Electron Spin Qubits on Liquid Helium

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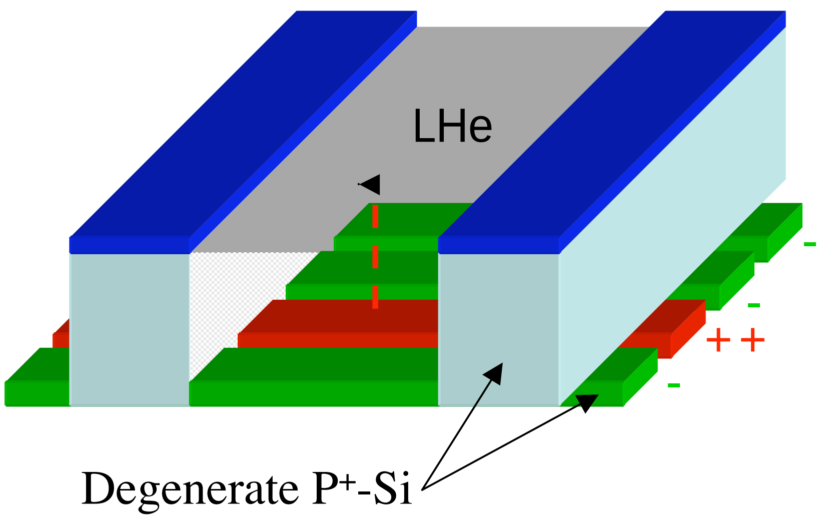
1. Electron spins as qubits
2. Quantum dot plans for single spin measurements
3. Clocking electrons on the surface of helium
4. Photoemission electron source

Helium channels for electron transport

- For storing and moving qubits, we need a fairly high qubit density – electrons a few μm apart
- To electrostatically control individual electrons, the electrodes must be no farther than a few μm from them
- The channels are a convenient way to produce helium films a few μm deep, in a controlled manner



- The electron motion is controlled with electrodes below the channels
- This is the structure of a buried-channel Si CCD
- Channel width and gate period = 4 μm; depth = 2 μm

Spin Decohence Times

- Can move qubits, so normally keep them far apart (dipole-dipole at 10μm ~ **10^4 sec**)
- Residual spin-orbit interaction (v x E)
  - v ~ 10^6 cm/sec, E ~ 10^4 V/cm ⇒ $B_{effective} = B_{\|} \sim 10^{-7}$ T
  - $B_{\|}$ changes direction as electron scatters, so
    $$1/T_2 = \frac{1}{2}\gamma^2 \overline{B_{\|}^2} \frac{\tau}{1+\omega_0^2\tau^2}$$
  - For τ ~ 100 nsec ⇒ T_2 ~ **10^6 sec**
- ^{3}He impurities on ^{4}He surface (~ 0.01/μm^2) with motional narrowing ⇒ T_2 ~ **10^5 sec**
- Johnson noise currents in gate layers:
  $$T_2 = \frac{64\pi}{\gamma^2\mu_0^2\sigma} \cdot \frac{d(d+t)}{t} \cdot \frac{1}{kT + \frac{3}{4}\hbar\omega_0 \coth(\frac{\hbar\omega_0}{2kT})}$$
  - d = distance to metal, t = metal film thickness
  - For degenerately-doped Si, d ~ 2μm, T ~ 30 mK ⇒ T_2 ~ **10^5 sec**
  - On thin helium (quantum dot & 2-qubit gate), degenerately-doped Si electrode, d ~ 400Å, t ~ 1000Å ⇒ T_2 ~ **1000 sec** at 30mK
- Fluctuations of local spin density in nearby metal
  - Thin helium, degenerately-doped Si electrode (p-type, T_1 for holes ~30ps), d ~ 400Å, t ~ 1000Å ⇒ T_2 ~ **2000 sec** at 30mK
- Nuclear spins in gates/channels (use degenerately boron-doped ^{28}Si)
  - Free carriers rapidly relax nuclear spins ⇒ > **10^4 sec**
- Paramagnetic defects?
  - Few defects with unpaired spins in Si, and those relaxed rapidly by free carriers

Quantum dots to measure spins

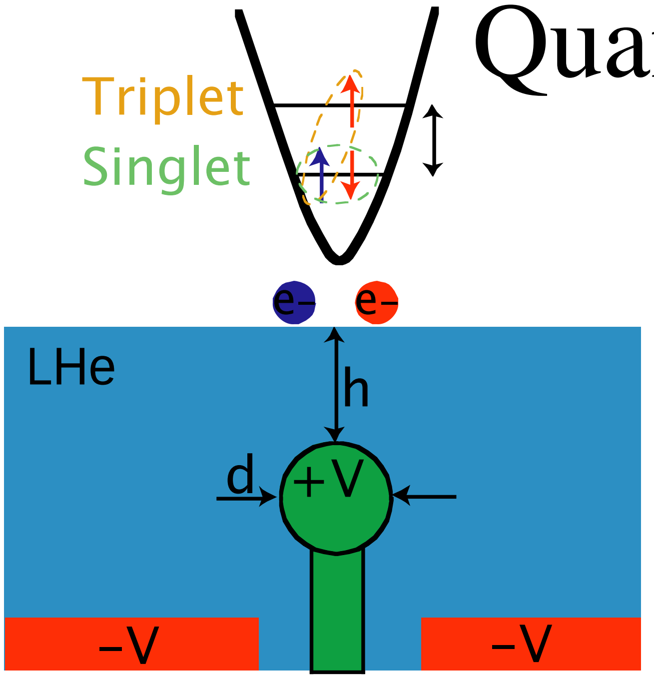
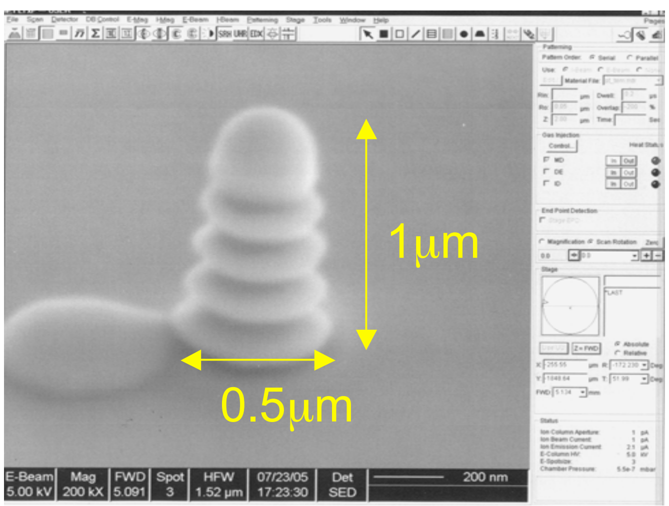
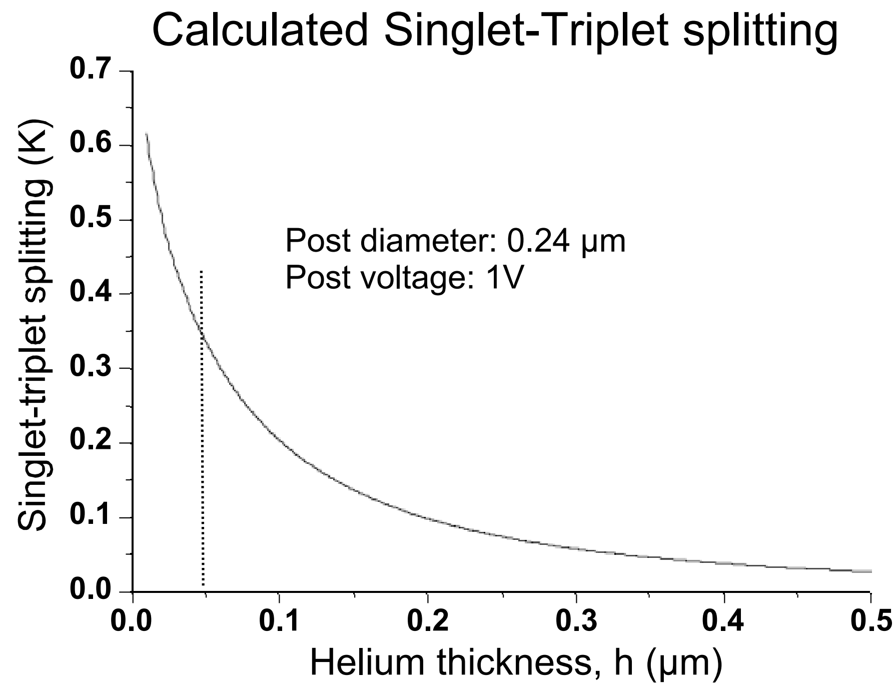


Diagram of a post and its harmonic potential

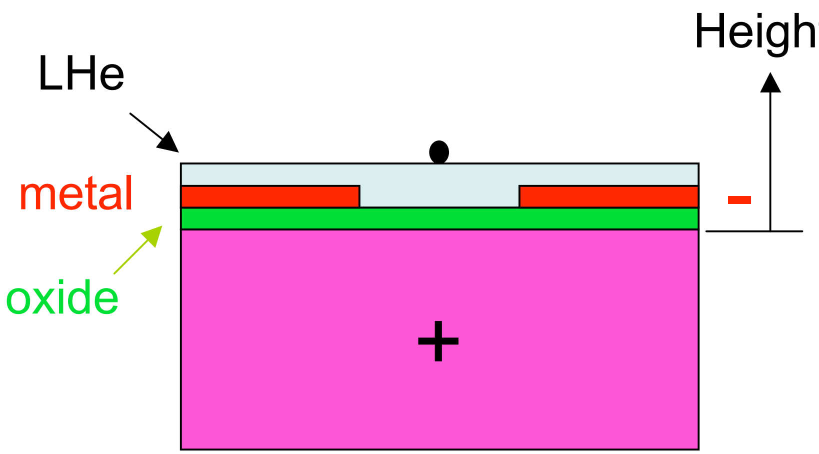


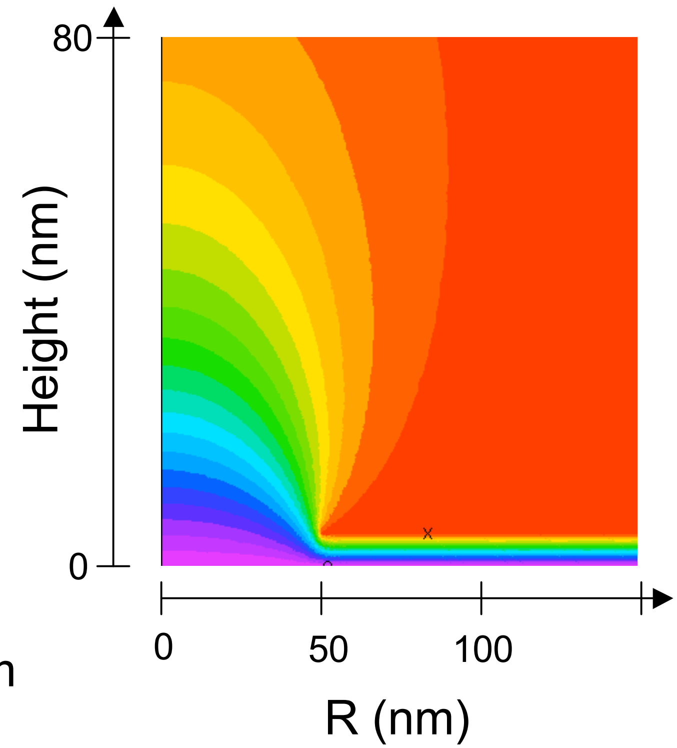
Platinum post made with FIB



A post creates a harmonic potential that splits the singlet and triplet energy levels.

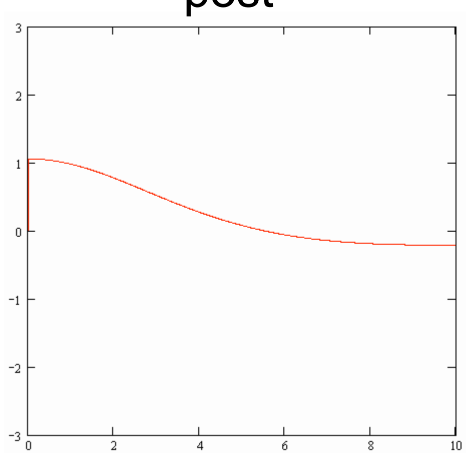
Planar quantum dot



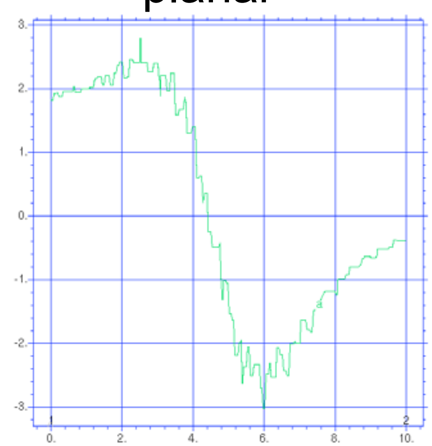


d^2V/dr^2 for post and planar dot, d=50nm and 1 volt bias (x100V/μm^2)

post



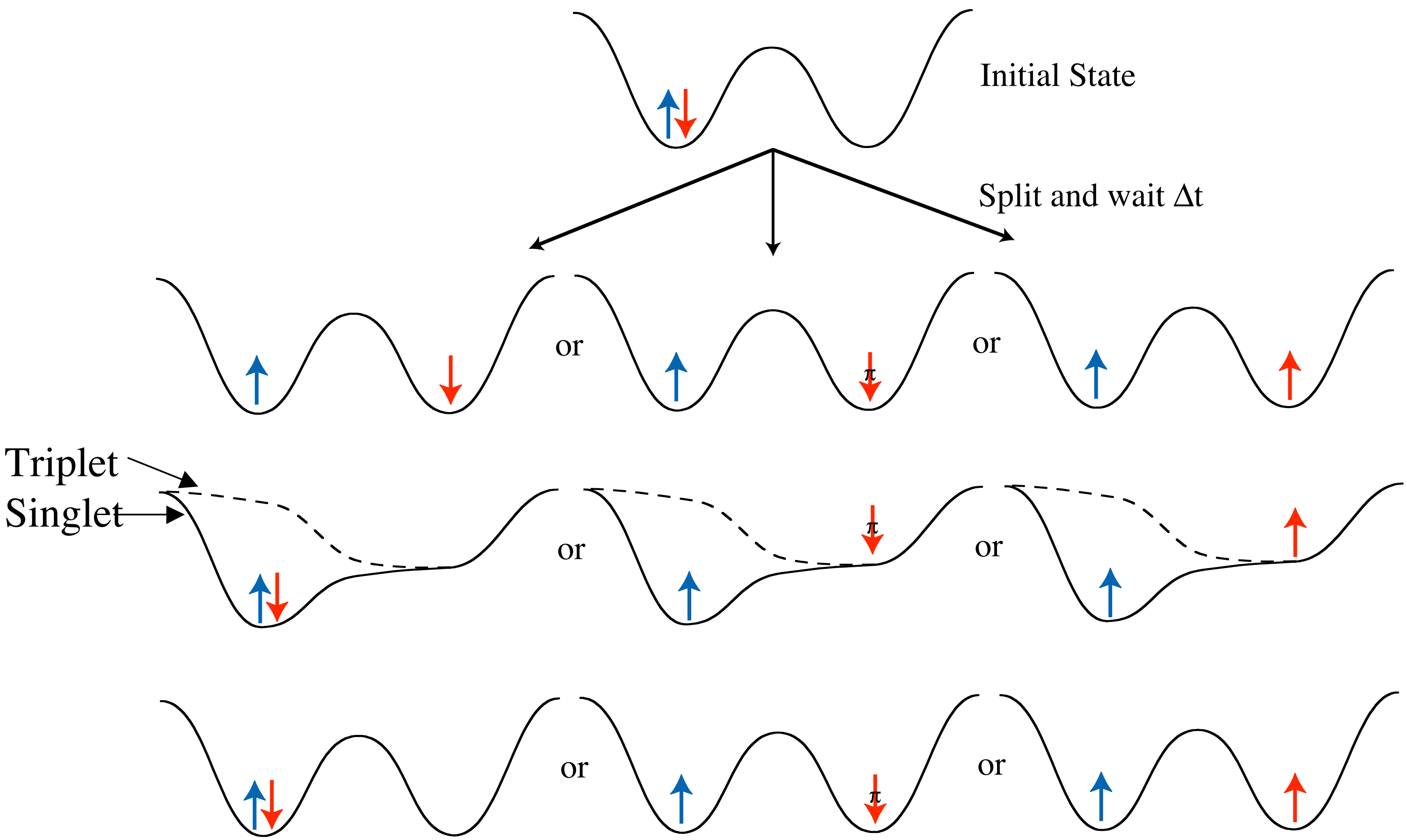
planar



Planar dot looks to be easier to make than the post, and should give ~2x larger level spacing ⇒ we'll try this first

Spin Coherence - Measurement Plans

(like in GaAs quantum dots)



Planar double quantum dot
(Dipole-Dipole CNOT)

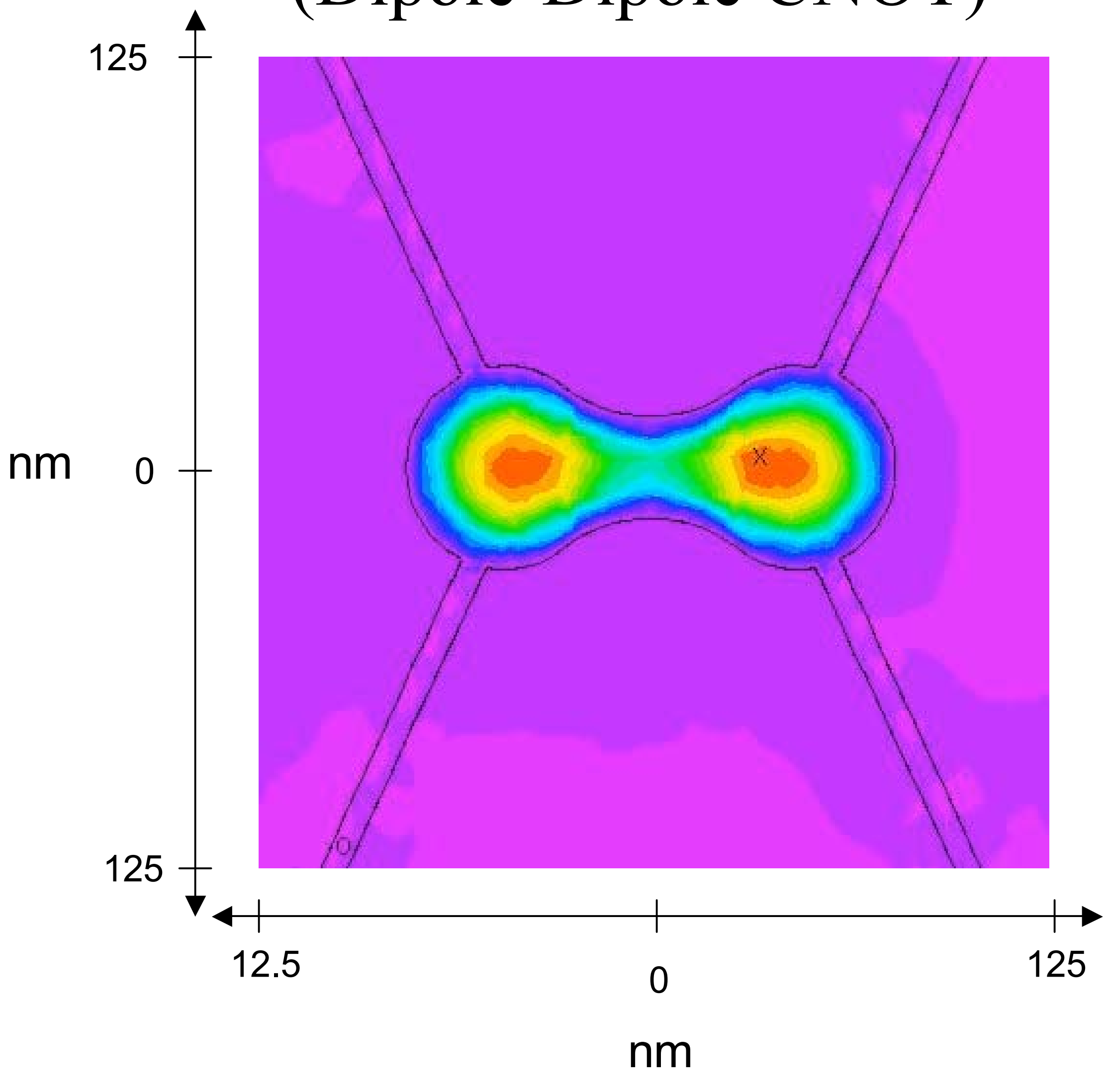
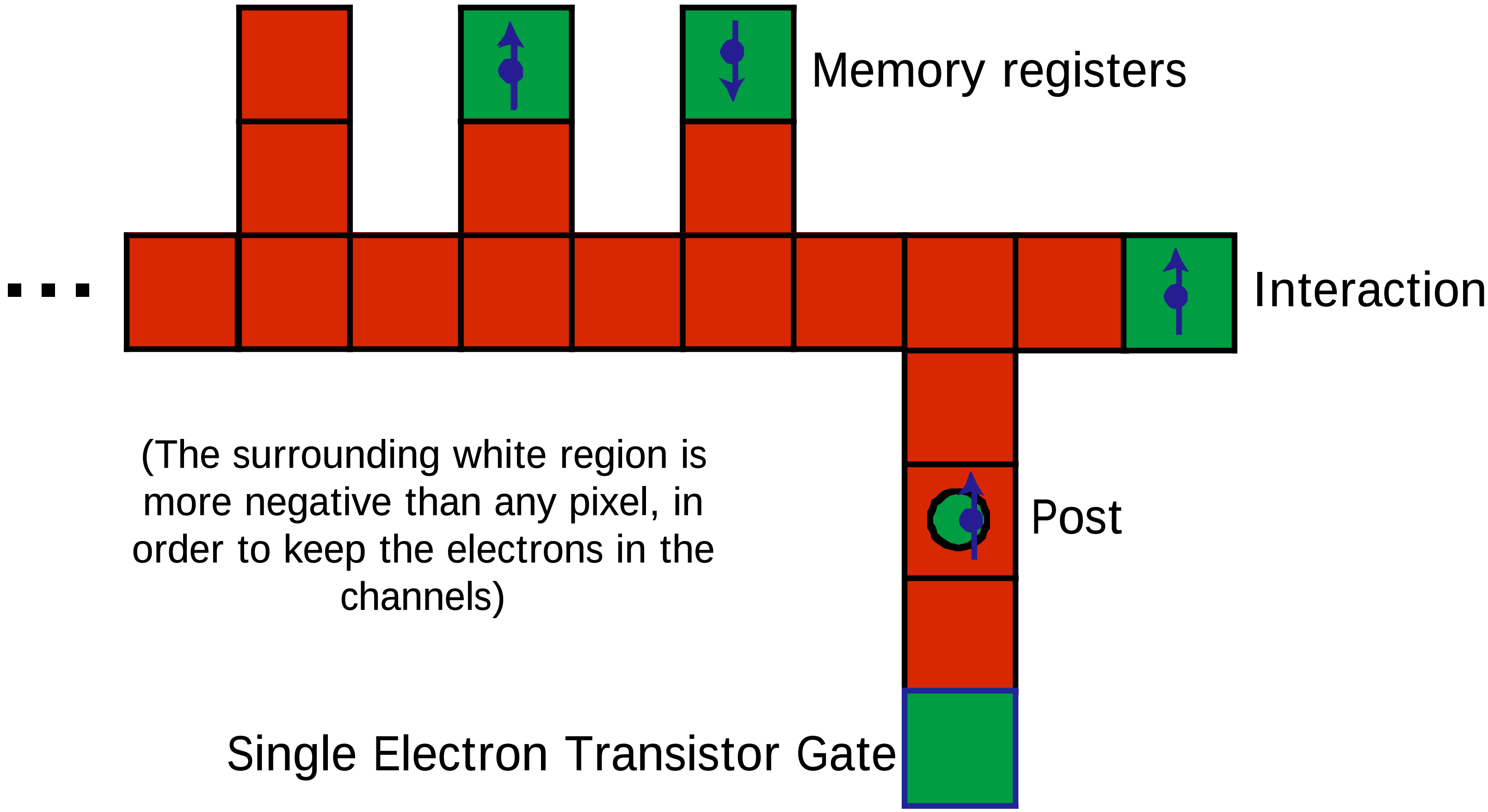


Illustration of Pixel Sequence



- An electron is taken out of memory, brought to interact with another electron and is then read.

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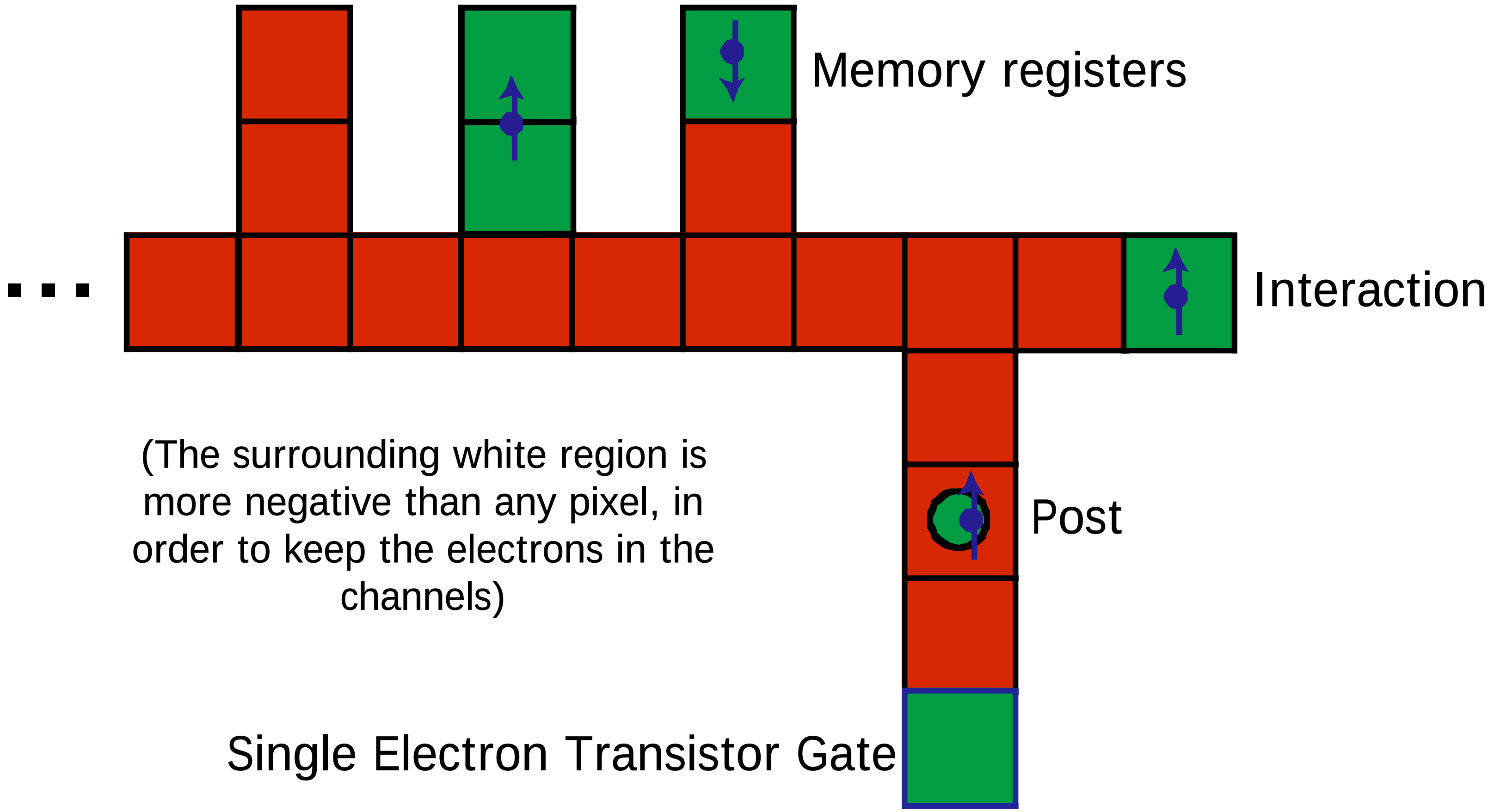

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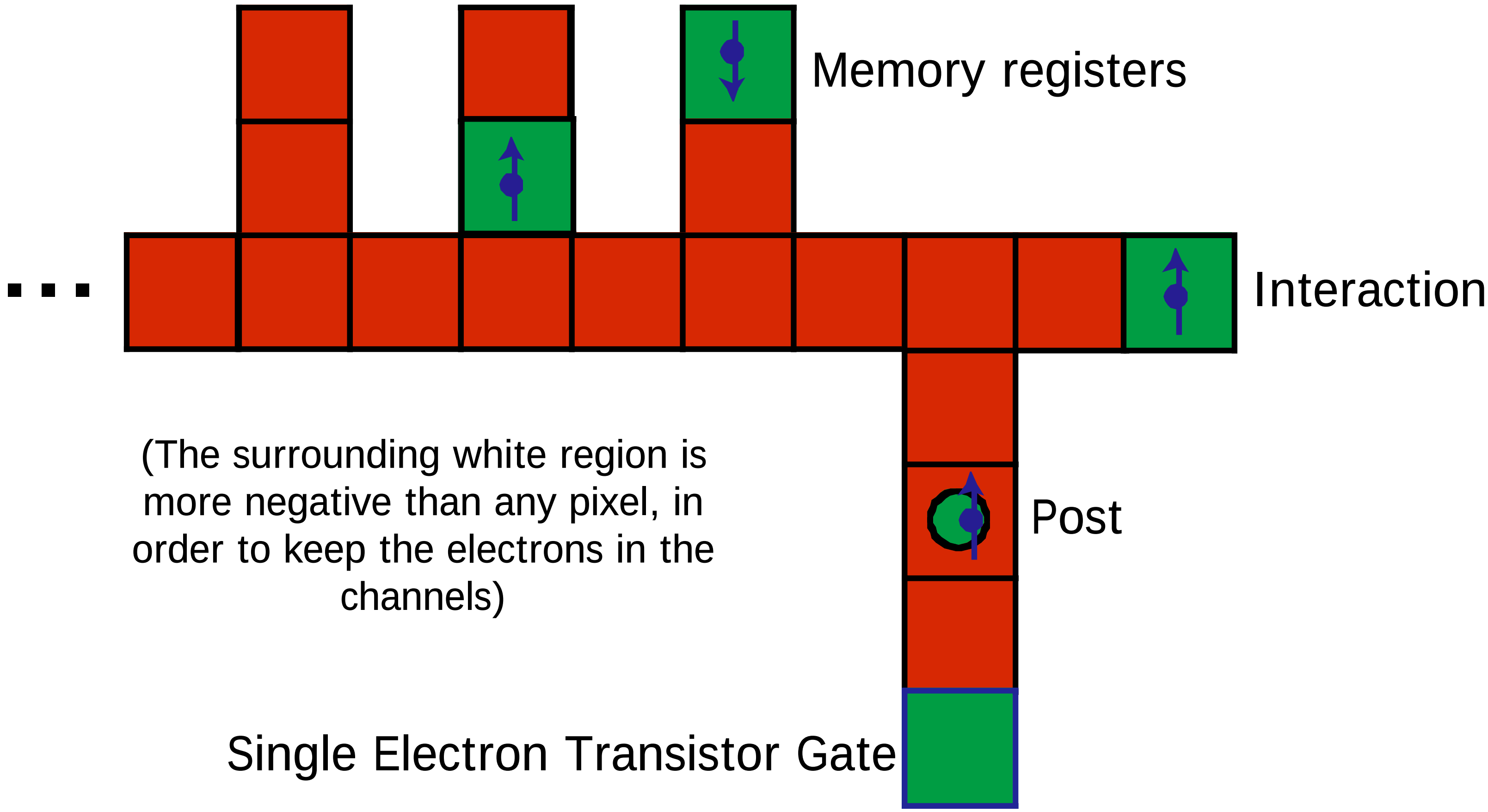

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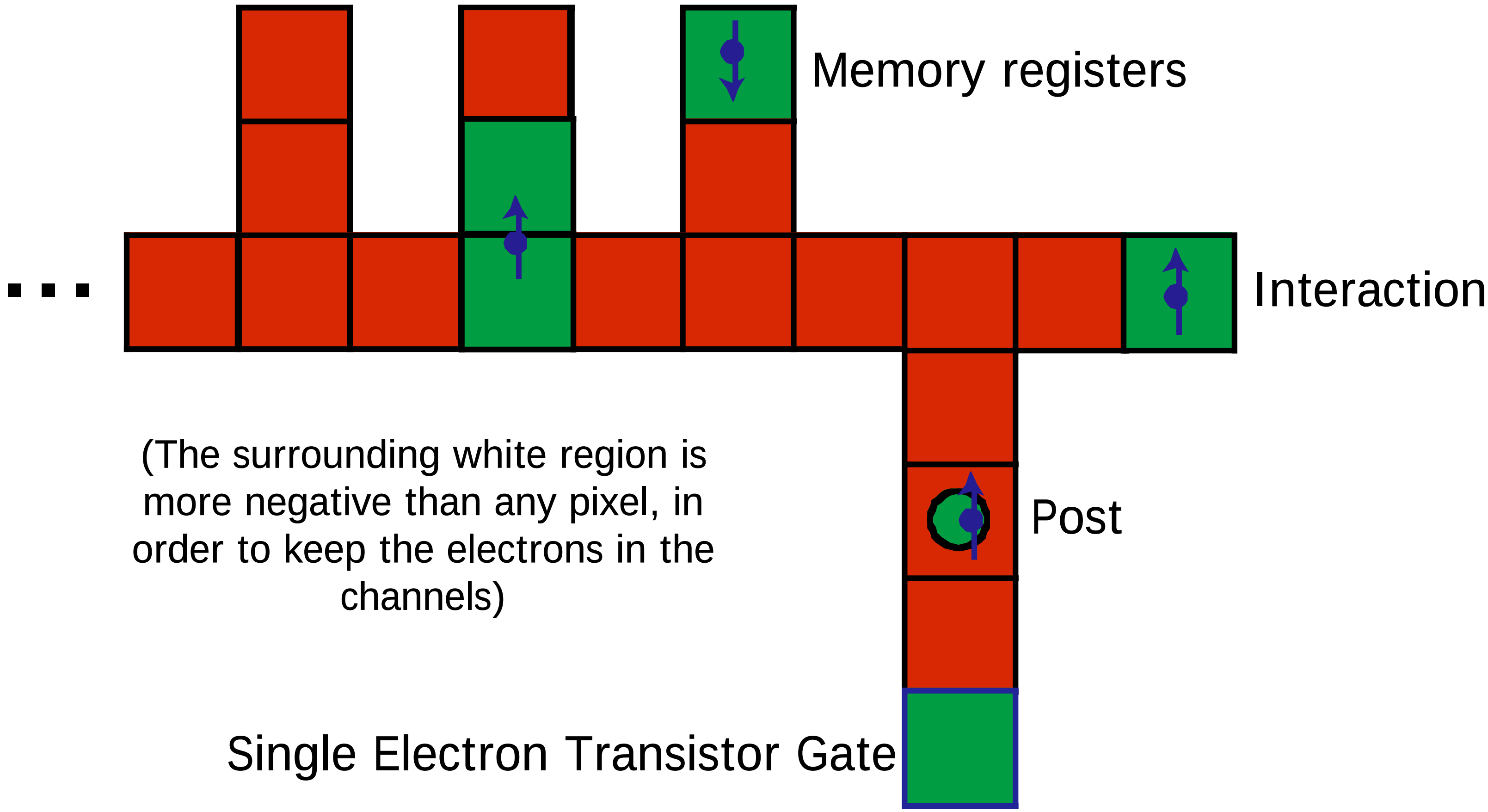

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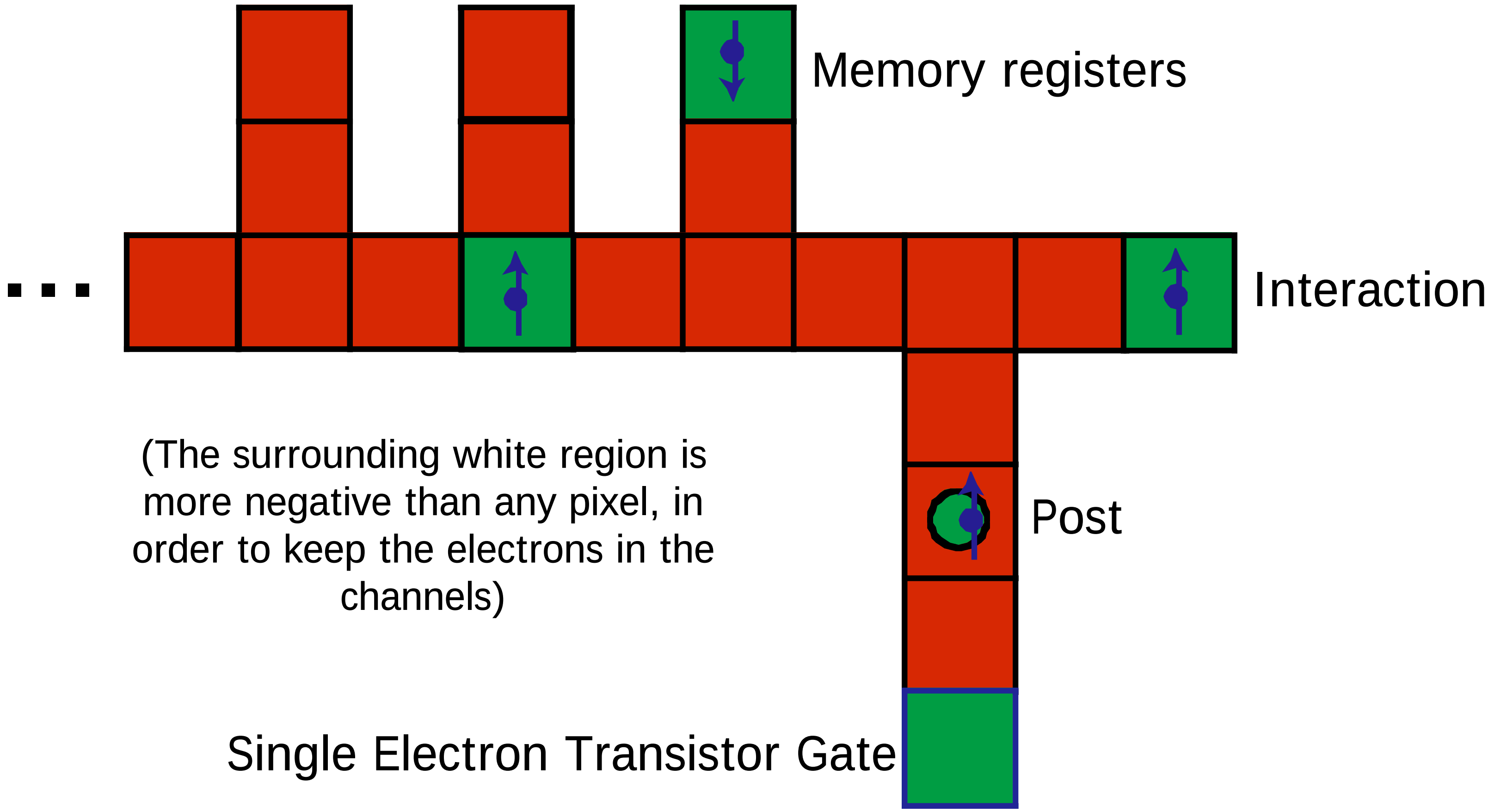

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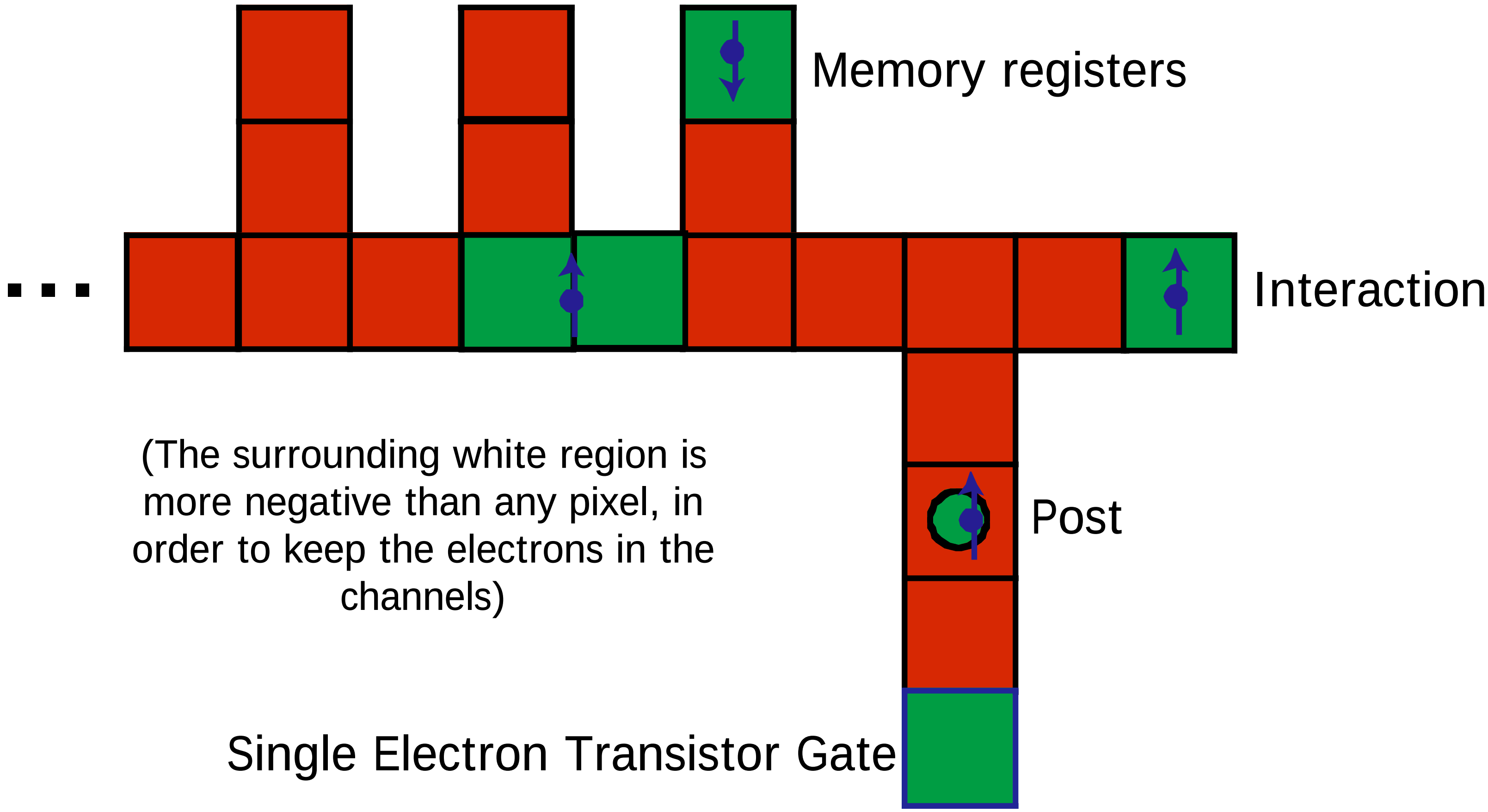

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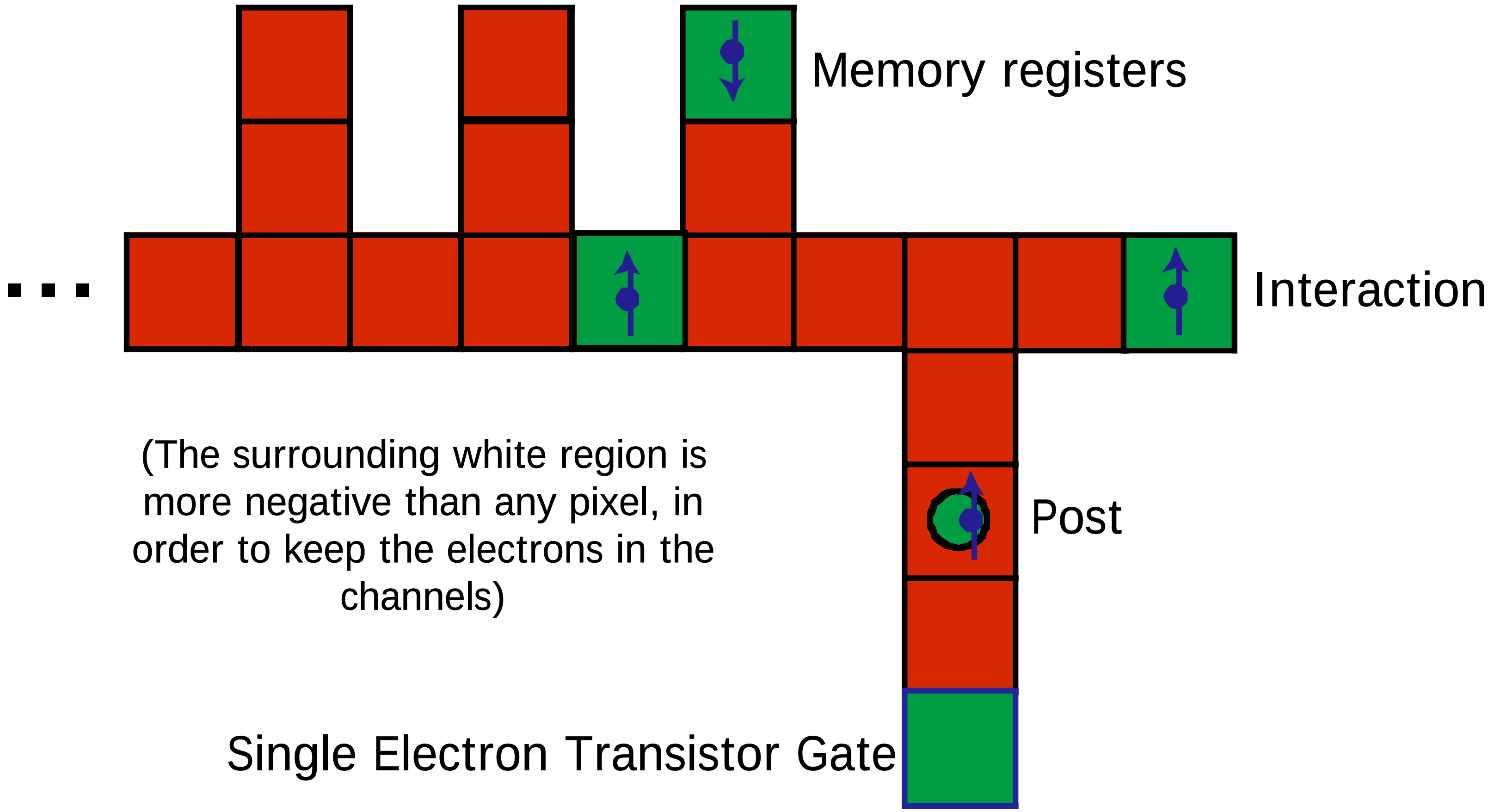

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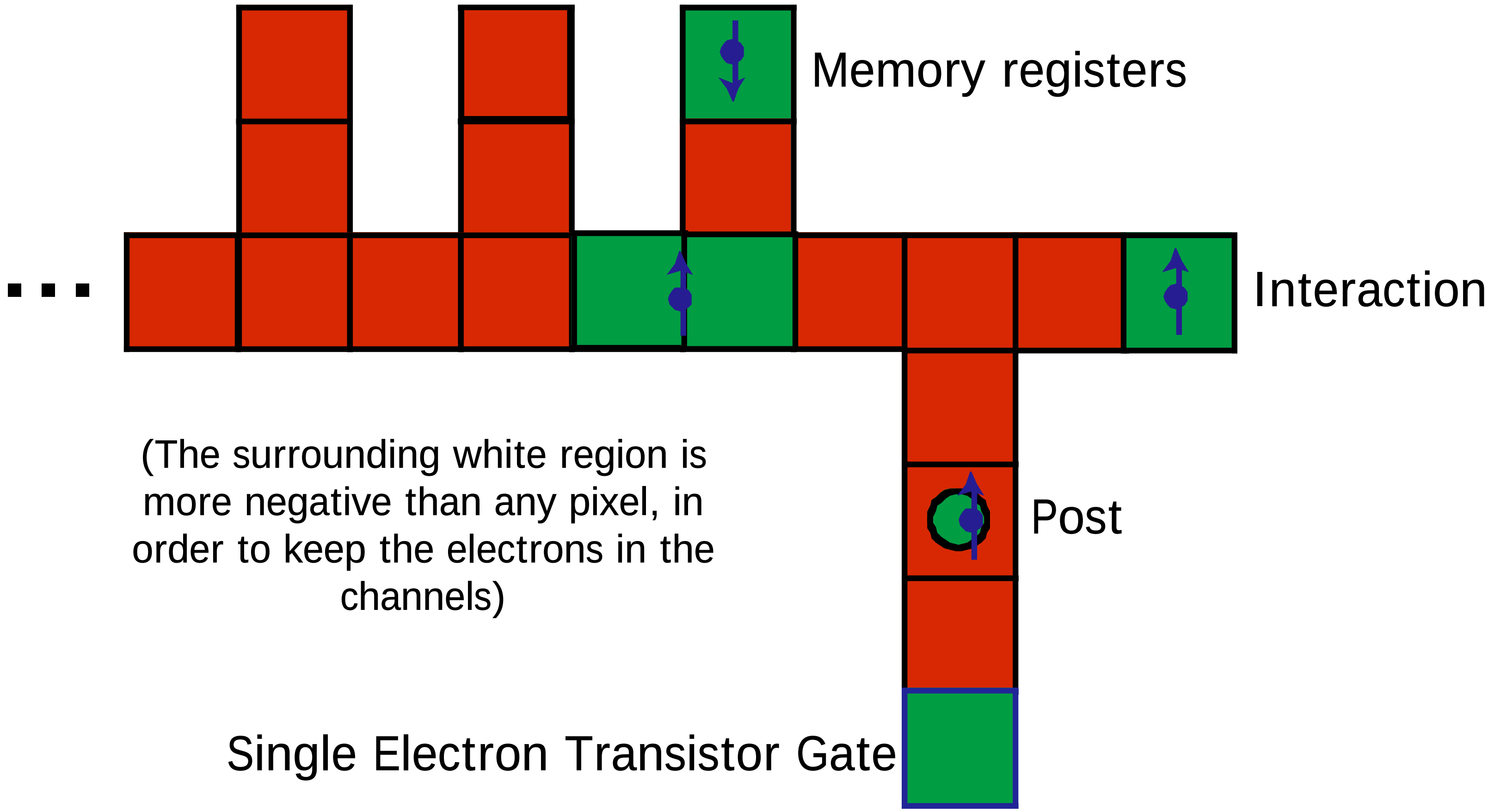

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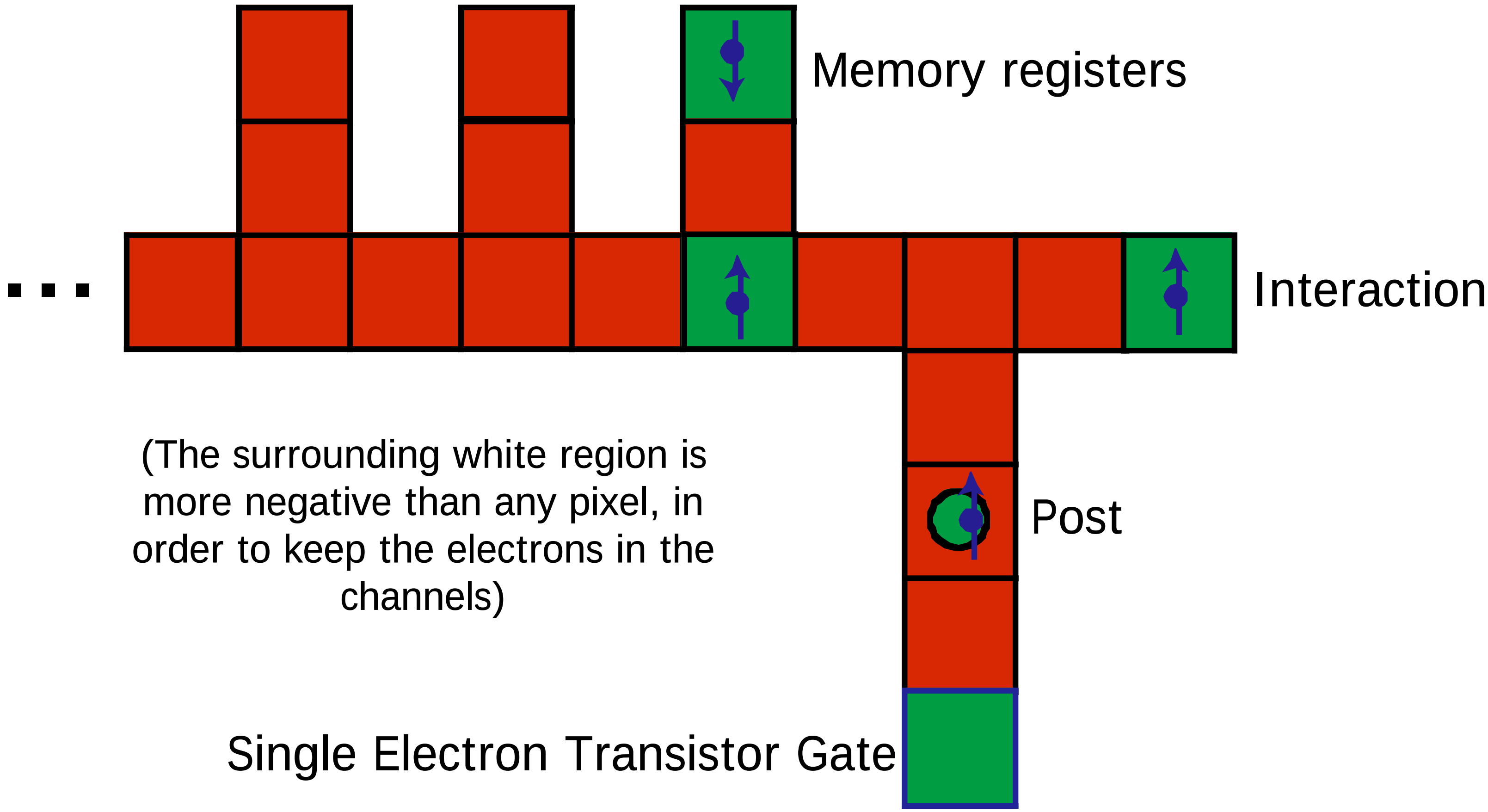

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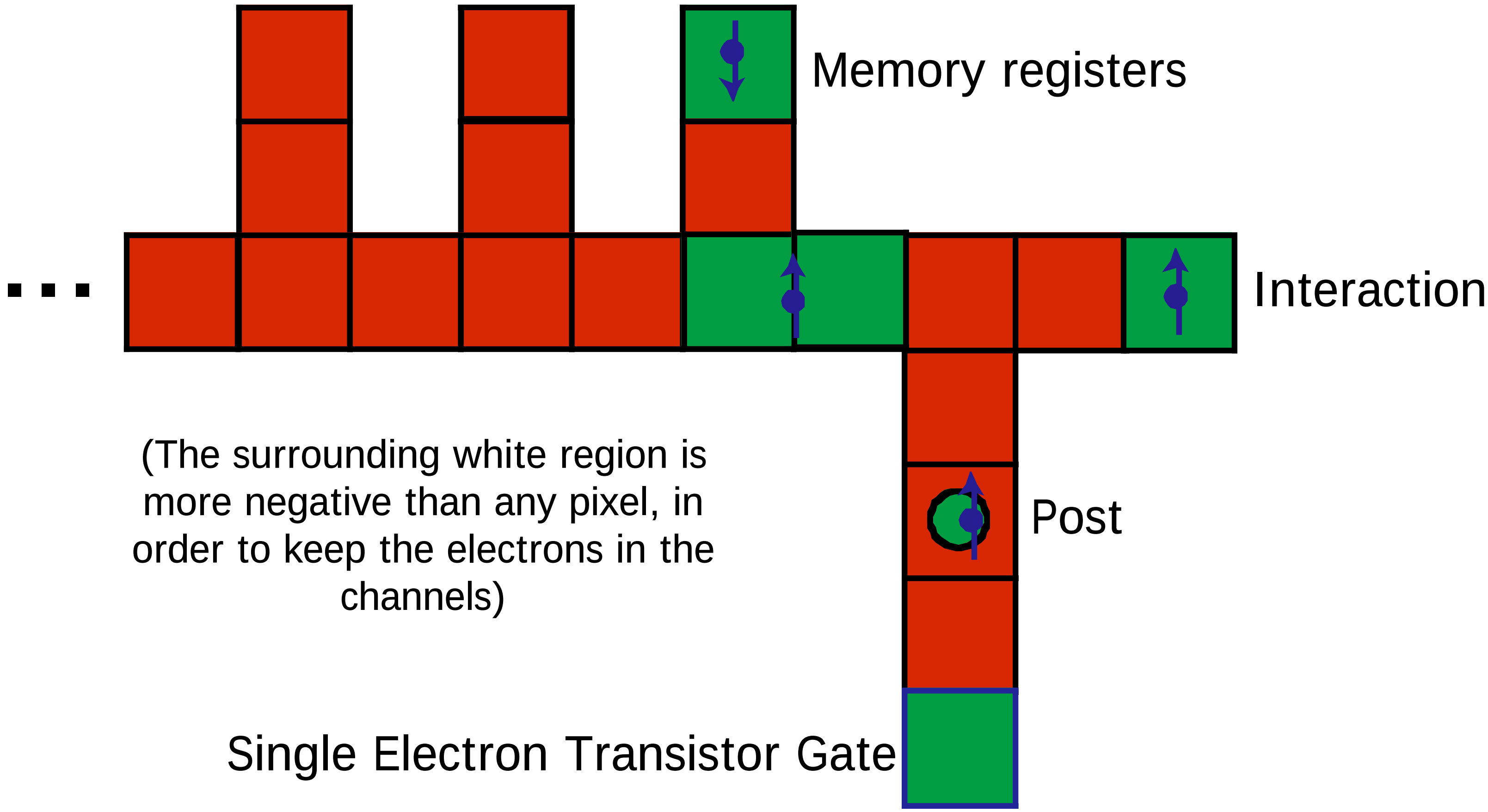

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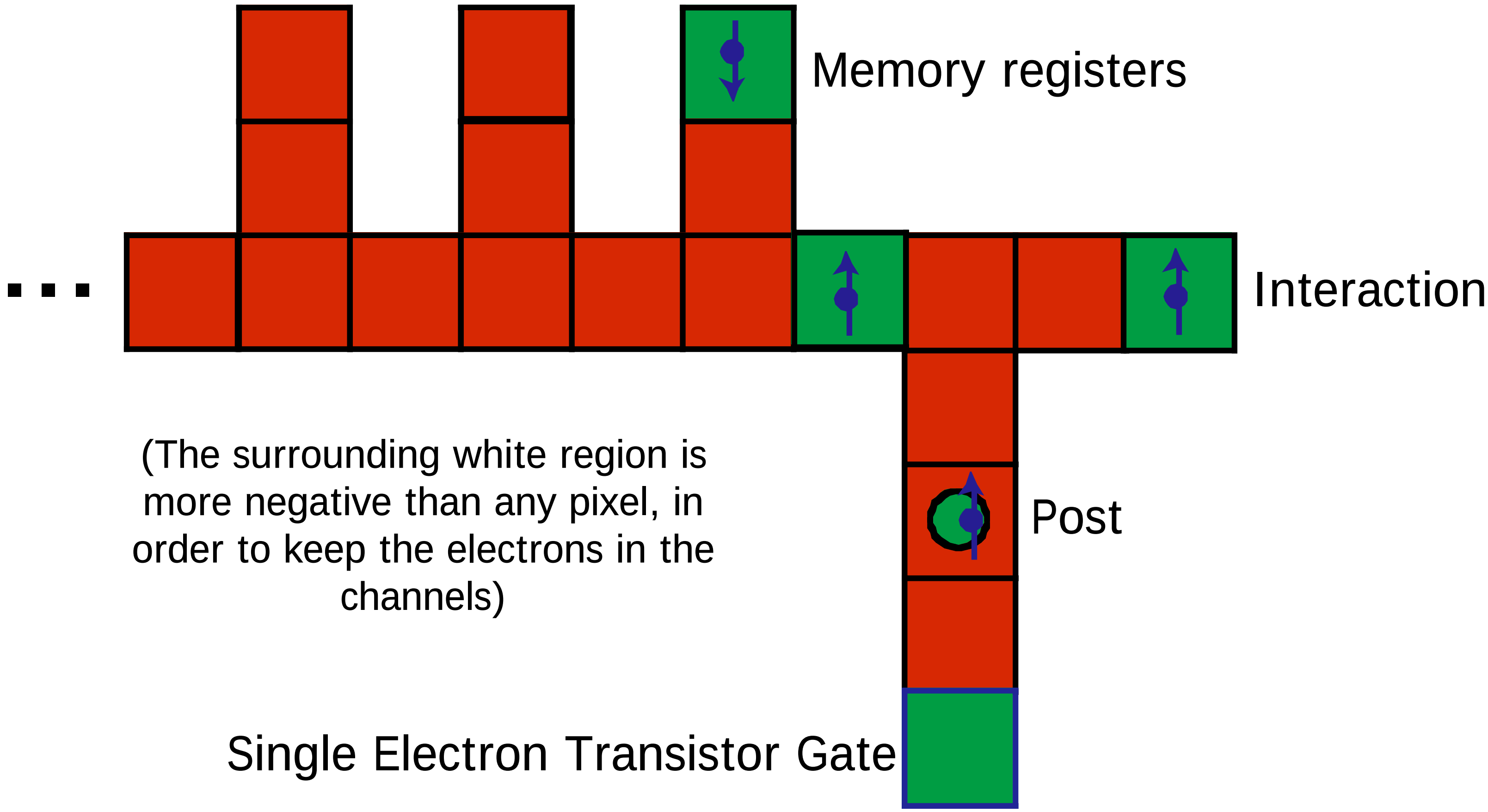

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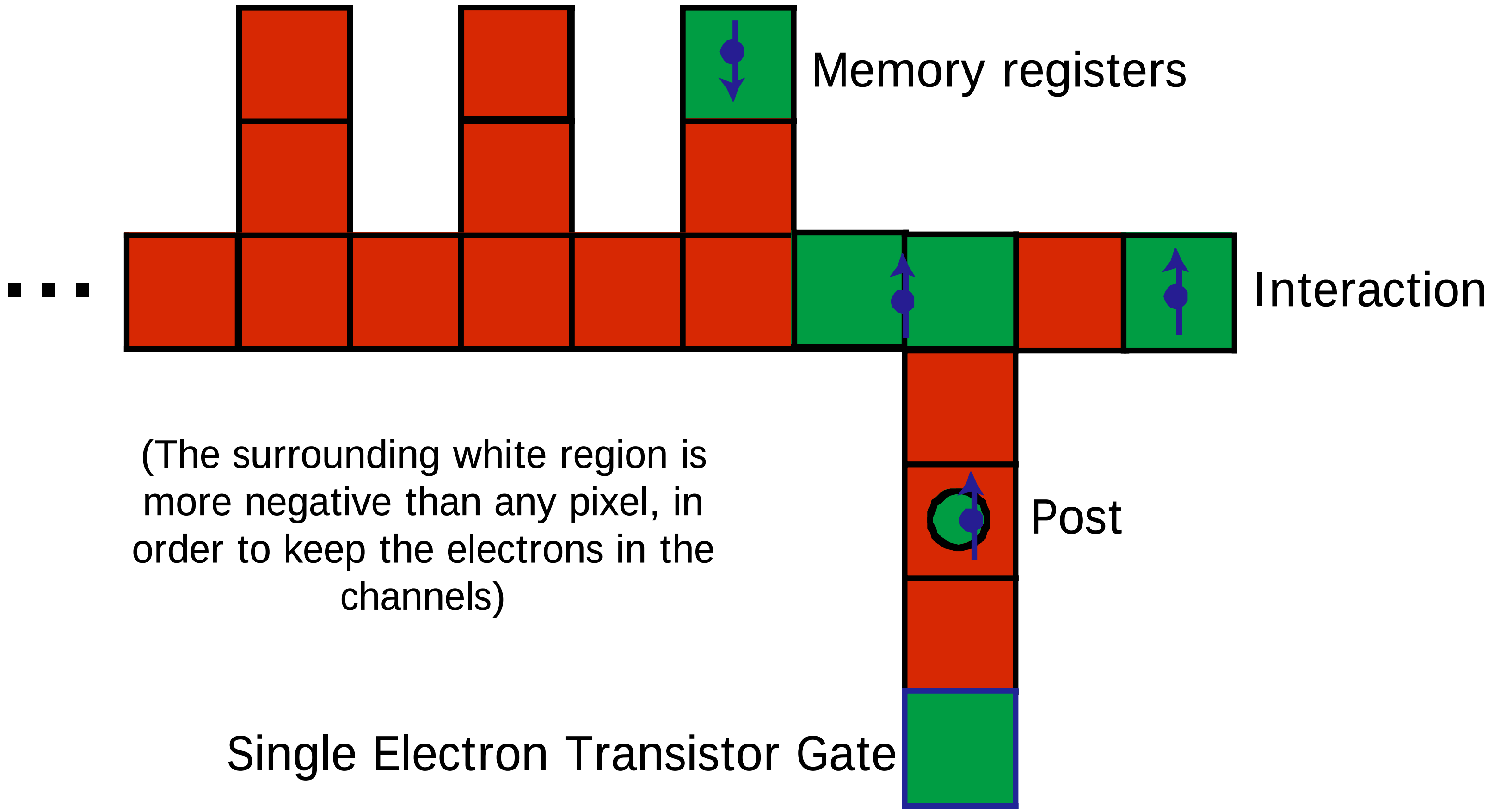

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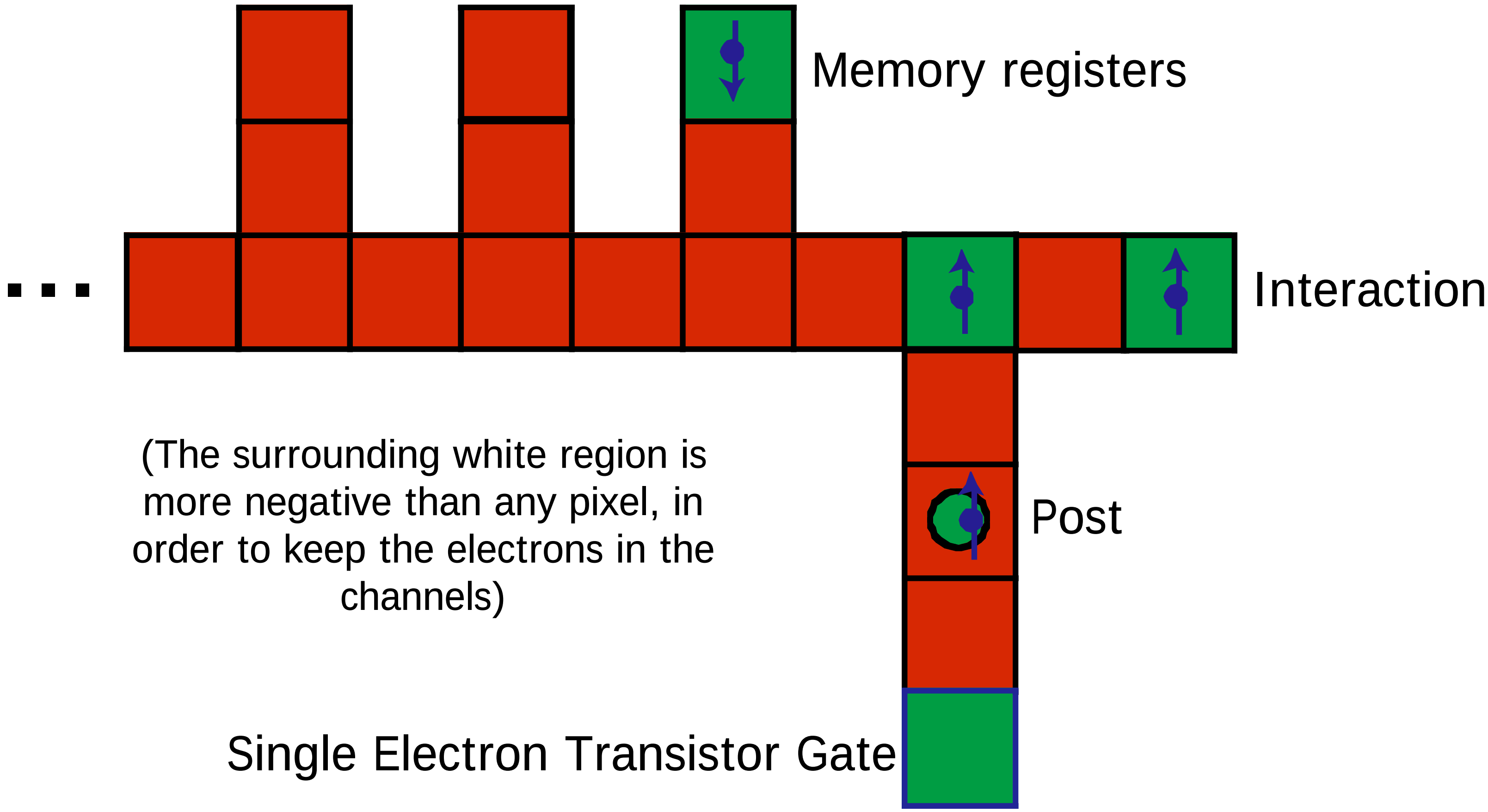

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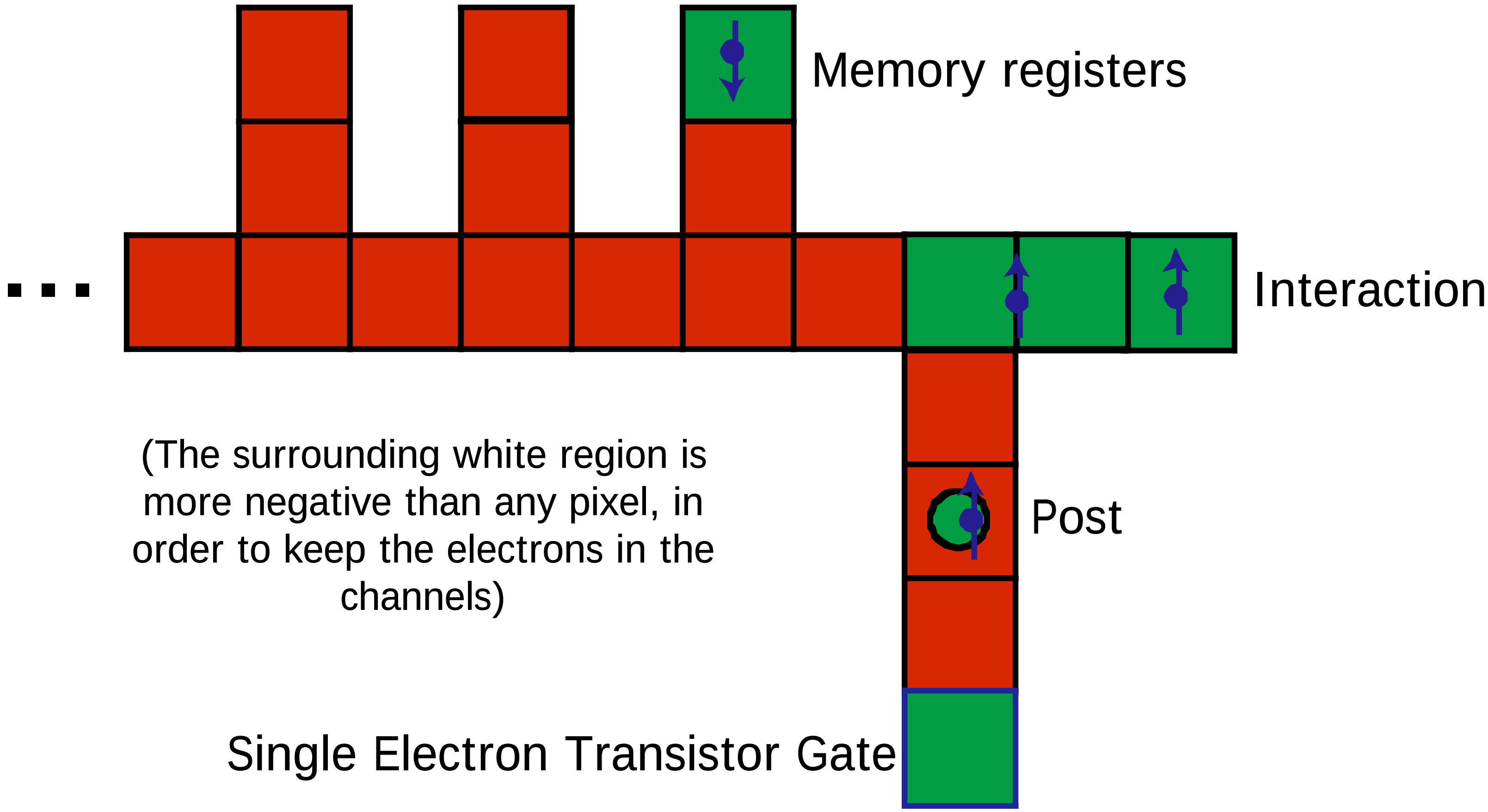

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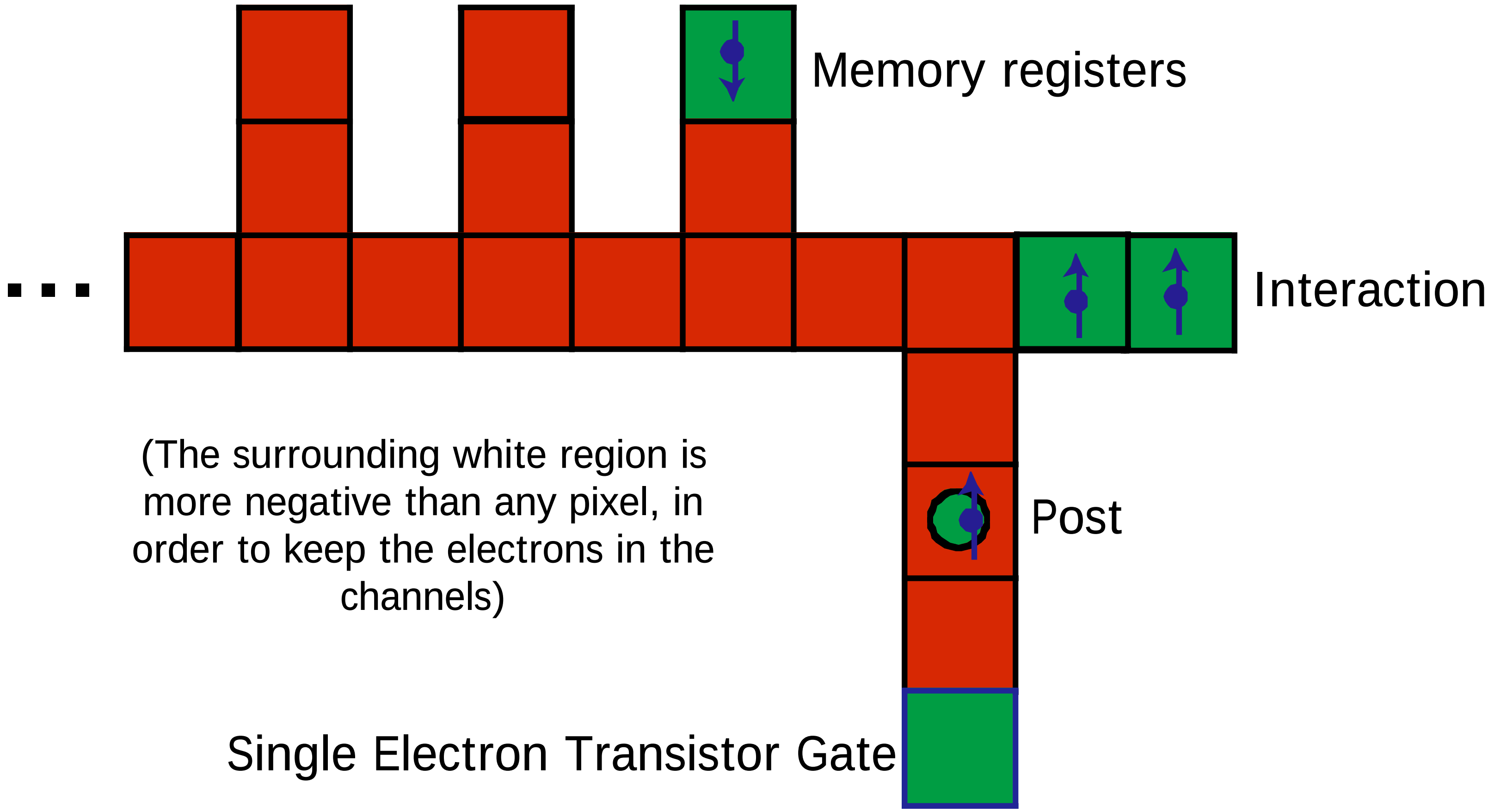

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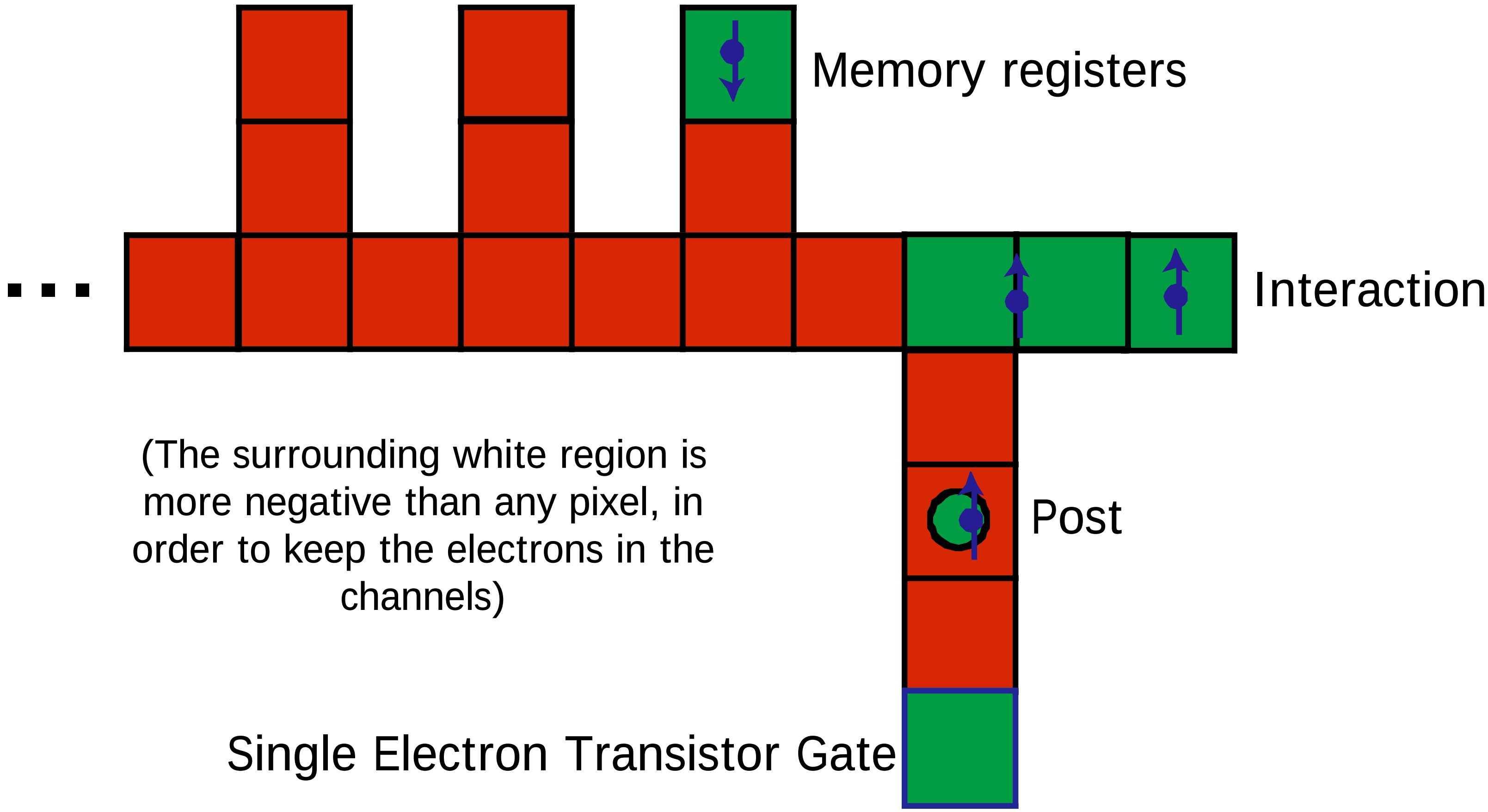

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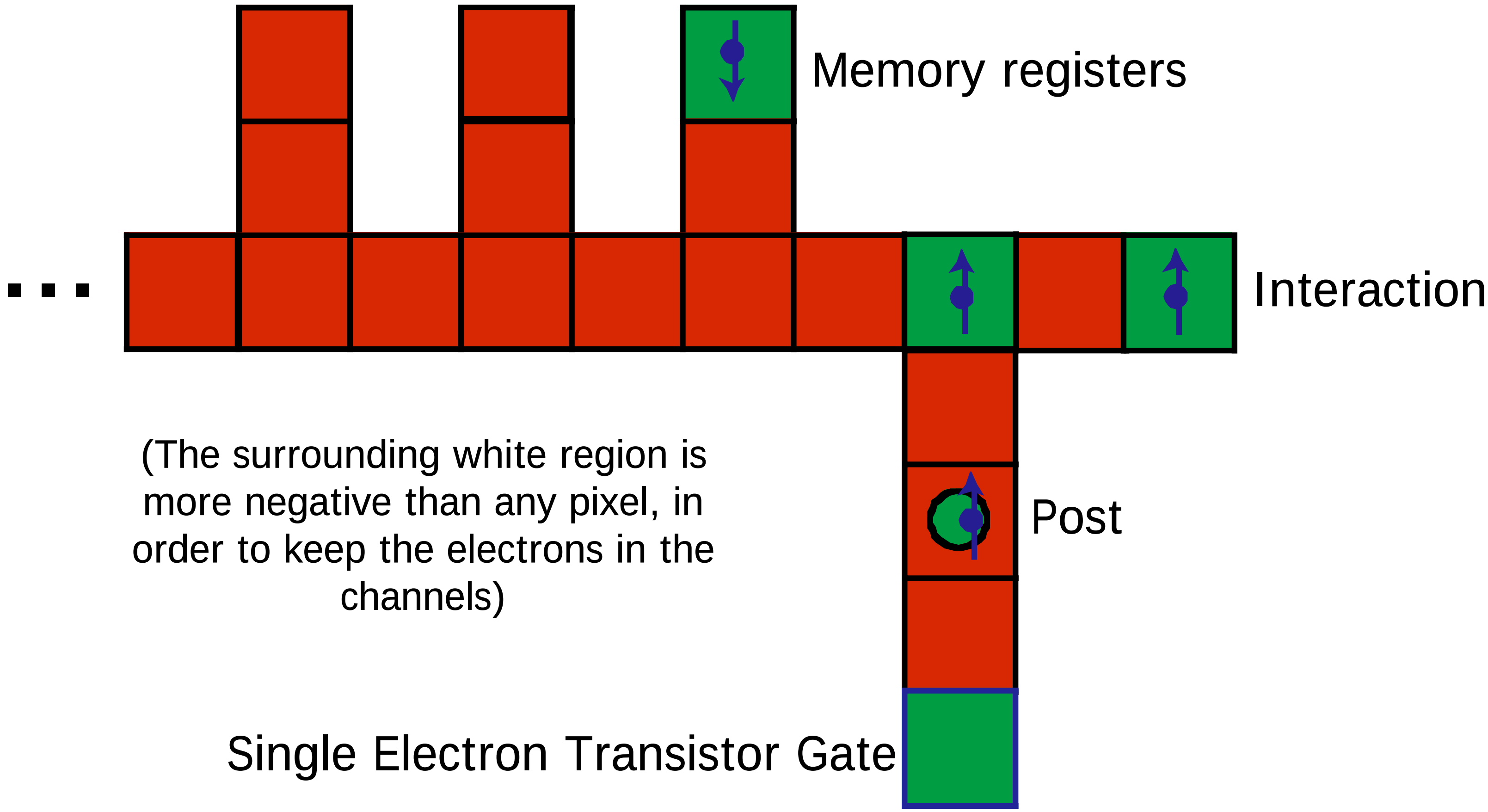

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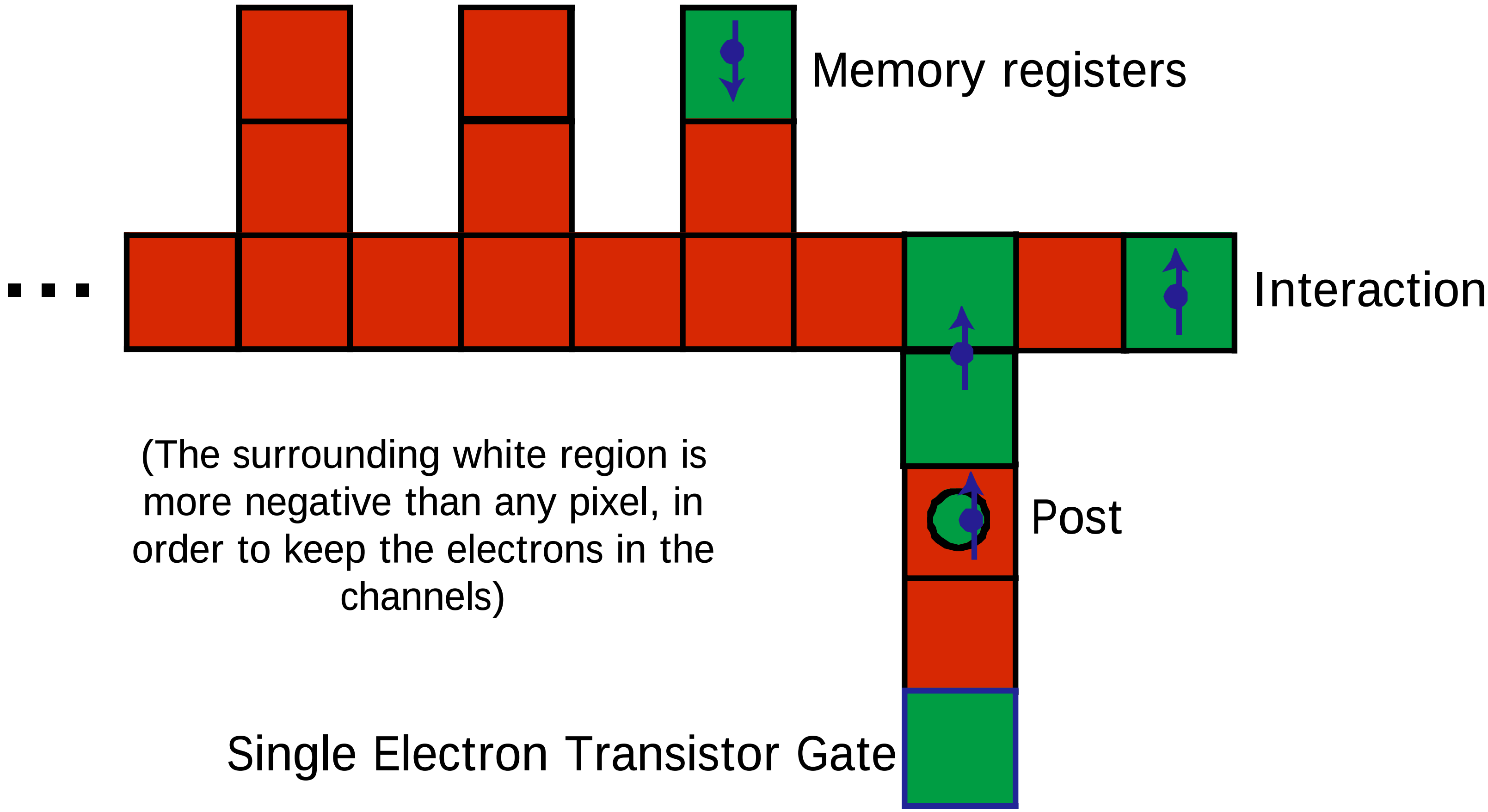

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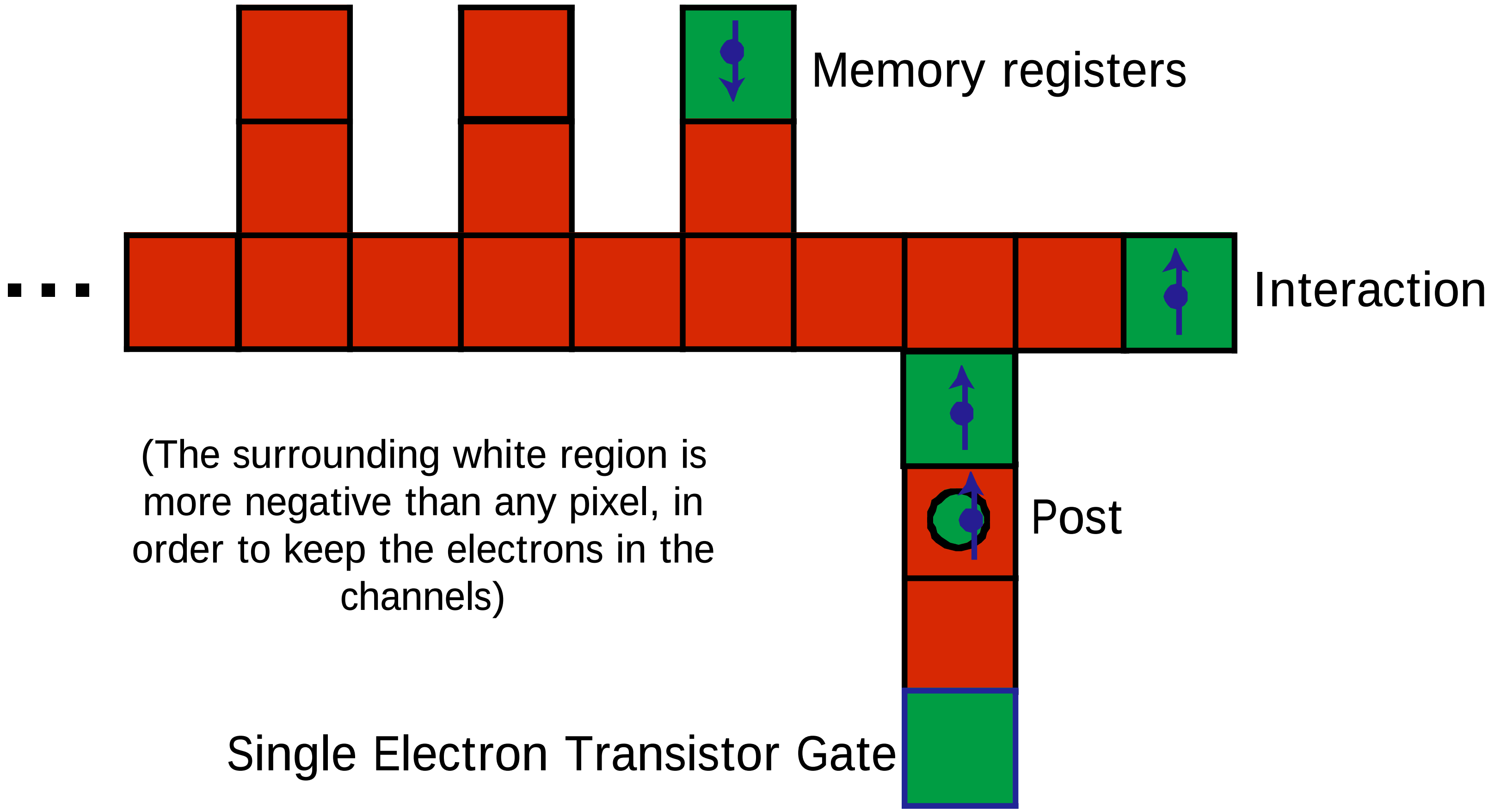

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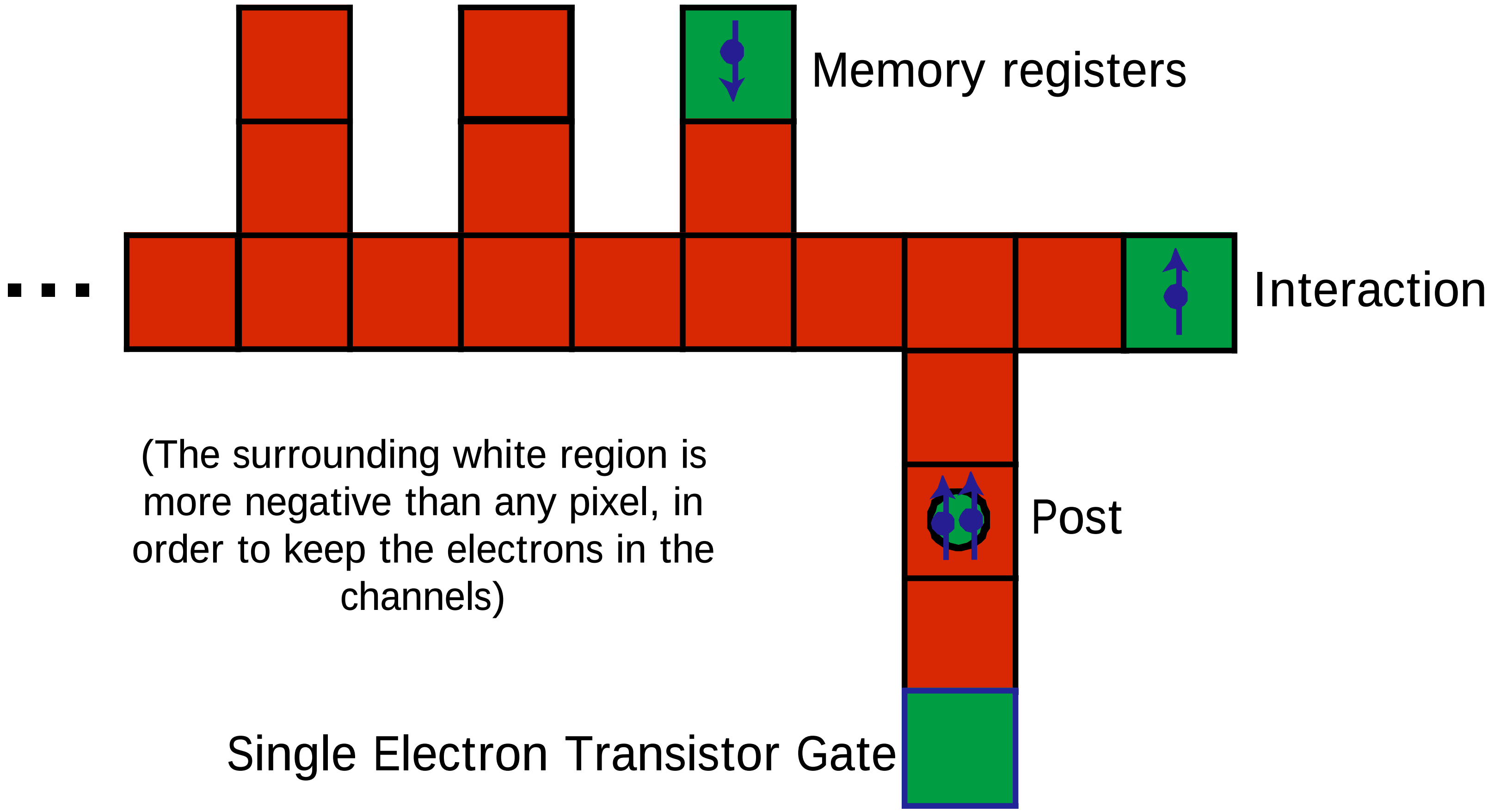

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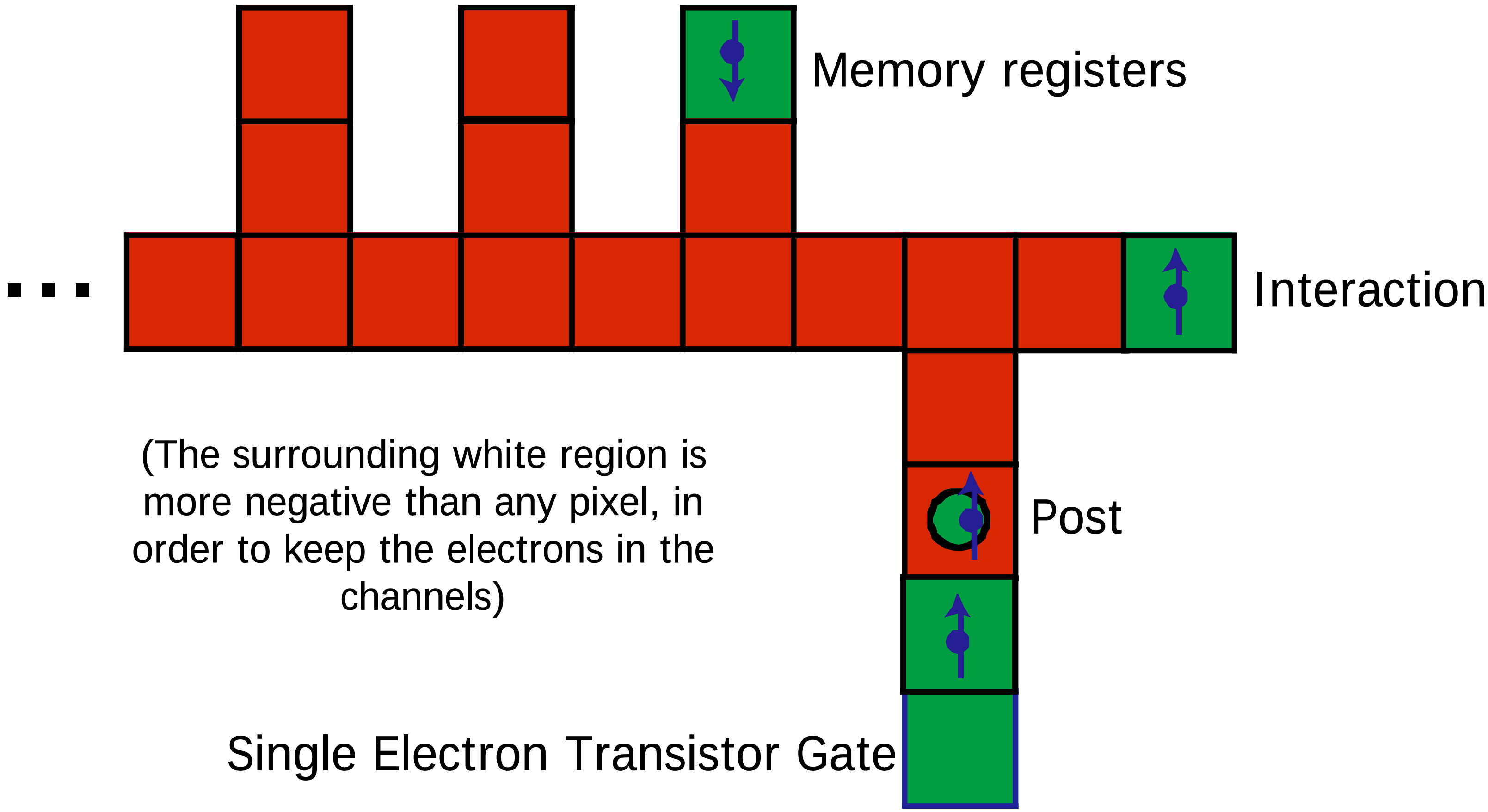

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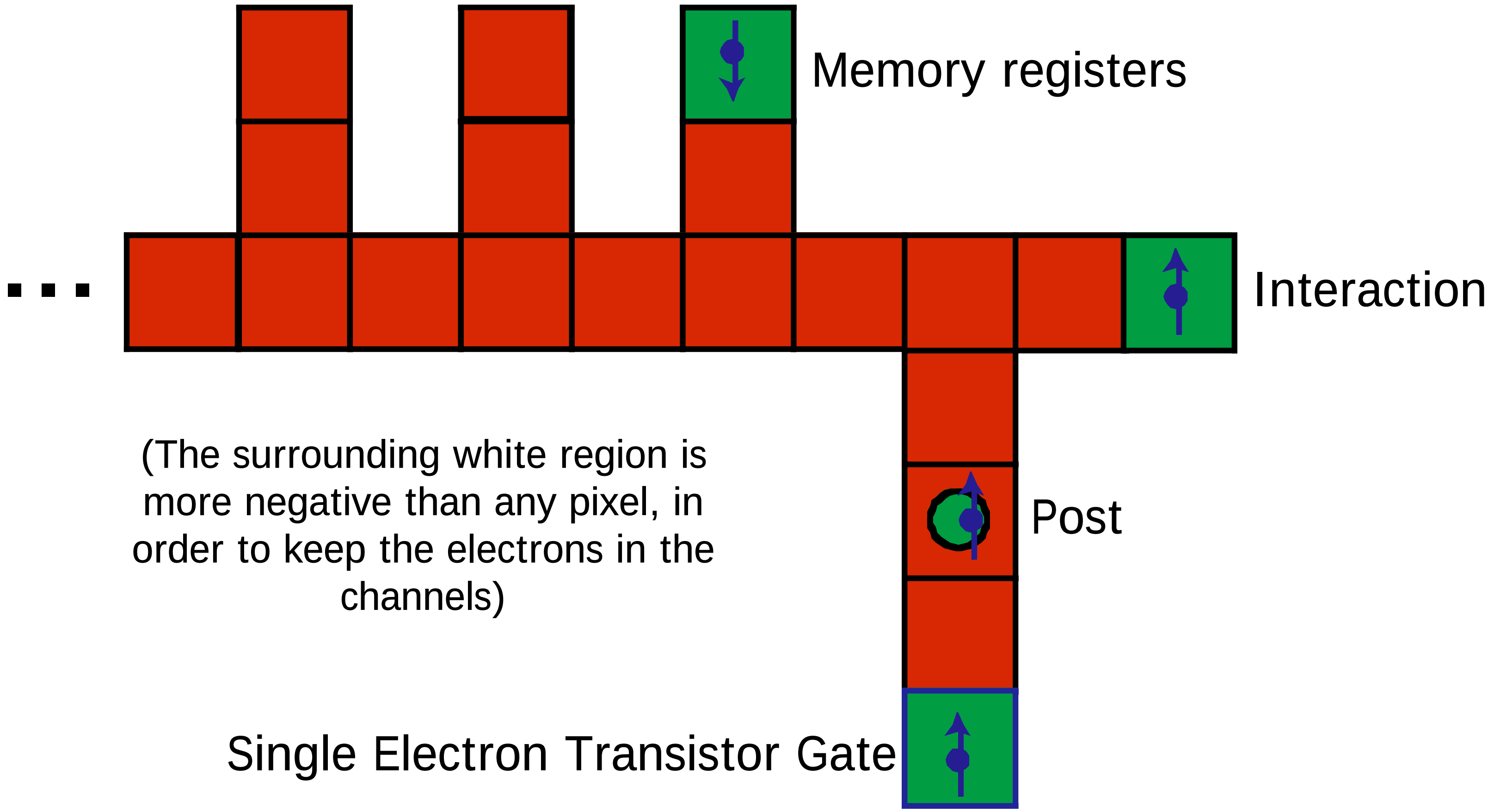

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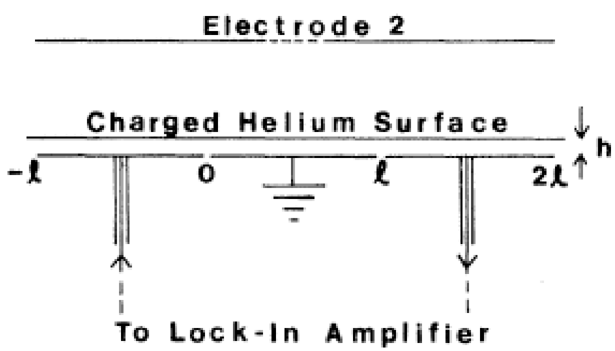
Clocking Electrons on Helium

- How readily can we shift electrons around?

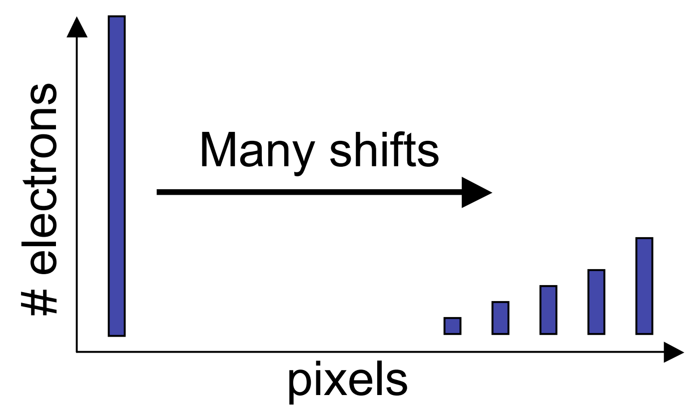


W. T. Sommer and D. J. Tanner, Physical Review Letters **27**, 20 (1971).

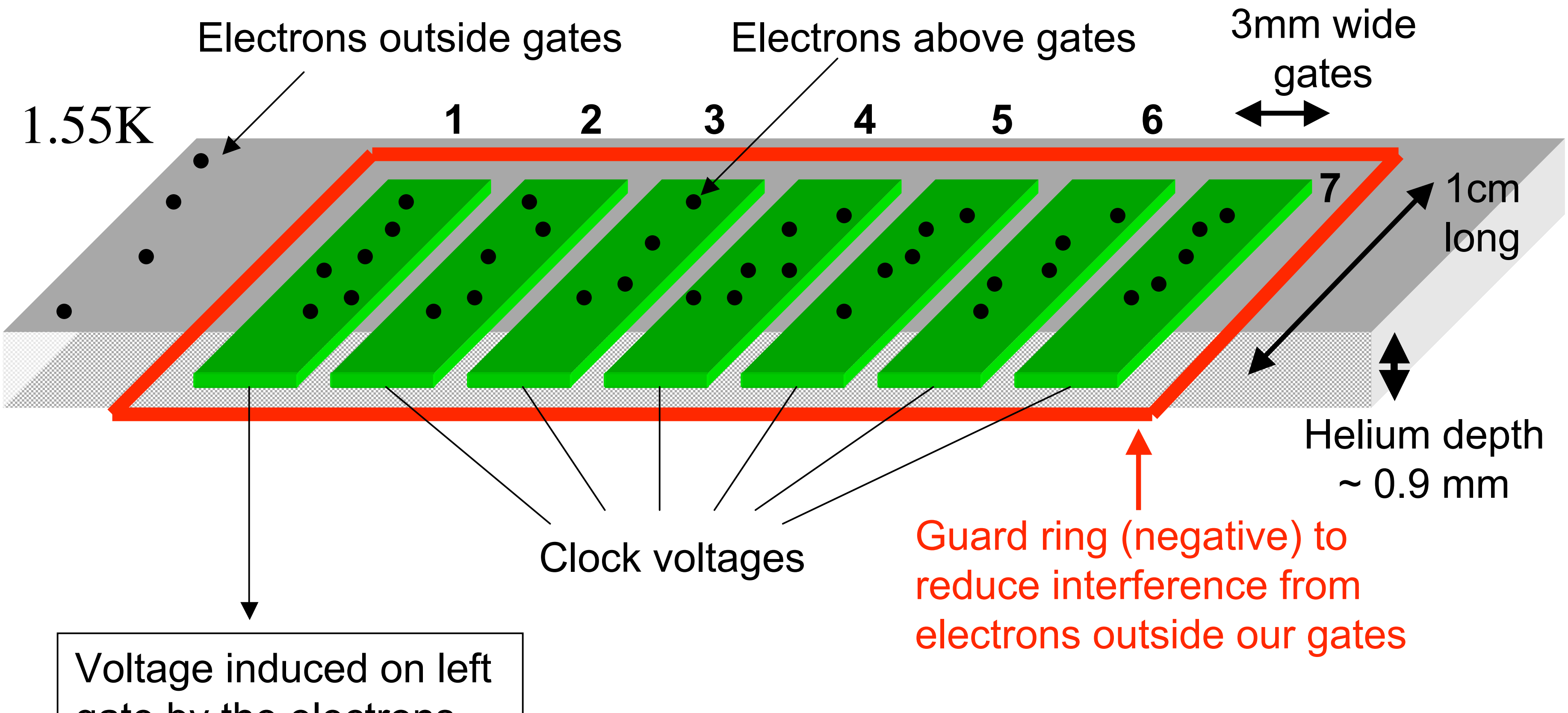
- Measurement of the mobility of the electrons that are free to move.

-These experiments do not tell us the efficiency with which we transfer electrons (CTE = charge transfer efficiency) – charge trapping ⇒ CTE ≠ 1.0

CTE is normally seen as a smearing of a signal – start with many electrons on one gate and some get left behind with each shift



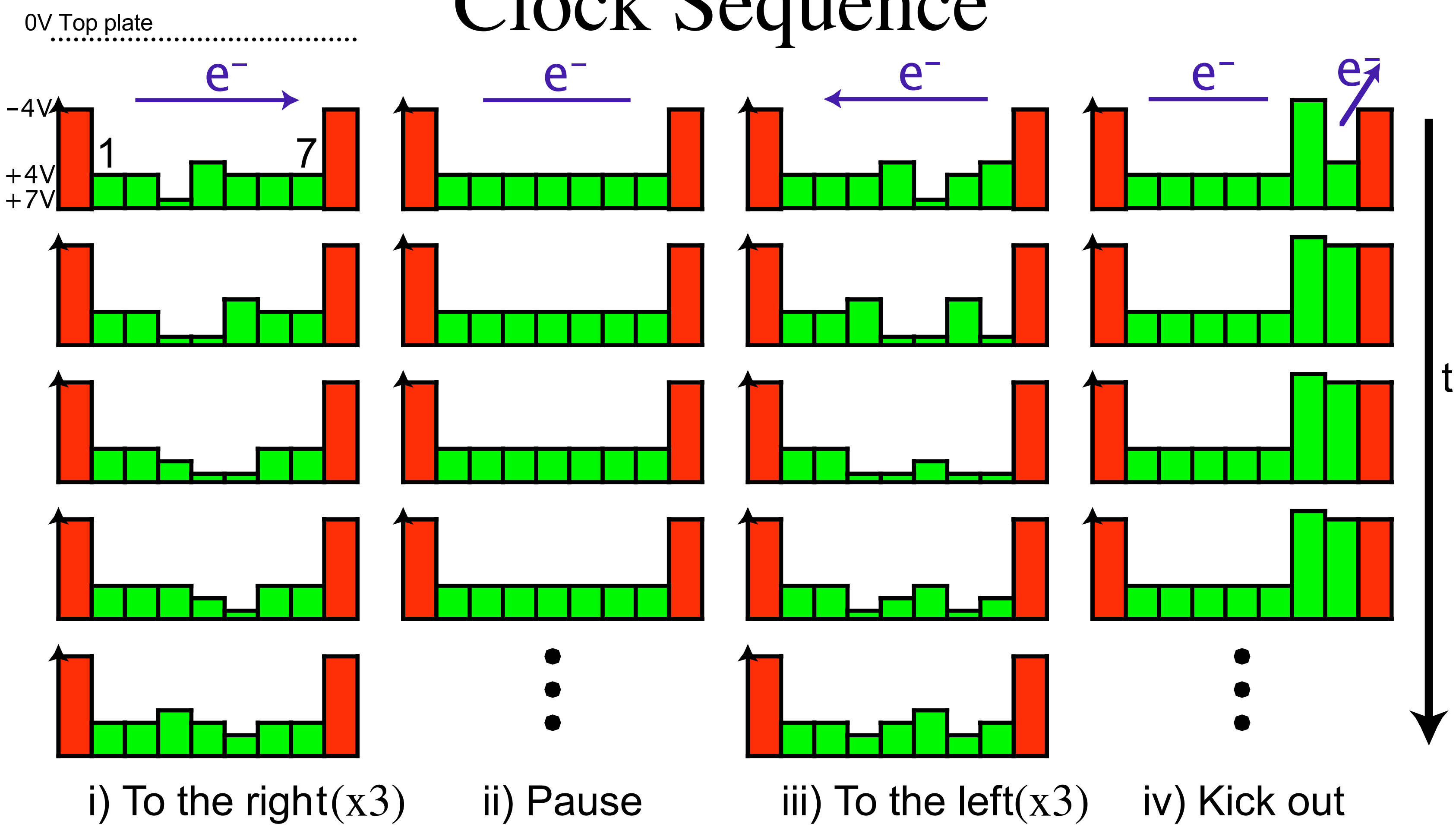
Thick (~ 0.9 mm) helium device



- All gates carry a common dc bias to hold electrons (+4V ⇒ ~ 2.6×10^7 electrons/cm^2 or 1 electrons per 4 μm^2)

Picture of the actual device

Clock Sequence

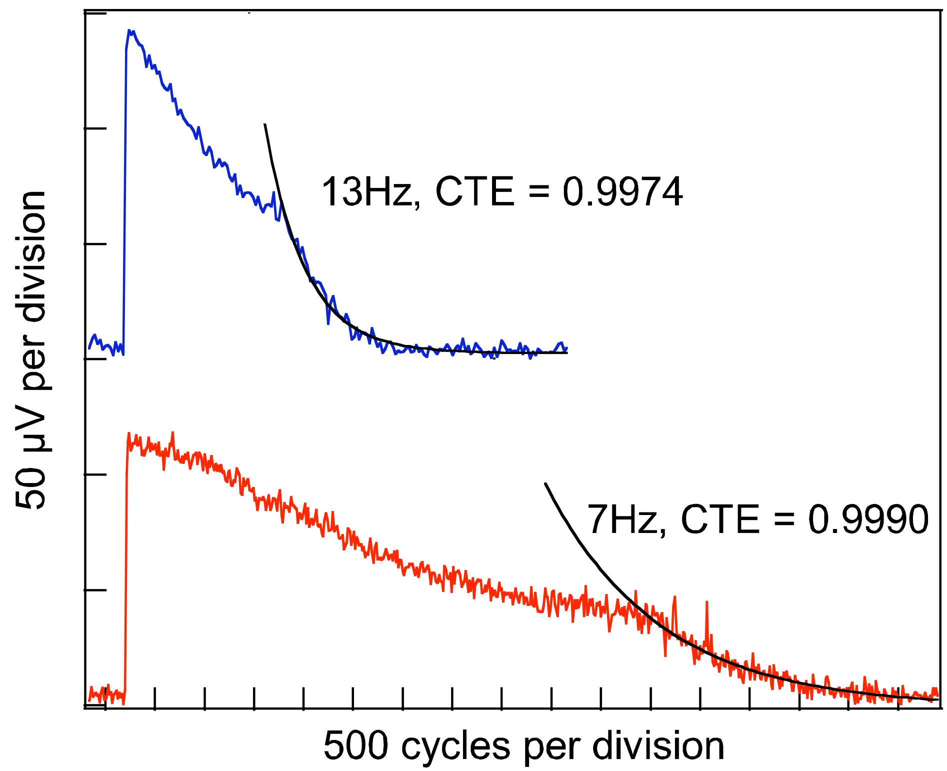


- We don't have long shift register, so use sequence which kicks electrons off the He if they get "stuck" on a gate
  - Clock electrons left and right but after transferring to gate 1 (left), raise energy on gates 6 & 7 (gates negative) to expel remaining electrons from the device

- Variable total period

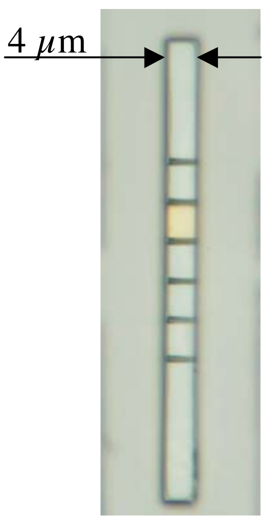
CTE Measurements

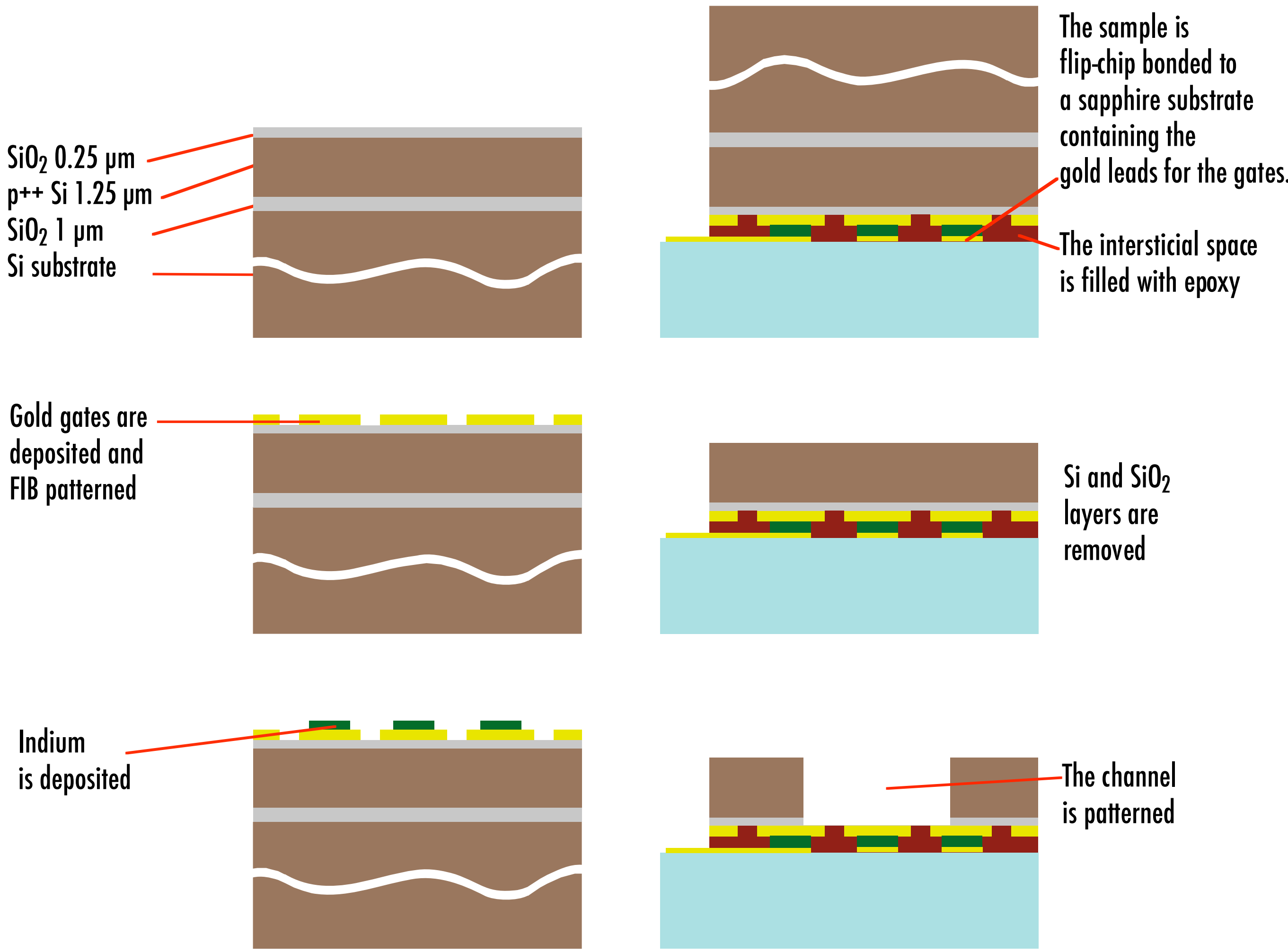
- At low frequency (7 Hz) find CTE = .999
- CTE decreases with increasing frequency because electrons must diffuse from one pixel to another, and pixels are huge (3mm)
- CTE would be negligible in Si for our pixel size and electron density



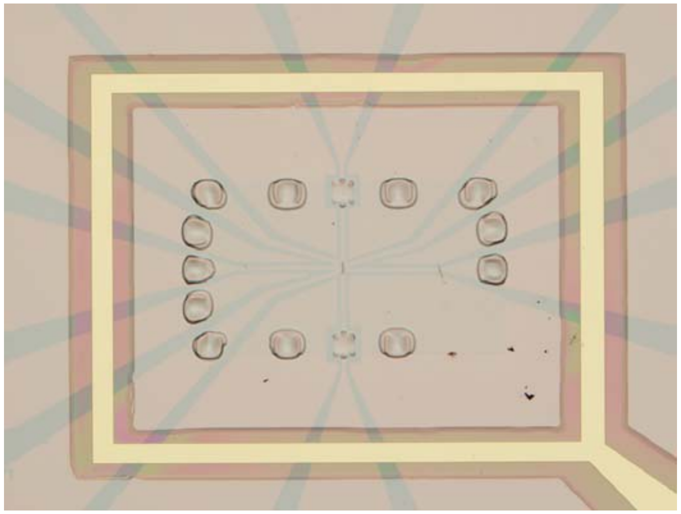
No evidence for strong electron trapping at low frequencies

Channel Device Fabrication

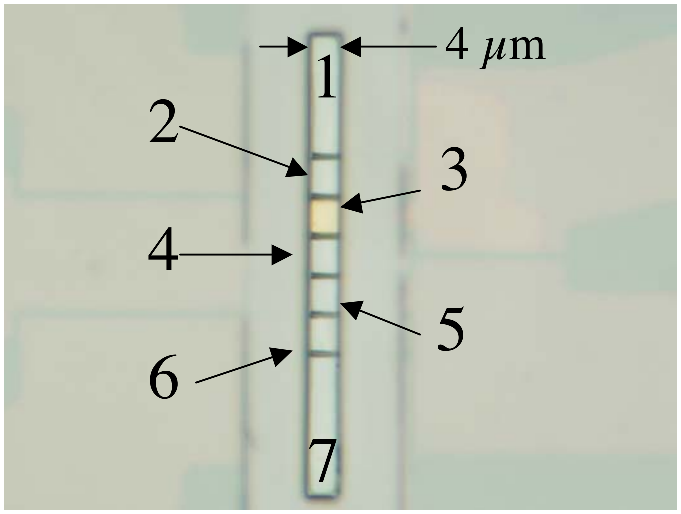




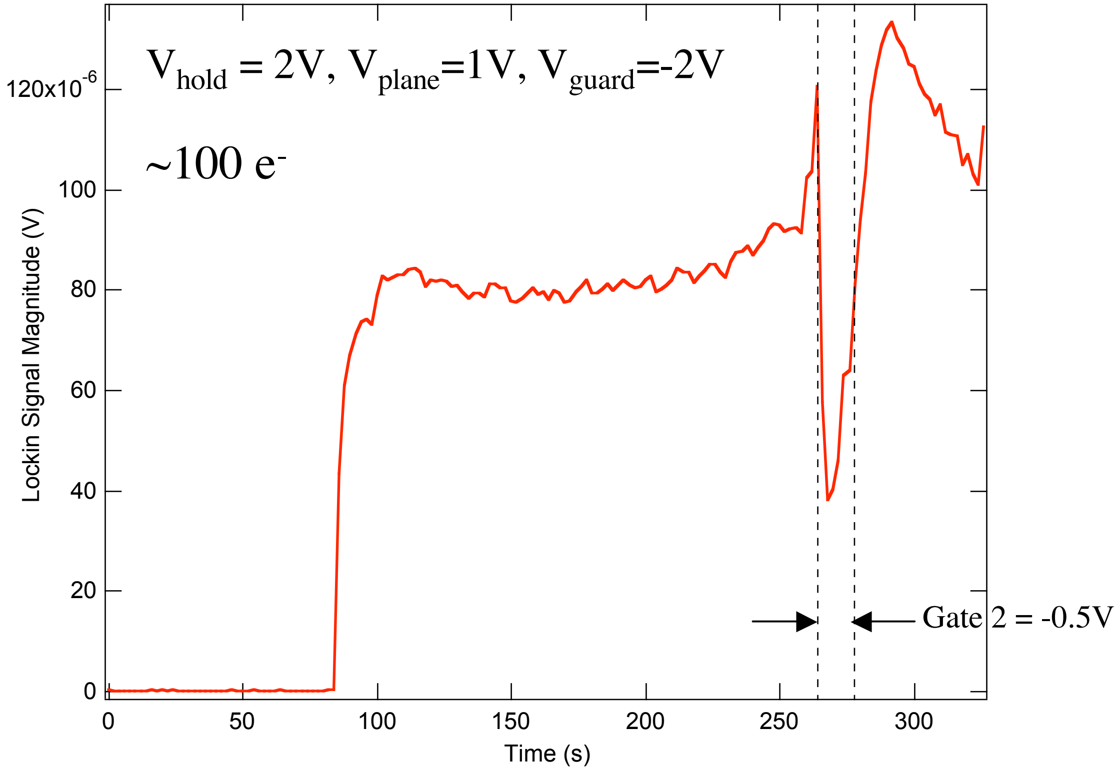
Channel Device (~1.5μm)



View of the sample with the guard ring. (The bumps arise from the strain of the flip-chipping)



Zoom on the channel. The 1.5 μm Silicon layer is open to reveal the underlying metallic gates.



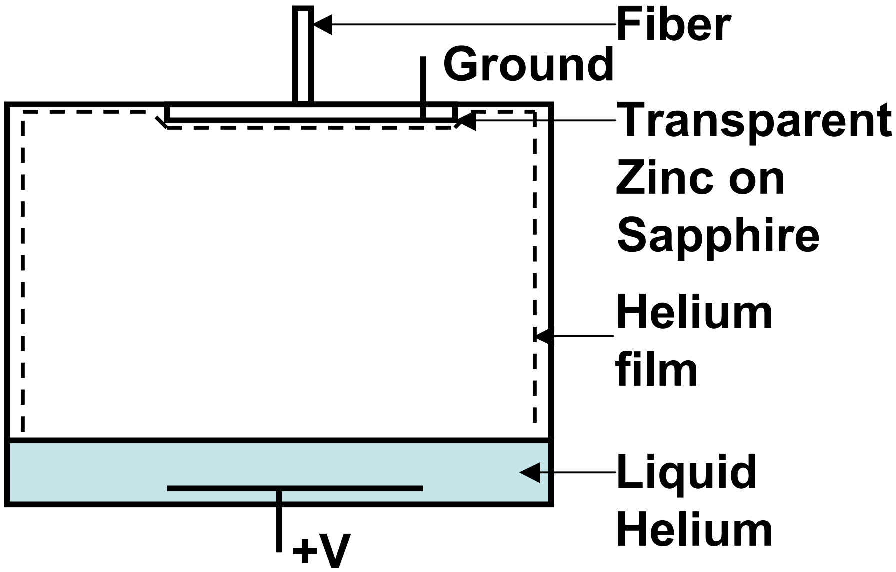
Lockin signal magnitude as a function of time. Making gate number 2 more negative interrupts the signal.

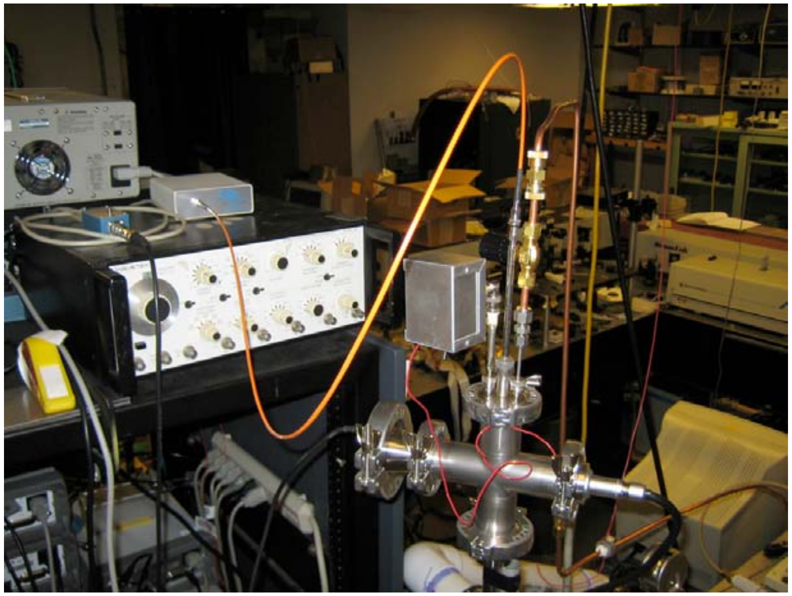
Commercial HEMT at low temperature for readout

Photoemission Source

(Shyam Shankar)

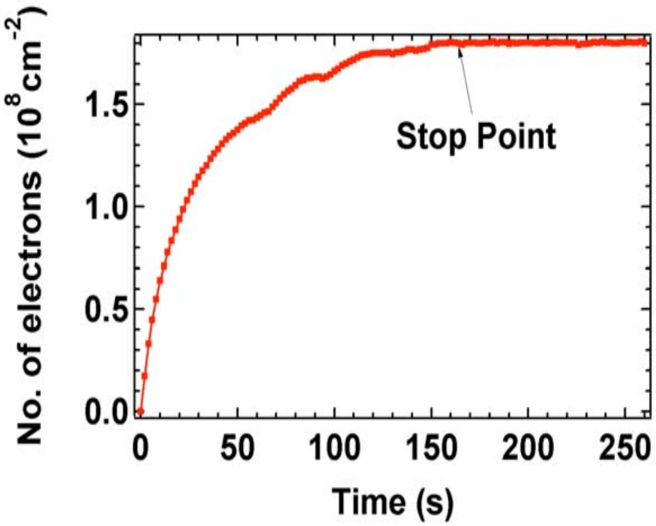
- Problem with filaments: too much heat

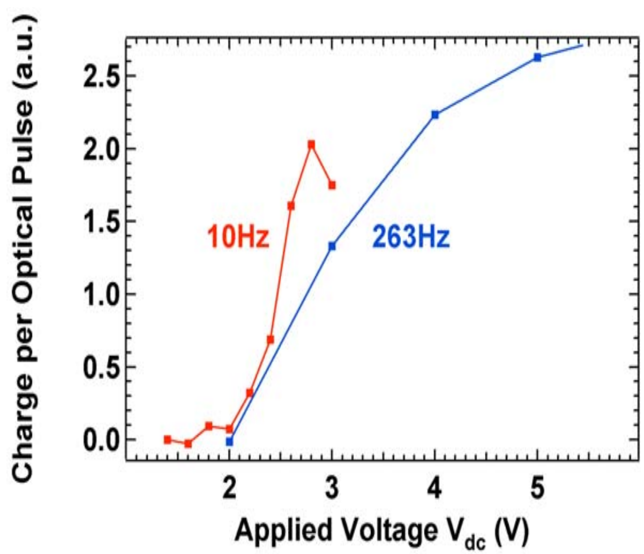




- Wilen and Gianetta (1985)
  - Photoemission from Zinc
  - 1KW arc lamp focused into fiber
- Try low power lamp and small setup

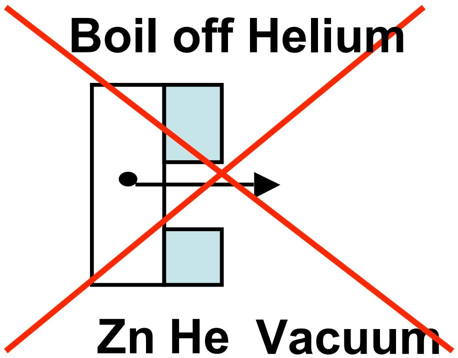
Photoemission Source



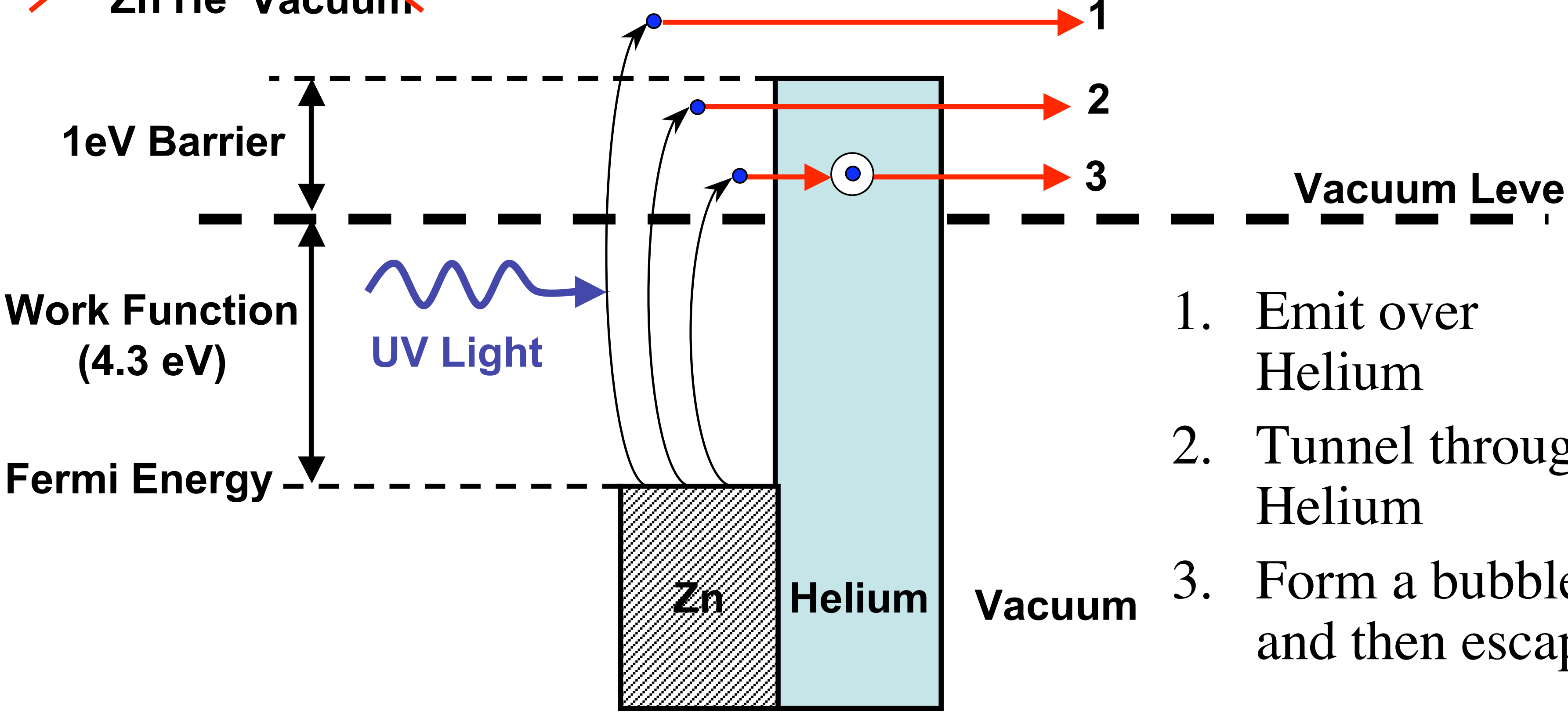


- Pulsed Xenon Source (Ocean Optics PX-2)
- 600 micron Solarization resistant fiber
- 10nm Ti / 20nm Zn on Sapphire substrate
- Get 10^7-10^8 electrons in about 20 seconds
- Adjust charge up rate by varying pulse rate
- Find threshold voltage of 2V (4V/cm)

How do the Electrons get through the Helium film?

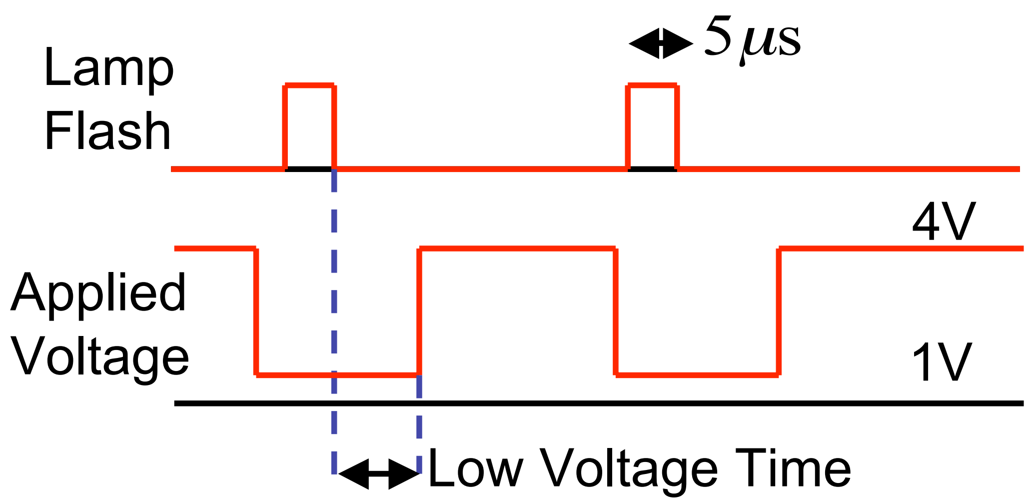


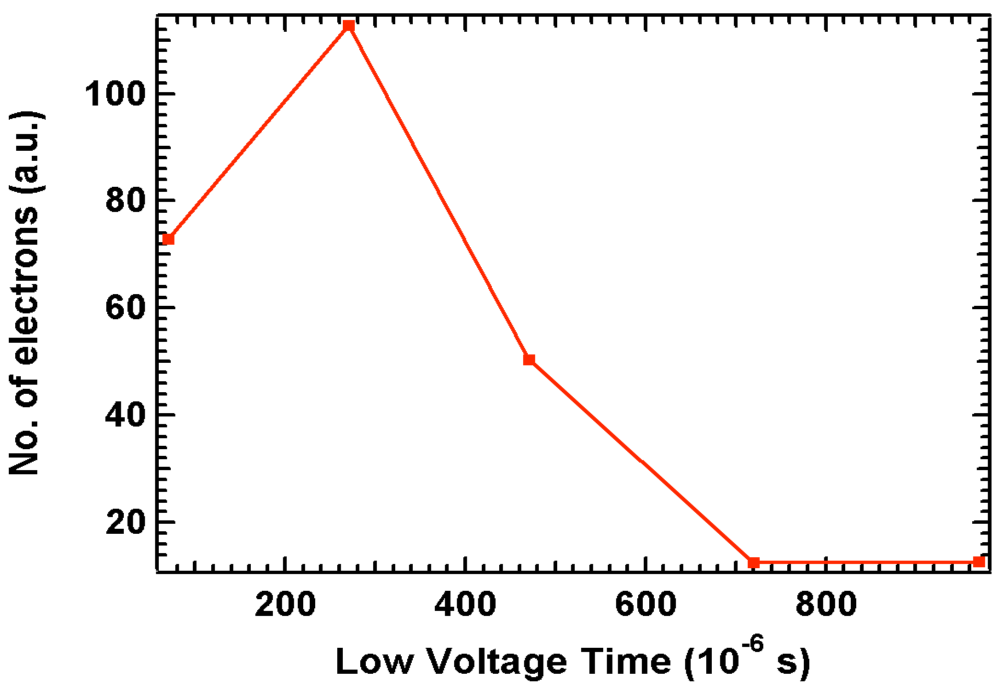
No
- Get 200 times more current if no Helium present
- Only ~100nJ total energy in UV pulse – can't boil film



1. Emit over Helium
2. Tunnel through Helium
3. Form a bubble and then escape

Bubble States?





- Lamp flashes for 5μs every 5ms (200 Hz)
- Low voltage (below 2V threshold) during lamp flash and for a variable time after flash

Some electrons even after almost 1ms

Summary

- Developed a method to measure charge-transfer-efficiency on thick helium without building a long array
  - Measured a of 0.999 at ~10^7 electrons/cm^2 and low frequency
    - CTE can be understood in terms of electron diffusion
    - No evidence of electron trapping
    - Cond-mat/0602228
- Demonstrated electron clocking in a 4 μm-wide channel
- Developed an electron photoemission source
  - Small, low power UV source
  - Photoemission mechanism not fully understood