THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

The Big Picture: CMOS Image Sensors From Zero to Billions and Beyond

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EECS Colloquium

University of California at Berkeley

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CMOS Image Sensors Enable Billions of Cameras Each Year

http://img.gawkerassets.com/img/18caaca96tsnsjpg/original.jpg

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Many kinds of digital cameras

Photography
- Camera phone
- Digital single lens reflex (DSLR)
- Mirrorless and Point-and-shoot

Video
- TV (0.3Mpix), HDTV (2Mpix) UDTV (133Mpixel)
- Webcam
- High speed – slow motion
- Motion capture
- Glass
- Body cam

Medical
- Endoscopy
- Pill camera
- Dental X-rays

Machine Vision
- Automotive
- Security
- Inspection

3D ranging
- Gesture control

Etc.



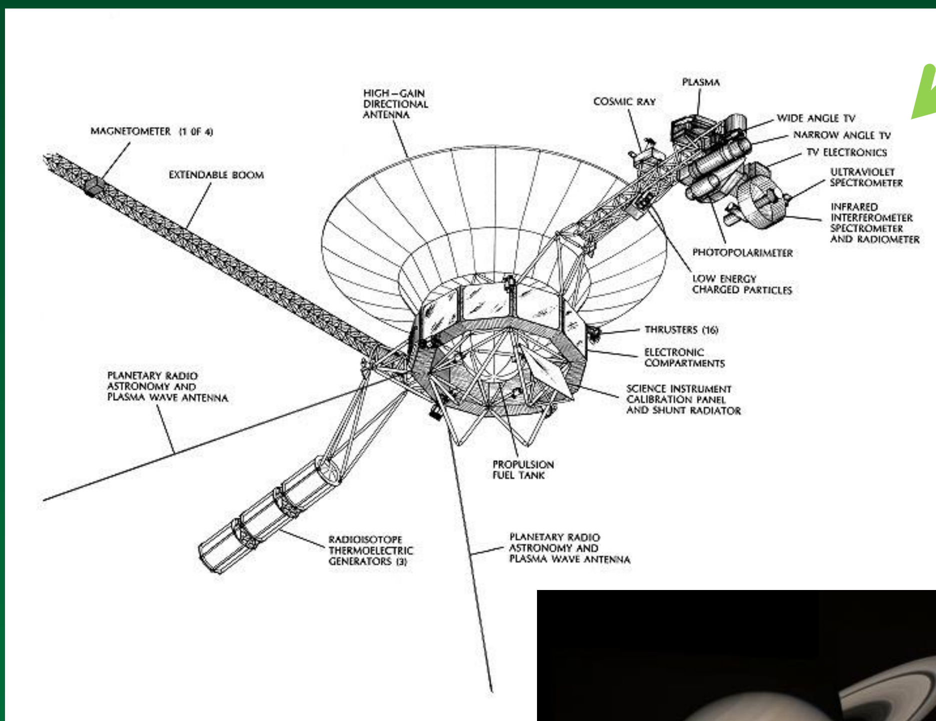




Inventions

"Necessity is the Mother of Invention"

Voyager (1977) ISS had vidicon cameras (wide angle and narrow angle)



Mass: 38.2 kg
Power (avg): 35.0 W

http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1977-084A-01

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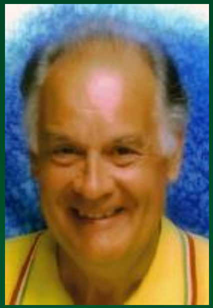
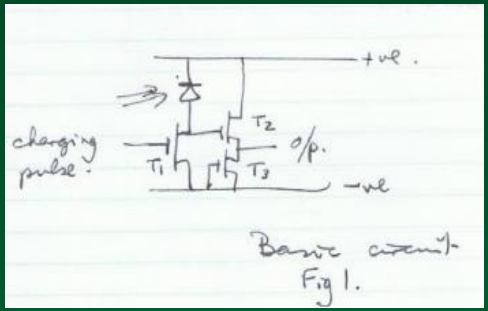
MOS "Photomatrices"
0^{th} Generation Image Sensor

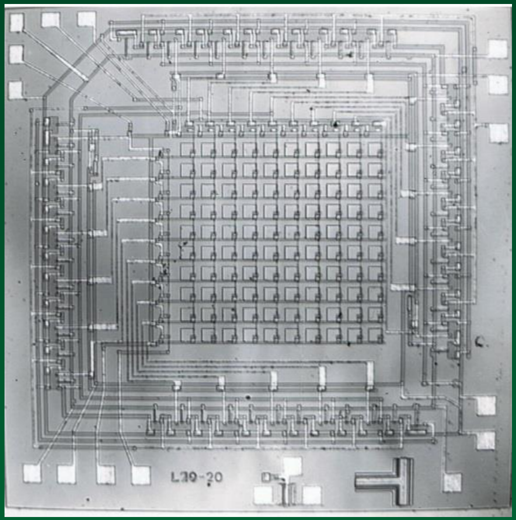


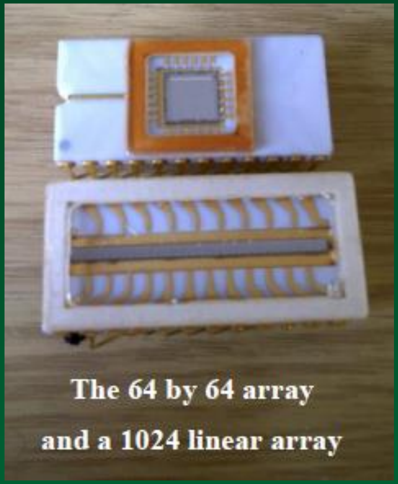
Peter JW Noble

~June 1966



First self-scanned →
Sensor 10x10 1966/67

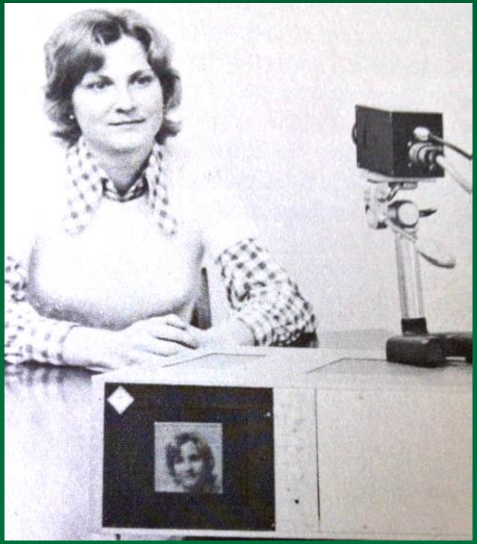




Gene Weckler

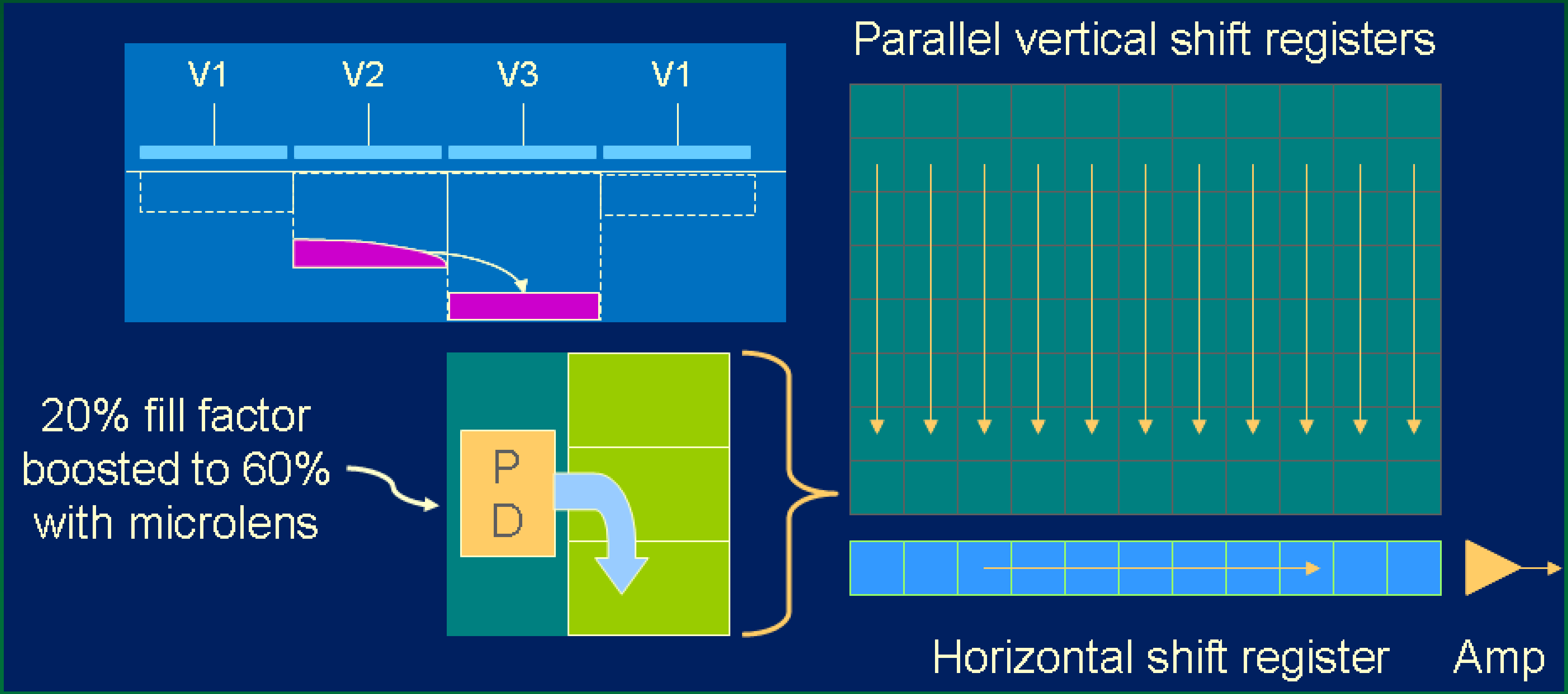
Mid-late 1960's
MOS arrays at Plessey
with startup Integrated
Photomatrix Ltd. (IPL)

And Fairchild with startup Reticon



Charge-Coupled Device
1st Generation Image Sensor

MOS-based charge-coupled devices (CCDs) shift charge one step at a time to a common output amplifier (1969 Bell Labs)



2009 Nobel Prize in Physics

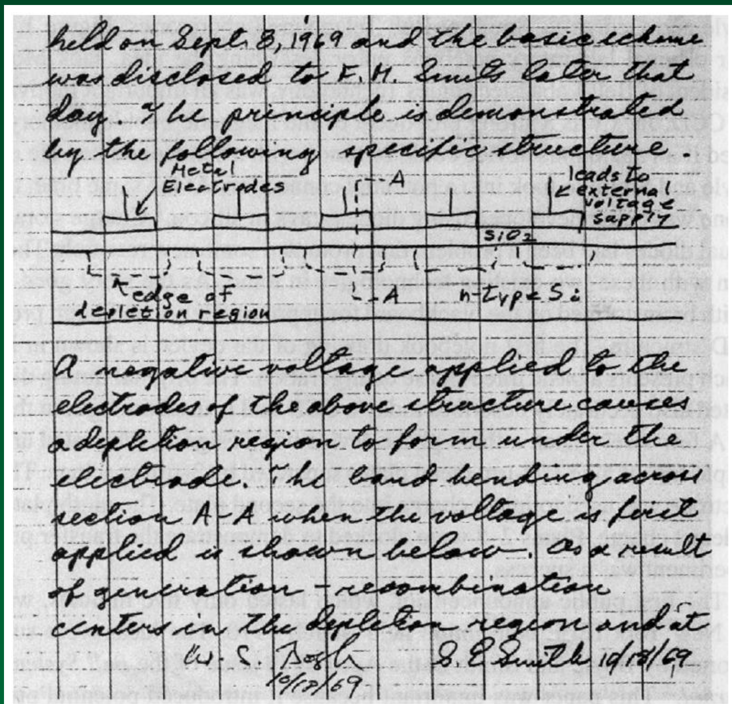
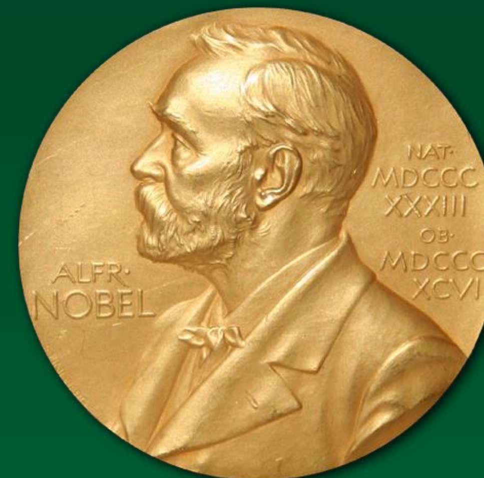


Figure 4. Original notes from the Boyle and Smith's brainstorm meeting on September 8 1969, when they made the first sketch of a CCD.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2009/popular-physicsprize2009.pdf

Photo: U. Montan
Willard S. Boyle

Photo: U. Montan
George E. Smith

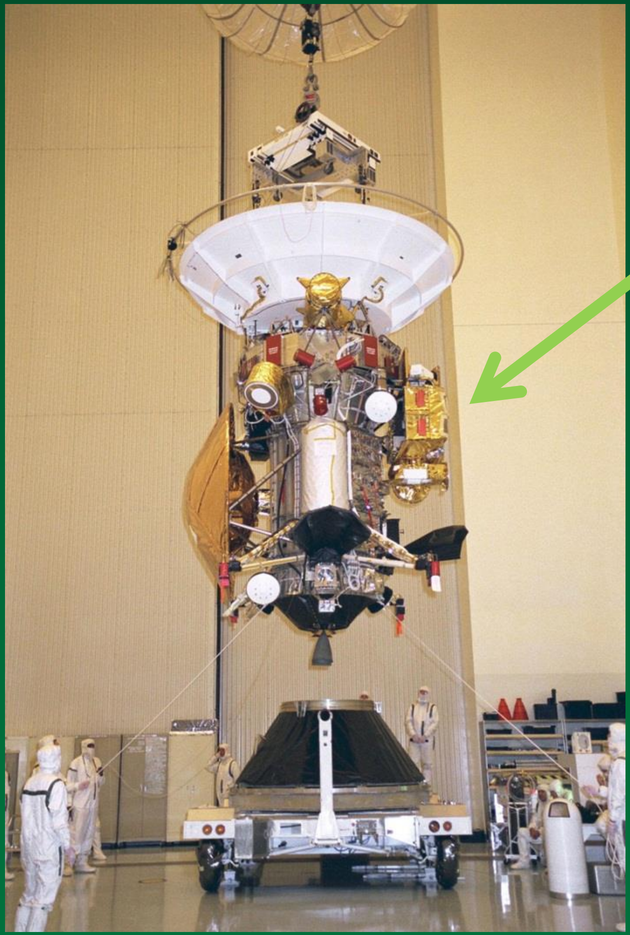


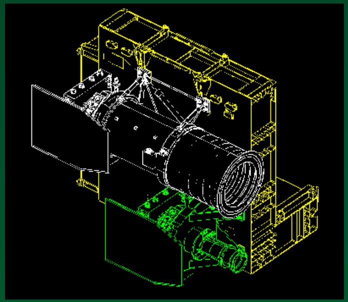
"for the invention of an imaging semiconductor circuit – the CCD sensor"

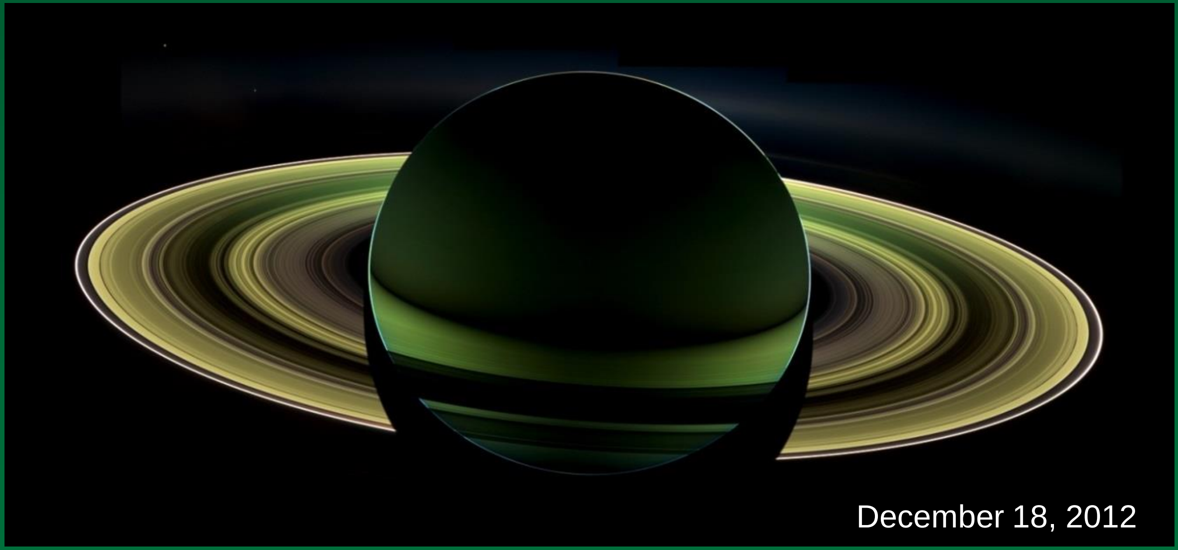
CCD image sensor inventor:
Michael F. Tompsett
US patent no. 4,085,456
National Medal of Technology and Innovation 2010

Cassini (1997) ISS has CCD cameras (wide angle and narrow angle)

Mass: 57.83 kg
Power (avg): 30.0 W
CCD: 1024x1024 pixels





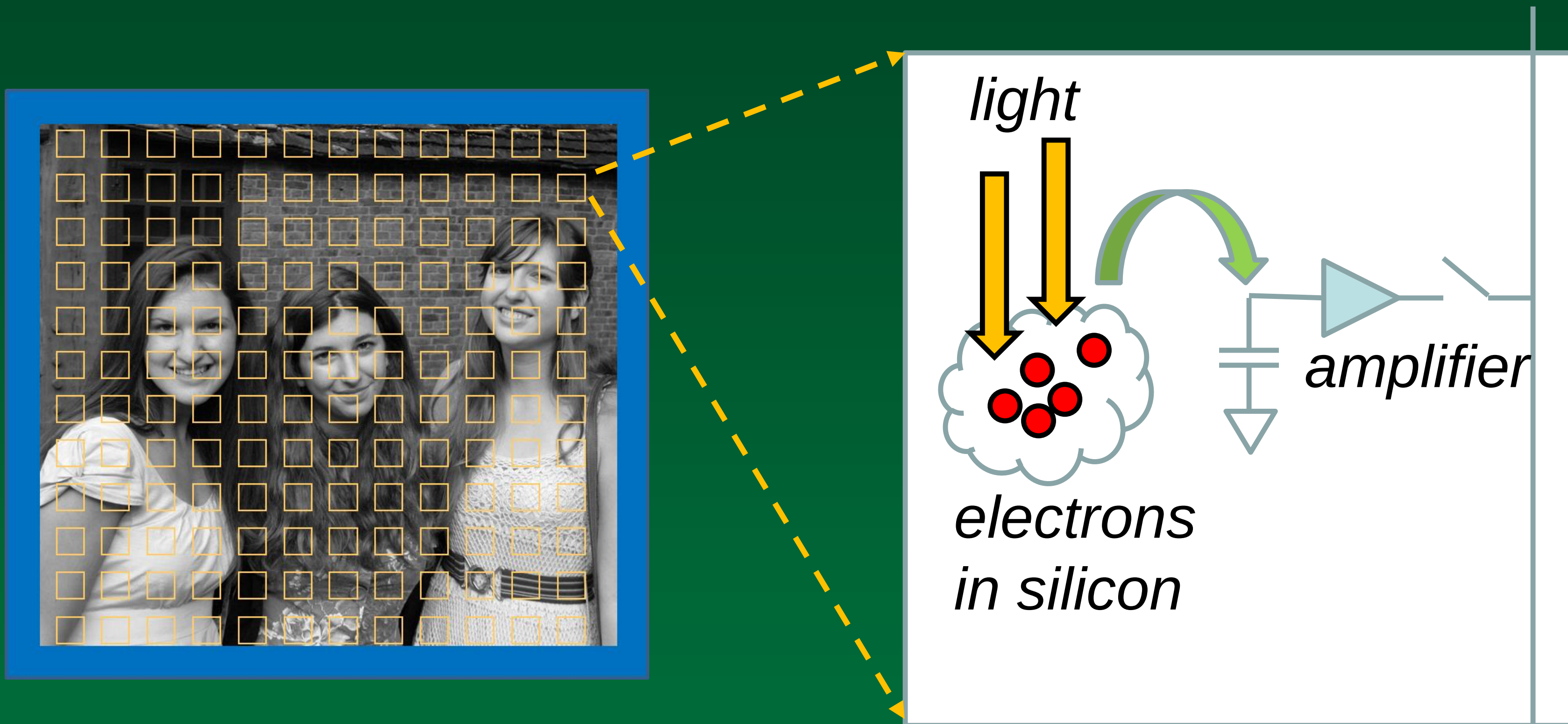


NASA's Administrator Daniel Goldin
"Faster, Better, Cheaper"

Need to Miniaturize Cameras
On Future Spacecraft to reduce mass, power, cost

- Electronics integration is well-worn path to miniaturization, and MOS-based image sensors predate CCDs (e.g. Peter Noble or Gene Weckler late 1960's) including passive pixel and active pixel (3T) configurations.
- BUT MOS image quality is quite poor compared to CCDs due to temporal noise, fixed pattern noise and other artifacts.
- How to make a high performance image sensor in a mainstream CMOS process?

Active Pixels with Intra-Pixel Charge Transfer



One pixel

- Complete charge transfer to suppress lag
- Correlated double-sampling to suppress kTC noise
- Double-delta sampling to suppress fixed pattern noise
- On-chip ADC, timing and control, etc.

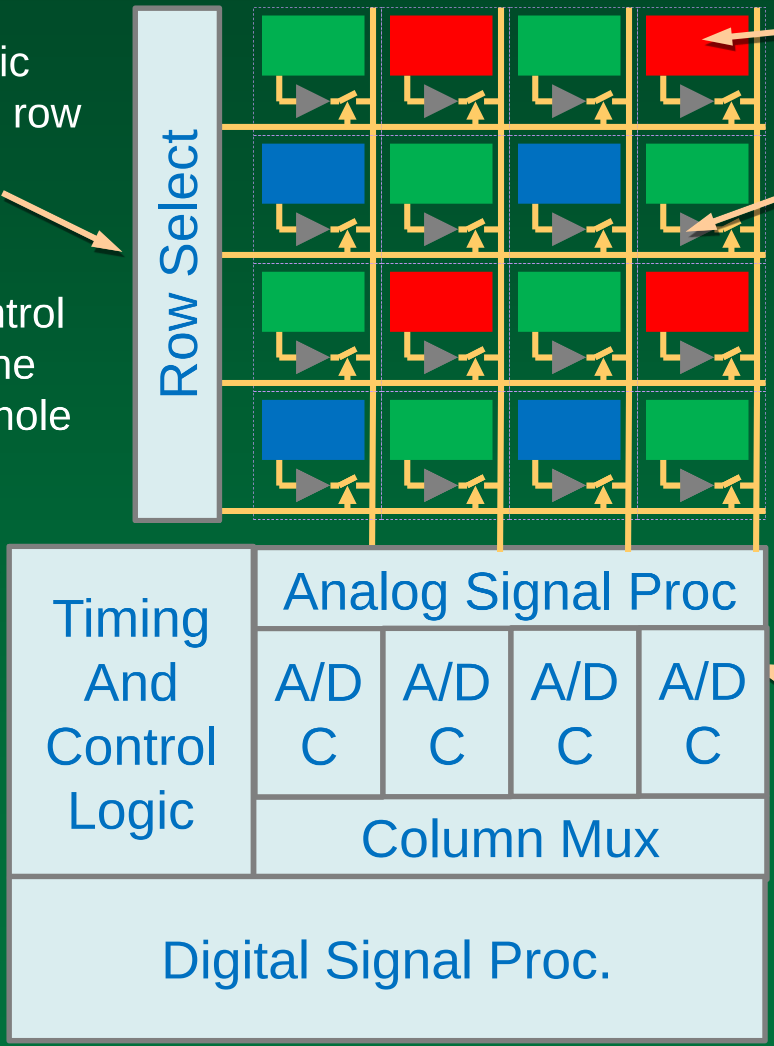
CMOS "Camera on a Chip" 2nd Generation Image Sensor

Read pixel signals out thru switches and wires

Row select logic chooses which row is selected for readout.

Timing and control logic controls the timing of the whole sensor

SoC functionality for color processing, compression, etc.



Photodetector converts photons to electrons

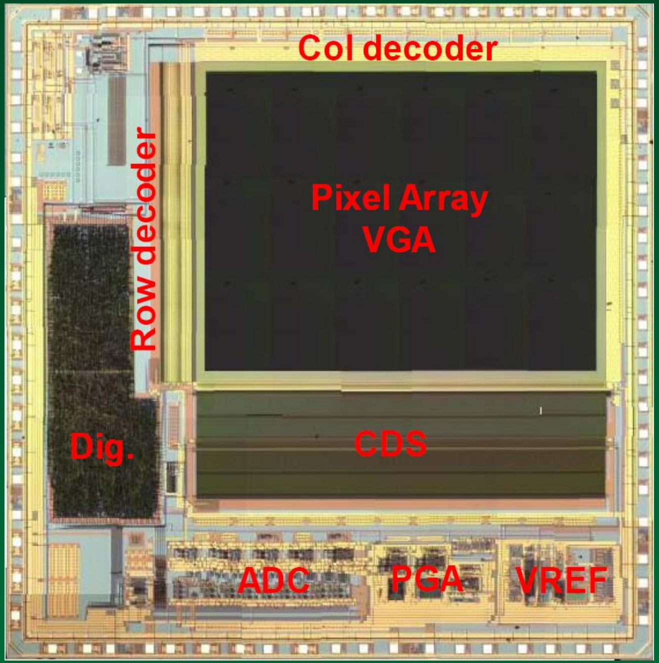
Amplifier converts electrons to voltage after intrapixel complete charge transfer

Analog signal processor suppresses noise and further amplifies signal

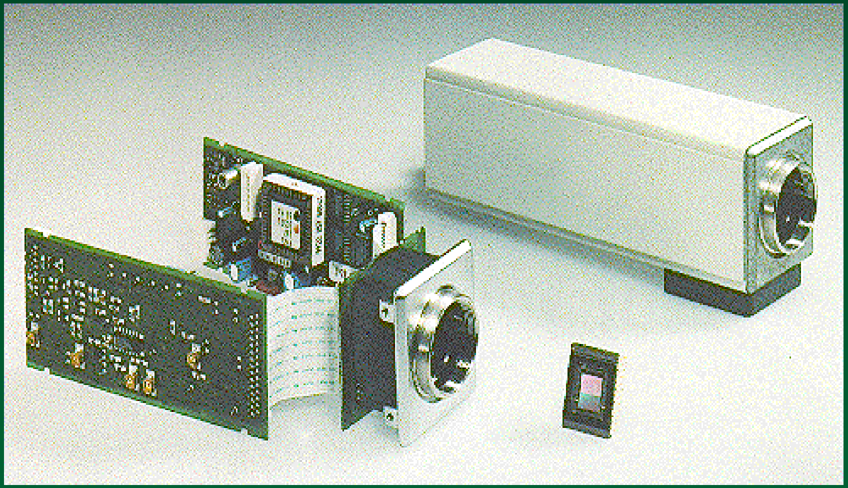
Analog-to-digital converters (ADC) convert signals from volts to bits (usually 10-12 bits resolution) in parallel

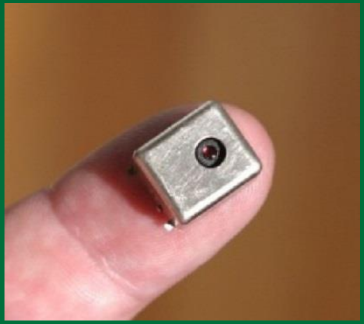
Column multiplexer used to scan ADC outputs

Camera-on-a-Chip Enables Much Smaller Cameras



CMOS Active Pixel Sensor
With Intra-Pixel Charge Transfer
Camera-on-a-chip





Siimpel
AF camera
module
2007

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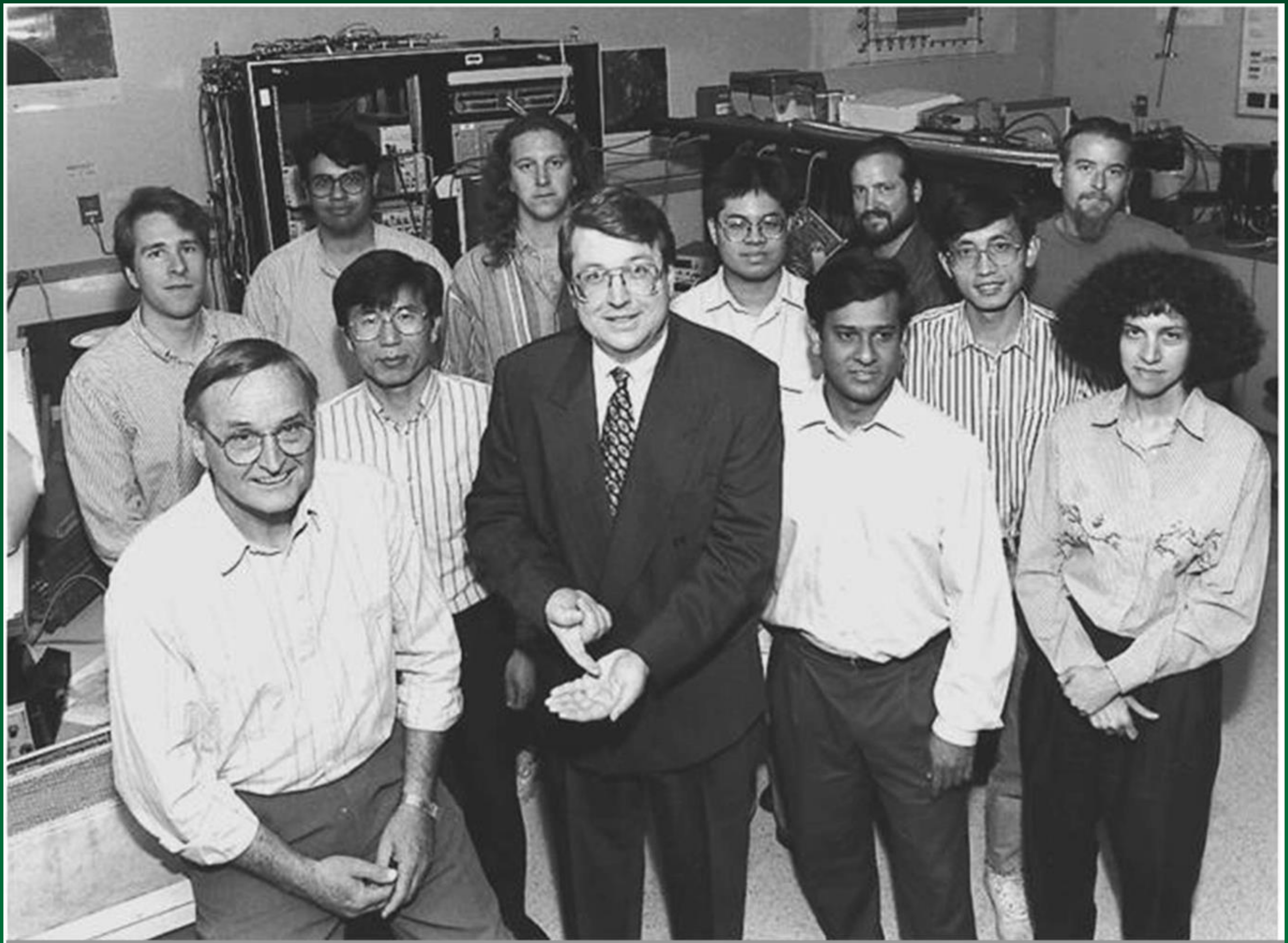
Most of the JPL Team



Advanced Imager Technology Group, Jet Propulsion Laboratory, California Institute of Technology 1995
Back row: Roger Panicacci, Barmak Mansoorian, Craig Staller, Russell Gee, Peter Jones, John Koehler
Front row: Robert Nixon, Quisup Kim, Eric Fossum, Bedabrata Pain, Zhimin Zhou, Orly Yadid-Pecht

Commercialization

Technology Transfer

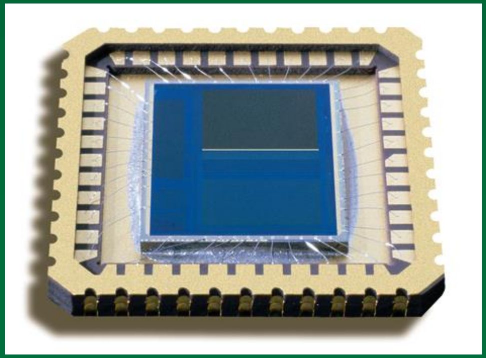
Entrenched industry moves slowly in adopting new technologies so in February 1995 we founded **Photobit Corporation** to commercialize the CMOS image sensor technology ourselves

S.Kemeny, N. Doudoumopoulos, E. Fossum, R. Nixon

Perspiration Phase

1995-2001 Photobit grows to about 135 persons

- Self funded with custom-design contracts from private industry
- Important support from SBIR programs (NASA/DoD)
- Later, investment from strategic business partners to develop catalog products
- Over 100 new patent applications filed



The Photobit Team Circa 2000

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Miller Time

Nov. 2001 – Photobit acquired by Micron Technology and license reverts back to Caltech

Meanwhile, by 2001 there were dozens of competitors emerging in the CMOS image sensor business due in part to the earlier efforts to promote the transfer the technology.

Examples: Toshiba, ST Micro, Omnivision

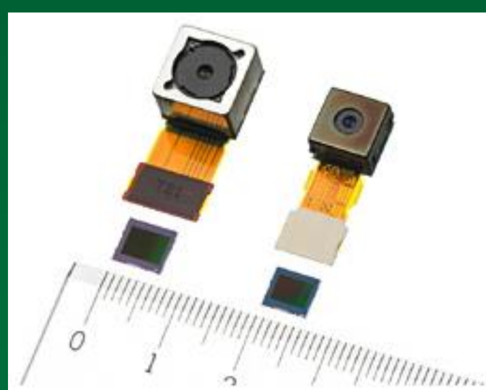
Micron becomes #1 in CMOS image sensor sales and market share

Later, came Sony and Samsung (now #1, #2 in worldwide market)

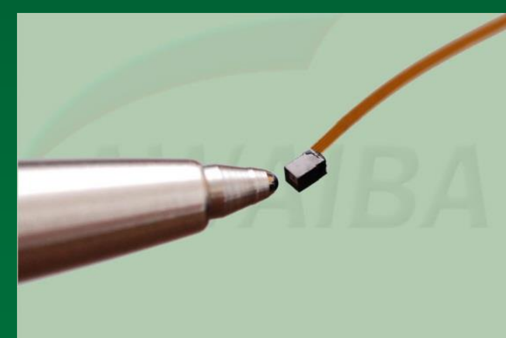
Micron spins out Aptina
Aptina acquired by ON Semi, currently #4

The Technology Develops a Life of its Own

- Today, over 2 billion cameras are manufactured each year that use the CMOS image sensor technology we invented at JPL, or more than 60 cameras per second, 24/7/52
- Semiconductor sales of CMOS image sensors will be $10B/yr by 2016.
- Thousands of engineers working on this.
- Caltech has successfully enforced its patents against all the major players.
- NASA is now just adopting the technology for use in space.



16Mpix camera modules
From Sony ~2012



Endoscopy Camera
From Awaiba ~2012

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New Technology Invariably Brings New Social Issues

Selfies and Instant Communications

Rapid Social Change (Arab Spring)

Drone Cameras

Body Cameras

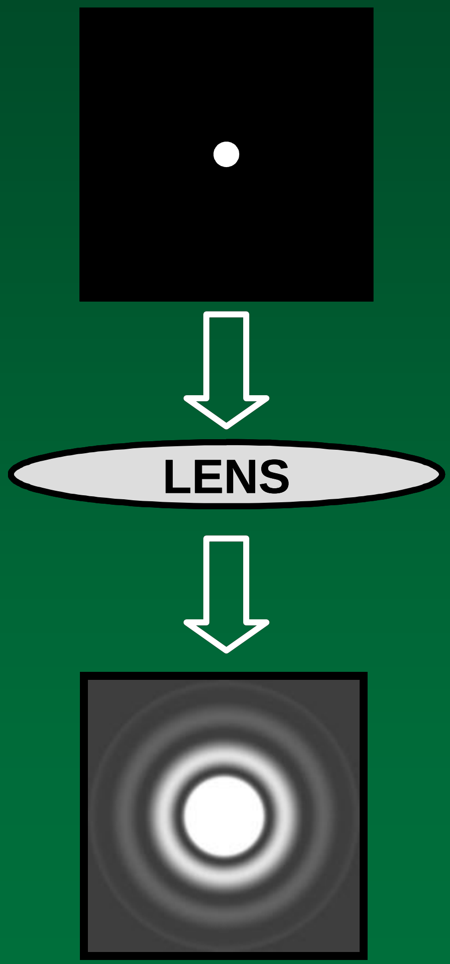
Visual overload (e.g. Japanese Tsunami)

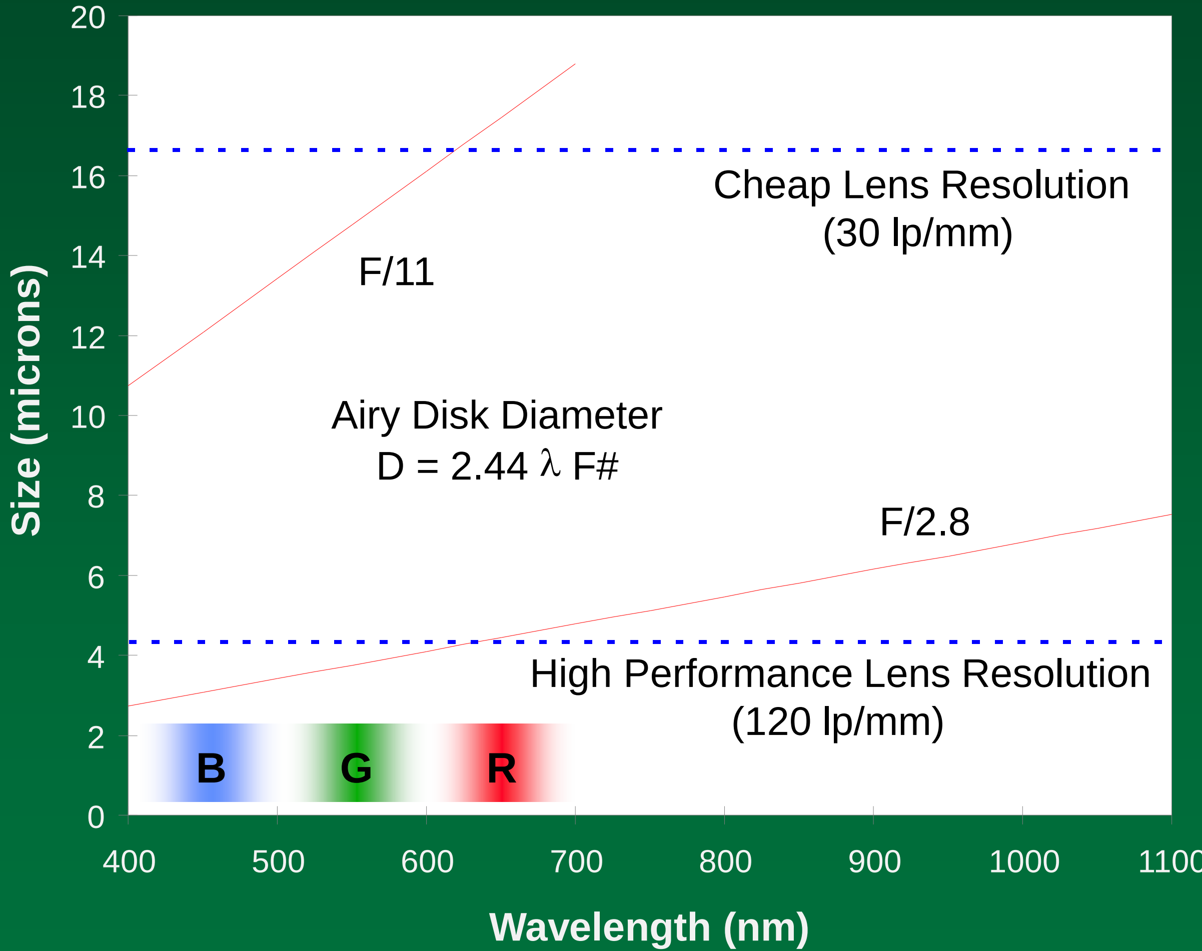
Security v. Privacy

Inappropriate use

Some Science and Technology

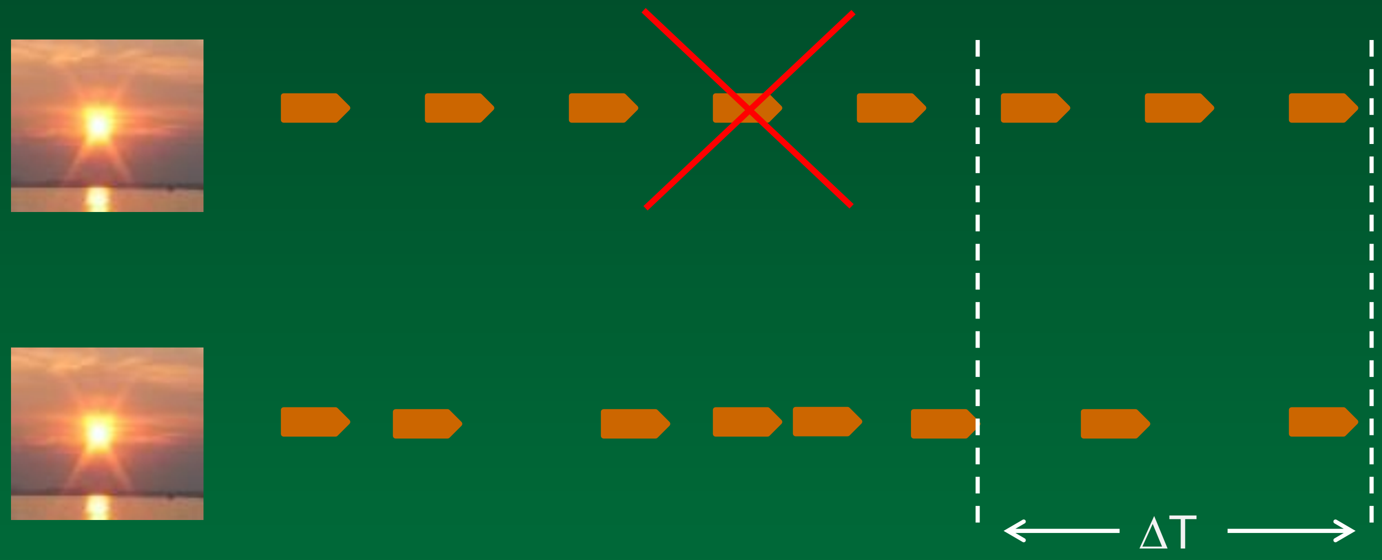
Diffraction Limit





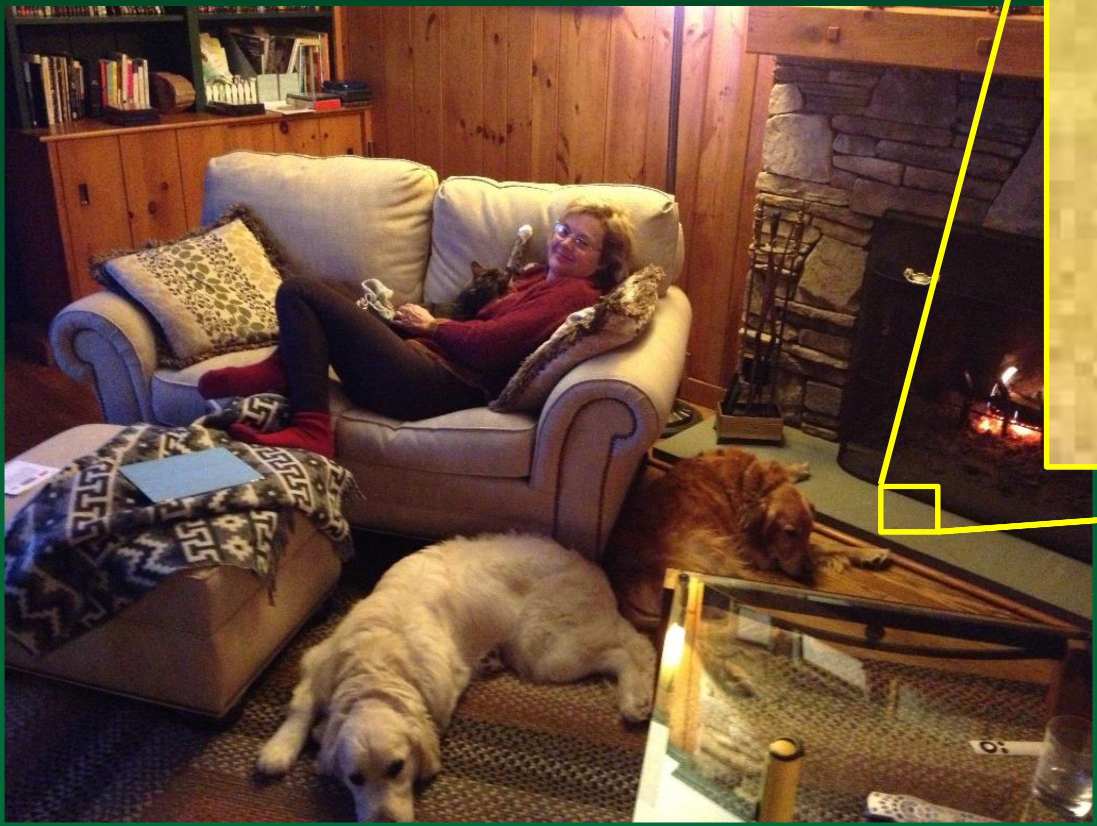
Photon Shot Noise

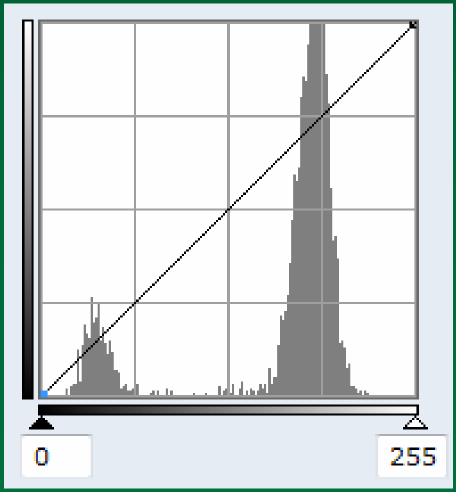
- Photon emission is a Poisson process. Stream of photons is NOT regularly spaced.



- Leads to variability when trying to determine average photon arrival rate. Gets better with longer measurement (more photons).

Photon Shot Noise in Pictures





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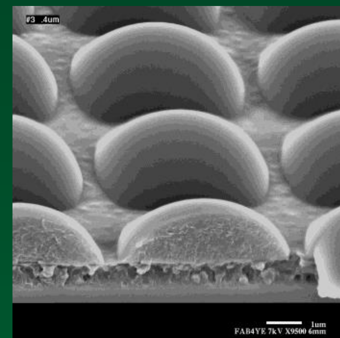
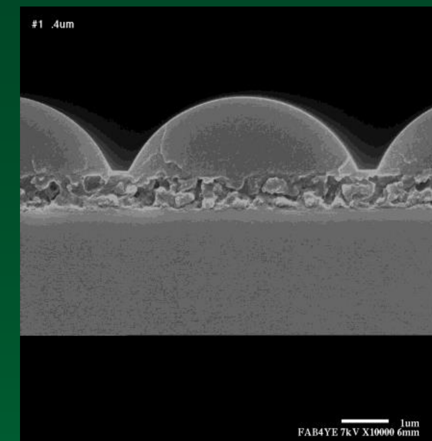
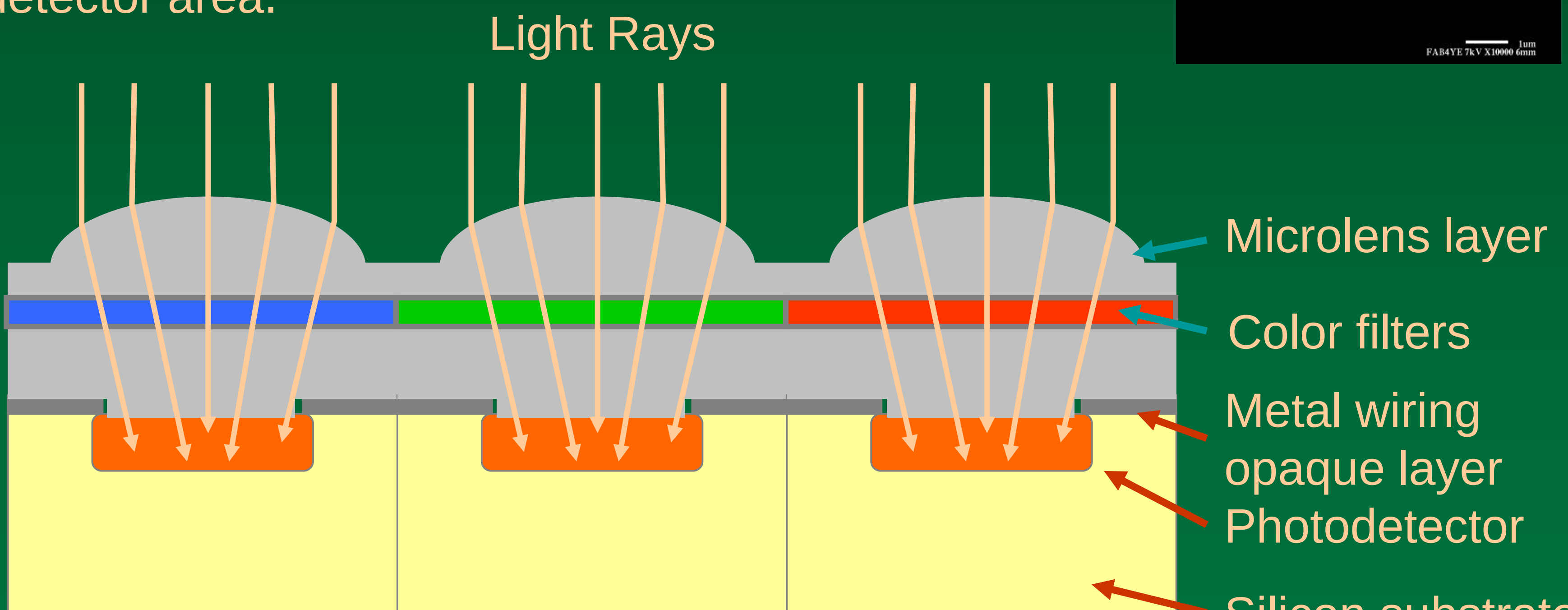
Microlenses

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



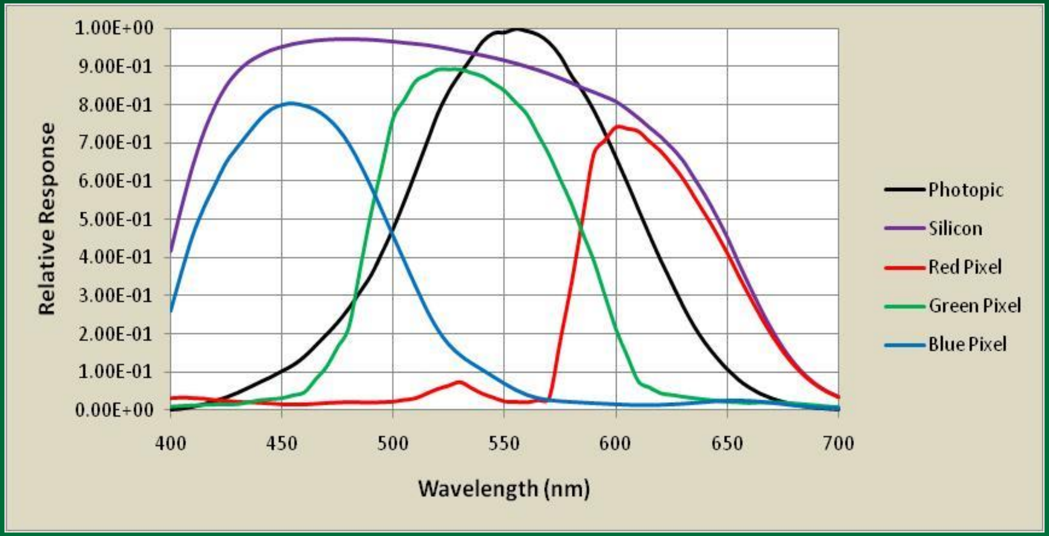




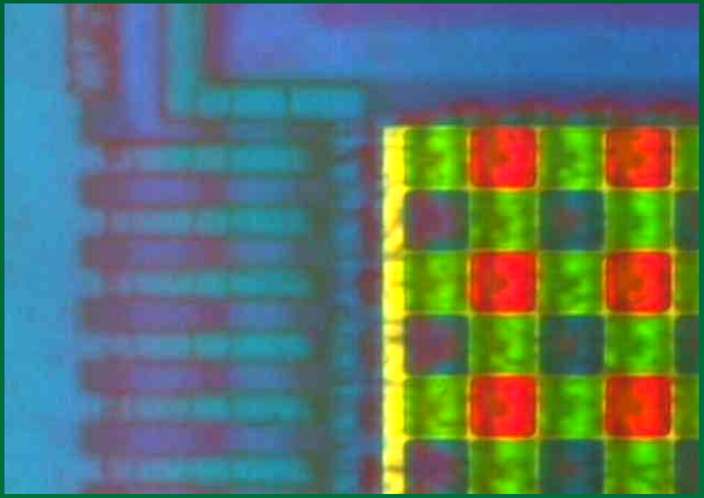
Color Filter Array (CFA)

- 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)



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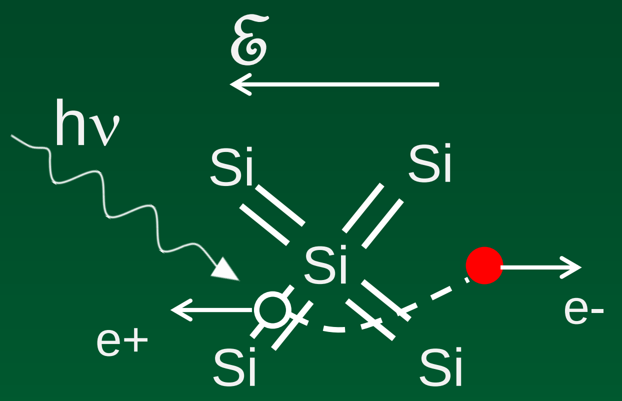
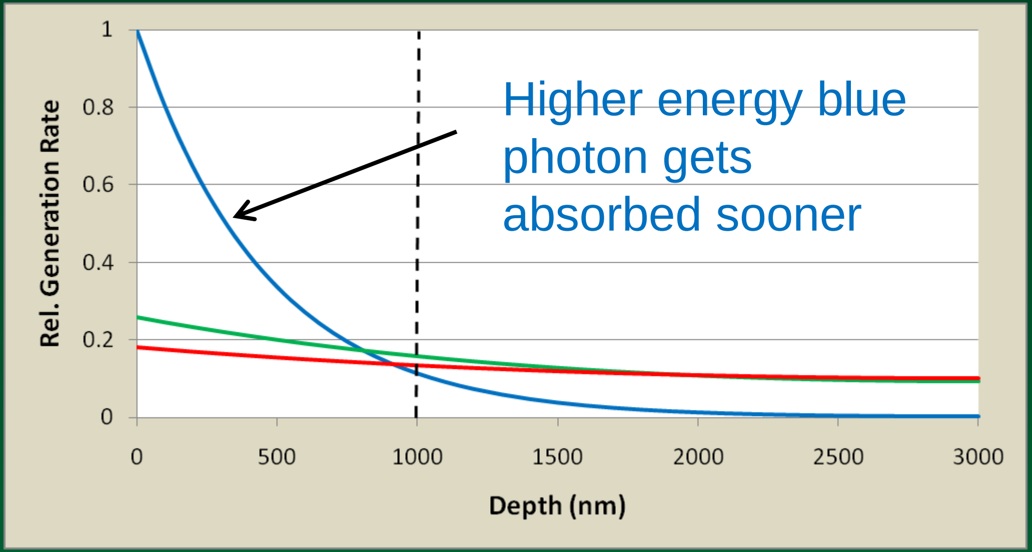
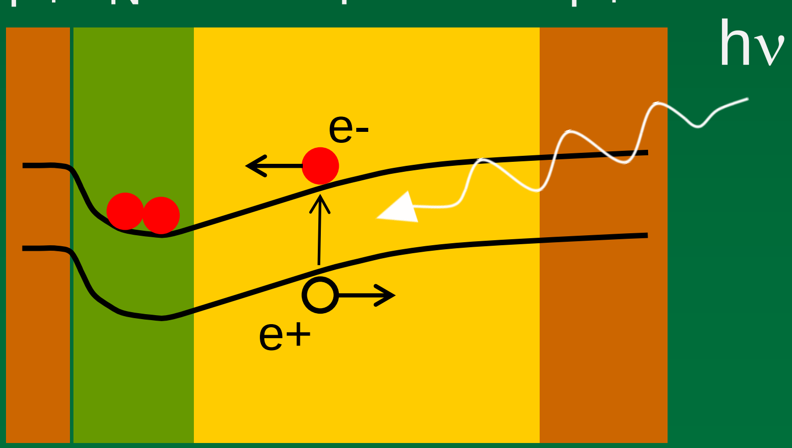
Photons to Electrons



Covalently bonded silicon





Pinned photodiode

N. Teranishi et al.1982 for ILT CCD

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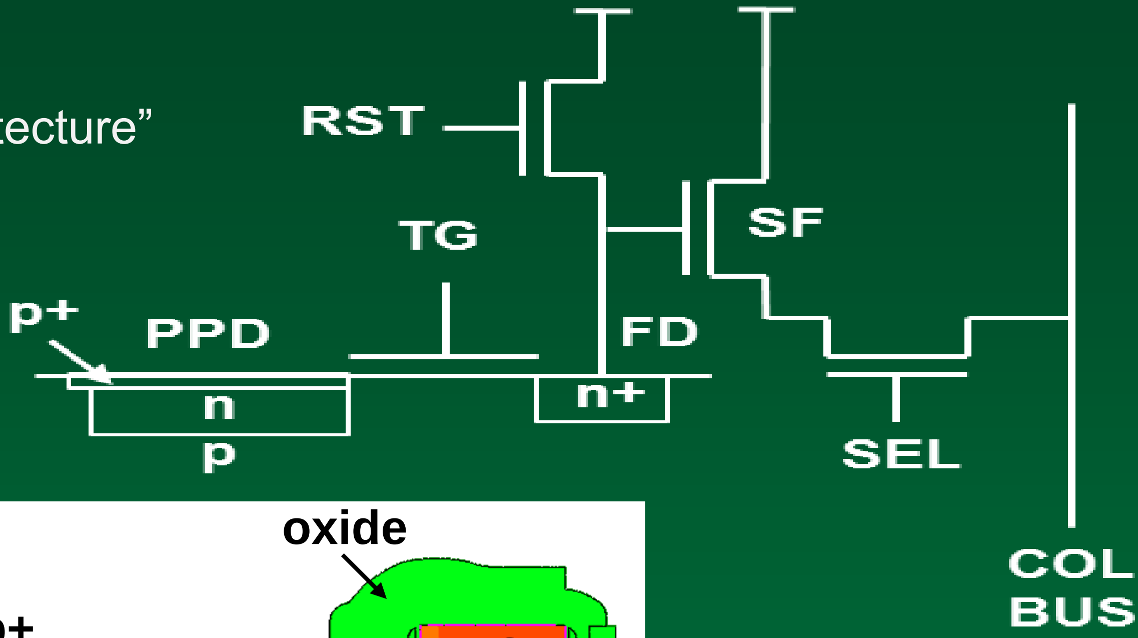
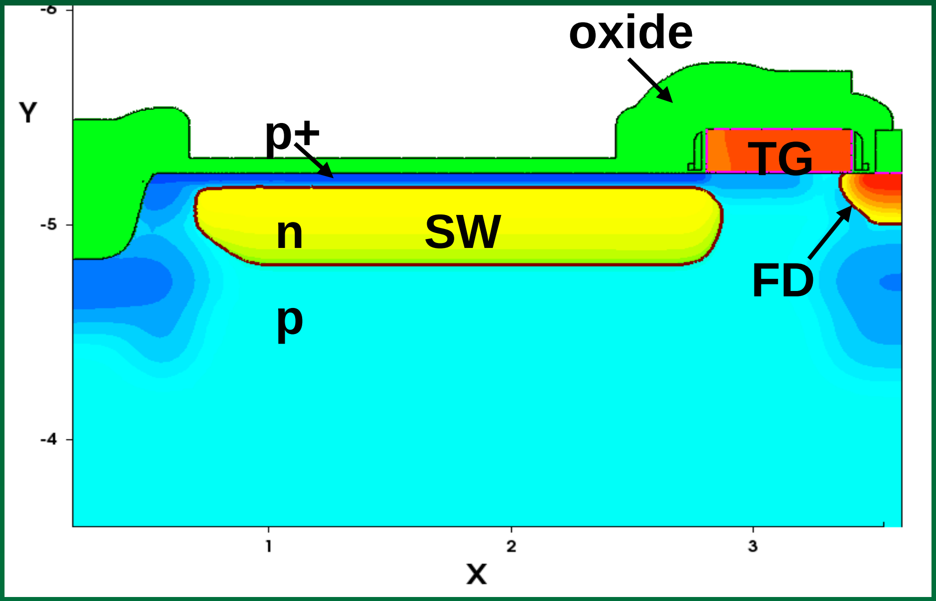
CMOS Pinned Photodiode Pixel

"4T architecture"





E.R. Fossum and D. Hondongwa, A review of the pinned photodiode for CCD and CMOS image sensors, IEEE J. Electron Devices Society, vol 2(3) pp. 33-43 May 2014.

Shared Readout Architecture

"1.35T architecture"

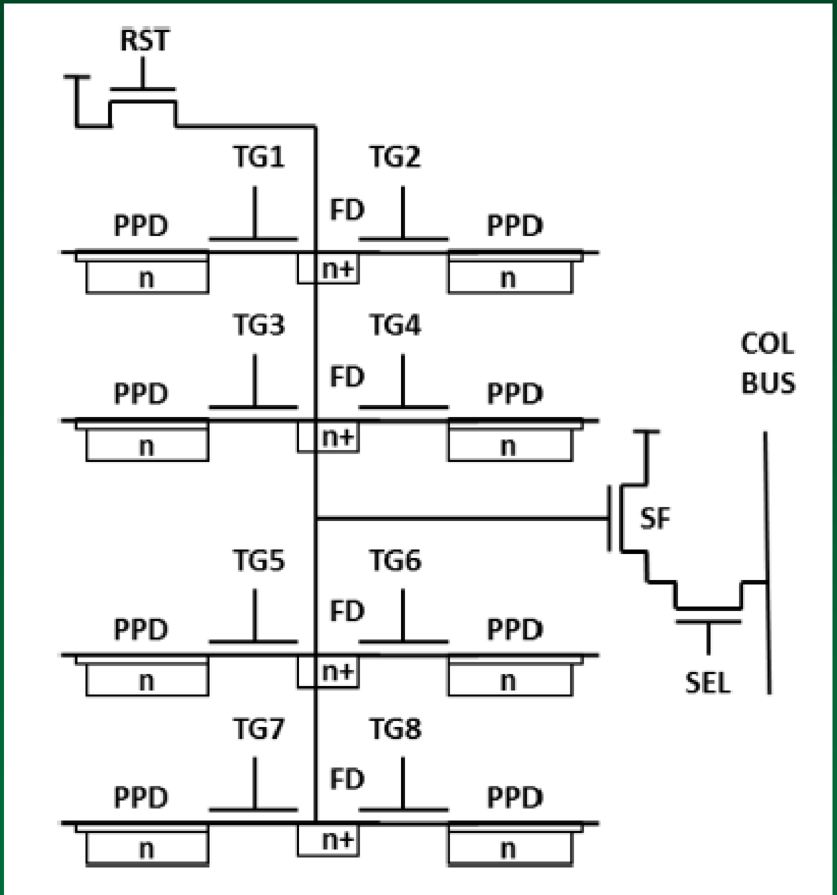
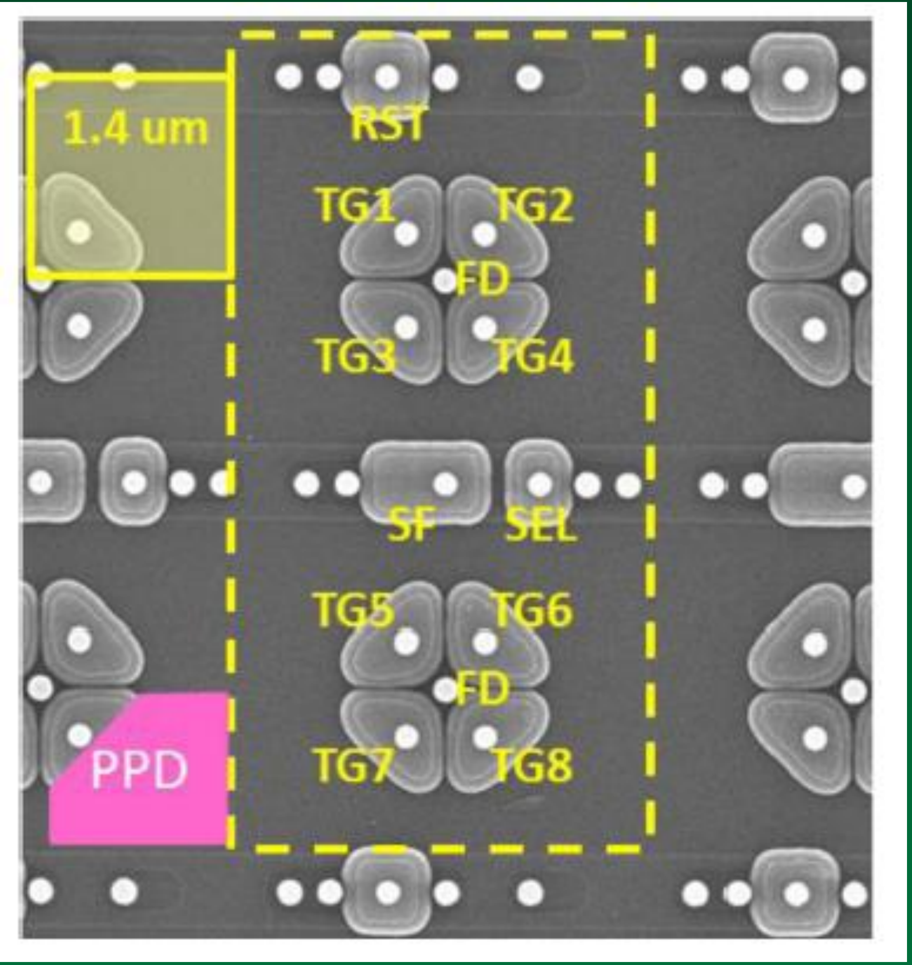
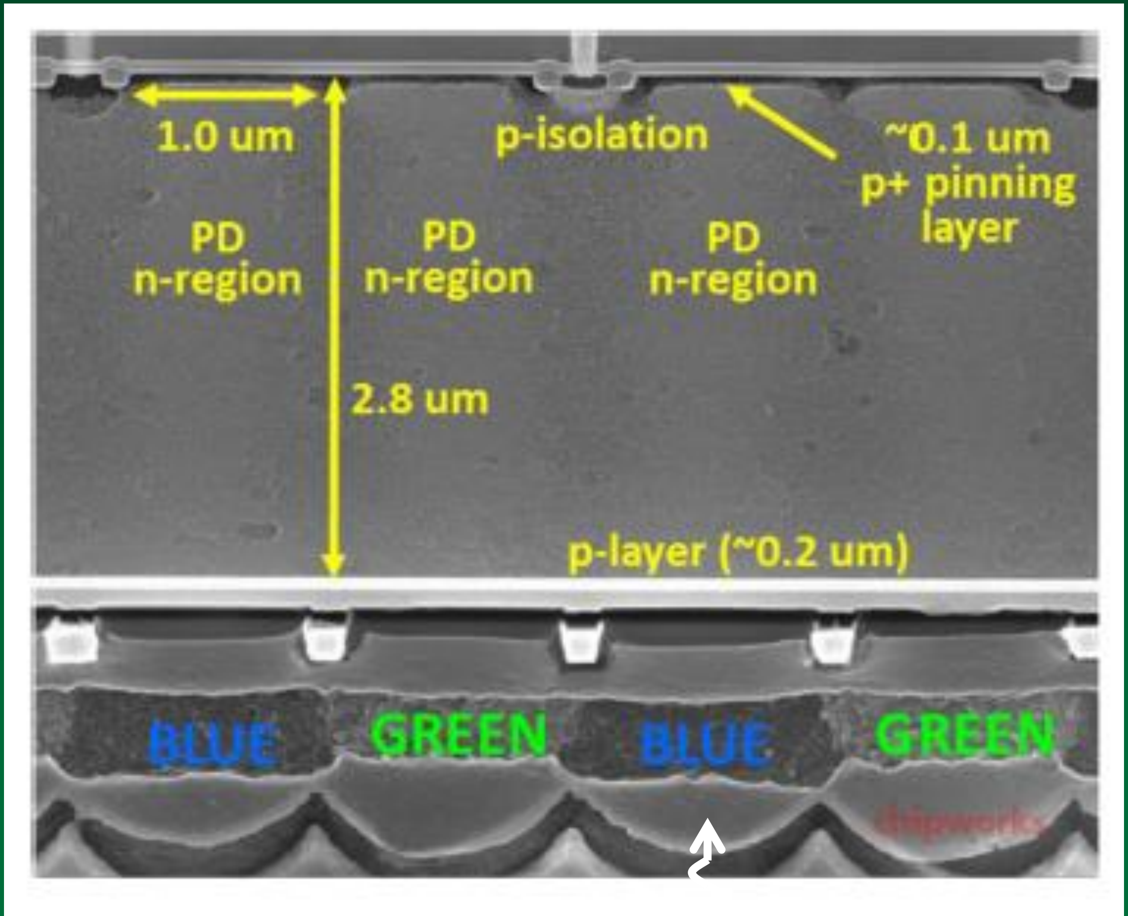


Fig. 9. 8-way shared readout 1.35T pixel schematic.



Sony 1.4 um BSI pixel

Backside Illumination (BSI)



Sony 1.4 um BSI pixel

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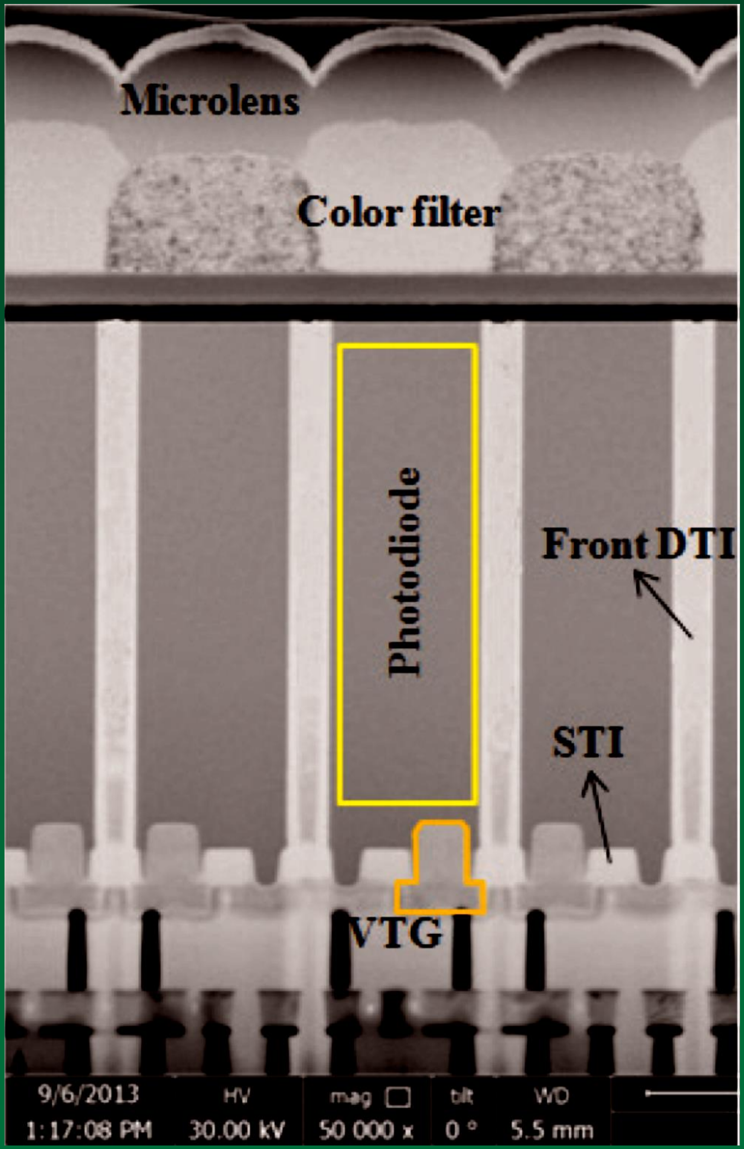
Deep Trench Isolation for Crosstalk



Samsung ISOCELL ISSCC 2013

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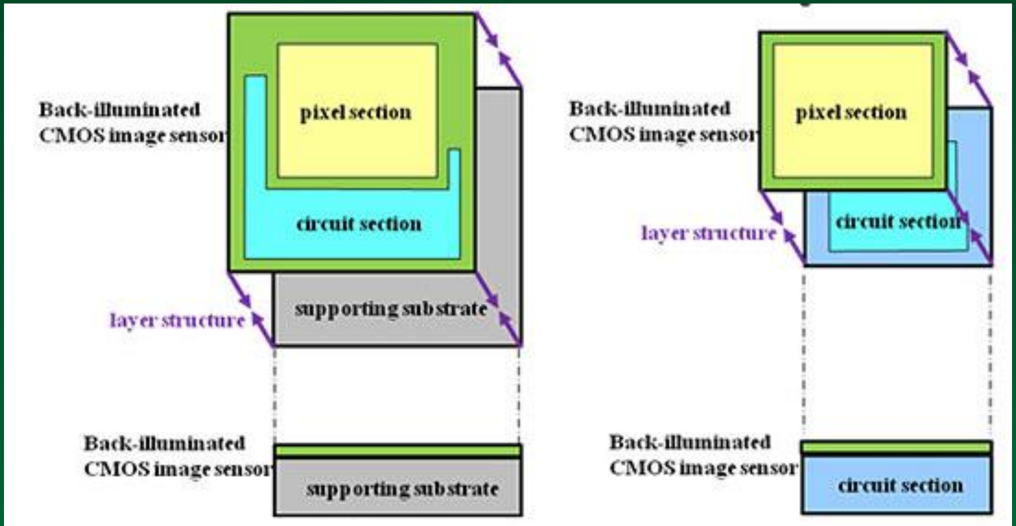
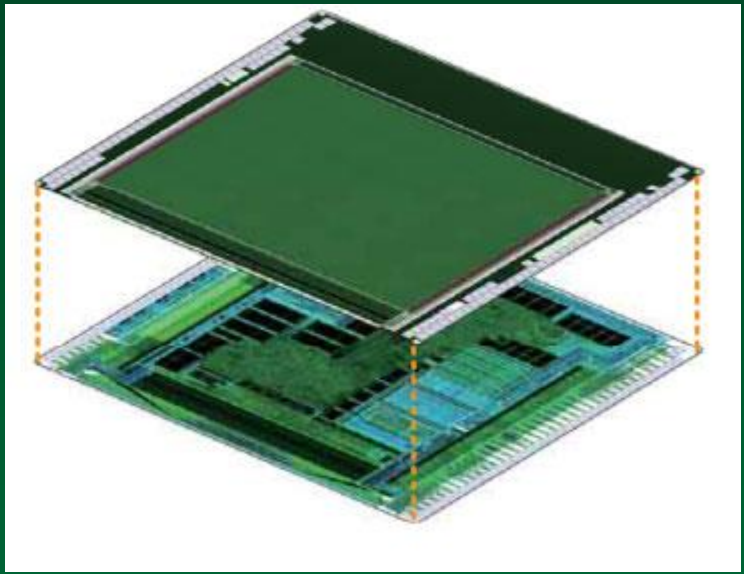
Stacked CMOS BSI





Sony

http://www.chipworks.com/en/technical-competitive-analysis/resources/blog/sony-out-of-the-gate-with-isx014-stacked-camera-sensor/

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Quanta Image Sensor

Group at Dartmouth

L-R: Song Chen, Saleh Masoodian, Rachel Zizza, Donald Hondongwa, Dakota Starkey, Eric Fossum, Jiaju Ma, Leo Anzagira

- Additional Members
  - Arun Rao
  - Yue Song
  - Prof. Kofi Odame
  - Mike Guidash (Rambus)
  - Jay Endsley (Rambus)
  - Prof. Yue Lu (Harvard)
  - Prof. Atsushi Hamasaki (Hiroshima)
  - Mr. Ryohei Funatsu (NHK)

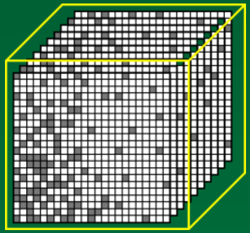
- QIS work supported, in large part, by
  - Rambus Inc.

Quanta Image Sensor
"Count Every Photon"

- Original goal for QIS was to take advantage of shrinking pixel size and make a very tiny, specialized pixel ("jot") which could sense a single photoelectron.
- Jots would be readout by scanning at a high frame rate to avoid likelihood of multiple hits in the same jot and loss of accurate counting.
- Image pixels could be created by combining jot data over a local spatial and temporal region using image processing.
- The first proposed algorithm was the "digital film sensor" using a "grain" and "digital development" construct.

E.R. Fossum, *What to do with Sub-Diffraction-Limit (SDL) Pixels? – A Proposal for a Gigapixel Digital Film Sensor (DFS),* Proc. Of the 2005 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, Karuizawa, Japan, June 2005

Pixels from Jots (Simulation)

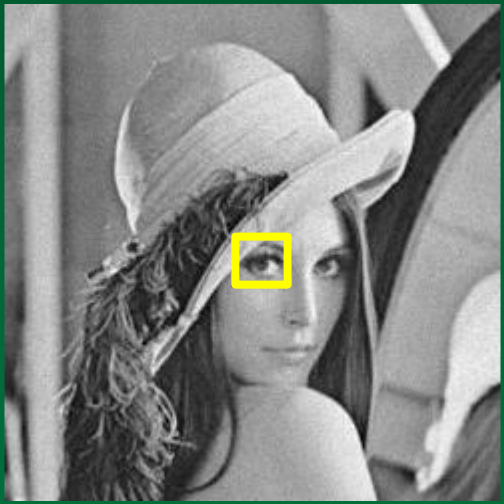


Simplest

$$\sum_{X'Y't'} j(X,Y,t)$$

16x16x16 “cubicle”

$$0 \le S \le 4096$$



R. Zizza, Jots to Pixels: Image Formation Options for the Quanta Image Sensor, (Dartmouth, 2015)

QIS Core Architecture

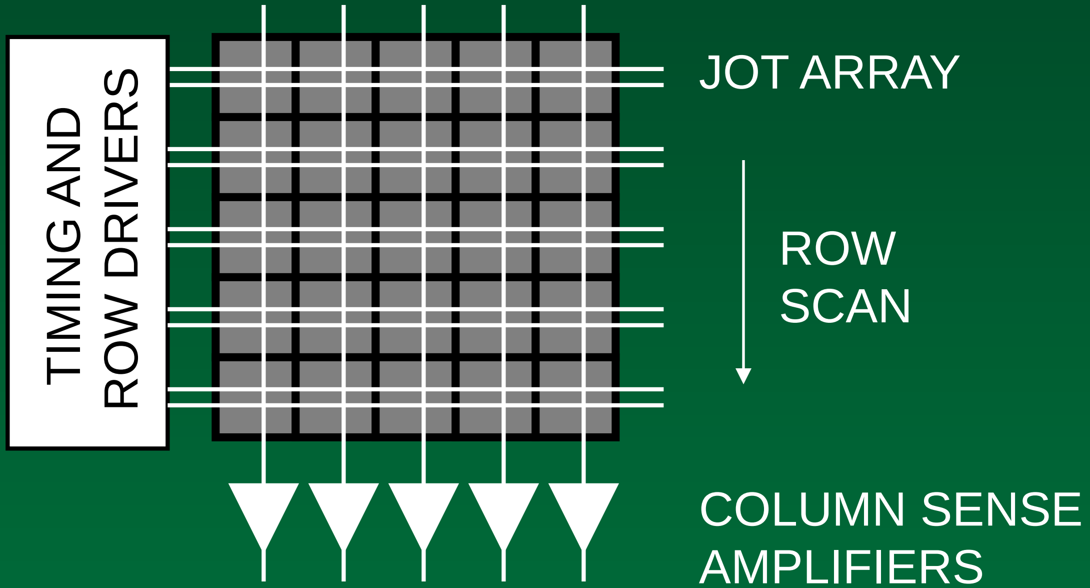
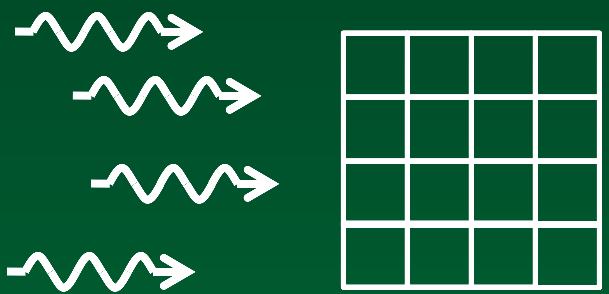


Figure of Merit: Flux Capacity ϕ_w



At the flux capacity, there is an average of one photoelectron per jot

$$\phi_w = jf_r/\sigma\bar{\gamma}$$

$j = jot\ density\ (per\ cm^2)$

$f_r = field\ readout\ rate\ (per\ sec)$

$\sigma = shutter\ duty\ cycle$

$\bar{\gamma} = average\ quantum\ efficiency$

- At 500nm jot pitch, 1000fps, 100% duty cycle and 35% QE, $\phi_w \cong 10^{12}/cm^2s$
- Corresponds to ~100lux (555nm, F/2.8, RT=80%)

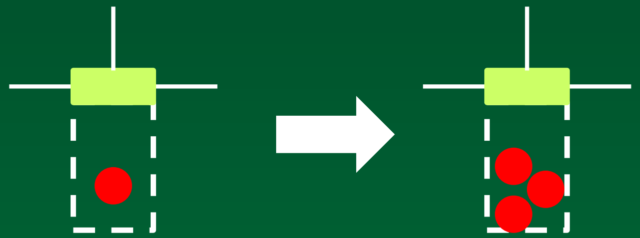
➔ Drives high jot density and field readout rate so can handle normal lighting conditions

➔ And improve SNR per sq. cm of sensor area.

Multi-bit Jot Increases Flux Capacity

At the flux capacity, there is an average of $2^n - 1$ photoelectrons per *n*-bit jot

$$\phi_{wn} = jf_r(2^n - 1)/\sigma\bar{\gamma}$$



Single bit jot
0, 1 electrons

Multi-bit (2b) jot
0, 1, 2, 3 electrons

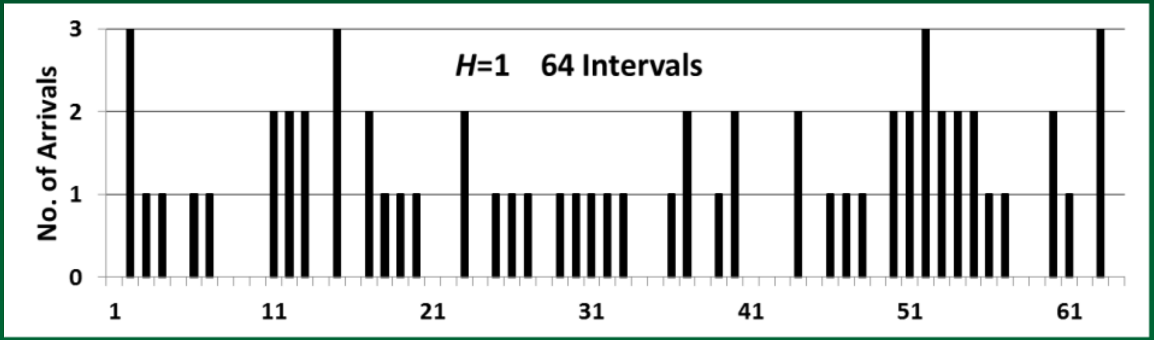
➔ Can increase flux capacity at same jot density and field readout rate
➔ Or, relax field readout rate and/or jot density for same flux capacity

Little impact on detector and storage well. Little impact on FD CG or voltage swing (e.g. 1mV/e -> 31mV swing for 5b jot.

Photon and photoelectron arrival rate described by Poisson process

Define *quanta exposure* $H = \phi\,\tau$ $H = 1$ means expect 1 arrival on average.

Monte Carlo



Probability of k arrivals

$$P[k] = \frac{e^{-H} H^k}{k!}$$

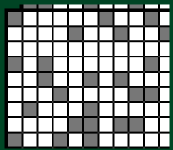
For jot, only two states of interest

$$P[0] = e^{-H}$$

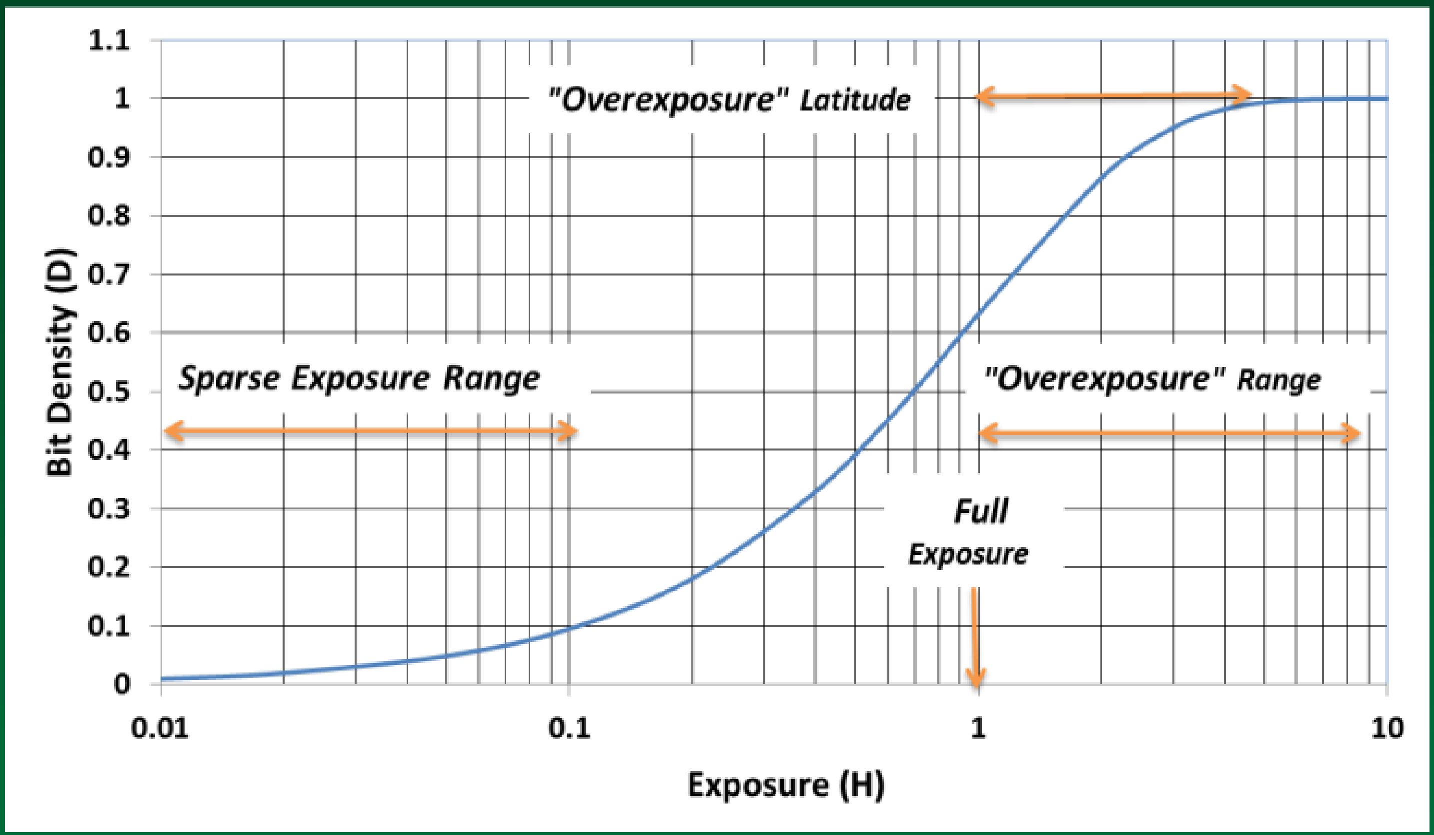
$$P[k > 0] = 1 - P[0] = 1 - e^{-H}$$

For ensemble of *M* jots, the expected number of 1's : $M_1 = M \cdot P[k > 0]$

Bit Density



$$Bit\ Density\ D \triangleq \frac{M_1}{M} = 1 - e^{-H}$$



$$D \cong H \quad \text{(linear)}$$

Can determine H from measured D

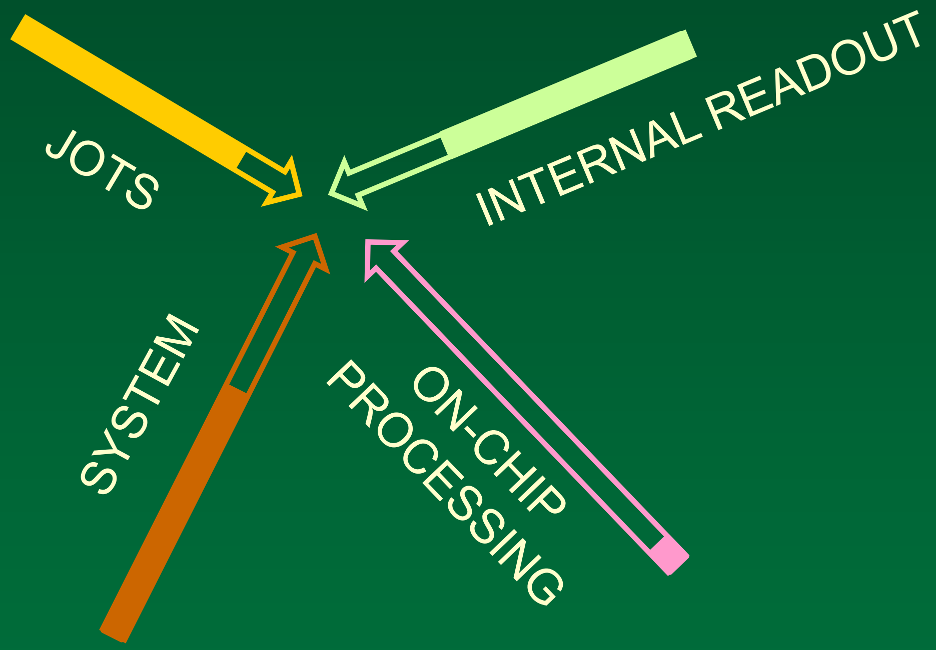
$$\mathrm{H} = \ln\left[\frac{1}{1-D}\right]$$

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

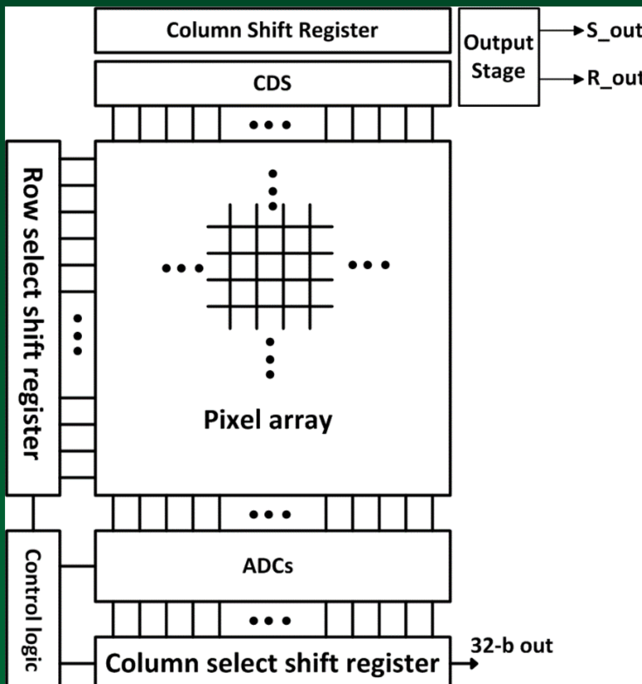
QIS implementation requires Devices, Circuits, and System

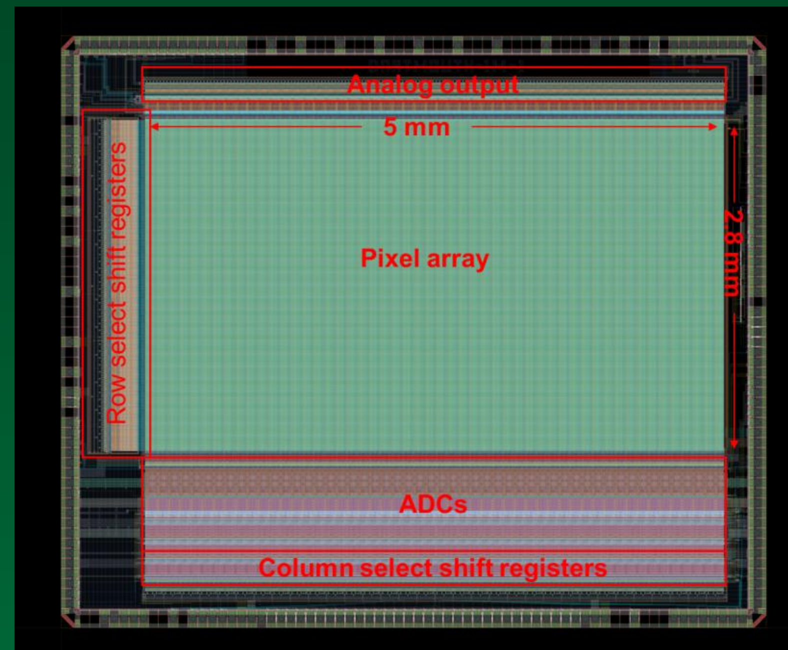
Strawman numbers

- <500 nm jot pitch
- Gigajot QIS (10^9 jots)
- 1000 fps
- 1 Tb/s data rate
- 1 Watt or less (<1pJ/b)



23mW 1000fps
1 Mpix binary image sensor





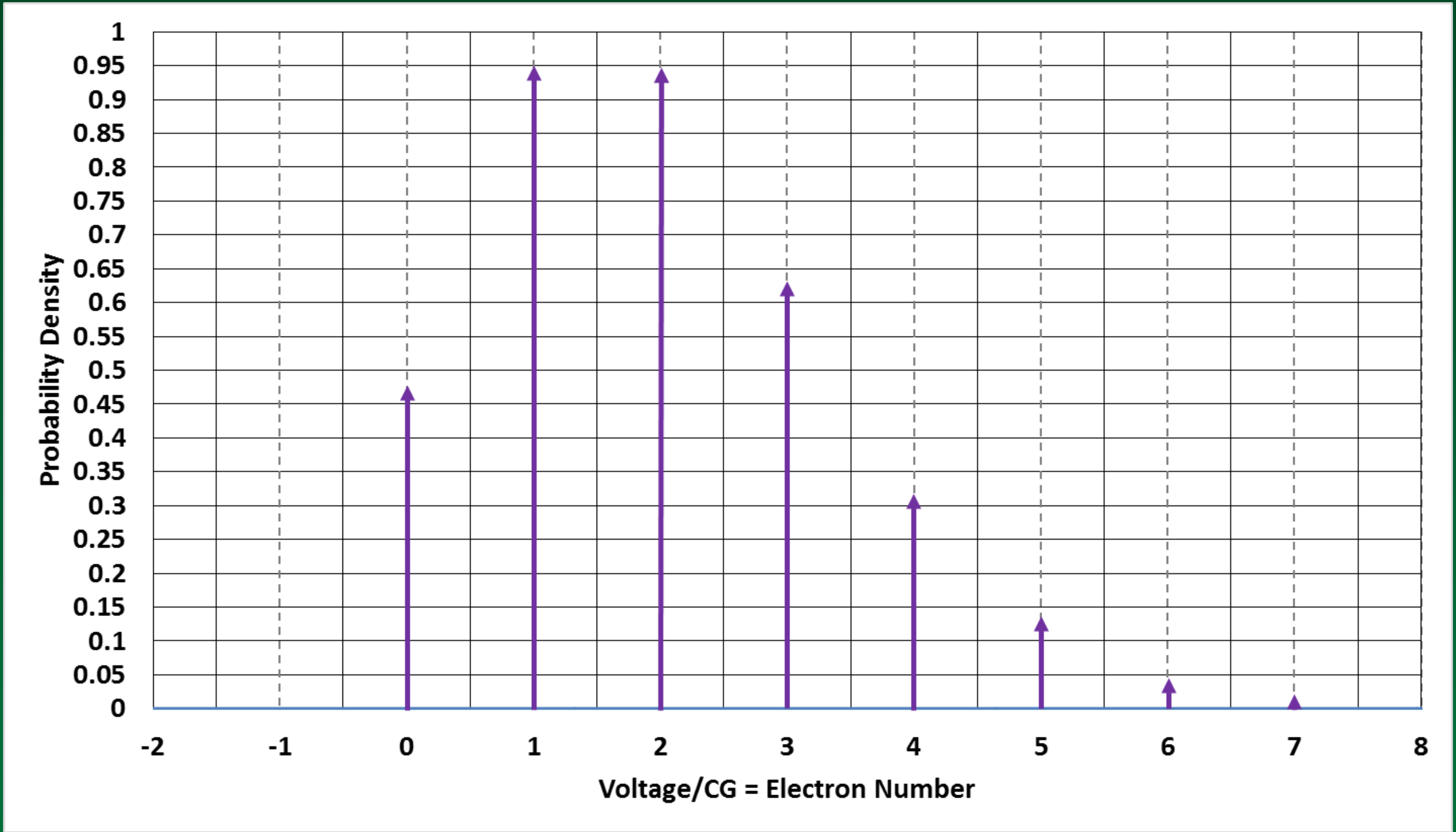
1 captured frame, $\lesssim$10e-

- XFAB 0.18um 1.8V
- 1376(H) x 768(V) 3.6um 3T CDS
- 119uV/e- , 2e- rms, ~5.2e- threshold
- 768KSa/s
- 1 Gb/s data rate
- Whole chip incl. pads 20mW
- ADCs 2.6mW
- Energy 2.5pJ/b

Masoodian, Rao, Ma, Odame, Fossum 2015 IISW

Poisson Distribution (scaled)

H=2



$$P[k] = \frac{e^{-H} H^k}{k!}, k = 0, 1, 2, 3 \ldots$$

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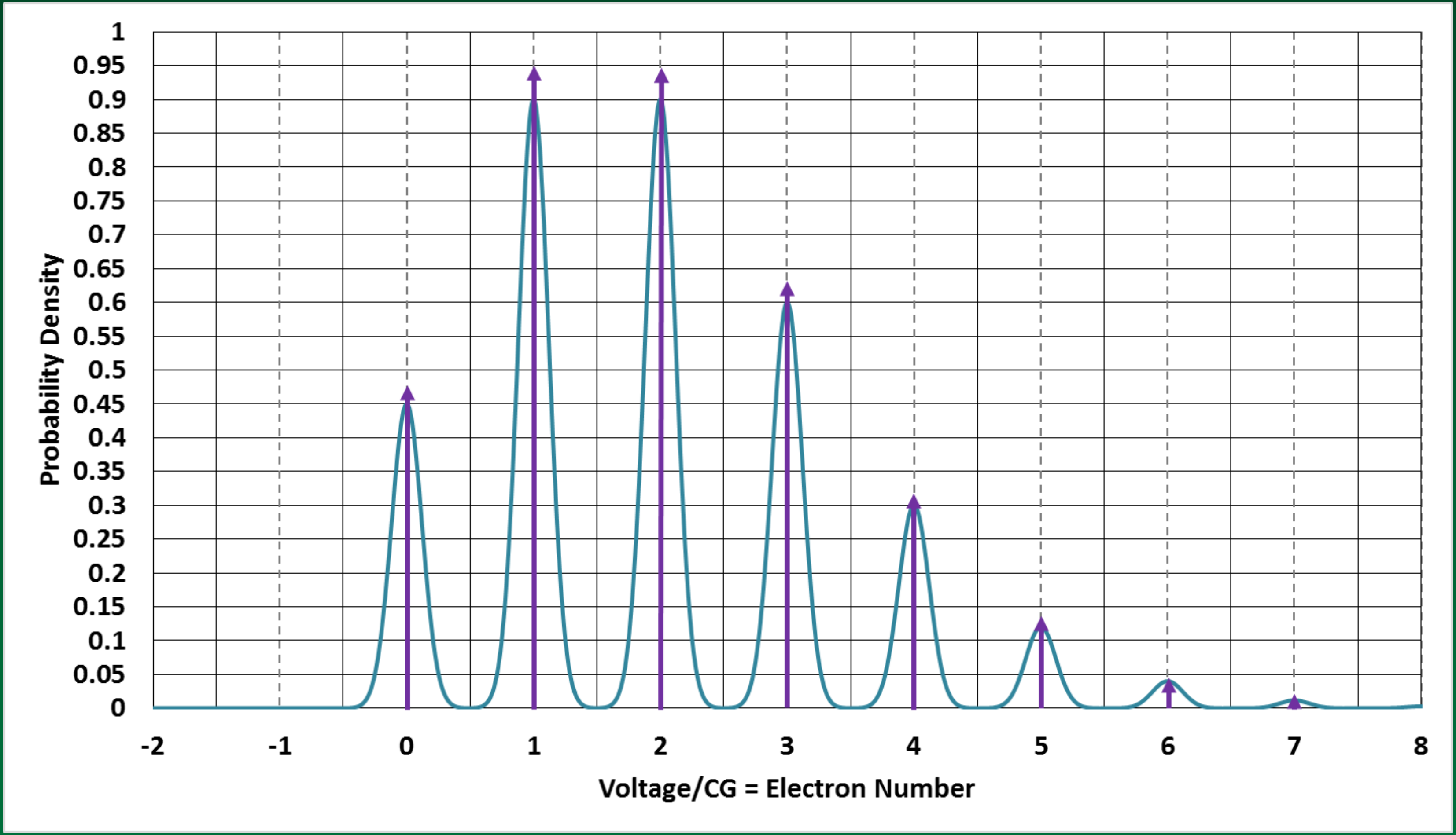
Broadened by 0.12e- rms read noise



Model

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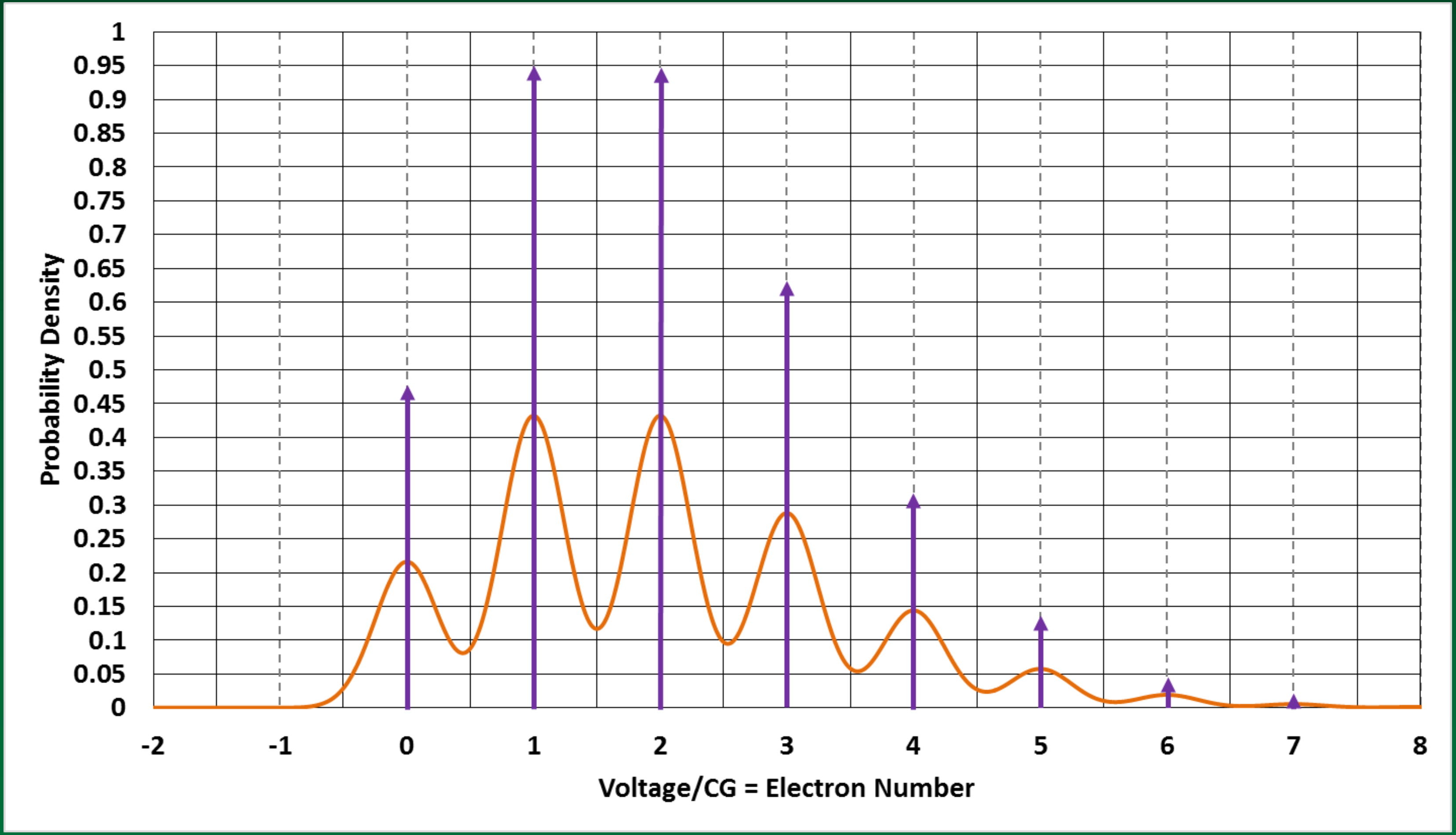
Broadened by 0.25e- rms read noise



Model

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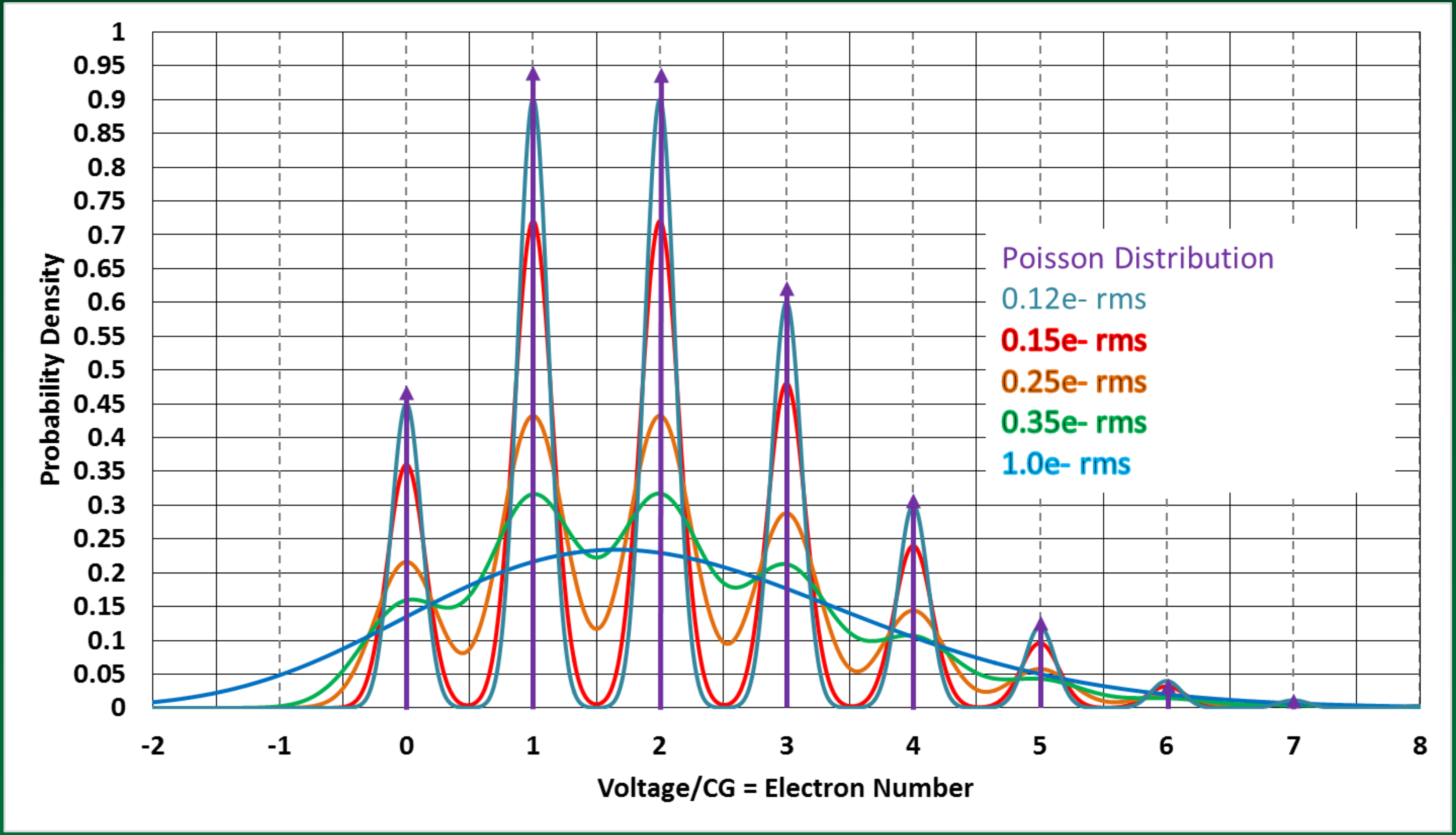
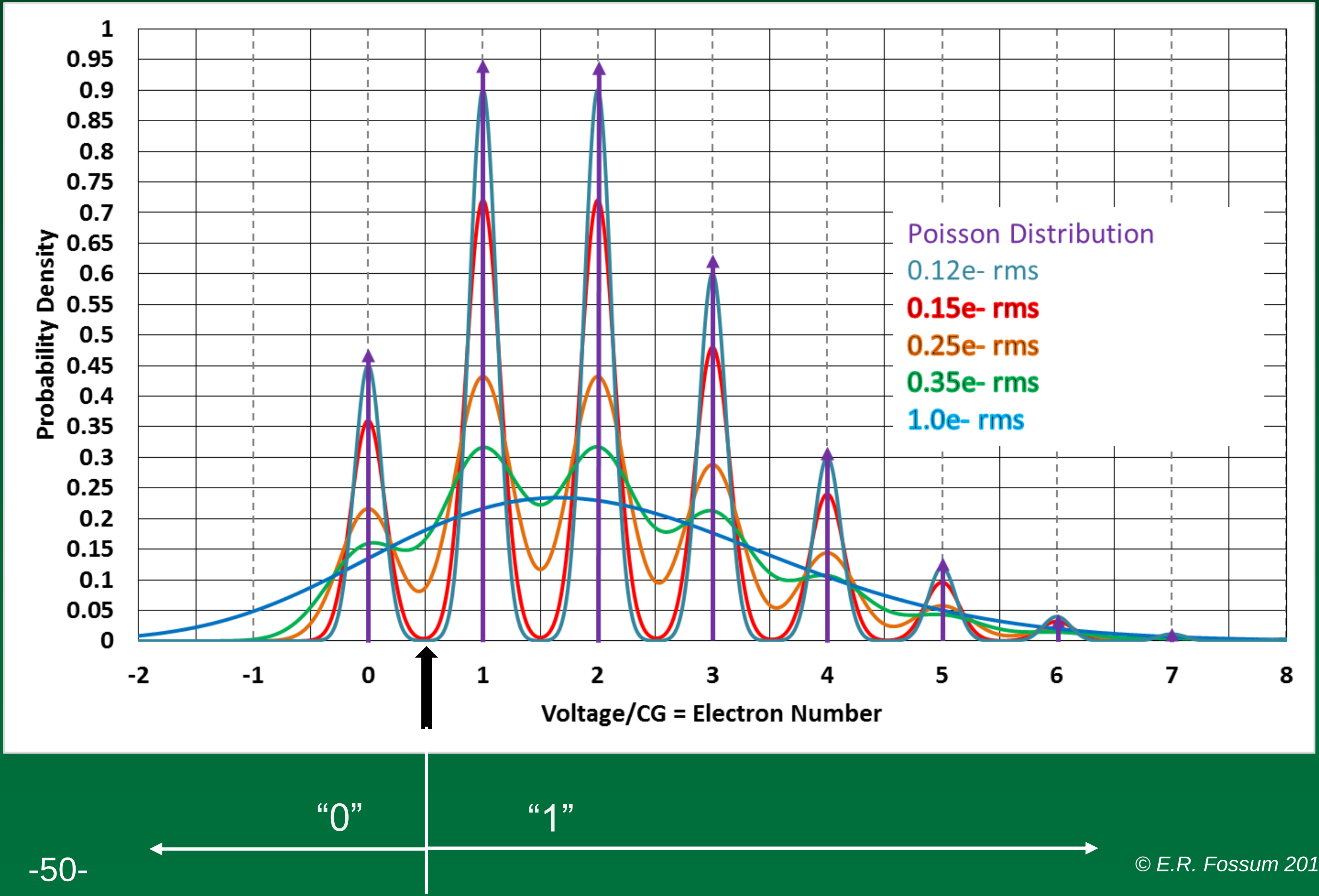
Probability Distribution for Various Levels of Read Noise

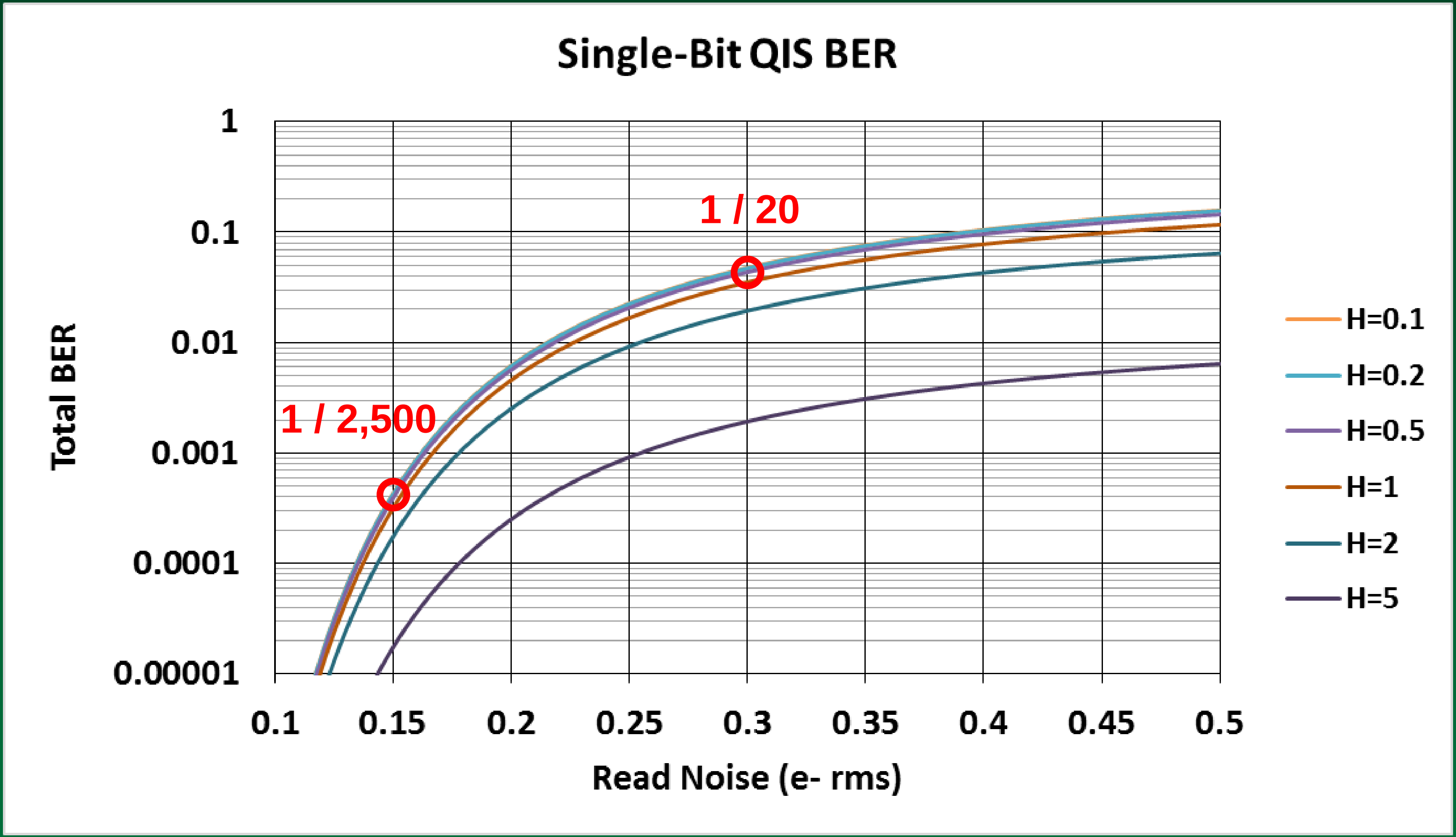


Model

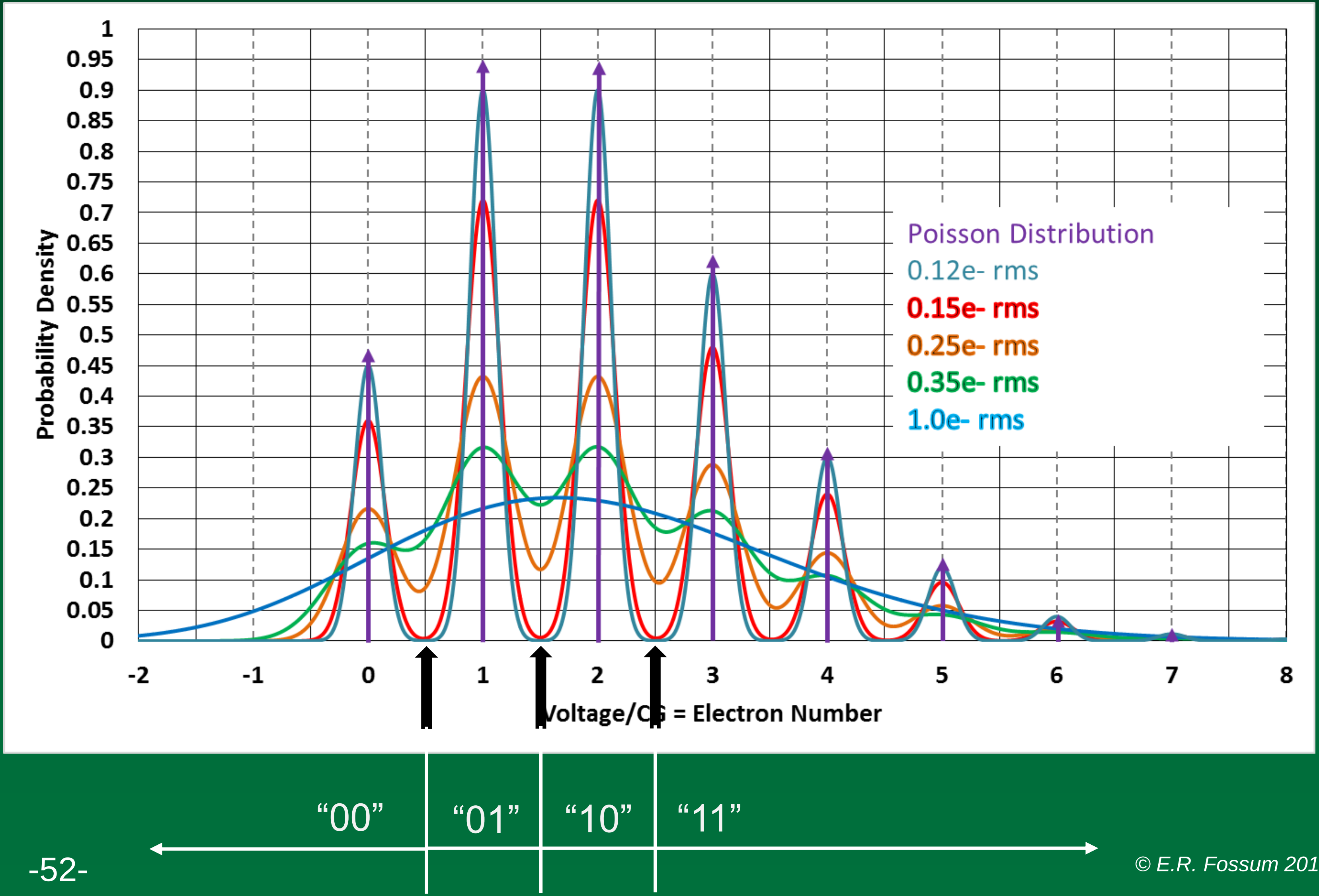
Single-bit QIS



BER vs. Read Noise



Multi-bit QIS (e.g. 2-bit)



Single Bit v. Multi-bit

Single Bit

- Each jot produces 1 bit
- 1 bit ADC
- For same flux capacity, need higher frame rate readout
- Conceptual simplicity
- Easier on chip digital electronics

Multi-bit

- Each jot produces n bits
- n-bit ADC
- For same flux capacity, lower relative frame rate $1/2^{(n-1)}$
- Like current CMOS APS but low FW capacity and high conversion gain

*S, Chen, A. Ceballos, E.R. Fossum, 2013 IISW

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Jot Device Considerations

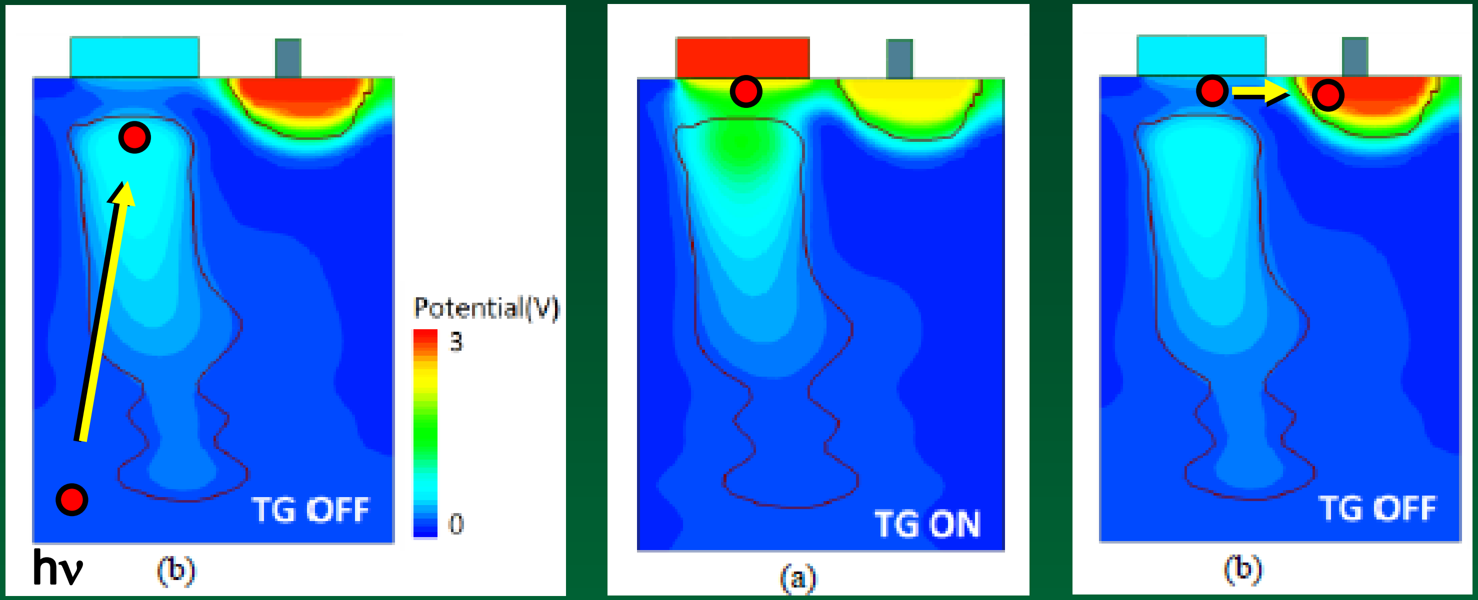
General targets:

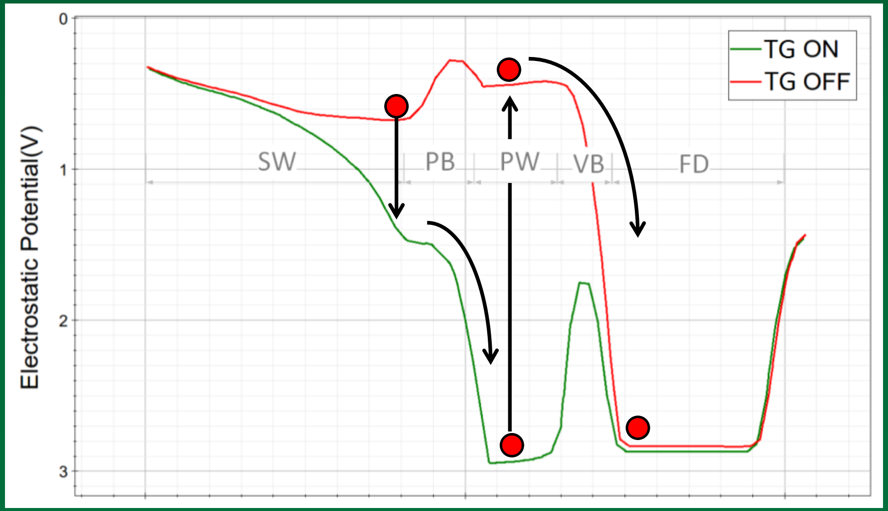
- 200 nm device in 22 nm process node (“10L”)
- 0.15e- rms read noise or less
- High conversion gain > 1 mV/e- (per photoelectron)
- Low active pixel transistor noise <150 uV rms
- Small storage well capacity ~1-100 e-
- Complete reset for low noise
- Low dark current ~ 1 e-/s
- Not too difficult to fabricate in CIS line

Candidate devices

- Single photon avalanche detector (SPAD)
- Single electron FET
- Bipolar jot
- Pump gate jot
- JFET jot

Pump-Gate Jot





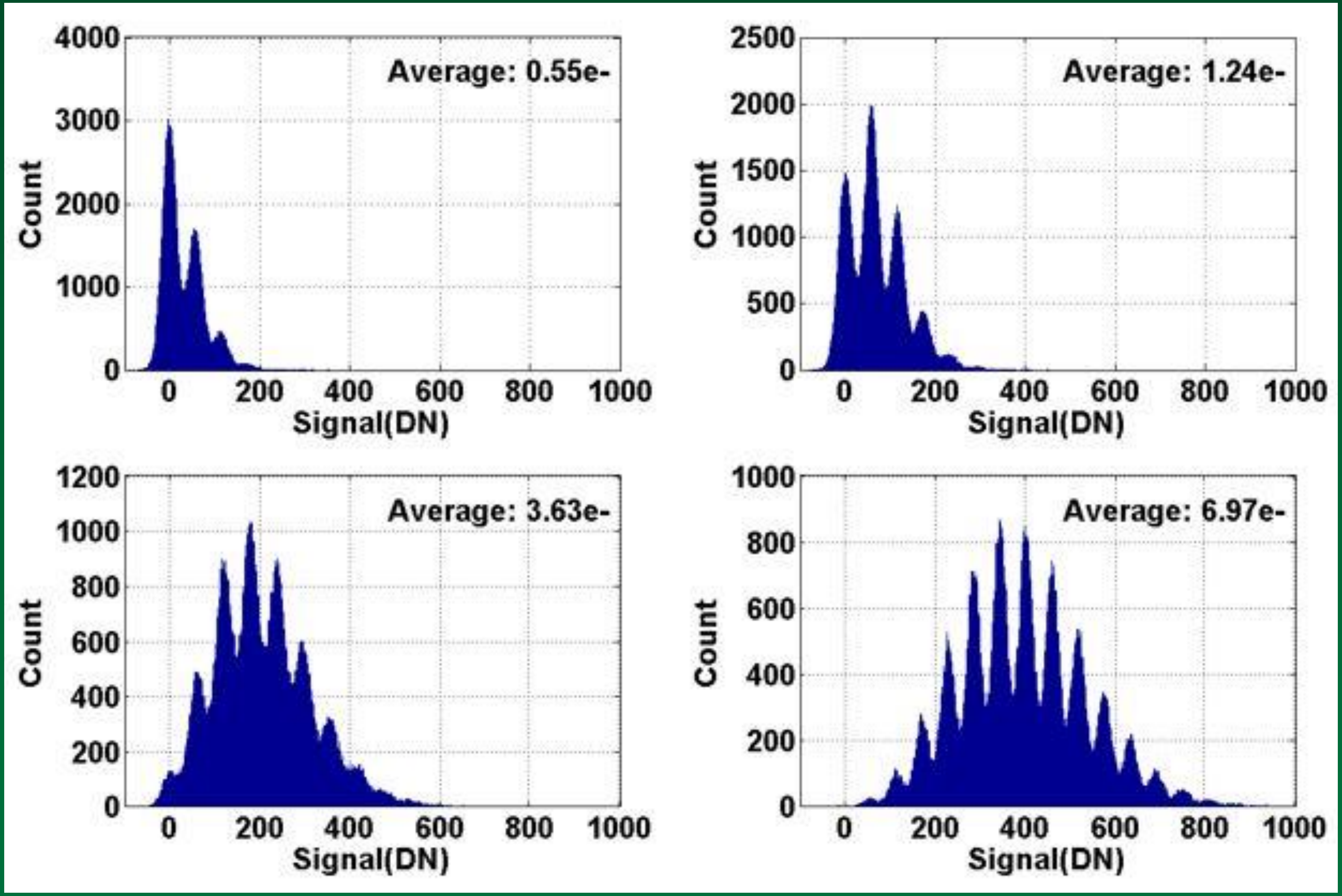
Fabricated in
TSMC 65nm
BSI CIS

1.4um pitch

Ma and Fossum
2014 IEDM, 2015 JEDS, 2015 EDL

Experimental Data
Photon-Counting Histograms

200k reads of same jot, ~0.28e- rms read noise, 120uV rms, 430uV/e-, ~60DN/e-
Room Temperature, No Avalanche, Single CDS readout



THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Dark Current

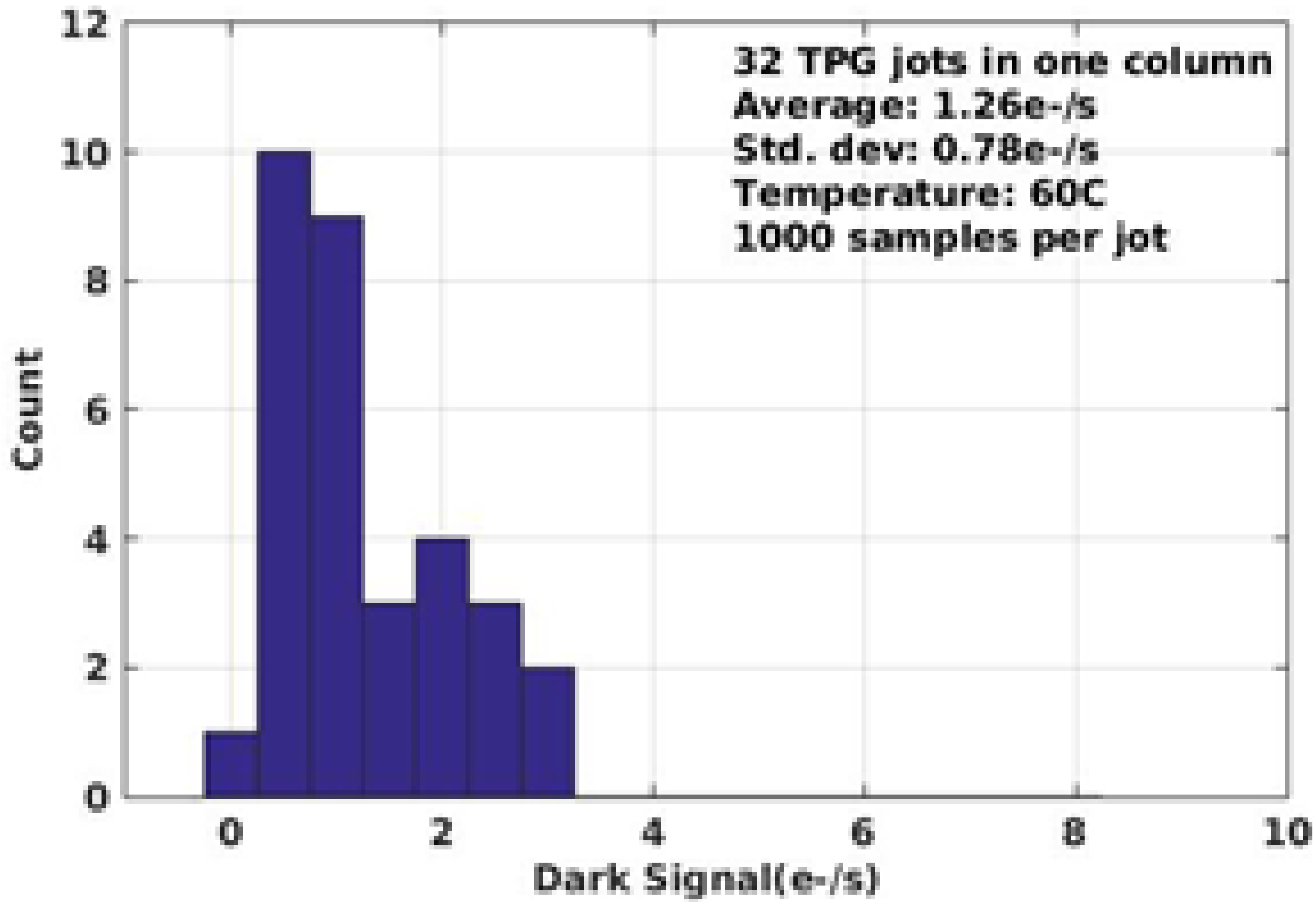
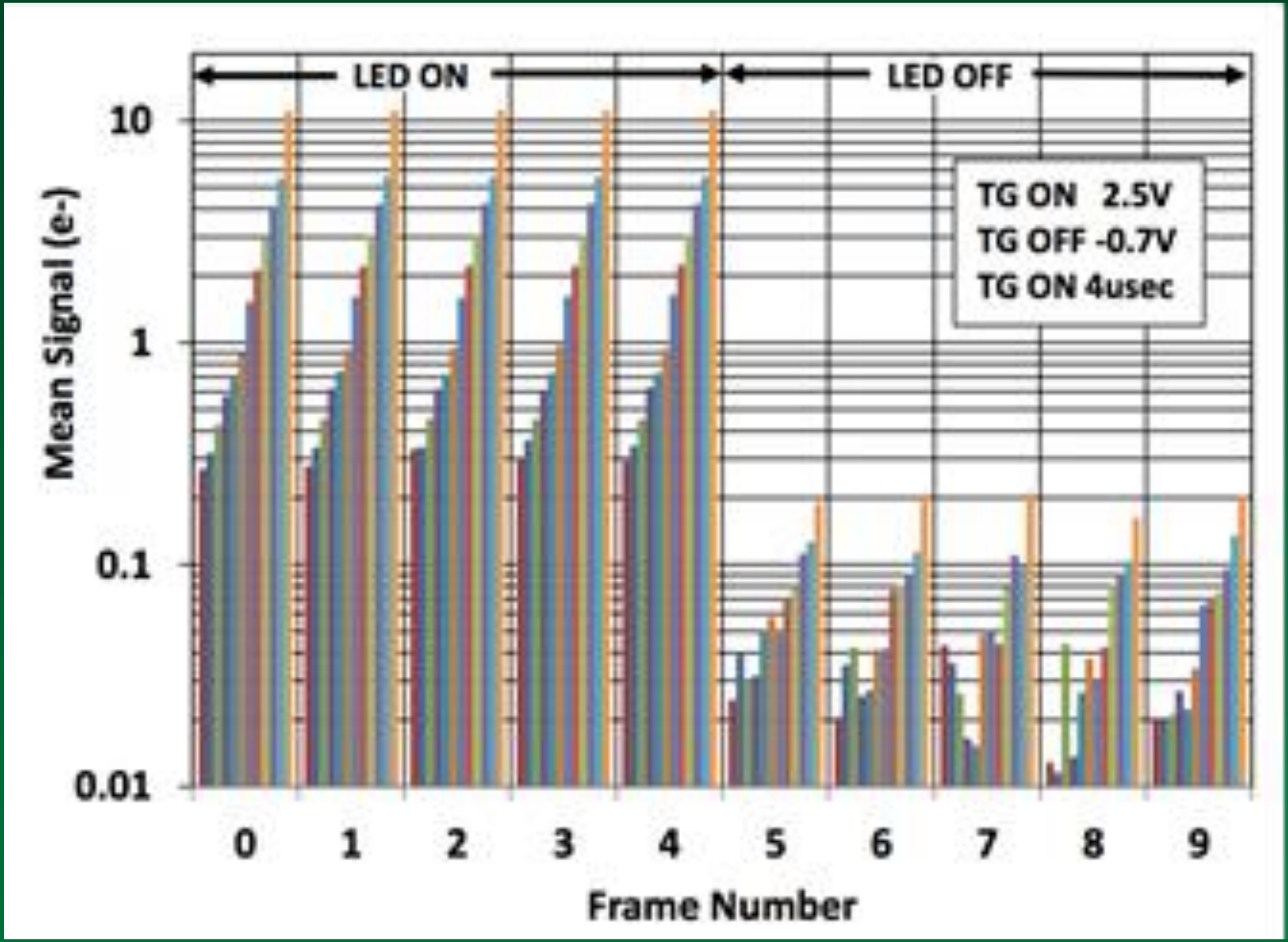


Fig. 11. The histogram of dark current among 32 PG jots in one column at 60C.

Ma, Starkey, Rao, Odame and Fossum, submitted to IEEE JEDS Aug 2015

Lag



Ma, Starkey, Rao, Odame and Fossum, submitted to IEEE JEDS Aug 2015

Experimental Data
Photon-Counting Histograms

200k reads of same jot, ~0.22e- rms read noise, 93uV rms, 423uV/e-, ~60DN/e-
Room Temperature, No Avalanche, Single CDS readout