# Gigapixel Imaging

## An Overview of the Technology and Related Technical Challenges



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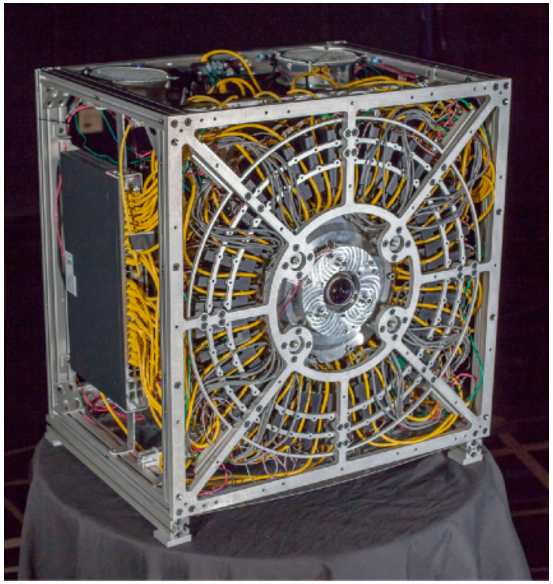
# Contents

# Motivation

- more details in image achieved through spatial resolution

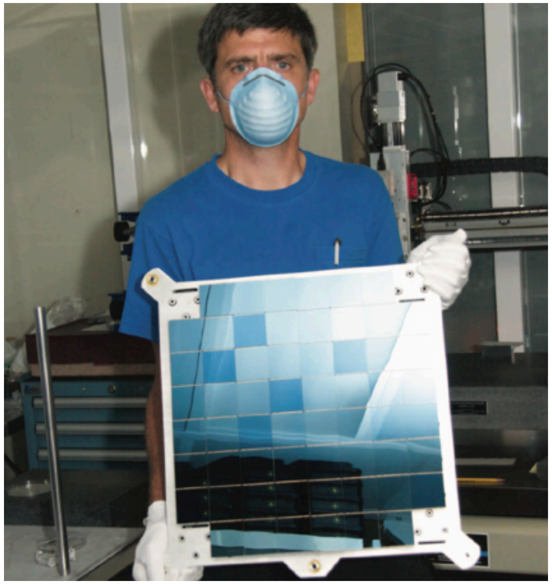
- large importance for scientific and industrial applications
  - preservation
  - entertainment (VR/AR)
  - surveillance
  - scientific research
  - astronomy
  - medical examinations
  - …

# Super-resolution on an industrial level…



**AWARE-2**

1Gpix



**PAN-STARRS 1**

Duke Information Spaces Project. AWARE2 Multiscale Gigapixel Camera. https://disp.duke.edu/research/aware2-multiscale-gigapixel- camera

**Super-resolution scanners**

Moshe Ben-Ezra. 2011. A Digital Gigapixel Large-Format Tile-Scan Camera. IEEE Computer Graphics and Applications 31, 01 (jan 2011), 49–61.

# … and on a budget*

*broadly defined

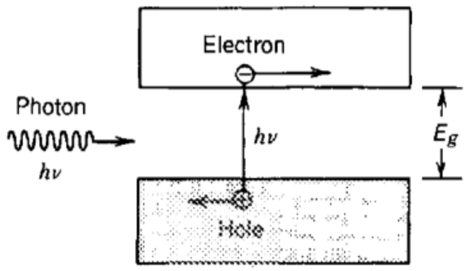


| Hasselblad H6D-400C Multi-Shot | Phase One XF IQ4 150MP Camera System | Pentax 645Z |
|---|---|---|
| 400Mpix<br>53.4 x 40mm CMOS | 151Mpix<br>53.4 x 40mm MF sensor | 51.4Mpix<br>44 x 33 mm CMOS |
| 47.598,81 € | 47.588,10 € | 3.989,58 € |

https://www.digitalcameraworld.com/buying-guides/the-10-highest-resolution-cameras-you-can-buy-today

# Inner photoelectric effect

Bahaa E. A. Saleh and Malvin Carl Teich. 1991. Fundamentals of Photonics. Wiley, New York.

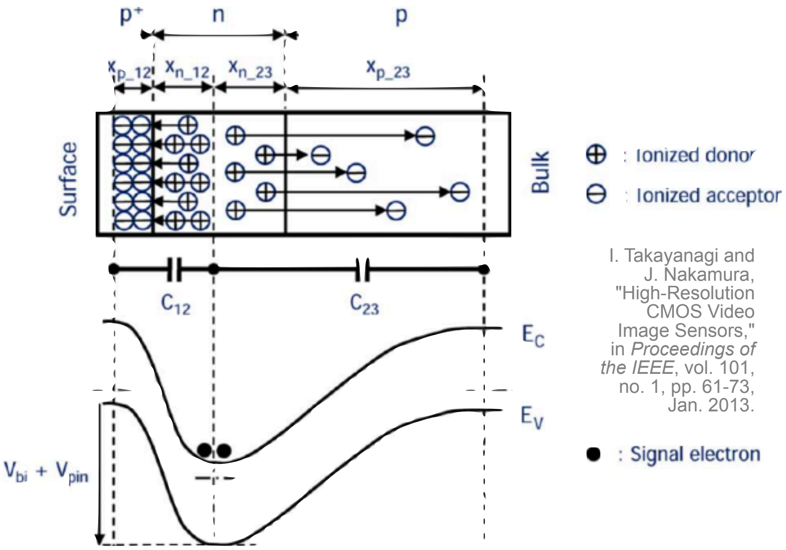



- exploitation of electrical and optical properties in semiconductor materials
- absorbed incident photons generate electron-hole pairs
  - generated charge is accumulated in the potential well
  - achieved by adding impurities to the semiconductor (=**doping**)
- transport through applied external voltage
  - electric current in the external circuitry

= charge-to-voltage-conversion

Energy of a single photon:

$$W = h \cdot v$$

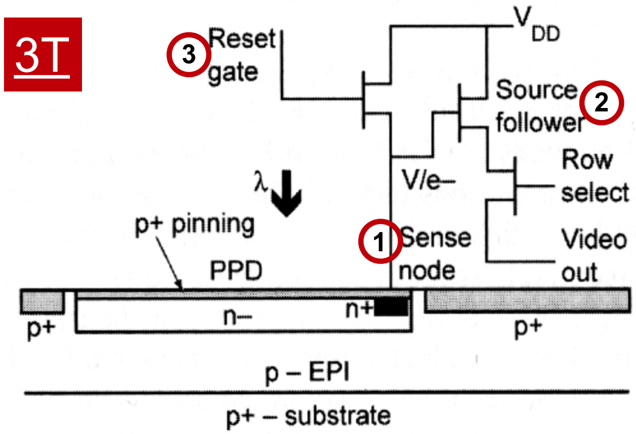



I. Takayanagi and J. Nakamura, "High-Resolution CMOS Video Image Sensors," in *Proceedings of the IEEE*, vol. 101, no. 1, pp. 61-73, Jan. 2013.

# Inner photoelectric effect

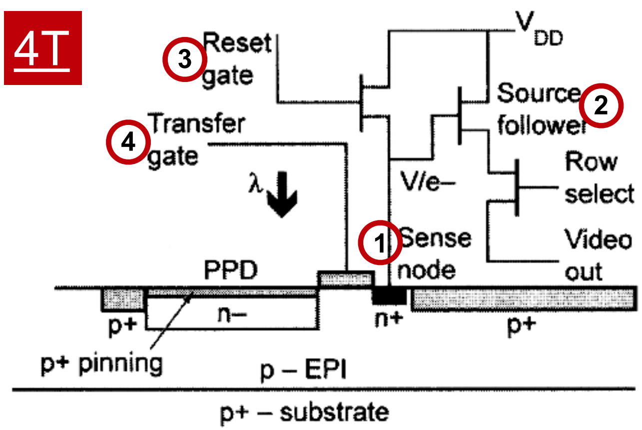
- converted charge is compared against the capacitances of the nodes
- after the readout, the pixel is reset
- at least 3 transistors required:
    - charge sense node (floating diffusion)
    - source-follower (readout)
    - reset node
- additional structures to ensure better conversion gain

3T




Gerald C. Holst and Terrence S. Lomheim. 2011. CMOS/CCD Sensors and Camera Systems -. JCD Publishing, Winter Park, FL.

4T



# State-of-the-art sensors

- current generation of **<u>C</u>onventional <u>I</u>mage <u>S</u>ensors** (CIS): **Complementary <u>m</u>etal-<u>o</u>xide-<u>S</u>emiconductor** (CMOS)
- developed by Eric Fossum in 1993 as successor to CCD

- higher conductivity through silicide metals
- charge-to-voltage conversion occurs inside each pixel
- lower power consumption
- higher-level operations implemented on-chip
  - control through flexible choices of architecture
  - noise suppression
  - parallel readout
  - random access of data
  - …

# Recent trends

- Moore's law: the number of transistors on microchips doubles every two years

  ~ steady (bi-)annual reduction of feature sizes

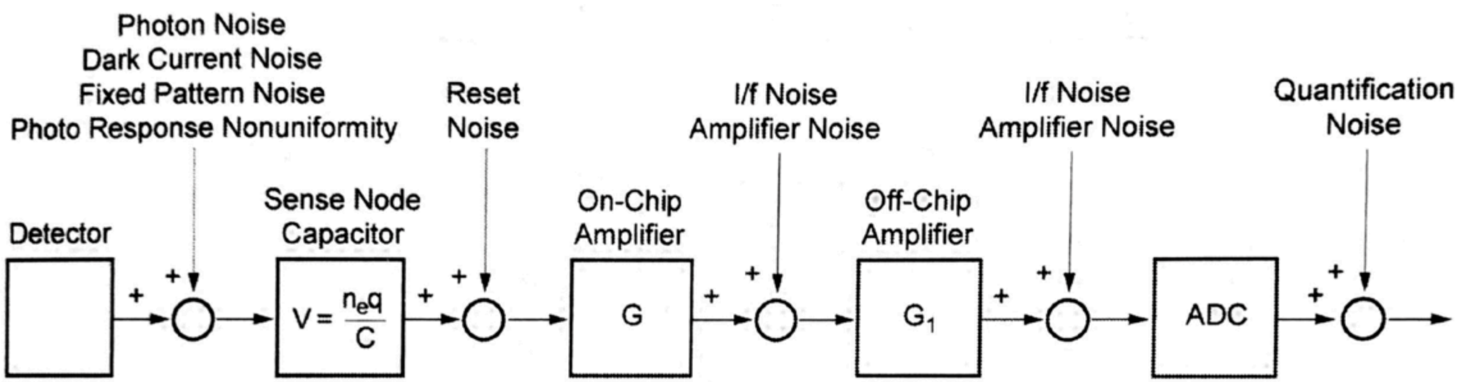
  - adoption of new technologies (SoC)
- advancements in semiconductor technologies allow for manufacturing of smaller circuits
  - lowered production costs
  - smaller optics
  - better integration into consumer products
  - E. Fossum: "camera in every pocket"
- minituarization of the sensor arrays and the photographic elements
  - "**pixel shrinkage**"

https://www.dpreview.com/news/4272574802/omnivision-has-created-the-world-s-smallest-commercially-available-image-sensor


https://www.theverge.com/2014/9/9/6091081/iphone-6-6-plus-camera-announced

# Consequences

- smaller pixel surfaces can store less photocarriers
  - lower full well capacities in detectors
  - pixels saturate under lesser lighting conditions
- unaltered amount of noise present due to the parasitic capacitances in the circuitry
  - corruption of signal during integration = lower SNR and dynamic ranges




Gerald C. Holst and Terrence S. Lomheim. 2011. CMOS/CCD Sensors and Camera Systems -. JCD Publishing, Winter Park, FL.

- bottleneck between the higher spatial resolution and the lower image quality

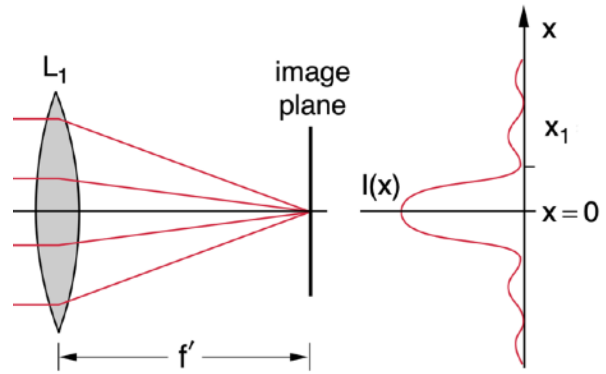
# Oversampling

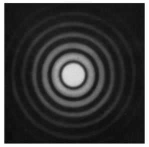
- diffraction of light:

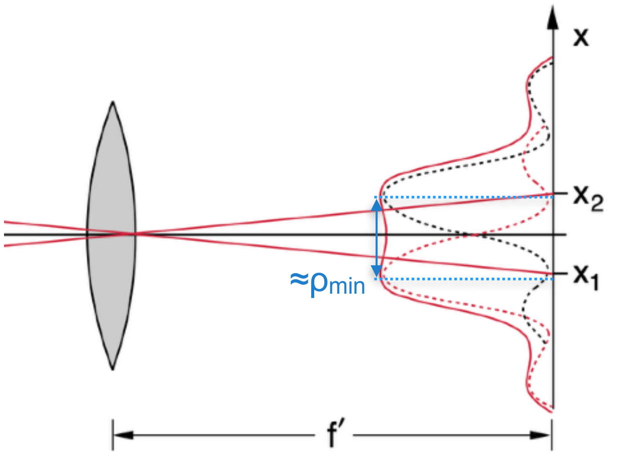
$$D_{Airy} \approx 2.44\frac{\lambda f'}{D} = 2.44\lambda k$$

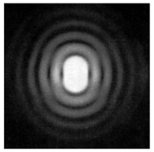
- two adjacent points are distinguishable at
  $\rho_{min}$ = 0.5 $D_{Airy}$ and above

  λ = 555nm, k = 2.8 → $\rho_{min} \approx$ 1,9 µm > 500nm
- spatial resolution of pixels is limited through
  optics
- *sub-diffraction limit* pixels
  - spatial oversampling of the light field
- small sizes ⇔ quick responses
  - temporal oversampling





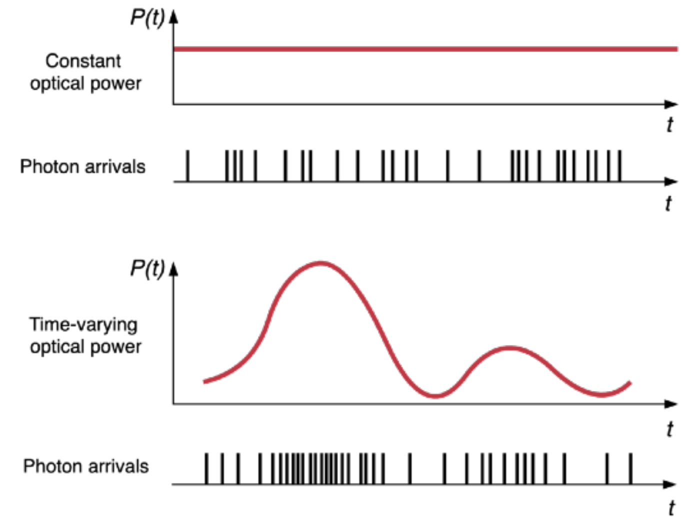



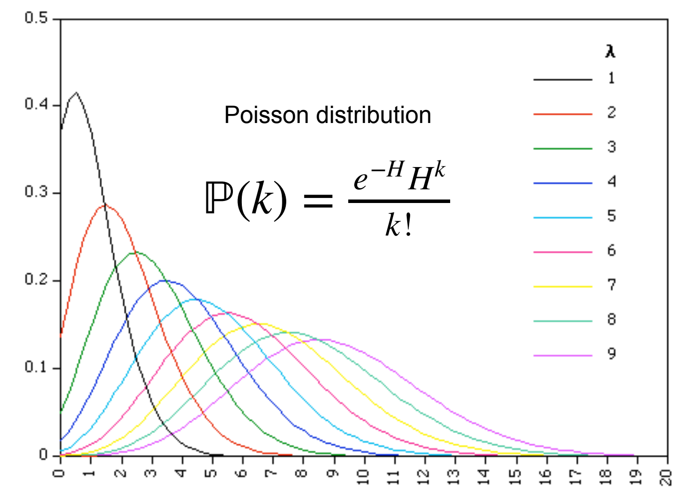
Wolfgang Demtröder. 2018. Experimentalphysik 2 - Elektrizität und Optik. Springer-Verlag, Berlin Heidelberg New York.

# Binary sensor

- pixels are made intentionally small as to store few carriers
- the amount of incident photons is mostly related to exposure with some fluctuations
- response is binary (either absorption took place, or not)
  - **photon-counting**
- smaller FWC leads to higher acquisition speeds and accelerated readout
- more smaller pixels on the same-sized array
  - higher spatial resolution
- state-of-the-art CMOS feature sizes: 1.1µm

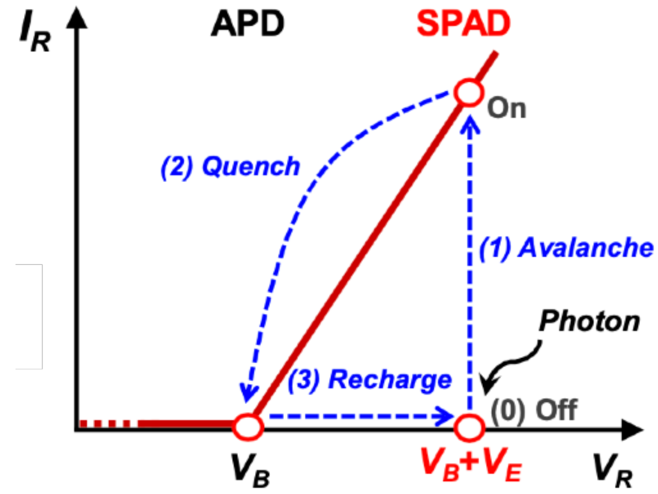
Bahaa E. A. Saleh and Malvin Carl Teich. 1991. Fundamentals of Photonics. Wiley, New York.



# Photon-counting with SPADs

- arrays of **<u>s</u>ingle-<u>p</u>hoton <u>a</u>valanche <u>d</u>iodes**
- internal amplification of the signal via **avalanche effect**
  - excited electrons are accelerated through large electric fields
  - collision frees further carriers via impact ionization
  - detection of a single photon through reaching the breakdown voltage
- no responsivity until the voltage is restored through “quenching”
  - additional in-pixel circuitry required




Edoardo Charbon, Claudio Bruschini, and Myung-Jae Lee. 2018. 3D- Stacked CMOS SPAD Image Sensors: Technology and Applications. In 2018 25th IEEE International Conference on Electronics, Circuits and Systems(ICECS).1–4.

# Photon-counting with SPADs

- large electric fields required for amplification of signals through avalanche
  - high operating voltage (20 V and above)
    - weak compatibility with baseline CMOS processes (2.5 / 3.3 / 5 V)
  - additional in-pixel electronics
  - relatively large pixel size with low quantum efficiency (7-8µm)

- generation of free carriers is based on thermal reaction
  - strong influence of dark current
  - may require cooling

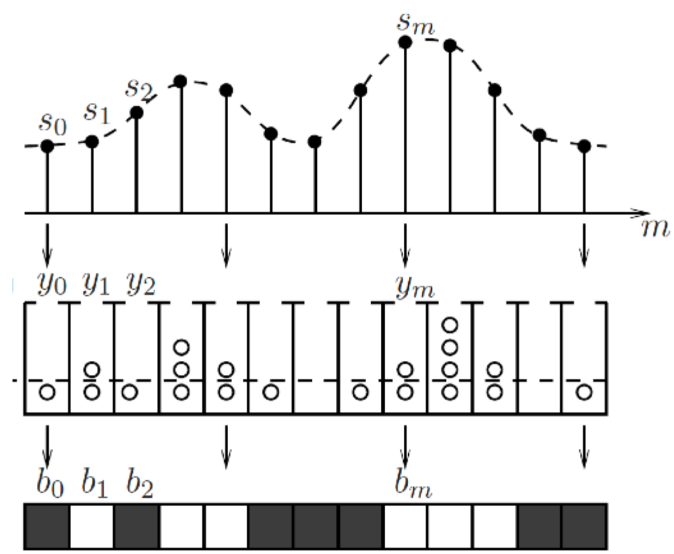
- impact ionization occurs rapidly
  - high readout rates (97 000 fps)

# Quanta Imaging Sensor

Feng Yang, Y. M. Lu, L. Sbaiz, and M. Vetterli. 2012. Bits From Photons: Oversampled Image Acquisition Using Binary Poisson Statistics. IEEE Transactions on Image Processing 21, 4 (Apr 2012), 1421–1436.

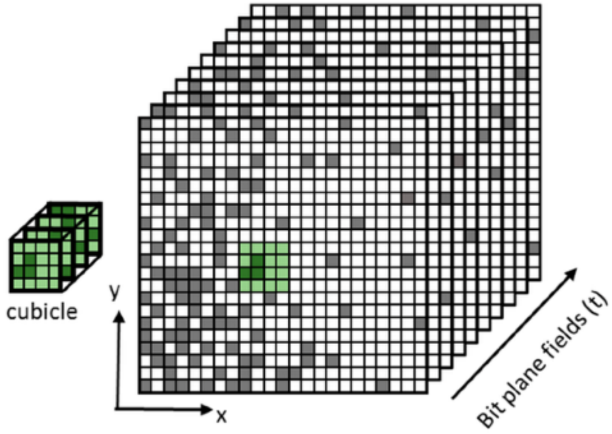
- proposed by Eric Fossum as a CMOS replacement
- goal: photon-counting without avalanche gain
  - envisioned pixel pitch of 200-500nm → “**jots**” → resolution in the gigapixel range
  - full well capacities of 1-3 $e^-$ per pixel
  - inherited advantages of CMOS in terms of operating voltage and processing

- collected photoelectrons form “buckets”, are compared against threshold *q* and
- trigger response of 0 or 1 depending on the amount
- transfer of a single bit instead of exact voltage = **binary quantization**
  - low ADC complexity (1b resolution)
  - high detection speeds

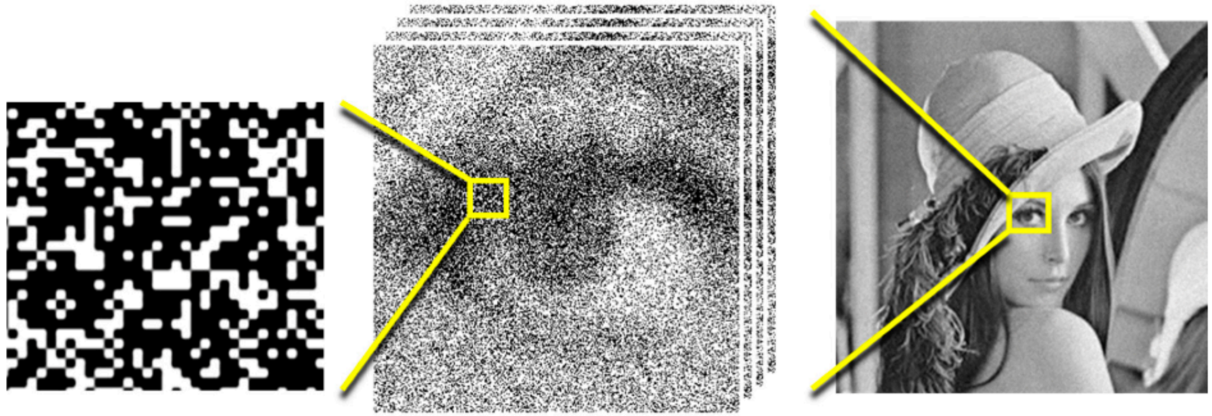


# From jots to pixels

- observations in time and space → jot data cube
- smaller regions of jots may be used for reconstruction of a conventional pixel
- assessment through statistics of incident photons
- reconstruction occurs post-acquisition
- envisioned: dynamic programming of the cubicles
  - sizes may vary in all dimensions
  - selected regions may overlap

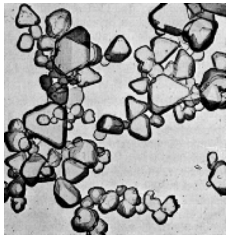


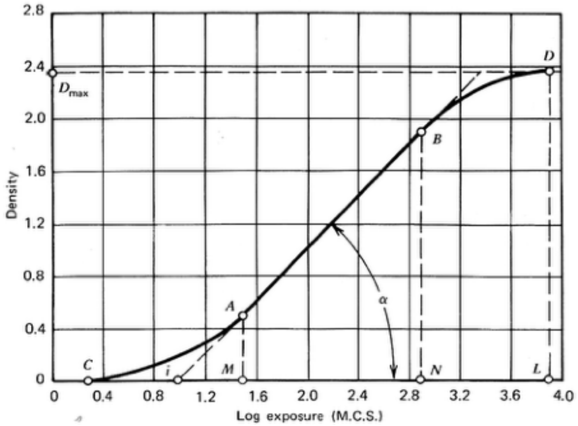

Eric R Fossum, Jiaju Ma, Saleh Masoodian, Leo Anzagira, and Rachel Zizza. 2016. The quanta image sensor: Every photon counts. Sensors 16, 8 (2016), 1260.



# From grains to jots

Burt Haring Carroll, George Clinton Higgins, and Thomas Howard James. 1980. Introduction to Photographic Theory - The Silver Halide Process. J. Wiley, New York.



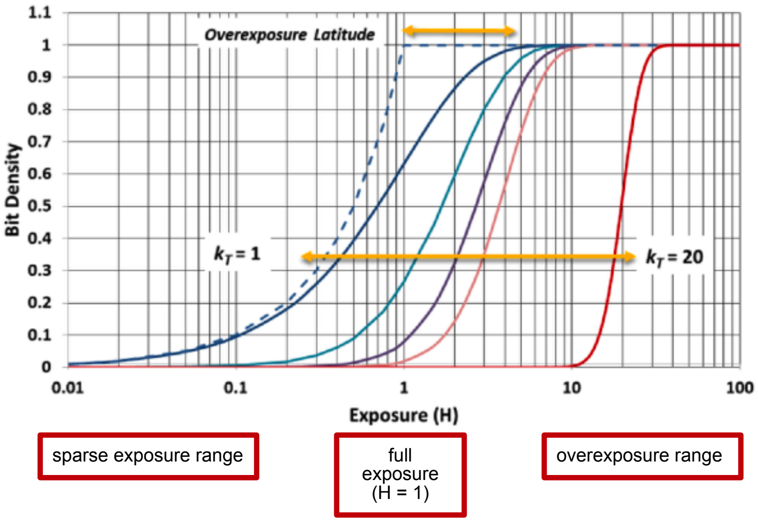



- photographic film emulsion: grains of silver halides
- either ionized and reduced to silver, or washed away during development
- binary response (black / white) depending on photon absorption

- diameters ranging from 0.048…1.71µm
- can absorb ca. 3-4e$^-$ per grain
- spatially discretized behavior

- characteristic curve: non-linear response relating exposure to optical density
- dictated by statistics of photon arrivals

- similarities to QIS




Eric R. Fossum. 2013. Modeling the Performance of Single-Bit and Multi-Bit Quanta Image Sensors. IEEE Journal of the Electron Devices Society 1, 9 (2013),166–174.

# Detection accuracy

CIS pixel:

- read noise: 1…2$e^-$ r.m.s.
- dark current: 10…5000$e^-$

QIS jot:

- read noise: <0.2 $e^-$ r.m.s.
- dark current: 0.16 $e^-$ r.m.s

- Single-bit, single-carrier QIS jot: noise is higher than the FWC
- Single-bit, multi-carrier QIS jot: noise dominates in low-light situations
  - read noise must be reduced
  - dark current is negligible due to short integration times

# Detection accuracy

- Read noise must be small enough to prevent bit flipping
  - ‣ **Bit Error Rate** (BER)
- modeling BER via noise levels $U_n$ with selected threshold $U_{th}$

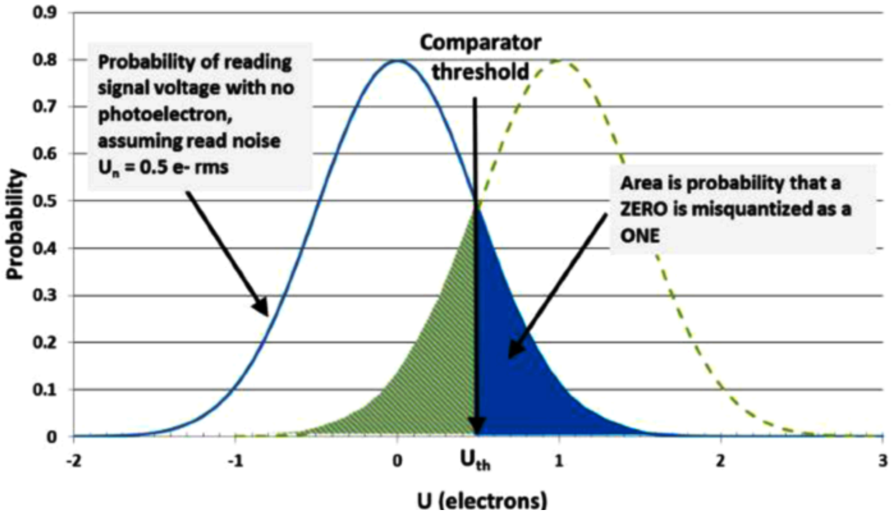
$$BER = \frac{1}{2}\,\mathrm{erfc}\left[\frac{1}{\sqrt{8}U_n}\right]$$

0.15e$^-$ r.m.s.: BER = 0.001143 (0.1%)
0.30e$^-$ r.m.s.: BER = 0.05989 (6%)

- higher noise levels are critical
- ‣ modify CMOS for higher conversion gain

QIS jot:

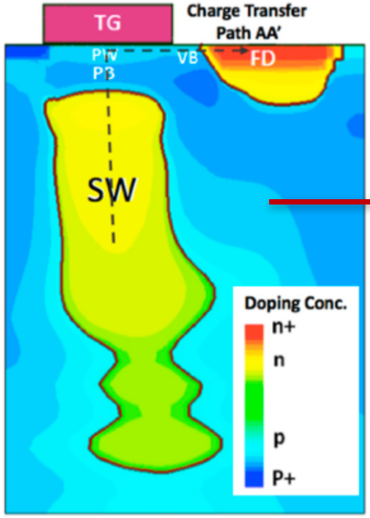
- read noise: <0.2 e$^-$ r.m.s.
- dark current: 0.16 e$^-$ r.m.s

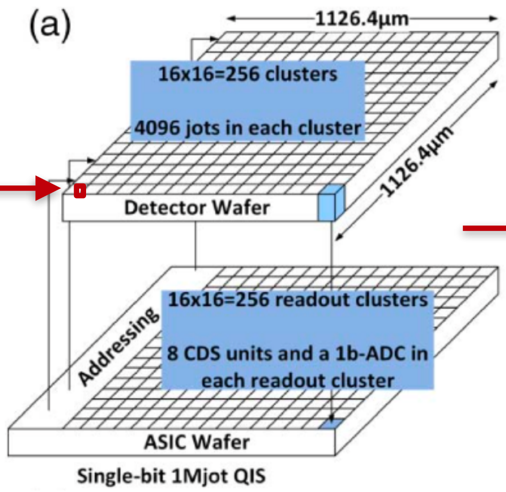


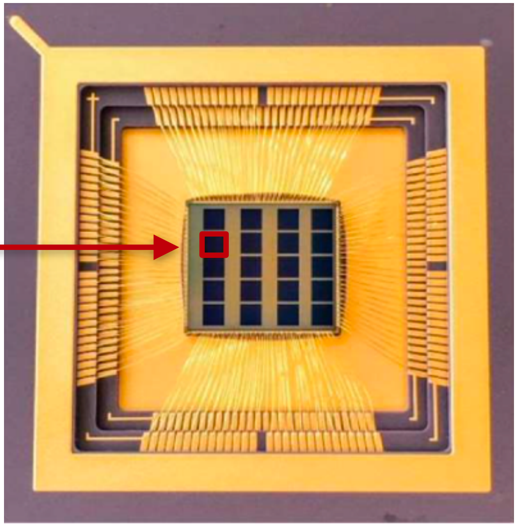

Eric R. Fossum. 2013. Modeling the Performance of Single-Bit and Multi-Bit Quanta Image Sensors. IEEE Journal of the Electron Devices Society 1, 9 (2013),166–174.

# Hardware architecture of jot devices

- based on **b**ack**s**ide **i**lluminated CMOS manufacturing process
  - BSI helps reduce reflections and increase fill factor
  - microlenses on pixels
  - standard techniques like **c**orrelated **d**ouble **s**ampling (CDS) to further reduce transistor noise
- jot arrays and read circuitry are stacked vertically
- higher conversion gain in pixels through doping



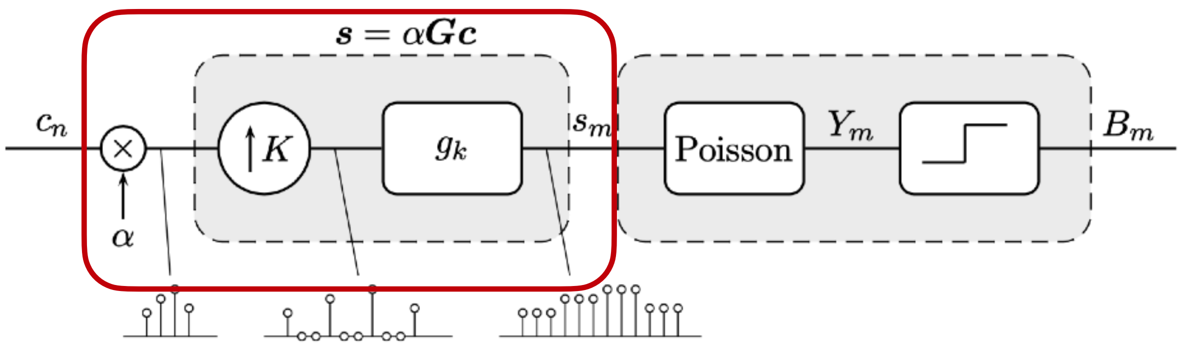




Eric R Fossum, Jiaju Ma, Saleh Masoodian, Leo Anzagira, and Rachel Zizza. 2016. The quanta image sensor: Every photon counts. Sensors 16, 8 (2016), 1260.
Jiaju Ma, Saleh Masoodian, Dakota A. Starkey, and Eric R. Fossum. 2017. Photon-number-resolving megapixel image sensor at room temperature without avalanche gain. Optica 4, 12 (Dec 2017), 1474–1481.
Abhiram Gnanasambandam, Omar Elgendy, Jiaju Ma, and Stanley H. Chan. 2019. Megapixel photon-counting color imaging using quanta image sensor. Optics Express 27, 12 (Jun 2019), 17298.

# Image formation in a single-bit QIS

- synthetic data from regular pixels can be recreated via:
  0. normalizing image to a range of [0,1] and scaling it with α
  1. oversampling of the light field = **interpolation**
     1. upscale the intensity values by the factor of *K*
     2. fill in the missing values via low-pass filtering

  - α represents sensor gain, the low-pass filter is equivalent to microlenses on the sensor array



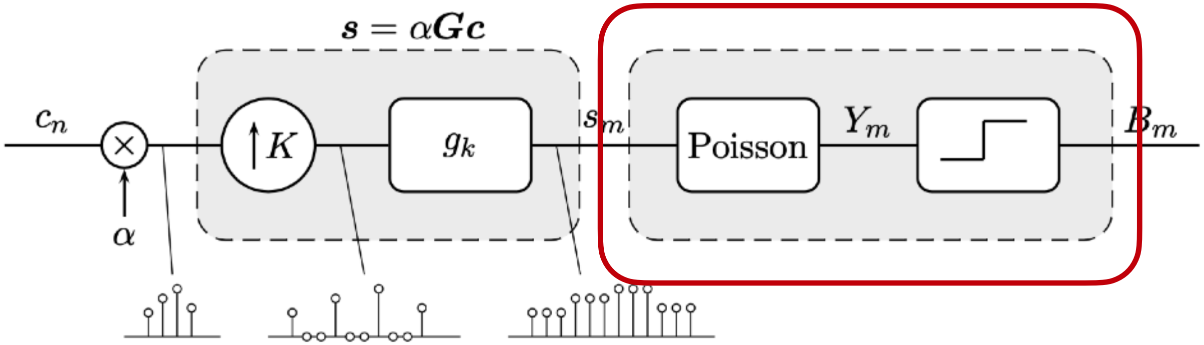



Feng Yang, Y. M. Lu, L. Sbaiz, and M. Vetterli. 2012. Bits From Photons: Oversampled Image Acquisition Using Binary Poisson Statistics. IEEE Transactions on Image Processing 21, 4 (Apr 2012), 1421–1436.

# Image formation in a single-bit QIS

- synthetic data from regular pixels can be recreated via:

  2. <u>binary sensing</u>
     i. add fluctuations in photon flux due to the Poisson distribution
     ii. quantization with a threshold *q*
  - each pixel in an image is either 1 or 0



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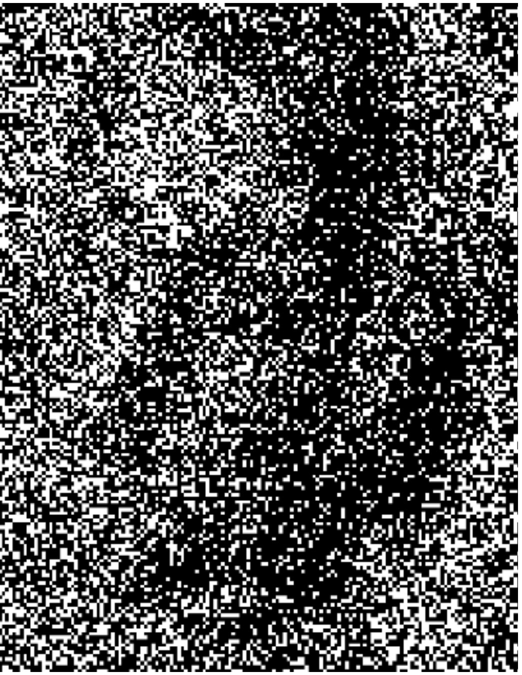
Feng Yang, Y. M. Lu, L. Sbaiz, and M. Vetterli. 2012. Bits From Photons: Oversampled Image Acquisition Using Binary Poisson Statistics. IEEE Transactions on Image Processing 21, 4 (Apr 2012), 1421–1436.

# Image formation in a single-bit QIS

- multiple observations comprise a single image during acquisition (ca. 1040fps)
- and have to be evaluated for reconstruction





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# Multi-bit QIS

- single-bit ADC: binary comparator
  - 1Mjot 1b chip delivers 1040 fps * 4096 jots * 256 clusters = 1.090.519.040 bits per second
  - trade high framerates of single-bit QIS for a higher resolution of ADC

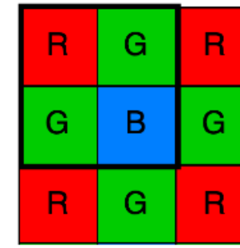
- carriers are mapped to their exact amount
  - the "middle" between CIS and QIS
- increase in complexity less significant than small data rates
  - 6b ADC: $1040/(2^6-1) = 16{,}5$ fps
  - no influence on reconstruction accuracy

# Image estimation

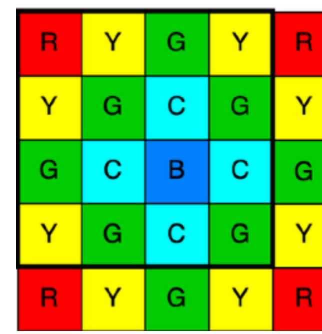
- <u>Optimization problem</u>
  - piecewise constant light fields can be estimated via
    - **Maximum-Likelihood** (ML)
    - **Maximum A-Posteriori** (MAP)
  - likelihood functions are dependent on the quantization threshold and the oversampling factor
    - numerical estimation required
  - iterative algorithms
- binary responses are spatially variant → **Transform-Denoise**
  - **variance stabilizing transform** (VST) converts truncated Poisson random variables to Gaussian
    - Anscombe Binomial Transform
  - reconstructed image is subjected to smoothing via denoising algorithms

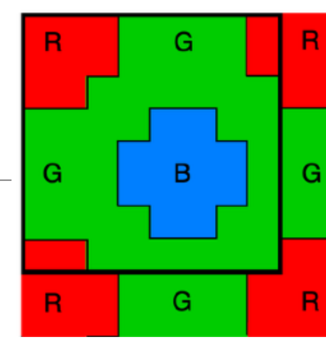
# Challenges - Color imaging in QIS

- Acquisition of color information via **<u>c</u>olor <u>f</u>ilter <u>a</u>rrays** (CFA) integrated onto the sensor
- collection and reconstruction of color through separate spectral intensity values
- low accuracy due to
  - even lower SNR (less light passes through CFA)
  - cross-talk (leakage of charges in adjacent pixels)
- solution:
  - CFA design for crosstalk reduction
  - algorithms for joint reconstruction <u>and</u> denoising

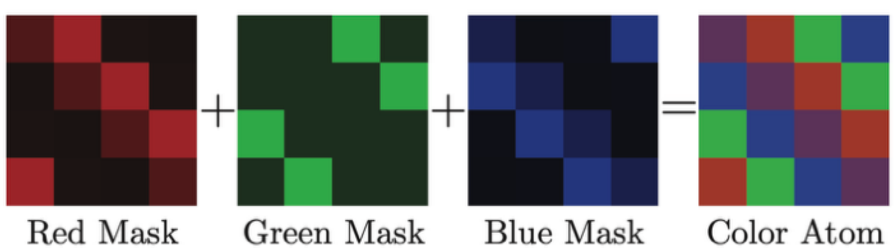



L. Anzagira and E. Fossum. 2015. Color filter array patterns for small-pixel image sensors with substantial cross talk. Journal of the Optical Society of America. A, Optics, image science, and vision 32 1 (2015), 28–34.



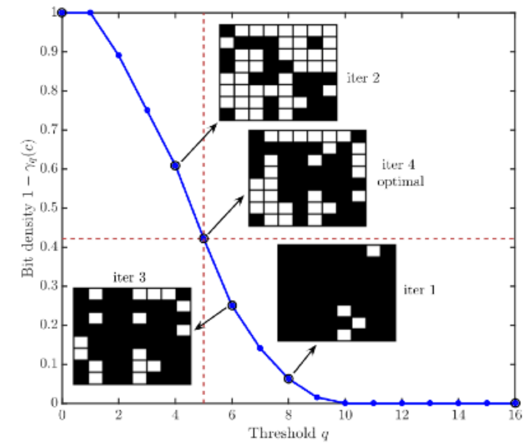



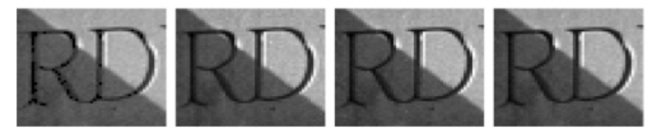

Omar A. Elgendy and Stanley H. Chan. 2019. Color Filter Arrays for Quanta Image Sensors.



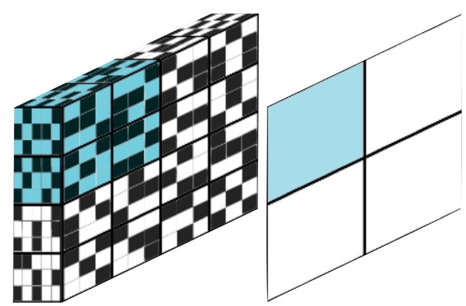
# Challenges - Choice of threshold

- threshold must fit the lighting conditions in the scene
  - QIS: q = 0.5 of the normalized voltage
  - when set incorrectly, image can be under- or overexposed
- CIS: dynamic range is affected by the resolution of ADC
  - loss of details in scenes with strongly varying illumination
- QIS could benefit from spatially variable thresholds
  - different for each region
  - iterative estimation based on predicted DR
  - can be shared between clusters
- requires additional circuitry
  - in development: per-pixel FPGAs



iter 1, 27.4 dB　iter 2, 37.1 dB　iter 3, 38.8 dB　iter 4, 39.1 dB



Omar A. Elgendy and Stanley H. Chan. 2018. Optimal Threshold Design for Quanta Image Sensor. IEEE Transactions on Computational Imaging 4,1(2018),99–111.

# Demonstration in MATLAB

Omar A. Elgendy and Stanley H. Chan. 2018. Optimal Threshold Design for Quanta Image Sensor. IEEE Transactions on Computational Imaging 4,1(2018),99–111:

- generation of synthetic data
- threshold manipulation
- estimated sensor response & general photon statistics

# Conclusion

**QIS**:

- suitable for low-lighting conditions and HDR applications
- working prototypes with low power dissipation and low noise levels
- desired dimensions are not yet achieved, but the research is going on strong
- promise of highly customizable photography
- viable candidate for the third-generation imaging sensor

**SPAD**

- mostly effective in Time-of-Flight applications

# Questions?