

Quanta Image Sensor (QIS): Early Research Progress*

Donald Hondongwa, Jiaju Ma, Saleh Masoodian, Yue Song, Kofi Odame and <u>Eric R. Fossum</u> *June 26, 2013*

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- Better images can be obtained by oversampling in time and space.
- Pixel shrink yields smaller full well capacity which impacts dynamic range and maximum SNR.
- Photons are digital in nature according to particle view of light.

➔ Quanta Image Sensor (QIS) counts photoelectrons at Tbits/sec.



Quantized Digital Integration Sensor (qDIS)

time

Conventional integration period

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- Temporal and Spatial Oversampling (e.g. fast field readout and subdiffraction-limit pixels)
- Multi-bit photoelectron counting pixels (read noise ≤ 0.15 e- rms)
- Exposure sub-integration times can be varied for high dynamic range (HDR)
- Frames can be shifted to remove motion blur or perform TDI

See Berezin US Patent No. 7,139,025 Hynecek US Patent No. 7,825,971 And Patent Applications by Fossum 2011





Quanta Image Sensor



Jot = specialized SDL pixel, sensitive to a single photoelectron with binary output, "0" for no photoelectron, "1" for at least one photoelectron.



Many jots are needed to create a single image pixel.

e.g. 16x16x16 = 4,096

A QIS might have 1G jots, read out at 1000 fields/sec or 0.5 Tbits/sec



Photon and photoelectron arrival rate described by Poisson process

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

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





ΤΗΑΥΕΡ

Т

SCHOOL OF **Film-like Exposure Characteristic** EERING ENGIN DARTMOUTH

QIS D – log H



Bit Density vs. Exposure

Film D – log H



Film Density vs. Exposure 1890 Hurter and Driffield





Raindrops on Ground



H~ 0.3 ?

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Multi-Arrival Threshold (Not QIS)

Binary output of sensor ="1" when # of arrivals $k \ge k_T$ Results in reduced higher slope and less overexposure latitude





"Shot" Noise

Variance of a binomial distribution $\sigma_1^{\ 2} = M \cdot P[0] \cdot P[k > 0]$







Exposure-Referred Noise

$$\sigma_H = \sigma_1 \frac{dH}{dM_1}$$
 $SNR_H = \frac{H}{\sigma_H} = \sqrt{M} \frac{H}{\sqrt{e^H - 1}}$



M=4096

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Exposure-Referred Noise

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Read Noise and Bit Error Rate (BER)





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BER vs. Read Noise



 $BER = \frac{1}{2} erfc \left(\frac{1}{\sqrt{8}n_r}\right)$ What is an acceptable bit error rate?



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BER vs. Read Noise



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Increased Dynamic Range

Sum of 16 fields 4@ T=1.0 4@ T=0.2 4@ T=0.04 4@ T=0.008







Multi-bit Pixels

Counting low number of photoelectrons, e.g. 4b yields FW = 15 e-



Sum 4x4x16 = 256 pixels Max = 15x256 = 3840



QIS: M=4096 4b: M=273





Shot Noise and Read Noise





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

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k=

___0

___2

----6

----7

- 8

- 10

—9

10

9

-4 5



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Effect of Read Noise on Photoelectron Counting for Multi-bit Pixel



Note "peak" for H=5 is not at 5 e-





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End to End System Simulation

Input Image 256x256 8b



→ 4096x4096 1b x 16 fields = 268 Mb



 $H = \frac{S_H h_o}{255}$

Output Image 1024x1024 8b



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in this example 1 pixel = Σ 4x4x16 jots $SNR \le \sqrt{256}$





Convolution



30

20

10

0 0

2D Examples:

Binary valued filter



Binaryweighted filter



10

40

Down

sample





Digital Film Sensor Algorithm





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Readout Signal Chain Strawman Design

General requirements:

- Need to scan 0.1-10 Gjots at 100-1000 fields per sec
- 8k 80k jots per column $\rightarrow 0.8 80M$ jots/sec

Assumptions:

- 0.1 Gjot at 100 fps \rightarrow 1Mjot/sec
- 1 mV/e- conversion gain
- 150 uV rms noise on column bus (0.15 e- rms)
- 0.18 um process
- Vdd = 1.8V



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Readout Signal Chain





| Process | V_{DD} | Jot array | Column Speed | Column power | Comp power | Total | Array Power | | | | |
|----------------|-----------------|--------------------------|---------------------|-----------------|---------------|---------|----------------|--|--|--|--|
| CURRENT DESIGN | | | | | | | | | | | |
| 0.18um | 1.8V | 0.001 Gjots (1k X 1k) | 1MJ/s (1000fps) | 0.71uW | 1.28uW | 1.99uW | 1.99mW | | | | |
| 0.18um | 1.8V | 0.1 Gjots (10k X 10k) | 1MJ/s (100fps) | 6.44uW | 1.28uW | 7.72uW | 77.2mW | | | | |
| SCALED DESIGN | | | | | | | | | | | |
| 0.18um | 1.8V | 0.1 Gjots (10k X 10k) | 10MJ/s (1000fps) | 64.4uW | 12.8uW | 77.2uW | 772mW | | | | |
| 45nm | 1.1V | 1 Gjots (24k X 42K) | 24MJ/s (1000fps) | 57uW | 2.9uW | 59.9uW | 2.5W | | | | |
| 22nm | 0.8V | 1 Gjots (24k X 42K) | 24MJ/s (1000fps) | 20uW | 0.74uW | 20.74uW | 0.87W | | | | |
| 45nm | 1.1V | 10 Gjots (75k X 133k) | 75MJ/s (1000fps) | 553uW | 9uW | 562uW | 75W | | | | |
| 22nm | 0.8V | 10 Gjots (75k X 133k) | 75MJ/s (1000fps) | 197uW | 2.3uW | 199.3uW | 26.5W | | | | |

Adapted from Kotani et al. 1998

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Jot Device Considerations

General requirements:

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

For early investigation

- Cobbled together an imaginary 85 nm process
- Students learning to use TCAD tools etc.
- Anticipate that device principles can be migrated to real process





Bipolar Jot Concept



- CMOS APS but use pinning layer as emitter, storage well as base
- Complete reset of base using "TG"
- Emitter follower to reduce base-emitter cap





BSI CMOS APS Jot with Storage under Transfer Gate



- Low capacity storage gate makes barrier easier to overcome with low TG voltage
- Minimum FD size to increase conversion gain

Storage under transfer gate first proposed in Back Illuminated Vertically Pinned Photodiode with in Depth Charge Storage, by J. Michelot, et al., 2011 IISW

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Summary

- Good progress in understanding response v. exposure, SNR, DR, etc. using photon statistics
- Early progress made on realizing Quanta Image Sensor
- >1 year support of Rambus (thanks Rambus!)
- Students up to speed and making headway
- Challenges don't look as challenging
- Lots of work to do!