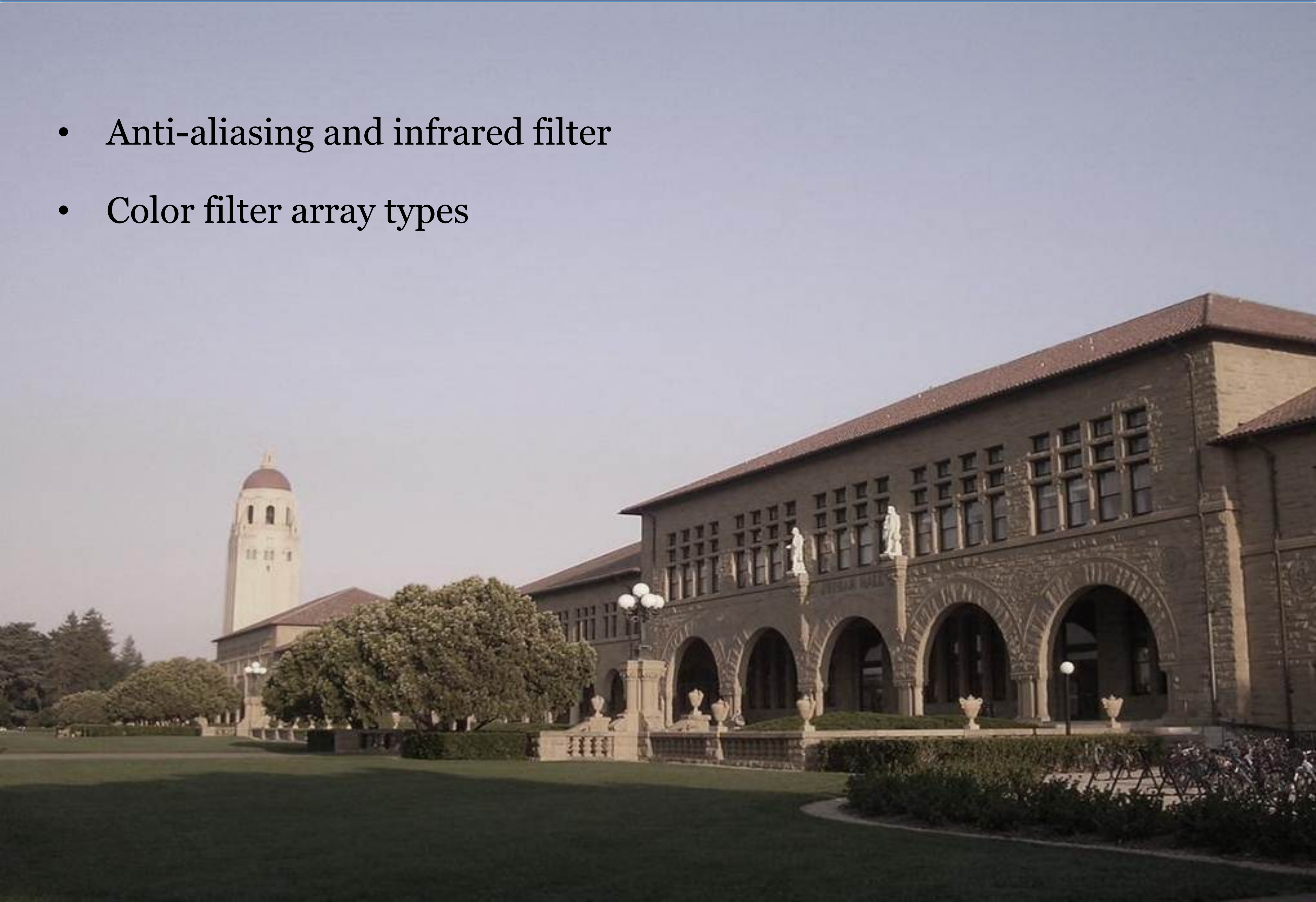




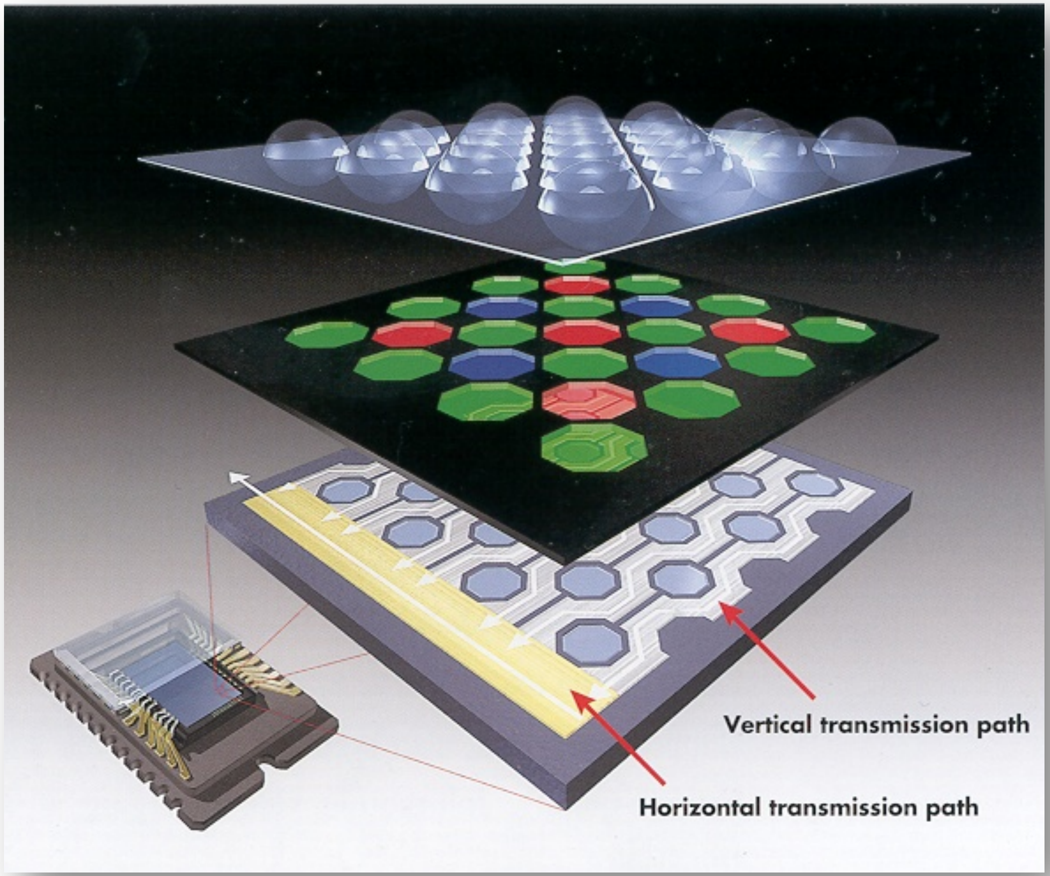
In some systems, an entire column shares an amplifier. In this case, variations between the column amplifiers produce unwanted variations (as above). Consistent column variations are very noticeable and thus must be eliminated.

Imager components

- Anti-aliasing and infrared filter
- Color filter array types



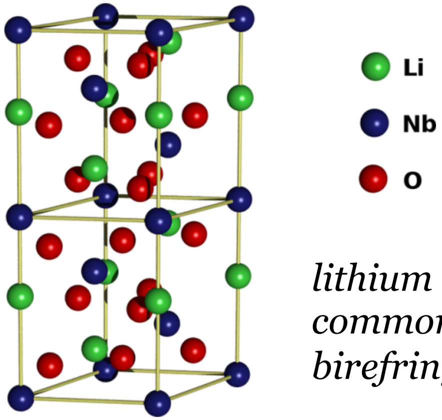
Sensor Properties: Overview



- Pixel Properties
  - Pixel height, width
  - Fill factor
  - Dark current
  - Read noise
  - Conversion gain
  - Voltage swing
- Array Properties
  - DSNU and PRNU
  - Pixel spacing
  - Number of pixels
- Color Properties
  - Color filter, transmittance
  - Photodetector QE
  - Infrared filter transmittance
  - Color filter array pattern
- Circuit Properties
  - Analog-to-digital conversion
  - Correlated Double Sampling
  - Column Amplifiers (Column FPN)
- Pixel Optics
  - Microlens array

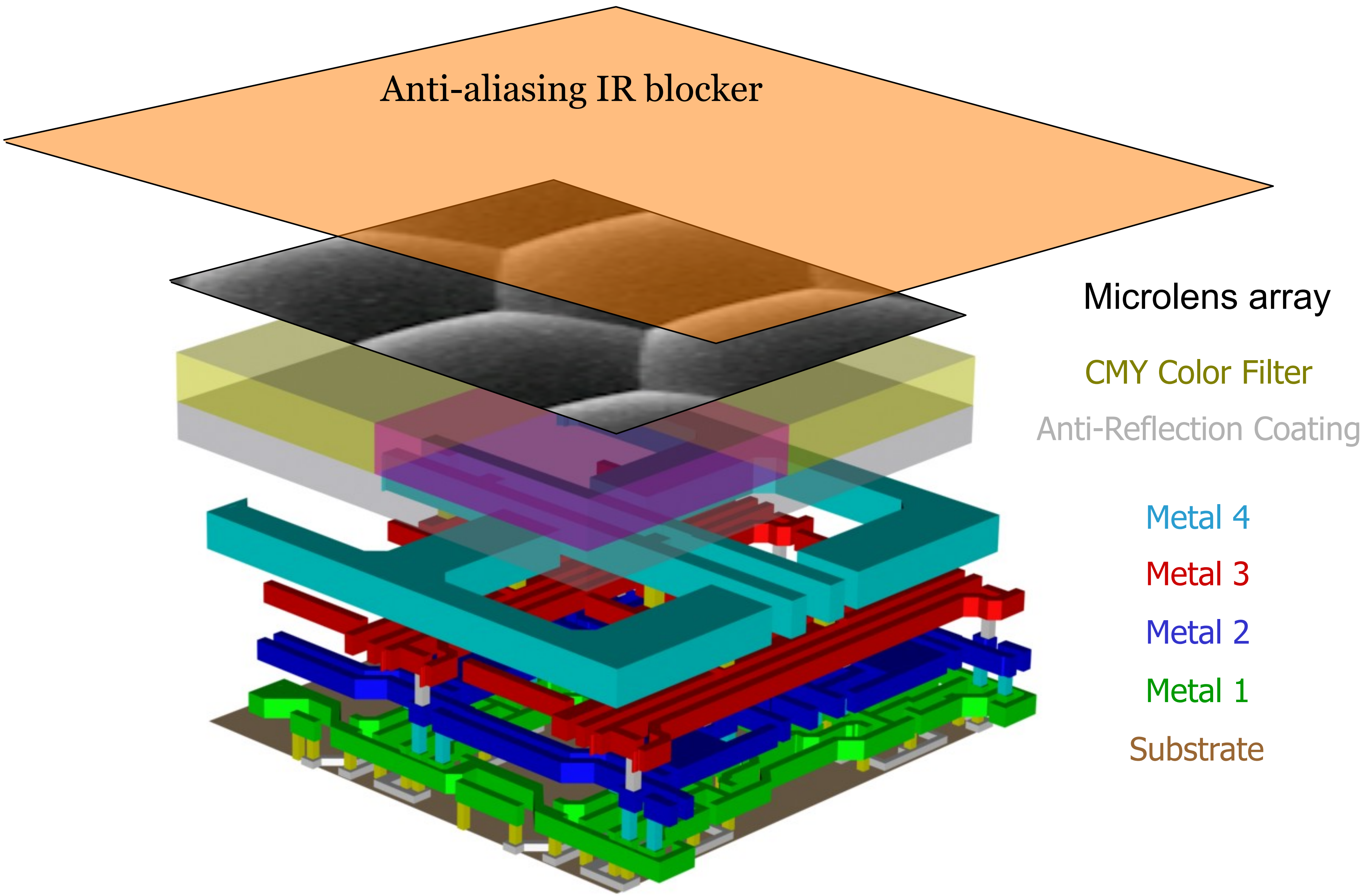
Anti-aliasing and infrared blocking filter

- Placed on the sensor surface
- Blocks IR – to discuss
- Blurs to prevent sampling artifacts –to discuss
- Two types – birefringent and diffusing



lithium niobate is a commonly used birefringent material

The microlens array

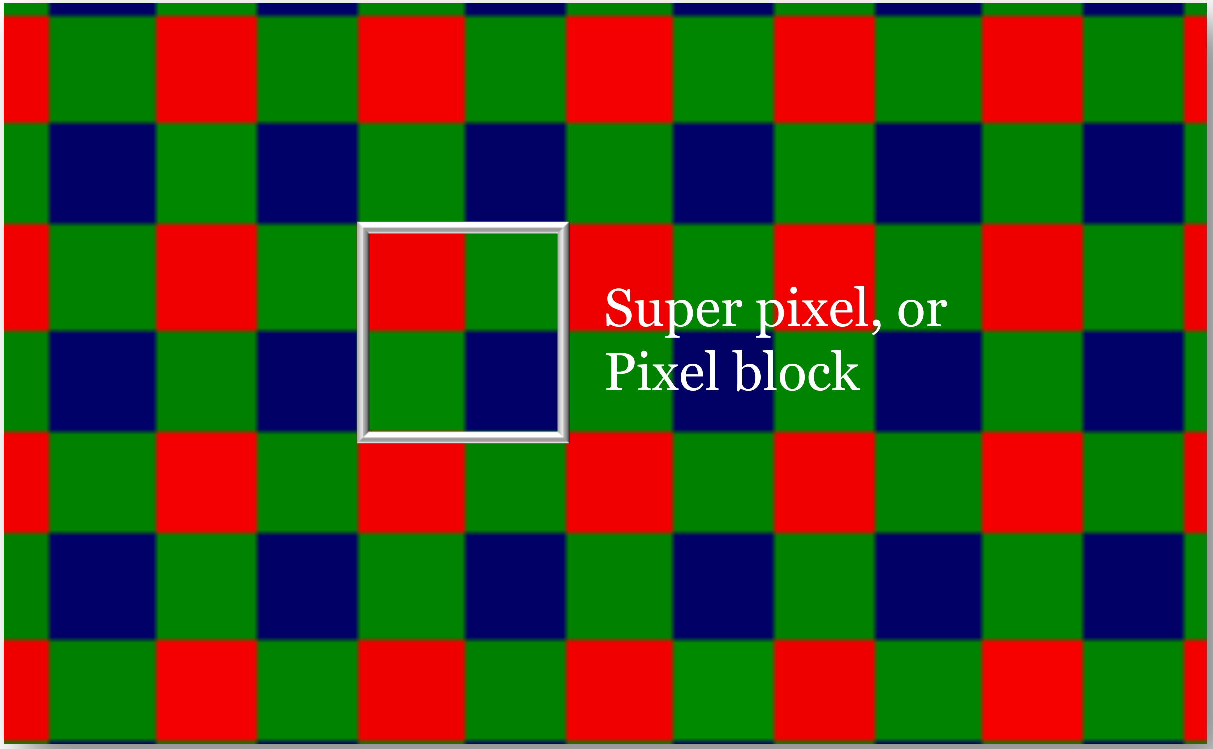


The anti-aliasing filter and the CFA

The 4 pixels in a Bayer pixel block are combined to produce the RGB values displayed in a single pixel in the display

Thus, we want these 4 pixels to see the same point in the visual field

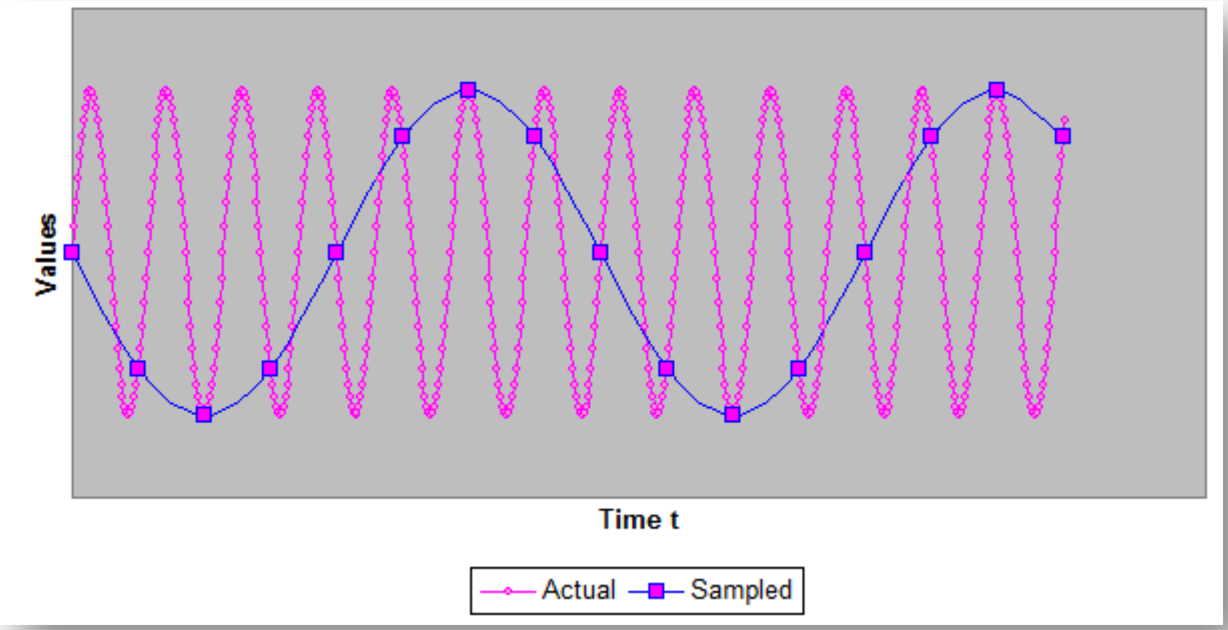
To achieve this, the image must not vary over space faster than the size of the pixel block



Anti-aliasing filter effect

t_cameraAntiAliasing.m

Classically, aliasing refers to the fact that when we under sample a space-varying image, the measured values appear to be at a different frequency from the original signal



In this case, the true signal is rapidly varying; the samples are evenly spaced by too slow to pick up the rapid variation

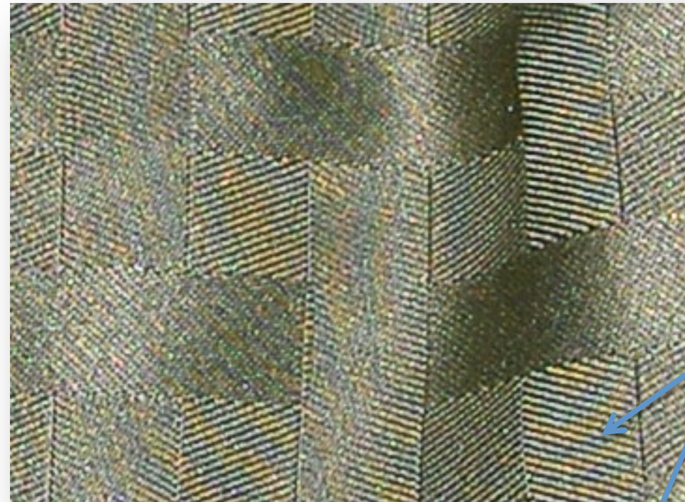
The sampled signal appears to be low, rather than high, frequency

Anti-aliasing effects

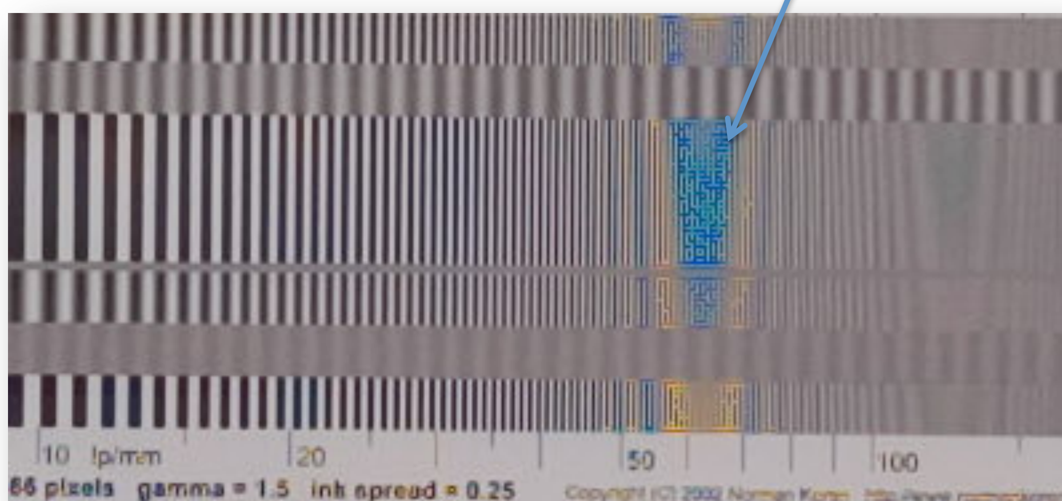
s_sensorAliasing.m

The consequence of this under-sampling in imaging with color sensors is a combination of aliasing and unwanted chromatic artifacts

The chromatic artifacts arise because we need to account not only for the sampling rate but for the fact that we are sampling with pixels that have different color sensitivities



Chromatic artifacts



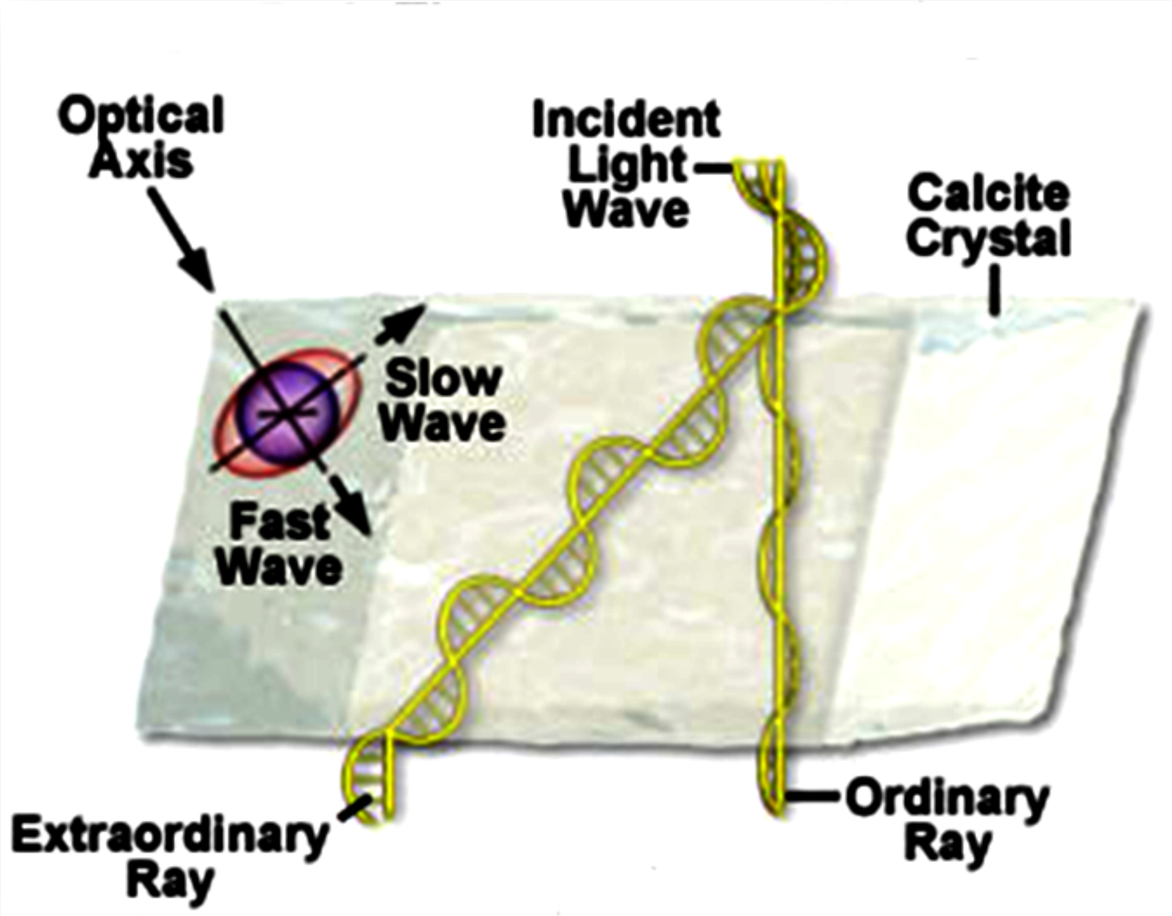
Anti-aliasing filter effect

No filter
(Sharp, but aliased)

With filter
(Blurry, but less aliasing)

Anti-aliasing with birefringence filters

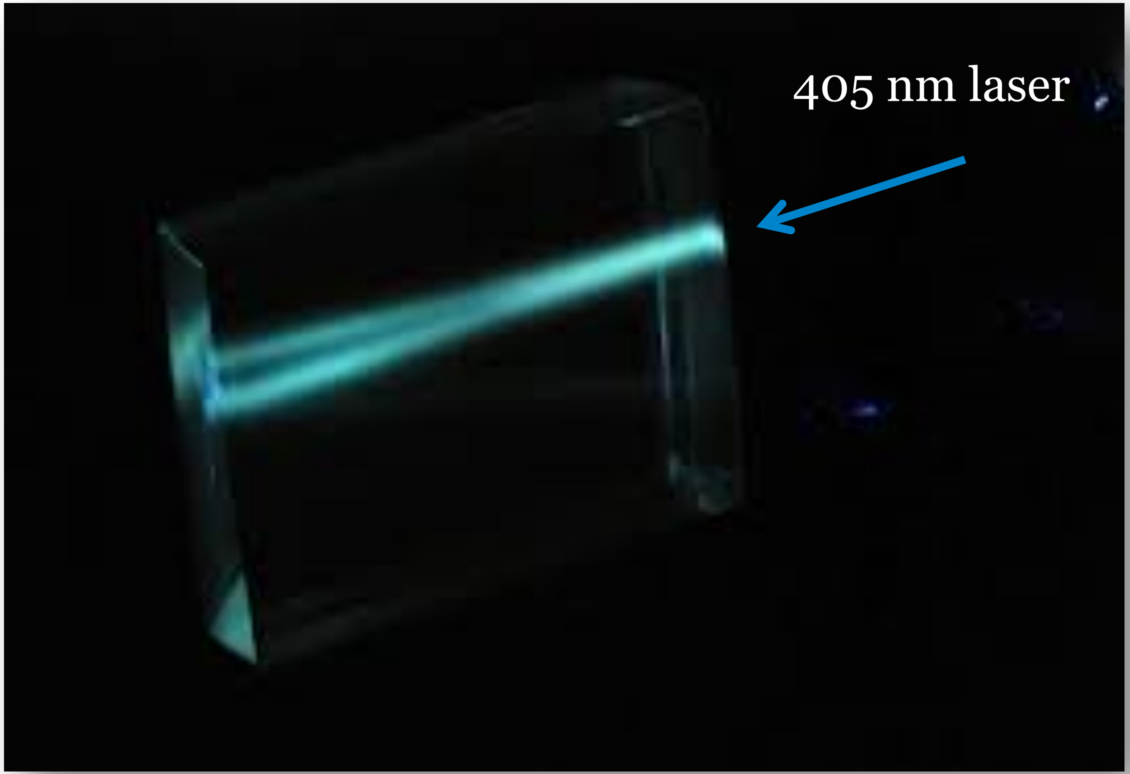
Light through a calcite crystal
Divided into an ordinary and extraordinary ray
Displaced in position
Different polarizations



Birefringence

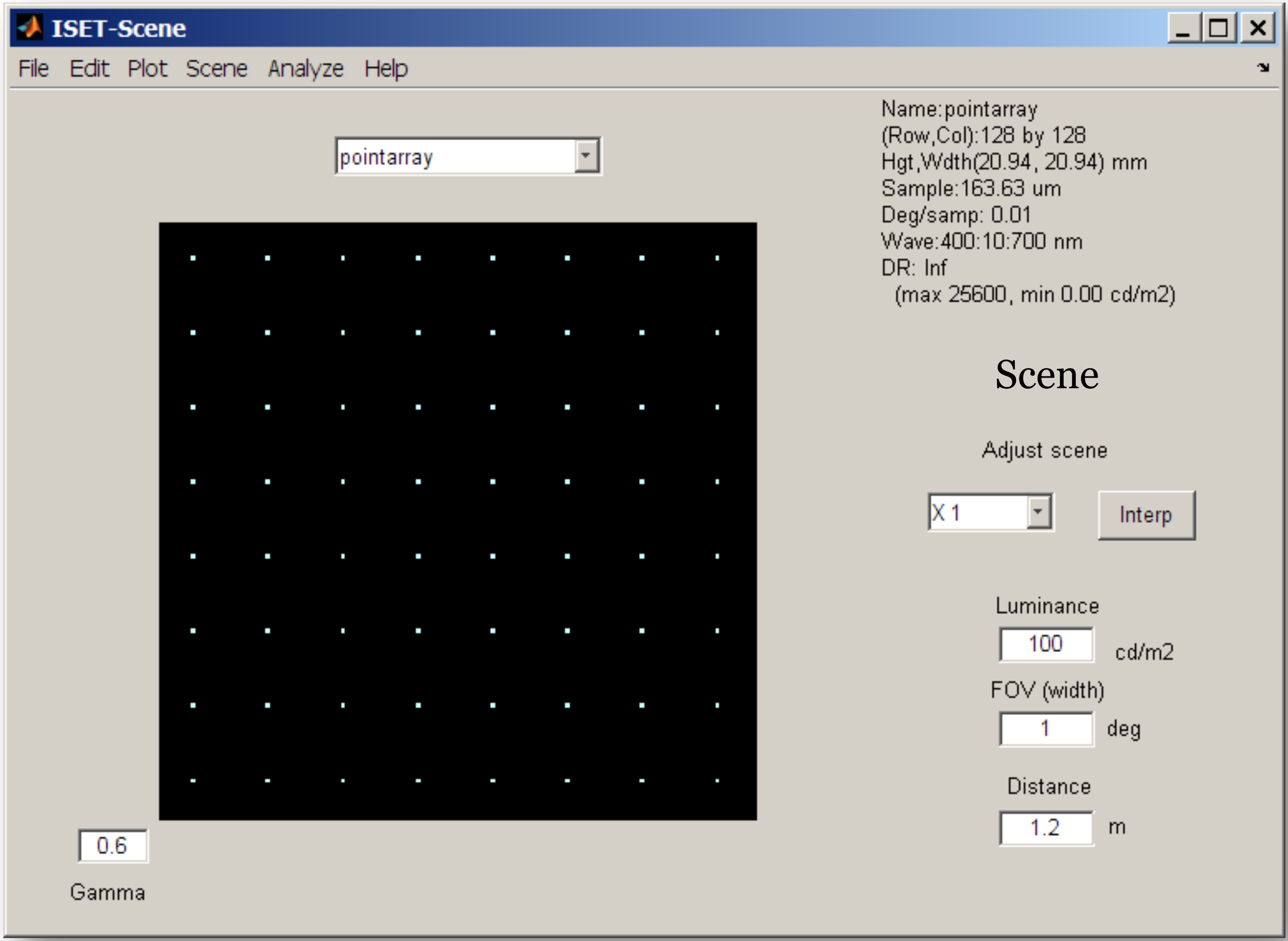
Ordinary and extraordinary ray positions can be seen easily

2mm block of calcite



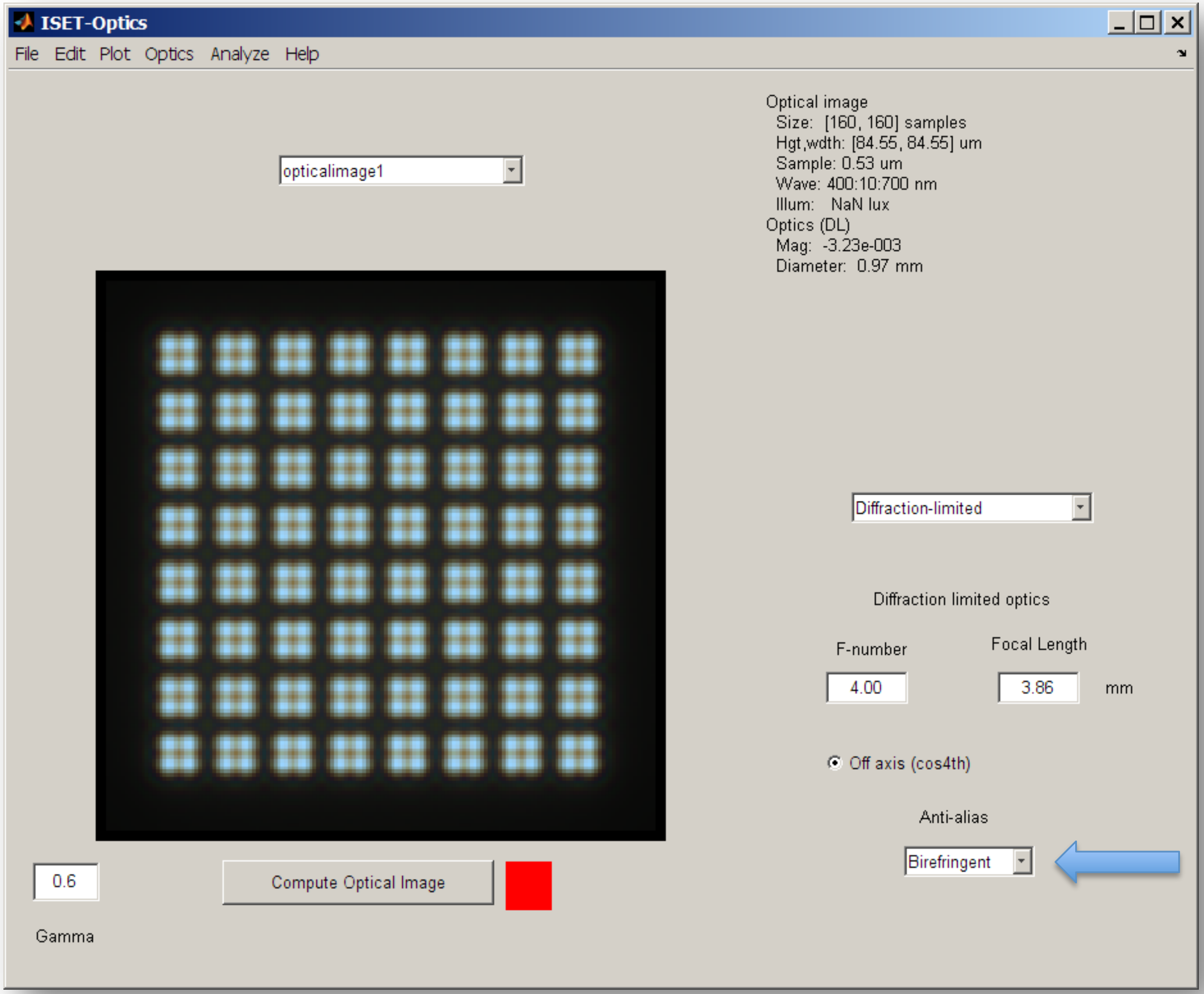
Modeling the anti-aliasing filters

Scene of point array



Modeling the anti-aliasing filter:

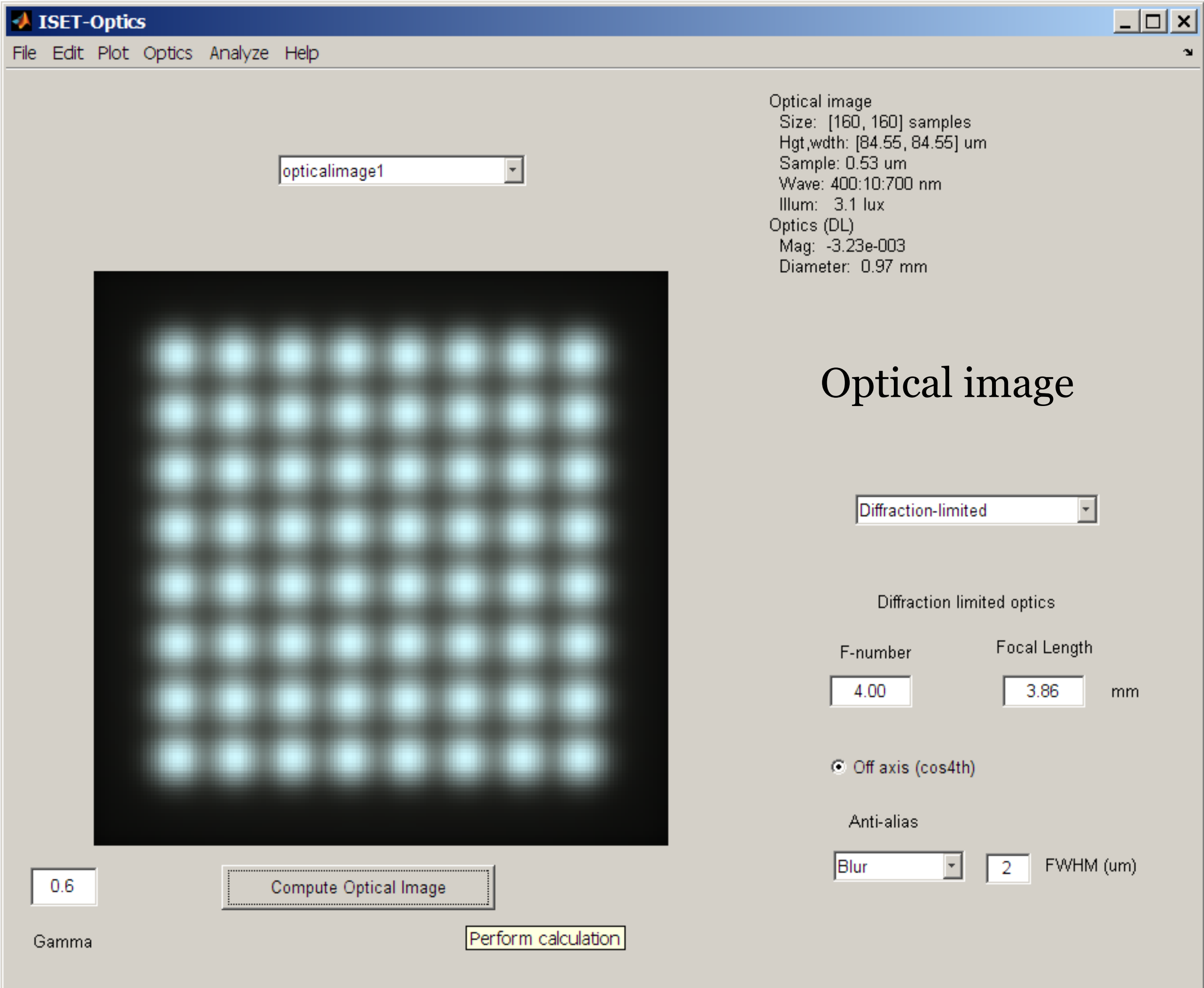
Optical image with birefringent filter



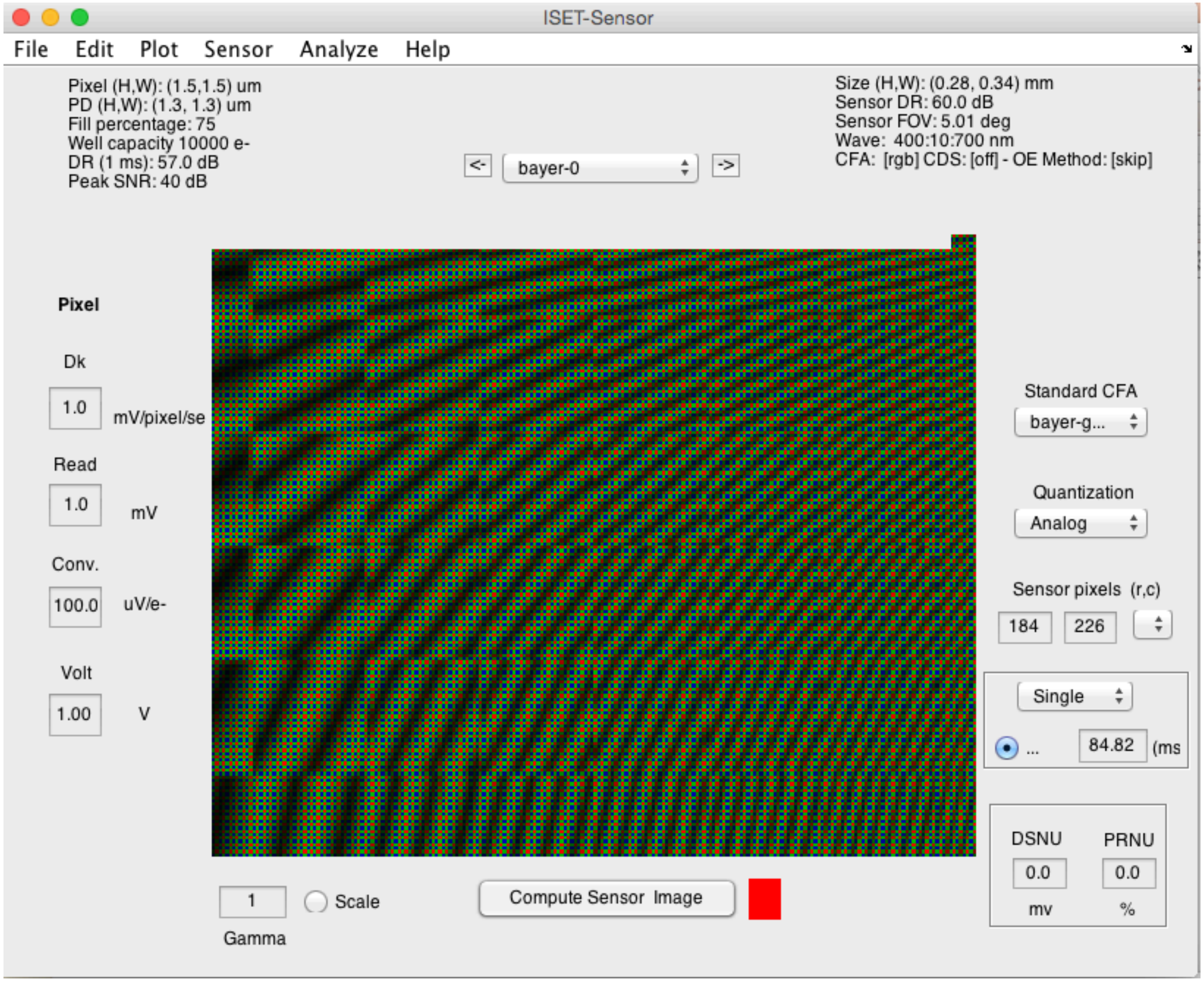
Two filter layers, rotated, produce four spots

Modeling the anti-aliasing filter:

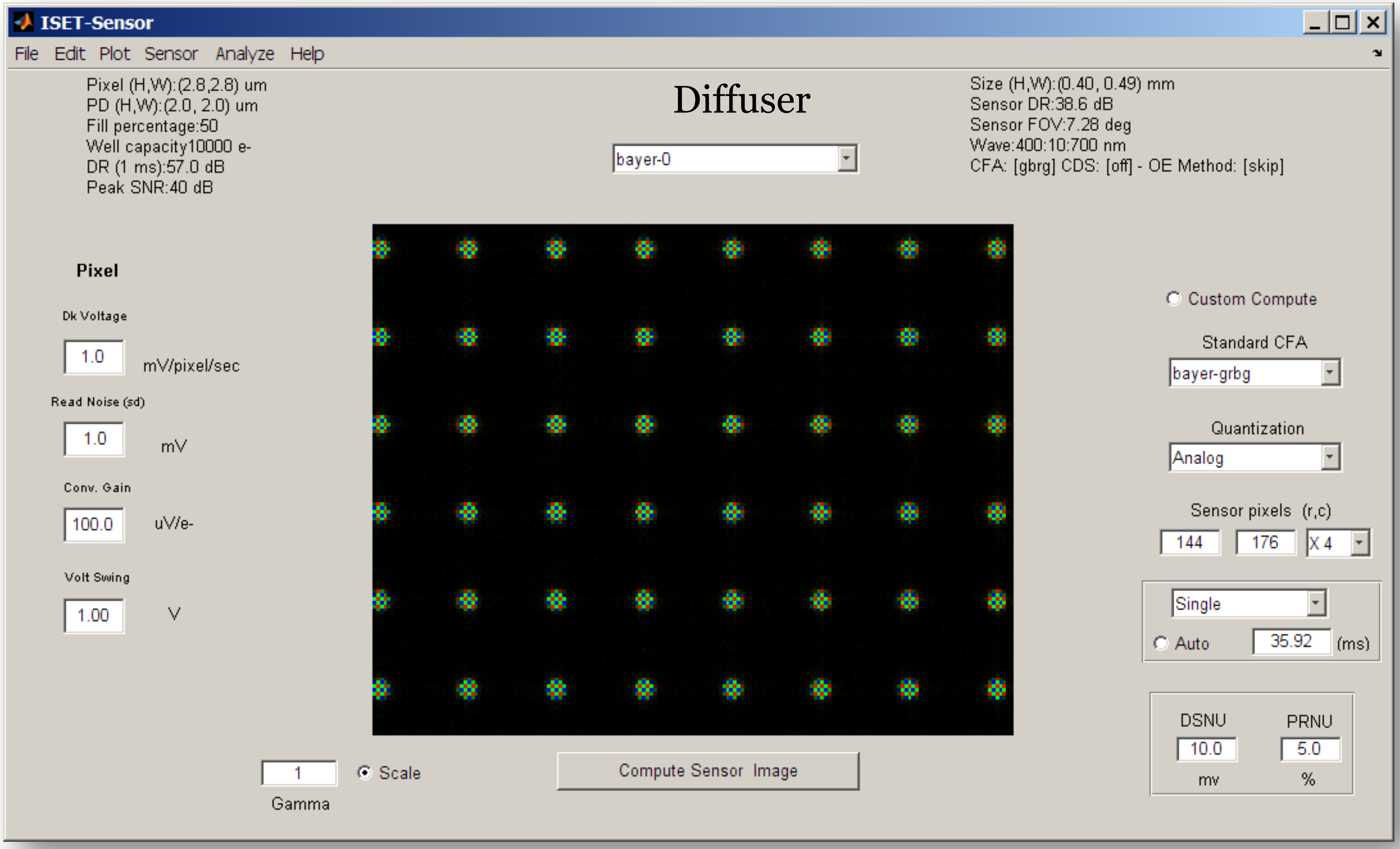
Diffusing filter



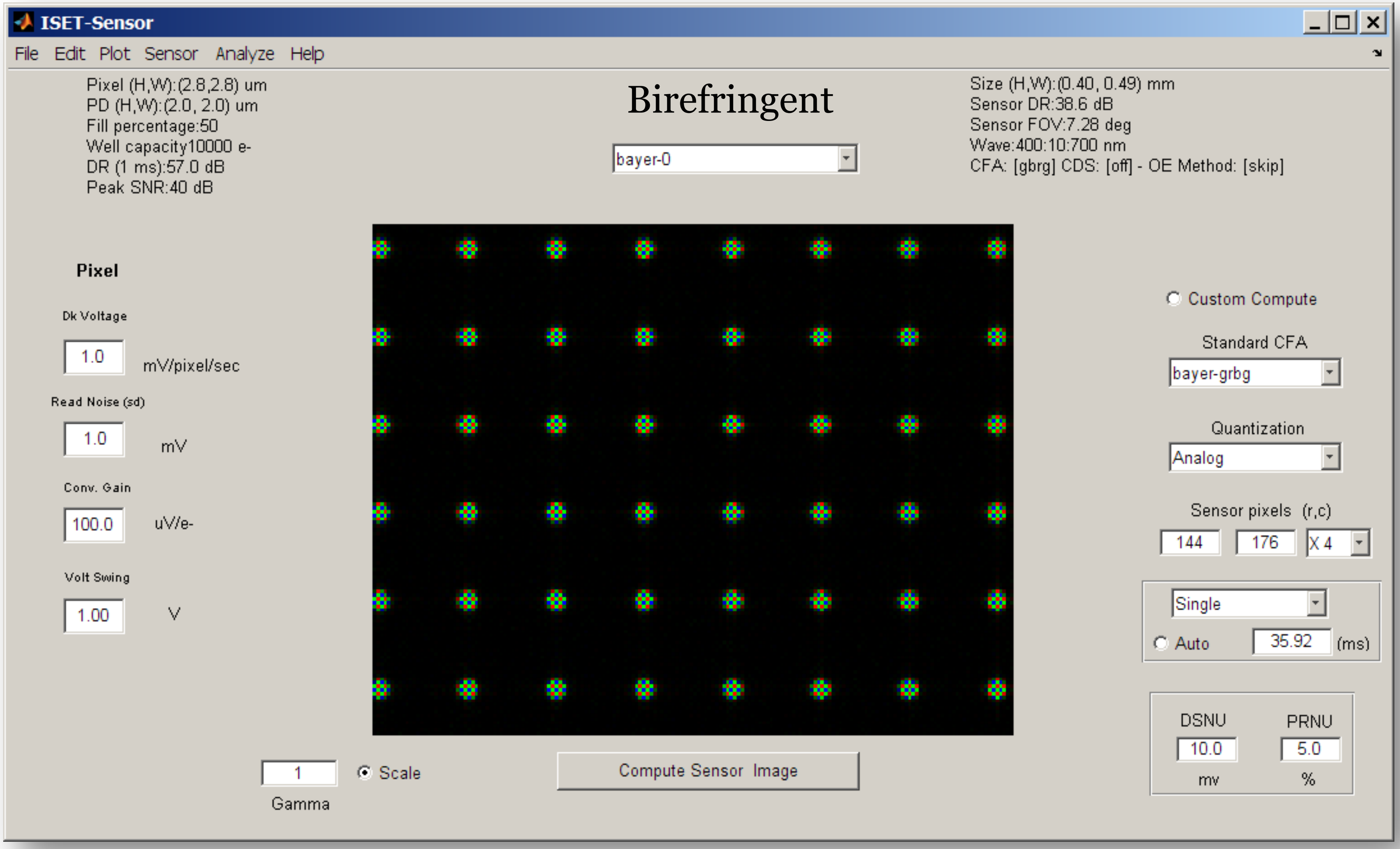
ISET simulation



No real difference at sensor



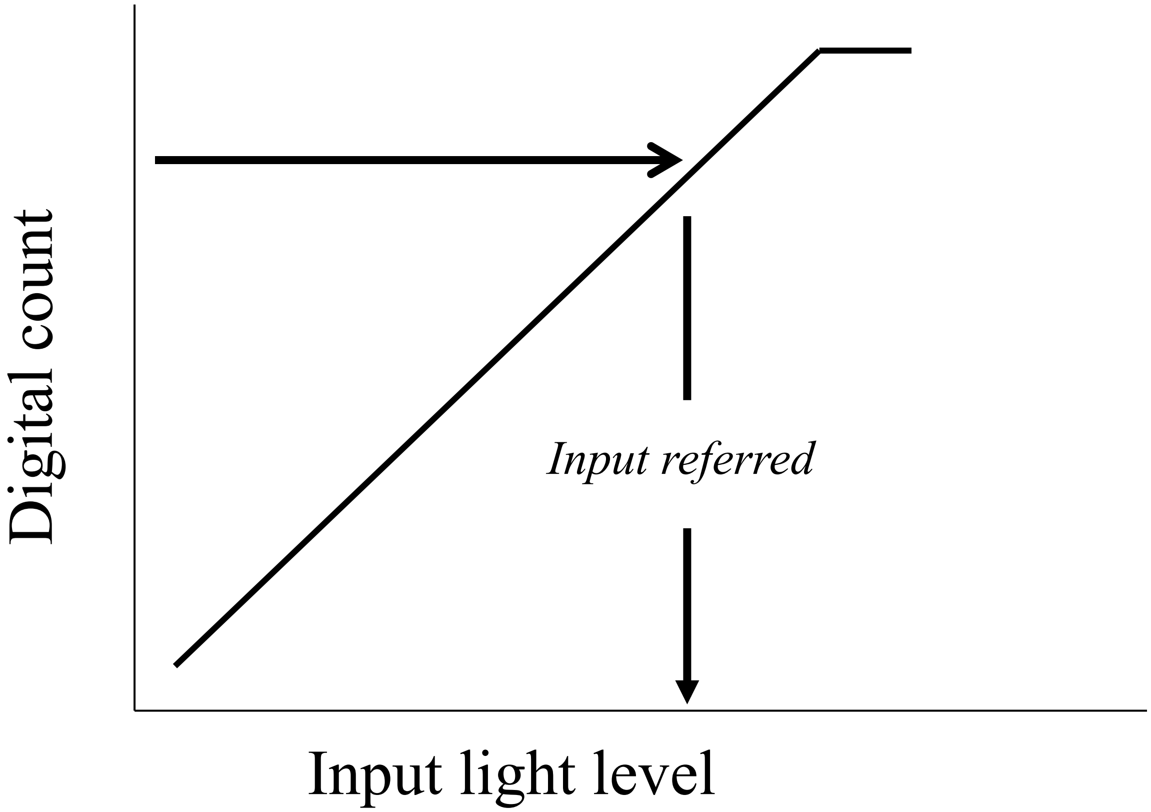
No real difference at sensor



Sensor dynamic range

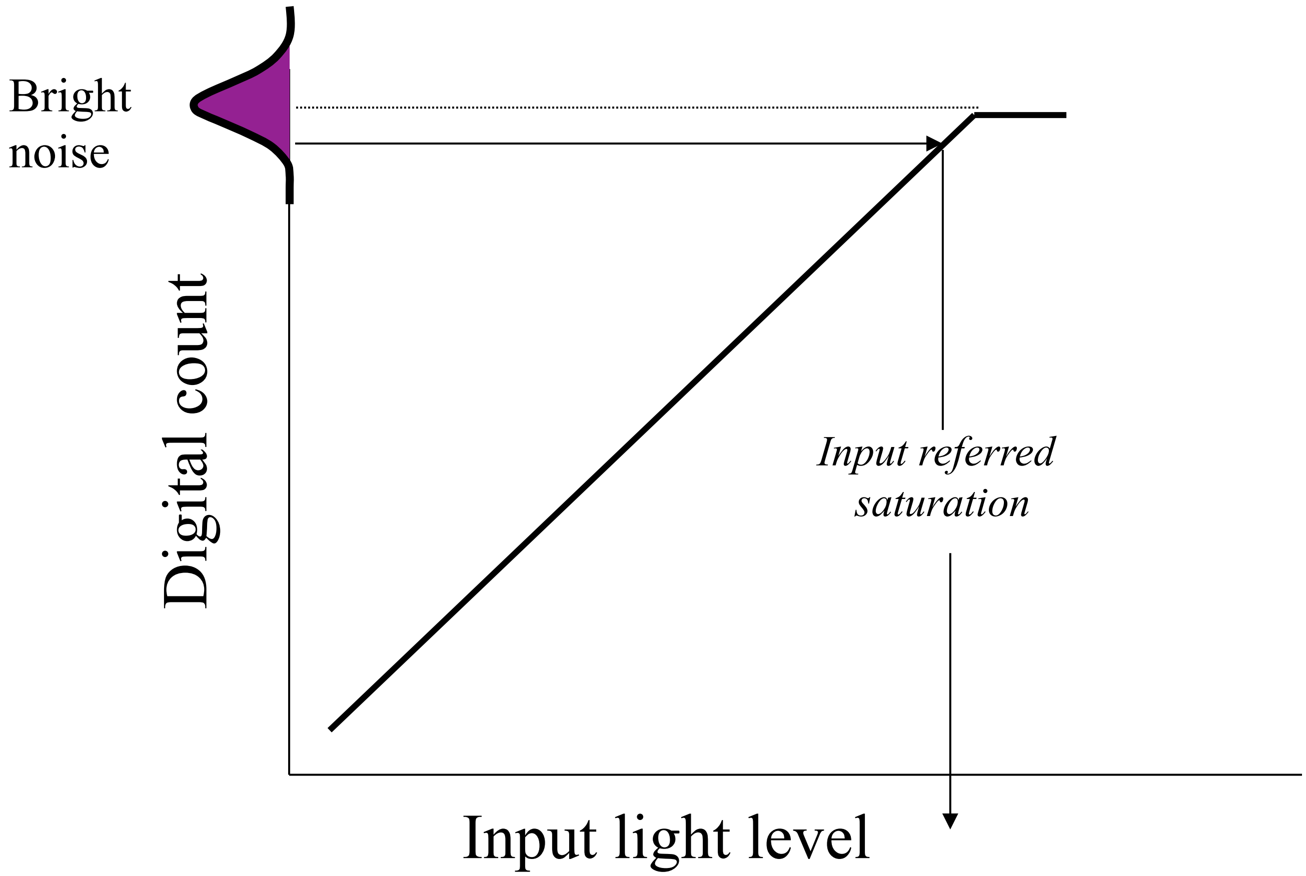
Sensor dynamic range

Input referred signals



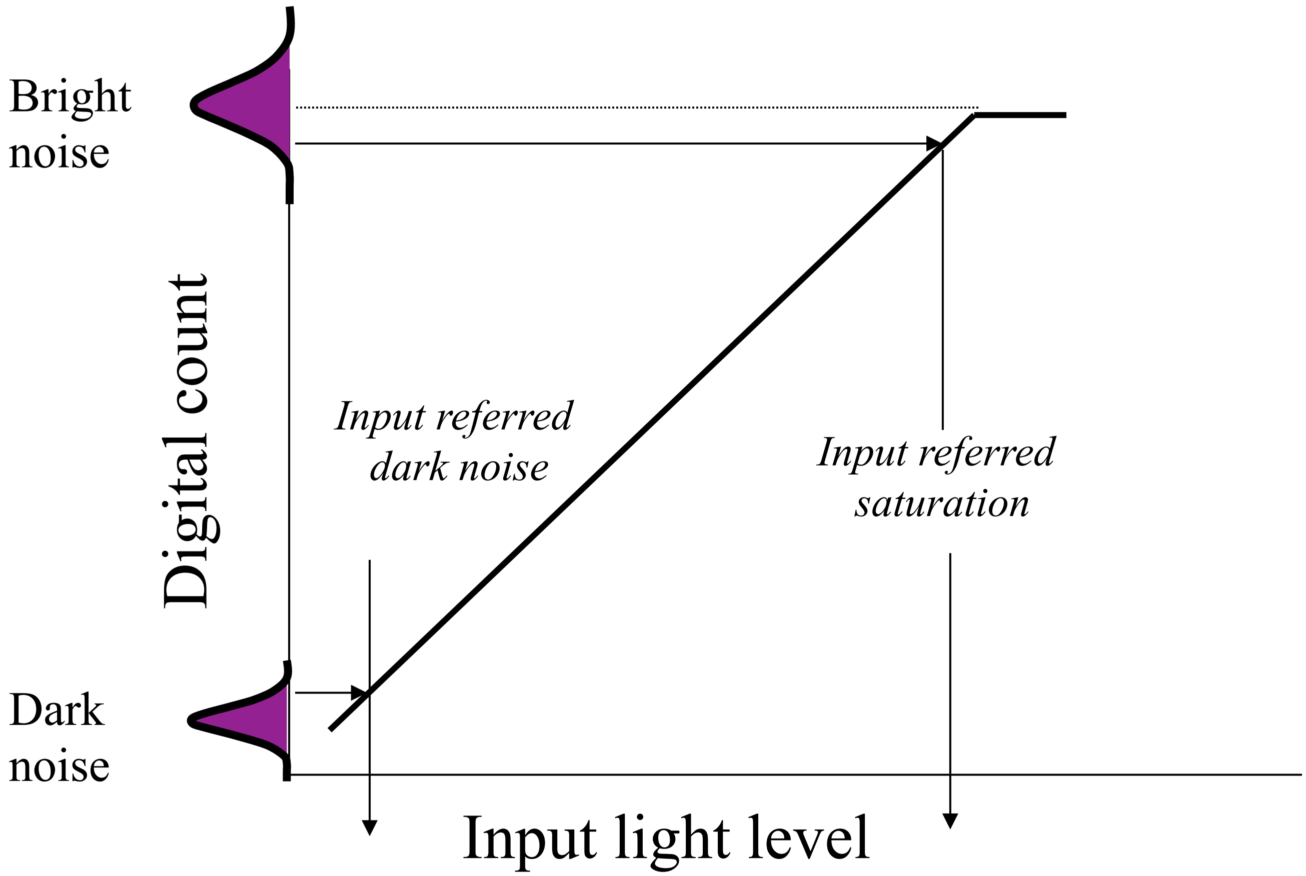
Sensor dynamic range

Saturation noise levels



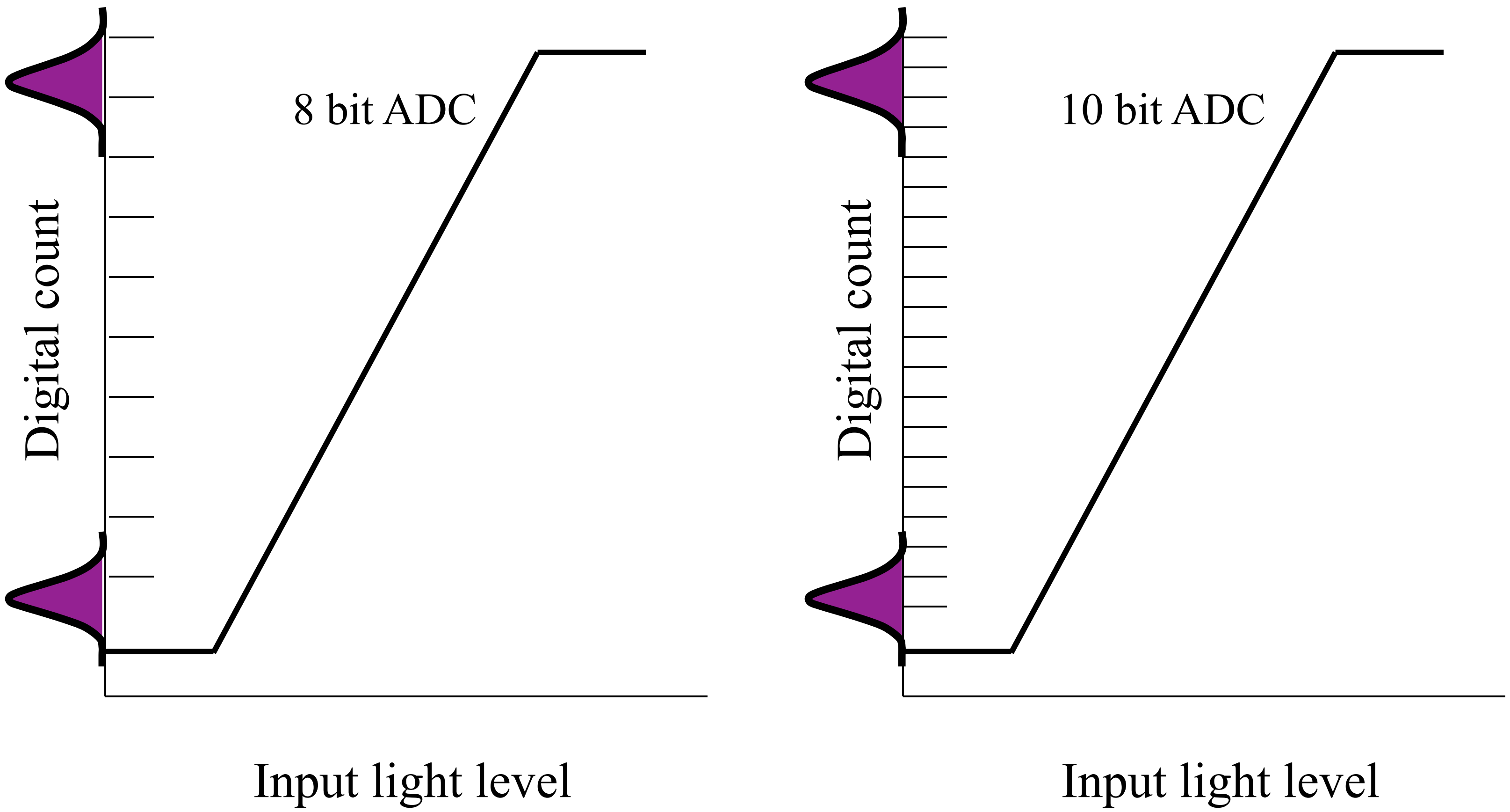
Sensor dynamic range

Ratio of saturation and dark noise levels



Dynamic range and quantization

*Because dynamic range is stimulus-referred, quantization doesn't influence DR -- unless the bin size was set **very** badly (coarsely)*



High Dynamic Range Imaging of Natural Scenes

Volume 10/Nov. 2002/ Color Imaging Conference

Feng Xiao, Jeffrey M. DiCarlo, Peter B. Catrysse and Brian A. Wandell
Stanford University
Stanford, California

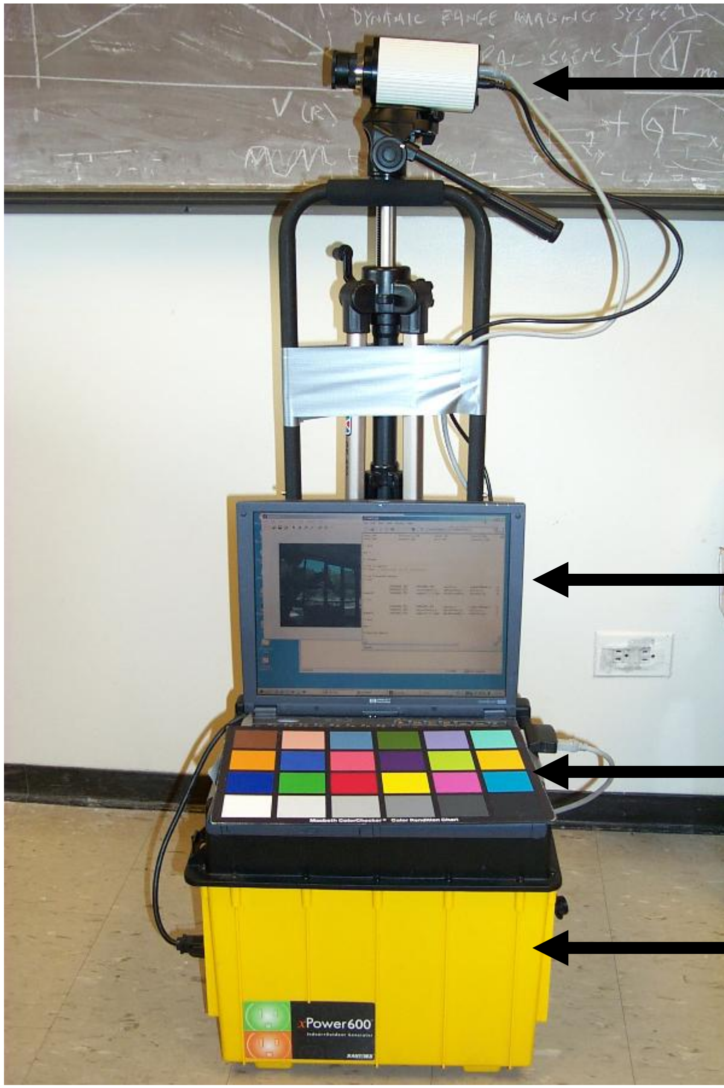
Rendering high dynamic range images

***Proceedings of the SPIE (2000),* V. 3965, pp. 392-401**

Jeffrey M. DiCarlo[*a] and Brian A. Wandell[a,b]

[a]Department of Electrical Engineering, Stanford University, CA 94305

HDR: How High Is High?



Camera

Laptop

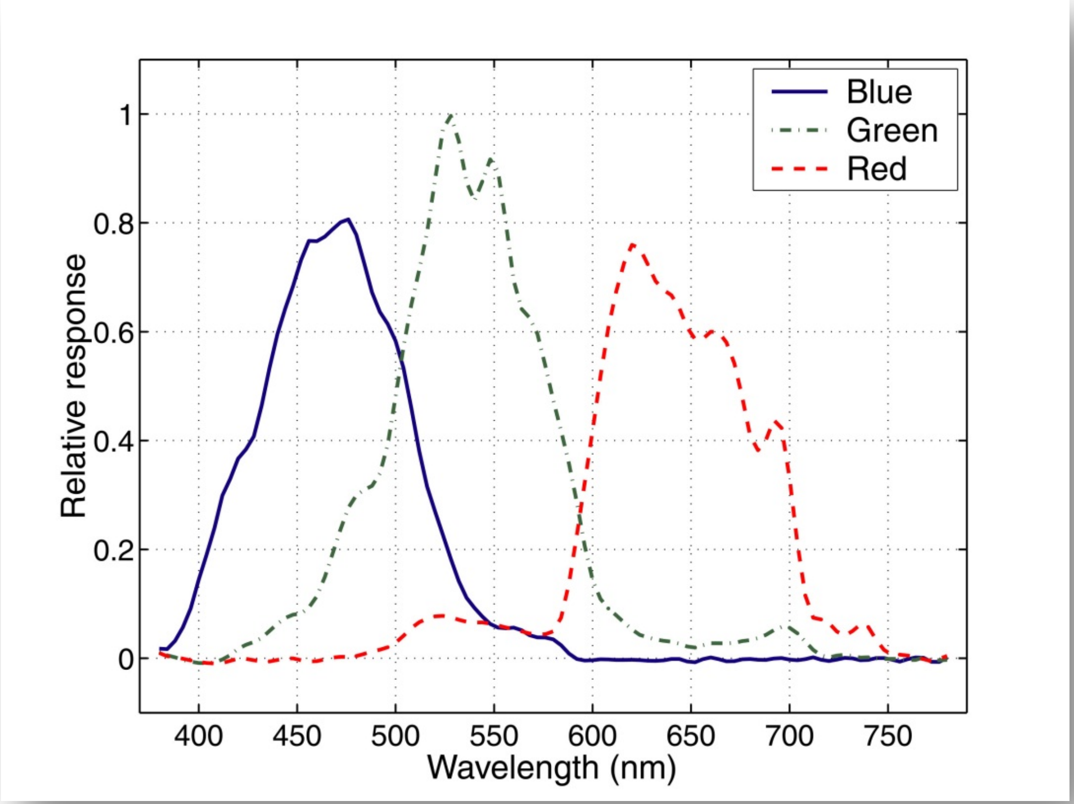
Calibration target

Battery

Sunlight

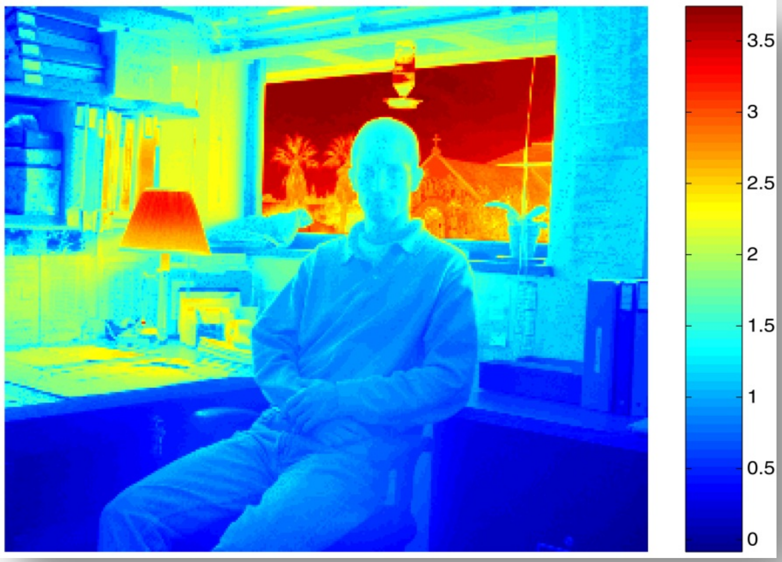
Shade

System calibration



Dark current < 0.03 DV/sec
Readout noise < 0.3 DV
Exposure 40us ~ 15 minutes
10-bit linear output
1024x1280 Bayer pattern

Multiple Exposures for HDR Capture



Increases DR by factor:

$$\frac{T_{long}}{T_{short}}$$ (Yang et al. 99)

5-6 exposures at interval of 4 times

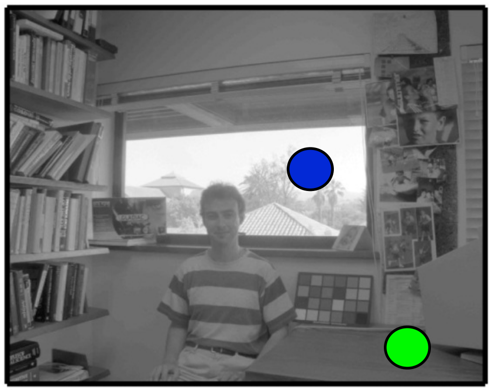
Measurable luminance range:

[10^{-1} ~ 10^{5} cd/m^2]

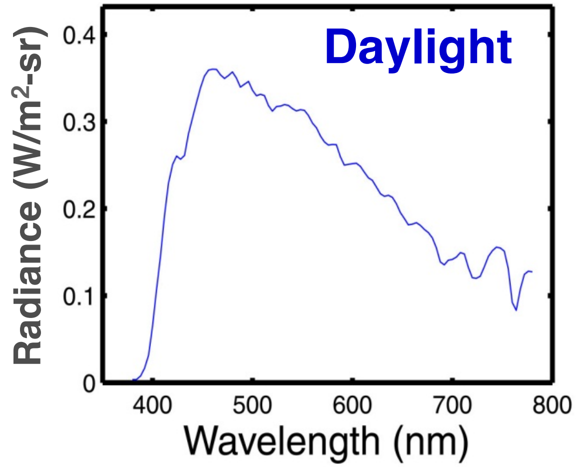
Dynamic range > 10^6:1

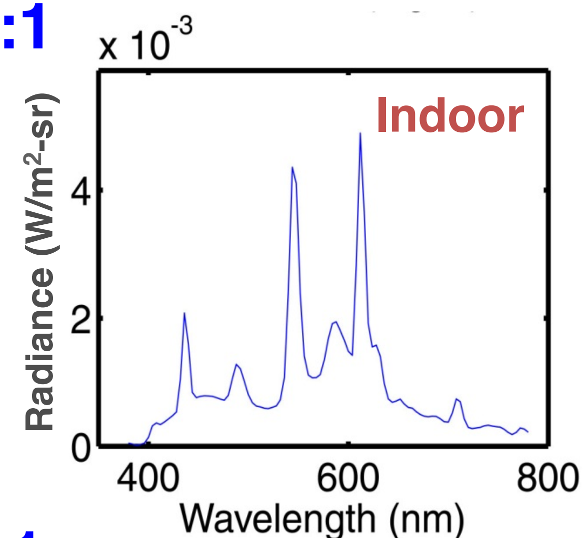
(1) HDR scenes have multiple illuminants

DR = 2000:1



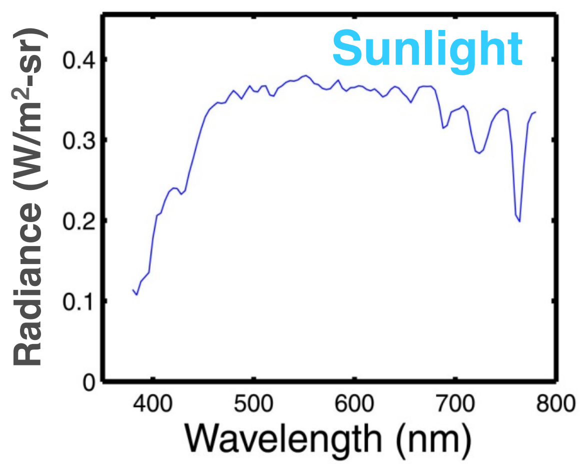
180:1

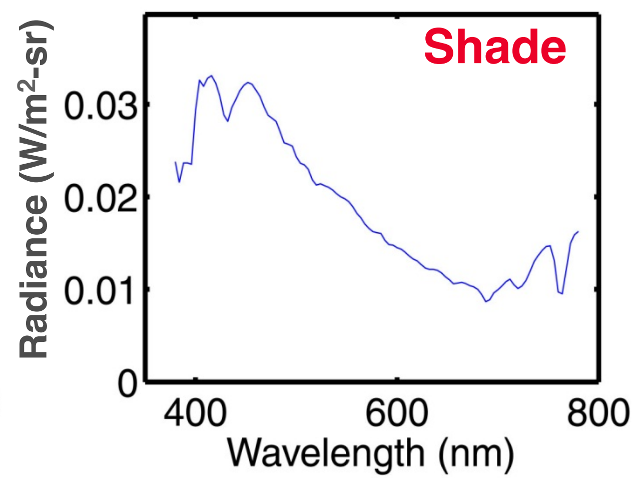




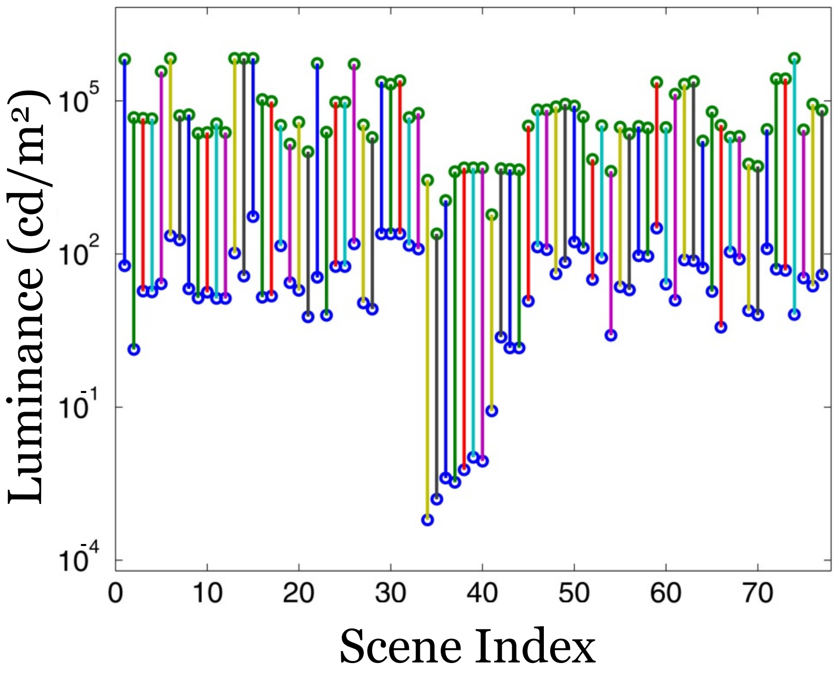
DR = 400:1

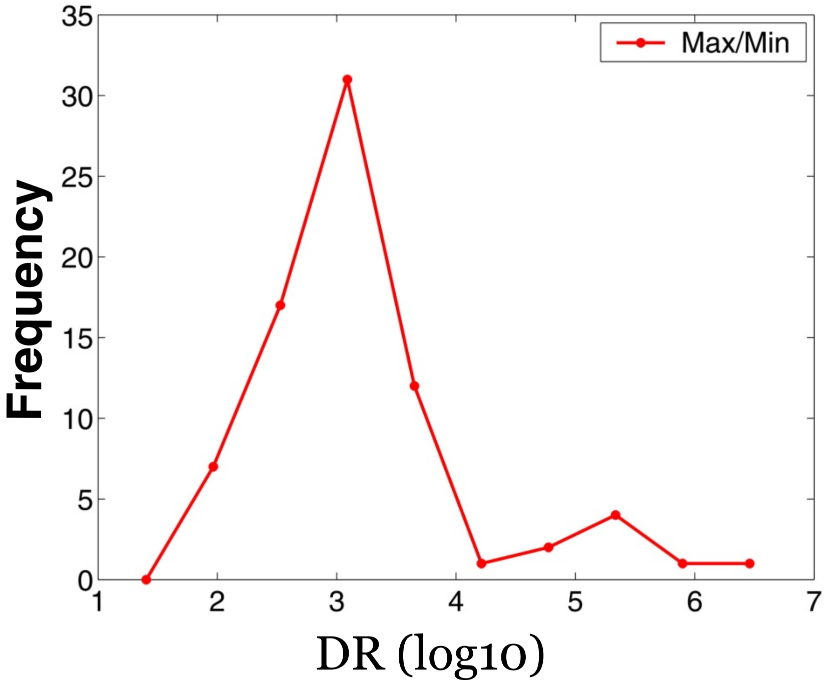
20:1





(2) Image DR is often 3-5 Log units



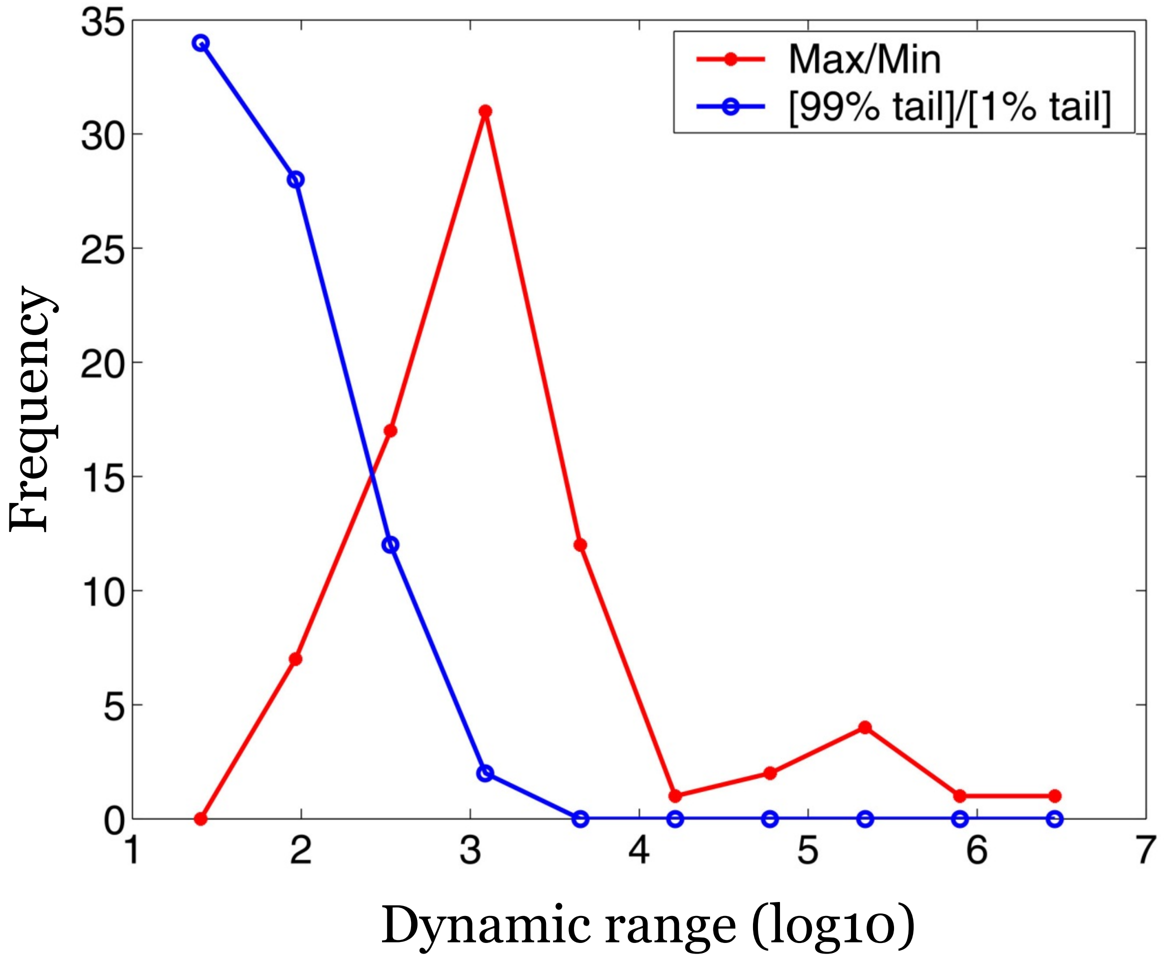


(3) The high range is often due to specular reflection or light

Original dynamic range = 6000:1

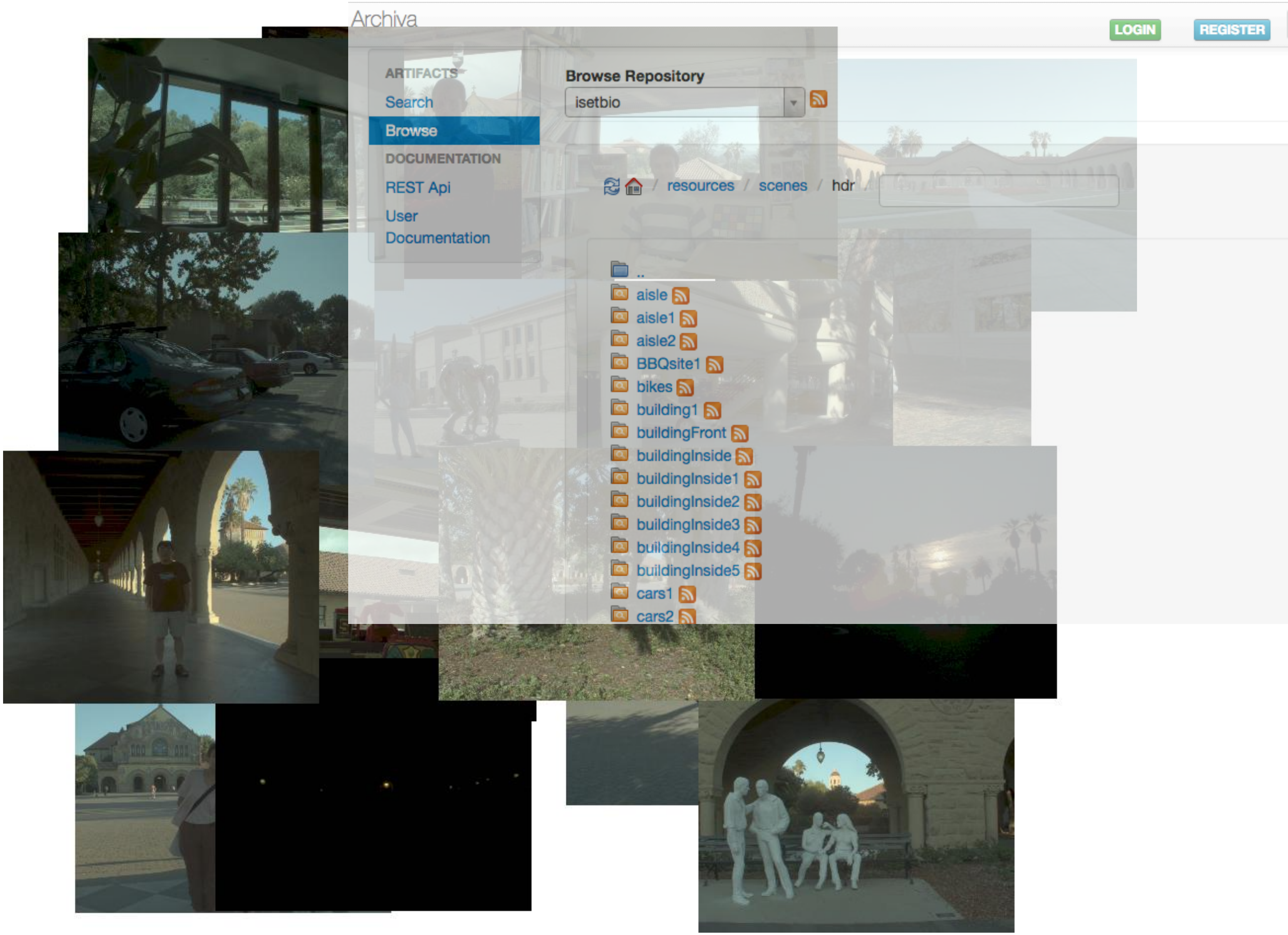
Effective dynamic range = [99% tail] / [1% tail]
6000:1 reduced to 350:1

Eliminating specular reflections and light sources reduces DR

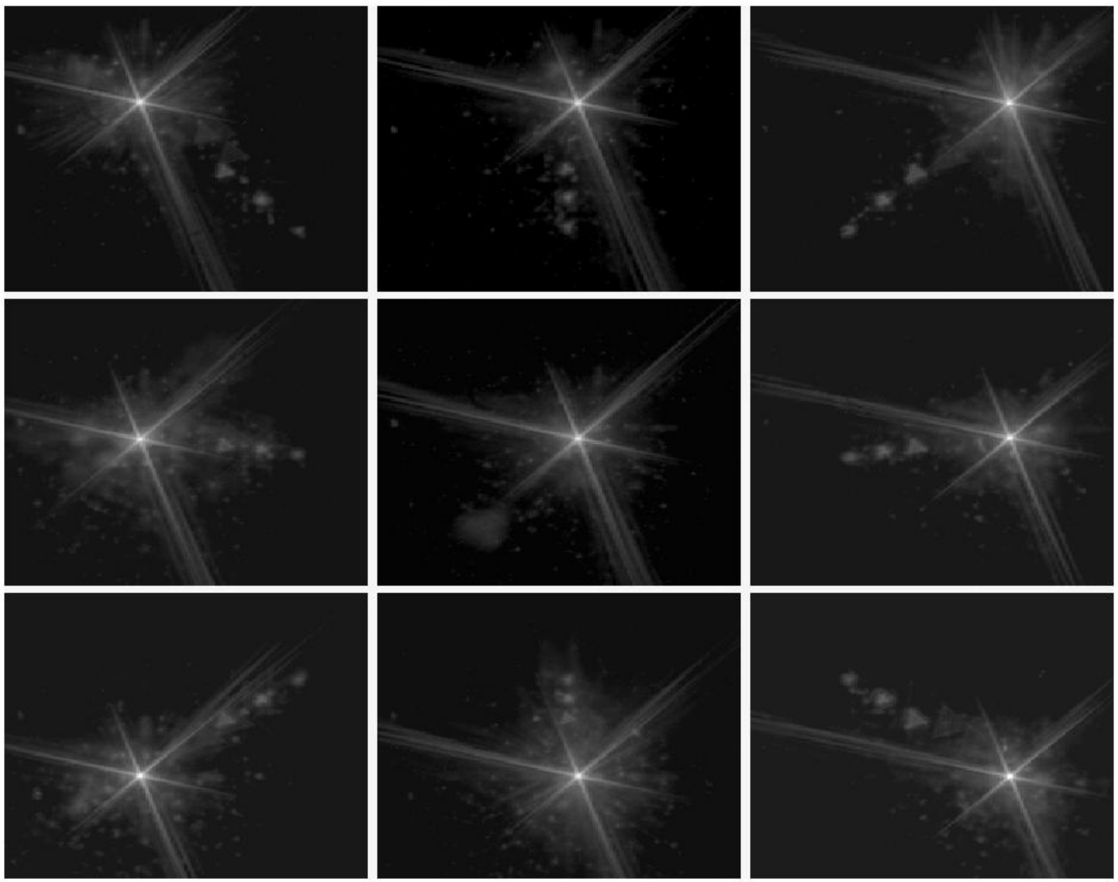


HDR image database (online)

http://52.32.77.154/#browse~isetbio/resources.scenes.hdr

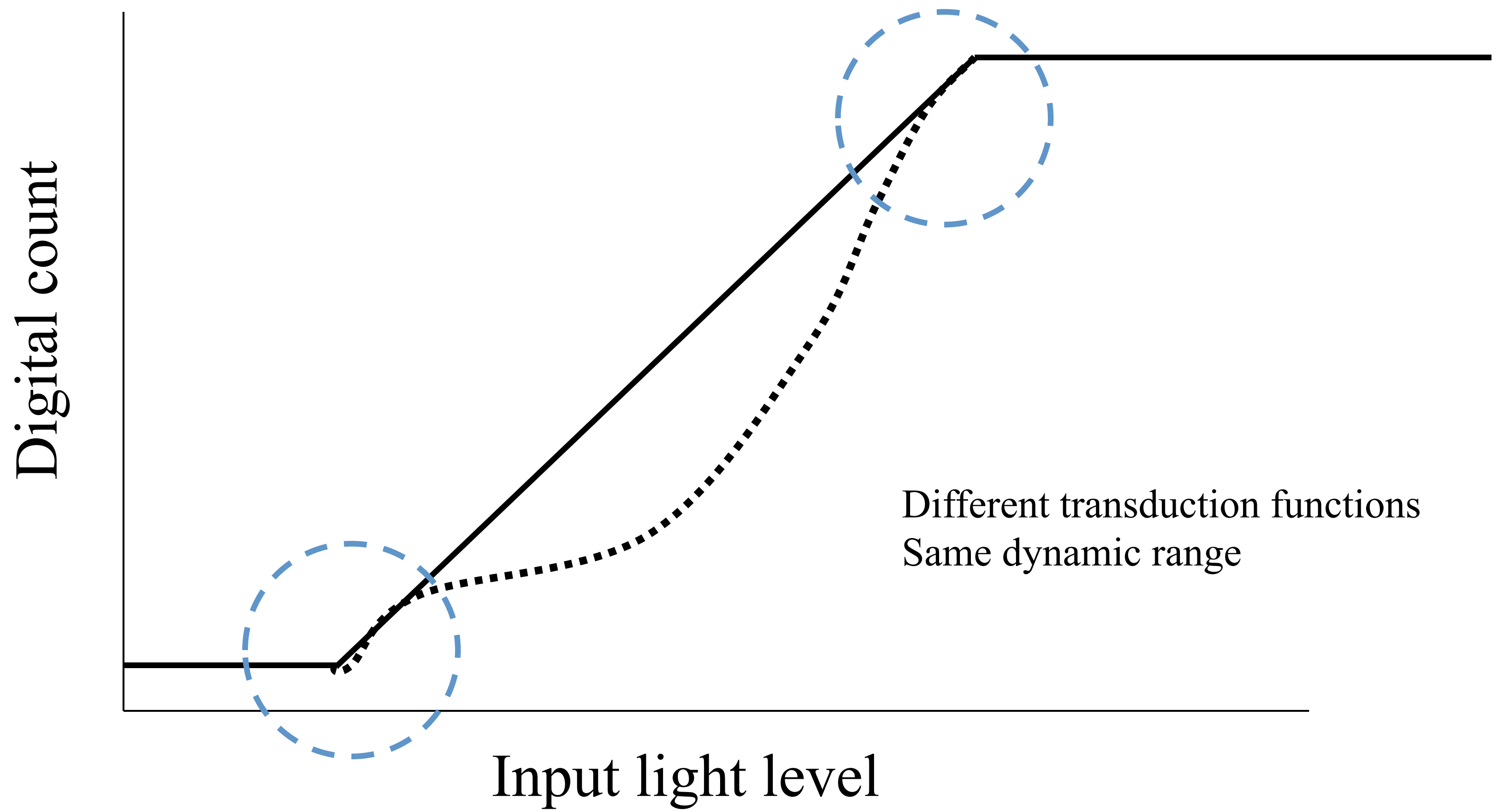


Lens Calibration: Flare for HDR



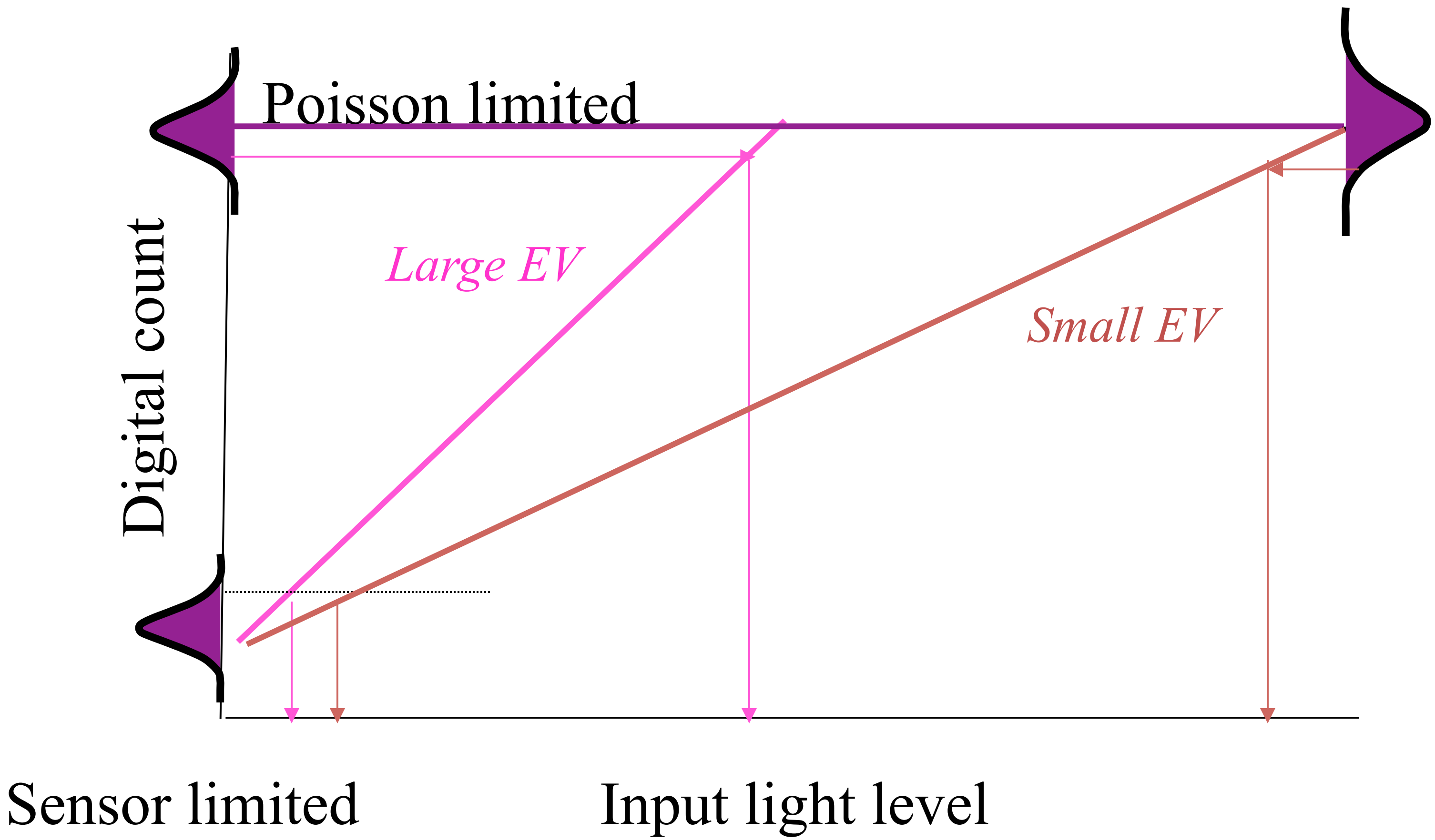
Shift-variant (but linear)

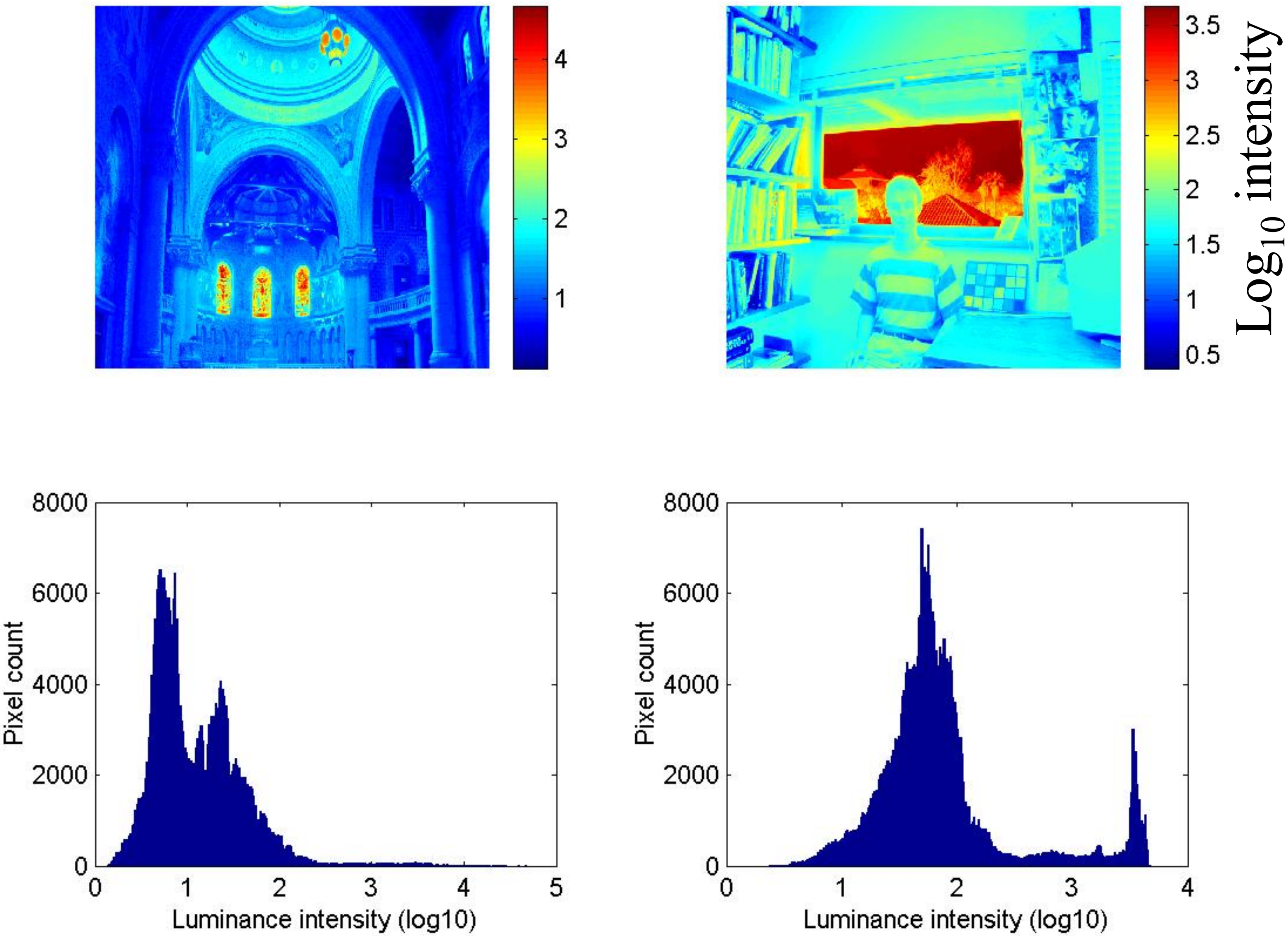
Dynamic range
Not the same as quantization



Dynamic range and exposure value

*Changing exposure value scales input-referred dark noise **and** input referred saturation. Hence, the dynamic range remains **roughly** constant*





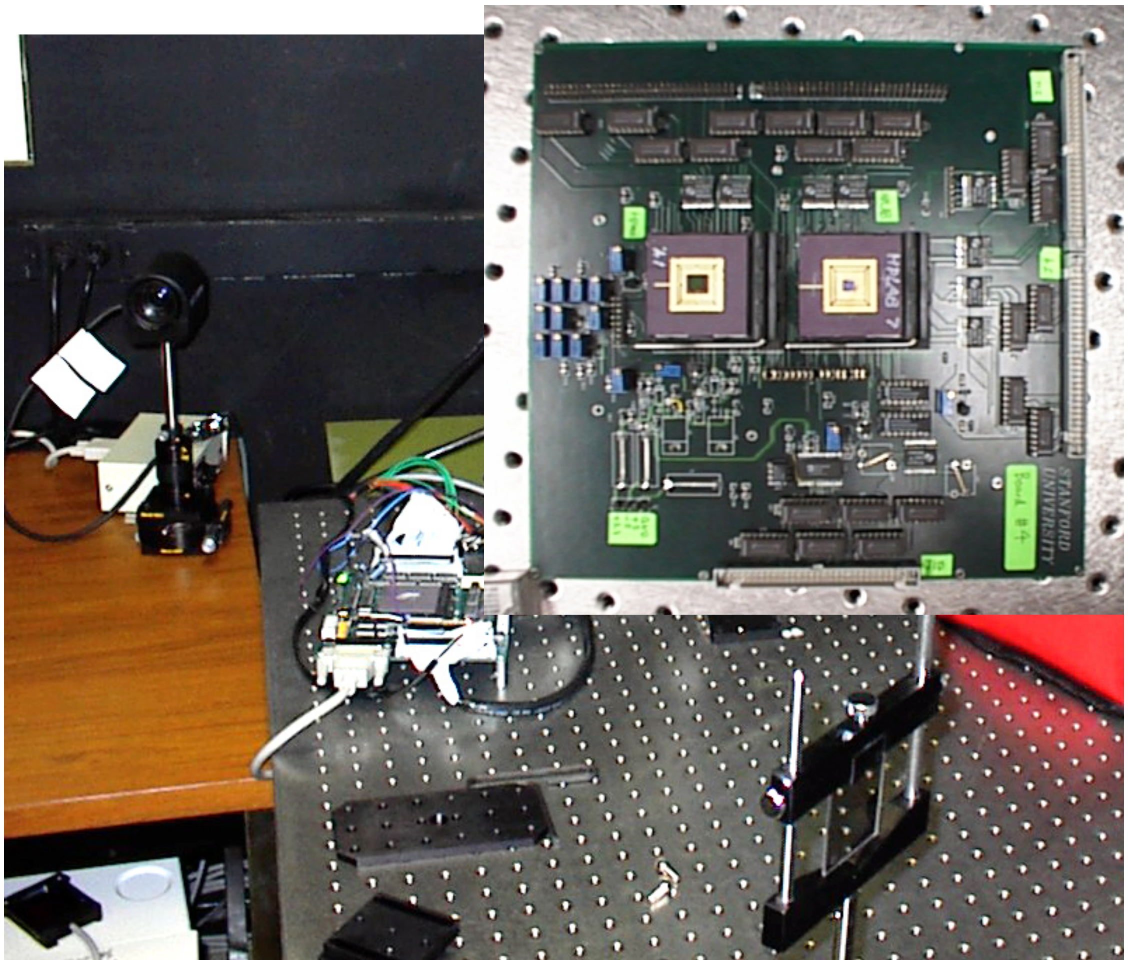
Log_{10} intensity
Pixel count
Luminance intensity (log10)
Pixel count
Luminance intensity (log10)

High dynamic range image capture

- There are software and multi-capture approaches
- We attend to hardware ideas
- Limitation is pixel well-capacity


HYATT

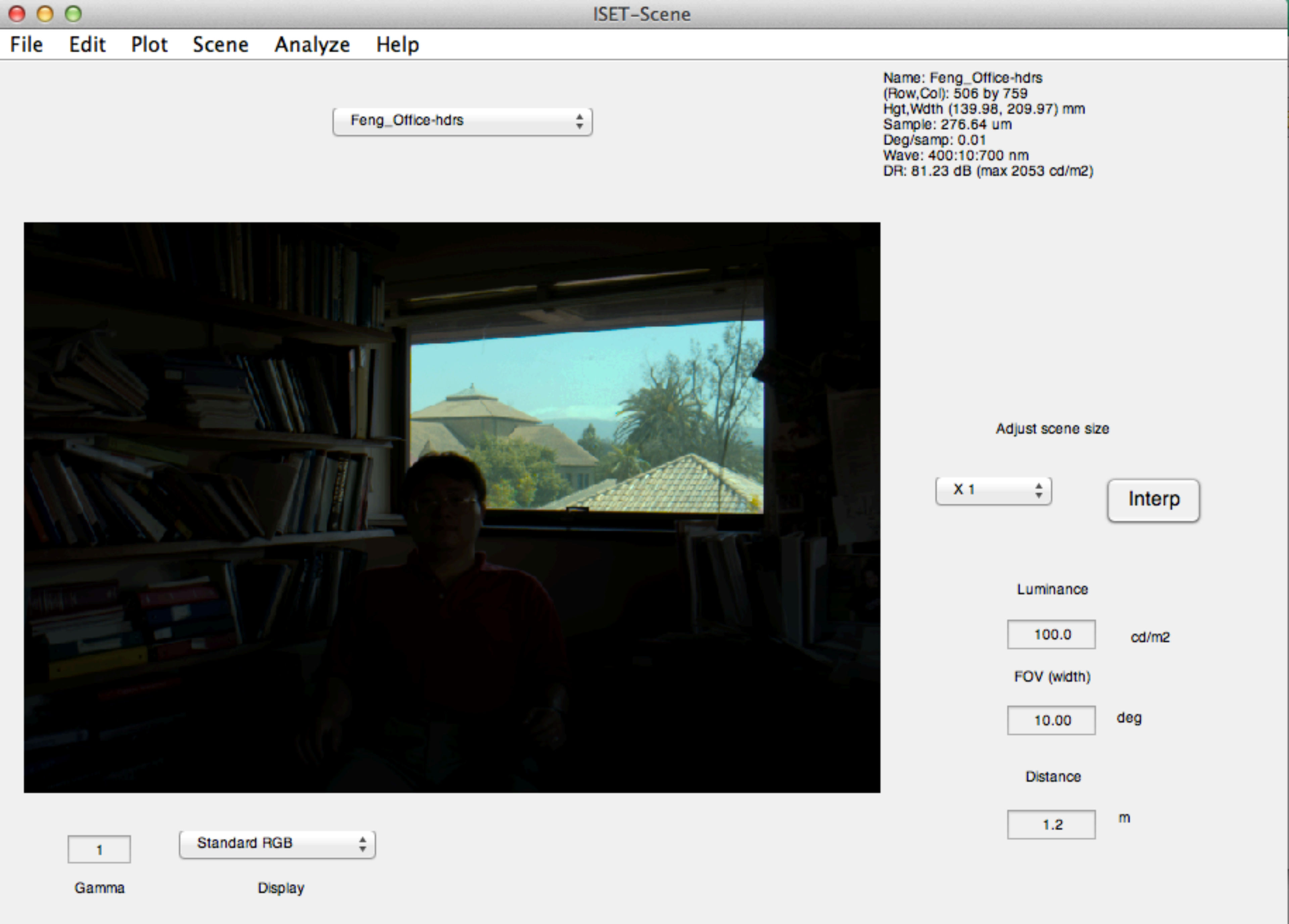
1st Generation Implementation
(D. Yang et al., IEEE JSSC, 1999)

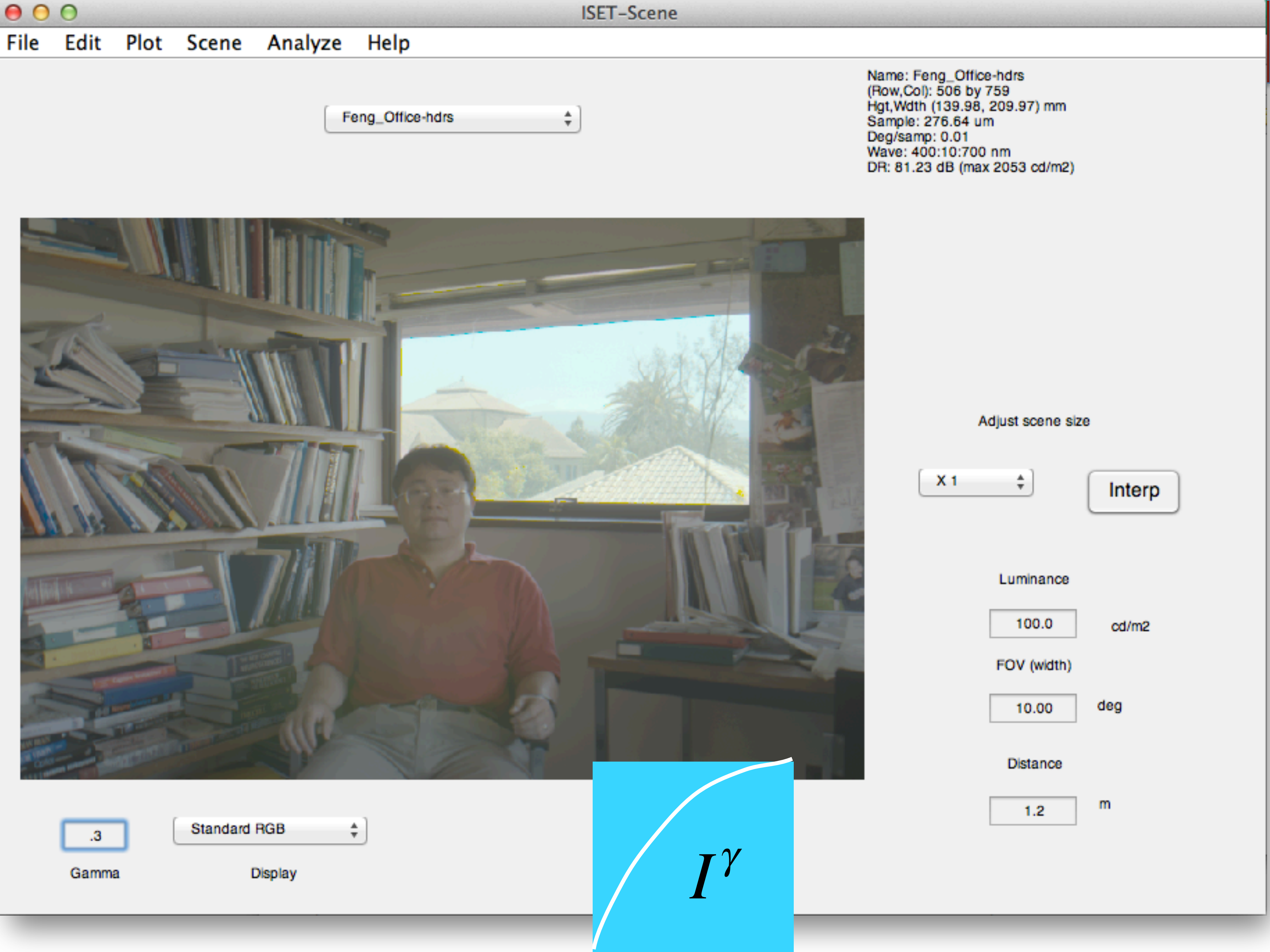


- *Imager: 640 x 512*
- *Pixel: 10.5 micron*
- *Technology: 0.35 micron*
- *ADC shared x 4*
- *Control signals FPGA*
- *Fill factor ~ 29%*
- *QE ~10%*
- *Really cool, though*

Multicapture HDR Illustration

Pixim


ISET–Scene
File
Edit
Plot
Scene
Analyze
Help
Feng_Office-hdrs
Name: Feng_Office-hdrs
(Row,Col): 506 by 759
Hgt,Wdth (139.98, 209.97) mm
Sample: 276.64 um
Deg/samp: 0.01
Wave: 400:10:700 nm
DR: 81.23 dB (max 2053 cd/m2)
Adjust scene size
X 1
Interp
Luminance
100.0
cd/m2
FOV (width)
10.00
deg
Distance
1.2
m
1
Gamma
Standard RGB
Display


ISET-Scene
File
Edit
Plot
Scene
Analyze
Help
Feng_Office-hdrs
Name: Feng_Office-hdrs
(Row,Col): 506 by 759
Hgt,Wdth (139.98, 209.97) mm
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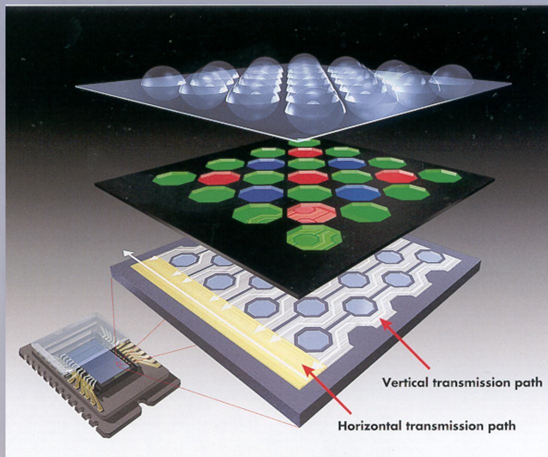
Adjust scene size
X 1
Interp
Luminance
100.0
cd/m2
FOV (width)
10.00
deg
Distance
1.2
m
.3
Gamma
Standard RGB
Display
I^{γ}

HDR range compression code from MIT

Li, Sharan, and Adelson

Novel camera architectures



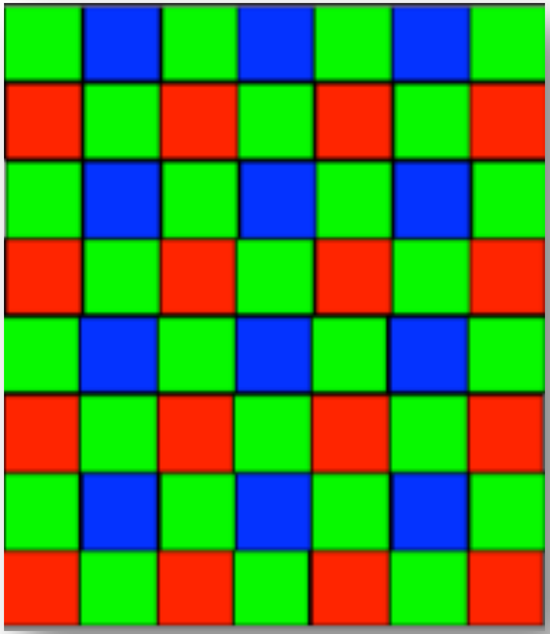
Fuji Corporation

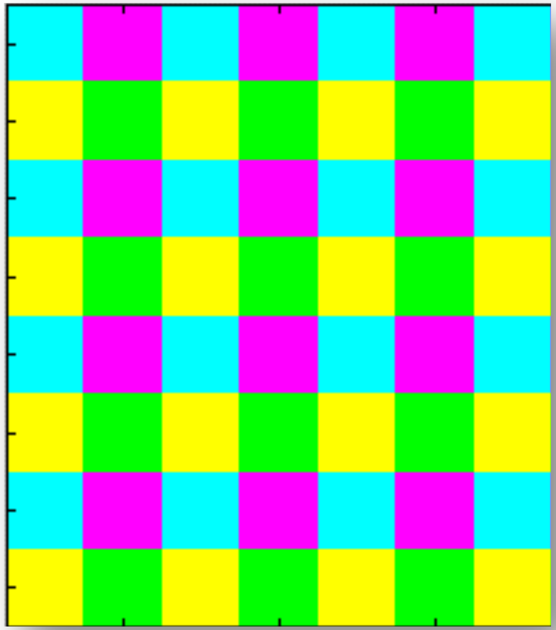
This is an overview. When we get to the image processing lectures in 2.5 weeks, I will explain more about how the data are processed and evaluated. Before that we need to review some human perception, which is next.

Camera CFA architectures

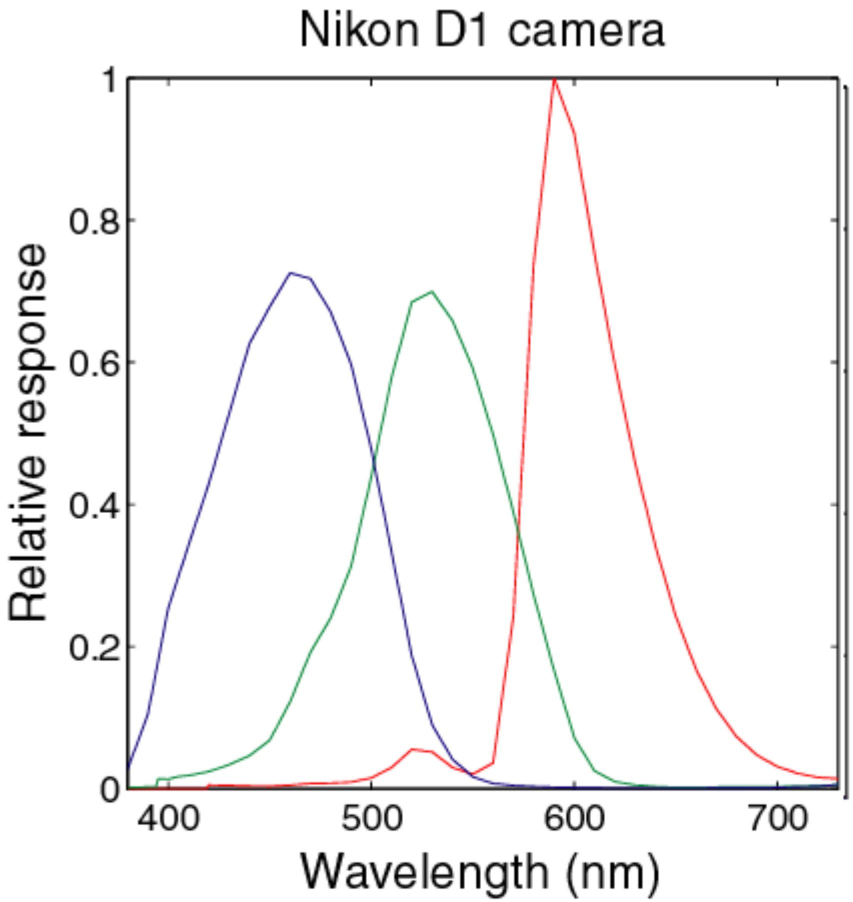
- Bayer array RGB
- Most common
- Green double the sampling rate
- Requires filling in missing pixel values – (demosaicking)

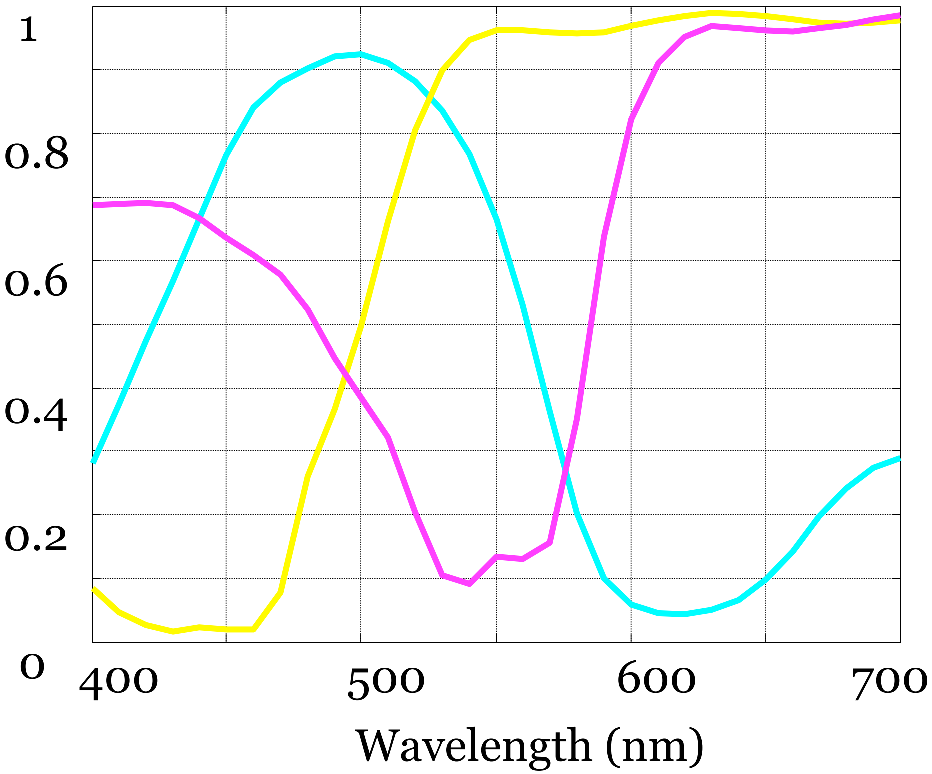
- CMYG – video cameras
- Fast demosaicking
- Broad filters, more photons
- Poor noise properties





Example sensor responsivities differ

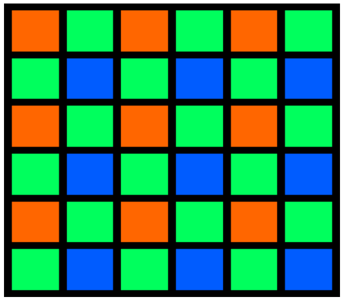




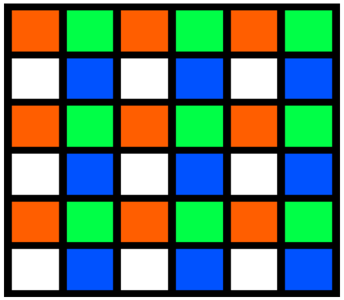
(Xiao and Wandell, personal comm.)

Opportunity and challenge

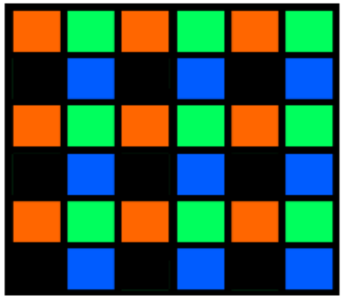
- High density (small size) and excellent electrical properties of modern pixels enable new sensors with new applications
- **Challenge**: design and deliver image processing pipelines that exploit the spatial spectral statistics of the target scenes, properly balancing noise



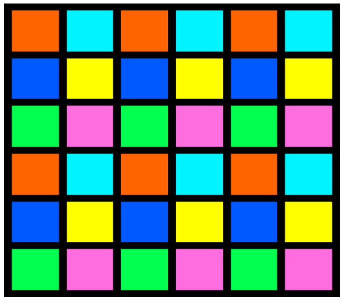
Bayer



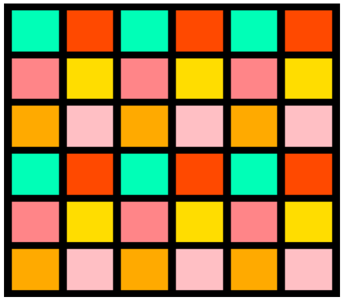
RGBW
low-light sensitivity
dynamic range



RGBX
infrared
light field



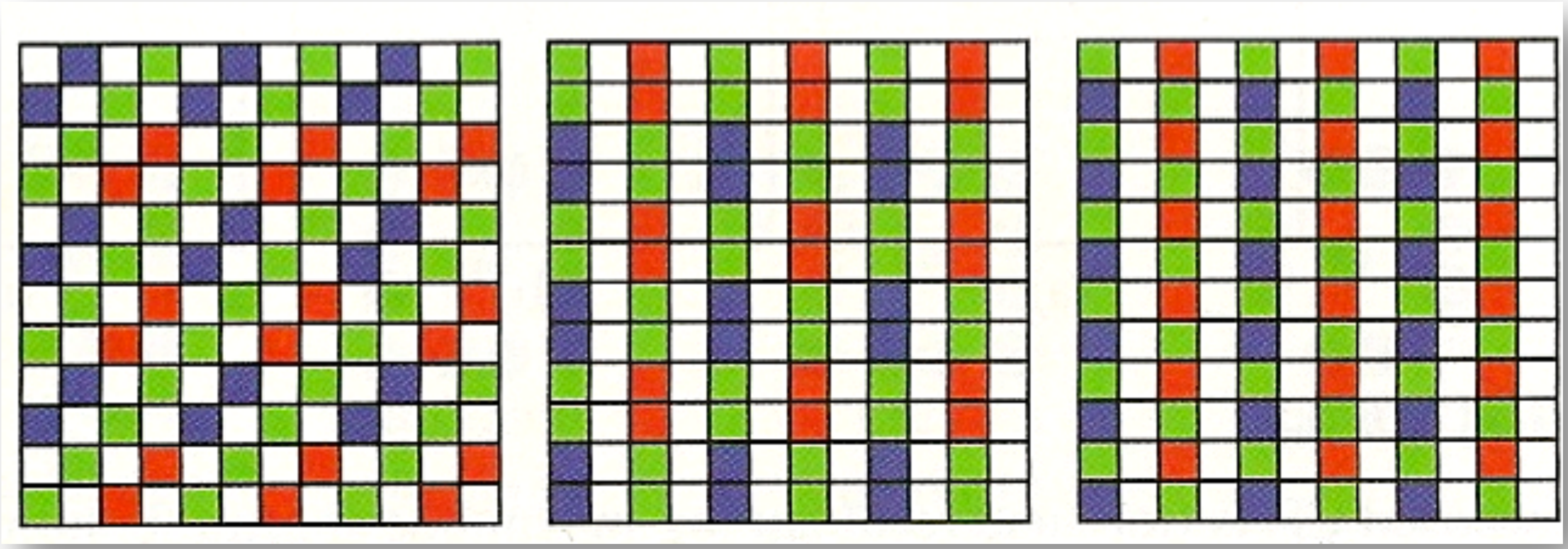
RGBCMY
multispectral



Medical
specialized
application

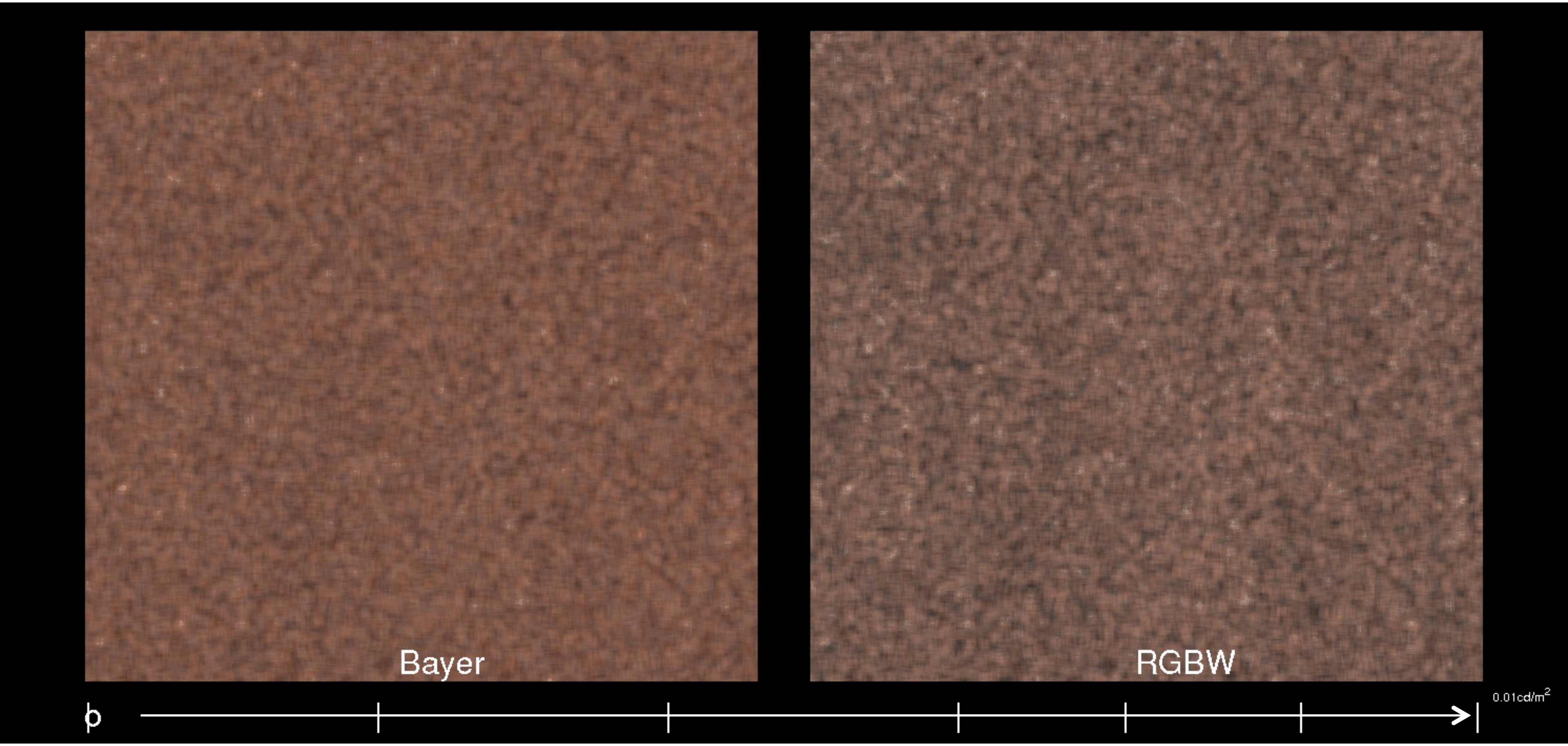
Arrays with white pixels

Under low illumination conditions, the white pixel still gathers some information.
The rendered scene, however, will not have good color reproduction



RGBW compared to Bayer

RGBW: better in low light & same in high light



.01 .1 1 10 100 200 300 cd/m^2

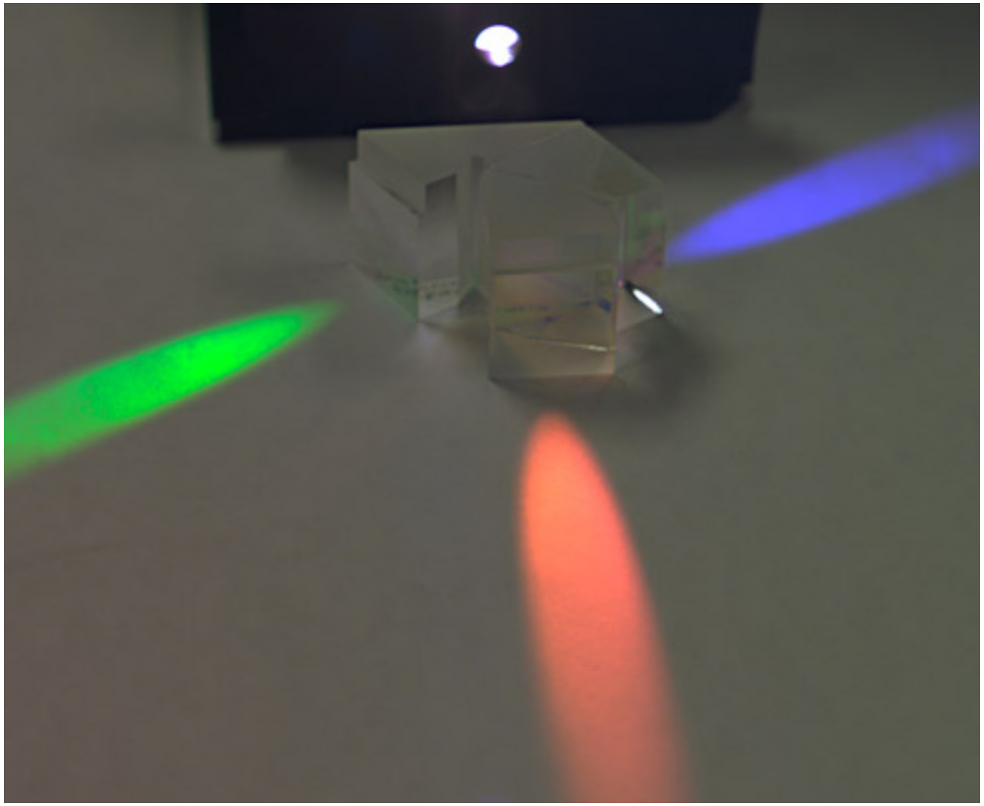
Scene luminance (cd/m^2)

Camera color architectures: 3-Sensor

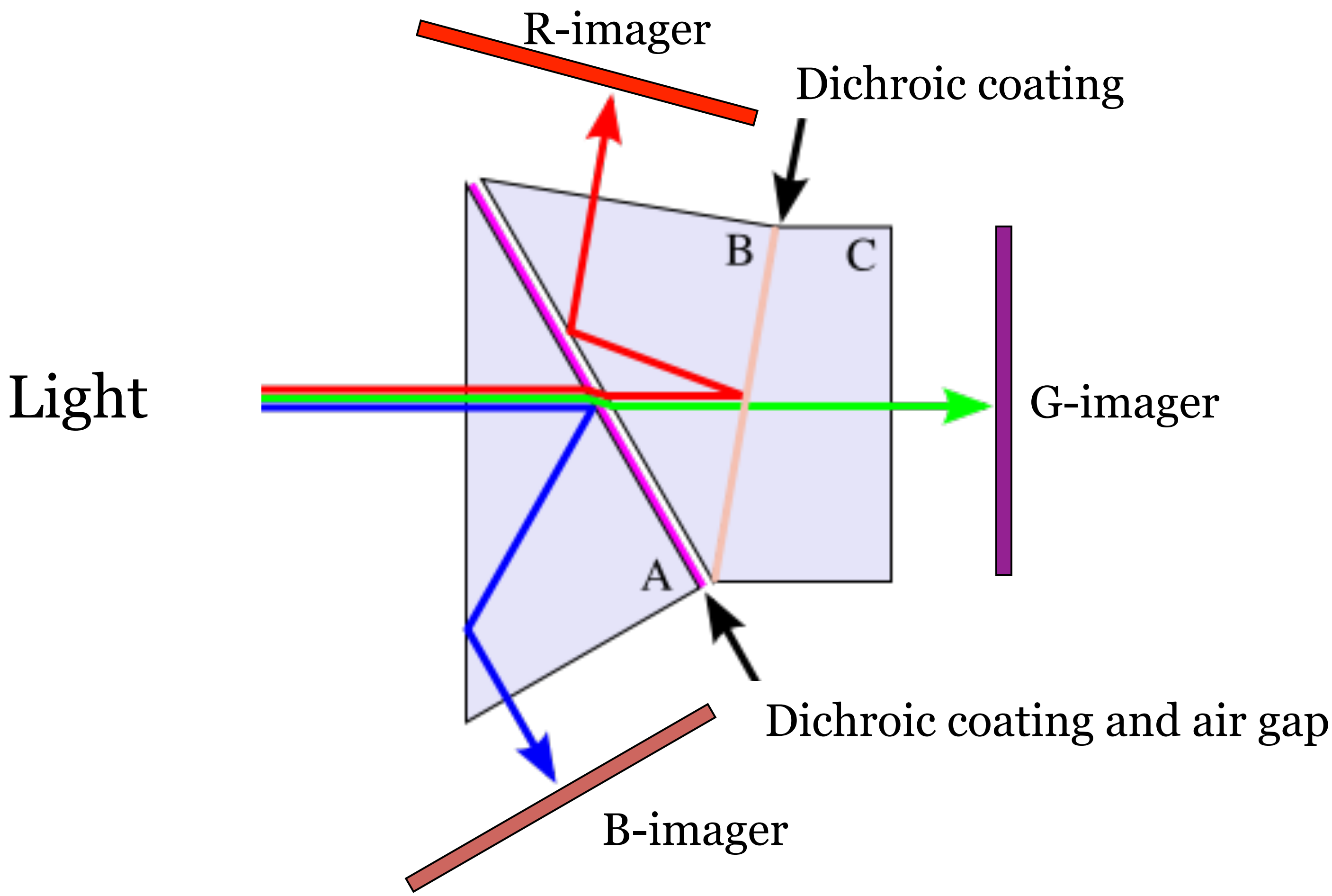
<u>Prismatic optics</u>

No demosaicking

Three (smaller) sensors and optical alignment



Philips total internal reflection dichroic prism

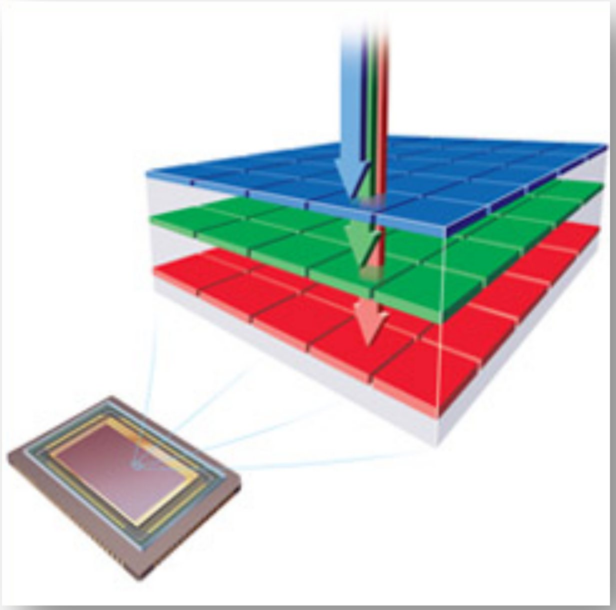


Foveon and Sigma

http://www.foveon.com/article.php?a=67

s_sensorStackedPixel.m

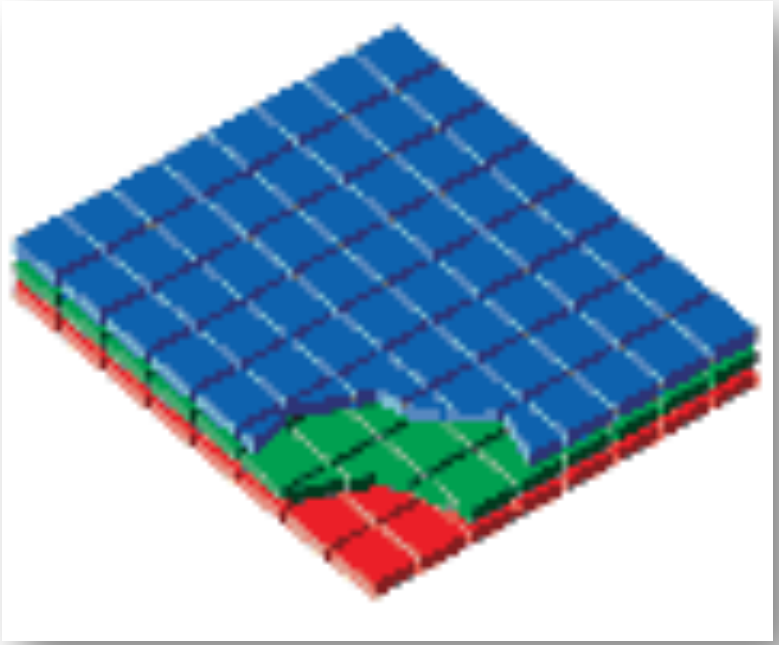
The Sigma SD9 was the first digital camera to use a full-color multi-layer sensor technology.

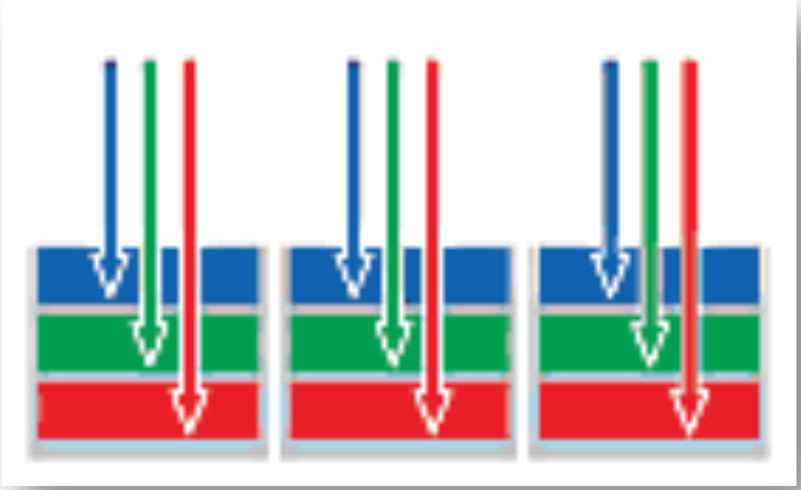


The sensor was called the Foveon X3.

Wavelengths penetrate to different depths

Long-wavelength photons penetrate deeper than short. The spectral response of electrons at the surface differs from electrons deeper in the material





Calculating absorption likelihoods

Probability of absorption in an infinitesimal slice

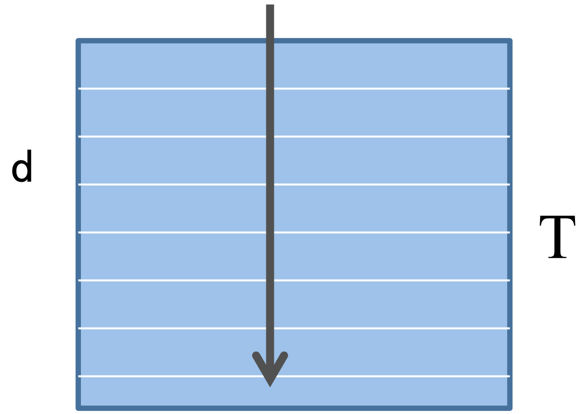
$$p(\lambda,\delta) = a(\lambda)\delta$$

Suppose that we calculate for a thickness, T, of N infinitesimal slices, each of thickness T/N = d the likelihood of **not** being absorbed up to that last slice

$$\lim_{N\to\infty}(1-a(\lambda)\frac{T}{N})^N = e^{-a(\lambda)T}$$

Probability of **being** absorbed in the next infinitesimal slice

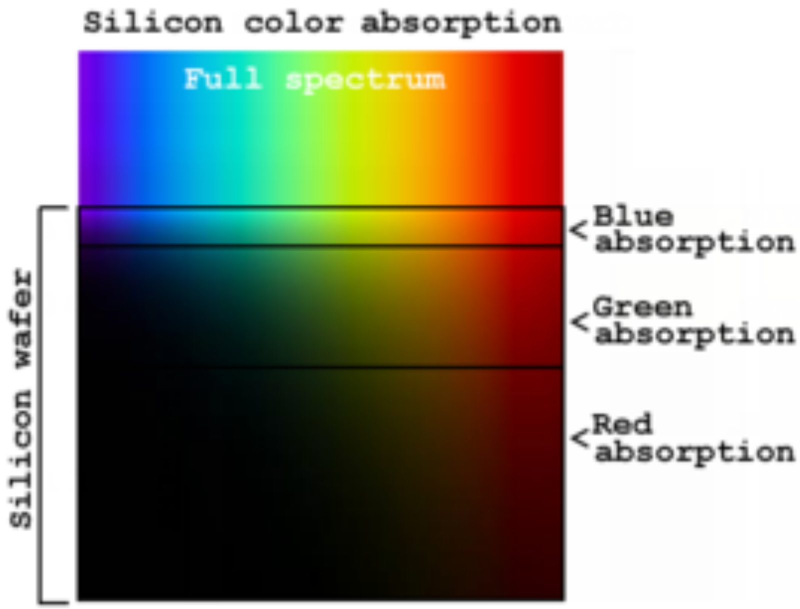
$$p(\lambda,\delta)e^{-a(\lambda)T} \sim a(\lambda)e^{-a(\lambda)T}$$

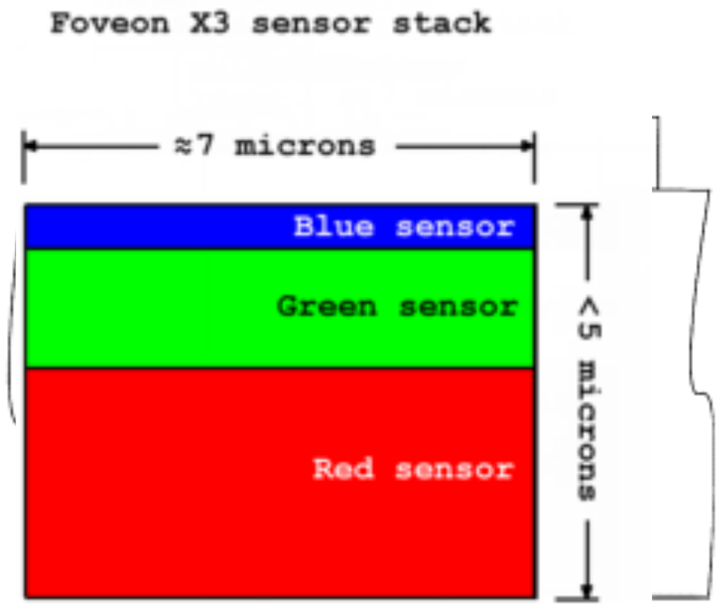


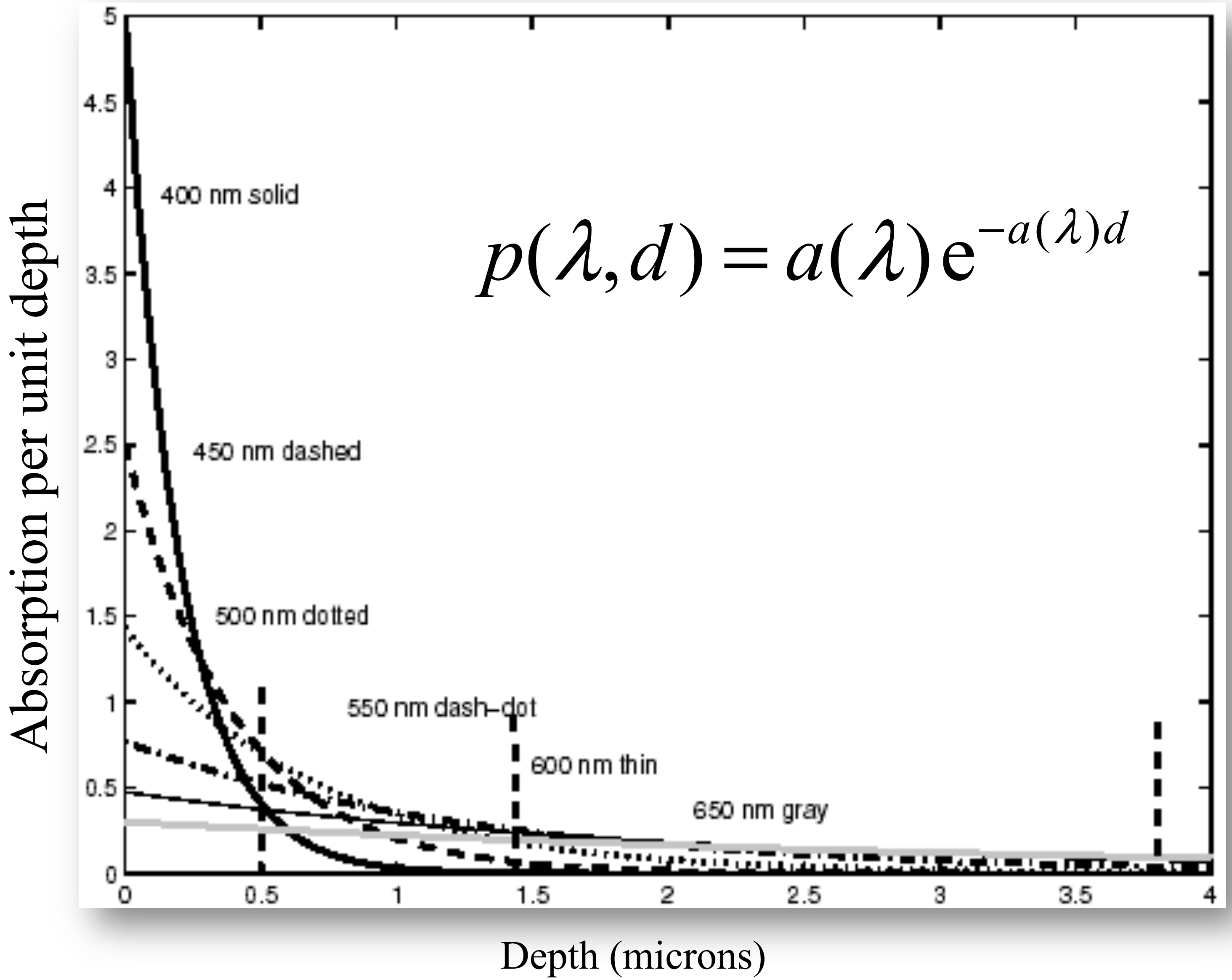
Photon penetration into silicon

$$p(\lambda, d) = a(\lambda)\mathrm{e}^{-a(\lambda)d}$$

Each photon goes somewhere

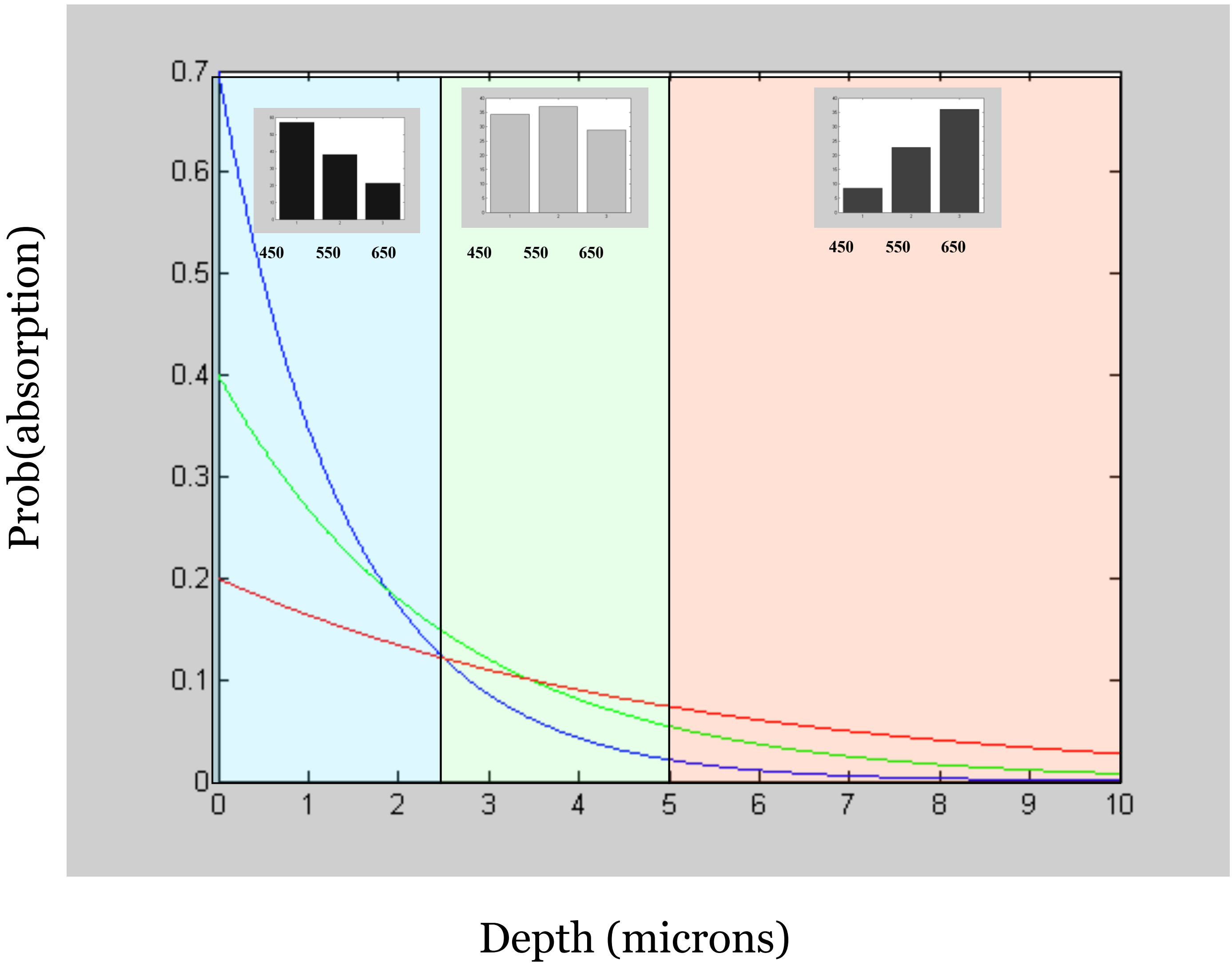




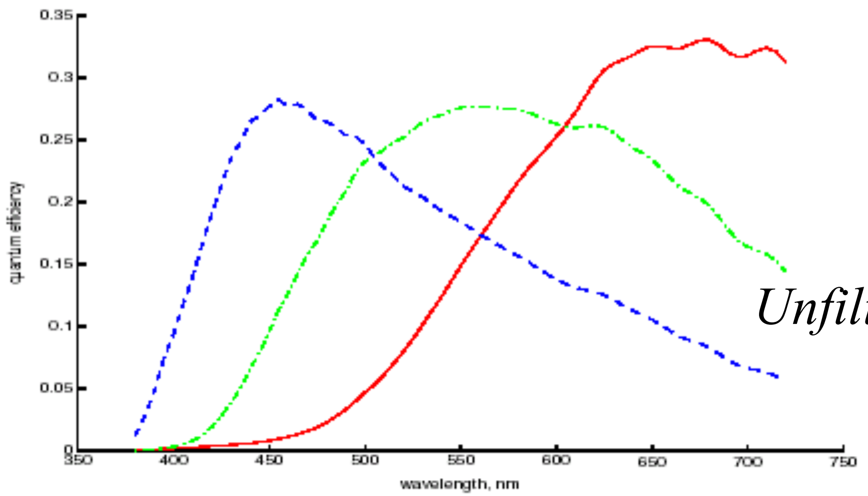


$$p(\lambda, d) = a(\lambda)\,\mathrm{e}^{-a(\lambda)d}$$

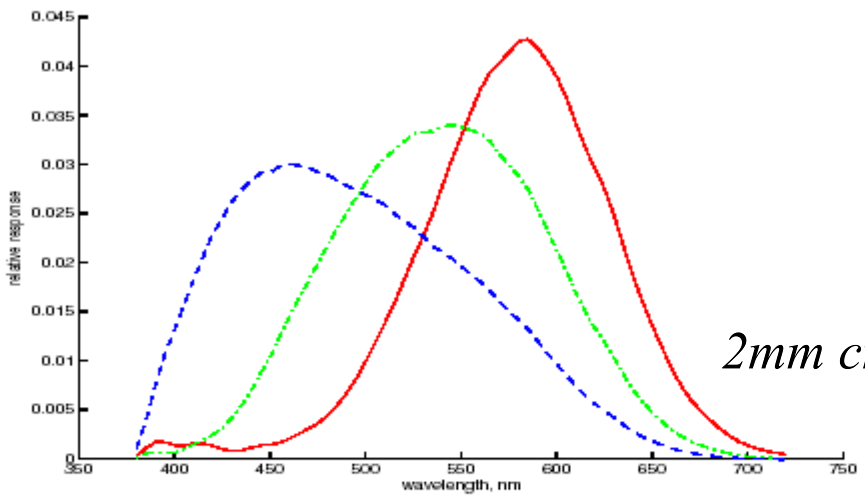
Foveon X3 Pixel (Triple-Well)



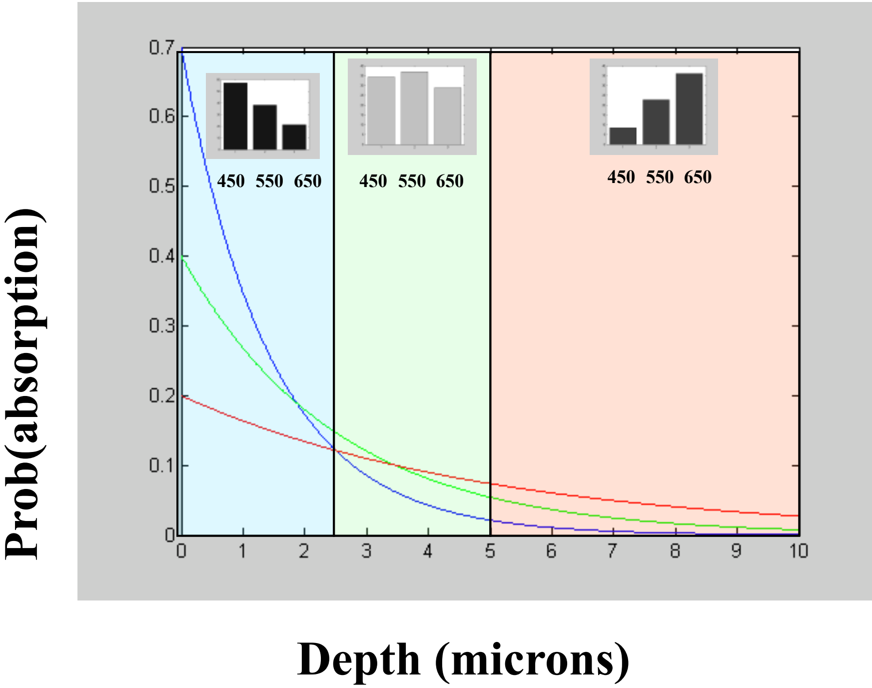
Quantum efficiencies of the three wells (Foveon)



Unfiltered



2mm cm500 IR filter



Having more photosites makes the luminance image sharper

<u>Foveon marketing</u>

Is slightly higher resolution what people really wanted?

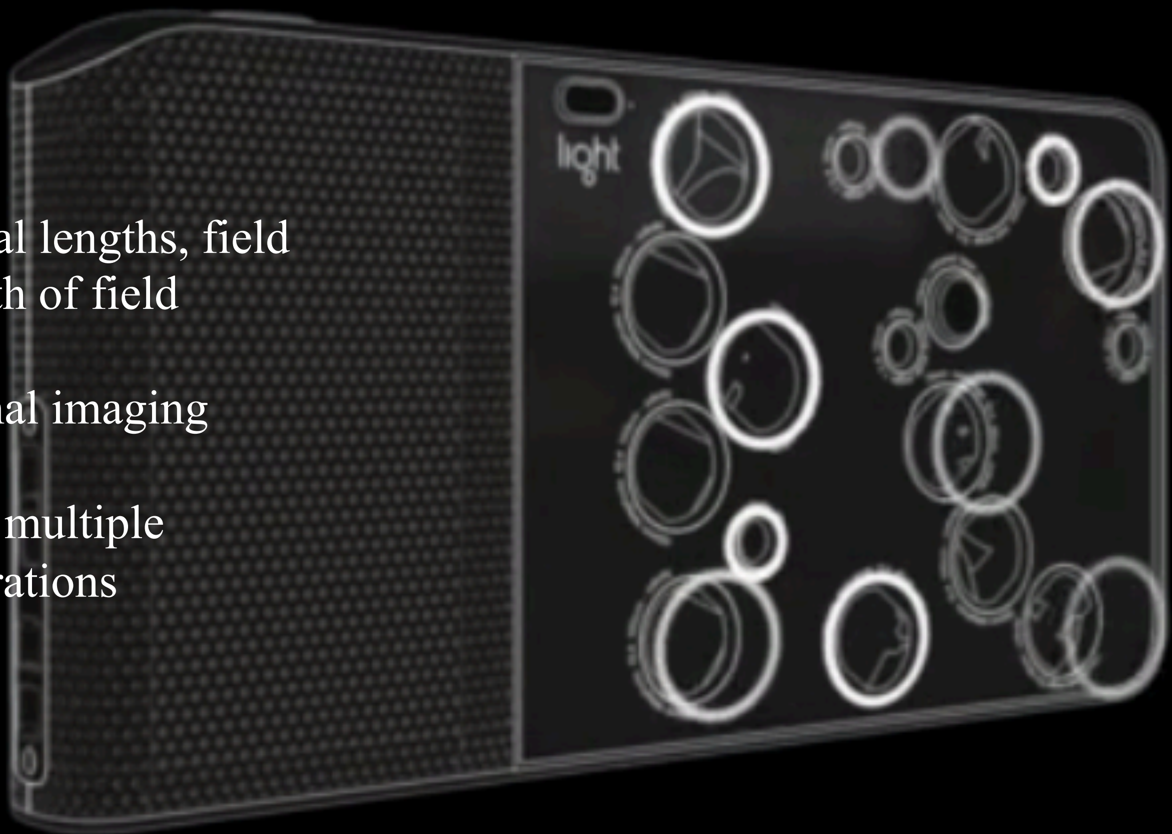
Bayer

Bayer + blur

Foveon X3

New high-end camera designs: Light L16

Choose 10 of 16

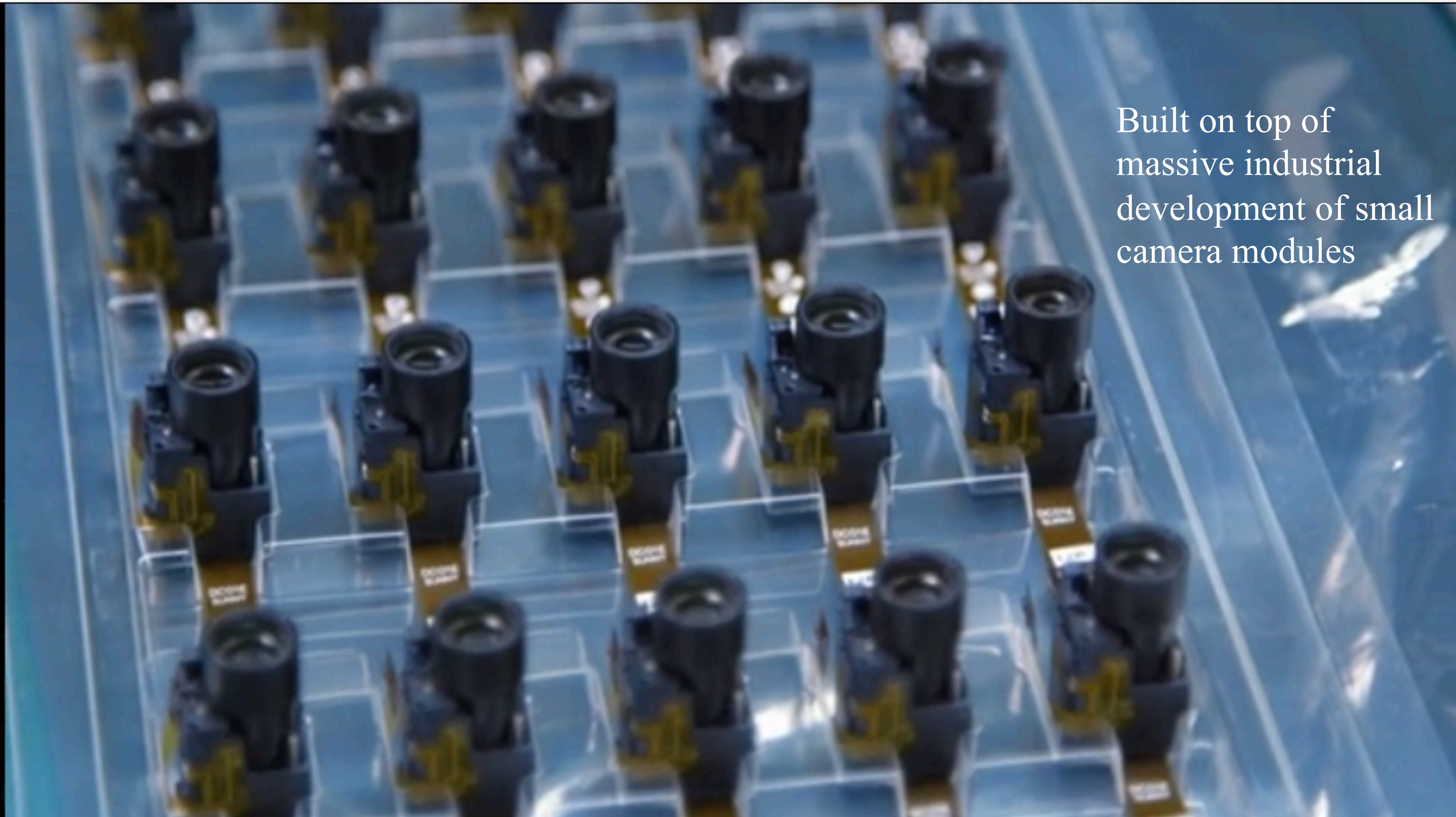


Multiple focal lengths, field of view, depth of field

Computational imaging

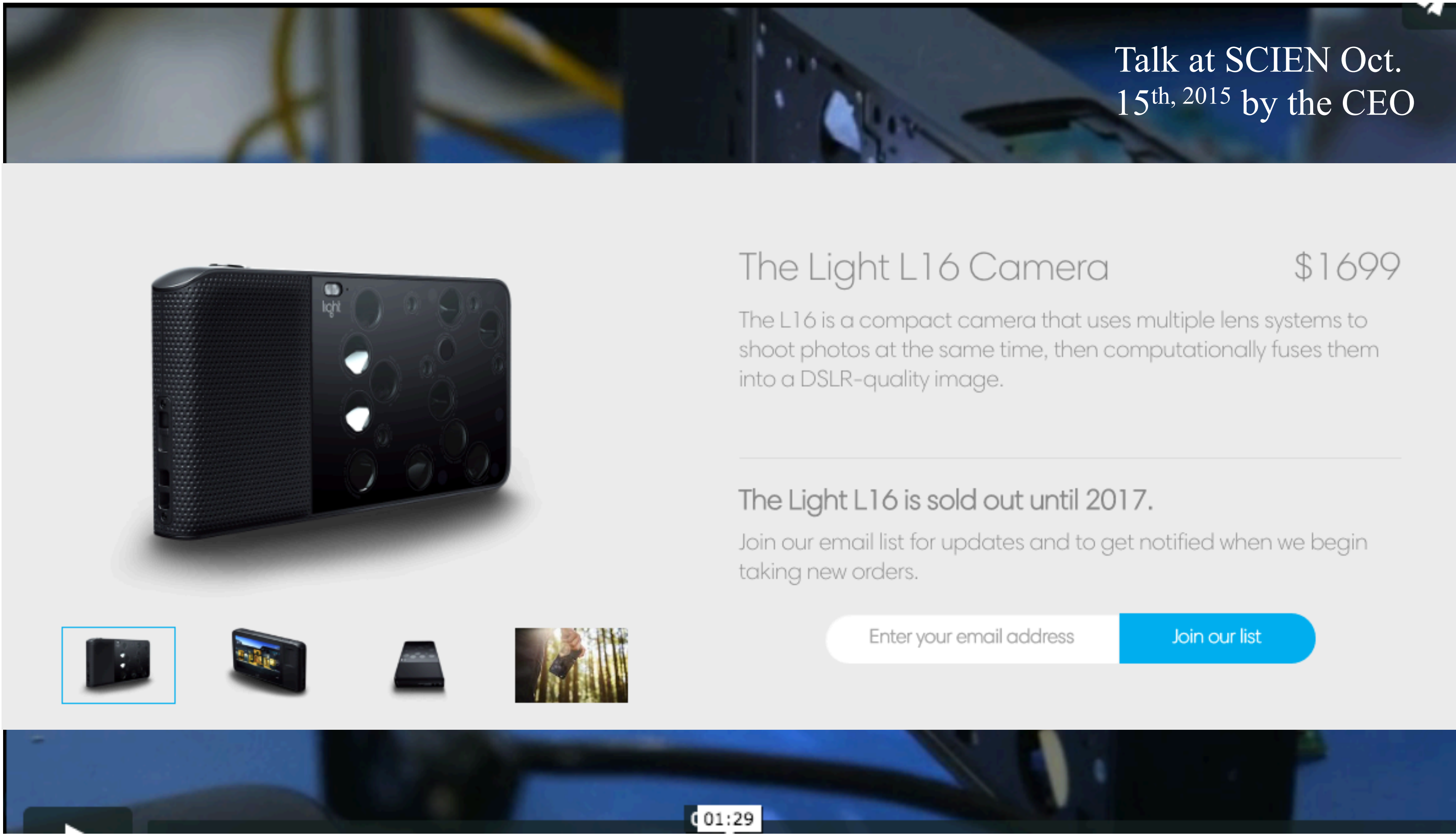
Potential for multiple exposure durations

Taking advantage of camera module scaling

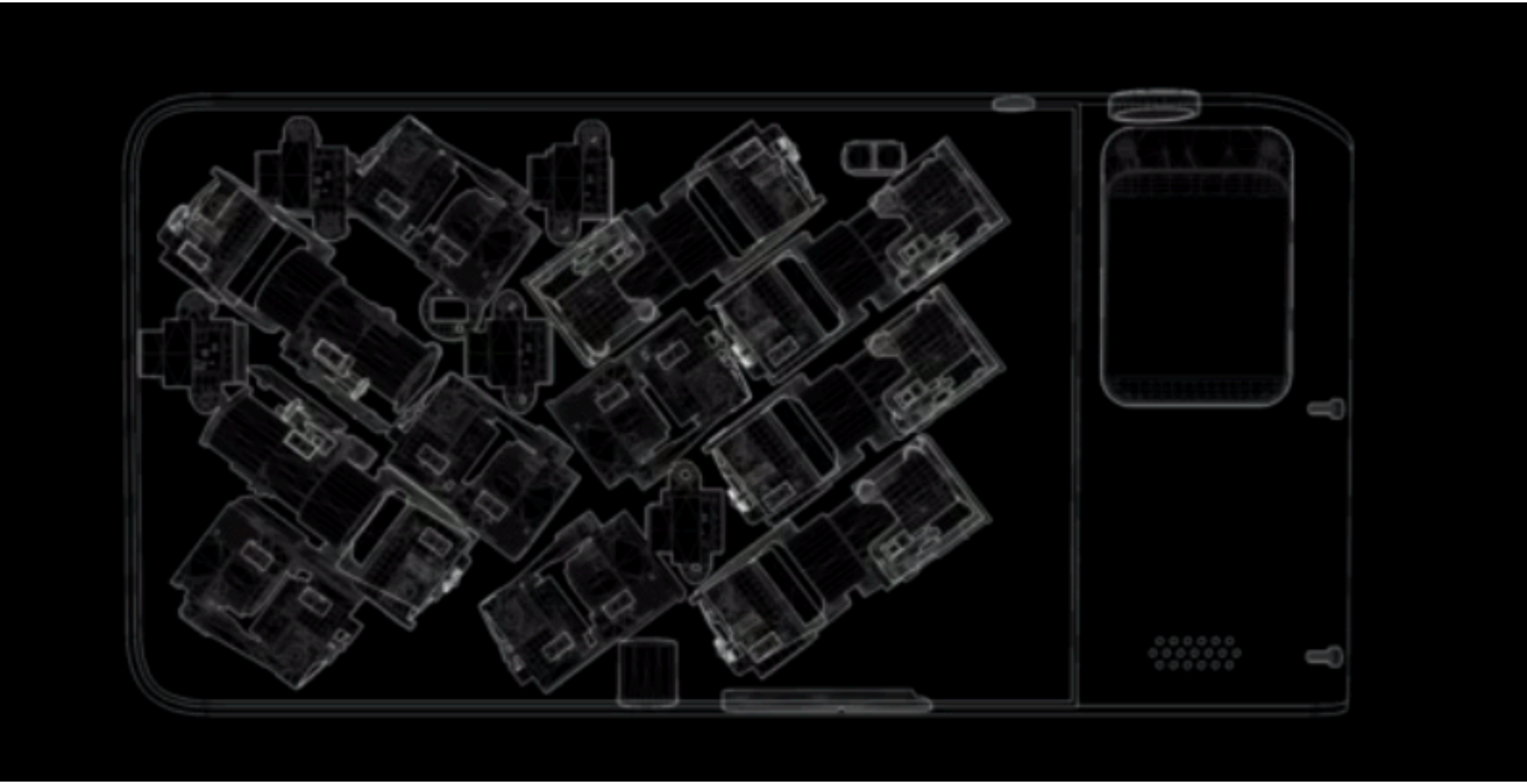


Light.co status

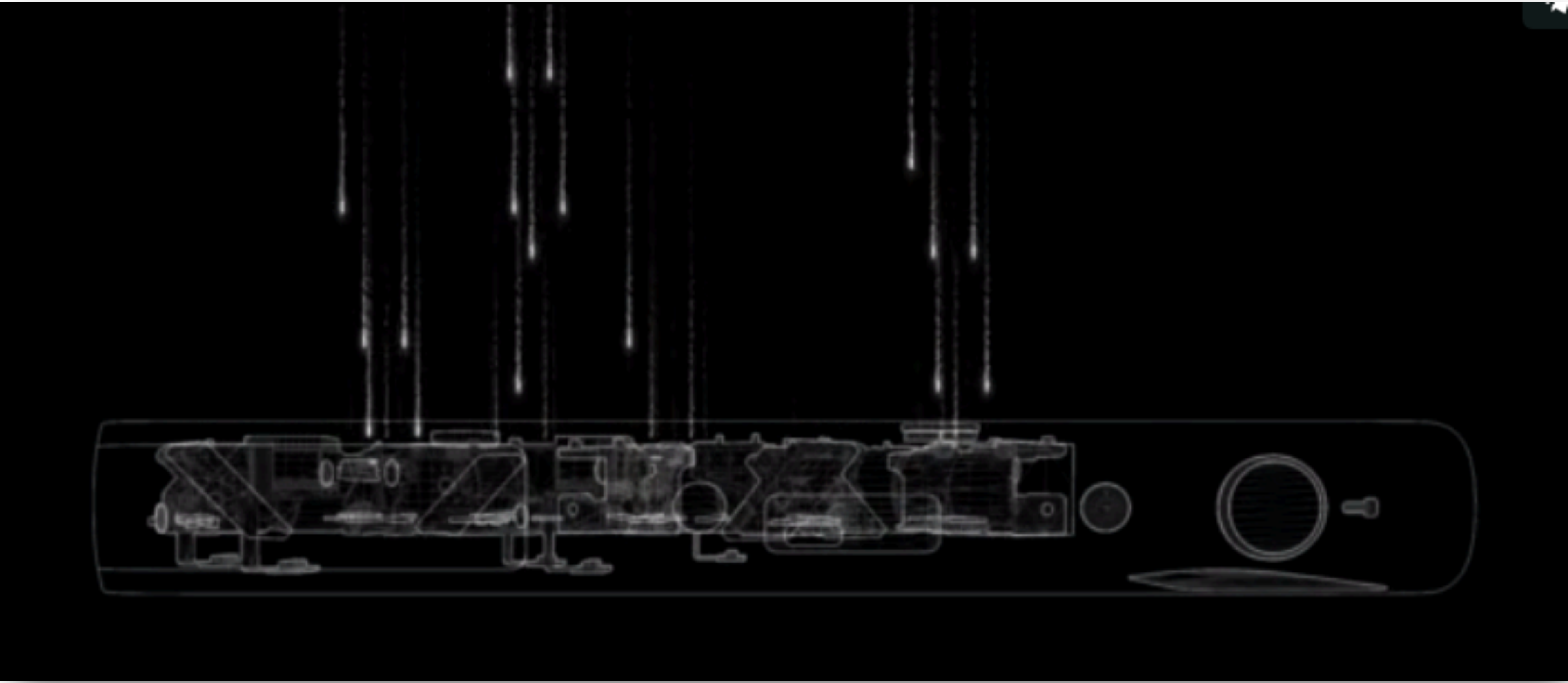
Talk at SCIEN Oct. 15th, 2015 by the CEO



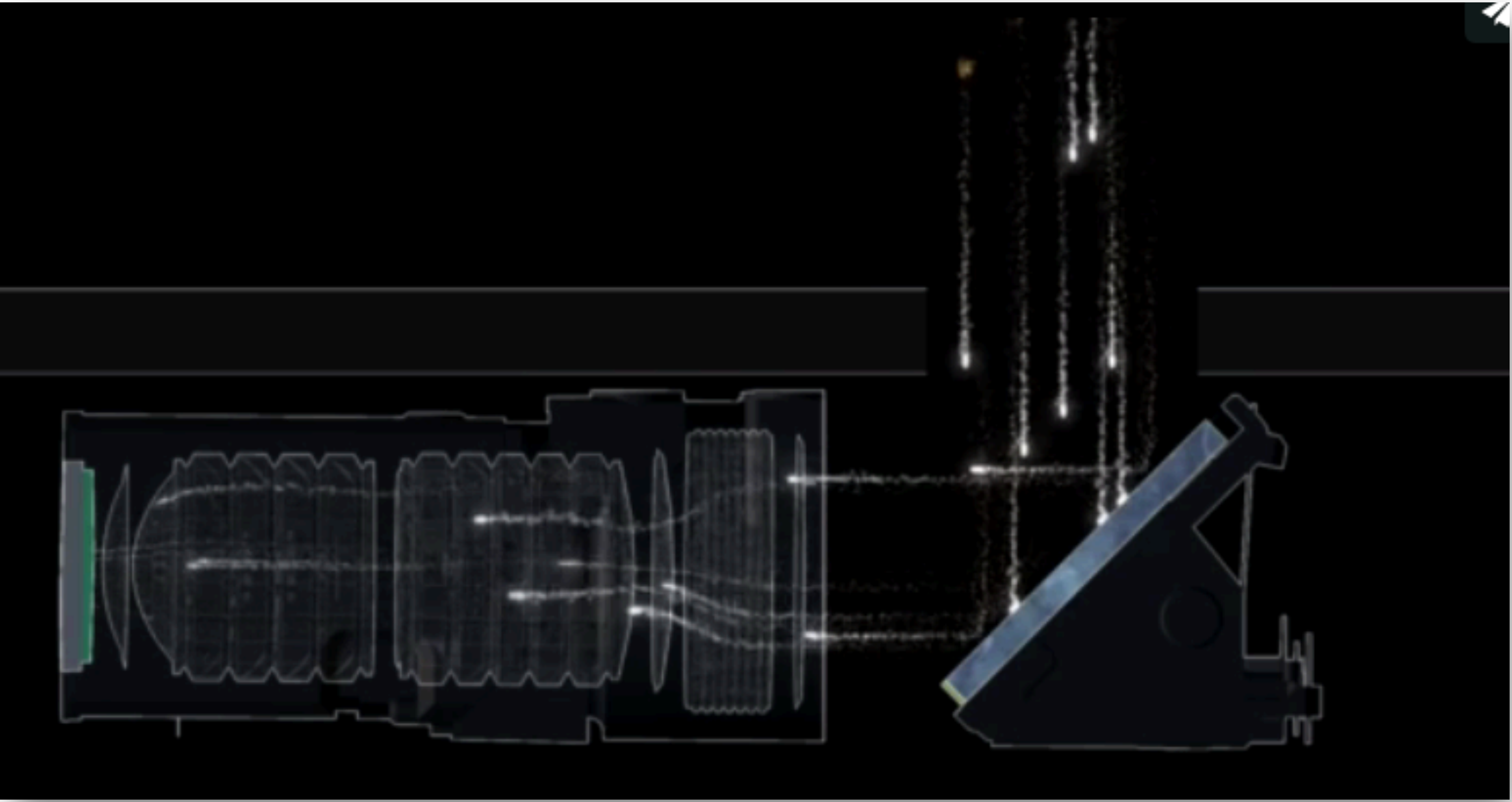
Innovative design using movable mirrors



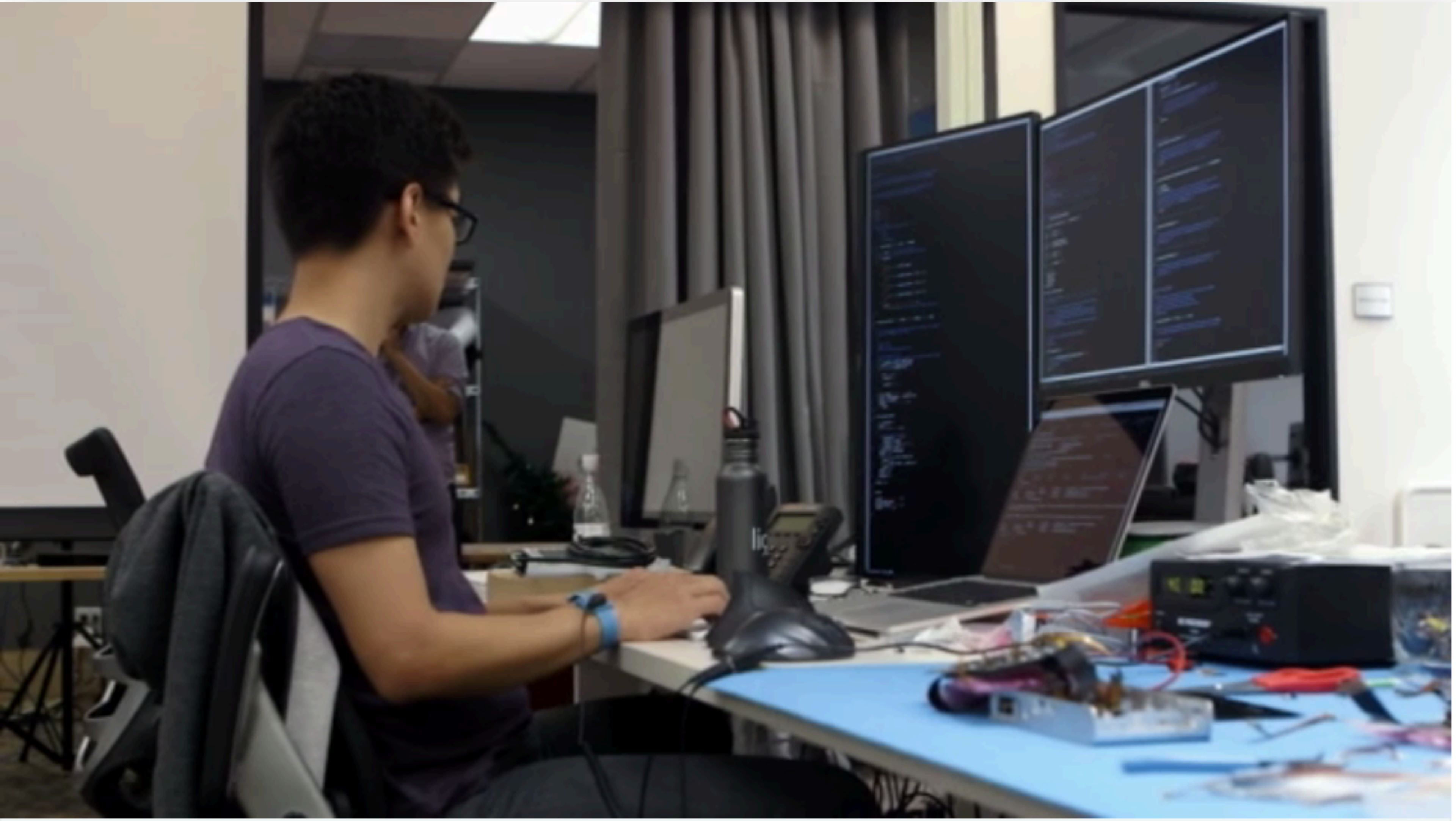
Innovative design using movable mirrors



Innovative design using movable mirrors



Put together by computational imaging ideas

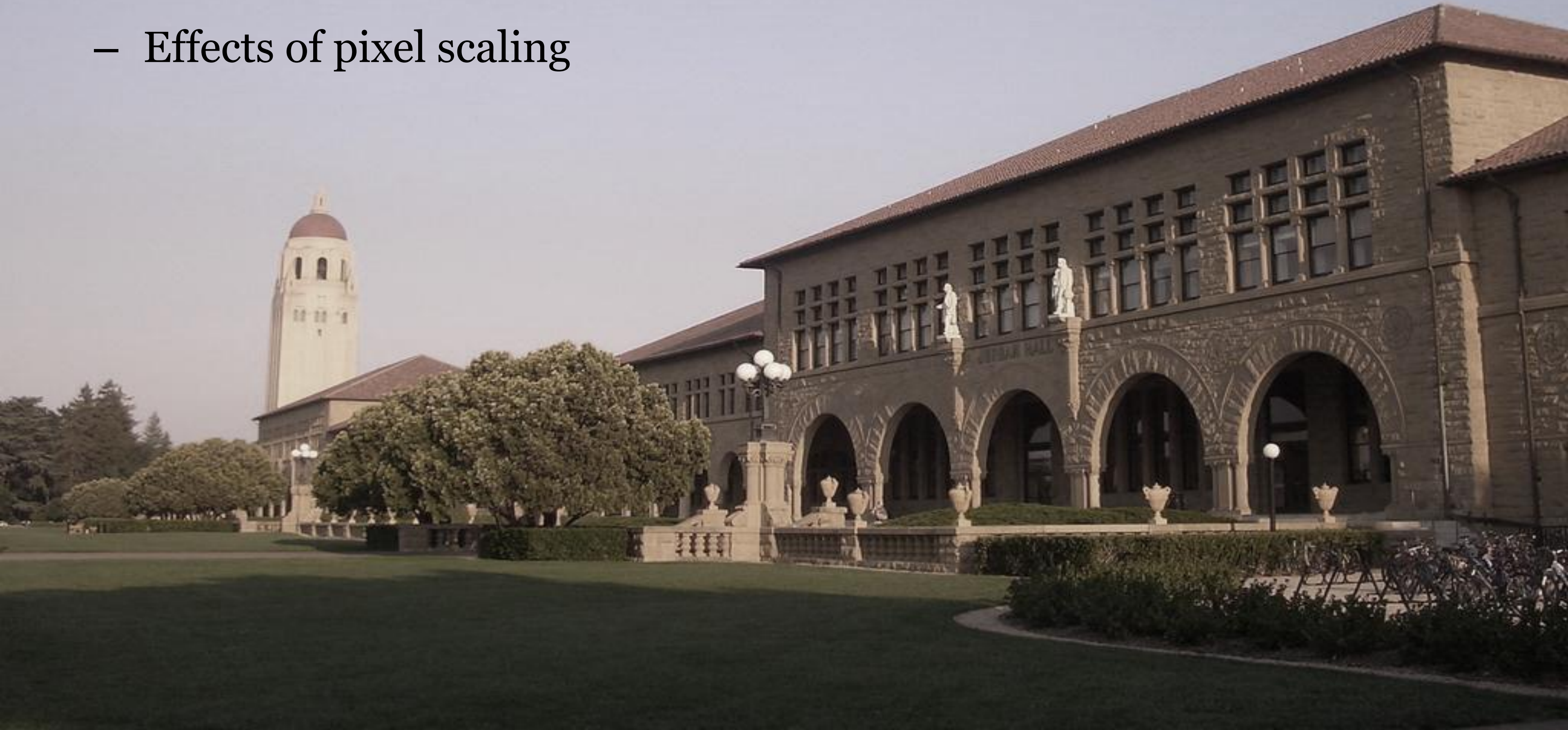


Is higher resolution and controlled properties of depth of field and bokeh[1] features in a cell phone form factor what people really want?

1. Bokeh: The visual quality of the out-of-focus areas of a photographic image, especially as rendered by a particular lens (pronounced both ways, in practice).

Pixel optics

- Light inside imagers
  - # photons at the pixel is finite
  - Light collecting and guiding in pixels
  - Effects of pixel scaling



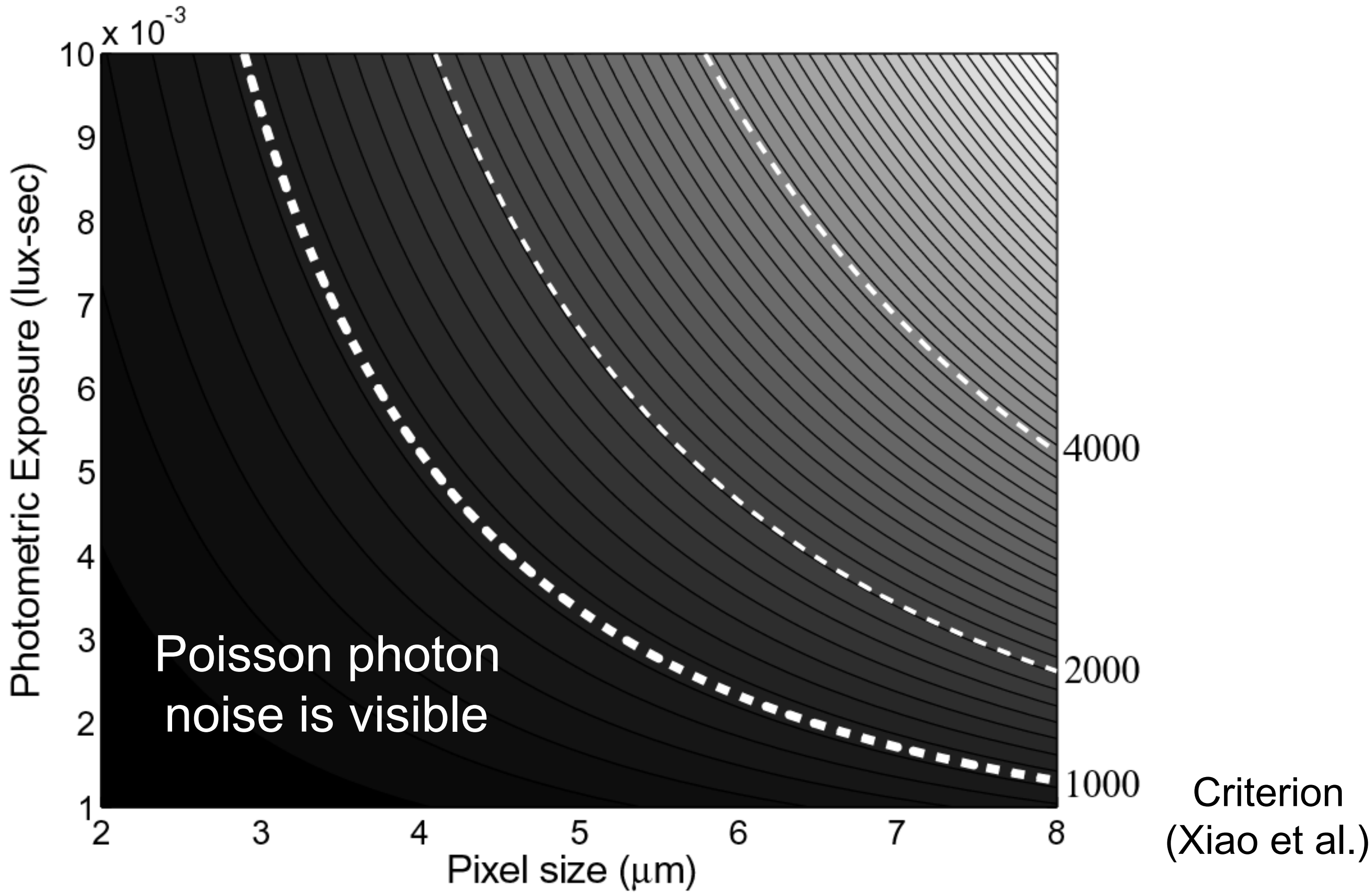
1,000 photon criterion (Xiao et al.)

3% contrast-threshold for spatially uniform photon noise
Photon noise becomes visible at 1,000 photons
(SNR = $1000/\sqrt{(1000)}$ = 33:1)

Figure 3: A pair of stimuli was displayed side by side: one was a uniform disk and the other one with noise superimposed.

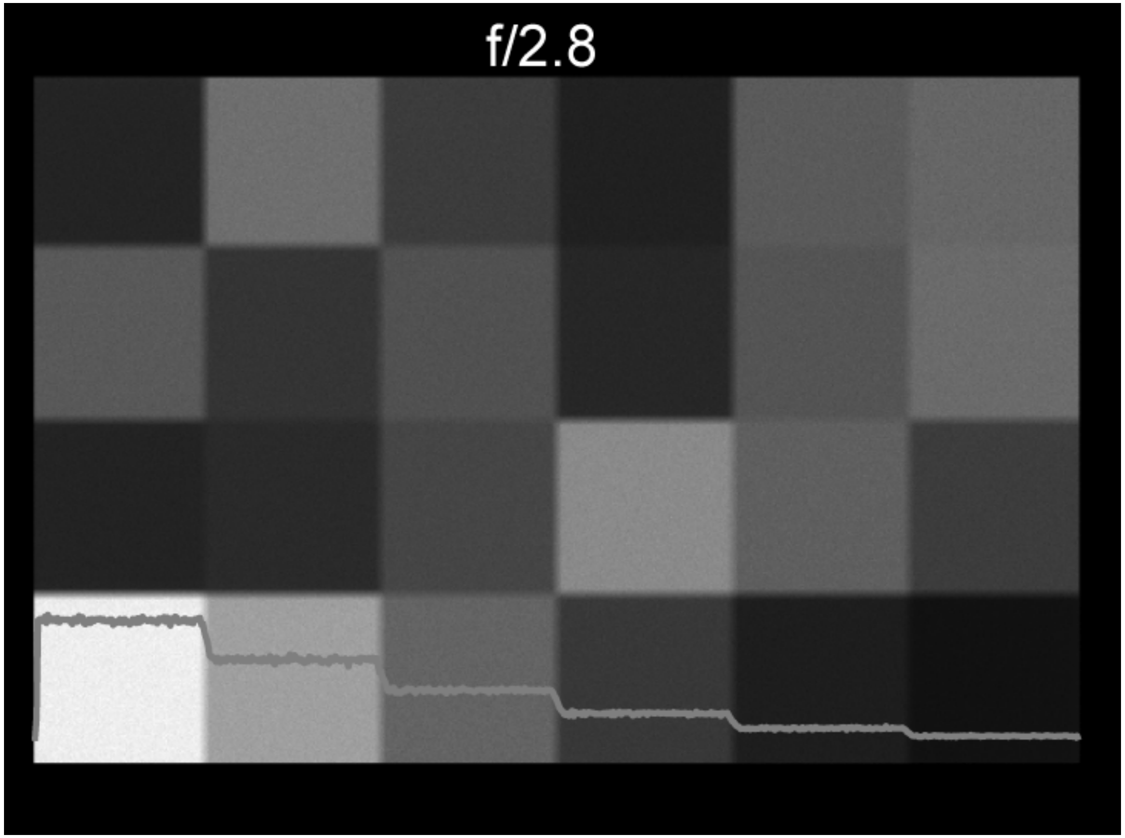
F. Xiao et al., EI 5678-07 (2005)

Photon noise: Photons per pixel



P. B. Catrysse et al., EI 5678-01 (2005)

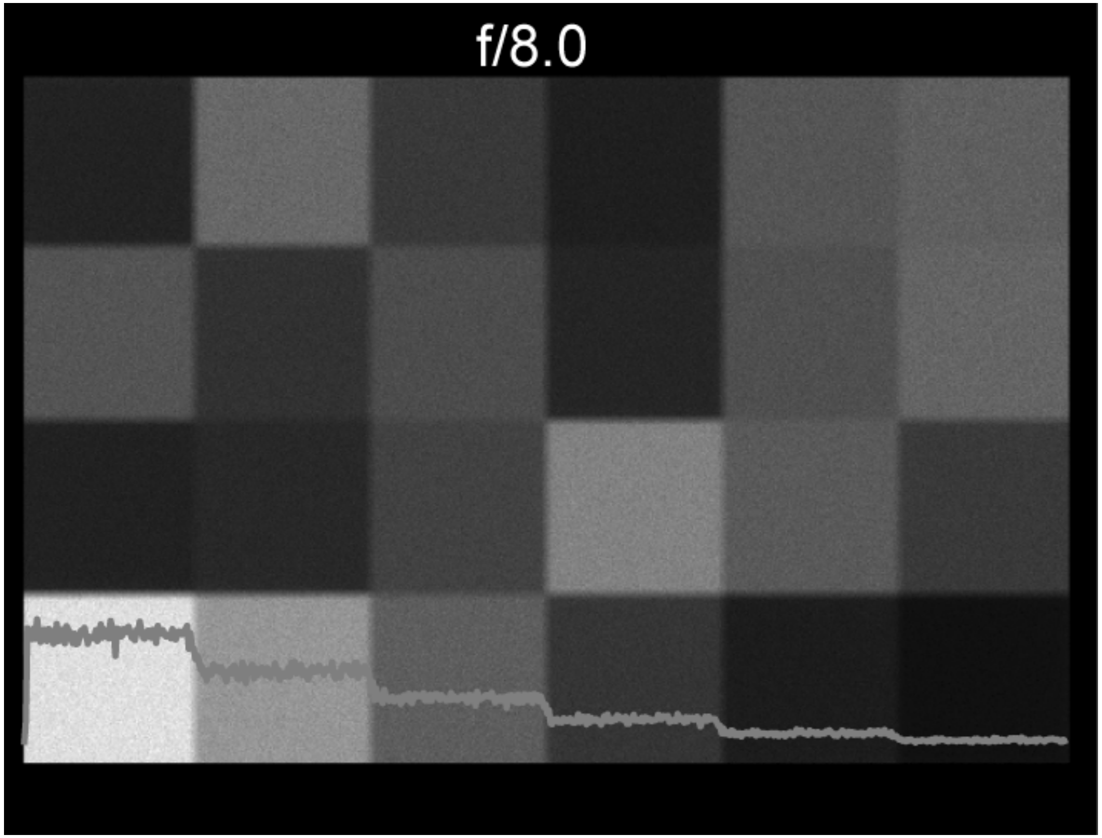
Photon noise: Visibility (monochrome)



Luminance range: 12 - 1.25 cd/m^2
Exposure time: 10 ms

P. B. Catrysse et al., EI 5678-01 (2005)

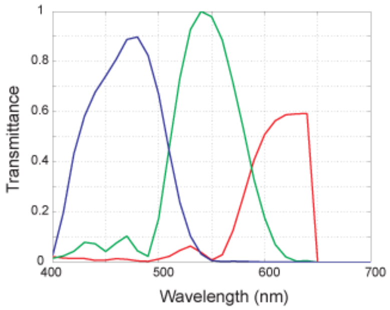
Photon noise: Visibility (monochrome)



Luminance range: 12 - 1.25 cd/m^2
Exposure time: 10 ms

P. B. Catrysse et al., EI 5678-01 (2005)

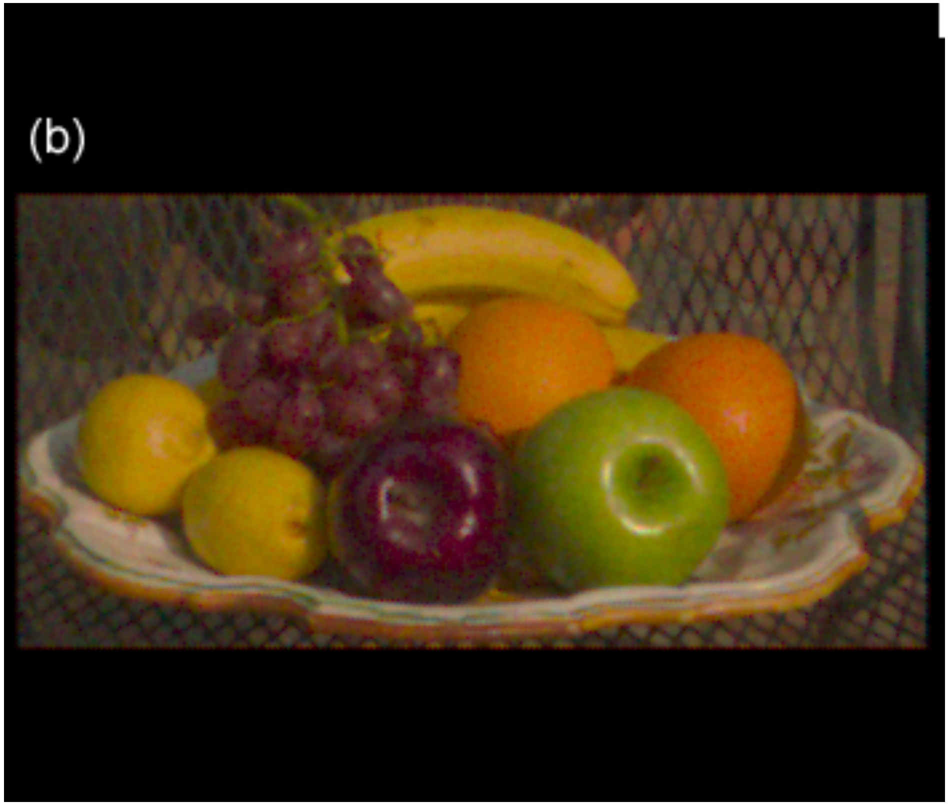
Photon noise: Visibility (color)



Additional processing steps usually amplify noise in color images

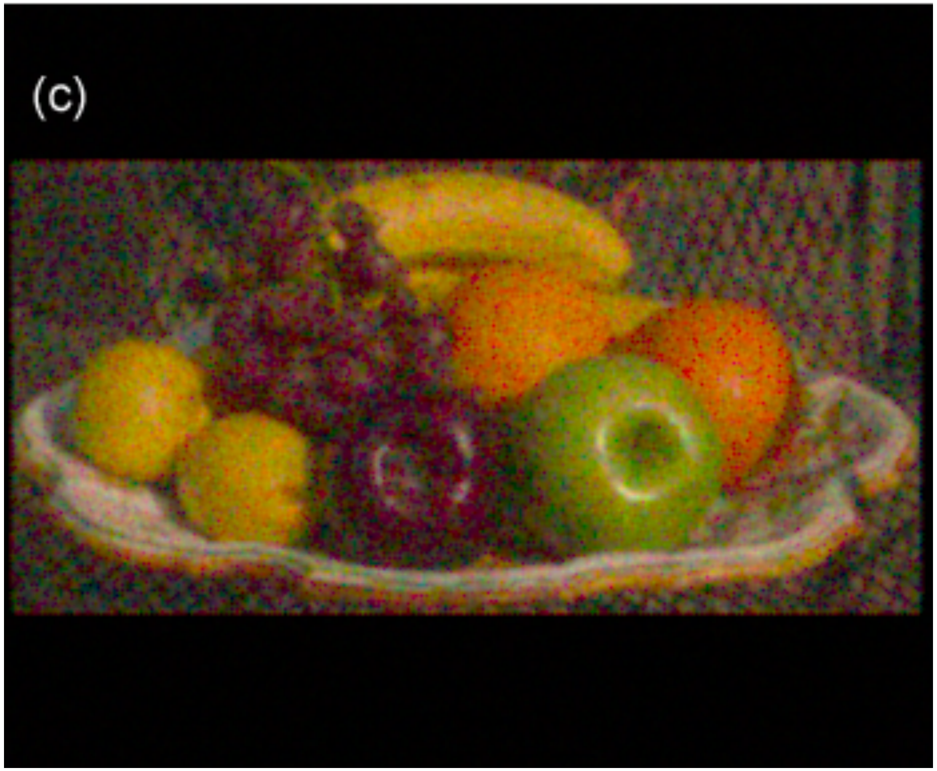
Mean luminance: 100 cd/m^2
Exposure time: 10 ms
Imaging lens: f/2.8

Photon noise: Visibility (color)



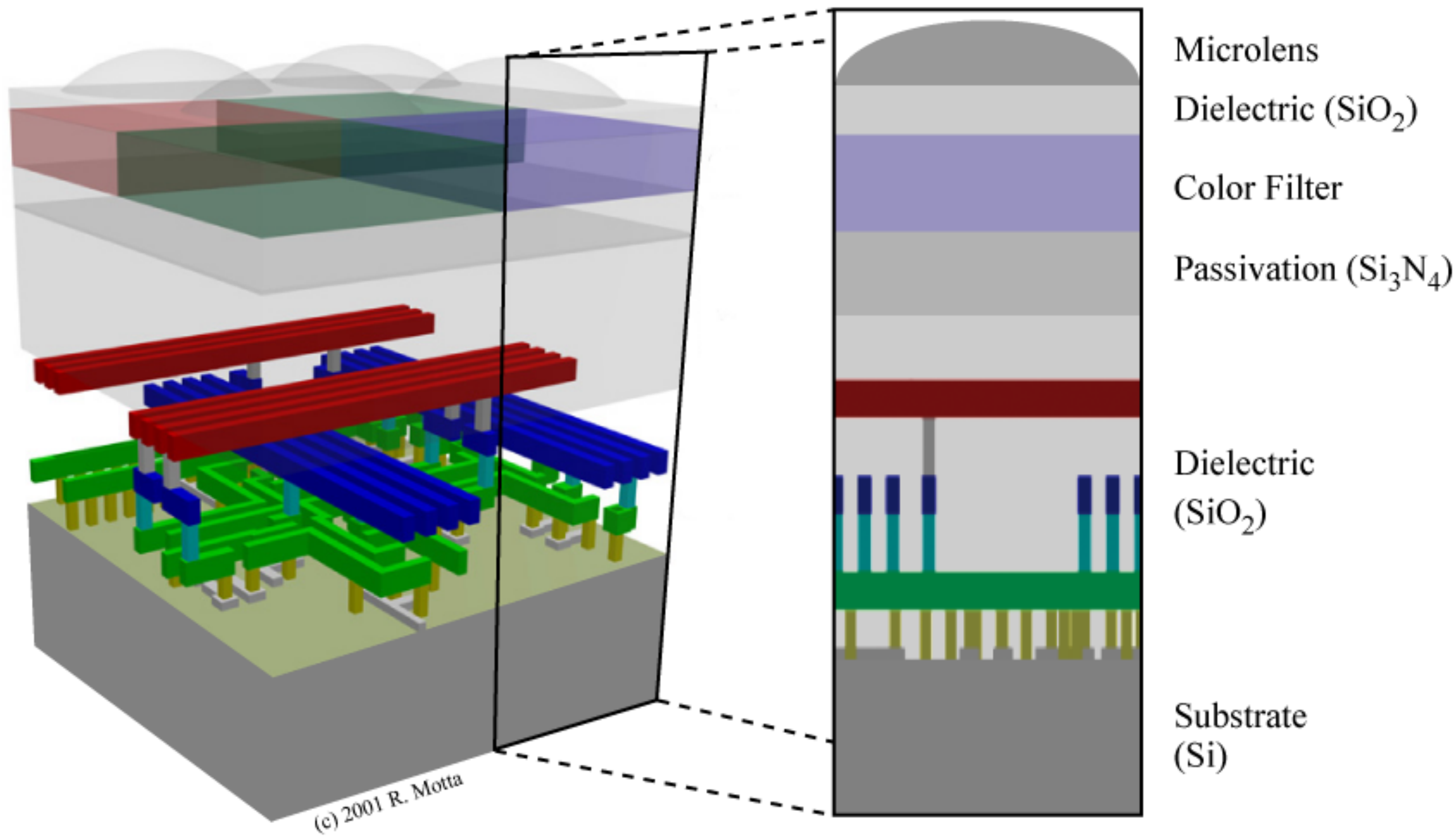
Mean luminance: 10 cd/m^2
Exposure time: 10 ms
Imaging lens: f/2.8

Photon noise: Visibility (color)

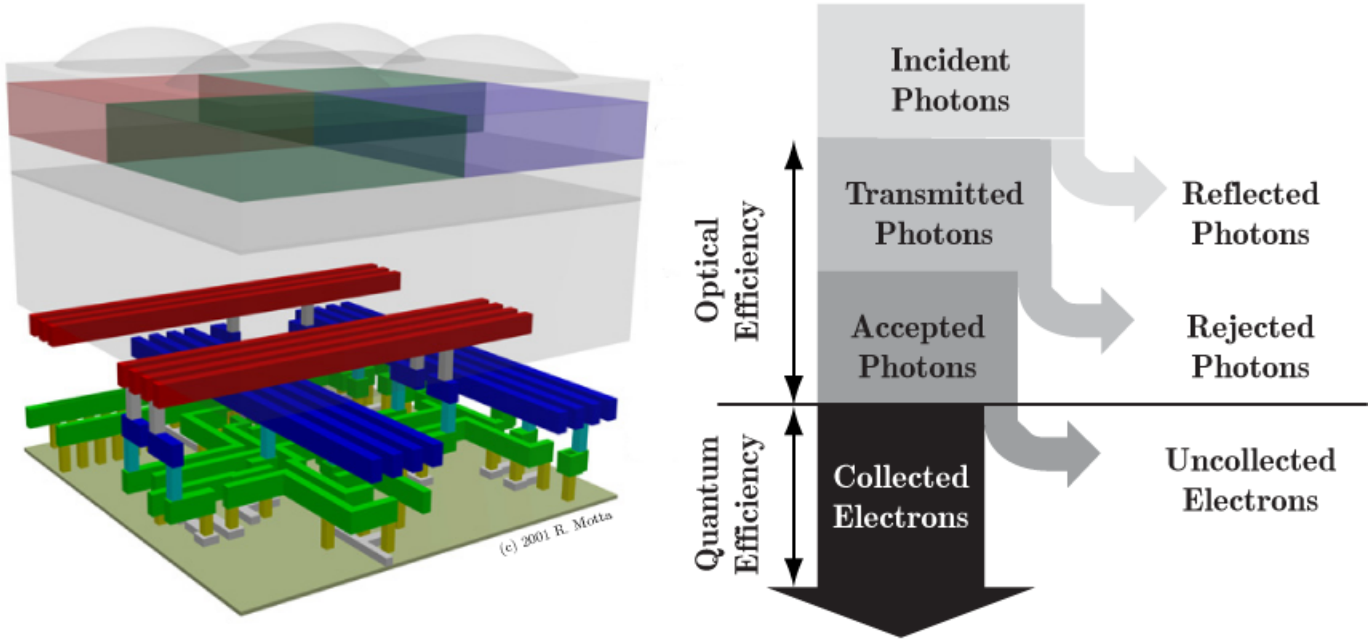


Mean luminance: 10 cd/m^2
Exposure time: 10 ms
Imaging lens: f/8.0

Typical image sensor pixel



Pixel optics: Capture every photon!



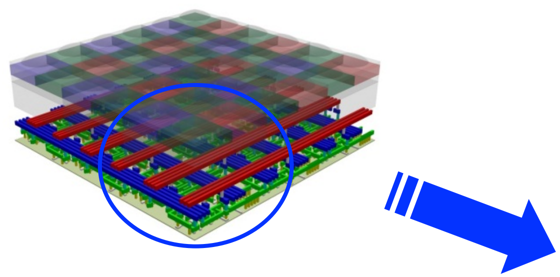
- Pixel QE = Optical Efficiency (OE) + internal QE
- Optical X-talk (OX) (in addition to electrical X-talk)
- Collecting and guiding: maximize OE & minimize OX

P. B. Catrysse *et al.*, JOSA A, Vol. 19, No. 8 (2002)

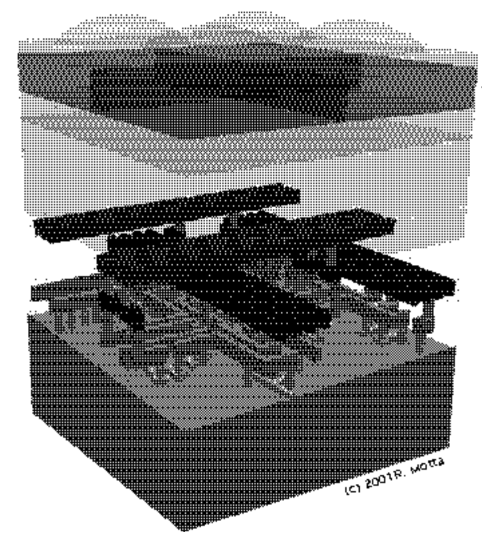
Optics of digital camera systems

Imaging optics
(>>l)

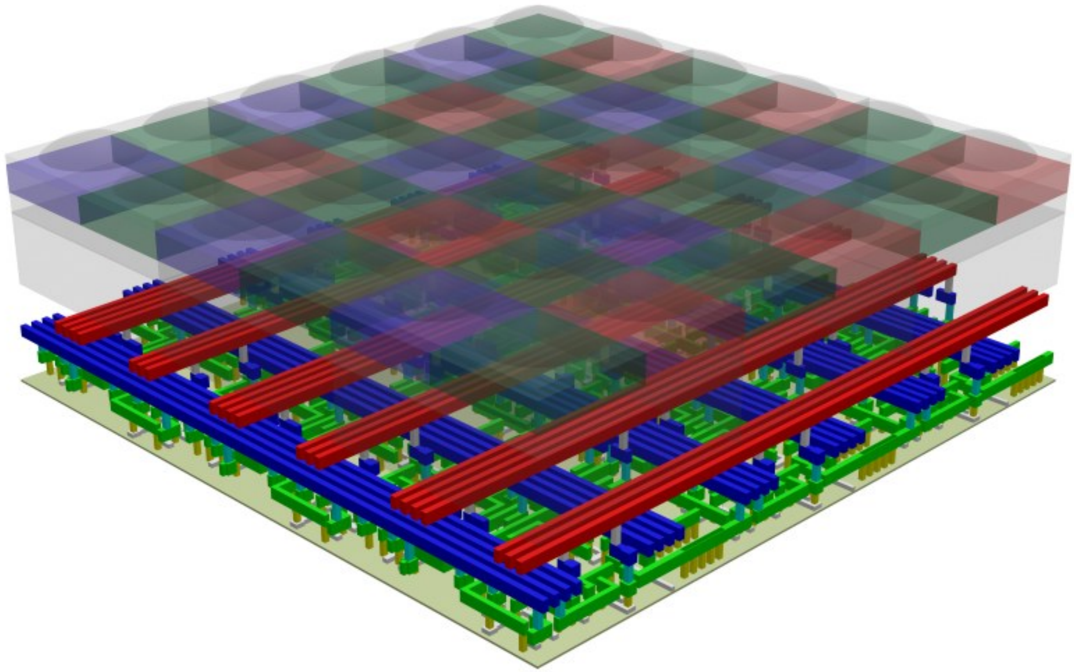
Collecting optics
(>l)



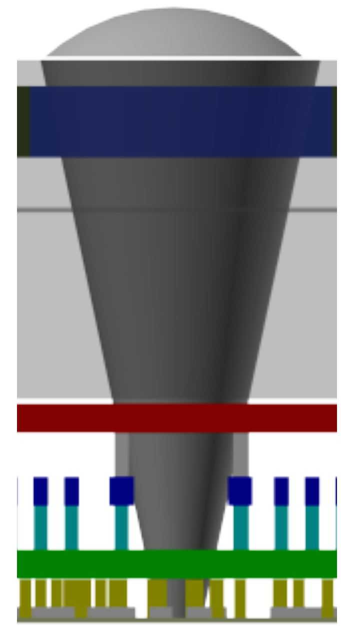
Guiding optics
(<l)



Collecting optics: The basics



$$G = 2NA_{Lens}\, w$$



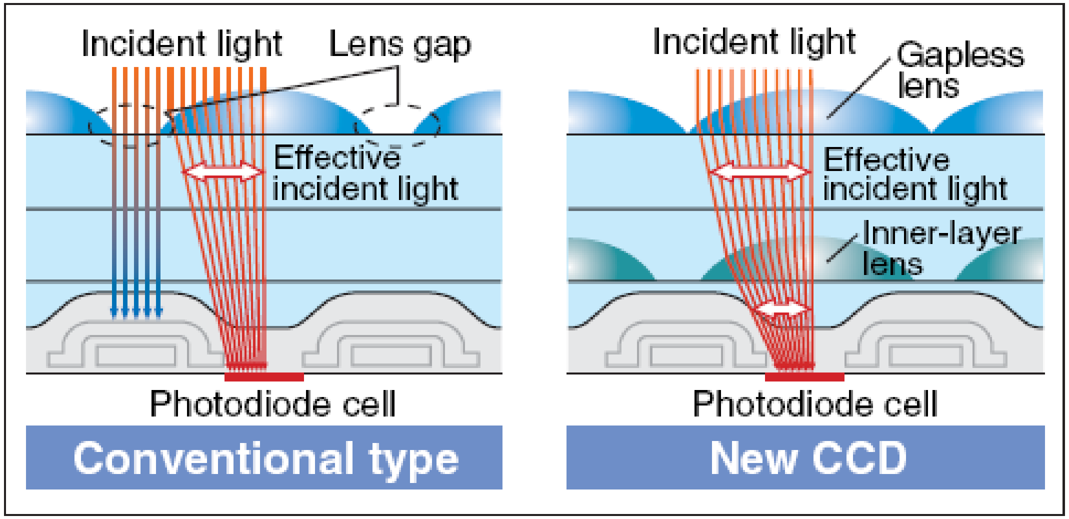
$$G = 2NA_{\mu Lens}\, w_{Diode}$$

- Etendue G, Concentration C

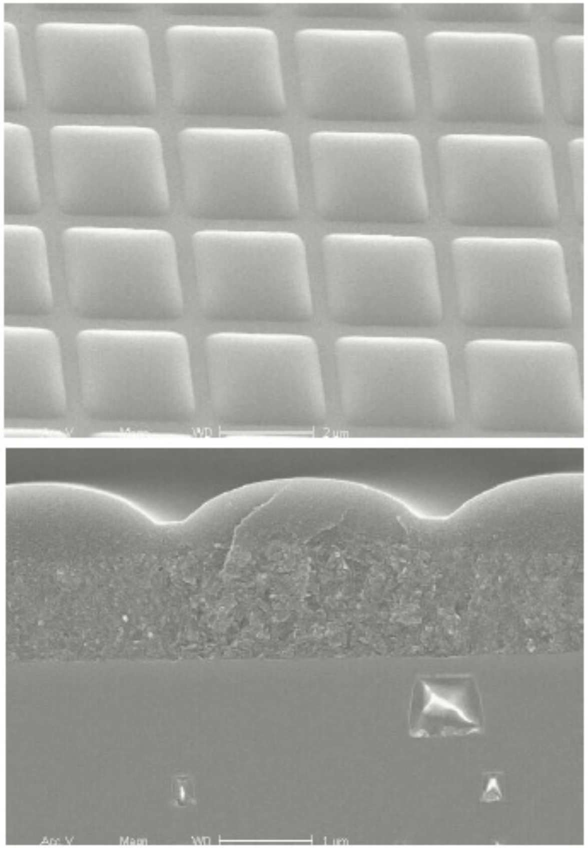
$$C = \frac{NA_{\mu Lens}}{NA_{Lens}} \approx \frac{n_{\mu Lens}}{n_{Lens}} \frac{f/\#_{Lens}}{f/\#_{\mu Lens}}$$

Collecting optics: Examples

- Micro-lens arrays
  - Single → double
  - Circular → gapless
  - Refractive → diffractive/Fresnel



Panasonic CCD technology

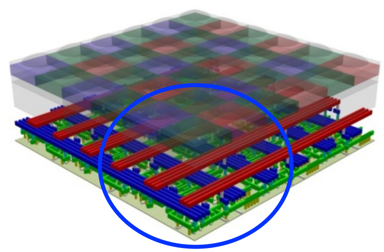


H. Rhodes *et al.*, IEEE (2004)

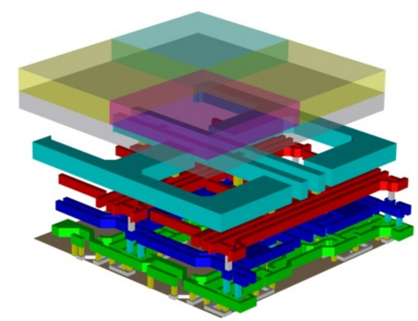
Optics of digital camera systems

Imaging optics
(>>l)

Collecting optics
(>l)

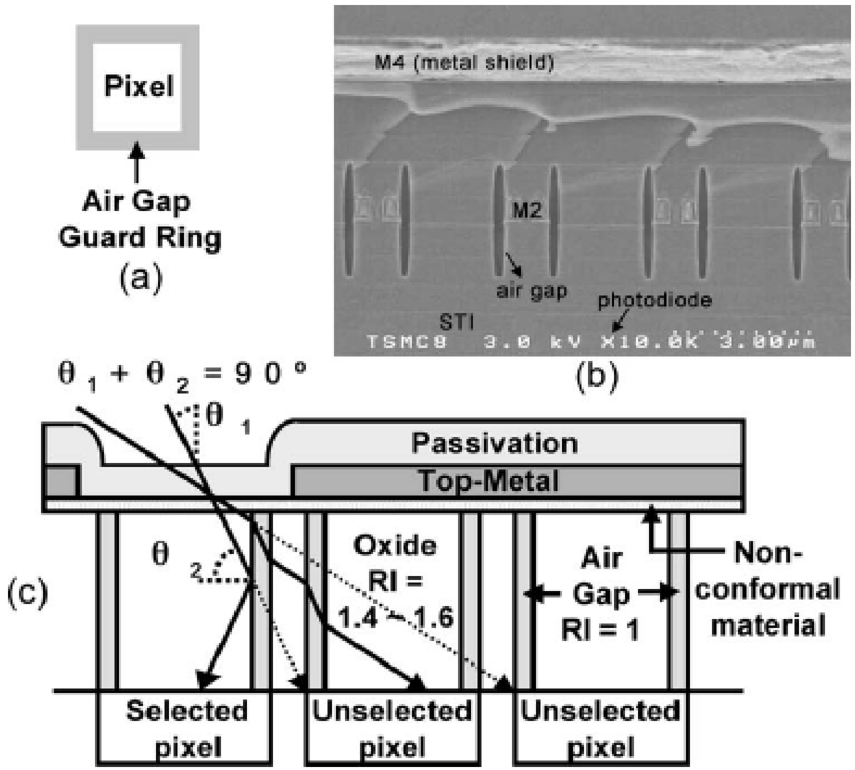


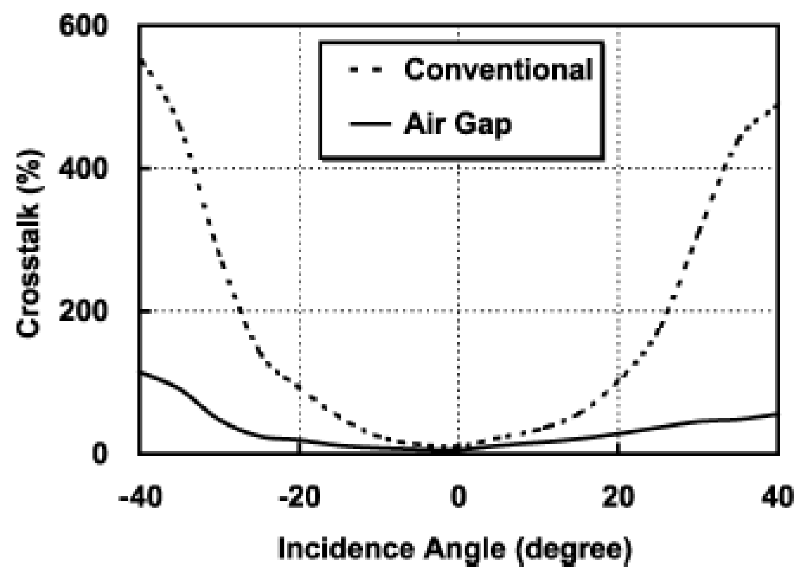
Guiding optics
(<l)



Guiding optics: Examples

- Air gap “Guard ring”: TIR waveguide





T. H. Hsu *et al.*, IEEE EDL 25, 6 (2004)

Pixel scaling = Optical problems

- Motivations for reducing pixel size
  - Decrease cost per sensor
  - Increase number of pixels per area (spatial resolution)
- Reducing pixel size leads to:
  - Less light incident on each pixel
    - Noise visible when less than 1000 photons
  - More diffraction, spreading out light
    - Decrease in Optical Efficiency (OE)
    - Increase in Optical Crosstalk (OX)

Catrysse, P.B. and Wandell, B.A., Proc. SPIE 5678, 1-13 (2005)
Xiao, F. *et al*., Proc. SPIE 5678, 75-84 (2005)

Definitions (Fuji, and others)

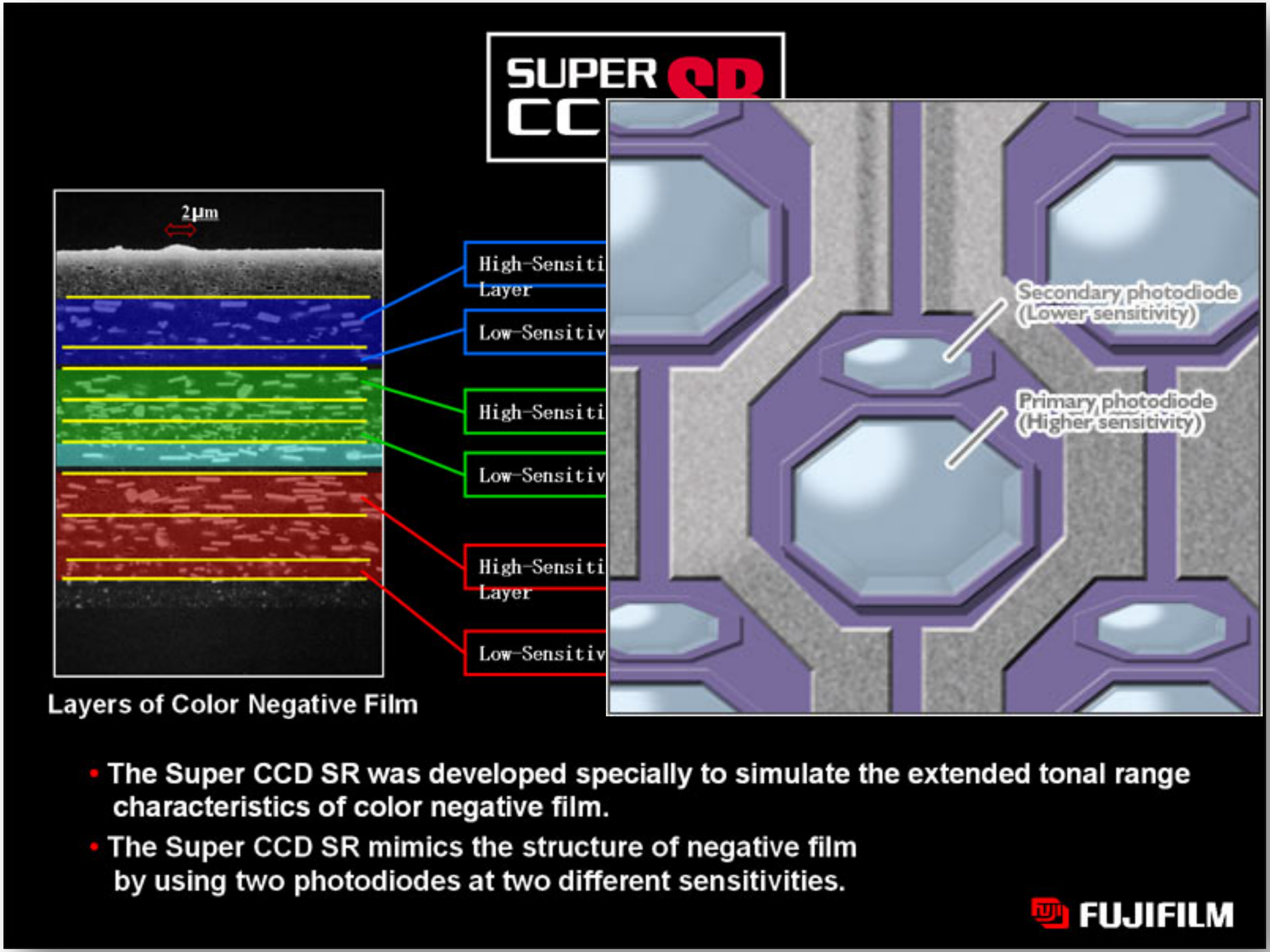
Photodiode: A single, light-sensing element on a sensor.

Photosite: The area on a sensor where the light from one point of the image is received. The light entering the photosite passes through one microlens and one color filter. With a traditional sensor, there is one photodiode beneath the microlens, whereas with Double Honeycomb Super CCD, there are two photodiodes: a primary and a secondary photodiode.

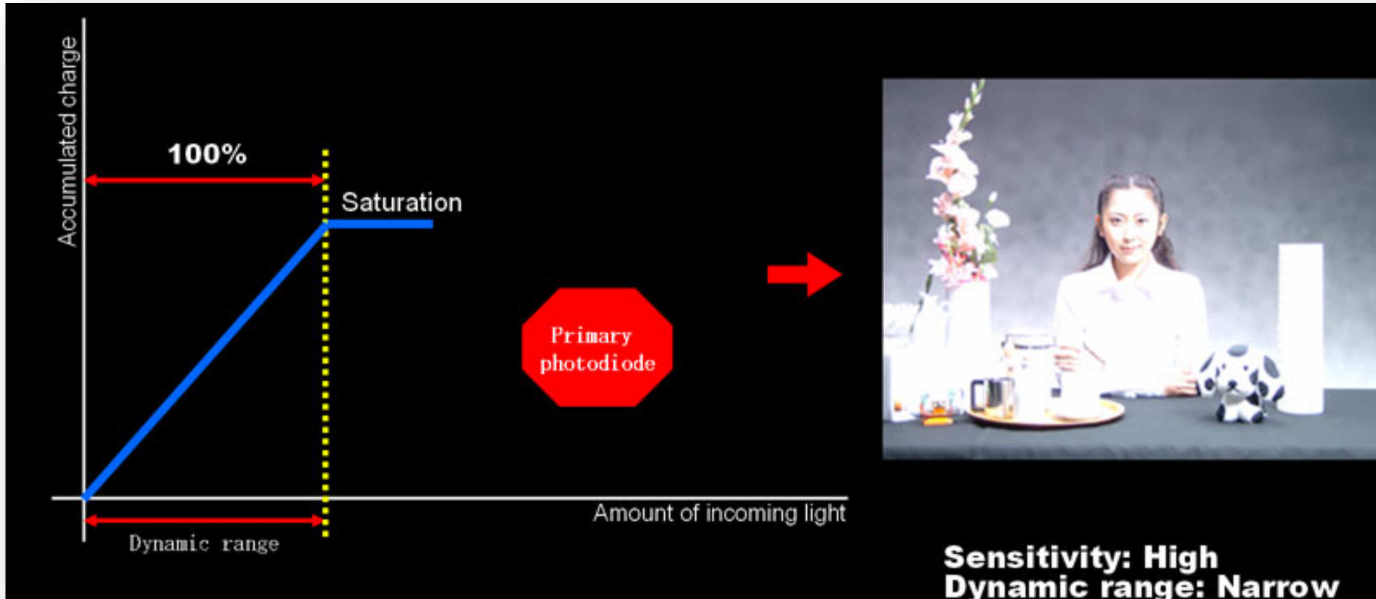
Pixel: A final point of picture information in the outputted image. This normally equates to one printed 'dot', or a square of information on the image when displayed on a monitor.

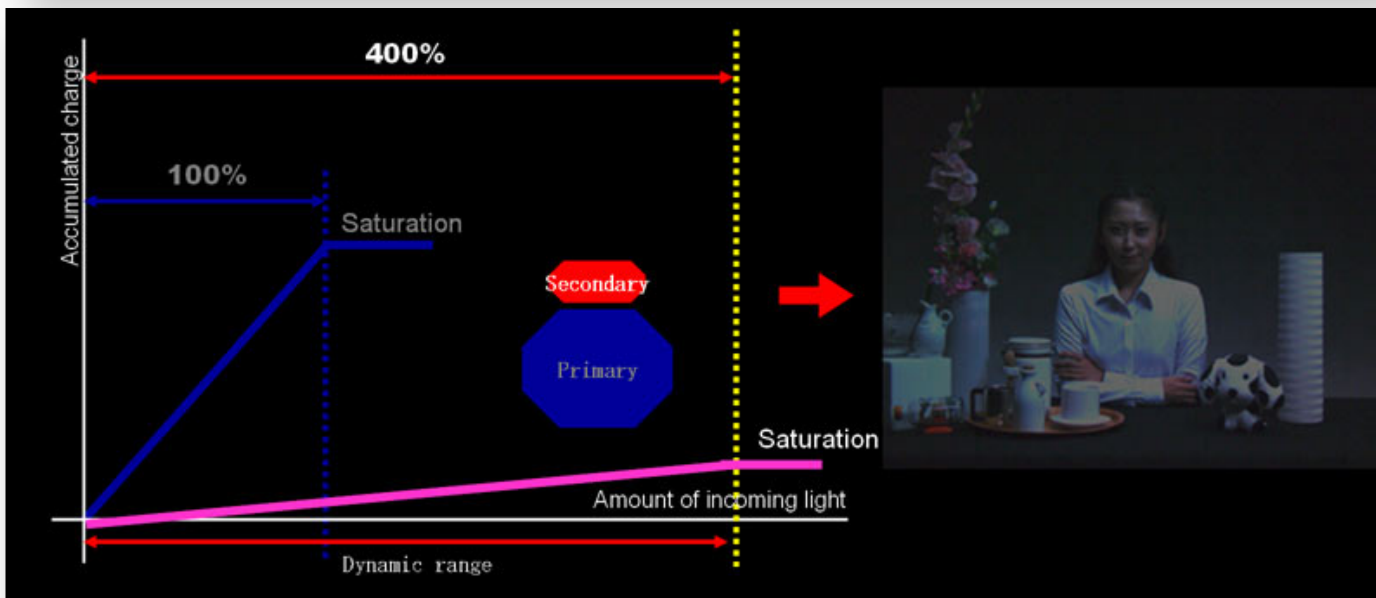
An explanation of Dynamic Range: Unlike the human eye, which can rapidly adjust to differing intensities of light inherent within a contrasty scene, photographic media (film and digital sensors) are constrained by having to align themselves to expose correctly for a given intensity of light. If the camera exposes bright areas correctly, the shadow areas darken out, and detail is lost. Conversely, if the camera exposes shadow areas correctly, the bright areas will appear as burnt-out whites. A camera with good dynamic range will possess the exposure flexibility to accommodate these extremes and expose both bright and shadow areas correctly.

High dynamic range CCD imager (Fuji)



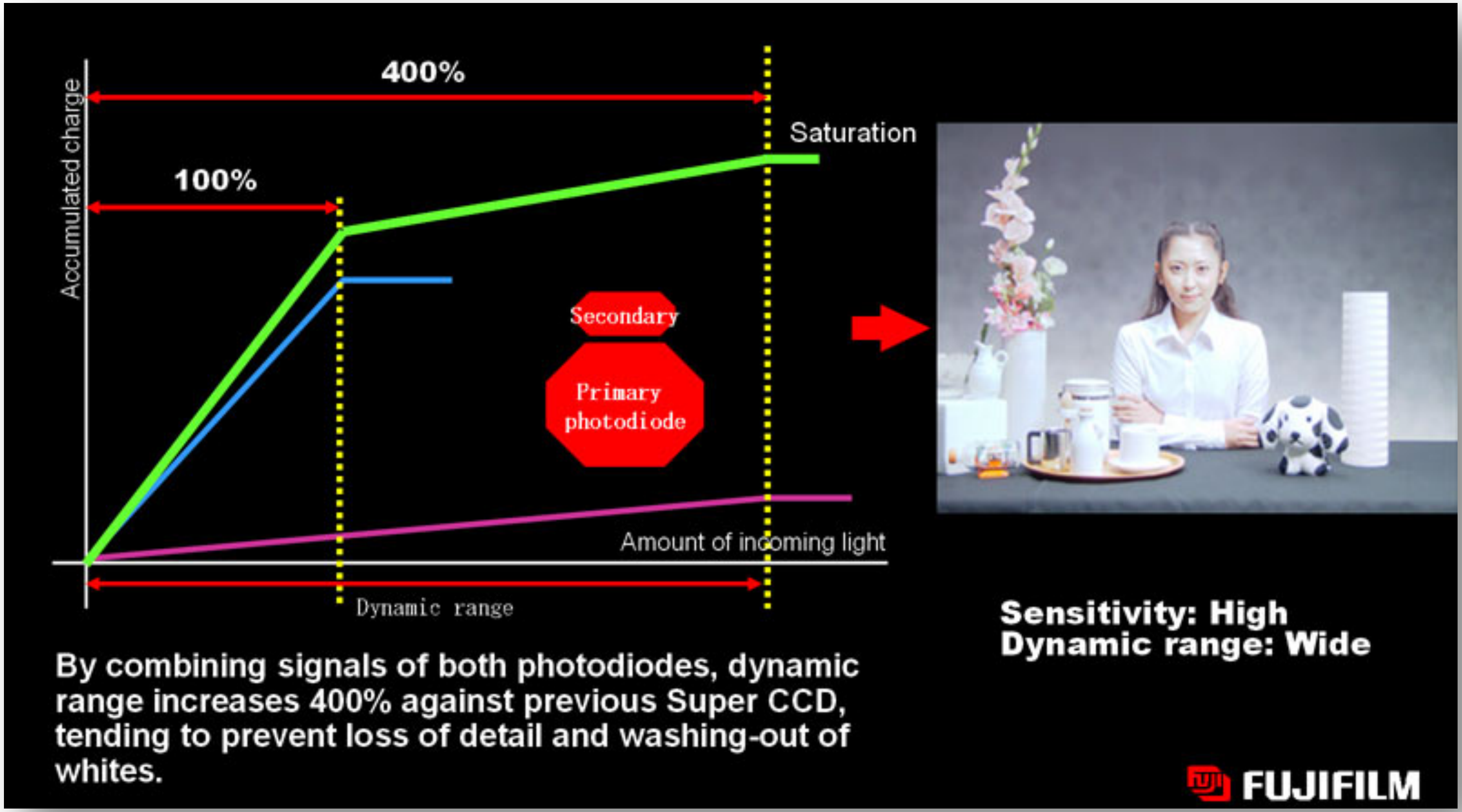
The secondary detector continues to accumulate charge after the primary saturates.



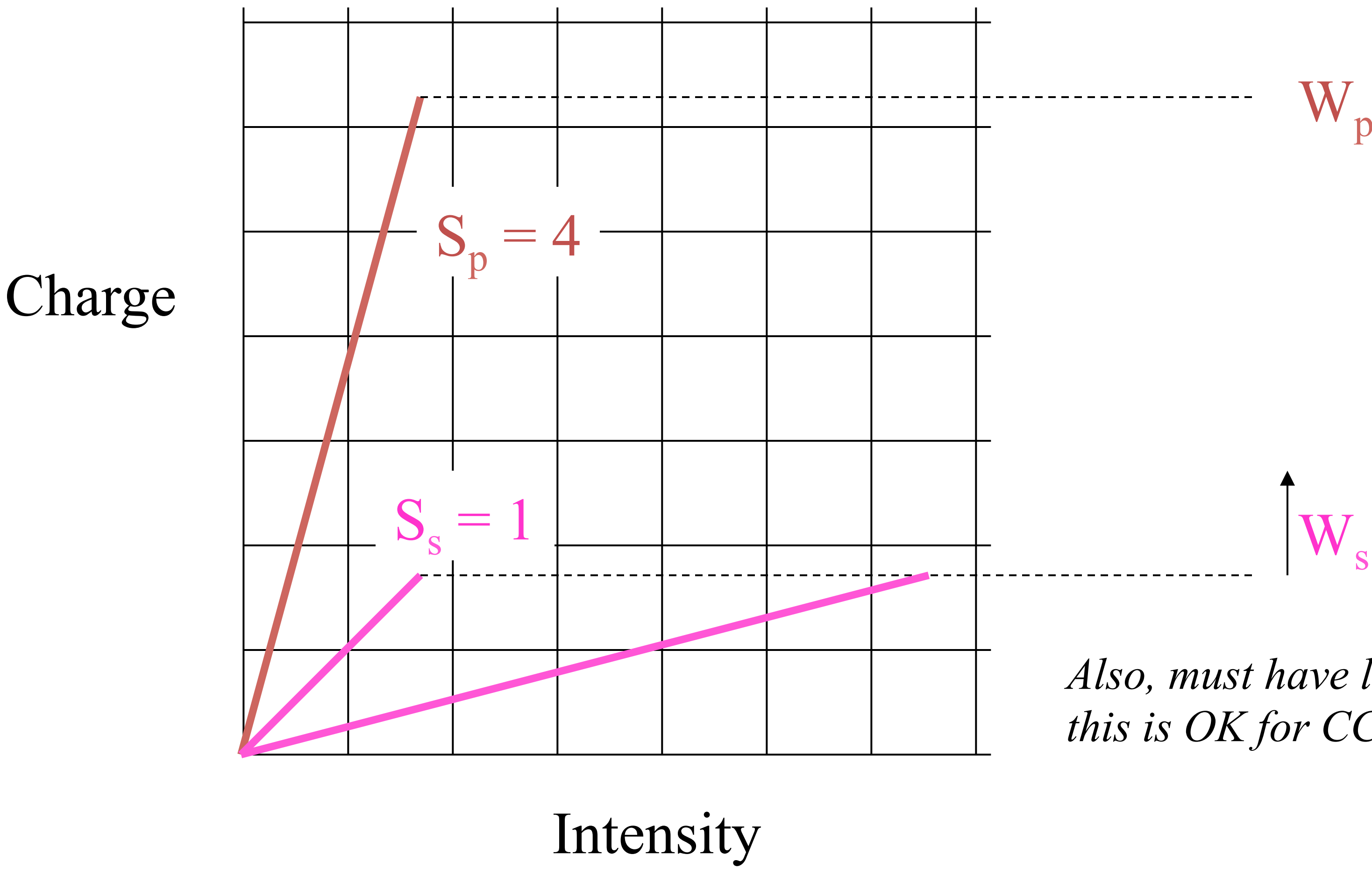


Dynamic range enhancement combines the two captures

Transduction function range is increased

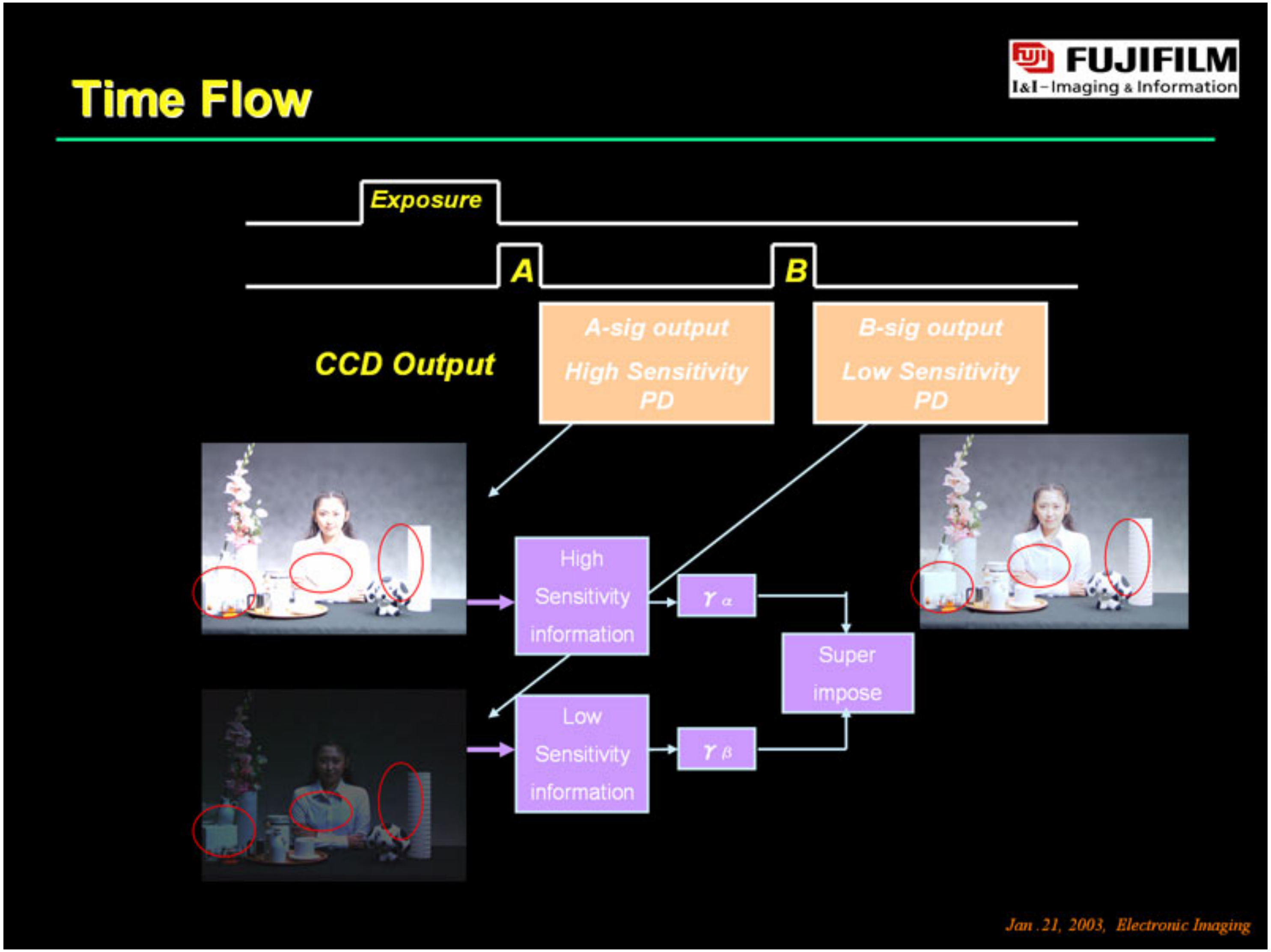


$$W_s/W_p > S_s/S_p$$



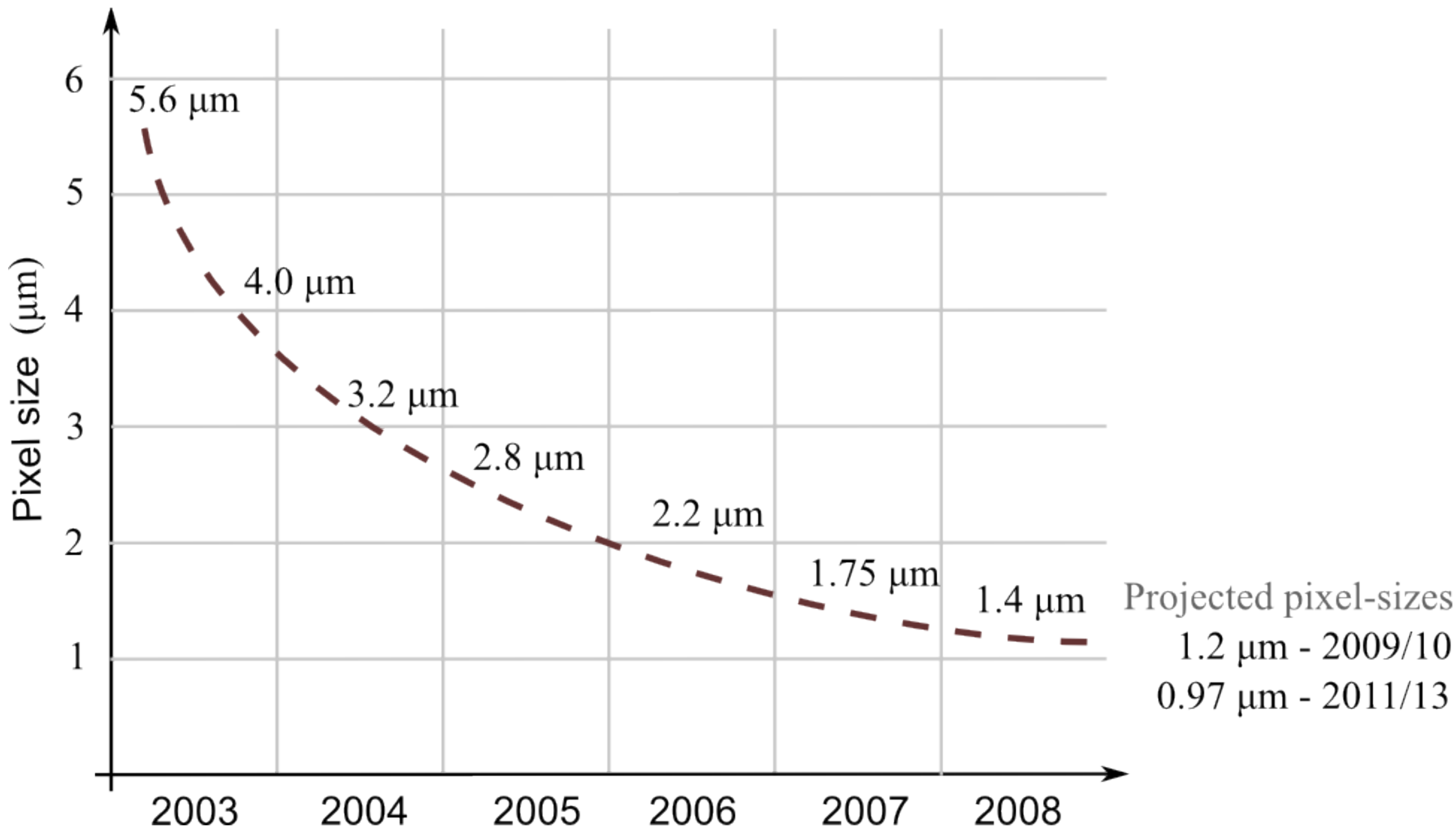
Also, must have low noise;
this is OK for CCD

Dynamic range



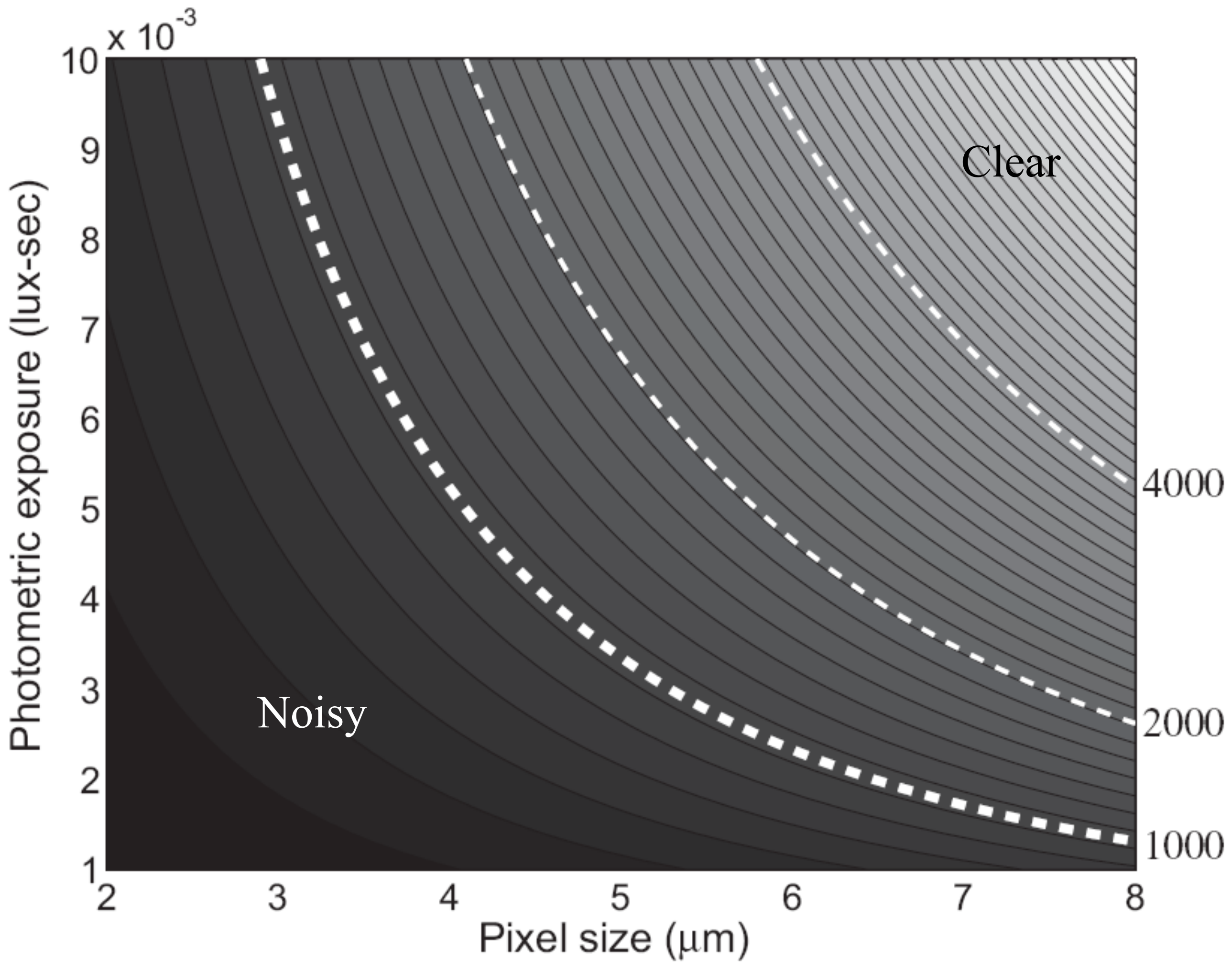
The problem is only getting worse

Pixel-size trends in ¼” Image sensors (cell phone cameras)

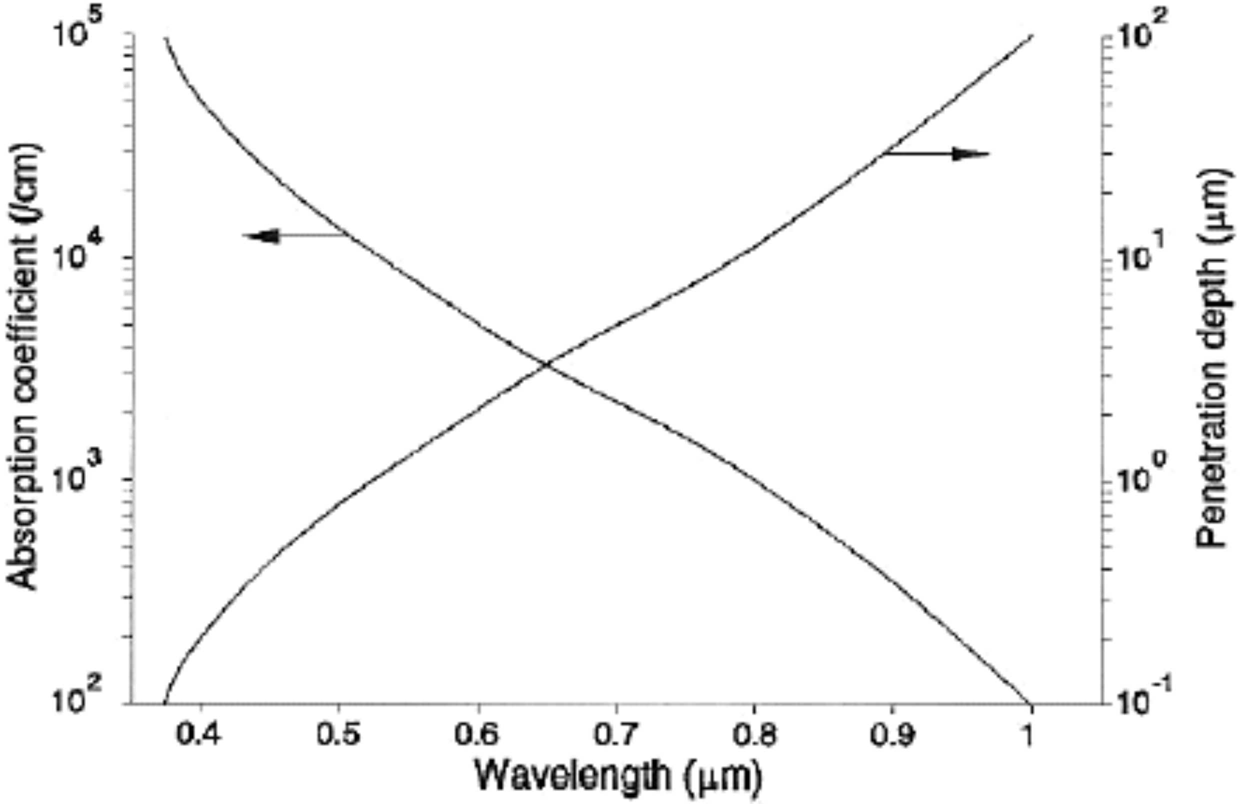


The problem is only getting worse

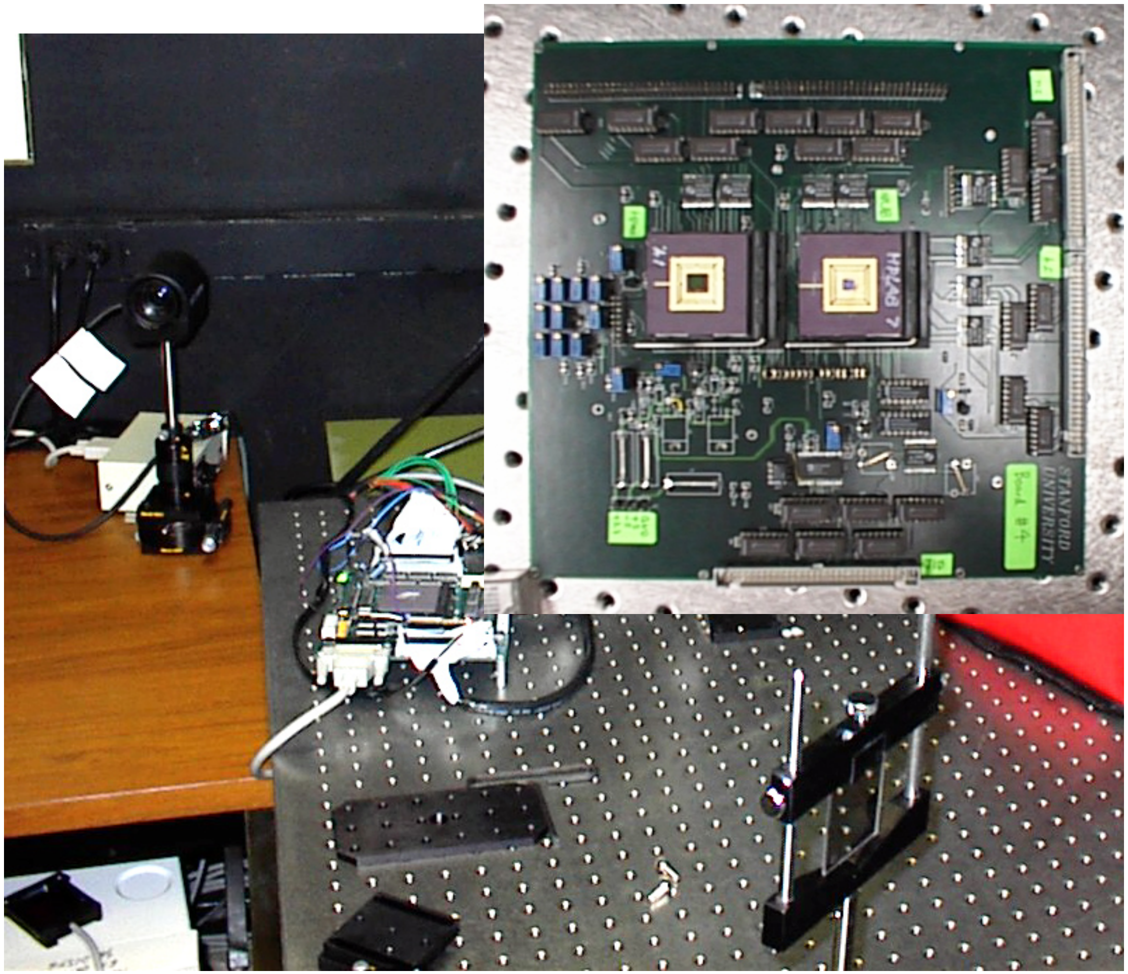
Pixel-size trends in ¼" Image sensors (cell phone cameras)



Mean photon absorption or penetration depth in silicon

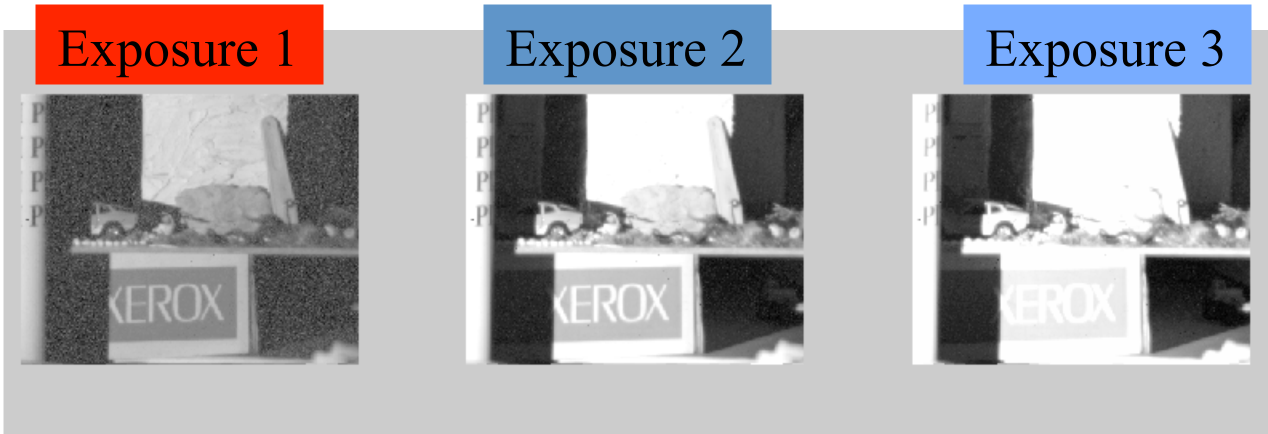


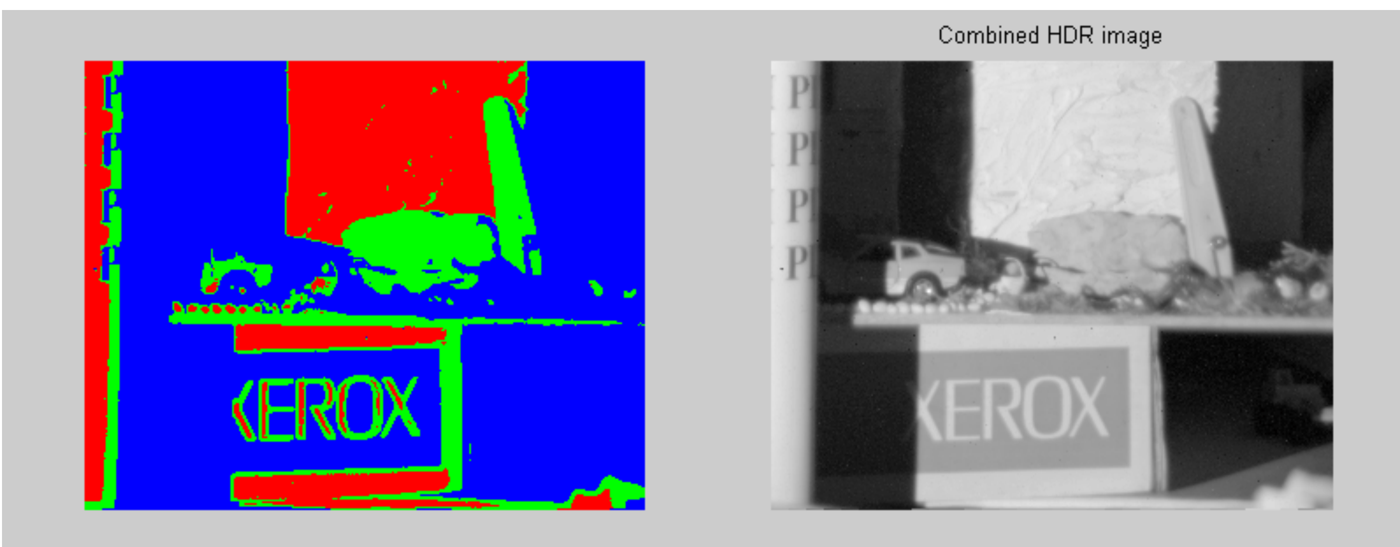
1st Generation Implementation
(D. Yang et al., IEEE JSSC, 1999)



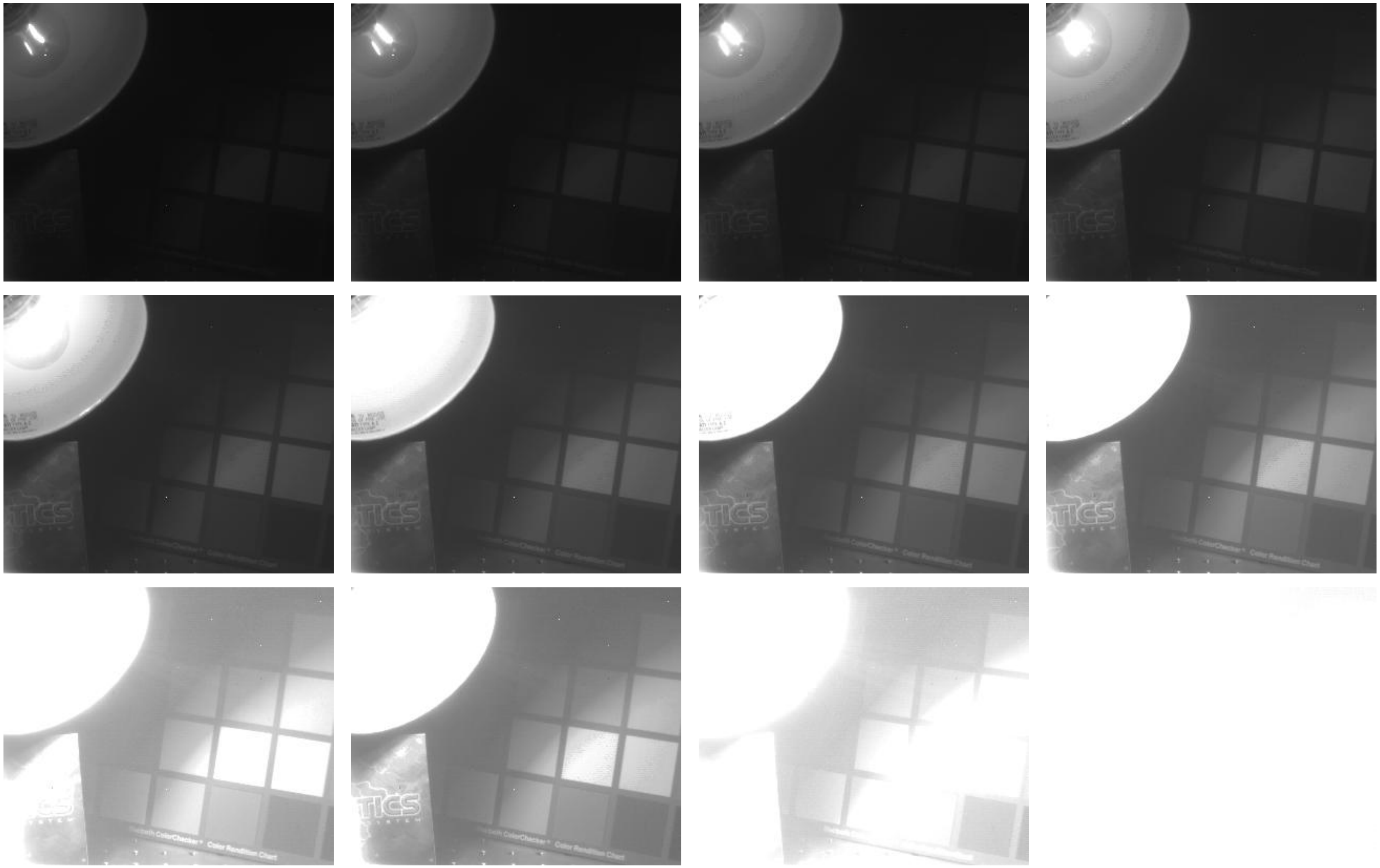
- *Imager: 640 x 512*
- *Pixel: 10.5 micron*
- *Technology: 0.35 micron*
- *ADC shared x 4*
- *Control signals FPGA*
- *Fill factor ~ 29%*
- *QE ~10%*
- *Really cool, though*

MCSI: HDR Example

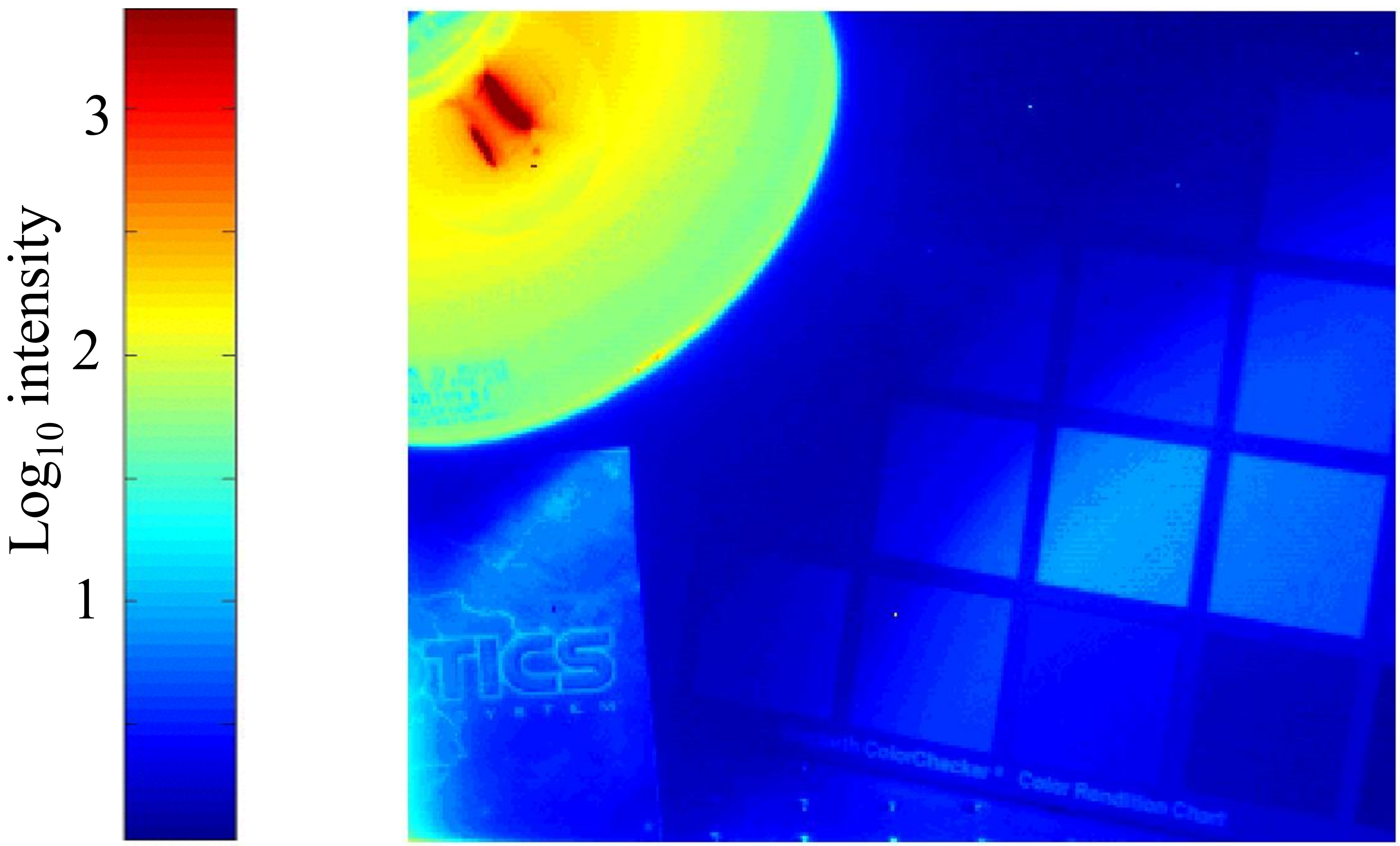




MCSI: HDR Example

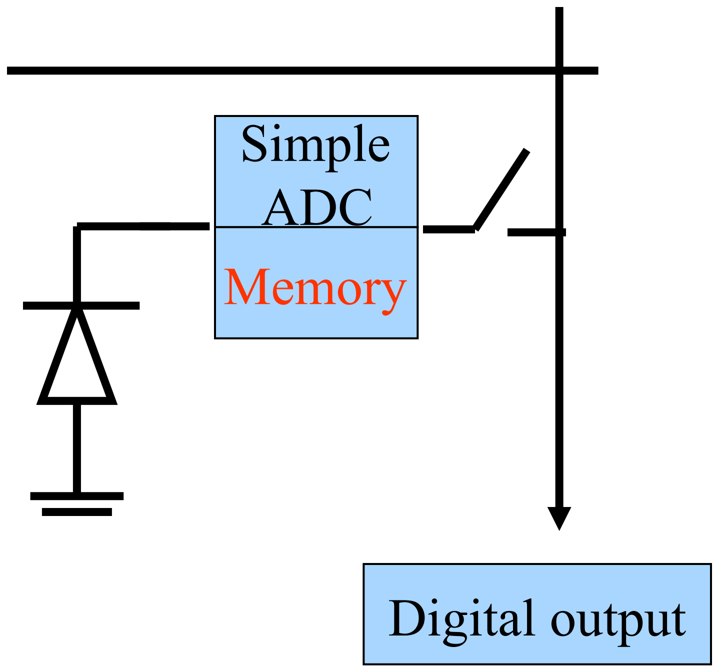


MCSI: HDR Example



2nd Generation: 10,000 Frames/Sec DPS Chip

(S. Kleinfelder et al., IEEE JSSC, 2001)

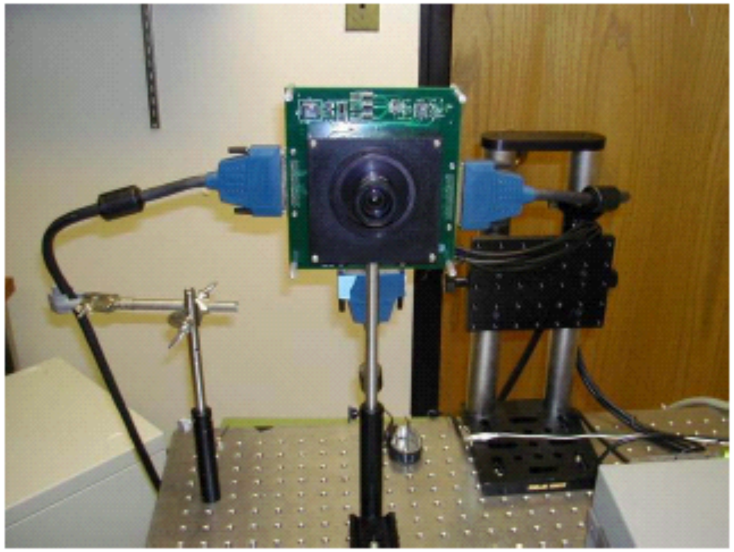


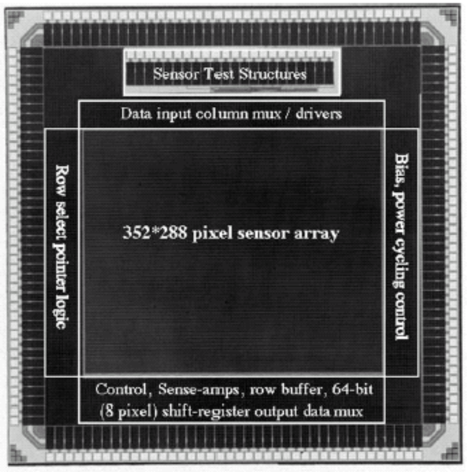
- *Imager: 352 x 288*
- *Pixel: 9.4 micron*
- *Technology: 0.18 micron*
- *ADC and 8bit memory per pixel*
- *Integrated*
- *QE ~14%*
- *Fill factor ~ 15%*
- *Significant dark noise*
- *Really cool, though*

2nd Generation System

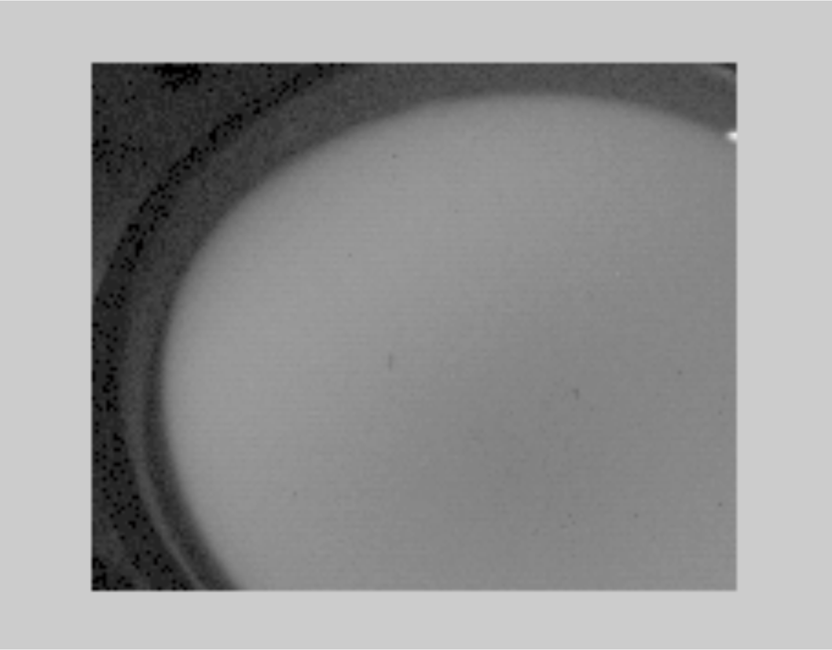
(Kleinfelder, Lim, Liu)

- *Based on CMOS-DPS (ADC, Memory)*
- *Interfaced via 3 NI cards to PC*
- *Programmable via Matlab interface*
- *Runs up to 1400 frames per sec*



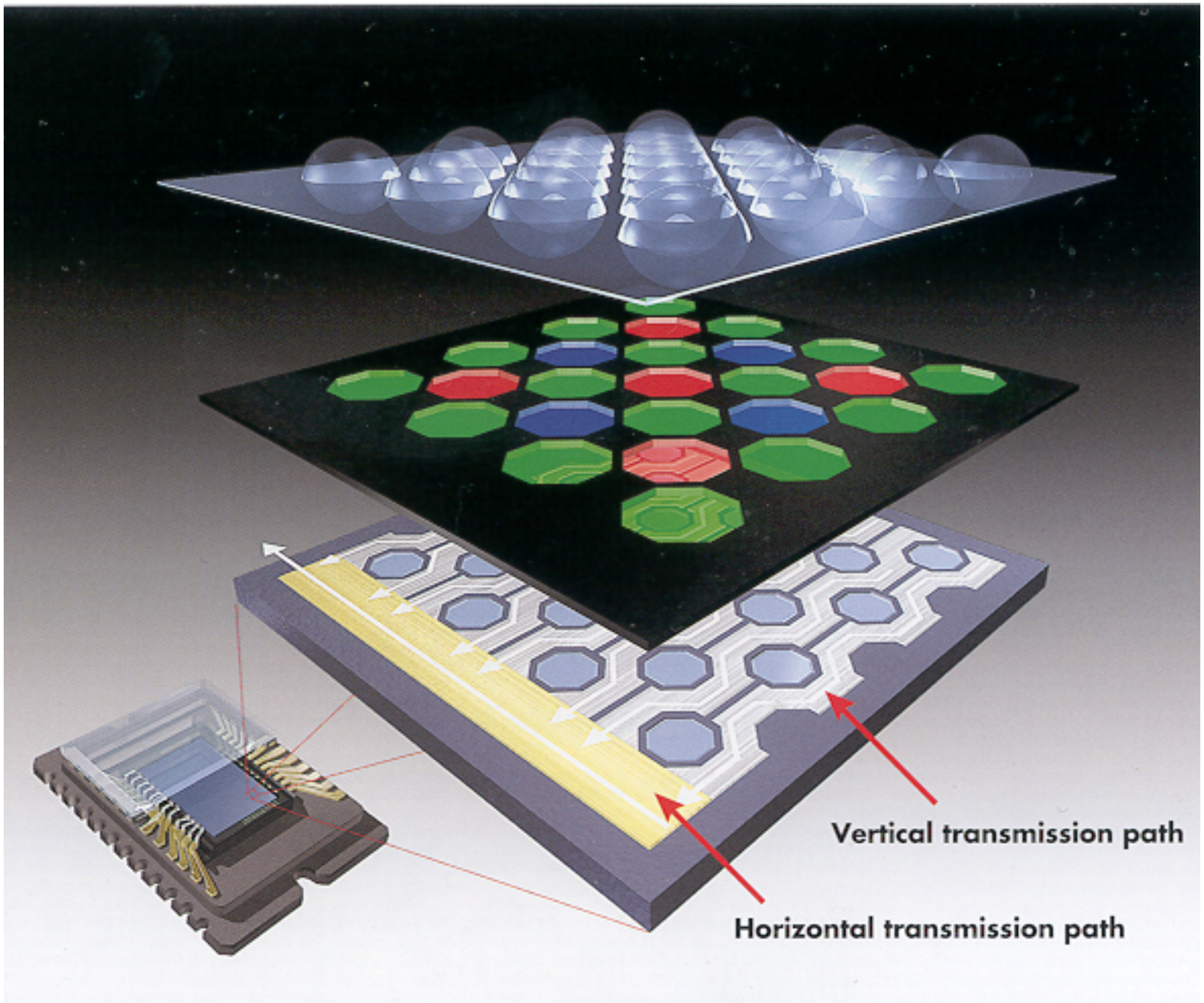


System Example: Milk Drop



Correlated double sampling
1400 fps
Play back at 30 fps

Image sensors: Structures and Capture



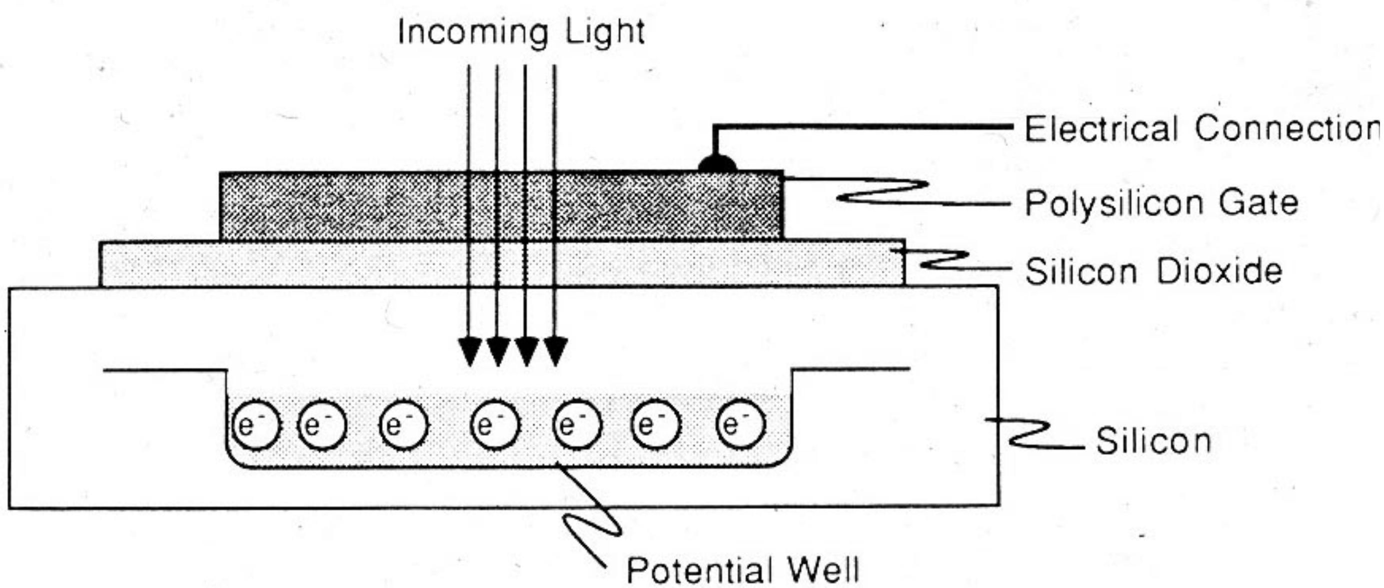
Fuji Corporation

CCD pixel structure

(Simon Tulloch smt@ing.iac.es)

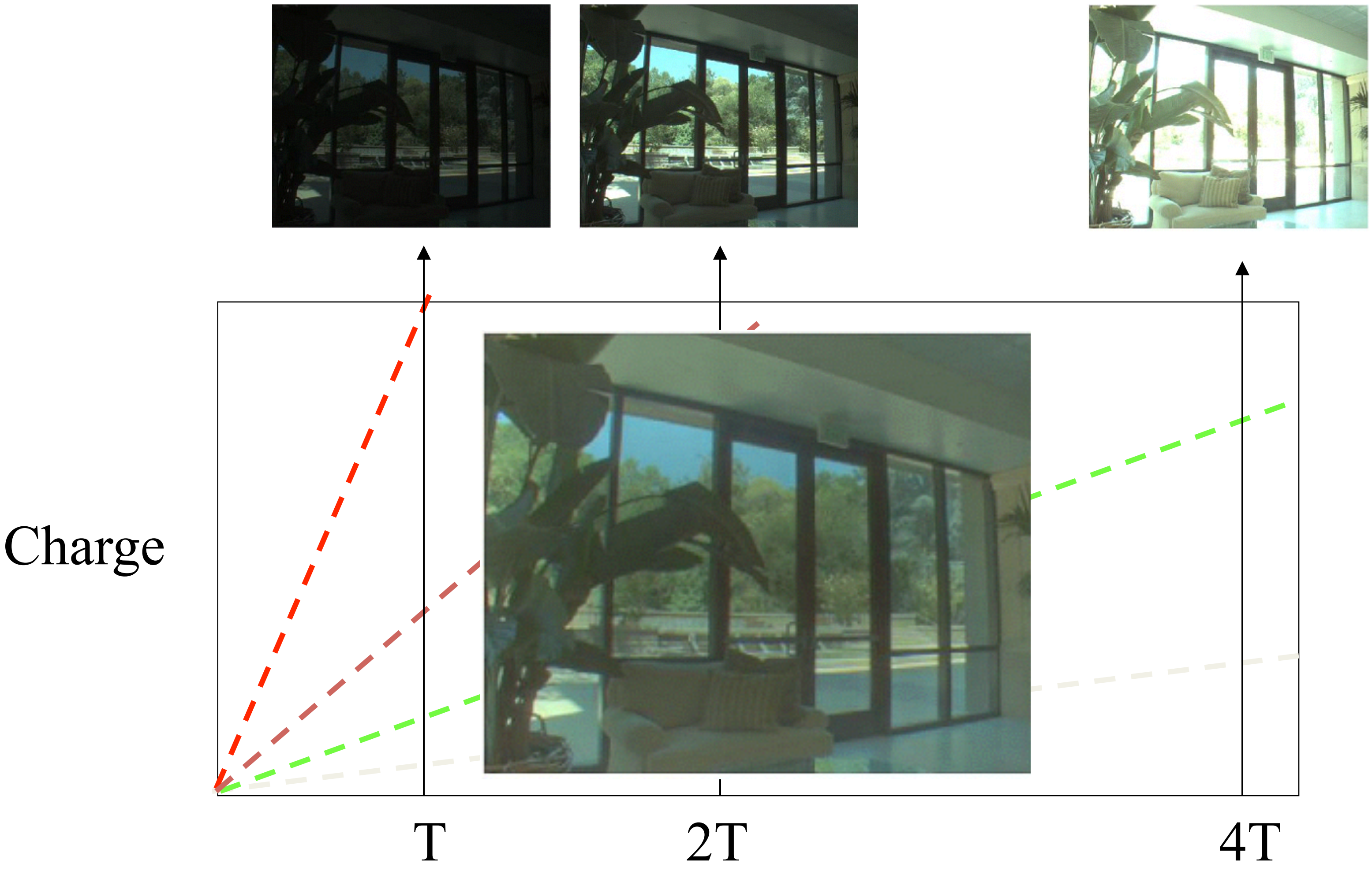
Invented in the 1970s as memory devices; light sensitive properties were exploited for imaging applications; a major revolution in Astronomy.

They improved the light gathering power of telescopes by almost two orders of magnitude. In 2001 an amateur astronomer with a CCD camera and a 15 cm telescope collects as much light as an astronomer of the 1960s equipped with a photographic plate and a 1m telescope.

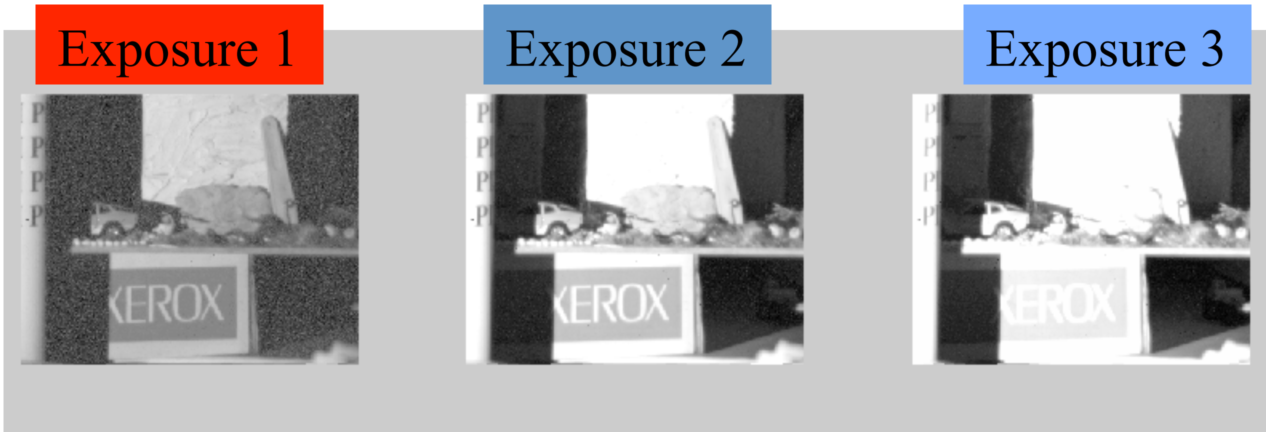


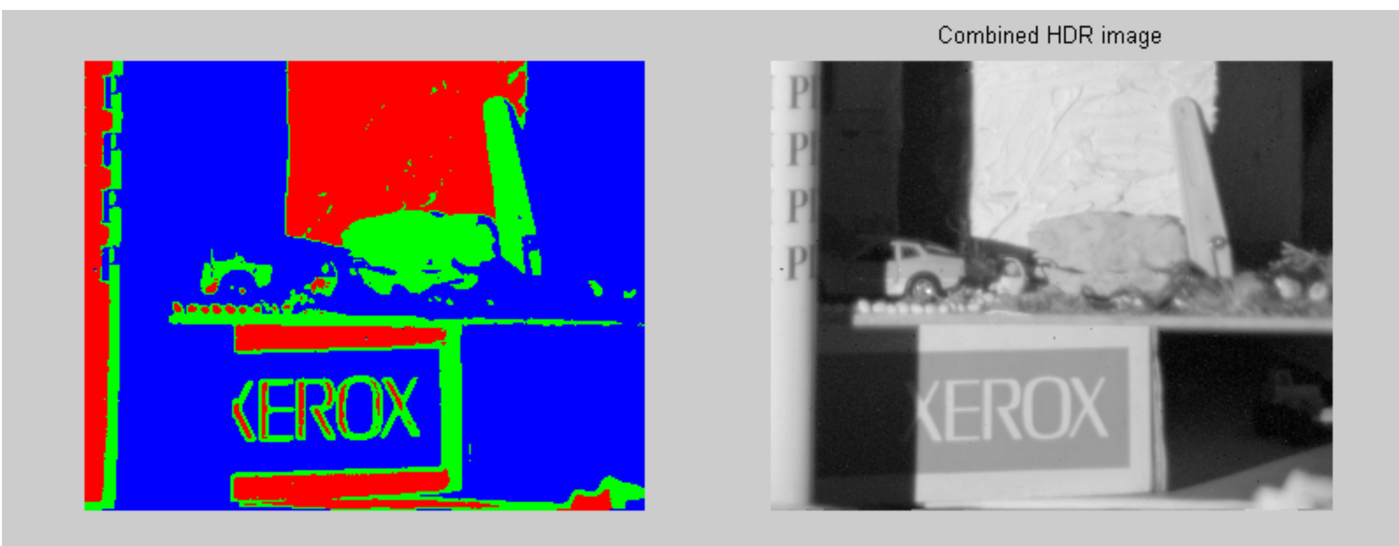
Stores as many as 10^5 electrons, though 10^4 more typical

Multiple Capture Single Image



Multiple Capture Single Image: High Dynamic Range Application





MCSI: High Dynamic Range (HDR)

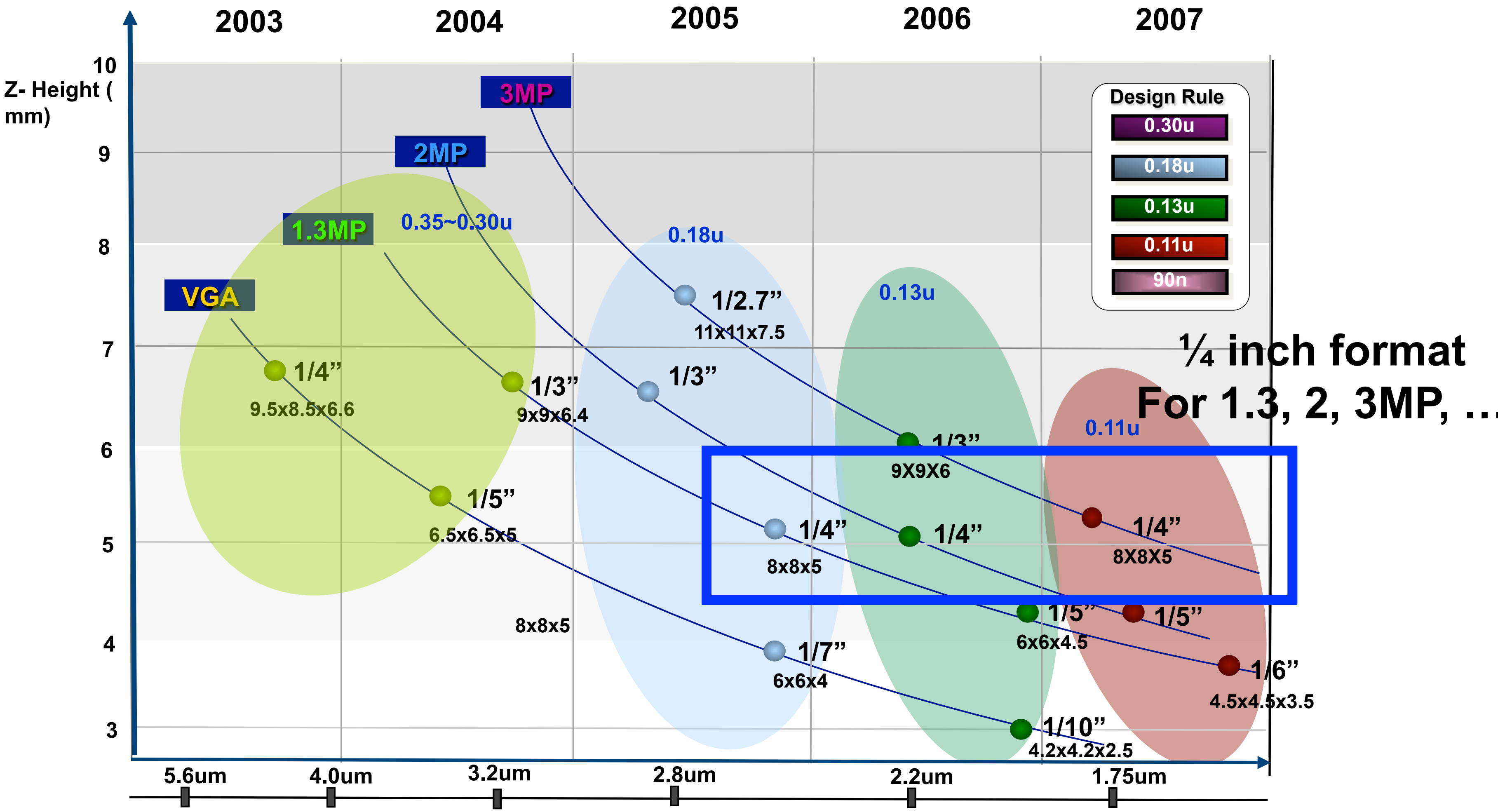
Multiple captures

Exposure bracketing

Single image

High dynamic range image

Camera Module – Trend by Optical format & form factor



This is from a public talk given by Magnachip. Use the information freely, but please do not use this slide directly in your presentation!

CMOS sensor characterization

Sensor Performance

- Goal:
  - Develop a noise model to analyze sensor performance
  - Use sensor model for system-level simulations
- Review sensor noise modeling terminology
  - Temporal
  - Spatial
- Sample characterization results

Sensor Noise Components

- Temporal noise components
  - Q_{shot} : shot noise during integration (photo and dark currents)
  - Q_{reset} : reset noise
  - Q_{read} : readout noise (including A/D quantization noise)
- Spatial noise components
  - Fixed pattern noise due to mismatches across the sensor
  - Offset and gain components
    - Offset: Canceled out by correlated double sampling, except DSNU
    - Gain: Pixel response non-uniformity (PRNU) not canceled

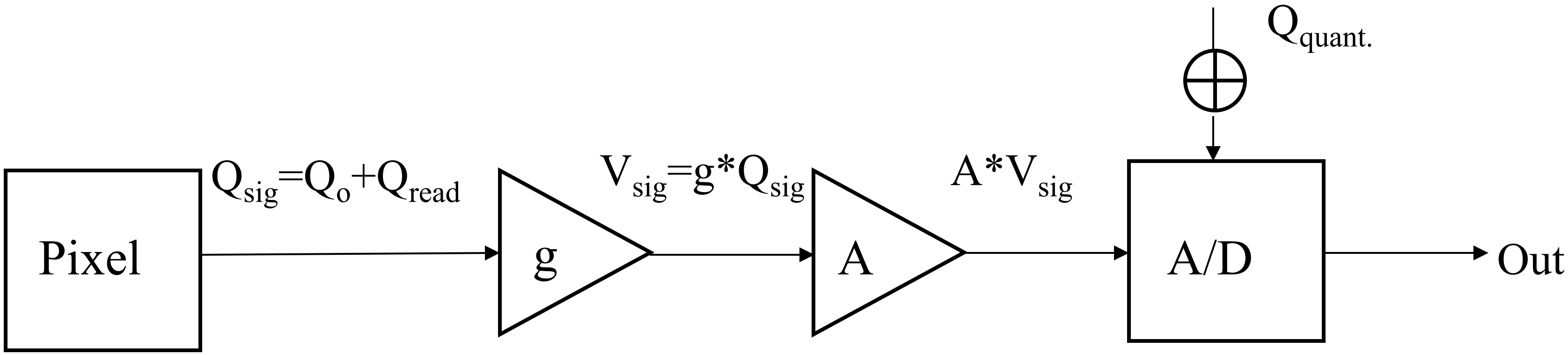
Sensor Noise Model

- Total input-referred noise charge
  - $Q_n = Q_{shot} + Q_{reset} + Q_{read} + Q_{fpn}$
  - After CDS, $Q_n = Q_{shot} + Q_{read} + Q_{prnu} + Q_{dsnu}$
- SNR
  - $$SNR = \frac{\left(\frac{i_{ph} t_{int}}{q}\right)^2}{\frac{(i_{ph} + i_{dc}) t_{int}}{q} + \frac{\sigma_{idc}{}^2 t_{int}{}^2}{q^2} + \sigma_{read}{}^2}$$
  - Neglecting PRNU for now

Characterizing Read Noise

- Setup
  - Dark conditions
  - Short integration time (0.1ms)
  - Analog gain (A) is 1
  - σ_{read} is std. deviation of temporal variations over 1000 frames
  - Only assumption is that i_{dc}/pixel is constant for 100ms
- Sample results
  - σ_{read} = 0.86 digital counts (full signal range = 1023)
  - But this is A/D quantization noise-limited
  - Also, need to convert to electrons (conversion gain)

- This clarifies read noise characterization



$$\sigma_{Out}^{2} = \left(\frac{2^{n}-1}{V_{max}}\right)^{2}\left[g^{2}A^{2}\sigma_{read}^{2} + \sigma_{quant.}^{2}\right]$$

- For A=1, dominated by $Q_{quant.}$
- Want to increase A to the point where Q_{read} dominates

Conversion Gain

THIS IS A MESS. FIX IT OR DELETE IT.

- Setup
  - Sensor is in shot-noise limited regime
  - Since ,
    - Conversion gain, $g = \frac{V_s}{SNR}$
  - In general, for 10-bit A/D with FSR of ,
  - So,
  - Since we don't know g , can define $V_{\max}$ as follows

$$SNR = \frac{CV_s}{q}$$

$$V_{\max} \quad V_s = I_{\substack{sig\\dig}} \left(\frac{V_{max}}{2^{10} - 1} \right)$$

$$g = \frac{I_{\substack{sig\\dig}} \left(\frac{V_{max}}{2^{10} - 1} \right)}{SNR}$$

$$g = \frac{I_{\substack{sig\\dig}}}{SNR} \quad \text{(counts/electron)}$$

Conversion Gain

- Results
  - What we measure is actually A*g, where A is analog gain
  - With A=1, approx. 20 electrons/count
  - Assuming FSR of 1.5V,
    - g = 70μV/electron
    - This is “true” conversion gain
- So in electrons
  - Read noise = 17 electrons (A/D quantization noise)
  - Full well = 20500 electrons
- Absolute read noise floor can be lowered with A gain

With Analog Gain

- Results
  - Analog gain = 16
  - σ_{read}= 3.2 digital counts
  - Approx. 2 electrons/count (theoretically 20/16)
  - Actual pixel read noise = 4-6 electrons

- May not want to operate at maximum analog gain
  - Limits dynamic range
  - A=8 is sufficient

Verification of Results

- What are the results sensitive to?
  - Confident of read noise in digital counts
  - But read noise in electrons sensitive to conversion gain
    - So verify conversion gain

- Can verify using dark current shot noise
  - Dark conditions, long integration times (2.5s)
  - Just look at one pixel over 40 minutes (1000 frames)
    -
    - Only assumption is that pixel dark current is constant over time

$$SNR = \frac{CV_s}{q}$$

Verification of Results

- Results
  - Conversion gain, g = 1/50 (counts/electron)
    - Assuming 1.5V swing, g = 30µV/electron → C = 5.5fF
    - Assuming 1.1V swing, g = 22µV/electron → C = 7.4fF
  - Read noise, σ_{read} = 10 electrons
    - Reproducible for A = 8 and A = 16
  - Full well = 51,150 electrons
    - So peak SNR, ignoring PRNU, is 47dB (datasheet says 45dB)

Dark Signal Characterization

- Setup
  - Dark conditions @ RT
  - Long integration time (2.5s)
  - Capture 1000 frames and average
  - Mean intensity is dark current, spatial variation is DSNU

- Results
  - Mean dark signal = 2200 electrons, or 0.14fA (0.6nA/cm^2)
  - DSNU = 80 electrons or 0.005fA

Characterization Summary

Read noise, σ_{read}	10 electrons
Dark current, i_{dc}	0.14fA (see next page for amps to electrons)
Dark signal non-uniformity, $\sigma_{i_{dc}}$	0.005fA (see next page for amps to electrons)
Full well capacity, Q_{max}	52000 electrons
Peak SNR	47dB
Dynamic range Think about noise-free dynamic range, meaning from 1000 electrons captured to well capacity, or maybe a little more to account for other noise components.	60dB (depends on duration because noise depends on duration)
Pixel conversion gain, g	22-30μV/e$^-$
Quantum efficiency (550nm)	0.5-0.6

1 Amp is a one coulomb (unit of charge) per second

the charge of an electron is 1.6 x10^-19 so the number of electrons in one coulomb is 1/1.6x10^-19

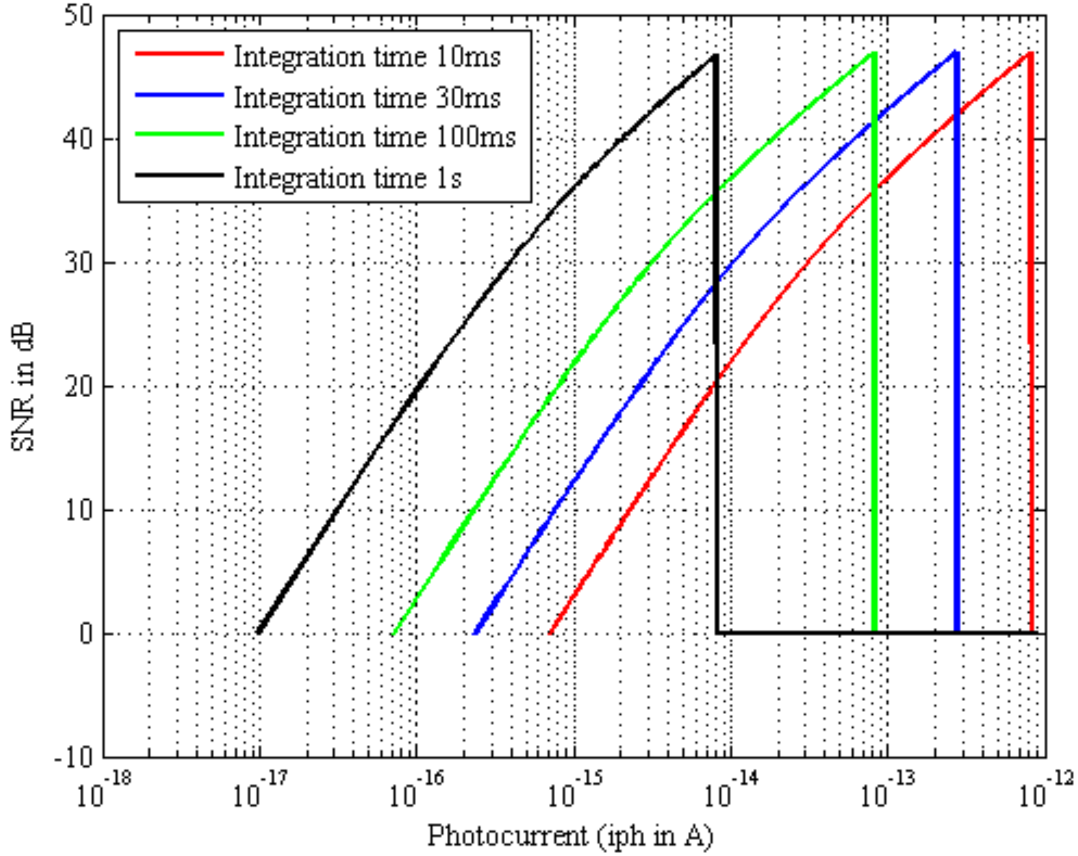
=6.25x10^18 electrons

so for one Amp that would be 6.25x10^18 electrons per second flowing around the circuit/component

Femto is 10^-15
Pico is 10^-12
Nano is 10^-9
Micro is 10^-6

So .14 femto amps is 6.25 x 10^18 x 10^-15 * .14 electrons per second
= (.14 * 6.25) * 10^3 e-/sec
So for a sensor like this, in 10 ms, you would have 0.010*10^3 e which is about 10 electrons of dark current.

- SNR vs. photocurrent (A = 1)

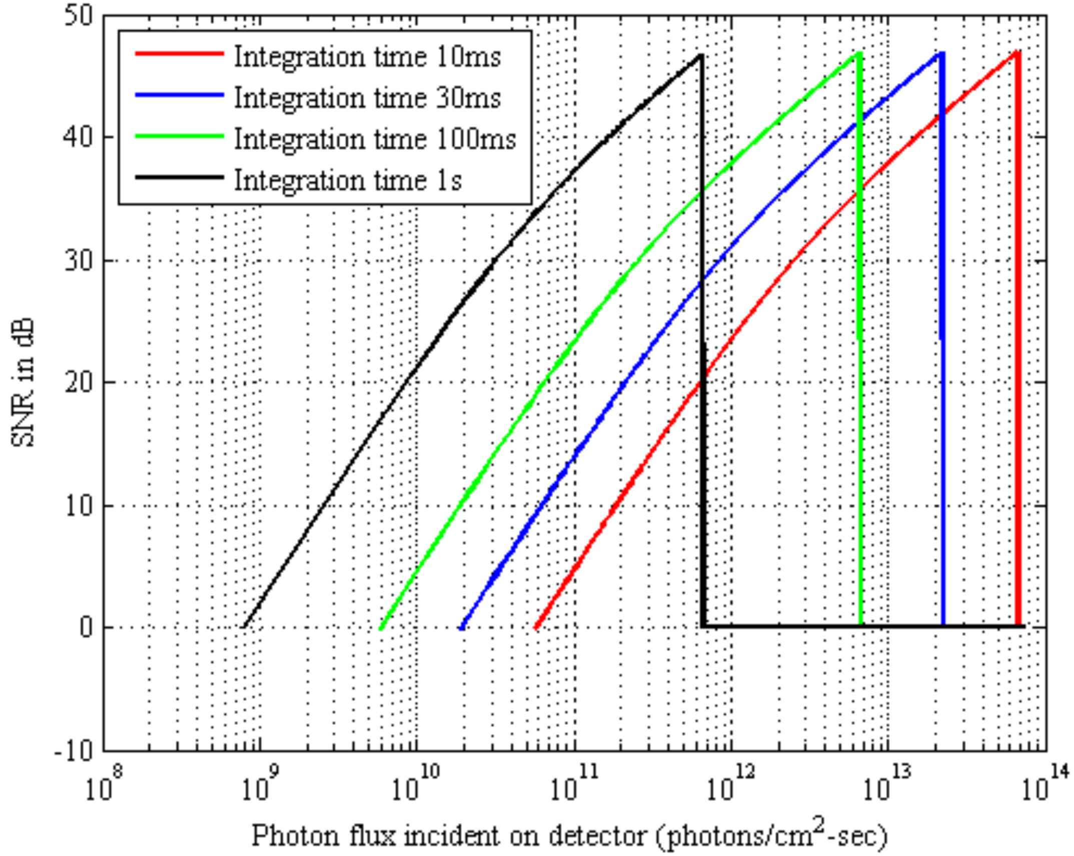


σ_{read} = 44 electrons

Peak SNR = 47dB

DR = 60dB

- SNR vs. photon flux (A = 1)



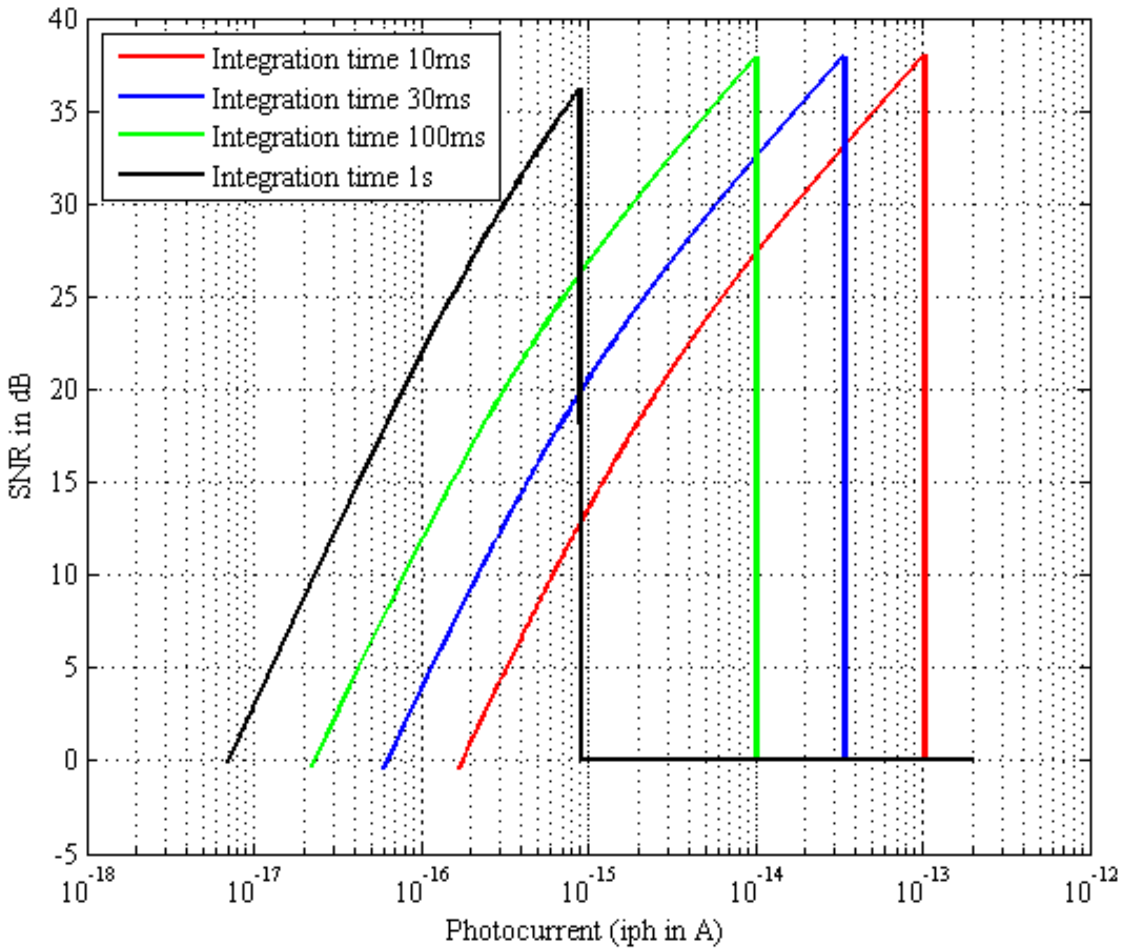
$\sigma_{read} = 44$ electrons

Peak SNR = 47dB

DR = 60dB

Complete Sensor Model

- SNR vs. photocurrent (A = 8)



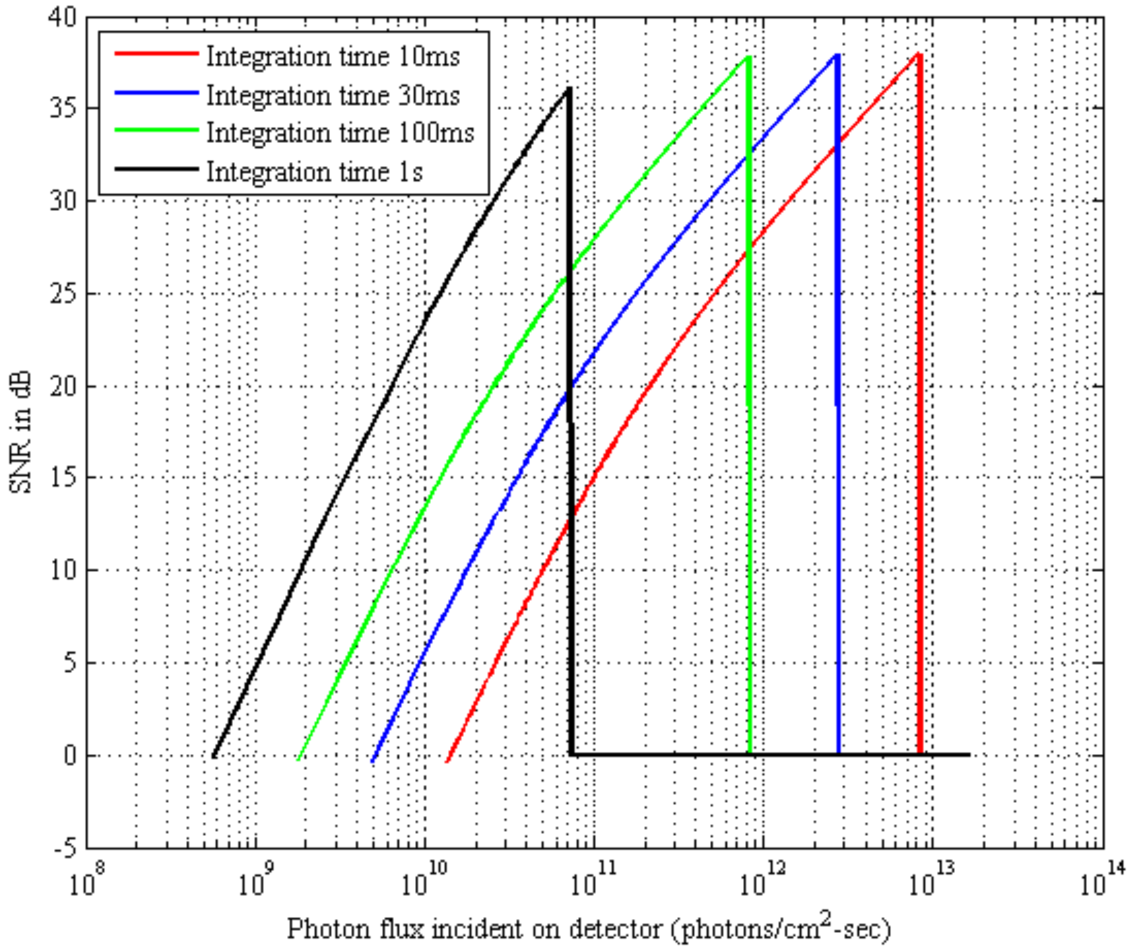
σ_{read} = 10 electrons

Peak SNR = 38dB

DR = 56dB (t_{int}<100ms)

Sensor Noise Model

- SNR vs. photon flux (A = 8)



σ_{read} = 10 electrons

Peak SNR = 38dB

DR = 56dB (t_{int}<100ms)