Integrated Multi-Aperture Imaging

SIGGRAPH2008

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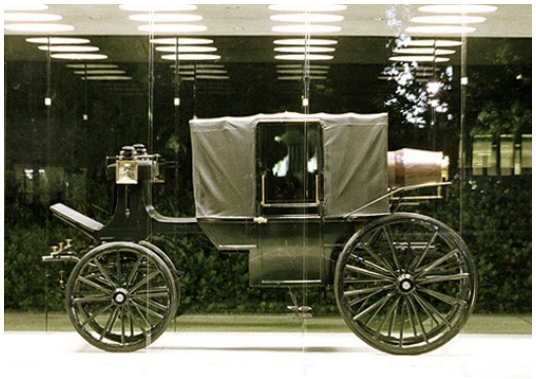
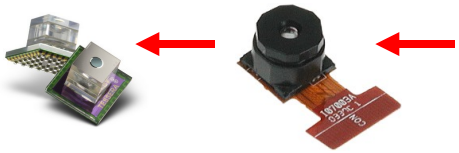
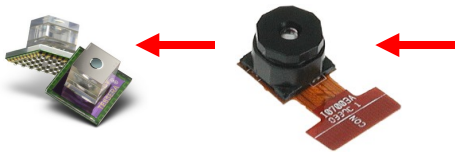
Camera History





Camera History



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

Image Formation in a Camera

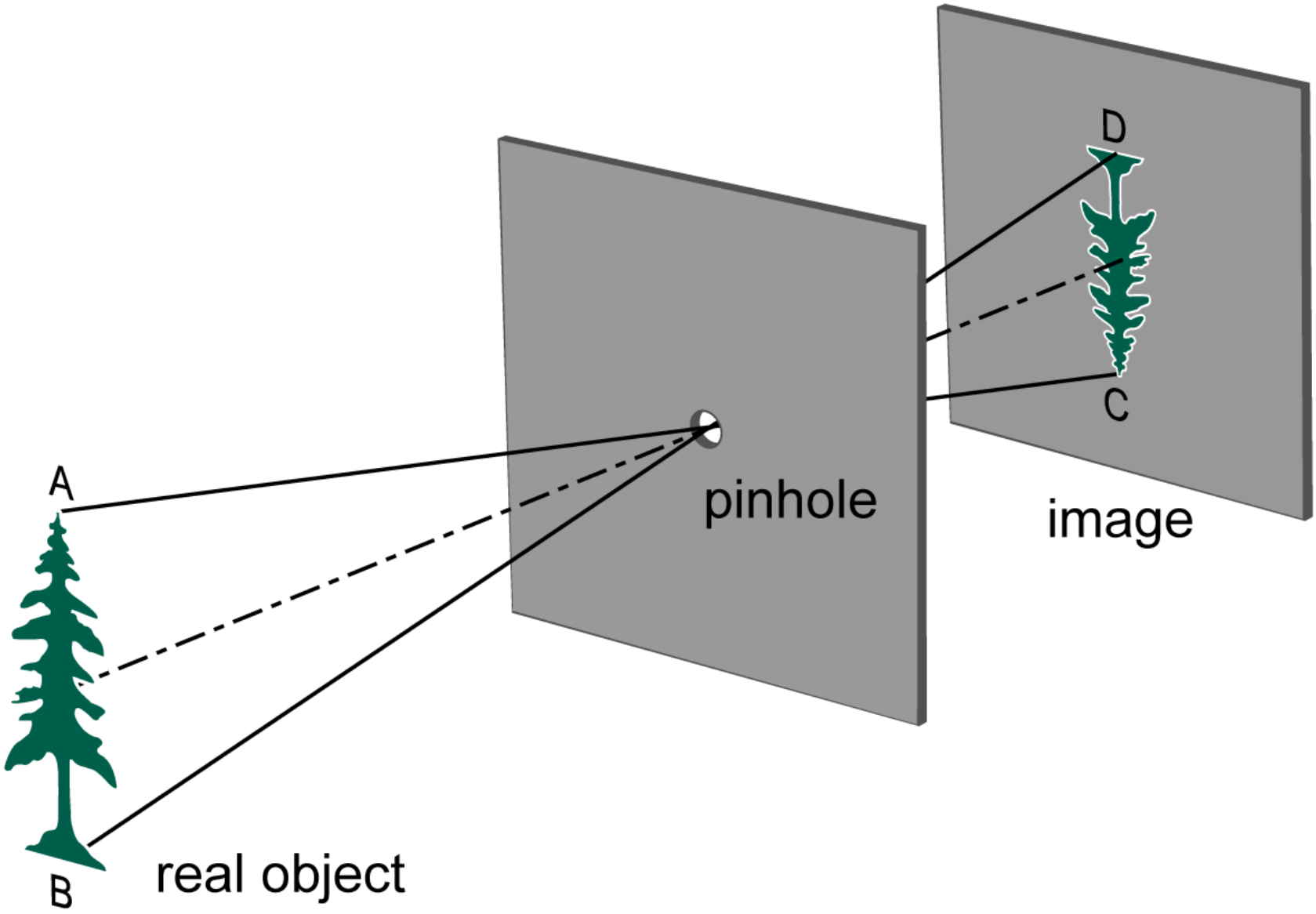


Image Formation in a Camera

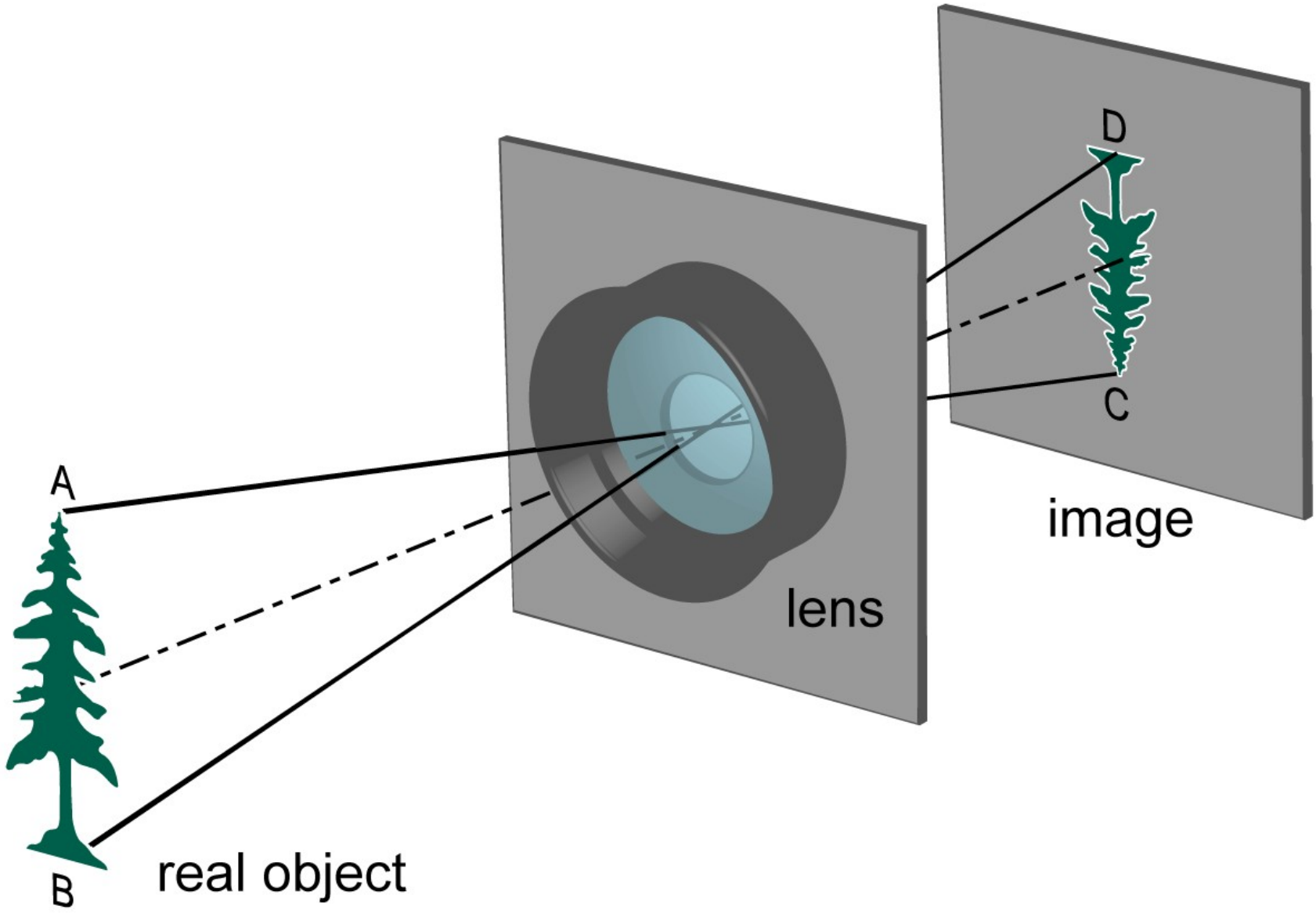
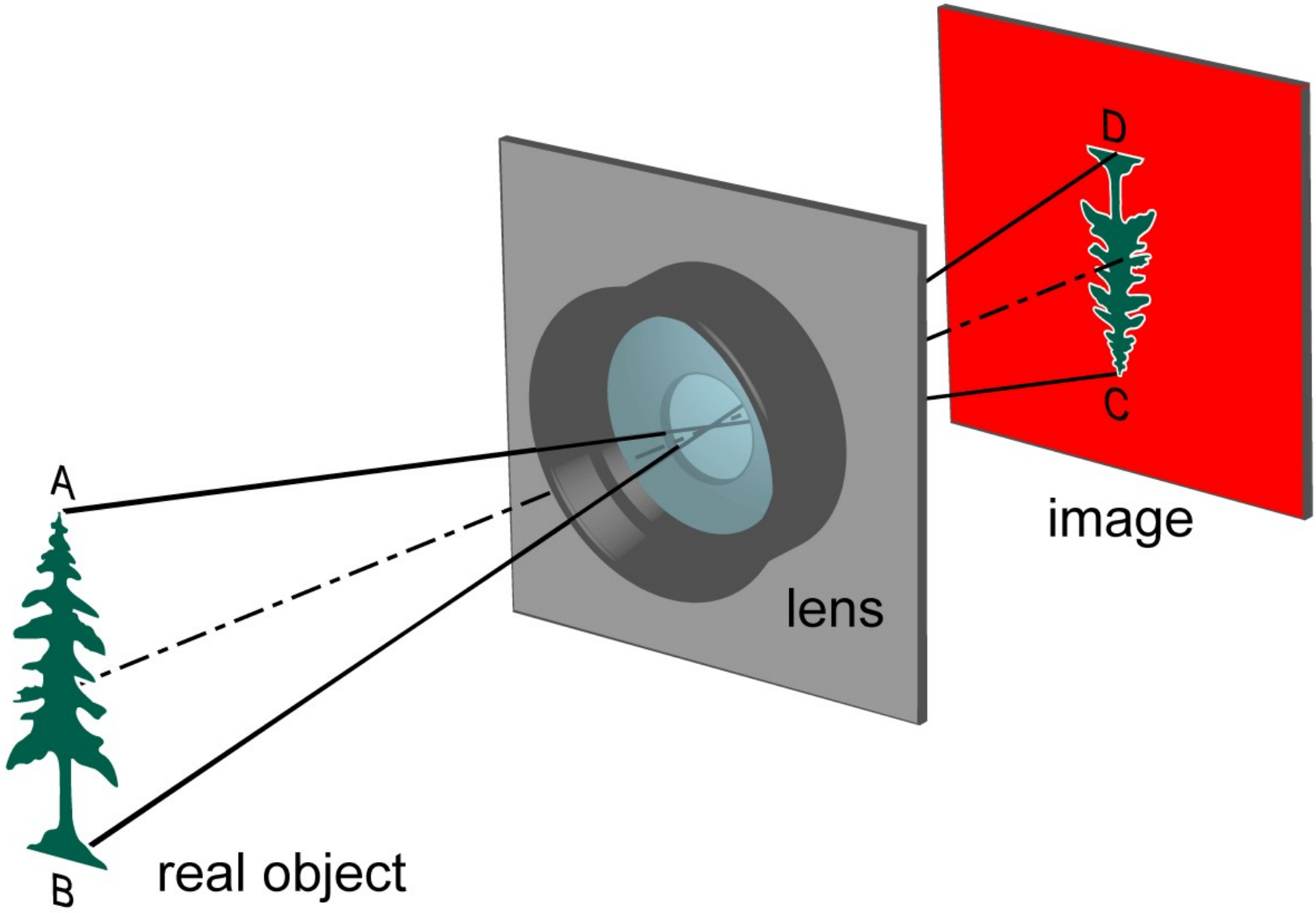


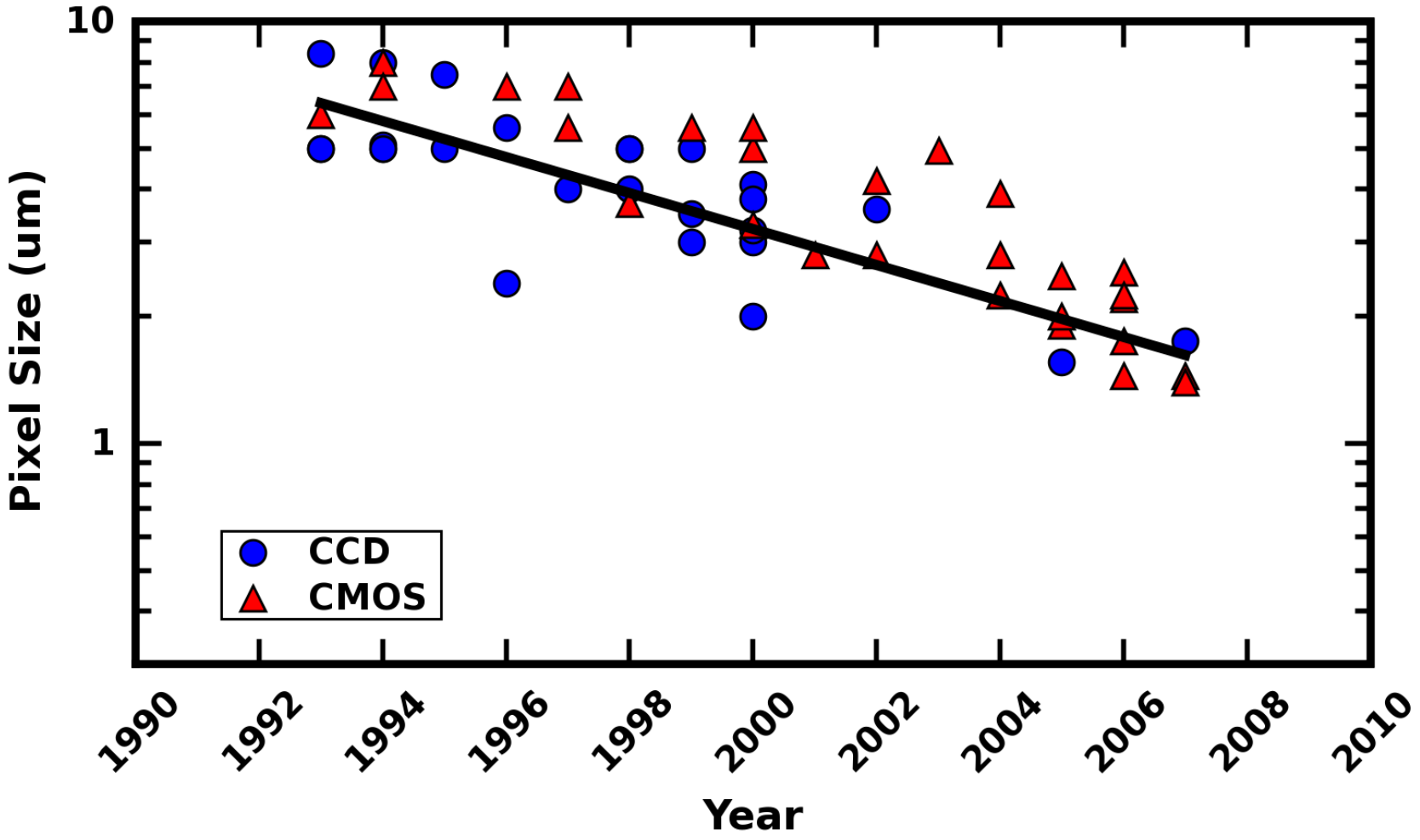
Image Formation in a Camera



Recent Pixel Scaling

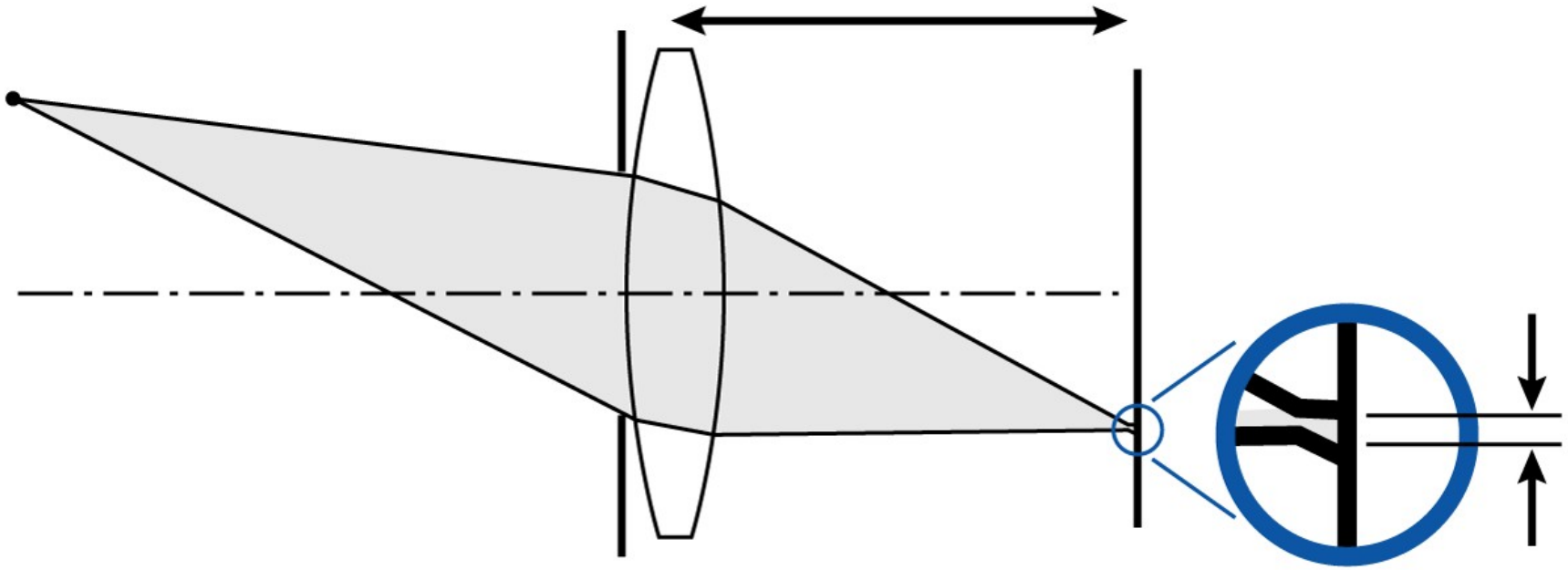
- Increase spatial resolution
- Decrease format size

Pixel Sizes reported at
IEDM, ISSCC, IISW

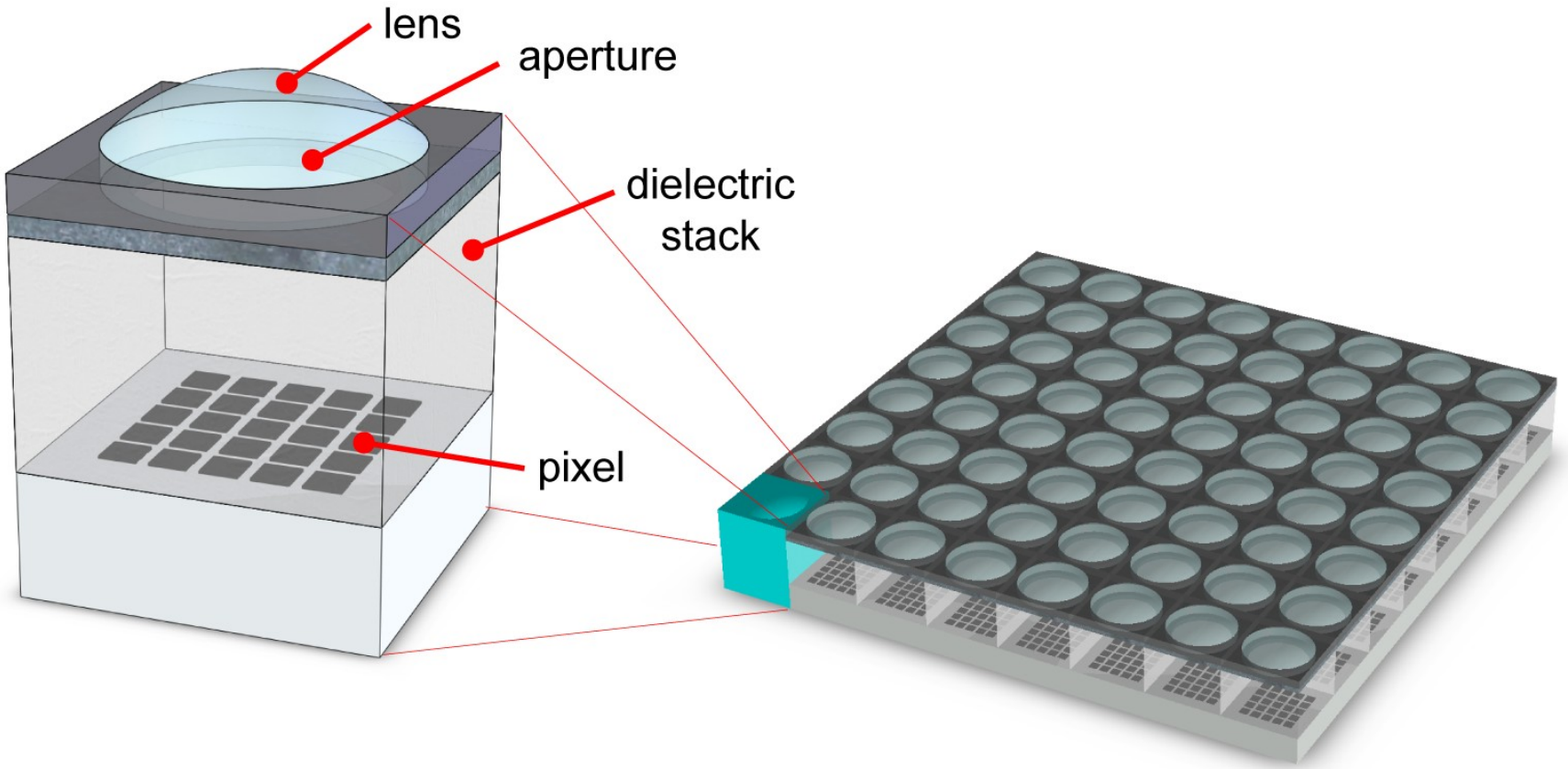


Spot Size Limitation

- 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



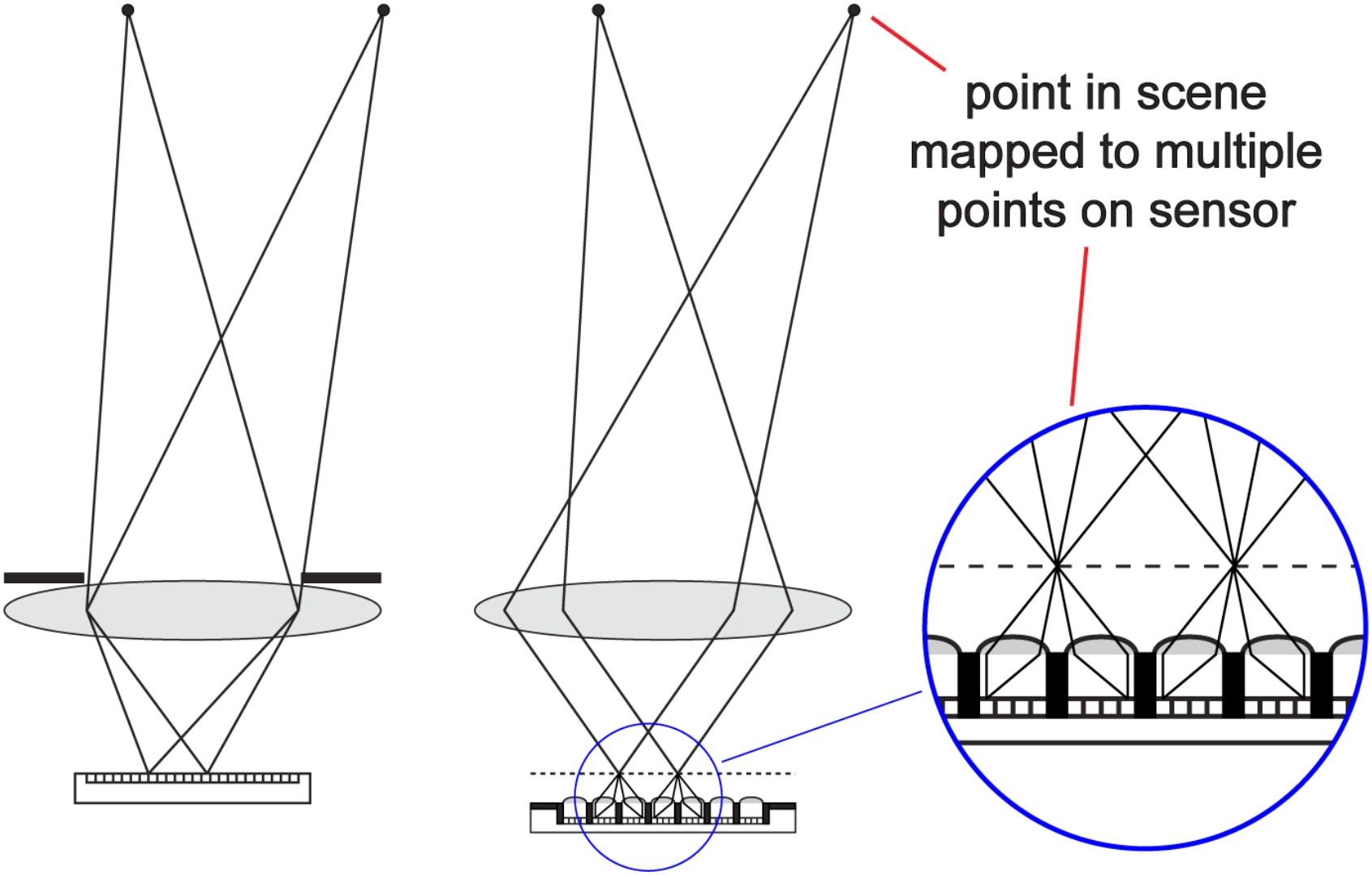
Multi-Aperture Image Sensor



Imager subarray with integrated optics

Imager subarrays integrated to form multi-aperture array

Conventional vs. Multi-Aperture



Conventional imaging

Multi-Aperture imaging

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

Multi-Aperture Imaging

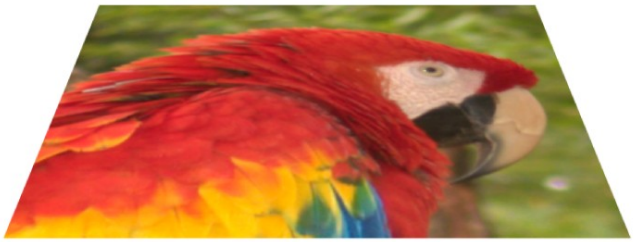


Image in focal Plane

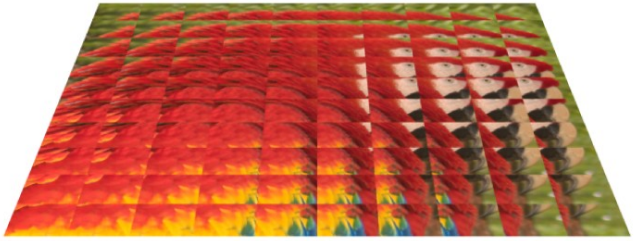
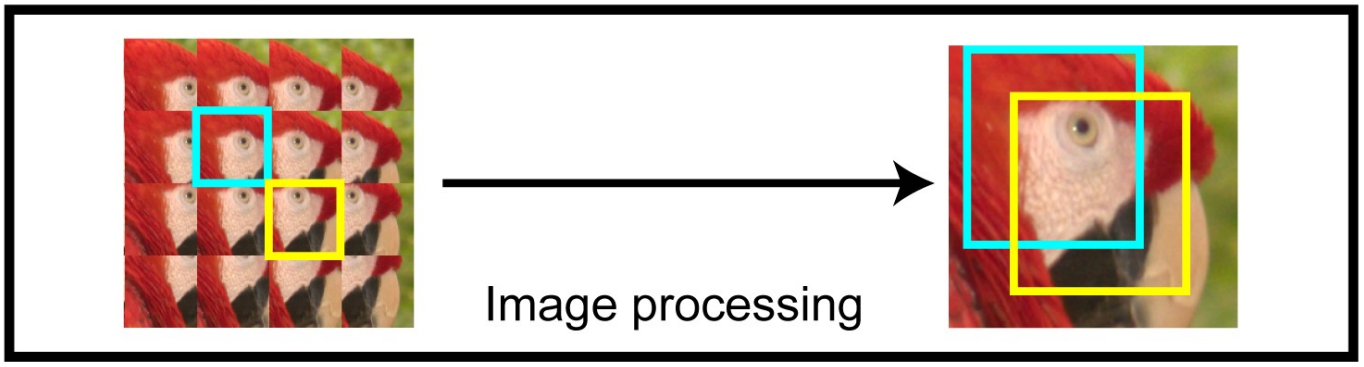


Image captured at MA-imager

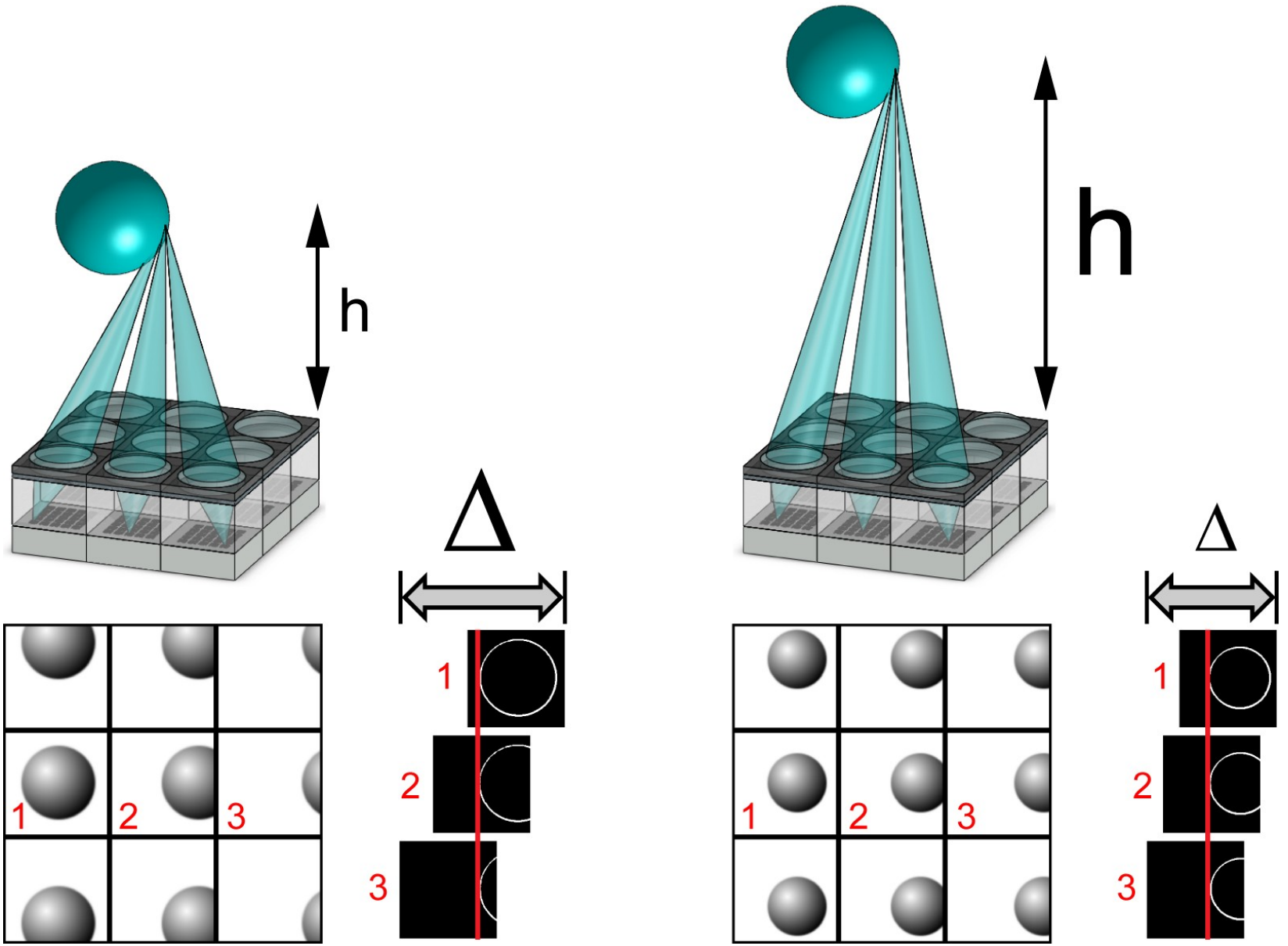
Final reconstructed image



Benefits of Multi-Aperture Imaging

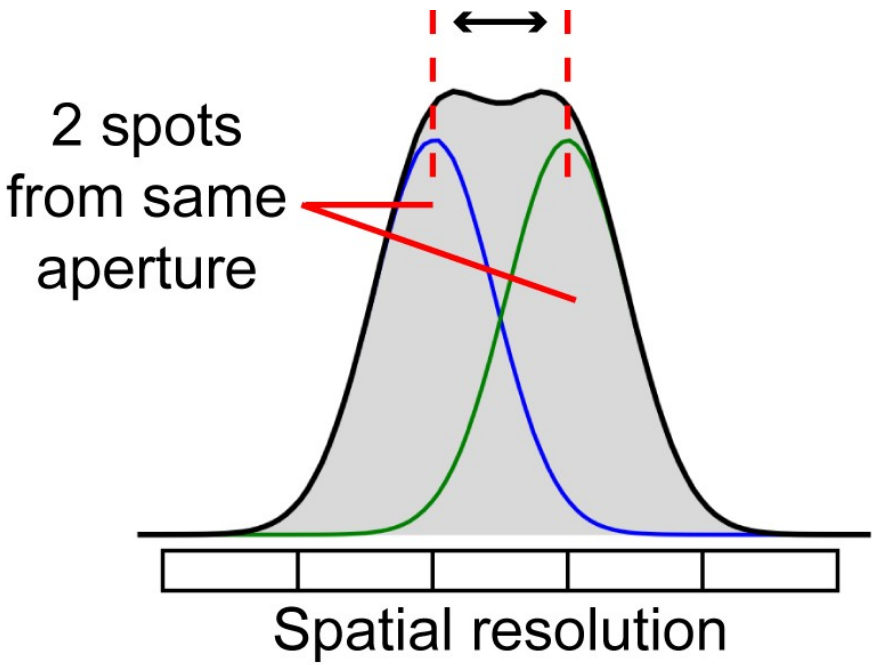
- Capture depth information
- Close proximity imaging
- Achieve better color separation
- Reduce requirements of objective lens
- Increase tolerance to defective pixels

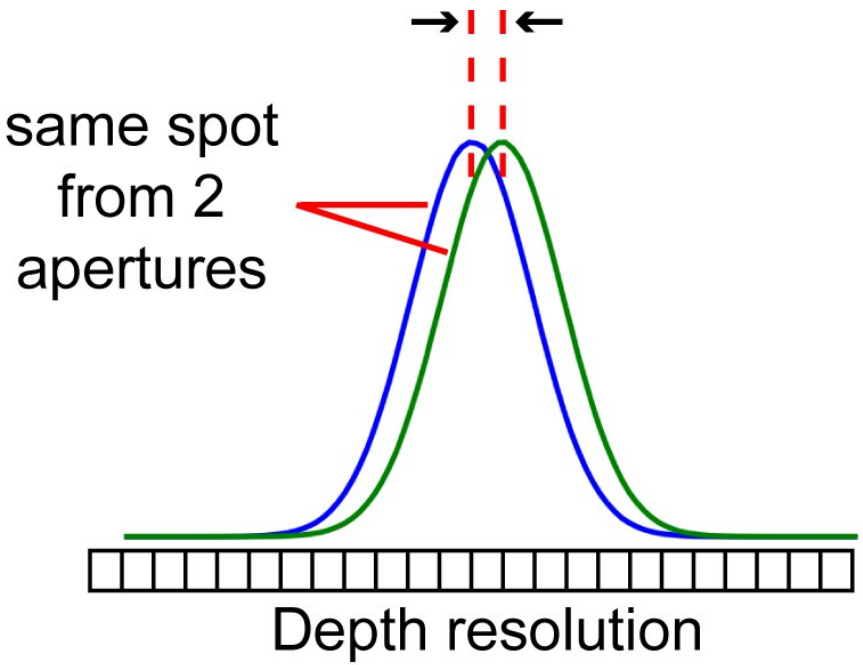
Depth from Multi-Aperture



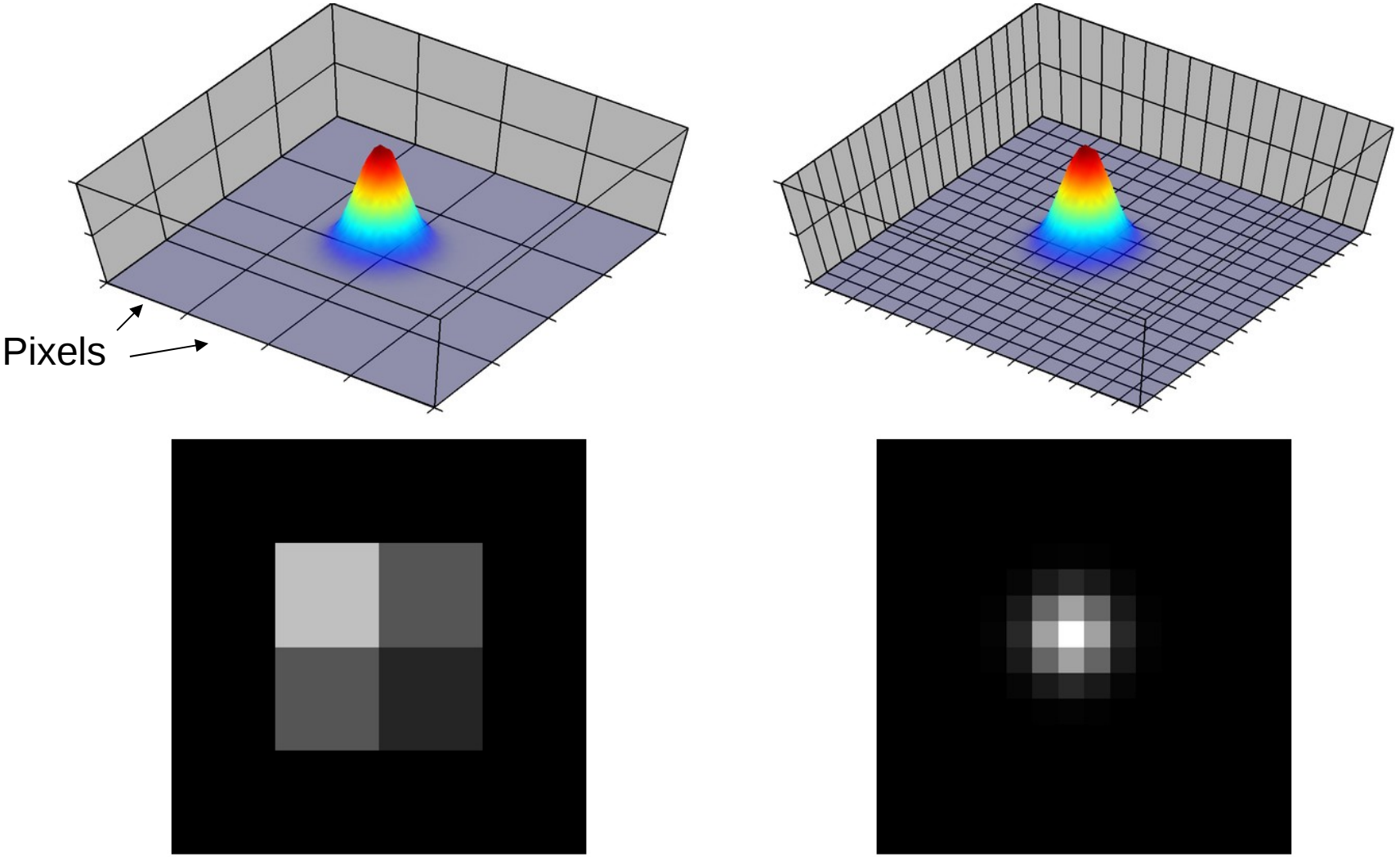
Why Use Small Pixels?

- 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





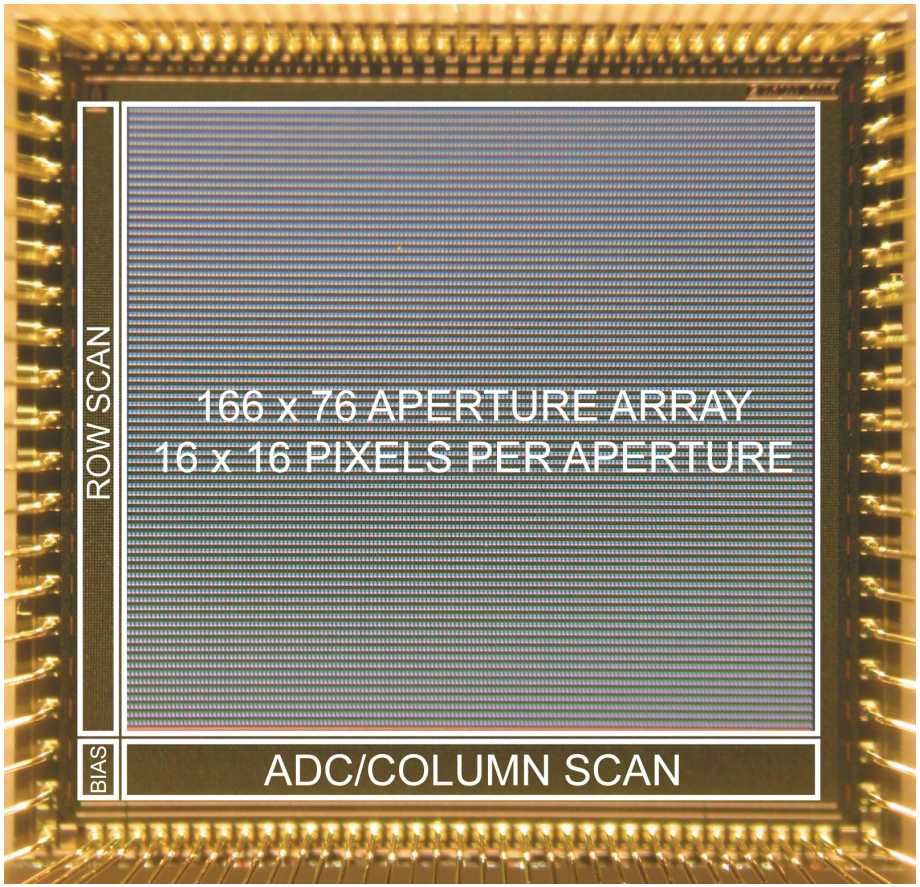
Feature Localization vs. Pixel Size



Poor location accuracy

High location accuracy

Fabricated Multi-Aperture Imager

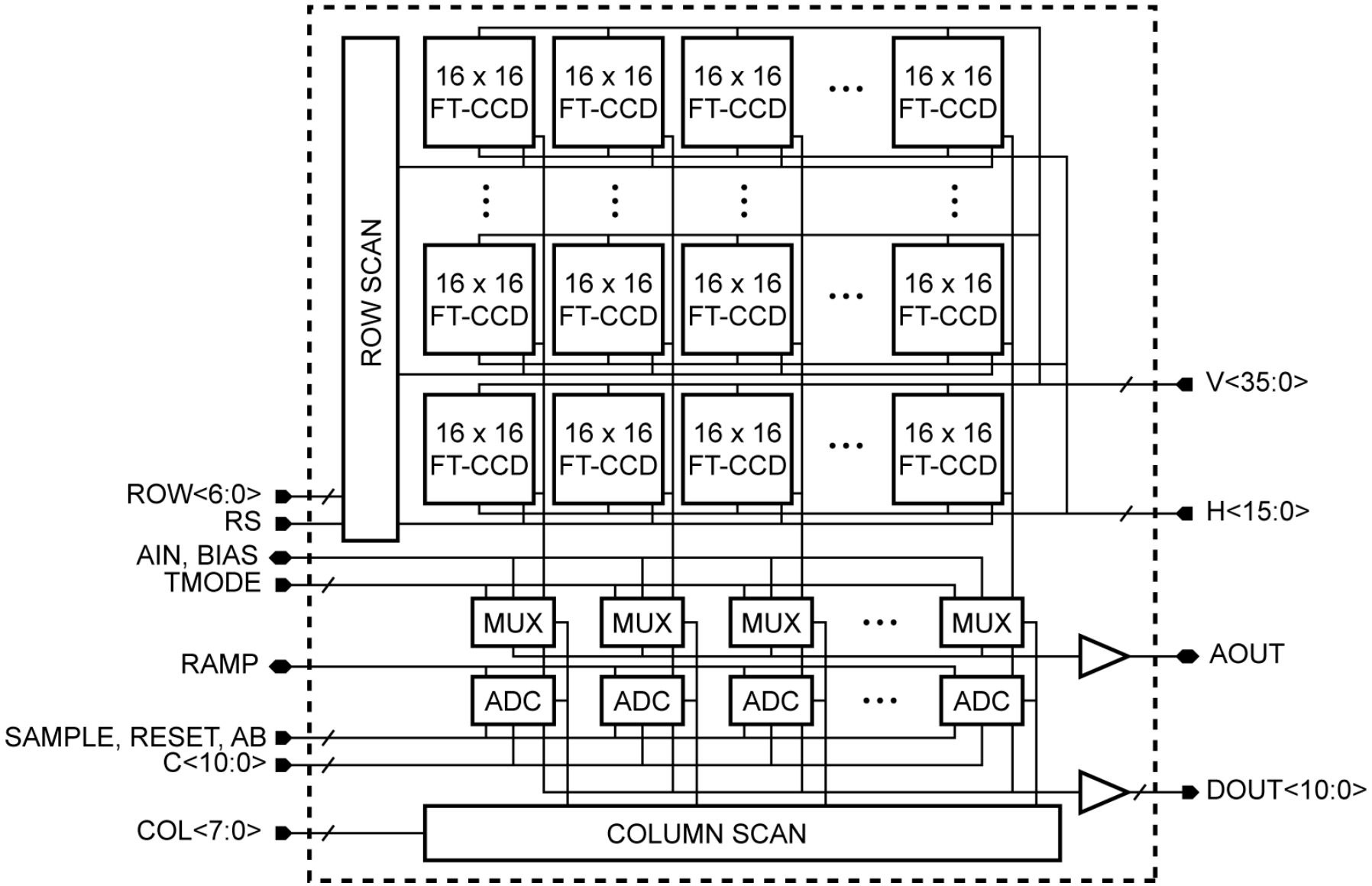


- 0.11μm CMOS (TSMC)
- Chip size: 3.0 x 2.9mm^2
- 166 x 76 aperture array
- 16 x 16 pixel FT-CCD per aperture
- Pixel size: 0.7 μm
- Max frame rate: 15fps
- ADC resolution: 10 bit
- Power: 10.45mW

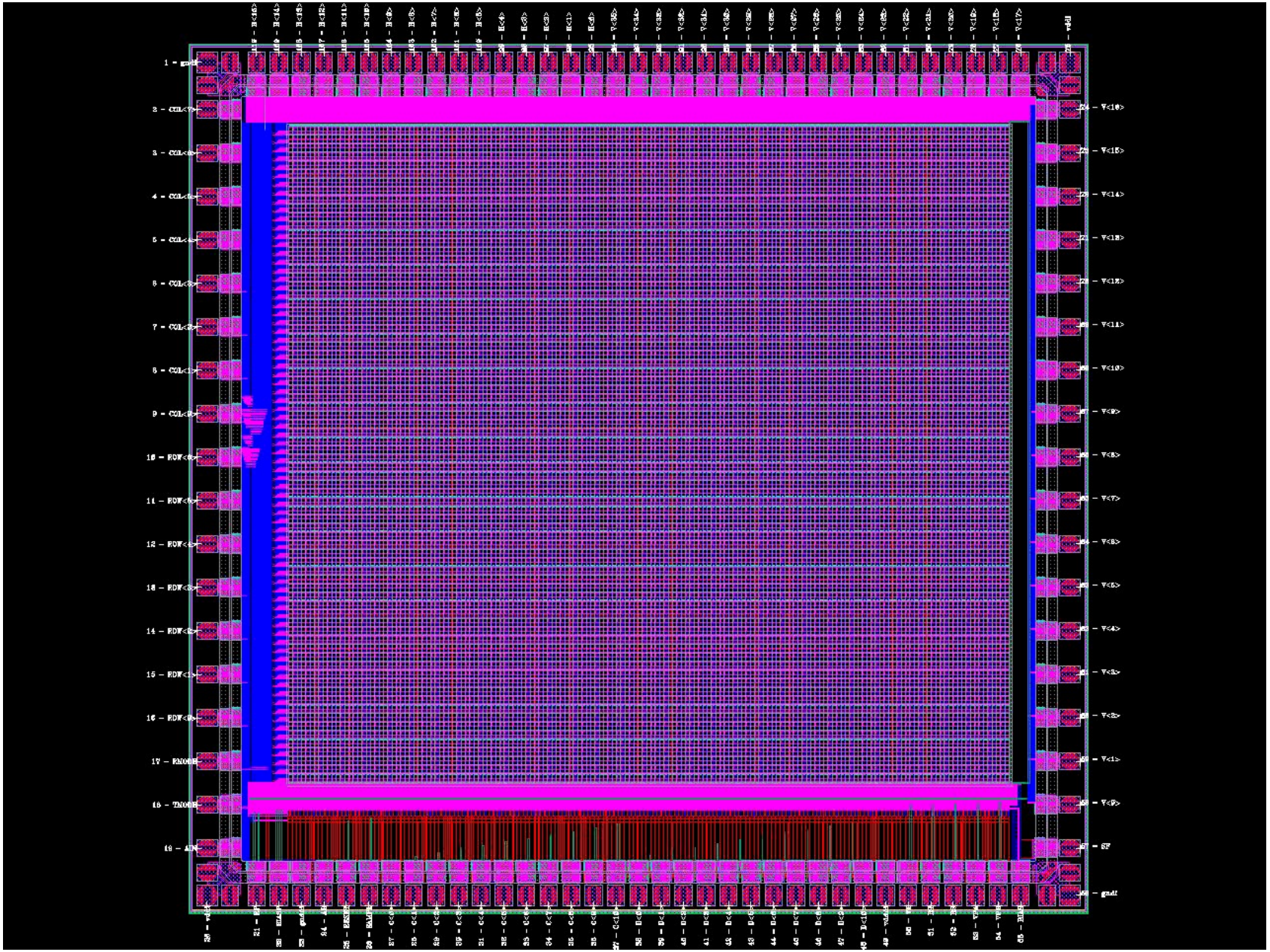
* Local optics are not integrated on this chip.

** K. Fife, A. El Gamal and H.-S. P. Wong, ISSCC 2008, p48-49*

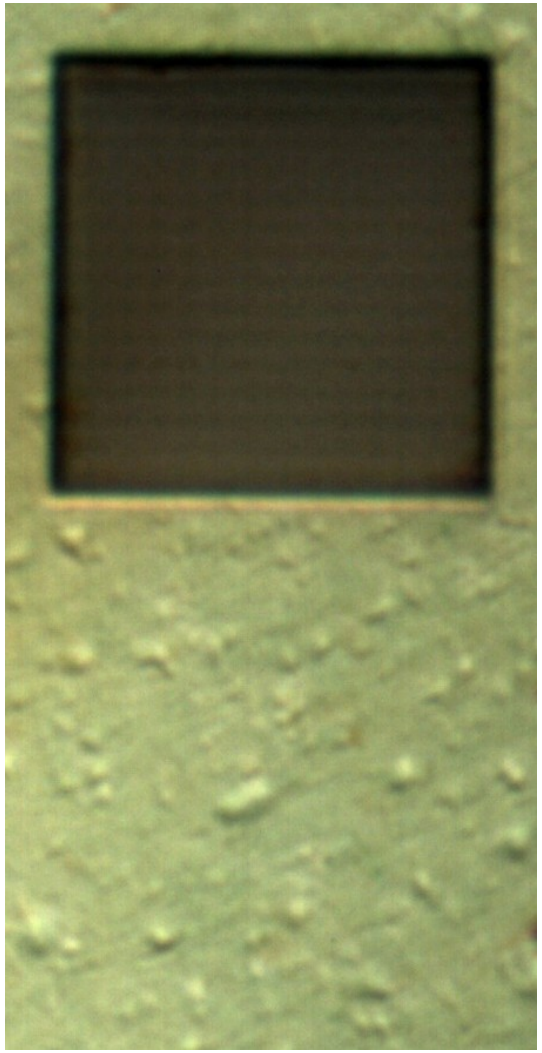
Block Diagram of Fabricated Chip

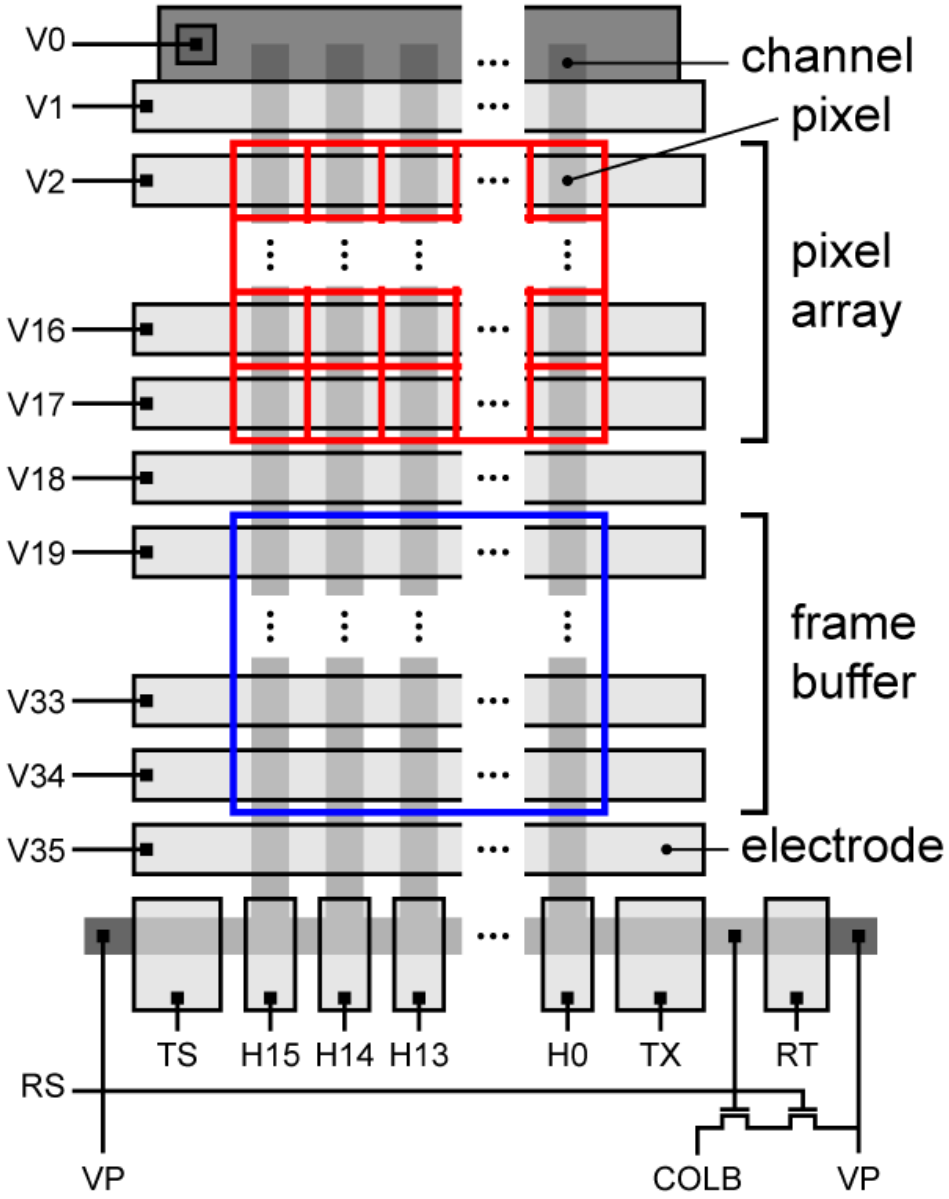


Layout Masks for Chip



16 x 16 FT-CCD schematic

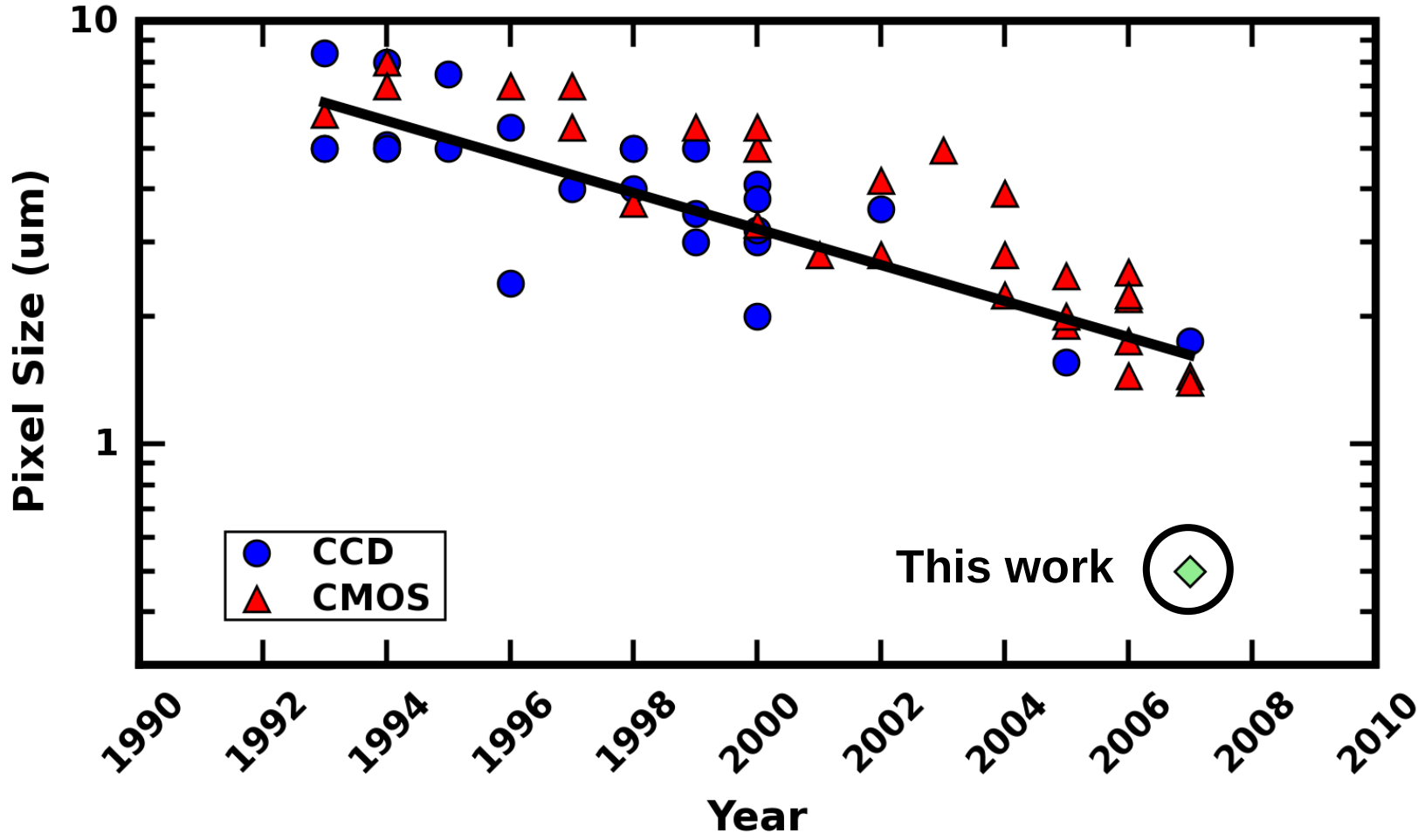




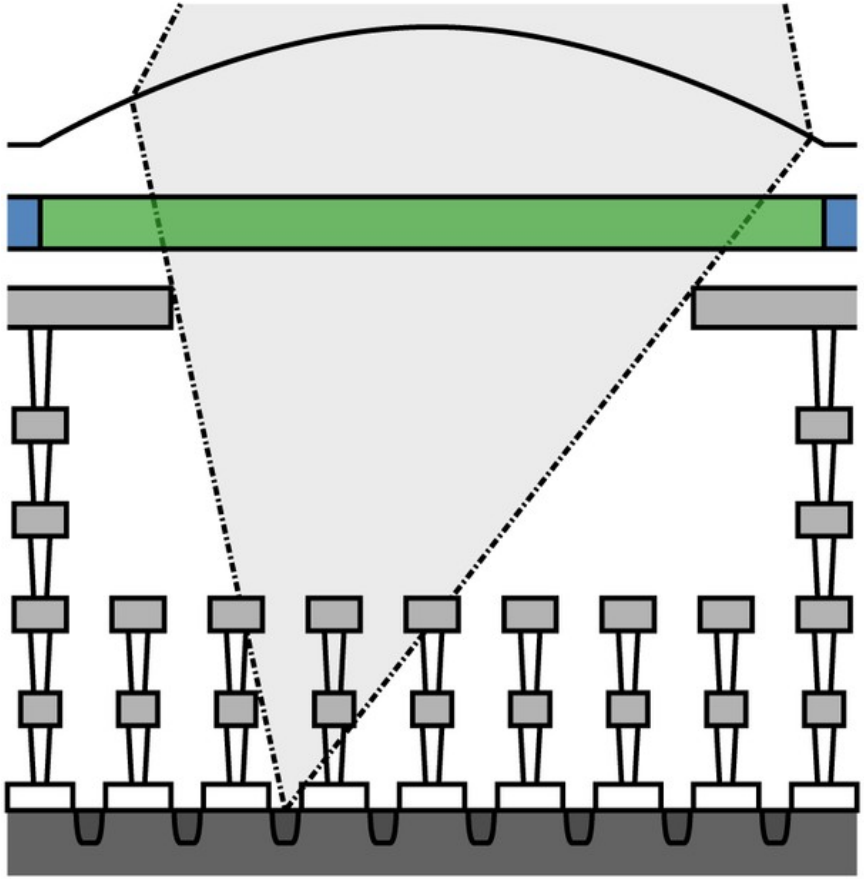
Relative Pixel Size for This Work

- Increase spatial resolution
- Decrease format size

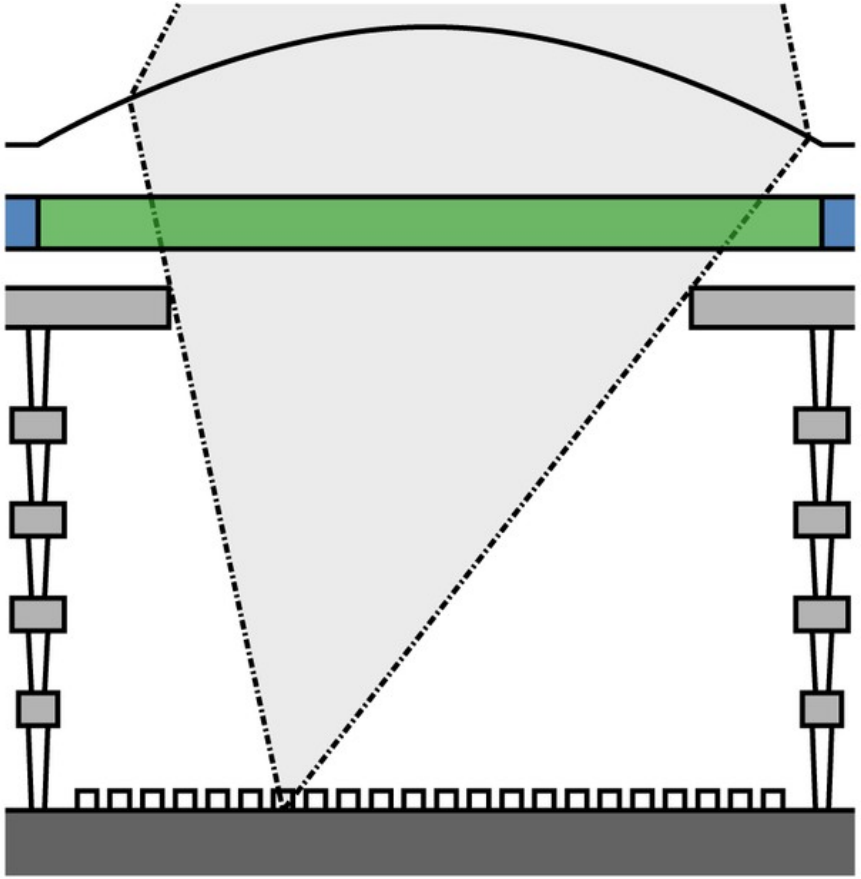
Pixel Sizes reported at IEDM, ISSCC, IISW



Multi-Aperture Optical Stack

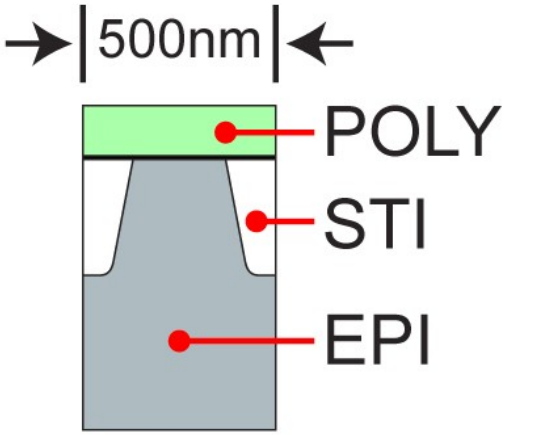


Using CMOS active pixels

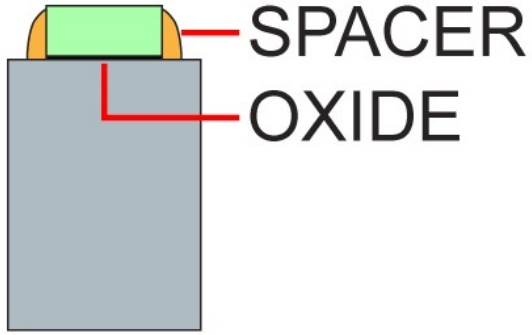


Using FT-CCD pixels

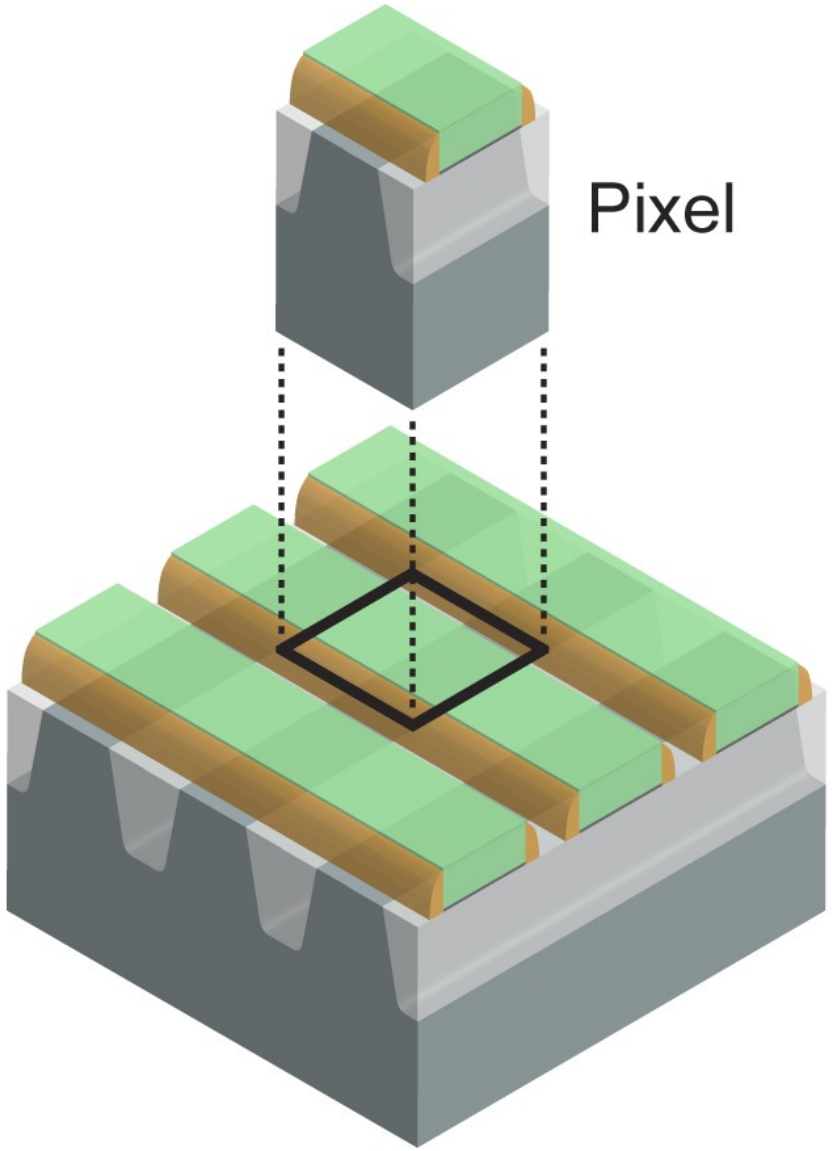
The Submicron Pixel



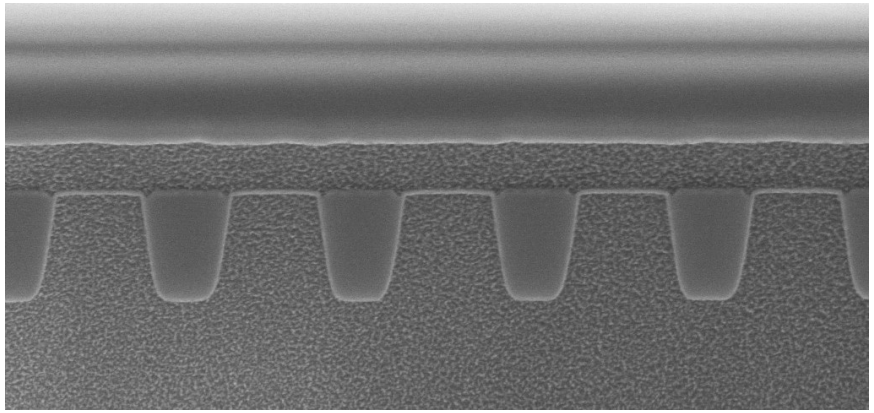
Across Channel



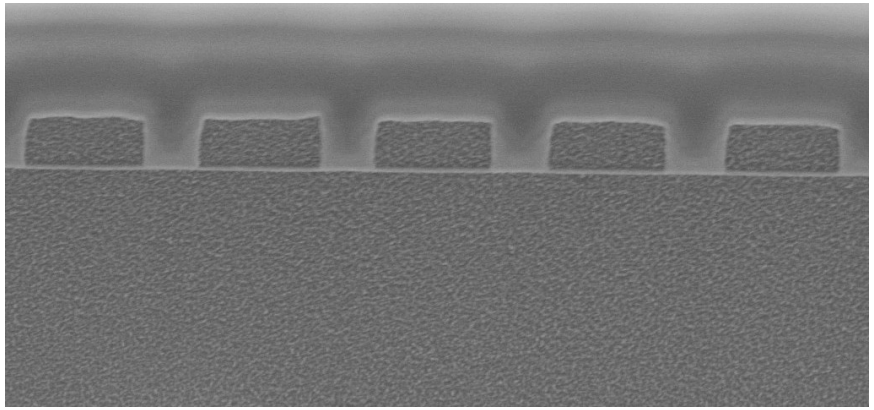
Along Channel



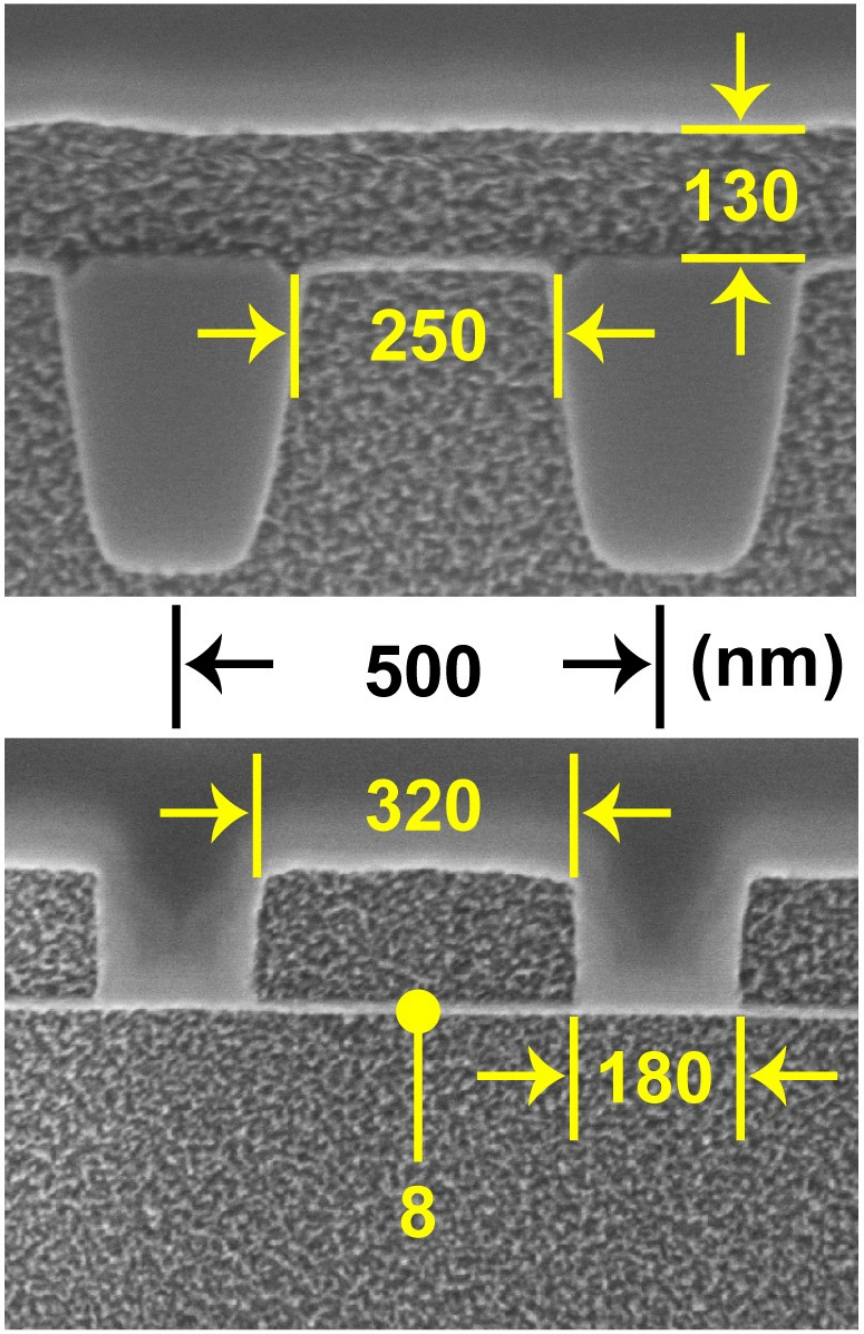
CCD Structure



STI forms the channel stop

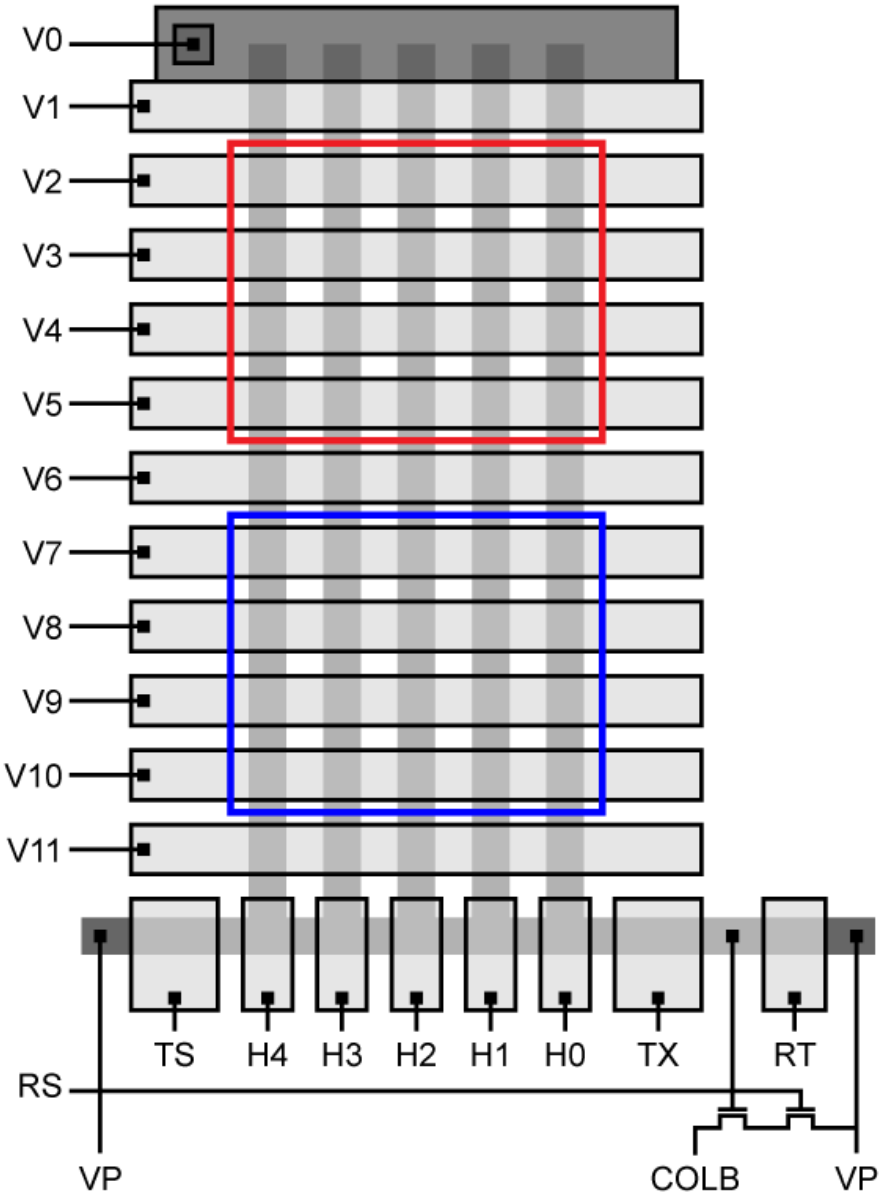


Single-level poly electrodes

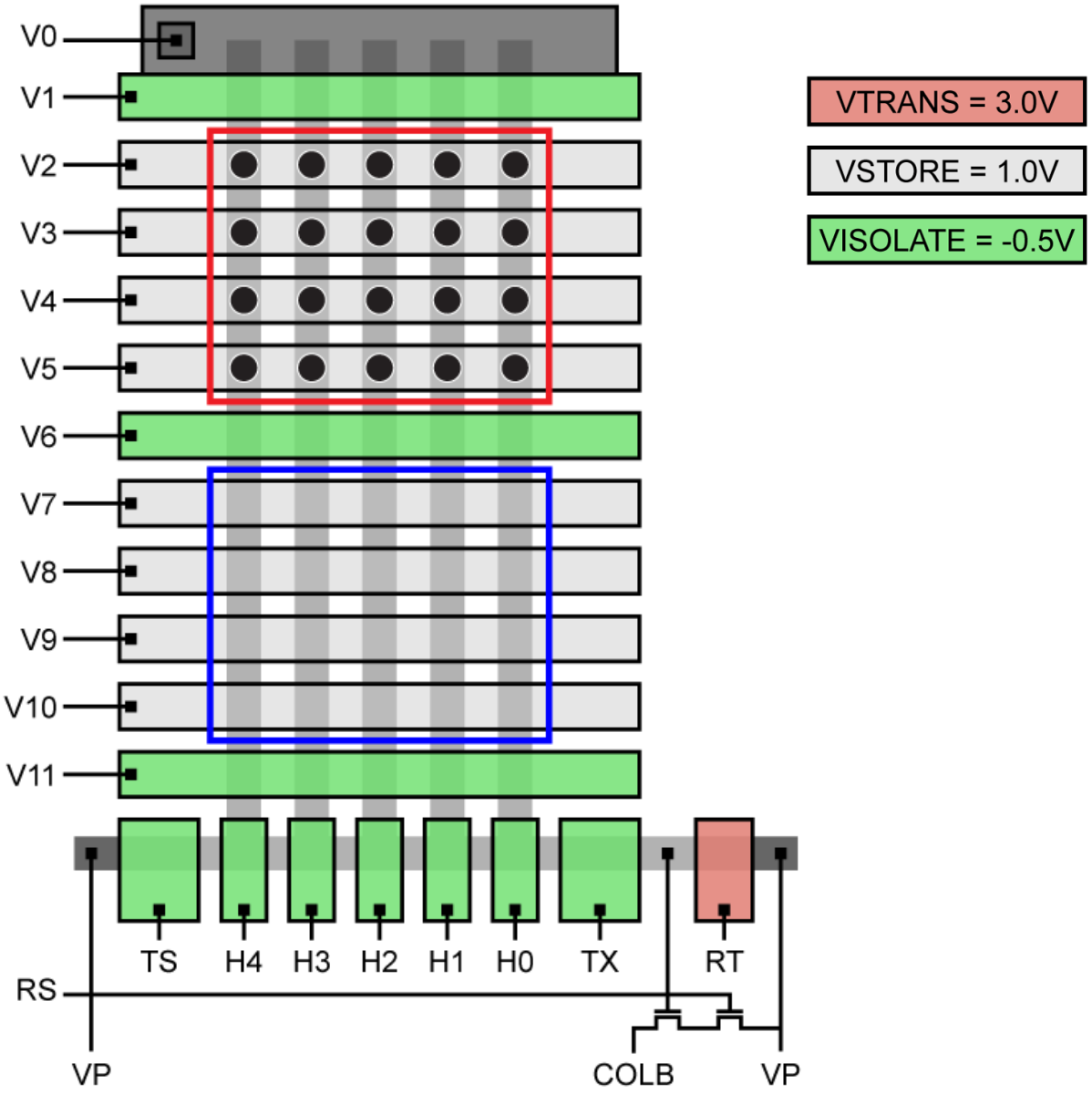


Operation

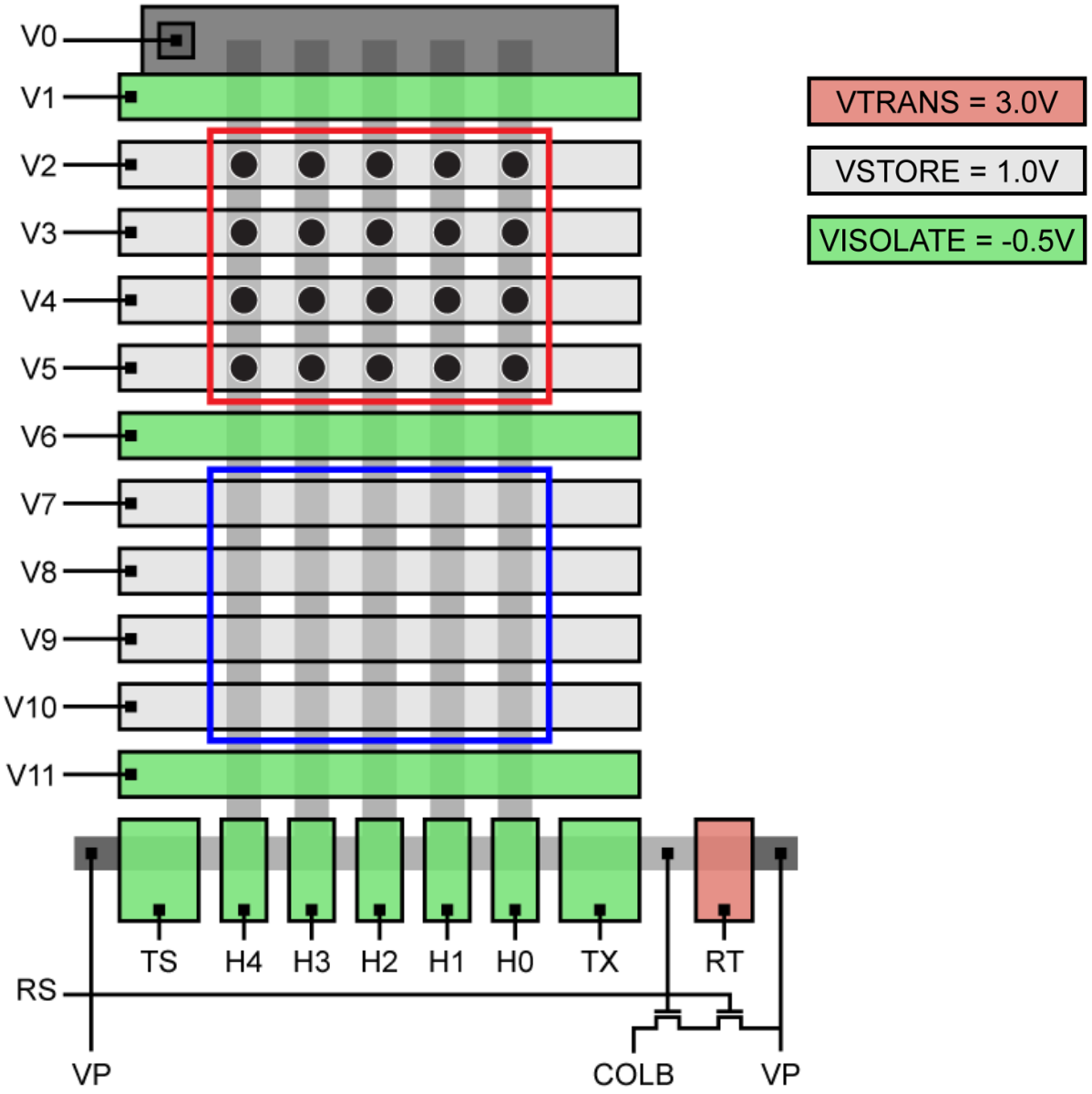
- Flush
- Integrate
- Frame Transfer
- Horizontal Readout



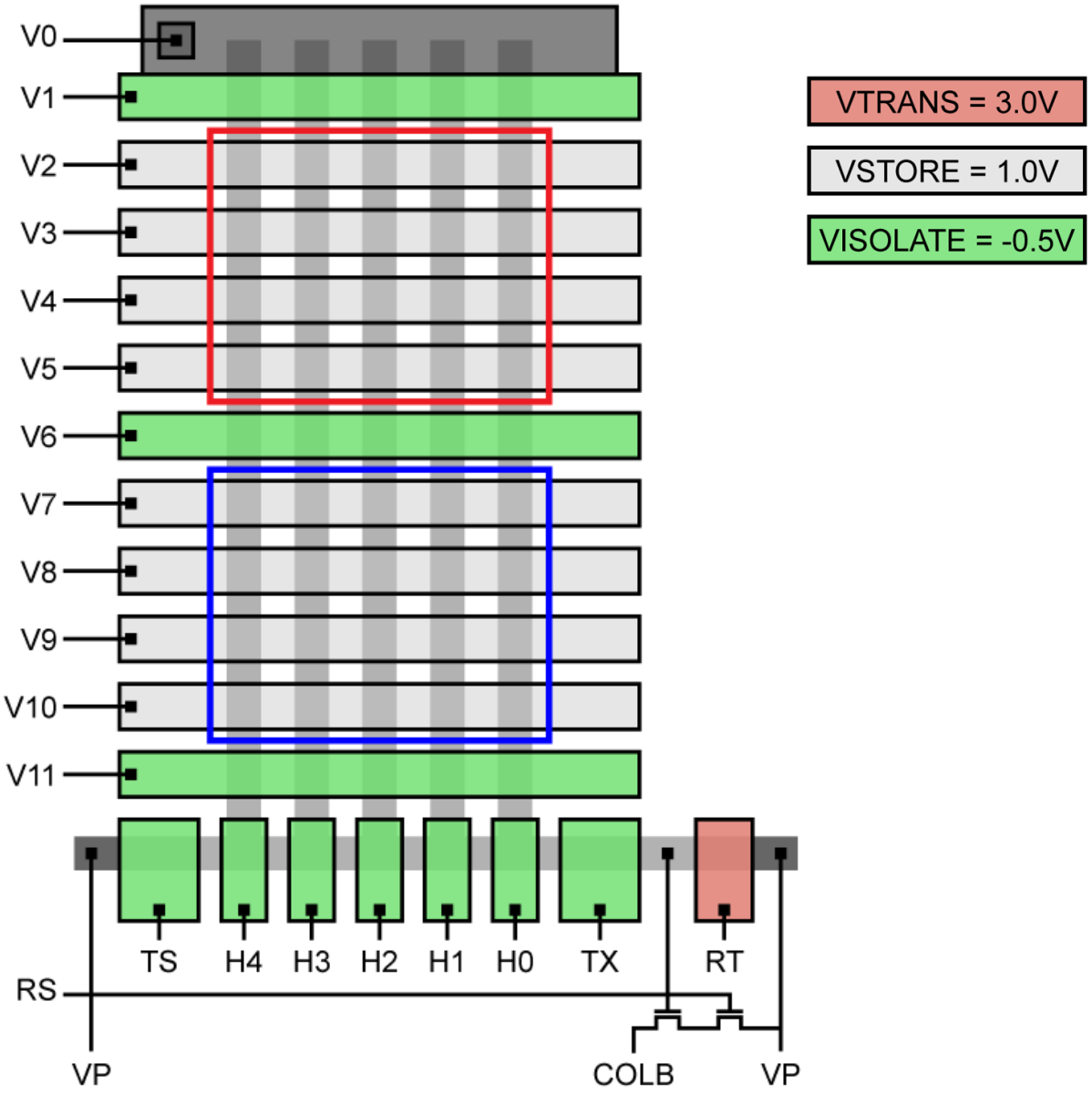
Operation (Flush)



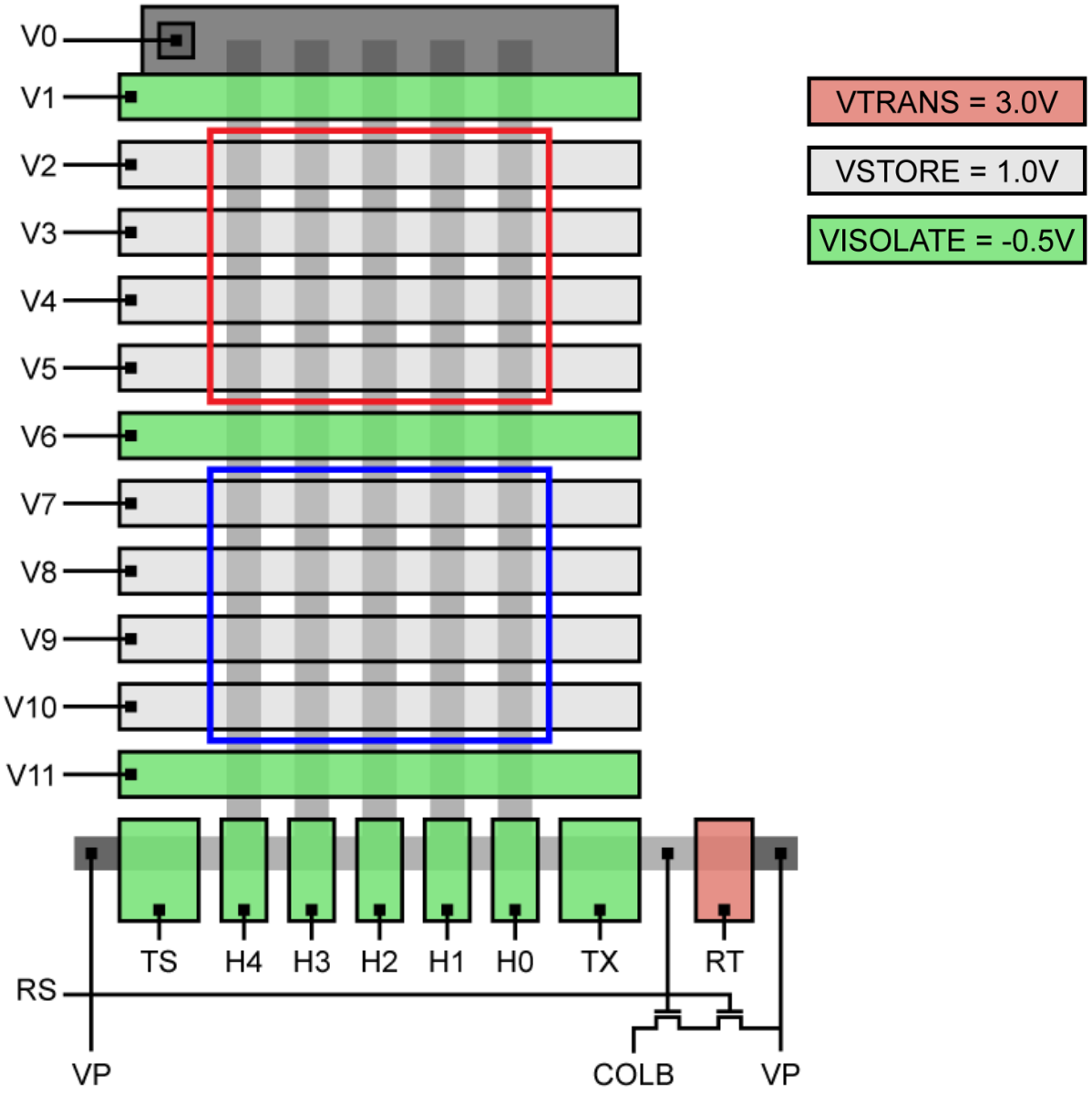
Operation (Flush)



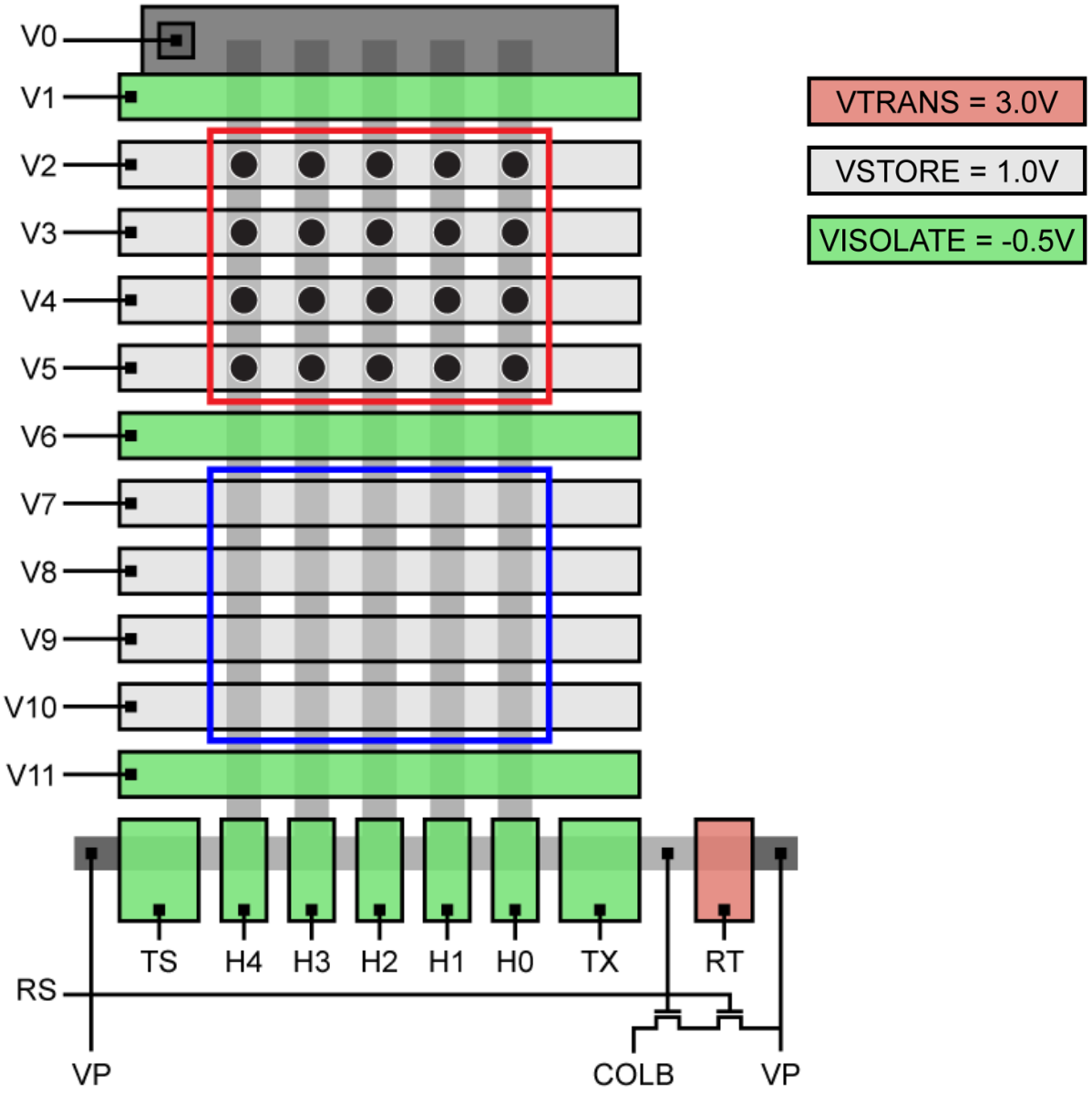
Operation (Integrate)



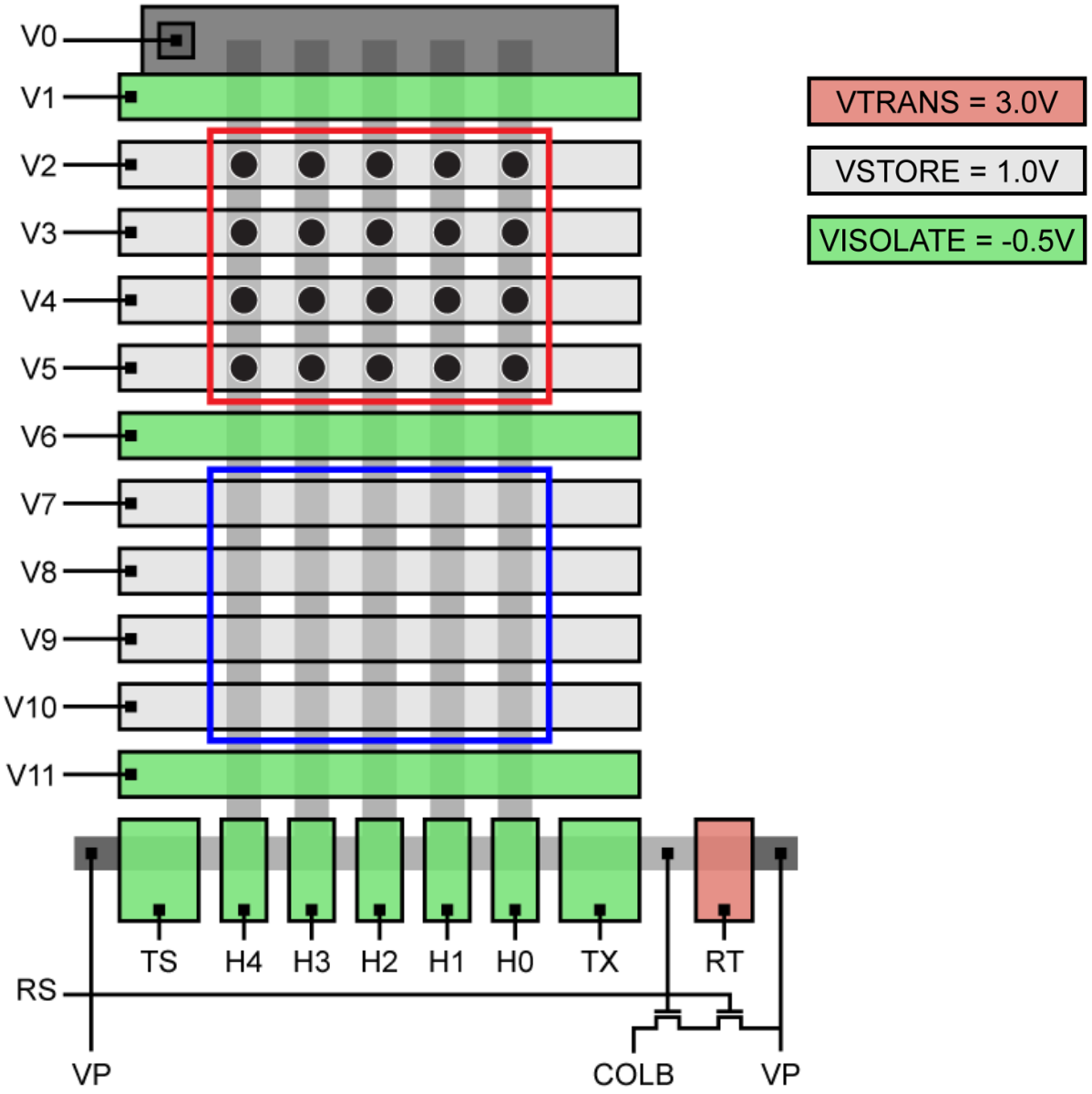
Operation (Integrate)



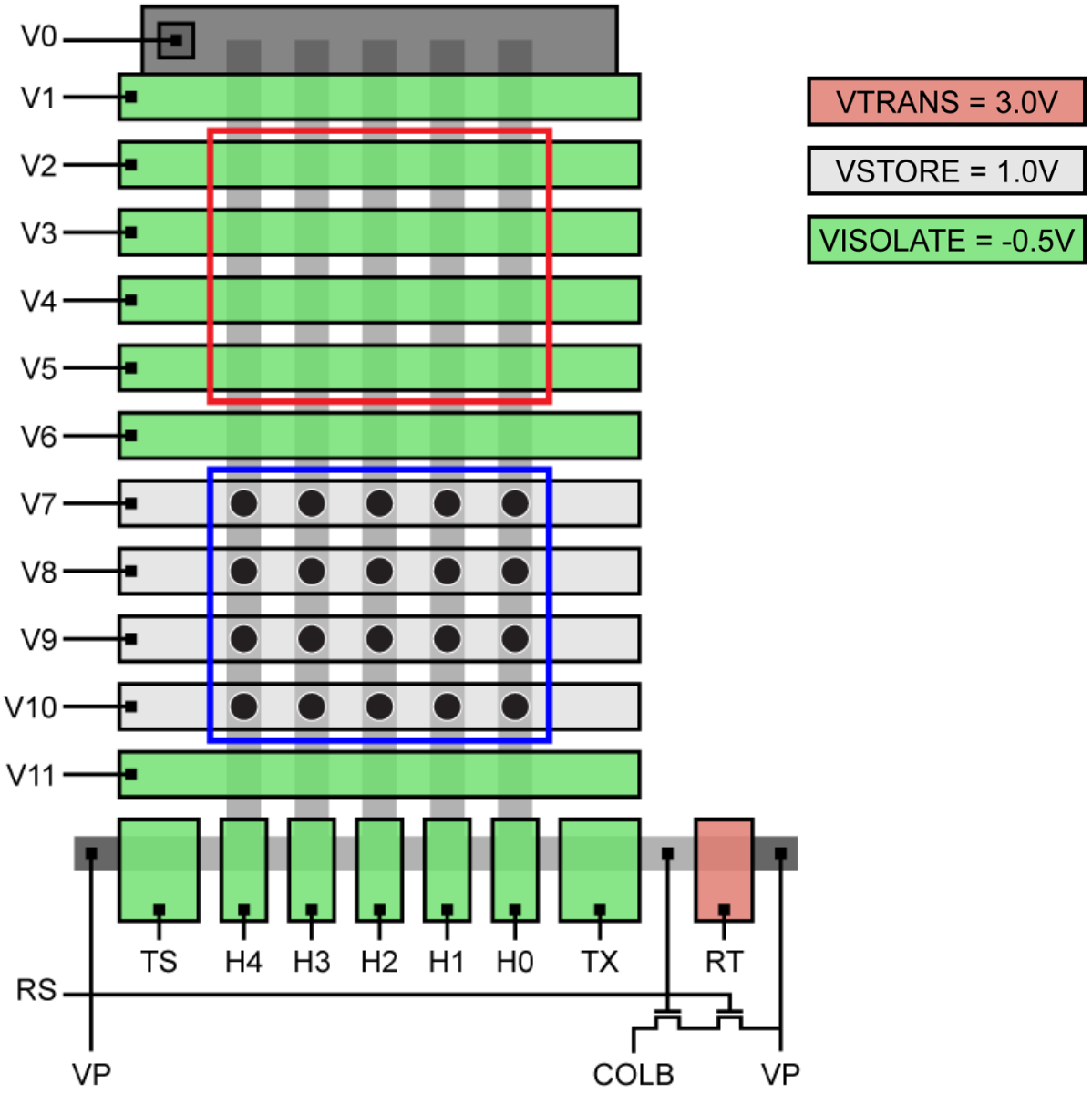
Operation (Frame Transfer)



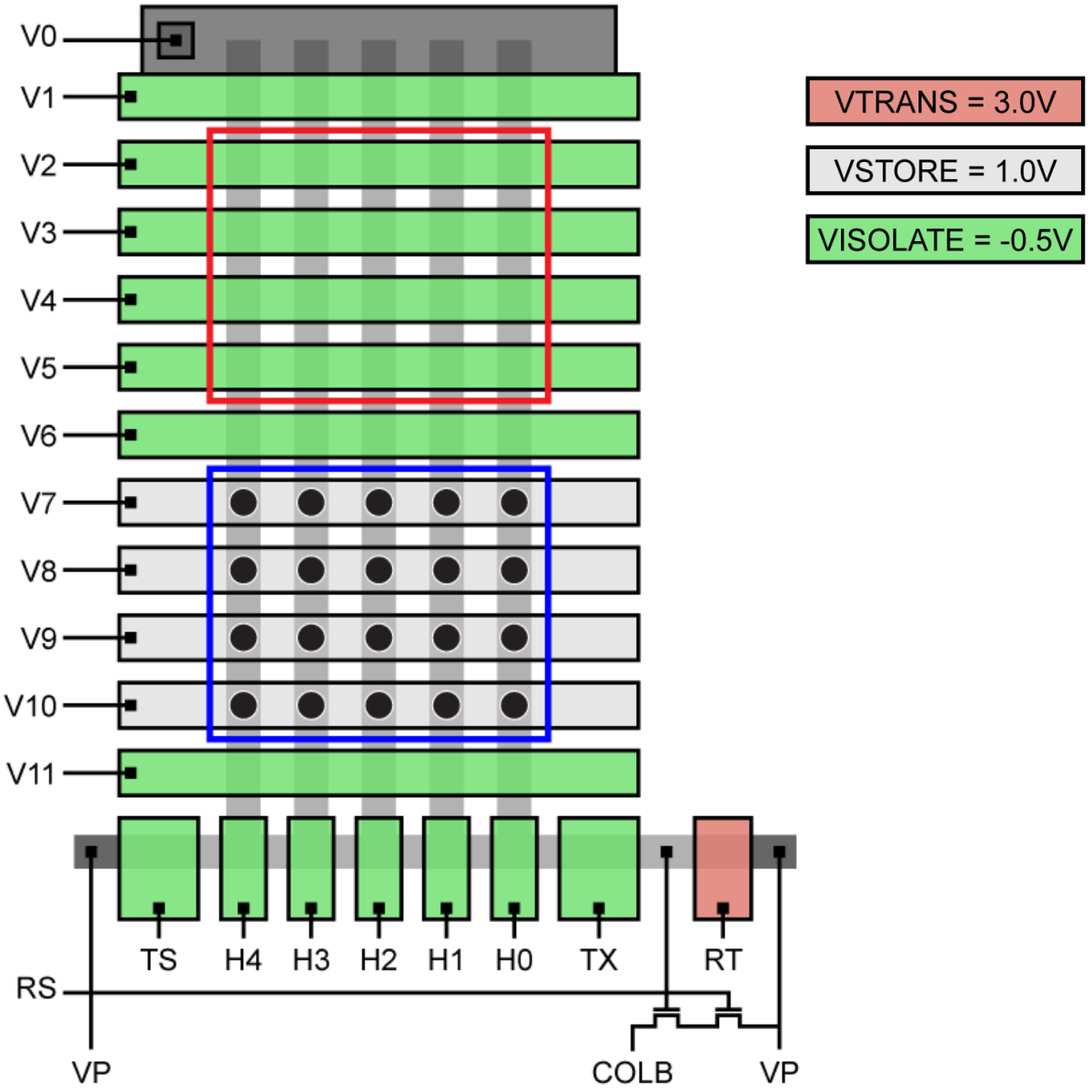
Operation (Frame Transfer)



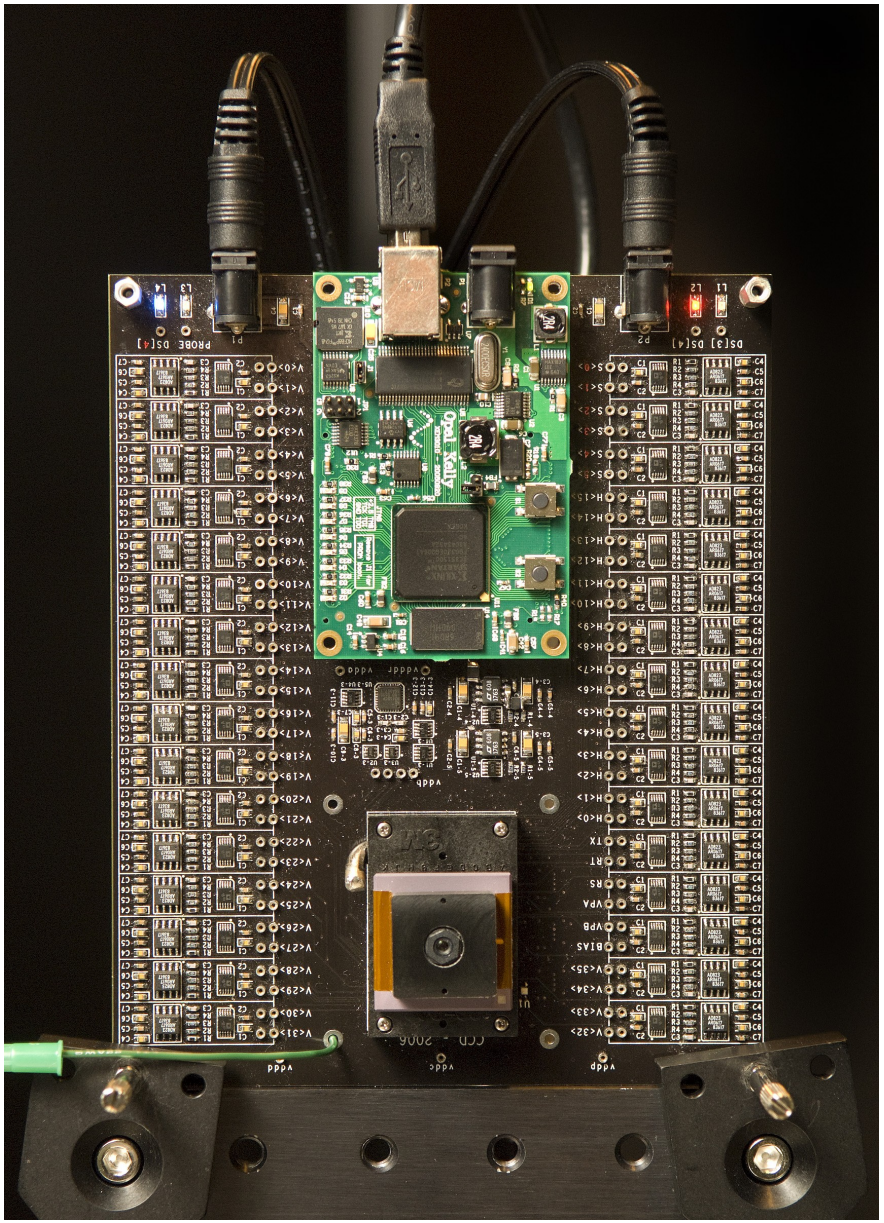
Operation (Horizontal Transfer)



Operation (Horizontal Transfer)

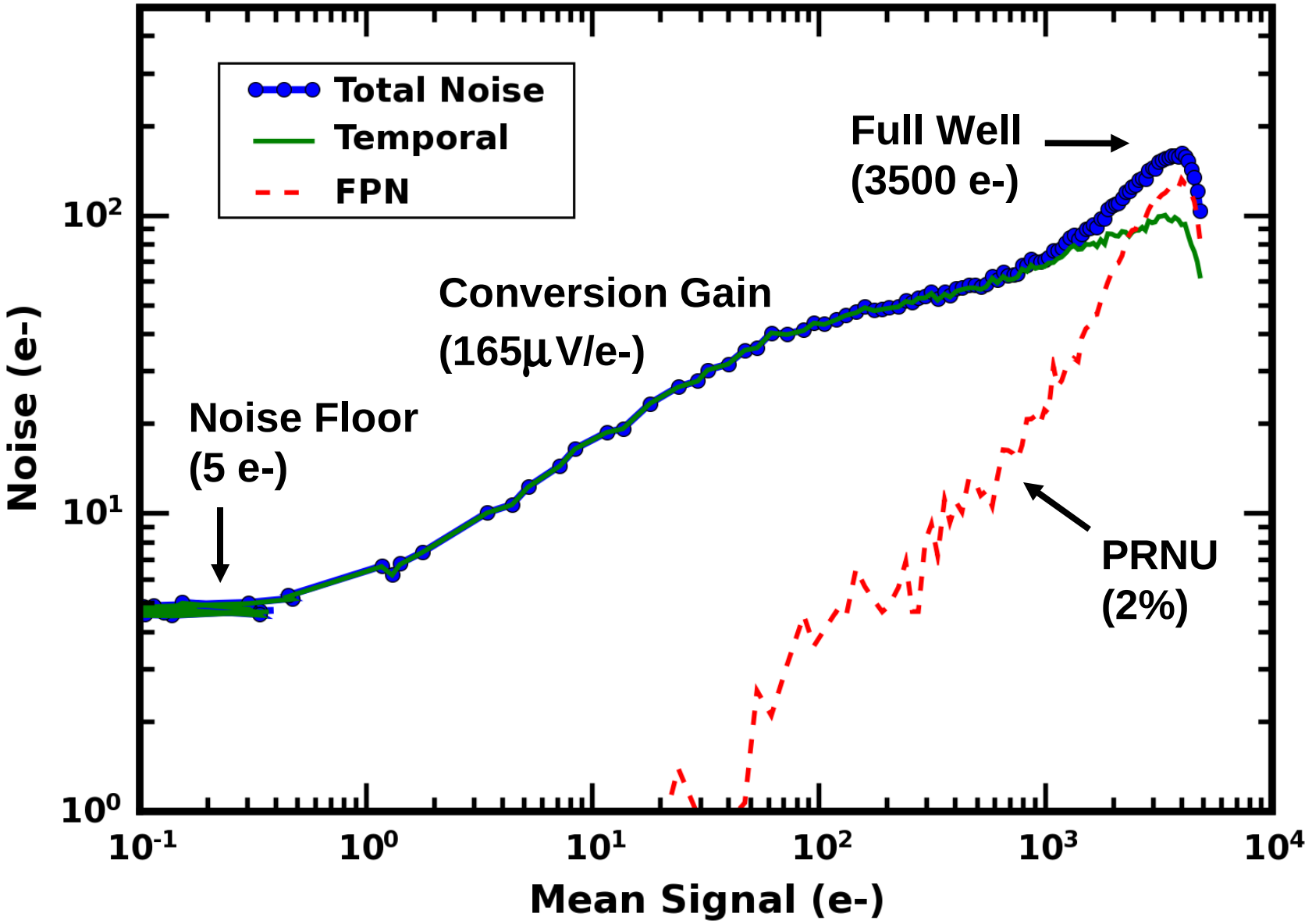


Test Board

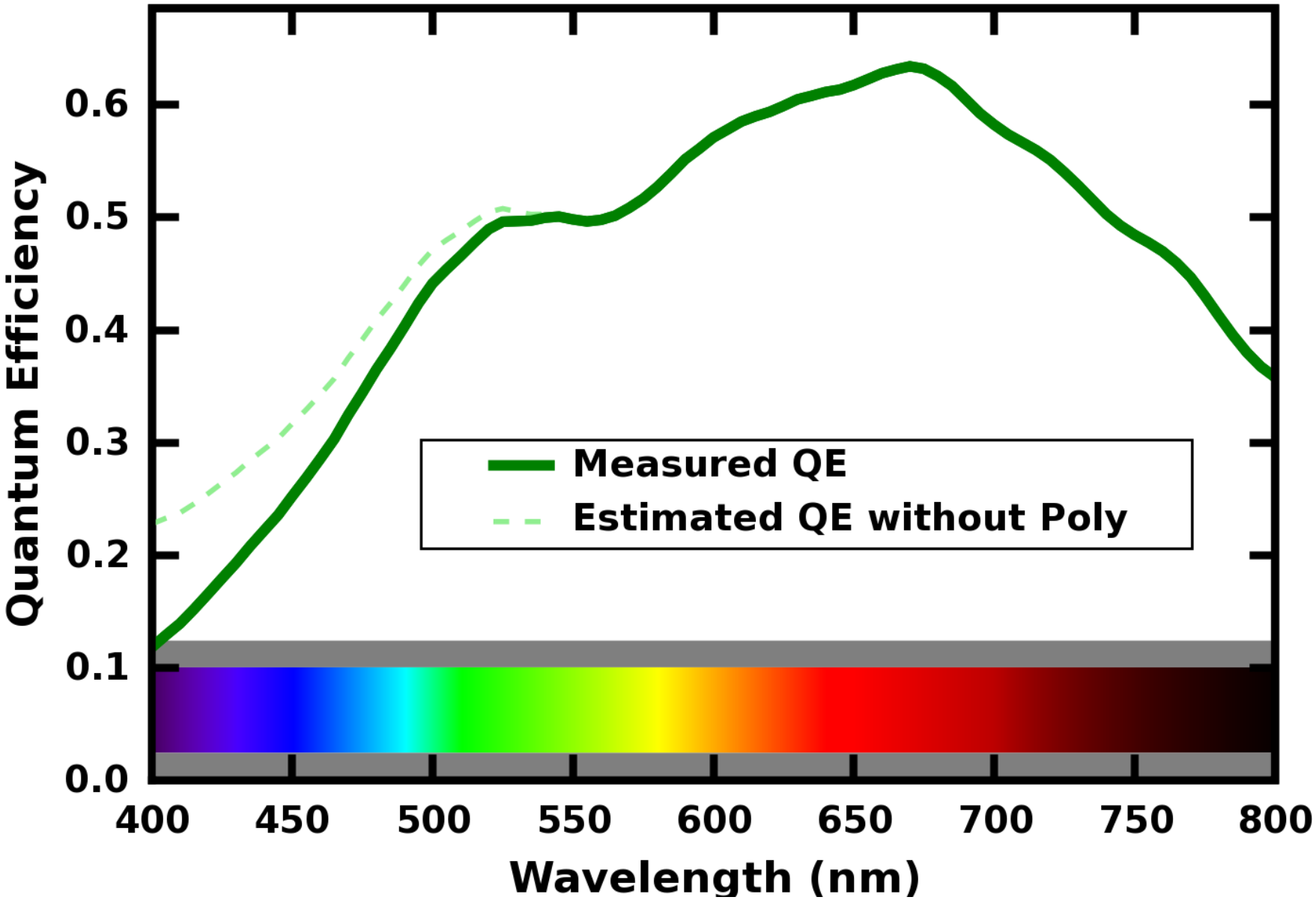


- FPGA control of CCD waveforms and chip operation.
- Python based sequencer run from FPGA RAM.
- USB 2.0 data transfer.

Photon Transfer Curve (0.7µm Pixel)



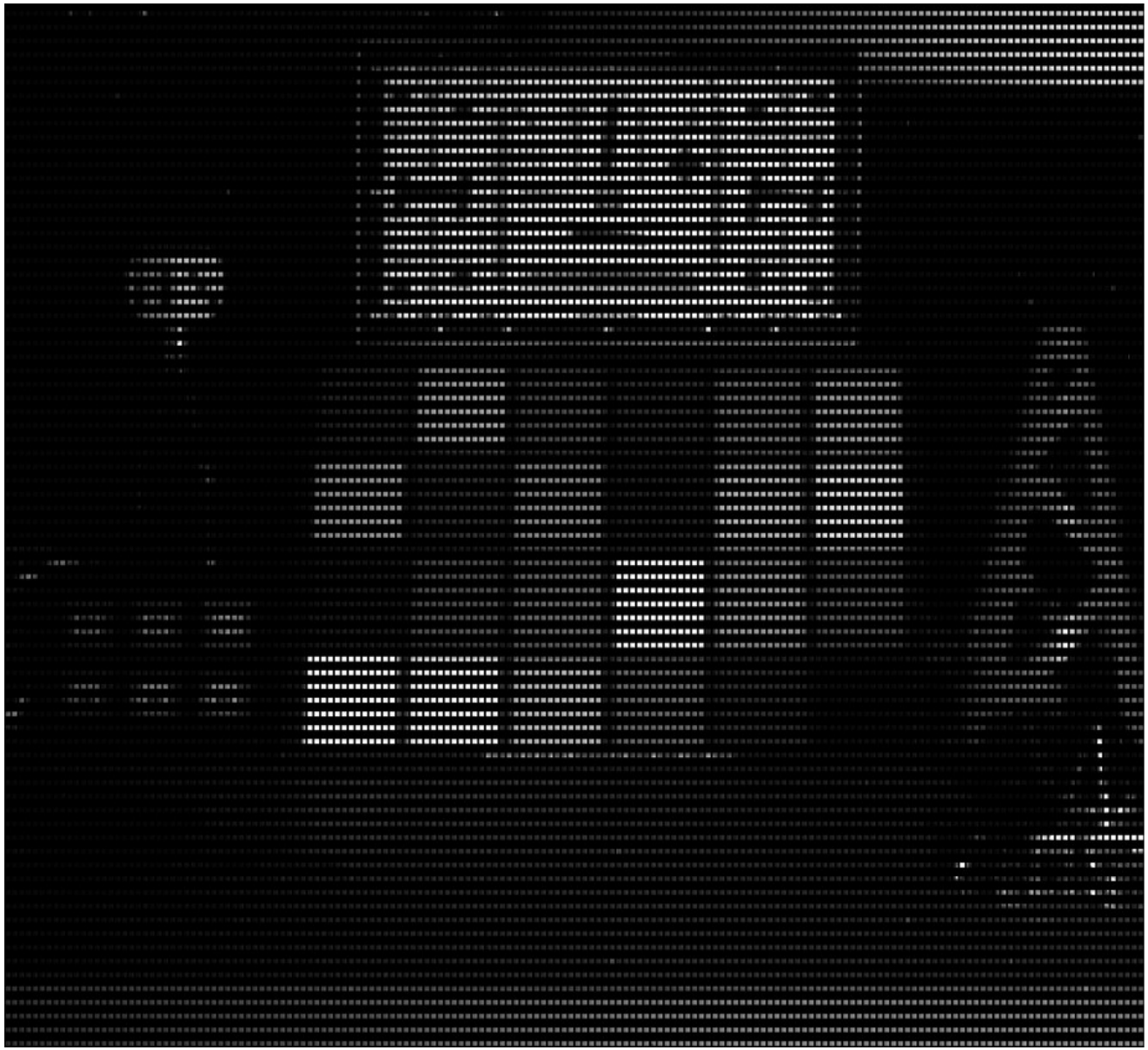
Measured Quantum Efficiency

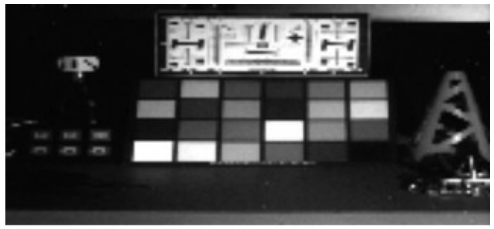


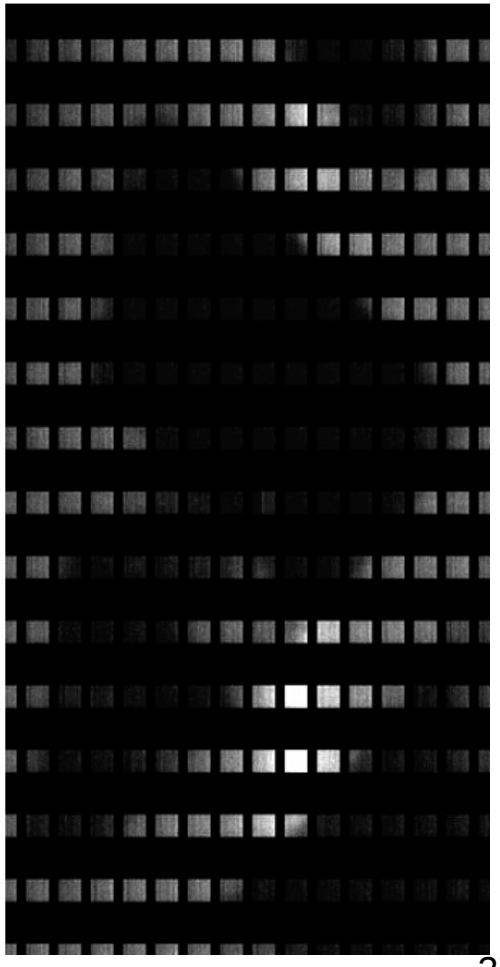
Measured Pixel Characteristics

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

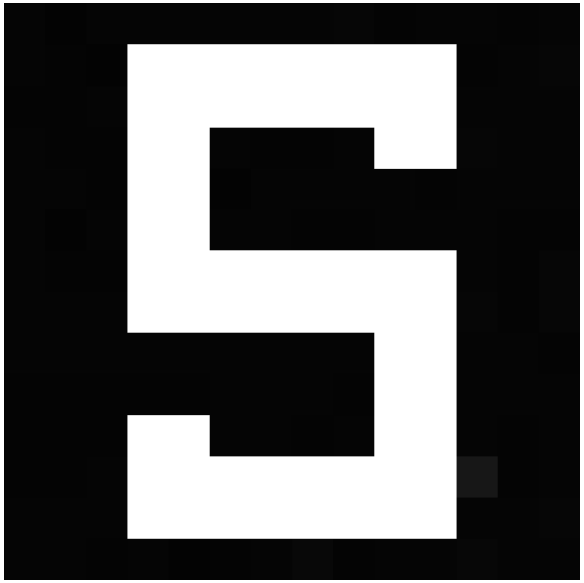






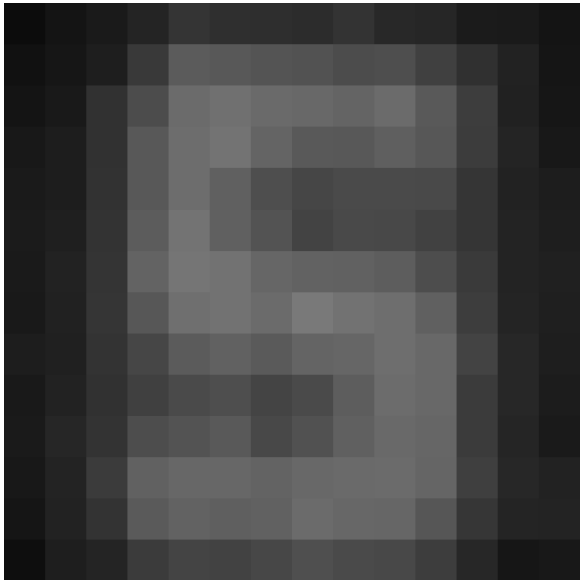
Images from Single Subarray

Electrical



3000 electron charge packets from fill/spill input

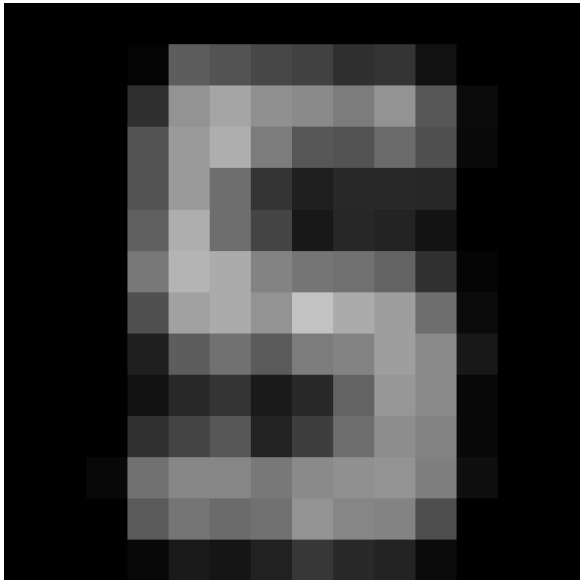
Optical



Raw data

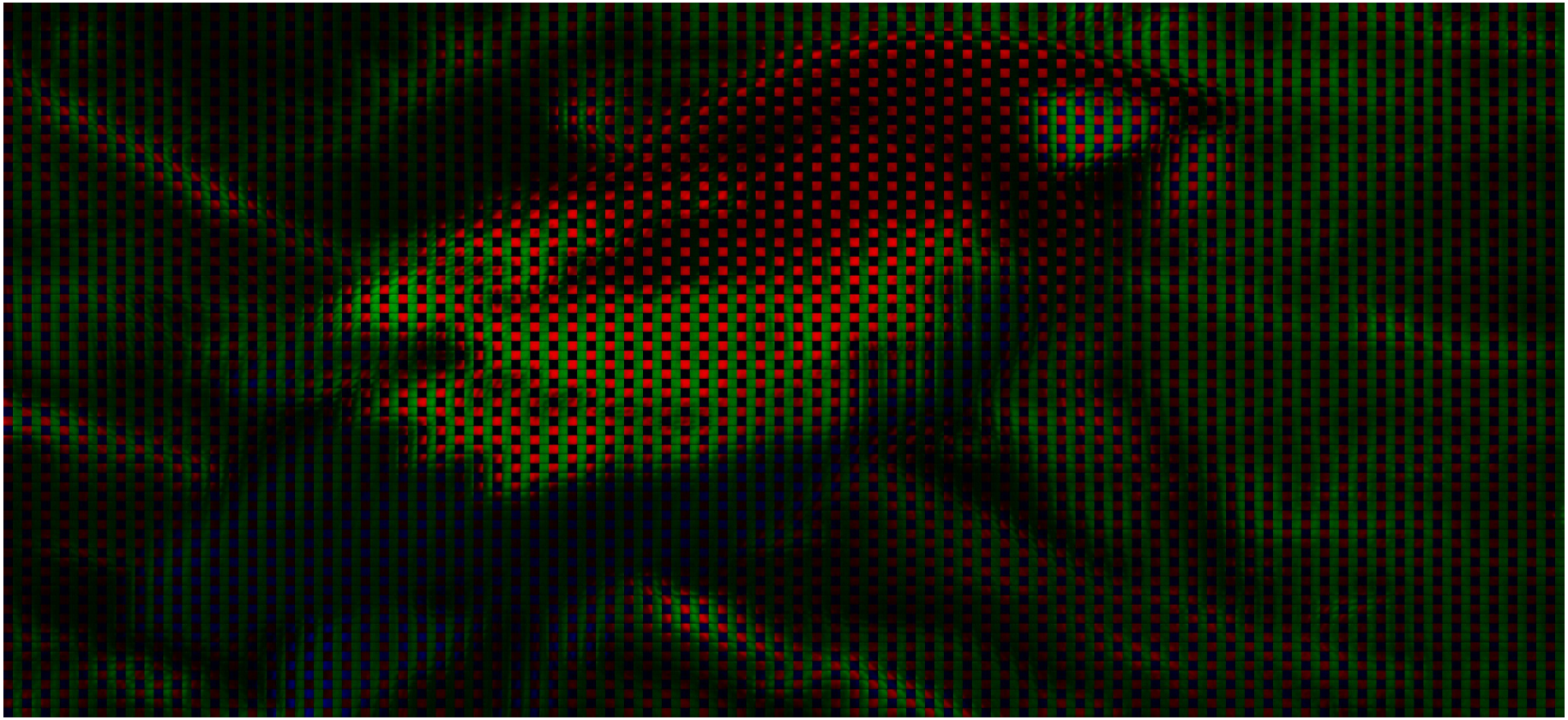
Captured with F/2.8, f=6mm lens at 1/10 sec

Optical



Added contrast

Raw Image Captured with Multi-Aperture Views



Processed Multi-Aperture Image

Summary

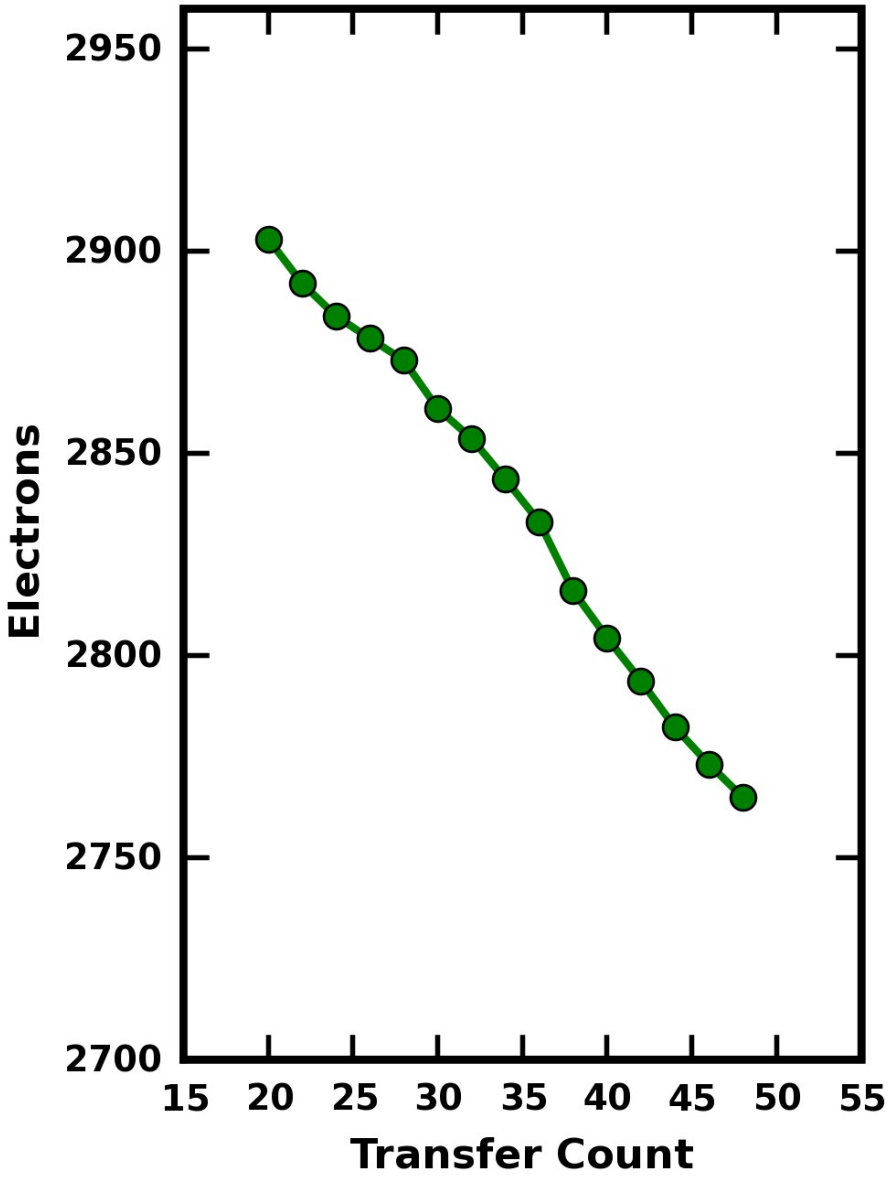
- Designed and characterized the first integrated multi-aperture image sensor
- Achieved good imaging performance with submicron pixels
  - FT-CCD structure in deep submicron CMOS
  - Ripple charge transfer
- Many potential applications or benefits
  - Depth
  - Close proximity imaging
  - Color imaging 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

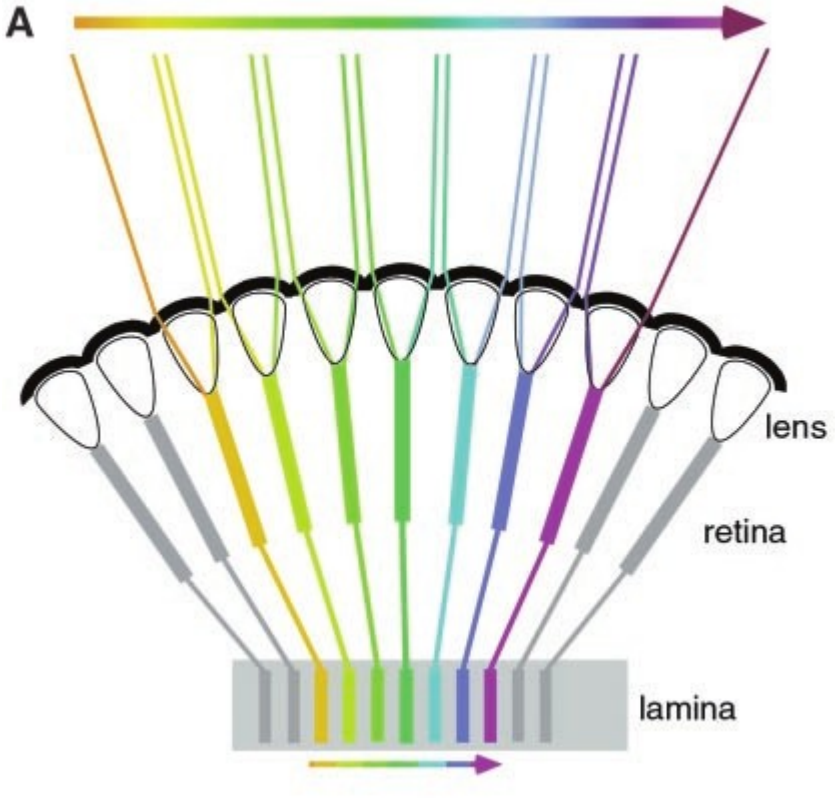
Measured Charge Transfer Efficiency

- 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?

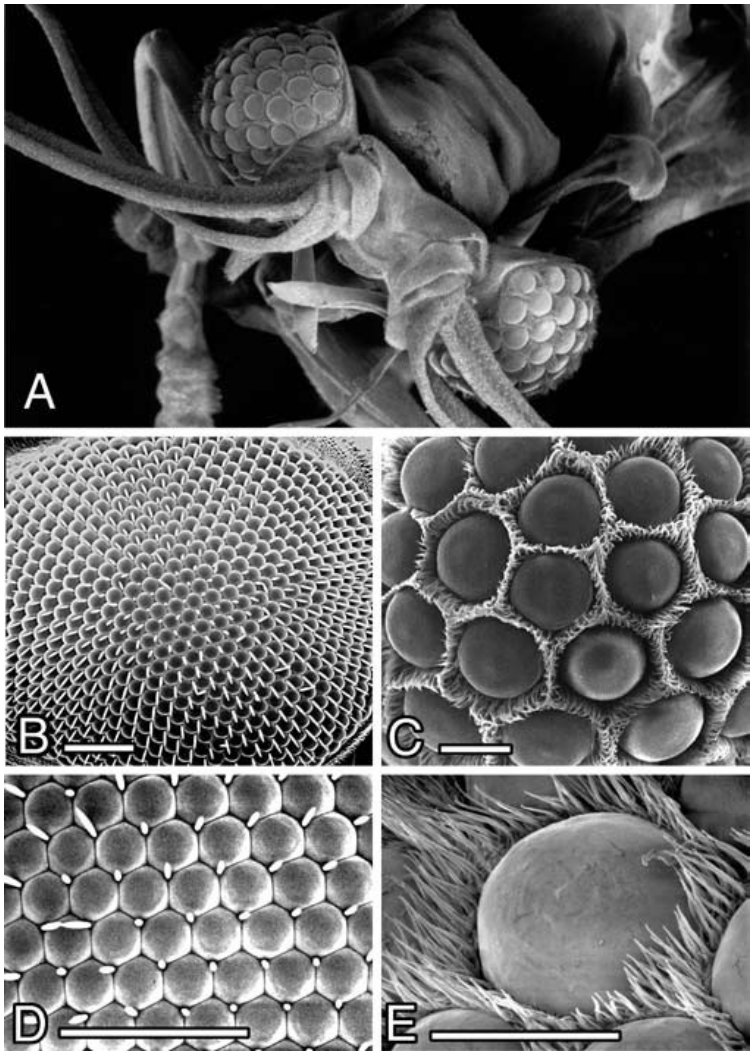
Compound Eye

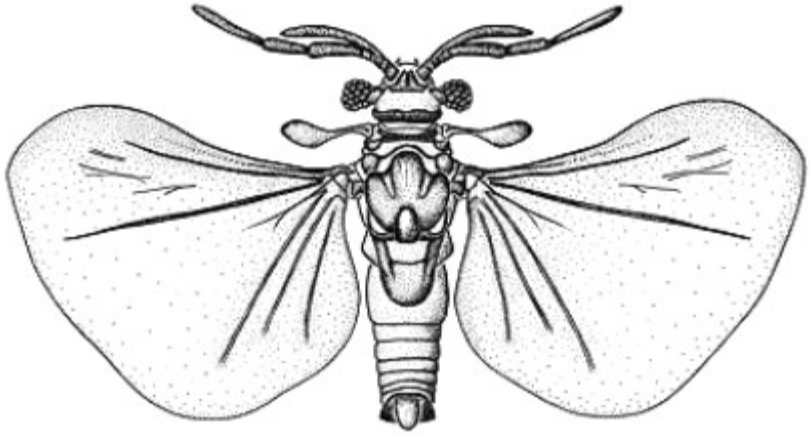


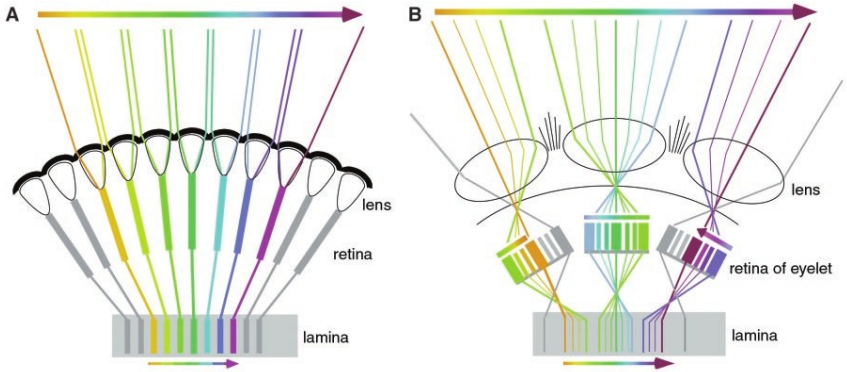
** Wikipedia, Compound Eye*

** Buschbeck, 1999*

Eye of the Strepsiptera







** Buschbeck, 1999*