THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

and societal issues

Photons to Bits and Beyond The Science and Technology ^ of Digital Imaging

Eric R. Fossum

Fall 2011

Versions of this talk have been presented at
Yale (10/13/11) Dartmouth (10/21/11) Columbia (10/25/11) Caltech (11/11/11) and Samsung (12/15/11)

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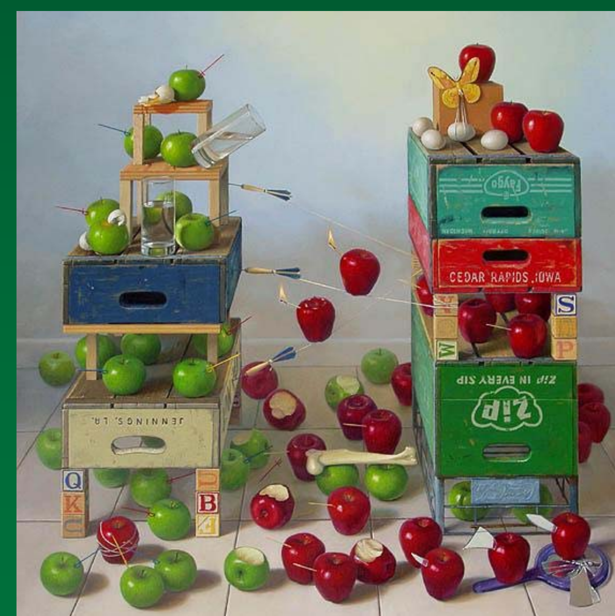
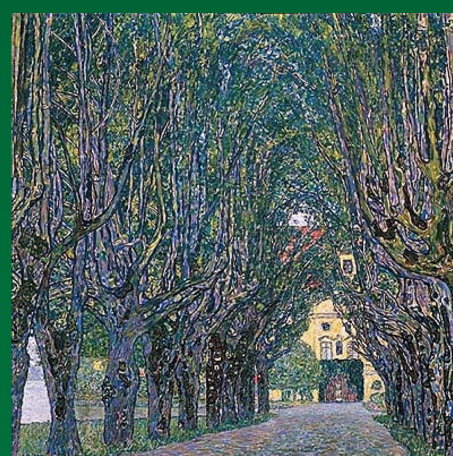
People have been capturing and creating images by hand for a long time

Cave drawing
~ 10,000 BC

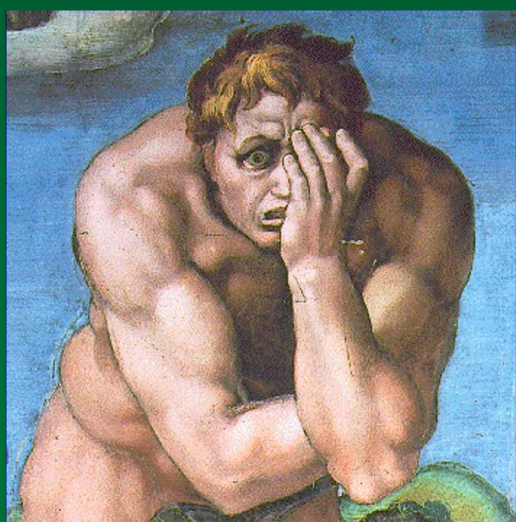
Jackson ~2006



Klimt ~1912



Michelangelo
~1540



And using cameras for about 200 years to record images "automatically"

Giroux Daguerreotype ~1839

SLR
~1976

Kodak Brownie Camera ~ 1889

Steve Sasson and first portable digital camera (invented 1975)

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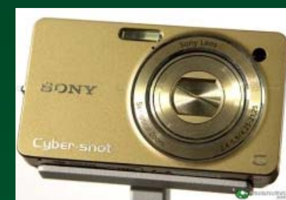
Many kinds of digital cameras

- Photography
  - Digital single lens reflex (DSLR)
  - Point and shoot
  - Camera phone
- Video
  - TV (640x480) and HDTV (1920x1080) camcorder, broadcast
  - Webcam
  - High speed – slow motion
  - Motion capture
  - Gaming
- Medical
  - Endoscopy
  - Pill camera
  - X-ray camera
- Machine Vision
  - Automotive (e.g. “smart beam” headlight dimmer)
  - Security
  - Inspection
- 3D ranging
  - Gesture control
- Etc.







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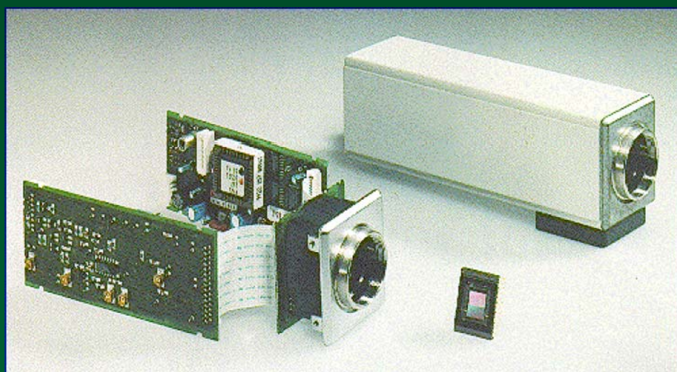
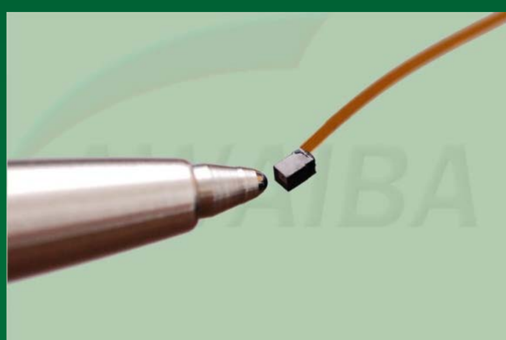
Congruent with Moore's Law, cameras have become smaller, faster, cheaper and everywhere

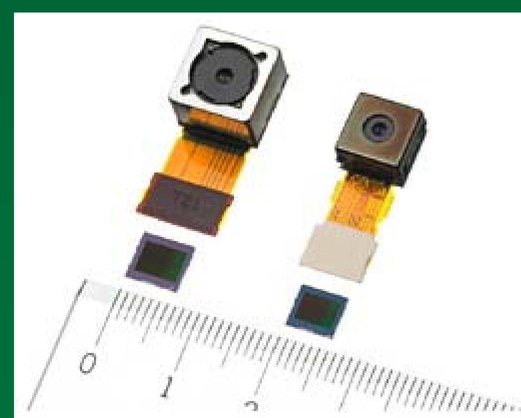


0.3 Mpixel
CCD camera
Circa 1993

2 Mpixel
Cell phone
AF Camera
Circa 2007



0.06 Mpixel CMOS endoscopy camera present day



16 Mpixel
Cell phone
Camera
Present day

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Impact on Society

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Image Centric Communications

- The ubiquitous nature of the mobile phone camera as a communications tool has led to new ways of interacting with each other, and “being there”.

YouTube Broadcast Yourself

1999 PB159 minicam Monument Valley Utah

facebook

2011 SBF and KEFL Stanford

2011 Fossum Farm New Hampshire

Large Scale Social Change

- Rapid change due to “feedback” from nearly real-time visual images.

Arab Spring 2011

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Too much visual information?

- Visual information overload from a few billion "overconnected" cameras.
  - God-like vision, participating yet helpless.

Japanese Tsunami 2011

see Bill Davidow, <u>Overconnected: ThePromise and Threat of the Internet</u>

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Privacy Issues

- Loss of privacy from networked security cameras and automatic facial recognition, tracking, and activity logging.
- Loss of privacy from “bad guys” and advertisers

Mall Scene Minority Report 2002

Inappropriate Use

- Inappropriate use like sexting, upskirting, spy cams, etc.

http://itbegsthequestion.com/wp-content/uploads/2010/11/sexting.jpg"

http://aftergrogblog.blogs.com/agb/2008/08/going-up-skirt.html

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Gray-Area Defense Applications

- Very smart weapons, very personalized weapons.
  - "i-bullets"

Laser guided rifle

Micro Autonomous Systems and Technology (MAST) consortium

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Science and Technology

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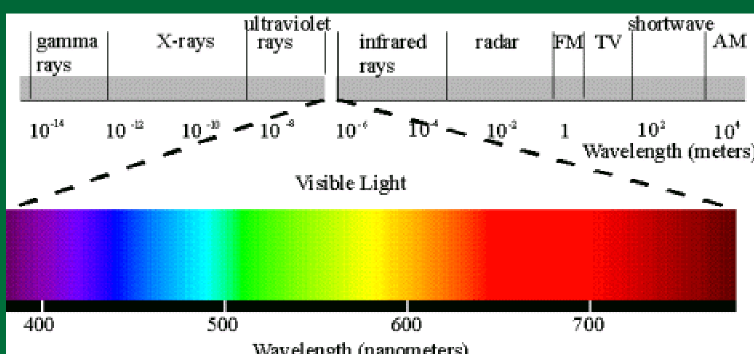
Light in

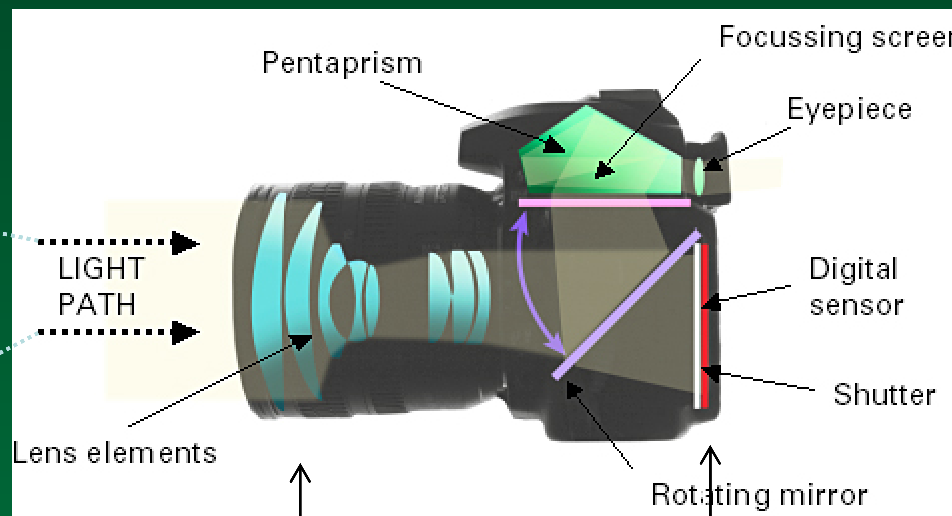
Blackbody emission of photons (~6000K)
-With photon shot noise
-Plus atmospheric scatter
-Plus scene reflection

↓ ~$10^{14\text{-}17}$ photons/cm^2/s



http://www.societyofrobots.com/images/sensors_color_spectrum.gif

http://www.jiscdigitalmedia.ac.uk/images/slr02.jpg

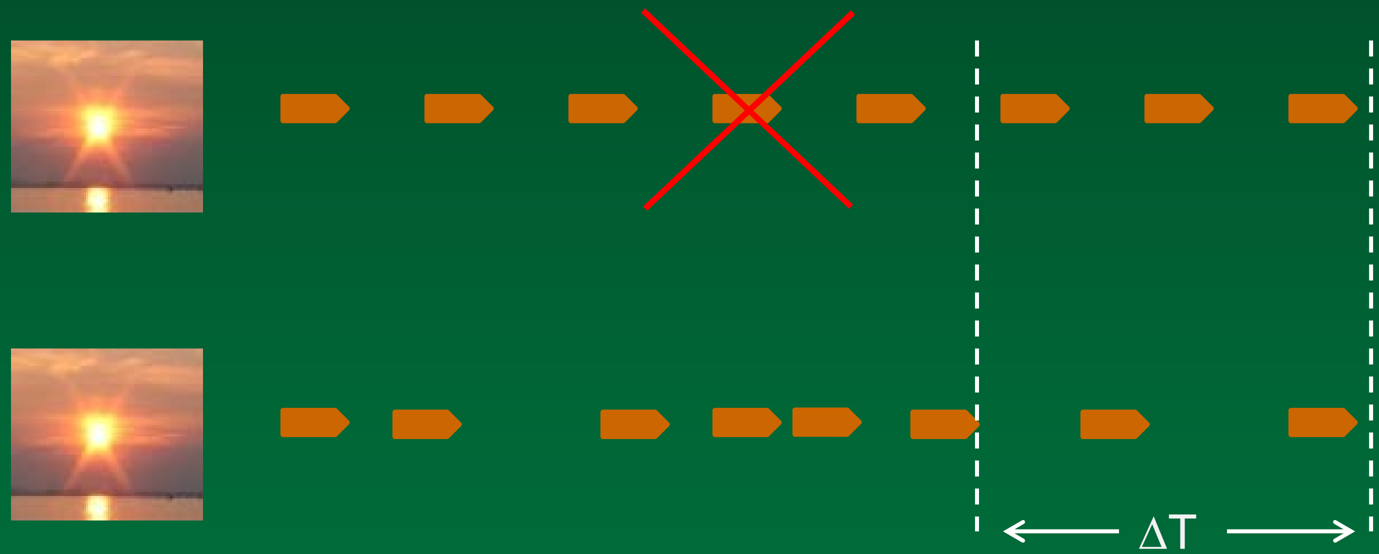


Lens collects and bends EM waves and focusses image

Photons strike image sensor and are absorbed by semiconductor

Photon Shot Noise

- Photon emission is a Poisson process. Stream of photons is NOT regularly spaced.

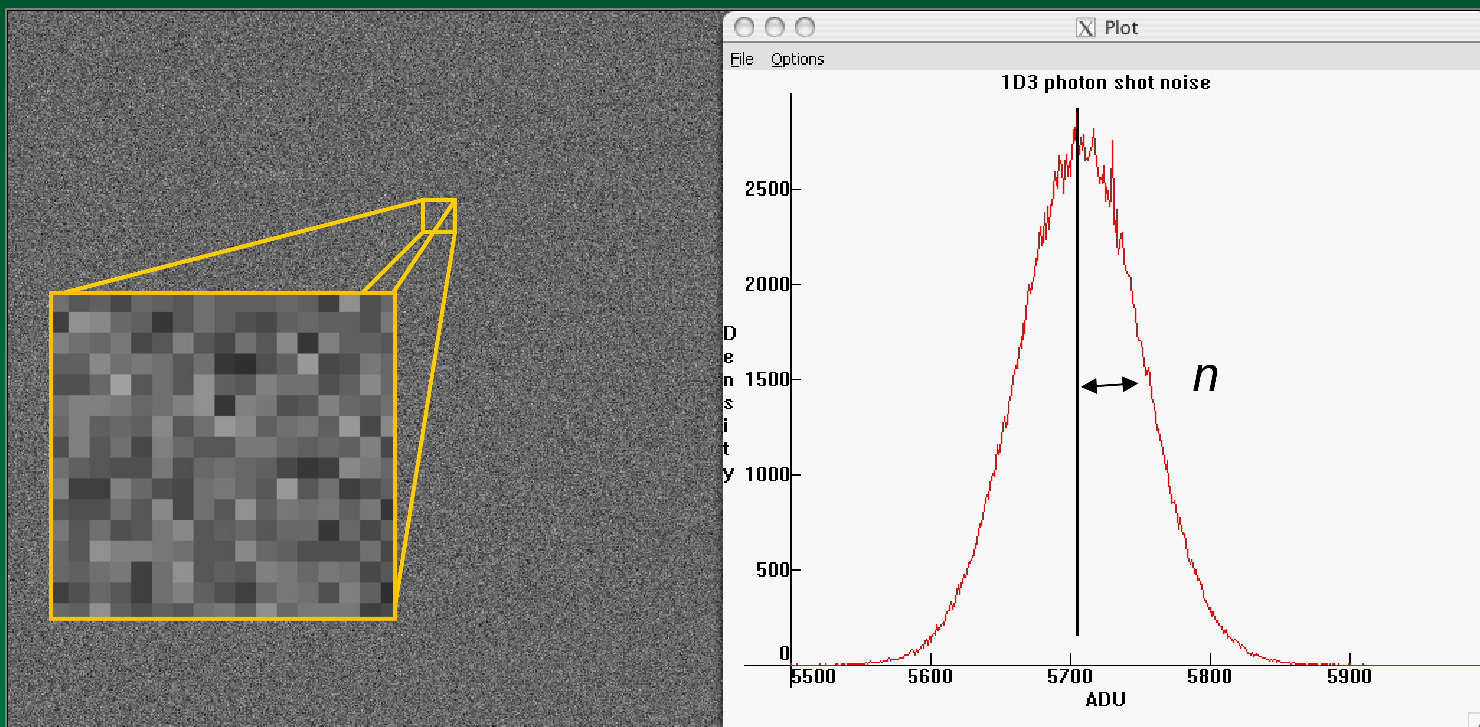


- Photon flux Φ characterized by:

$$< (\Phi - <\Phi>)^2 > \sim \Phi$$

Photon Shot Noise

- Let Signal be N, so Photon Shot Noise n = sqrt (N)
- SNR=sqrt(N)   Want SNR>10 and usually higher
- Effect for “uniform lighting” shown below (Nikon D3)



by Emil Martinec © **2008**

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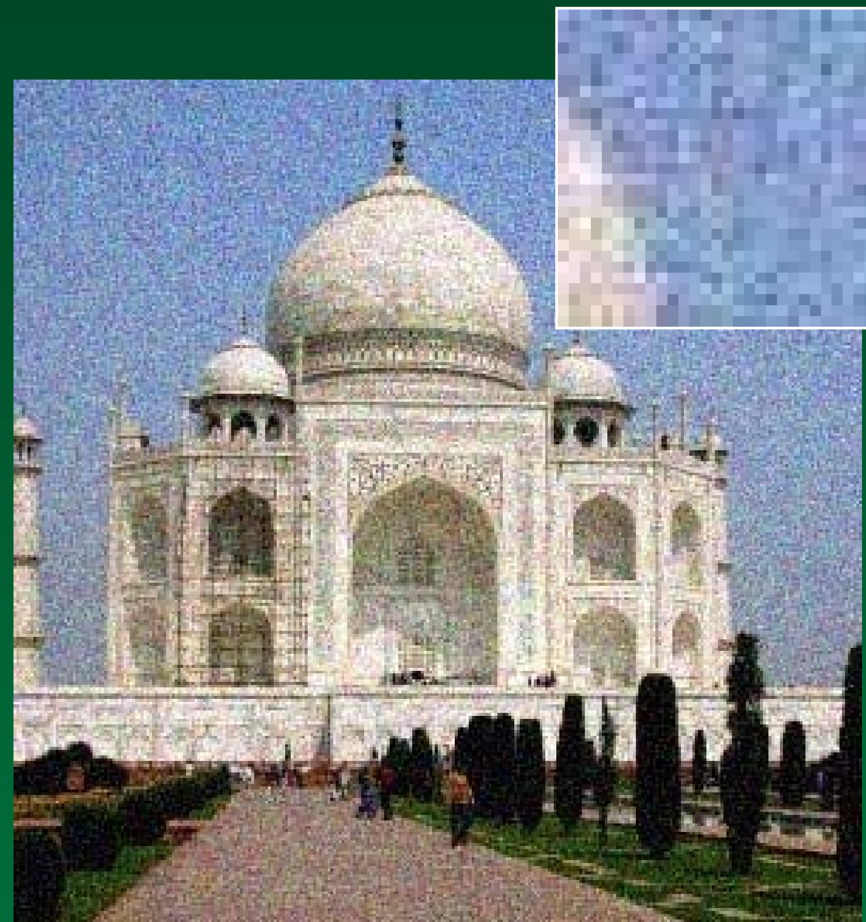
Simulated effect of noise

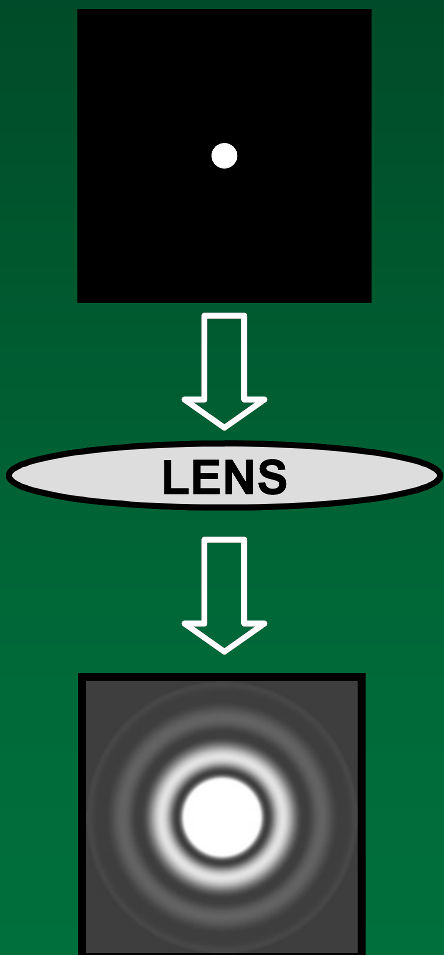
Low noise

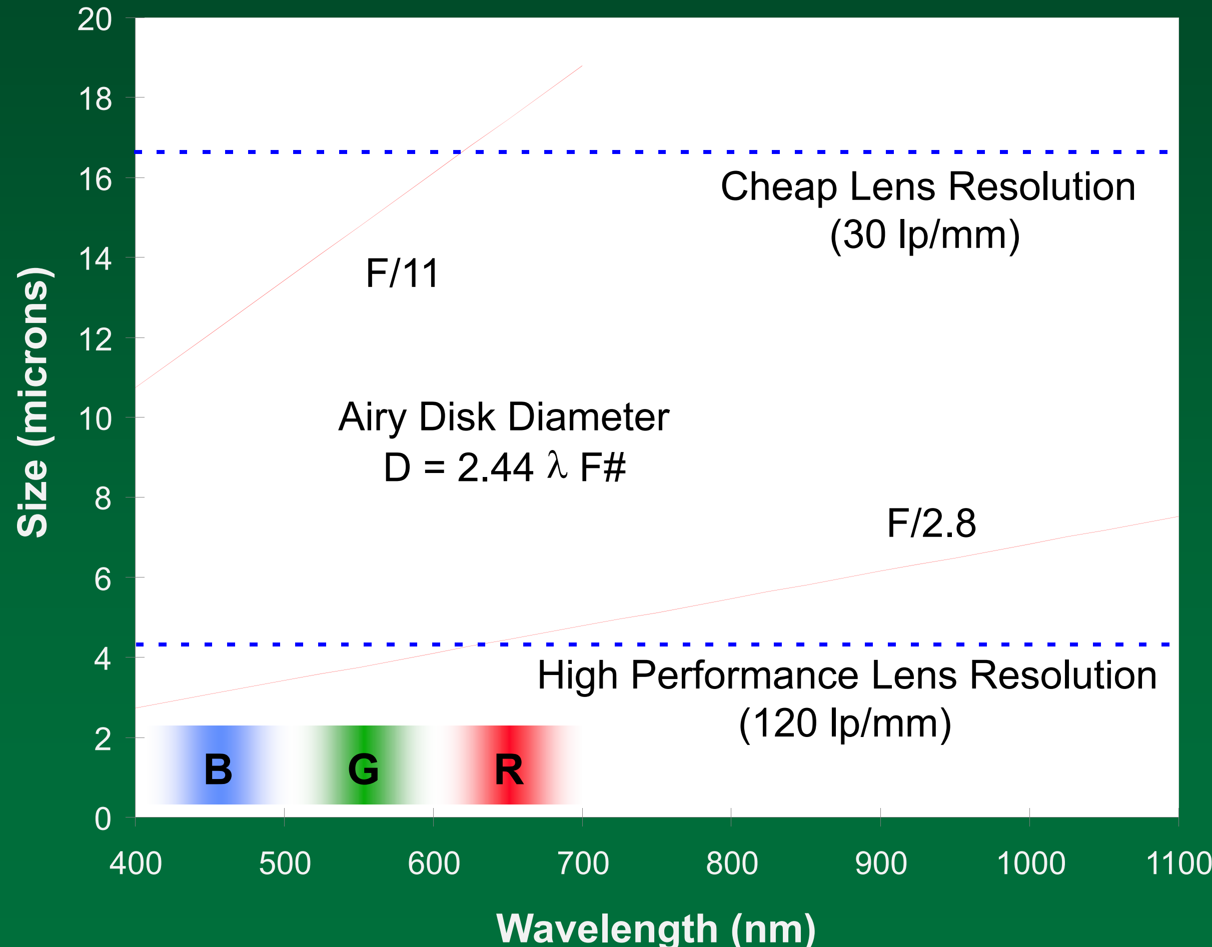


Noise impacts luminance and color

http://docs.gimp.org/ko/plug-in-rgb-noise.html

Diffraction Limit





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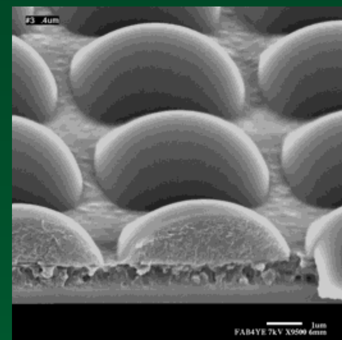
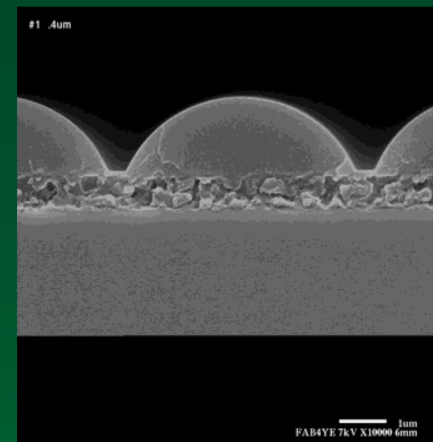
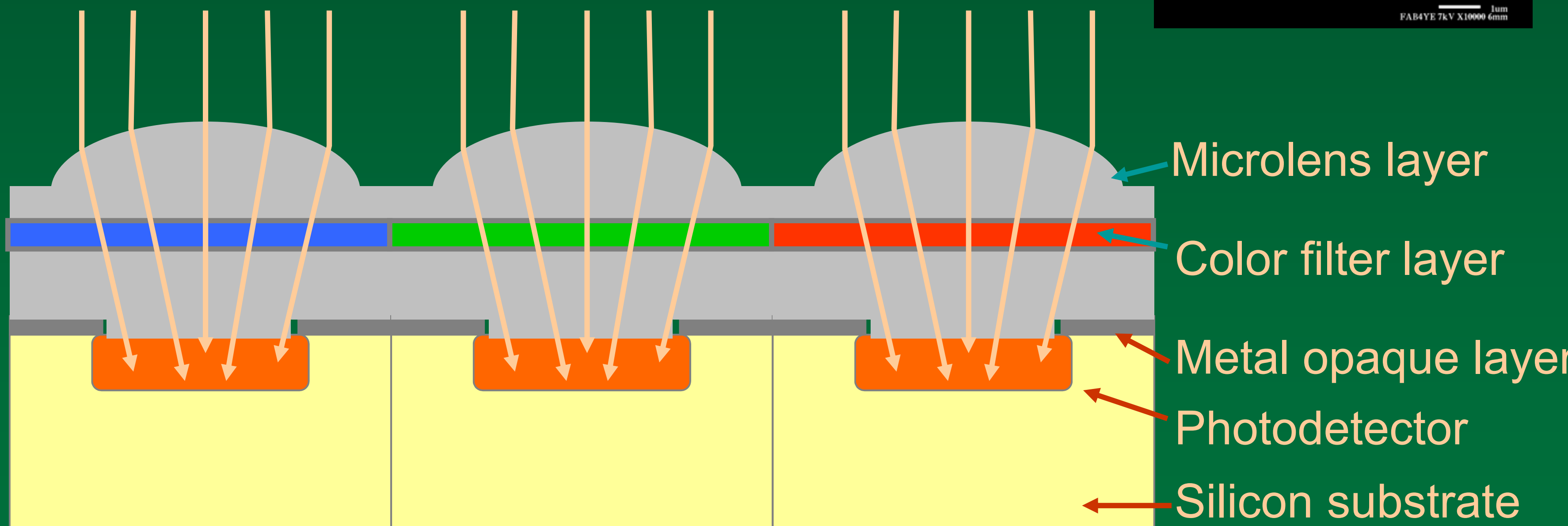
Microlenses

- Main camera lens brings image to microlenses
- Microlens funnels photons to active detector area.



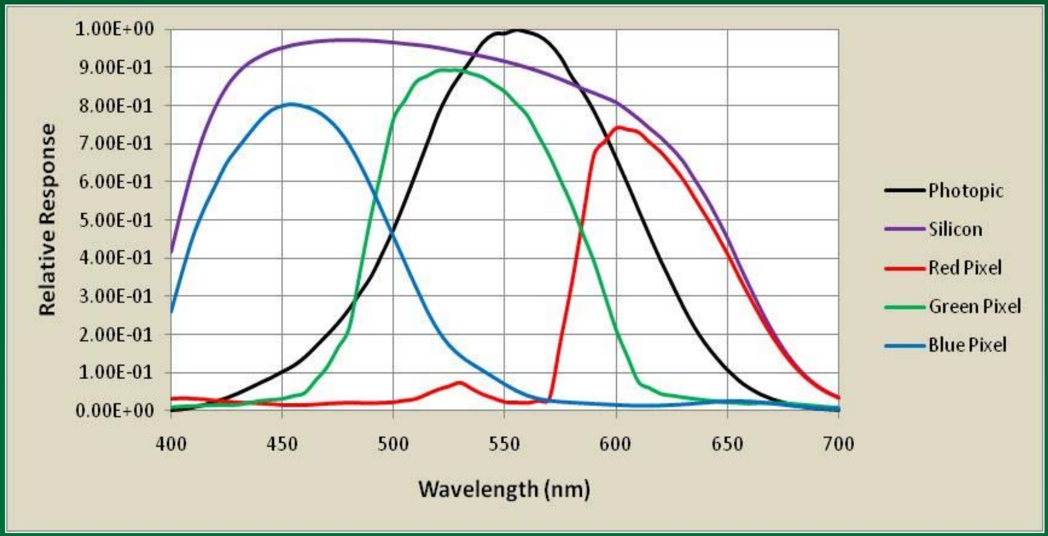




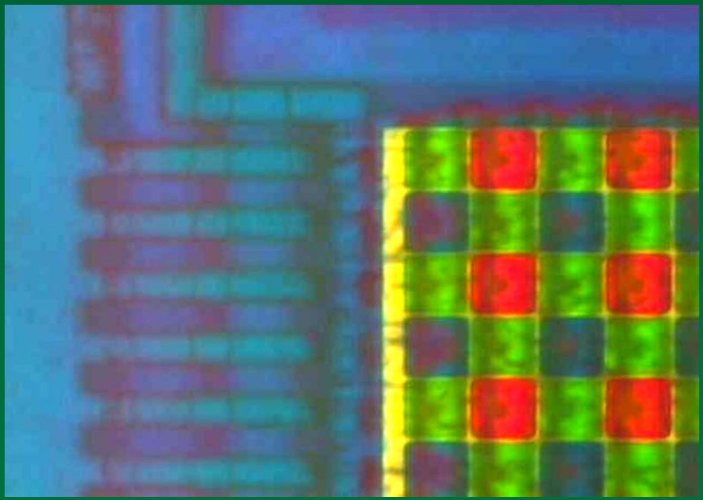
Color Filter Array (CFA)

- Each pixel gets covered by a colored filter
  - We use red, green, blue (RGB) CFA - best match for RGB displays
  - Pixel colors arranged in “Bayer” pattern

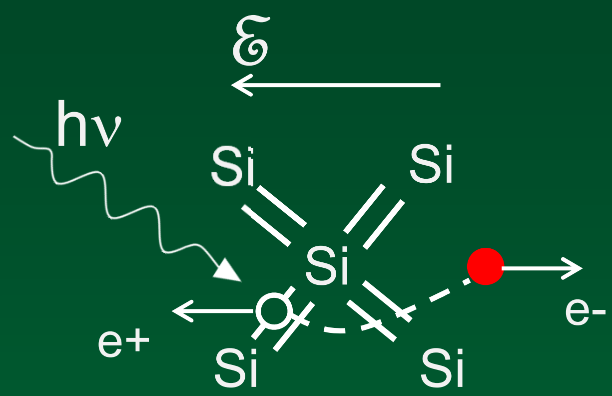
G	R
B	G



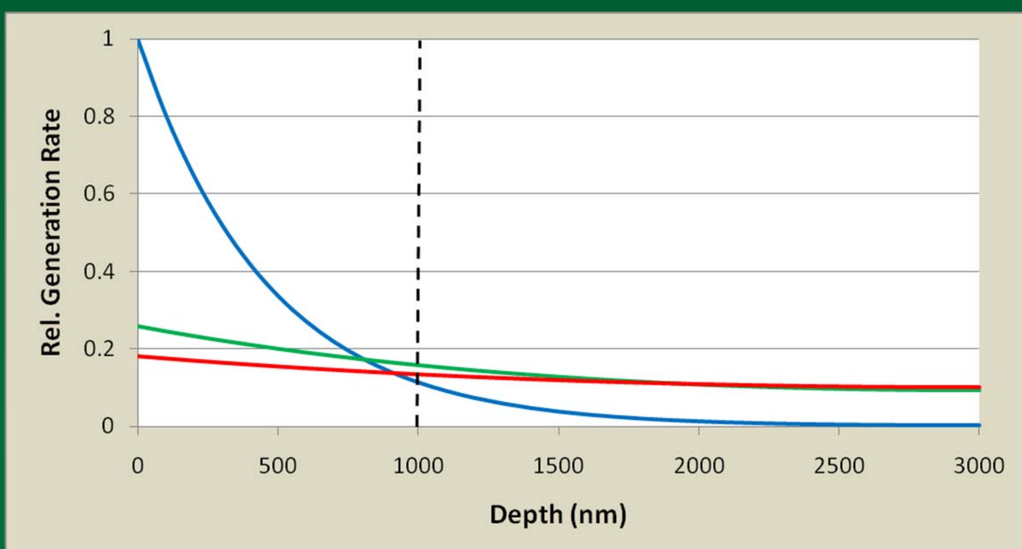
(assumes UV and NIR filters)

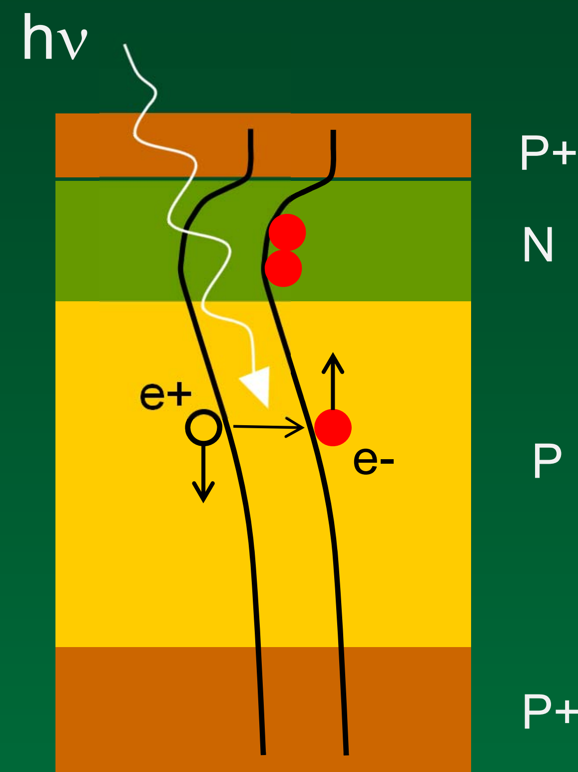


Photons to Electrons



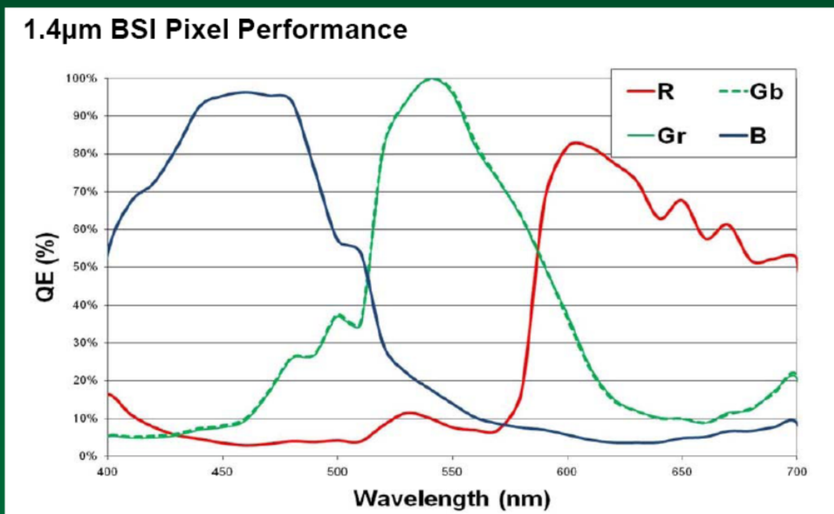
Covalently bonded silicon





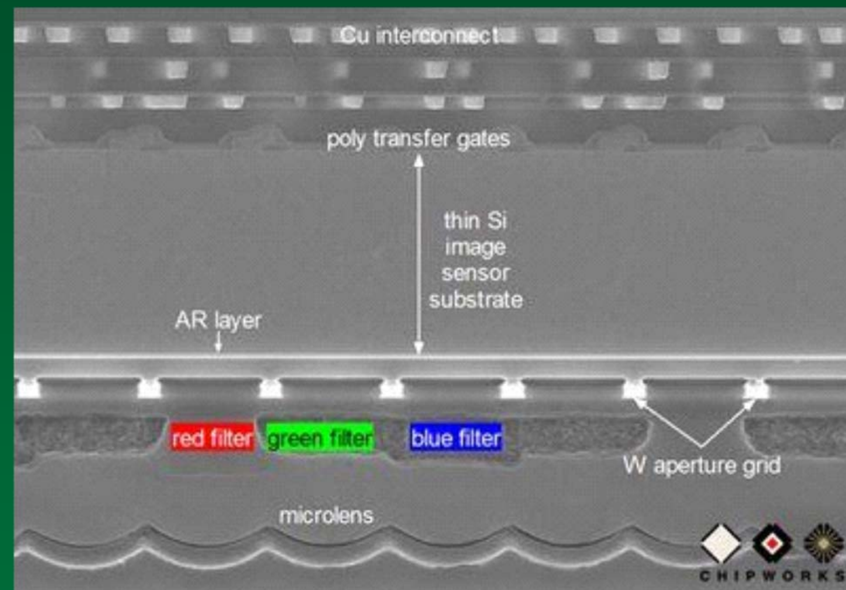
Pinned photodiode

Backside Illumination

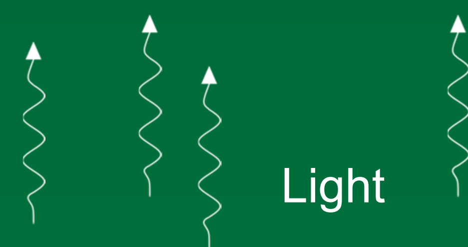


Example from Omnivision

Front side of wafer

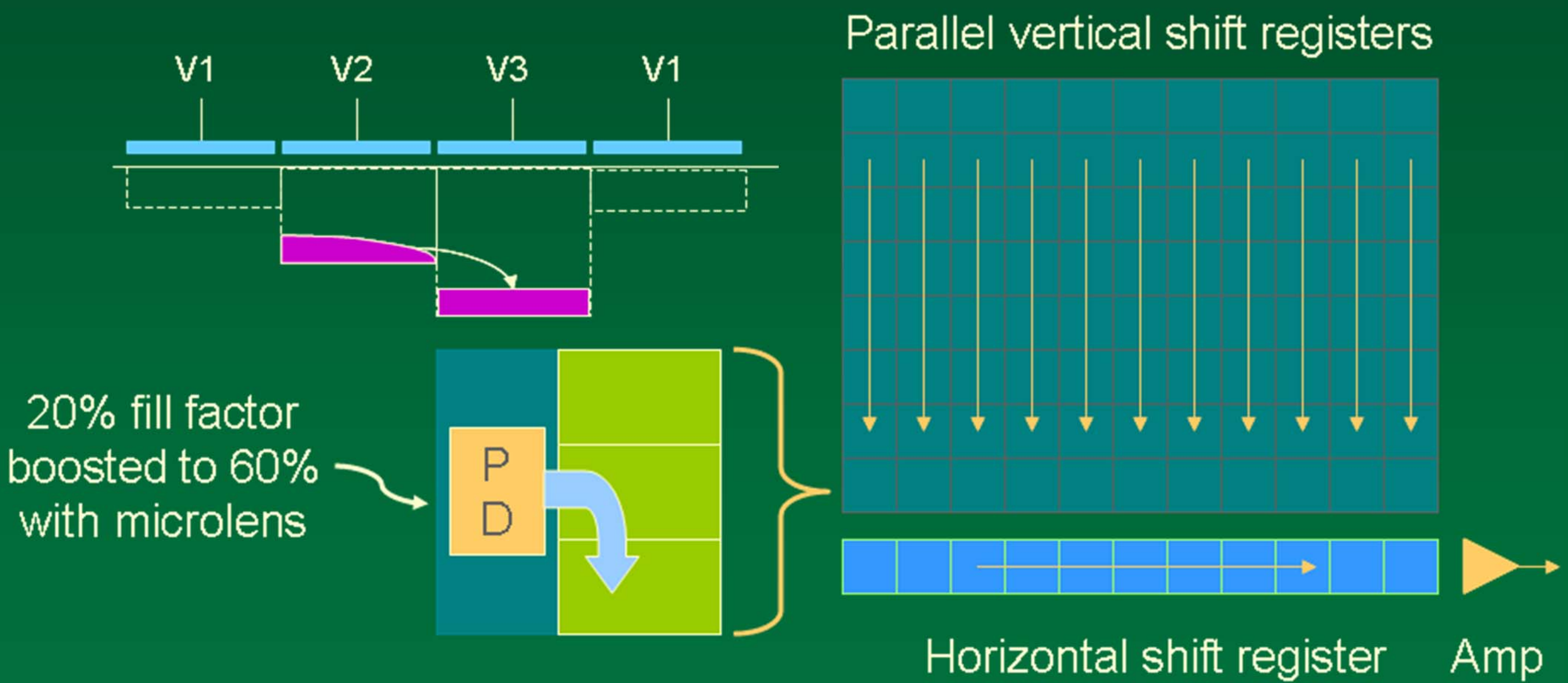


Example from Sony

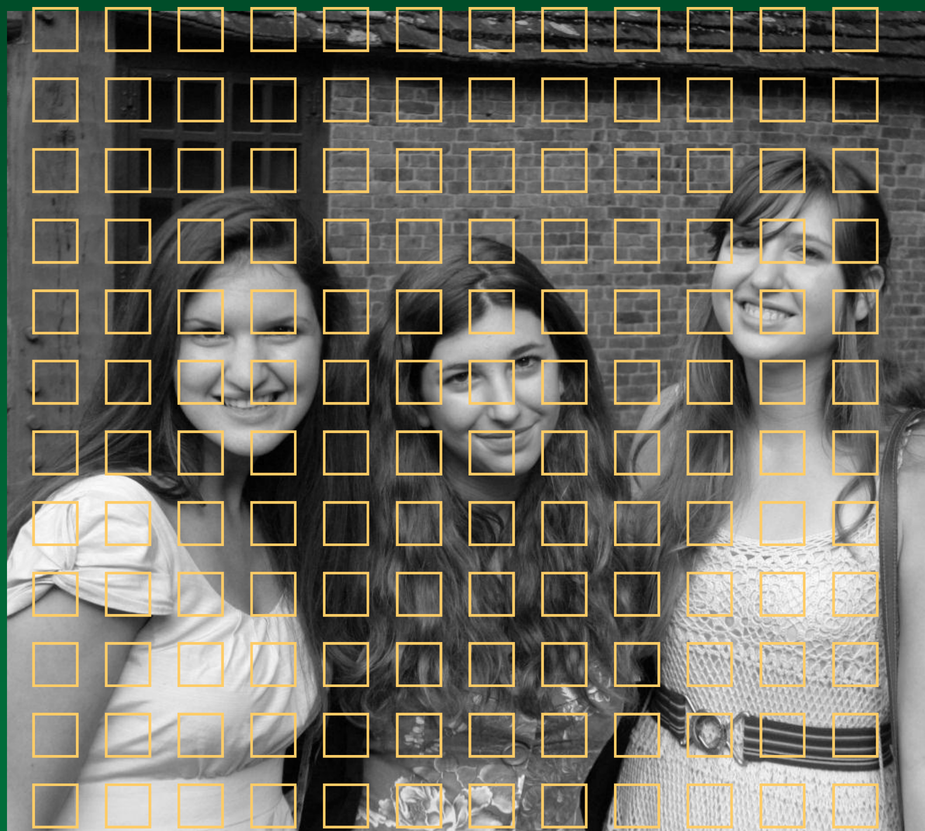


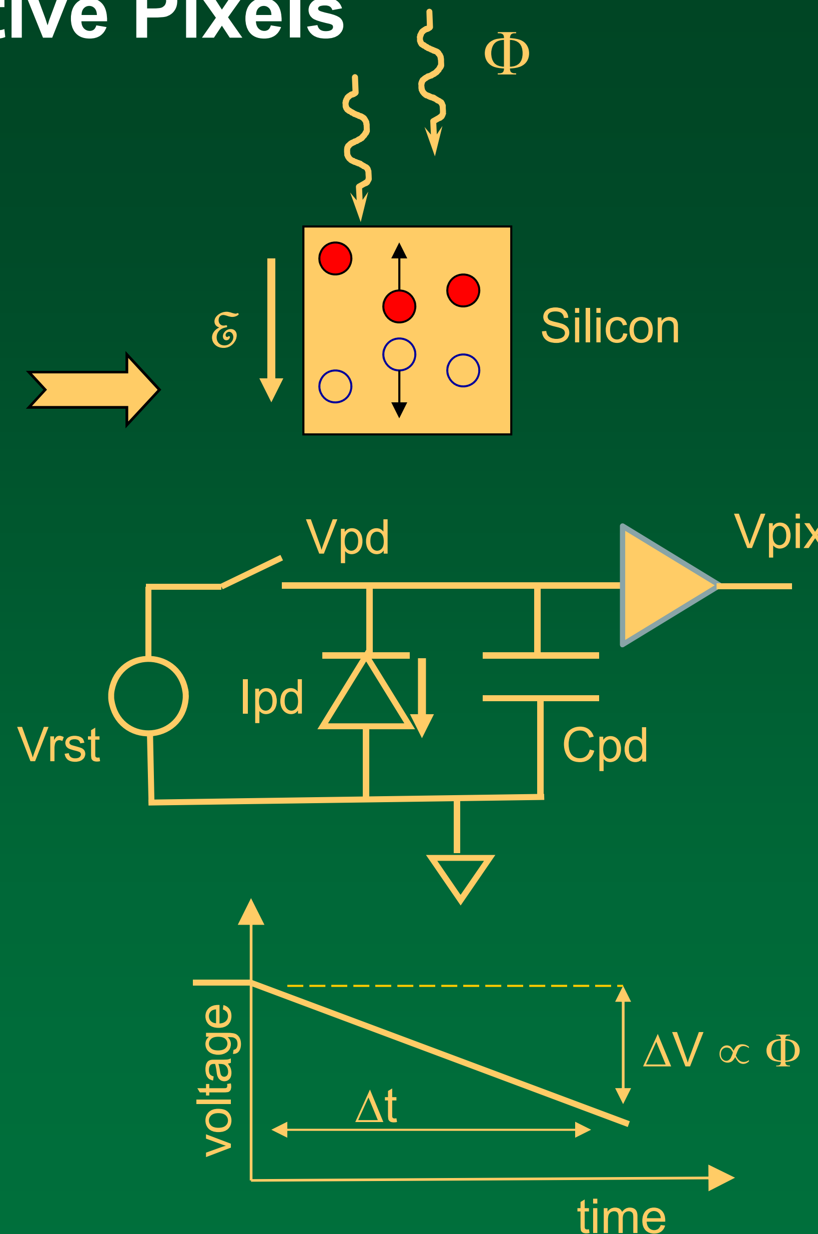
Charge-Coupled Device
1st Generation Image Sensor
(2009 Nobel Prize to Boyle and Smith)

- MOS-based charge-coupled devices (CCDs) shift charge one step at a time to a common output amplifier



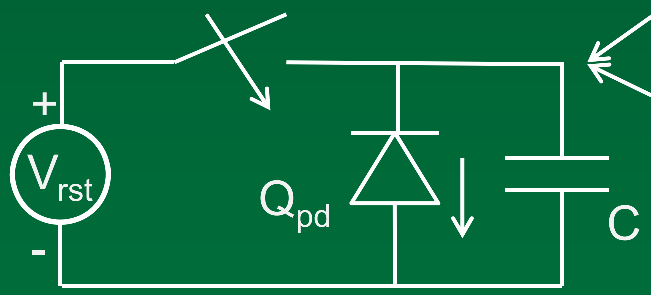
Active Pixels





Electronics Noise

- Many sources of electronics noise: pick-up, thermal, 1/f, trap-induced field effect (RTS), etc.
- “kTC” noise is fundamental – comes from Brownian-like motion of electrons in a conductor.
- Can be suppressed using CDS = correlated double sampling.



Measure after reset
$V_1 = V_{rst}+v_n$

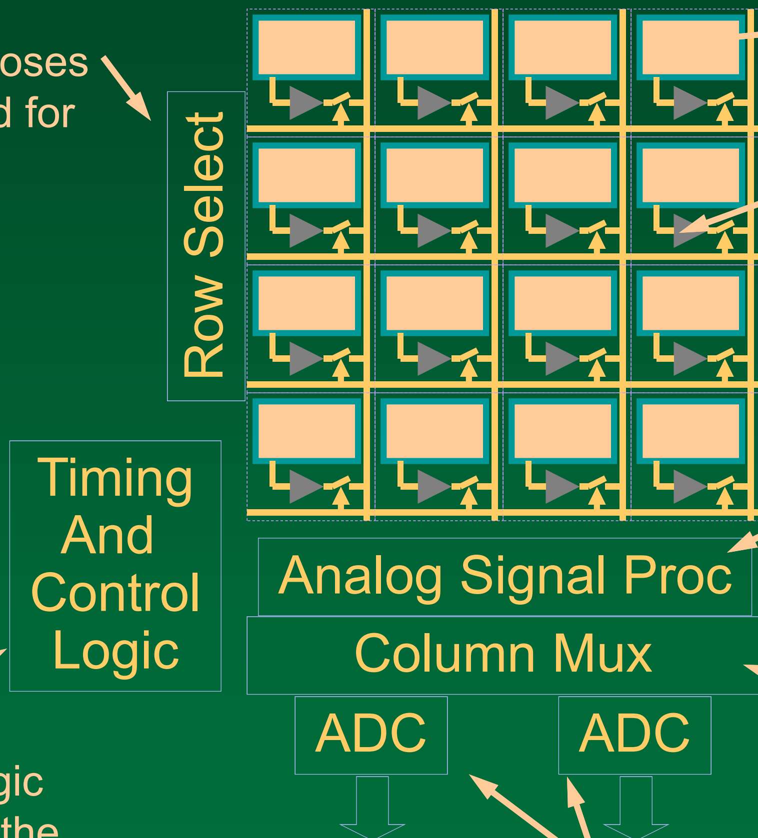
Measure after photo-current subtracted
$V_2 = V_{rst}+v_n-Q_{pd}/C$

Take Difference
$\Delta V = V_1-V_2$
$= Q_{pd}/C$

CMOS Active Pixel Sensor
2nd Generation Image Sensor

Read pixel signals out thru switches and wires

Row select logic chooses which row is selected for readout.



Photodetector converts photons to electrons

Amplifier converts electrons to voltage after intrapixel complete charge transfer

Analog signal processor suppresses noise and further amplifies signal

Column multiplexer selects particular column(s) for routing to ADC(s)

Timing and control logic controls the timing of the whole sensor

Analog-to-digital converters (ADC) converts signal from volts to bits (usually 10 bits resolution)

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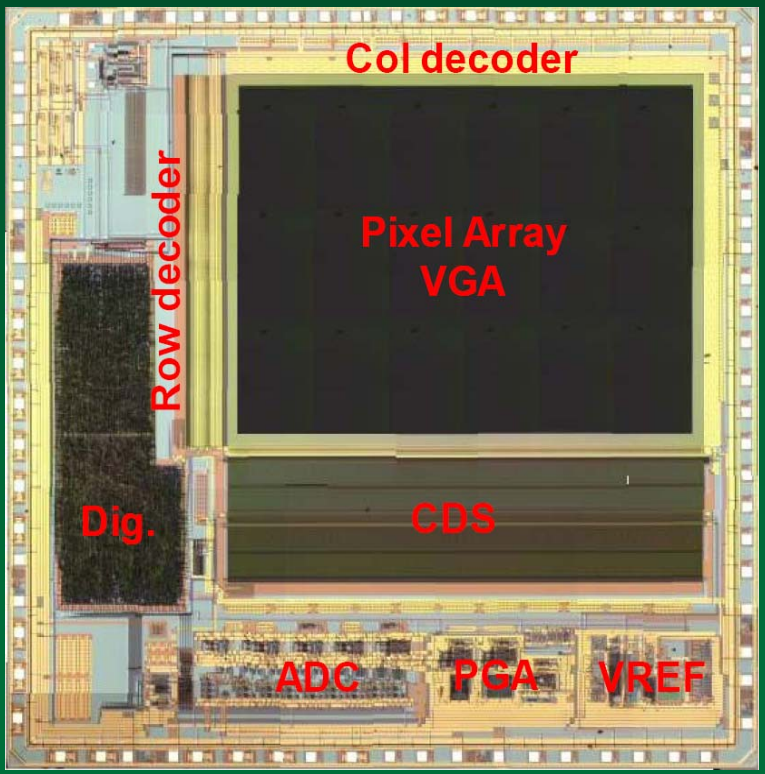
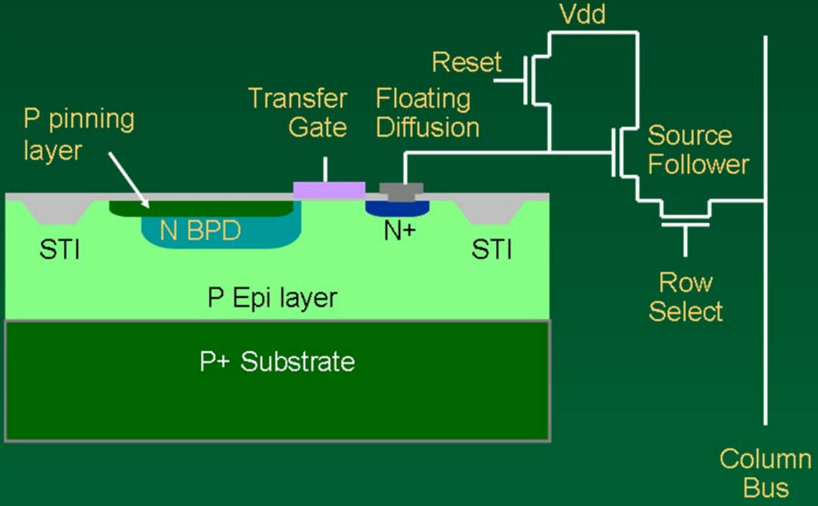
CMOS Active Pixel Sensor 2nd Generation Image Sensor



Pain et al.
2007 IISW



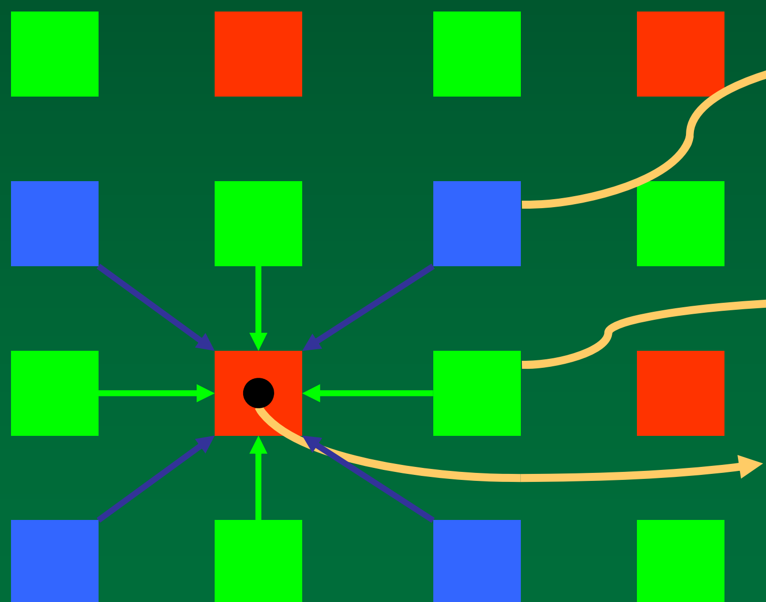
Camera on a Chip
- Active pixel array
- Analog signal chain
- Analog-to-Digital Conv.
- VLSI Digital logic
  - I/O interface
  - Timing and control
  - Exposure control
  - Color processing
  - Ancillary circuits

On-Chip Image Signal Processing

- Camera System-on-a-Chip integration is extensive
  - Color interpolation
  - Color correction, white balance
  - Dark signal correction, gamma and other normal corrections
  - Lens shading corrections
  - Format conversion and compression
  - Exposure control
  - Flicker detection and avoidance
  - Defect identification and correction
  - Auto focus support (focus score, actuator control)
  - Etc.

Color Interpolation

- Goal is to get best approximation for RGB at each pixel site but we start with just red, green or blue, not all 3.
- Many ways to do color interpolation, for example:



- Have blue, need green & red
  - G = average of 4 neighboring greens
  - R = average of 4 neighboring reds
- Have green, need blue & red
  - B = average of 2 neighboring blues
  - R = average of 2 neighboring reds
- Have red, need green & blue
  - G = average of 4 neighboring greens
  - B = average of 4 neighboring blues

Light Out

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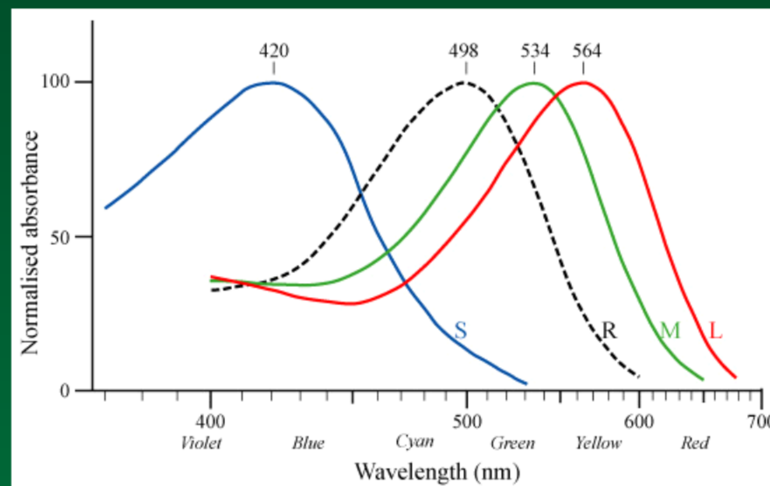
Image on screen should look like image seen, but better

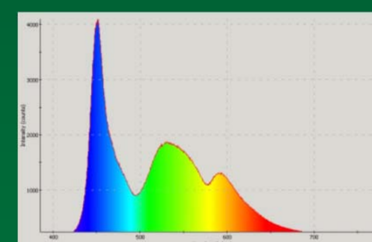


Human eye response to color

Silicon response and On-chip processing

Camera processing

Computer processing



LED LCD display color Spectrum and tuning

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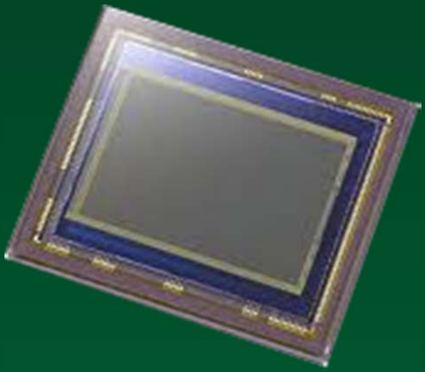
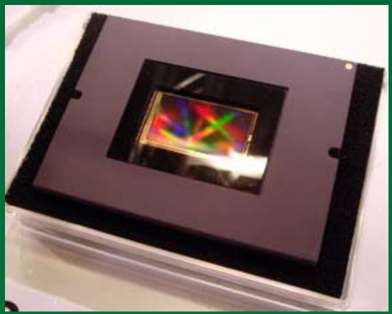
State of the Art



Sony
24 Mpixel
DSLR sensor

- Pixel counts for consumers are in the 8-16 Mpixel range.
- Pixel counts for professional cameras are in the 20-40 Mpixel range
- Pixel counts for aerospace application are approaching 100 Mpixels.
- Pixel size is 2.2 um to 1.1 um for common consumer applications.



UDTV or Super-High Vision
- 7680 x 4320
- 33 Mpixels, 60 fps
- 2 Gp/s

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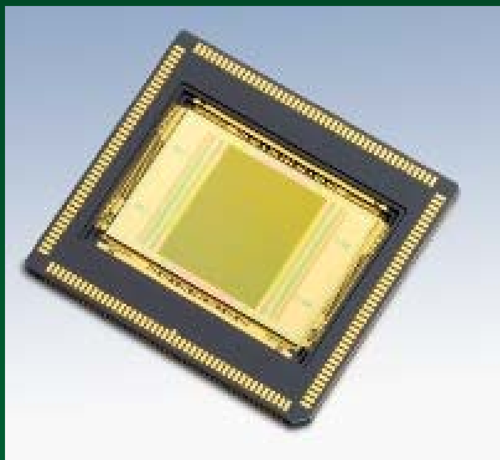
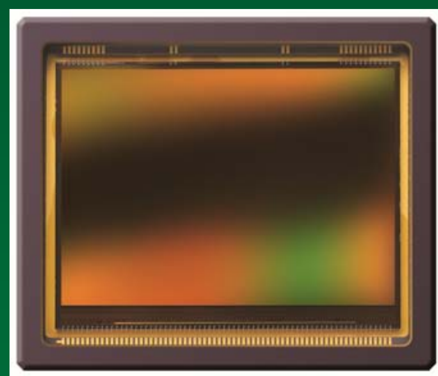
Science and Space Sensors

High-Accuracy CMOS Image Sensors Fly Into Space On-Board European Space Agency's Proba-2 Satellite



Fairchild Imaging sCMOS
•2560 x 2160 pixels
•6.5μm x 6.5μm pixel
•Readout noise less than 2 electrons at 30 f/s and less than 3 electrons at 100 f/s
•100 f/s max at full-res
•Dynamic range: > 16000:1
•QE: >60% at 550 nm
•Rolling- or Global-Shutter readout (user selectable)



CMOSIS 70 Mpixel 3.5 um
8 analog outputs 3 fps

E2V 2Mpixel CMOS image sensor
In weather satellite

106-CCD Gigapixel
Gaia Sensor

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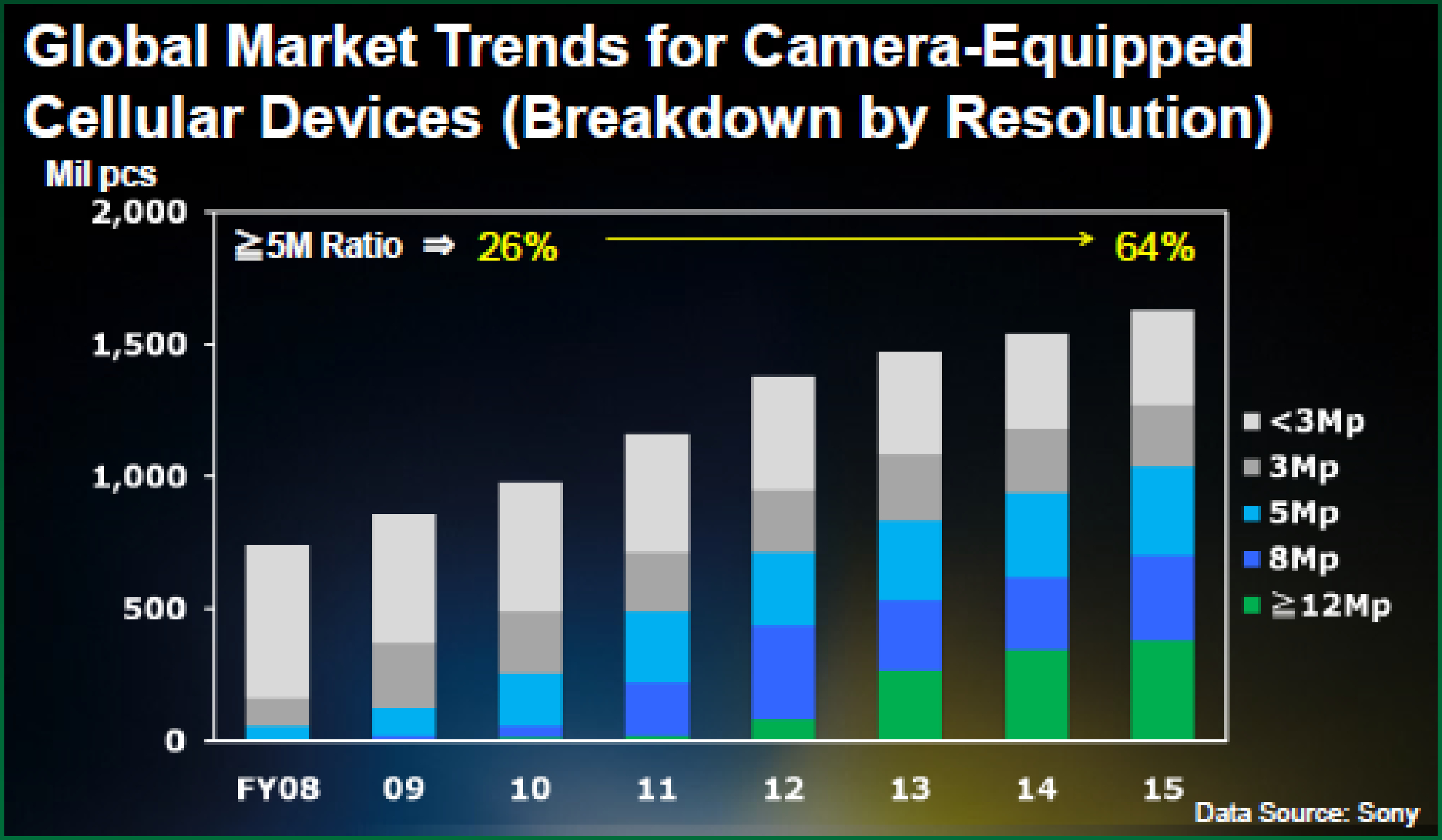
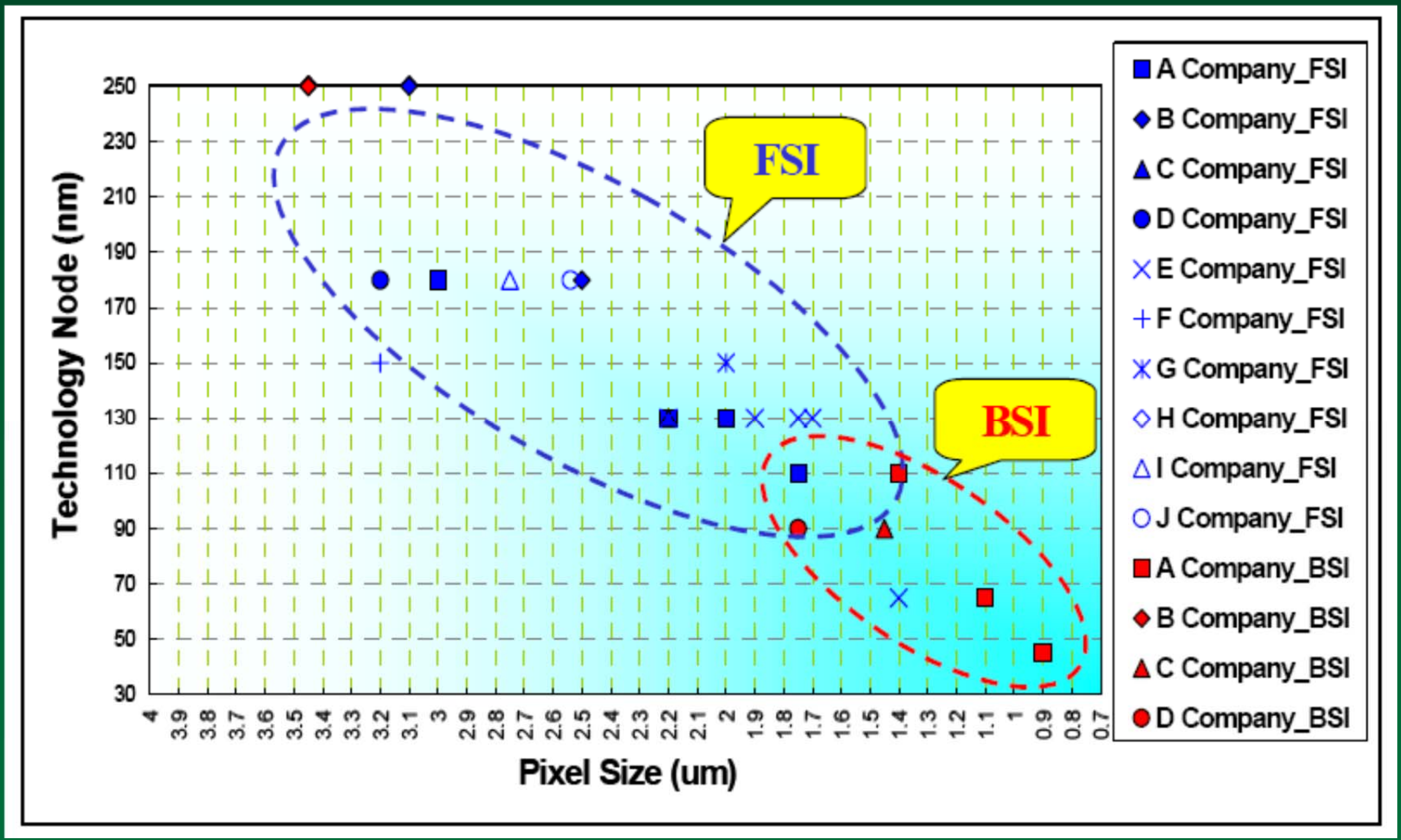
Coming Attractions

More Camera Phones



Smaller Pixels and Backside Illumination (BSI)



From Wuu et al. 2009 IISW Bergen, Norway

Smaller Pixels, More Pixels

- Smaller pixels allow smaller chips
  + Reduces chip cost to camera module maker
  + Reduces optics size and cost
  + Smaller camera modules more desirable for integration into consumer products
  - NRE cost for chip higher
  - Performance of pixel usually degraded
    - Lower quantum efficiency due to fill factor
    - Reduced SNR under low light
    - Smaller full-well so worse dynamic range
    - Increased optoelectronic crosstalk
    - Stack height and aperture degrades chief ray angle
    - Lower voltages bad for analog circuits

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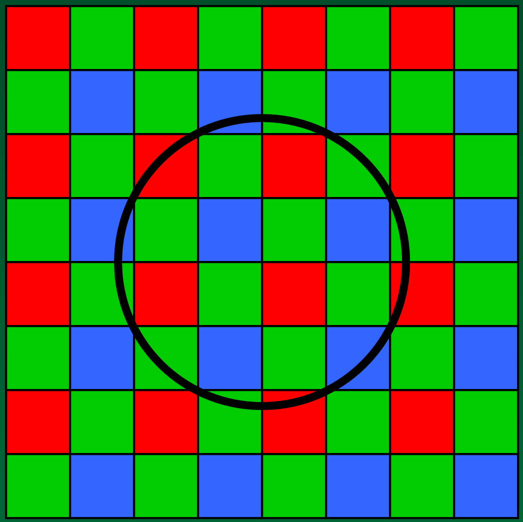
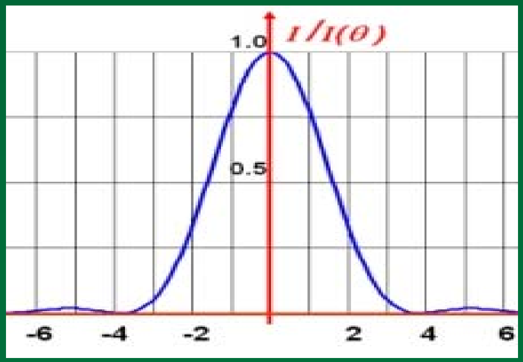
Smaller Pixels, More Pixels (2)

- Smaller pixels means more megapixels.
  - \+ Higher resolution images for same optics
  - \+ Pixel count often sells cameras and gadgets.
  - \+ More megapixels sells more cellular service traffic, bigger computers, better software, mass storage
  - \- Entering visible light diffraction limit zone with SOA pixel pitch so less return on resolution
  - \- More stringent requirements on optical system quality
  - \- More megapixels makes getting data off chip at same frame rate more challenging
  - \- More megapixels increases power requirements of sensor.

Sub-Diffraction Limit (SDL) Pixels

0.9 um pixel pitch





- Marginal return on shrink for real resolution improvement
- Sort of a spatial and color oversampling
- Anti-aliasing filter not needed

- Some real limit on how small is practical according to current pixel paradigm

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Improved Functionality

- High dynamic range (HDR)
- Global electronic shutter
- Higher speed readout (slow motion, blur reduction)
- Handshake blur reduction
- Embedded focus pixels for mirrorless DSLRs

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Paradigm Changing Research Activity

- Digital Integration Sensor
  - Signal integration in-pixel and digital off-array
- Quanta Image Sensor (QIS)
  - Counting individual photons
- 3D Range (Z) Image sensors
  - Range only
  - RGBZ
- Computational Imaging
  - Extended depth of field, refocusing
- Plenoptic Sensor
  - Multiple lenses and small arrays
- Stacked Sensor
  - Quantum dot film sensor, Organic film sensor

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Digital Integration Sensor (DIS)

- Current paradigm: Integrate signal in well, readout. Full well needs to be as large as possible -> device and circuit constraints.
- DIS: Make smaller full well and higher conversion gain. Readout sensor 4x or 8x per final frame and sum (integrate) in digital memory. Can allow lower noise and higher dynamic range and easier pixel design. Lower ADC resolution needed. Needs faster readout circuit and increase in power.

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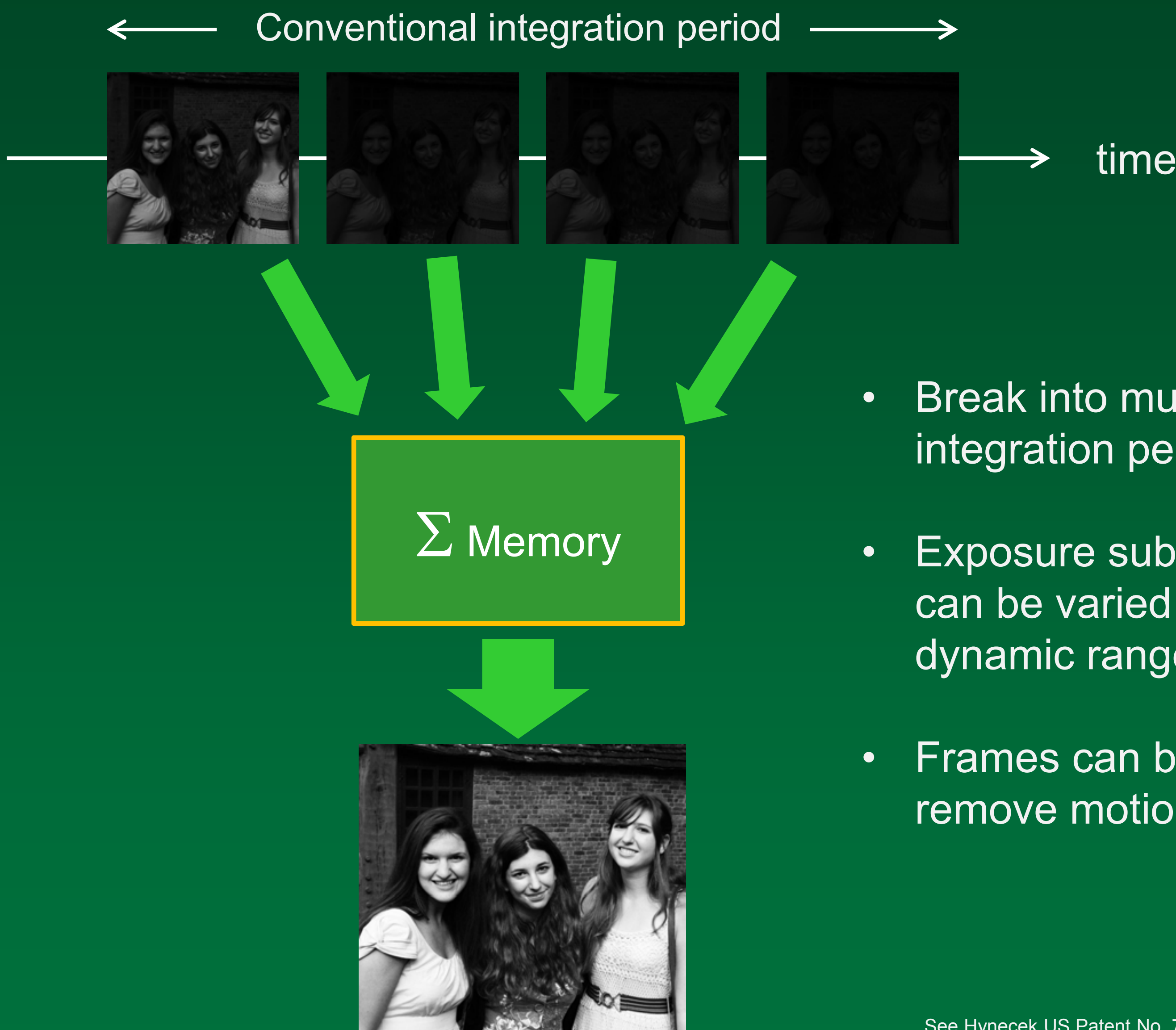
Digital Integration Sensor (DIS)



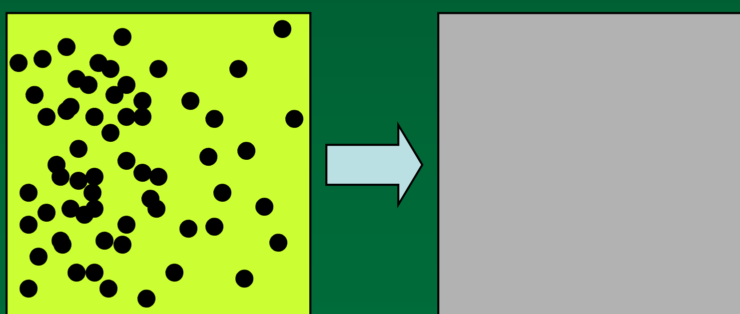
- Break into multiple sub-integration periods
- Exposure sub-integration times can be varied to increase dynamic range
- Frames can be shifted to remove motion blur

See Hynecek US Patent No. 7,825,971
And Patent Applications by Fossum 2011

Quanta Image Sensor (QIS)

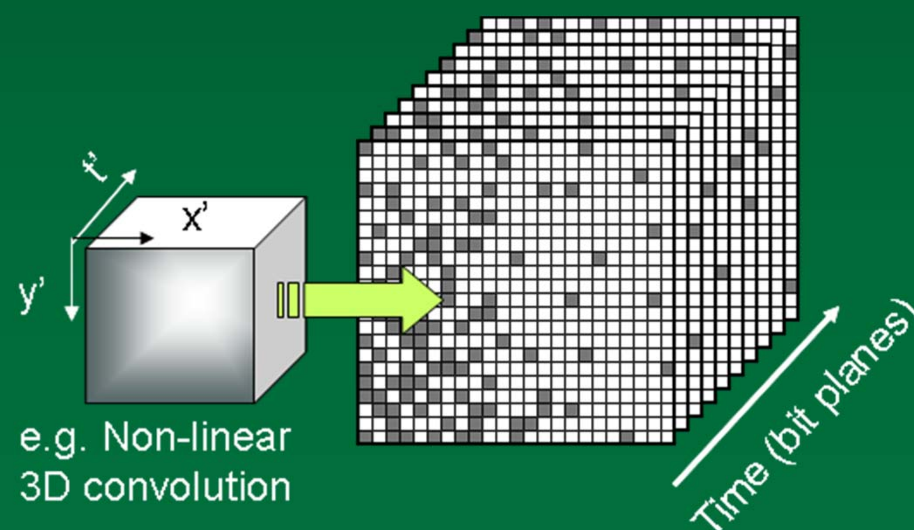
Current paradigm:

- We collect photons for a predetermined amount of time in a silicon “rainbucket” determined by physical size and capacity of silicon pixel.



New paradigm:

- Let’s count each photogenerated carrier and record time and location, creating binary bit planes for each time slice, and then digitally form image by digital convolution over X,Y, t.



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Need Gigapixels at Terabits/Sec

- Consider a tiny pixel ("jot") that is sensitive to a single photoelectron.
- Jot state changes from "0" to "1" when a photoelectron is present
- Requires a single-electron amplifier or single-electron transistor.
- Want billions on a single chip so must be small, e.g. 0.1 - 0.5 um pitch.
- At 0.1 um jot pitch, 16:9 gigajot sensor would be 4.2 mm x 2.4 mm or about ¼" optical format.

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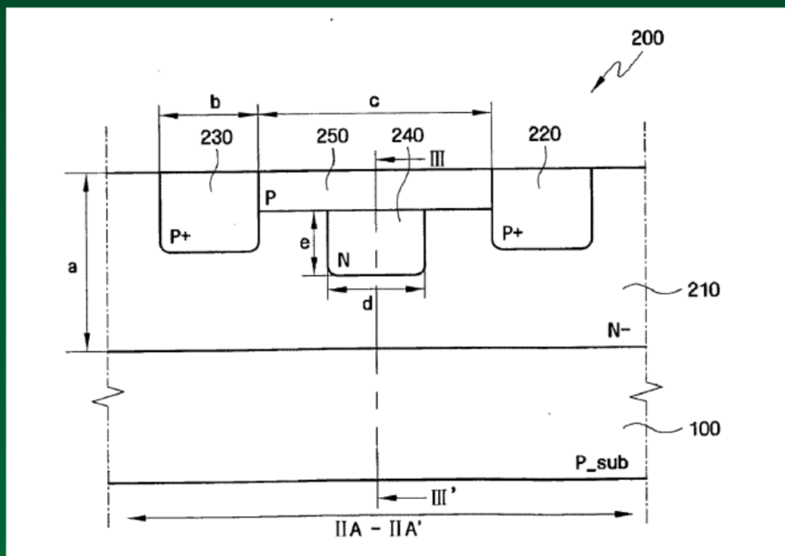
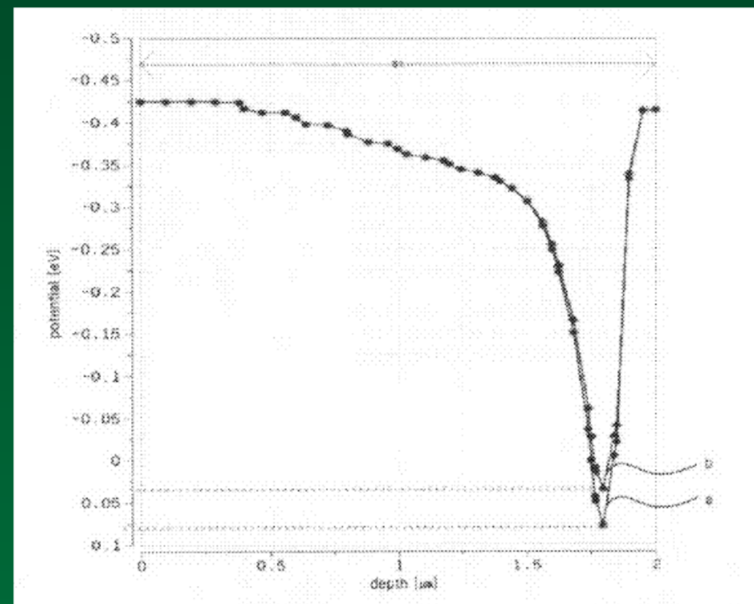
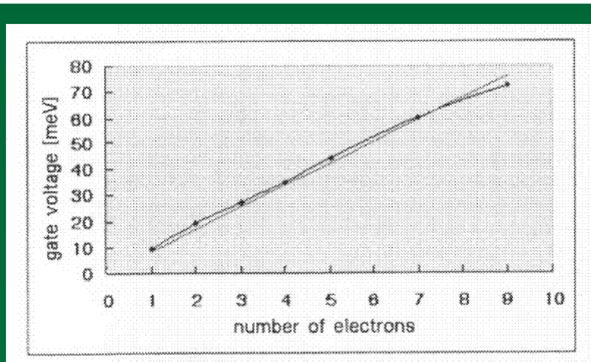
SEFET

Samsung

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2010/0320515 A1**
Fossum et al. (43) **Pub. Date: Dec. 23, 2010**







Status:
- TCAD model only
- Shows about 5 mV/e- signal
- More work required

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Pixels to Jots Equivalency

Sensor	**sCMOS**	**Aptina 8M**	**sCMOS**	**Aptina 8M**
Pixel Pitch (nm)	6500	1400	6500	1400
Pixels H	2560	3264	2560	3264
Pixels V	2160	2448	2160	2448
Total (Mpix)	5.5	8.0	5.5	8.0
Full Well (e-)	31700	3000	31700	3000
Frame Rate (Hz)	30	15	30	15
Te-/sec	5.3	0.4	5.3	0.4
Jot Pitch (nm)	100	100	200	200
Jots/Pixel	4225	196	1056	49
Jots H	166400	45696	83200	22848
Jots V	140400	34272	70200	17136
Total (Gjot)	23.4	1.6	5.8	0.4
e-/jot/frame	7.5	15.3	30.0	61.2
Bit plane readout (Hz)	225.1	229.6	900.4	918.4
Column scan rate (MHz)	31.6	7.9	63.2	15.7
Total jot rate (Tb/sec)	5.3	0.4	5.3	0.4
After KP (Gb/s)	1.2	1.8	5.0	7.3

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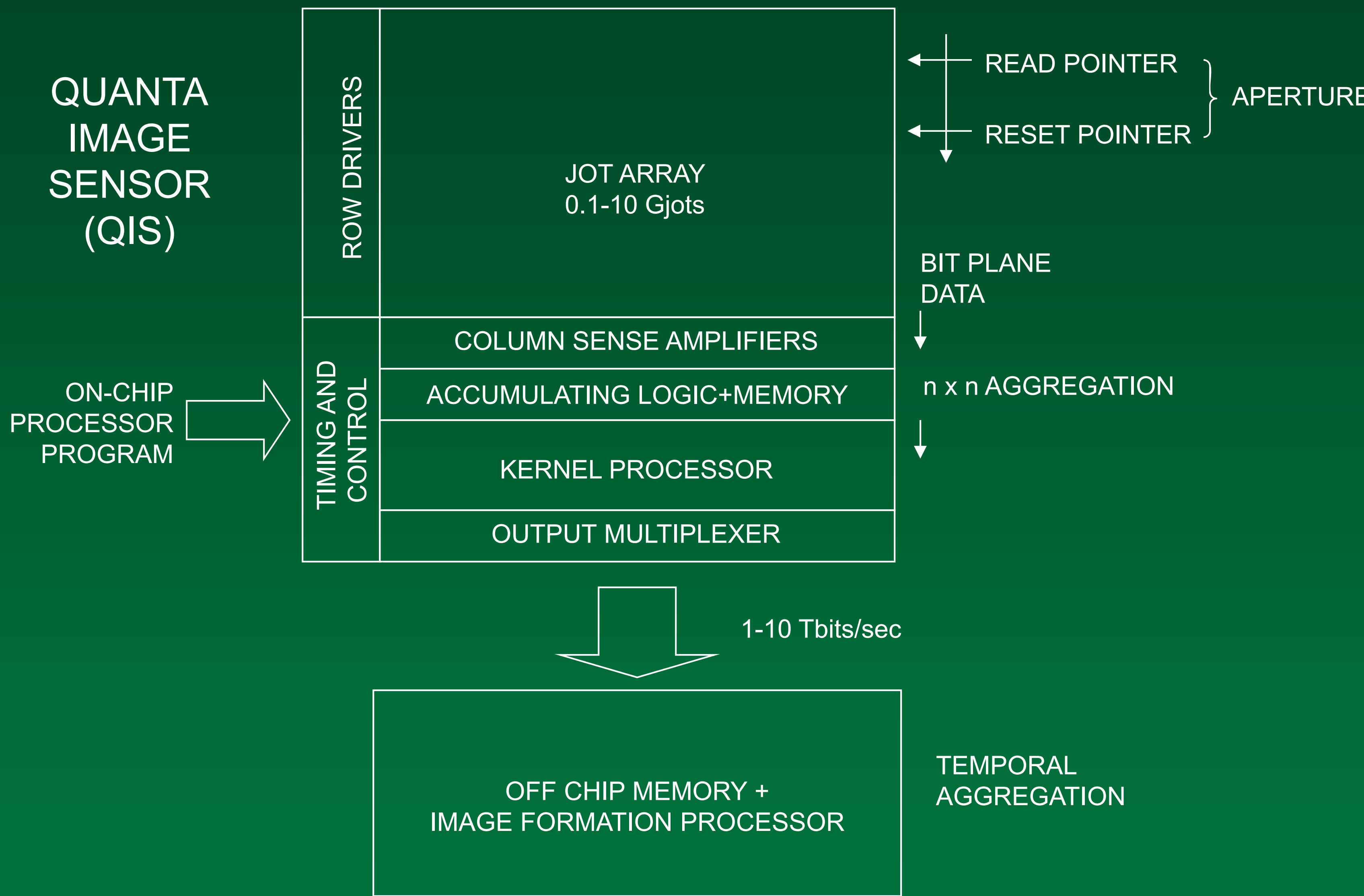
QIS Planar Architecture

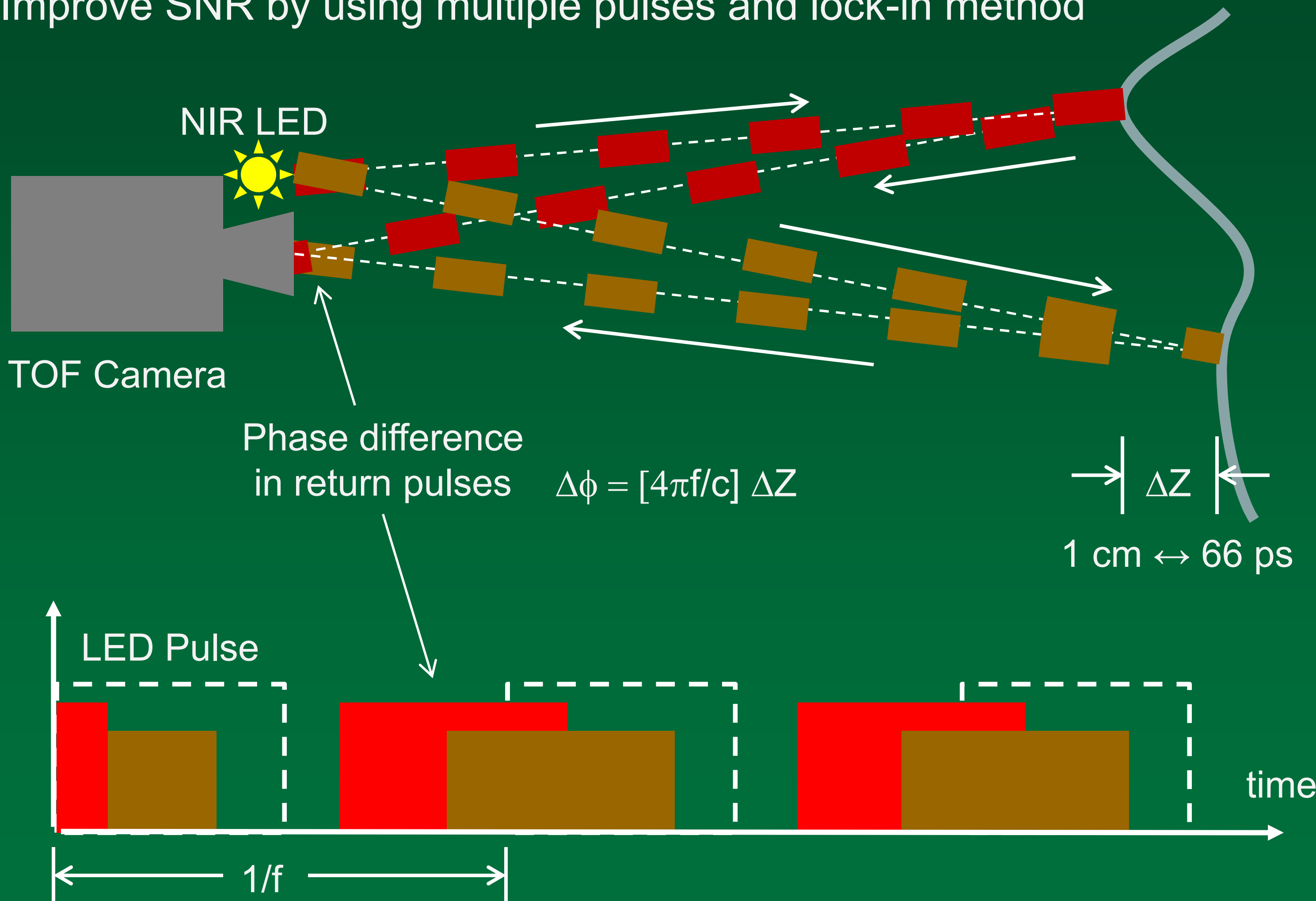
QUANTA IMAGE SENSOR (QIS)



Time of Flight Range Sensor

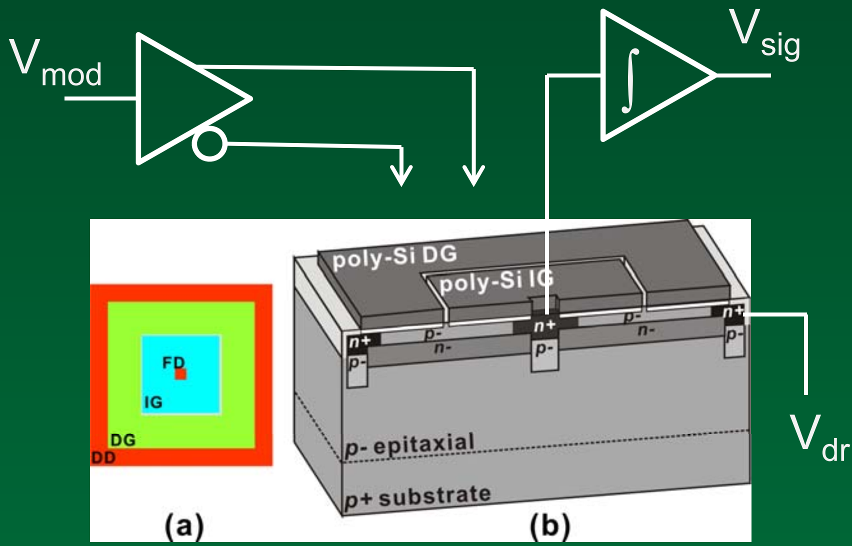
Single "Ping" $Z = \frac{1}{2}\ c\ \Delta t$

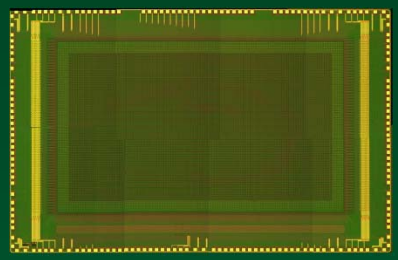
Improve SNR by using multiple pulses and lock-in method



Time-of-Flight Range Sensor

Lock-in single-tap pixel
using pinned photodiode

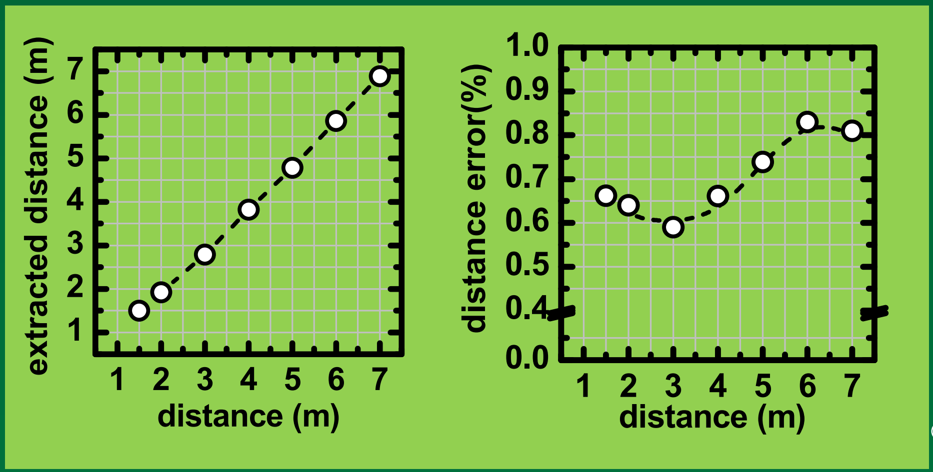




192x108 28x28 um pixels

Range image

Conv. gain 72 uV/e-
Full well 28ke-
DC at 20 MHz >50%

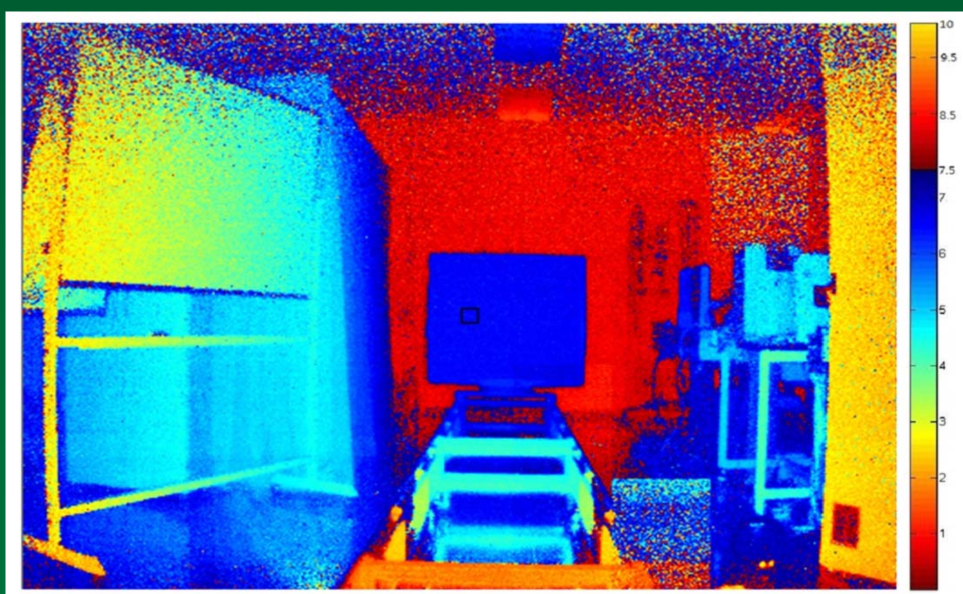


Samsung
T-Y Lee et al. IEDM 2011

RBGZ - 3D Color Image Sensor

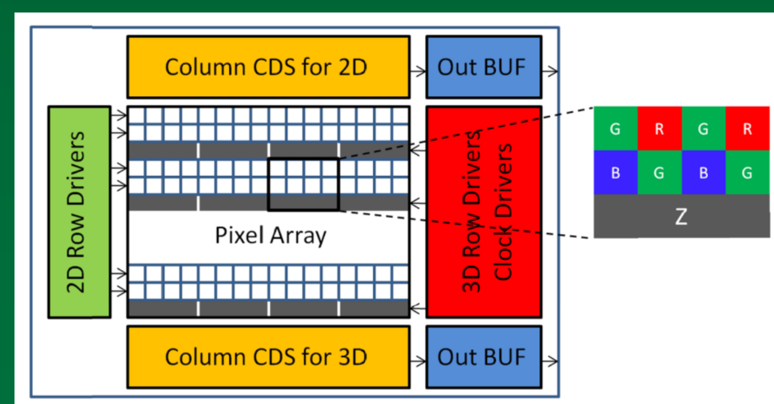
The Vision

3D Display



Color-coded range image

480x360 TOF embedded in 2Mpixel color sensor



2011 Samsung

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Conclusions

- Image sensors have come along way since the 1st generation device – the CCD.
- The 2nd generation device, the CMOS active pixel image sensor is going strong. “Billions and billions served”
- Much interesting work lies ahead as we move the digital divide as close as possible to the digital nature of photons.
- “Overconnection” of billions of massive-information gathering engines leads to interesting societal issues and questions.