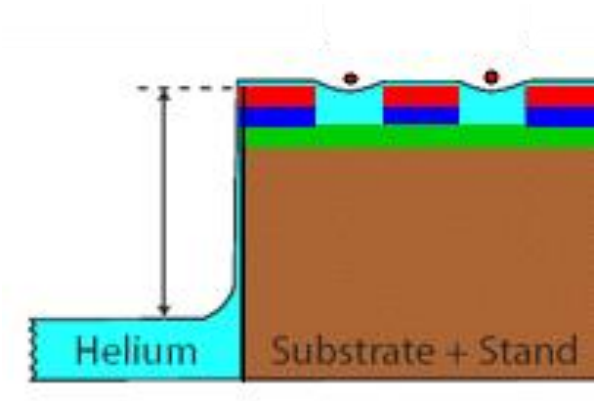
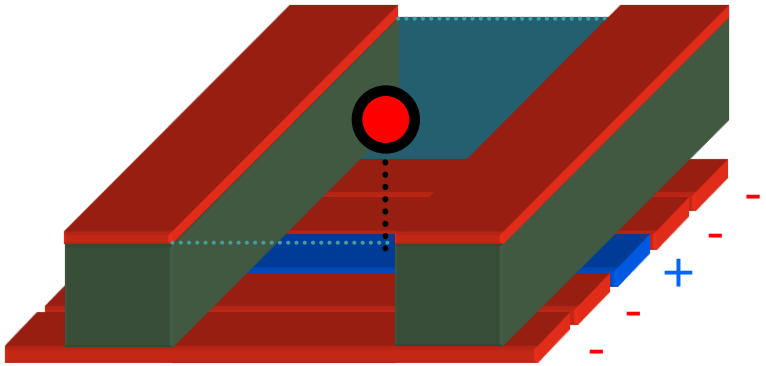
Efficient electron transport on helium with silicon integrated circuits





Forrest Bradbury[1] and Maika Takita[1],

Kevin Eng[2], Tom M Gurrieri[2], Kathy J Wilkel[2], Stephen A Lyon[1]

[1]Princeton University
[2]Sandia National Laboratories

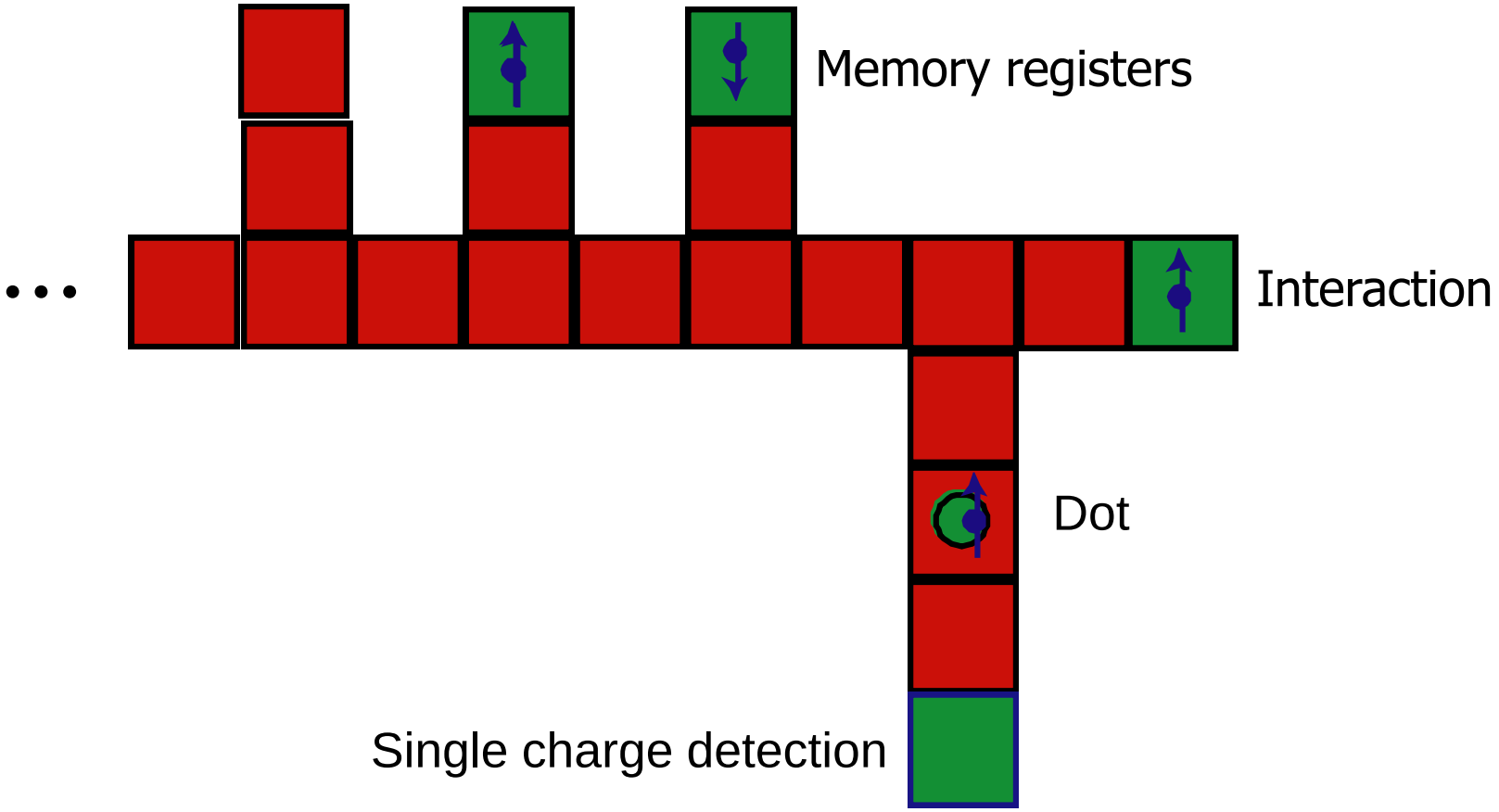
Electron spins on helium are low density, but independent, flexible, and mobile:

the Quantum Information American Dream

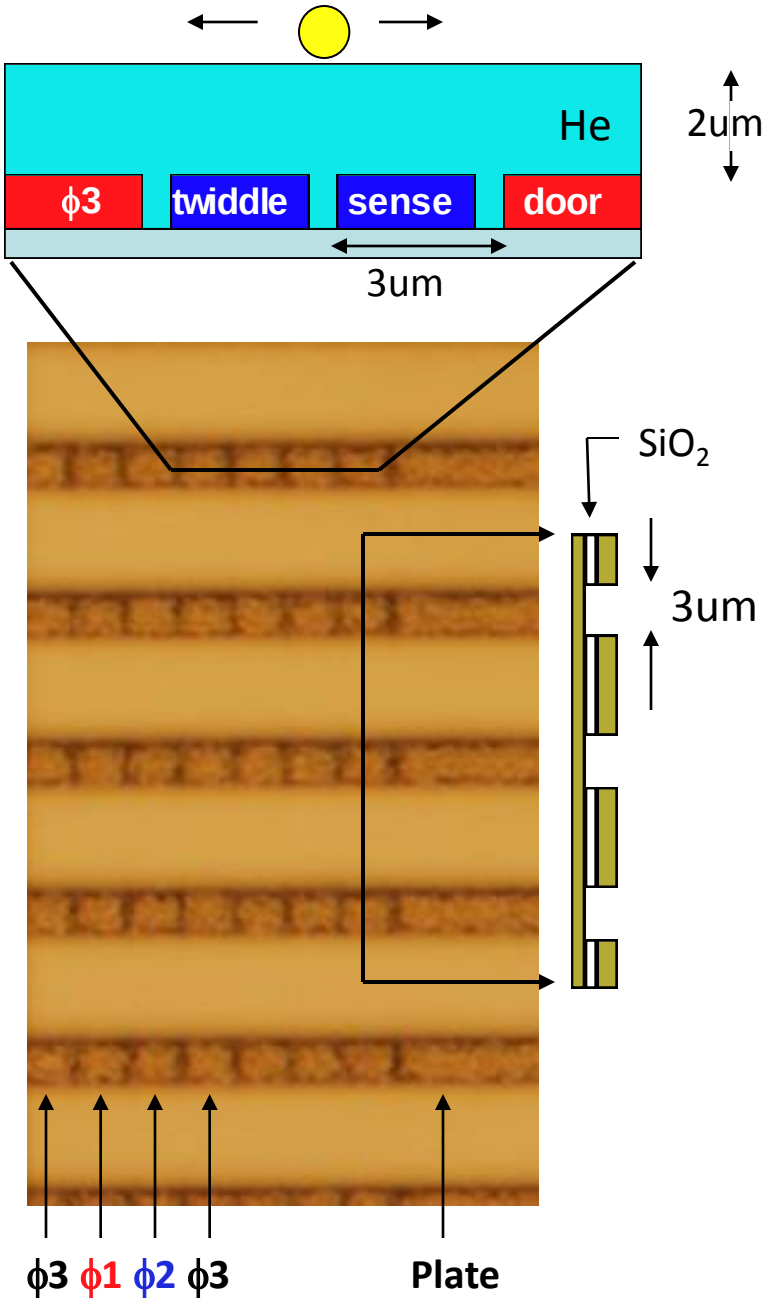
Electron spins on helium are low density, but independent, flexible, and mobile:

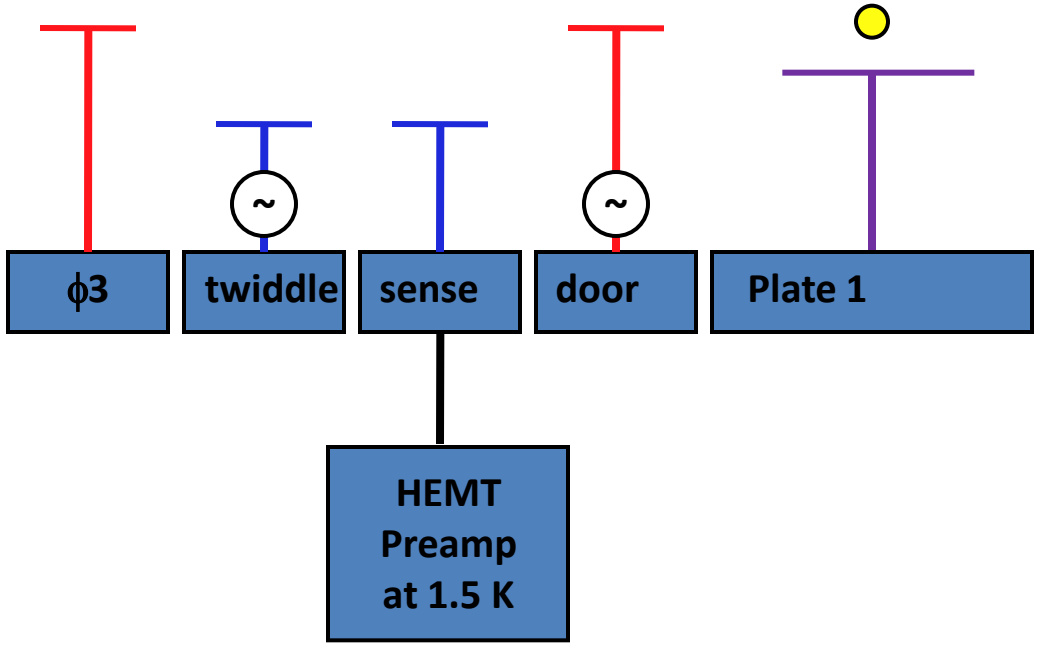
- Stationary qubits necessitate continual SWAP operations on neighboring qubits for information propagation
- Mobile qubits obviate this extra requirement
- Mobile electron spins in silicon are so far the best, but their coherence is limited by the Rashba interaction to $T_2 = 3\ \mu s$
- Electron spins on helium expected $T_2 > 100$ seconds

Transport enabled computation



Twiddle Sensing





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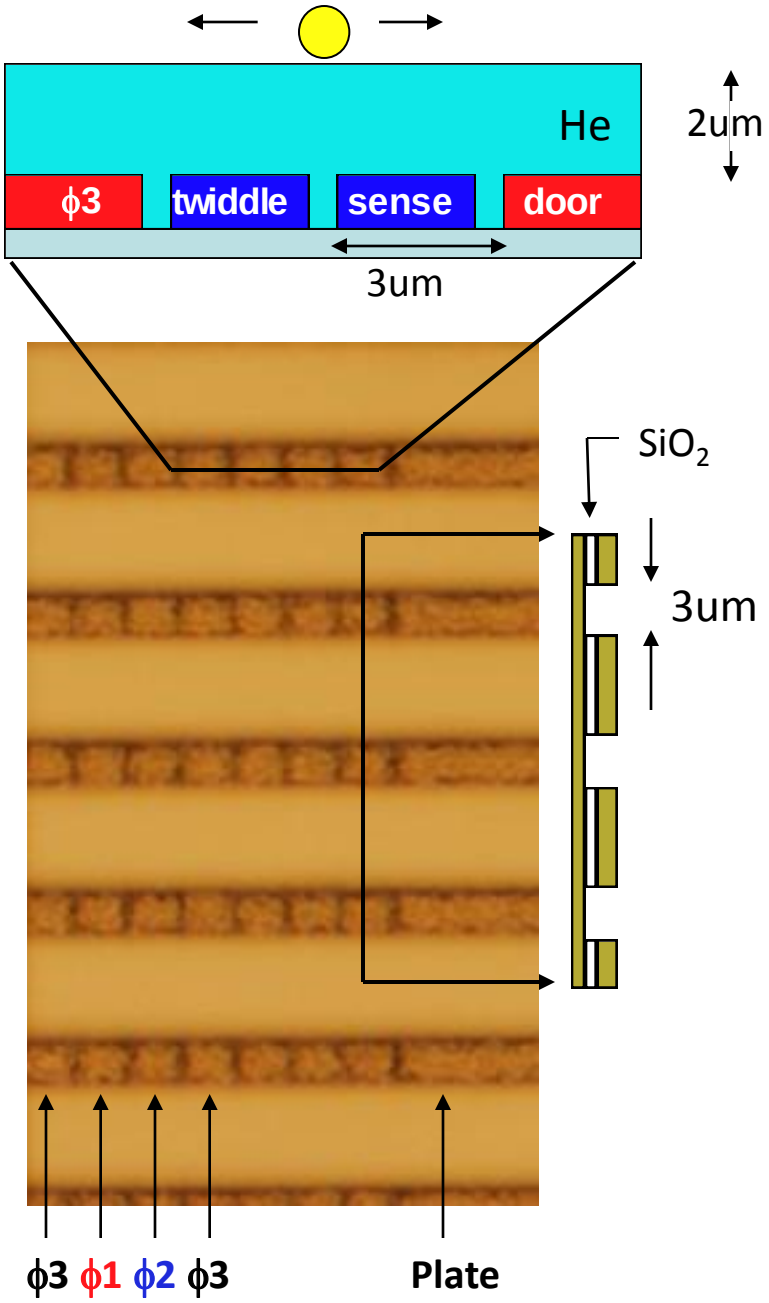
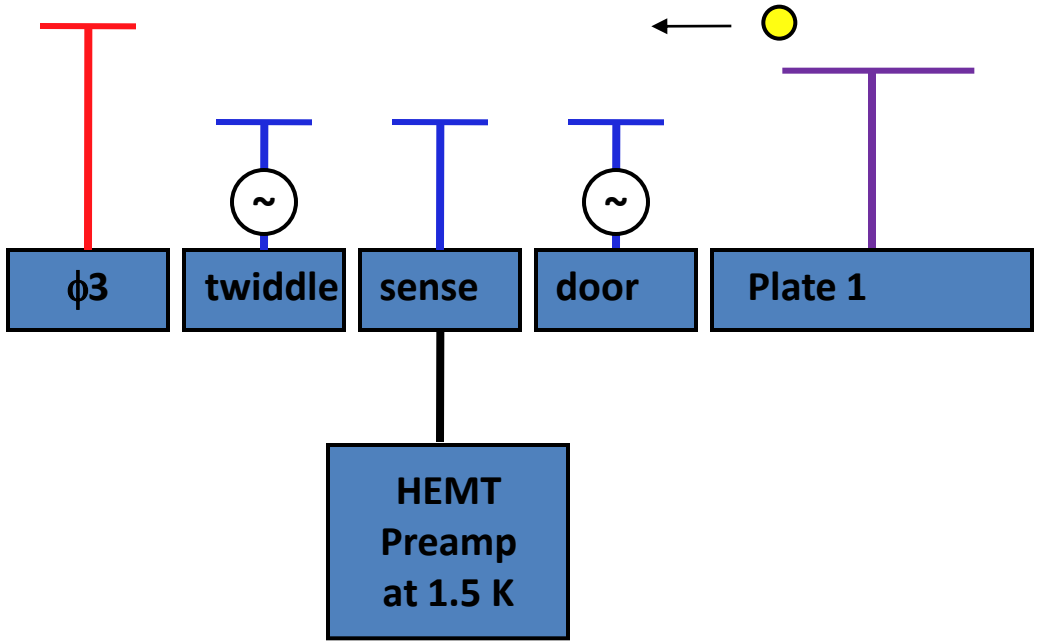
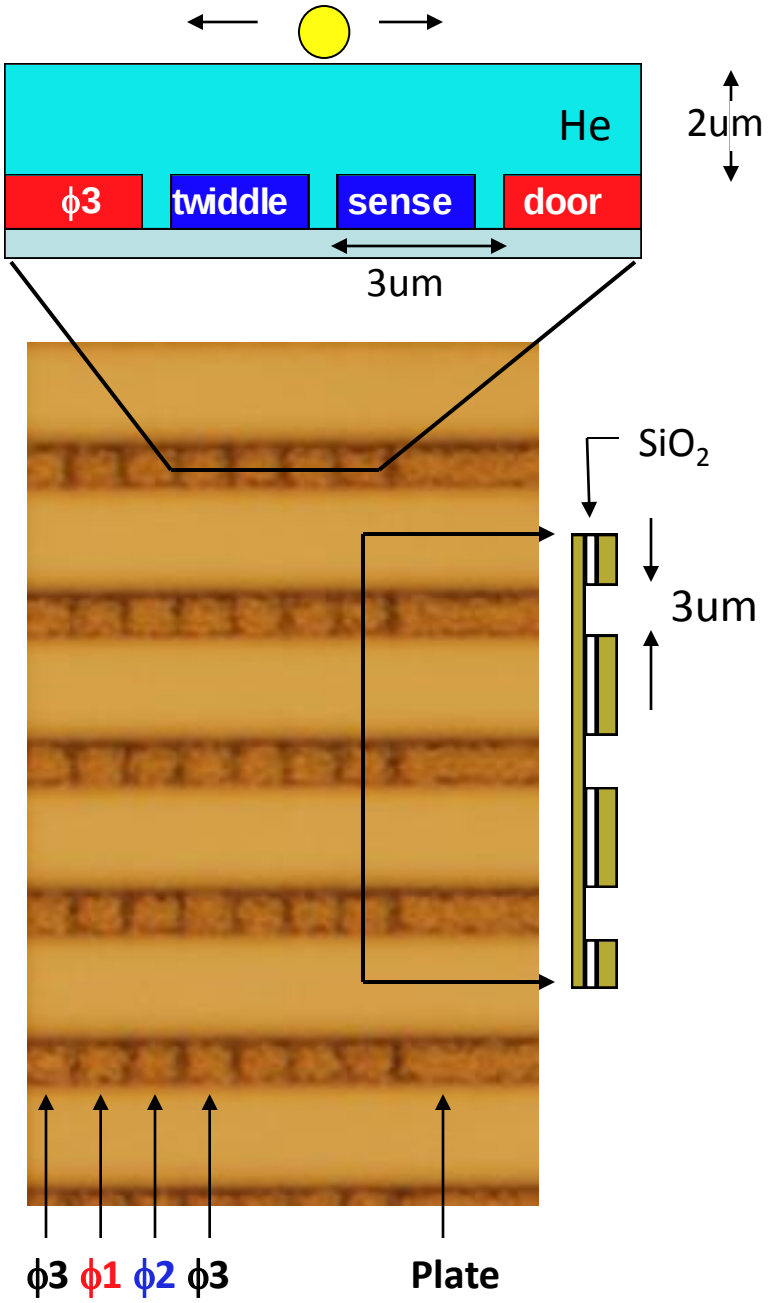
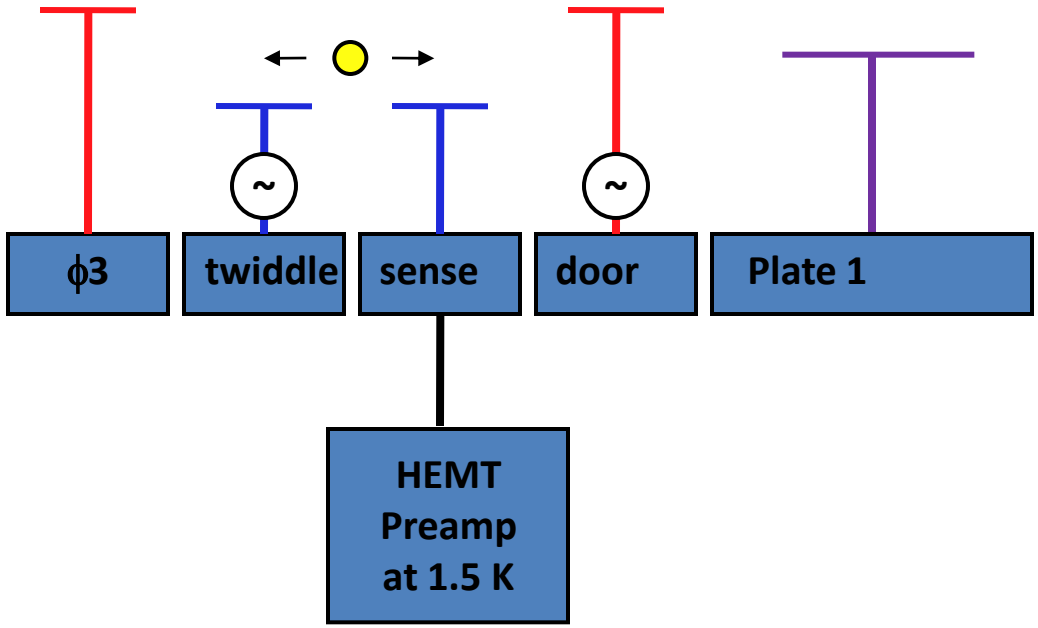


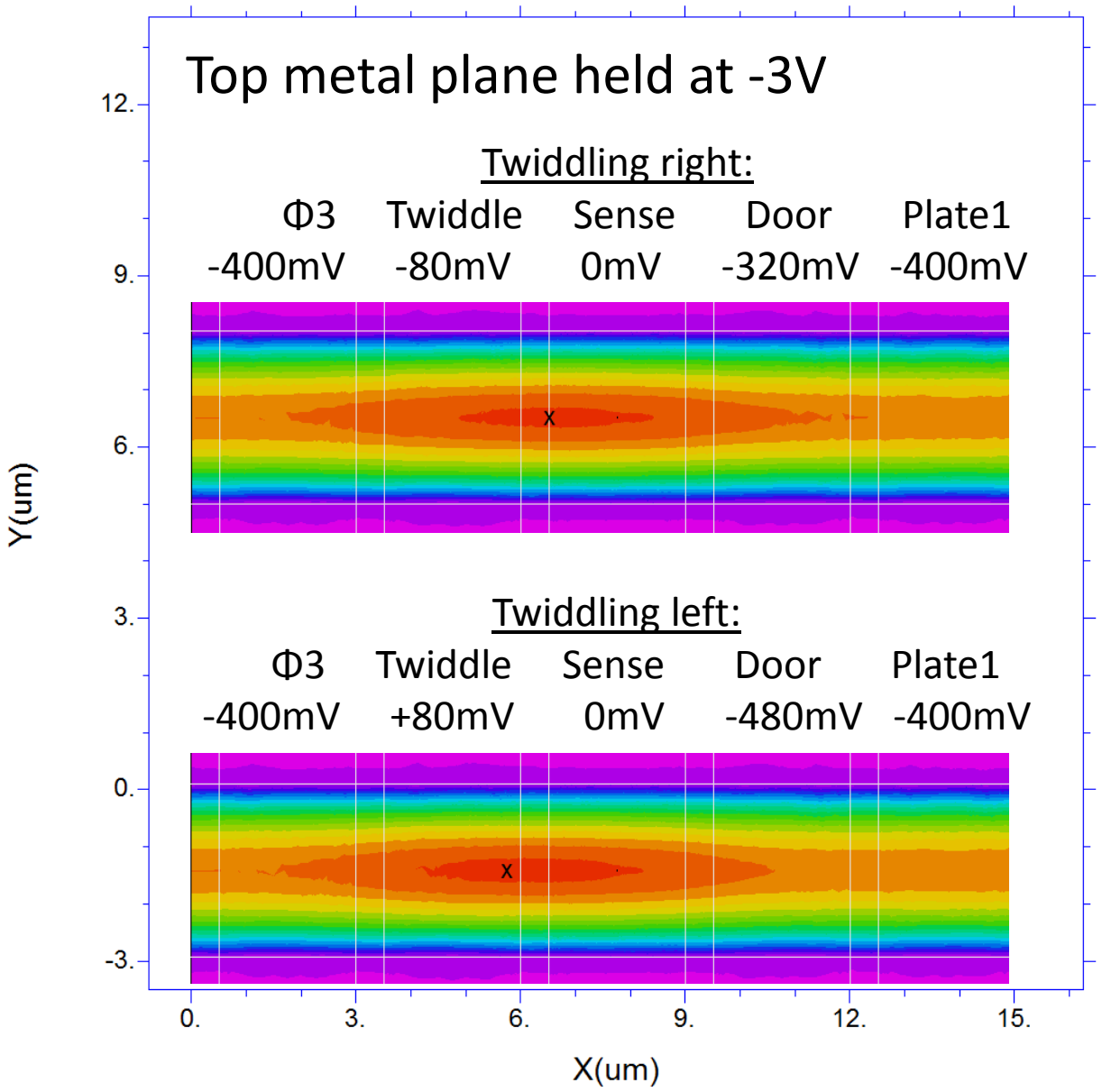


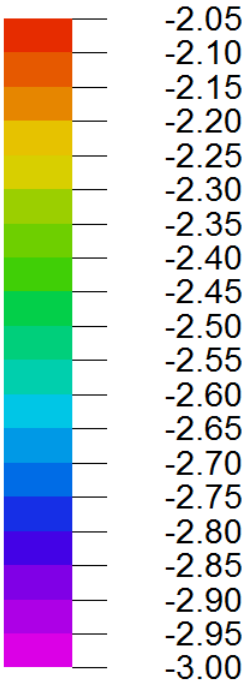
Twiddle Sensing





Twiddle Sensor: Potential Simulations





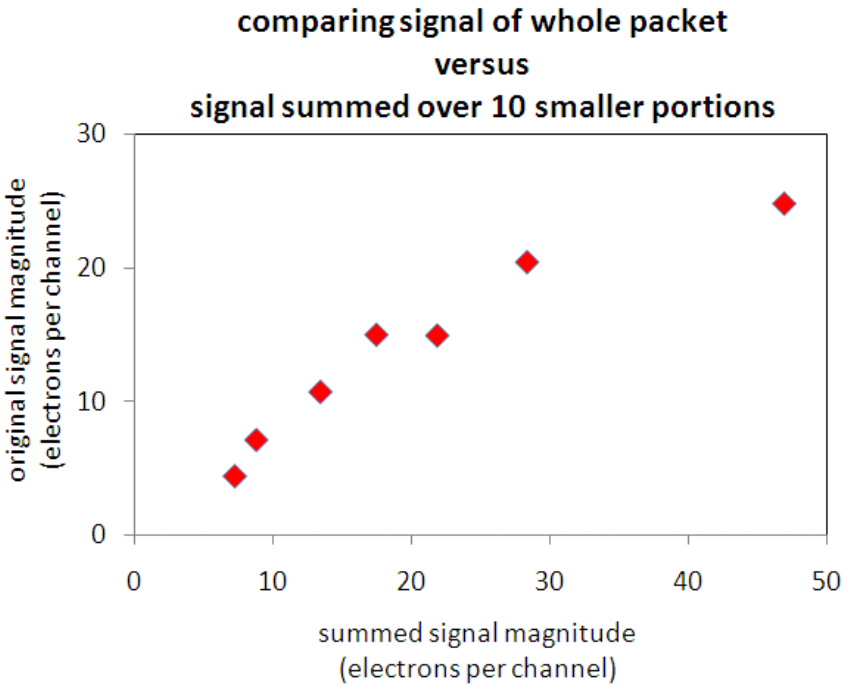
Electrical potential in volts at the helium surface above the channels

Twiddle Sensing Results

Calibration

- Voltage signal is converted to number of electrons per channel via gain calibration of the amplification circuit and capacitance estimate of the sense line + HEMT input.
- This predicts the observed signal saturation where detector is no longer linear.

Linearity



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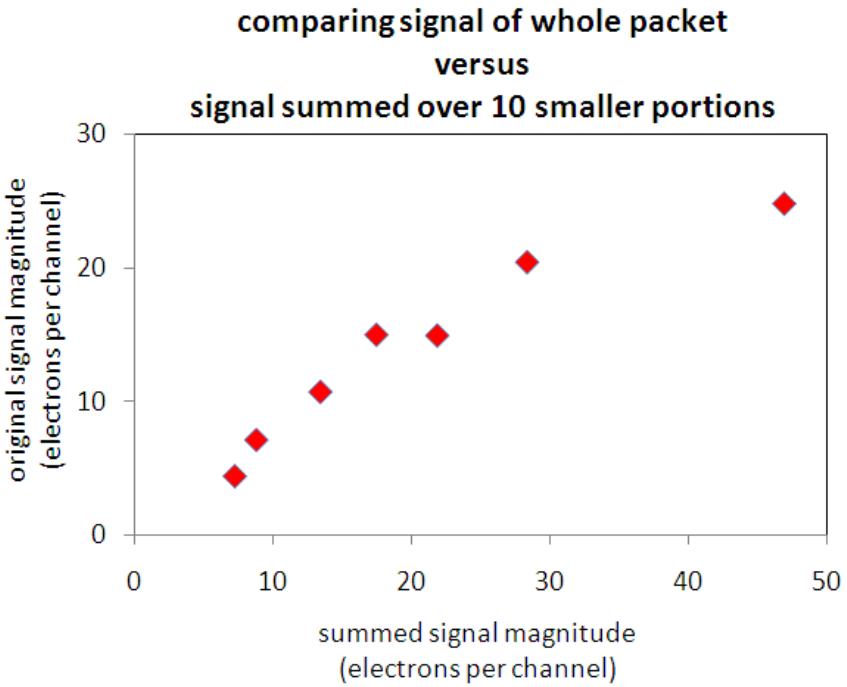

Twiddle Sensing Sensitivity

- Noise in silicon samples

  ~ 360 electrons per $Hz^{½}$

  with 120 parallel channels
  ~ 3 electrons per channel per $Hz^{½}$

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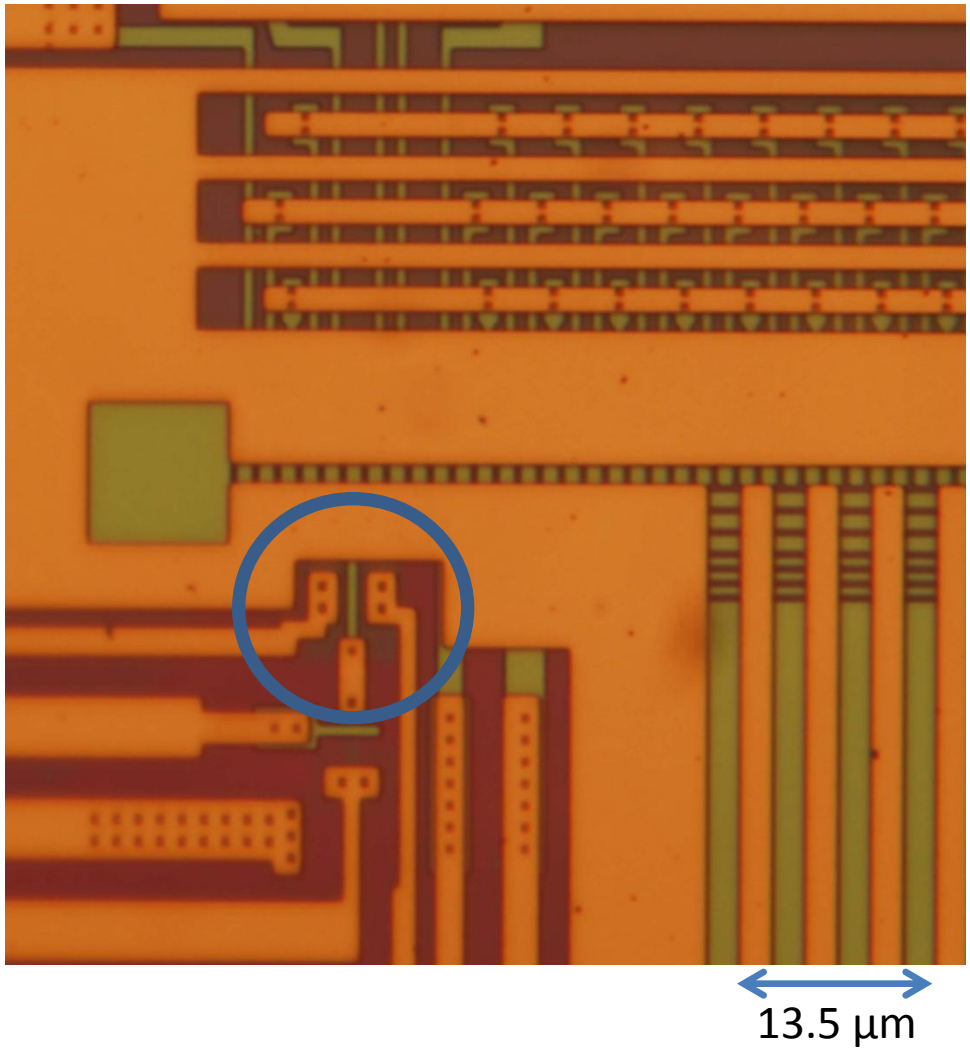
Electrons per Channel Quantization Measurements

- Electron turnstile for confinement
- Lower temperature

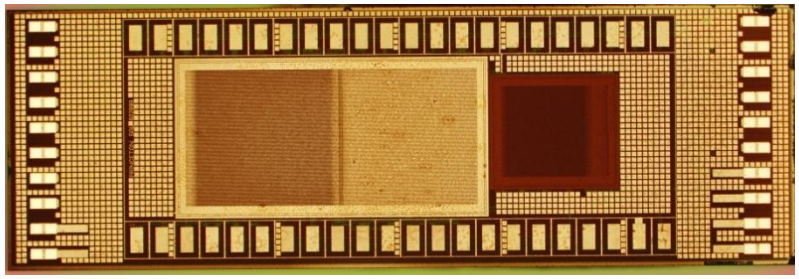
Twiddle Sensing with On-chip Amplification

Better sensing by proximity:

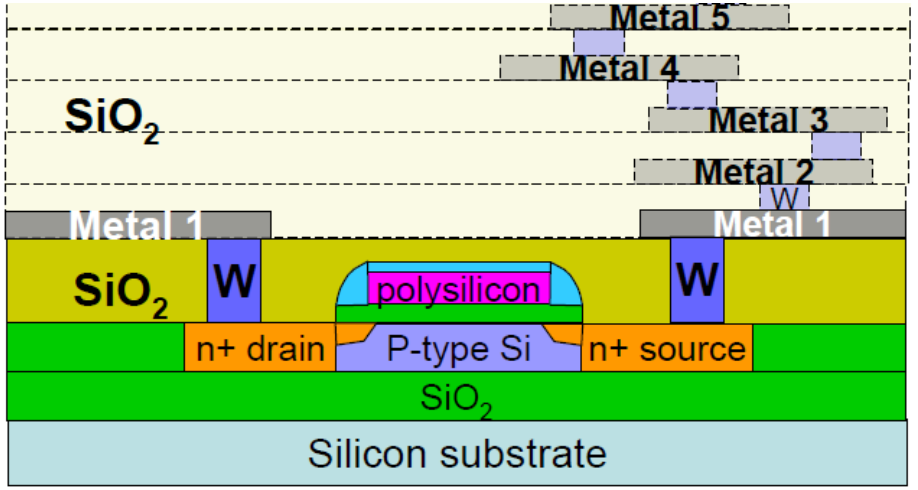
- With HEMT preamp, ~2 pF
- With on-chip FET, ~0.02 pF
- Induced voltage is 100x

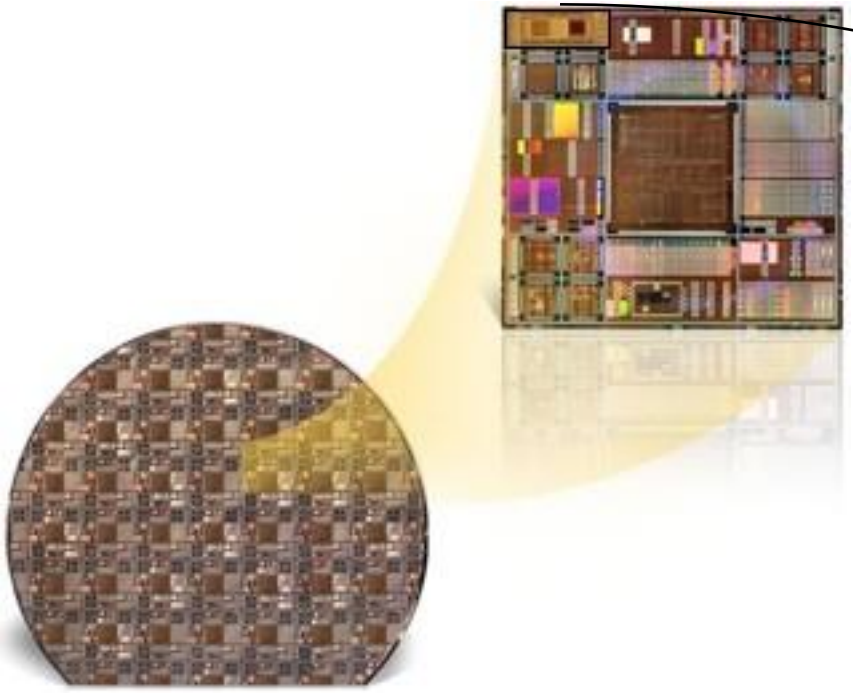


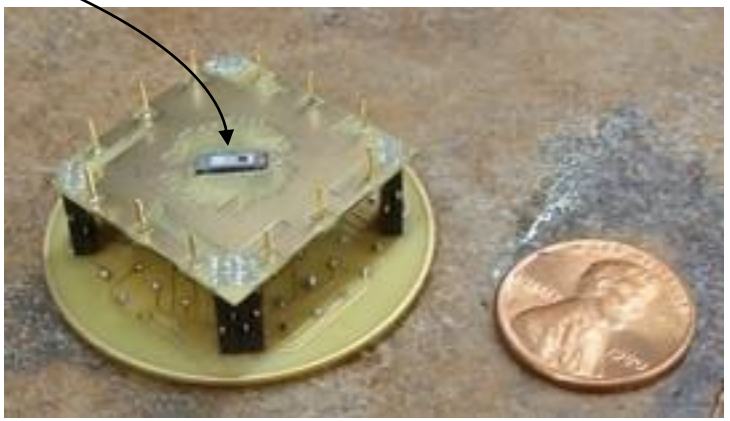
Multi-Project Wafer from Sandia



CMOS7 Process

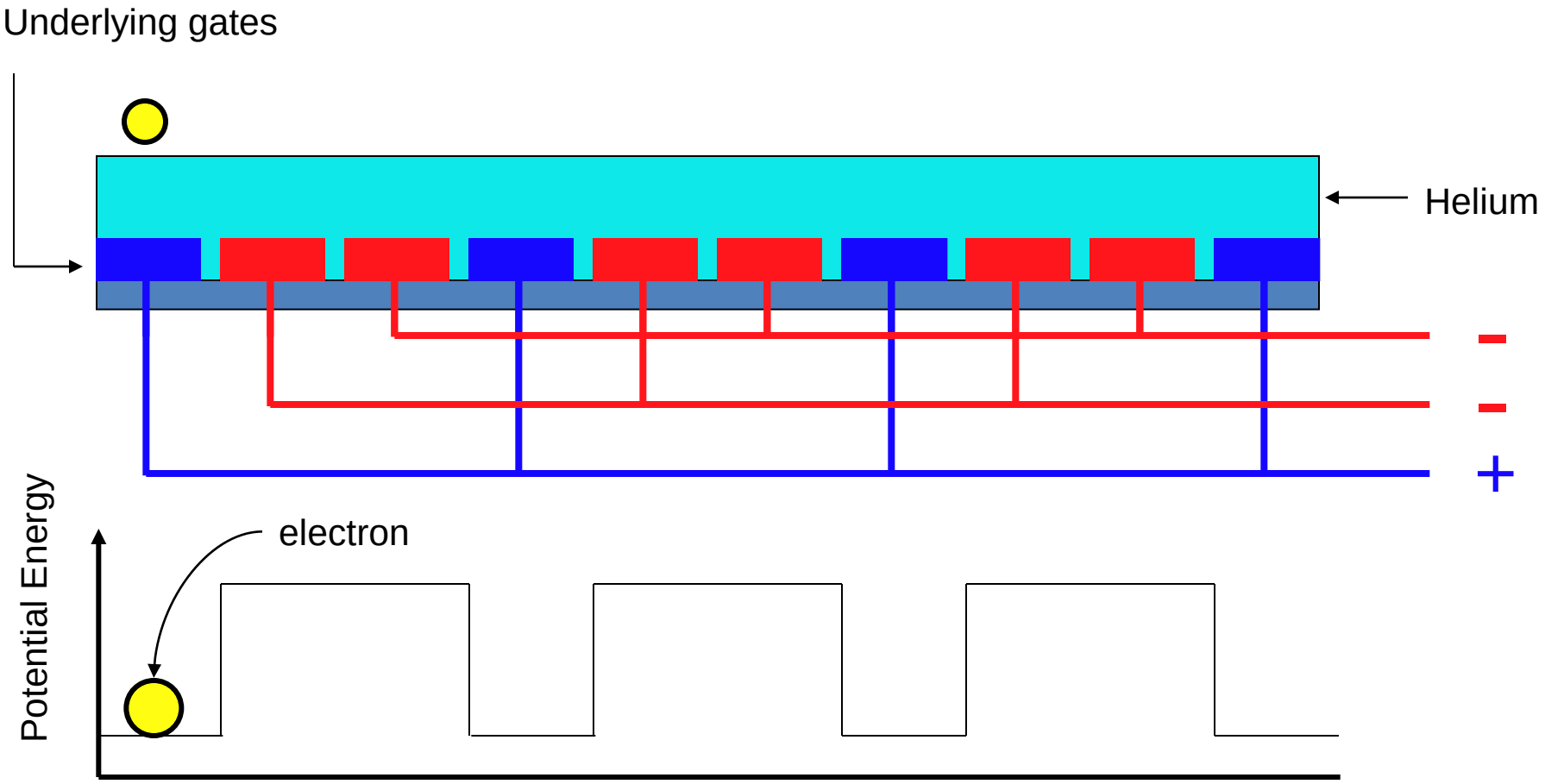






3-phase CCD

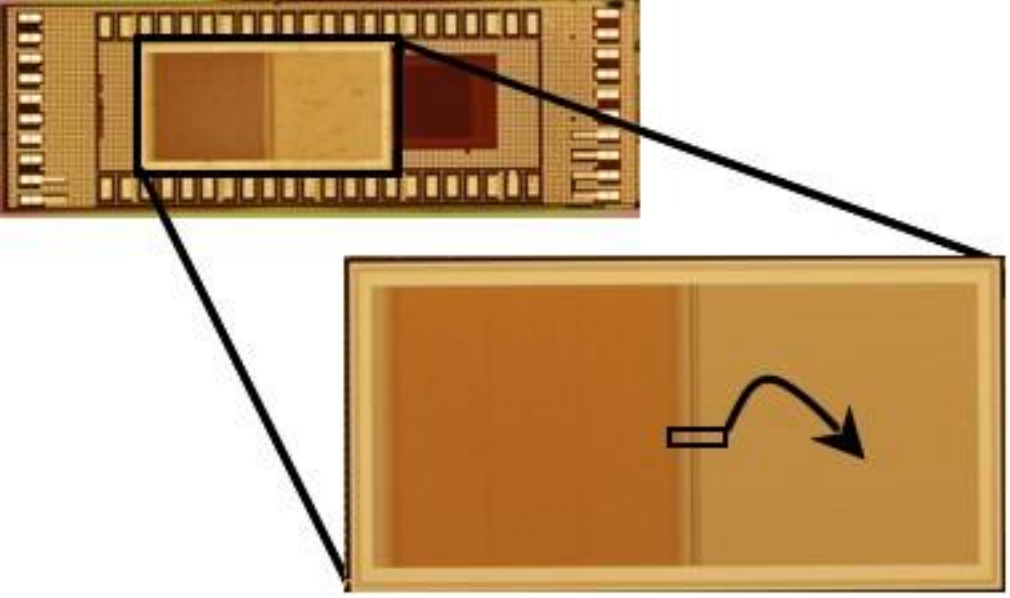
Potential

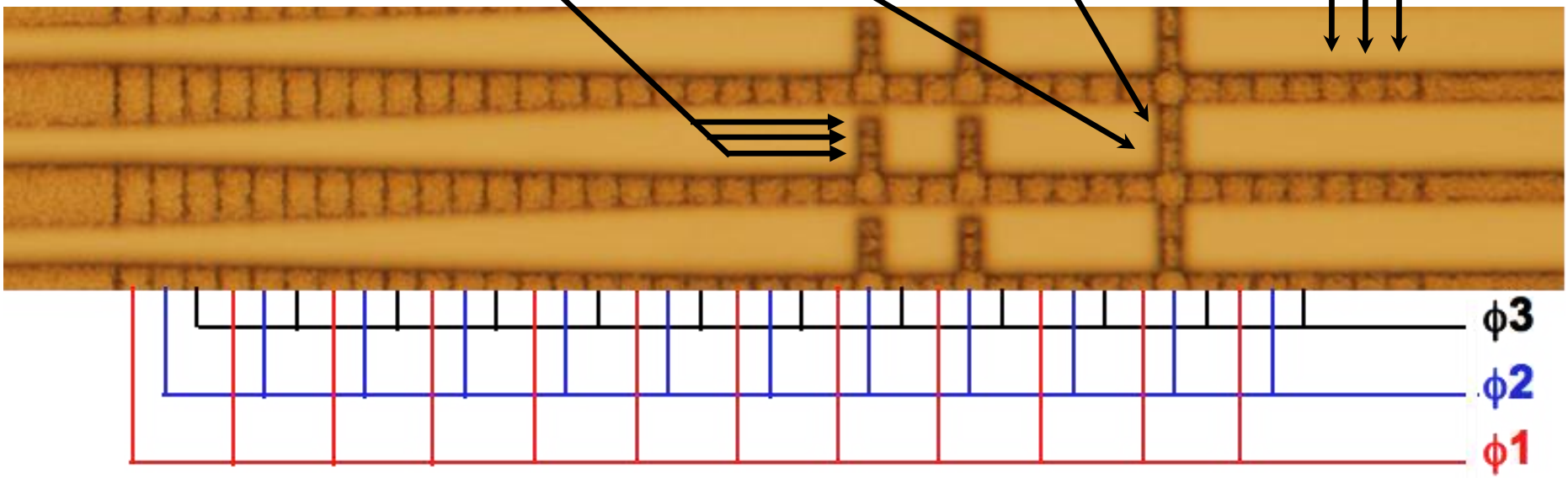


Device structure

120 horizontal channels

Measurement gates for electron detection





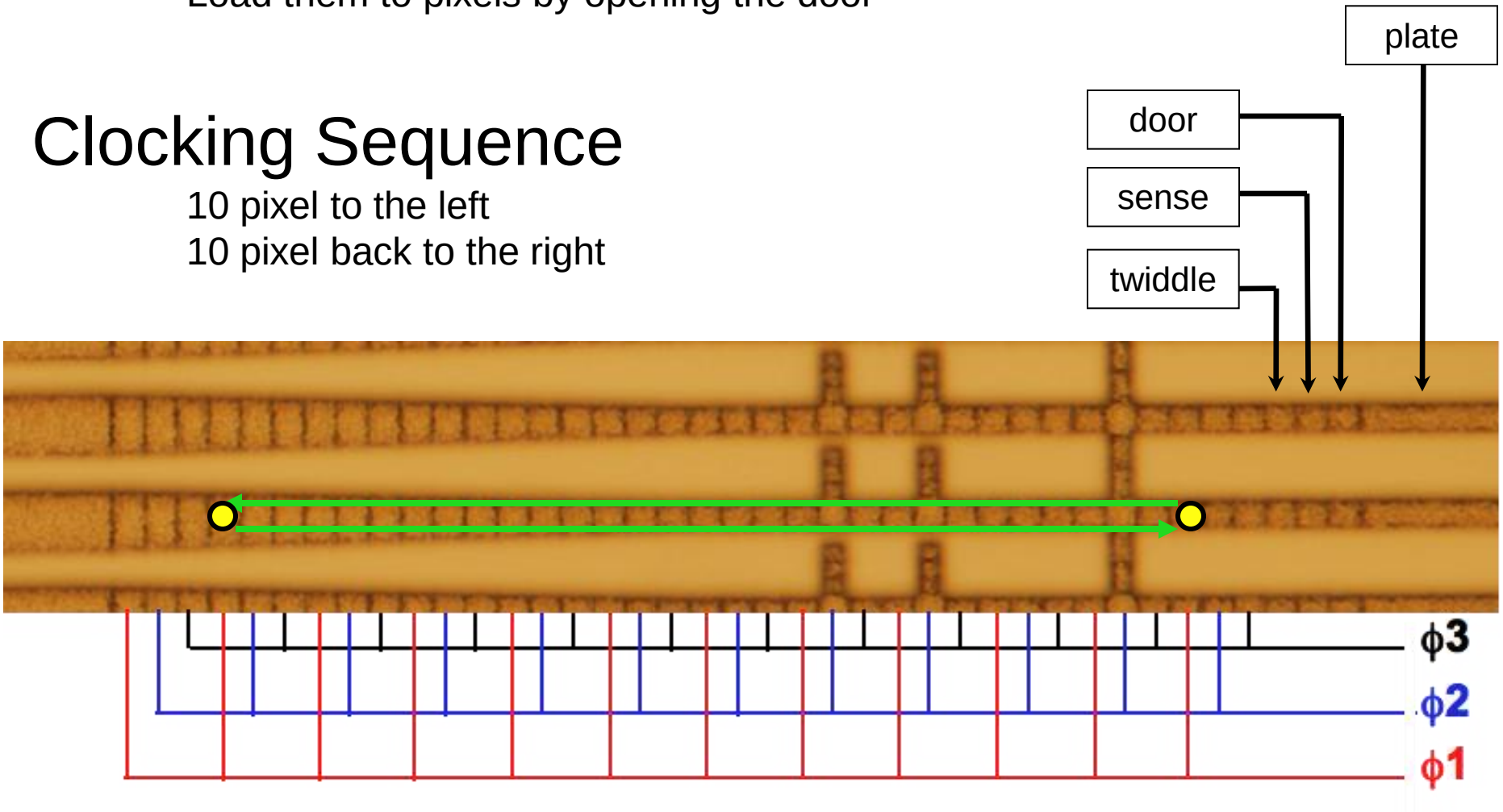
Horizontal CCD

Loading:

Photoemit electrons on plates
Load them to pixels by opening the door

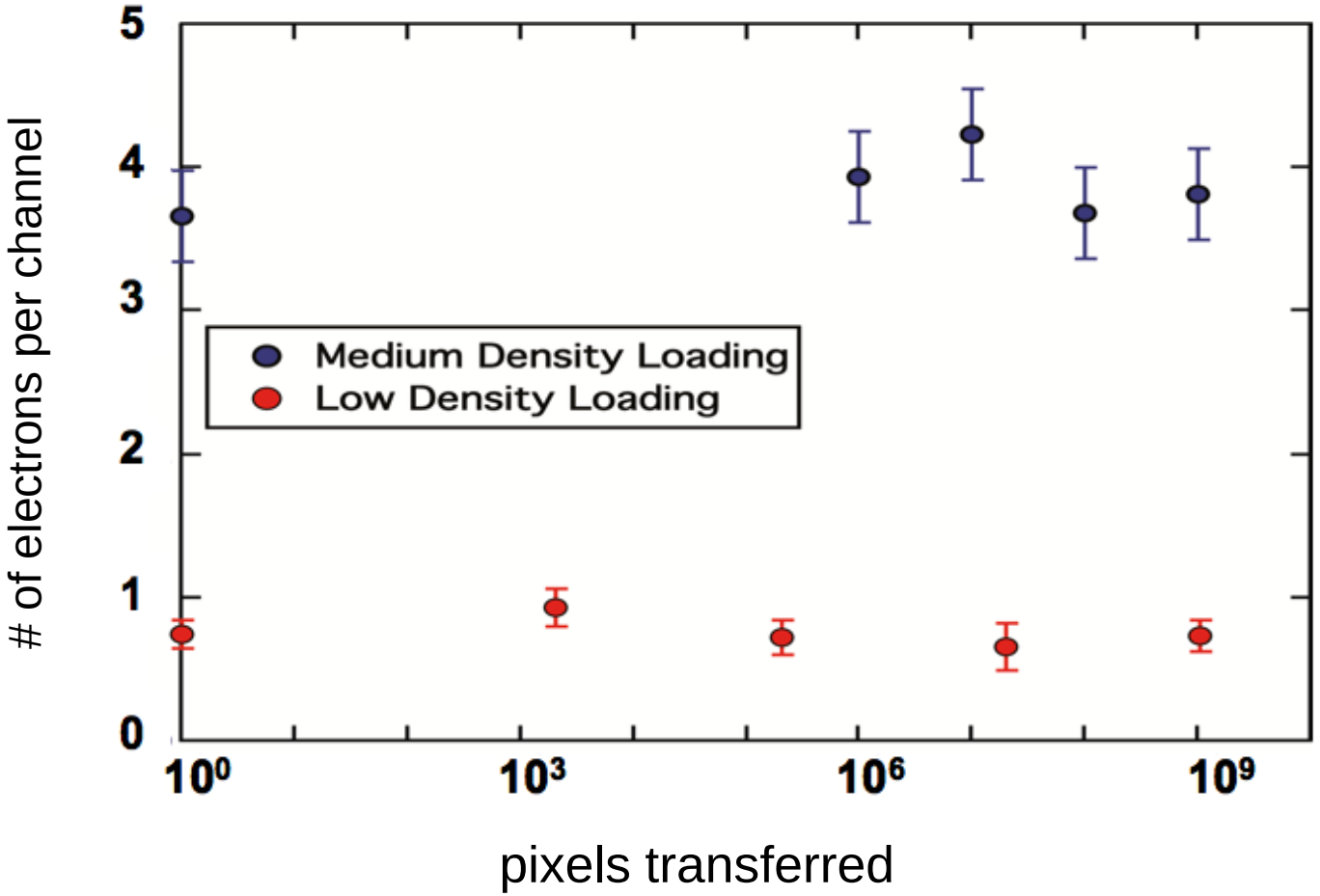
Clocking Sequence

10 pixel to the left
10 pixel back to the right



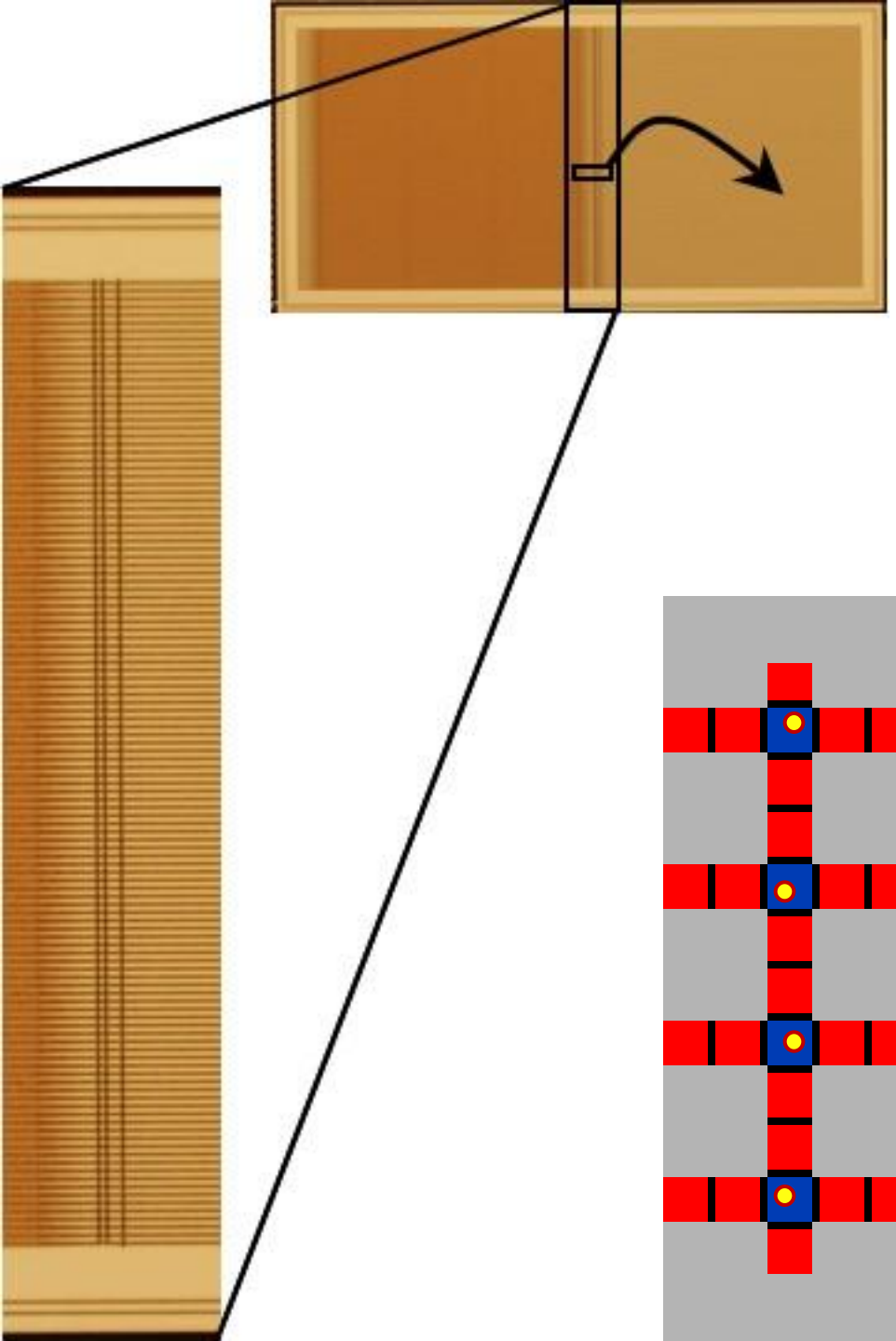
Horizontal Clocking Efficiency

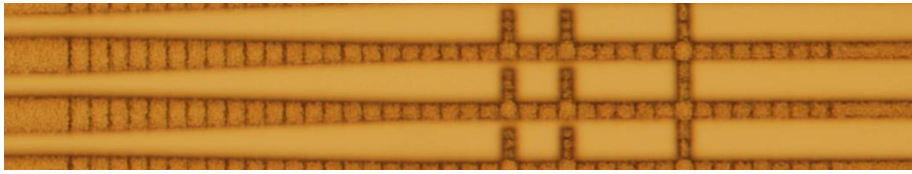
Clock (pixel) rate = 240kHz



No measurable loss after 10^9 cycles!

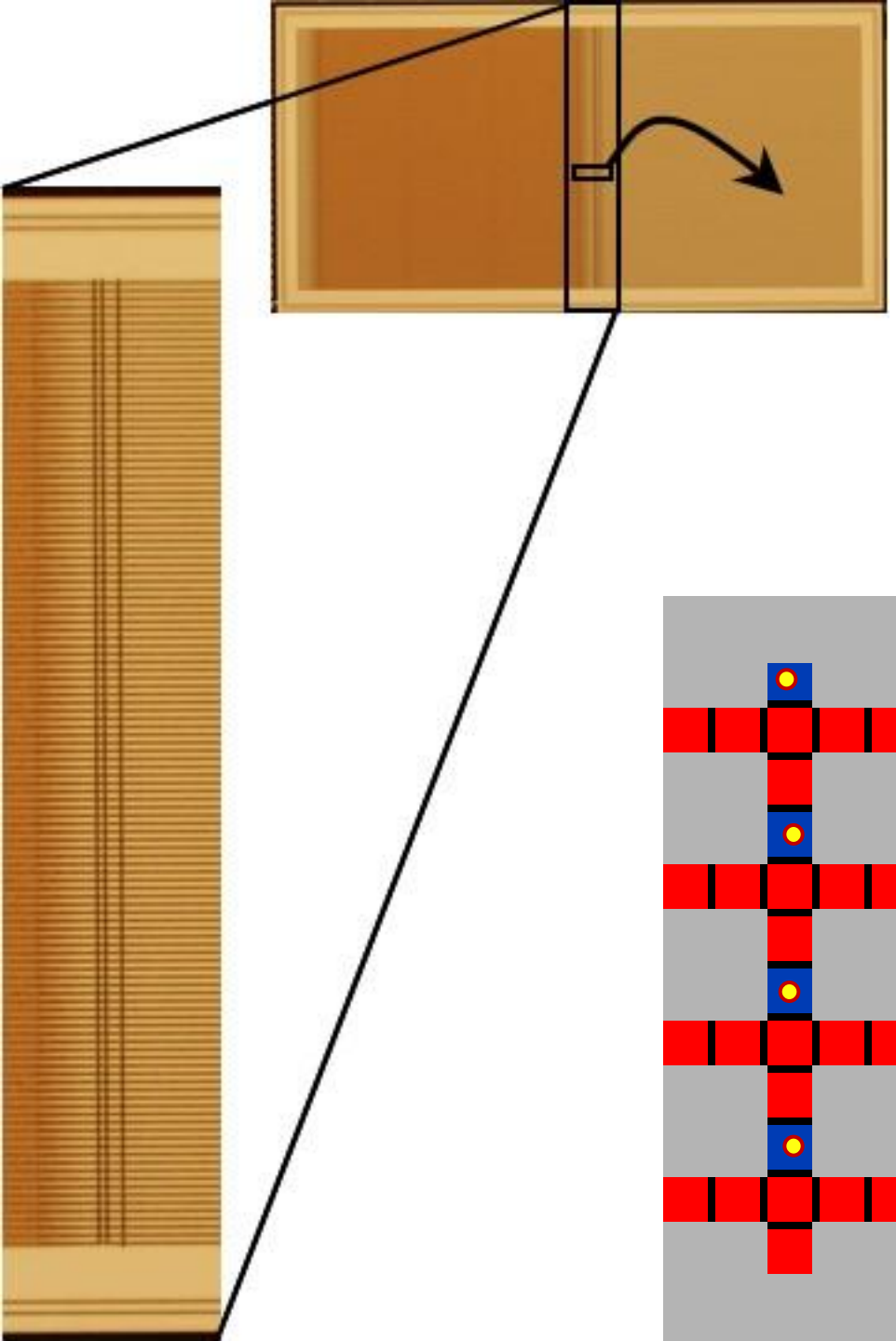
Vertical channel CCD

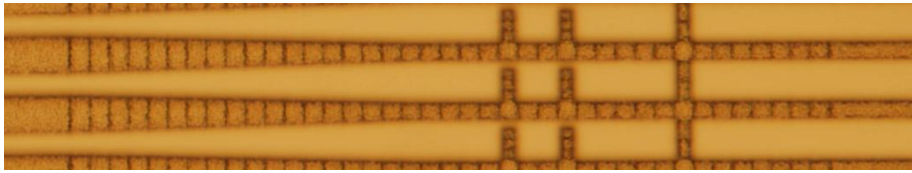




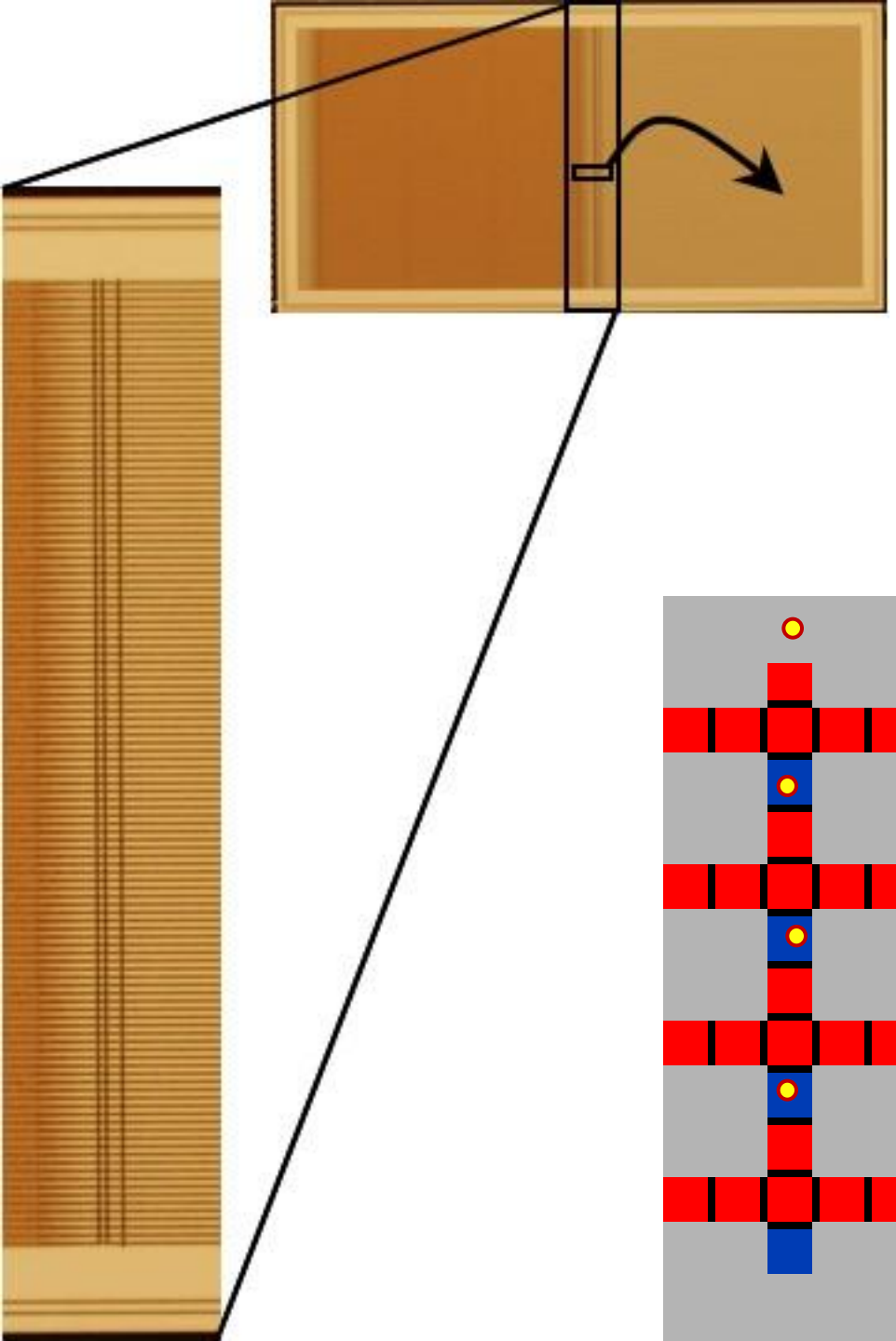
- Vertical Clocking Efficiency
- Cornering Efficiency
- Distribution of electrons in horizontal channels

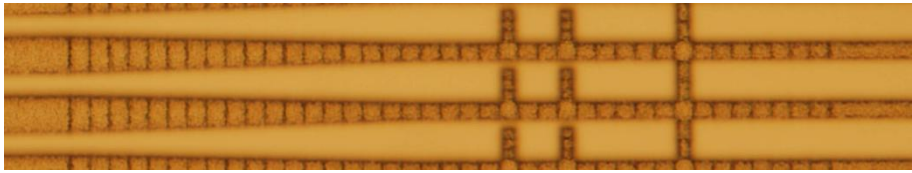
Vertical channel CCD





Vertical channel CCD





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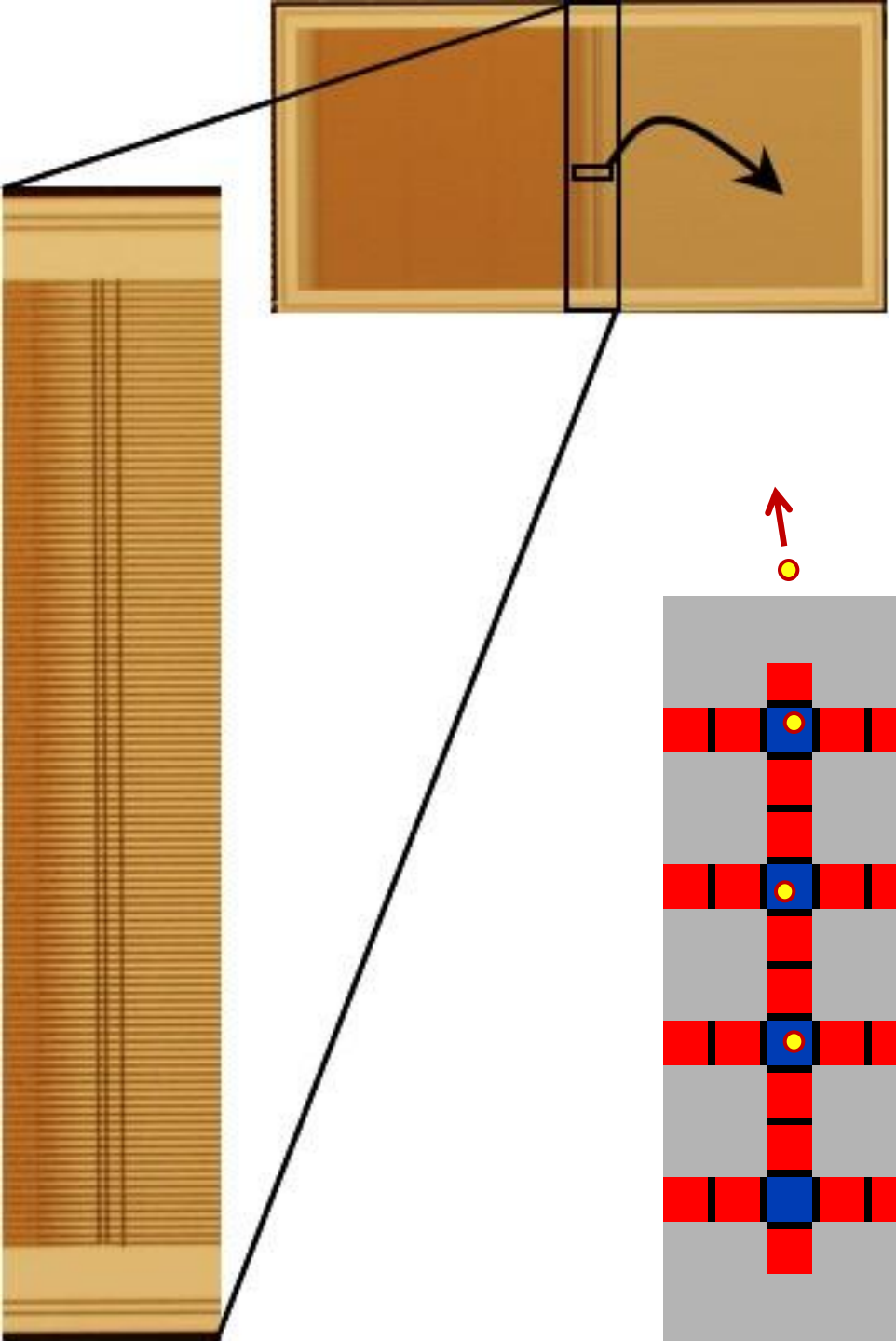
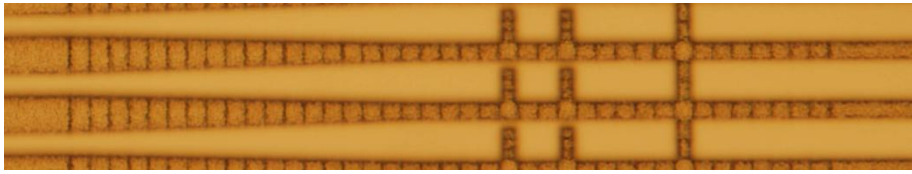
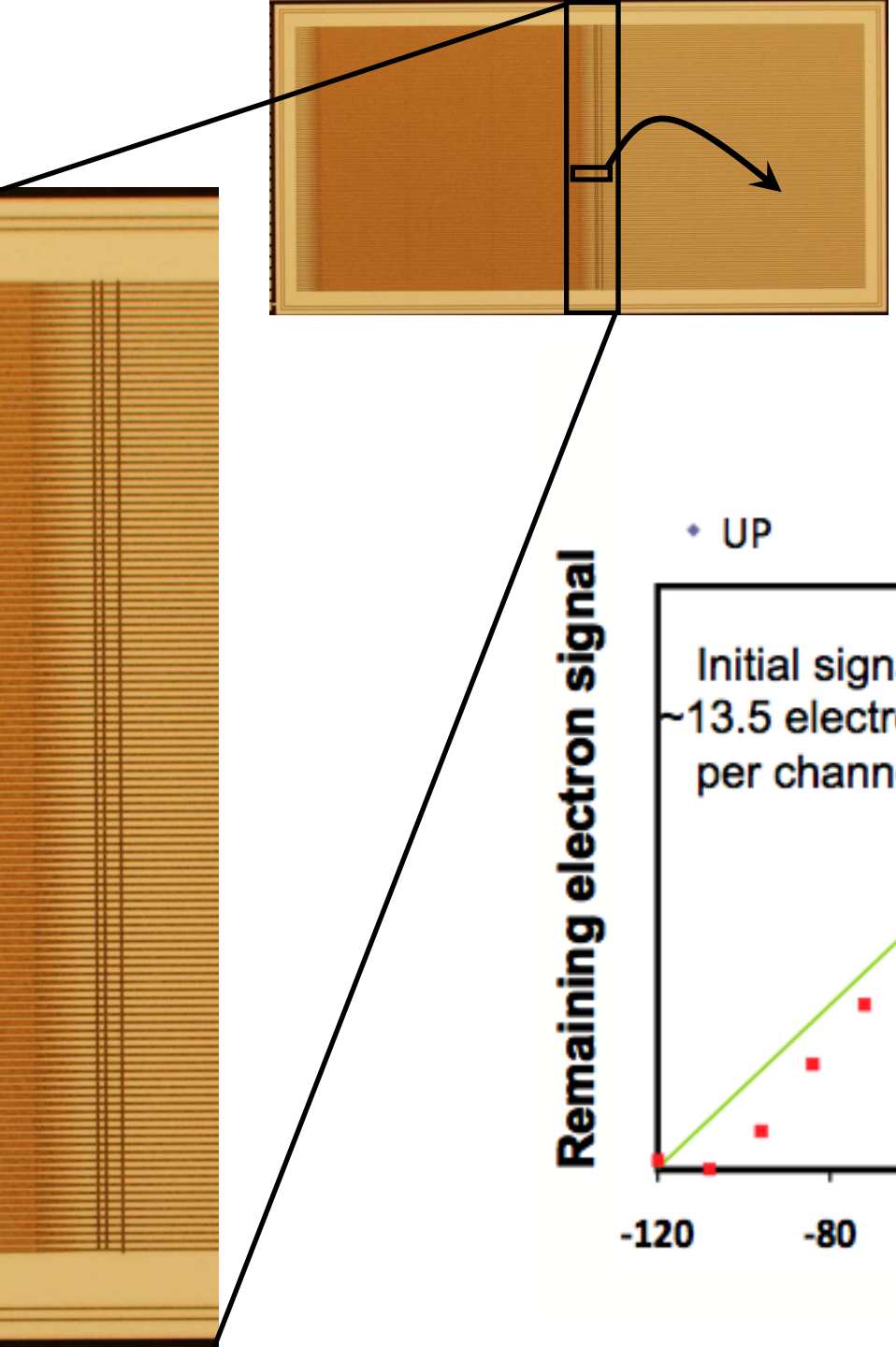
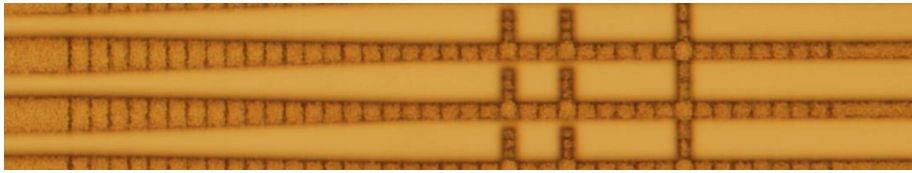


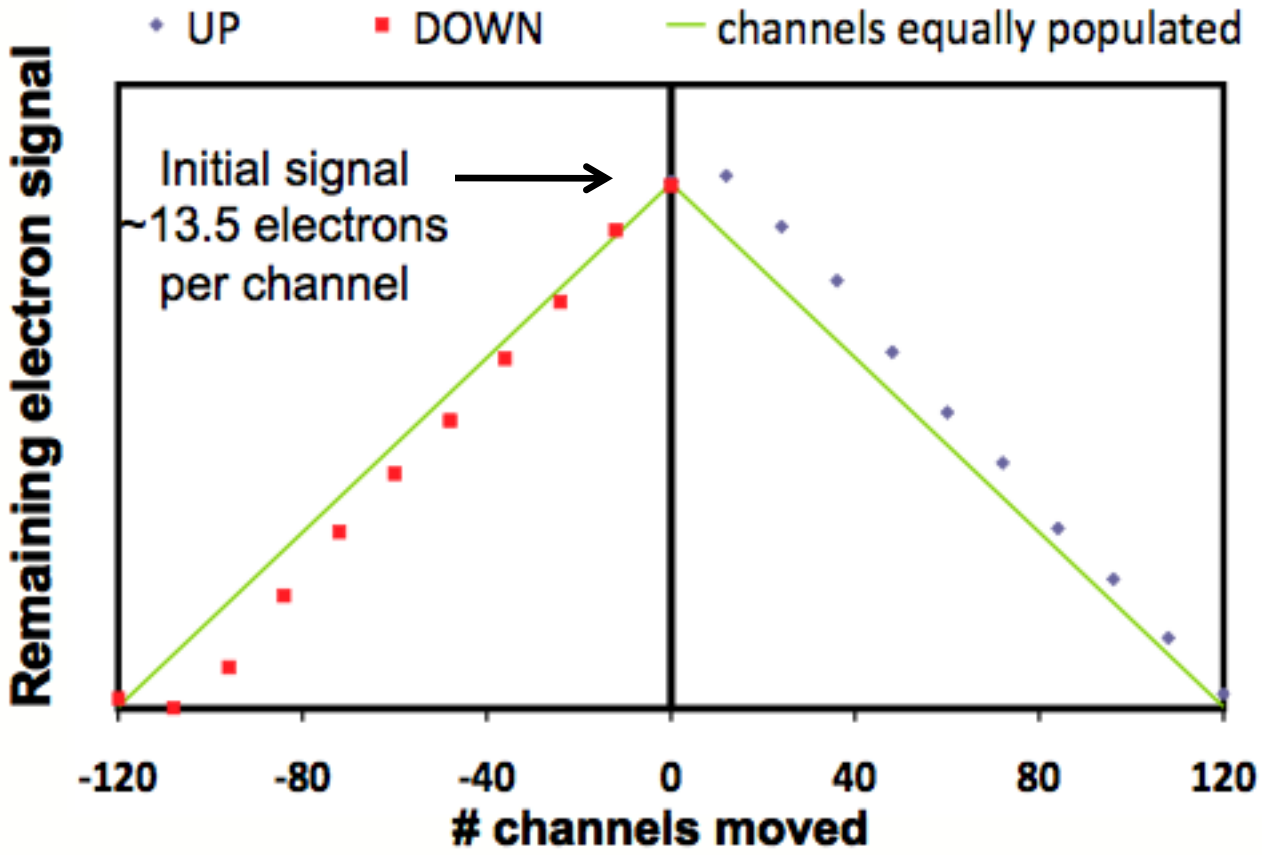


Vertical channel CCD

Distribution of electrons in horizontal channels







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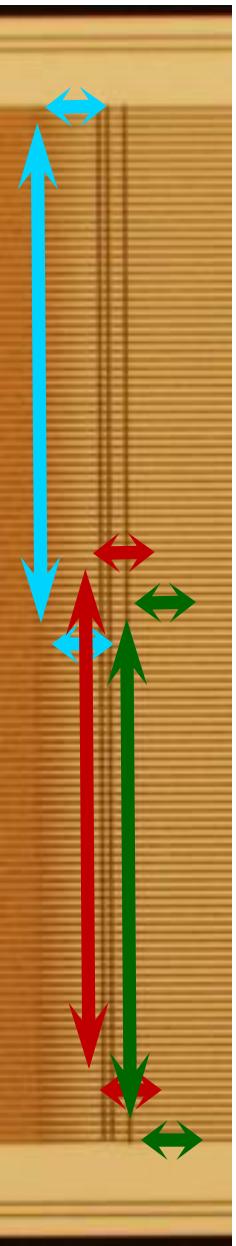
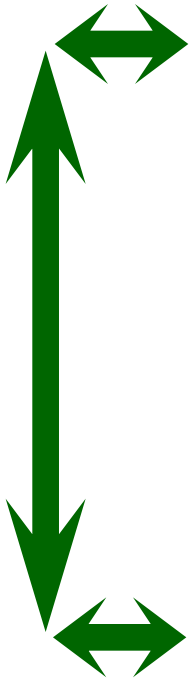


Channel N+60

each packet of electrons travels up and down 60 channels

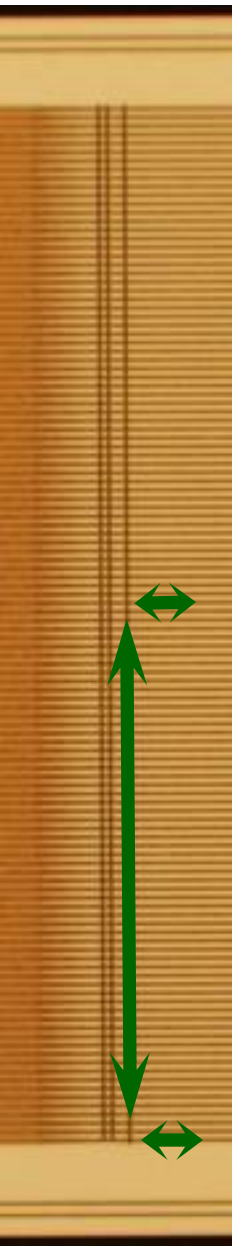
Channel N



C-cycling Demonstrates

- vertical channel CCD
- cornering efficiency
- 2D control

Vertical channel CCD

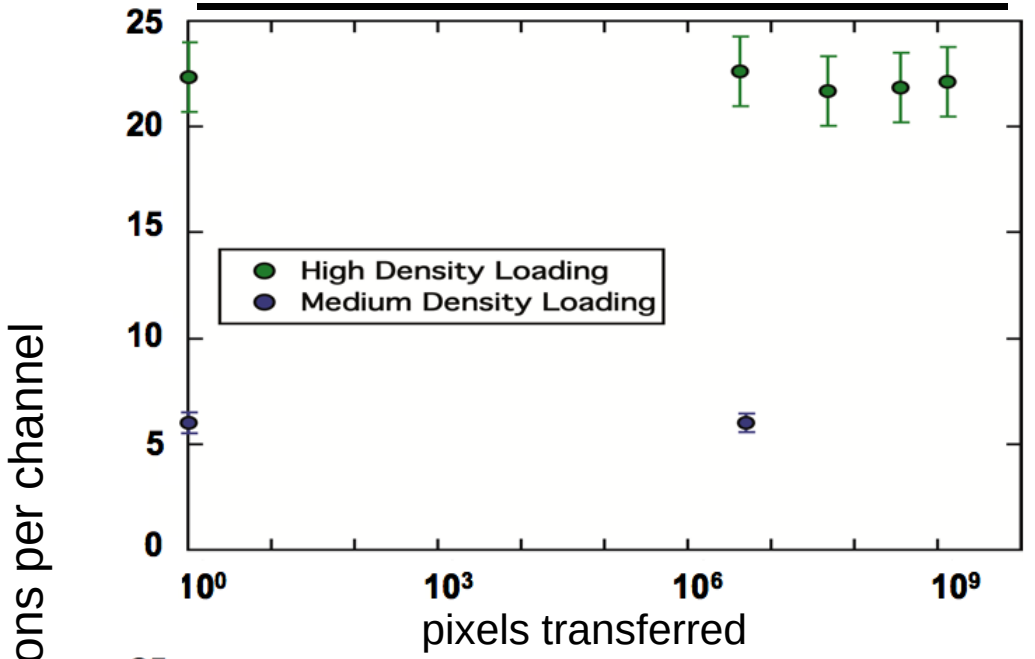


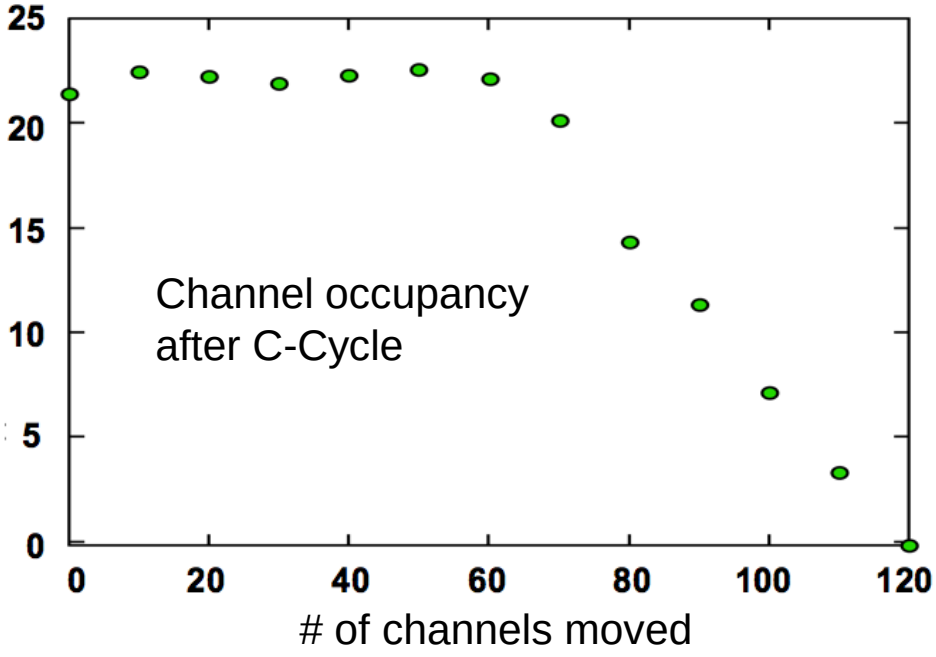
- Vertical CCD
- Cornering
- 2D control

Channel 61

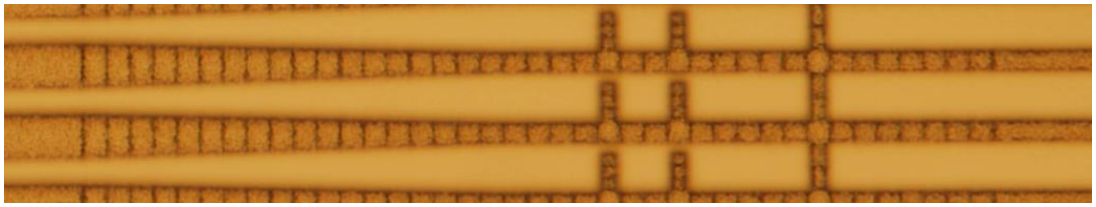
One packet of electrons travels between

Channel 1





Conclusion



- Electron detection with twiddle gate

- Unprecedented reliability of a Charge Coupled Device
  - -Essentially a perfect Electron Transfer Efficiency

- 5 clock lines for full control
  - -2D Scalability: Move anywhere in our ~5000 position gate & channel array

- Si-Processing
  - -First, non-optimized design with standard silicon processing
  - -Possibilities for on-chip amplification