Integrated Multi-Aperture Imaging

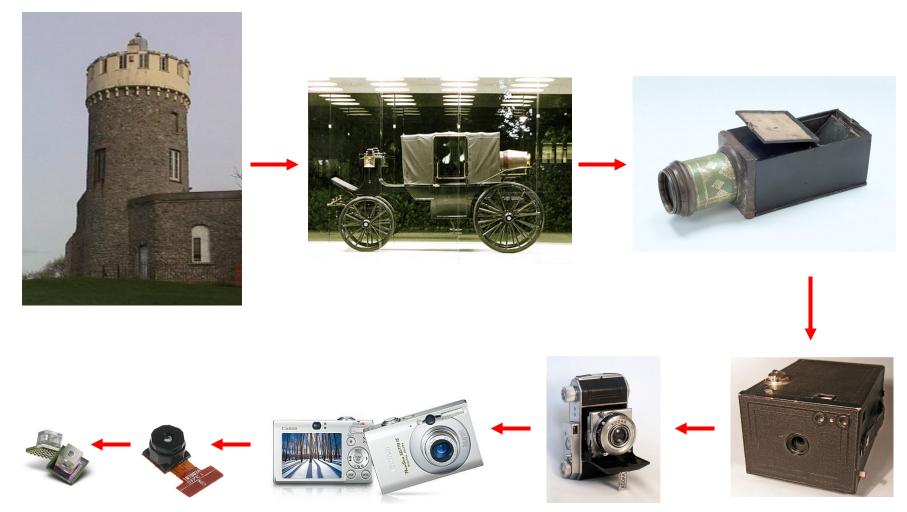


SIGGRAPH2008

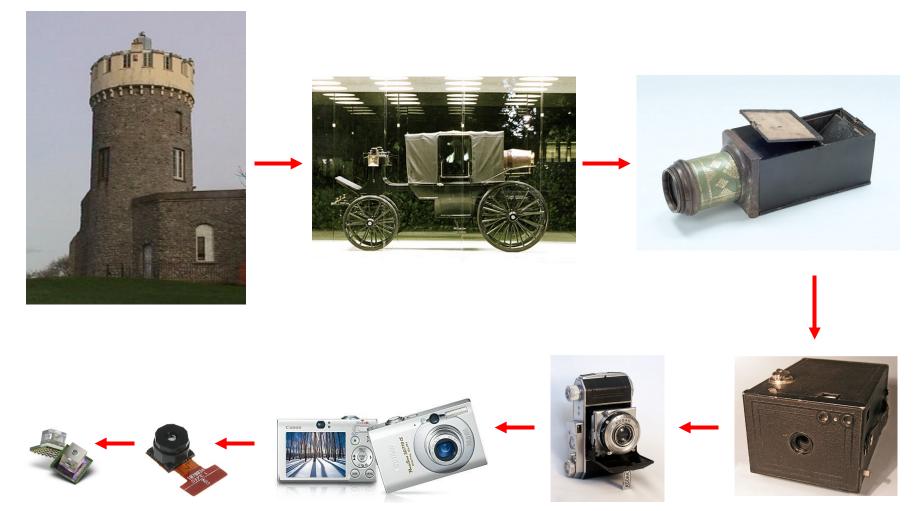


Keith Fife, Abbas El Gamal, Philip Wong Department of Electrical Engineering, Stanford University, Stanford, CA 94305

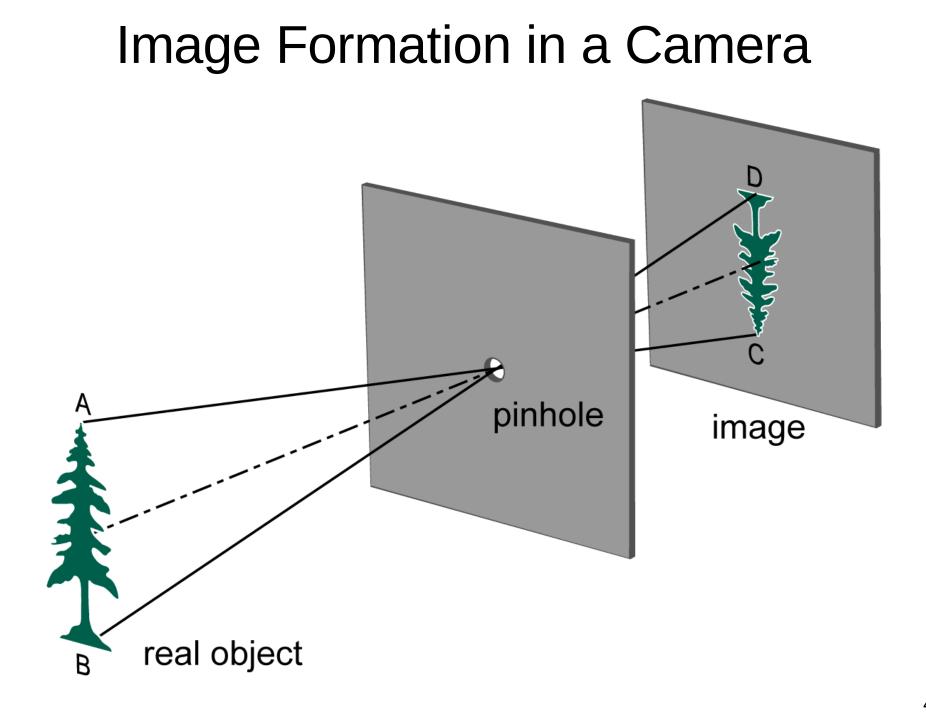
Camera History

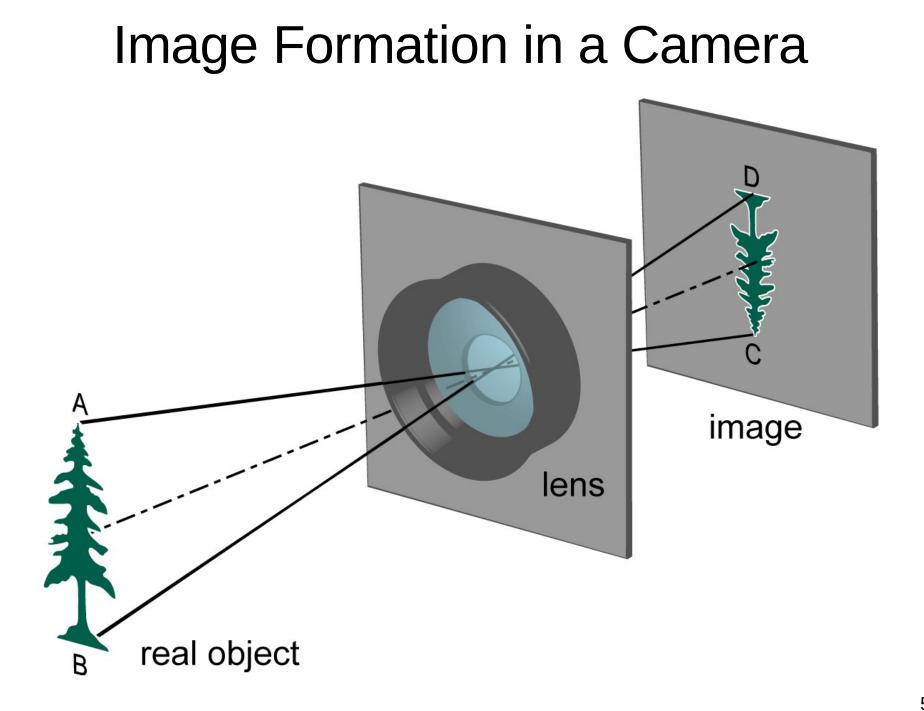


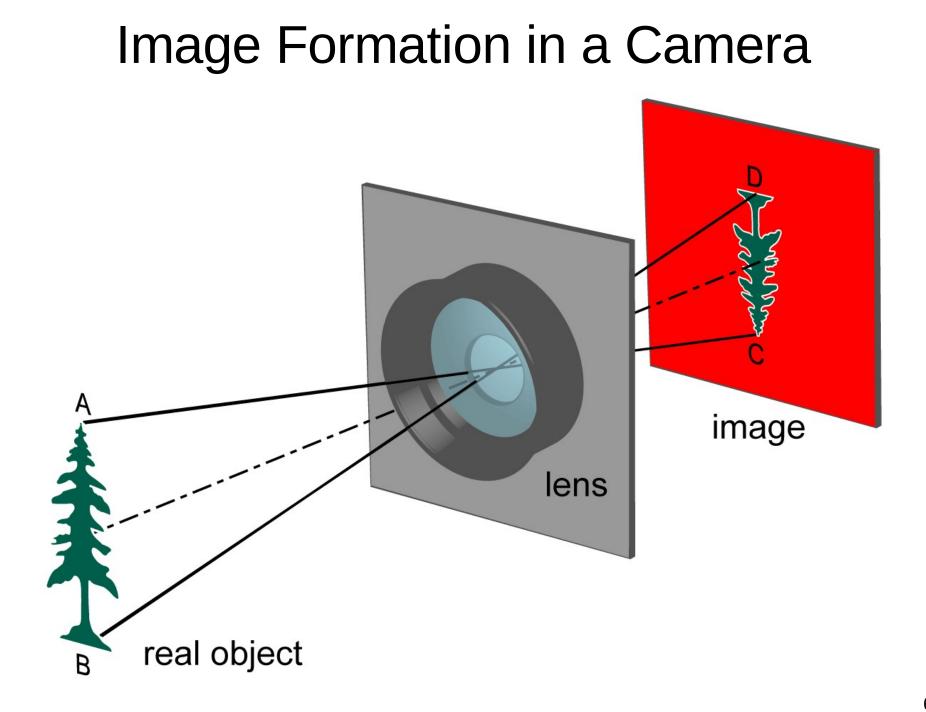
Camera History



 Despite progress, each of these cameras form images in the same way



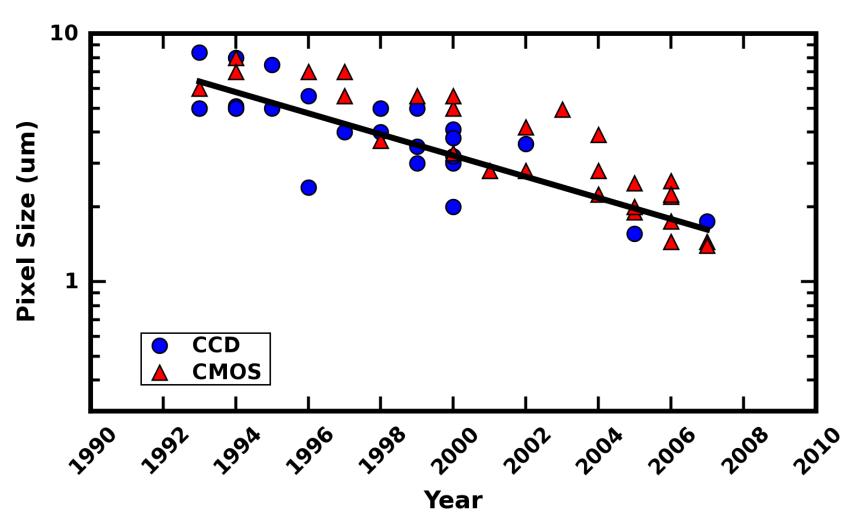




Recent Pixel Scaling

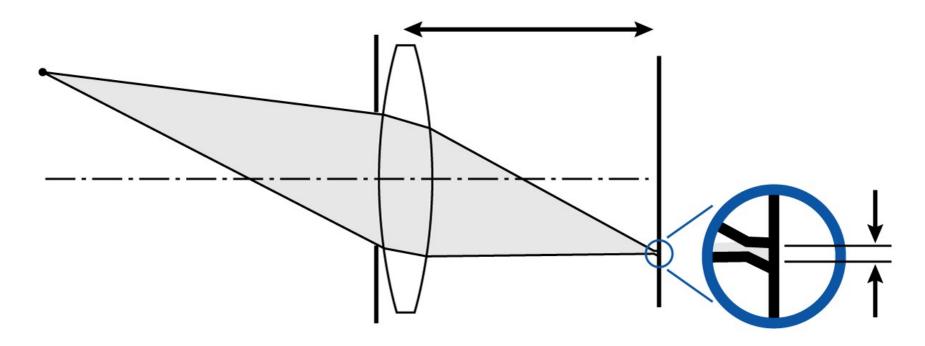
- Increase spatial resolution
- Decrease format size

Pixel Sizes reported at IEDM, ISSCC, IISW

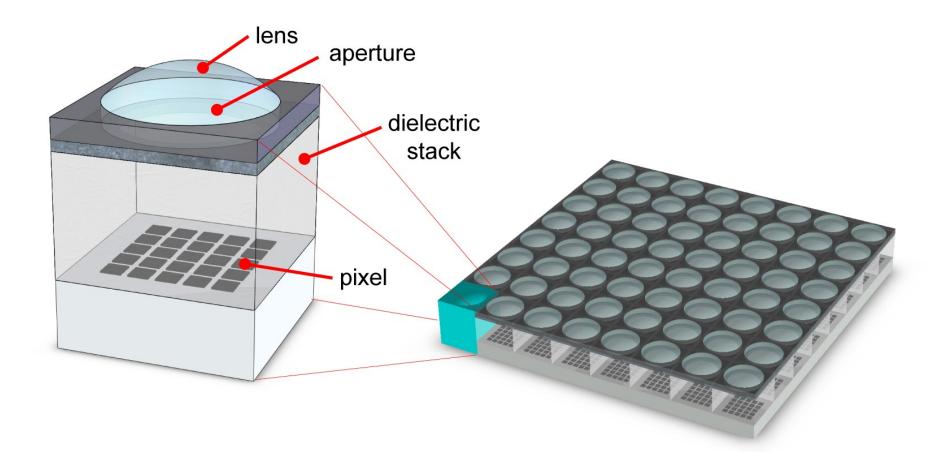


Spot Size Limitation

- Point in object space is focused to a small spot in focal plane
- Spot size is limited and dependent on:
 - Relative size of the aperture
 - Aberrations of lens
 - Wavelength of the source

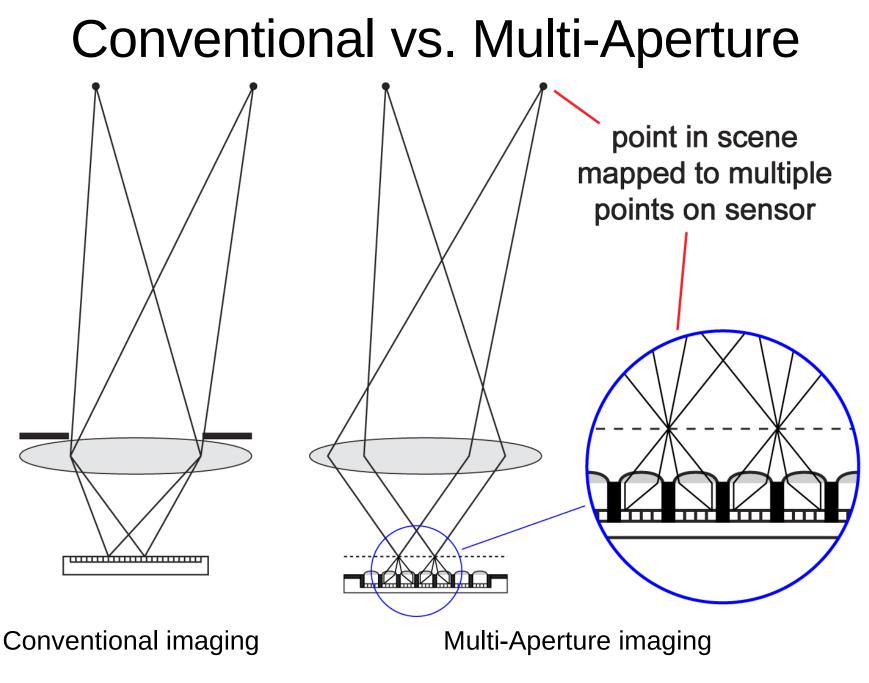


Multi-Aperture Image Sensor



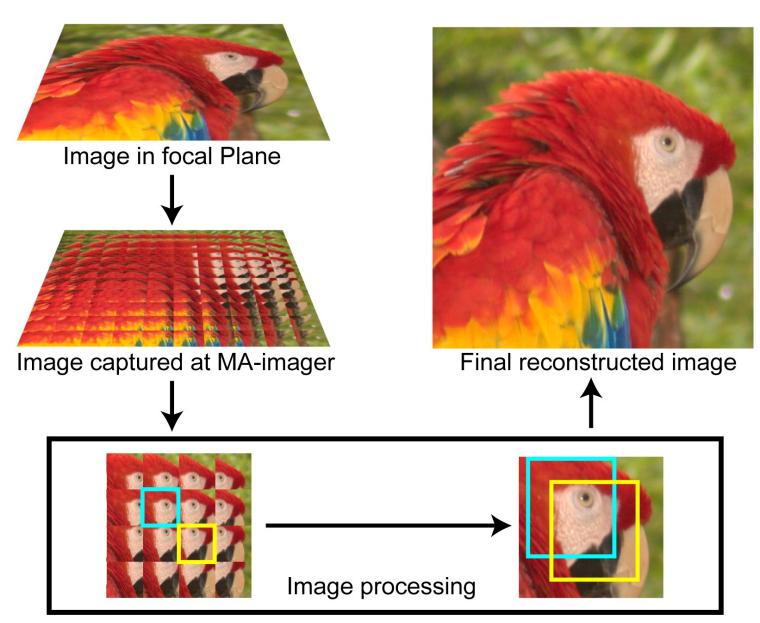
Imager subarray with integrated optics

Imager subarrays integrated to form multi-aperture array



* K. Fife, A. El Gamal and H.-S. P. Wong, CICC 2006, p281-284

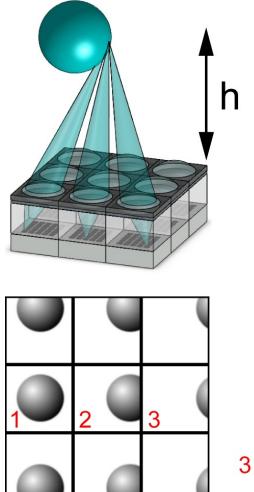
Multi-Aperture Imaging

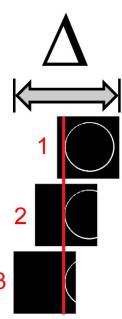


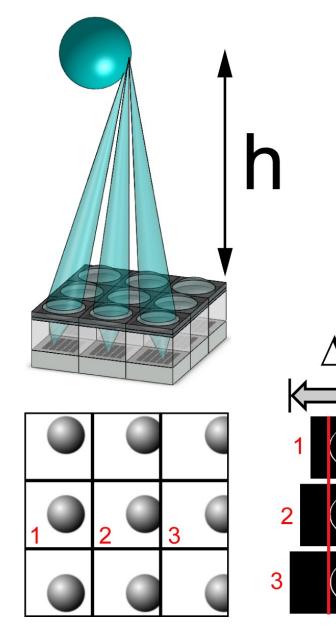
Benefits of Multi-Aperture Imaging

- Capture depth information
- Close proximity imaging
- Achieve better color separation
- Reduce requirements of objective lens
- Increase tolerance to defective pixels

Depth from Multi-Aperture

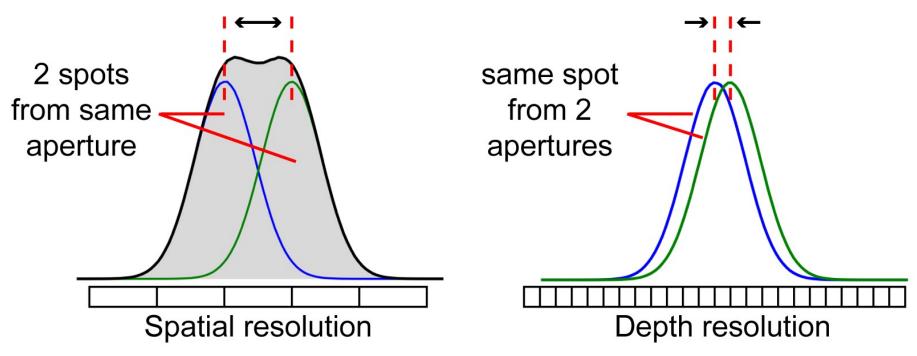




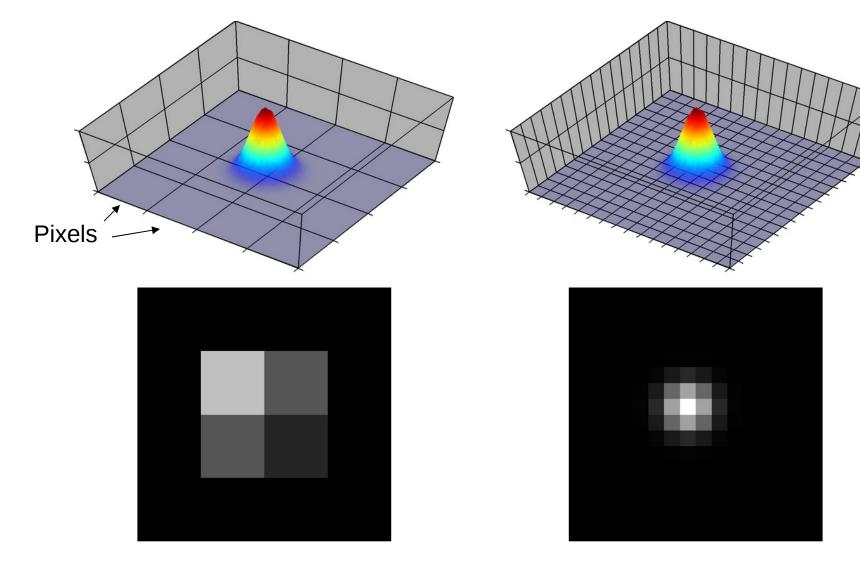


Why Use Small Pixels?

- Depth resolution improves with pixels smaller than the spot size
- Spatial resolution is limited by the spot size
- Depth resolution is limited by accuracy in localization of the spot



Feature Localization vs. Pixel Size



Poor location accuracy

High location accuracy

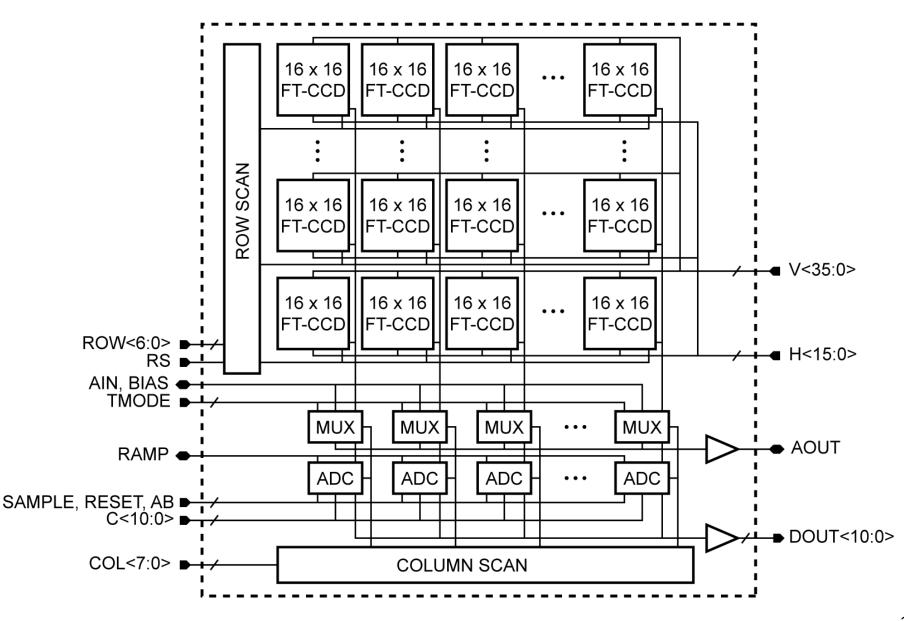
Fabricated Multi-Aperture Imager

ROW SCAN	166 x 76 APERTURE ARRAY 16 x 16 PIXELS PER APERTURE	
BIAS	ADC/COLUMN SCAN	4 4 4

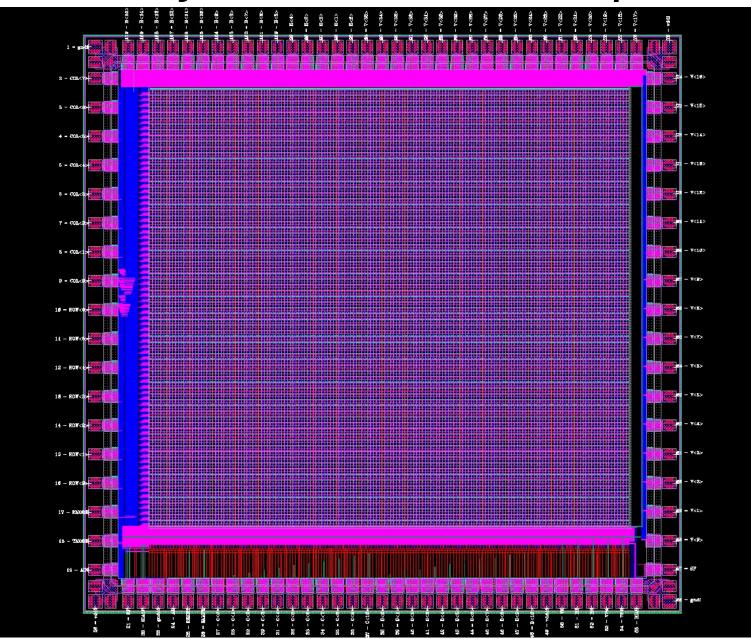
- 0.11µm CMOS (TSMC)
- Chip size: 3.0 x 2.9mm²
- 166 x 76 aperture array
- 16 x 16 pixel FT-CCD per aperture
- Pixel size: 0.7 μm
- Max frame rate: 15fps
- ADC resolution: 10 bit
- Power: 10.45mW

* Local optics are not integrated on this chip.

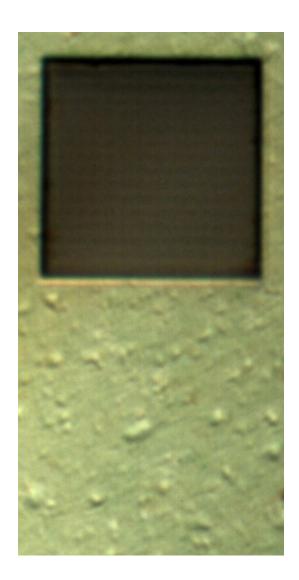
Block Diagram of Fabricated Chip

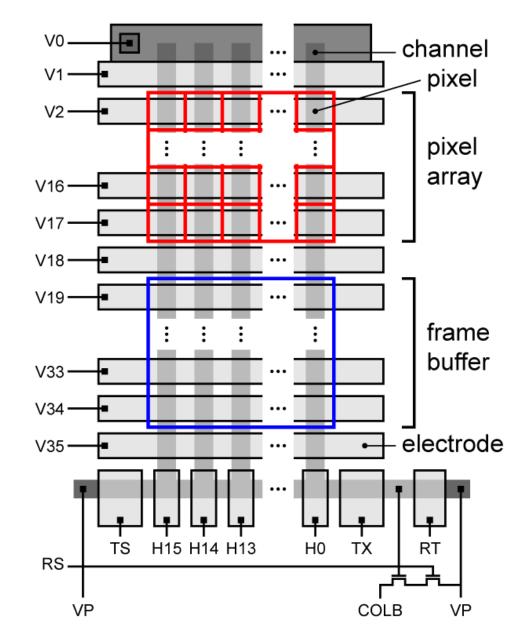


Layout Masks for Chip



16 x 16 FT-CCD schematic

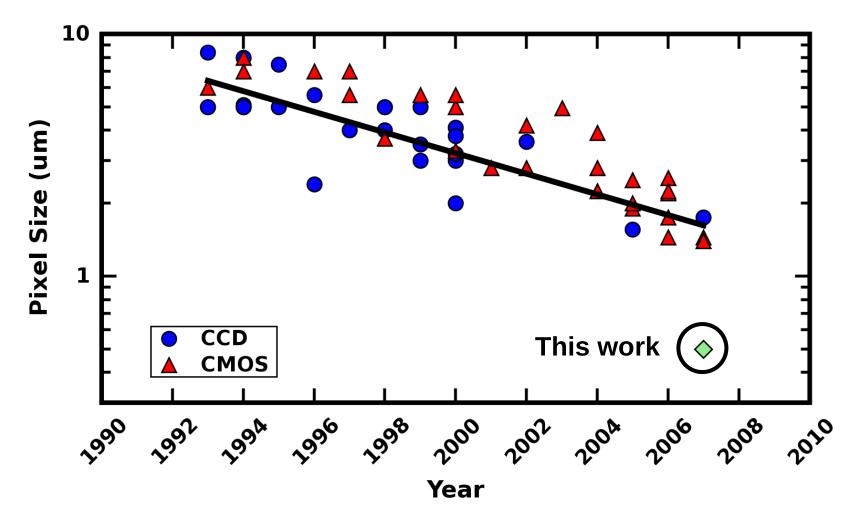




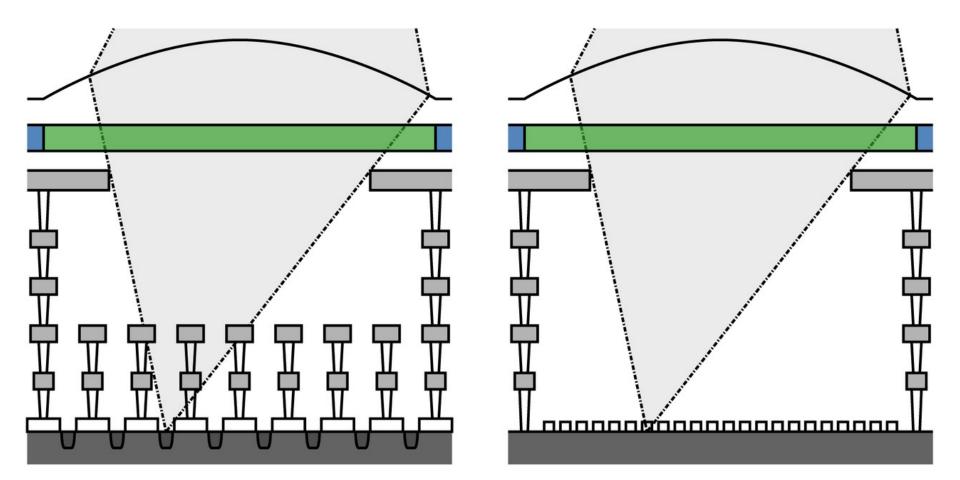
Relative Pixel Size for This Work

- Increase spatial resolution
- Decrease format size

Pixel Sizes reported at IEDM, ISSCC, IISW



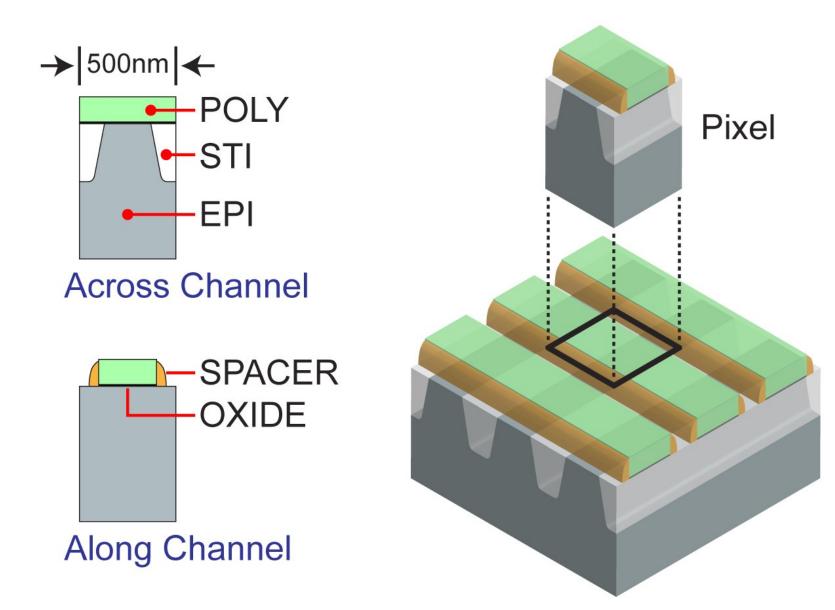
Multi-Aperture Optical Stack



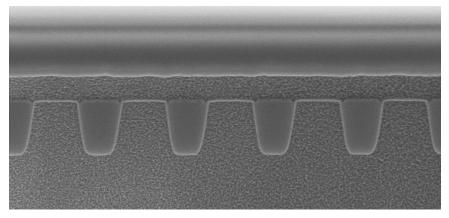
Using CMOS active pixels

Using FT-CCD pixels

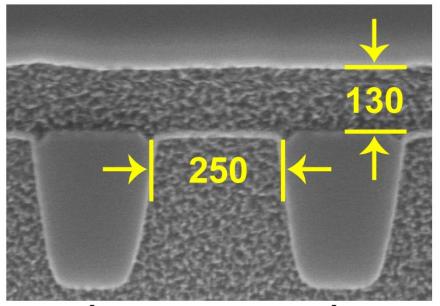
The Submicron Pixel



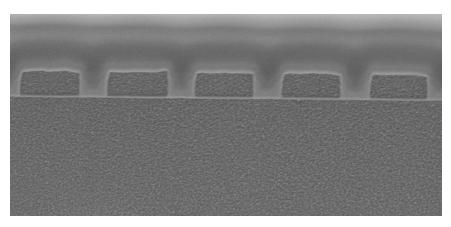
CCD Structure



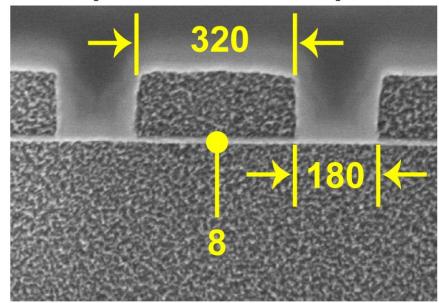
STI forms the channel stop



← 500 → (nm)

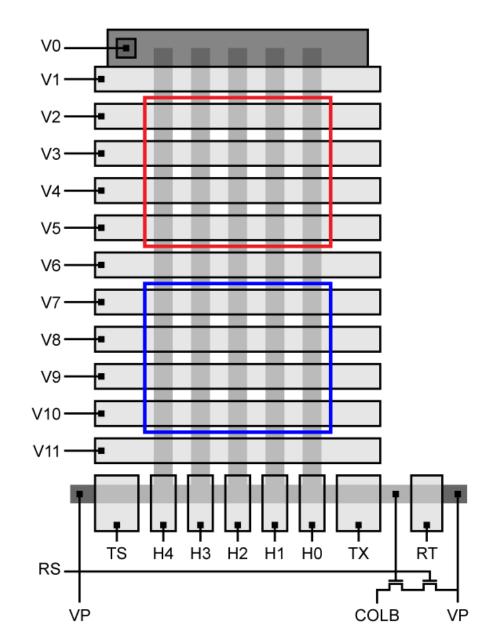


Single-level poly electrodes

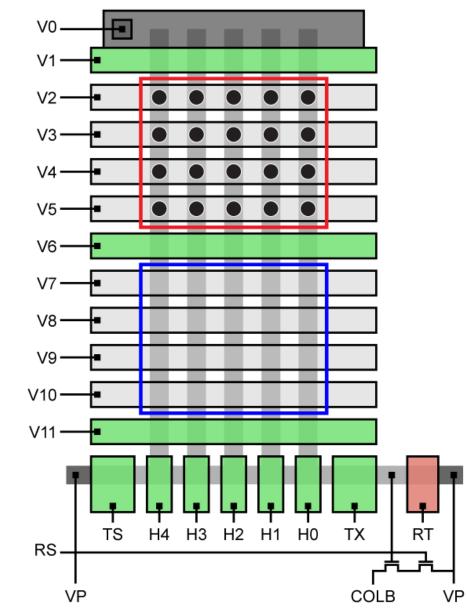


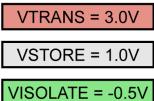
Operation

- Flush
- Integrate
- Frame Transfer
- Horizontal Readout

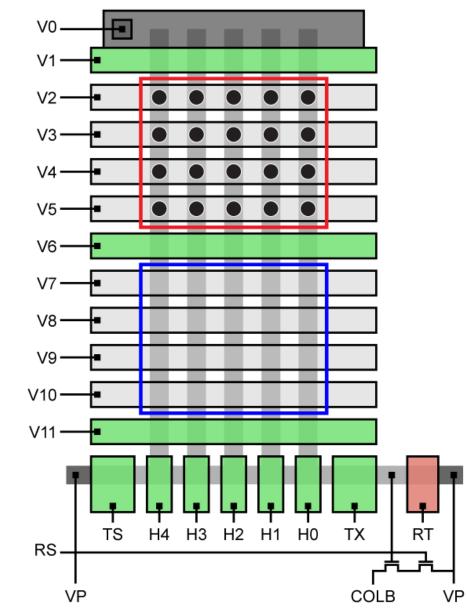


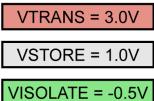
Operation (Flush)



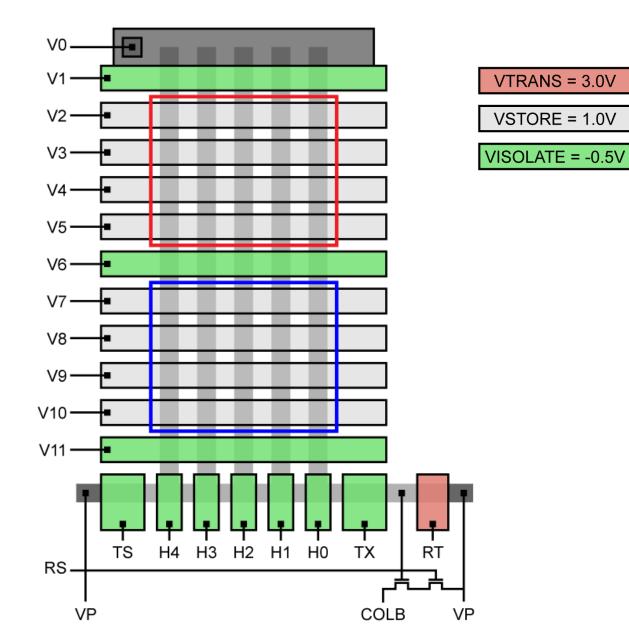


Operation (Flush)

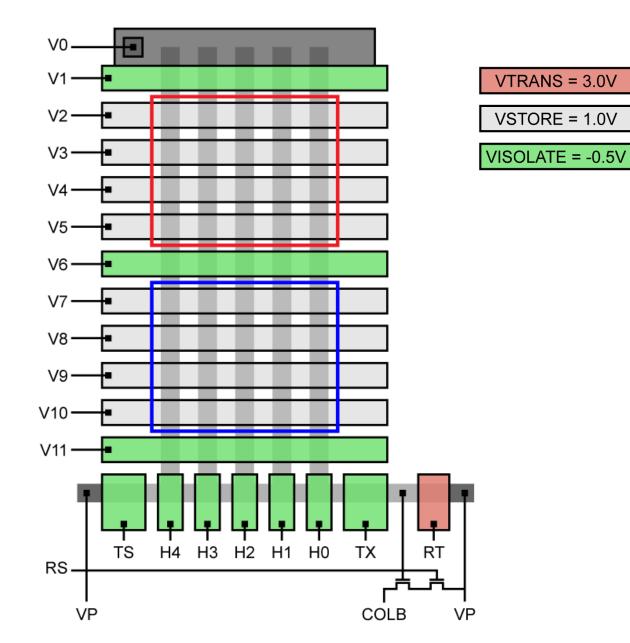




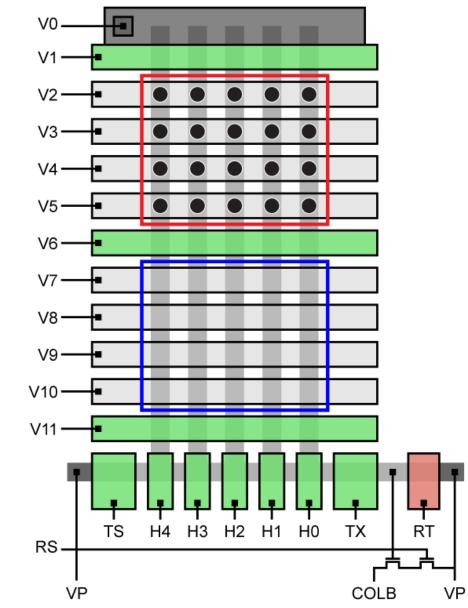
Operation (Integrate)



Operation (Integrate)

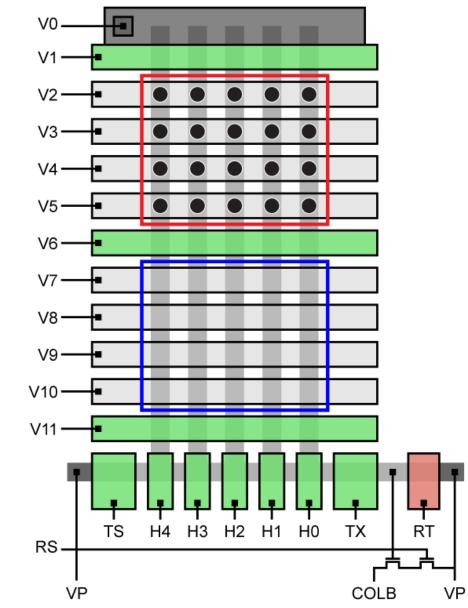


Operation (Frame Transfer)



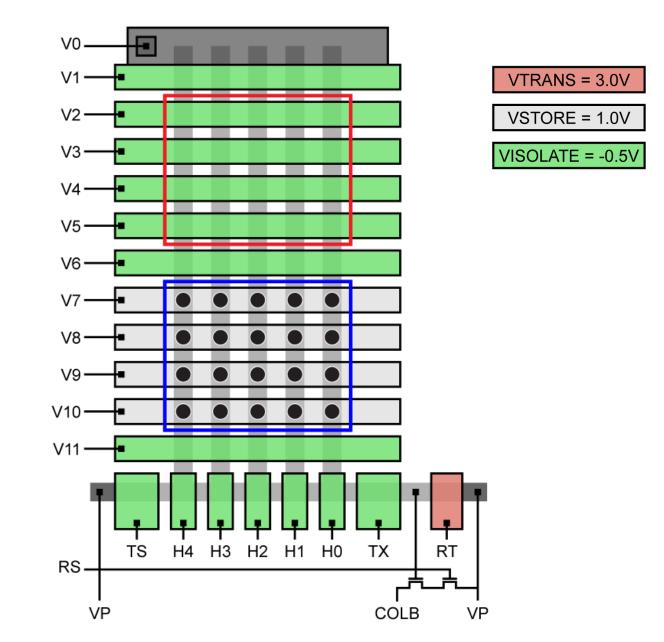
VTRANS = 3.0V
VSTORE = 1.0V
VISOLATE = -0.5V

Operation (Frame Transfer)

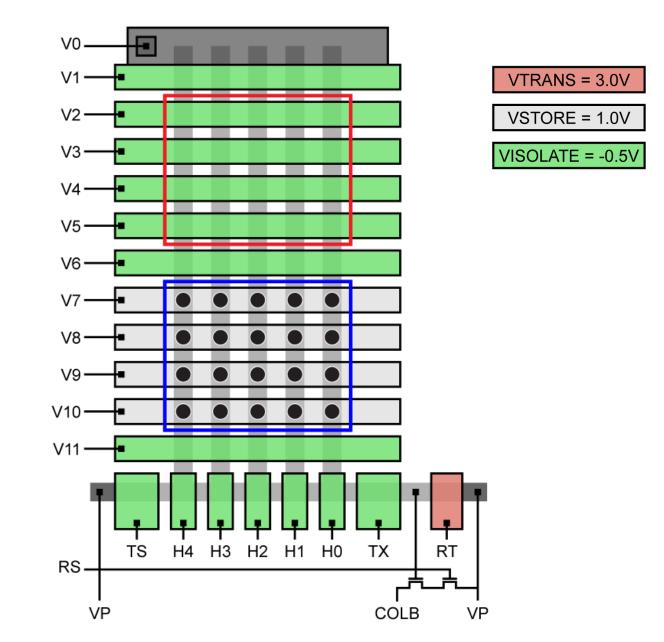


VTRANS = 3.0V
VSTORE = 1.0V
VISOLATE = -0.5V

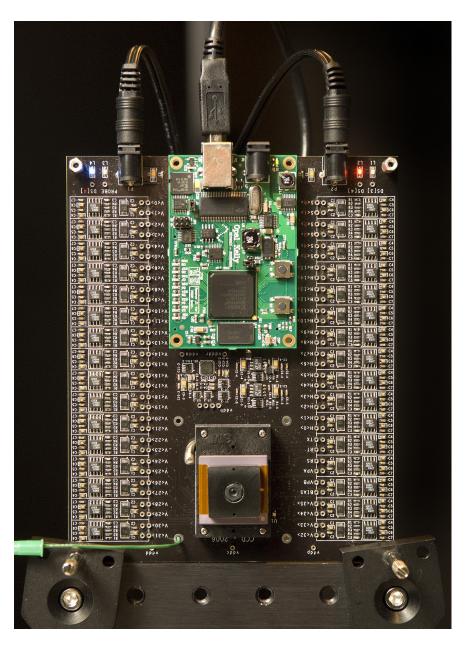
Operation (Horizontal Transfer)



Operation (Horizontal Transfer)

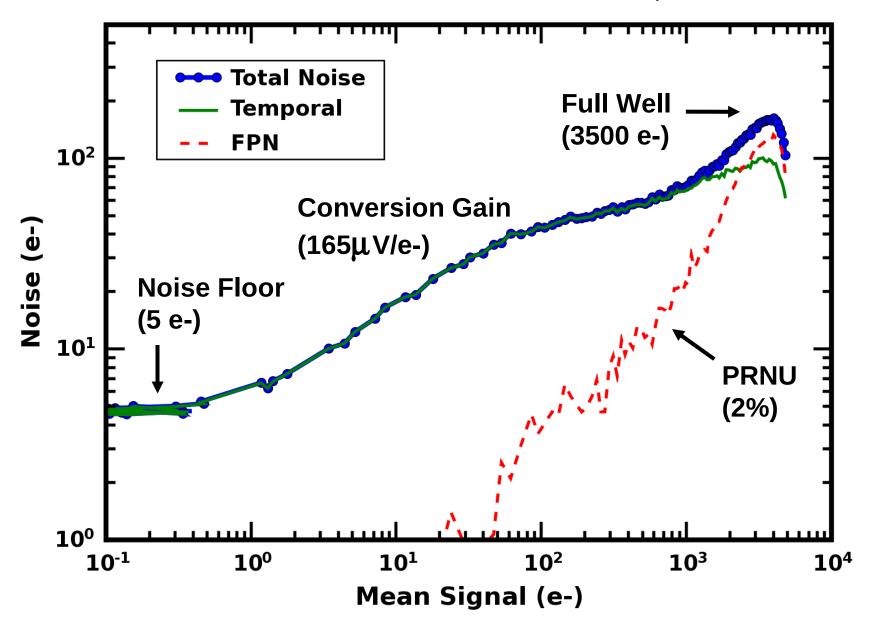


Test Board

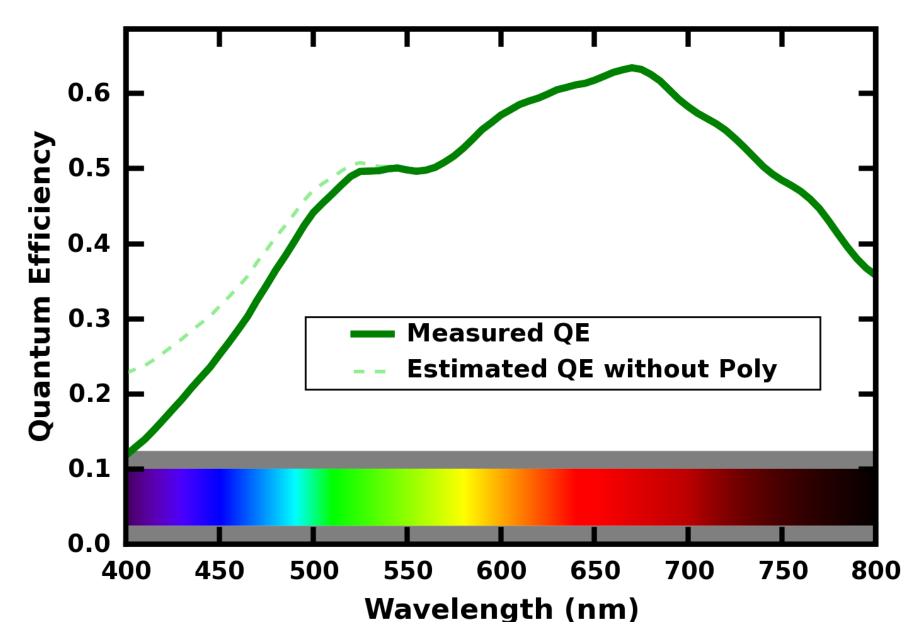


- FPGA control of CCD waveforms and chip operation.
- Python based sequencer run from FPGA RAM.
- USB 2.0 data transfer.

Photon Transfer Curve (0.7µm Pixel)



Measured Quantum Efficiency



Measured Pixel Characteristics

Well capacity	3500 e-			
Conversion gain	165 μV/e-			
Sensitivity at 550 nm	0.15V/lux-sec			
QE at 450, 550, 650 nm	20, 48, 65 %			
Pixel read noise	5 e- rms (1mV)			
Dark current at RT	33 e-/sec (5.5 mV/sec)			
DSNU	35 % rms			
PRNU	2 % rms			
Peak SNR	35 dB			
Dynamic range	57 dB			

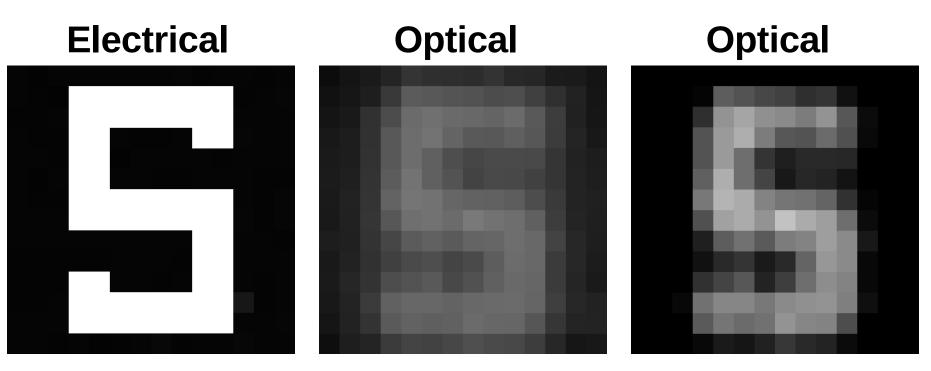
Sample Image

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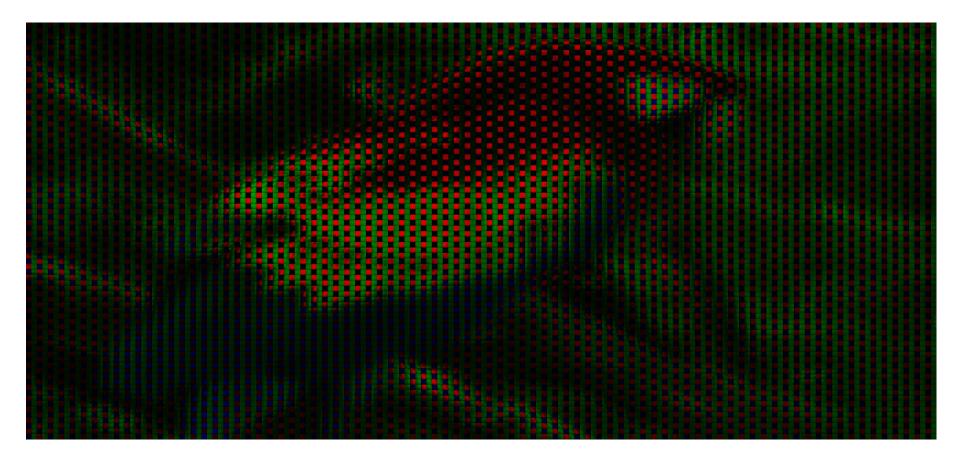
Images from Single Subarray



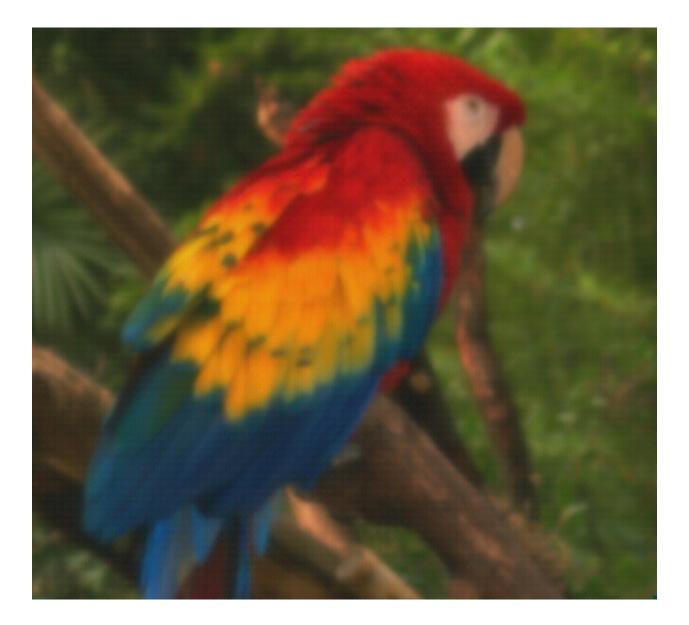
3000 electron charge packets from fill/spill input Raw data

Captured with F/2.8, f=6mm lens at 1/10 sec **Added contrast**

Raw Image Captured with Multi-Aperture Views



Processed Multi-Aperture Image



Summary

- Designed and characterized the first integrated multi-aperture image sensor
- Achieved good imaging performance with submicron pixels
 - FT-CCD structure in deep submicron CMOS
 - Ripple charge transfer
- Many potential applications or benefits
 - Depth
 - Close proximity imaging
 - Color imaging with good spectral separation
 - High defect tolerance
 - Relaxed external optical requirements
- Results suggest that further scaling while maintaining performance is possible

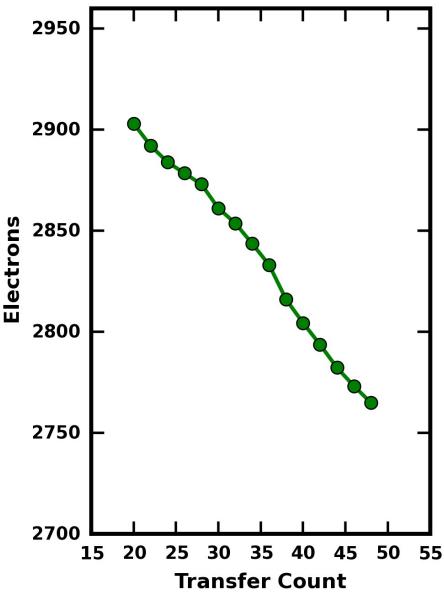
Acknowledgement

- Hertz Foundation

 Fellowship support
- TSMC
 - C.H. Tseng, David Yen, C.Y. Ko, J.C. Liu, Ming Li, and S.G. Wuu for process customization and fabrication
- Lane Brooks, MIT EECS
 - Collaboration on the design of the testing platform and software system
- GNU/Linux, FSF, open source community – Providing the best software development tools

Measured Charge Transfer Efficiency

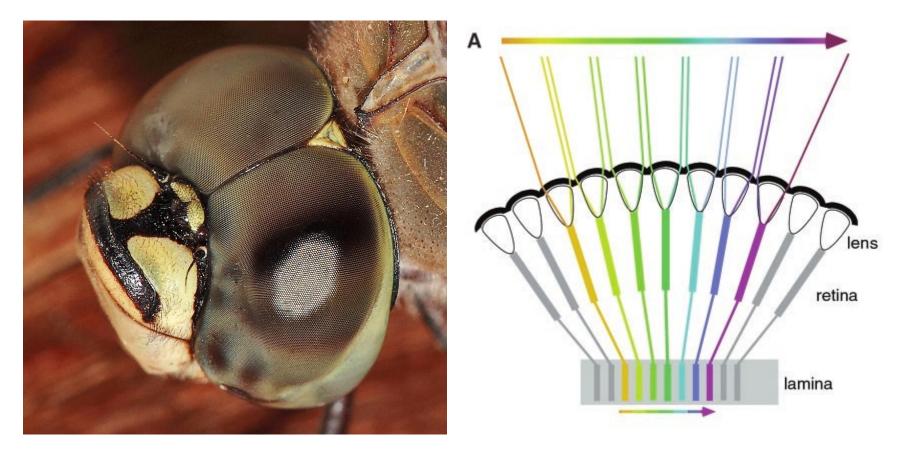
- CTE is 99.9% with 3000 electron charge packets for surface channel
- CTE limited by surface interface traps
- CTE is reduced to 98% if holes are accumulated between storage electrodes.



Is There a Biological Equivalent?



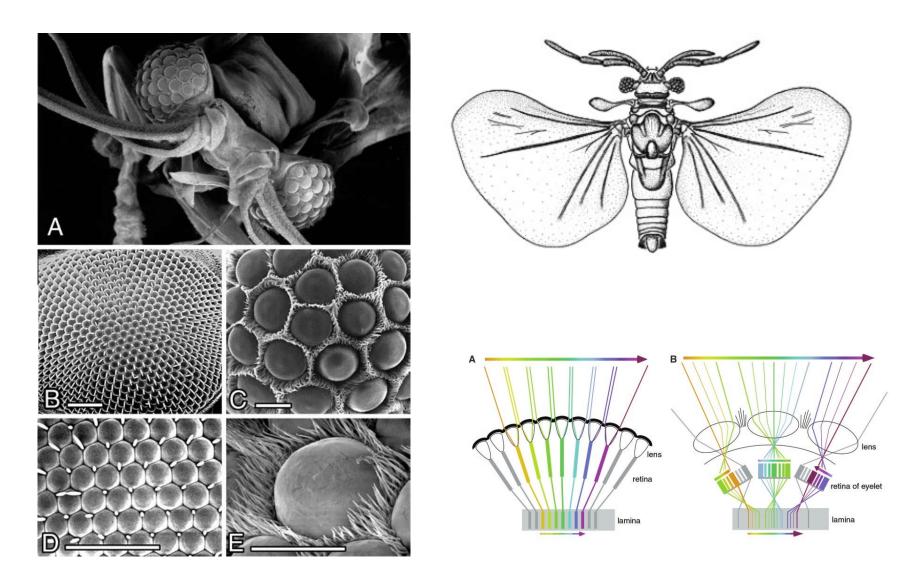
Compound Eye



* Wikipedia, Compound Eye

* Buschbeck, 1999

Eye of the Strepsiptera



* Buschbeck, 1999