A 3MPixel Multi-Aperture Image Sensor with 0.7µm Pixels in 0.11µm CMOS

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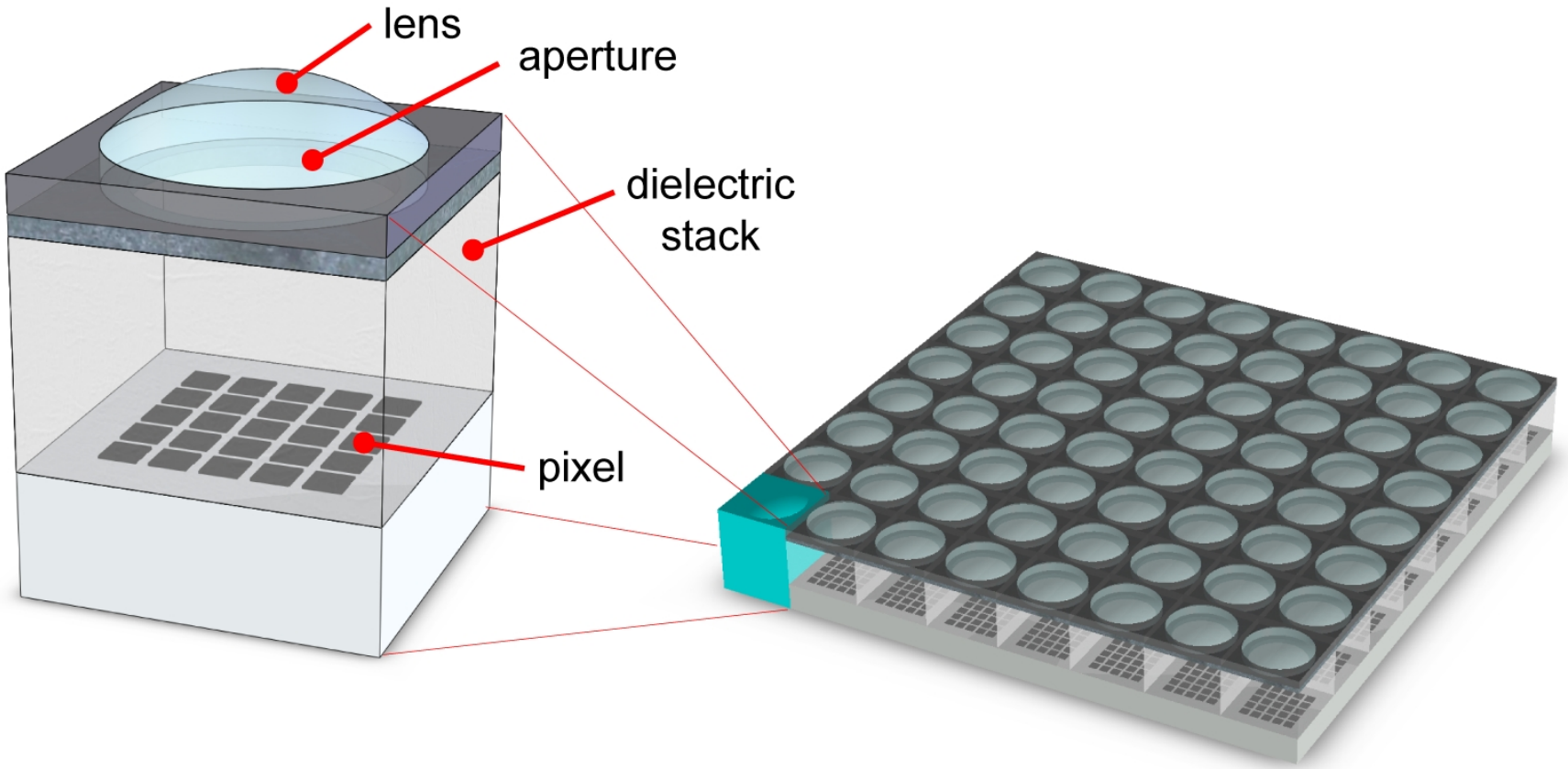
Outline

- Introduction
- Chip Architecture
- Detailed Operation
  - FT-CCD array
  - Multi-Aperture array
  - Column ADC
- Results
- Summary

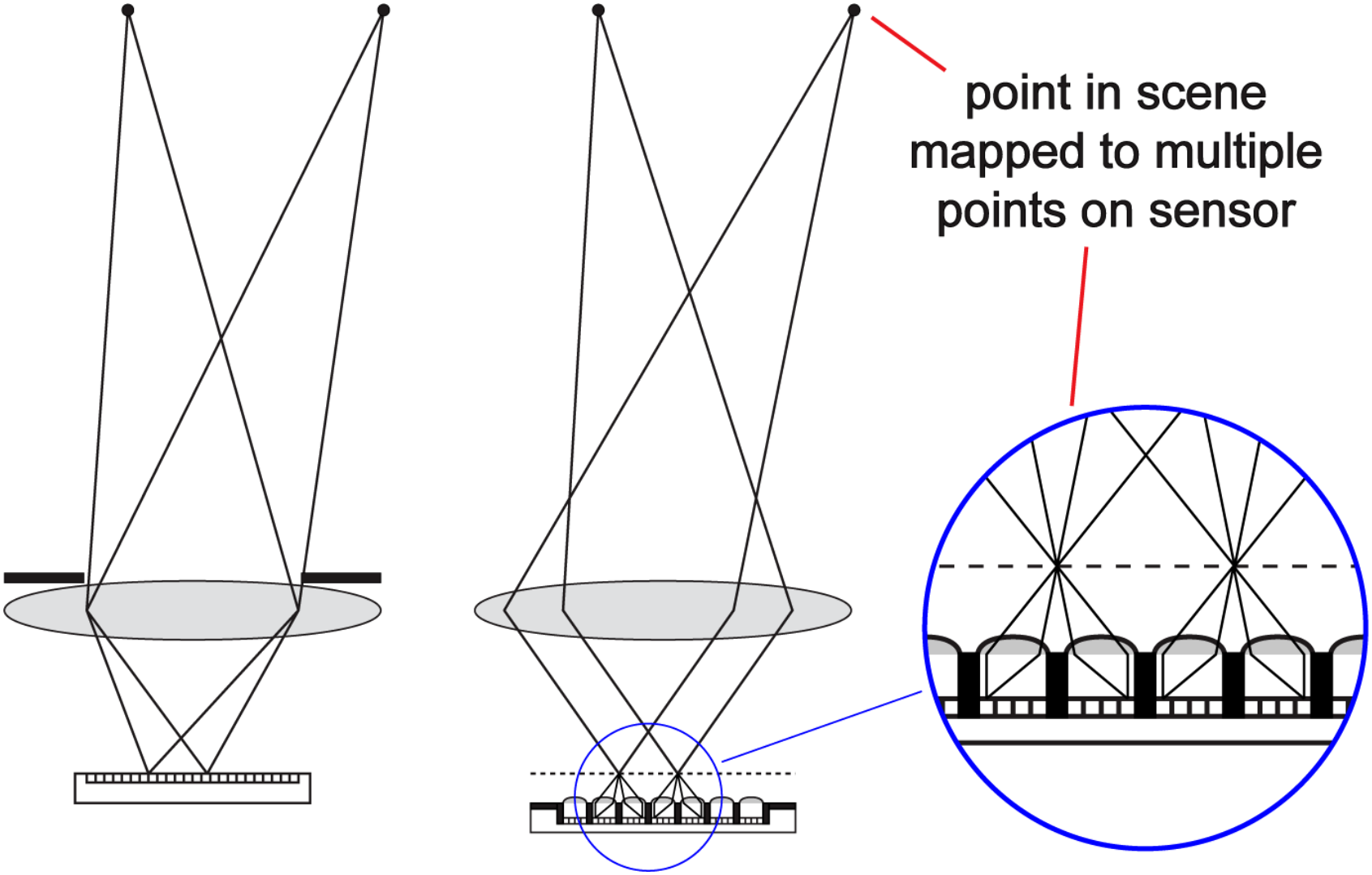
Multi-Aperture Image Sensor



Imager sub-array with integrated optics

Imager sub-arrays 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

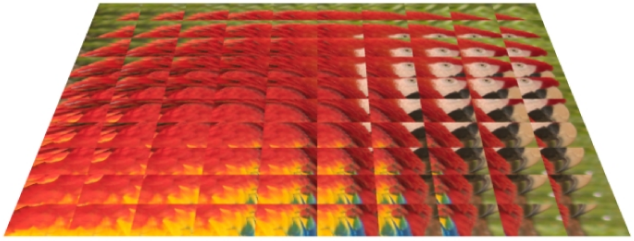
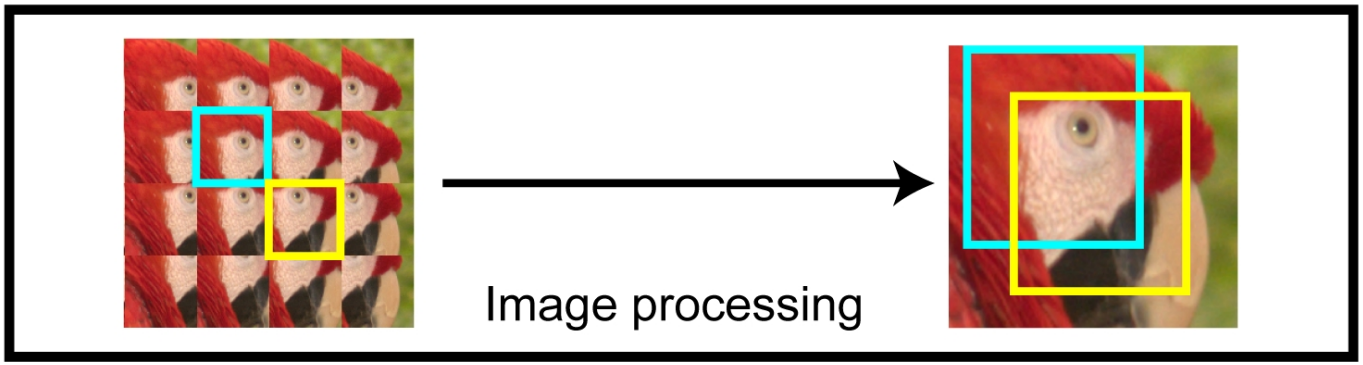


Image captured at MA-imager

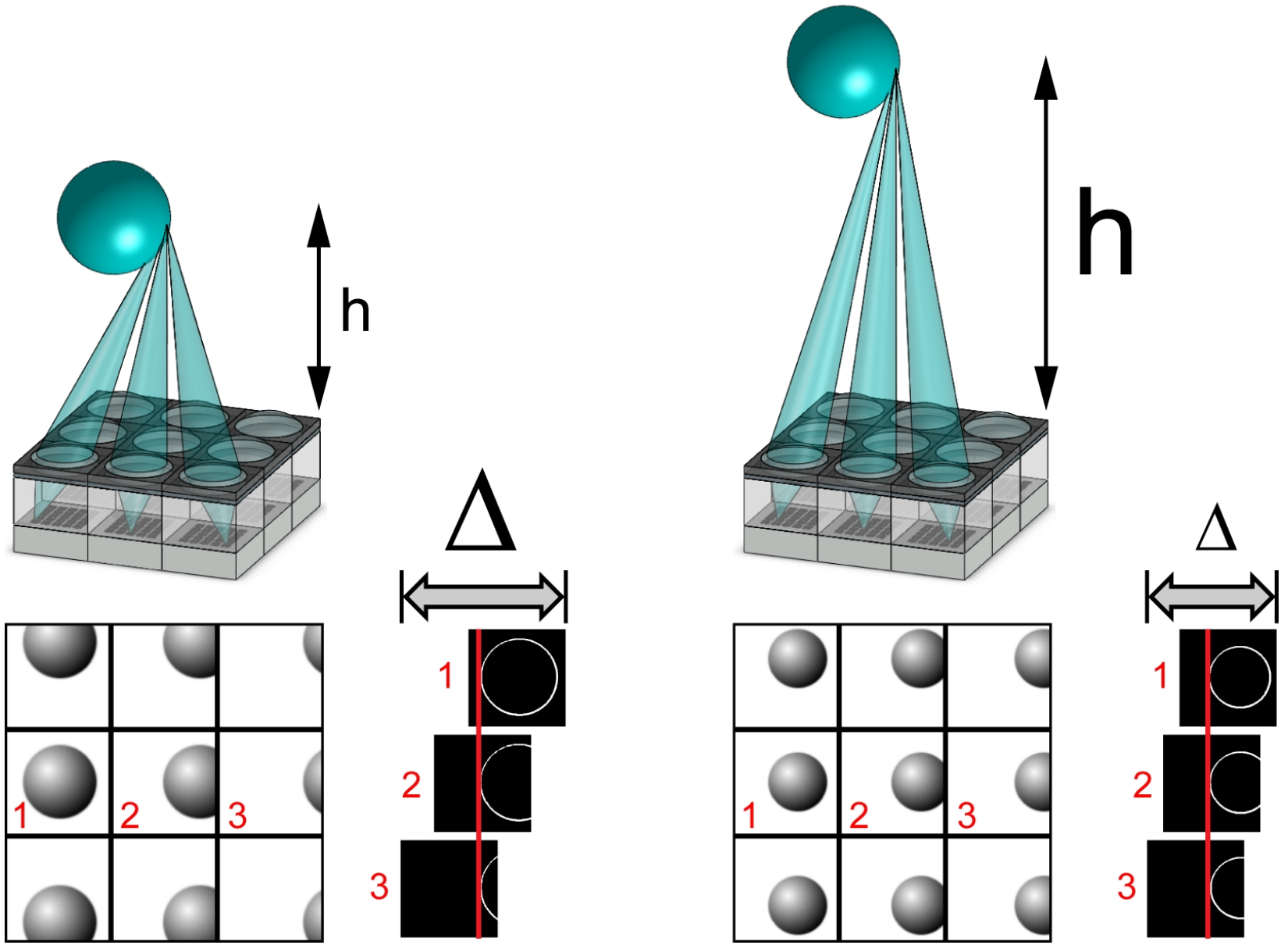
Final reconstructed image



Benefits of Multi-Aperture Imaging

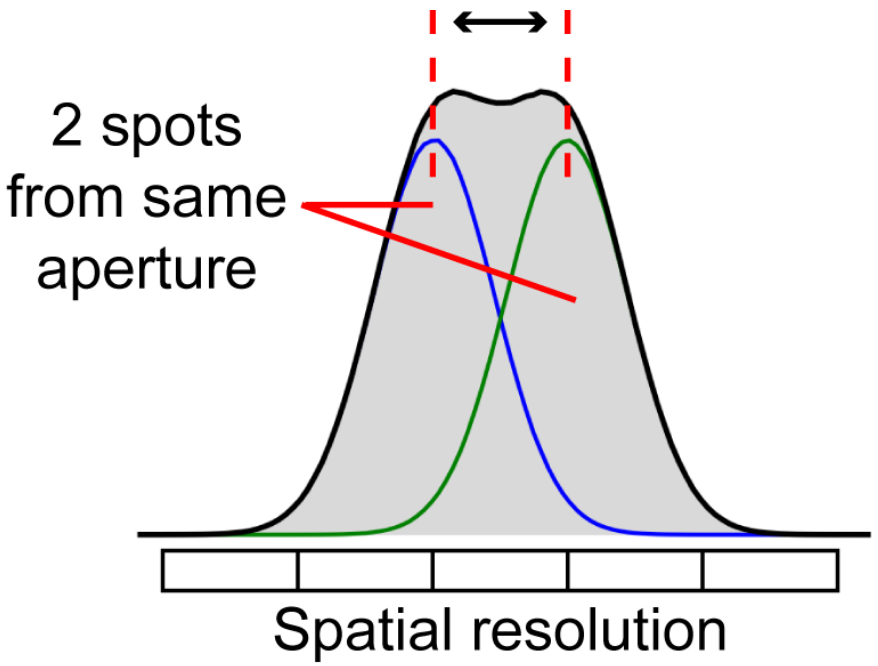
- Capture depth information
- Close proximity imaging
- Achieve better color separation
- Reduce requirements of objective lens
- Increase tolerance to defective pixels

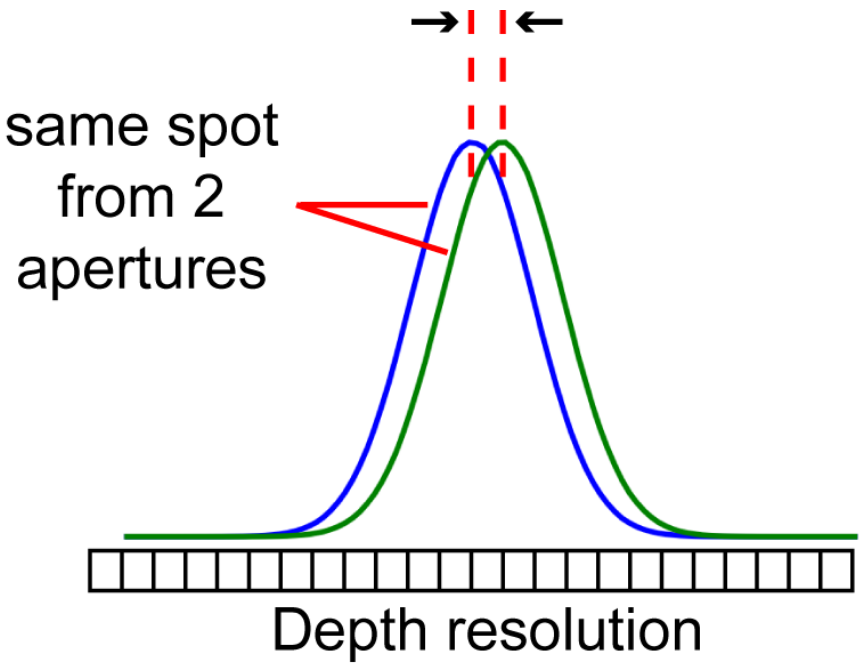
Depth from Multi-Aperture



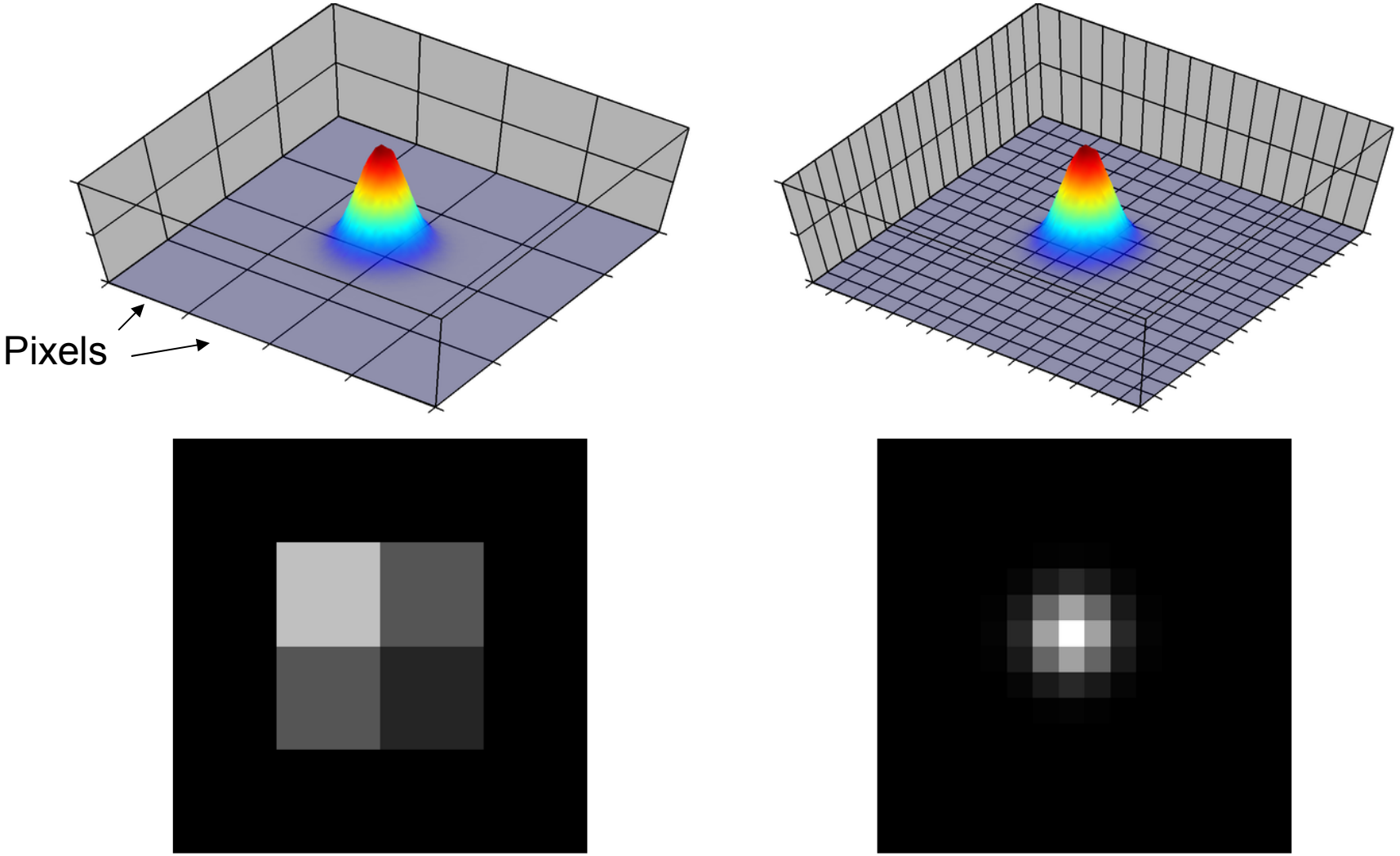
Why Use Small Pixels?

- 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





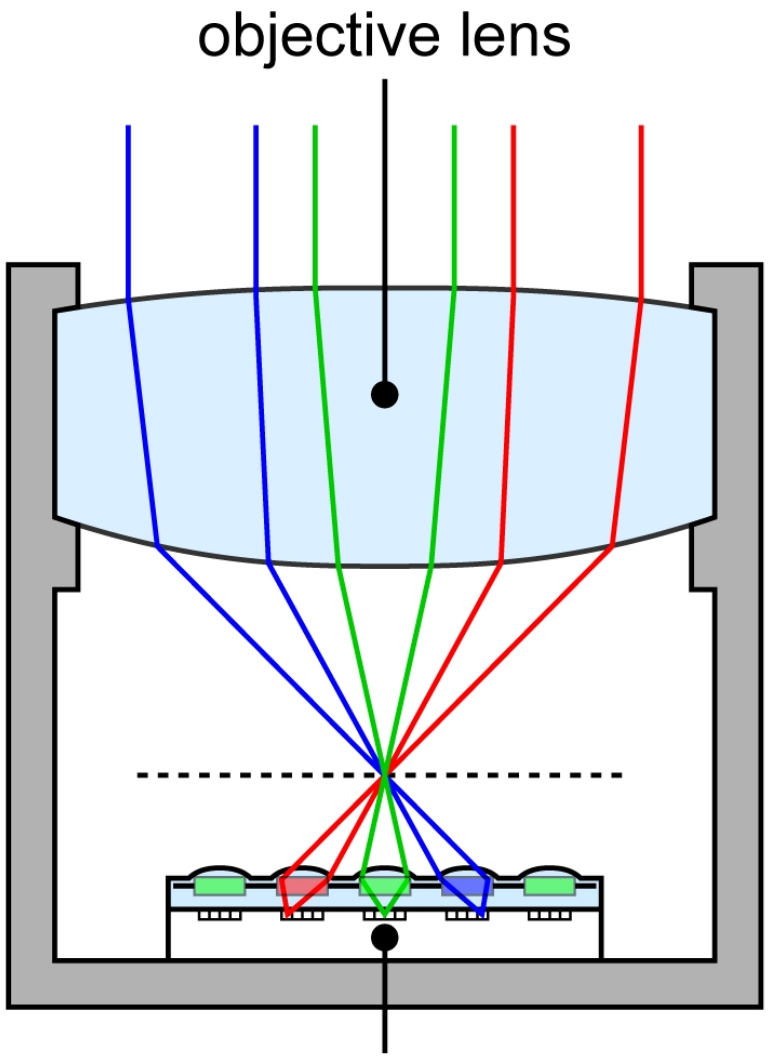
Feature Localization vs. Pixel Size

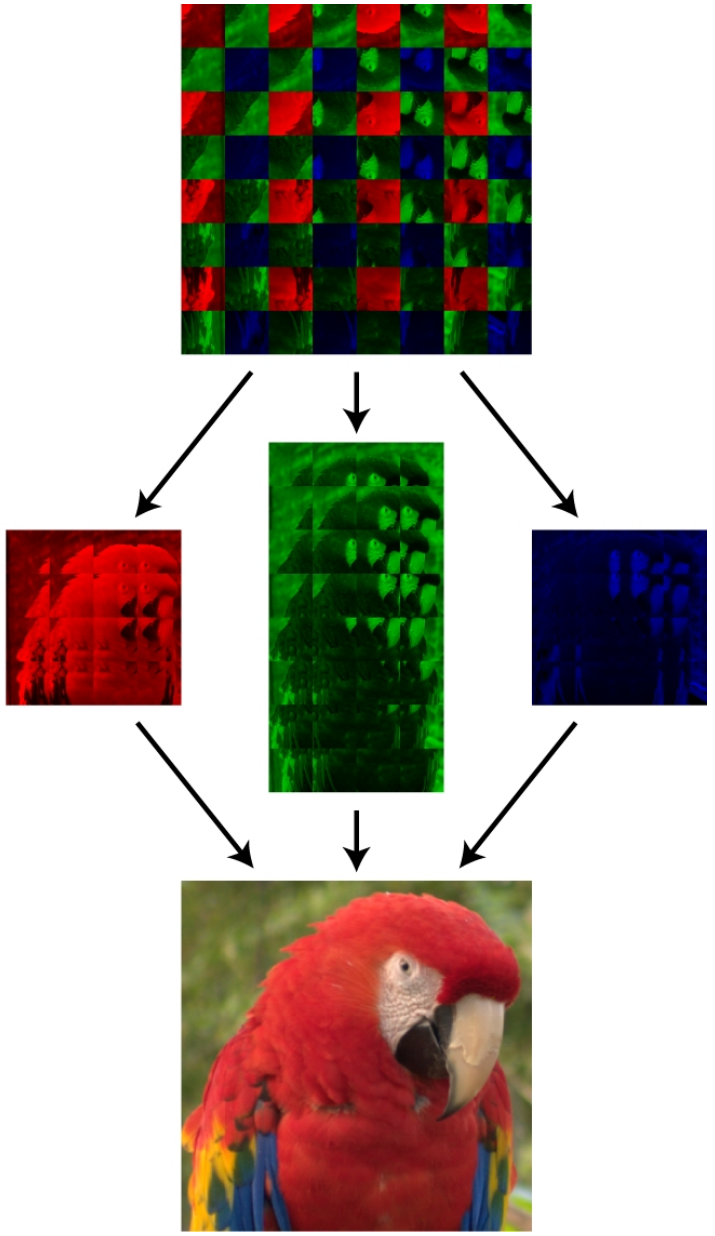


Poor location accuracy

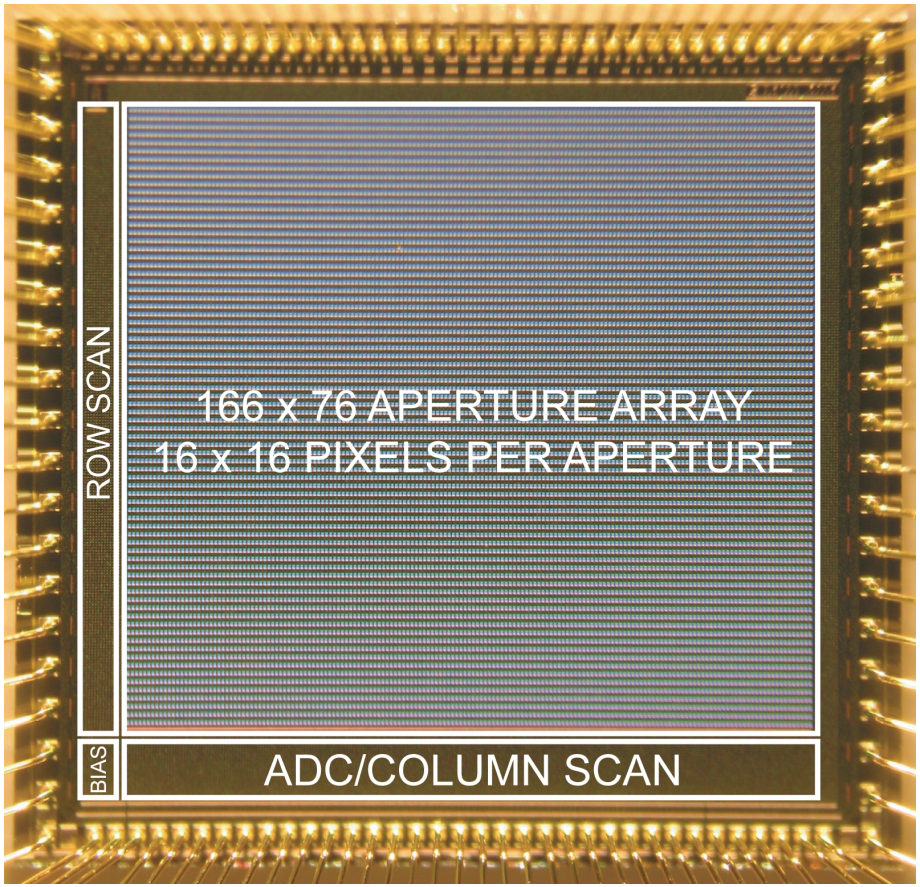
High location accuracy

Color with Multi-Aperture





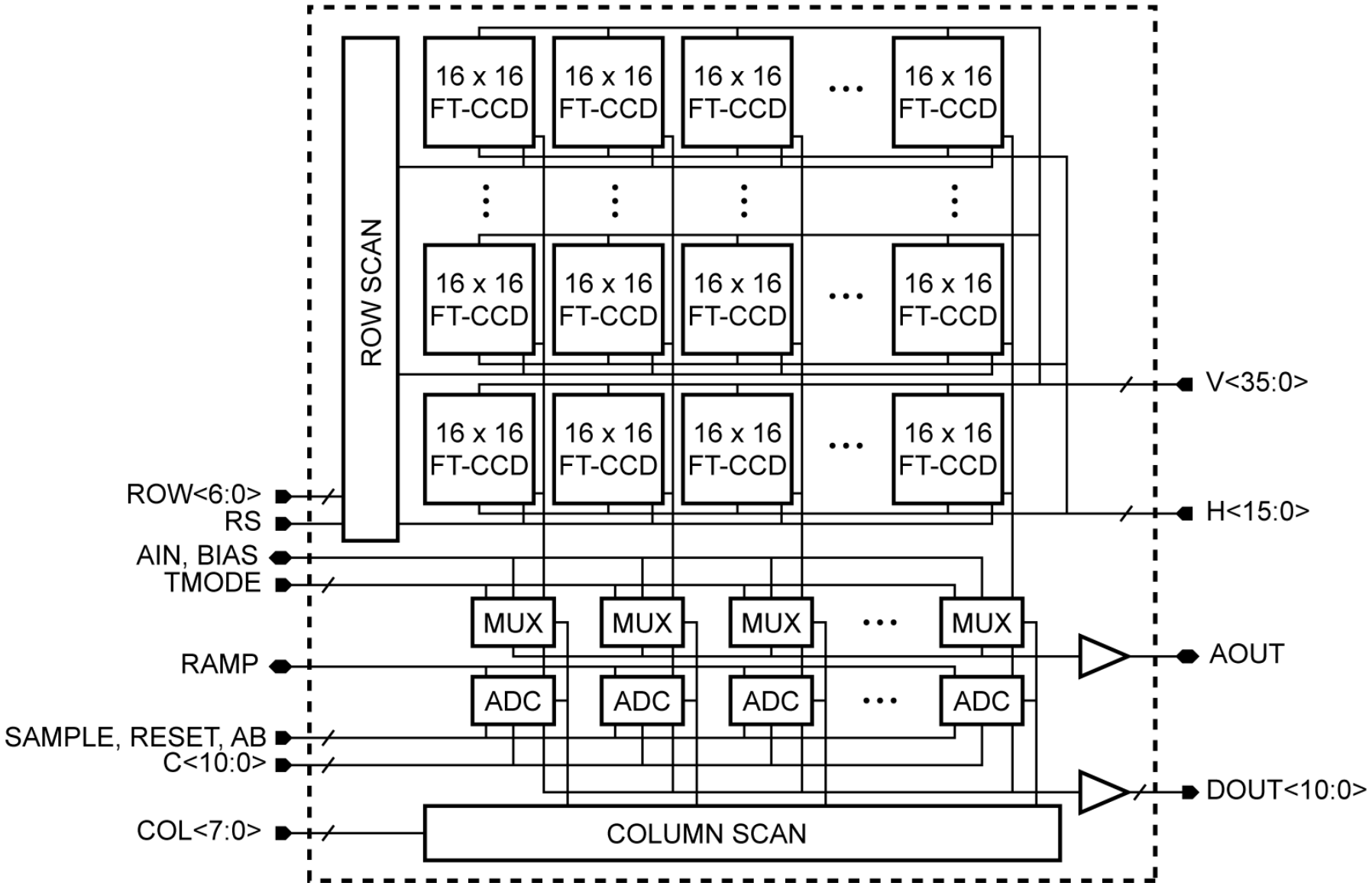
Fabricated Multi-Aperture Imager



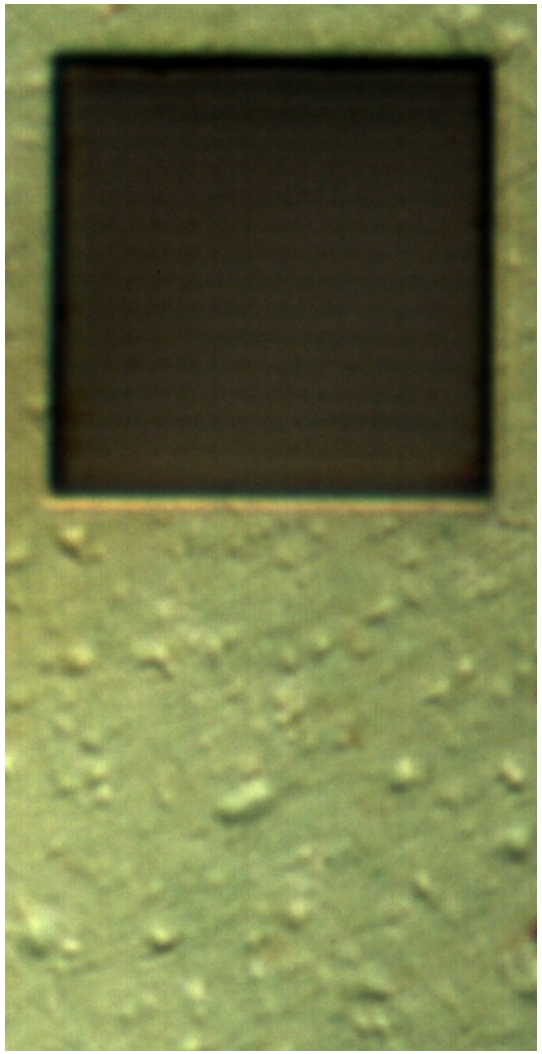
- 0.11μm CMOS (TSMC)
- Chip size: 3.0 x 2.9mm^2
- 166 x 76 aperture array
- 16 x 16 pixel FT-CCD per aperture
- Pixel size: 0.7 μm
- Max frame rate: 15fps
- ADC resolution: 10 bit
- Power: 10.45mW

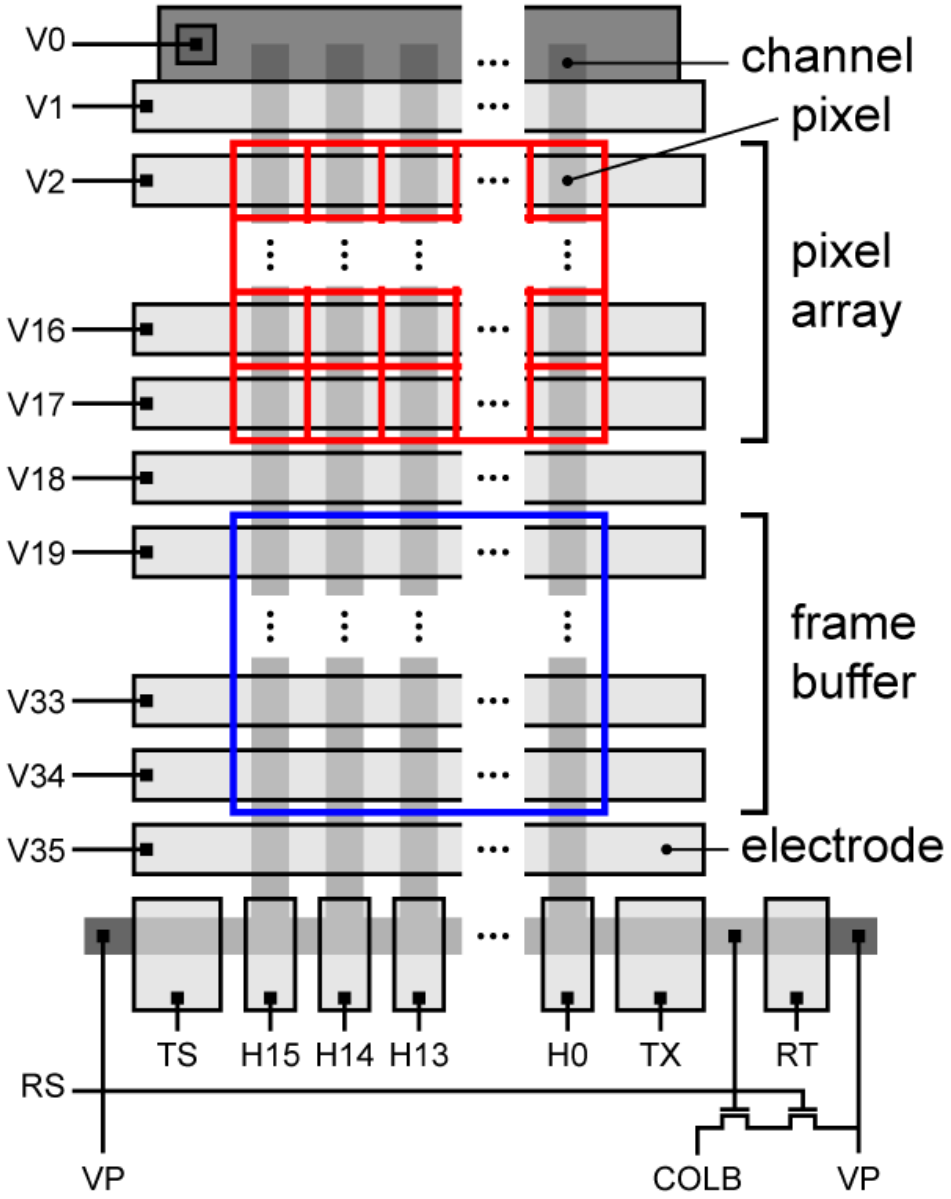
* Local optics are not integrated on this chip.

Block Diagram of Fabricated Chip



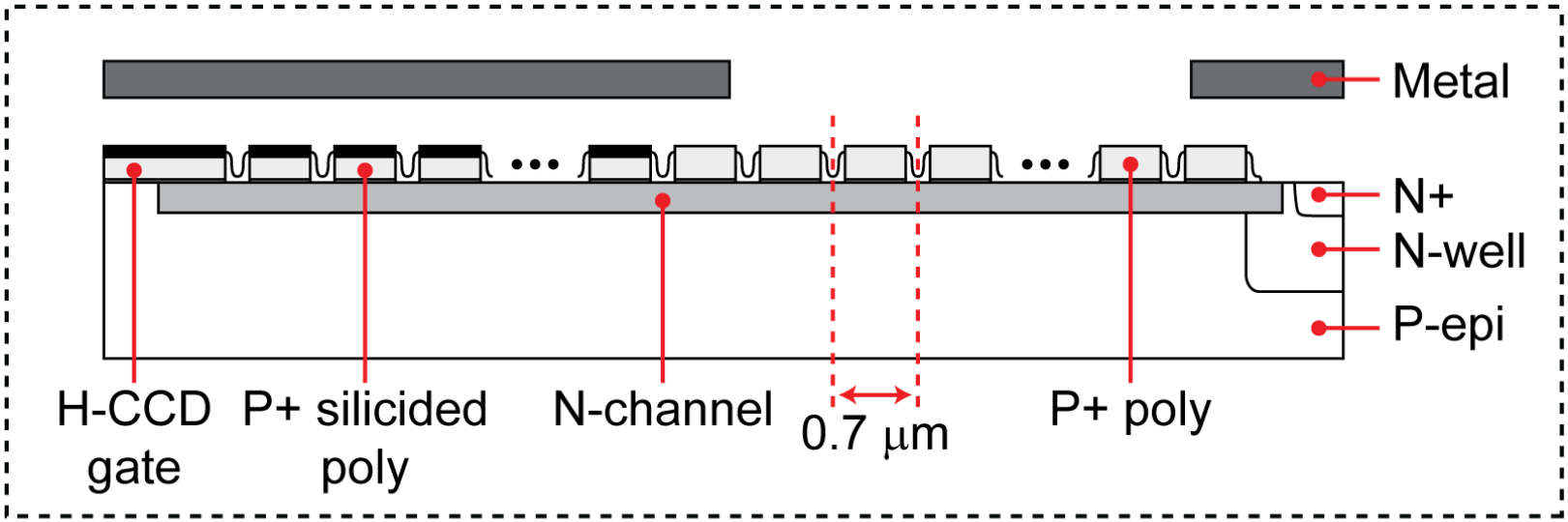
16 x 16 FT-CCD schematic



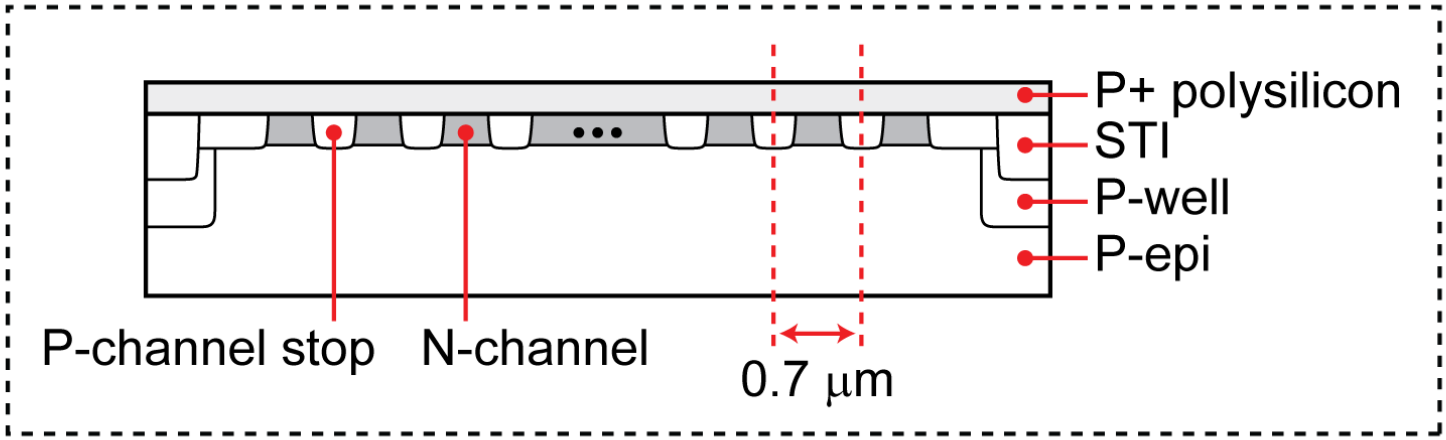


** K. Fife, A. El Gamal and H.-S. P. Wong, IEDM 2007, p1003-1006*

CCD Cross Sections



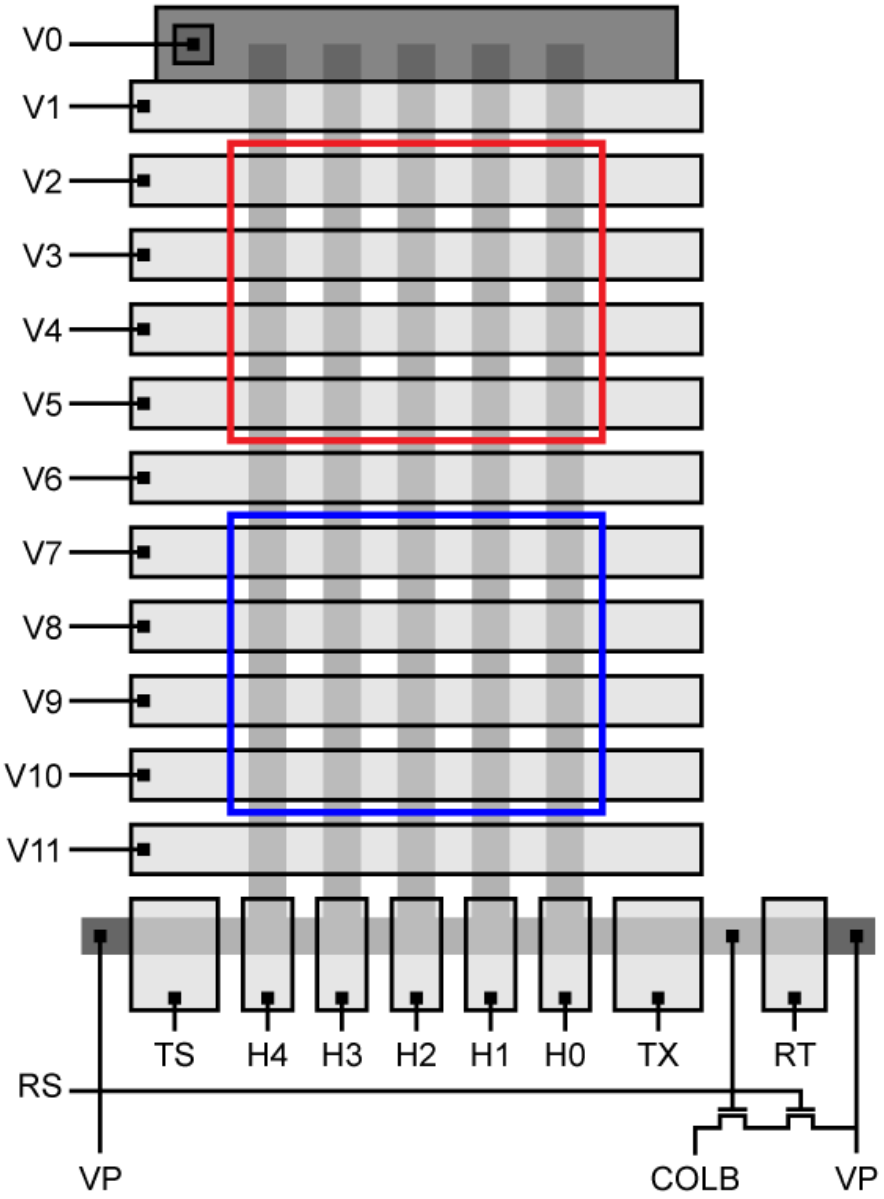
cross section along channel



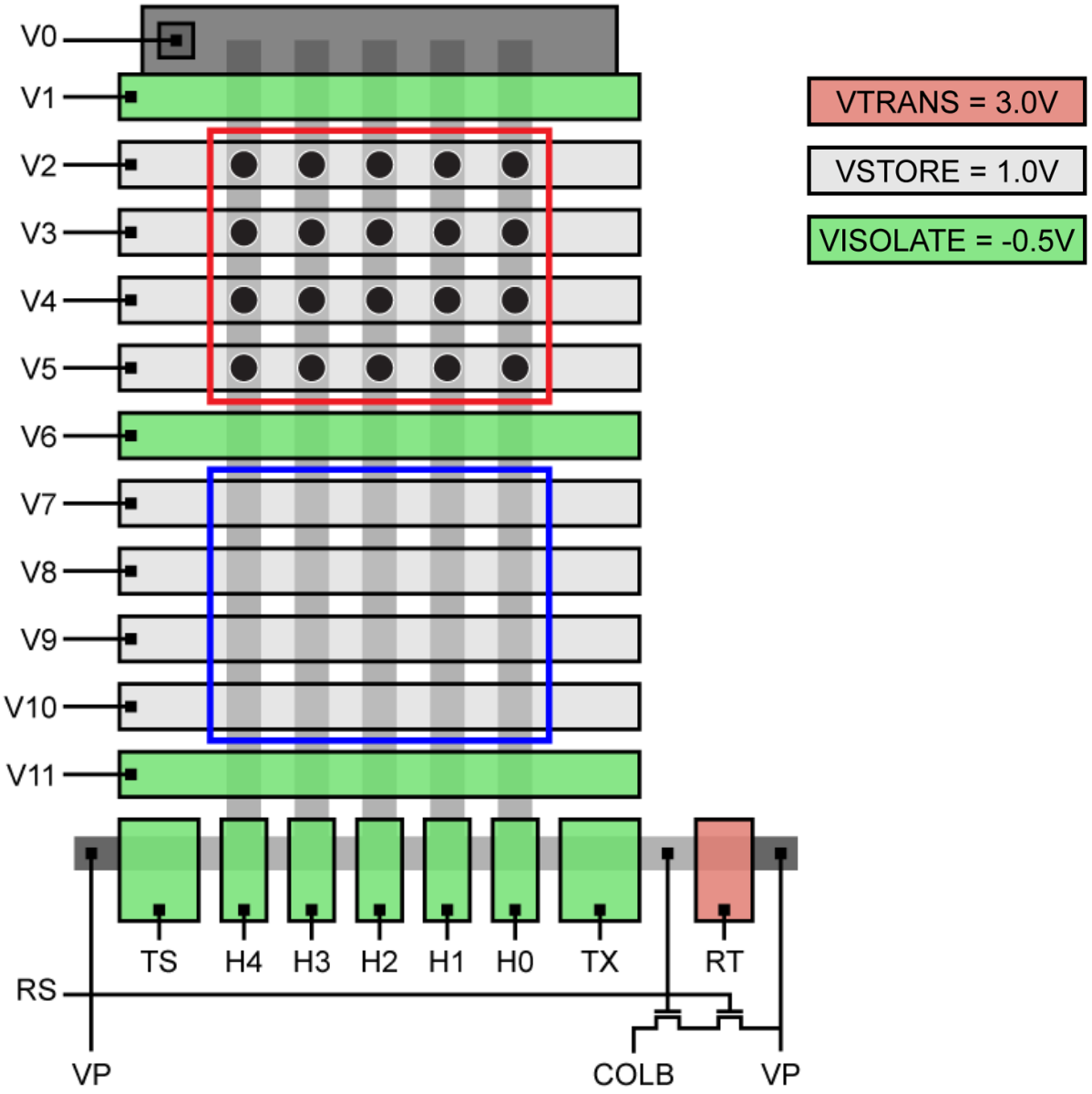
cross section against channel

Operation

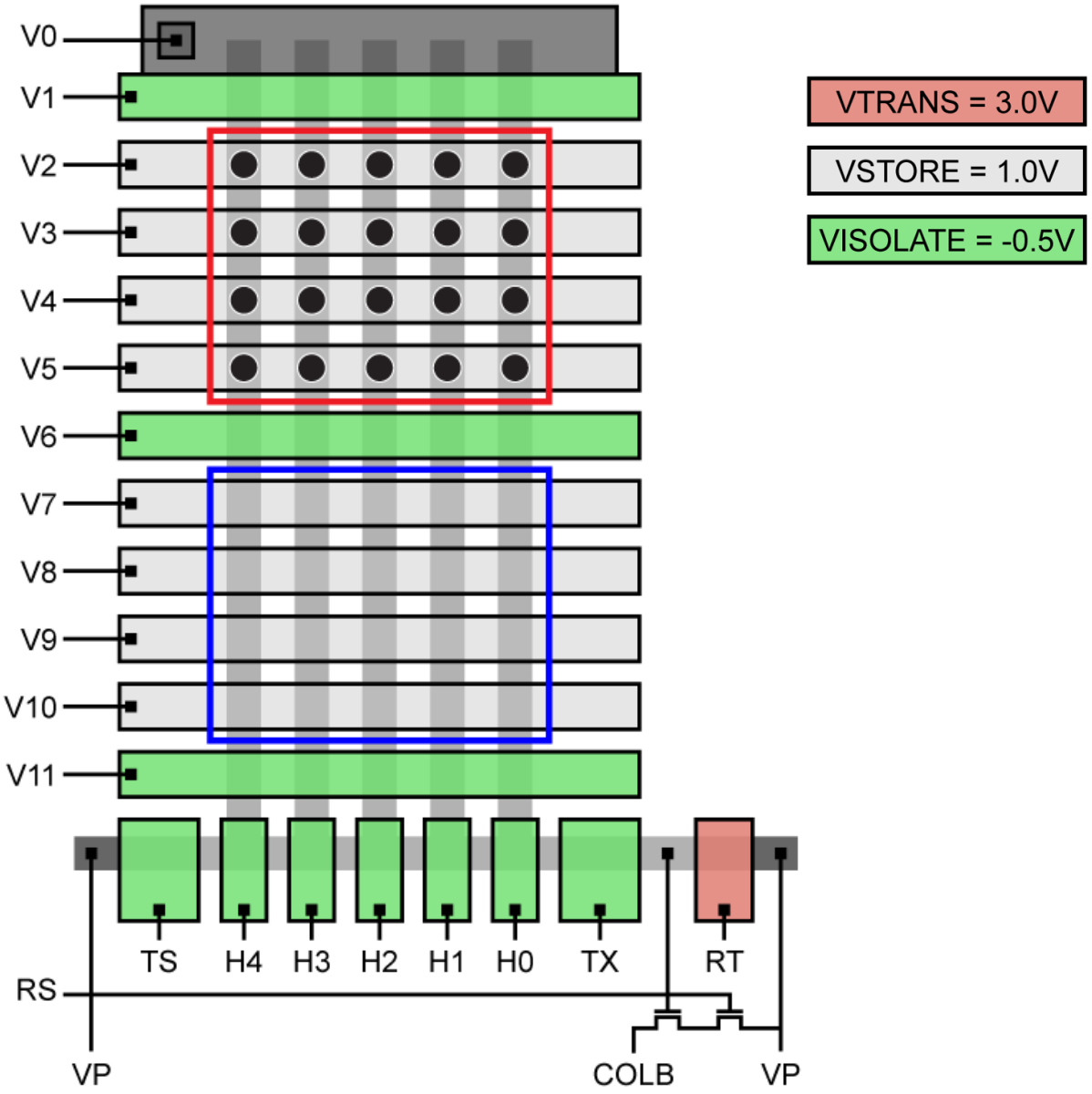
- Flush
- Integrate
- Frame Transfer
- Horizontal Readout



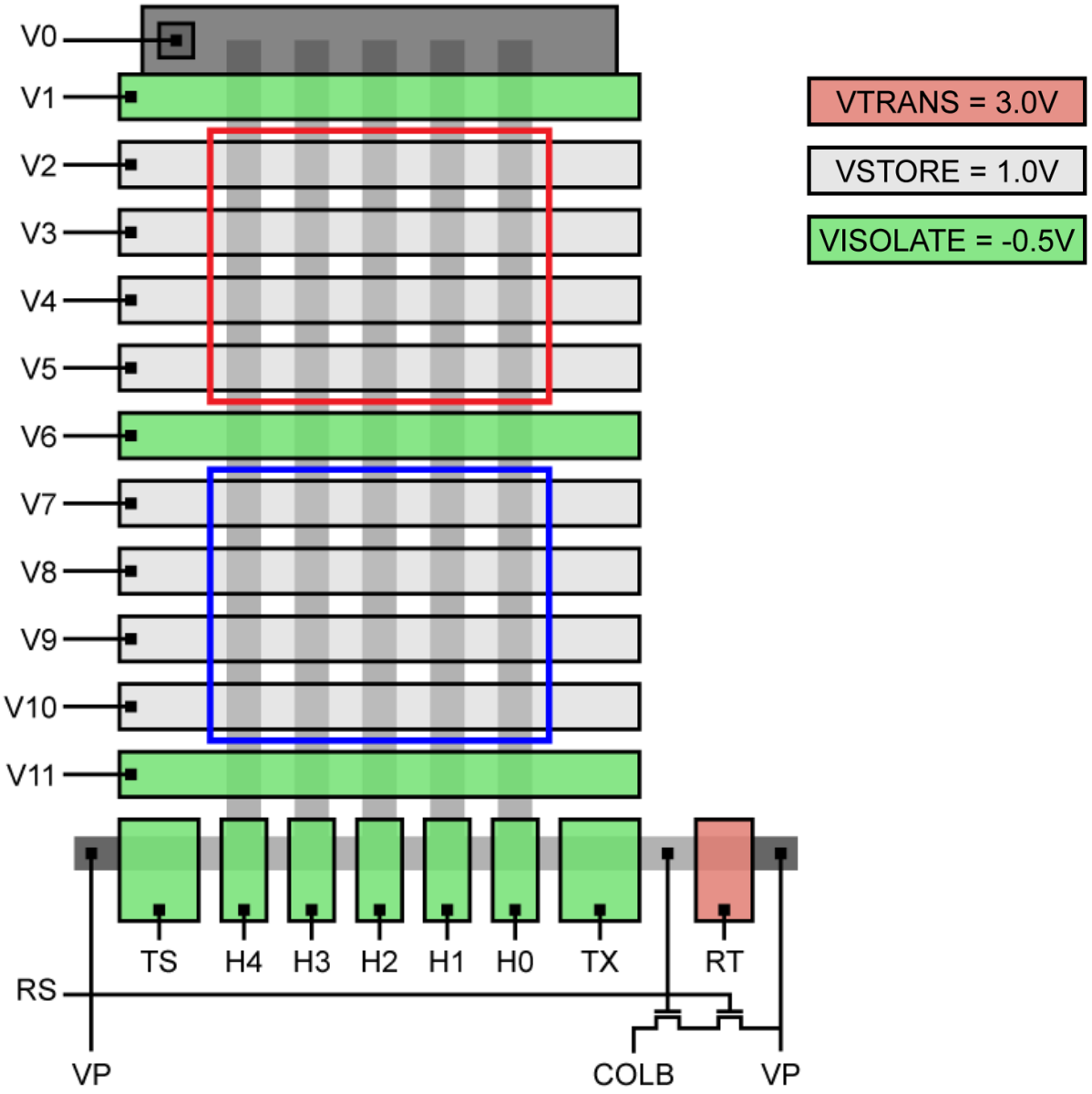
Operation (Flush)



Operation (Flush)



Operation (Integrate)



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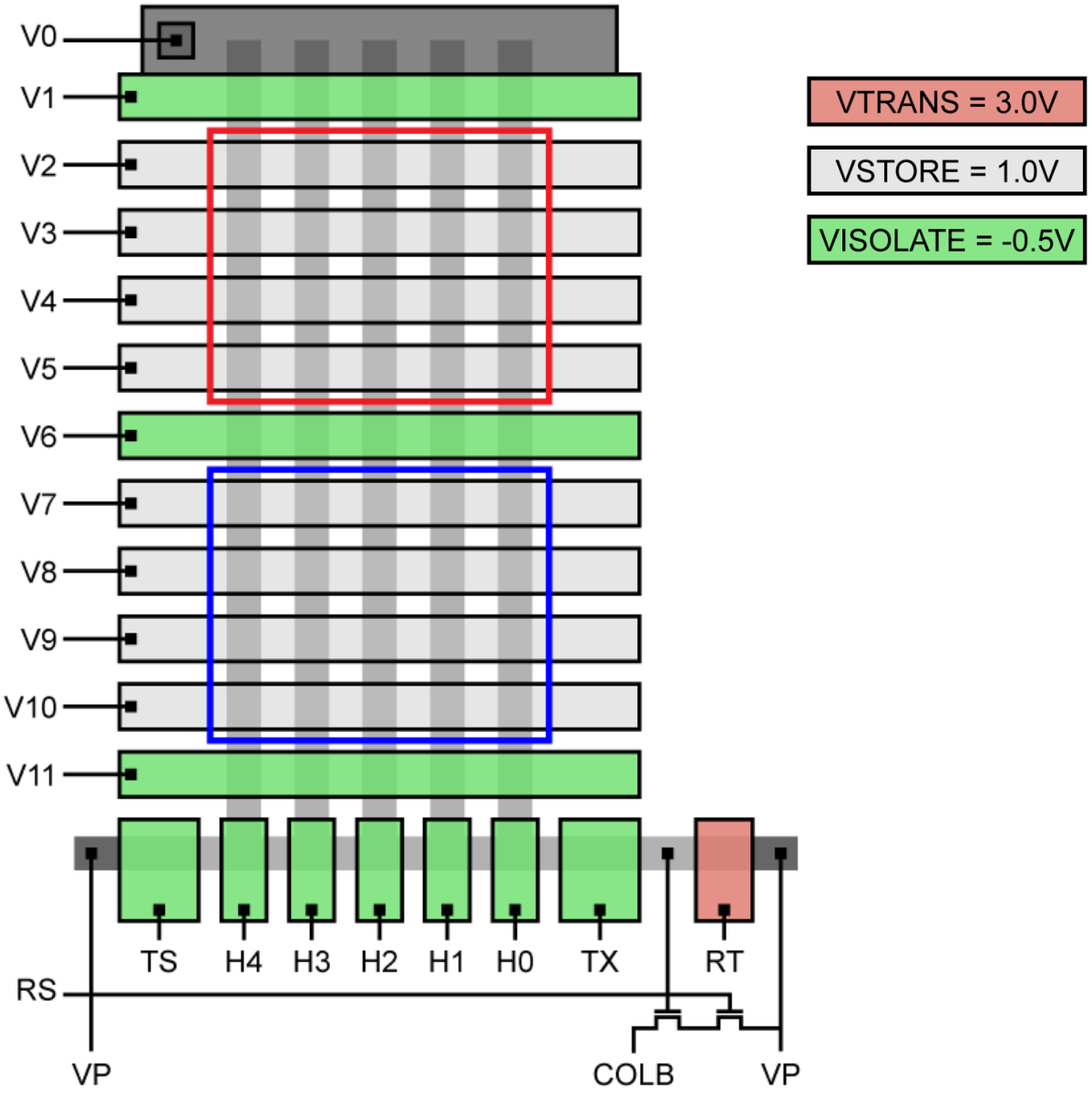
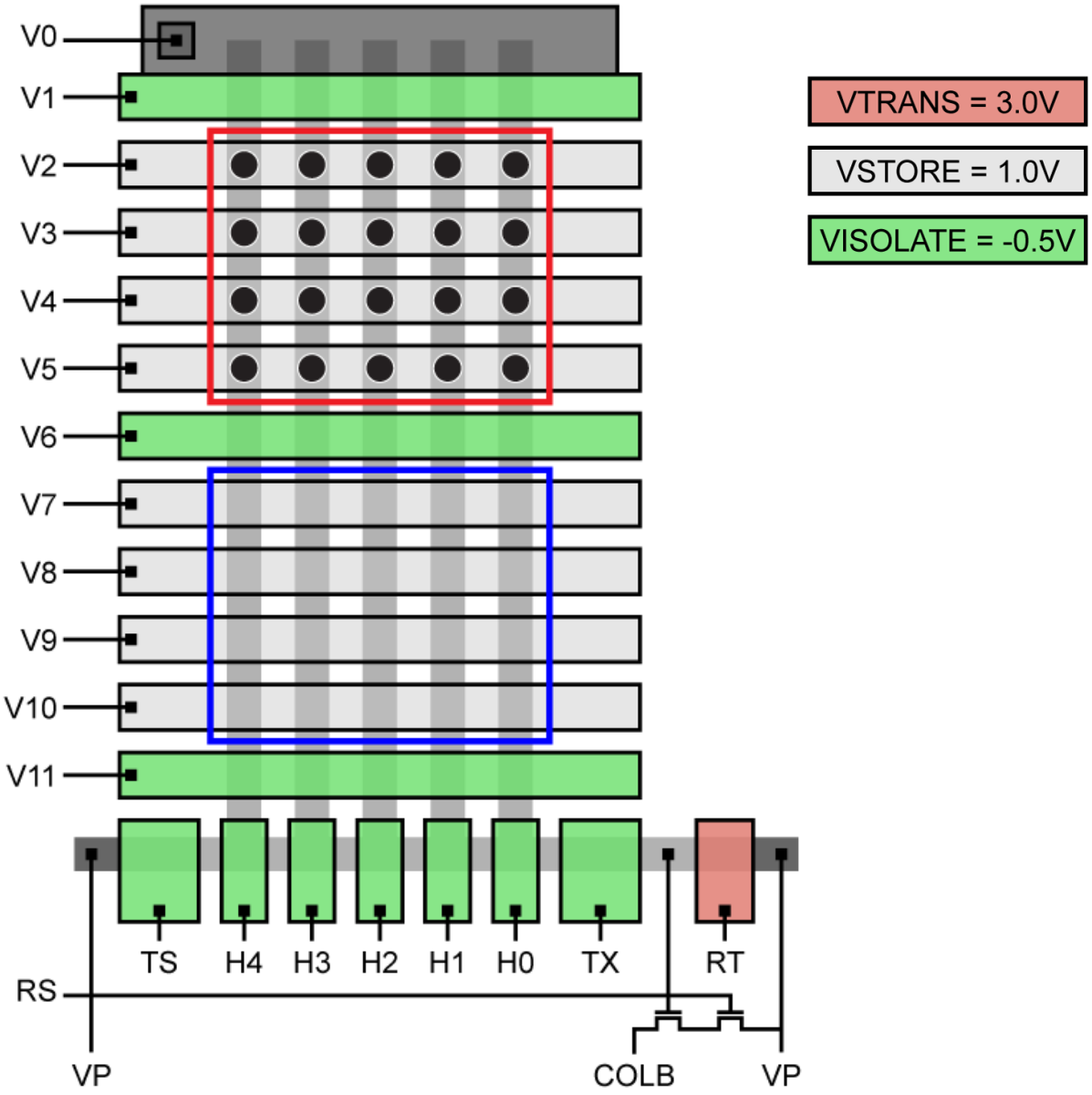


Operation (Frame Transfer)



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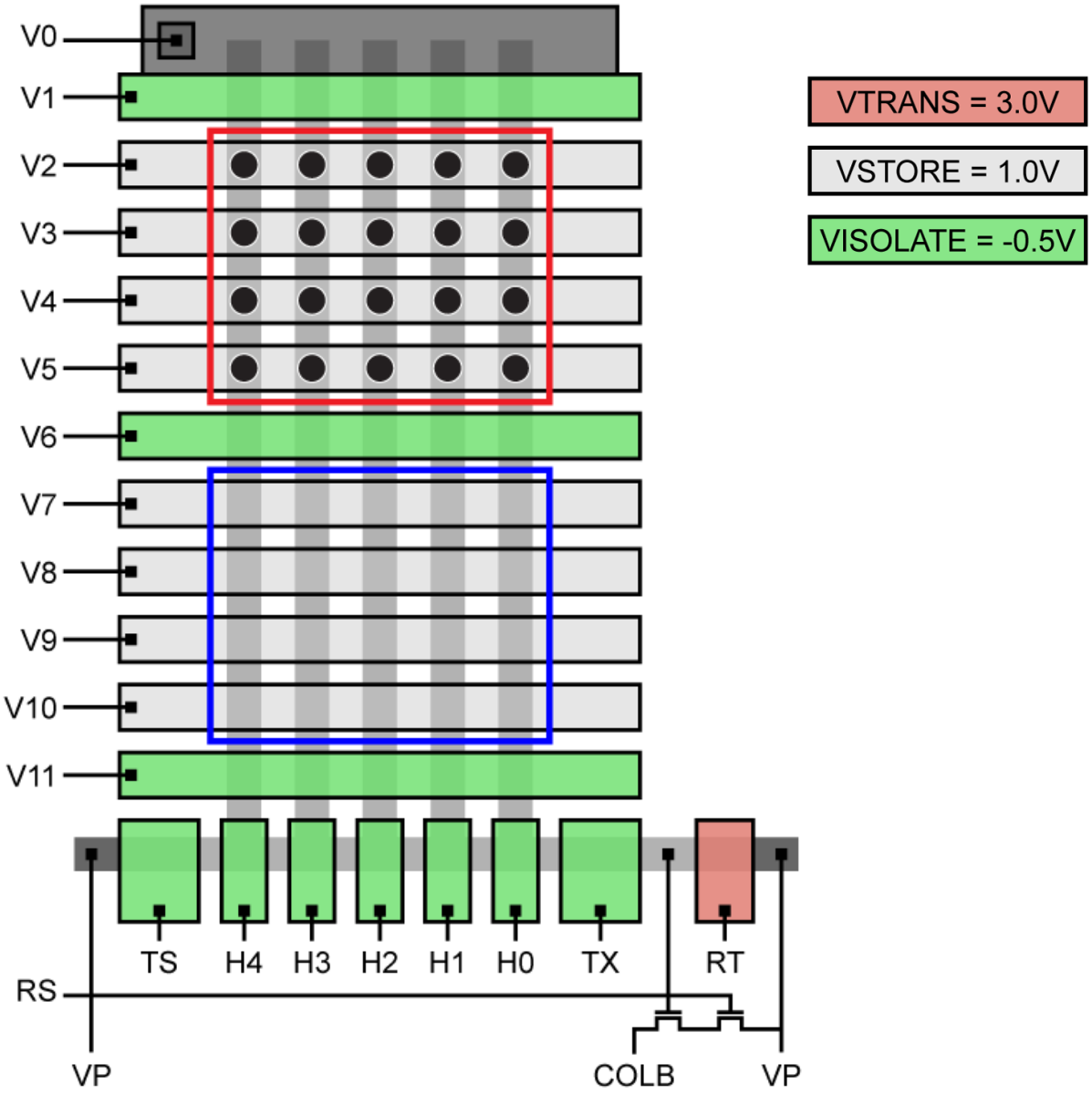
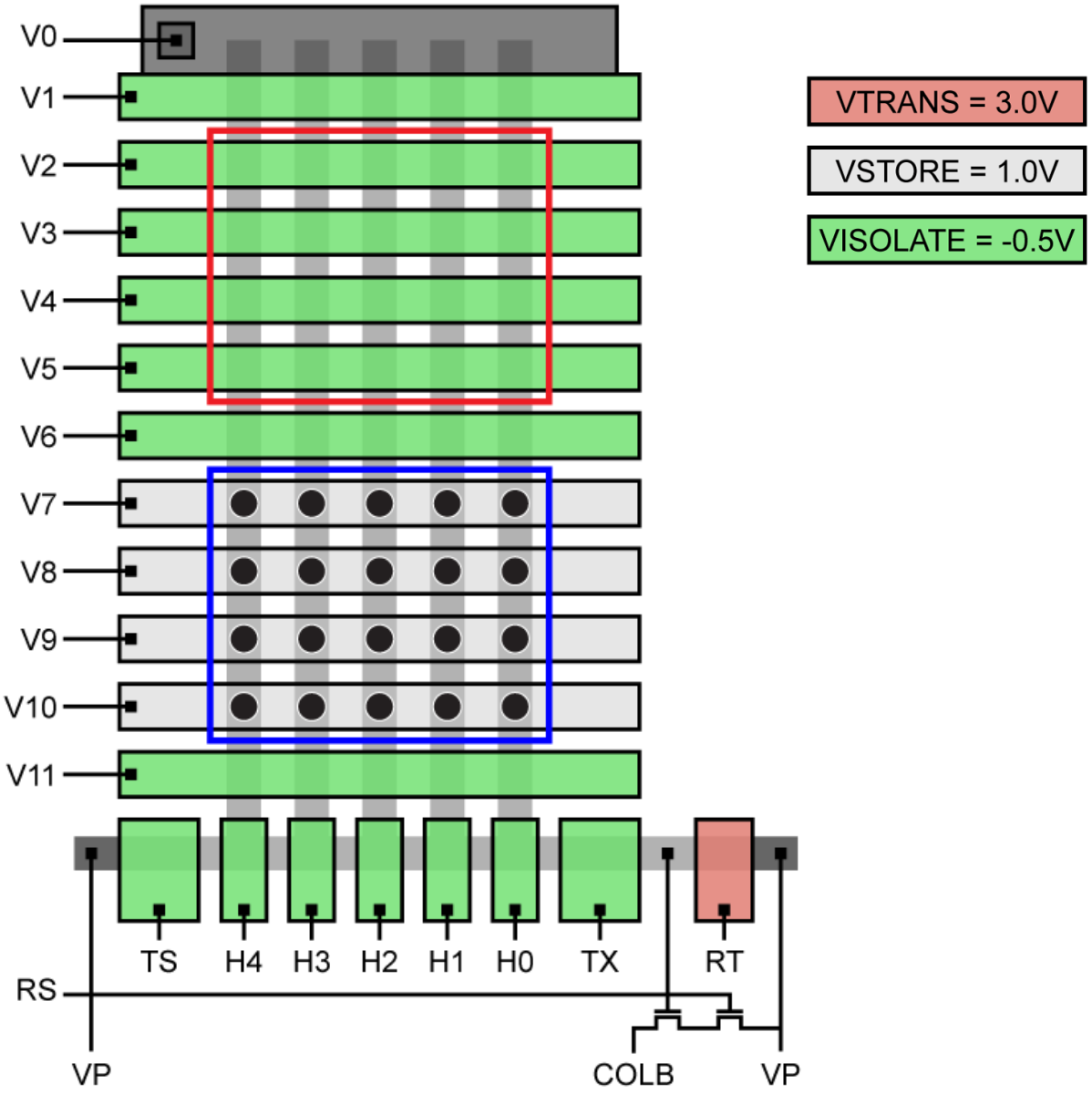
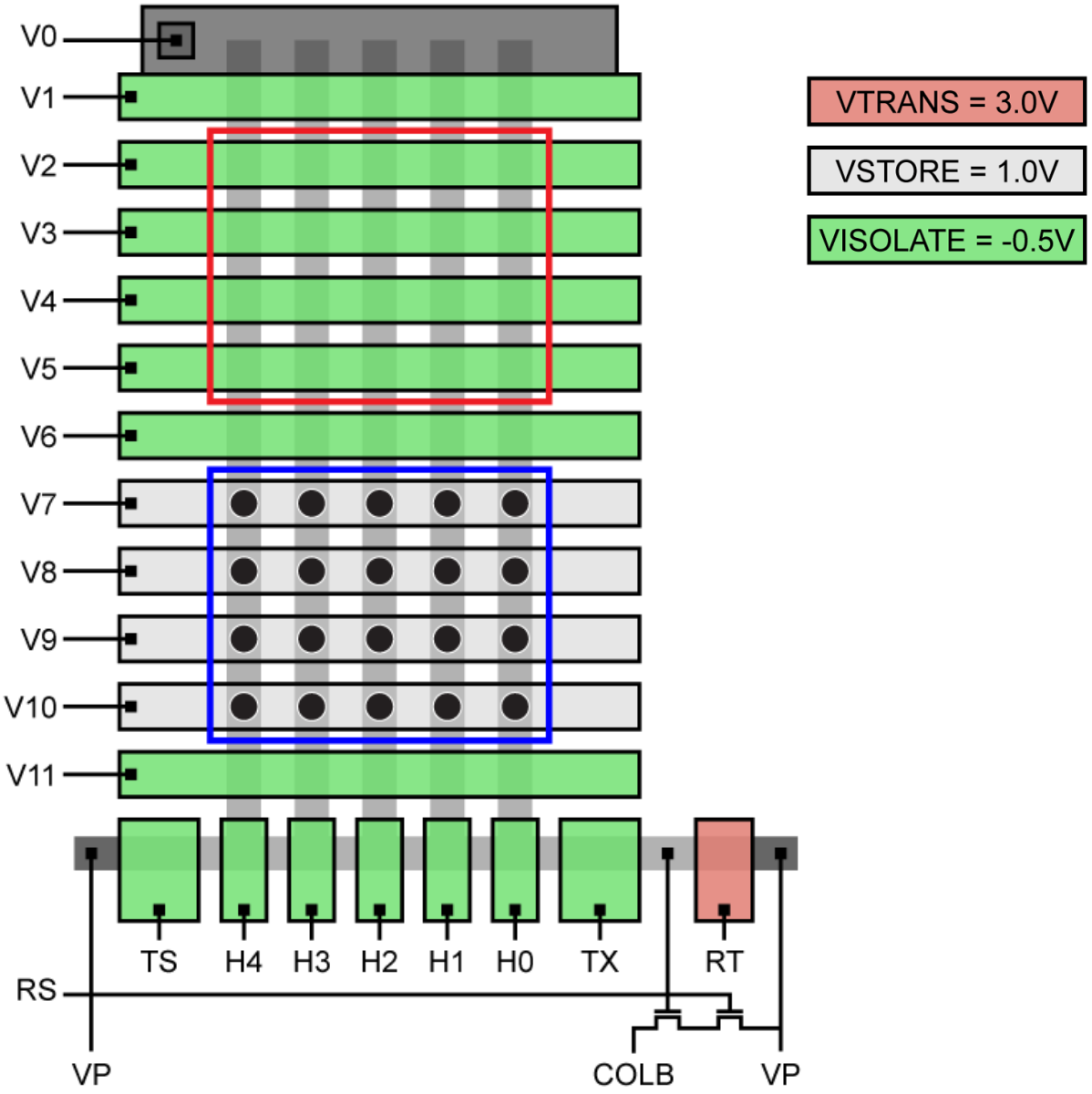


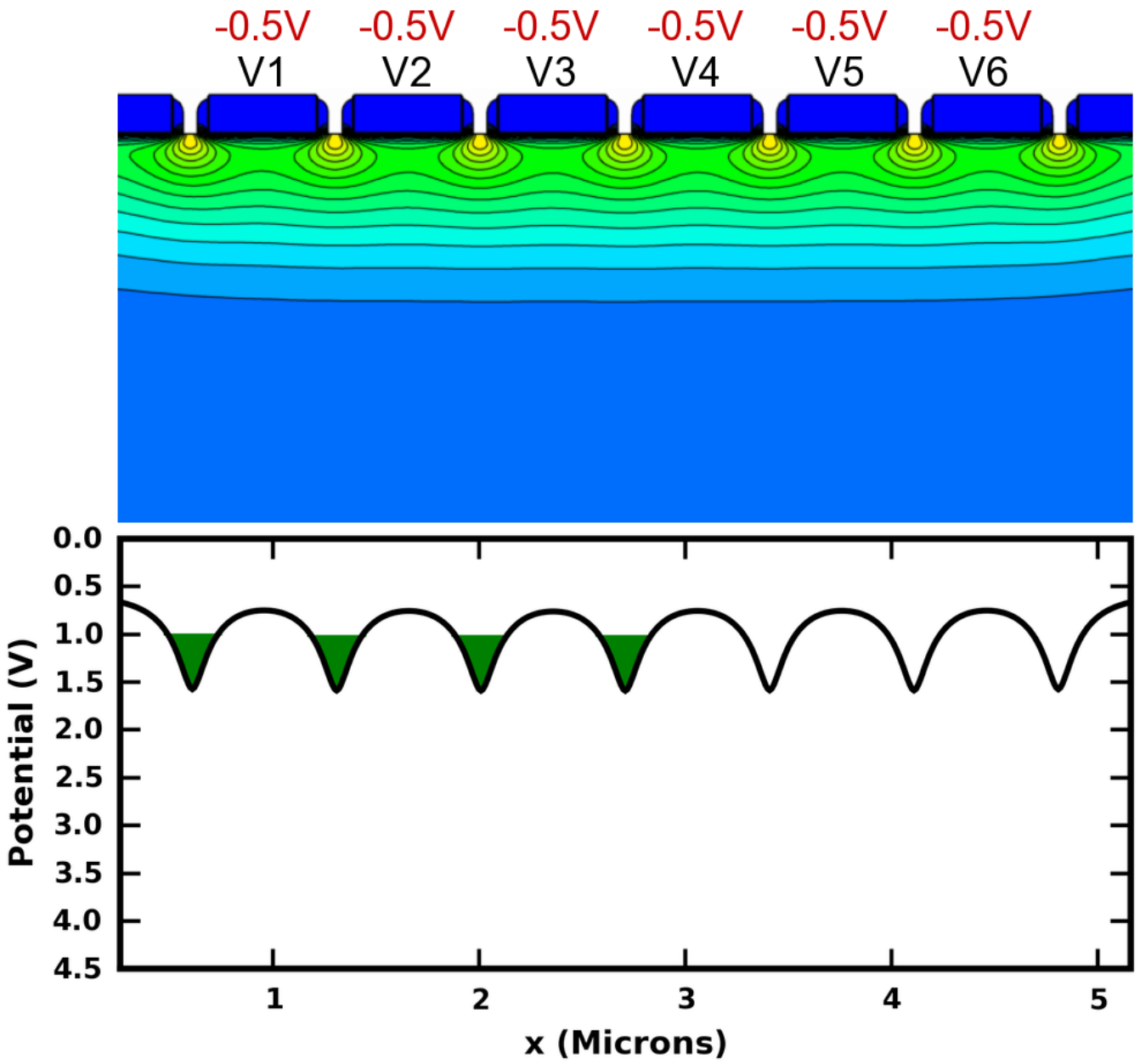
Operation (Horizontal Transfer)



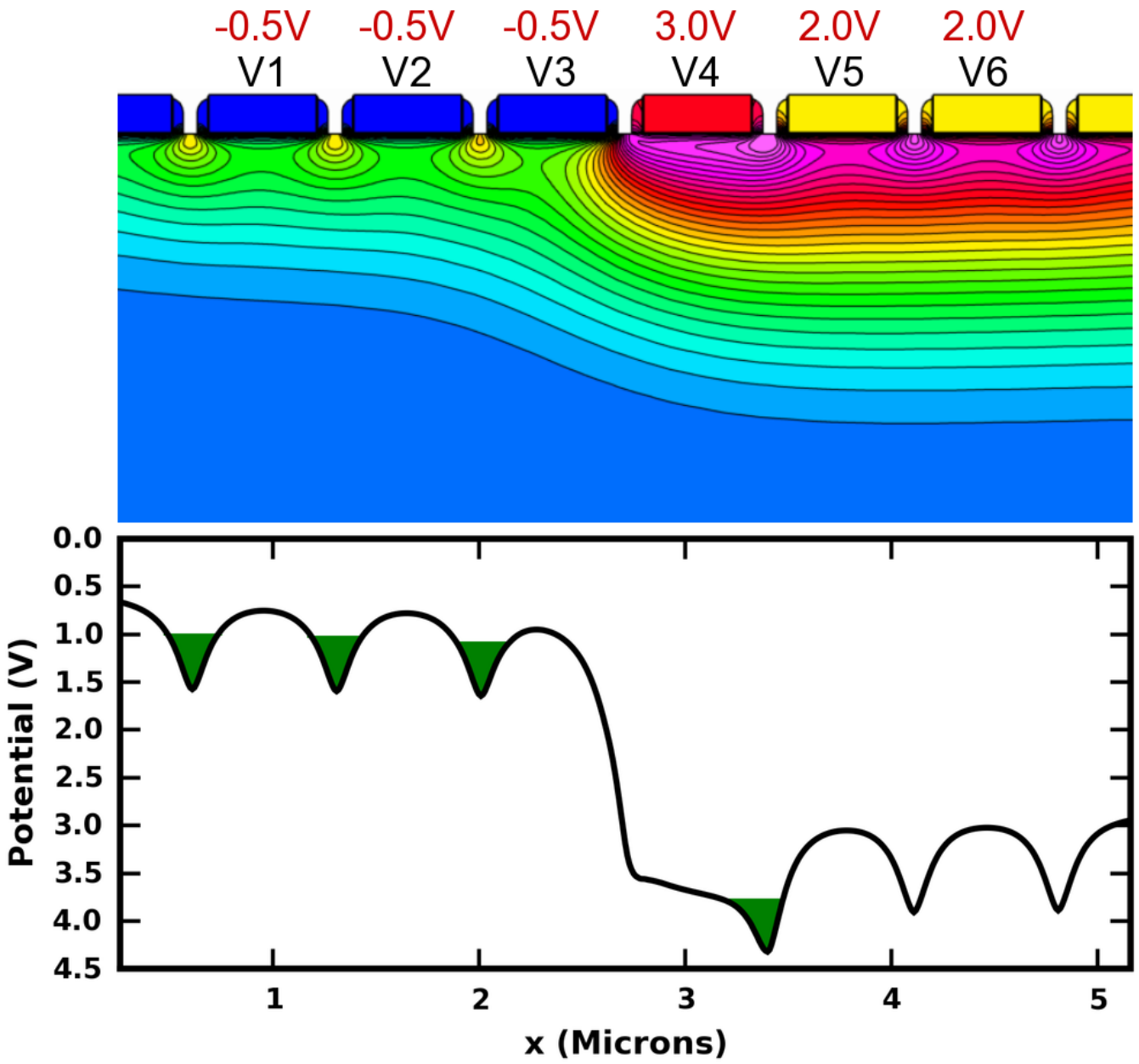
Operation (Horizontal Transfer)



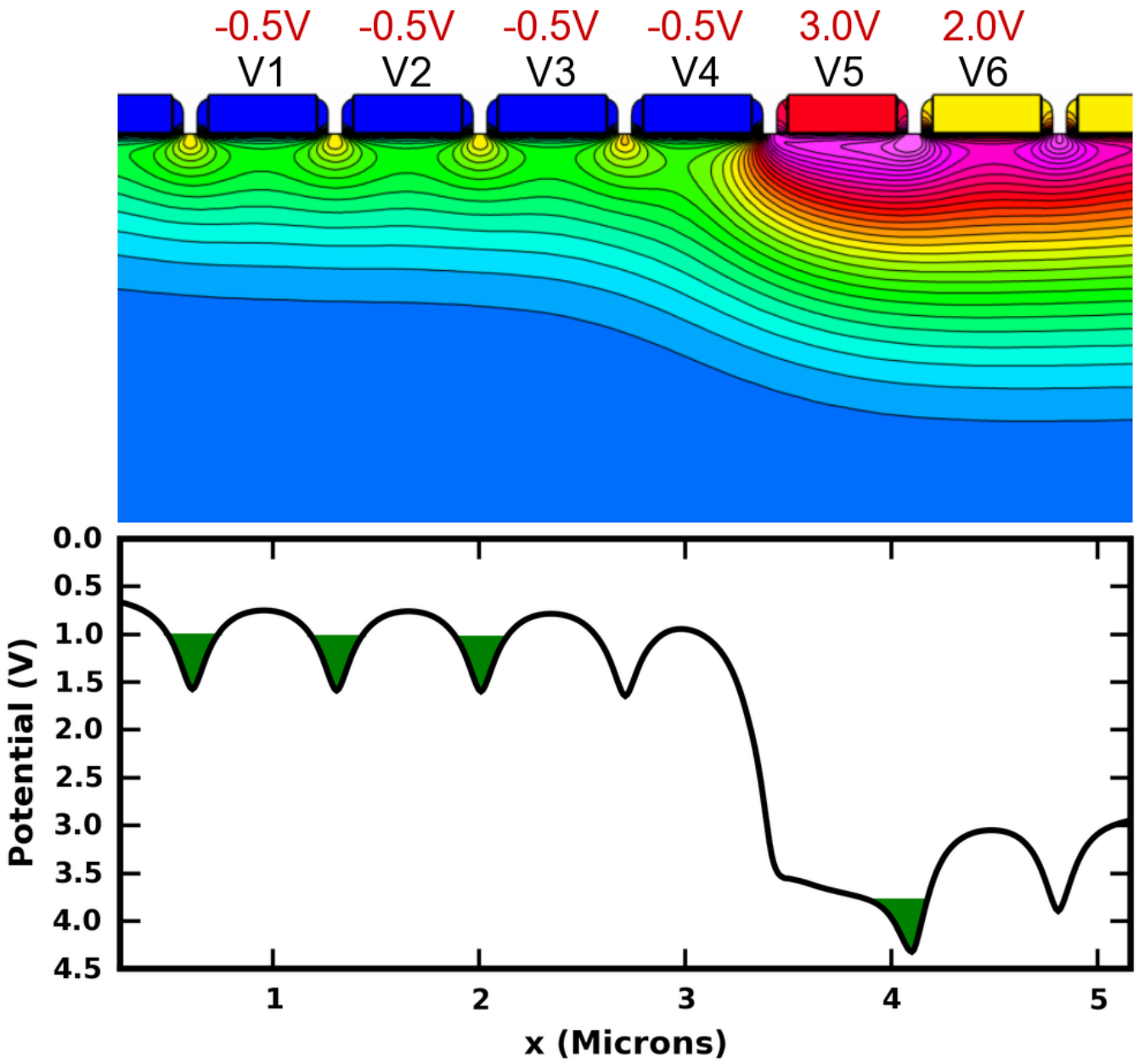
Potential Profile Along Channel



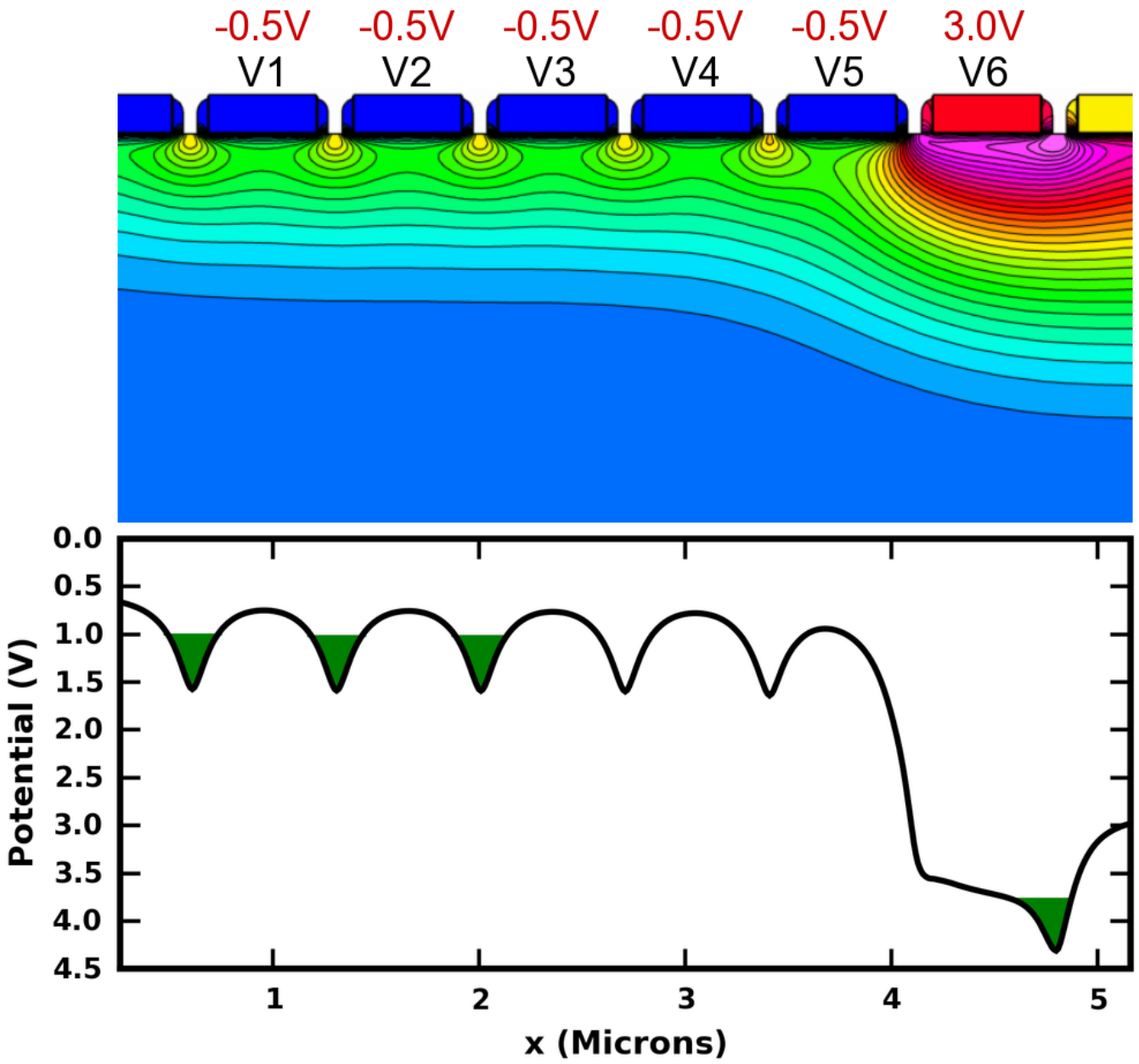
Potential Profile Along Channel



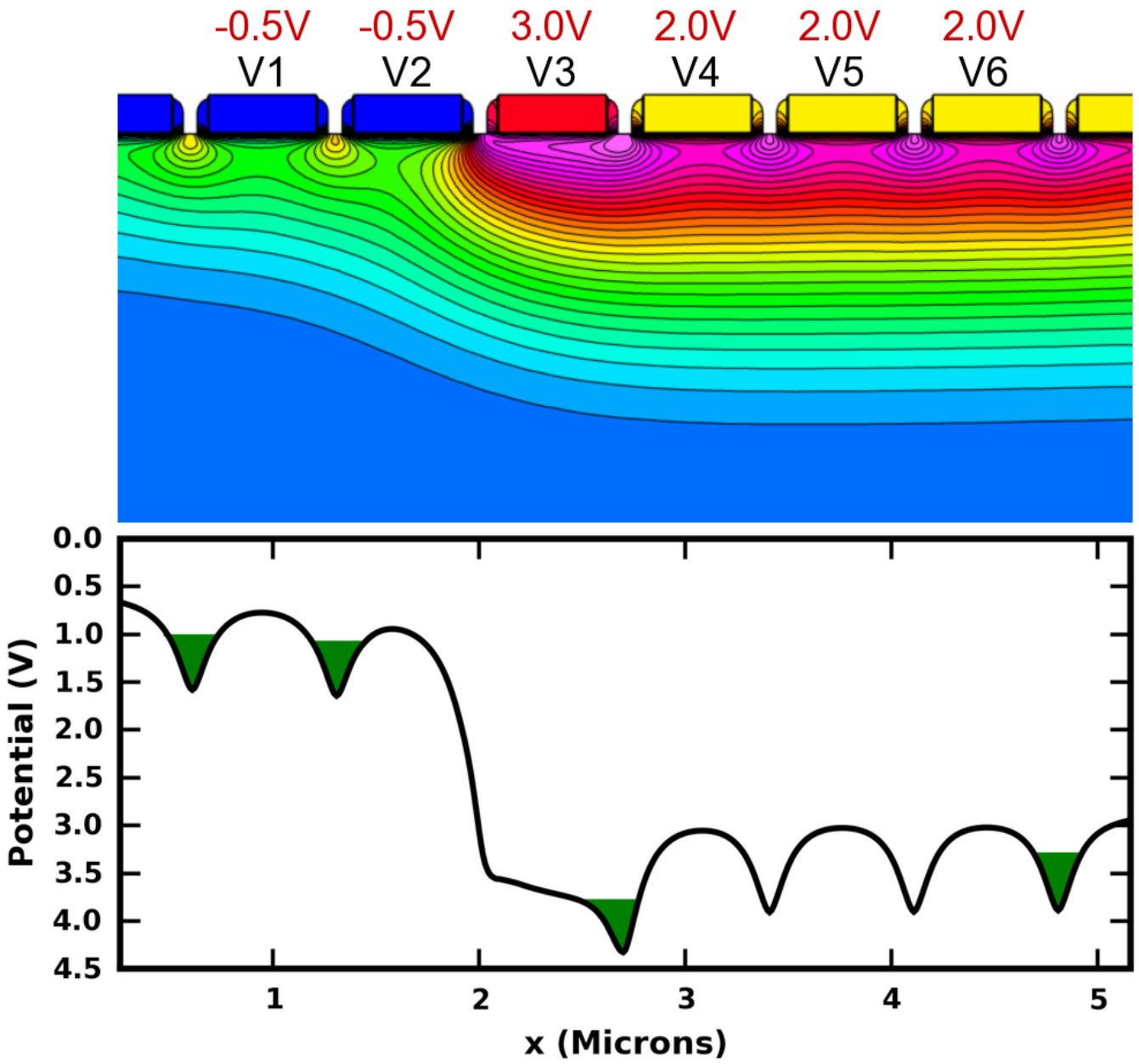
Potential Profile Along Channel



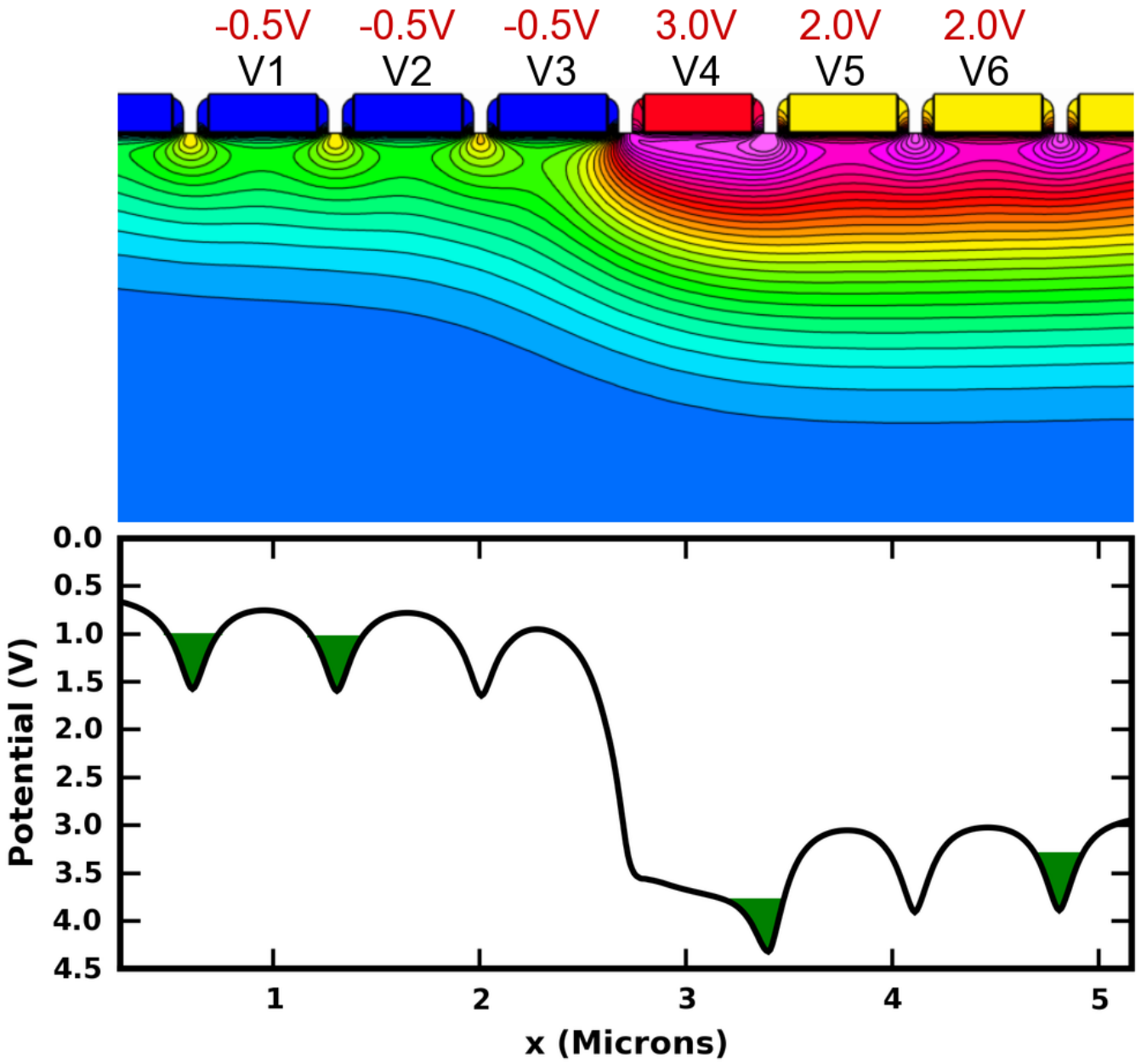
Potential Profile Along Channel



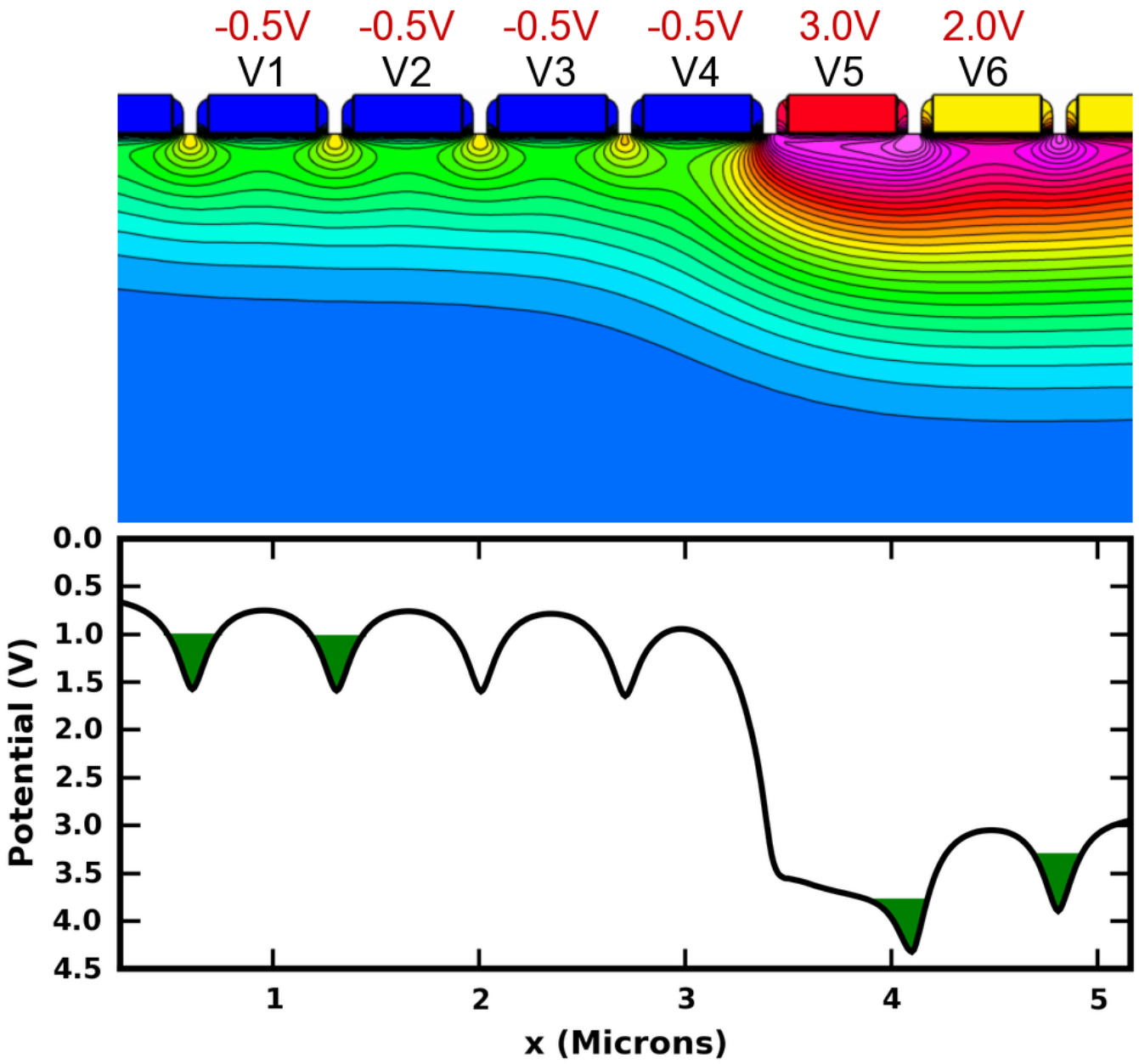
Potential Profile Along Channel



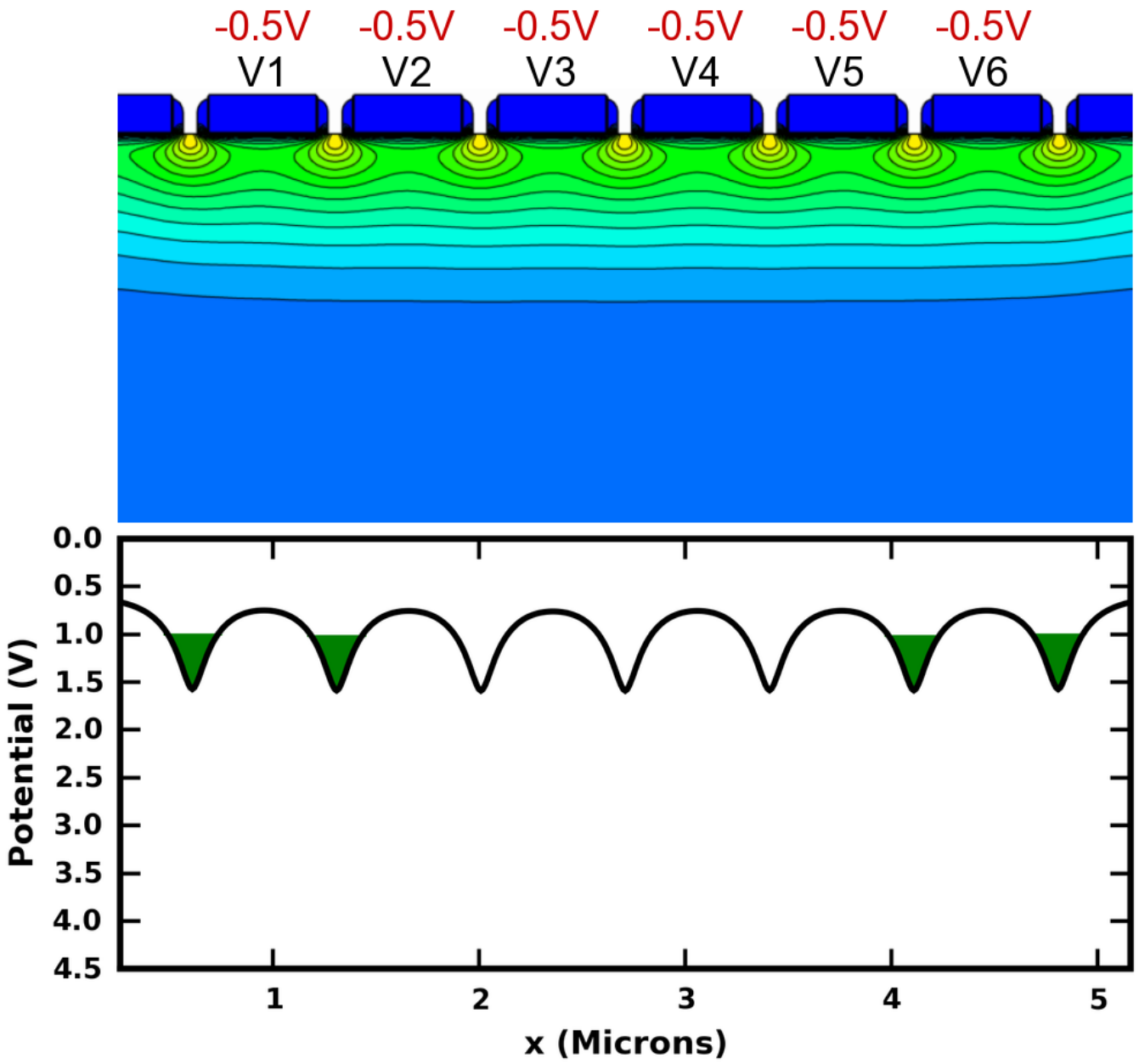
Potential Profile Along Channel



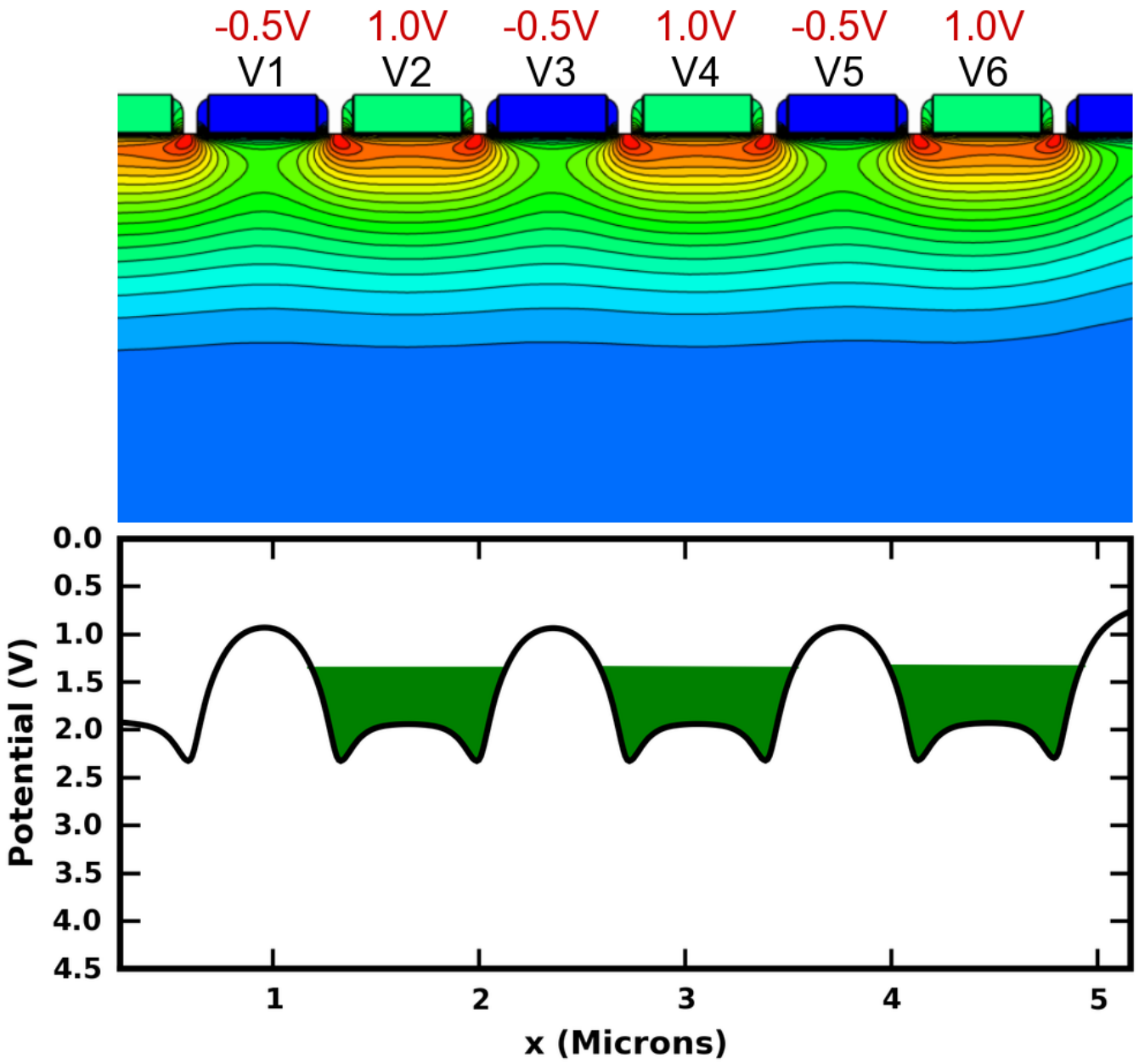
Potential Profile Along Channel



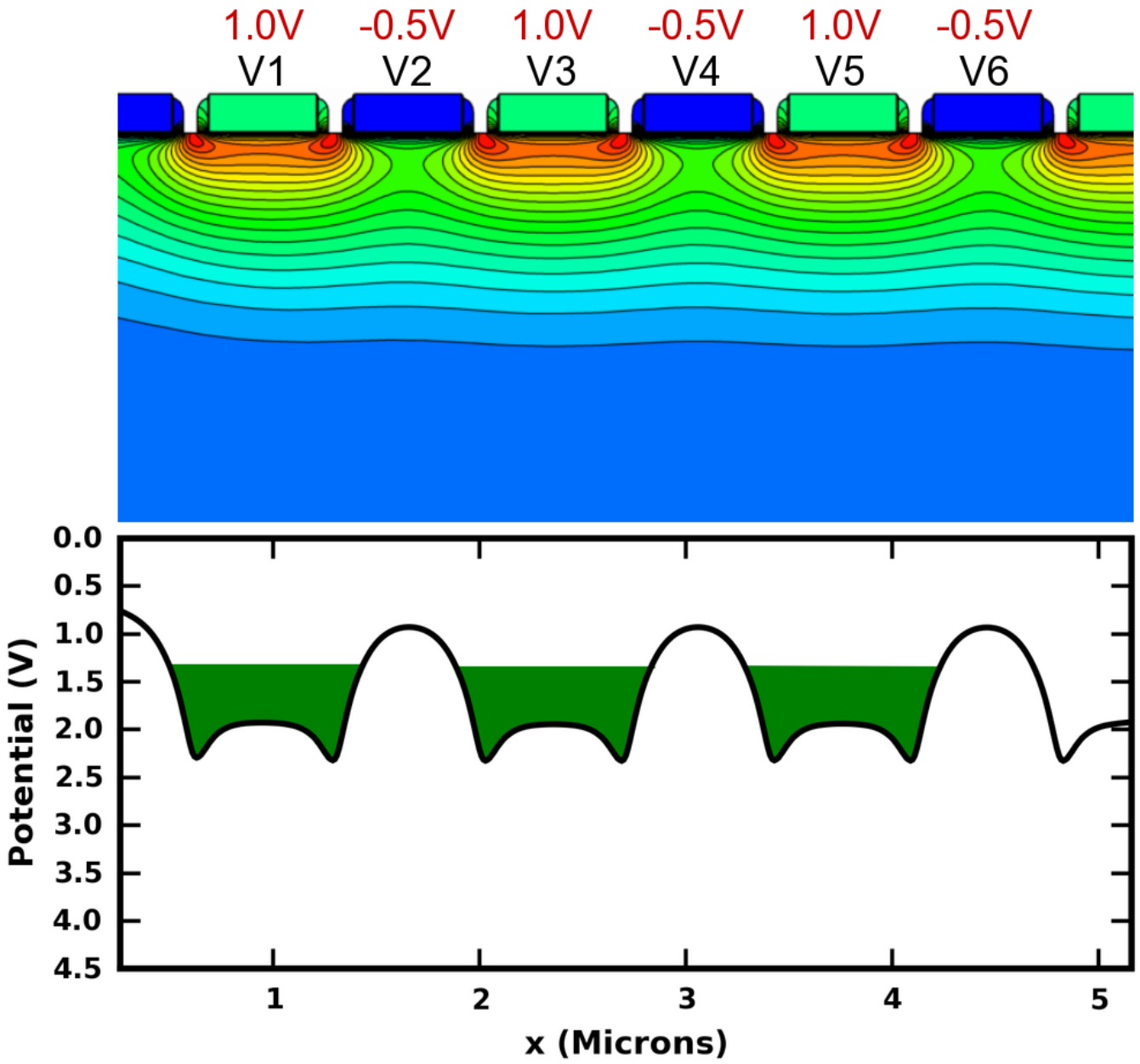
Potential Profile Along Channel



Interlaced Mode (Even Field)

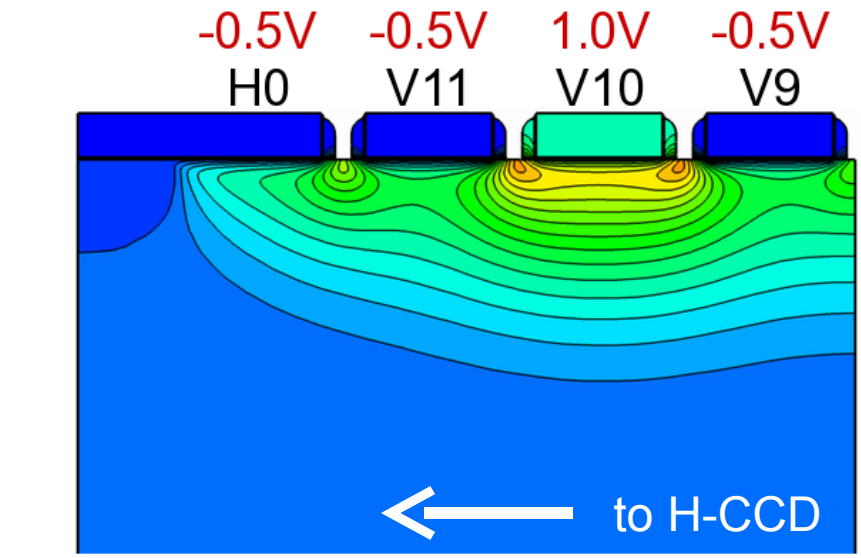


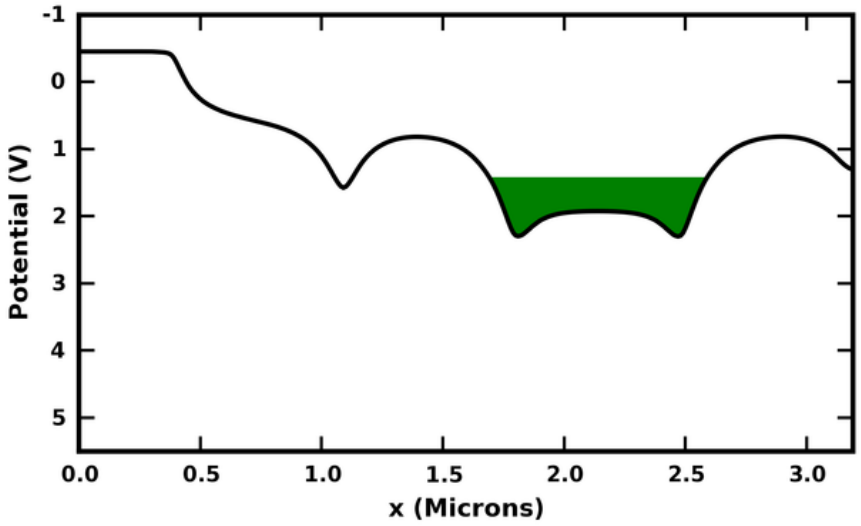
Interlaced Mode (Odd Field)



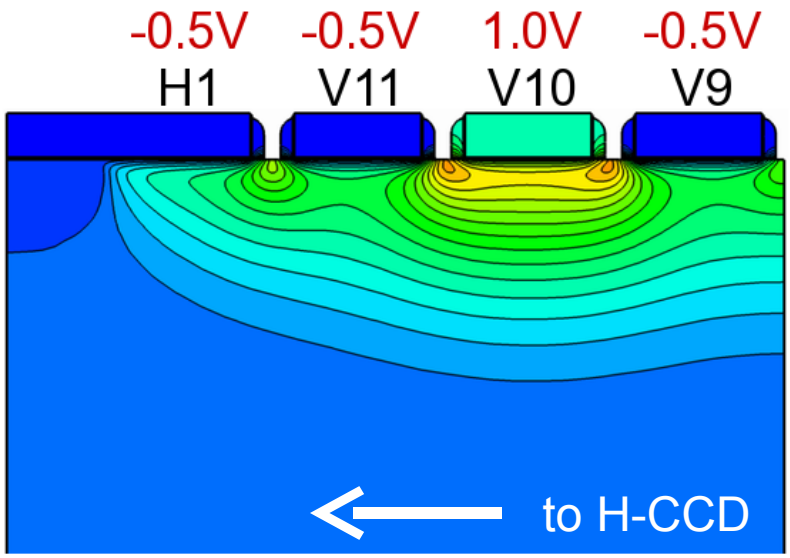
Vertical to Horizontal Transfer

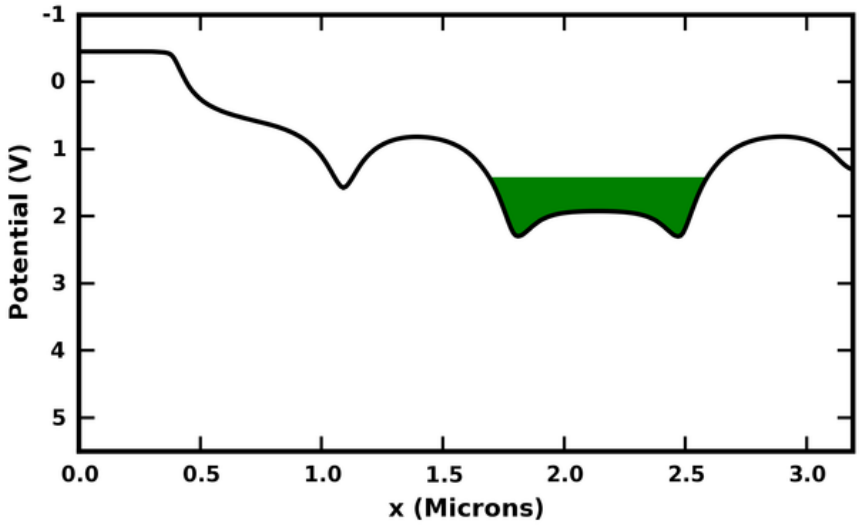
Even column





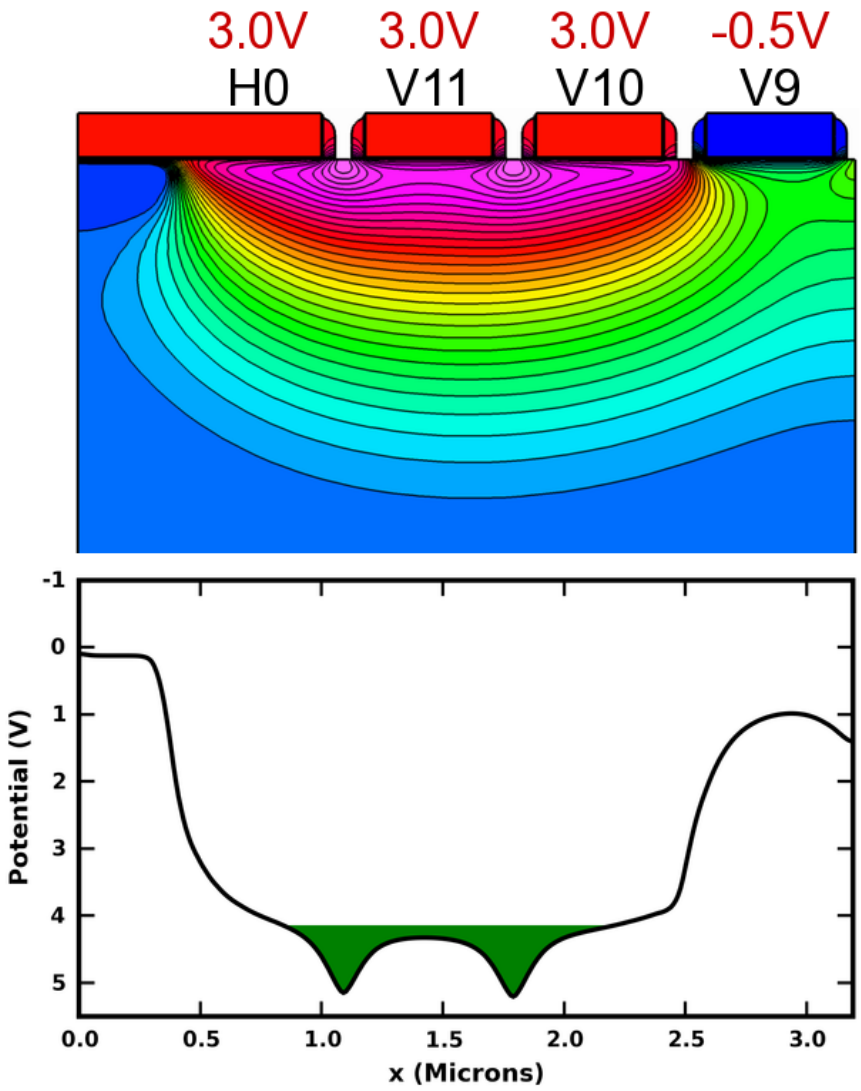
Odd column



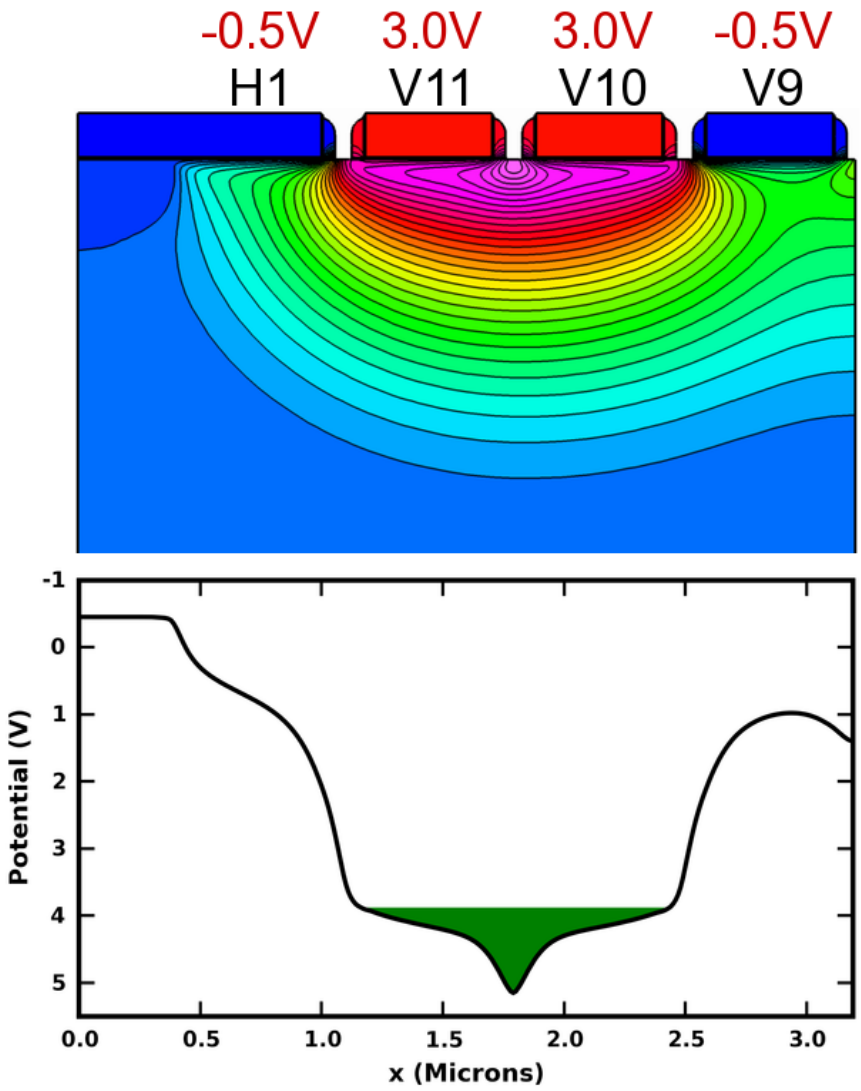


Vertical to Horizontal Transfer

Even column

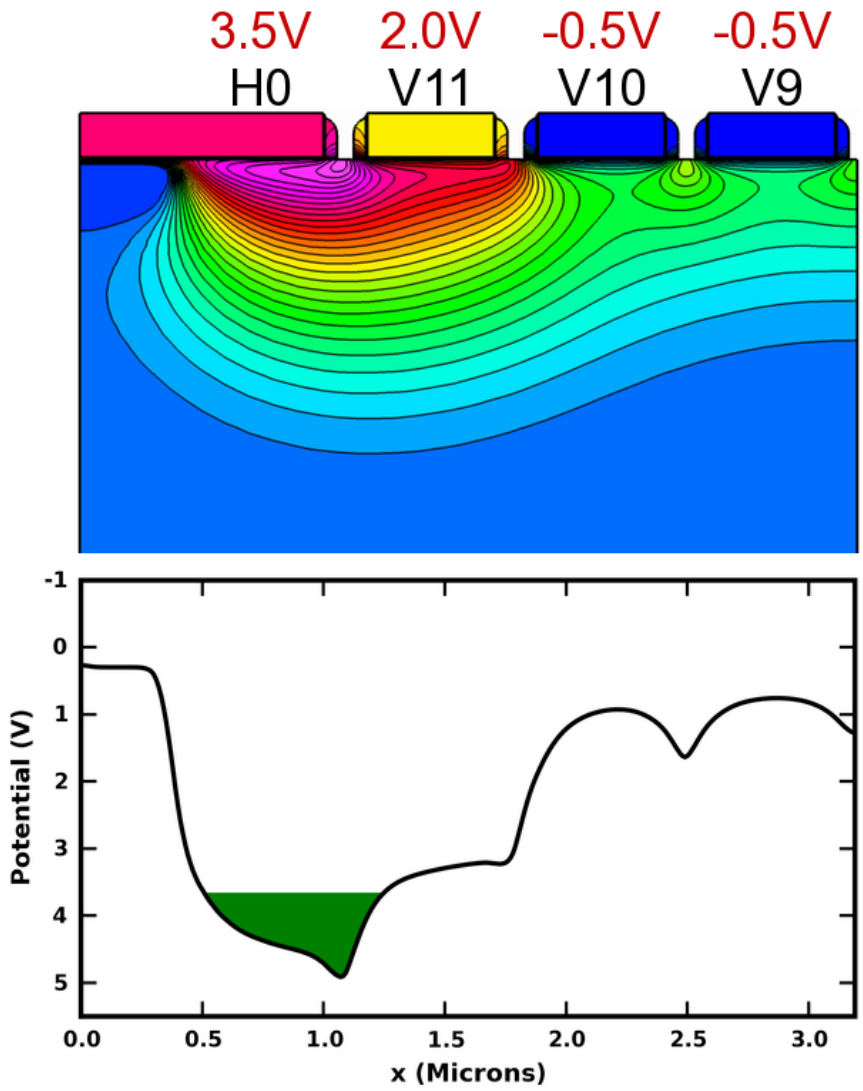


Odd column

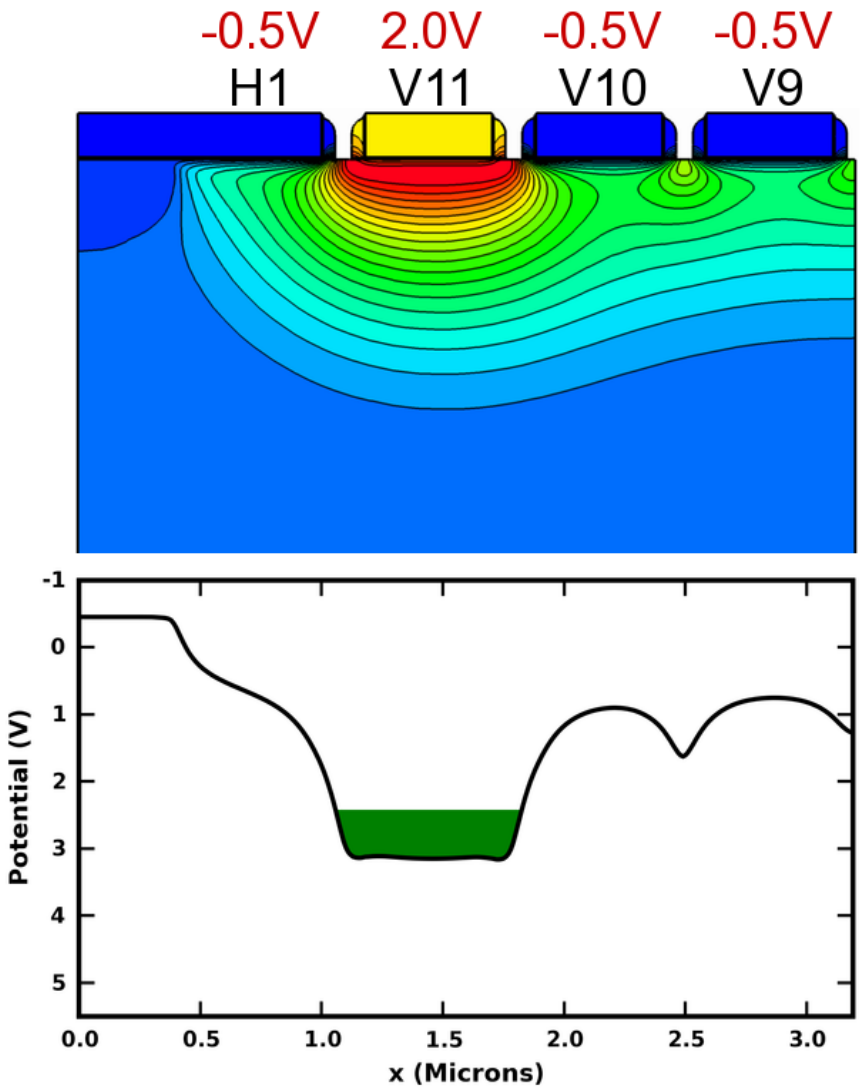


Vertical to Horizontal Transfer

Even column

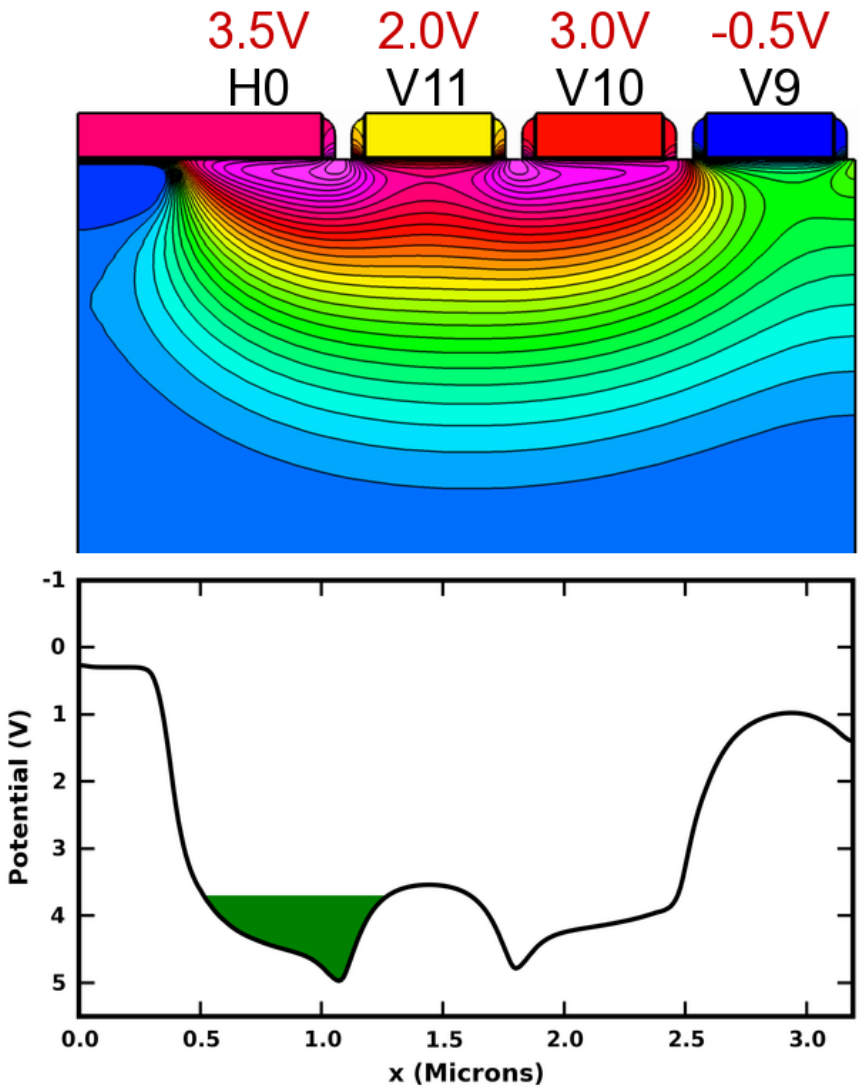


Odd column

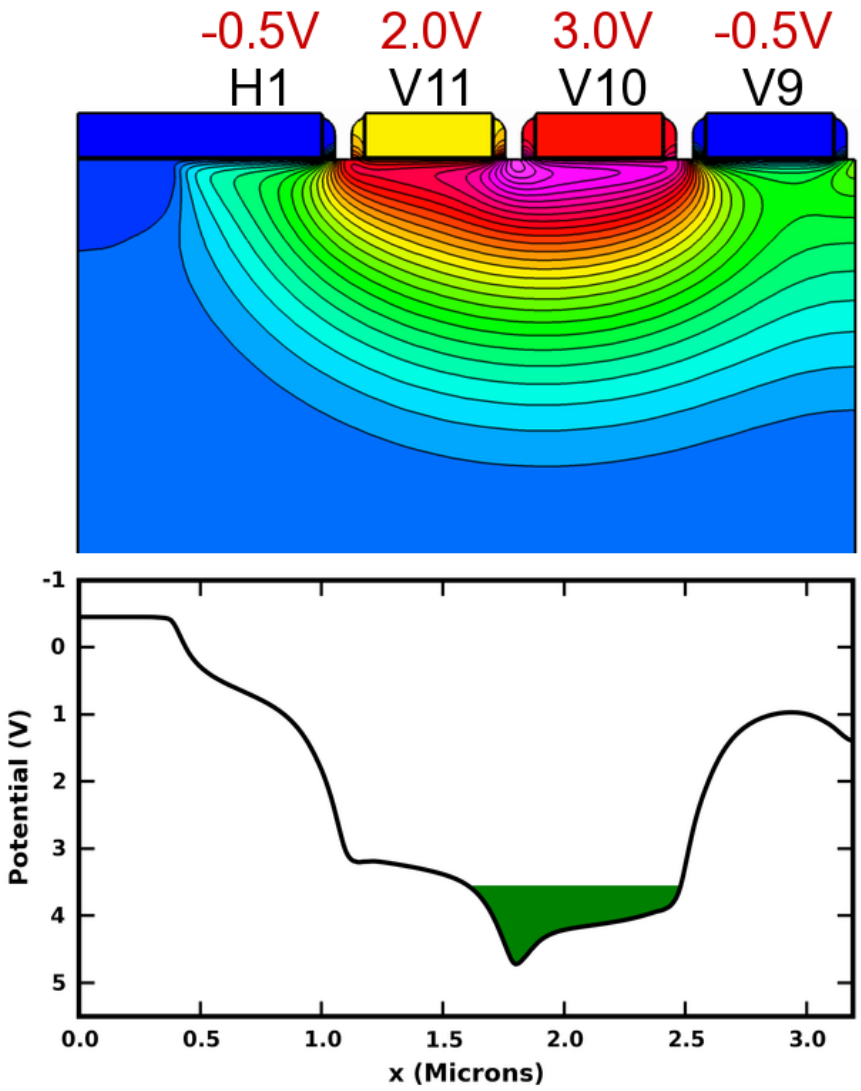


Vertical to Horizontal Transfer

Even column

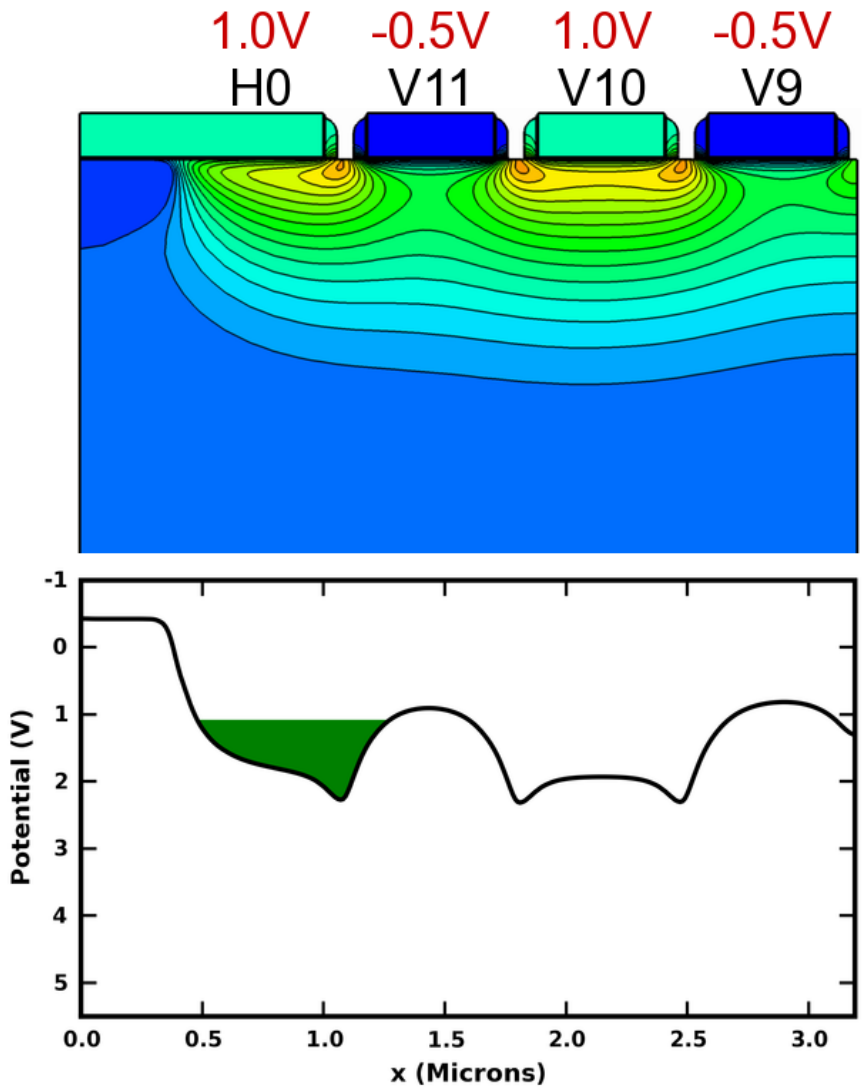


Odd column

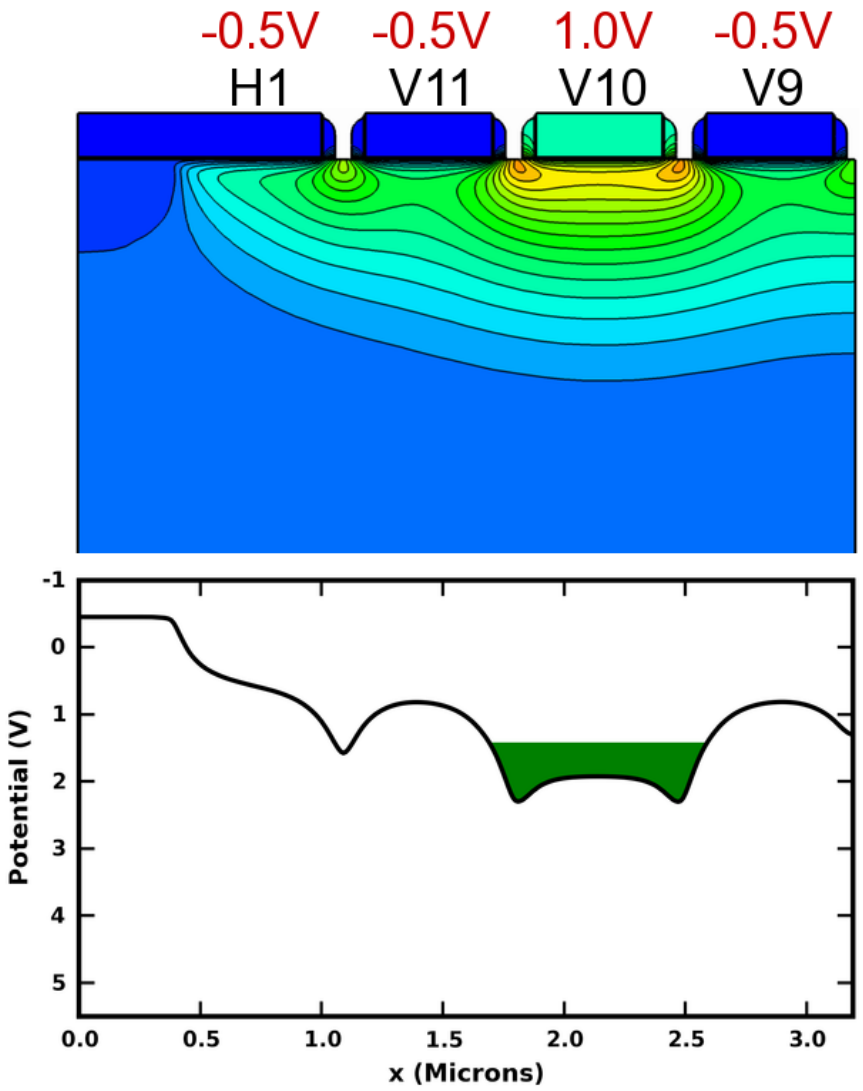


Vertical to Horizontal Transfer

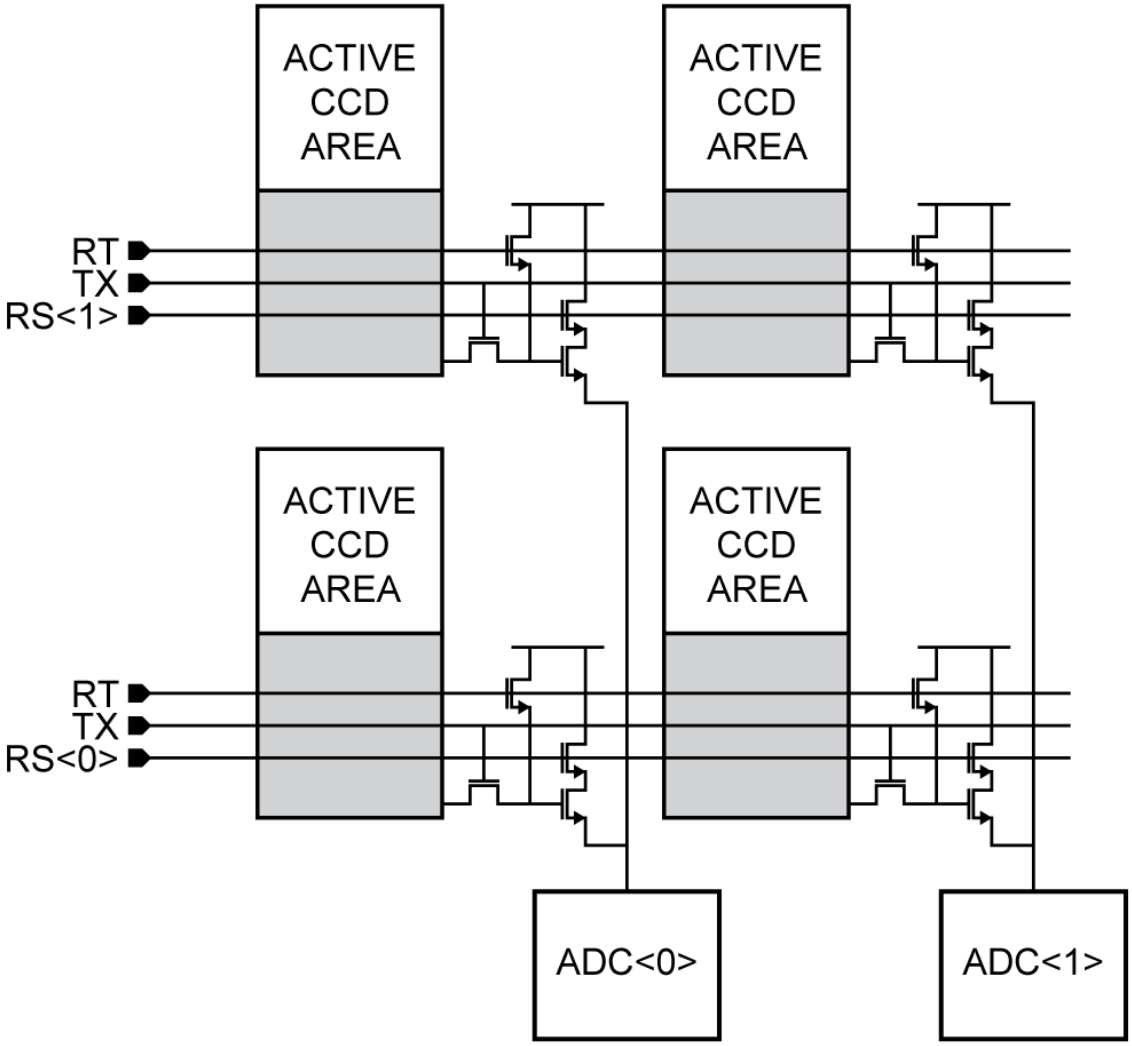
Even column



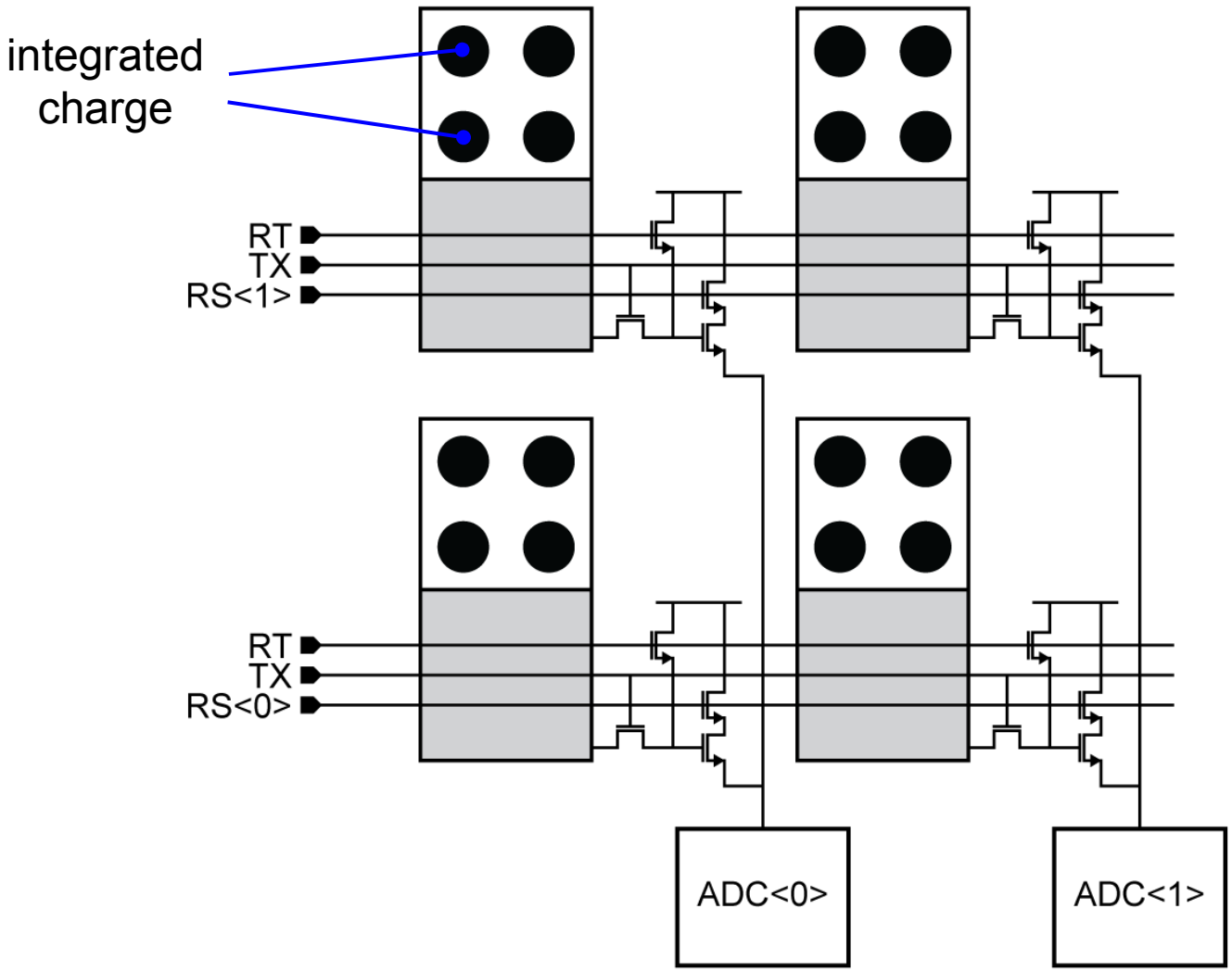
Odd column



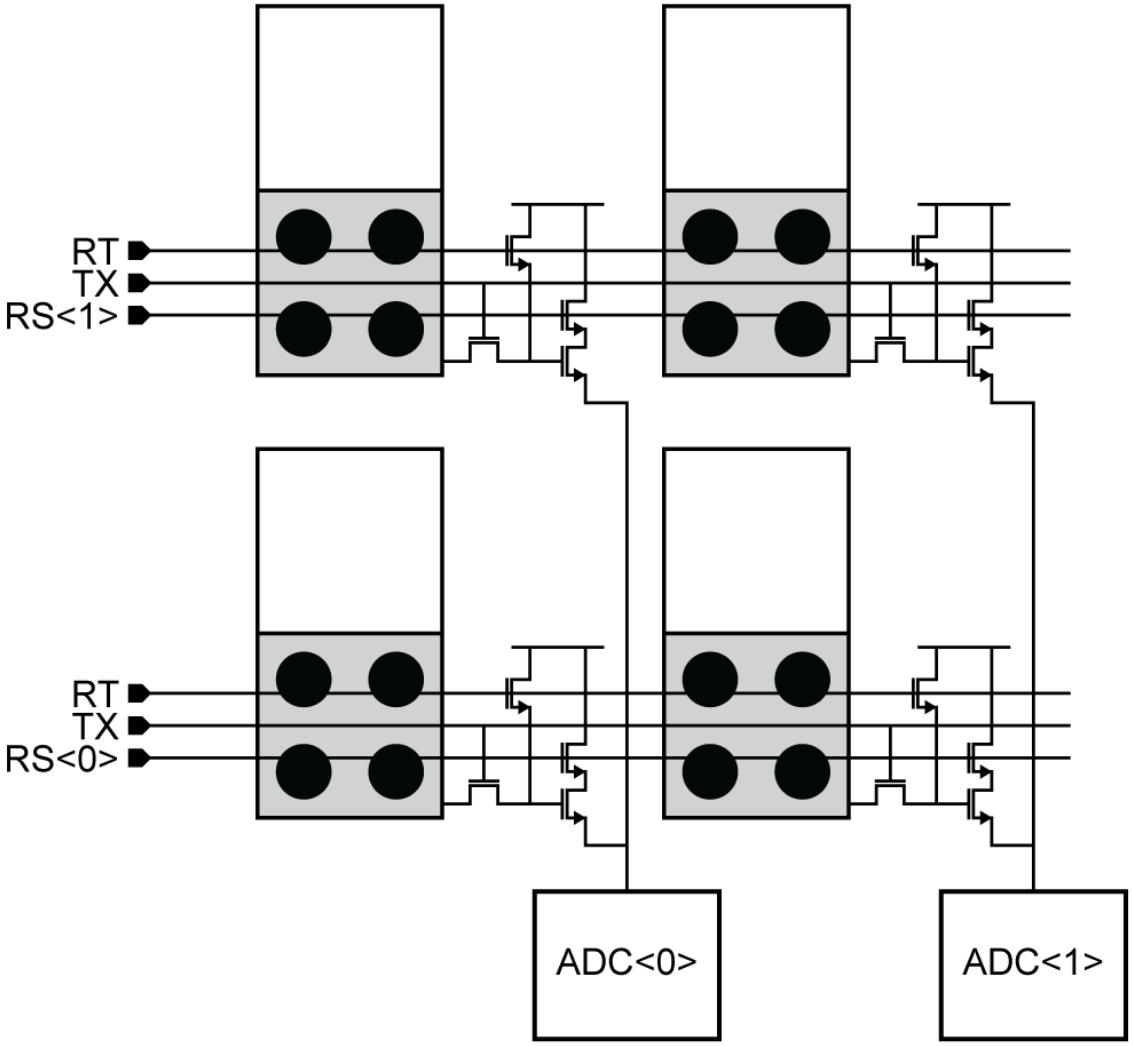
Chip Operation



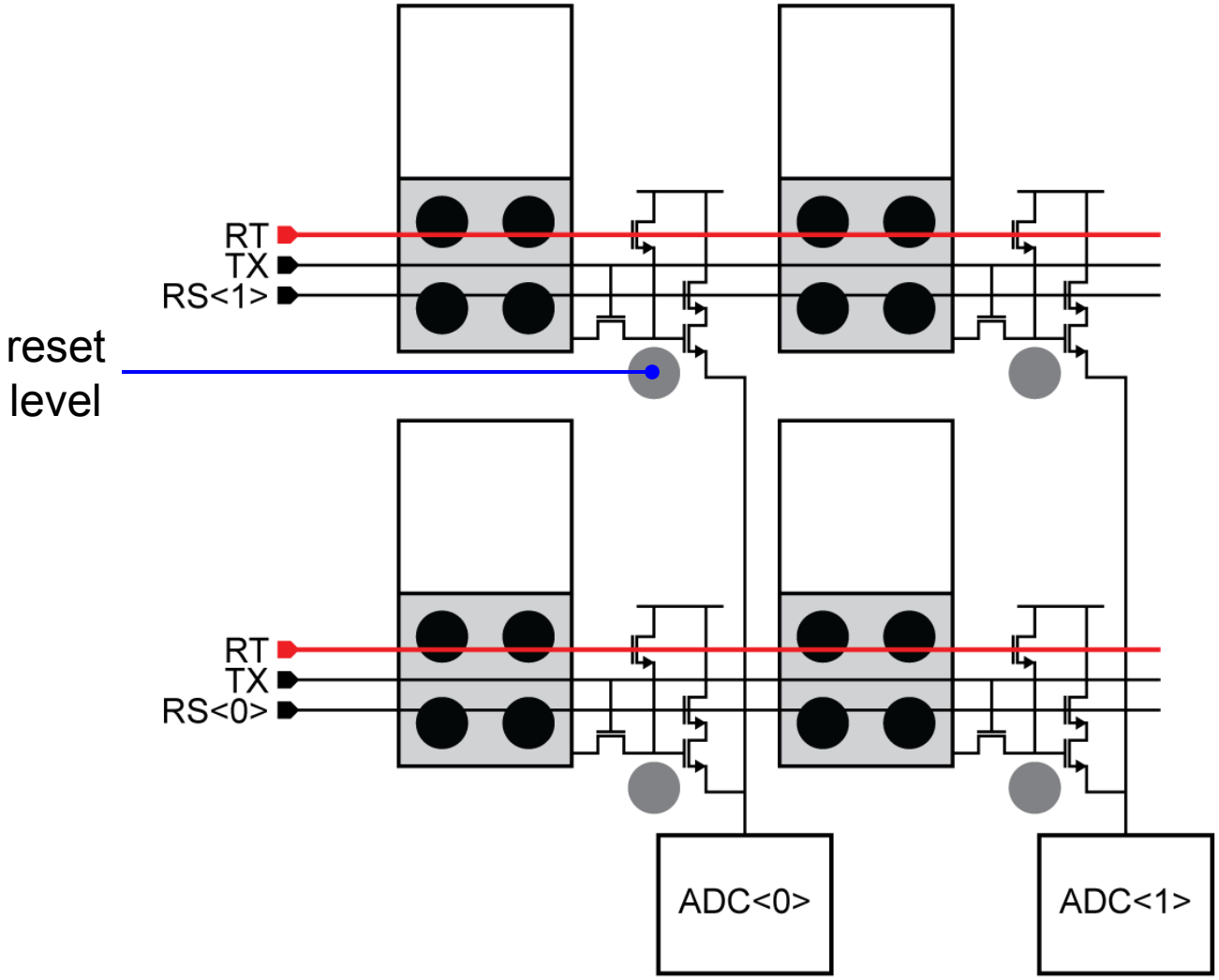
Chip Operation (Integrate)



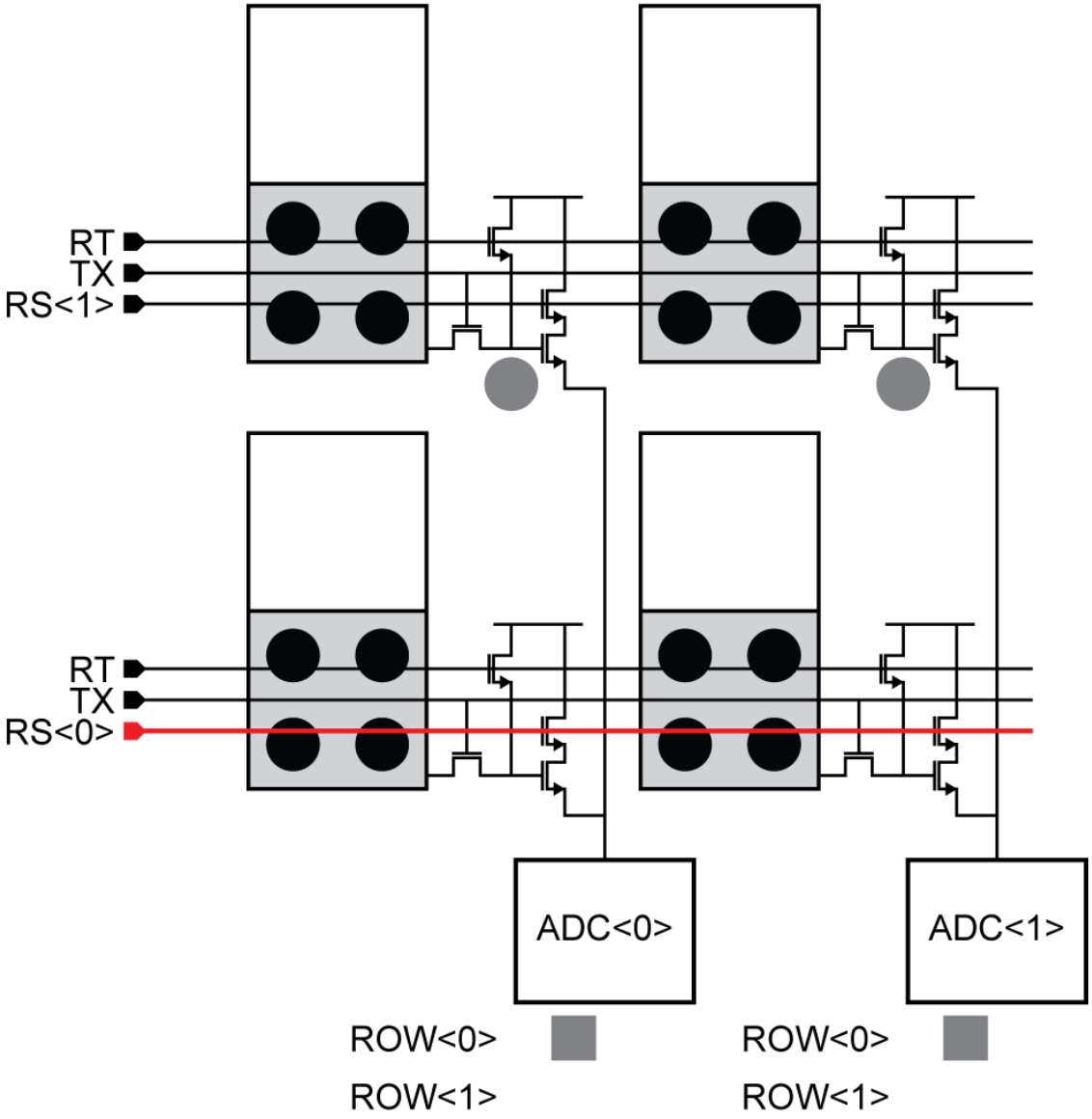
Chip Operation (Frame Transfer)



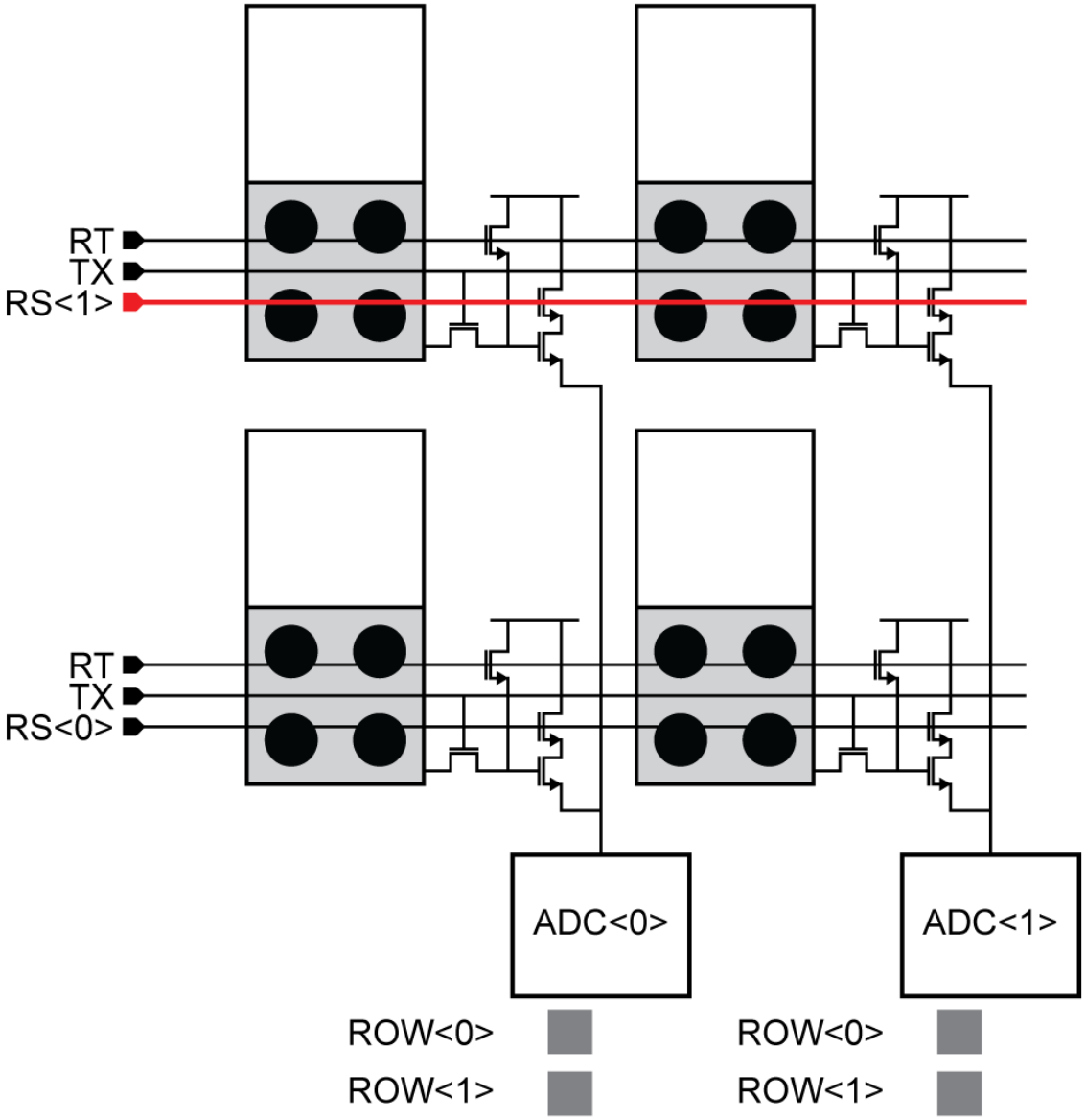
Chip Operation (Reset FD)



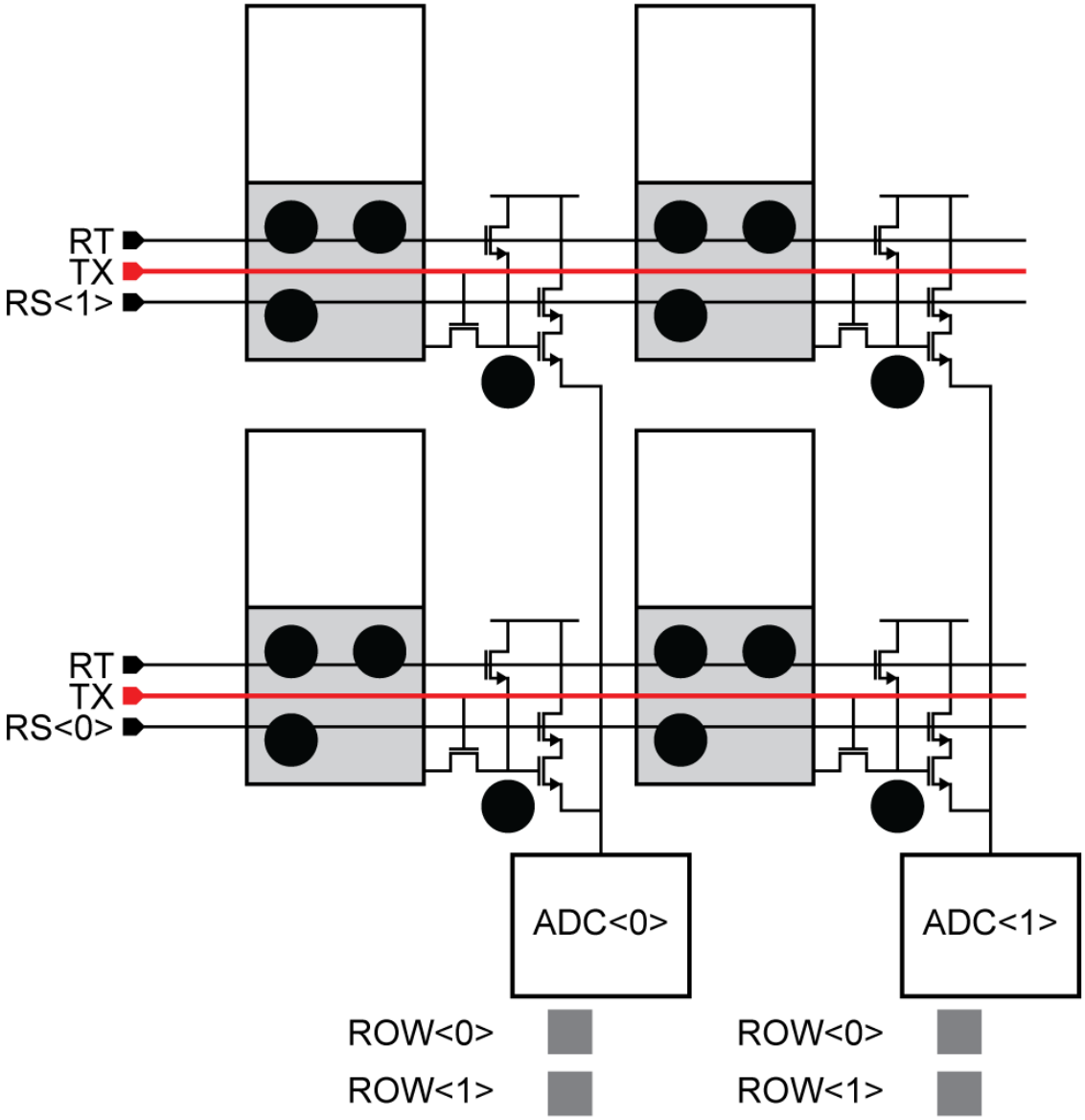
Chip Operation (Read Row<0>)



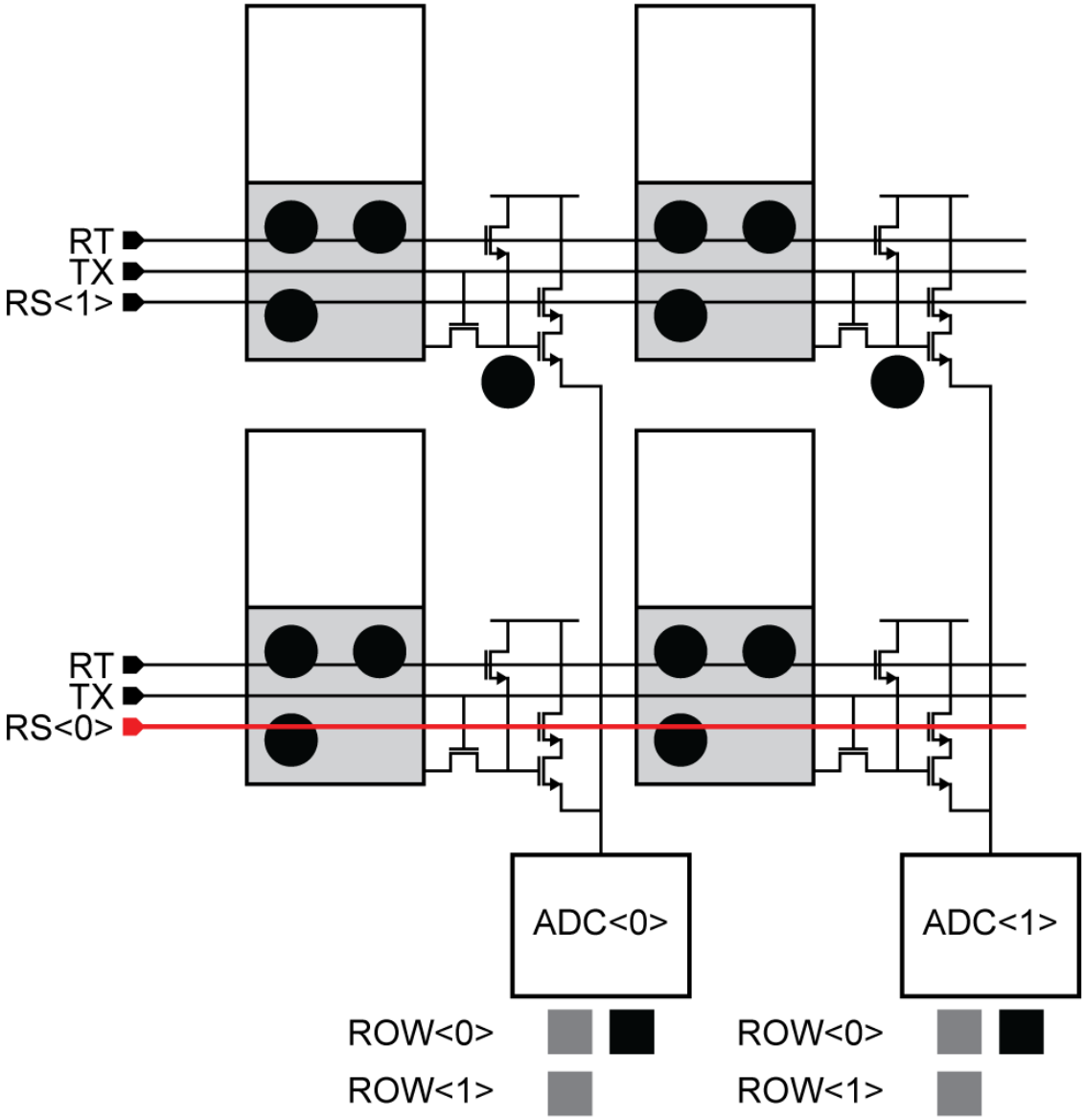
Chip Operation (Read Row<1>)



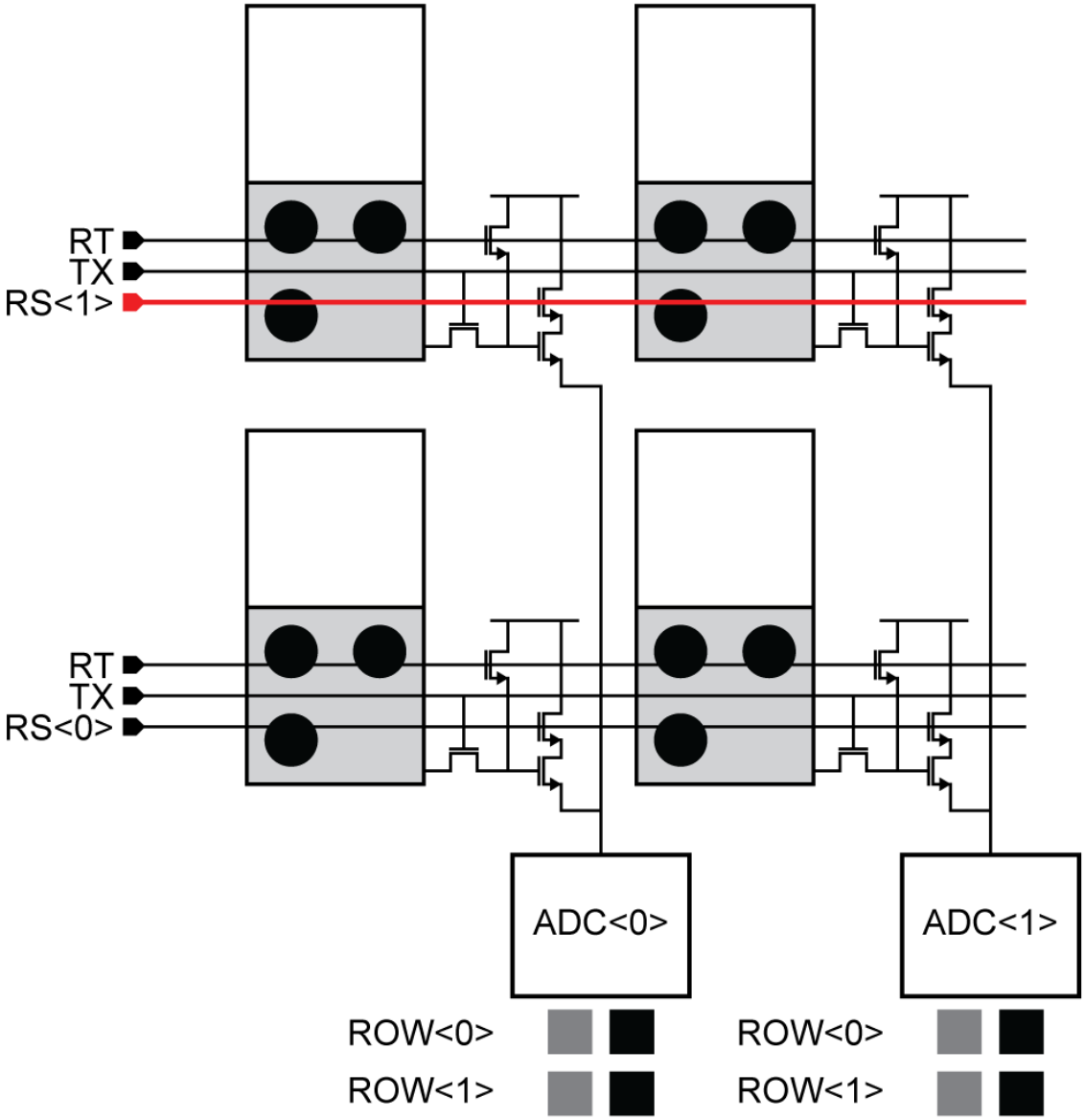
Chip Operation (Transfer Charge)



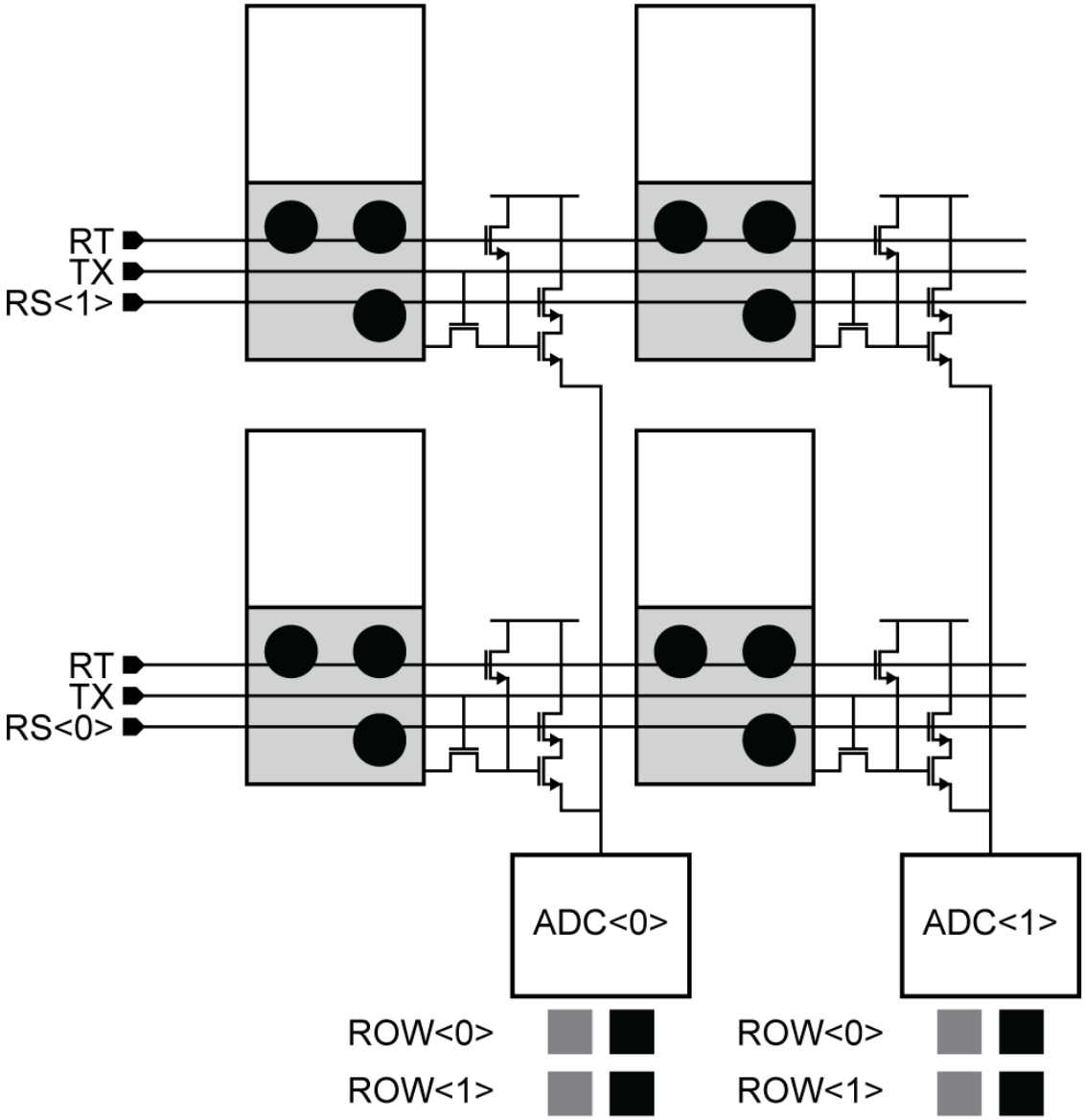
Chip Operation (Charge Row<0>)



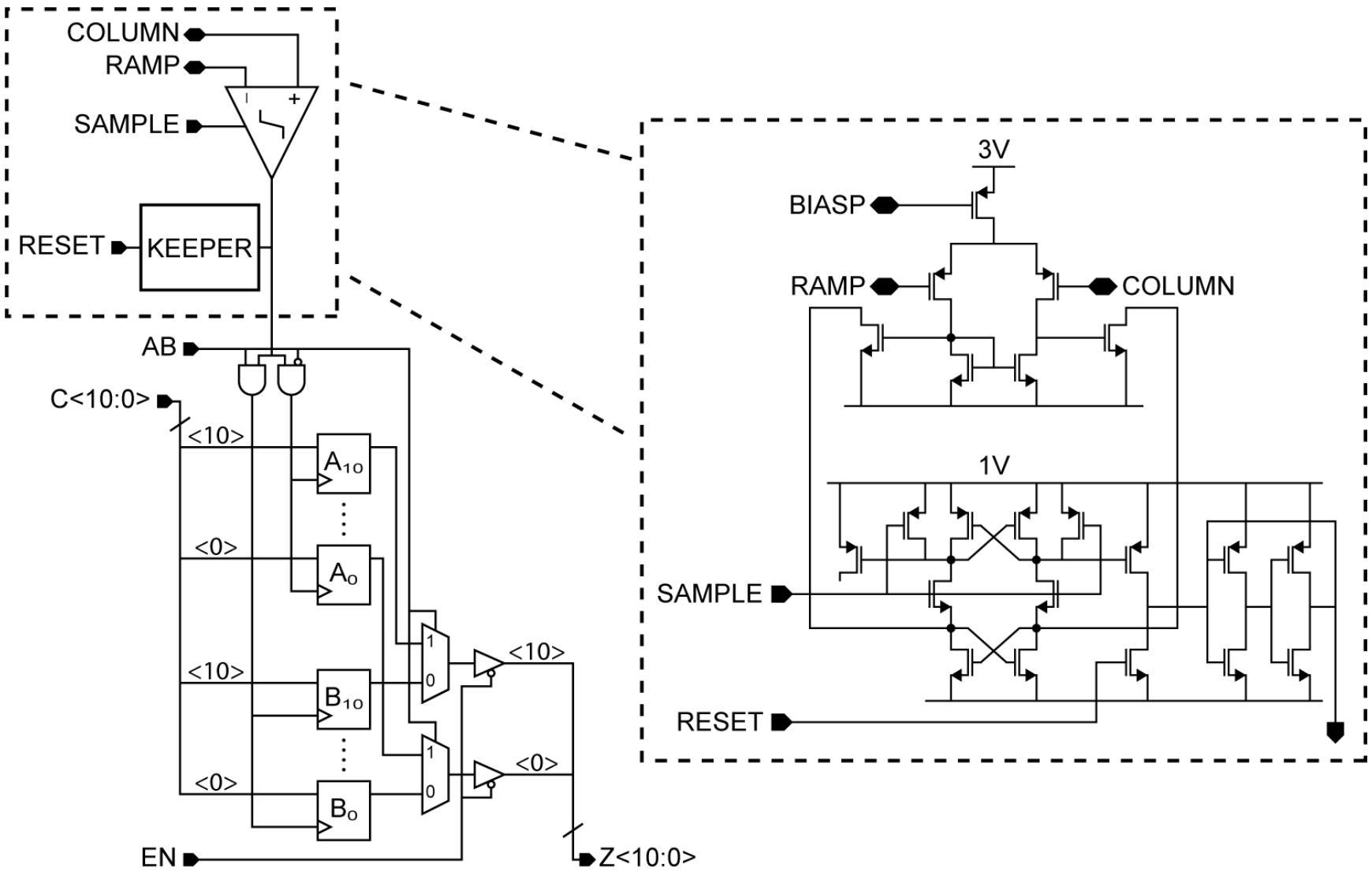
Chip Operation (Charge Row<1>)



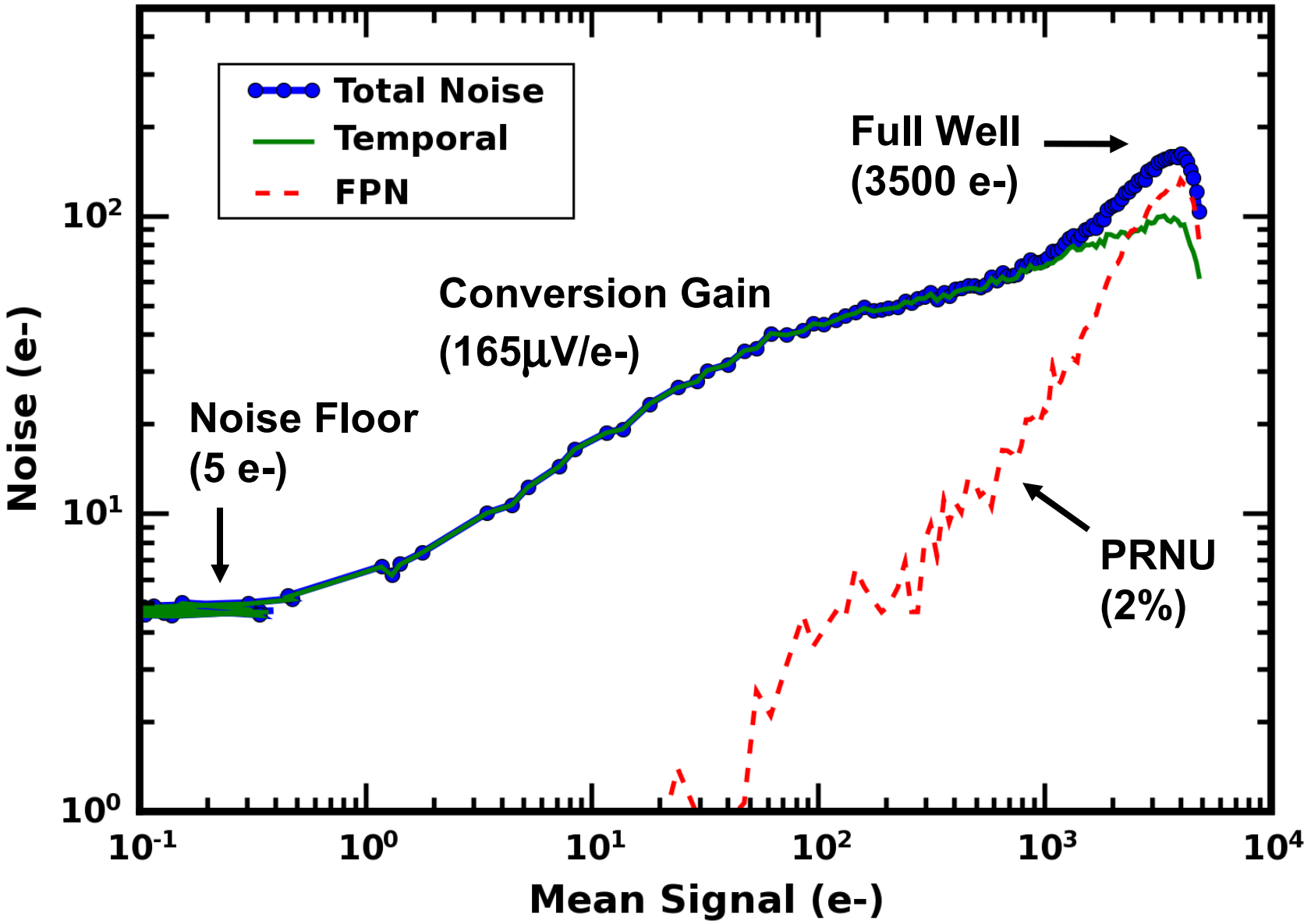
Chip Operation (Shift Charge)



Column ADC Schematic



Measured Photon Transfer Curve



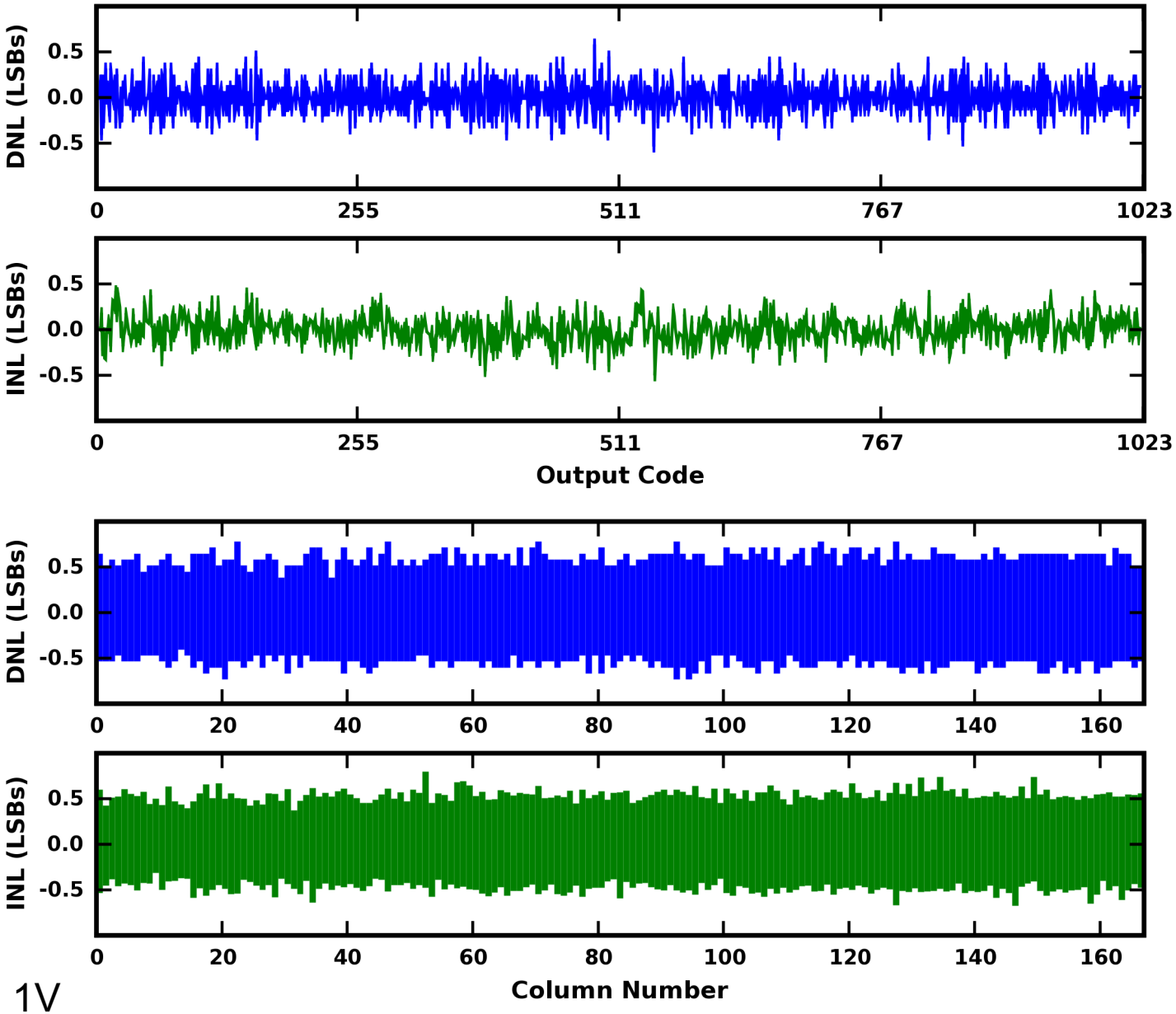
Measured Pixel Characteristics

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

Measured ADC Linearity

Single Column (10-b)

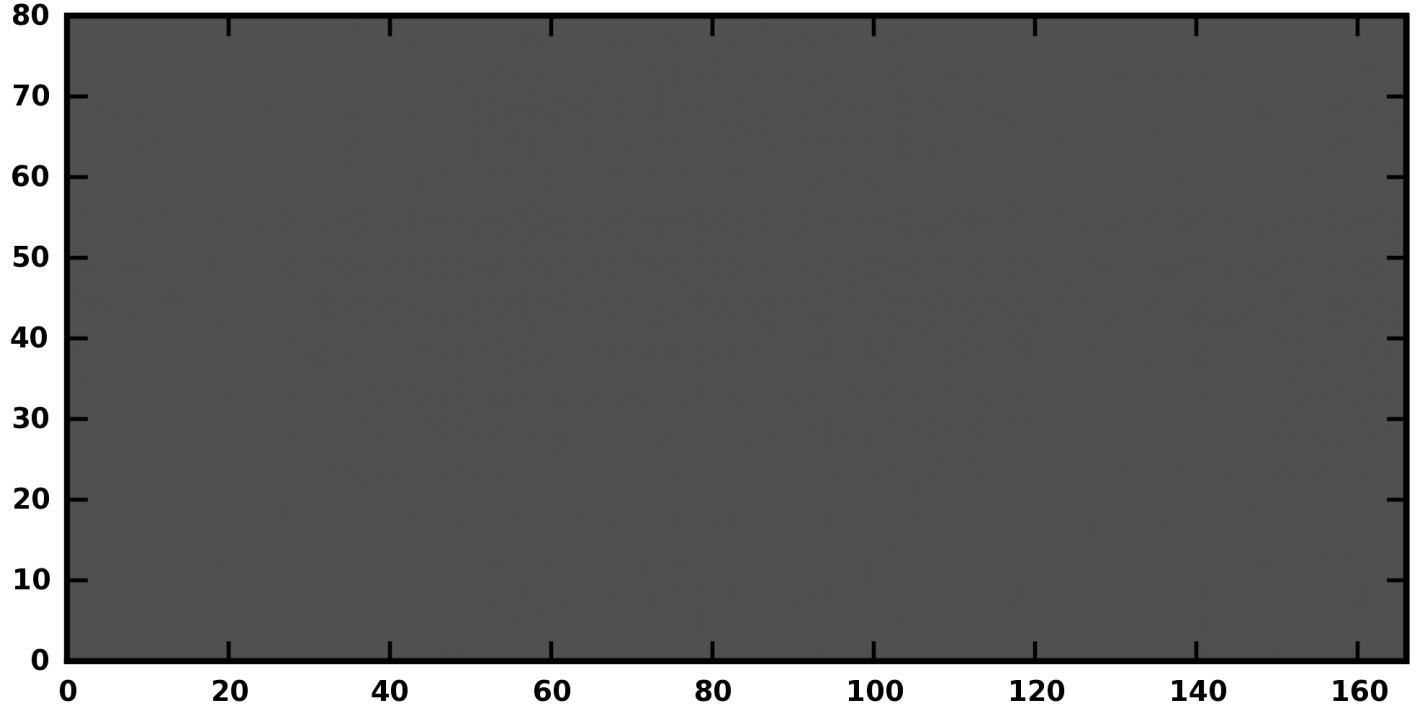
All Columns (10-b)



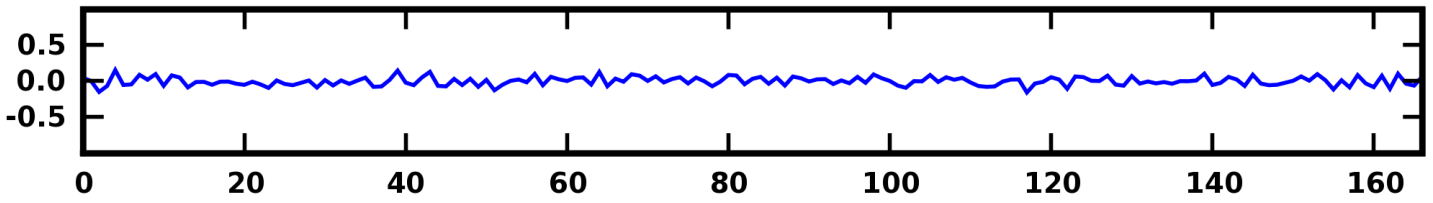
Input Range = 1V

Measured ADC Noise

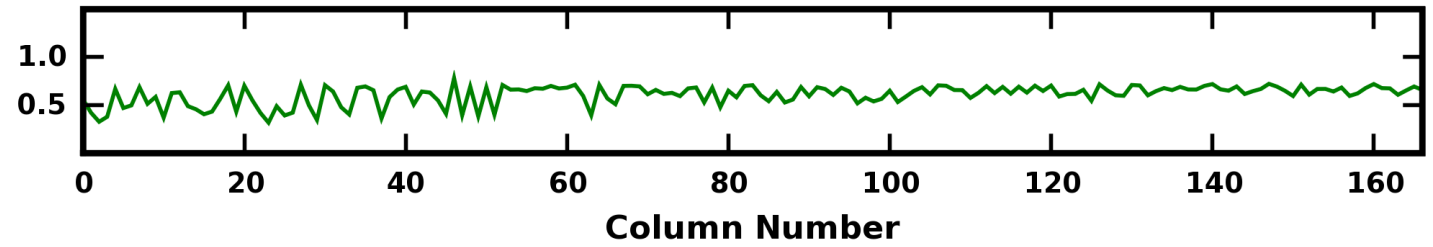
Image at constant ADC test input level



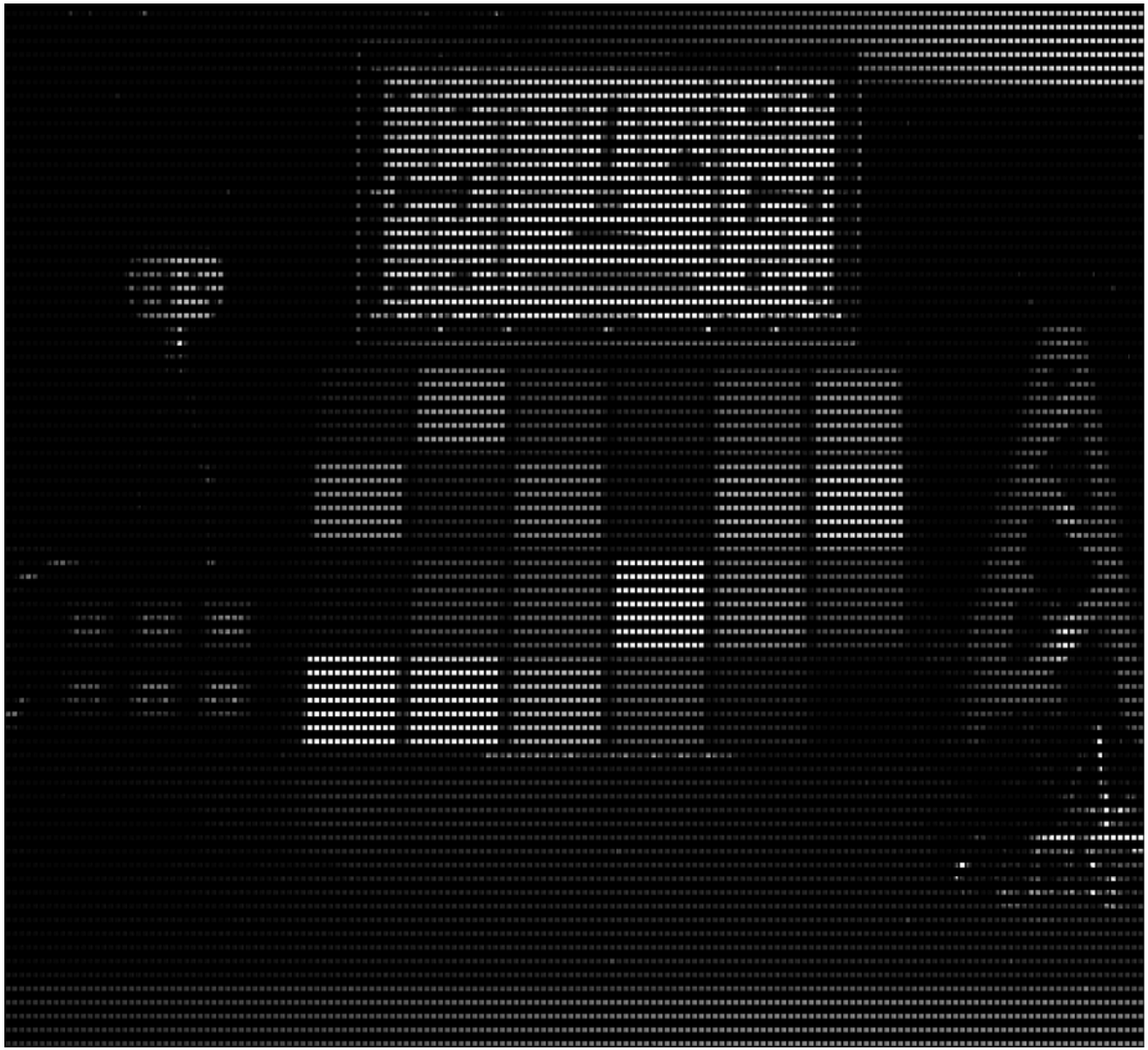
FPN (10-b LSBs)

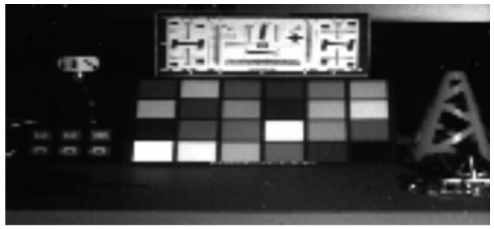


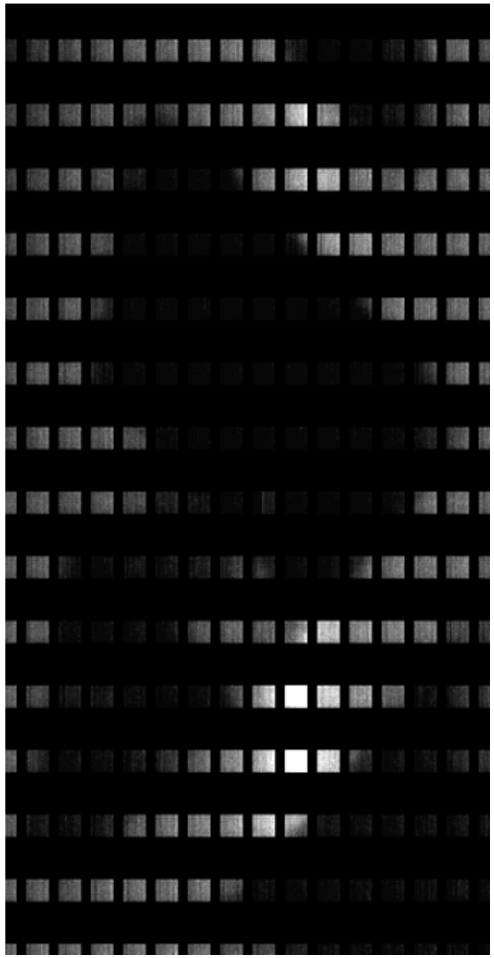
Temporal (10-b LSBs)



Sample Image







Summary

- Designed and characterized the first integrated multi-aperture image sensor
- Achieved good imaging performance with 0.7μm pixels
  - FT-CCD structure in deep submicron CMOS
  - Ripple charge transfer
- Extensible architecture well suited for ultra-high pixel count imagers
- 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

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