SIMILAR AIMS, DIFFERENT SYSTEM

Efficient electron transport on superfluid helium

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Based on 2010 dissertation in Princeton University's electrical engineering department under Steve Lyon:
"Cold electrons in silicon and on superfluid helium"

Outline:

- Introduction and motivation for electron spin qubits
- Background for electrons on helium
- Experimental methods
- Experimental results for electron transport above superfluid helium channels
- Ideas, uncertainties, and plans for pumping

Cold electrons in silicon and on superfluid helium

Acknowledgments:

Collaborators:

Steve Lyon	Princeton University
Alexei Tyryshkin	Princeton University
Guillaume Sabouret	Princeton University
Maika Takita	Princeton University
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Jeff Bokor	Lawrence Berkeley National Lab and UC Berkeley
Kevin Eng	Sandia National Lab, currently HRL Laboratories
Tom Gurrieri	Sandia National Lab
Kathy Wilkel	Sandia National Lab

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My PhD Thesis title:
“Cold electrons in silicon and on superfluid helium”

Focus: materials with zero spin nuclear isotopes:

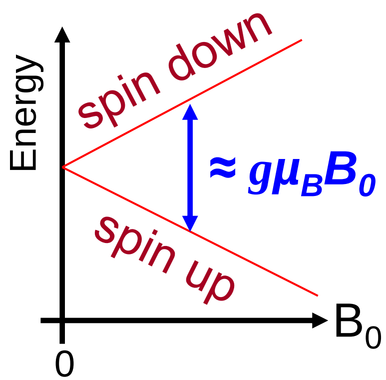
^{28}Si – regular silicon wafer

^{4}He – liquid helium surface

Promising material systems for electron spin qubits?

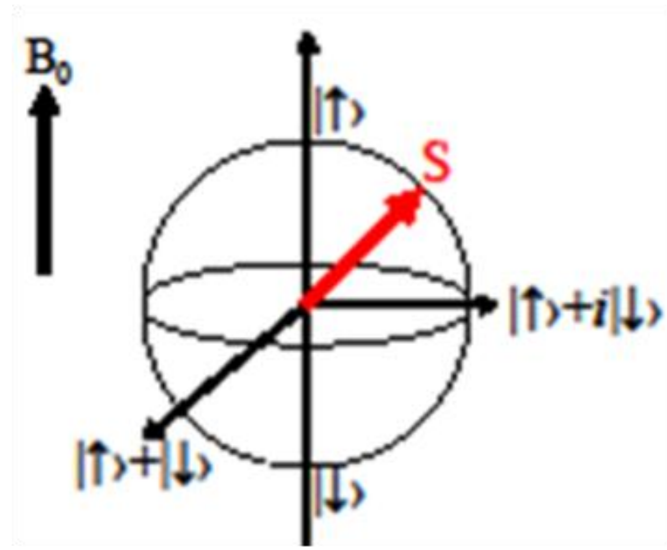
Cold electrons in silicon and on superfluid helium

(for electron spin qubits)



The Bloch Sphere

(image courtesy Shyam Shankar)



Excited state — anti-aligned ↓ — $|1\rangle$

Ground state — aligned ↑ — $|0\rangle$

DiVincenzo Criteria
for a quantum information processor

scalable array of qubits

initialization

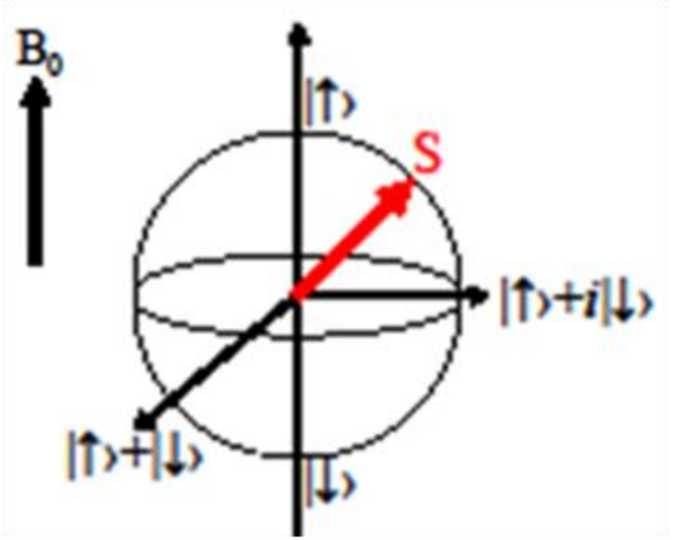
“flying” qubits

long T_1 & T_2

universal set of qubit operations

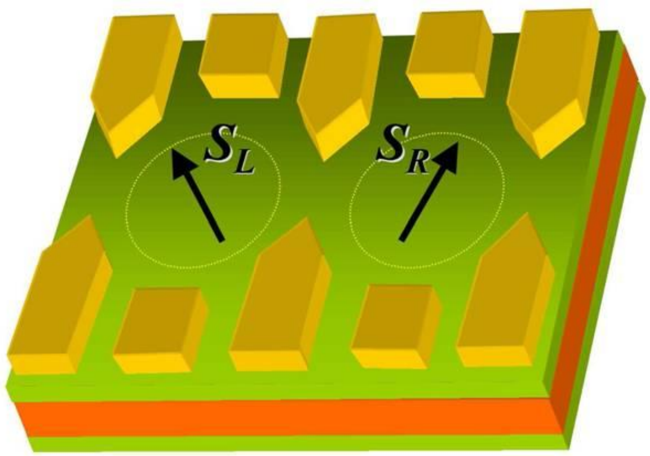
efficient measurement

The Bloch Sphere
(image courtesy Shyam Shankar)



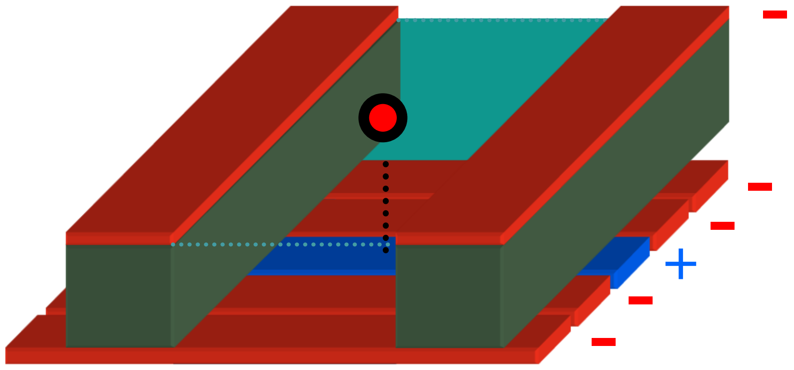
Electrostatic gate-defined dots for electron spin qubits

Lithographically defined dots in semiconductor heterostructures



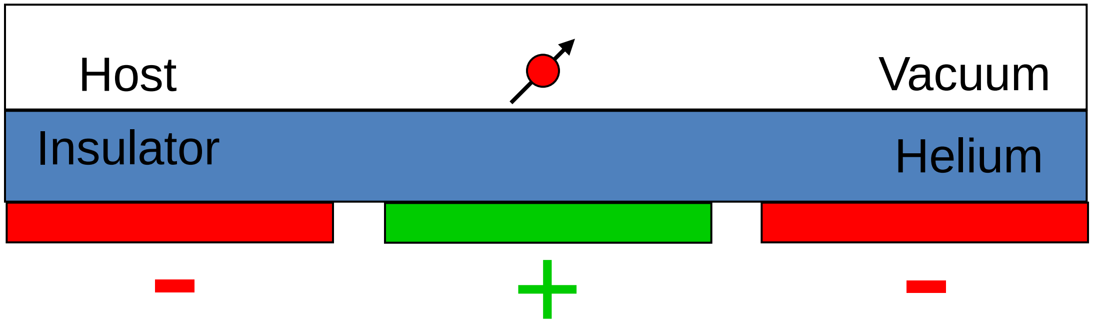
Loss & DiVincenzo, *Phys. Rev. A* **57**, 120 (1998)

Electrons in channels of superfluid helium

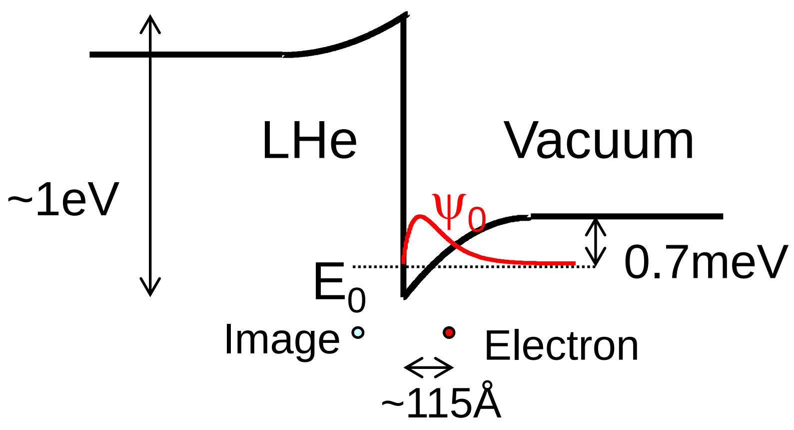


Lyon, *Phys. Rev. A* **74,** 052338 (2006)

Electrons on superfluid helium



Energetics



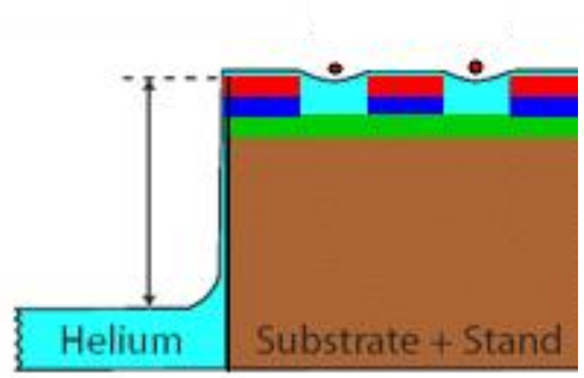
⇒ Able to move electrons without spin decoherence!

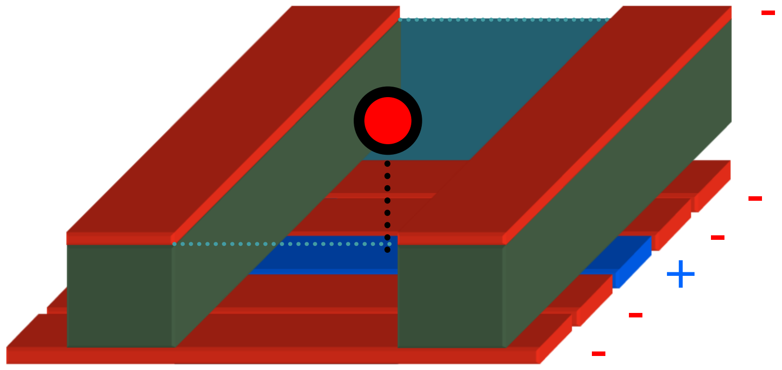
Electrons on liquid helium: a brief history

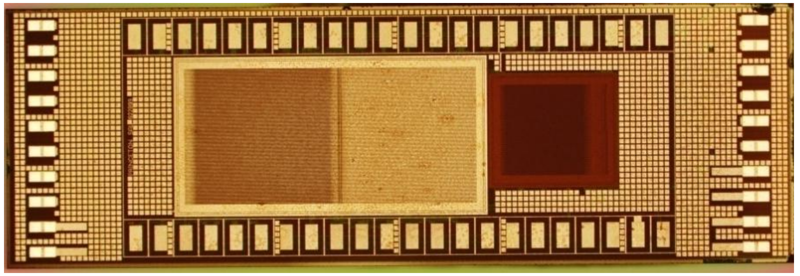
- Proposed in 1964 by W.T. Sommer
- Demonstrated in 1971 by Williams, Crandall, and Willis
- Classical Wigner crystal in 1979 by Grimes and Adams
- Low densities (10^5-10^9 e/cm^{-2}), non-degenerate regime!
  - limited due to hydrodynamic instability
- Highest mobility 2D electrons
  - 100 x10^6 cm^2/Vs measured by Shirahama et al @ 50mK
- Channels 1st employed in 1986 by Marty in PCB devices

The physical system:

Efficient electron transport on superfluid helium channels with silicon integrated circuits







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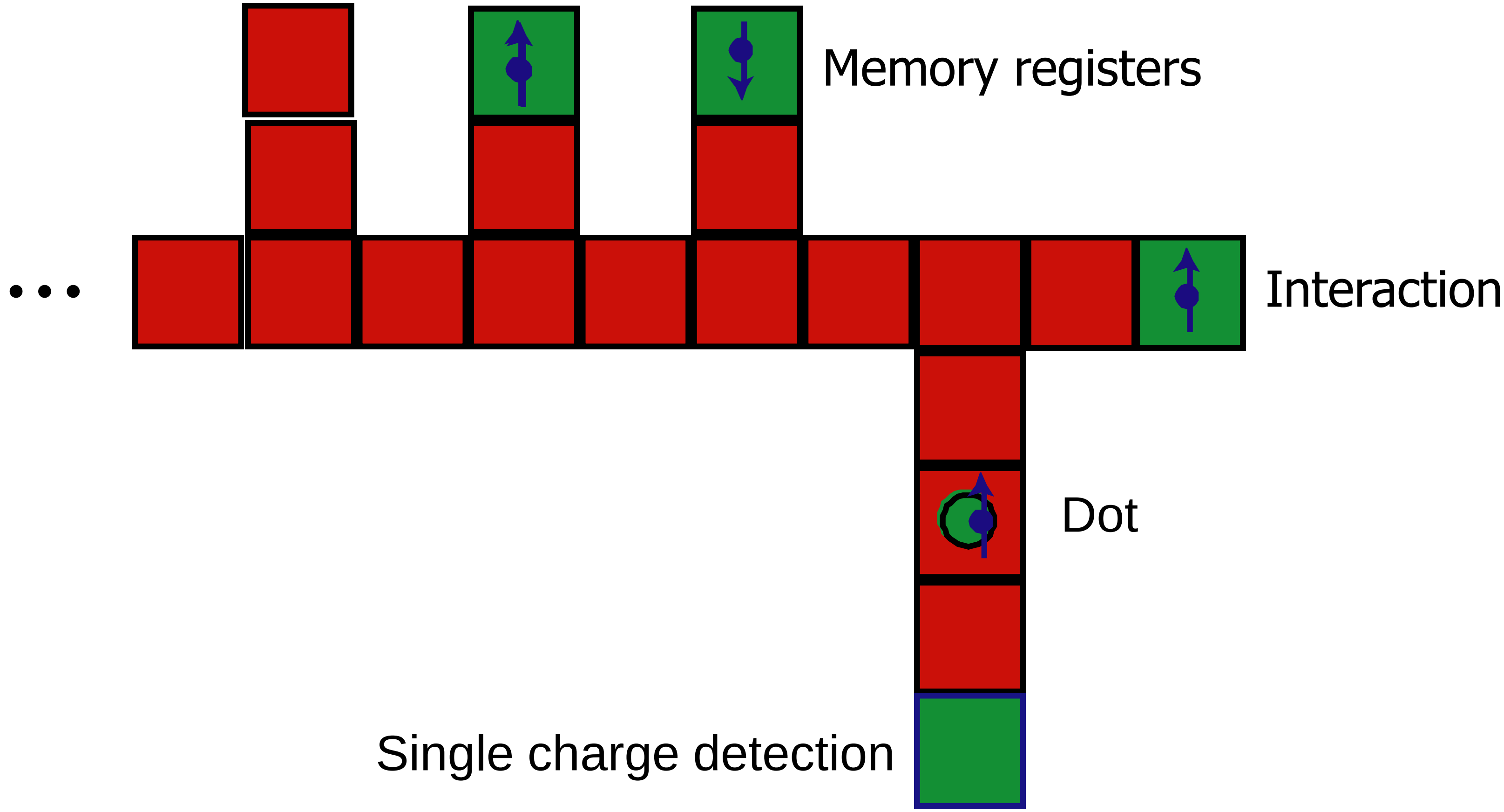

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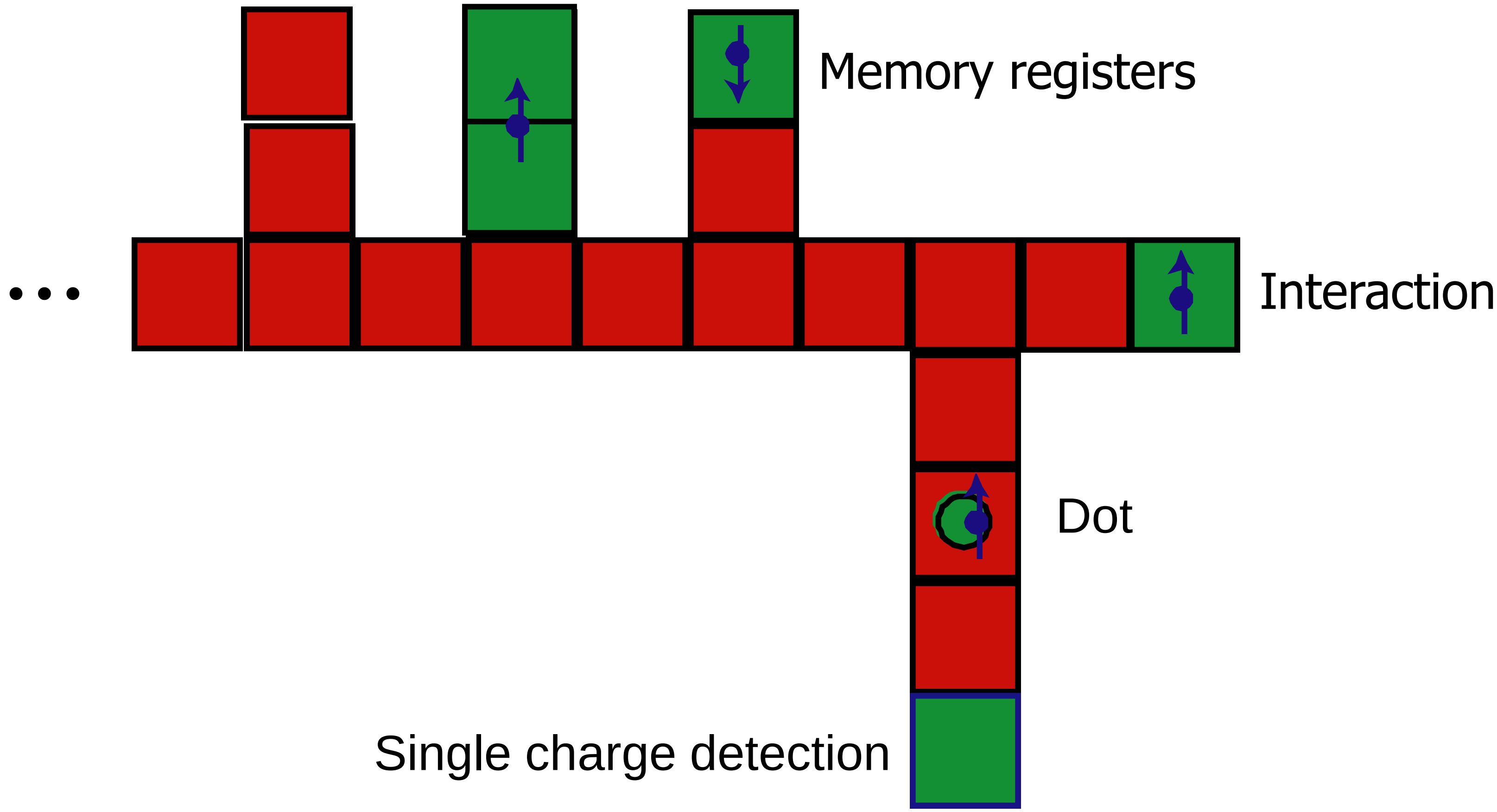

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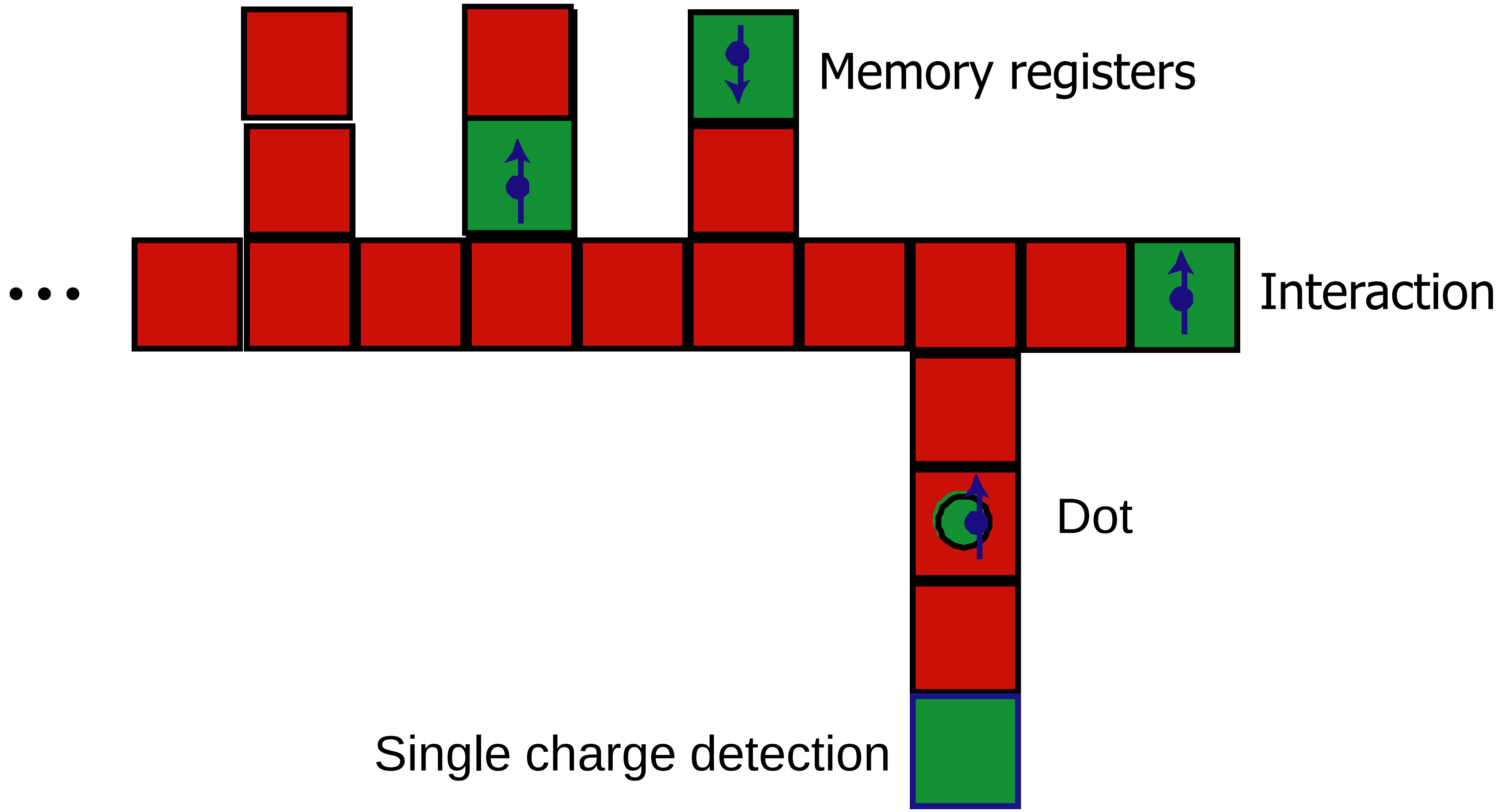

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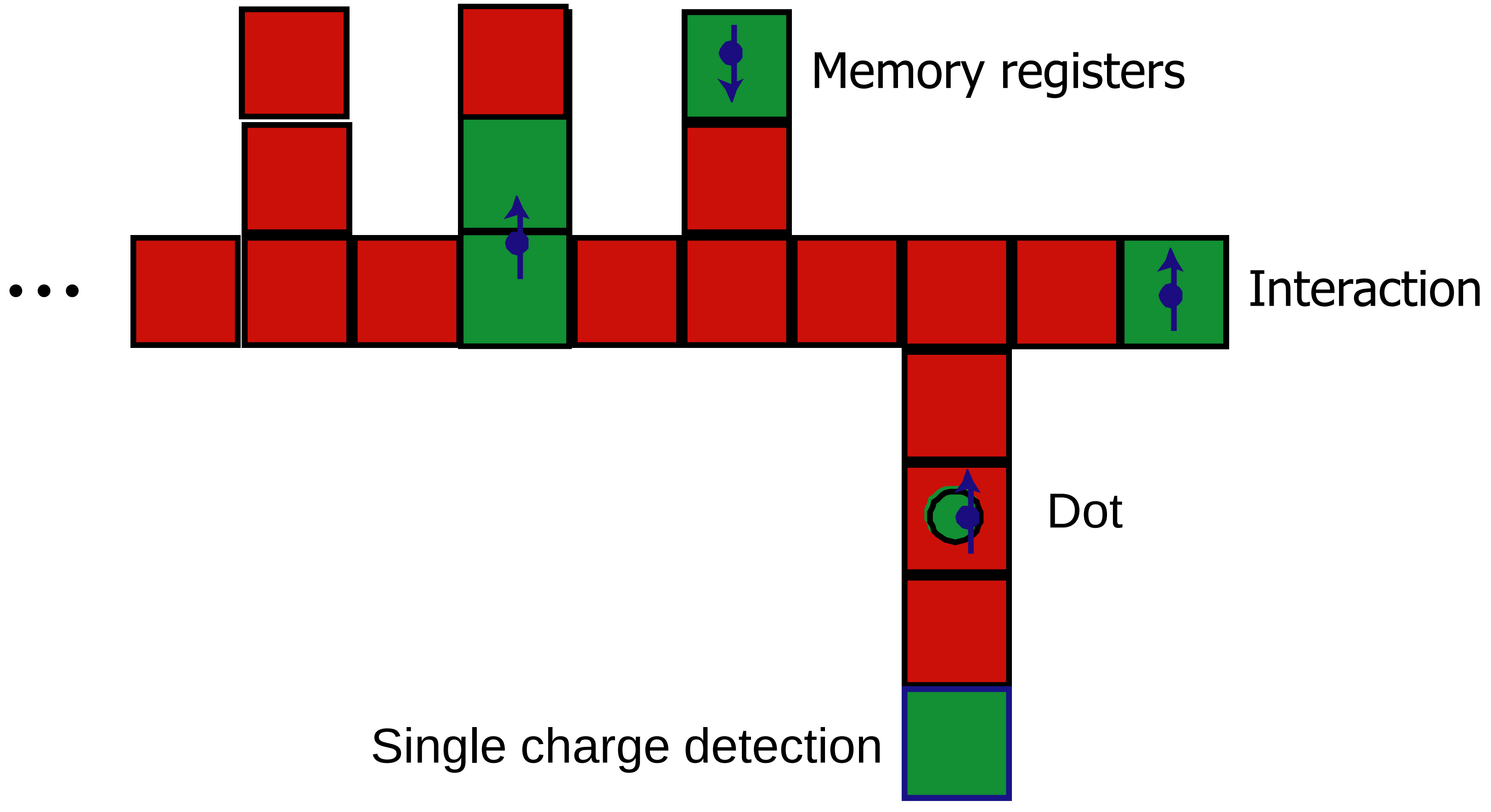

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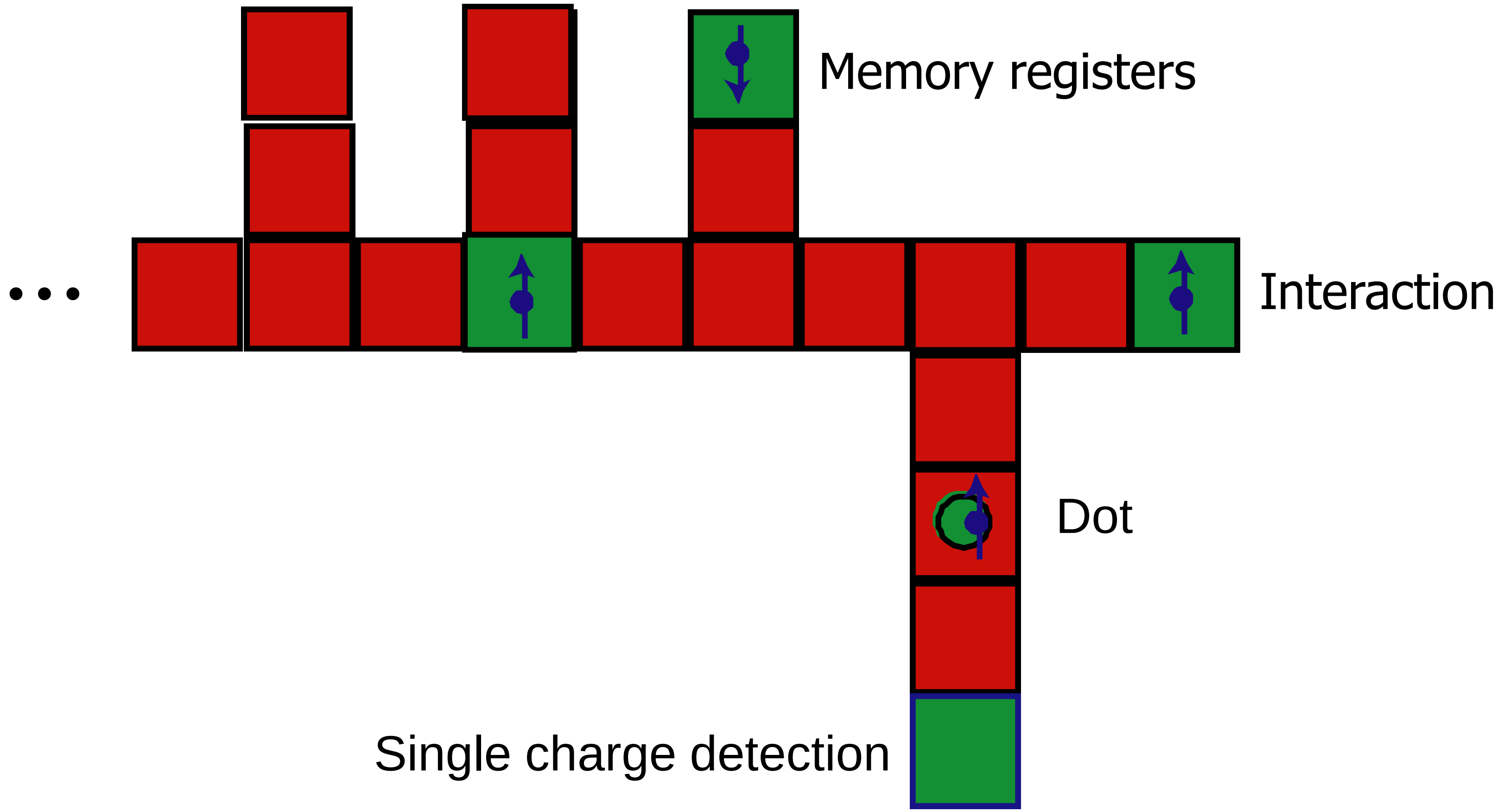

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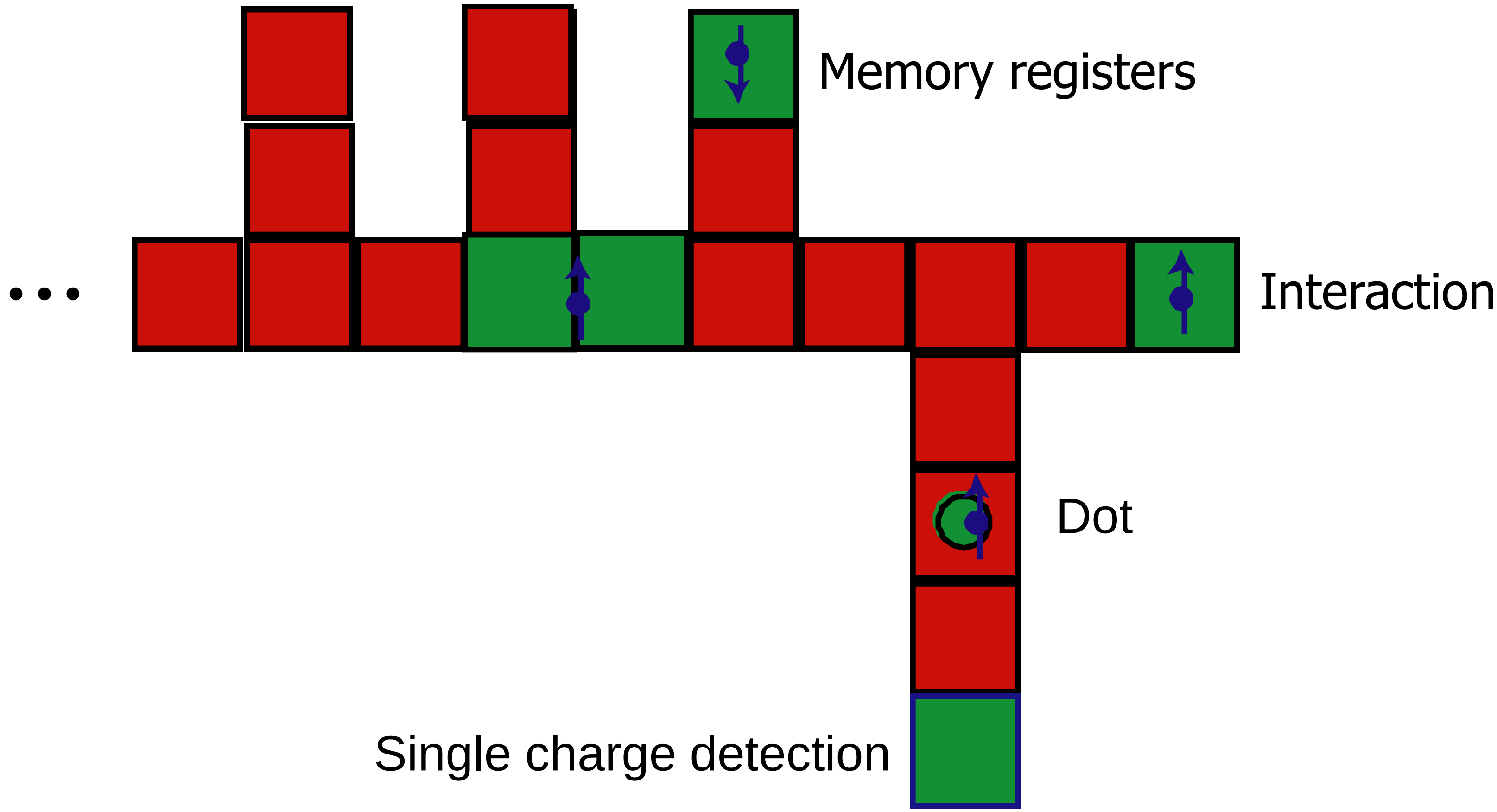

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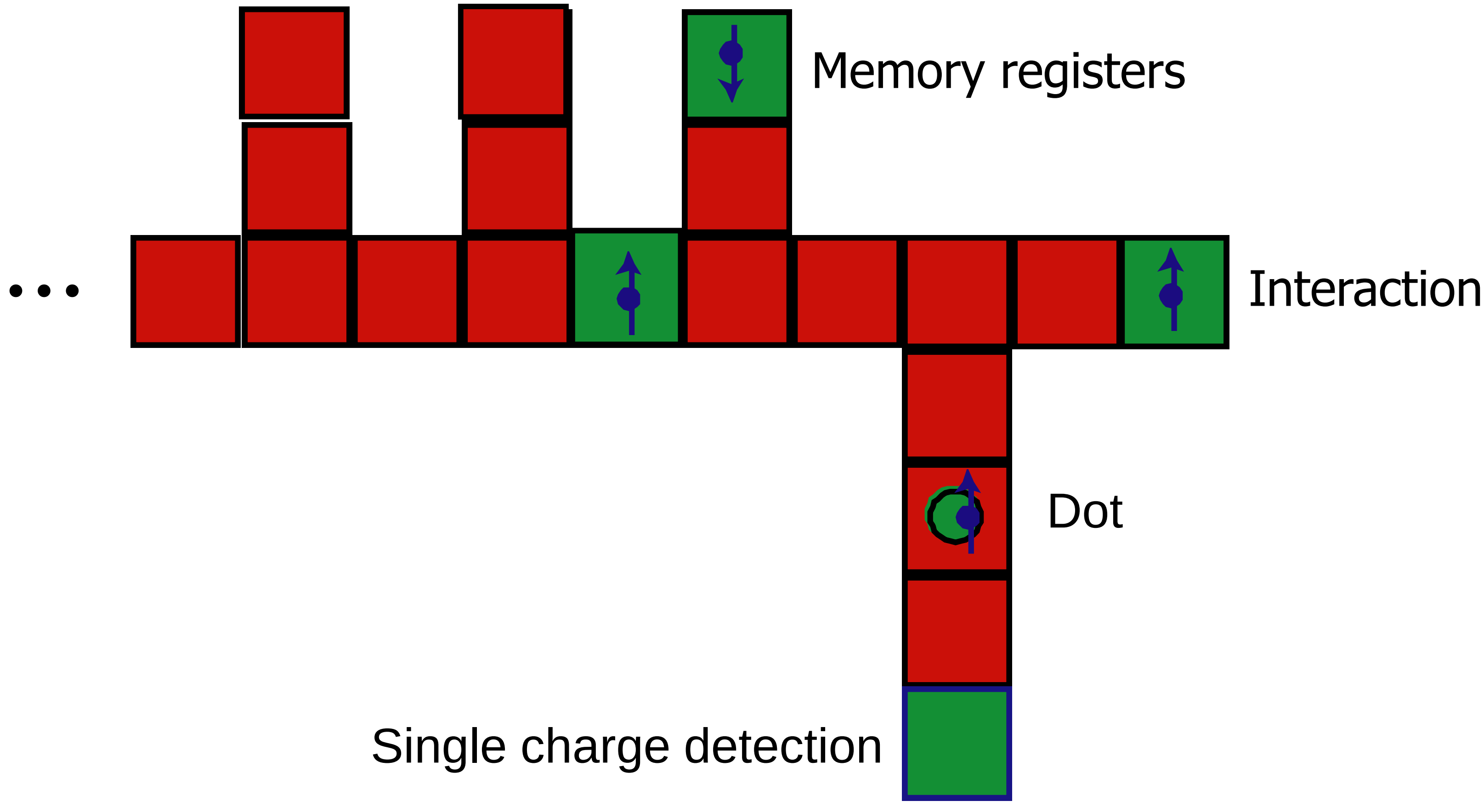

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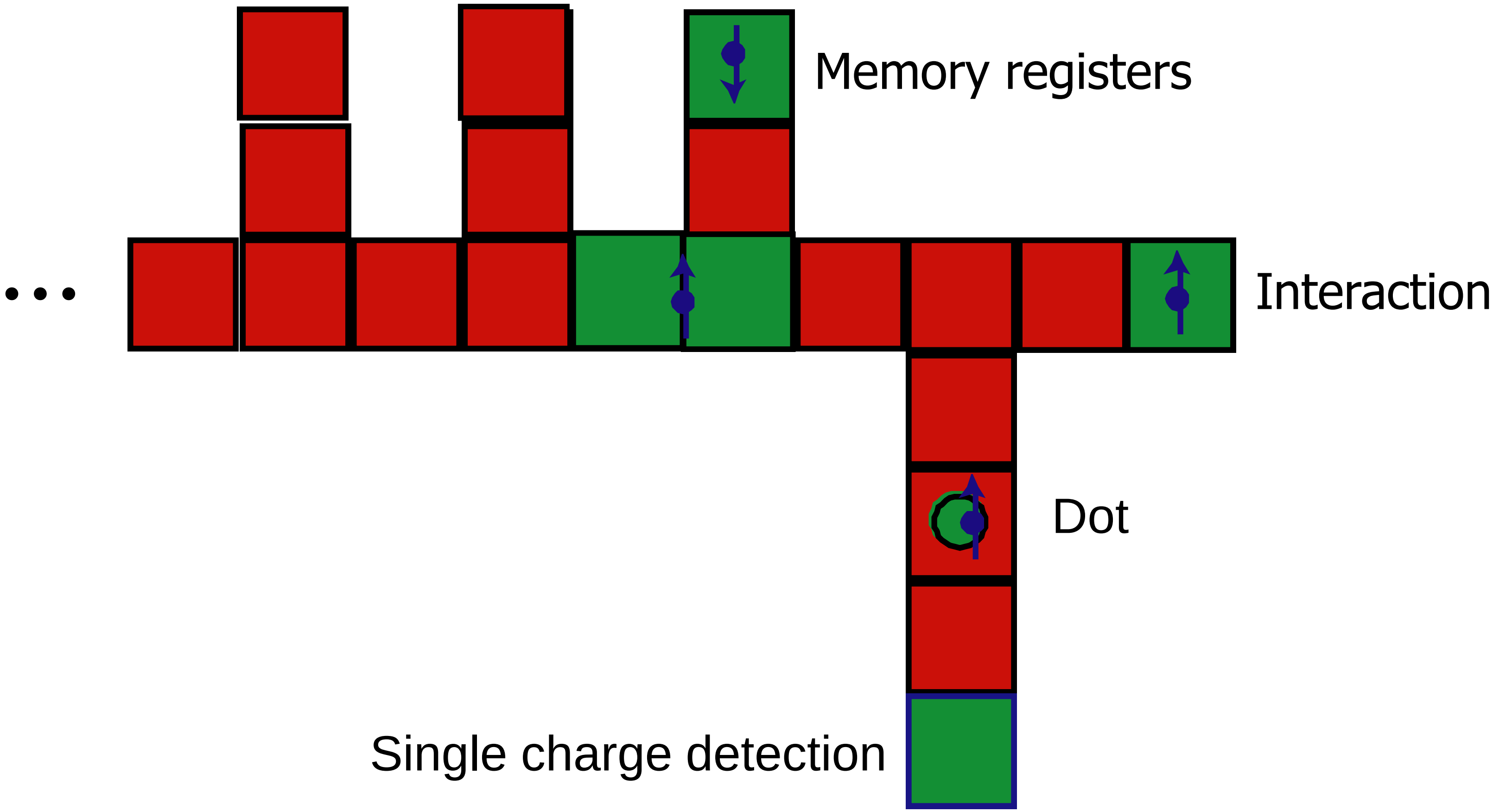

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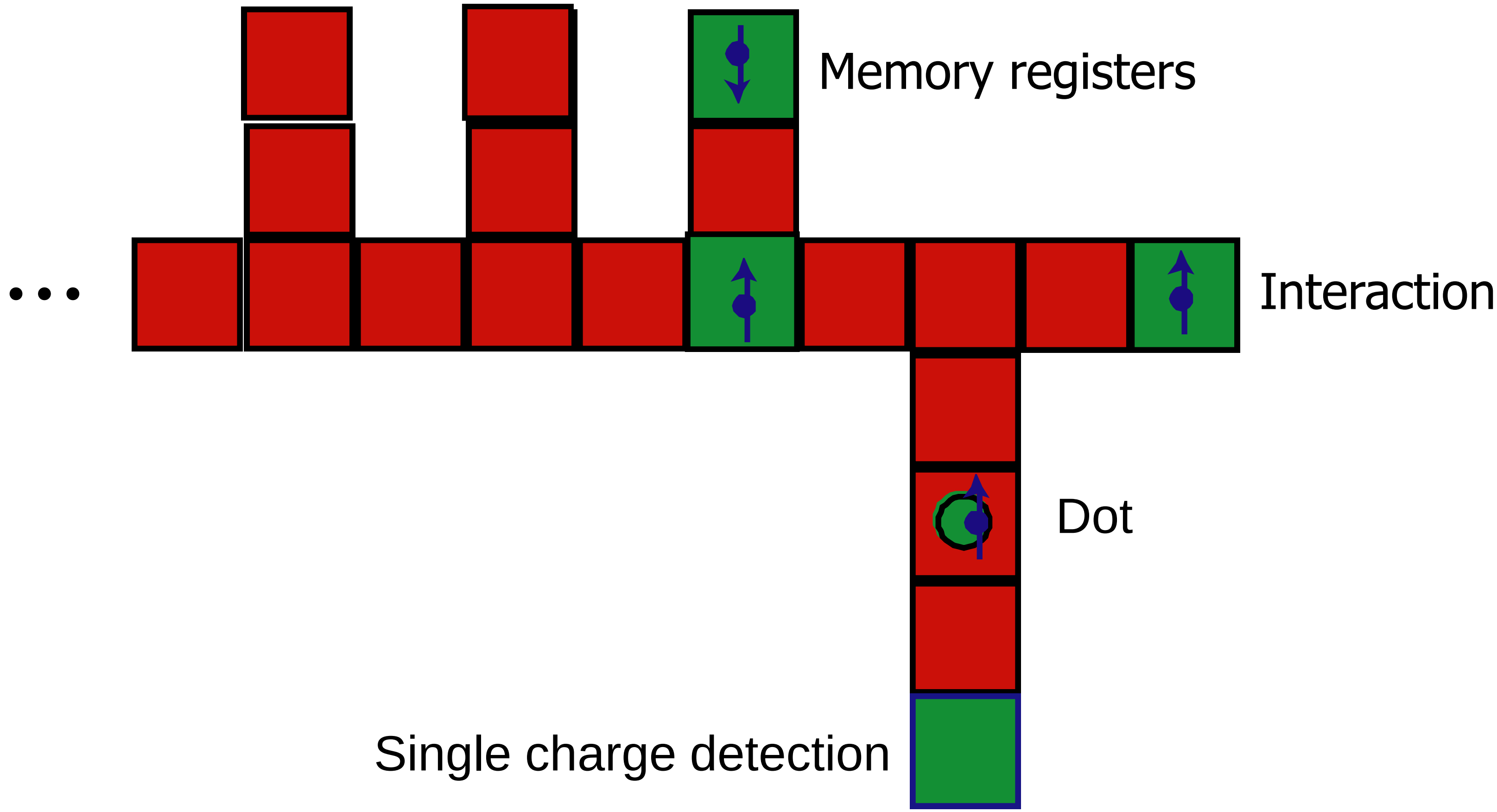

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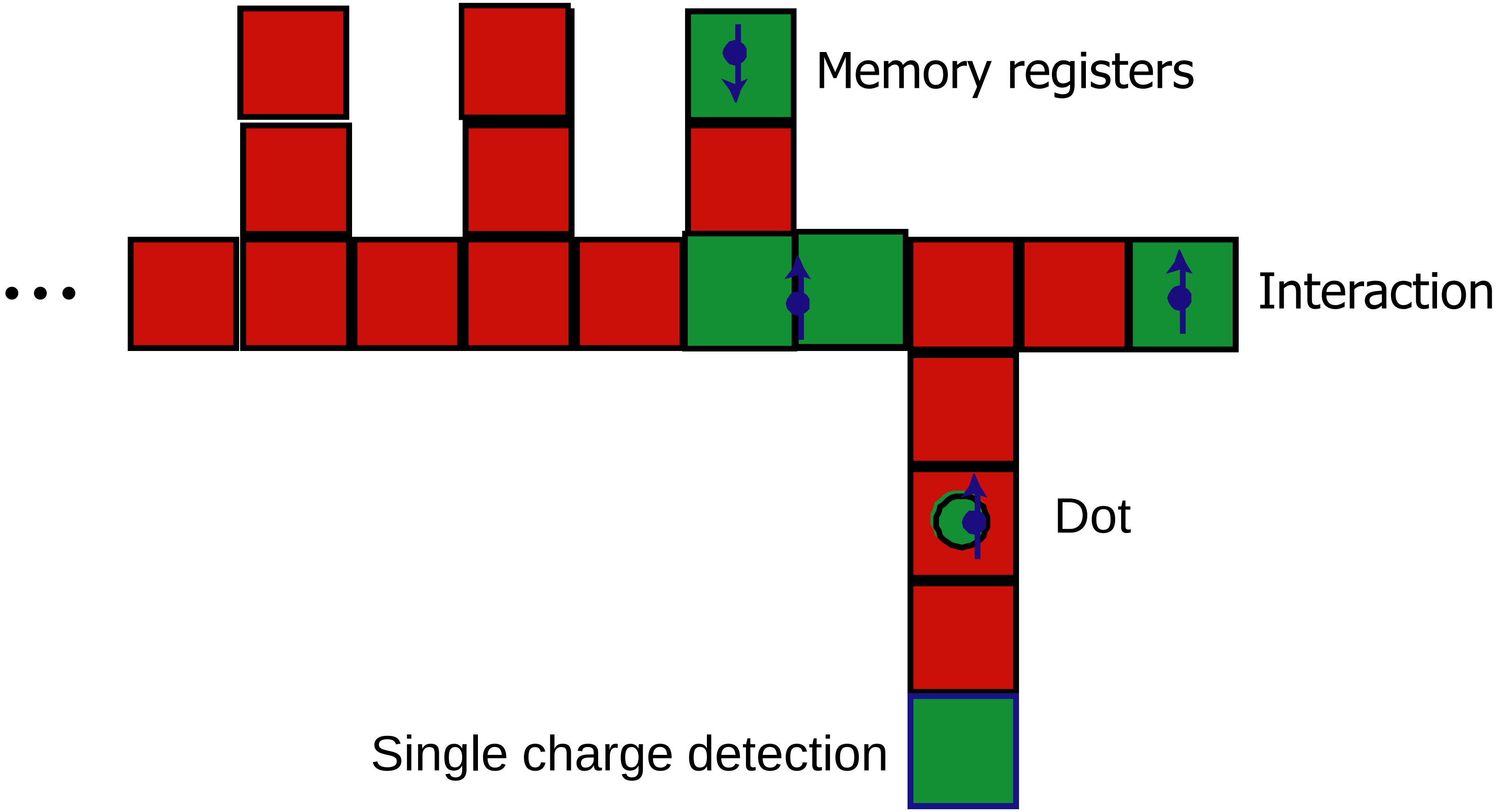

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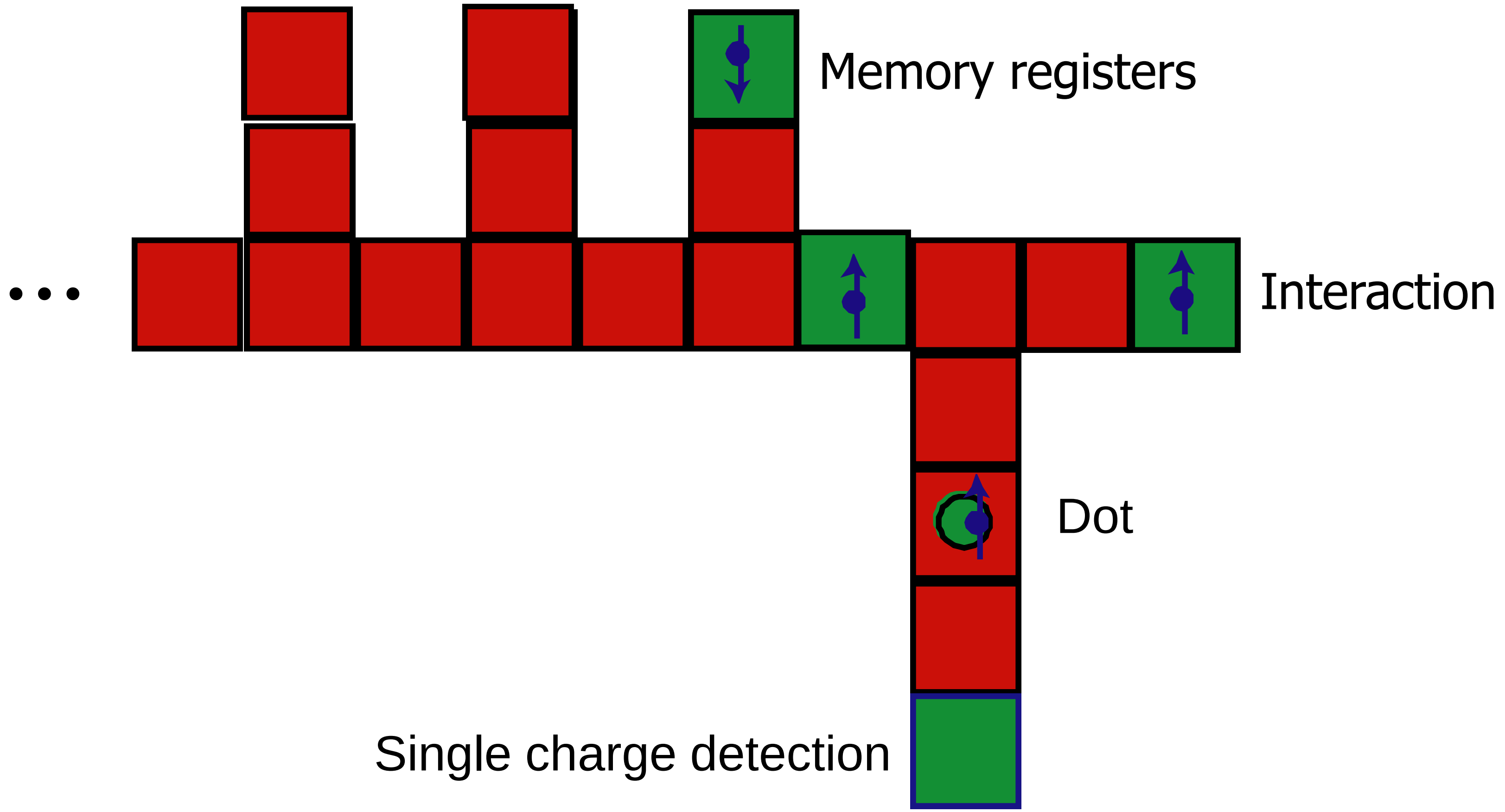

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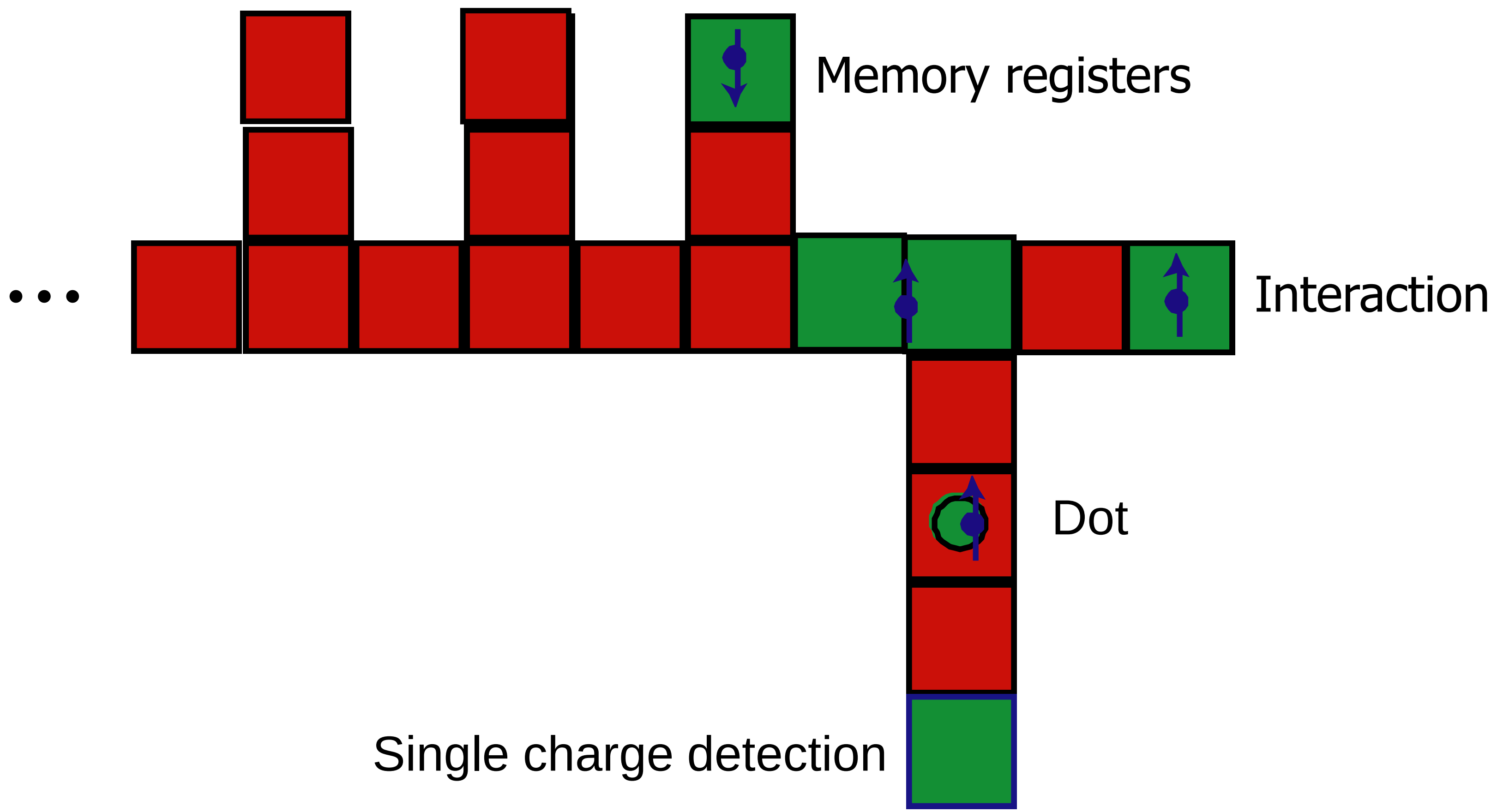

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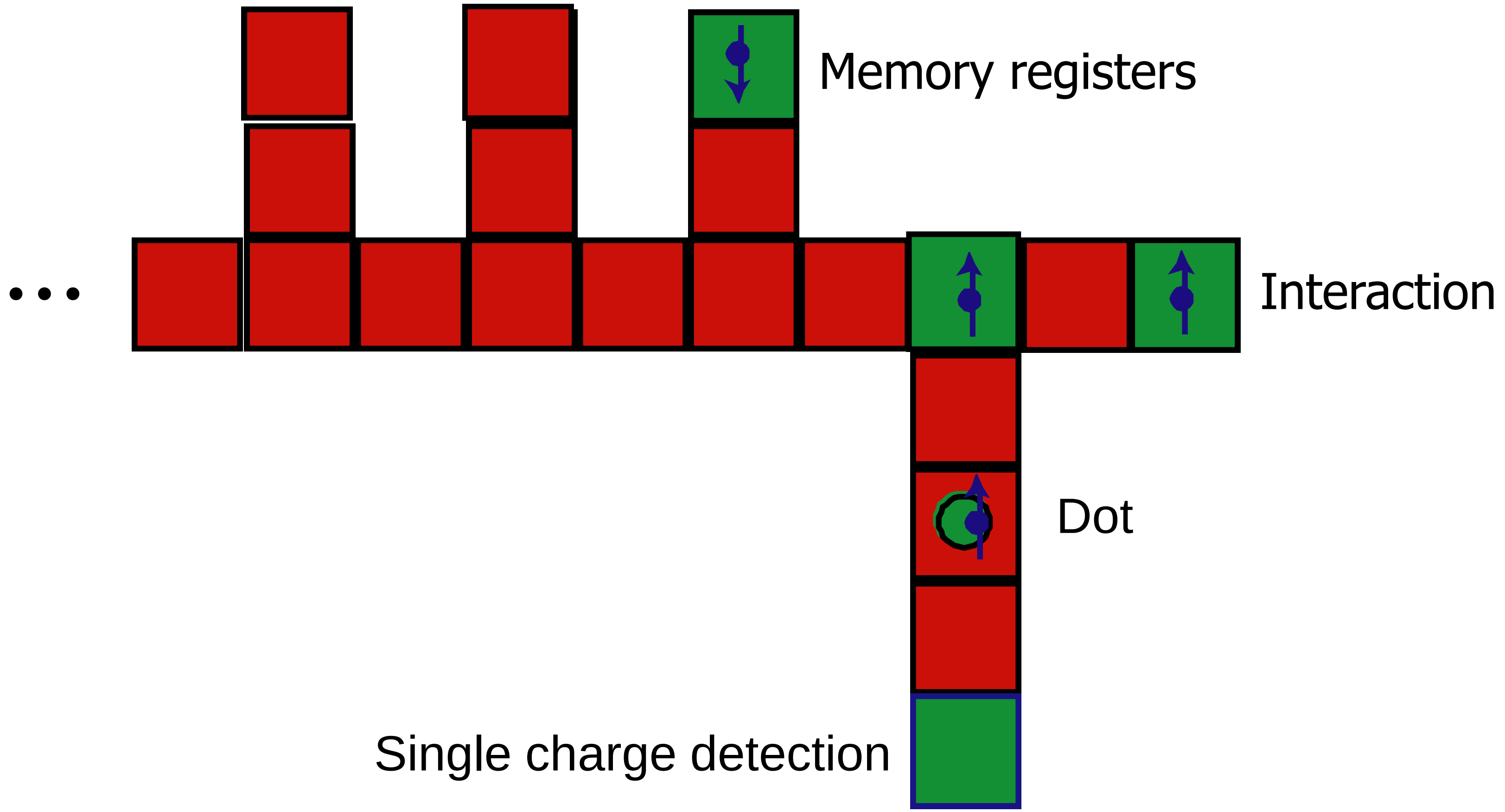

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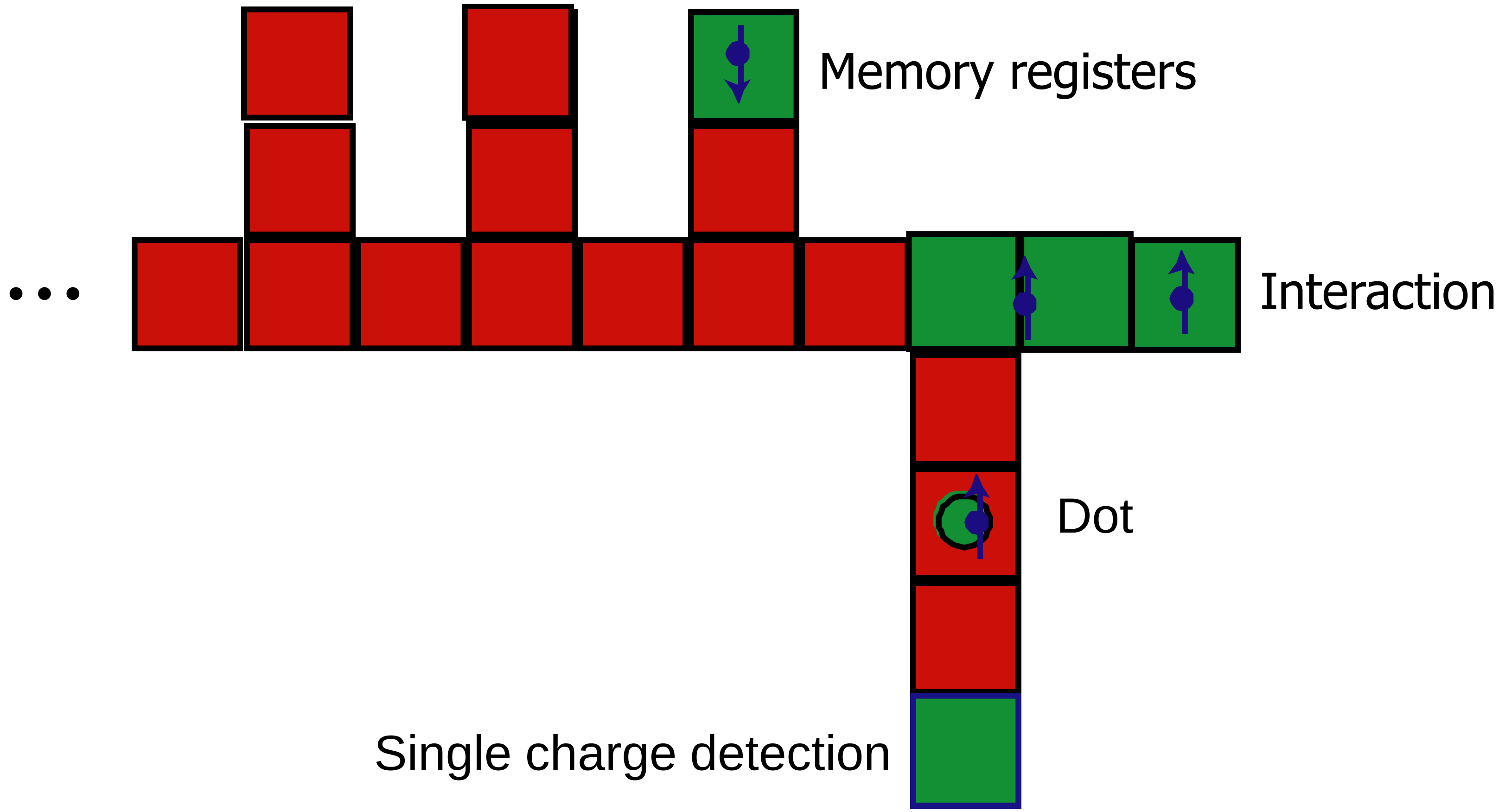

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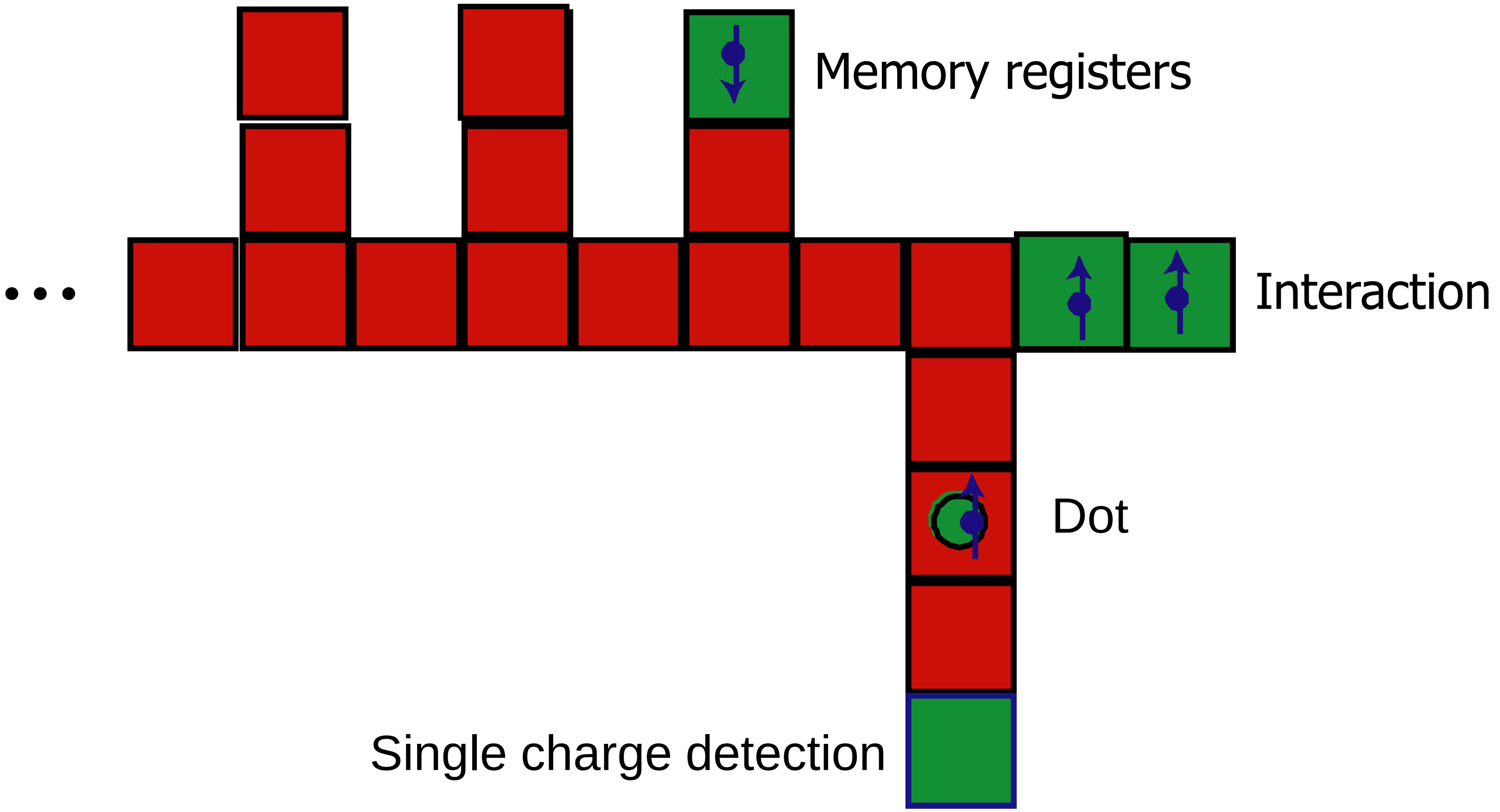

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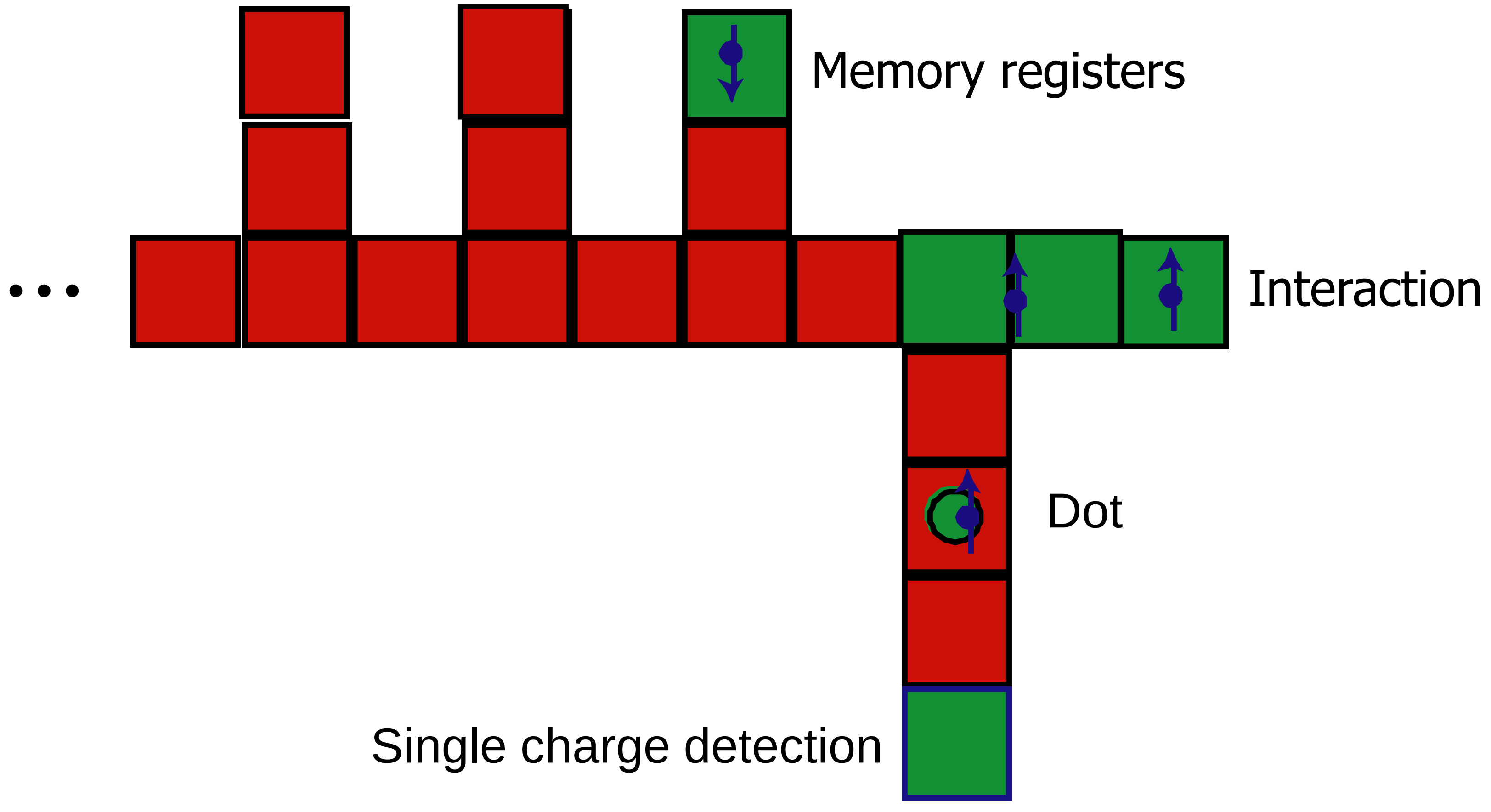

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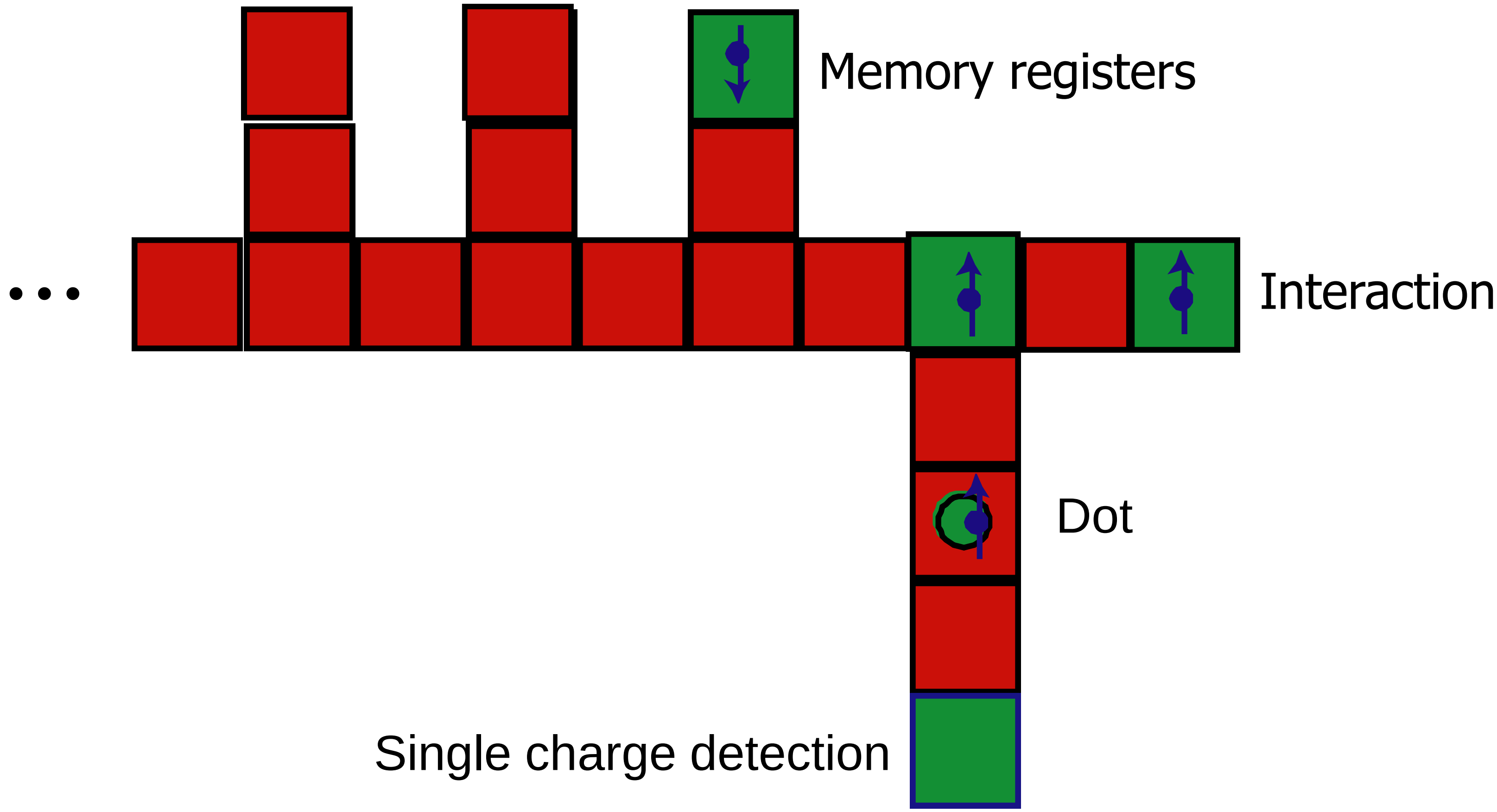

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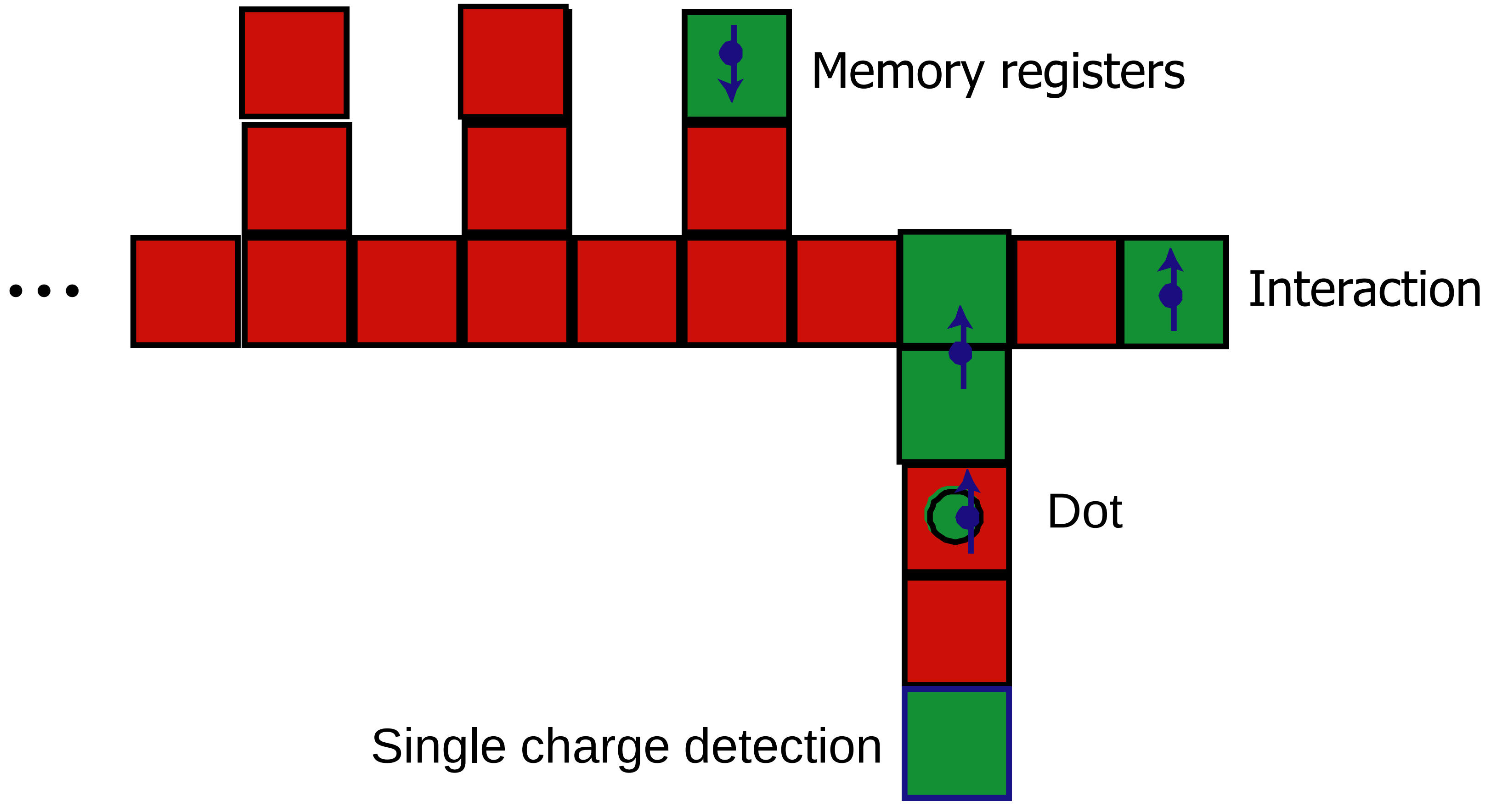

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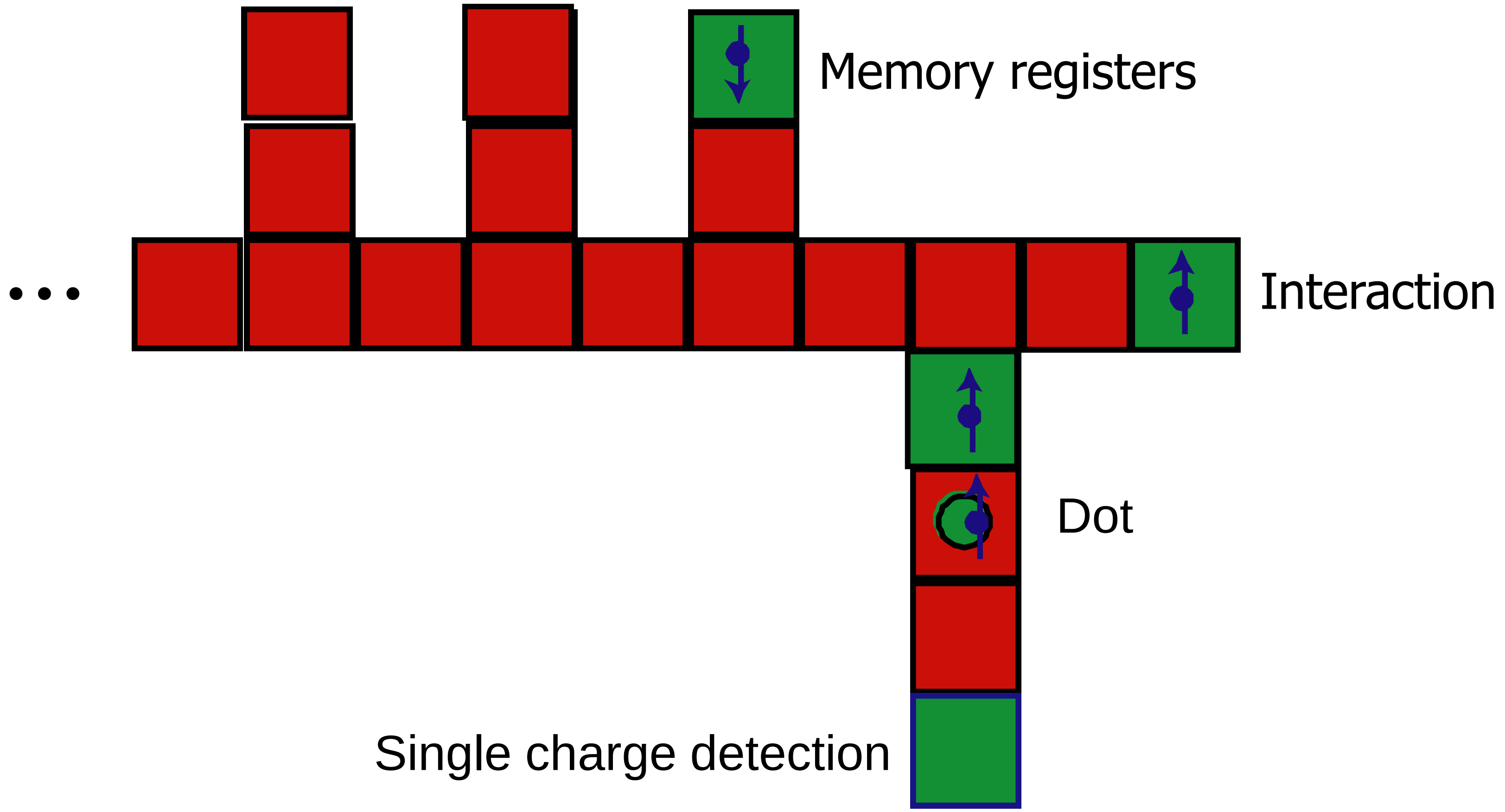

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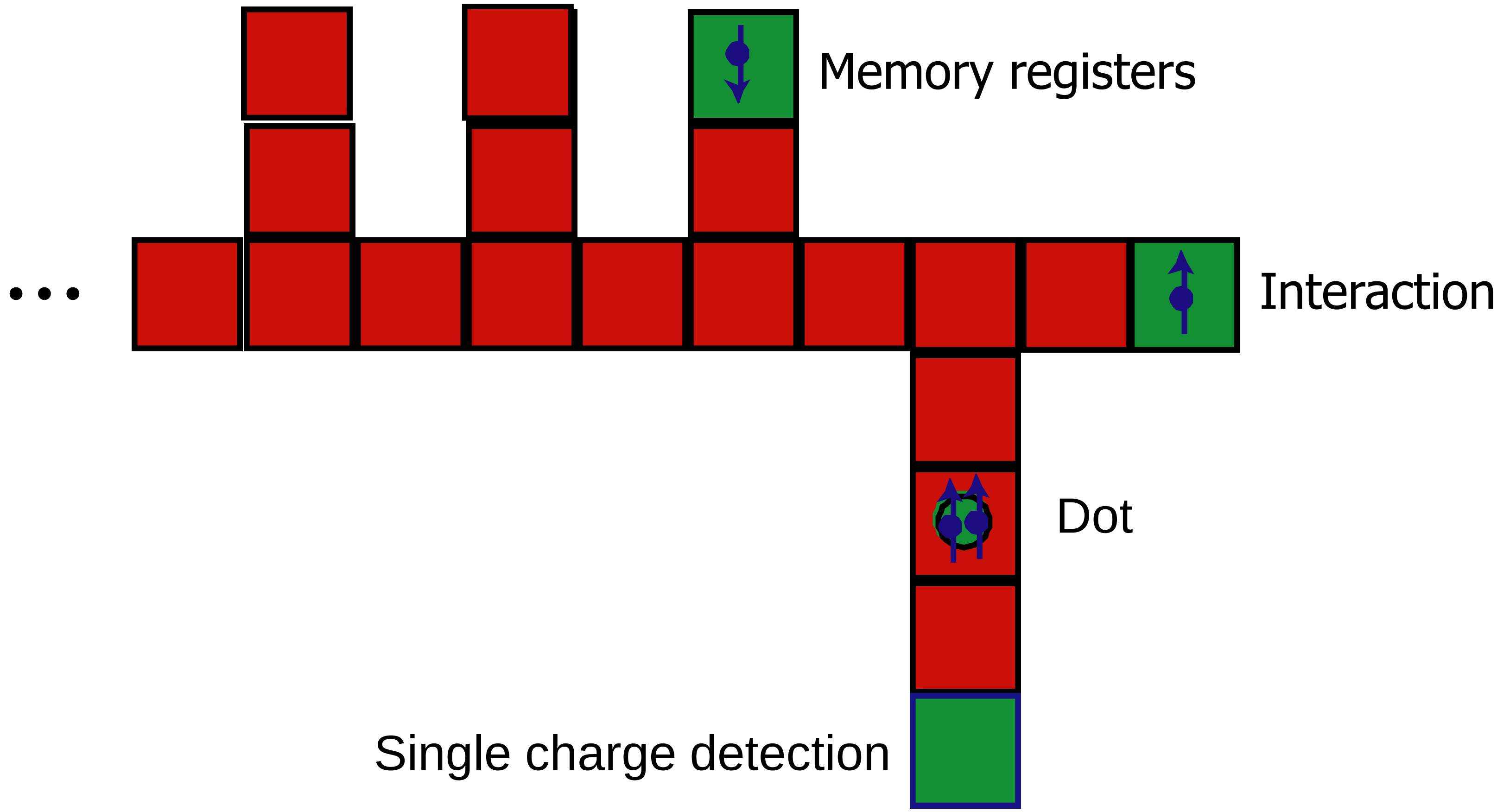

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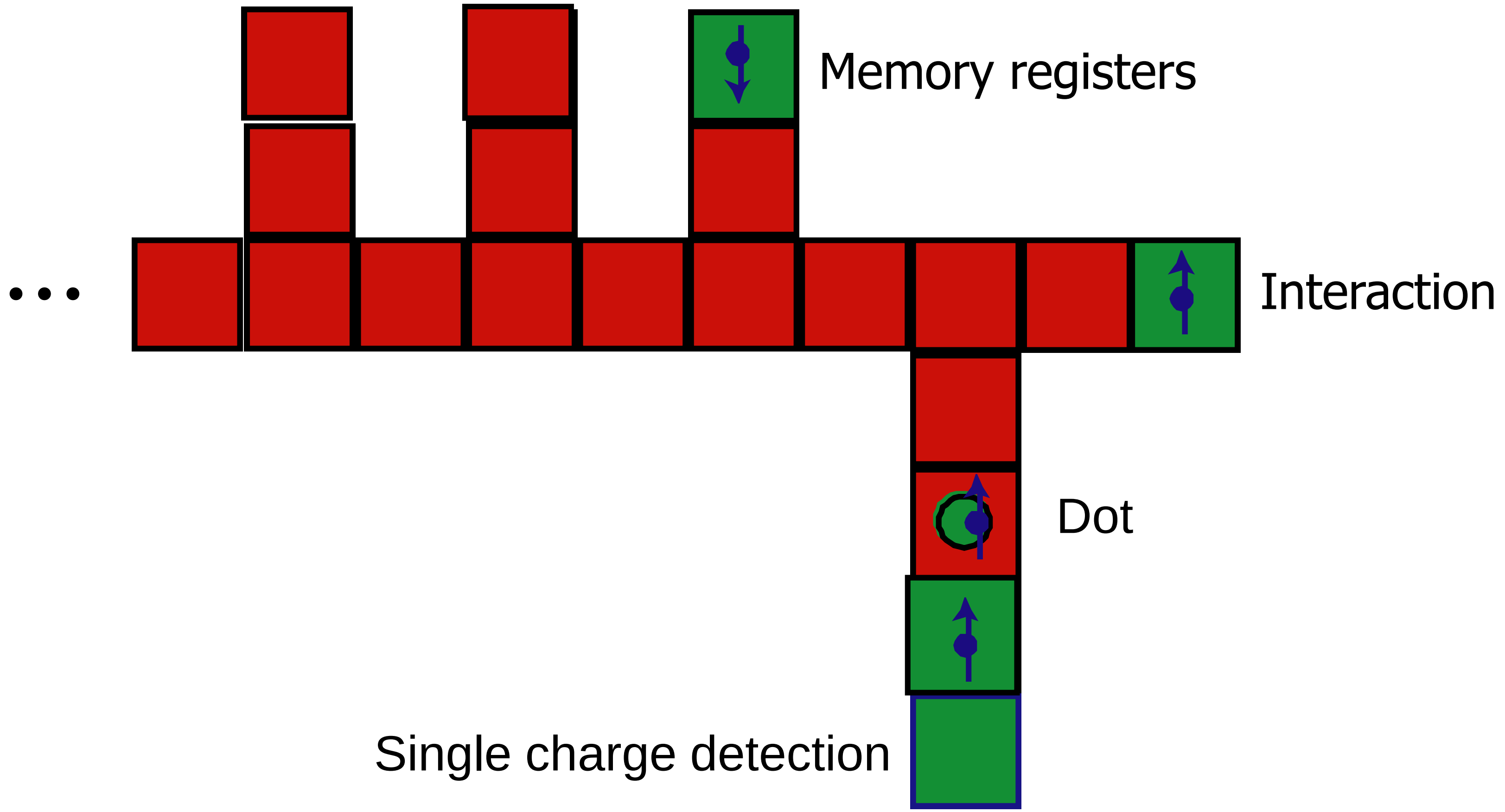

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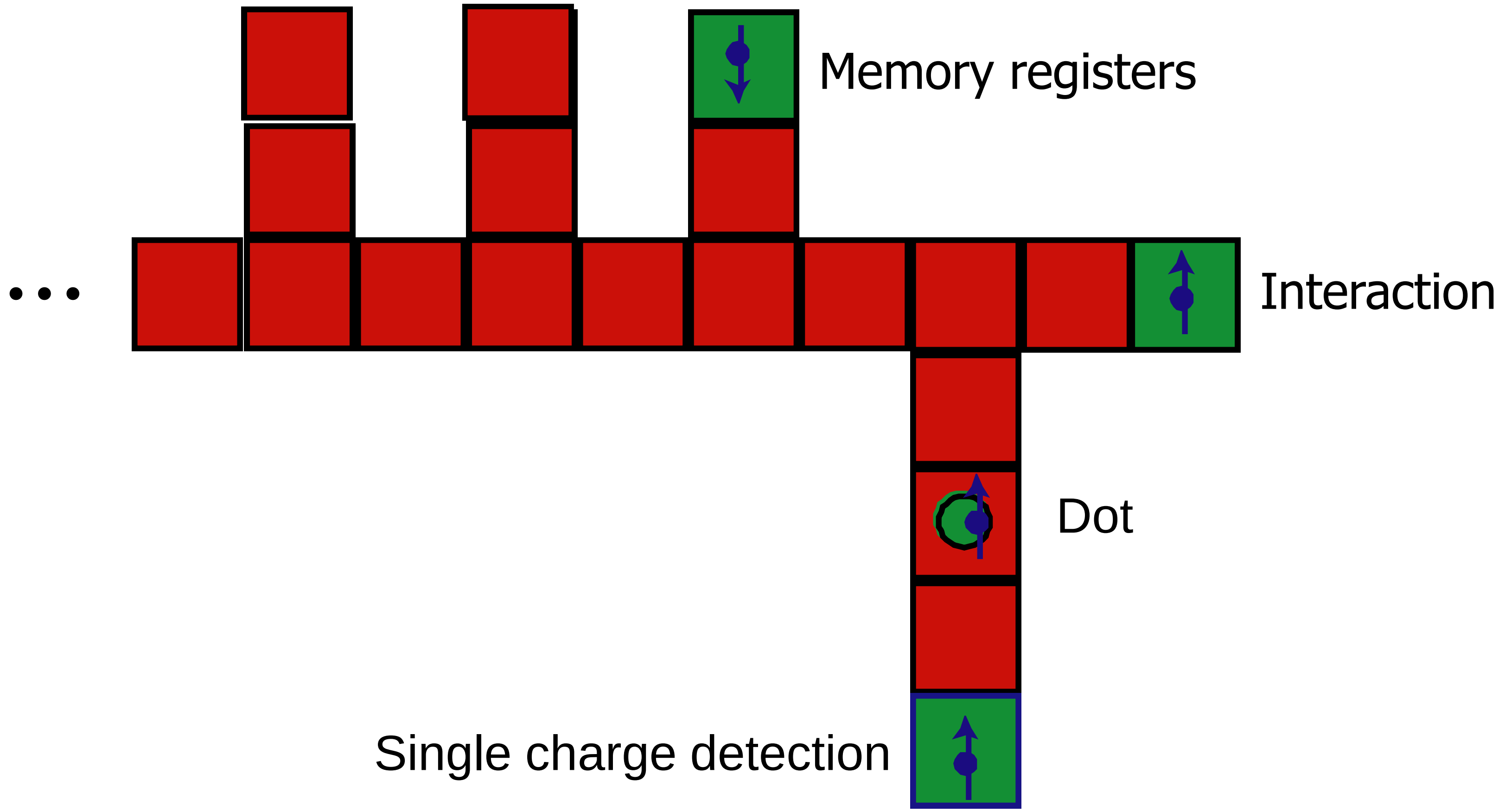
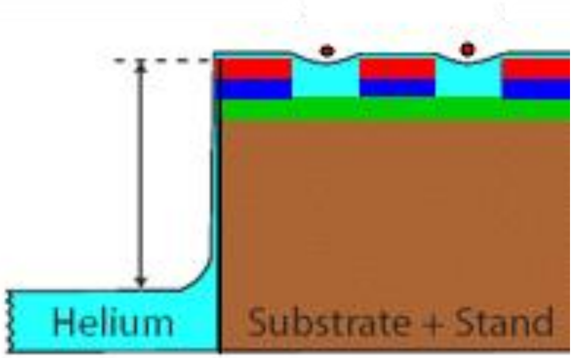
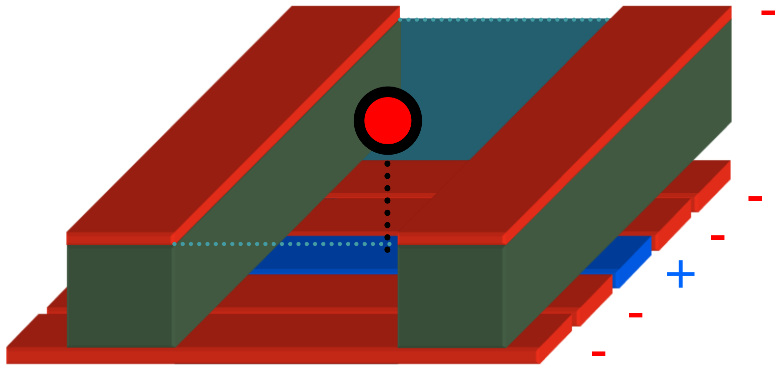
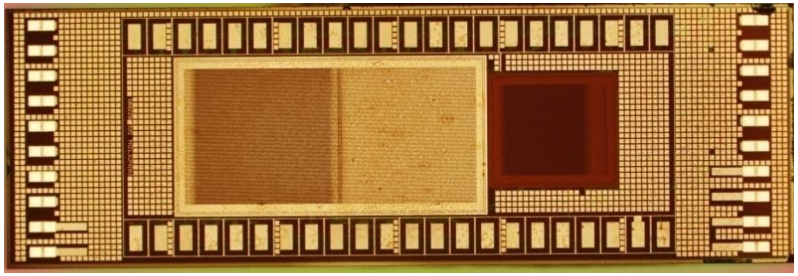


The physical system:

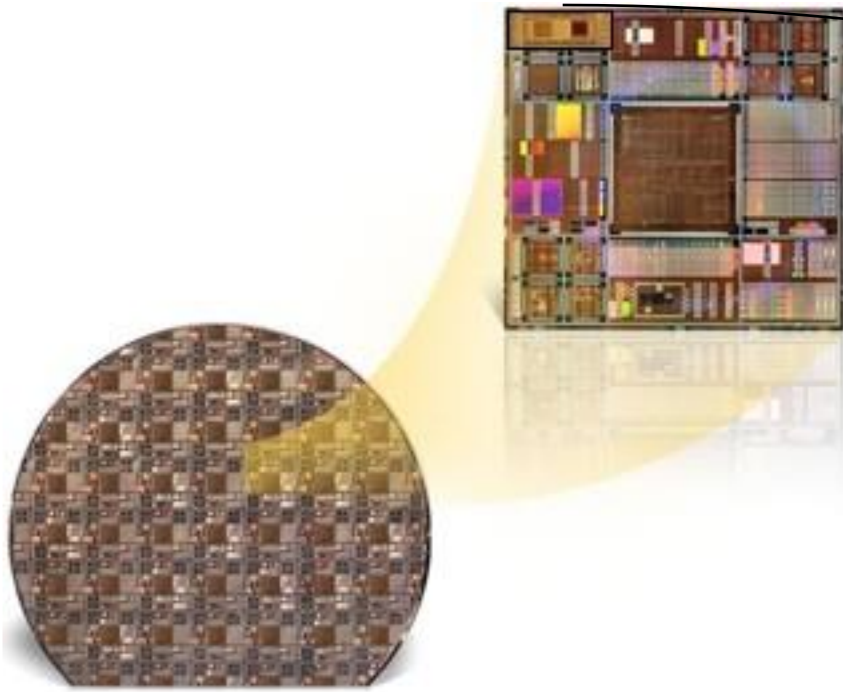
Efficient electron transport on superfluid helium channels with silicon integrated circuits

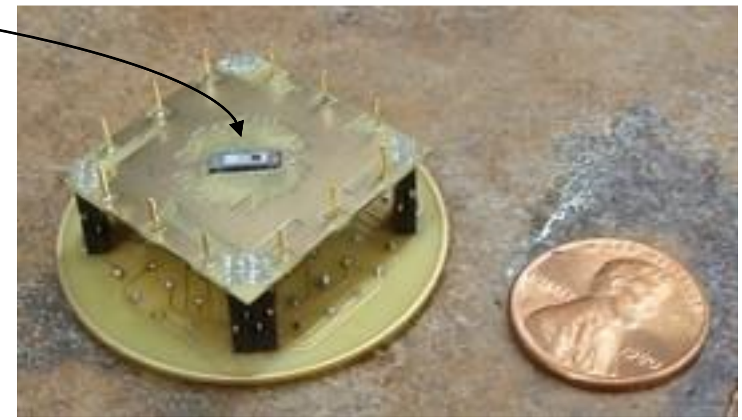


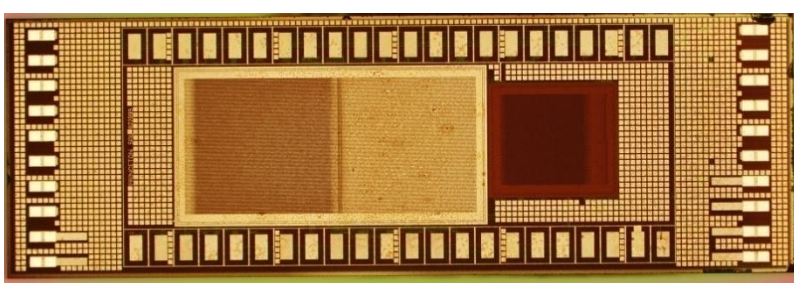




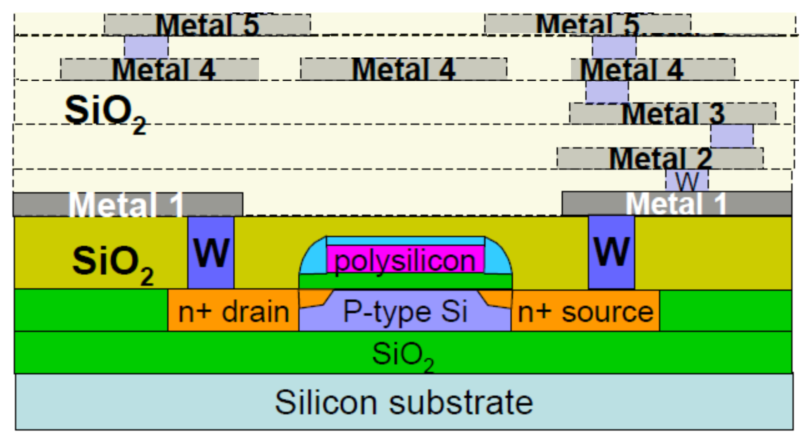
Multi-Project Wafer from Sandia



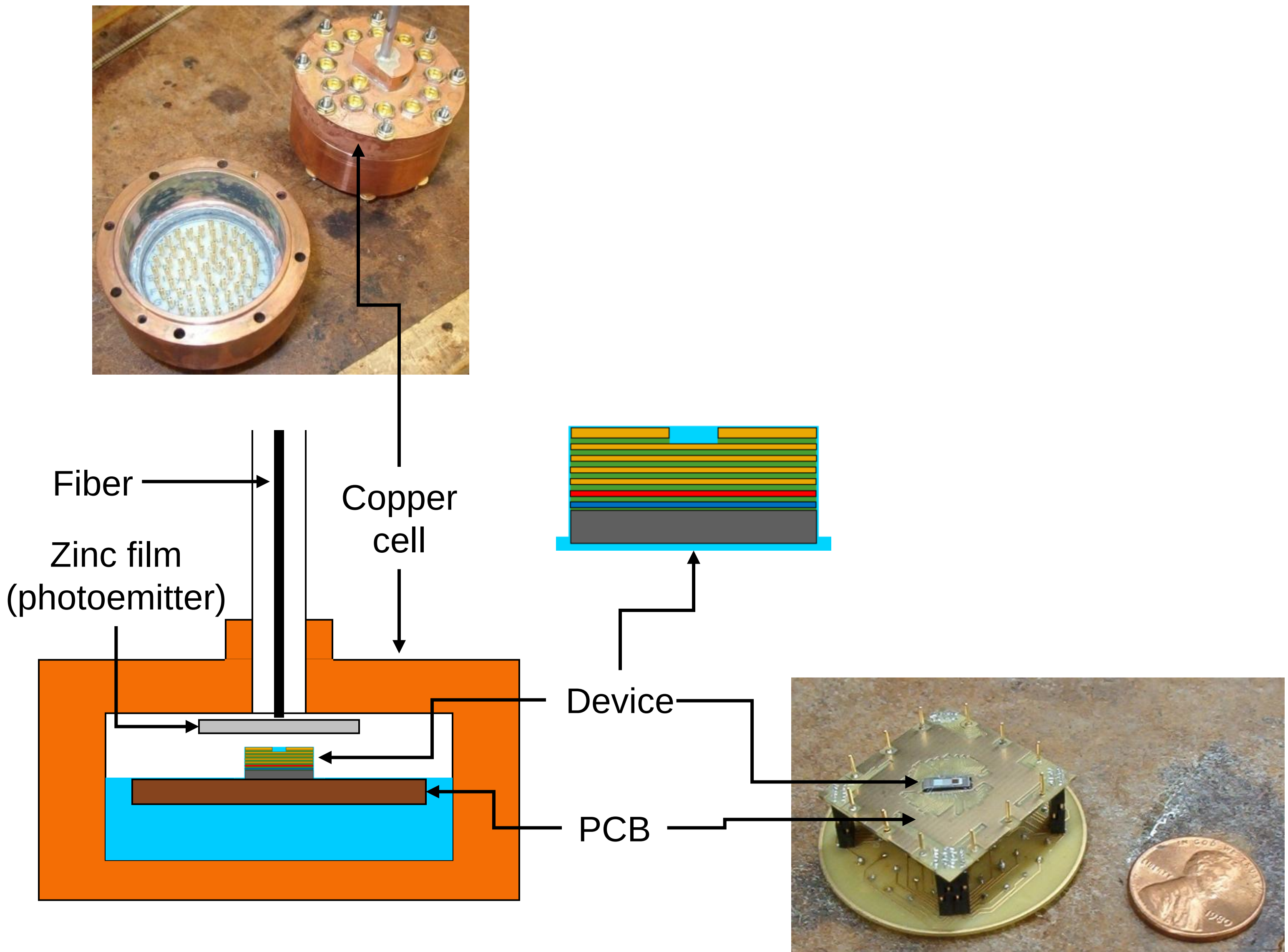




CMOS7 Process

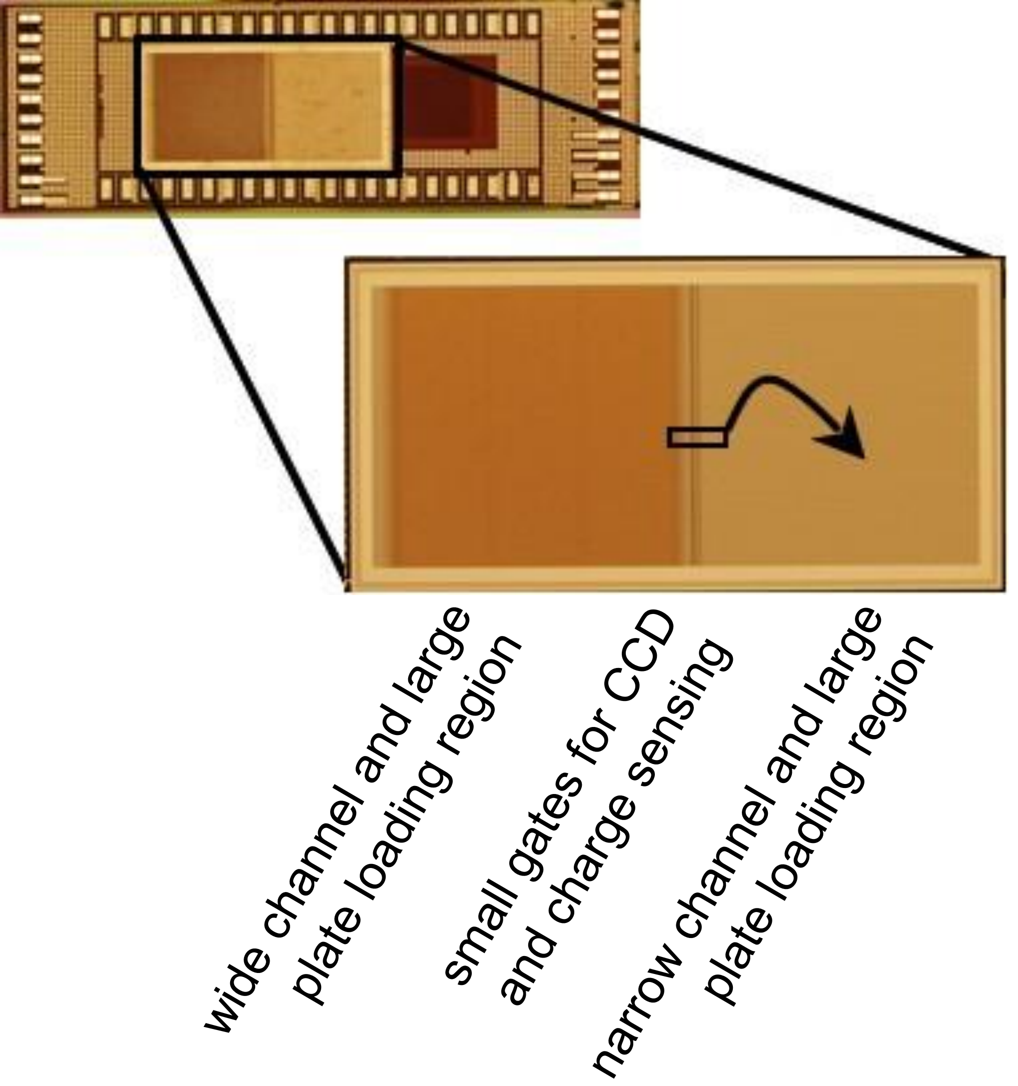


Experimental Cell



Device structure

120 horizontal channels which are 2 microns deep and vary from 3 to 6 microns wide



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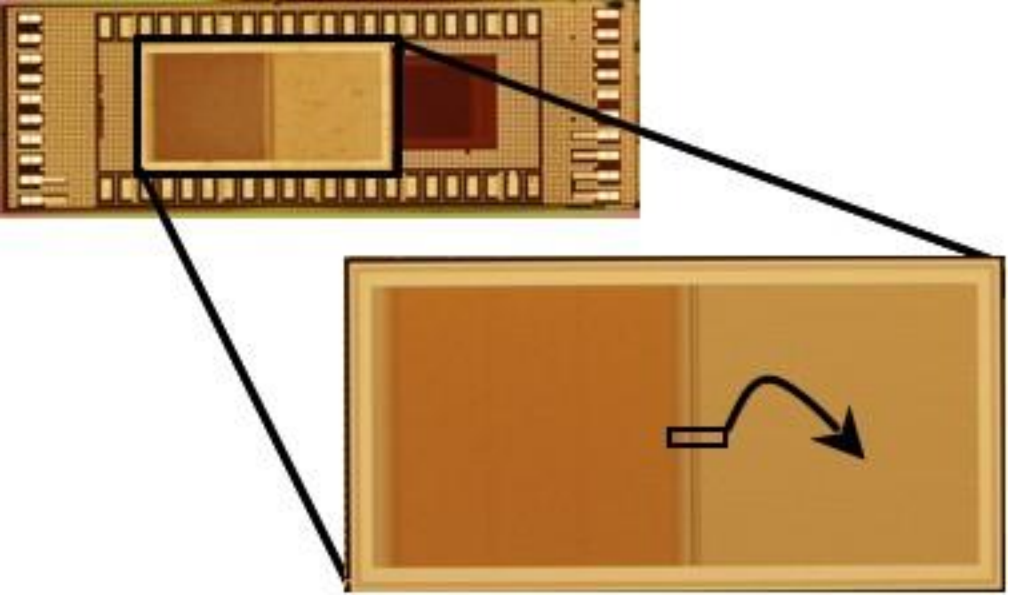
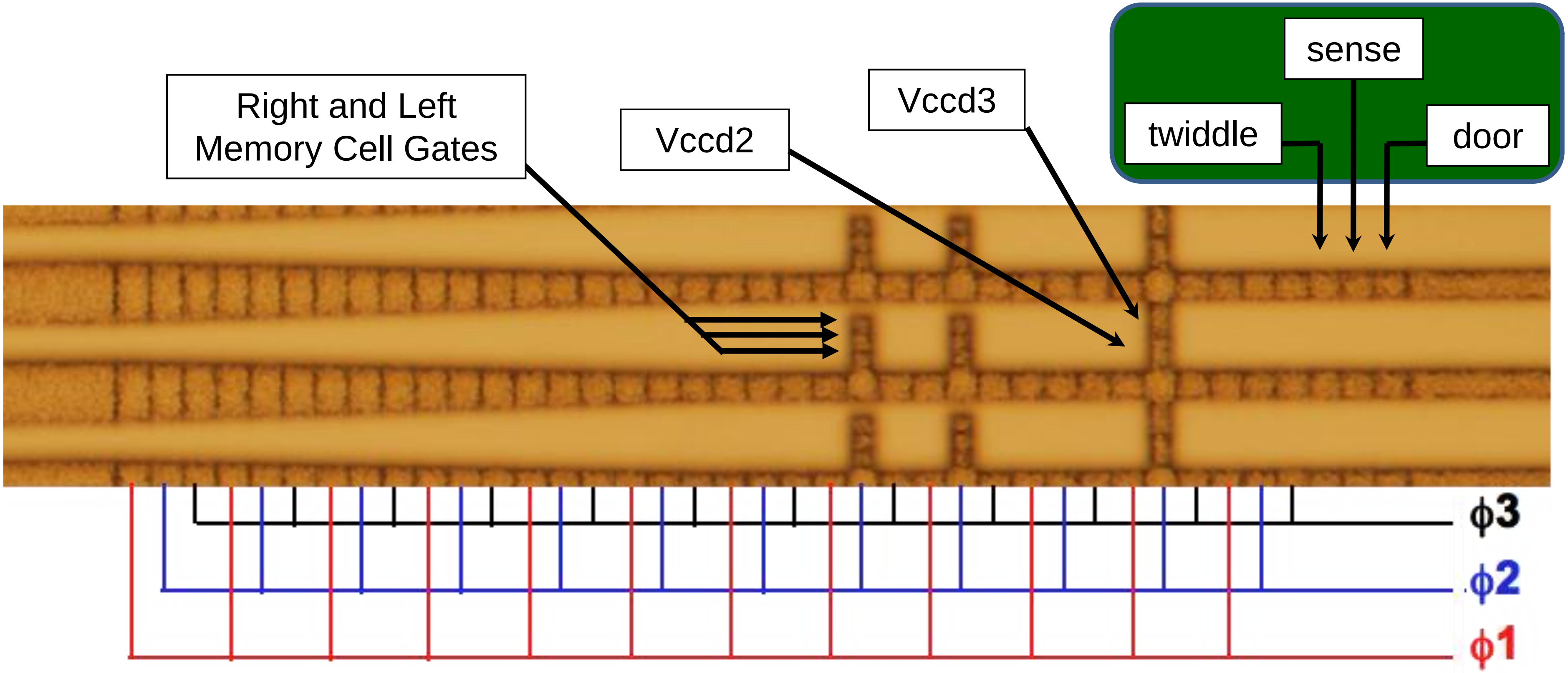
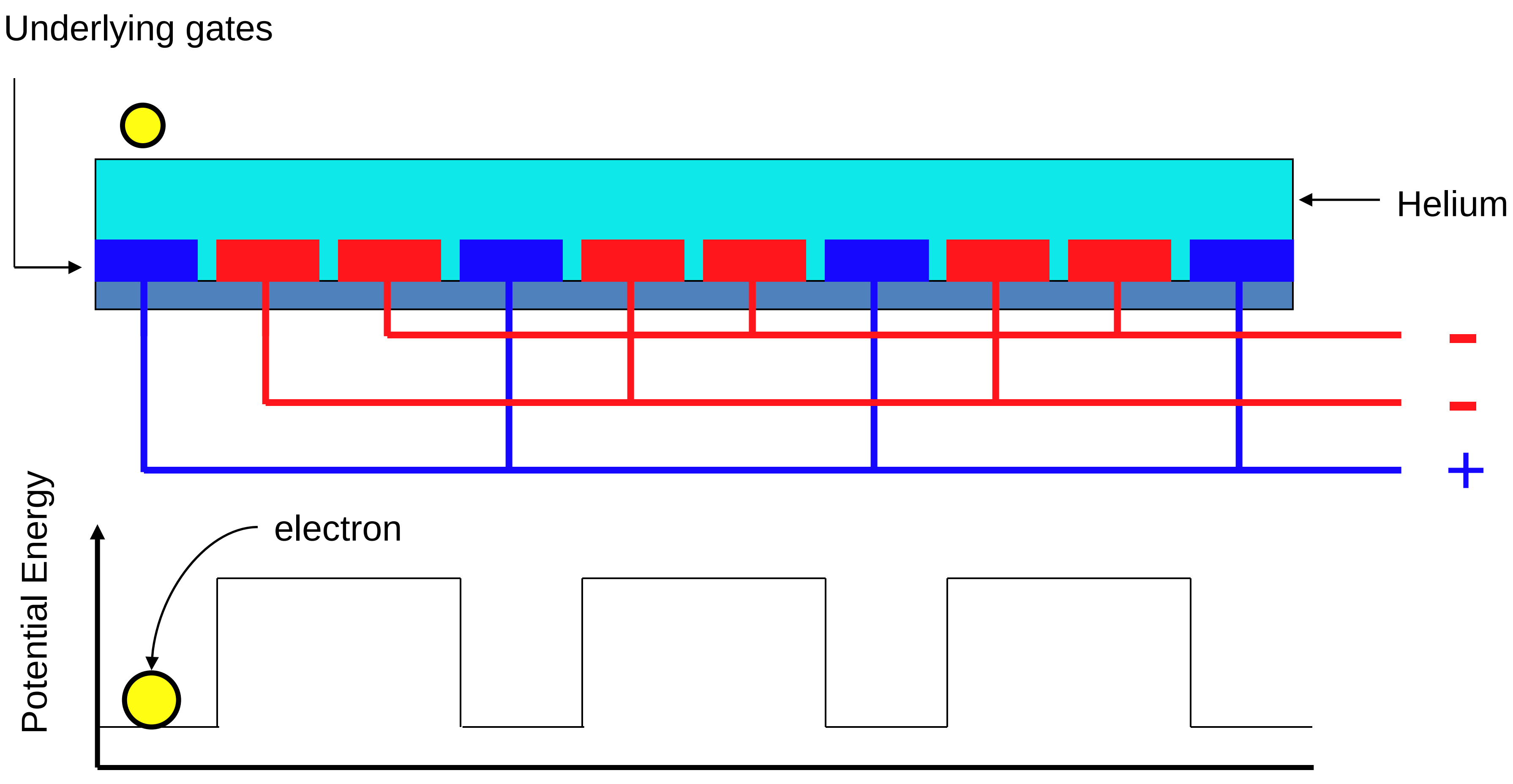




3-phase CCD

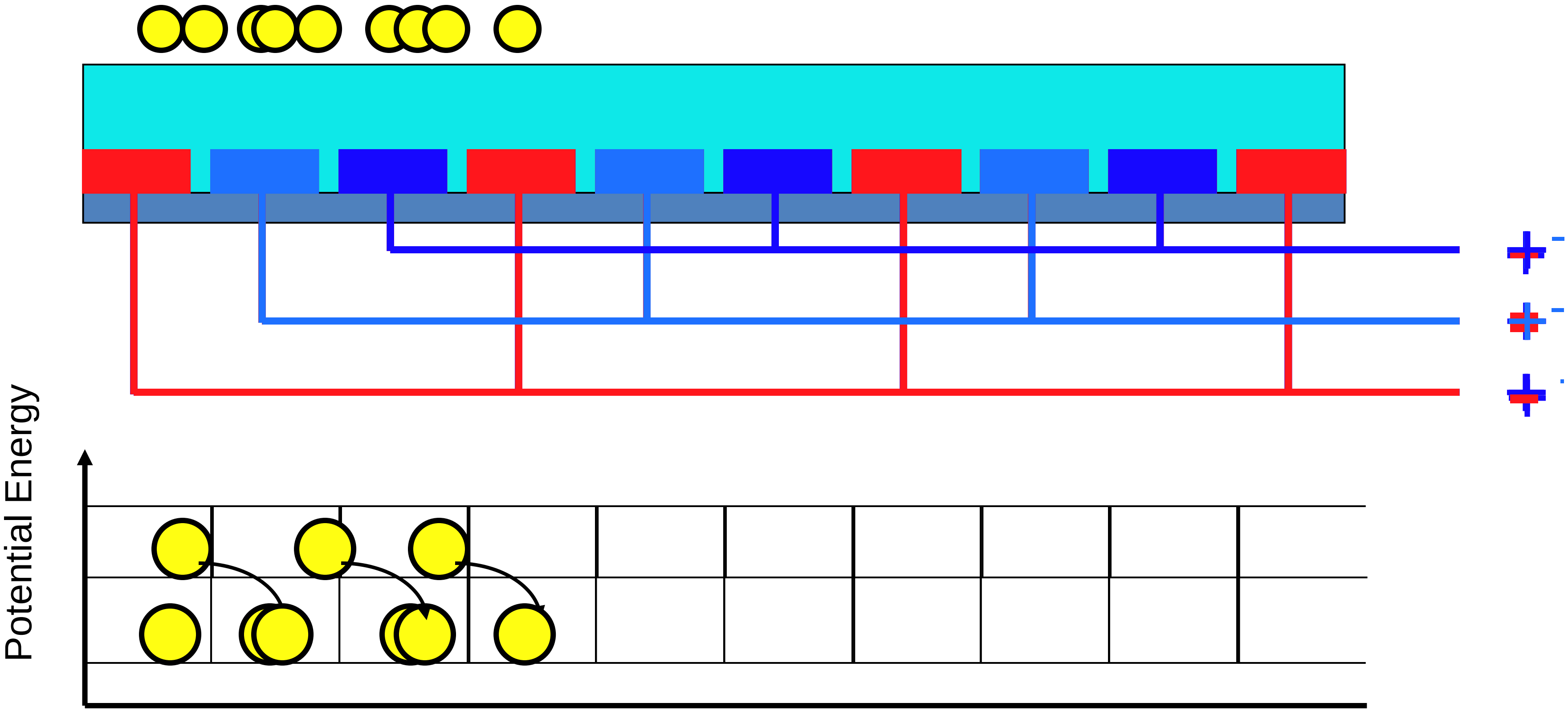
Potential



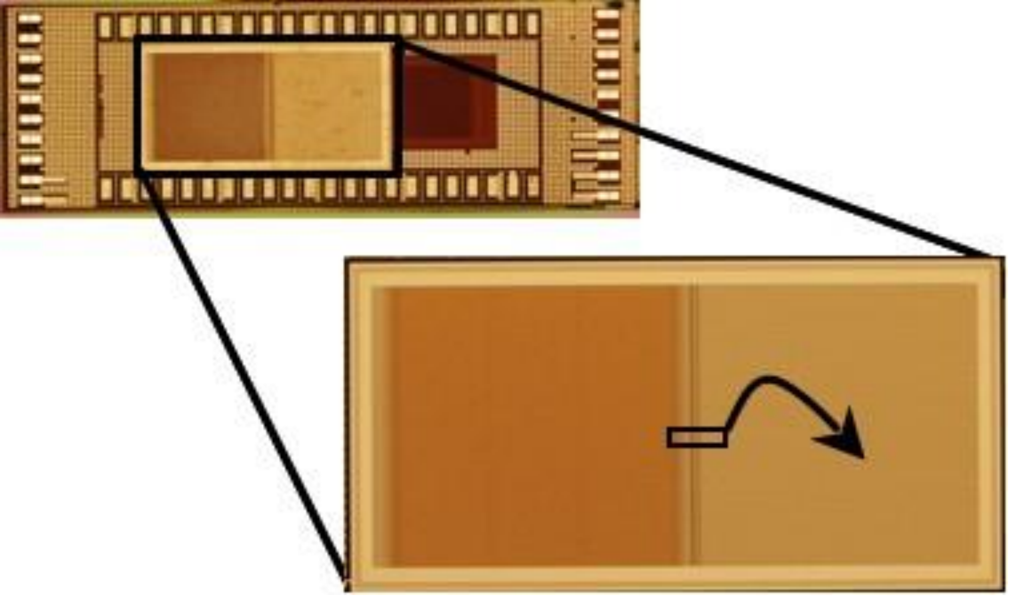
3-phase CCD

Clocking 7

Electron has moved one pixel (3 gates) to the right

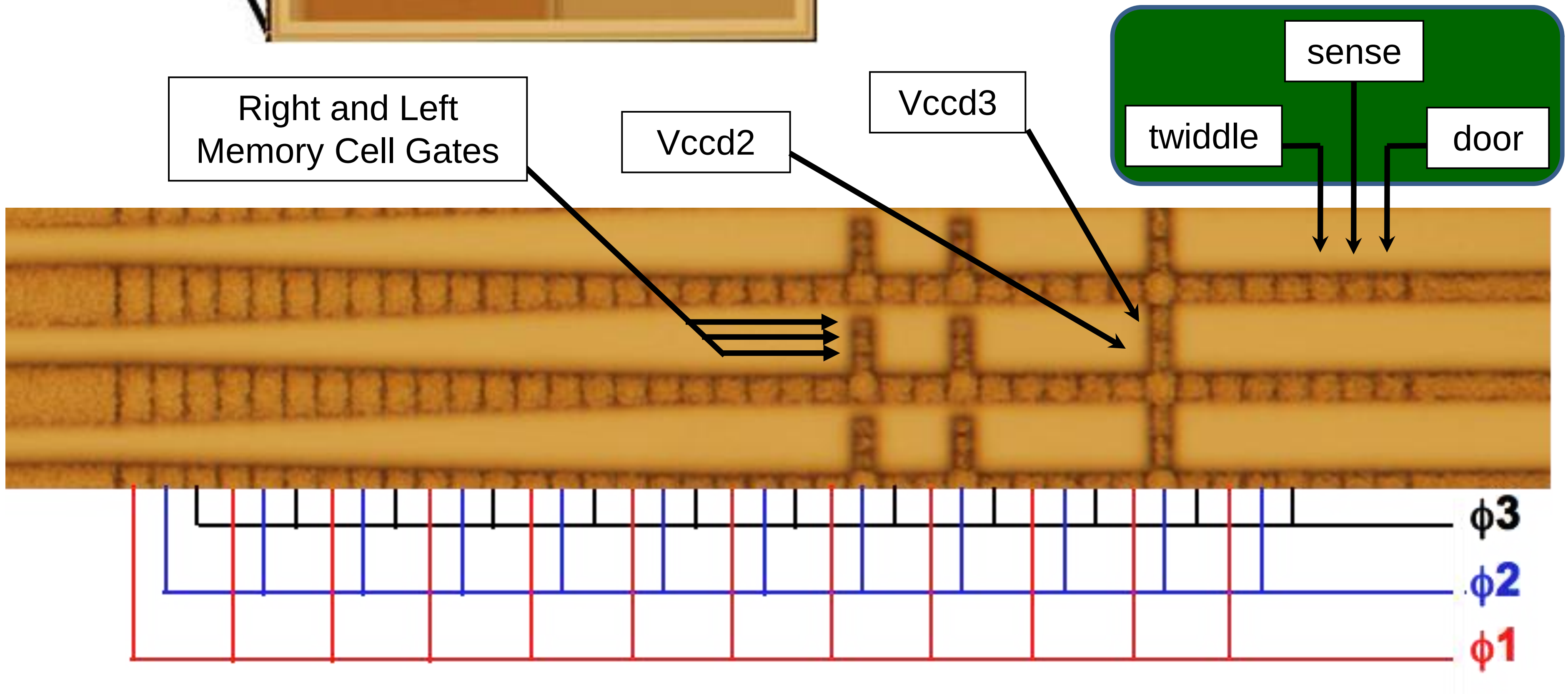


Electron Detection?

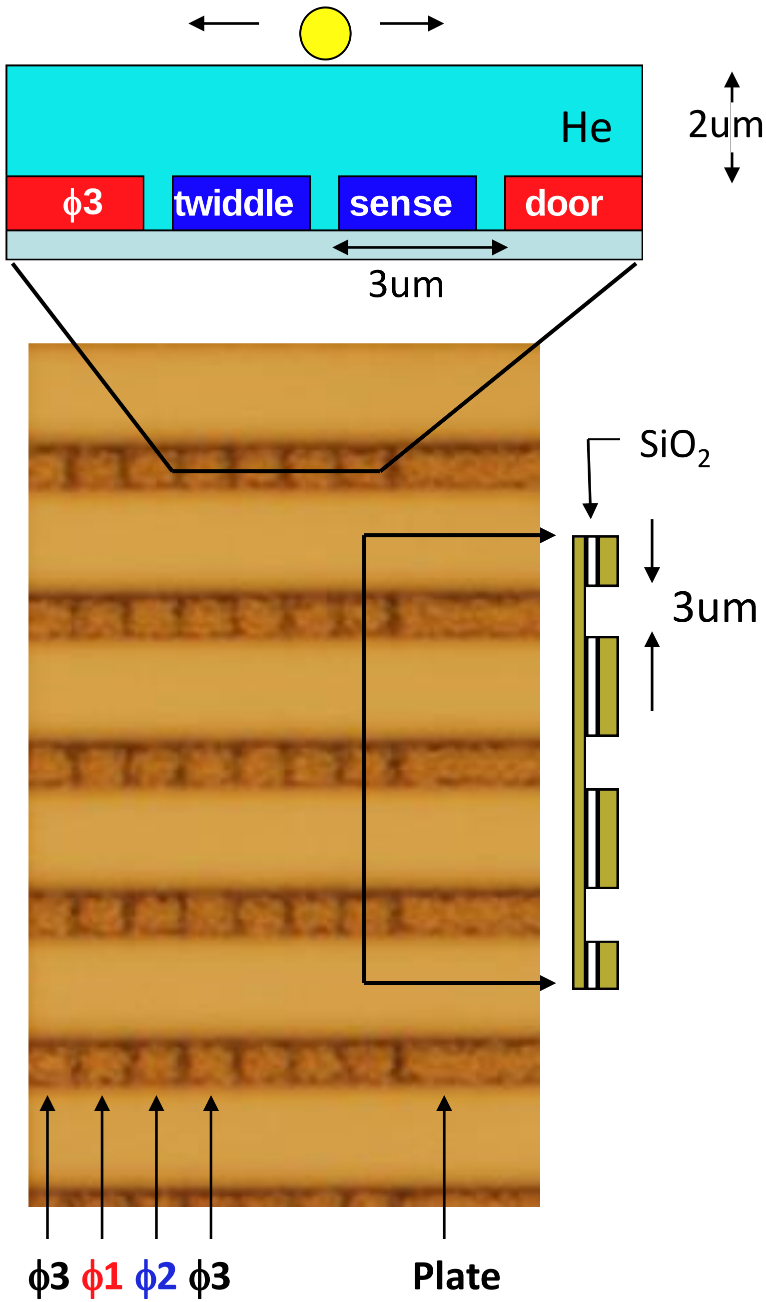


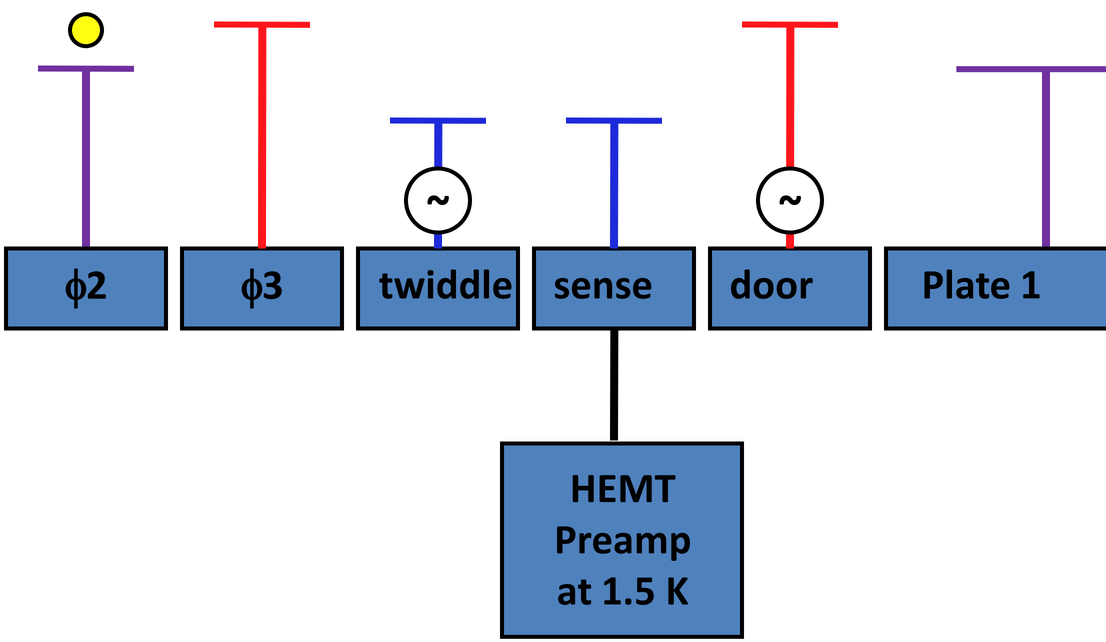
NOTE:

Sensing is done capacitively!
Not ohmically!

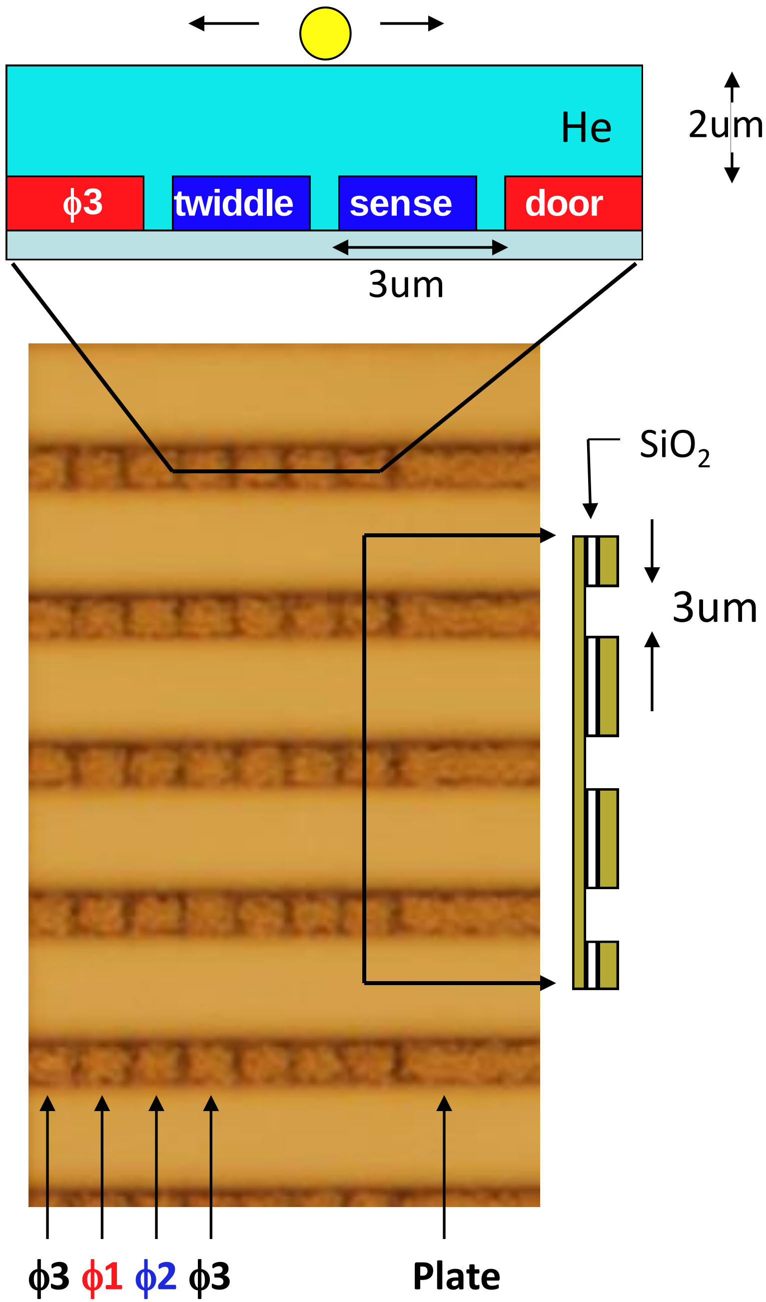


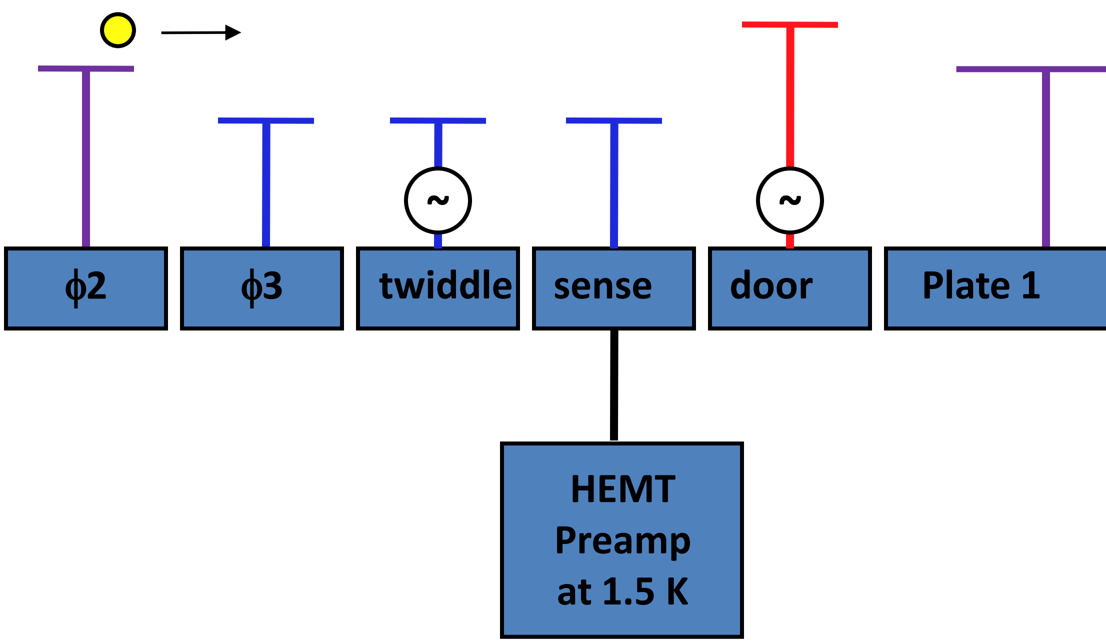
Twiddle Sensing



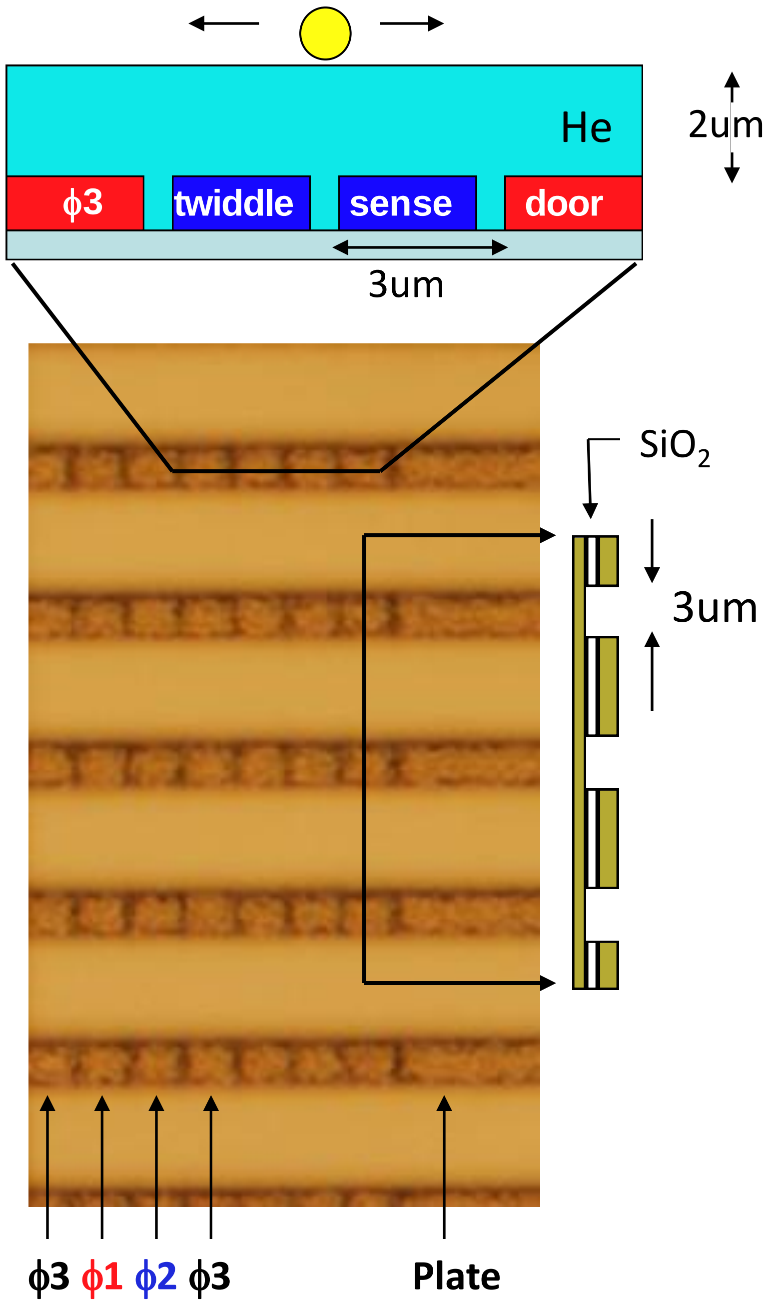


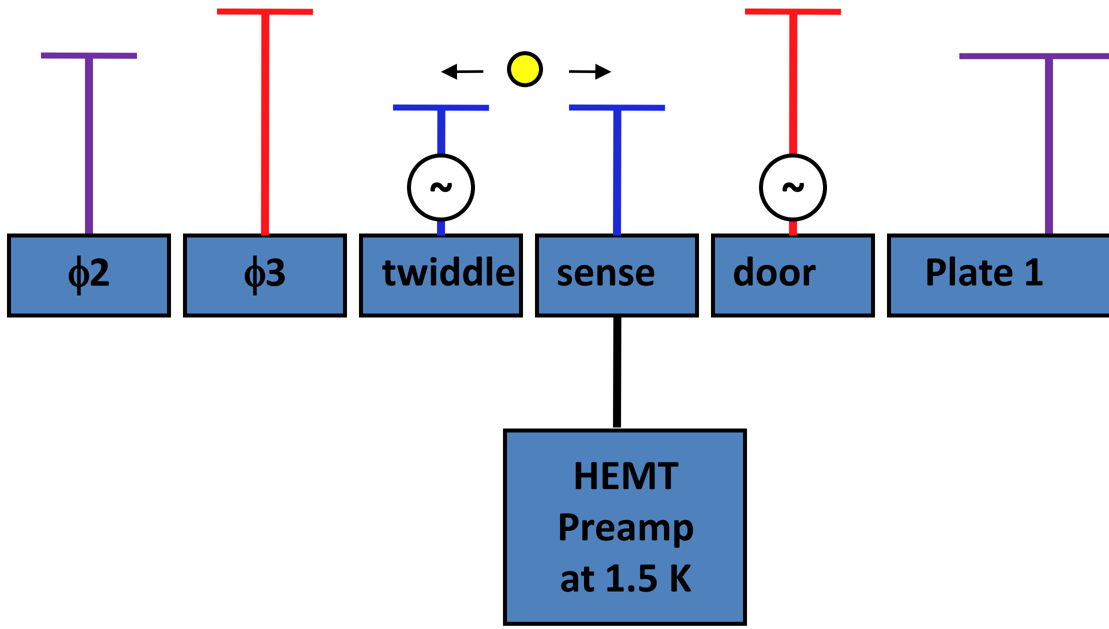
Twiddle Sensing

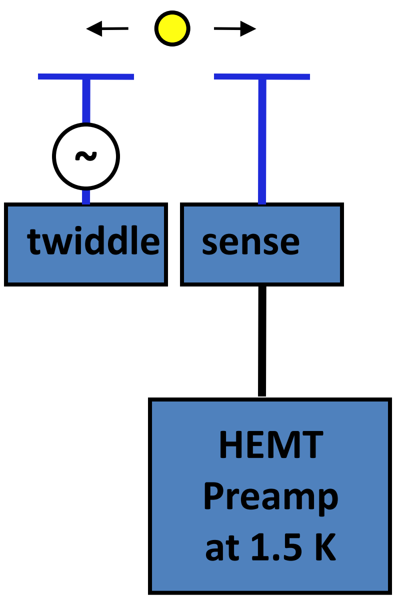




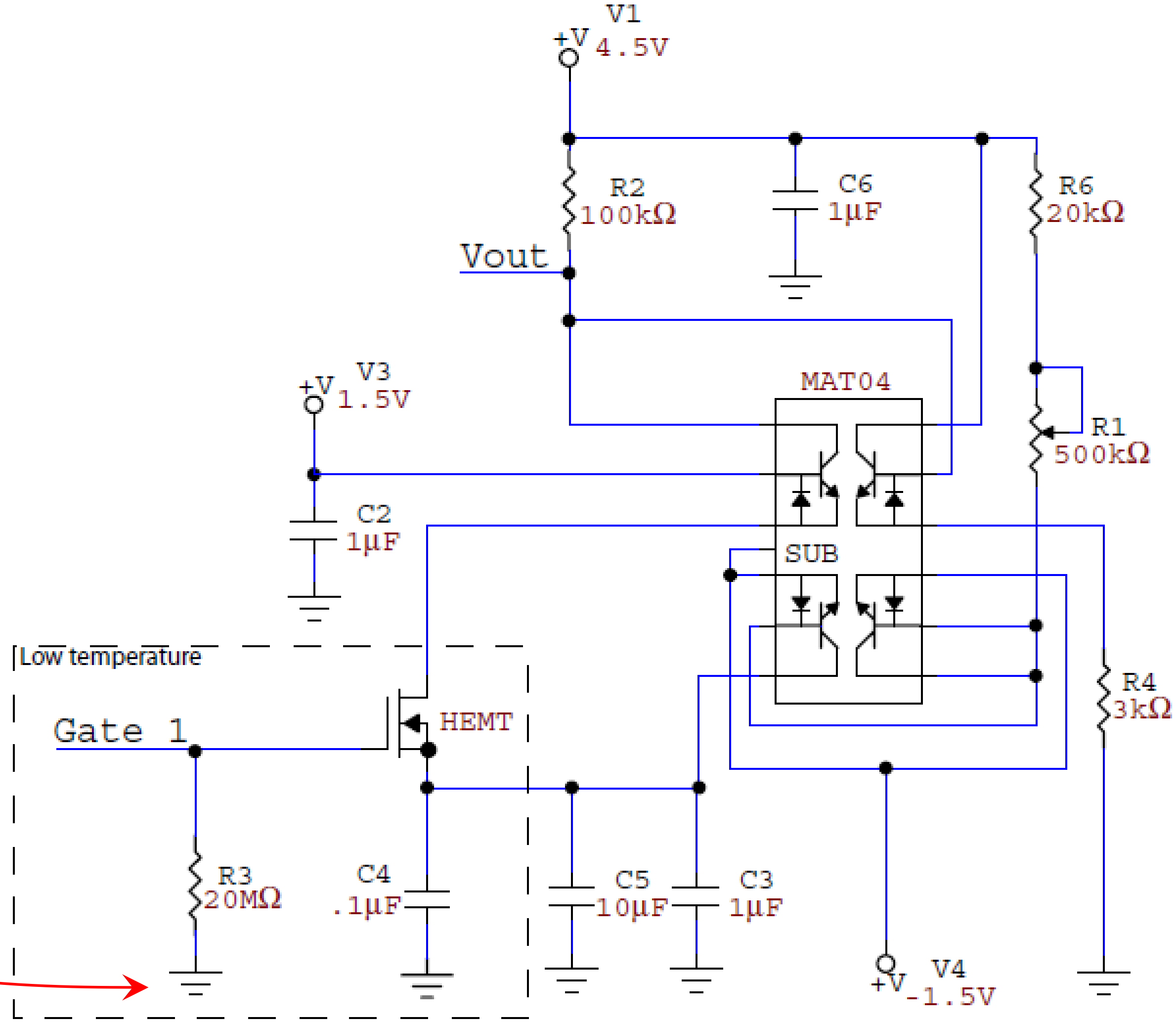
Twiddle Sensing







Actually, this is not always grounded, but rather serves as the DC offset for the sense gate:



Cascode amplifier

The theoretical noise figure of merit of this amplifier at helium temperature is 4 nV/√Hz at 100 kHz (which translates to being able to detect one electron per second with a signal to noise ratio of 5). There are two modes: when R2=100 k, the amplification factor is 40 but the amplifier is slow, and when R2=10 k, the amplification factor is only 8 but the amplifier can handle a signal modulation of 100 kHz.

Guillaume Sabouret thesis, 2007.

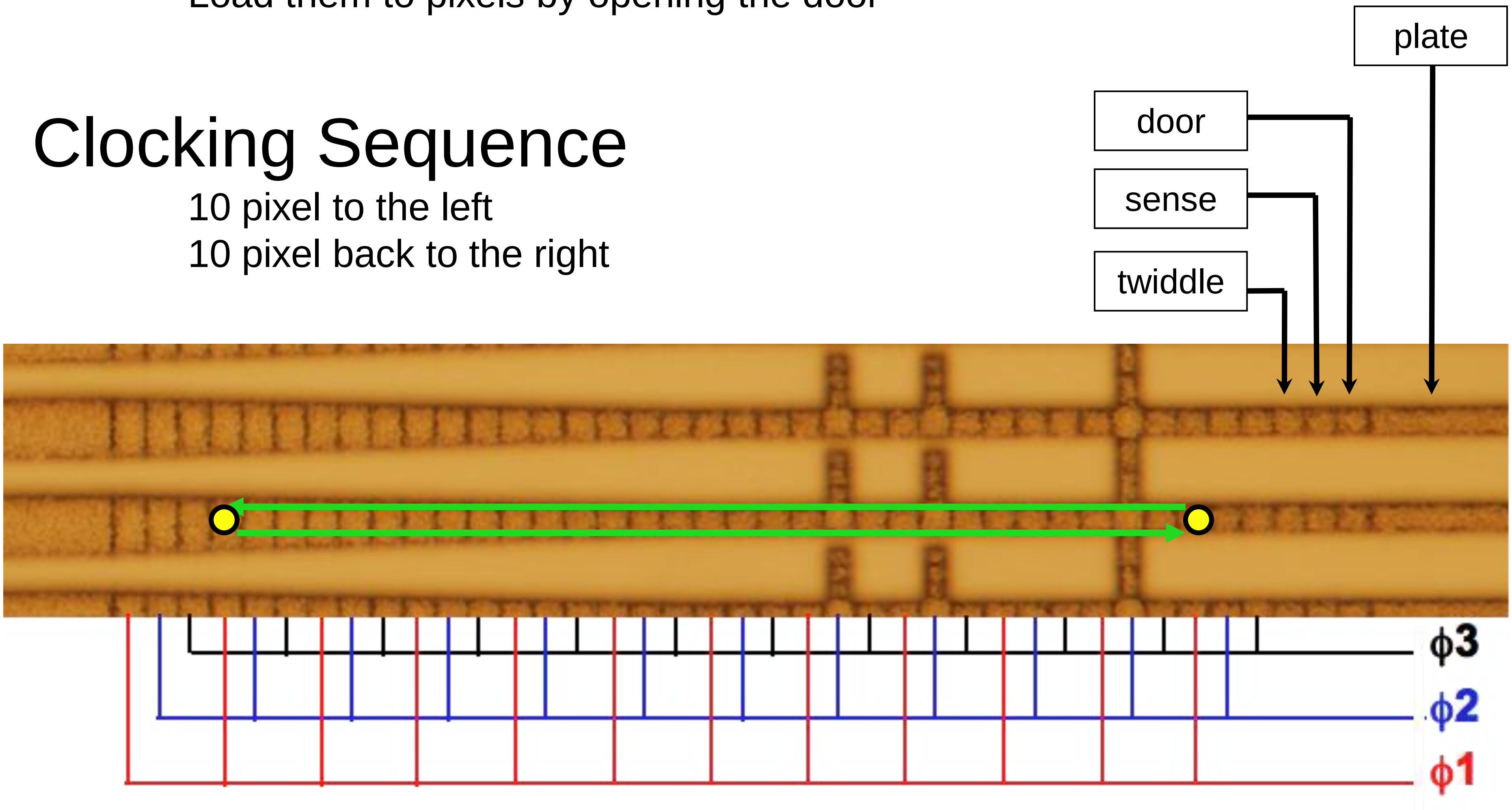
Horizontal CCD

Loading:

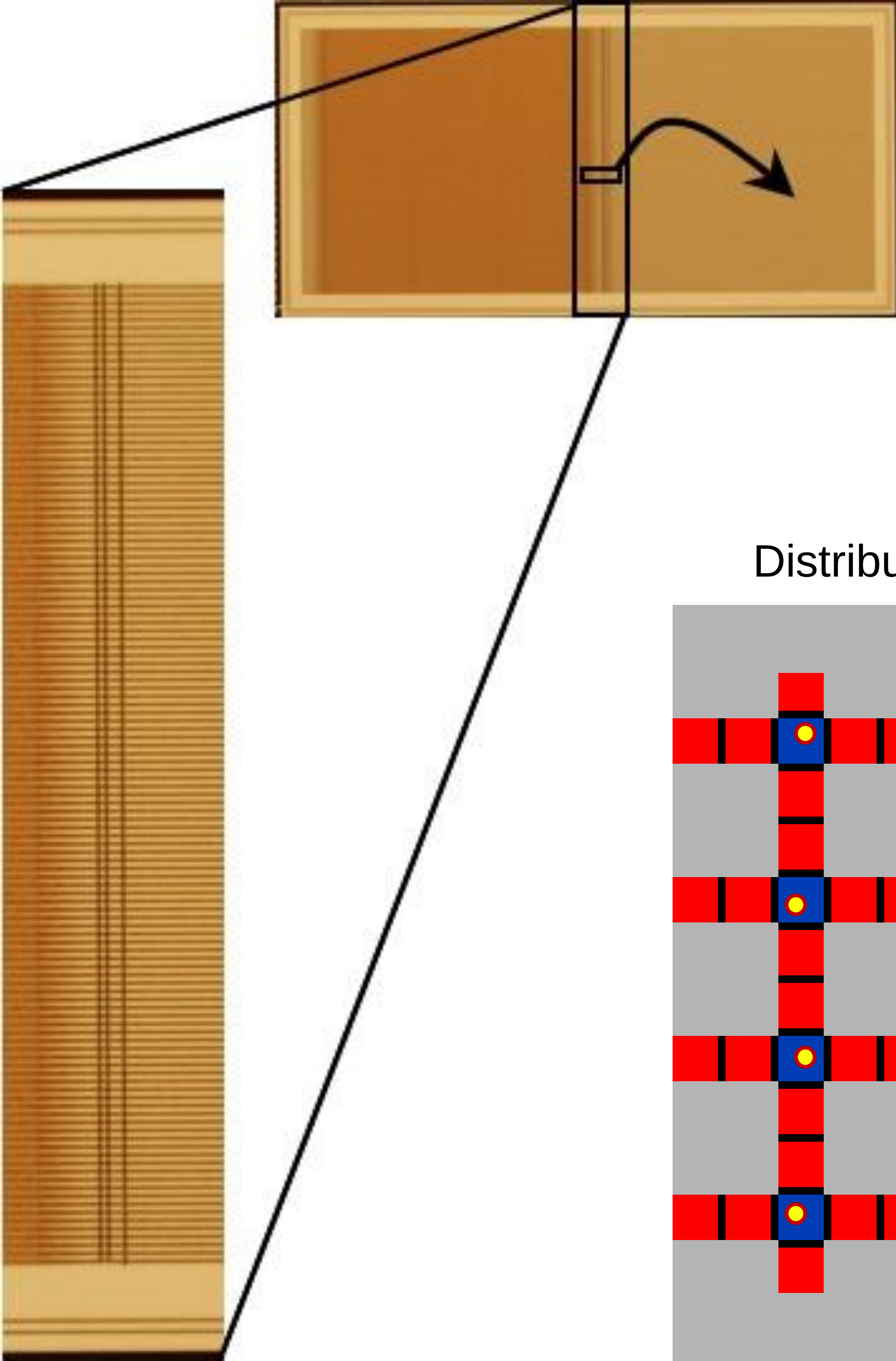
Photoemit electrons on plates
Load them to pixels by opening the door

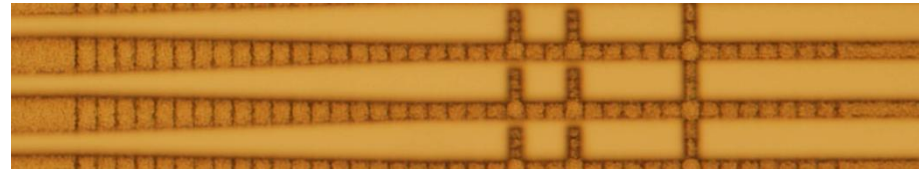
Clocking Sequence

10 pixel to the left
10 pixel back to the right



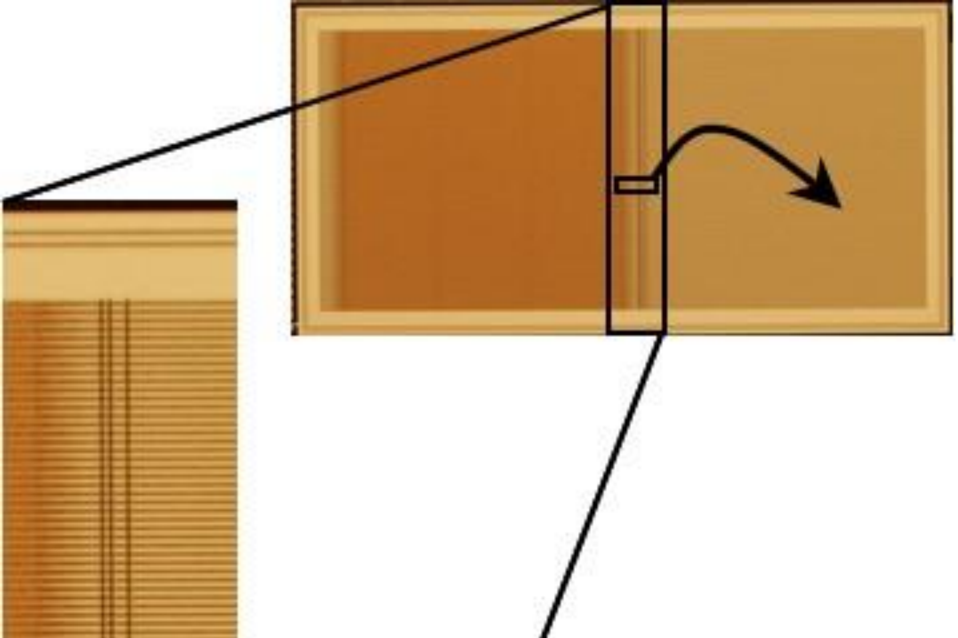
Vertical channel CCD

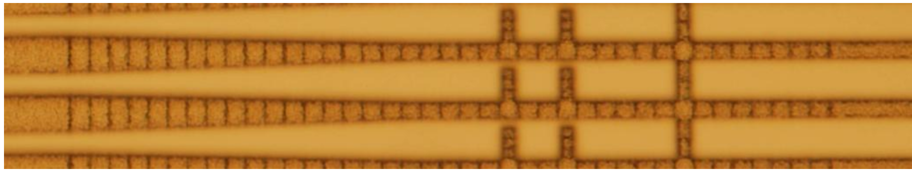


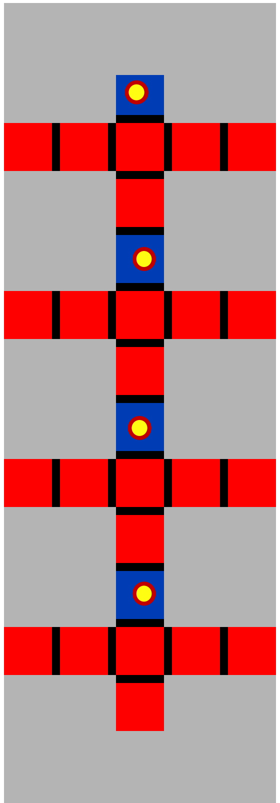


Distribution of electrons in horizontal channels?

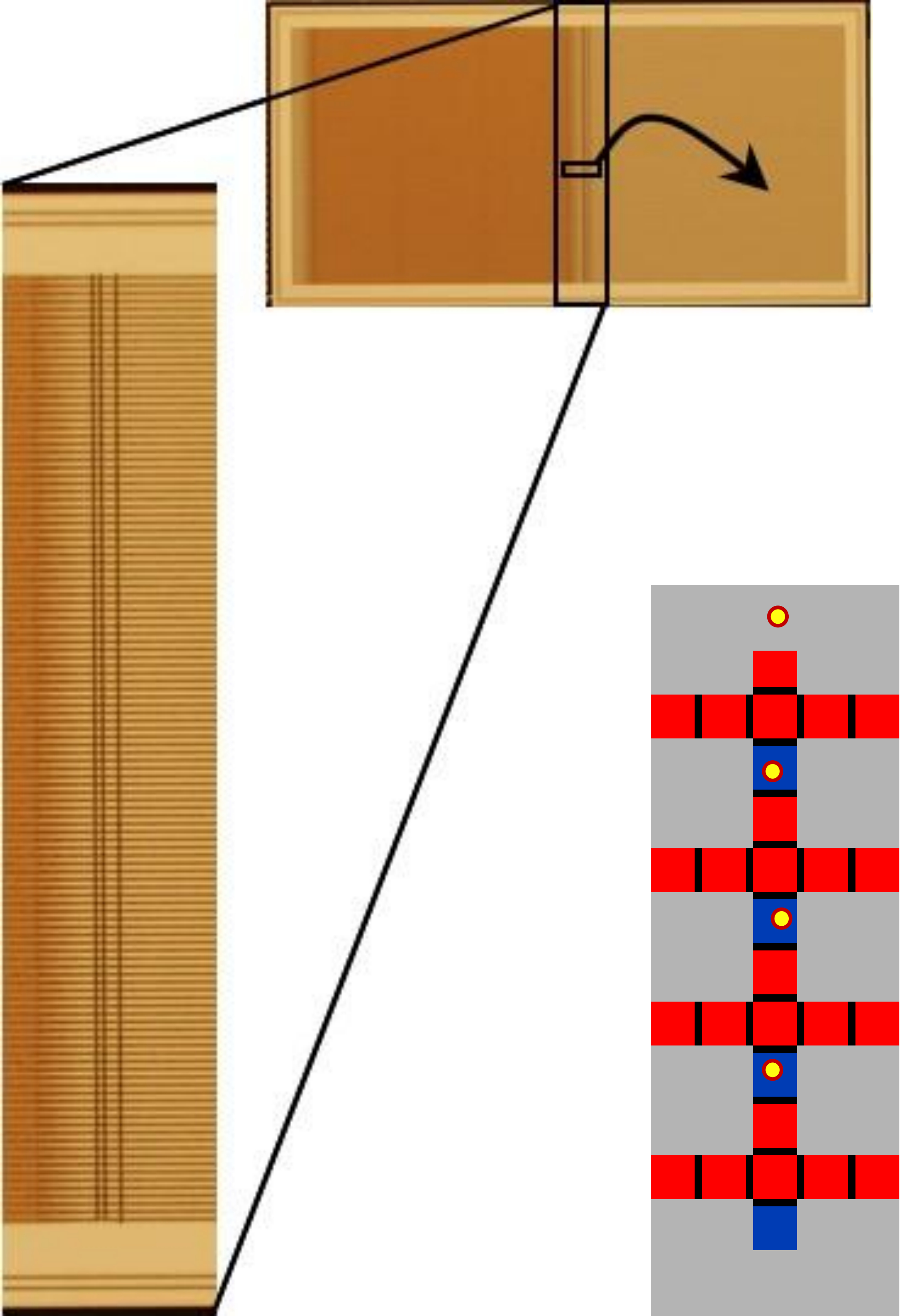
Vertical channel CCD

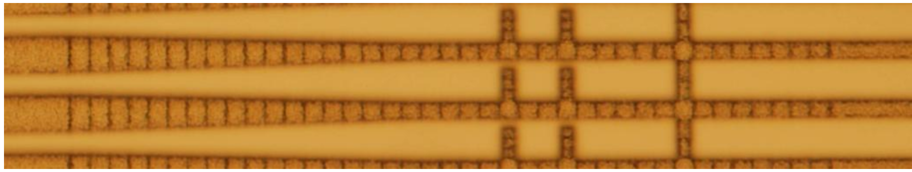




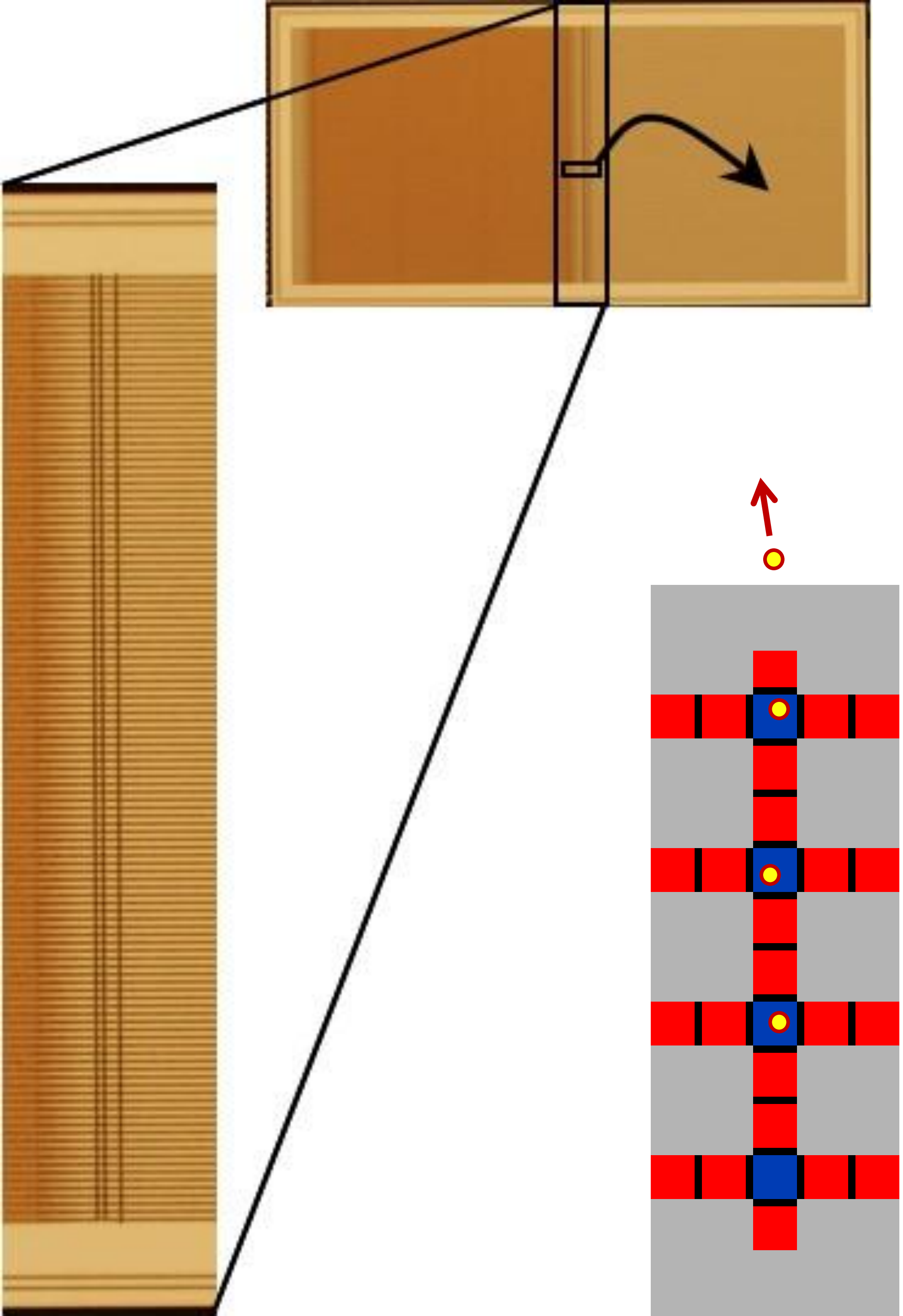


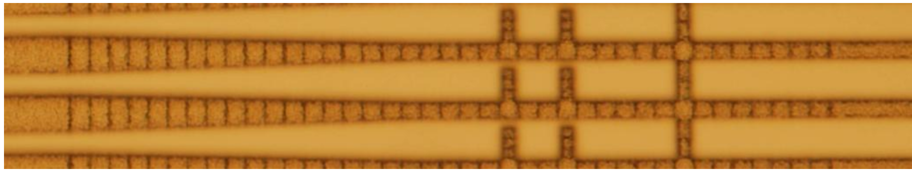
Vertical channel CCD

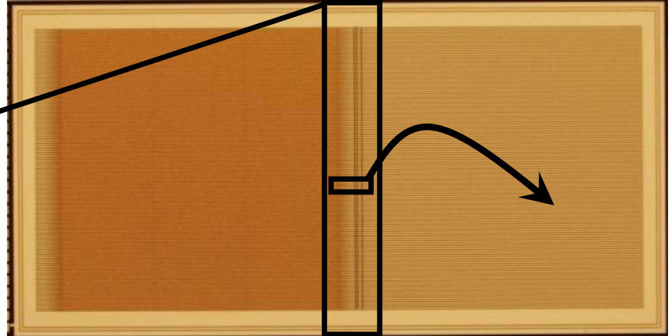


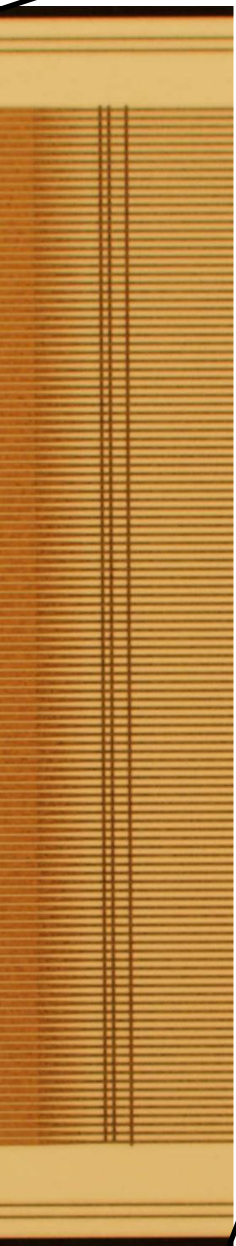


Vertical channel CCD



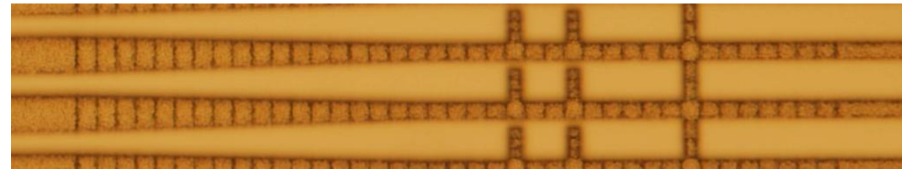


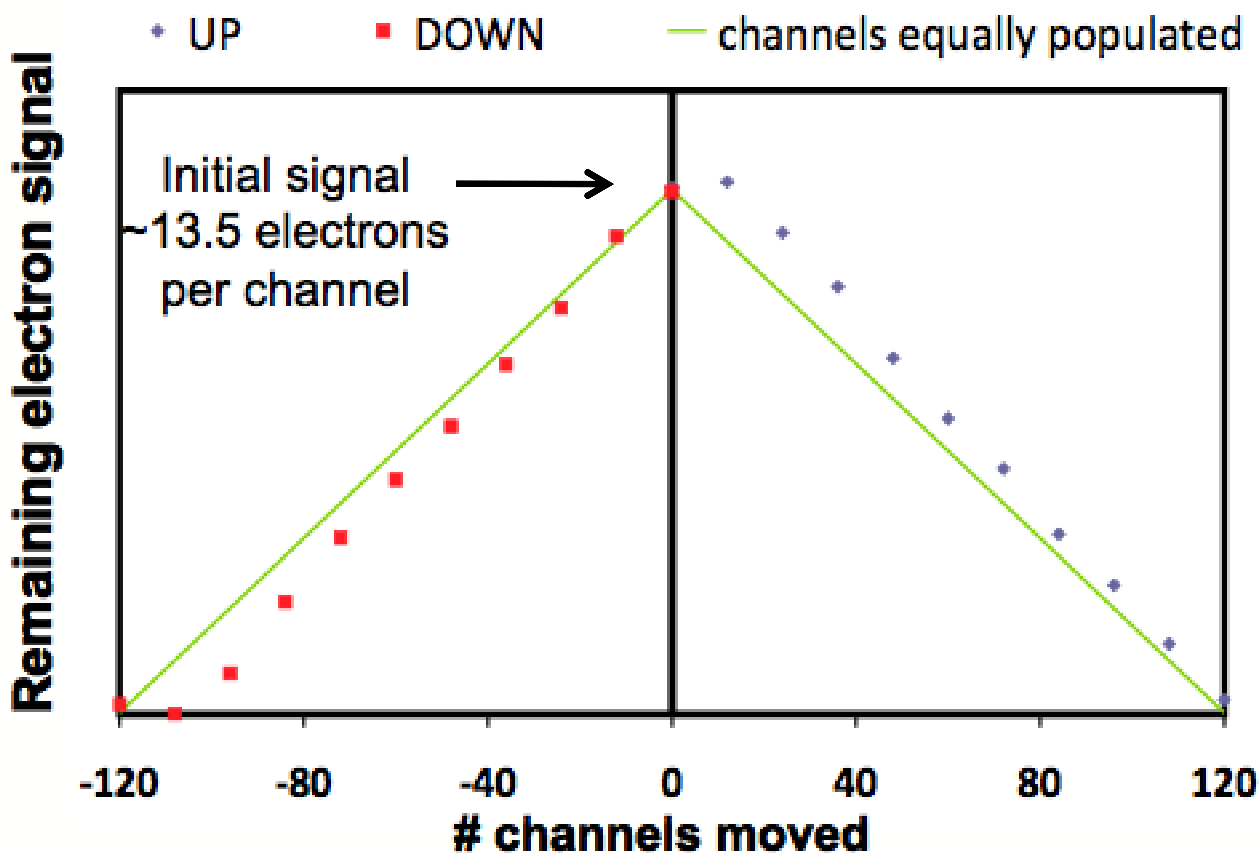




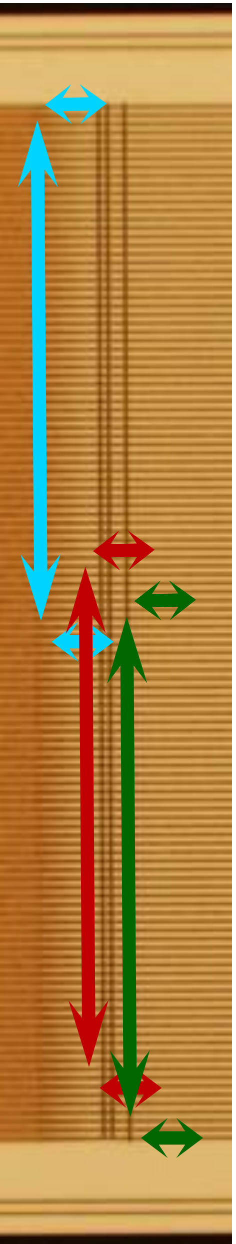
Vertical channel CCD

Distribution of electrons in horizontal channels





Vertical channel CCD



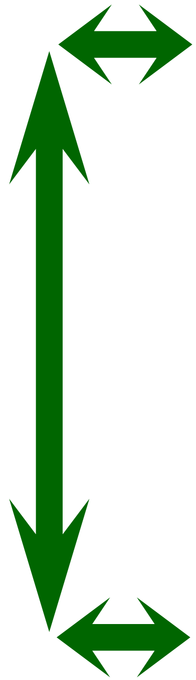
Channel N+60

↑

each packet
of electrons
travels up
and down 60
channels

↓

Channel N

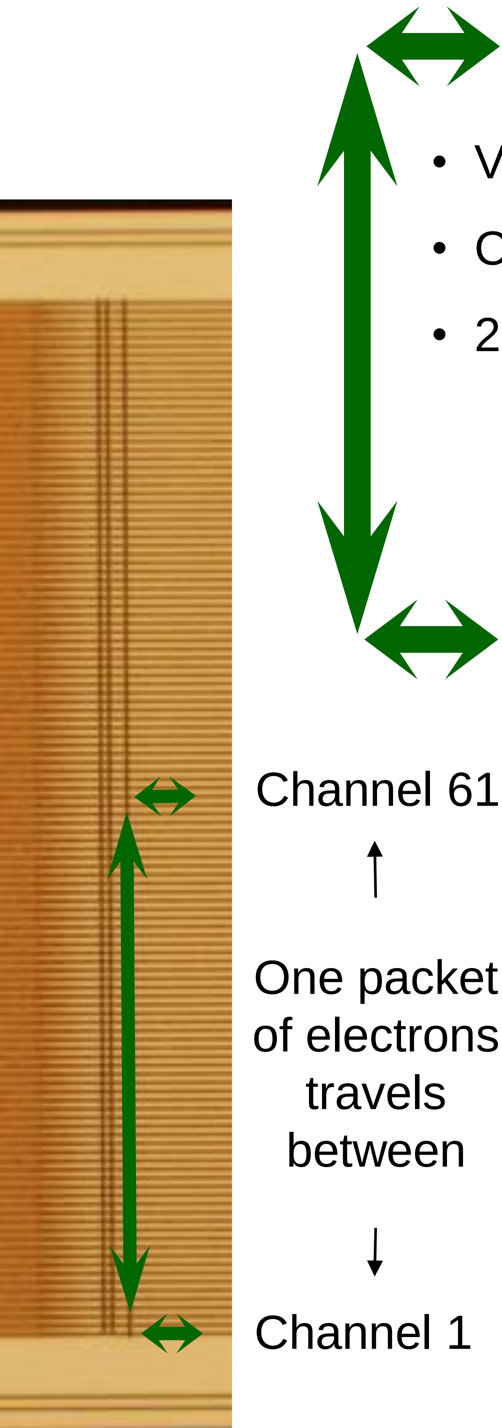


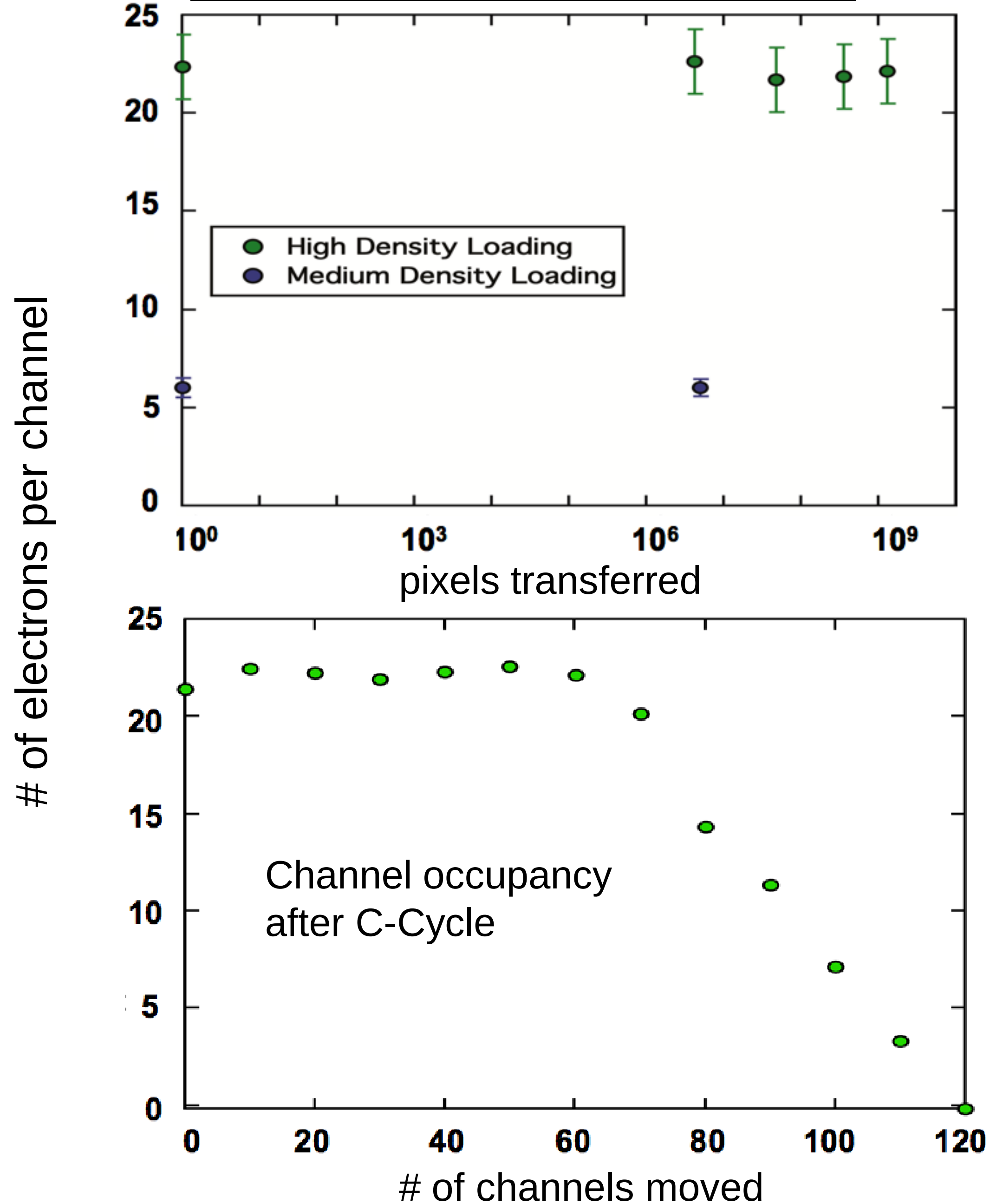
C-cycling Demonstrates

- vertical channel CCD
- cornering efficiency
- 2D control

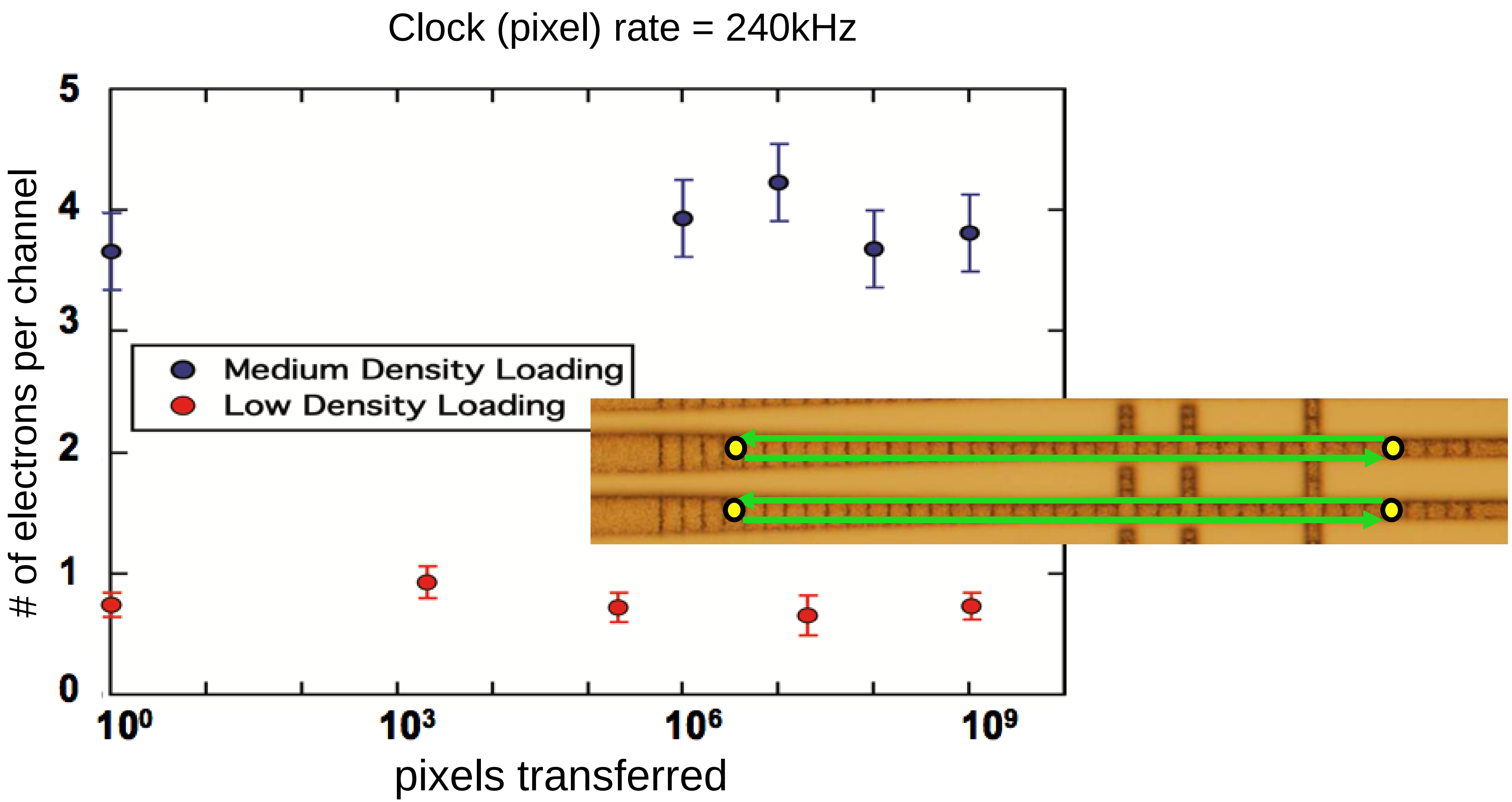
Vertical channel CCD

- Vertical CCD
- Cornering
- 2D control

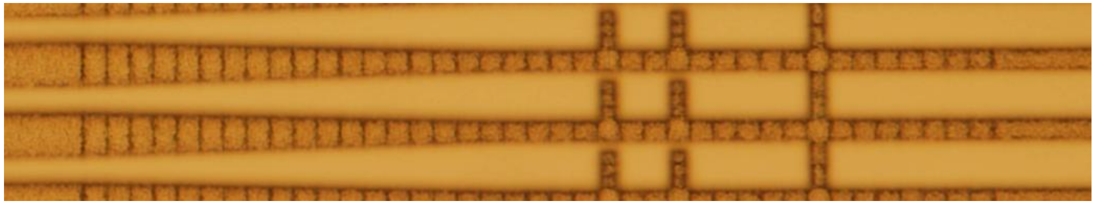




Horizontal Clocking Efficiency



No measurable loss after 10^9 cycles!



Overview of the relevant results from my PhD work:

- Twiddle detector for electron measurement (noise level > 15 e)
- Unprecedented reliability of a Charge Coupled Device
  -Essentially a perfect Electron Transfer Efficiency
- Only 5 clock lines needed for full control
  -2D Scalability: Move anywhere in our ~5000 position array
- Si-Processing
  -First, non-optimized design with standard silicon processing
  -Possibilities for on-chip amplification (& one day control)

Outline:

- Introduction and motivation for electron spin qubits
- Background for electrons on helium
- Experimental methods
- Experimental results for electron transport above superfluid helium channels
- Ideas, uncertainties, and plans for pumping

Electrons on liquid helium: a brief history

- Proposed in 1964 by W.T. Sommer
- Demonstrated in 1971 by Williams, Crandall, and Willis
- Classical Wigner crystal in 1979 by Grimes and Adams
- Low densities (10^5-10^9 e/cm^{-2}), non-degenerate regime!
  - limited due to hydrodynamic instability
- Highest mobility 2D electrons
  - 100 x10^6 cm^2/Vs measured by Shirahama et al @ 50mK
- Channels 1st employed in 1986 by Marty in PCB devices

Two Phases of electrons on bulk or thick helium:

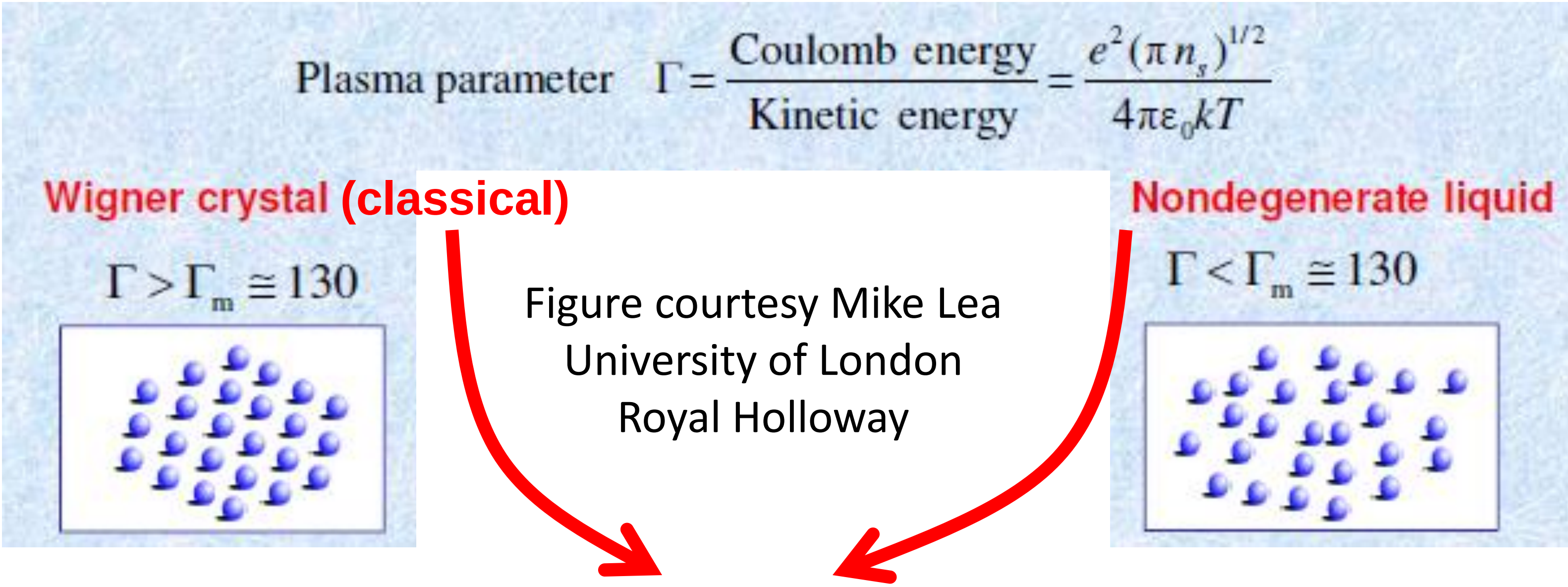
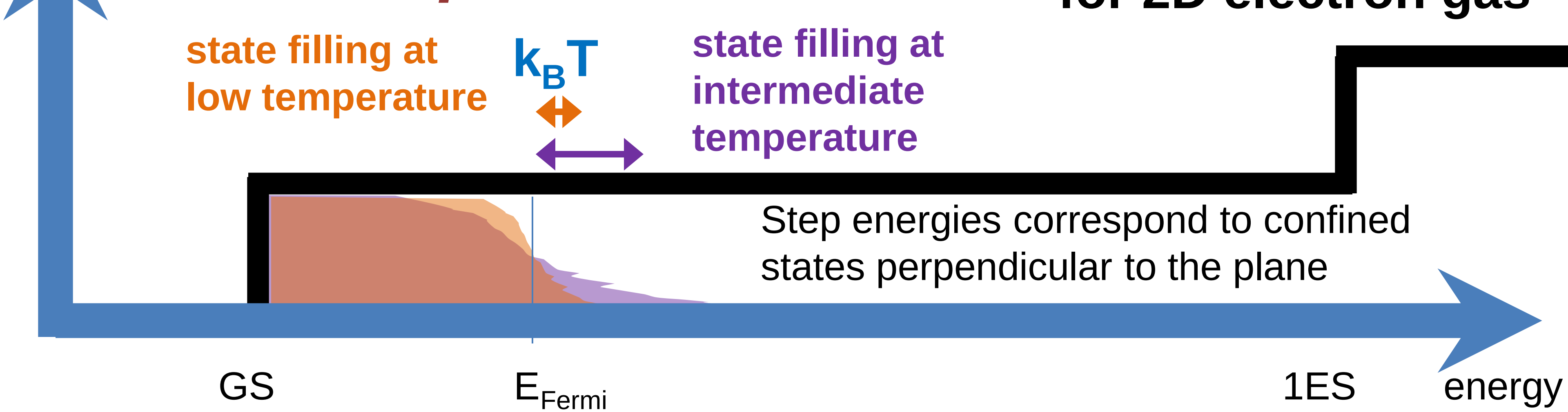


Figure courtesy Mike Lea
University of London
Royal Holloway

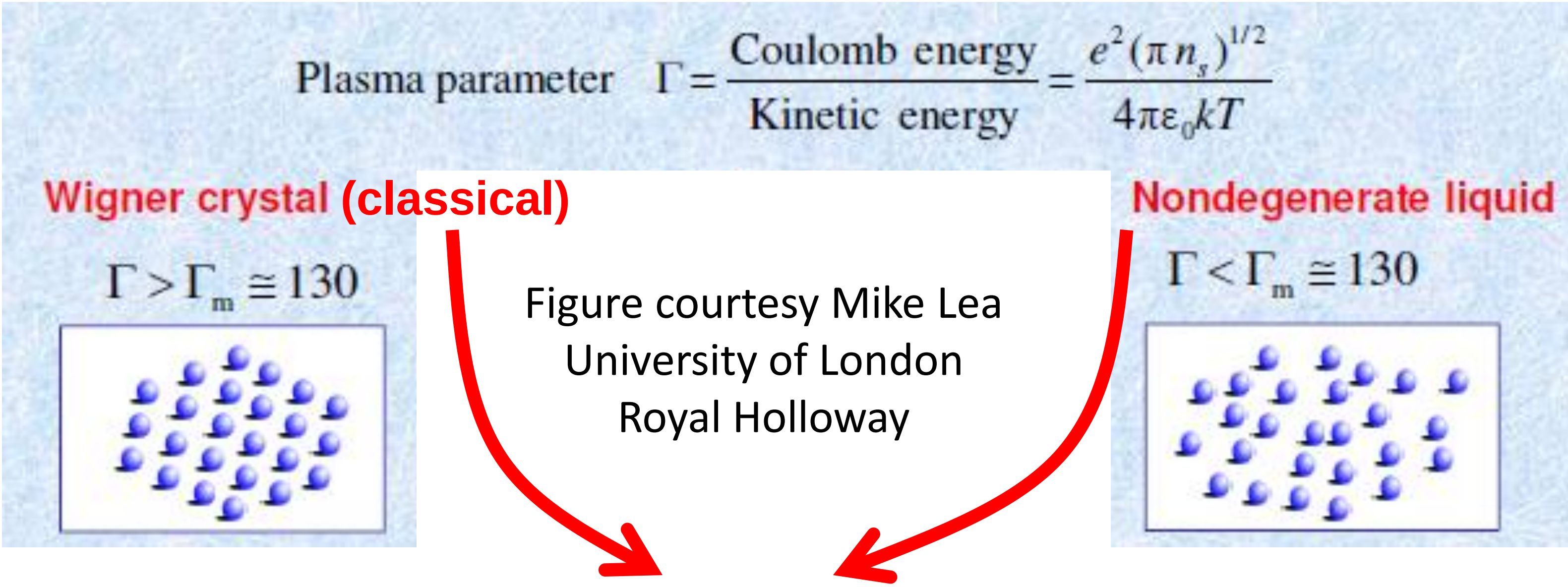
What does "degenerate/quantum" mean?

"Fermi-liquid in 2D"

DoS is step-like for 2D electron gas



Two Phases of electrons on bulk or thick helium:

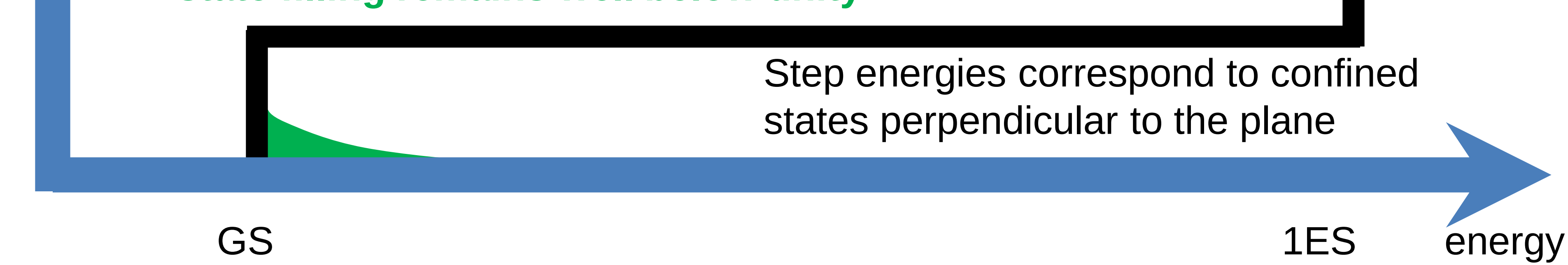


What does "nondegenerate/classical" mean?

"classical ideal gas in 2D"

due to hydrodynamic instability, upper density limit is low enough such that state filling remains well below unity

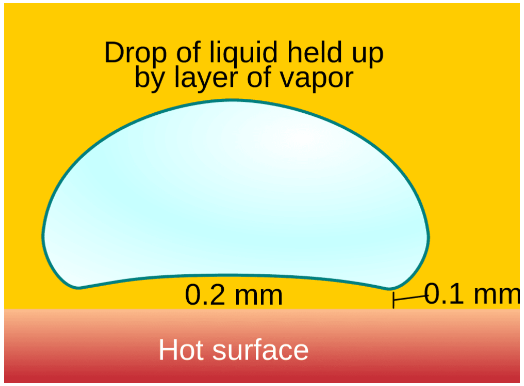
DoS is step-like for 2D electron gas



Degenerate fluid fills up to Fermi level with thermal fluctuations ($\sim k_B T$) around it

http://www.strangehistory.net/2013/12/05/the-medieval-water-that-would-not-boil/

Besides being upside down, the classical densities make things tricky!



https://www.thoughtco.com/leidenfrost-effect-demonstrations-604259

Non-degenerate fluid more similar to collection of Leidenfrost droplets on a hot pan

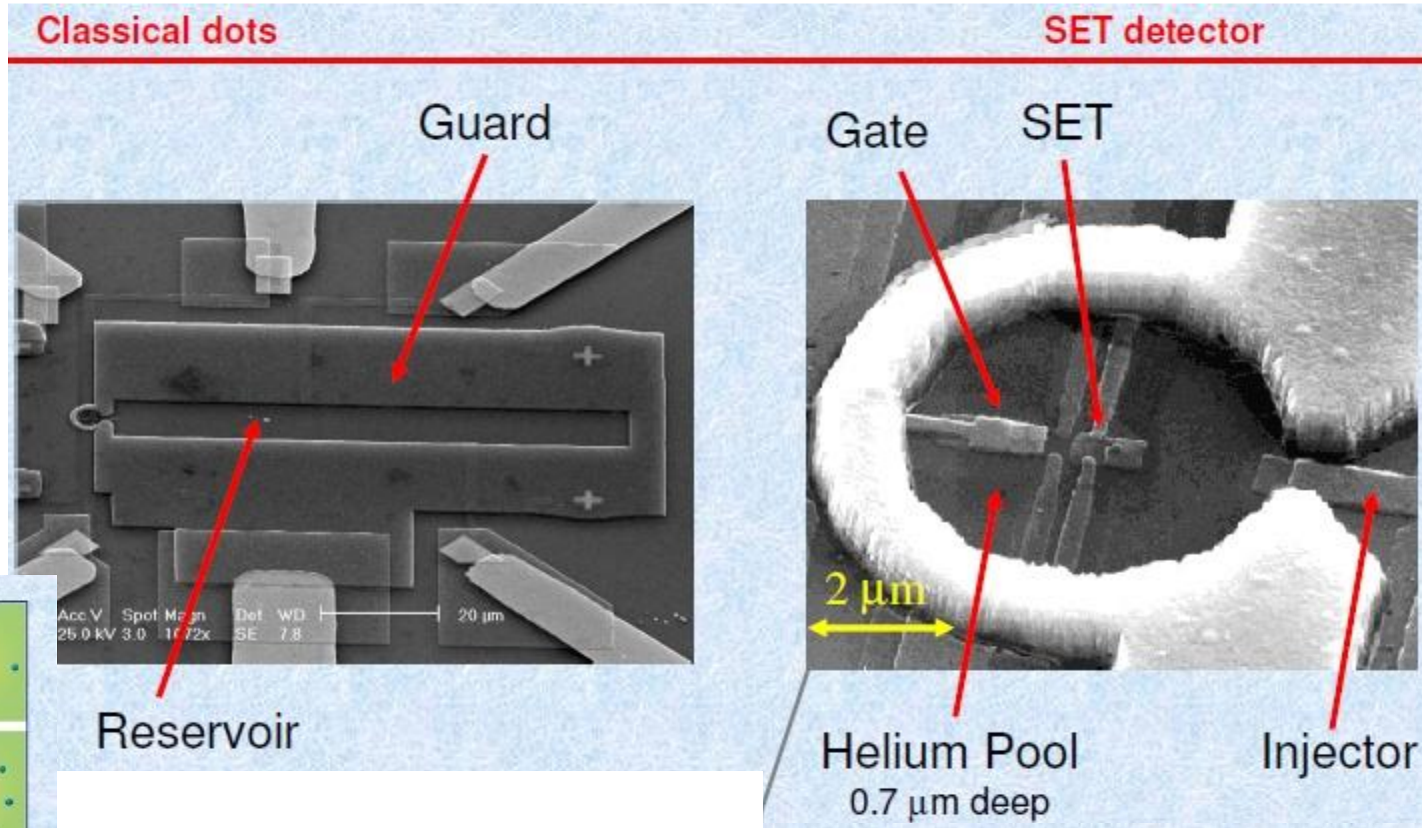
https://www.youtube.com/watch?v=6CLavQ7KS_Q

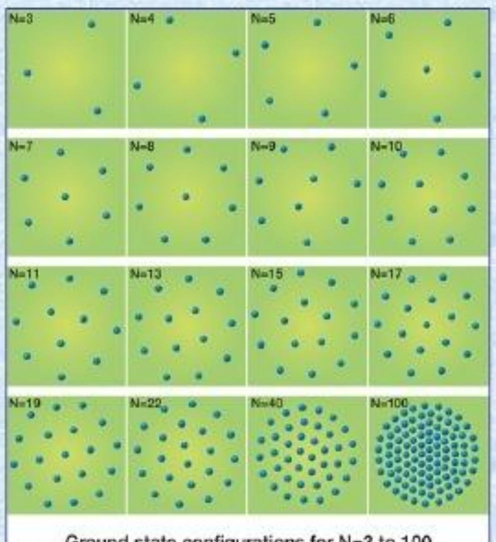
<u>For non-degenerate electrons on helium:</u>

- Addition to a dot/region is not deterministic.
- Uncontrolled overloading followed by controlled unloading might achieve thermalized occupation (for quantized pumping).

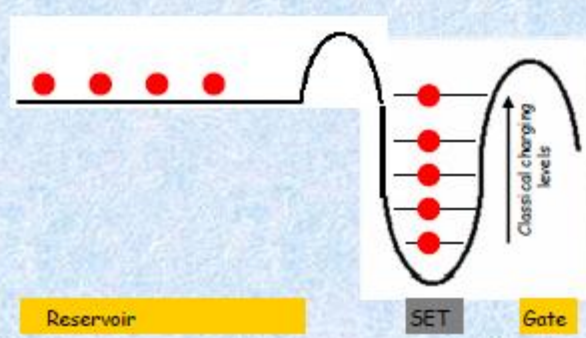
~~Quantum~~ Quantized Dots?

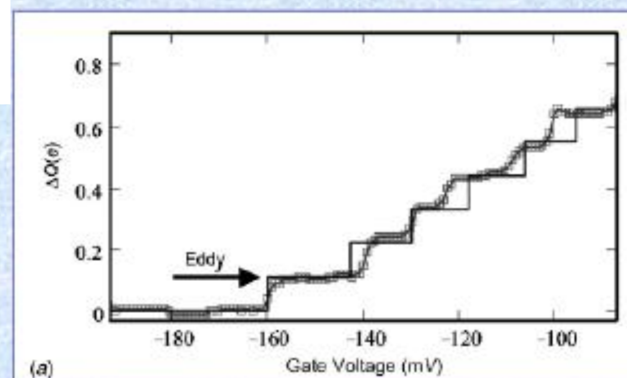
Mike Lea's slides: Royal Holloway University of London in collaboration with SEA Saclay





Viewpoint: Electron crystallites floating on superfluid helium
François Peeters
V. M. Bedanov and F. M. Peeters, **PRB 49**, **2667 (1994)**





Papageorgiou et al, APL, **86**, 153106 (2005)
Simkins et al, J.Appl.Phys. **106**, 124502 (2009)

Electrons on helium versus electrons in heterostructure 2DEGs

For Coulomb blockade (and pumping):

Heterostructure (e.g. GaAs) dots must be much smaller because of the screening inside a solid state material. The lack of e-e screening in the vacuum above low dielectric helium means that Coulomb repulsion is able to yield quantization effects measurable at dil.fridge temperatures for dots up to 5 um diameter!

DiVincenzo Criteria for a quantum computer?

scalable array of qubits

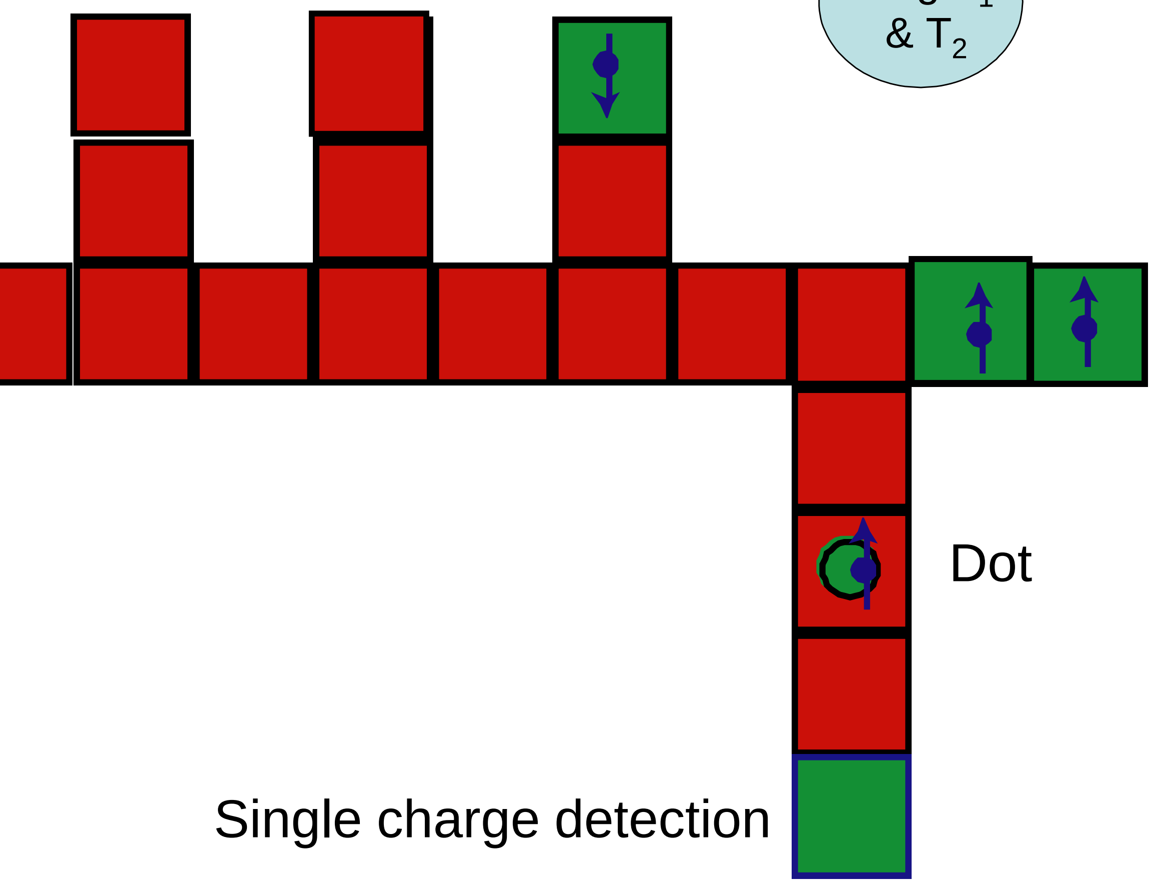
initialization

"flying" qubits

long T_1 & T_2

universal set of qubit operations

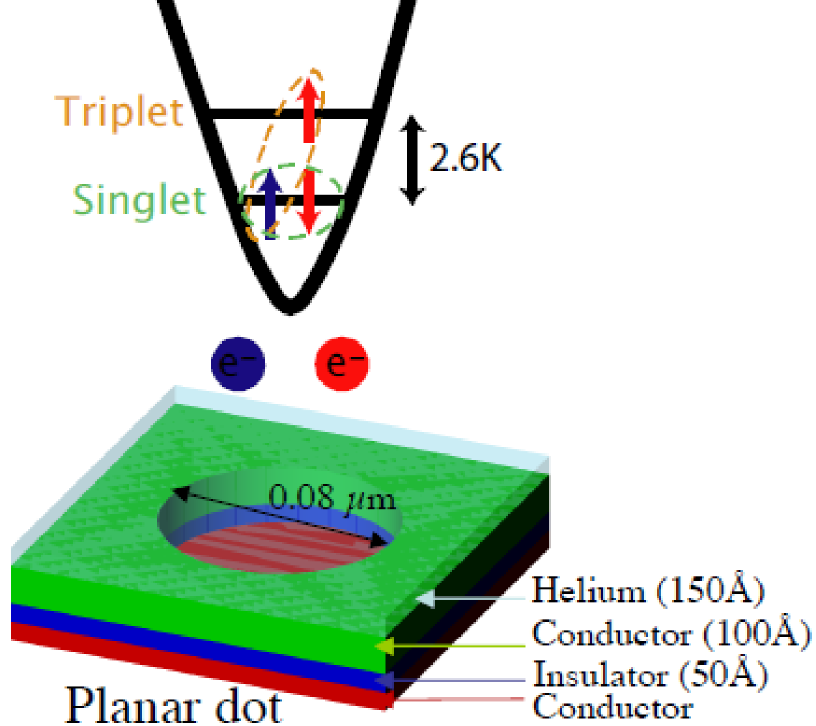
efficient measurement

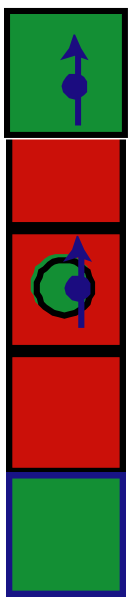


universal set of qubit operations

efficient measurement

require exchange interaction, which requires tight confinement





dot

single charge detection

<u>Exchange Interaction and Spin to Charge Readout</u>

The splitting between the first singlet and triplet states is 2.6 K (or 0.23 meV) for technologically achievable dimensions (shown of the figure) and a 2 V potential difference across the conductors.
Guillaume Sabouret thesis, 2007.

<u>Heterostructure (e.g. GaAs) dots are easier because:</u>

-densities easier to achieve (due to material screening of e-e and there is no hydrodynamic instability to worry about)
-effective mass is smaller than free electron's, so larger dots possible thanks to larger de Broglie wavelength

electrons on helium versus electrons in heterostructure 2DEGs

For Coulomb blockade (and pumping): (electrons on helium win!)

Heterostructure (e.g. GaAs) dots must be much smaller because of the screening inside a solid state material. The lack of e-e screening in the vacuum above low dielectric helium means that Coulomb repulsion is able to yield quantization effects measurable at dil.fridge temperatures for dots up to 5 um diameter!

For exchange interaction: (electrons in heterostructures win!)

Heterostructure (e.g. GaAs) dots are easier because densities can be larger and he effective mass is smaller than the free electron's (thus its easier to reach quantum concentration).

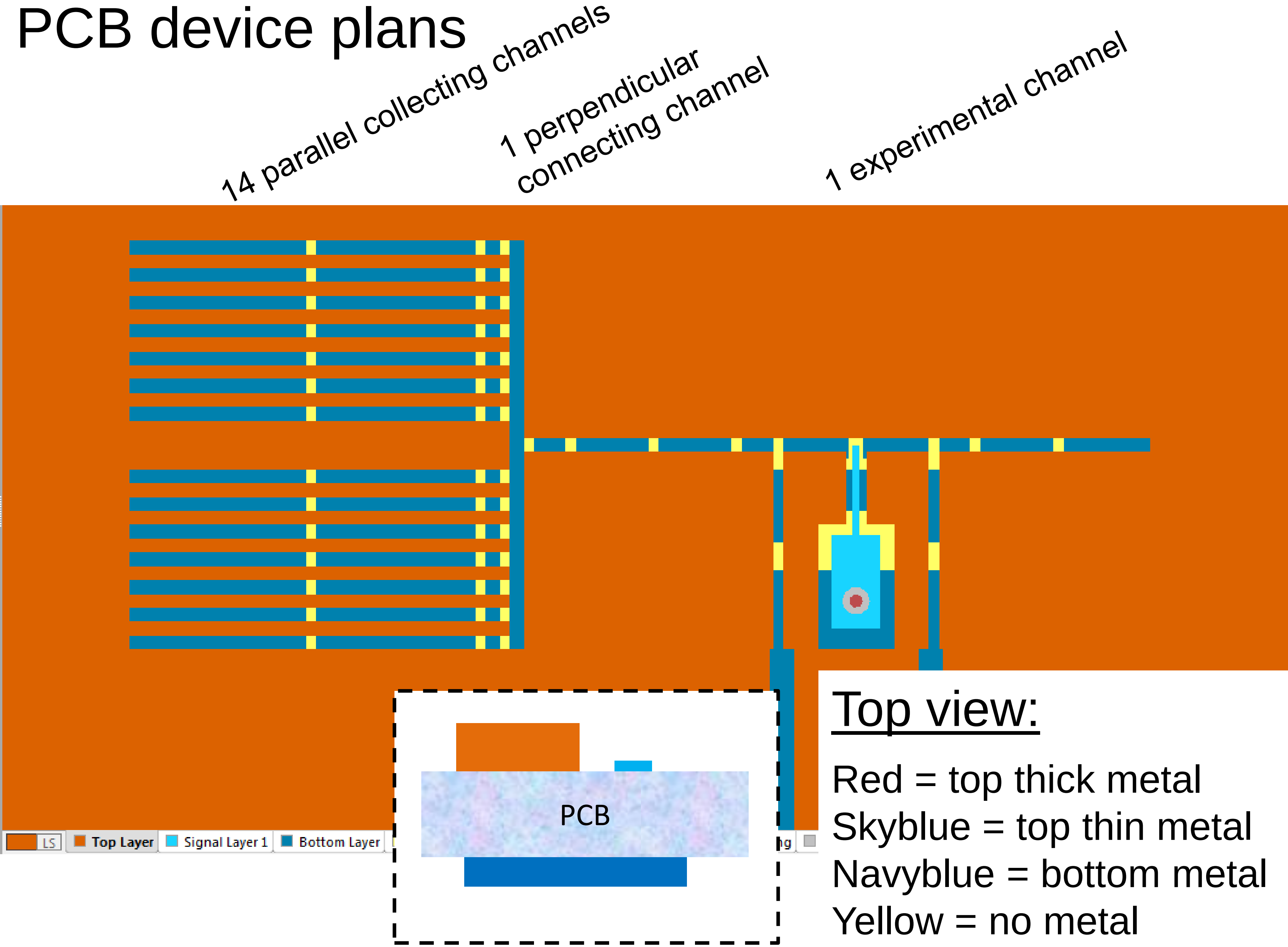
For quantum transport: (depends on the purpose…)

Electrons on helium can have longer mean free path (good for self-interference like in Aharanov Bohm), but due to classical densities, there can be no saturated quantized conductance like in a quantum point contact.

Electrons on liquid helium: a brief history

- Proposed in 1964 by W.T. Sommer
- Demonstrated in 1971 by Williams, Crandall, and Willis
- Classical Wigner crystal in 1979 by Grimes and Adams
- Low densities (10^5-10^9 e/cm^{-2}), non-degenerate regime!
  - limited due to hydrodynamic instability
- Highest mobility 2D electrons
  - 100 x10^6 cm^2/Vs measured by Shirahama et al @ 50mK
- Channels 1st employed in 1986 by Marty in PCB devices

PCB device plans

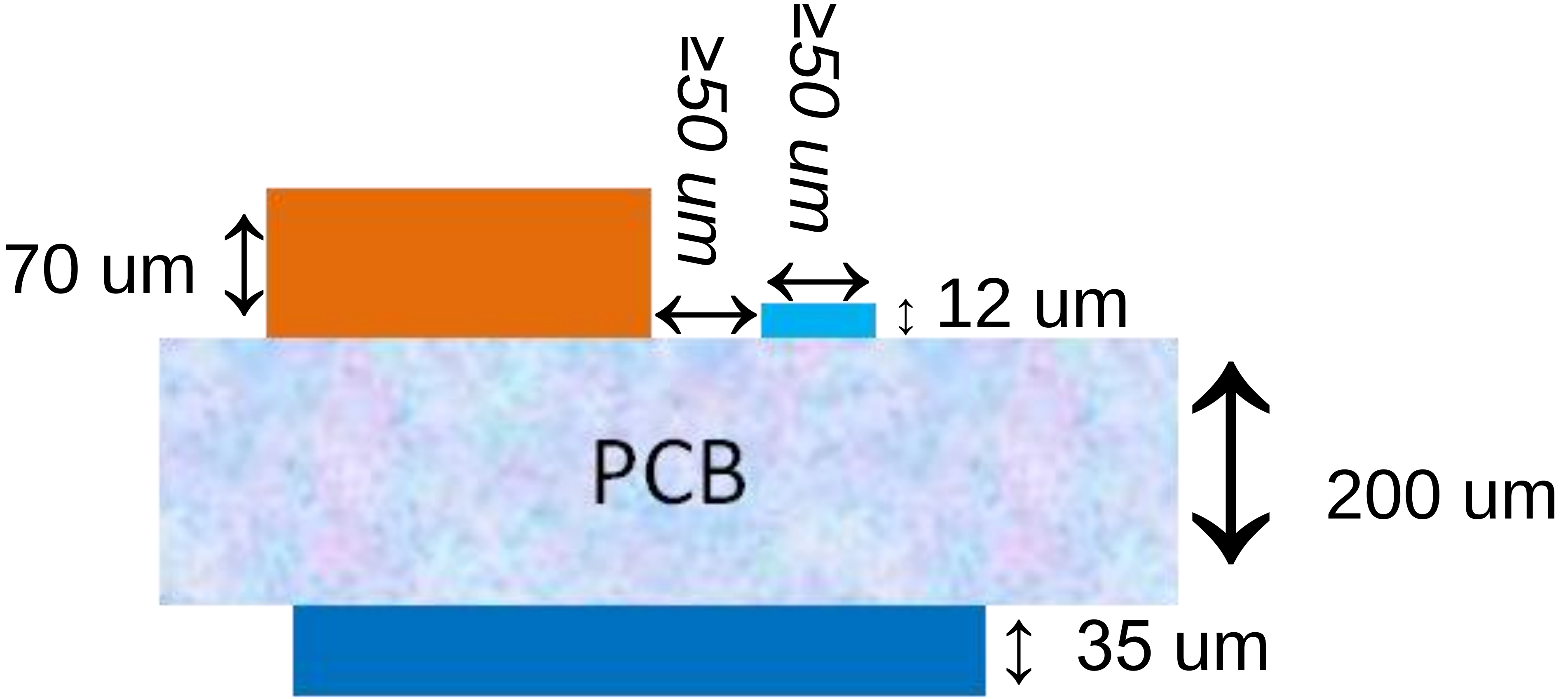


Top view:

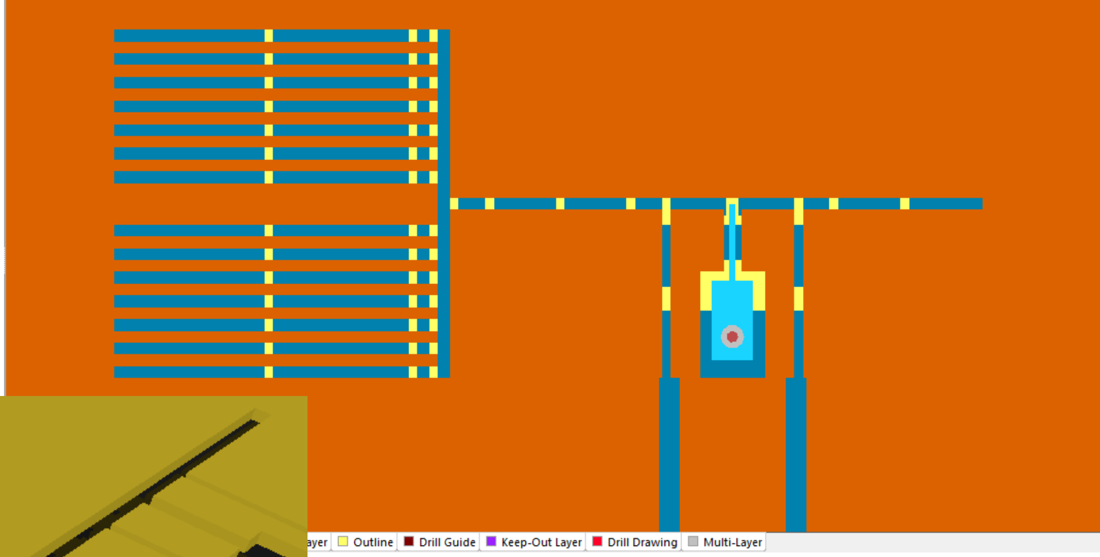
Red = top thick metal
Skyblue = top thin metal
Navyblue = bottom metal
Yellow = no metal

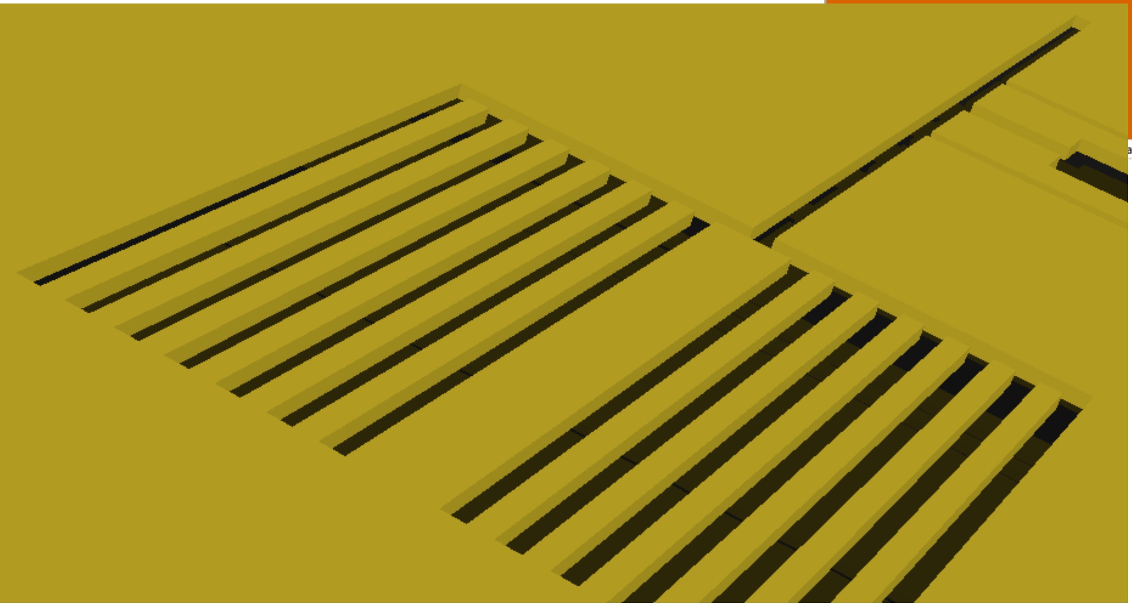
PCB device plans

<u>layer widths and spacing constraints:</u>



PCB device plans

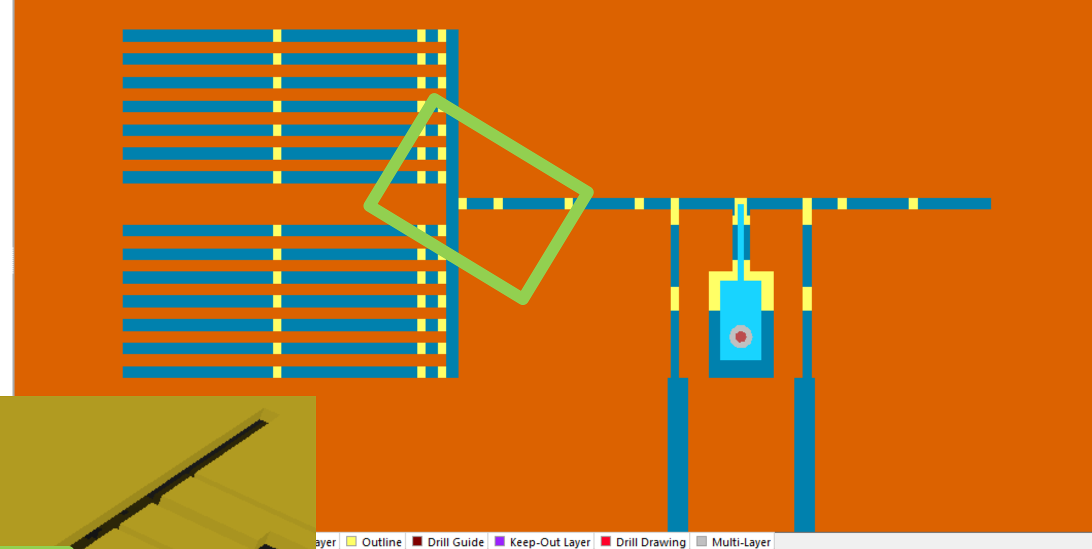


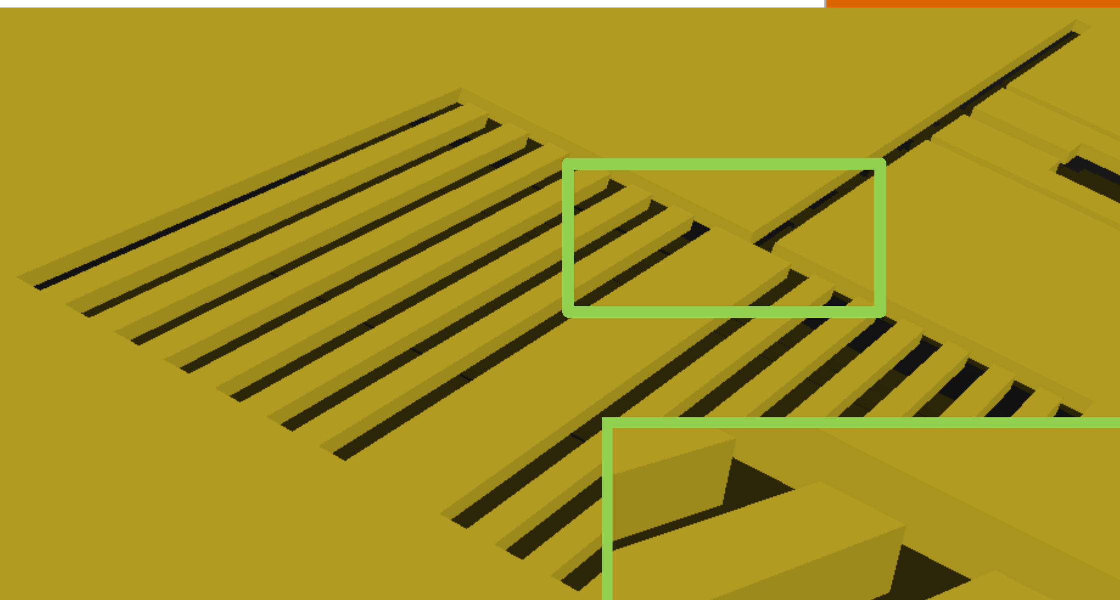


3D view

(just top thick metal
defining channels)

PCB device plans





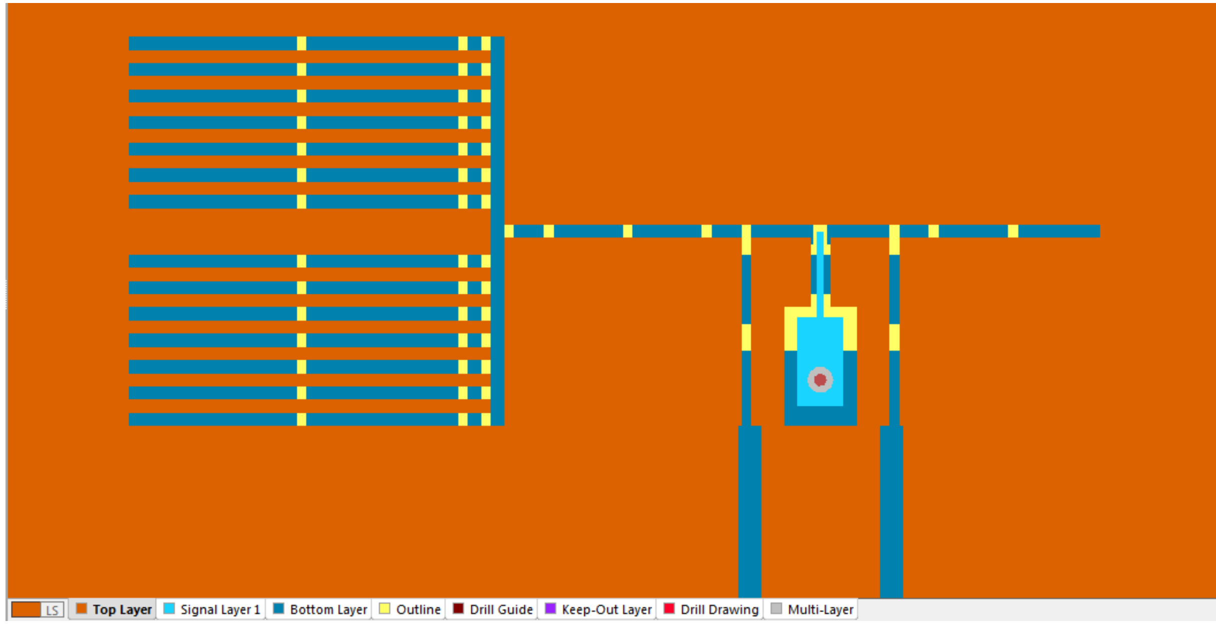
3D view

(just top thick metal defining channels)

PCB device plans

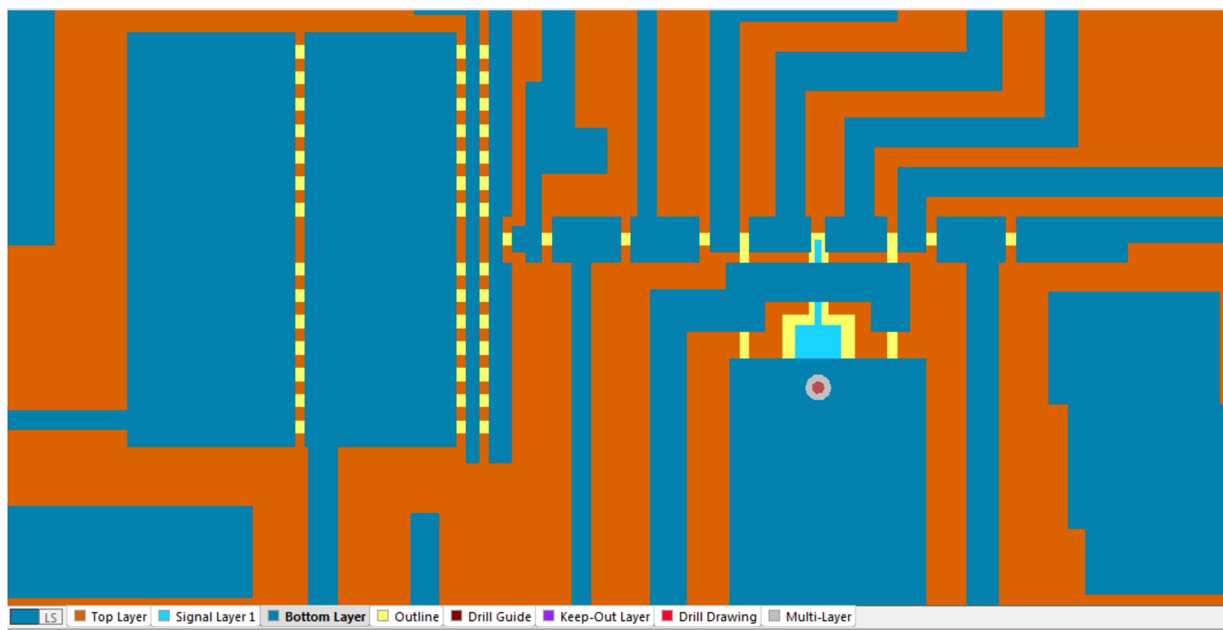
Regular top view:

Red = top thick metal
Skyblue = top thin metal
Navyblue = bottom metal
Yellow = no metal



Inverted top view:

showing bottom layer in front of top layers…



PCB device plans

<u>Regular top view:</u>

Red = top thick metal
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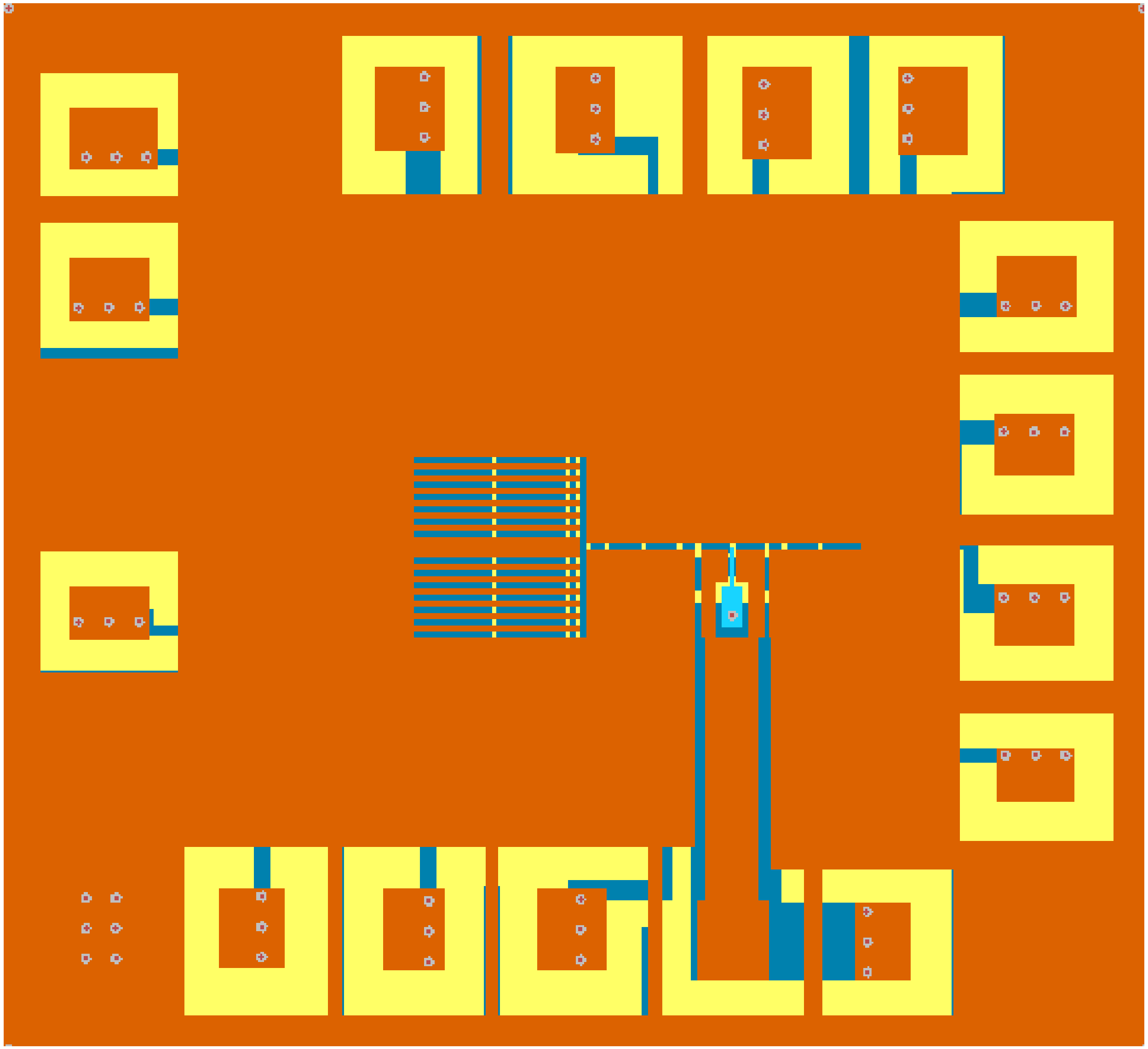
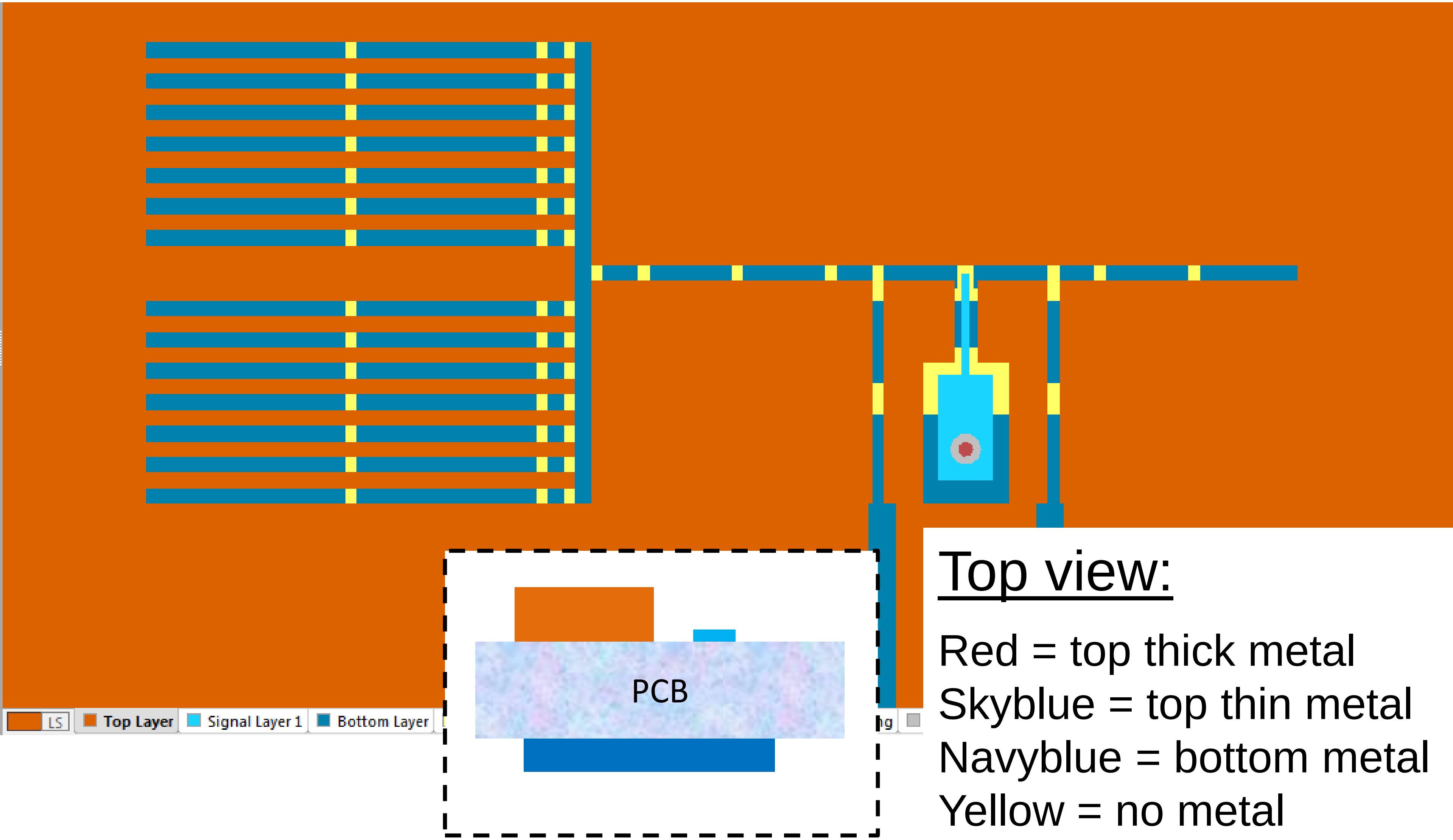


Zoomed out to show entire device: 19mm X 19mm

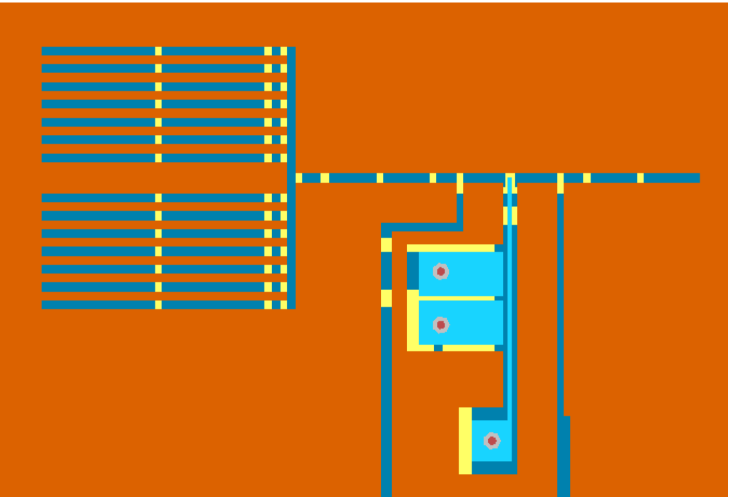
PCB device plans

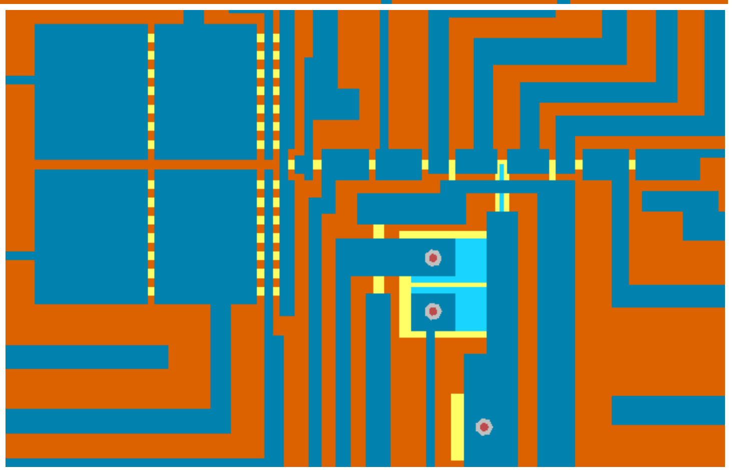


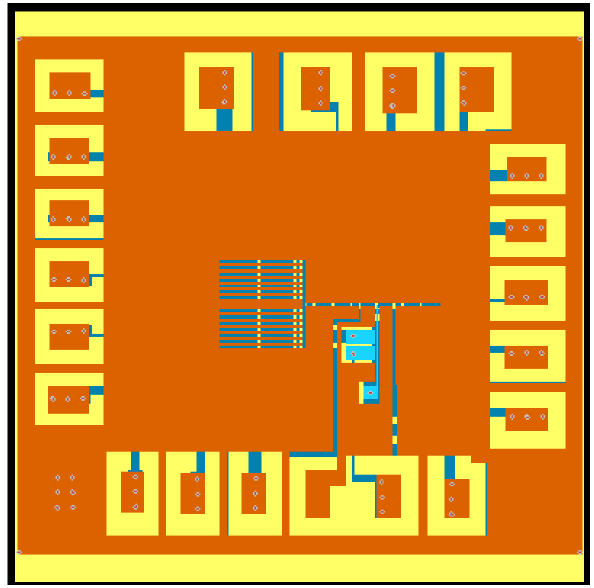
Top view:

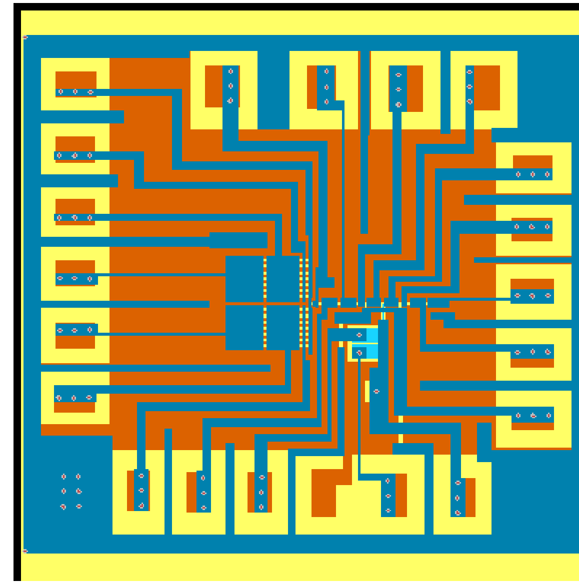
Red = top thick metal
Skyblue = top thin metal
Navyblue = bottom metal
Yellow = no metal

Finalized hybrid PCB device !

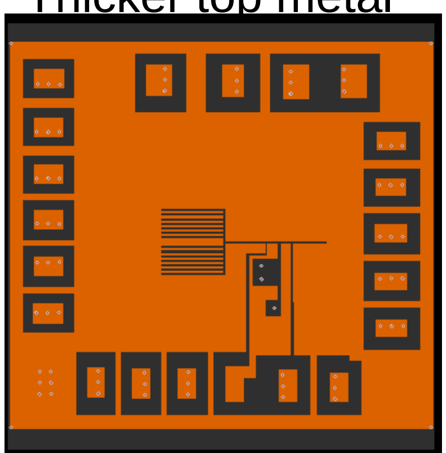




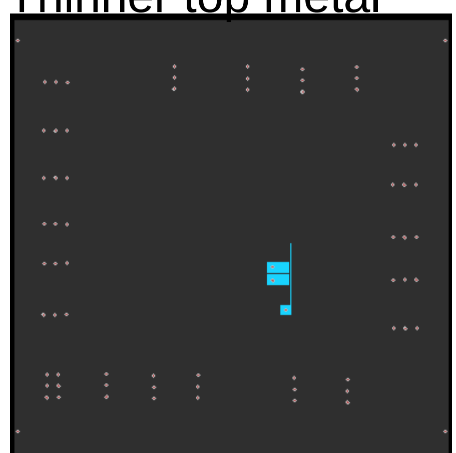




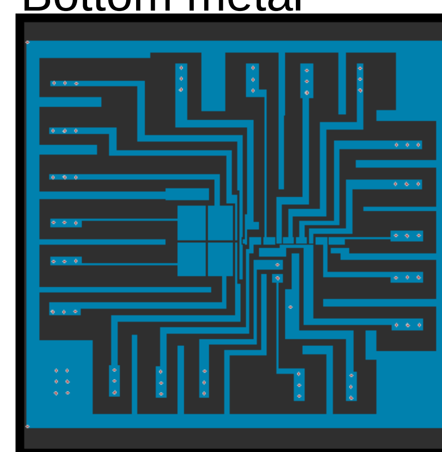
Thicker top metal

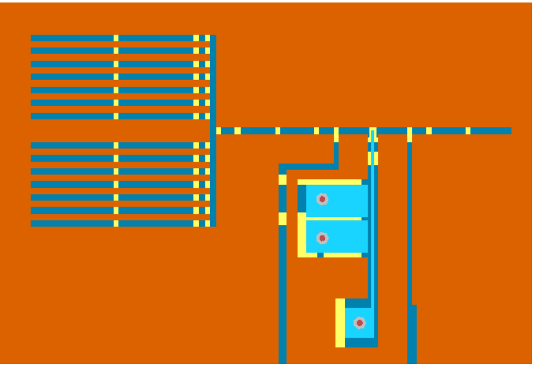


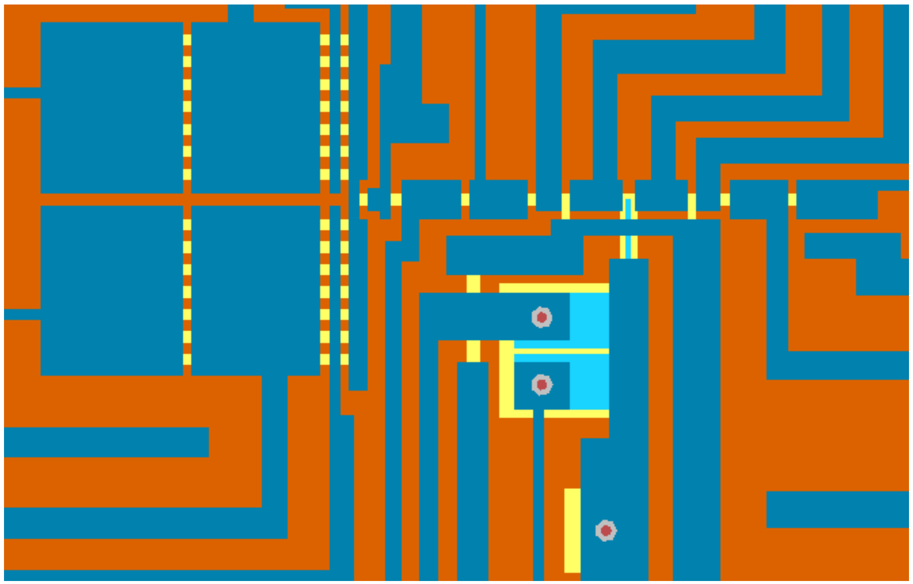
Thinner top metal



Bottom metal







<u>Extra wires needed for:</u>

-Utilized Twiddles/Senses in experimental channel require a total of 2 DC wires to control Sense offset & HEMT sourse offset (true?) and 2 AC wires for twiddle modulation and HEMT drain current

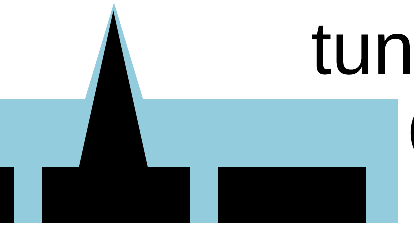
- 2 wires for thermal emission filament
- 2 wires for He level meter capacitor
- 2 wires for thermocouple?

<u>Electrical leads not shown:</u>

- The main top negative plane needs a bond wire
- The separated piece of top metal plane needs a separate bond wire to act as an ohmic drain

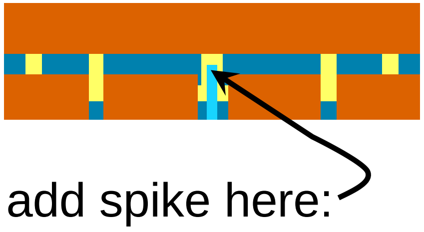
PCB device plans

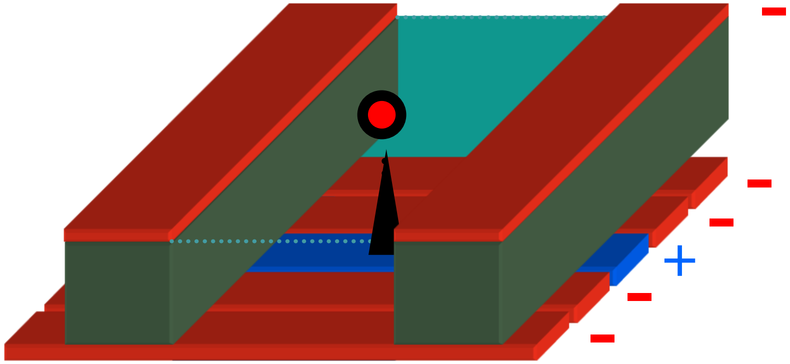
Device-mod ideas (FIB deposition)



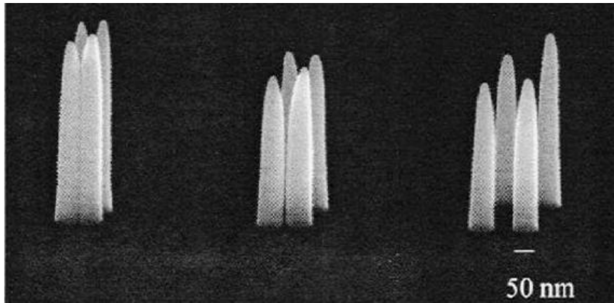
- protruding spike: Nanosized Ohmic drain for tunneling thru v.d.Waals film
  (Proof of principle and control experiment for…)

- submerged spike: quantized "dot" occupation for classical gas
  (Coulomb repulsion but no quantum interference)





FEI Company



Plans and crazy ideas

Short term:

- work with Clint in making cascode amplifier and test its gain as function of drive frequency (and input capacitance?) Repeat with HEMT at low T?
- work with Jay and UCT machine shop(s) in designing, fabricating, and installing the hermetic superfluid helium cell including its wiring and plumbing
- design, fabricate, and install holder PCB (with R,C&HEMT and connectors)
- plan and install wiring from connectors (24 pin DC and Coax) to cell feedthrus
- characterize the PCB devices with optical (and electron beam with Nasheeta's help) microscopy
- model the electric potential at the helium surface for some combinations of gate voltages using a 2D or 3D Poisson solver

Medium term:

- design & test circuit for flashing the thermal emission filament & collecting electrons in vacuum at RT and again in vacuum at low T
- design & test superfluid helium level meter & injection system (just a calibrated volume at RT?, or prefer a gas flow controller?)
- experiments with PCB device
- design & fabricate micro/nano devices with Oak Ridge National Labs, including PCB device modifications
- consider improvements and alternative applications