Nanocrystal based memory Design : Application of semiconductor electrostatics

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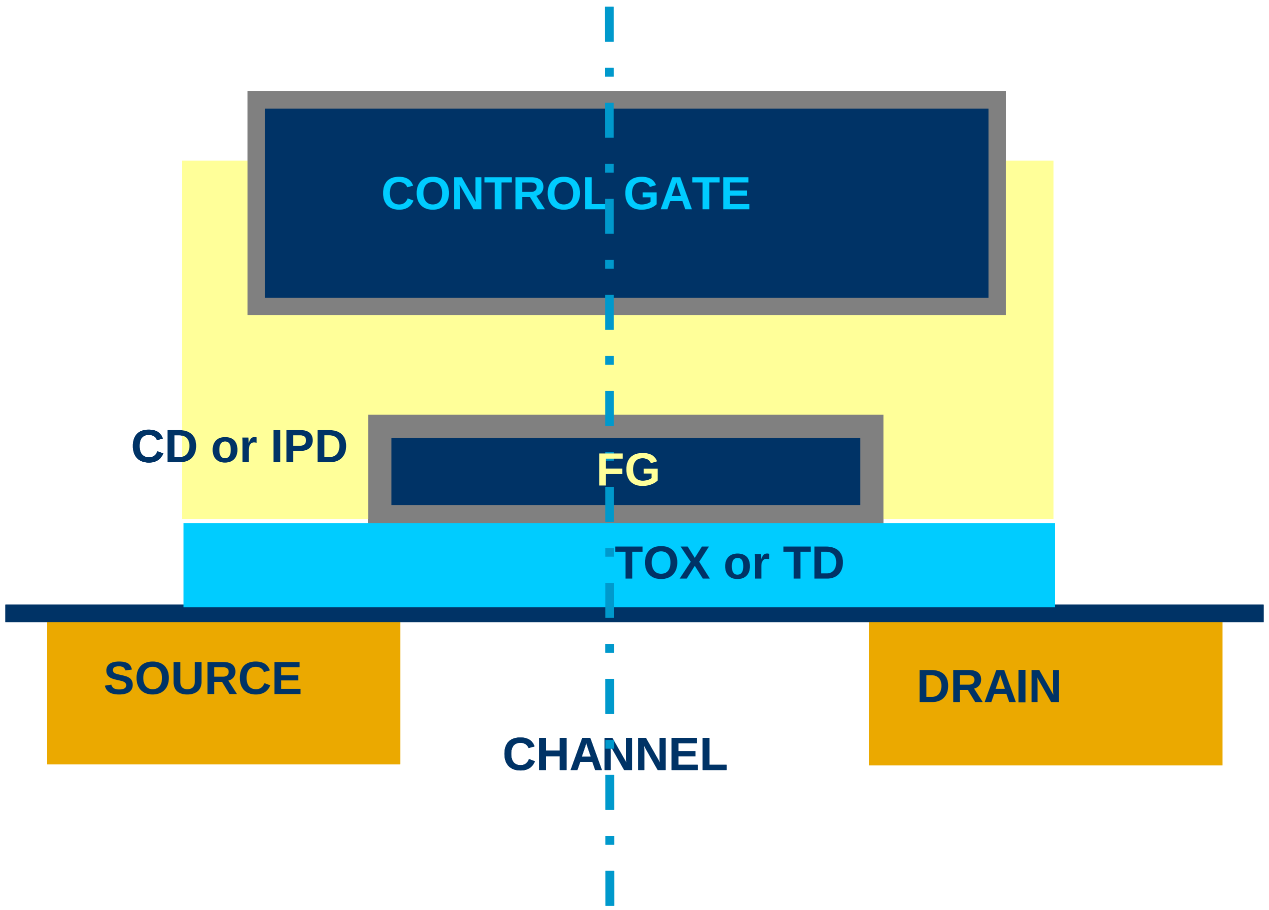
Udayan Ganguly

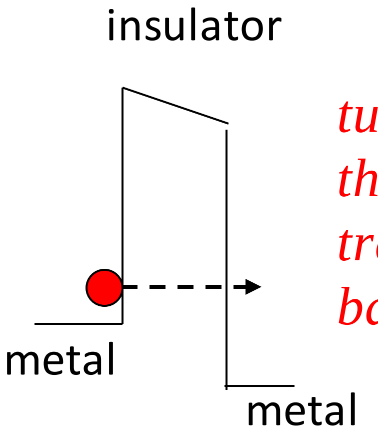
Reference: A simple FG Flash memory tutorial
https://www.youtube.com/watch?v=s7JLXs5es7I

The CNT vs planar FET based nanocrystal memory study is taken from this paper
https://doi.org/10.1109/TNANO.2006.888529

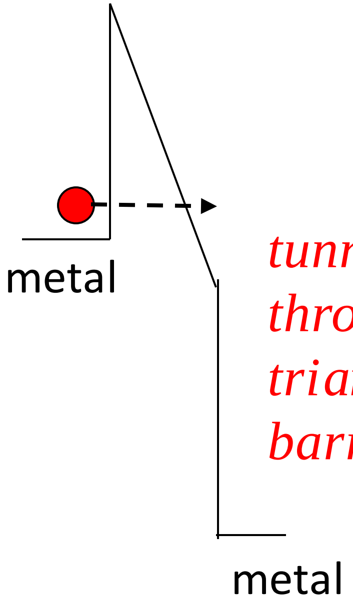
Background: A memory transistor: Floating Gate Flash



New Physics: Tunneling



tunneling through trapezoidal barrier



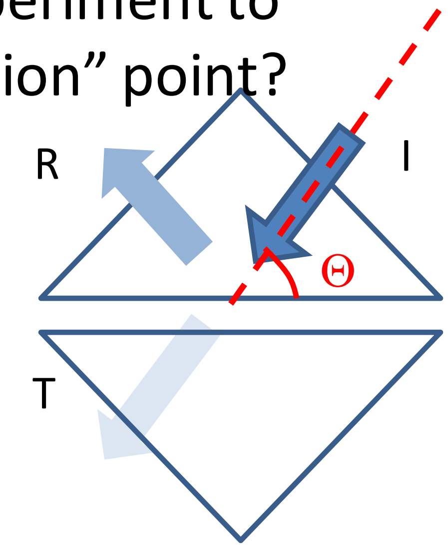
tunneling through triangular barrier

The light analogy:

If we place a prism with light and go beyond a critical angle Θ we get Total Internal Reflection

Think: Where does the light “decide” to turn around? (a) At (b) before (c) after the interface (d) irrelevant?

Pair: What is an experiment to measure this “decision” point?



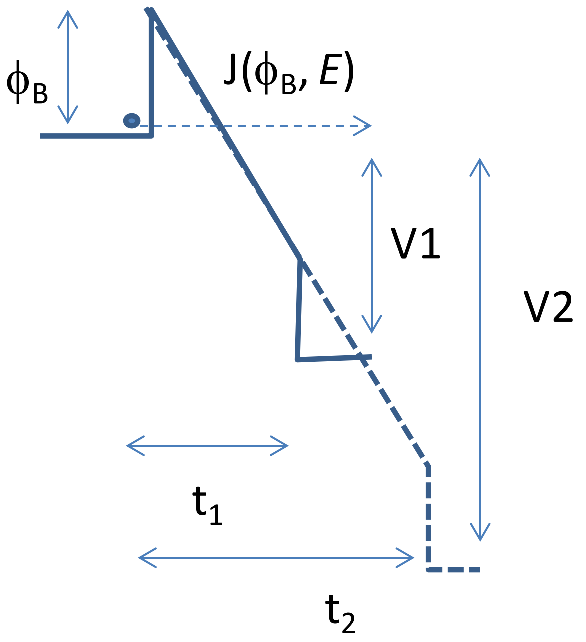
Electron as a wave can “tunnel” through barriers!

Any wave can tunnel!

Result: Light decays exponentially in the gap!

A bit more on Tunneling

We have 2 capacitors make of Pt/SiO2 / Pt with oxide thickness t_1 and t_2 respectively.



Think: Is the current V dependent?

Pair: If the barrier is triangular, can I claim

(a) Current Density (J) depends only on V and ϕ_B

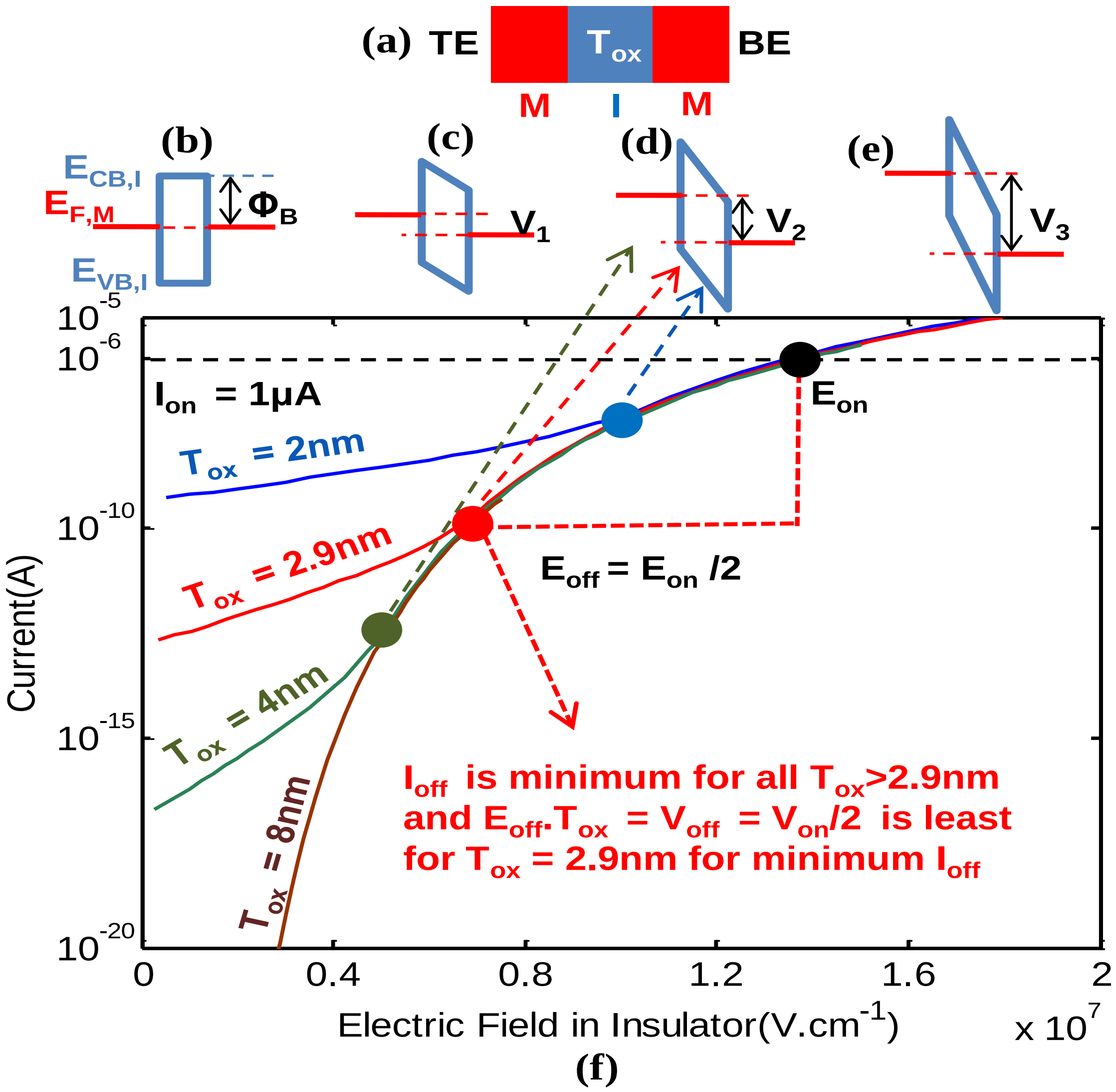
(b) Current Density (J) depends only on Electric field and ϕ_B

(c) Current Density (J) depends only on V and Electric field

State the basis of the choice & elimination?

Bias can modulate the "transparency" of the barrier to electron tunneling J (ϕ_B, E) ➔ exponential function!

DT and FN comparison

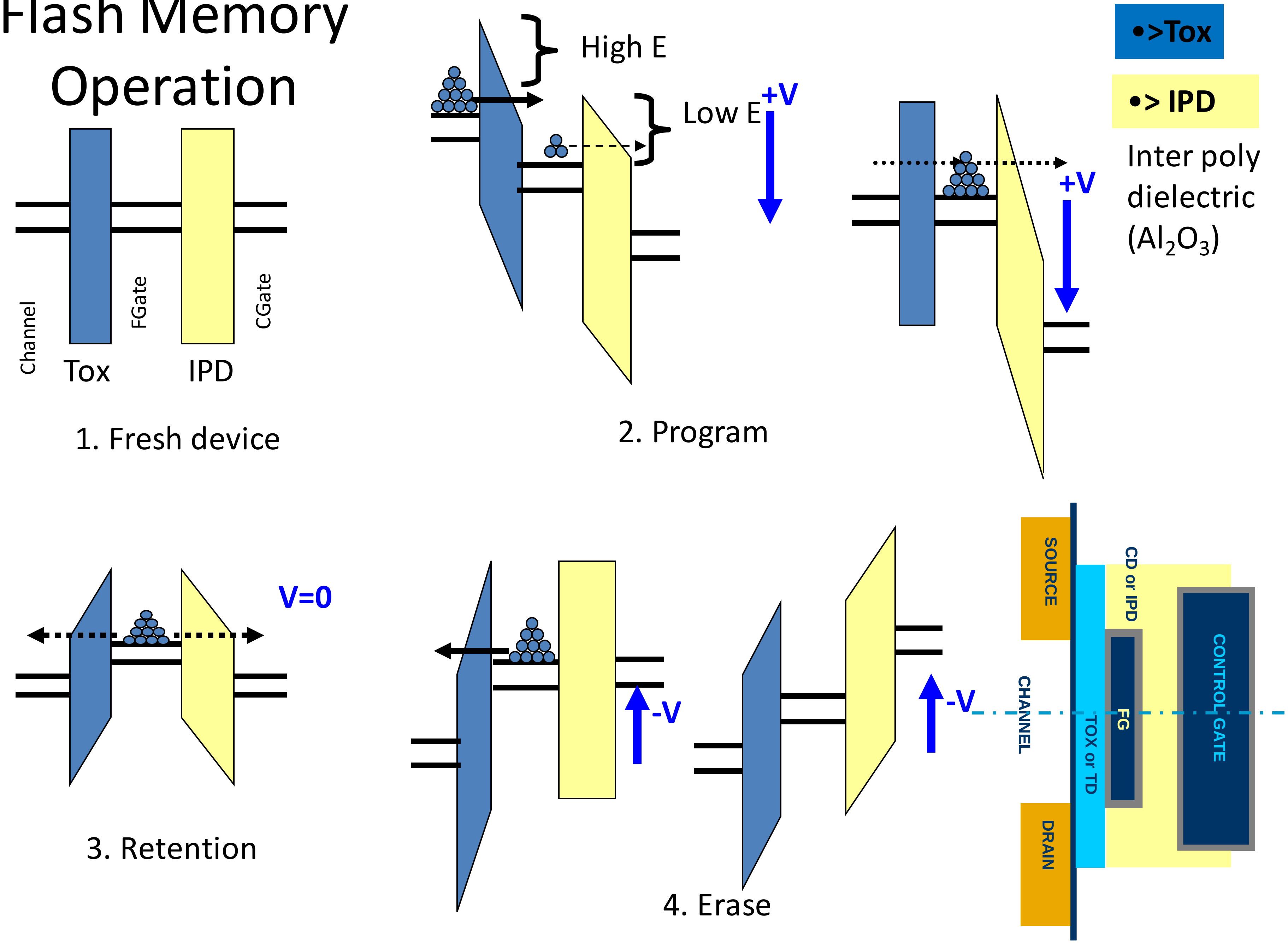


Since both DT and FN is exponential in E field we can use a simple current addition of FN and DT.

Approximation is valid because only one function will dominate – except in the small transition region

DT is also thickness dependent – so it dominates FN for thinner oxides

Flash Memory Operation

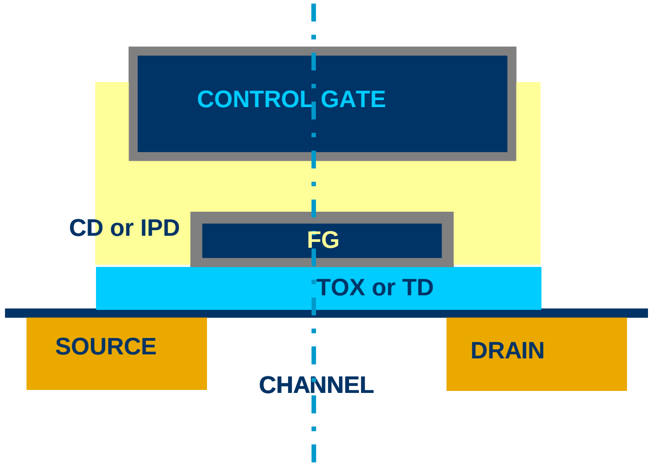


Assume: Tunneling is exponential with electric field;

Write down the requirements of tunnel oxide vs. IPD for Prog (18V) vs Retention (0V) to set the thickness

- IPD

- Tun Ox

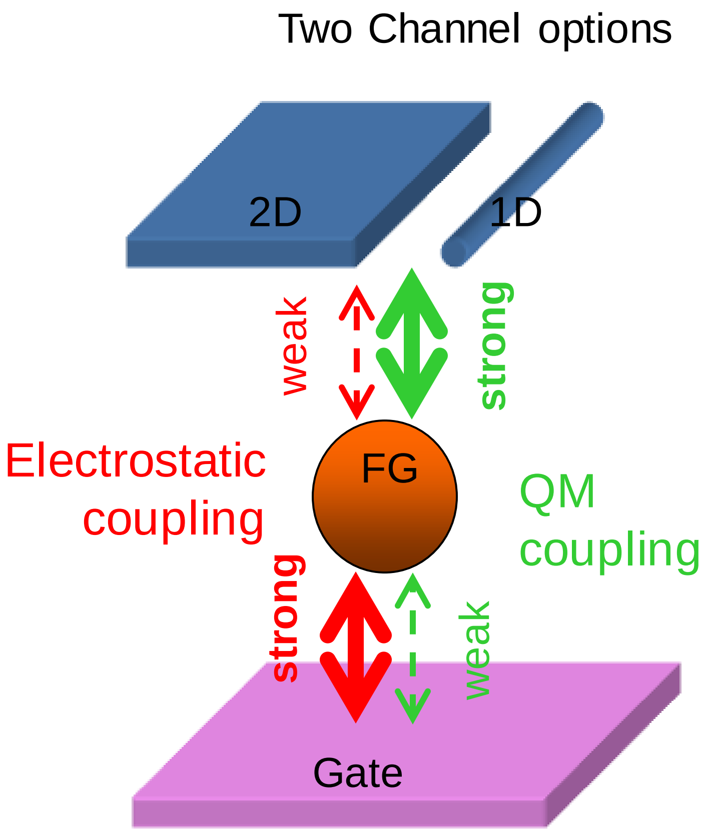


- Is there a dilemma or a design challenge?

Answer in the next slide; do not turn until you have spent 10 min to write this down

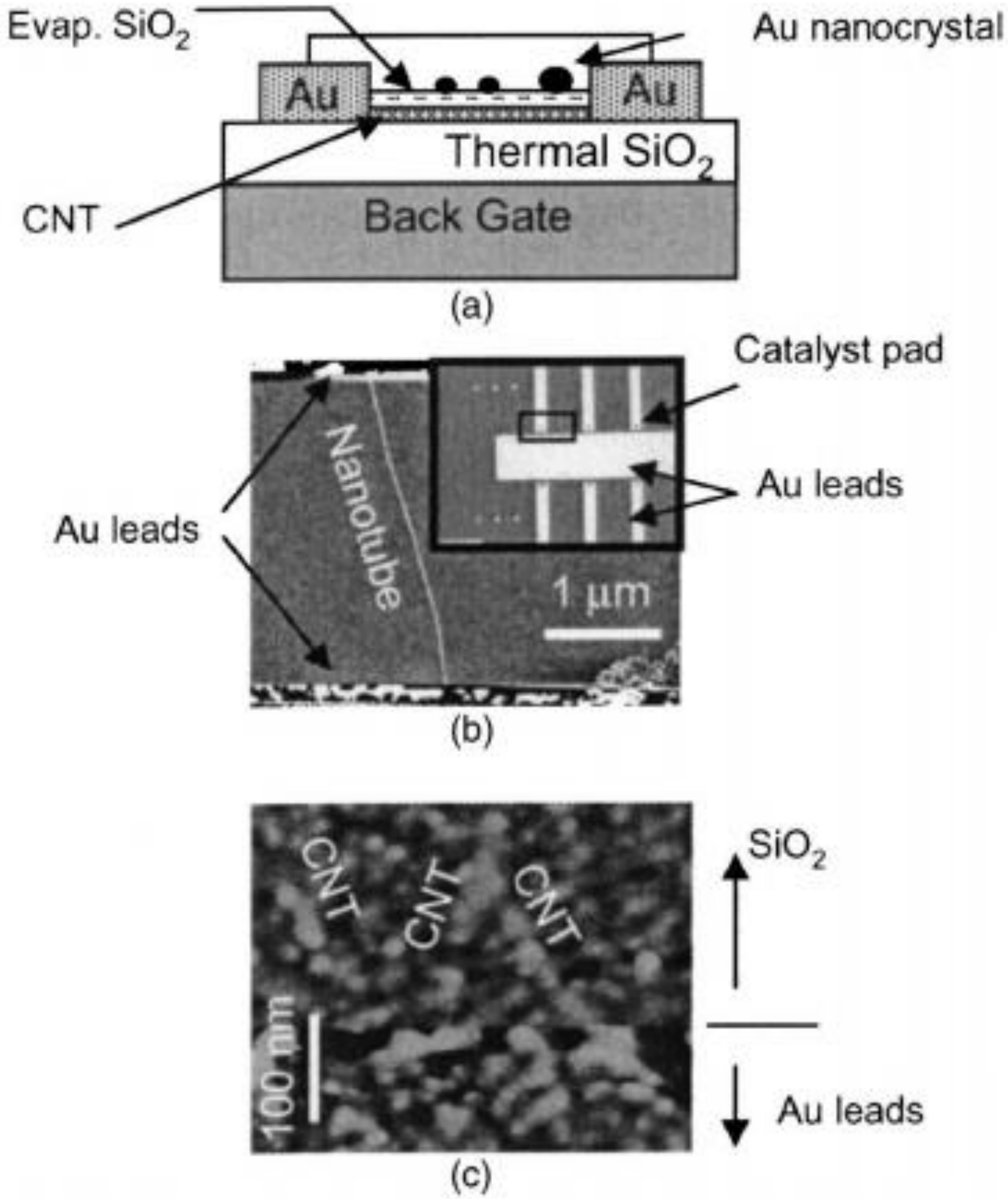
Dilemma in Memory Design

- Electrostatic coupling
  - NC-GATE
- Quantum Mechanical coupling
  - NC-Channel

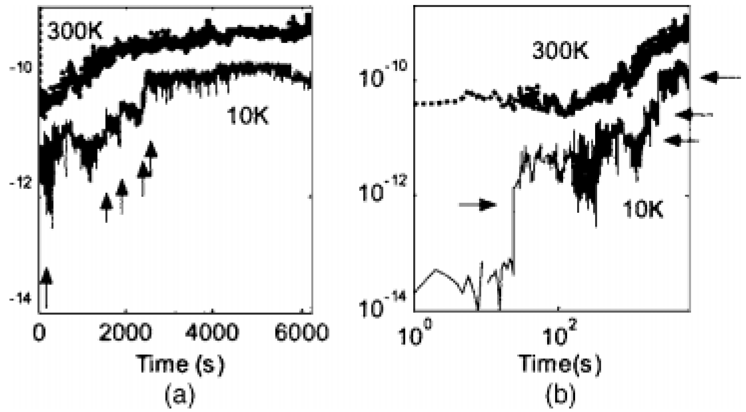


Both tunneling and electrostatics are function of distance

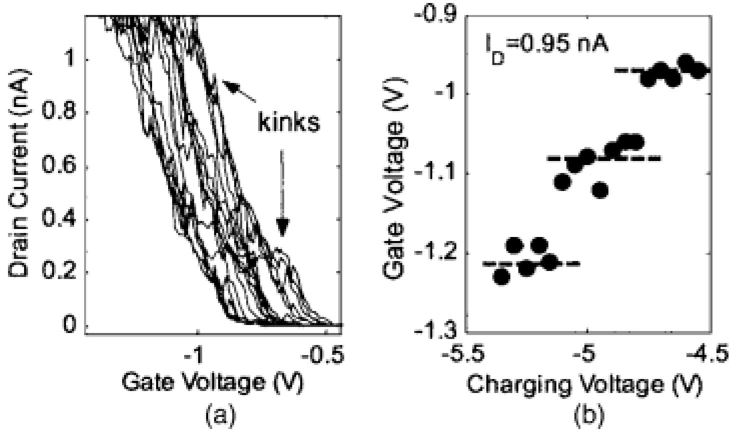
https://doi.org/10.1063/1.1999014



IV characteristics (an example)



Single electrons can jump out of the nanocrystal

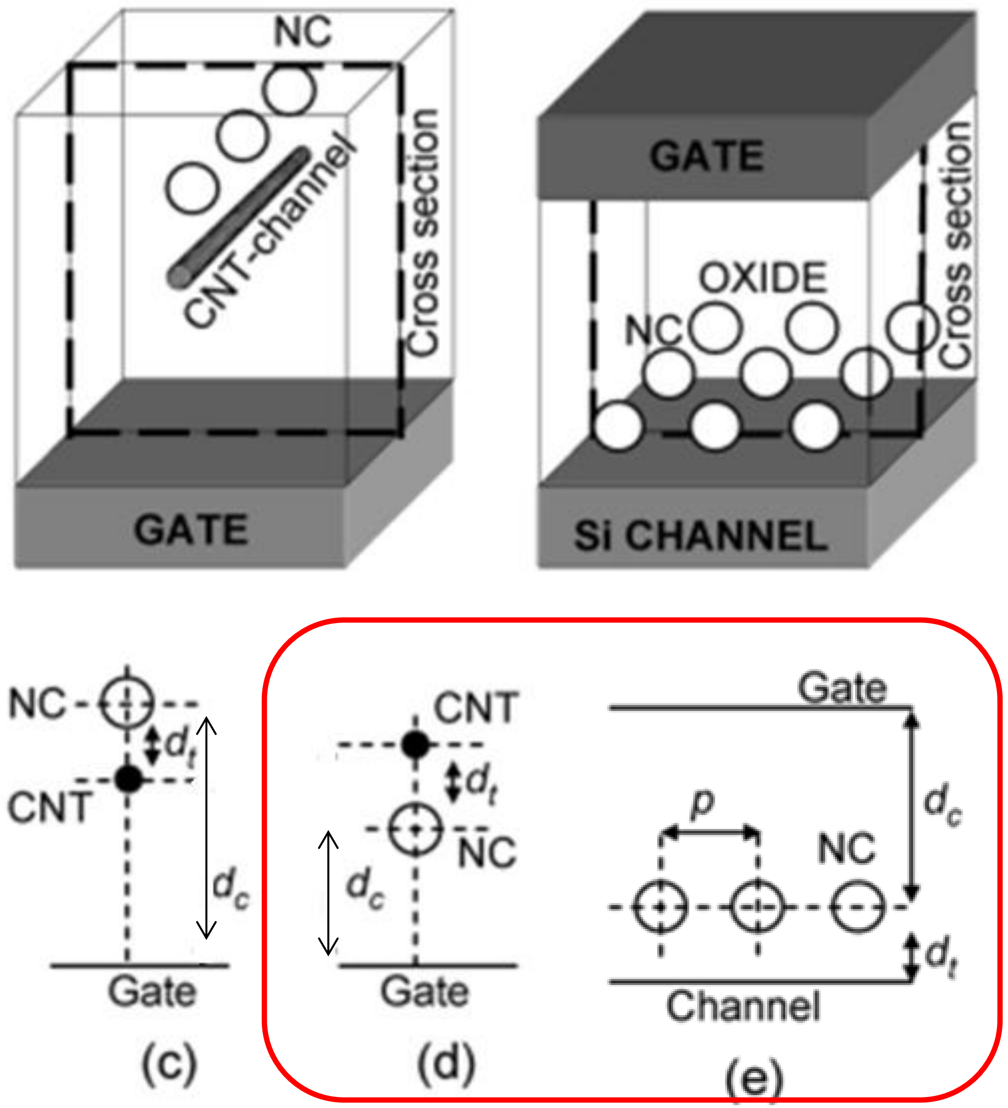


Single electrons can jump into the nanocrystal

NC based memory

Technology Options:
1. Carbon Nanotube channel- Metal NC
2. Si channel- Metal NC

Operation (requirement):
1. Program/ Erase : Fast @±20V
2. Retention: Slow @ 0V but NC has stored electronic charge



Which one will produce a better performance?

Answer in the next slide; do not turn until you have spent 20 min to write this down

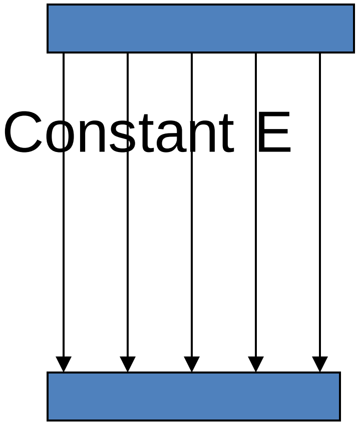
How to proceed?

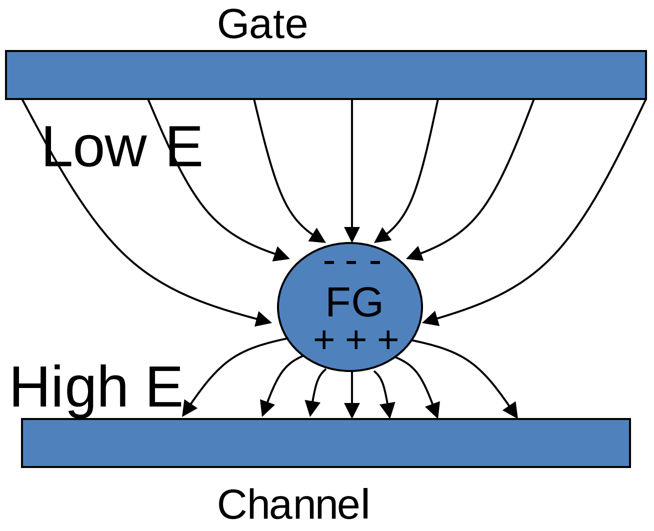
- Can we understand the capacitive coupling difference in the two systems
  - In program
  - During retention

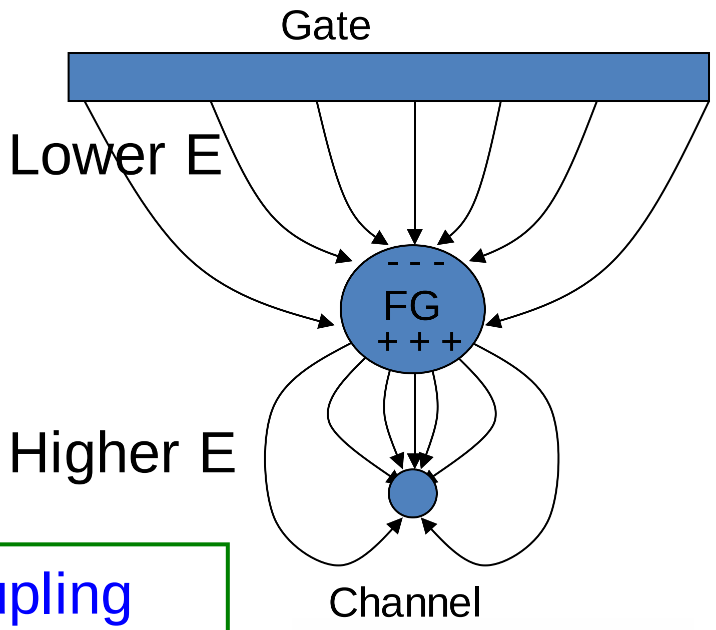
1D vs. 2D channel

PROGRAM CONDITION

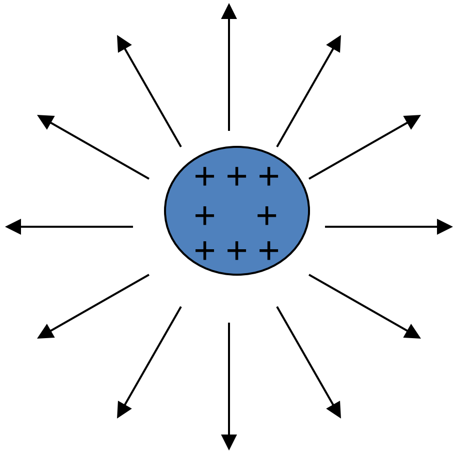
- Channel ON
- assume METALLIC





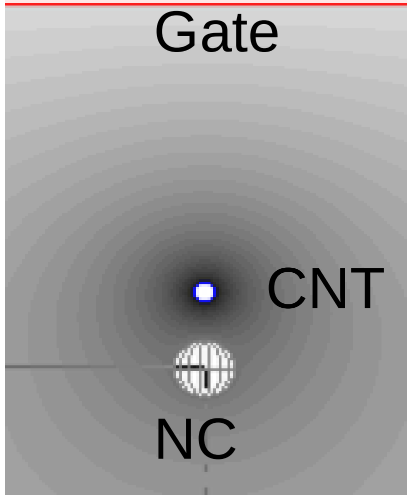


Low E=> Low V drop=> Strong Gate coupling



Self Capacitance

- $E \sim 1/r^2$
- Not affected by surroundings



U. Ganguly et al, T Nano, 2006

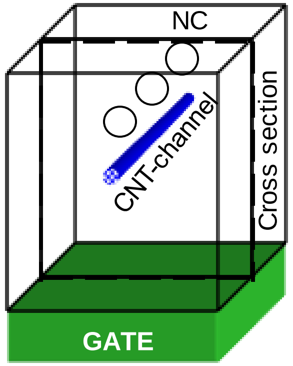
Program

Simulation results to validate the model

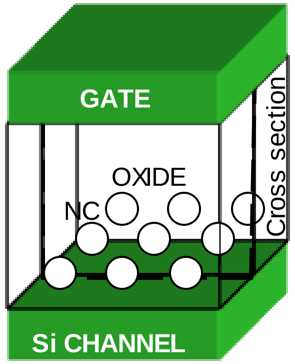
Structural Parameters		Potential on NC (V)	
	d_c (nm)	Capacitive Coupling V_G=5	Self Capacitance q_{NC}=5e
1NC-CNT BG	21	2.52	-0.517
	30	2.35	-0.519
	100	1.77	-0.528
1NC-CNT TG	30	2.69	-0.509
3NC-CNT BG	30	2.33	-0.68
1 NC-Si		0.81	-0.46
3×3 NC -Si		0.74	-0.67

~ 15e

~ 5e

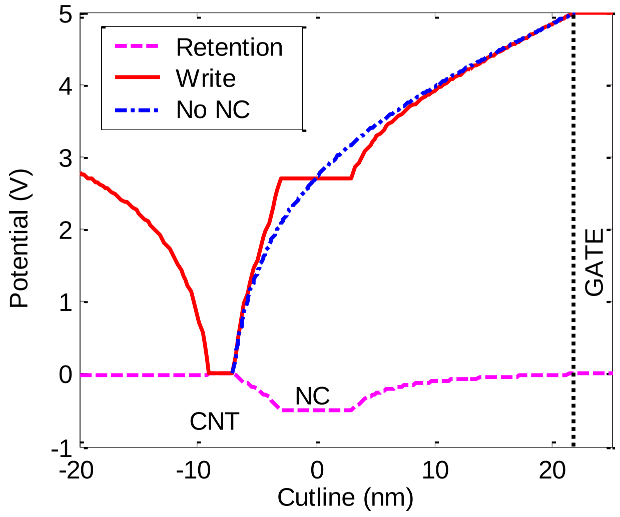


CNT (1-D) channel



Si (2-D) channel

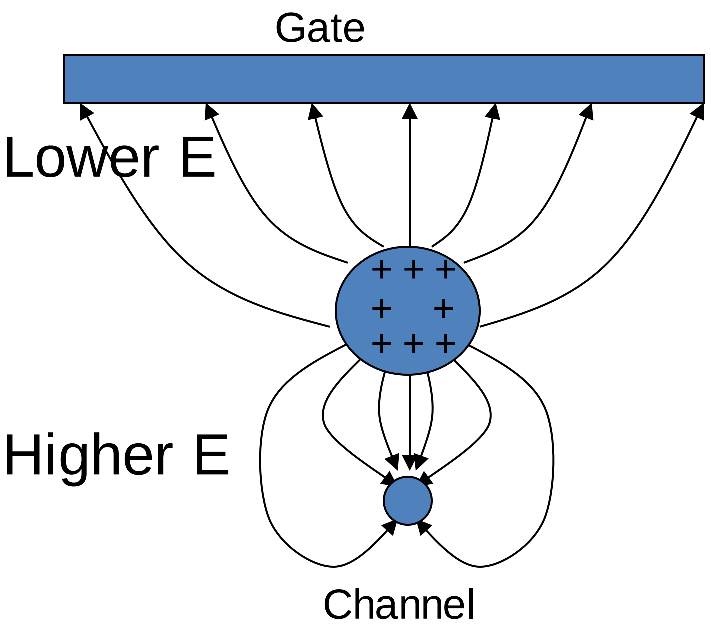
Large electric fields than 2D Si channel!!!



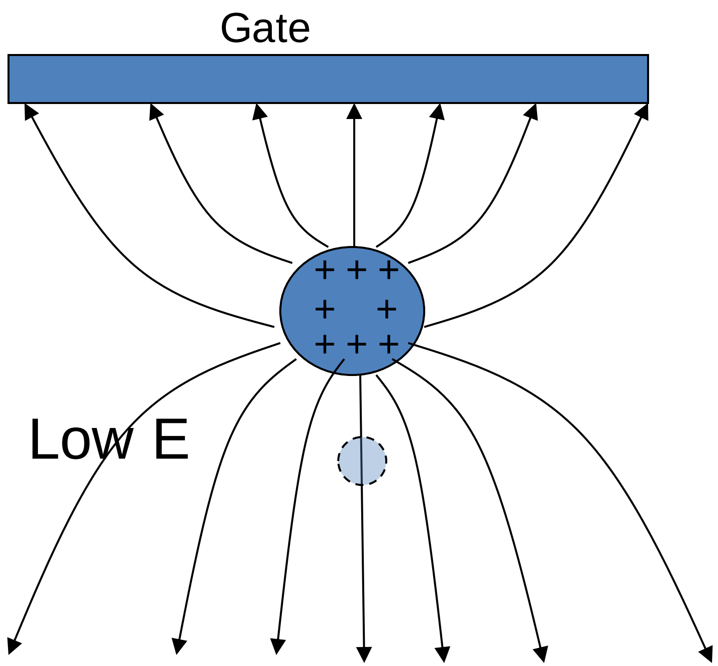
Retention Condition

- ➢Channel OFF
- ➢assume DIELECTRIC

Retention



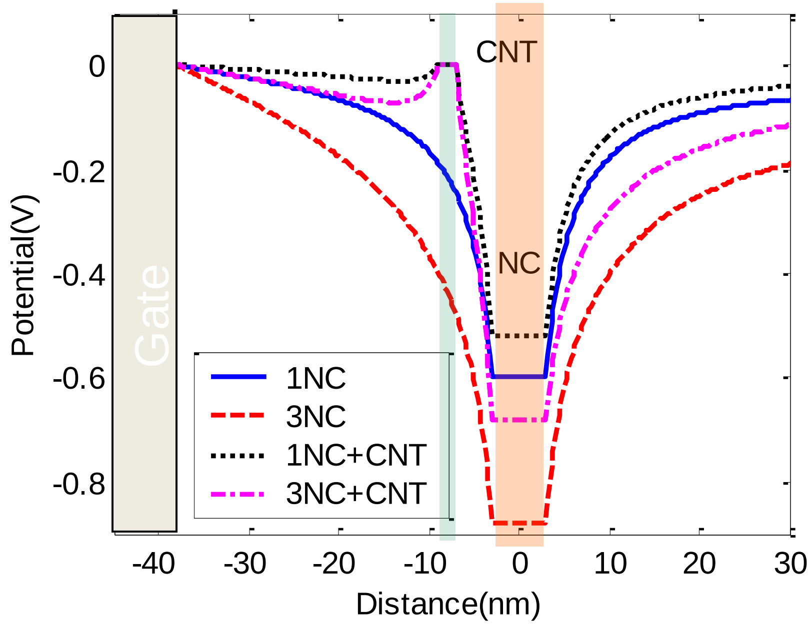
Metallic Channel

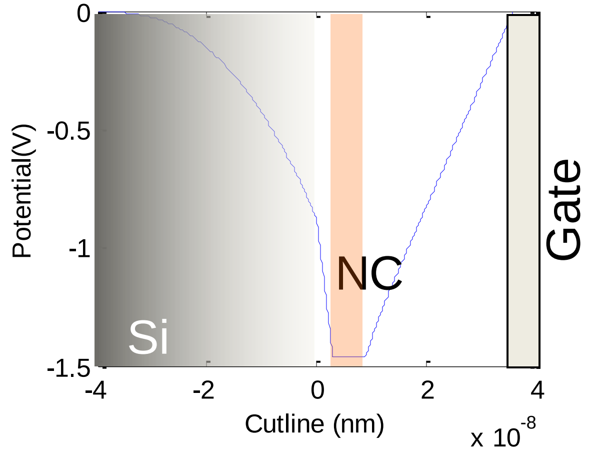


Dielectric Channel

Retention

- In this case, CNT is a conveniently a dielectric
  - 1NC case -0.35V
  - 3NC case -0.39V
- 2D Si channel
  - 1NC case -0.46V (Si: metallic)
  - 3x3 NC case -0.67V (Si: metallic)
  - NC array case -0.58V (doping $1x10^{18}cm^{-3}$)
- CNT metallic
  - 1NC case -0.51V
  - 3NC case -0.68V





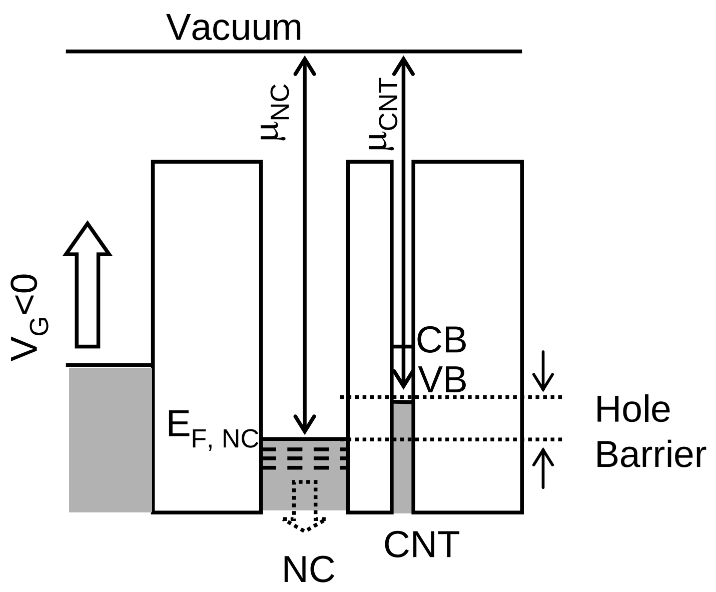
40% reduction in electric fields with CNT

Validation

Charge injection at V_{CH}=5V

From experiment

- Total V_T shift of 1.24 V
- V_T shift of 130mV per electron
- 9.4 electrons storage detected (incredibly large electron # for 5V charging!!!)
- ΔV_{CH} per electron~ 0.4V



From theory

- Total hole well depth 1.26V
  - Gate bias 5V => NC is at 1.86V
  - Band offset correction of 0.6V i.e. Au 5.1eV, CNT valence band ~ 4.5 eV
- Self capacitance energy 104 meV

1. Max electrons that can be stored ~ 12 (c.f. 5 electrons in 2D channel)
2. ΔV_{CH} per electron~ 0.42V (from gate coupling calculations)

✓Validation is OK

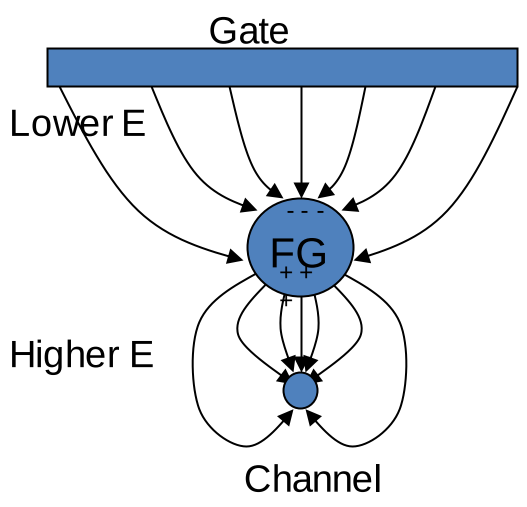
- ✓Explains large # of electrons
- ✓Slightly lower experimental value is due to read disturbance

Results

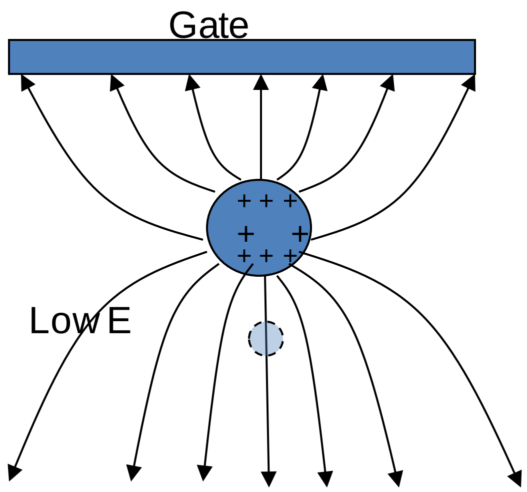
- Ideal structure for electrostatics
  - Strong gate coupling
    - High write field (FN tunneling)3-4x larger
  - 40% lower retention field

  =>Better Write/retention ratio possible
  - <5V operation inspite of thick gate stack
  - 3x number of electron per NC compared

Program



Retention



Questions for conceptual reinforcement

- In this class, we worked on a “judge” type question – the highest skill level in learning! To reflect on the process, here are a few practice questions.
- Write down the steps of approaching the problem – like a computer algorithm. e.g.
  - What is the goal? tunneling rate control
  - what is that main metric of success? electric field
  - How to evaluate/ judge this?..
  - …
  - Conclusion
- For Program and Erase Case
  - Present the key arguments for program case –
  - state in 1 sentence the associated principle learnt in class for each argument
  - state the final conclusion;
  - can you validate quantitatively with simplifying assumptions?

Solving any such unstructured problem

Steps

- Step 1: Define the critical physical phenomenon

- Step 2: Define model

Example

- Transport in low V (retention) vs high V (Program) states needs to be modeled

- Given we only know in tunneling $J \sim \exp(k\vec{E})$, we need to model $\vec{E}$
- Given structure, model $\vec{E}(x, y)$;

Solving any such unstructured problem

Steps

- Step 3: Define metric of comparison

- Step 4: Make a judgement

- Step 5: Validate

Example

- We need to compare J at high vs. low V. Which $\vec{E}(x, y)$ affects tunneling? Decide/guess that $\vec{E}$ at the injecting surface matters. Compare this.

- Compare the $\vec{E}$ at relevant surface and judge

- Either use expt or simulation to test model and conclusions