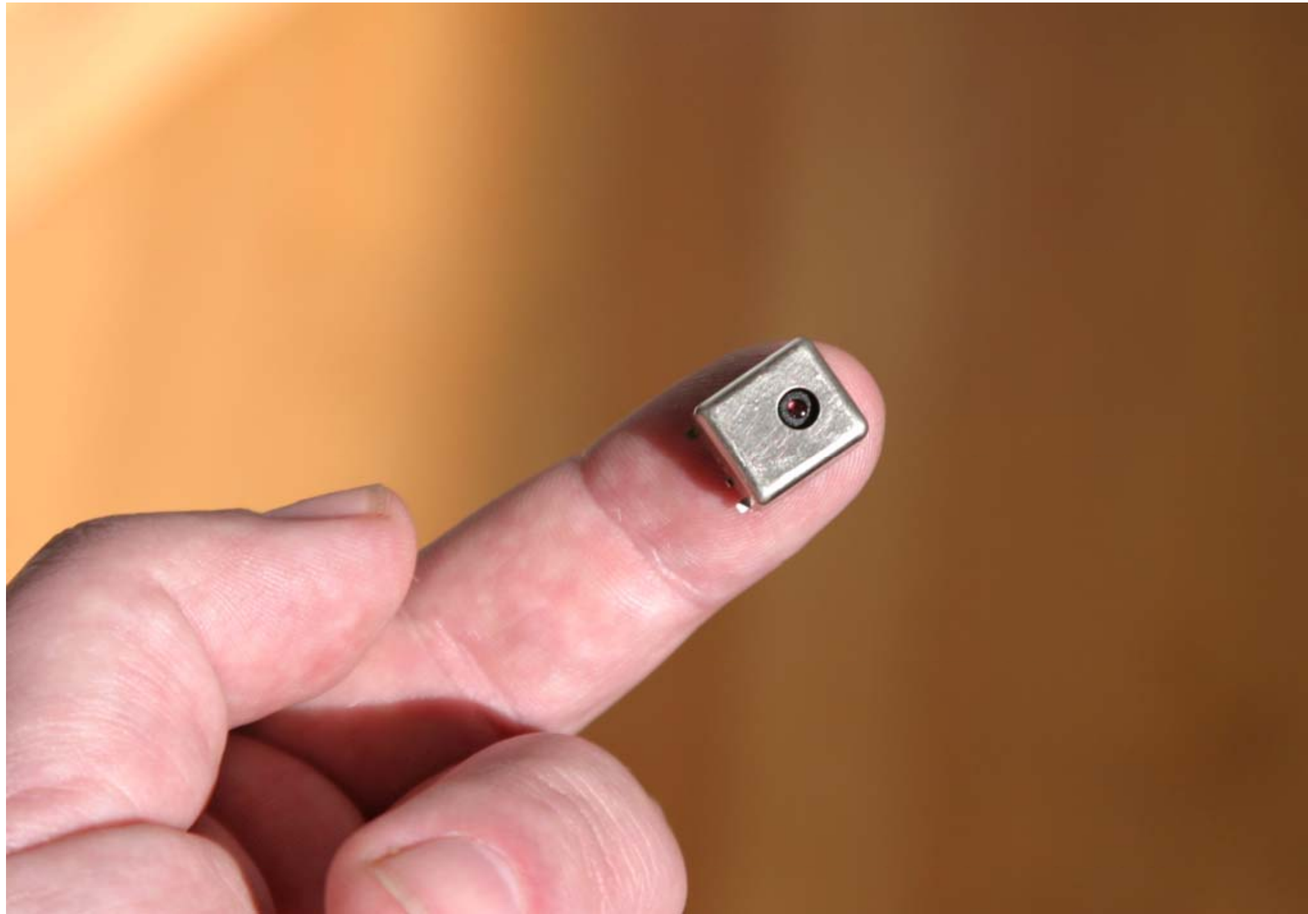
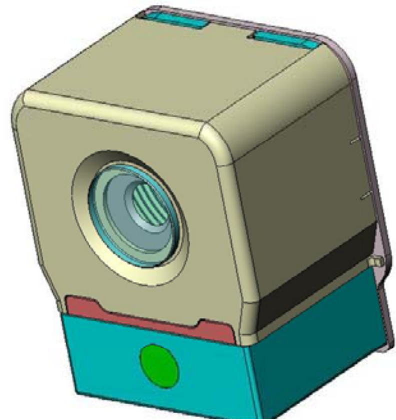
Adventures with Image Sensors

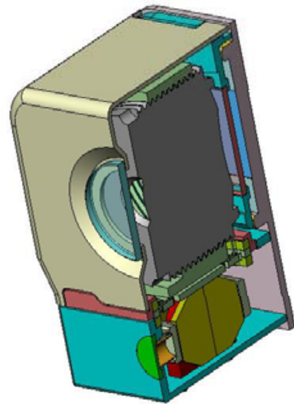
Dr. Eric R. Fossum
Chairman and Chief Executive Officer
Adjunct Professor of Electrical Engineering, USC

2Mpixel Camera with Autofocus



Components





Lens Barrel

Lens Mount

Axial Snubbers (2)

MEMS Stage Assembly

Actuator Magnet Module

IR Filter

Sensor & flex circuit

EMI Shield

Housing and Actuator Coils (2)

Preload Spring

Preload Spring Cap

ASIC driver

The Team

November 2005

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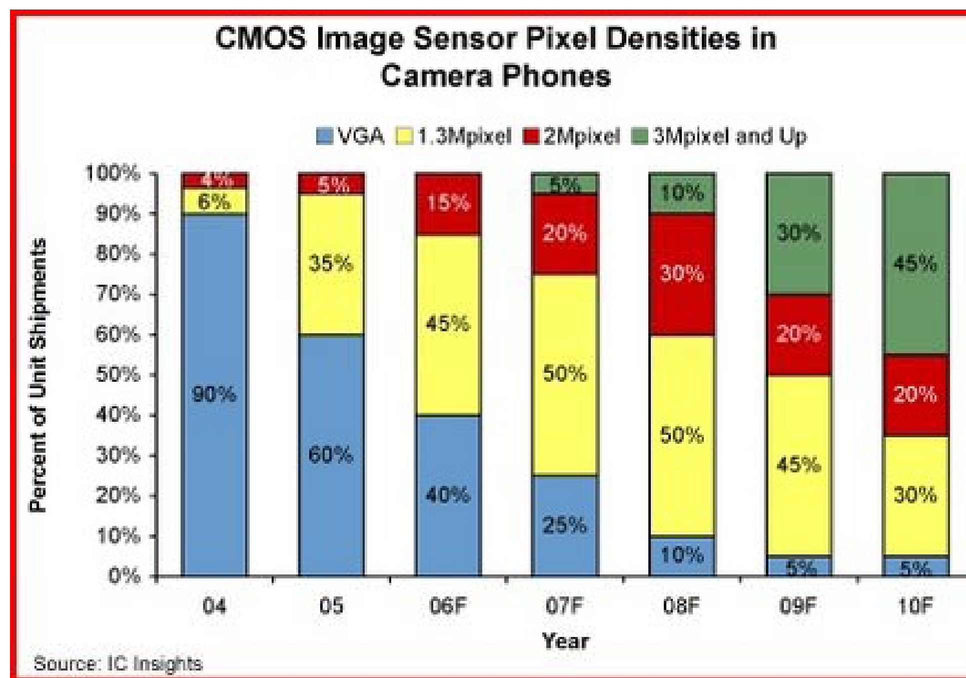
Market Opportunity



- Camera phone market forecasted growth from over 600 million units in 2006 approaching 900 million units by 2009
- Camera phone with resolutions of 2Mp+ projected to grow to more than 50% of total units during the same period
- Cameras with 2Mp+ resolution desire Auto Focus capability for good image quality

Fossum's Job

- CEO's job is to turn this technology into a business that makes a profit for the investors.

2008
- ☐ Significant market share
- ☐ Additional customers
- ☐ Profitability

2007
- ☐ 2000K unit/month production
- ☐ 2nd product in production

2006
- ☐ 2nd and 3rd customers
- ☐ 500k unit production
- ☑ Preproduction

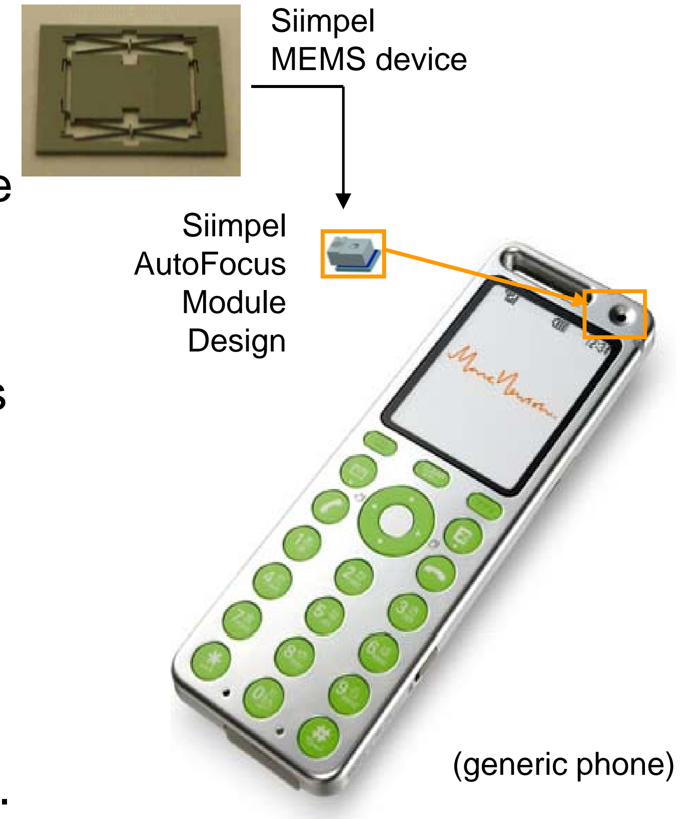
2005
- ☑ Product development
- ☑ Management team and Series C funding
- ☑ Key customer engagement

EF joins Siimpel →

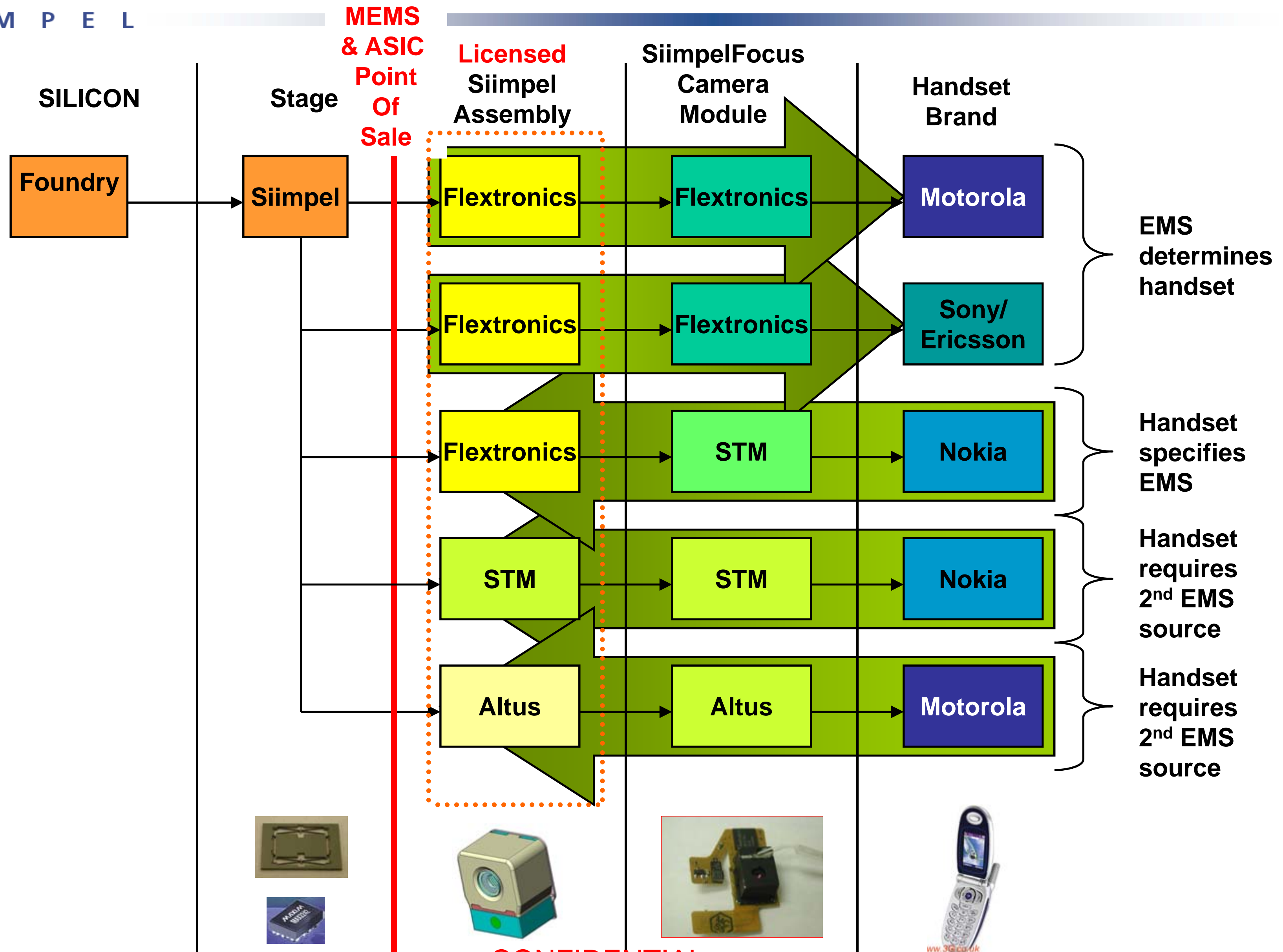
2004
- ☑ Series B funding
- ☑ First prototype
- ☑ Conceptual Design

Business Thesis

- MEMS enables high precision integrated optical microsystems for high volume consumer products
- Handset applications:
  - Move to higher resolution (megapixel) camera phones requires AF, zoom, shutters to produce acceptable image quality
  - Higher quality photo/video capability and improved user experience of handset cameras increases customer usage and ROI for carriers
  - MEMS best meets handset requirements related to size, power, cost, performance and reliability
- Strategy is to sell or license high-margin camera module components such as MEMS AF actuator, MEMS shutter, MEMS zoon, ASIC driver, lens, etc.



Camera Phone Business Model



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Autofocus Actuator Competition

	Voicecoil Magnetic	Stepper Motor	Helimorph Piezo-electric	Varioptic Liquid Lens	Konica-Minolta Ultrasonic	Siimpel MEMS
Size	Good	Poor	Poor	OK	OK	Good
Cost	Very Good	OK	OK	OK	OK	OK
Optical Perform-ance	OK	Good	OK	OK low res	OK	Good
Power	Poor	Poor	Good	Good	OK	Good
Reliability	Poor	Unknown	Very Poor	Unknown	Unknown	Good
Scalable platform	Poor	Poor	OK	Poor	Poor	Good
Precision/ Repeat-ability	Poor	Good	Poor	OK low res	Needs feedback	Excellent

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Competitive Barriers

- First to market with MEMS AF technology
- AF module design complexity requires well rounded multi-disciplinary engineering team in critical areas of electro-magnetic, electro-optical and mechanical design which impact power, speed, shock specs
- Rapid pace of handset design changes and size and power constraints require 'nimble' engineering team and fast product development
- Building strong relationships with 'Tier 1' module and handset manufacturers
- Primary focus on high value MEMS device designs with module component manufacturing outsourced to low cost manufacturers
- Strong IP and patent position

Some Of The Risks

- Miss insertion window due to series of “small” technical problems
- Large scale manufacturability not yet proven (tolerances/yield -> cost)
- AF camera phone market does not emerge
- Competitors overcome their limitations faster/cheaper than expected

Business Development Status

- World's largest camera module maker is investor and first customer
- World's 2nd largest camera module maker is enthusiastically evaluating technology
- We are one of only 2 approved AF solutions for Motorola. Samsung to begin evaluation
- We are fulfilling a 500k unit early production order
- Working towards design in and design win for several handset opportunities
- Manufacturing capacity on ramp up from 10k units/week to 125k units/week to 500k units/week

Fossum's Headaches

- Customer wants us to ramp to 2M-4M/month asap!
- Capital Equipment $
  - It costs about $10 in capex to increase capacity by 1 unit per month. (e.g., $10M for 1M/month capacity)
- Facility
  - It takes about 12,000 sq ft of space for 1M/month capacity
- People
  - It takes about 60 operators to build 1M/month
  - It takes a strong staff of engineers for manufacturing, new product development, and application support
- Where is a good 8" MEMS foundry when you need it??

How Did I Get Here?

Adopted personal motto: "Have Fun, Make Money, Learn Along the Way"

- 1981-1983 Summer intern at Hughes Aircraft to work on infrared image sensors
- 1984 Yale Ph.D. dissertation on smart image sensors
- 1984-1990 Columbia EE Assoc Prof. on CCD focal plane image processing and GaAs CCDs
- 1990-1996 NASA Jet Propulsion Laboratory - Imaging Systems
- 1995 Photobit spin off
- 2001 Micron acquisition
- 2003-2005 "Retirement"
- 1999-present USC Adj. Professor
- 2005-present Siimpel

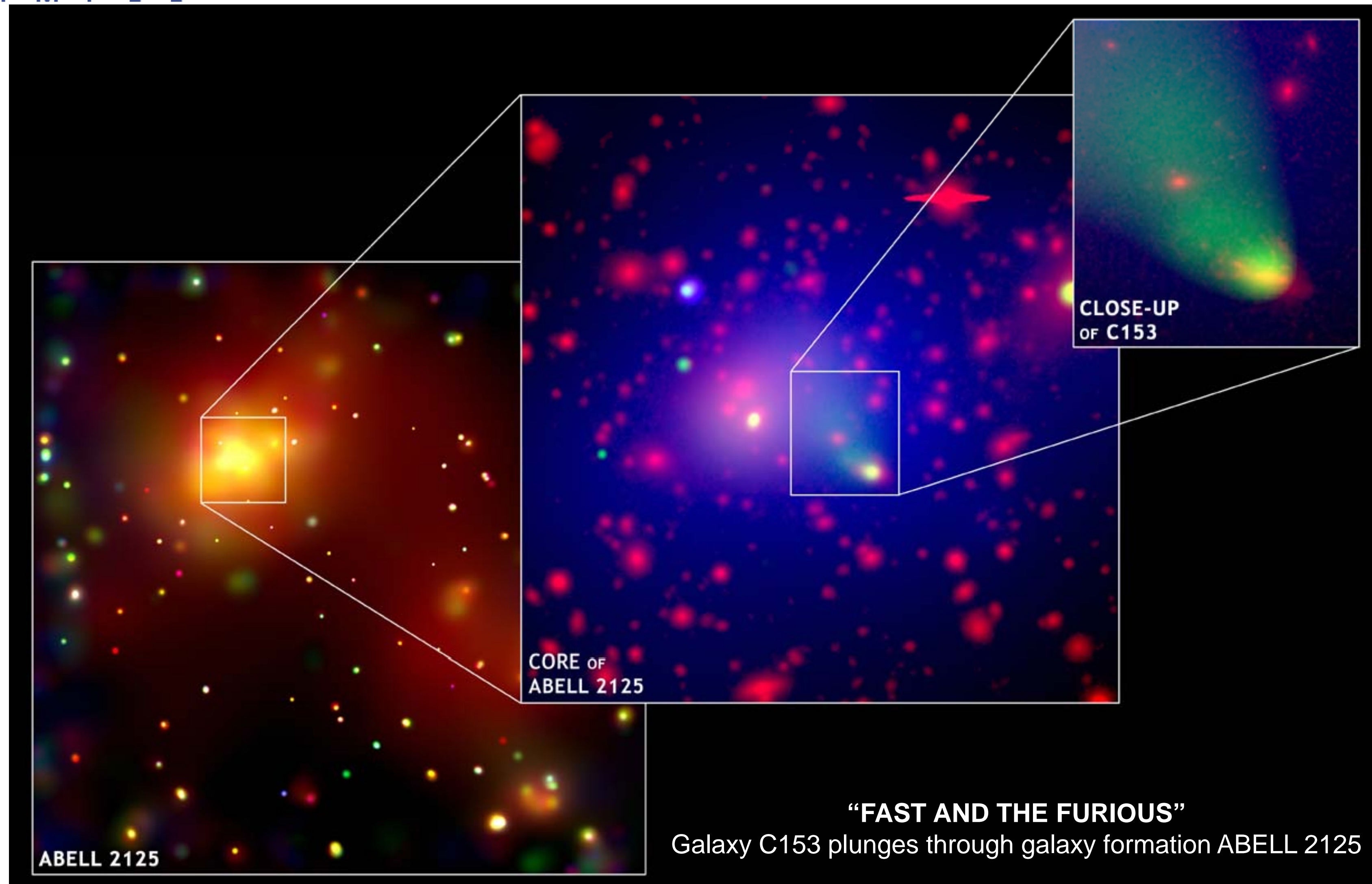
- 16 Megapixel image sensors
- 32 Megapixel UDTV
- What to do with gigapixel sensors

16 Megapixel sensor

From the Ph.D. dissertation research of
Dr. Suat Ay
USC and Micron Technology

SIIMPEL

Big sensors for big questions



Credit: D. Wang (UMass) et al., CXC, NASA
Source : http://antwrp.gsfc.nasa.gov/apod/ap040906.html

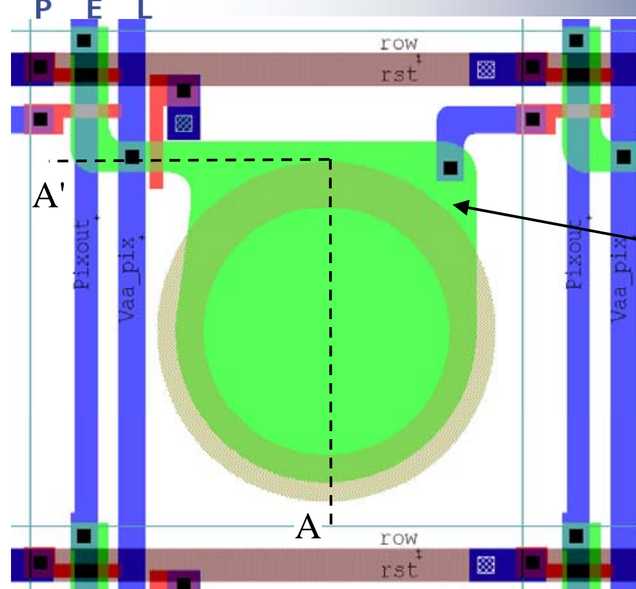
A big chip

World's largest single die
CMOS Integrated Circuit (IC)
and APS Image Sensor
(58.98 cm^2)

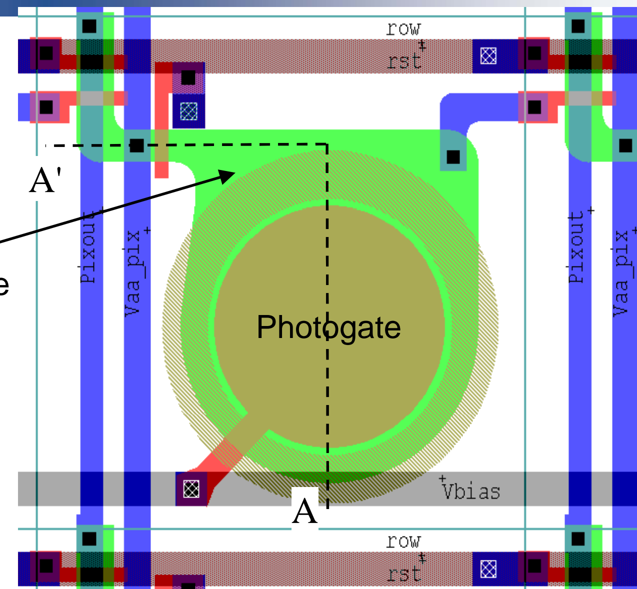
World's largest array
CMOS image Sensor
4096x4114
(16.85Mpixel)

World's largest well-depth
imaging pixel
(1.35 Million electrons)

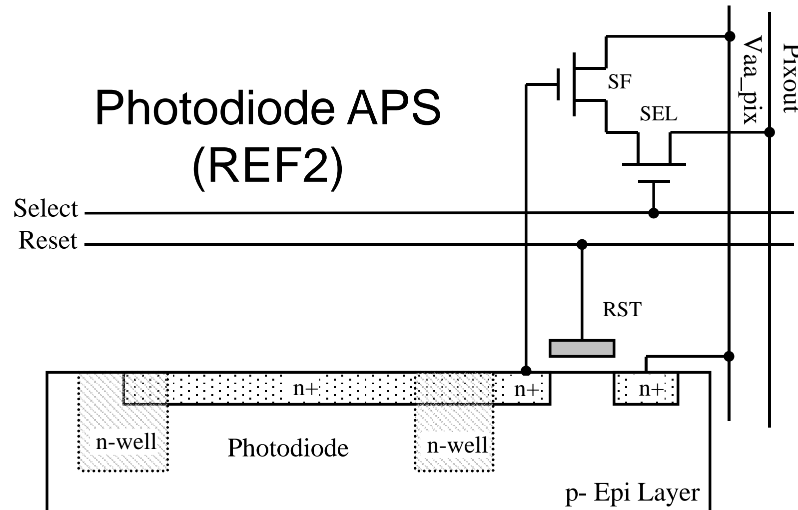
HPDPG APS Pixel Design



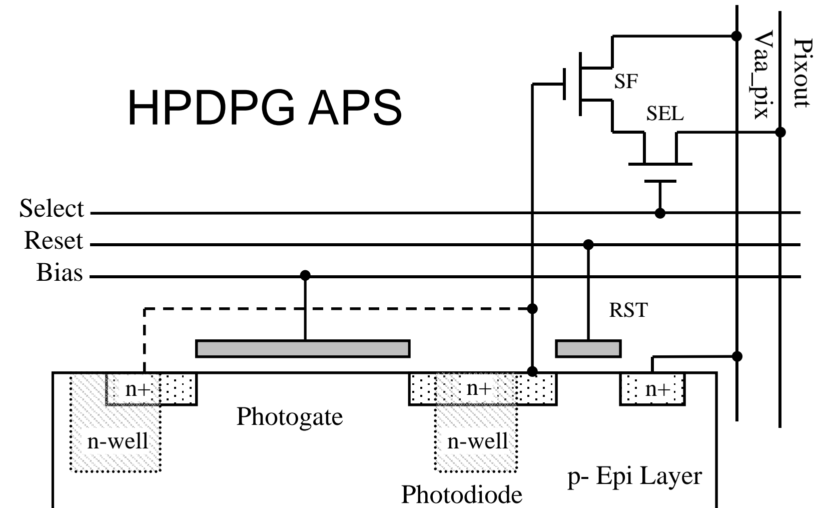
Photodiode



Photodiode APS (REF2)



HPDPG APS



Photodiode-Photogate Pixel

Layout

V_{AA} RST C_{PIX} V_{PG} Photogate (PG) Photodiode (PD)

V_{AA} V_{PG} RST PG PD C_{PIX} SEL OUT

Cross Section

Light C_{PIX} RST=0 V_{PG}=const. V_{AA} n+ n+ Photogate Photodiode p-

- $C_{PIX}=C_{PD}+C_{PG}$
- $C_{PG}>>C_{PD}$ and $C_{PIX}\sim C_{PG}$ — Photogate ON
- $C_{PG}<<C_{PD}$ and $C_{PIX}\sim C_{PD}$ — Photogate OFF

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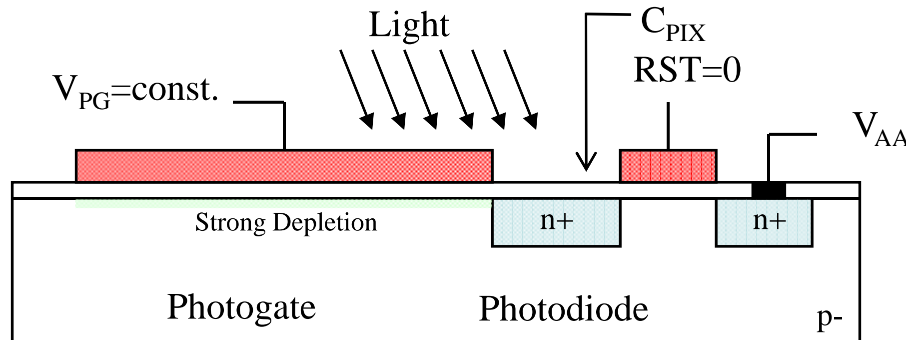
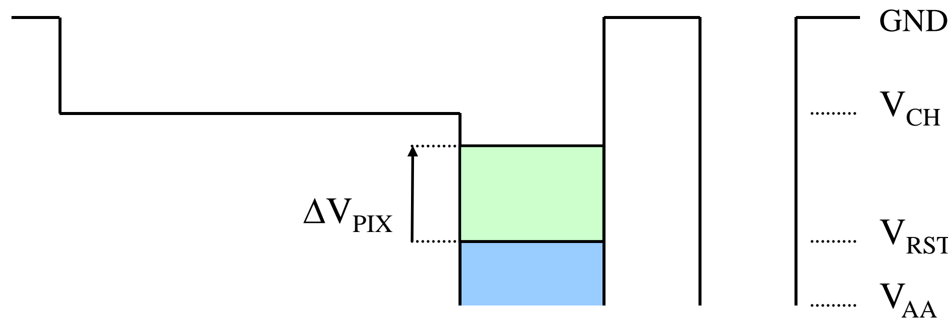
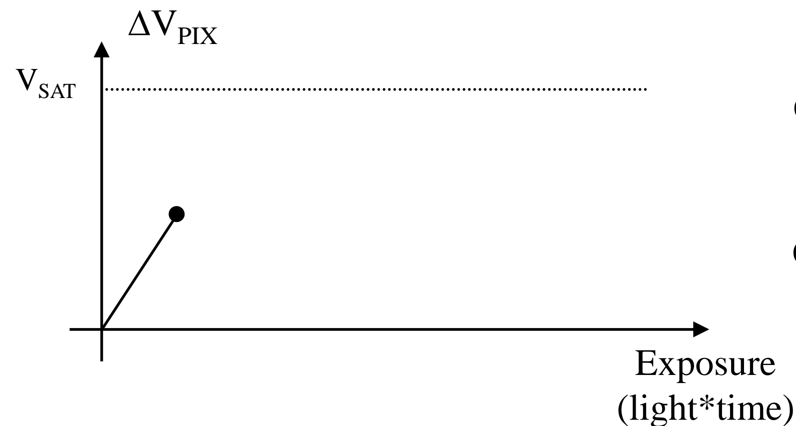
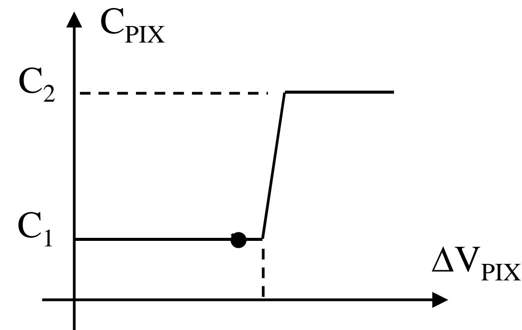
PDPG Pixel Operation



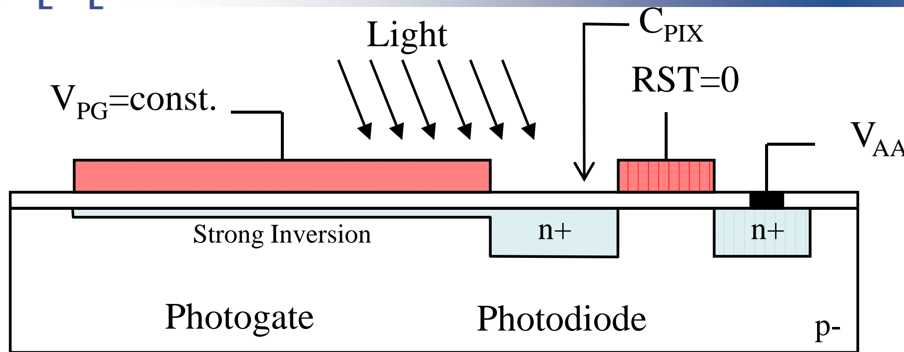


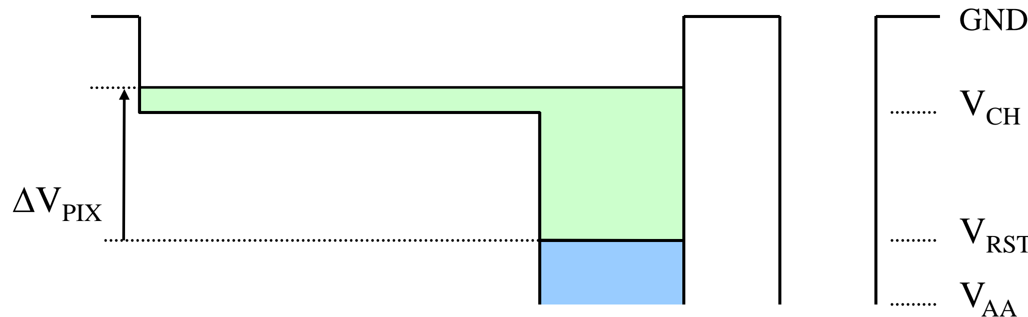


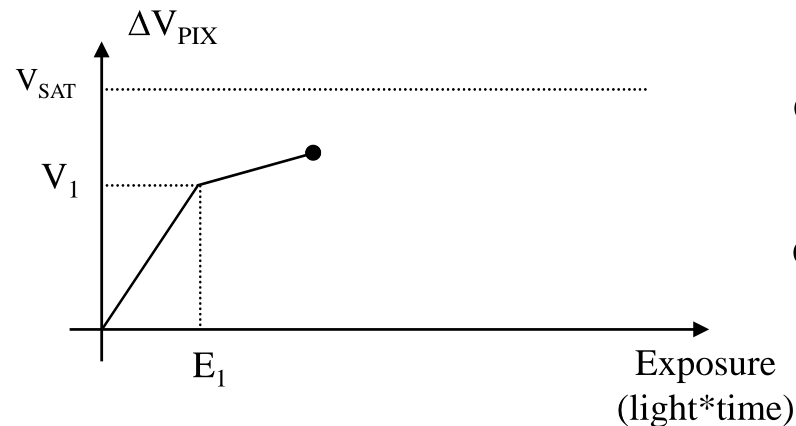


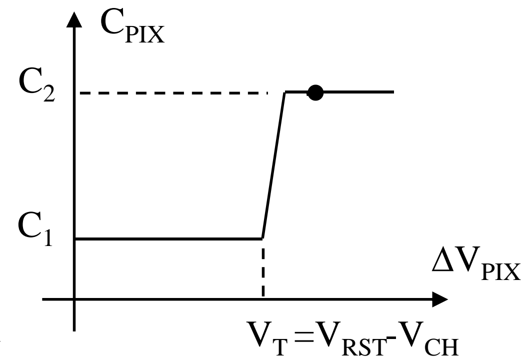
- Initial condition
- Reset the pixel
- Start integrating photons
- Integrating

PDPG Pixel Operation









- Initial condition
- Reset the pixel
- Start integrating photons
- Integrating
- Reach “First Knee”
- Slow response

HPDPG Pixel – Light Sensitivity Measurement Results

5X Exposure enhancement

Decreased V_{PG}

E_1

E_2

Effective Pixel Signal (Volt)

3.0
2.5
2.0
1.5
1.0
0.5
0.0

0 1 2 3 4 5 6 7 8 9 10 11

Exposure (Lux.sec)

REF2
5.0 V
4.5 V
4.0 V
3.0 V
0.1 V

HPDPG Pixels in First Prototype Imager

HPDPG Pixels

Standard Photodiode Pixels

512x512 Array size, 15 μm pixel, 6-pixel design (PROTO1_2)

4Kx4K Device Architecture Partitioning

A	B	B	B	B	B	B	B	B	C
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
D	E	E	E	E	E	E	E	E	F
G	H	H	H	H	H	H	H	H	I

Block	Width (µm)	Height (µm)
A	7766	1000
B	9216	1000
C	1000	1000
D	1351	9216
E	9216	9216
F	1000	9216
G	1351	2825
H	9216	2825
I	1000	2825

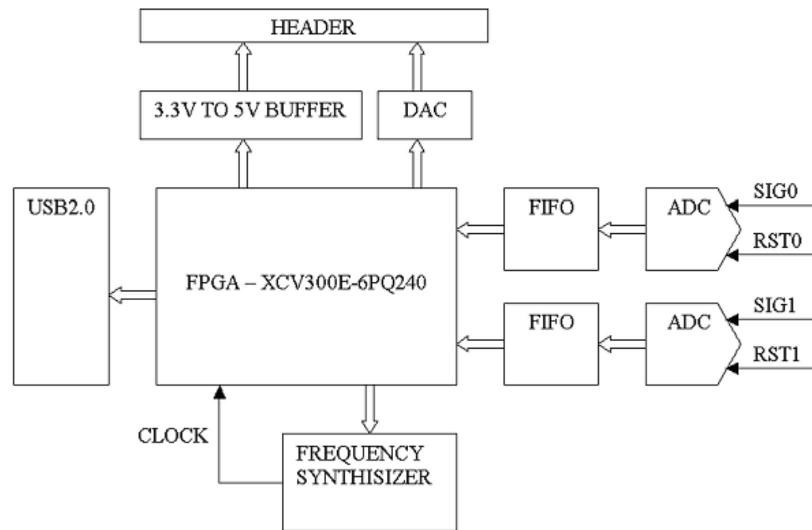
Stitching-Block Name	Block Functional Definition
A	• Digital Power Routing • Covered/Open Pixels
B	• Pixel Power Supply Pads • Pixel Power Routing • Covered/Open Pixels
C	• Pixel Power Routing • Covered/Open Pixels
D	• Row Decoder/Drivers • Digital Input Pads • Digital Power Pads • Covered/Open Pixels • Signal/Digital Power Routing
E	• 512 x 512 Pixel Array
F	• Analog Power Pads • Power Routing • Covered/Open Pixels
G	• Analog/Digital Power Pads • Analog Signal Pads • Digital/Analog buffers • Row Clock Generator • Power/Signal Routing • Covered/Open Pixels
H	• Analog/Digital Input/Output Pads • Analog Signal Chain (ASC) • Column Decoder/Driver • Global Amplifiers • Column Timing and Control Logics • Analog/Digital Power Pads • Signal/Power Routing • Covered/Open Pixels
I	• Analog Input Pads • Analog/Digital Power Pads • Power routing • Covered/Open Pixels

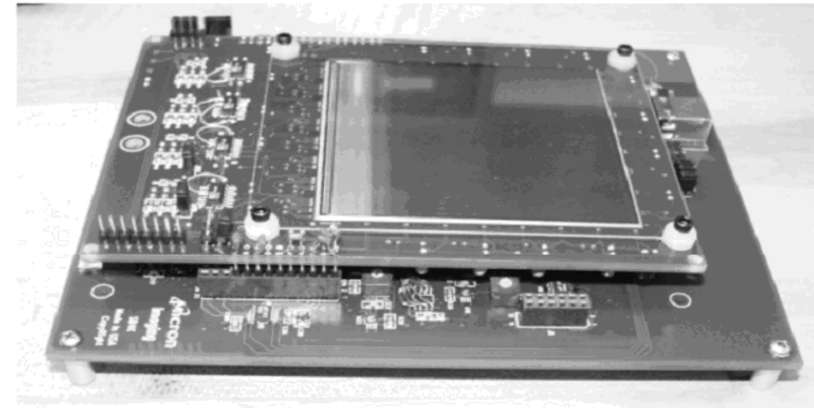
4Kx4K Imager after fabrication (before dicing)

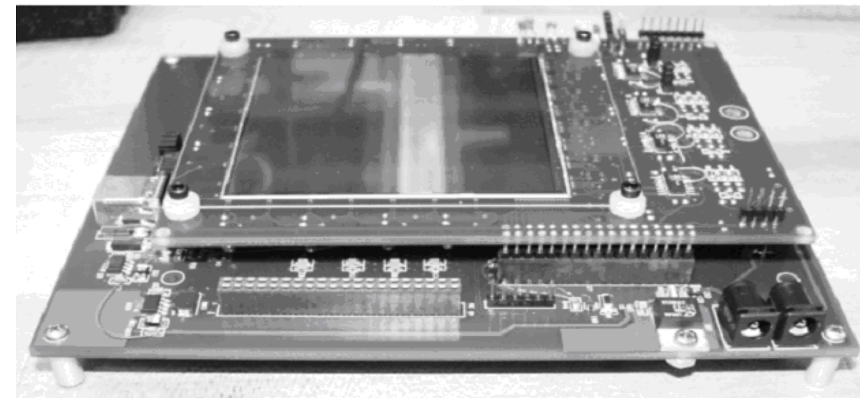
6-inch Wafer

4Kx4K imager die

Controller and Demonstration System Solution







- Packaging PCB plugs onto the controller PCB,
- Controller does all the interface, ADC, DAC, timing, FIFO, bias generation.
- Two ADC for channel readout,
- Xilinx FPGA as main controller.
- Analog frame grabber from packaging PCB for analysis,

S I I M P E

Reproduced 4Kx4K image

32 Megapixel UDTV

From a collaboration between
Photobit Technology Corporation (now Micron)
And
NHK Laboratories, Tokyo

Ultra-Definition Television

Our Goal

Future TV System with Greater Sensation of Reality

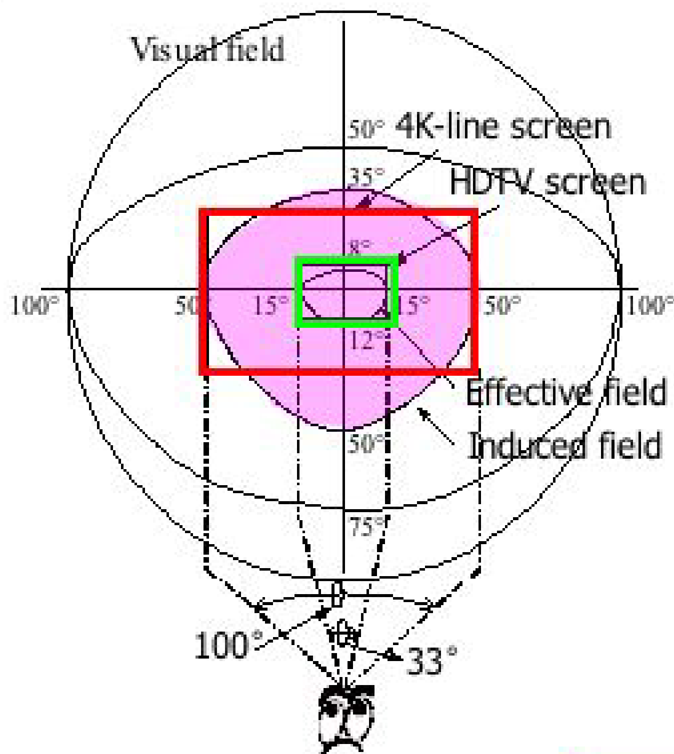
Effects

- High sensation of reality as if we are there
- More exciting in live TV programs

Our objectives

- Examine physical and psychological effects
- Enhance sensation for future TV system

Why 8k?



Viewing angles of displays for HDTV and 8k x 4k pixel image system

- The sensation of reality increases with the viewing angle and saturates at around 100 deg. Horizontally*1
- The spatial resolution of Human vision perceives 60 pixels per deg.*2

Requirement of 8k pixels in the horizontal direction

*1:T. Hatada, et al., "Psychophysical Analysis of the Sensation of Reality Induce by a Visual Wide-Field Display," SMPTE Journal, Vol.89, pp.560-569, 1980
*2:High-Definition Television, p.6 Van Nostrand Reinhold, New York, 1992

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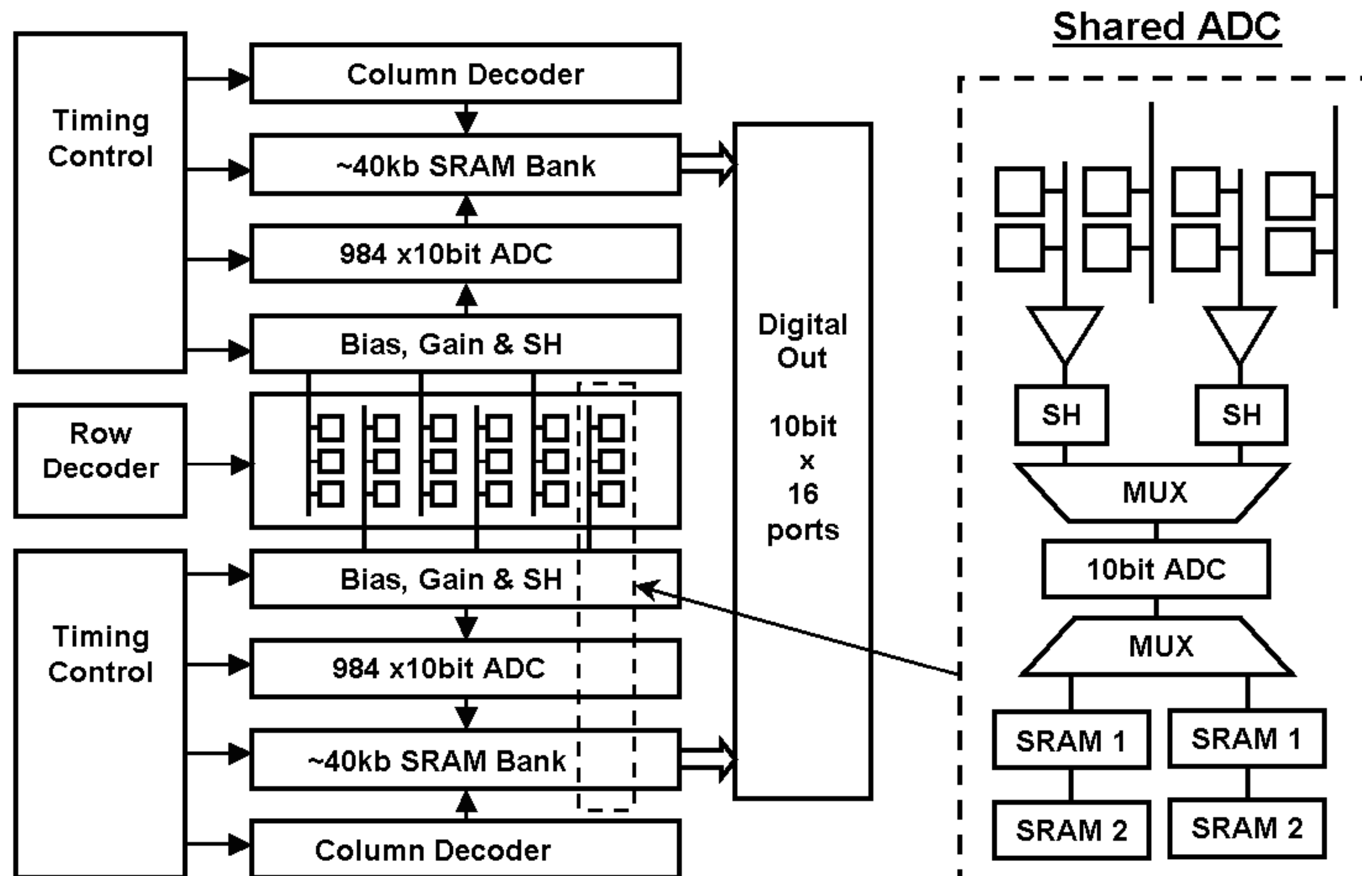
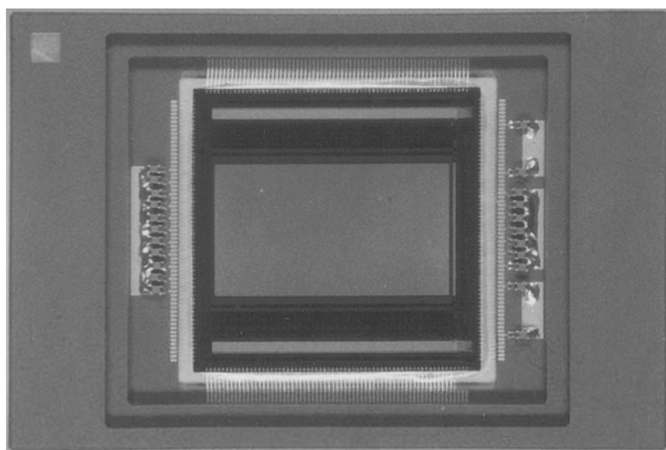
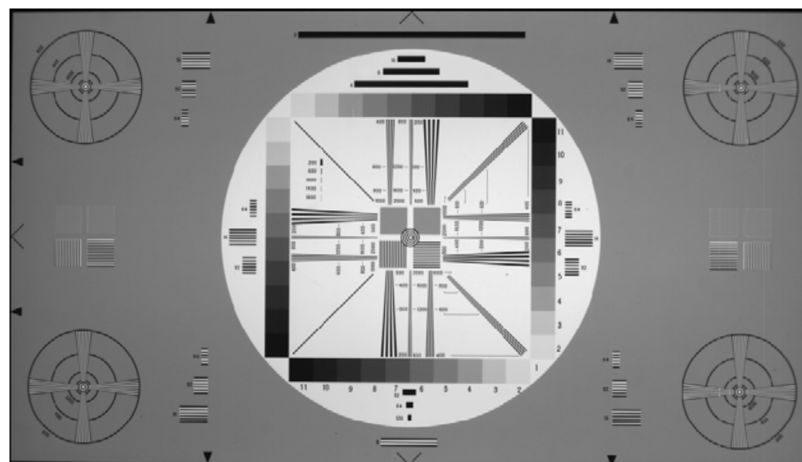
8 Mpixel UDTV Sensor

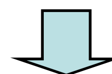


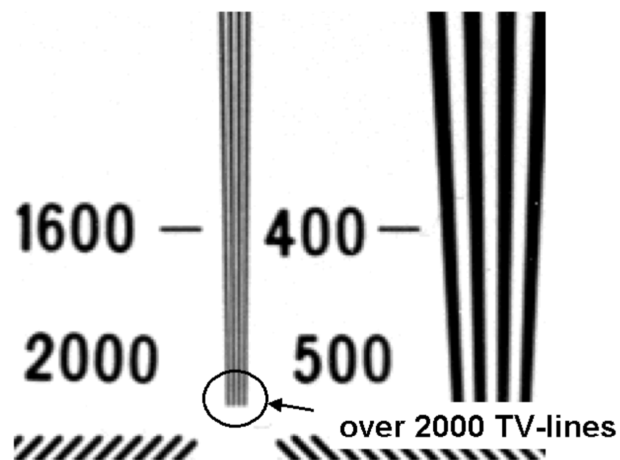
8 Mpixel image (60 fps)

Chip Photo





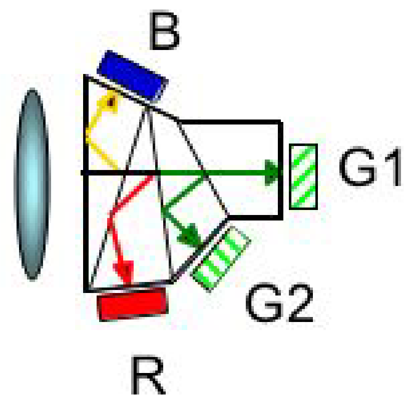


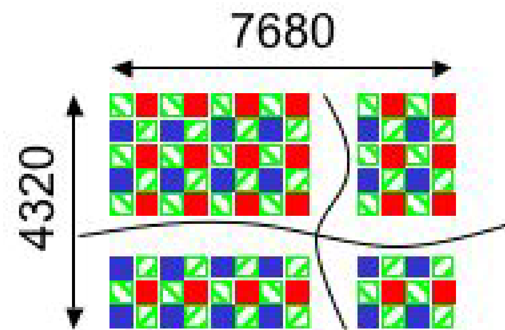


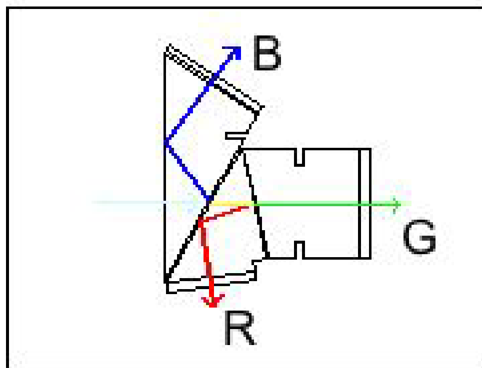
UDTV Sensor Performance

Parameter	Value	Comments
Number of total pixels	3936 (H) × 2196 (V)	
Number of effective pixels	3840 (H) × 2160 (V)	8.3 M-pixels; 4 times the HDTV resolution
Pixel size	4.2 µm × 4.2 µm	NW/P-sub photodiode APS with on-chip microlens
Optical format	1.25-inch	Aspect ratio; 16:9
Die size	19.7 mm (H) × 19.1 mm (V)	No stitching is used
Conversion gain	0.06 LSB/electron	Output referred
	43 µV/electrons	at pixel sense node
Full well capacity	25,000 electrons	@ADC input range of 750 mV
Noise floor	42 electrons	
Dynamic range	55.0 dB	
Sensitivity	4200 bits/lux-sec	Output refereed 2700K light source, IR filter with cut-off wavelength of 650 nm
	3.0 V/lux-sec	at ADC input
Scanning	Progressive	
Frame rate	60 fps	
Output signal	10-bit digital 16 parallel output ports	
Output frequency	49.5 MHz	792 MHz (6.3 Gbps) total throughput
Electronic shutter	Electronic rolling shutter	
Process technology	0.25 µm double-poly, triple metal CMOS	
Supply voltage	3.3V	
Power consumption	597 mW	at dark
Package	262 pin PGA	

Four-pickup Imaging



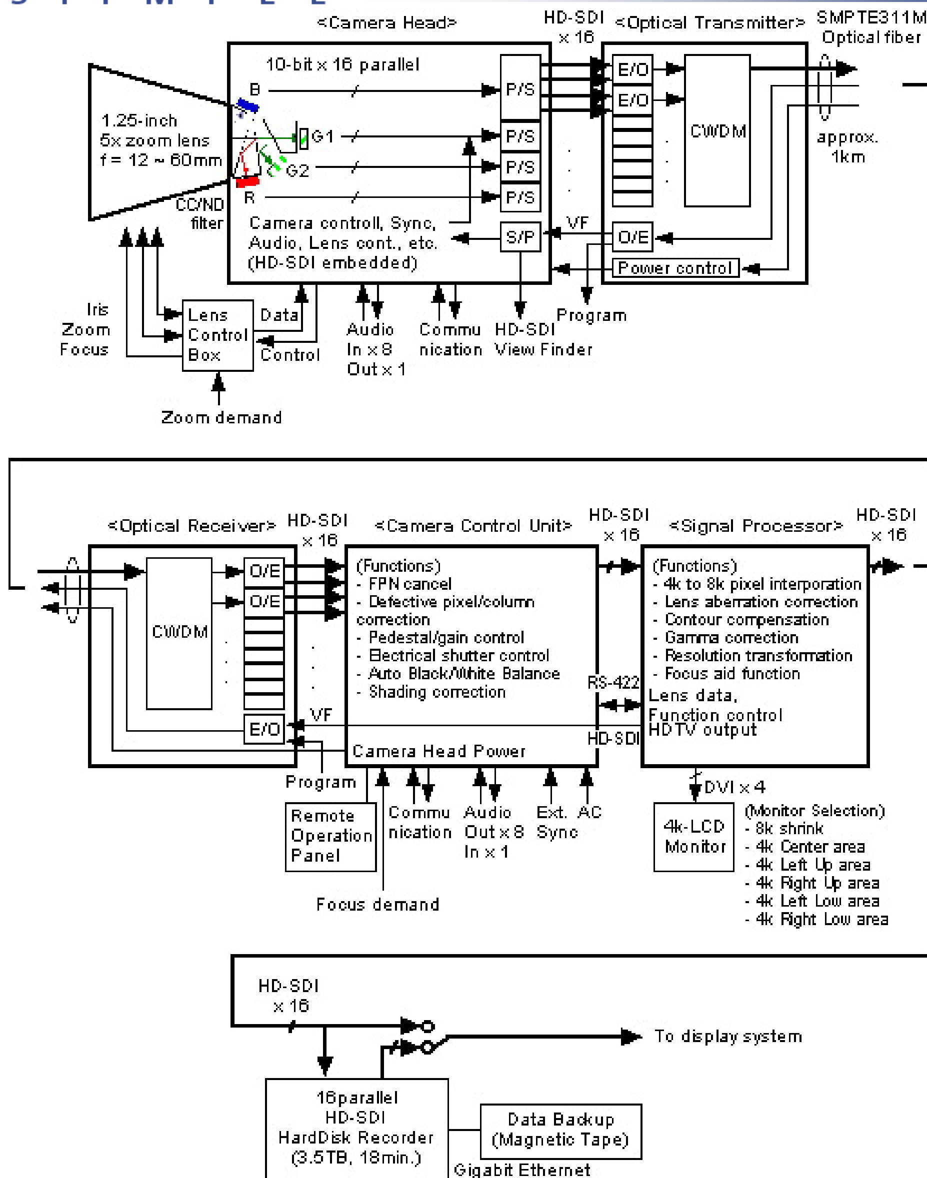




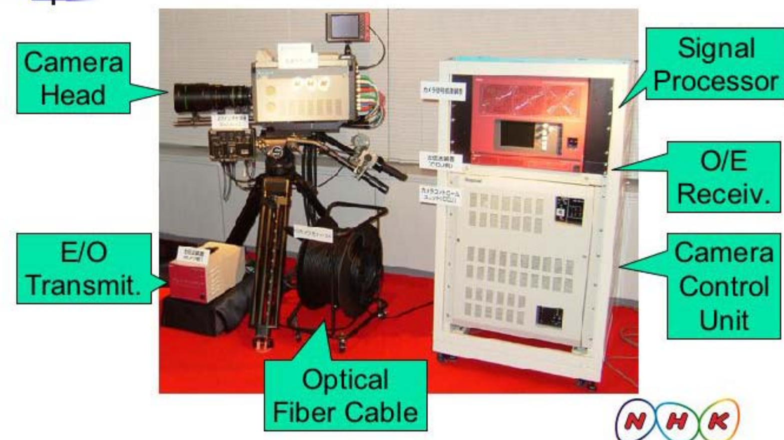
Usual Three-pickup Imaging

- Two imagers for Green channel
- Diagonal Pixel Offset between G1、G2、R、B channel Imagers
- Total Pixel Count of 7680 x 4320 (Similar to 32M-pixel Single-Chip Color Device)

Camera System



Camera System (outline)



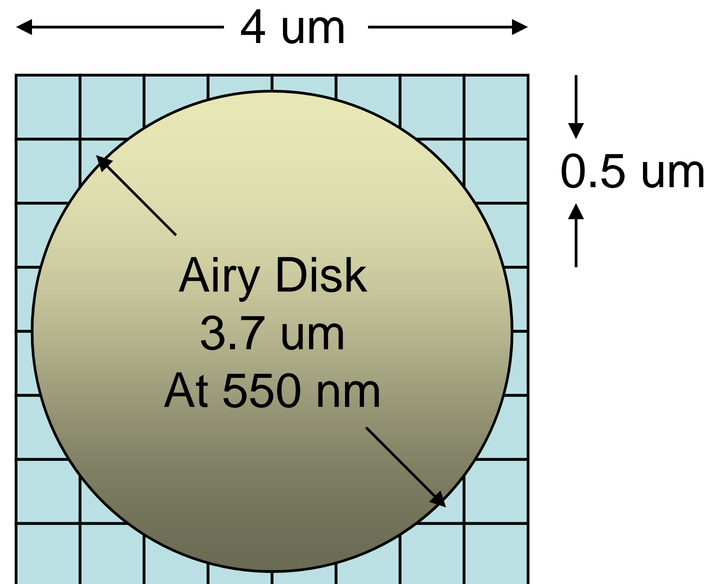
UDTV Camera

What to do with gigapixel sensors?

Or how I spent part of my retirement

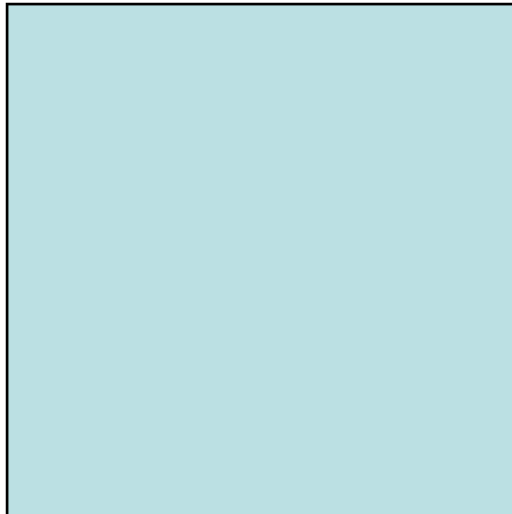
Sub-Diffraction Limit (SDL) Pixels

- Consider a pixel 0.5 microns x 0.5 microns
- A sensor of 24 mm x 12 mm is 48,000 x 24,000 pixels or 1.152 gigapixels.



Same F#, Scene, Exposure

4 um pixel



0.5 um pixel

5000 e-/exposure
Shot noise SNR = 71:1
Capacity 20,000 e-
5 e- read noise
Dynamic range = 72 dB

78 e-/exposure
Shot noise SNR = 8.8:1
Capacity 312 e-
5 e- read noise
Dynamic range = 36 dB

SDL Pixels Hardly Make Sense

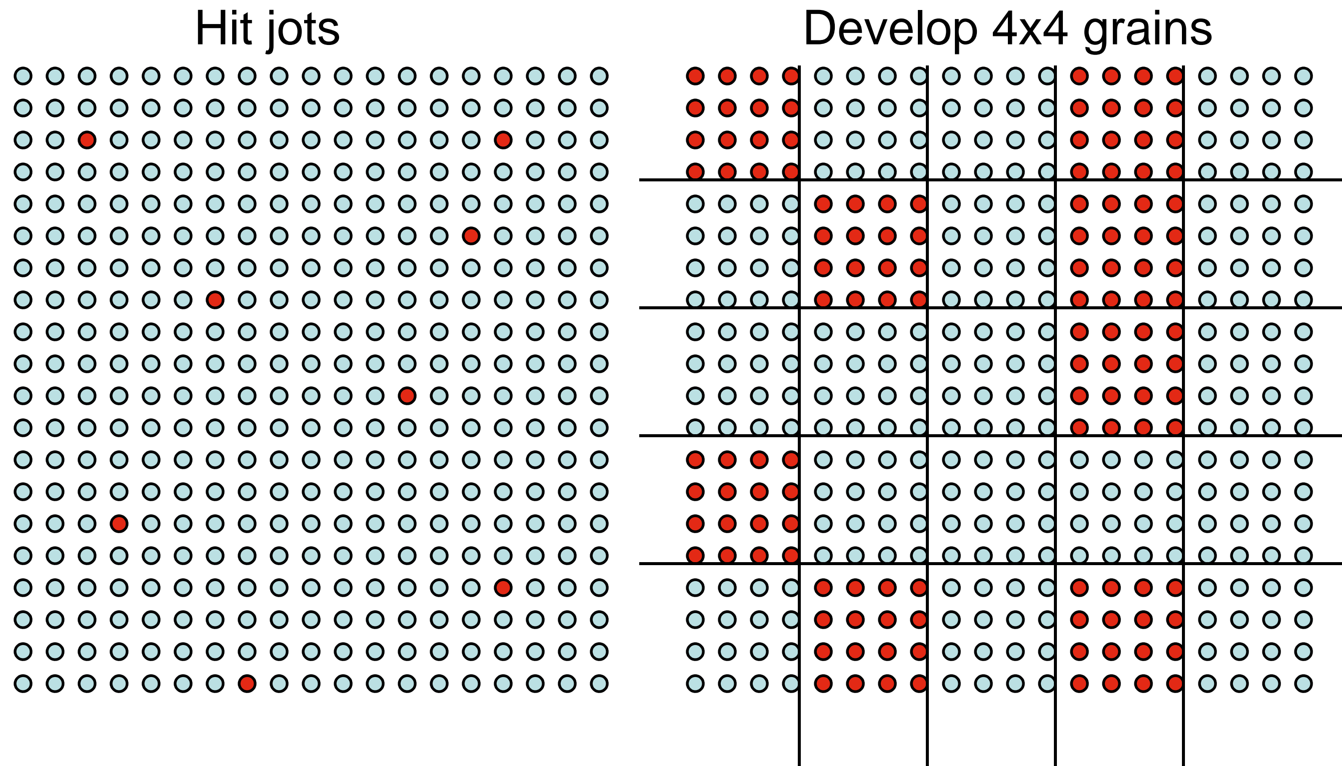
- Can’t collect much light or charge
- Can’t hold much charge
- Can’t image details at pixel resolution
- Uniformity questionable

What to do with SDL Pixels?

- Oversampling of spatial and color information?

Digital Film

- Each pixel could act like a binary detector (photon hit or not) – call it a "jot"
- Jot doesn't need any capacity or much uniformity
- Trade off grain size (resolution) and "film speed"
- D-Log H exposure behavior



Making Nano-scale Pixels

- Pixels need not be silicon PN-junction-like – just need to be able to "flip" if hit by photon
- Quantum dots?
- Molecular pixels?
- a-Si:H or organic pixels?
- Probably still need silicon readout.