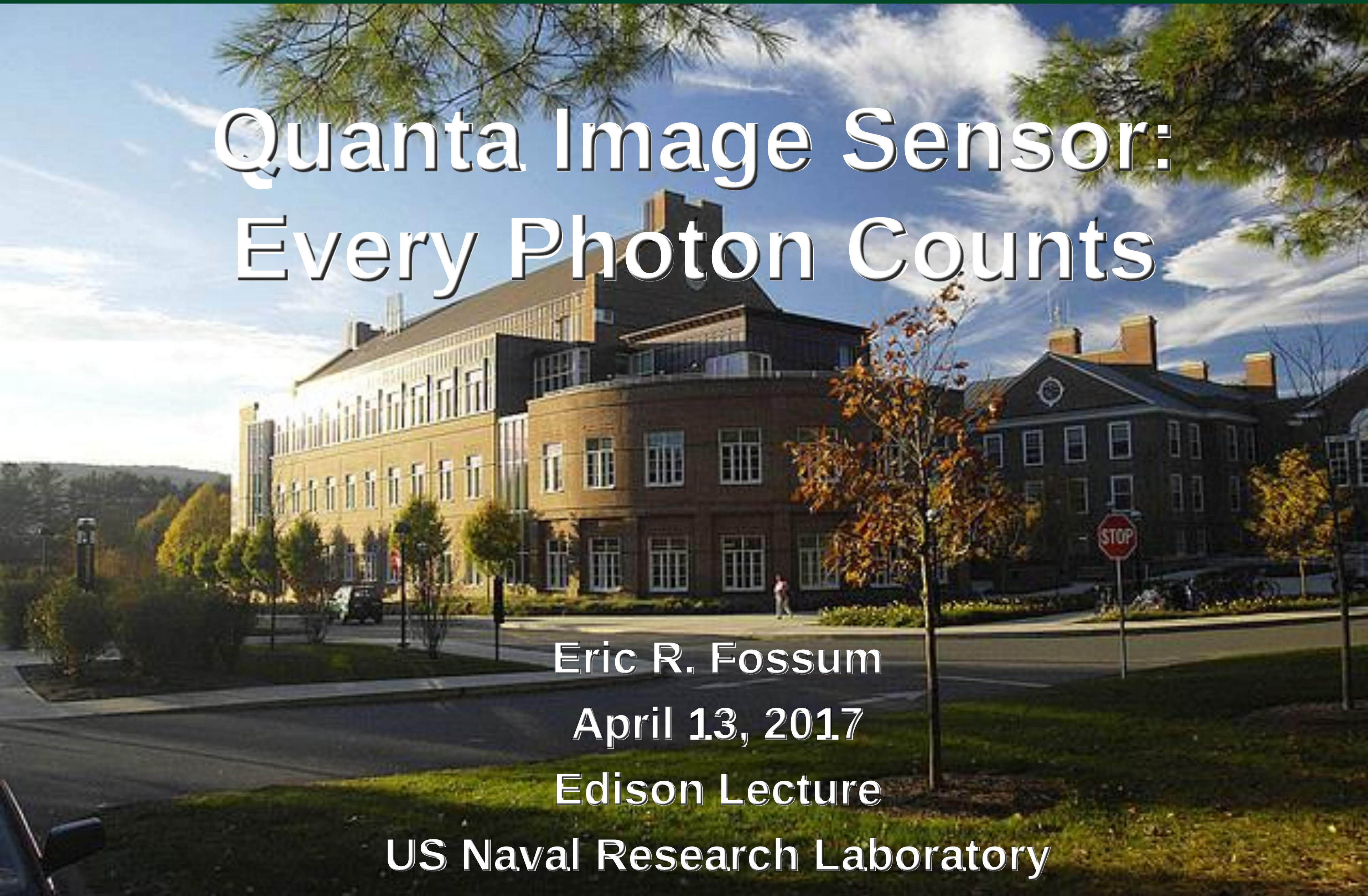
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Quanta Image Sensor: Every Photon Counts



Eric R. Fossum

April 13, 2017

Edison Lecture

US Naval Research Laboratory

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Prelude

CMOS IMAGE SENSORS: HISTORY, PHYSICS AND TECHNOLOGY

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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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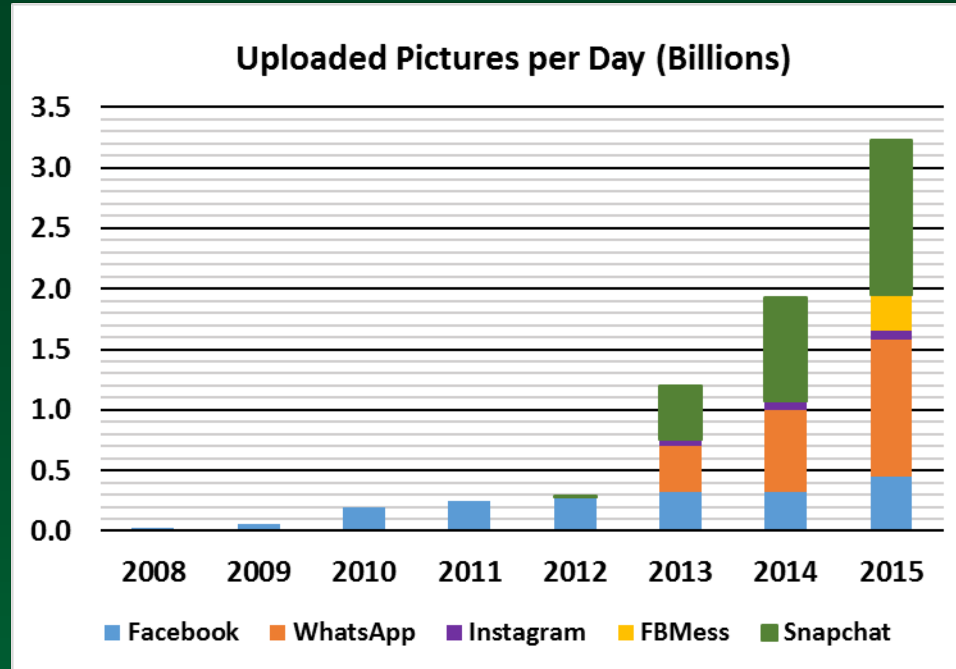

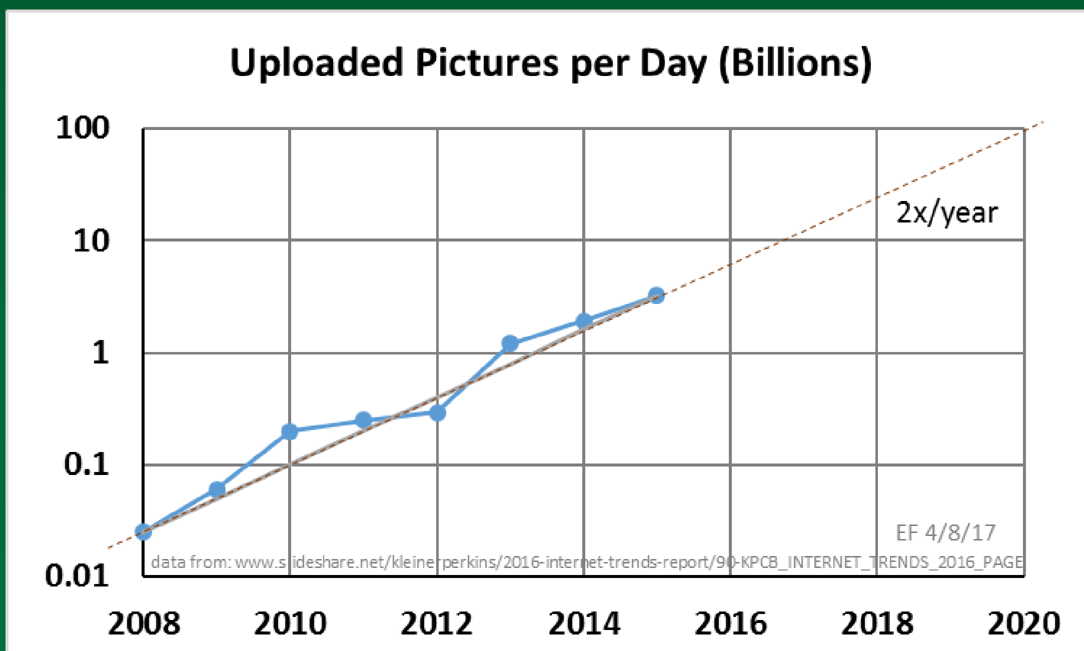

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Many kinds of digital cameras

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

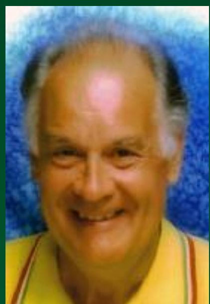
Medical
- Endoscopy
- Pill camera
- Dental X-rays

Machine Vision
- Automotive
- Security
- Inspection

3D ranging
- Gesture control

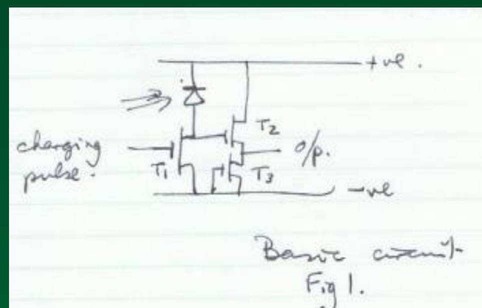
Etc.

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

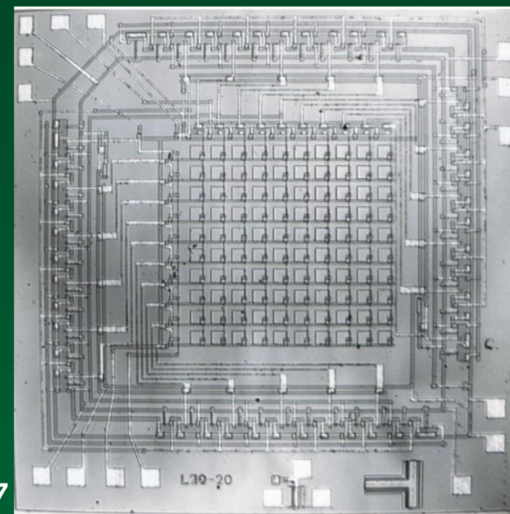


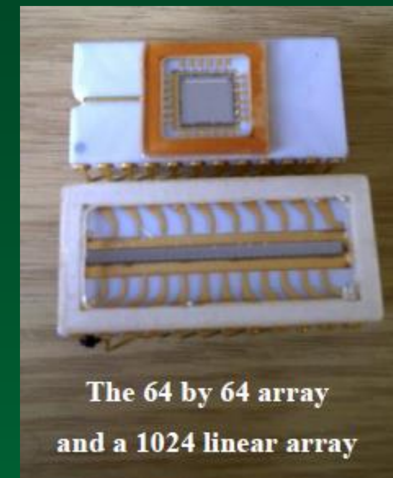
Peter JW Noble

~June 1966



First self-scanned →
Sensor 10x10 1966/67





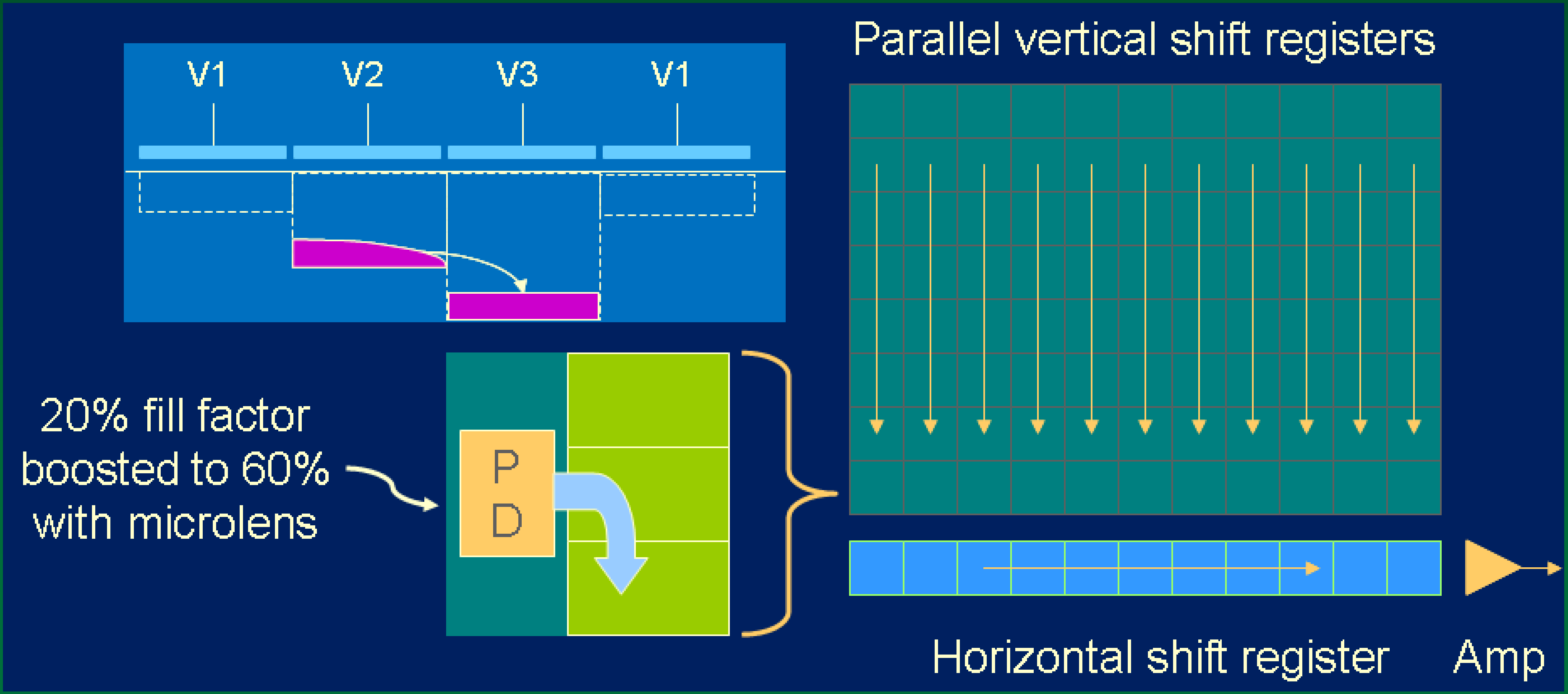
Gene Weckler

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

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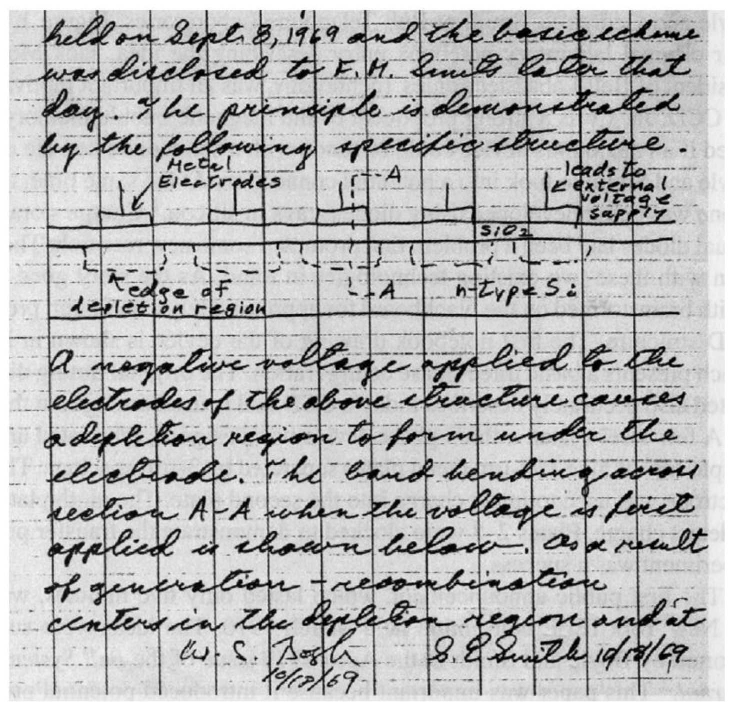

held on Sept. 8, 1969 and the basic scheme was disclosed to F.M. Smith later that day. The principle is demonstrated by the following specific structure.

A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation - recombination centers in the depletion region and at

W. S. Boyle 10/17/69   G. E. Smith 10/17/69

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

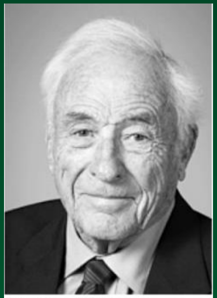
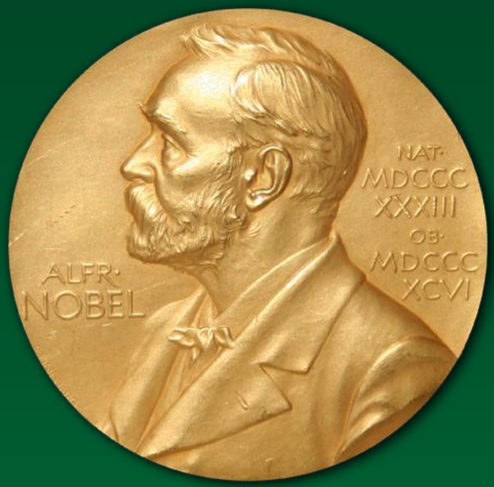


Photo: U. Montan
Willard S. Boyle


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

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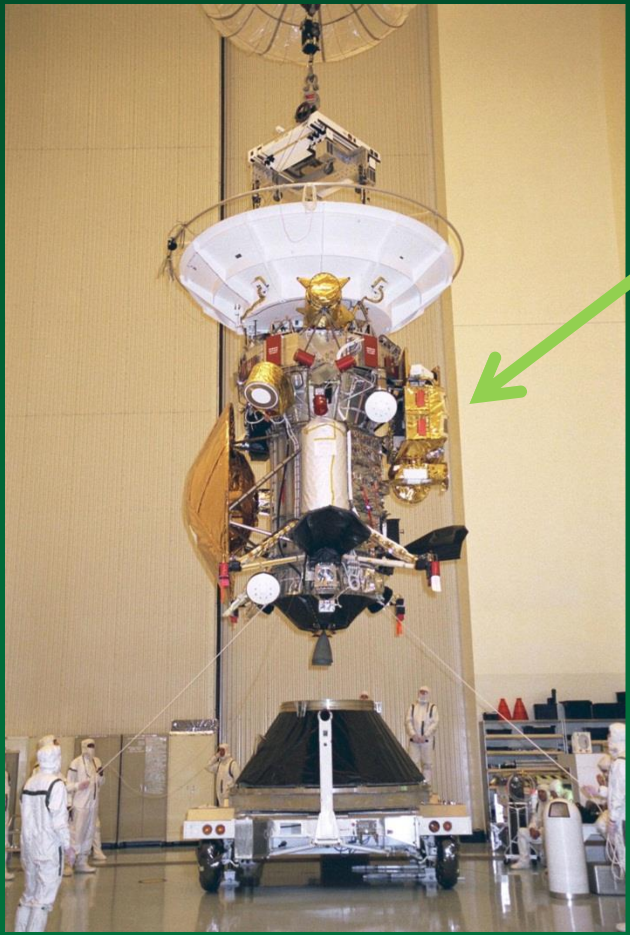
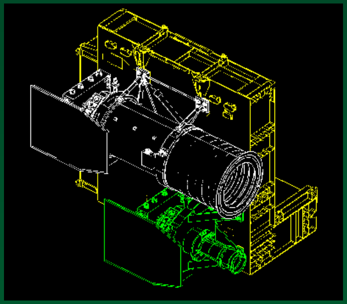
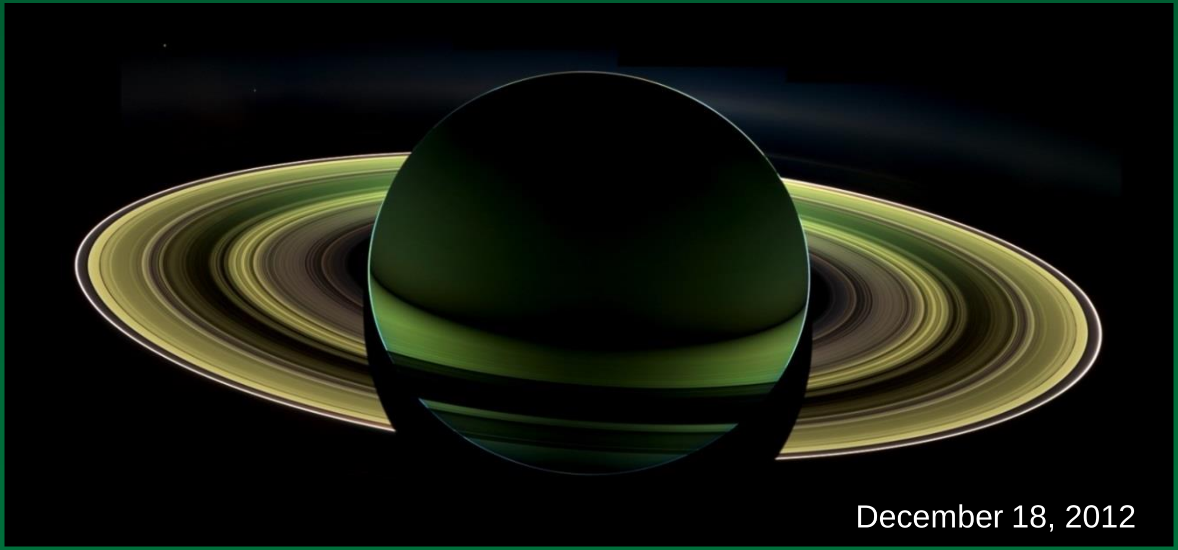
NASA/JPL – Caltech 1990s Cassini ISS has CCD cameras

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







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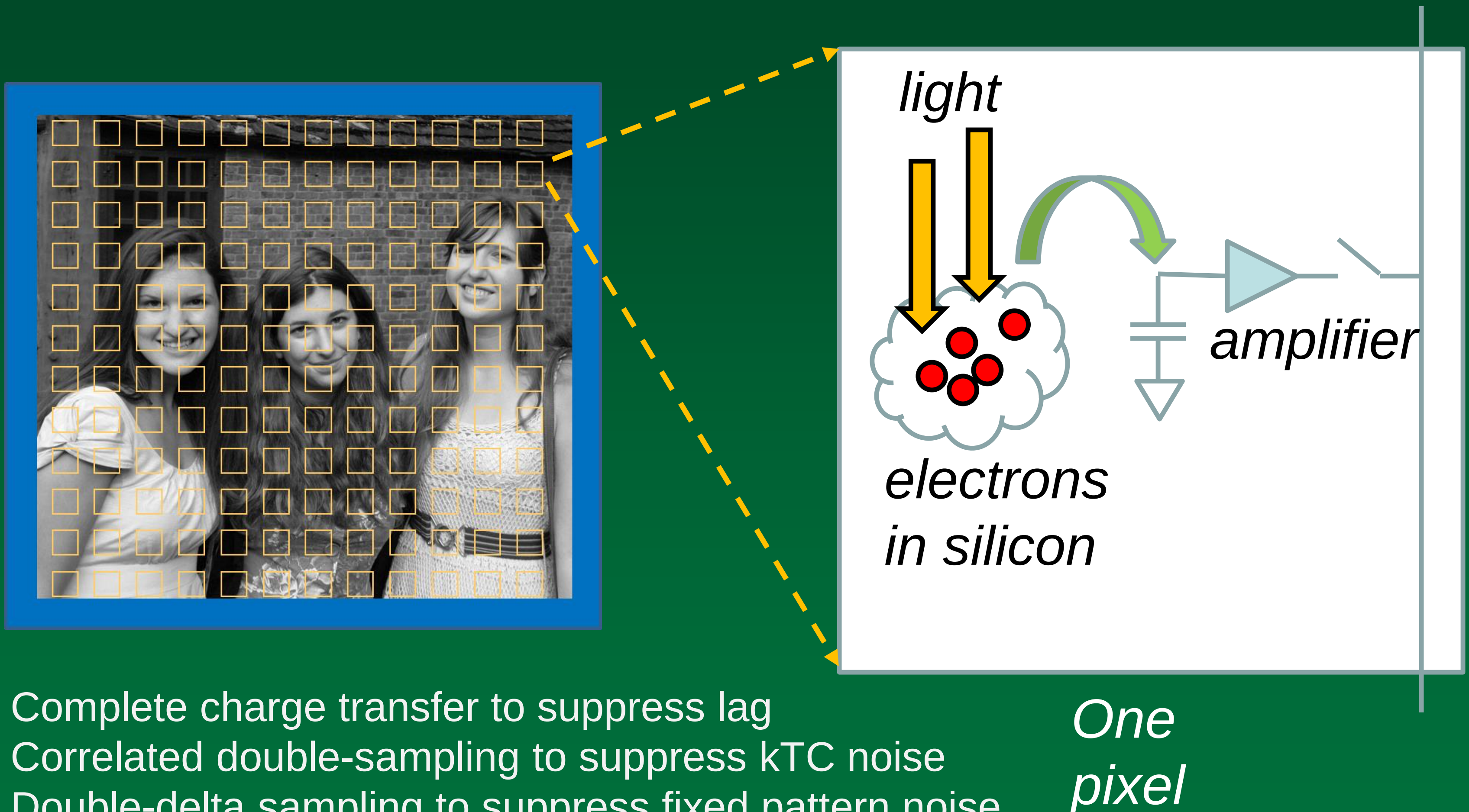
~1992 NASA's Administrator Daniel Goldin
"Faster, Better, Cheaper"

↓

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

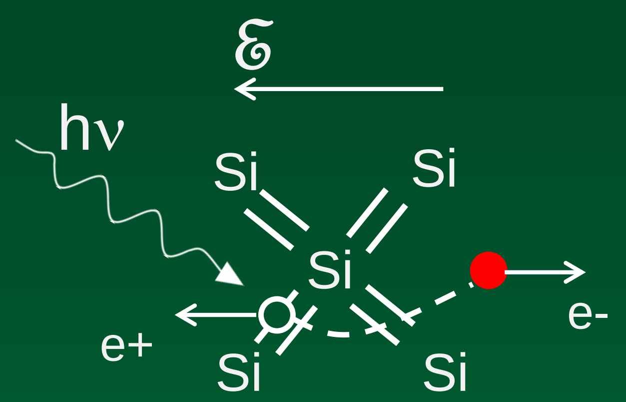
- Electronics integration is well-worn path to miniaturization, and MOS-based image sensors predate CCDs (e.g. Peter Noble or Gene Weckler late 1960's) including passive pixel and active pixel (3T) configurations.
- BUT MOS image quality is quite poor compared to CCDs due to temporal noise, fixed pattern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

Active Pixels with Intra-Pixel Charge Transfer

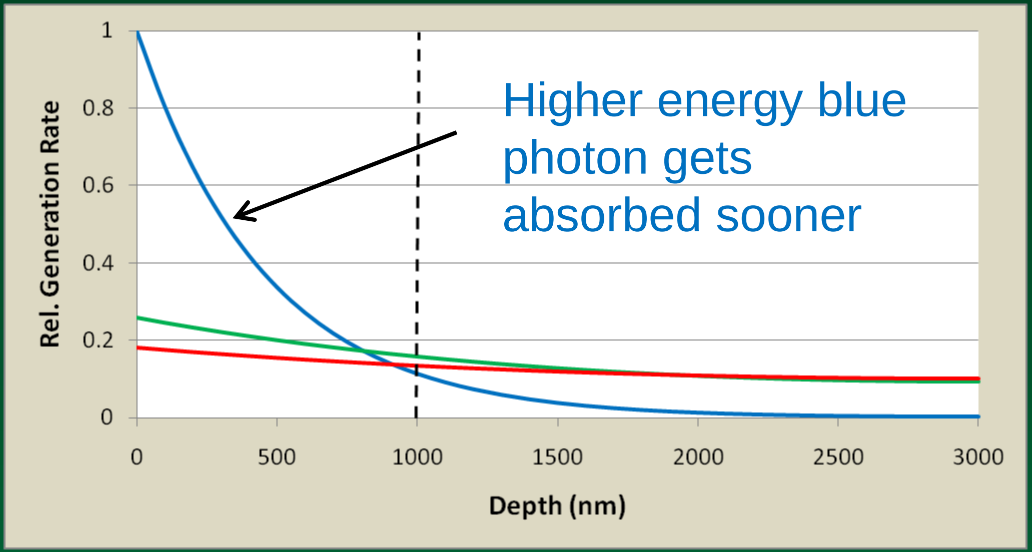


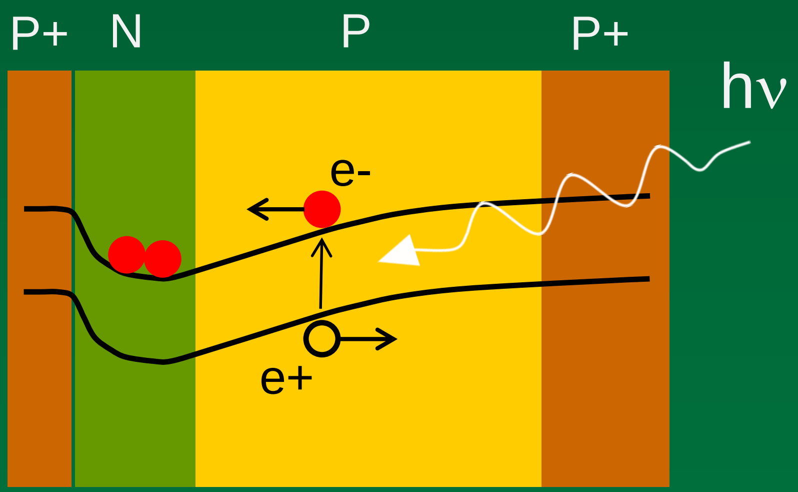
- Complete charge transfer to suppress lag
- Correlated double-sampling to suppress kTC noise
- Double-delta sampling to suppress fixed pattern noise
- On-chip ADC, timing and control, etc.

Photons to Electrons



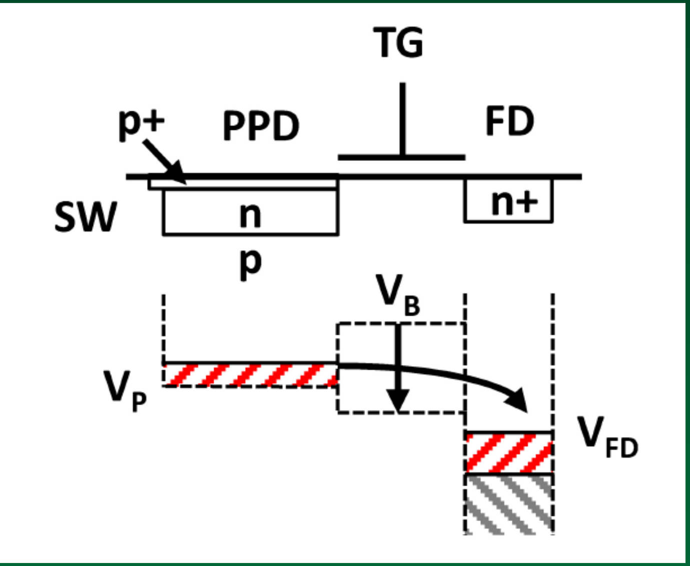
Covalently bonded silicon



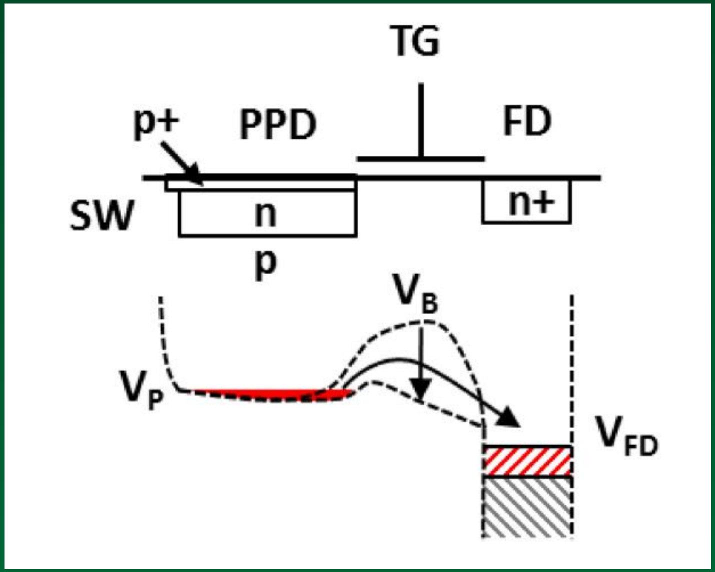


Pinned photodiode (PPD)
N. Teranishi et al.1982 for ILT CCD

Pinned Photodiode Basic Operation



Ideal device with no residual barrier



Barriers lead to lag and noise

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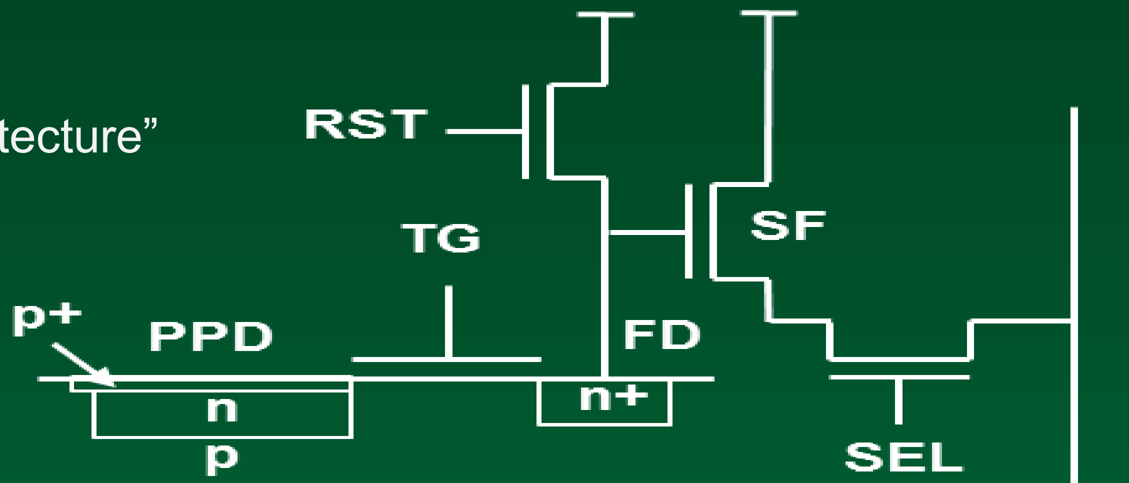
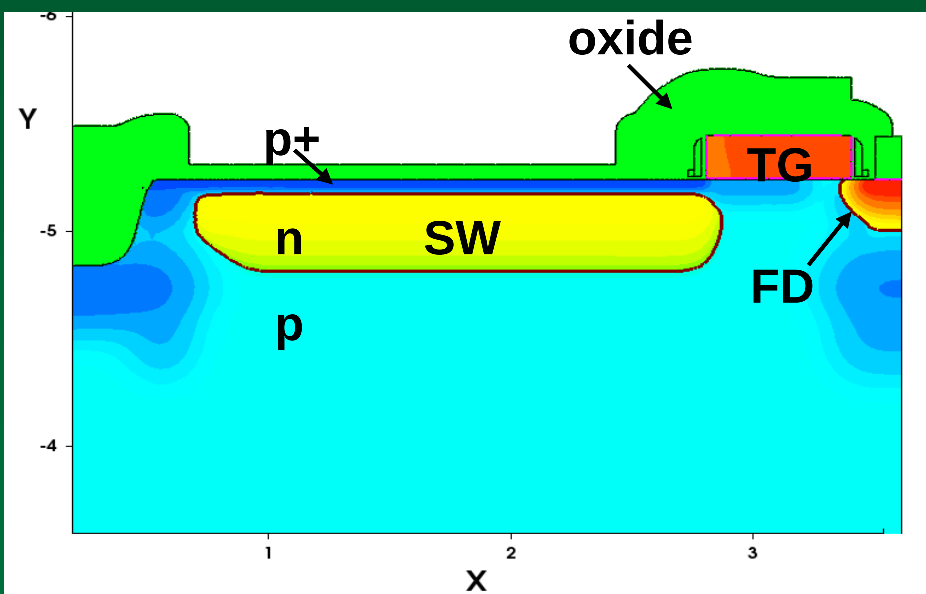
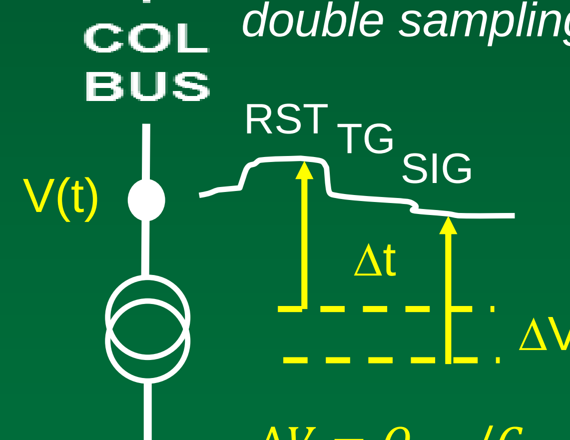
CMOS Pinned Photodiode Pixel

“4T architecture”





Correlated double sampling



$\Delta V = Q_{SIG}/C_{FD}$

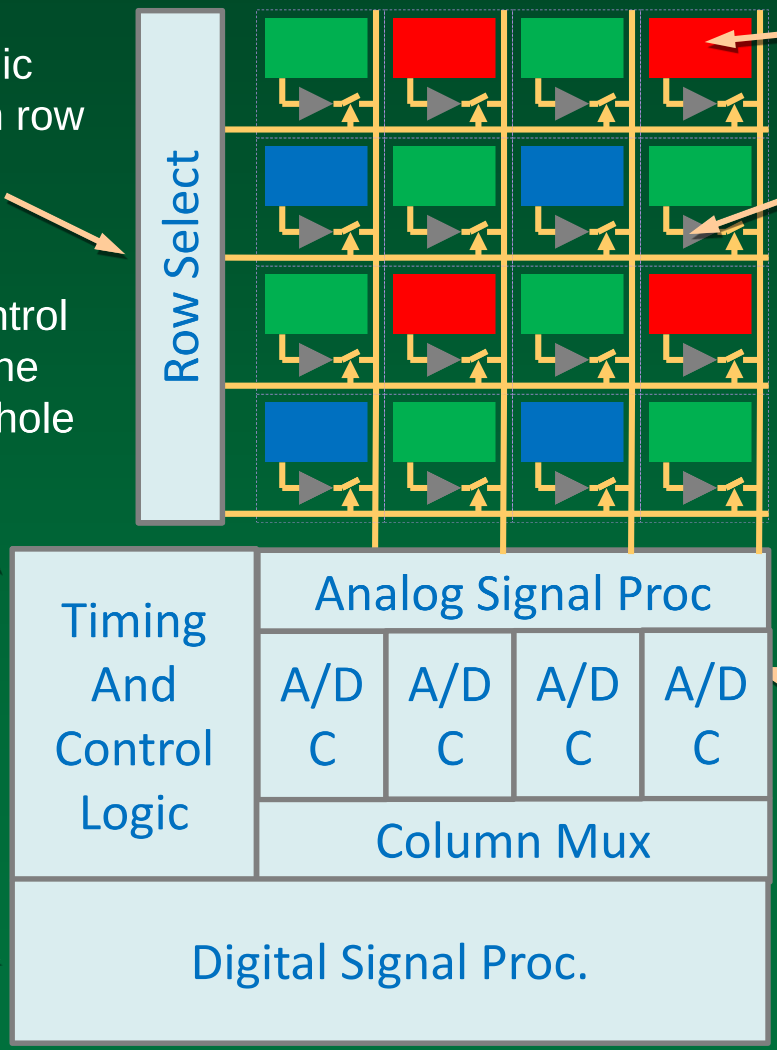
E.R. Fossum and D. Hondongwa, A review of the pinned photodiode for CCD and CMOS image sensors, IEEE J. Electron Devices Society, vol 2(3) pp. 33-43 May 2014.

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

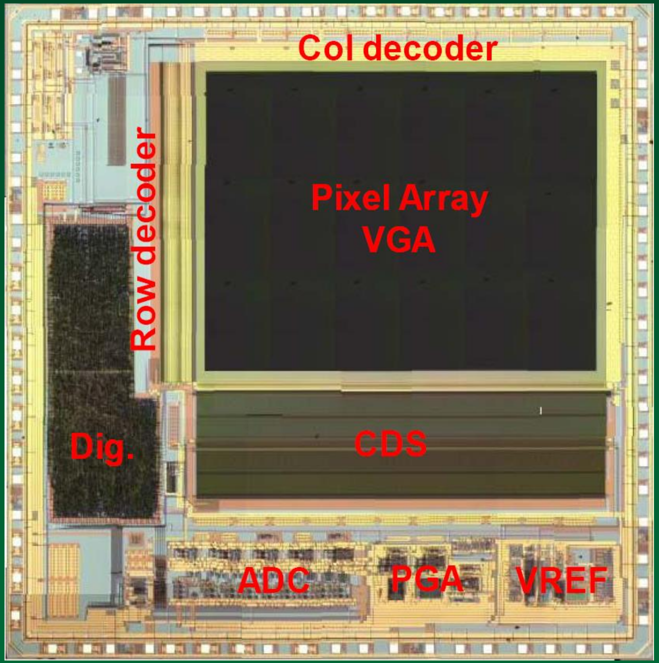
Amplifier converts electrons to voltage after intrapixel complete charge transfer

Analog signal processor suppresses noise and further amplifies signal

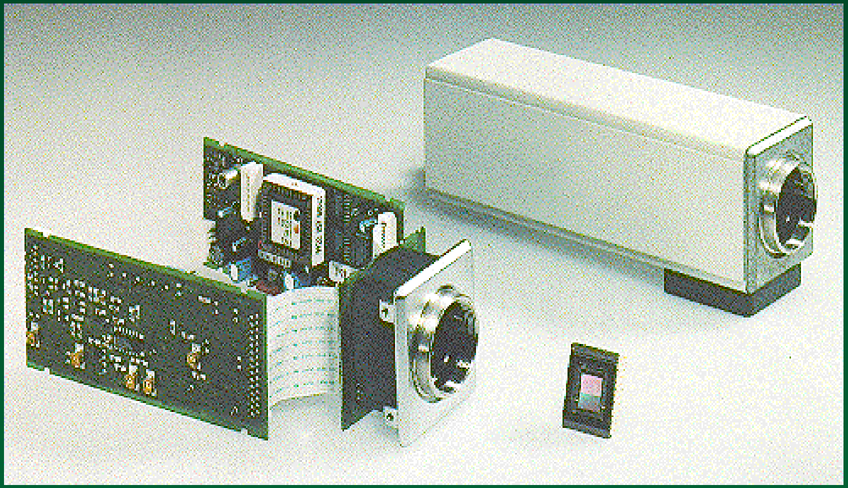
Analog-to-digital converters (ADC) convert signals from volts to bits (usually 10-12 bits resolution) in parallel

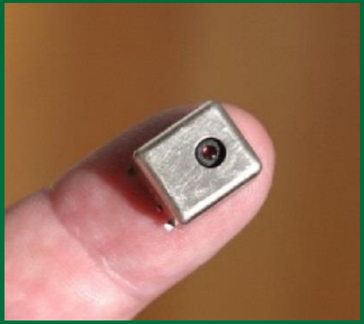
Column multiplexer used to scan ADC outputs

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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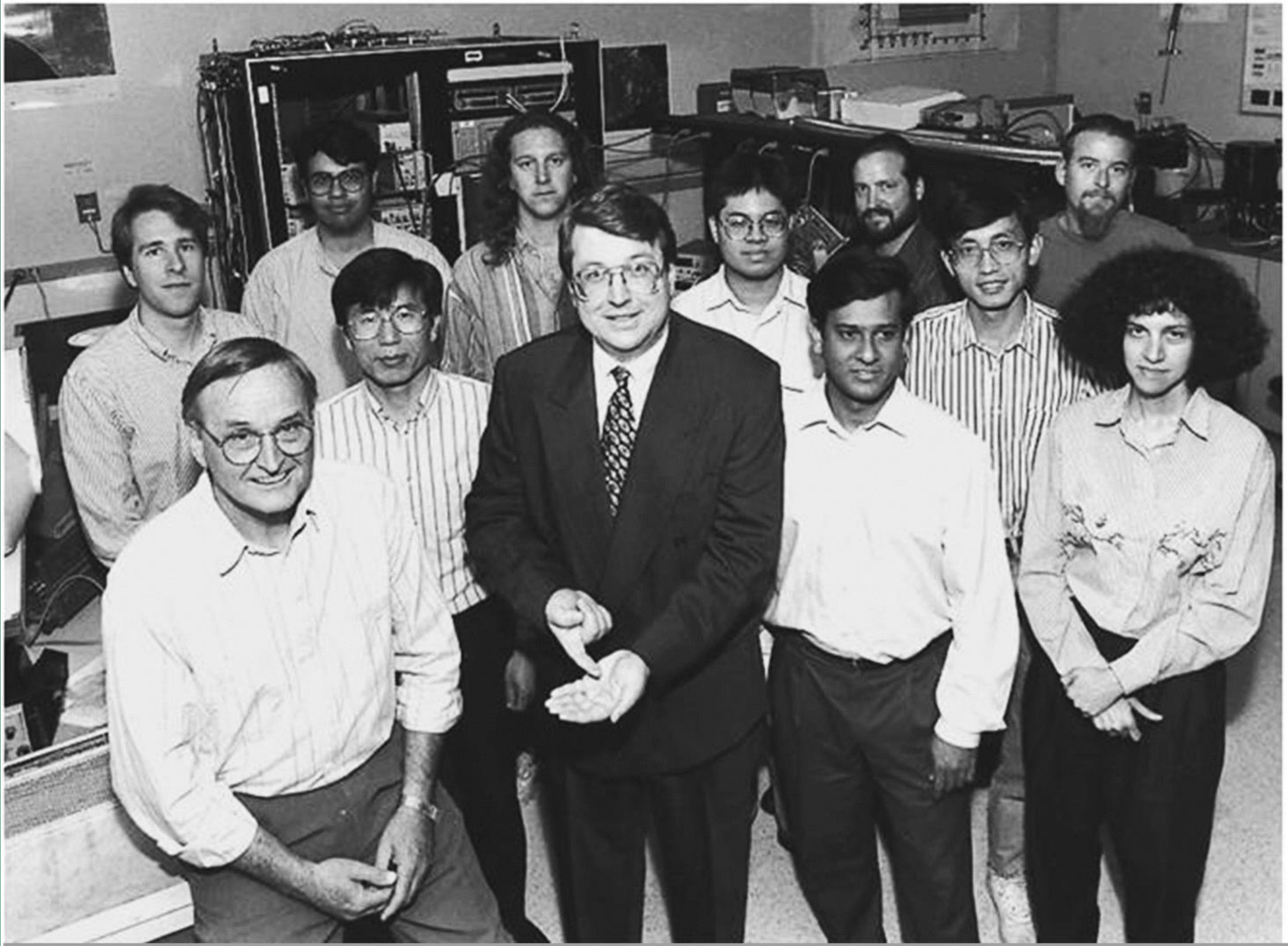
Most of the JPL Team



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

Missing: Sabrina Kemeny, Junichi Nakamura, Sunetra Mendis

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

Lucky Break

Science & Technology

INVENTIONS

NASA'S TINY CAMERA HAS A WIDE-ANGLE FUTURE

It may still be in the lab, but the latest advance in capturing images has very bright prospects, indeed

Get ready for the camera-on-a-chip. Since the 1970s, camera makers have dreamed of a one-chip camera containing all the components necessary to take a snapshot or make a movie. With all the smarts on one chip instead of several, designers figure they could make a camera small and cheap enough to open vast new markets for everything from dolls that "see" to rear-bumper cameras that would help drivers back up.

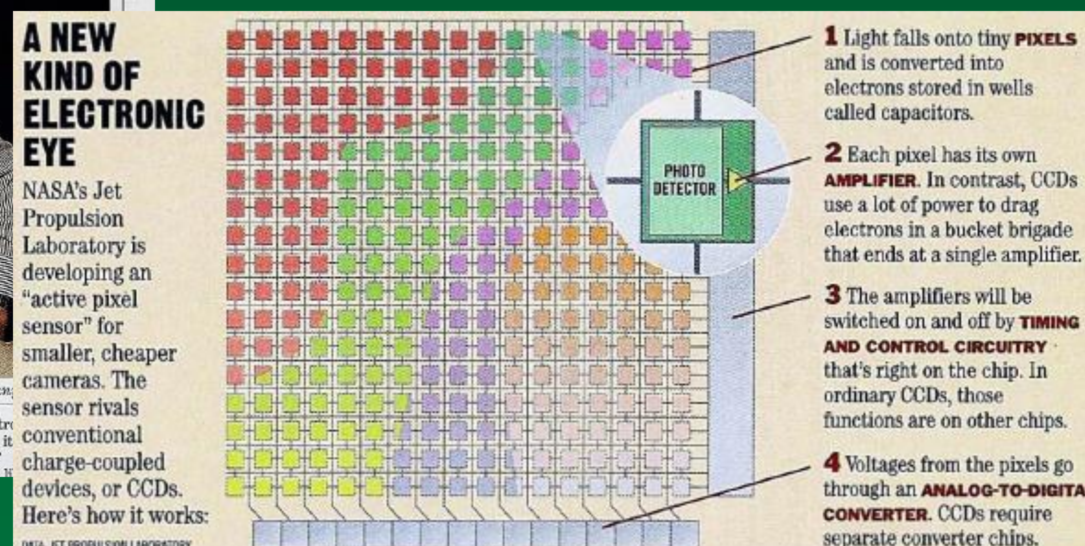
Such devices are impractical with today's standard electronic image sensor. It's called a CCD, for charge-coupled device, and it's at the heart of every fax machine and camcorder. Japanese powerhouses such as Sony, Matsushita, and NEC churn out millions a year. CCDs offer good image quality. But they are costly, power-hungry, and—with the accessory chips they require—bulky.

TEAMWORK. Now, the one-chip dream appears on the verge of being fulfilled, thanks to three inventors from NASA's Jet Propulsion Laboratory at California Institute of Technology in Pasadena. The leader is Eric R. Fossum, 37, who

FOSSUM: *The project leader and his co-inventors will share in an*

cost much less than CCDs. One chip can incorporate all manner of electronic controls that are usually on multiple chips,

ter for Space Microelectro gy at JPL. "For them, it leapfrog the Japanese."



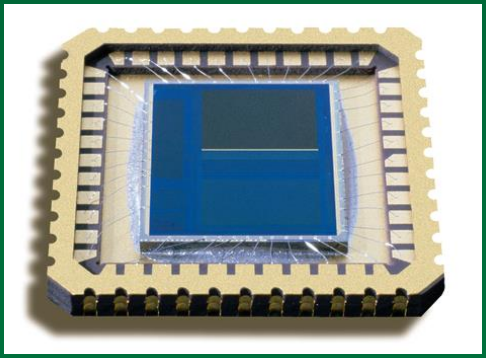
March 6, 1995 Business Week article

Perspiration Phase

1995-2001 Photobit grows to about 135 persons

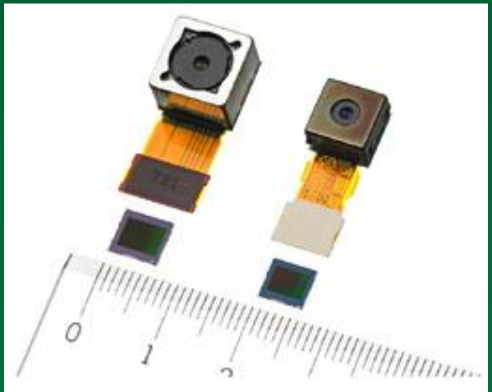
- Self funded with custom-design contracts from private industry
- Important support from SBIR programs (NASA/DoD)
- Later, investment from strategic business partners to develop catalog products
- Over 100 new patent applications filed

Nov 2001 Photobit acquired by Micron Technology

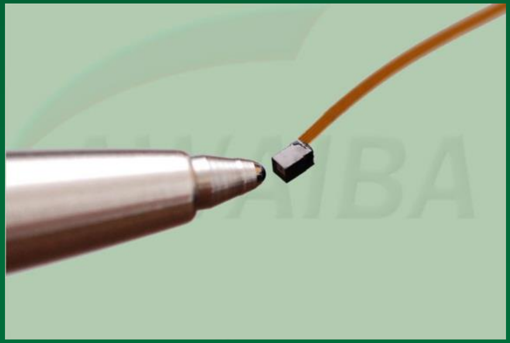


The Technology Develops a Life of its Own

- Today, over 4 billion cameras are manufactured each year that use the CMOS image sensor technology we invented at JPL, or more than 120 cameras per second, 24/365.
- Semiconductor sales of CMOS image sensors were over $10B/yr in 2016.
- Thousands of engineers working on this around the globe.
- 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

http://image-sensors-world.blogspot.com/2016/01/camera-module-industry-report.html

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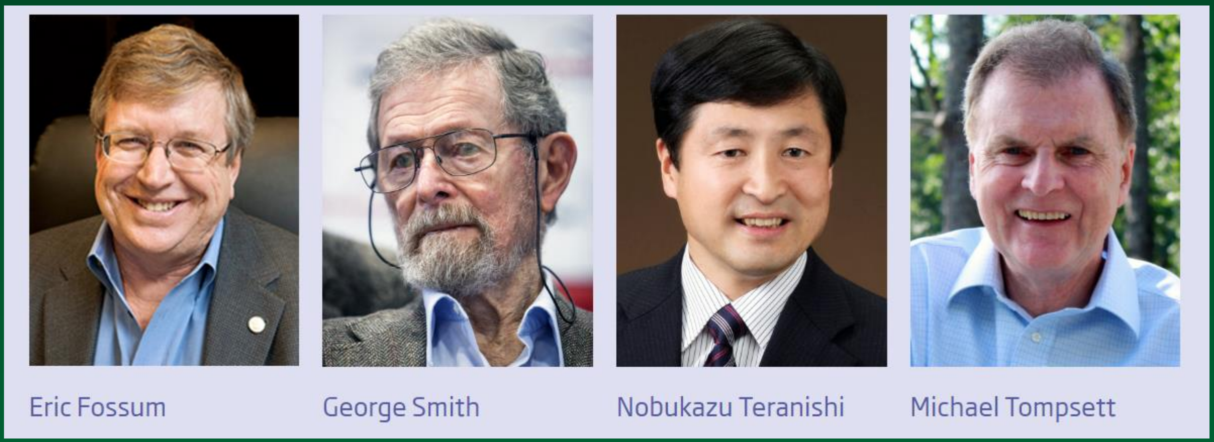
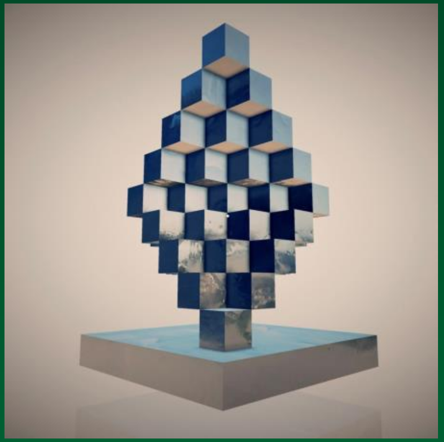
2017 Queen Elizabeth Prize for Engineering

CMOS image sensor	CCD	Pinned photodiode	CCD image sensor





"for the creation of digital Image sensors"

Tompsett, Fossum and Teranishi
at announcement Feb 1, 2017
Royal Academy of Engineering, London, UK

www.qeprize.org

Shared Readout Architecture

“1.35T architecture”

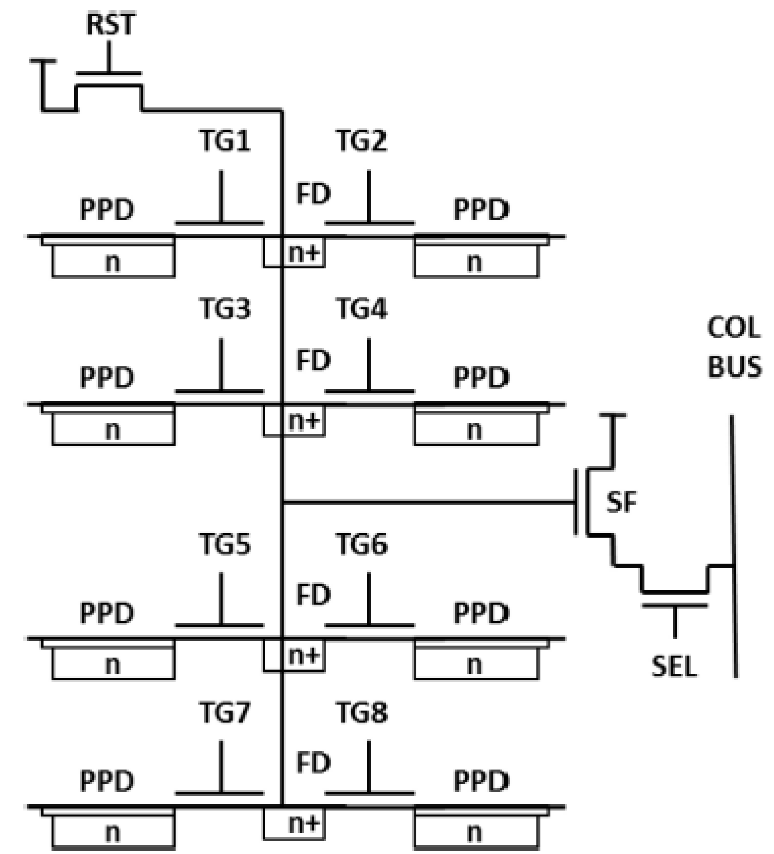
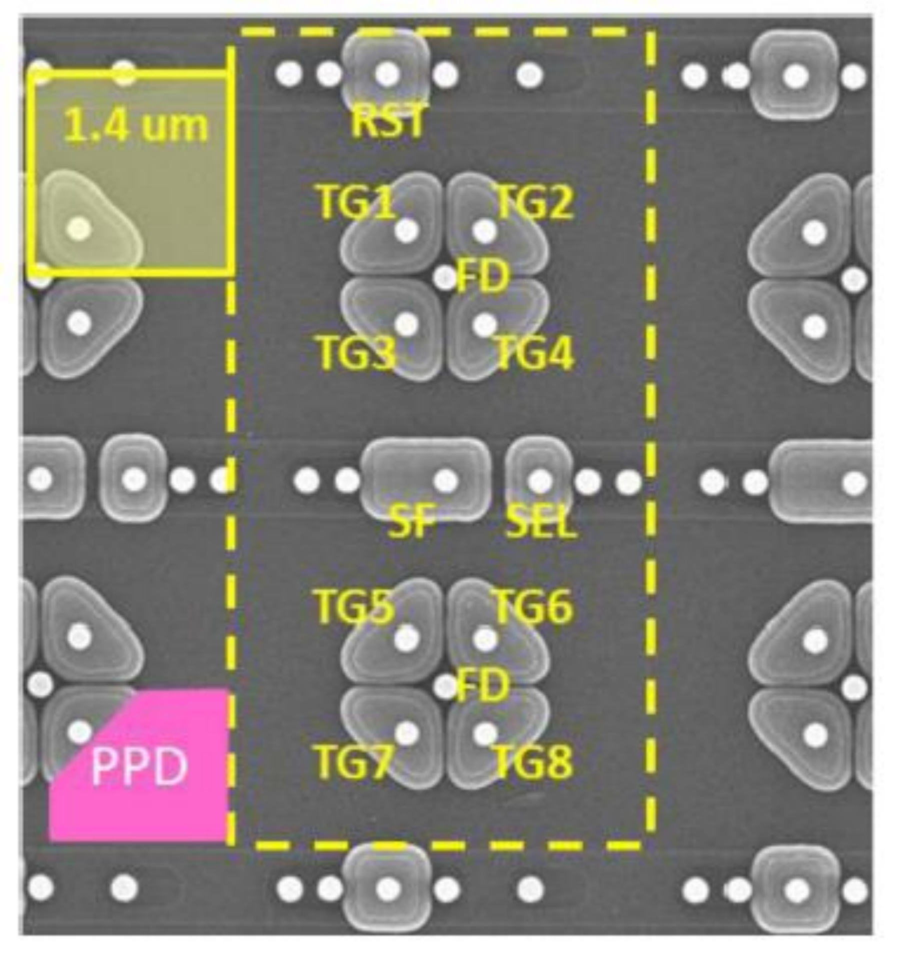


Fig. 9. 8-way shared readout 1.35T pixel schematic.



Sony 1.4 um BSI pixel

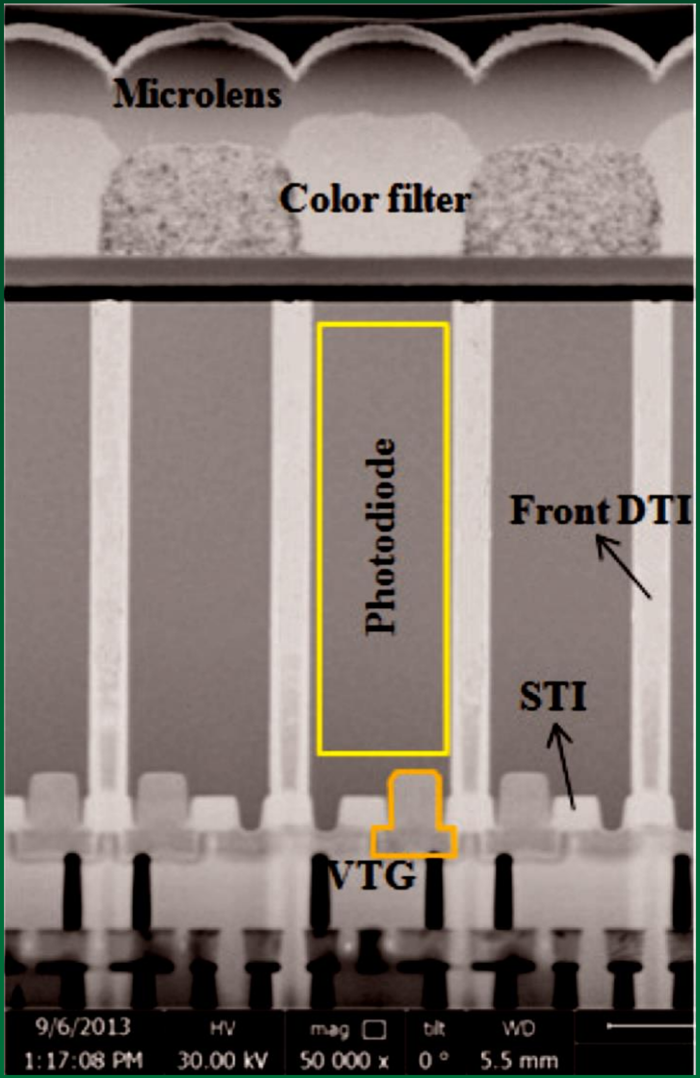
M. Guidash, Kodak, US6352869 B1

Backside Illuminated (BSI) CMOS Image Sensors

"Backside"

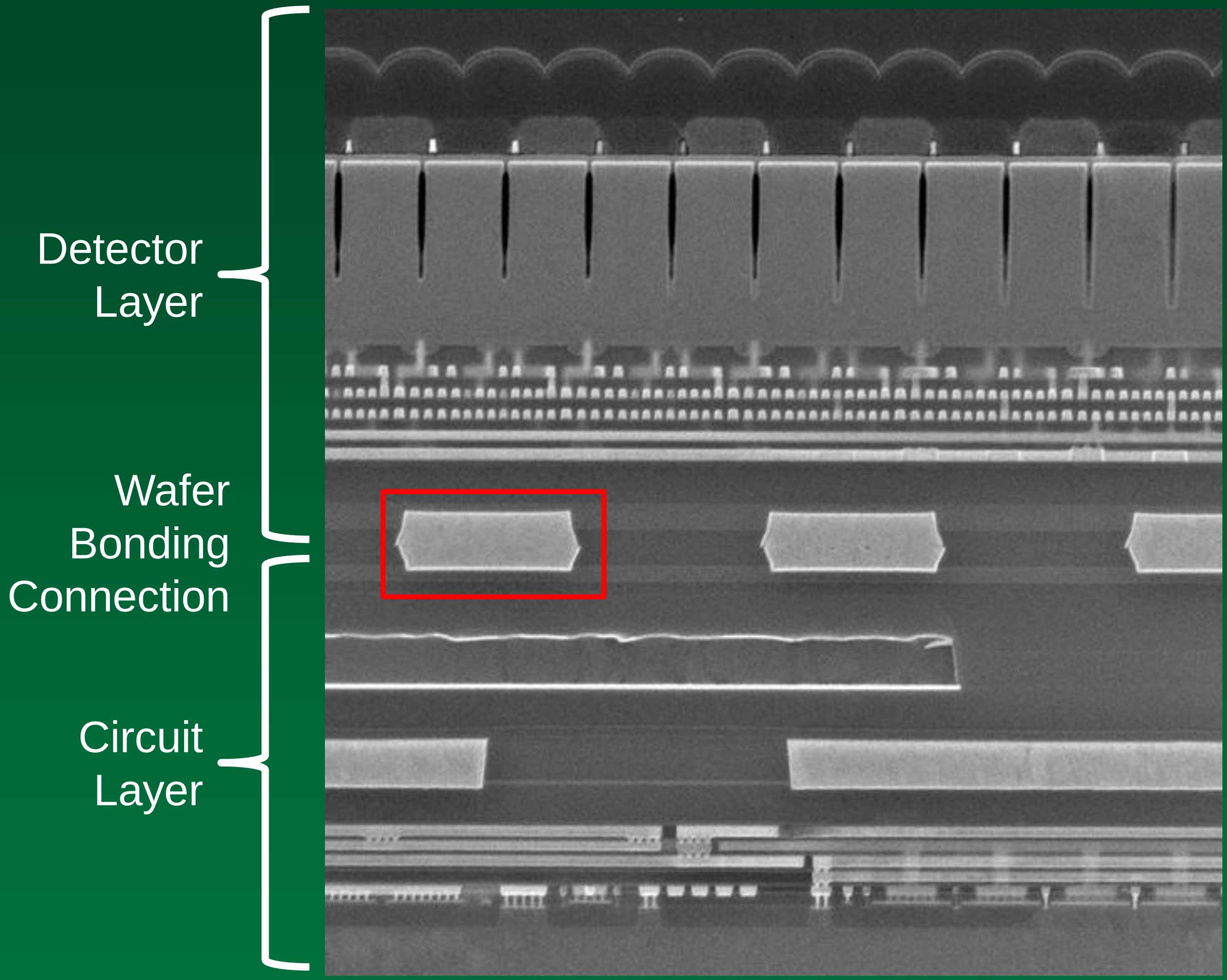
Thinned silicon detection layer 3-5um

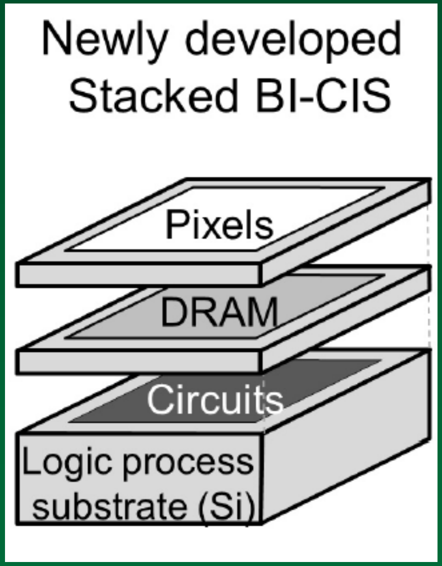
"Frontside"



Samsung ISOCELL ISSCC 2013

Stacked BSI CIS Using Wafer Bonding





Sony 2017 ISSCC

Sony IMX260 dual pixel AF sensor from Samsung S7 teardown

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New Technology Invariably Brings New Social Issues

Selfies and Instant Communications

Rapid Social Change (Arab Spring)

Drone Cameras

Body Cameras

Inappropriate use

Visual overload (e.g. Japanese Tsunami)

Security v. Privacy

Main Story

QUANTA IMAGE SENSOR

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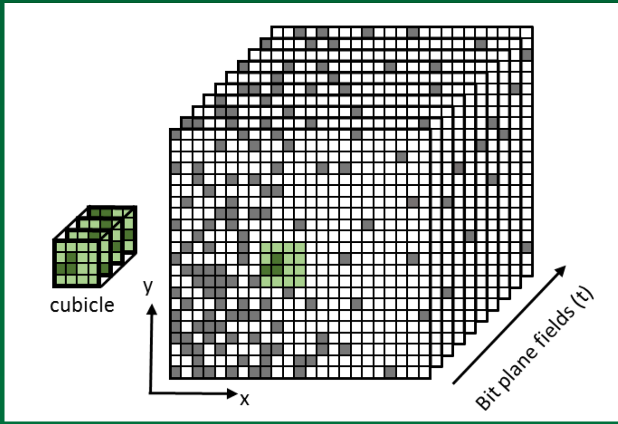
Quanta Image Sensor
"Count Every Photon"

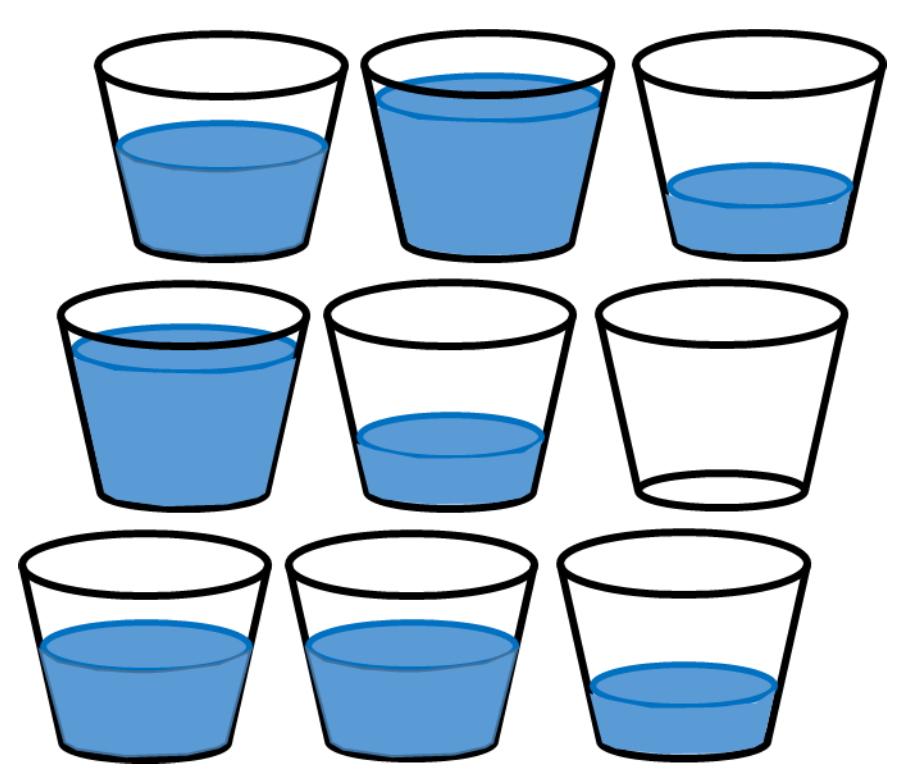
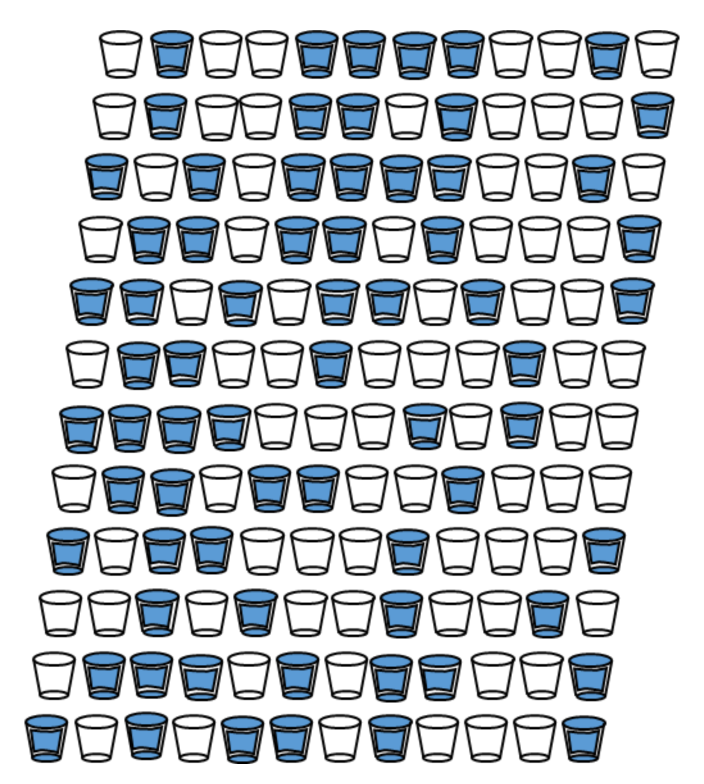
- Original goal for QIS was to take advantage of shrinking pixel size and make a very tiny, specialized pixel ("jot") which could sense a single photoelectron.
- Jots would be readout by scanning at a high frame rate to avoid likelihood of multiple hits in the same jot and loss of accurate counting.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

Vision: A billion jots readout at 1000 fps with single photon counting capability (1Tb/s) and consuming less than a watt.



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

Paradigm Shift

Measuring Rainfall	Counting Raindrops
	
CCD and CMOS Image Sensors	*Quanta Image Sensor*

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Pixels from Jots (Simulation)

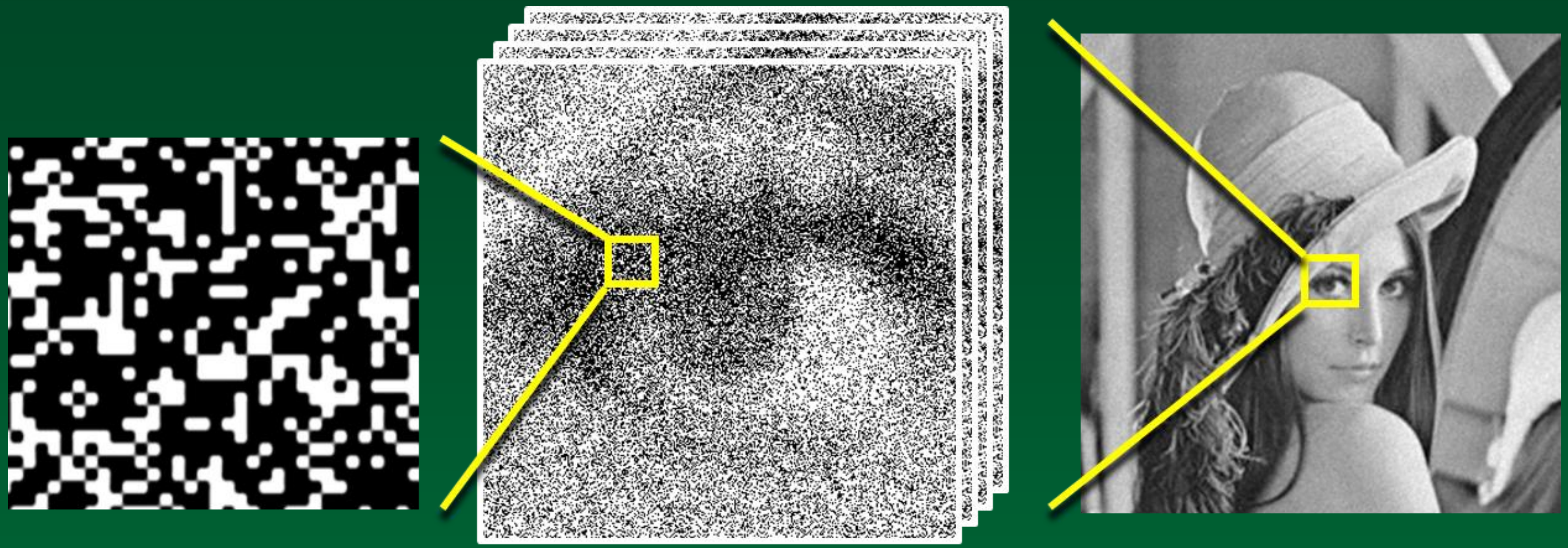
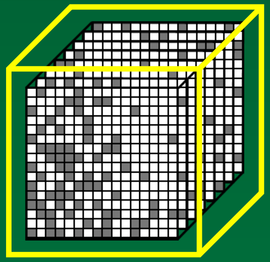


Image reconstruction example



Cubicle

$$S = \sum_{x,y,t} j(x,y,t)$$

16x16x8 “cubicle”

$$0 \leq S \leq 2048$$

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

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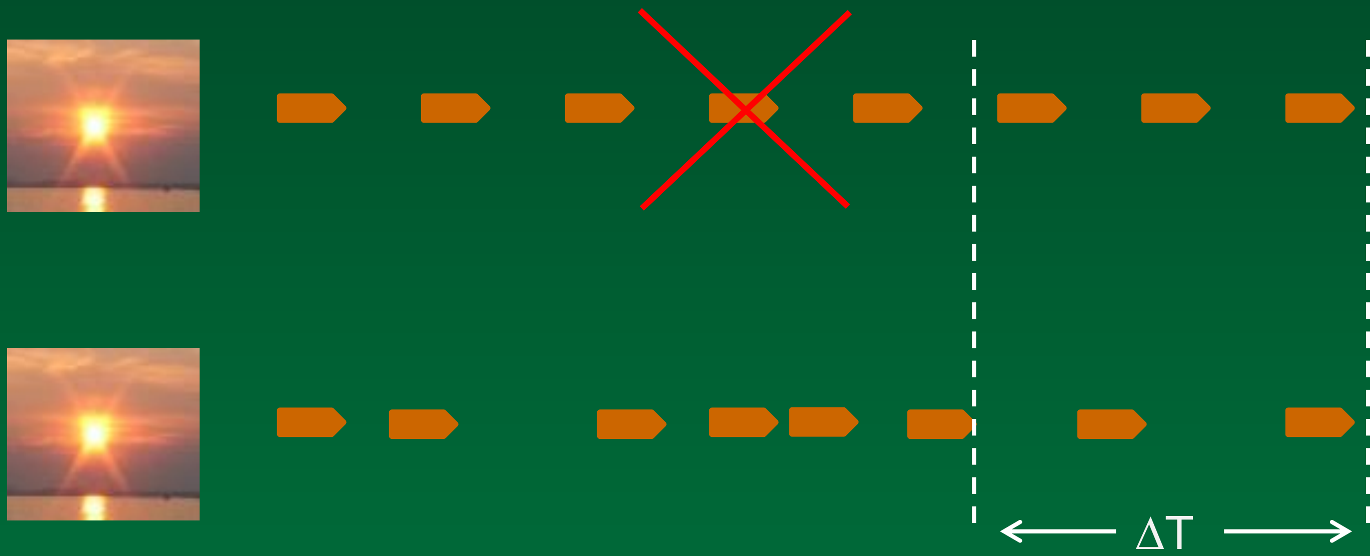
Photon Shot Noise

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

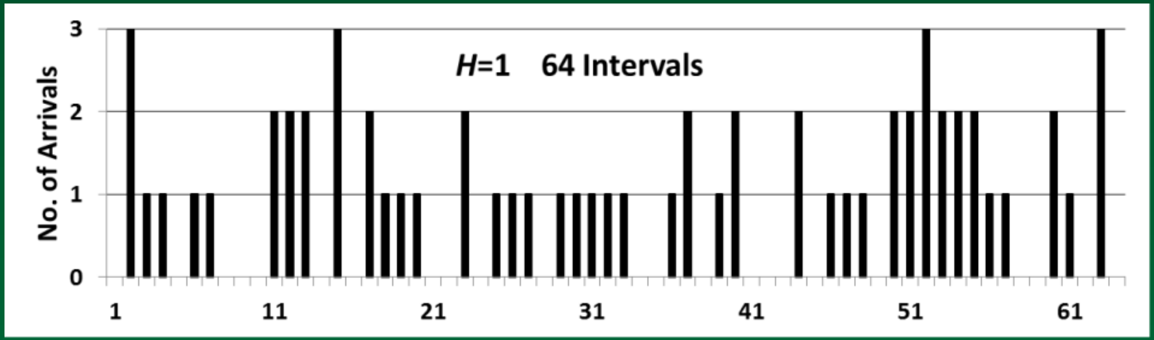


- Leads to variability when trying to determine average photon arrival rate. Gets better with longer measurement (more photons).

Photon and photoelectron arrival rate described by Poisson process

Define *quanta exposure* $H = \phi\ \tau$ $\quad$ $H = 1$ 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 : $M_1 = M \cdot P[k > 0]$

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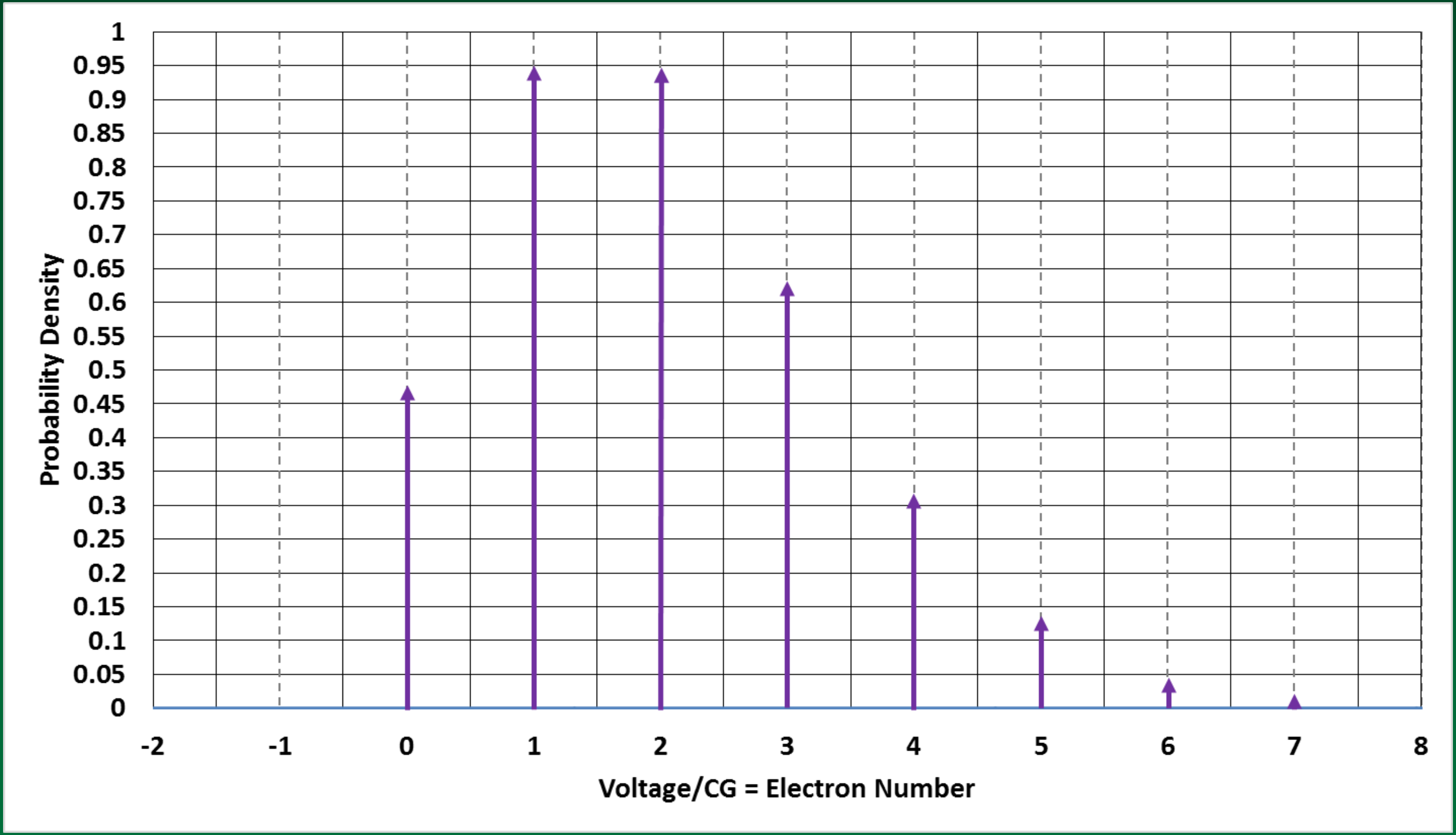
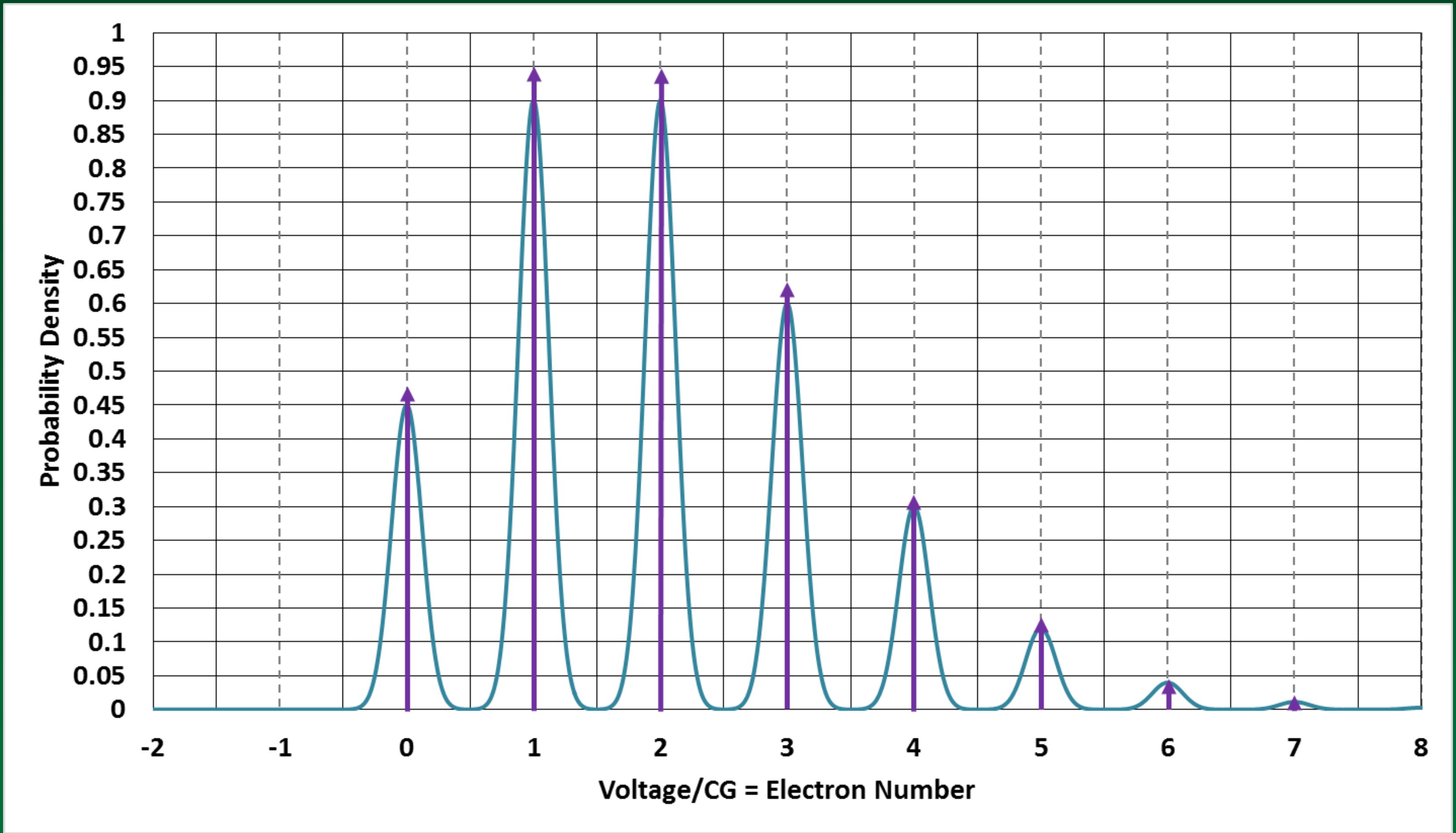
Poisson Distribution (scaled)

H=2



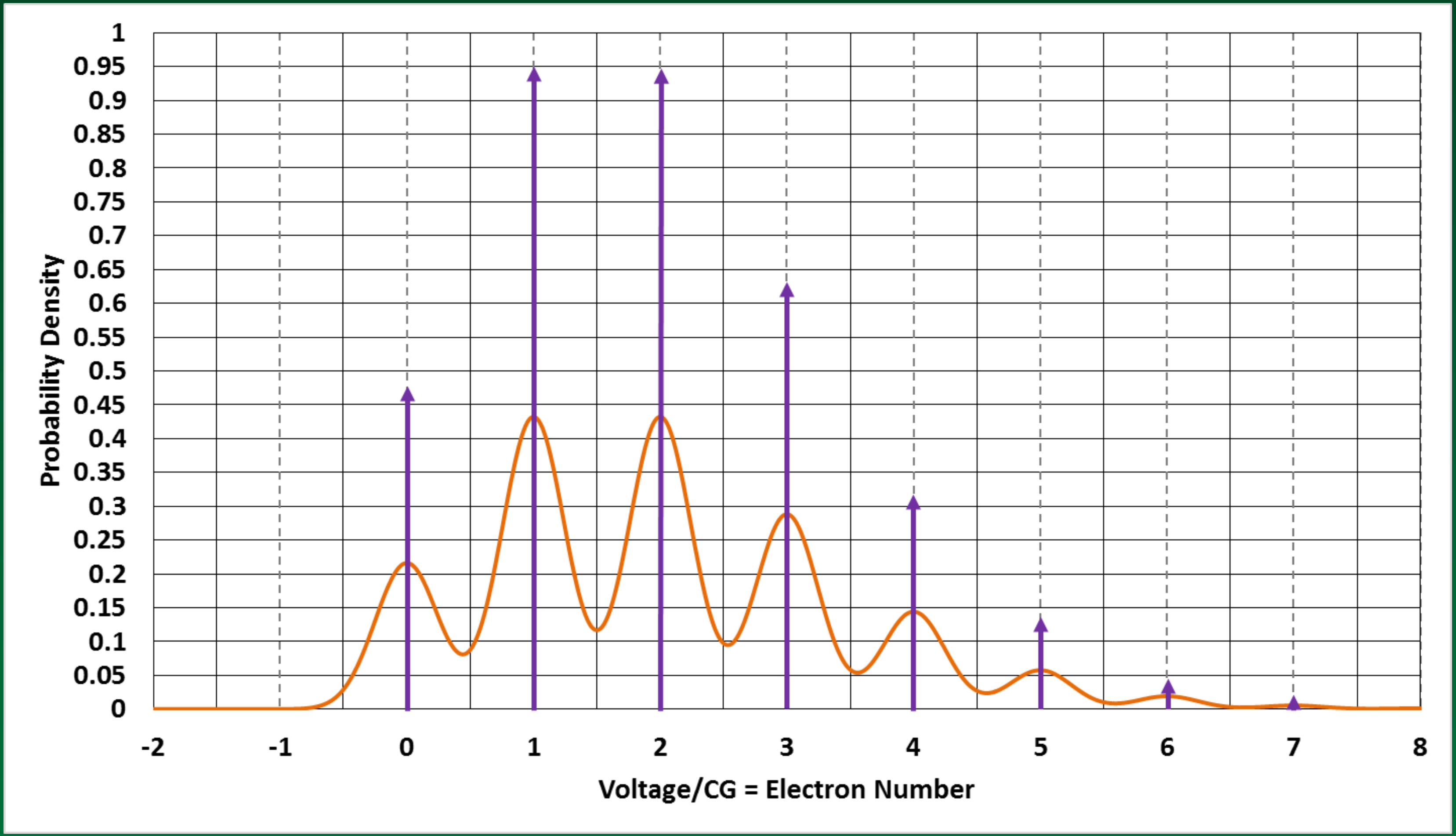
$$P[k] = \frac{e^{-H} H^k}{k!}, k = 0, 1, 2, 3 \dots$$

Broadened by 0.12e- rms read noise



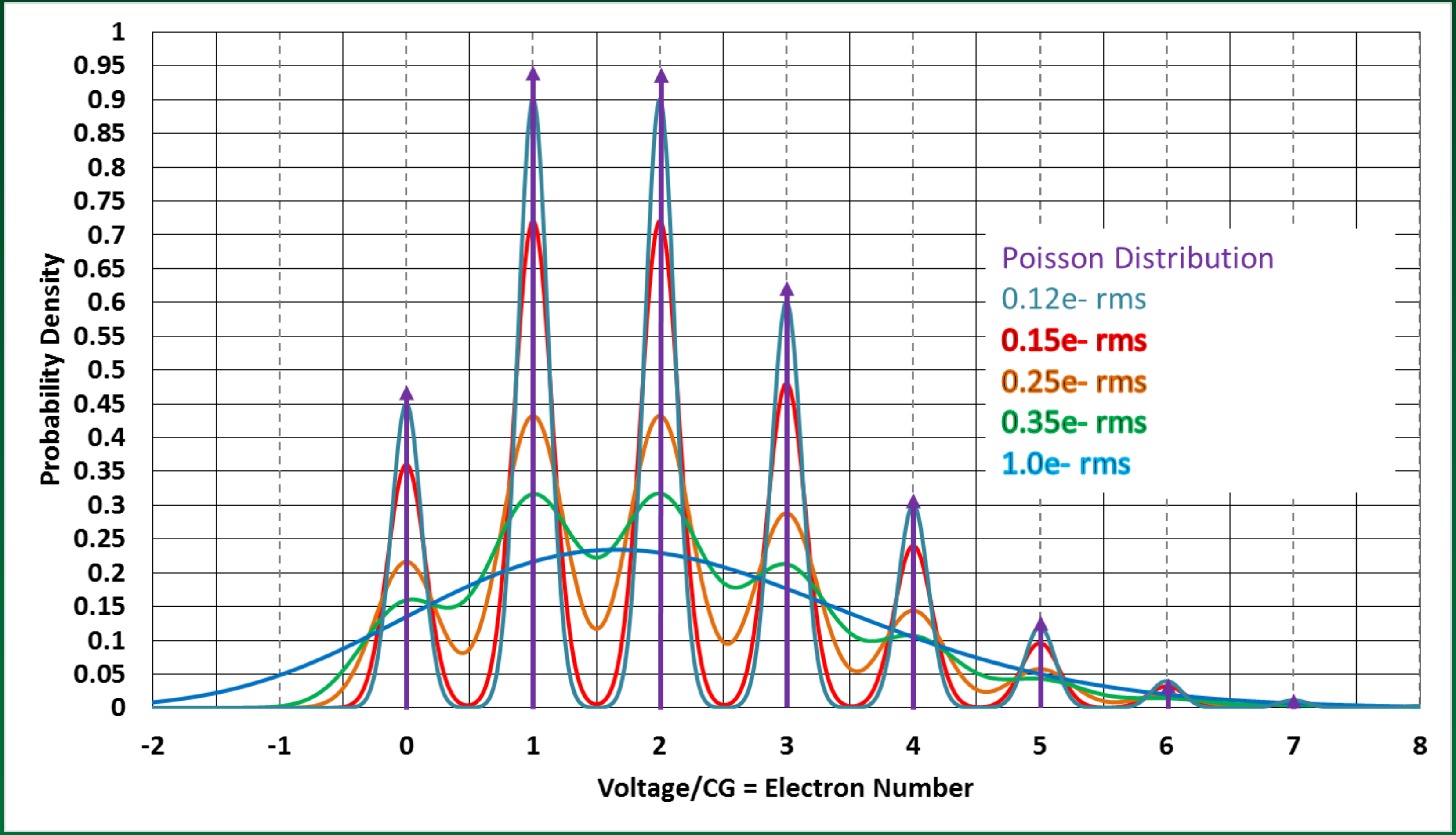
Model

Broadened by 0.25e- rms read noise



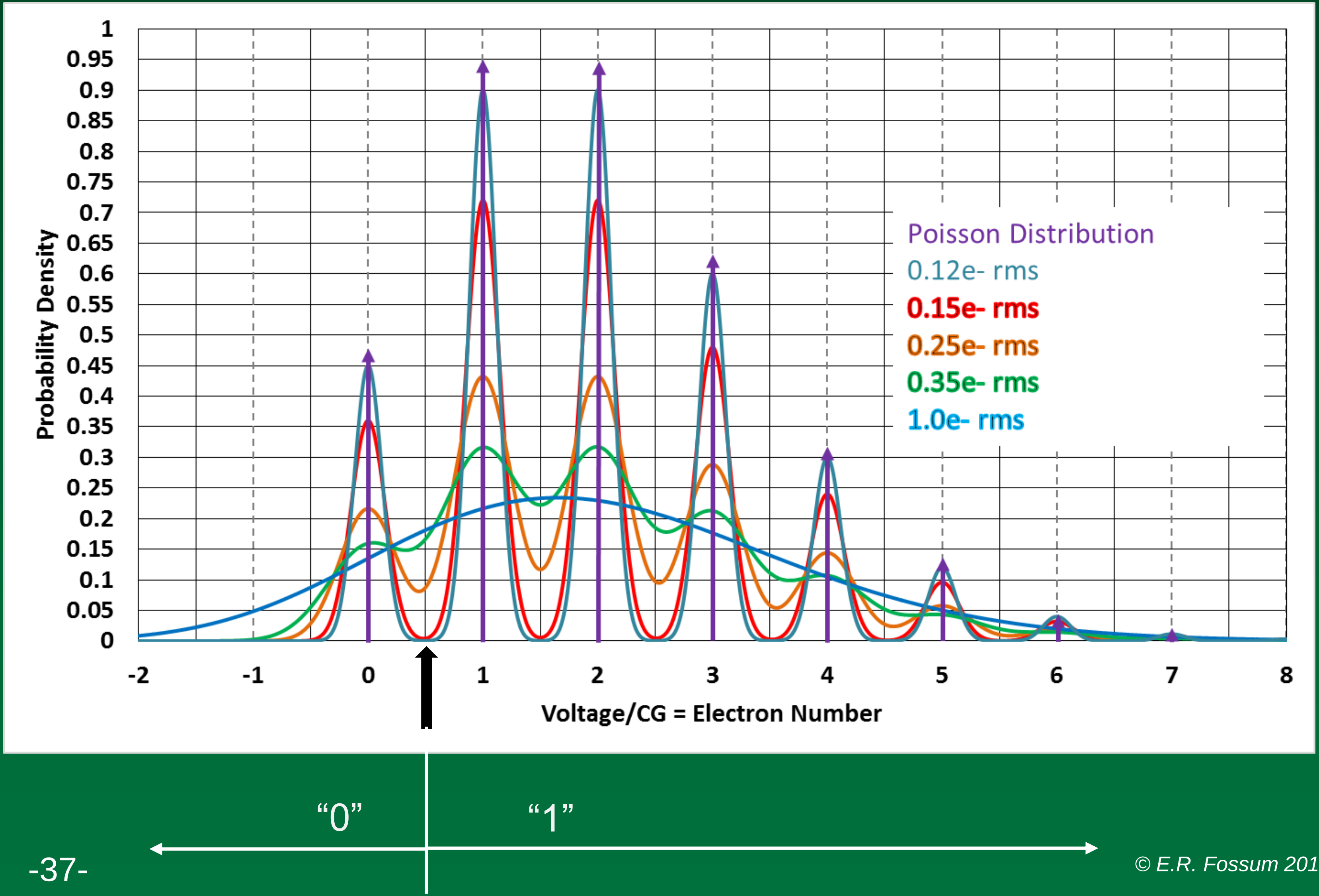
Model

Probability Distribution for Various Levels of Read Noise

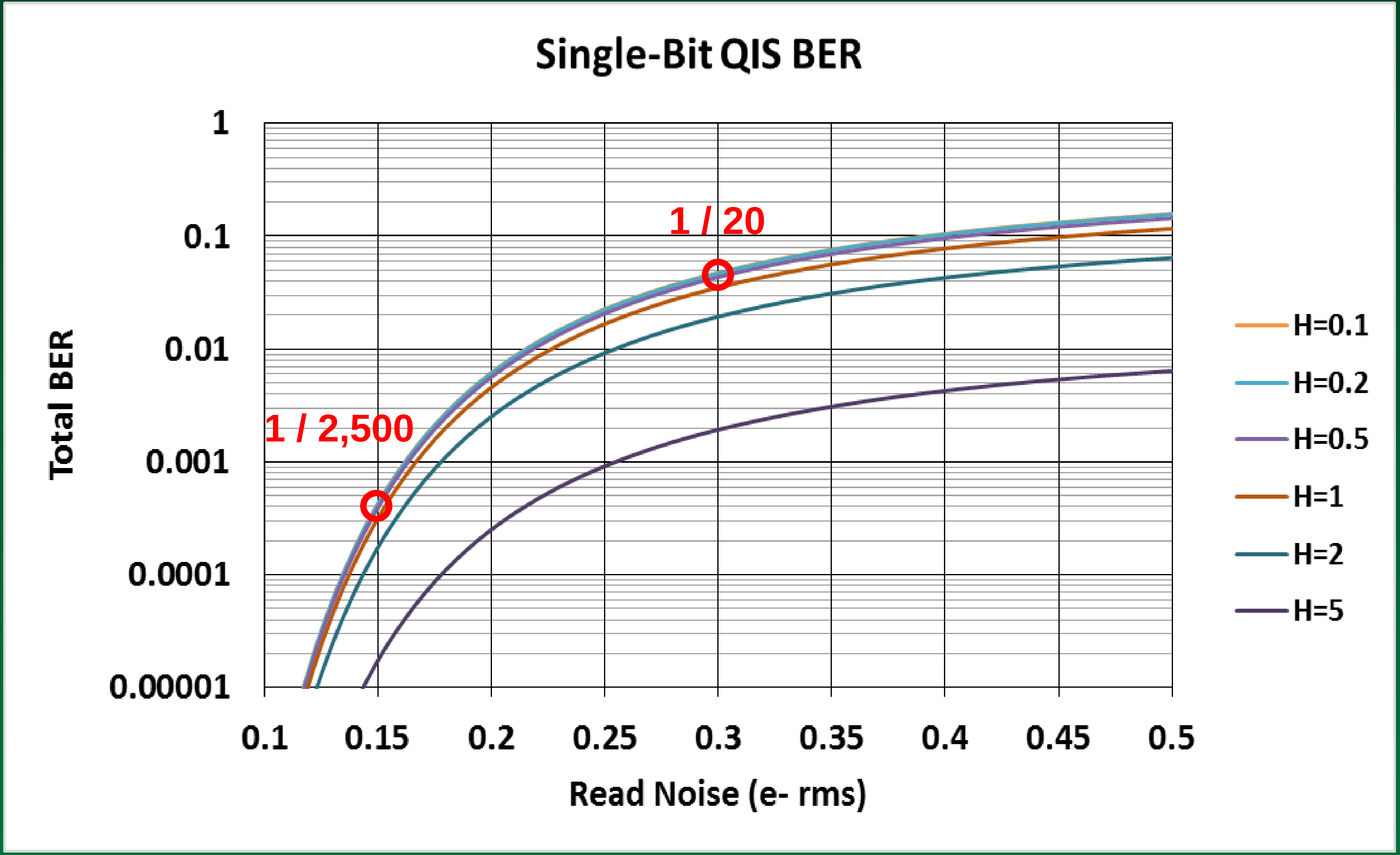


Model

Single-bit QIS

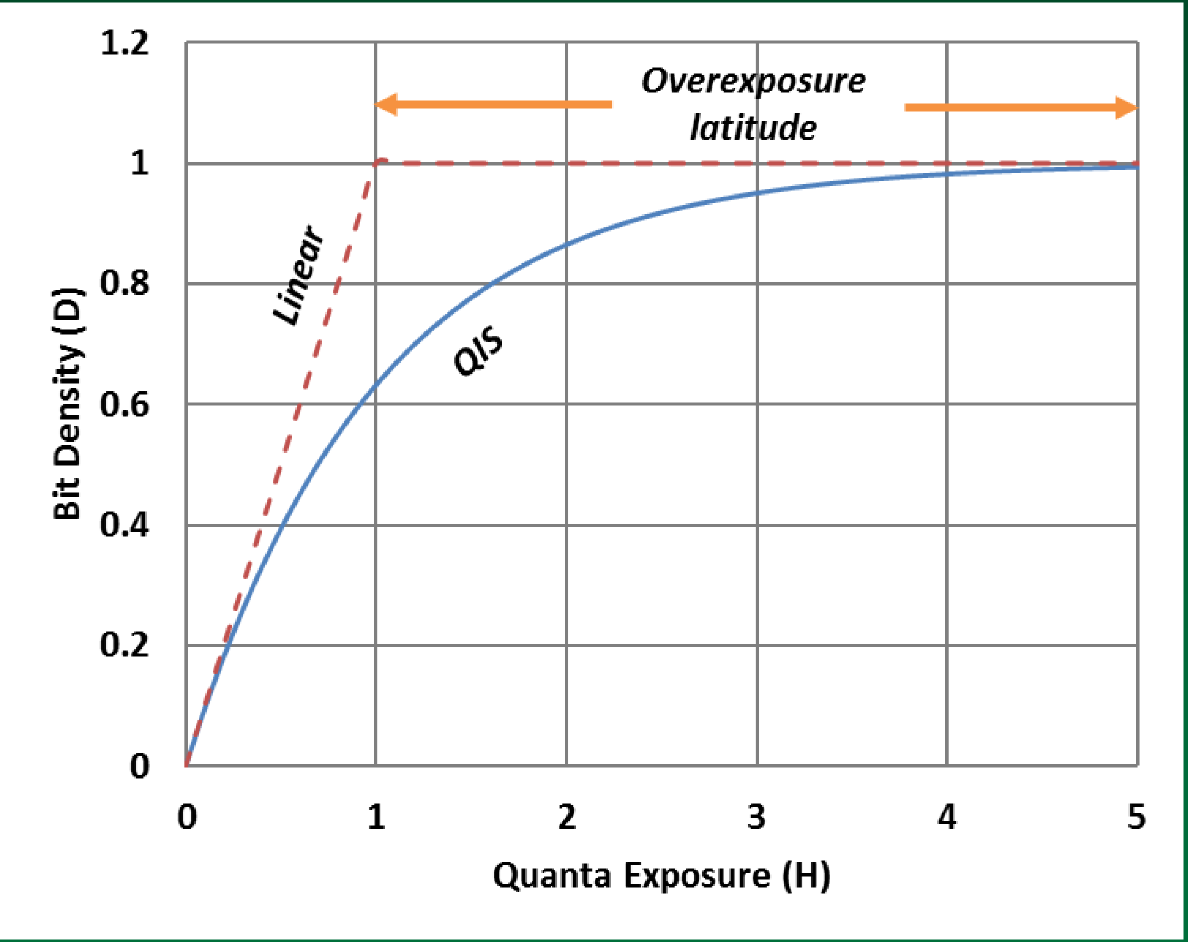


Bit Error Rate (BER) vs. Read Noise



Photoresponse in Bit Density

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



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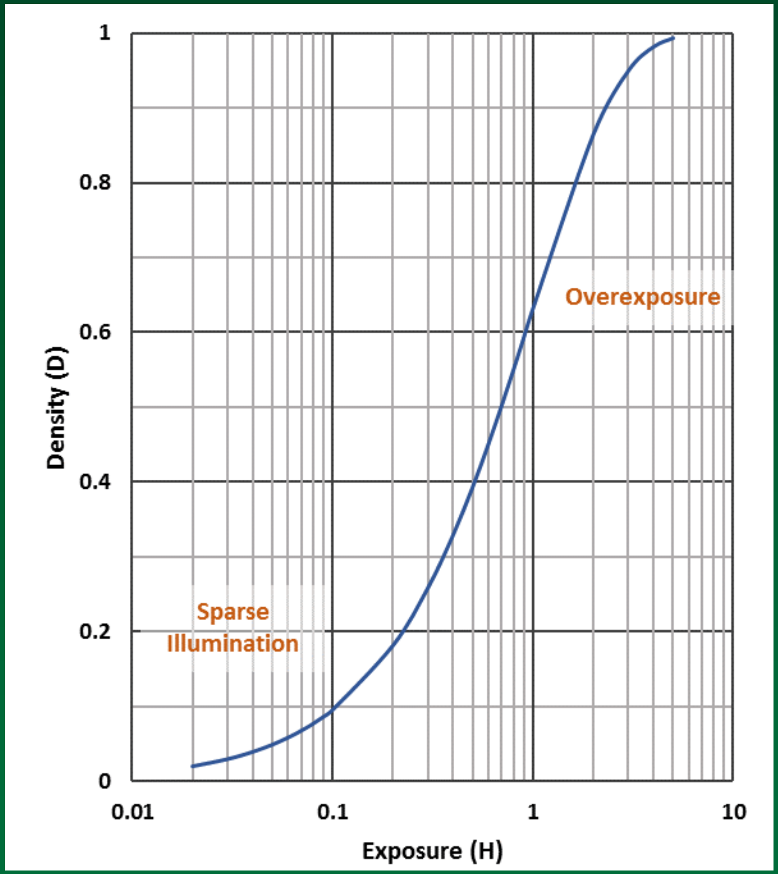
Responds to Light Like Film

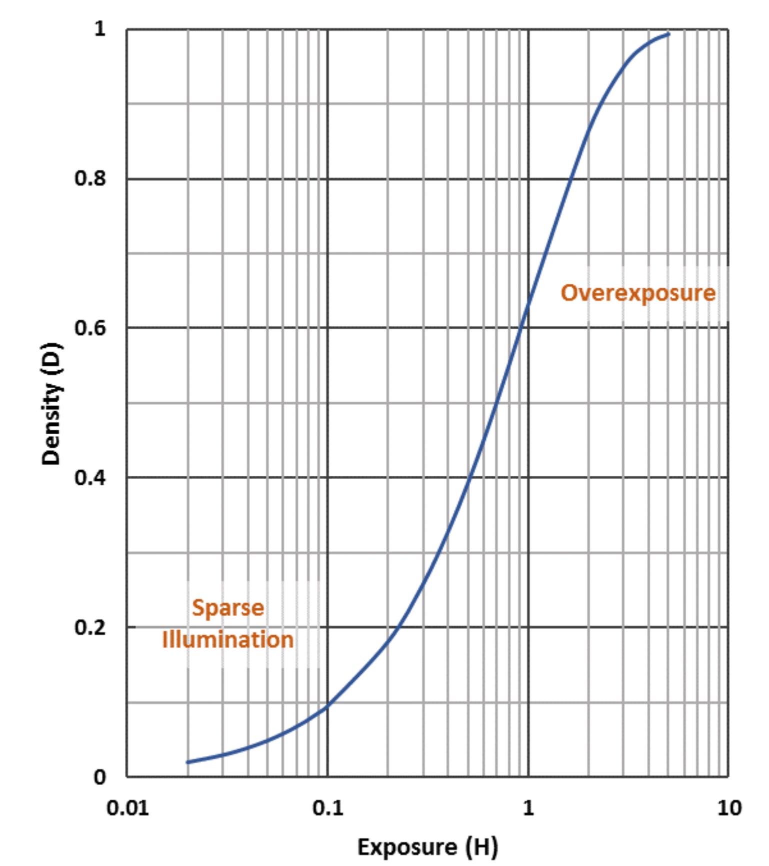
QIS D – log H



Bit Density vs. Exposure

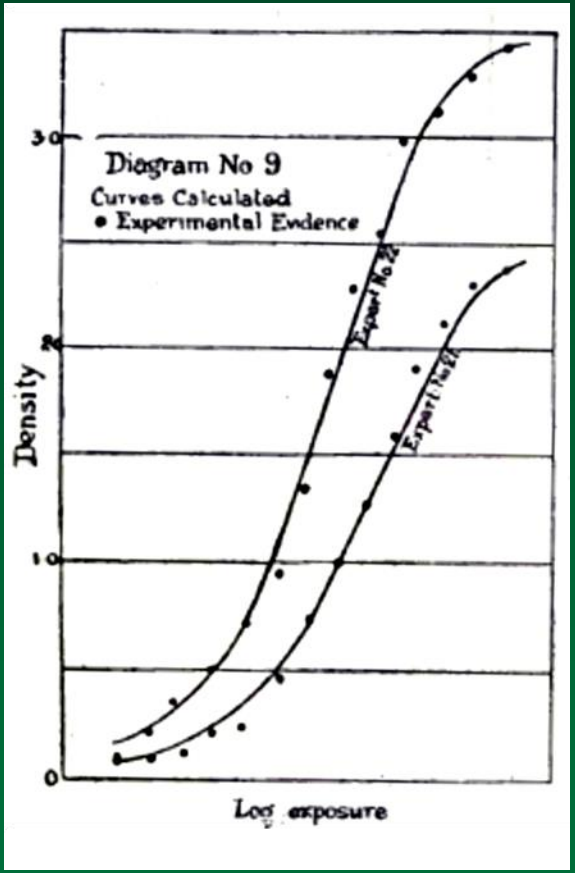
Responds to Light Like Film

QIS D – log H



Bit Density vs. Exposure

Film D – log H

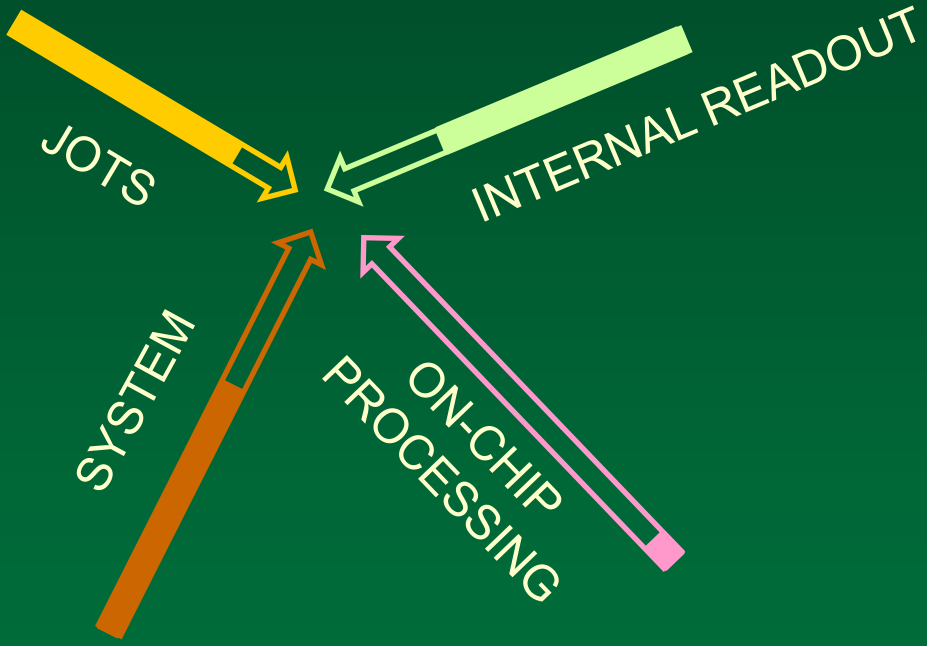


Film Density vs. Exposure
1890 Hurter and Driffield

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)



Group at Dartmouth

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

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Jot Device Considerations

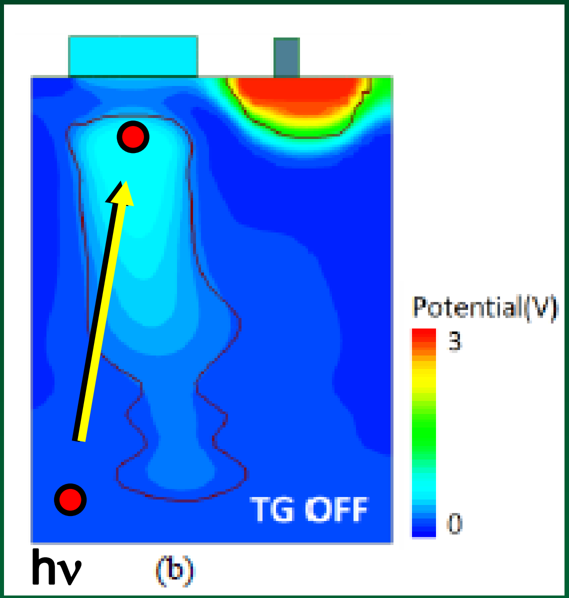
General targets:

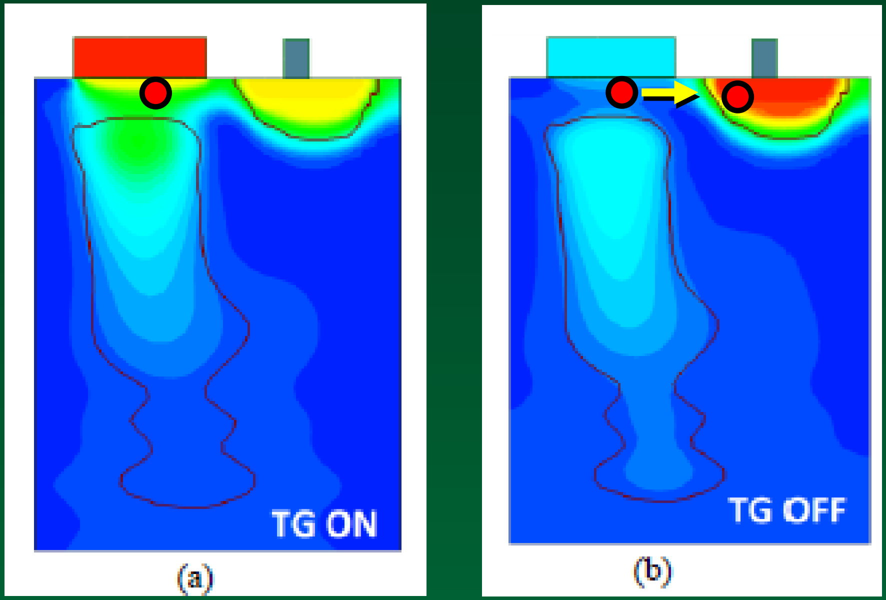
- 200 nm device in 22 nm process node ("10L")
- 0.15e- rms read noise or less
- High conversion gain > 1 mV/e- (per photoelectron)
- Low active pixel transistor noise <150 uV rms
- Small storage well capacity ~1-100 e-
- Complete reset for low noise
- Low dark current ~ 1 e-/s
- Not too difficult to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

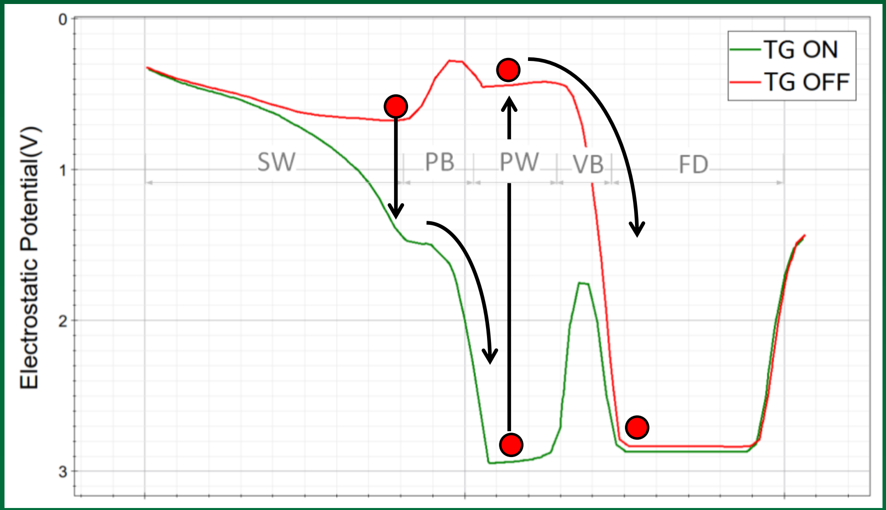
Candidate devices

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

Pump-Gate Jot with Distal FD







- 1st gen fabricated in TSMC 65nm BSI CIS with implant adjustments, 1.4um pitch, 32x32 jot arrays
- 2nd gen fabricated TSMC 45/65nm stacked BSI CIS, 1.1um pitch, shared readout 1024x1024 jot arrays

Ma and Fossum
2014 IEDM, 2015 JEDS, 2015 EDL

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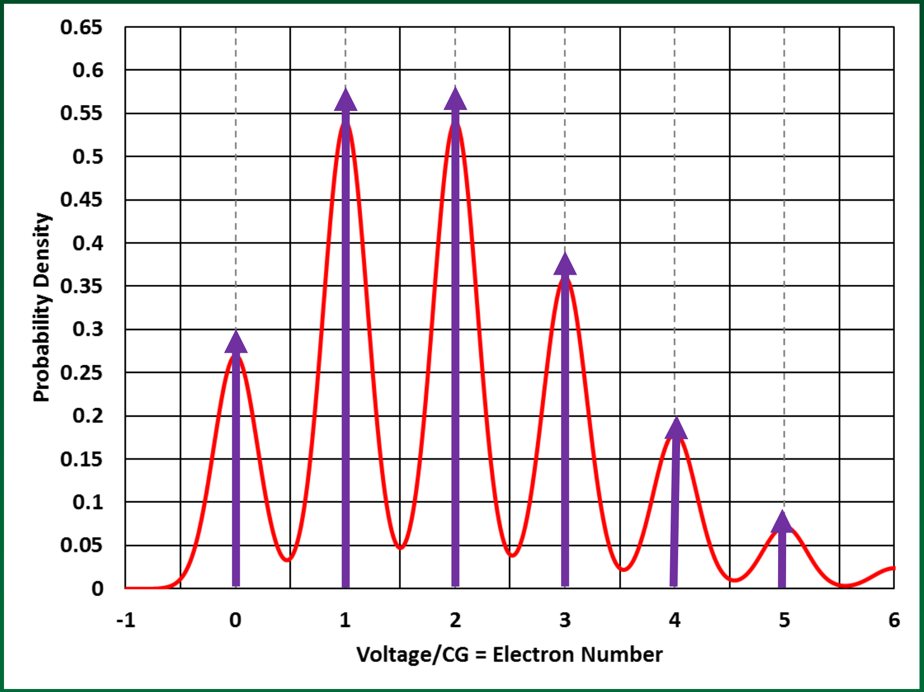
Recall our Poisson Probability Mass Function Broadened by Read Noise



Model
0.20e- rms read noise, H=2.0

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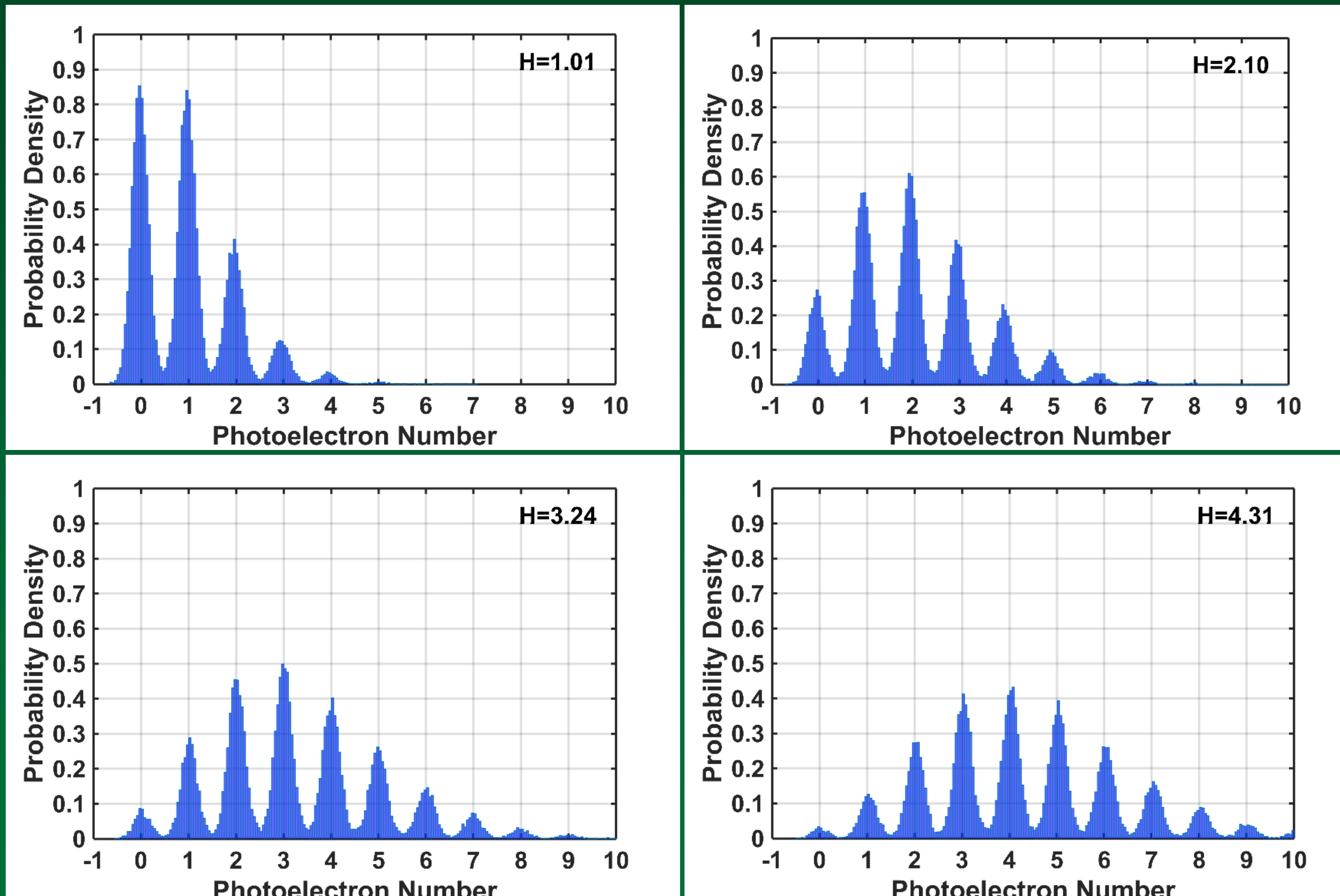
Experimental Data Photon Counting Histograms

20k reads of same jot, 0.175e- rms read noise ~21DN/e- (61.2uV rms 350uV/e- or 0.45fF)
Room temperature, no avalanche, 20 CMS cycles, jot:TPG PTR BC



Ma, Masoodian, Wang, Fossum 2017

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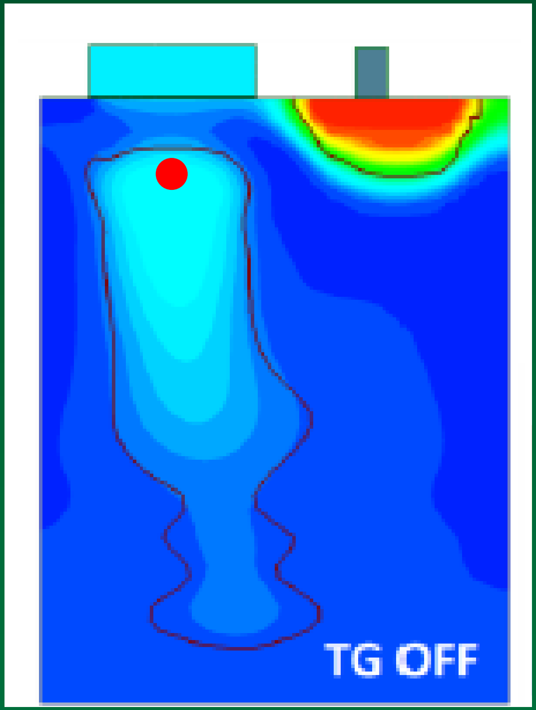
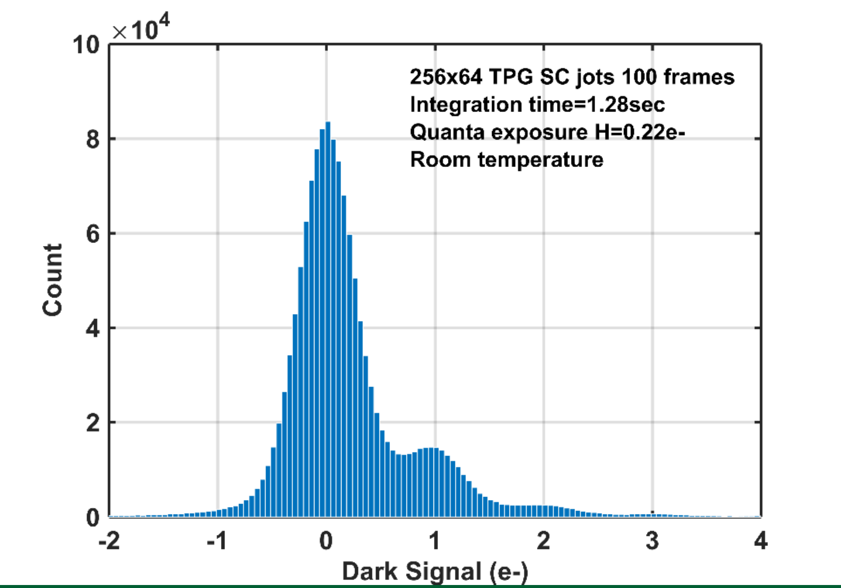
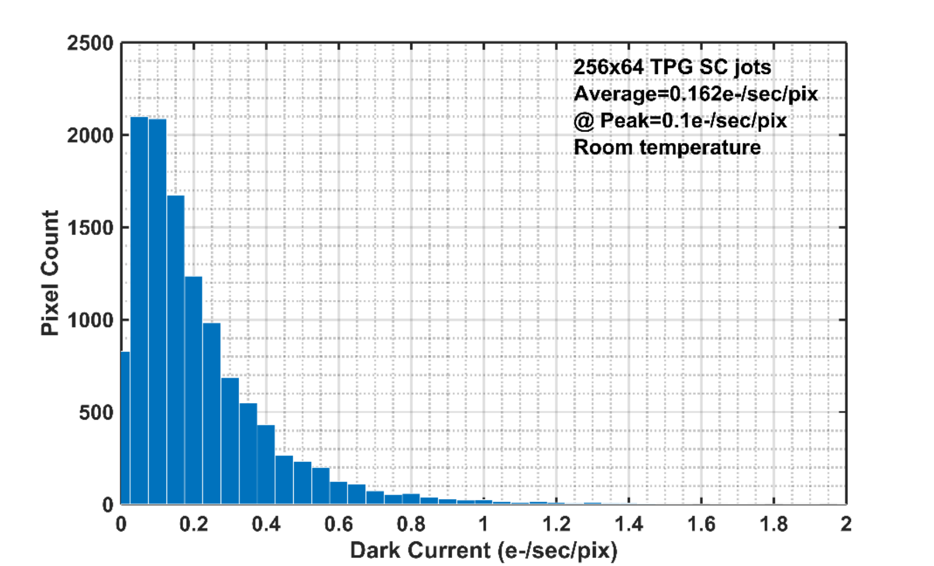
Dark Current

Room Temp: ~0.16e-/s avg. (~2pA/cm^2)
Previously measured ~2x every 10C

Storage well isolated from surface







Ma, Masoodian, Wang, Fossum 2017

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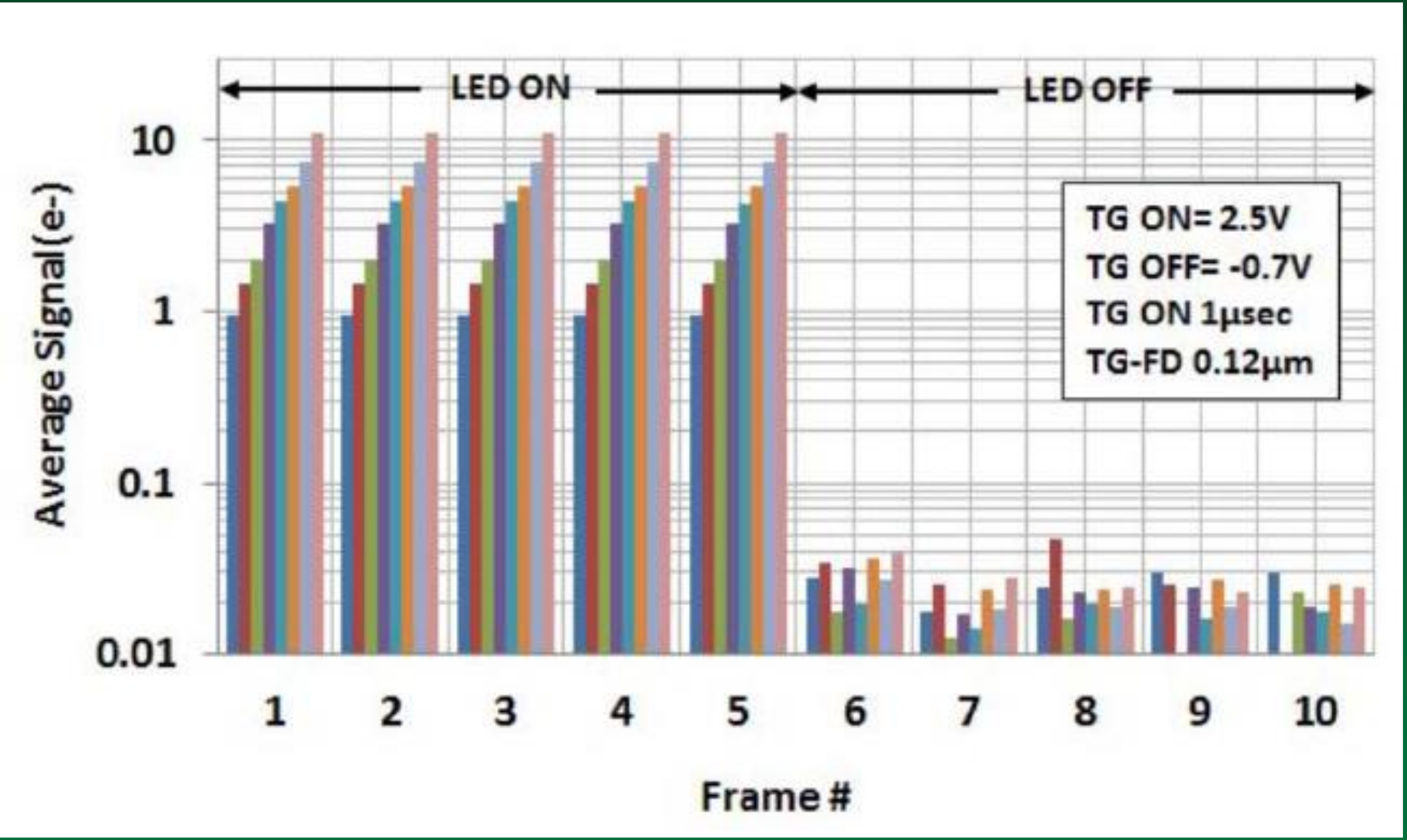
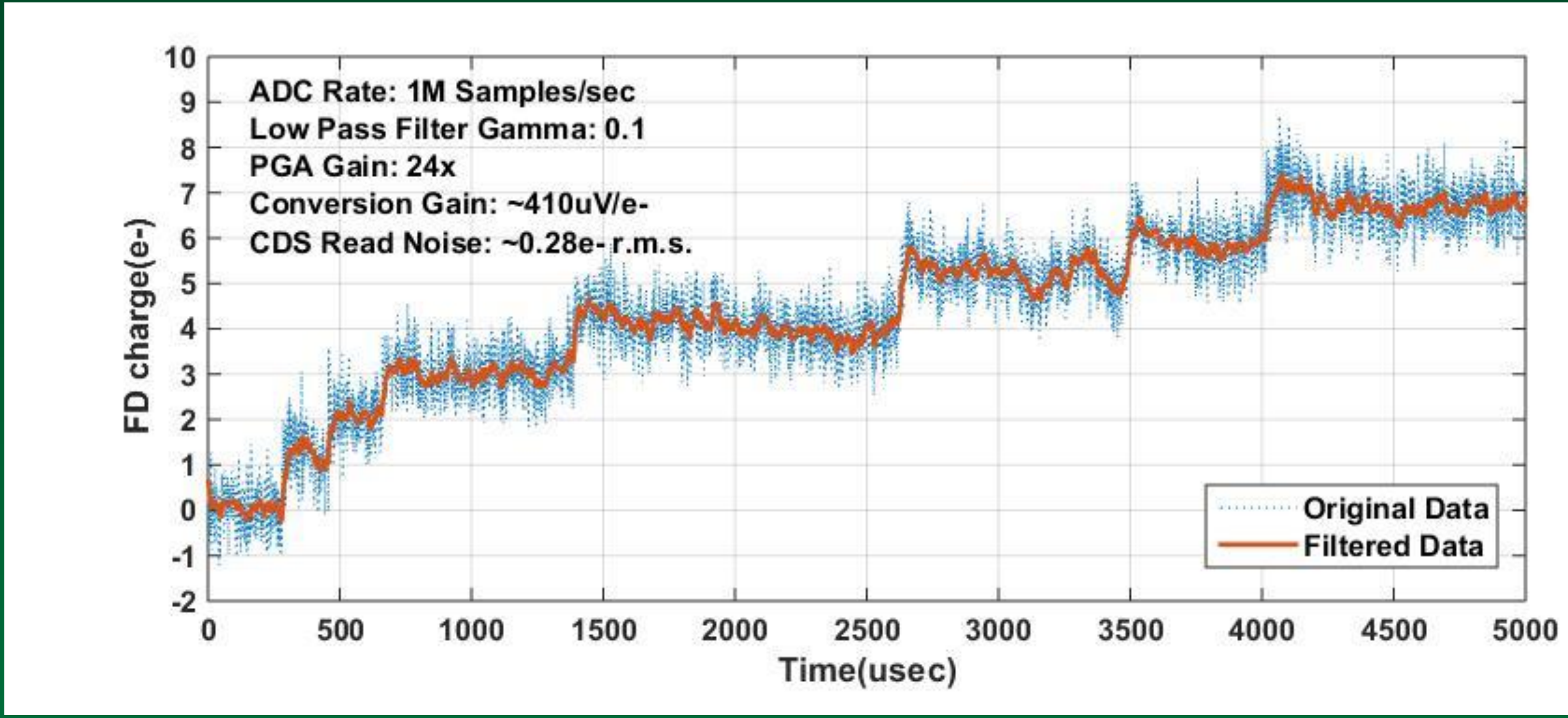
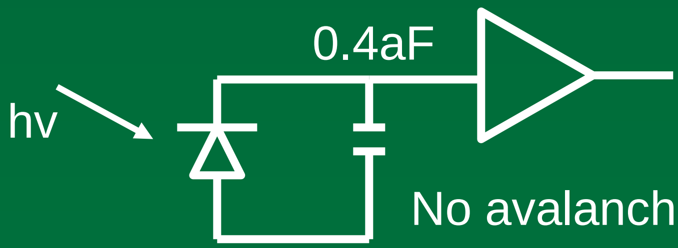
Lag



Ma, Anzagira and Fossum IEEE JEDS 4(2) 2016

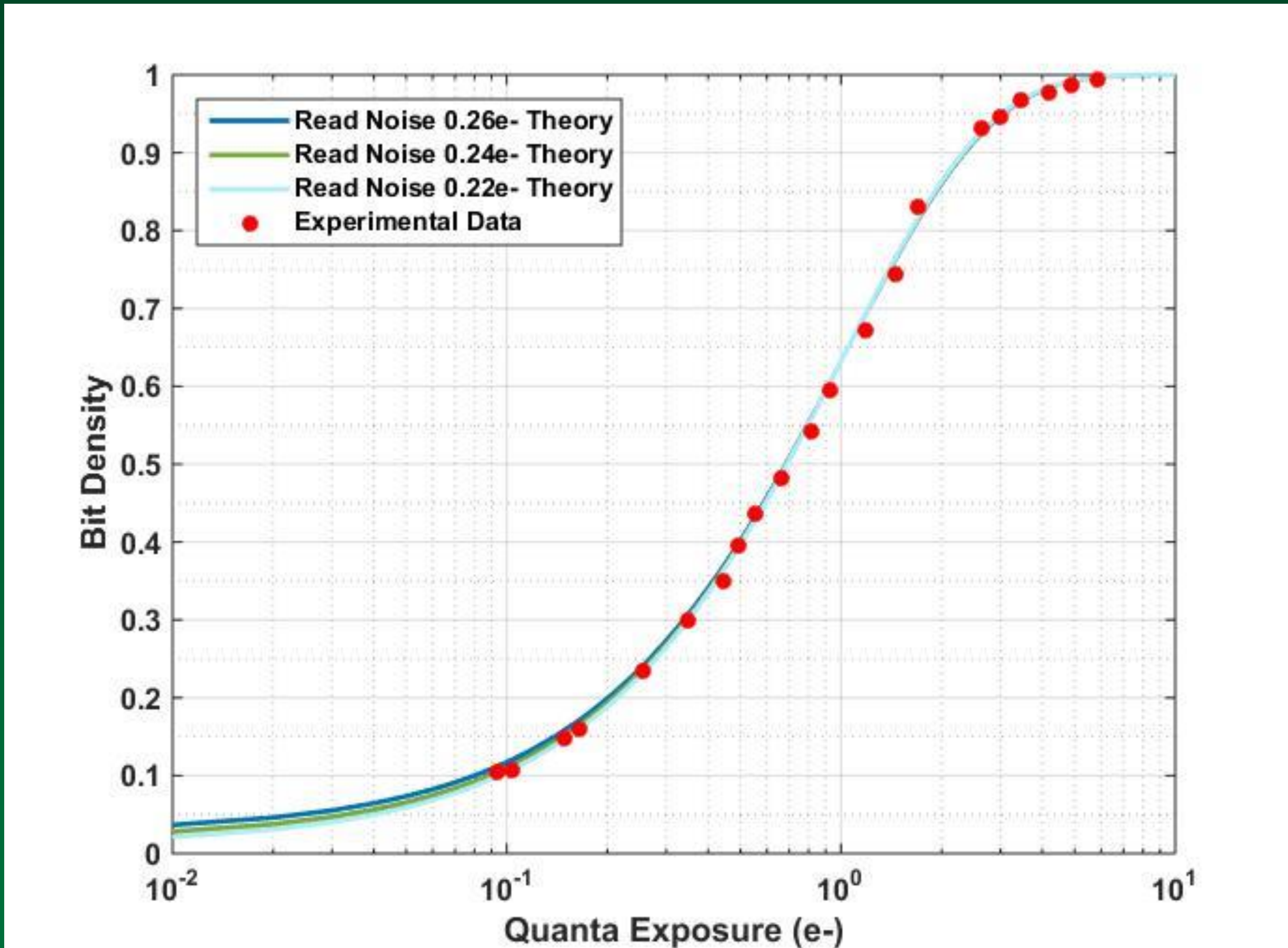
RTS and Single Electron Integration Steps



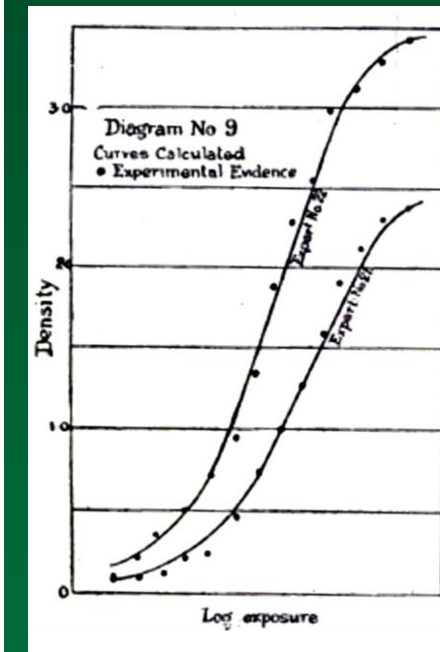


No avalanche multiplication

Bit Density v. Log Exposure (D log H)

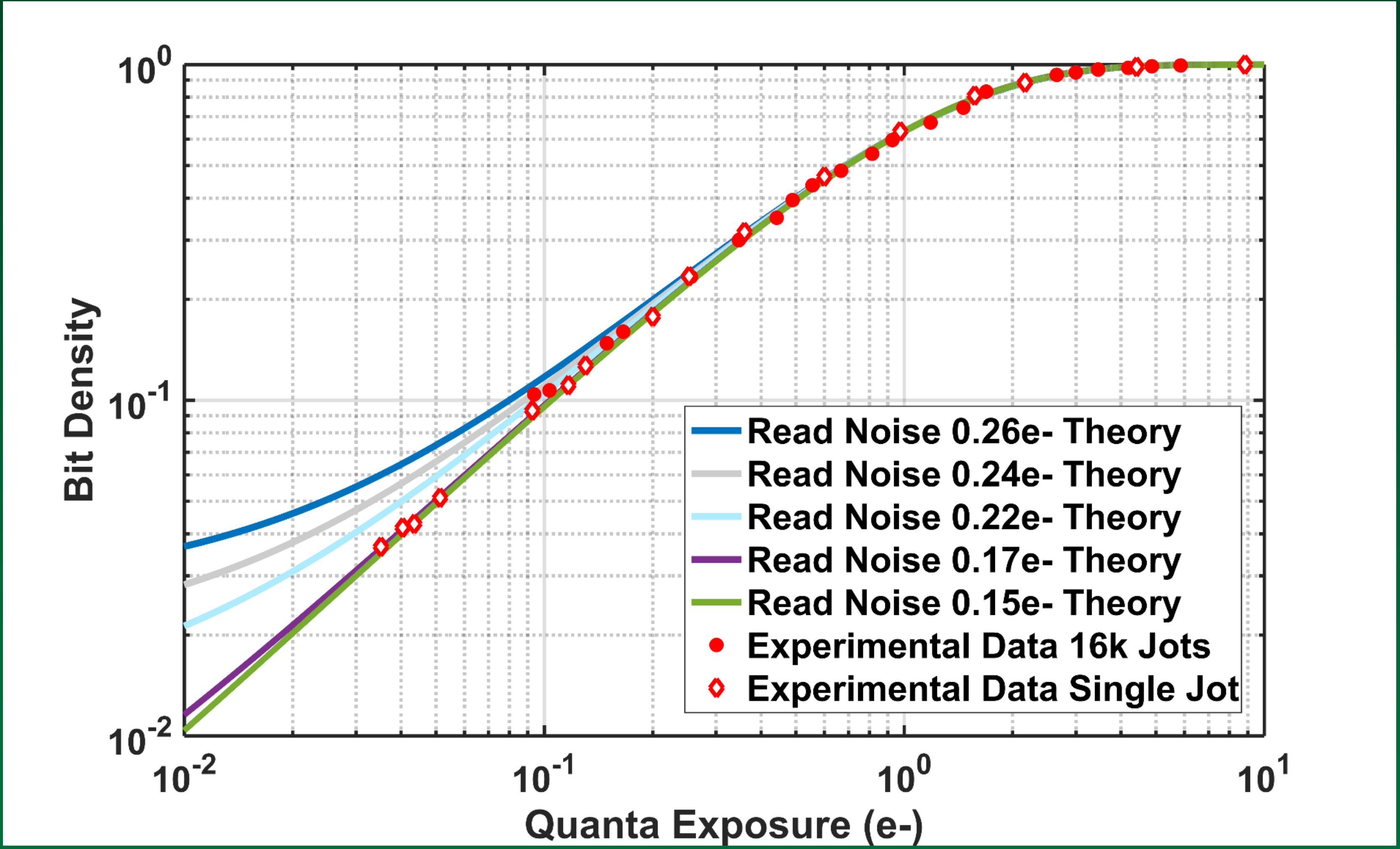


QIS Experimental Data
2017 J. Ma et al., unpublished

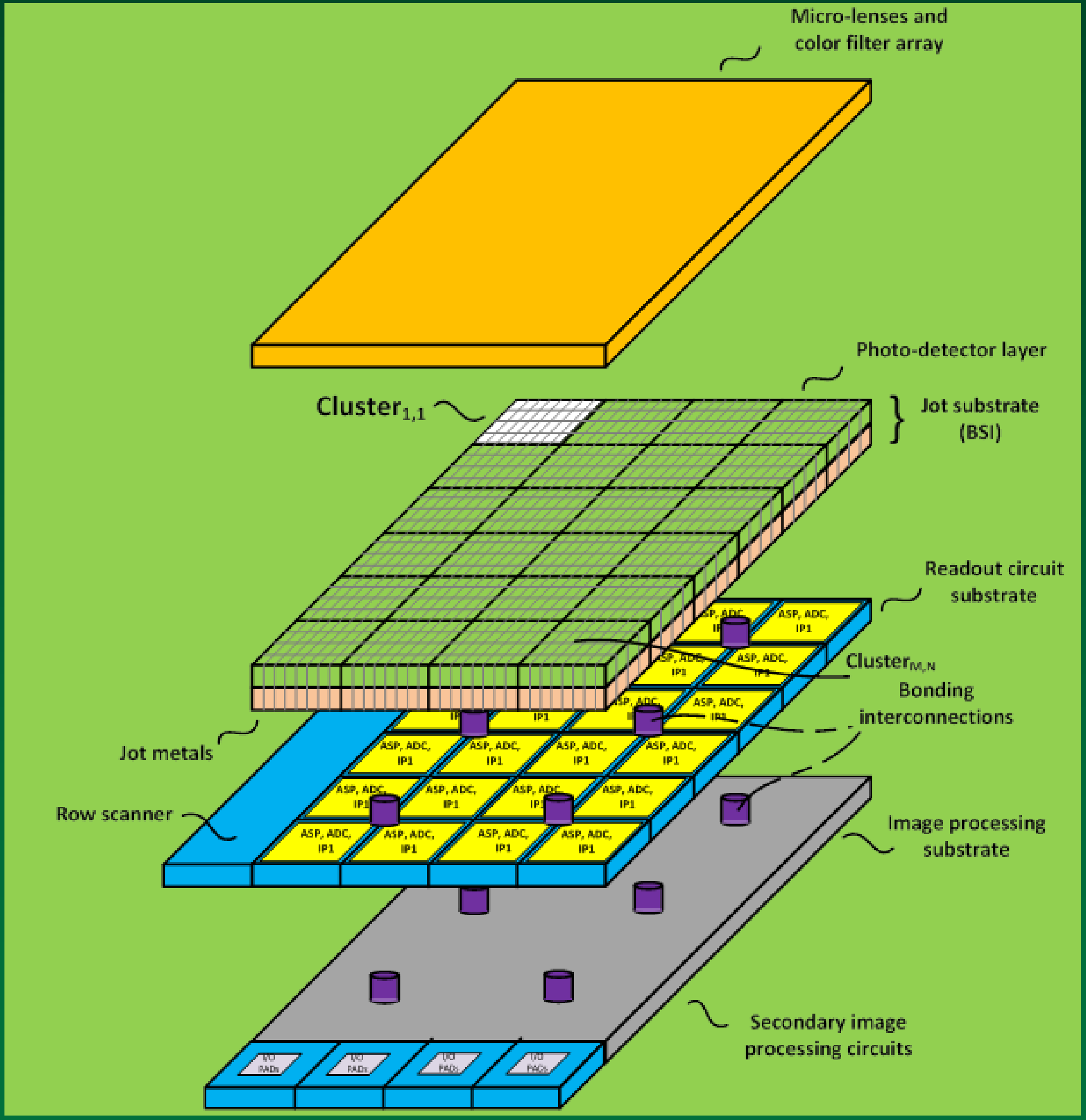


Film Density vs. Exposure
1890 Hurter and Driffield

Read Noise and Photon-Counting Error



Stacked QIS with Cluster-Parallel Readout



>10x reduction in power due to lower capacitance and slower operation

Fossum and Masoodian 2015

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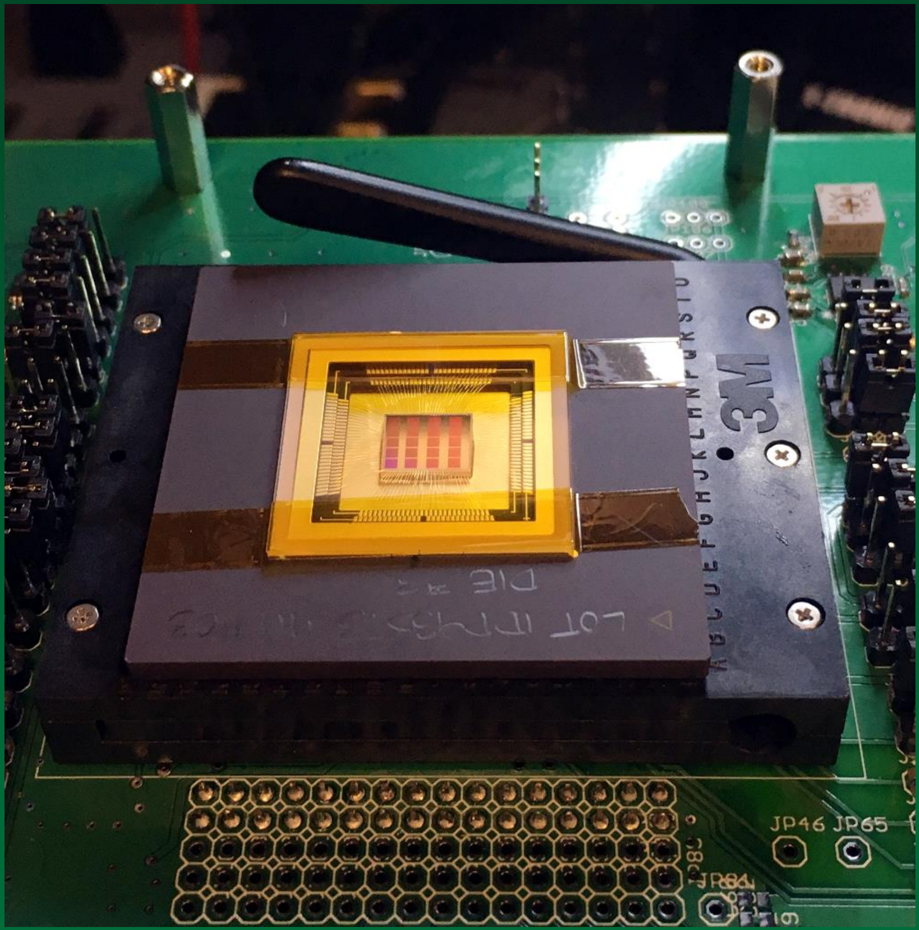
Stacked BSI QIS in Test

Designed and tested at Dartmouth
Implemented in TSMC foundry

- 65nm readout chip
- 45nm detector layer
- 1.1um jot pitch
- CFA and microlenses
- 20 1Mjot arrays
- 1024x1024 jots/array
- Analog output arrays with on-chip PGA
    - 8x8x(128x128jot) analog clusters
- 1b QIS output arrays
    - 16x16x(64x64jot) digital clusters
- MOSFET-type readout
- JFET-type readout
- Punchthru reset readout

Jot device design: Jiaju Ma
Readout design: Saleh Masoodian & Dakota Starkey



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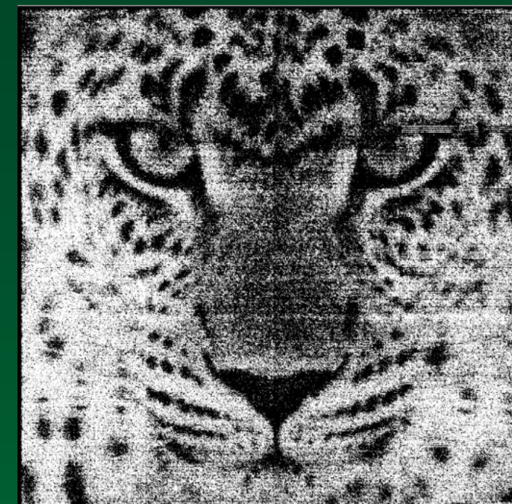
First 1Mjot QIS

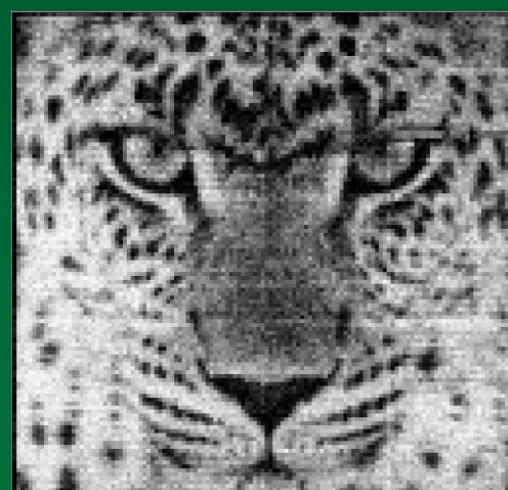
Specs & Measured Data

Process		45nm (jot layer), 65nm (ASIC layer)
VDD		1.8V & 2.5V (Analog, digital and array), 3V & 2.2V (I/O pads)
Jot type		BSI Tapered Pump Gate/2-Way Shared RO
Jot pitch		1.1µm
BSI Fill Factor		~100%
Quantum Efficiency		To be measured, visible band
CG on column		345µV/e-
Input Referred Noise		0.22e- r.m.s.
Corresponding BER		~1%
Avg. Dark current		0.16e-/s
Equiv. Dark Count Rate		0.16Hz/jot
Equiv. PD Dead Time		<0.1%
Array		1024 (H) x 1024 (V)
Field rate		1040fps
ADC sampling rate		4MSa/s
ADC resolution		1 bit
Output data rate		32 (output pins) x 34Mb/s = 1090Mb/s
Package		PGA with 224 pins
Power	Array	2.3mW
	256 ADCs	7.5mW
	Addressing	4.1mW
	I/O pads	3.7mW
	Total	17.6mW
FOM ADC		6.9pJ/b

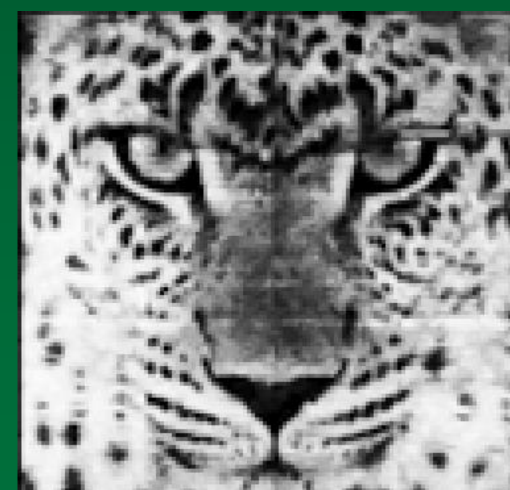
Target scene

1Mjot binary field @1040fps





8x8x8 cubicle sum



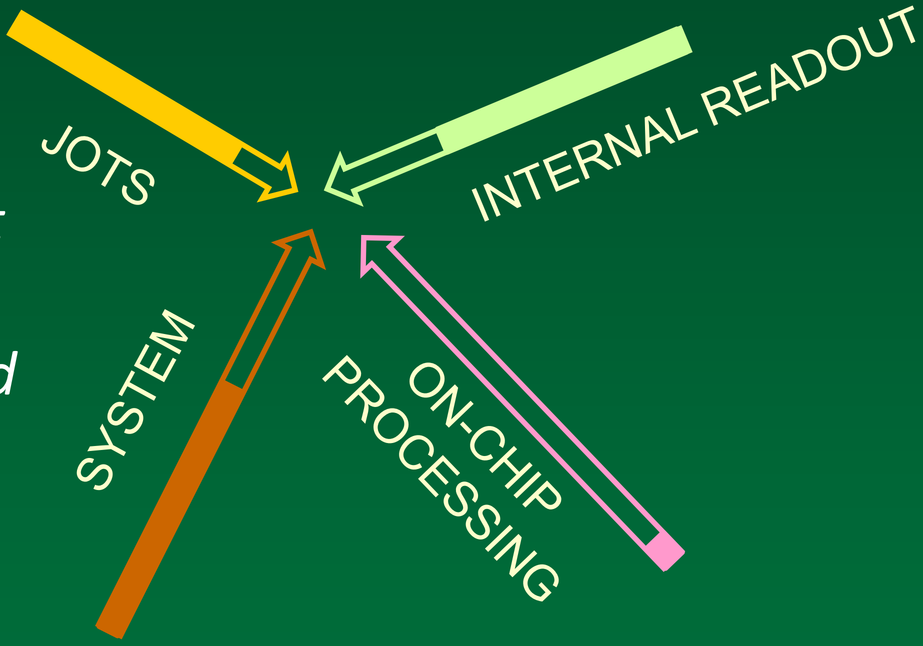
Purdue* reconstruction

Masoodian, Starkey, Yamashita, Fossum 2017

*courtesy of Prof. Stanley Chan

QIS implementation requires Devices, Circuits, and System

Vision: A billion jots readout at 1000 fps with single photon counting capability (1Tb/s) and consuming less than a watt.



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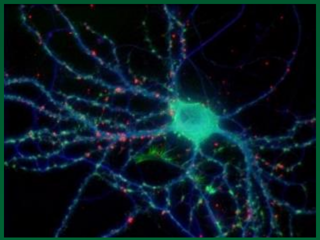
Quanta Image Sensor: Applications for Photon Counting

- Cinematography and Photography
  - Gigajot sensors – billions and billions of pixels
  - Computational imaging
- Scientific sensors for ultra-low light imaging
  - Astronomical searches for another Earth
  - Neuroscience microscopy
  - Biological processes for understanding diseases
- National defense applications
  - Better situational awareness for our soldiers
  - Better eyes in the sky
- Quantum random number generator
- *"You don't find killer apps, they find you"*


2001: A Space Odyssey


Natalie Dowell-Mesfin


NASA Earth Observatory

January 2017 Dartmouth Spinoff

gigajot

Where every photon counts®

Dr. Saleh Masoodian

Dr. Jiaju Ma*

Dr. Eric R. Fossum

- **Gigajot Technology LLC** was founded to commercialize QIS technology
- Gigajot will focus on niche sensor applications such as photon-counting, scientific imaging, space, automotive, and others

*after completing PhD summer 2017