Negative Capacitance Transistors: Physics, Materials and Devices

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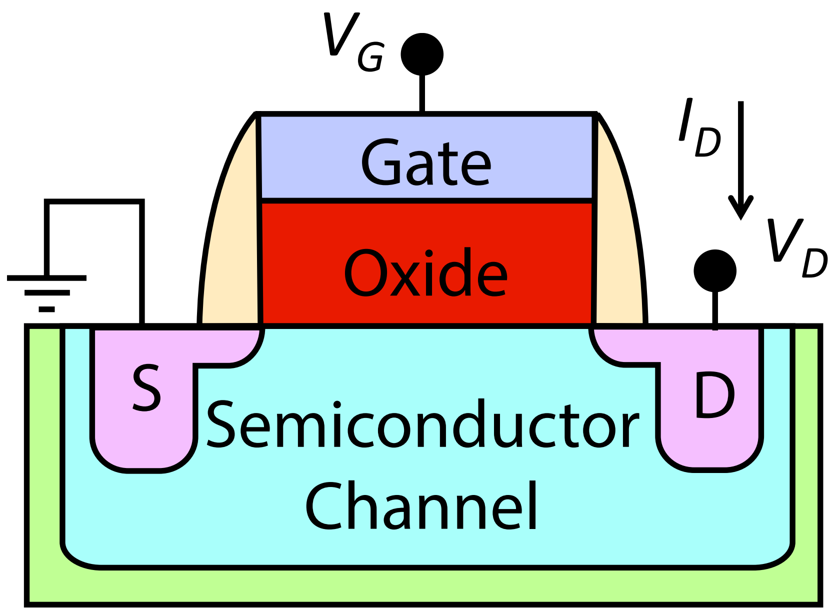
31 January 2018

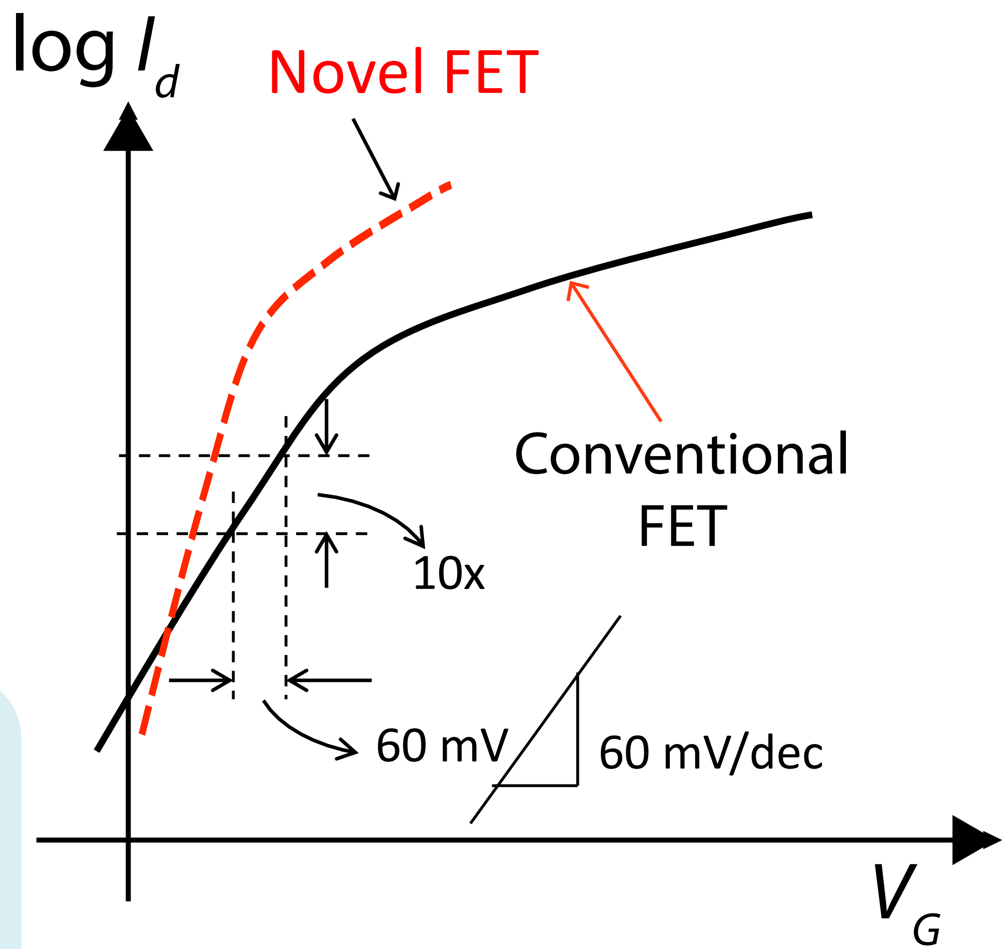
Energy Challenge in Computing



Boltzmann distribution dictates that
Channel charge, Q α $e^{\frac{q\psi_s}{k_B T}}$

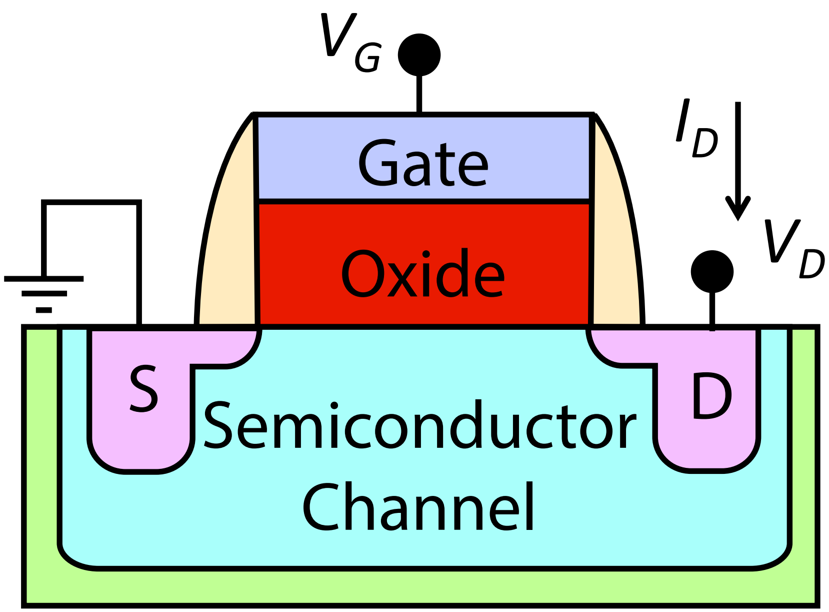
Minimum Subthreshold Swing

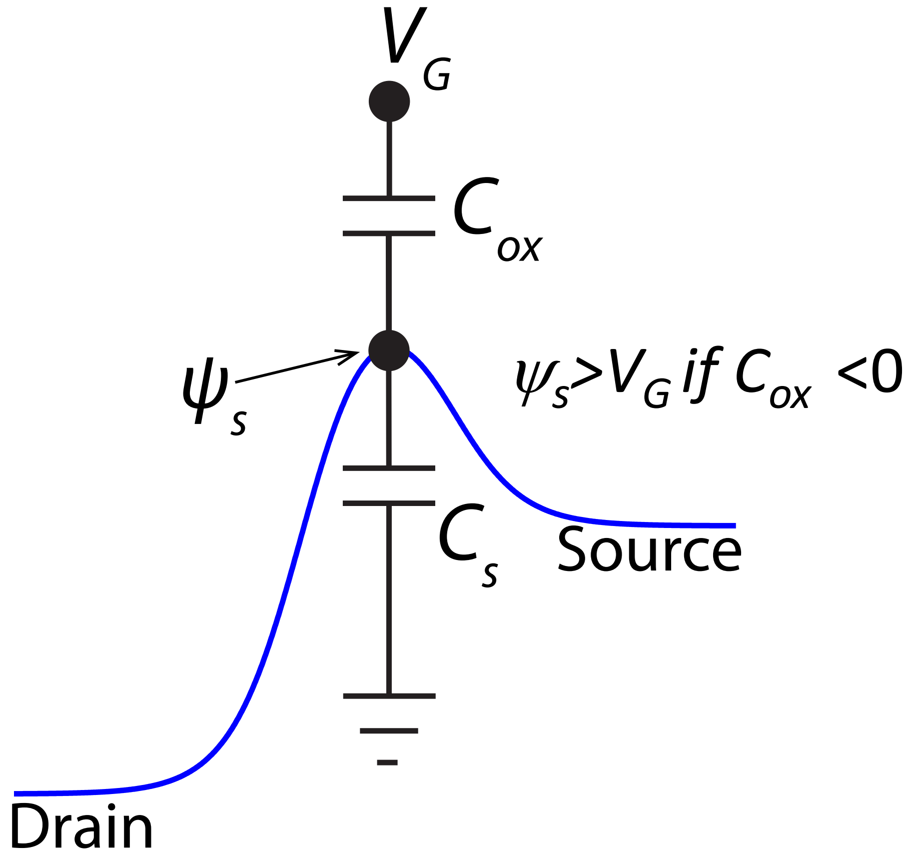
$$S_{\min} = \frac{k_B T}{q}\log_e(10)$$
$$= 60mV/dec$$



We are in search of an Ultra-low Power MOSFET!

The Negative Capacitance Approach





Subthreshold Swing
$$S = \frac{\partial V_G}{\partial(\log_{10} I_D)}$$
$$= \underbrace{\frac{\partial V_G}{\partial \psi_s}}_{\equiv \mathrm{m}} \frac{\partial \psi_s}{\partial(\log_{10} I_D)}$$
$$= m \times 60 \text{ mV/decade}$$

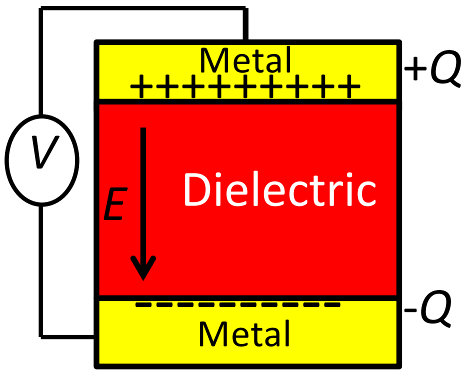
Body Factor
$$m = \frac{\partial V_G}{\partial \psi_s} = 1 + \frac{C_s}{C_{ox}}$$

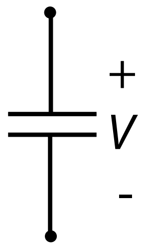
$$m = 1 + \frac{C_s}{C_{ox}} < 1$$ if C_{ox} is negative

Negative capacitance can result in a $S <$ 60 mV/decade

Salahuddin et al. Nano Lett. 8, 405 (2008)

Capacitance: Positive and Negative





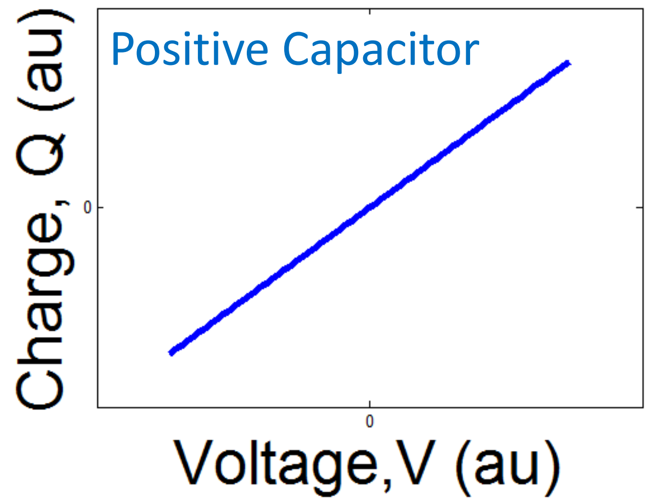
Capacitance $$C = \frac{dQ}{dV}$$

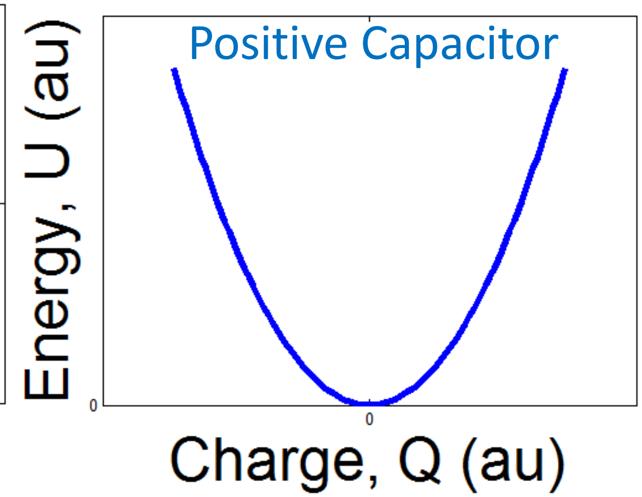
Stored Energy $$U = \frac{Q^2}{2C}$$

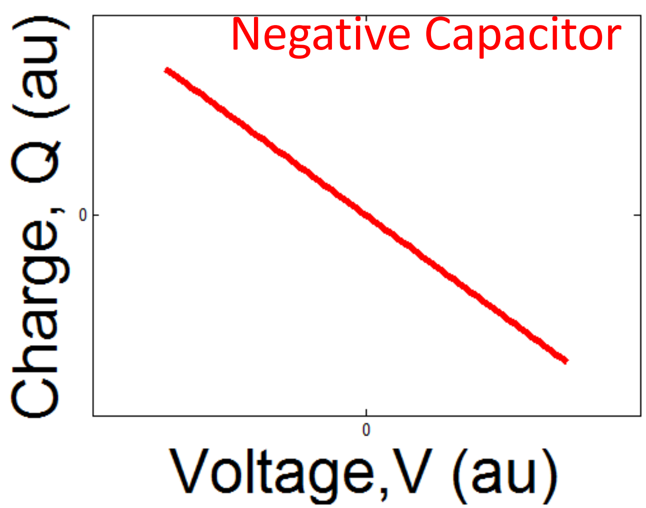
$$C = \left[\frac{d^2U}{dQ^2}\right]^{-1}$$

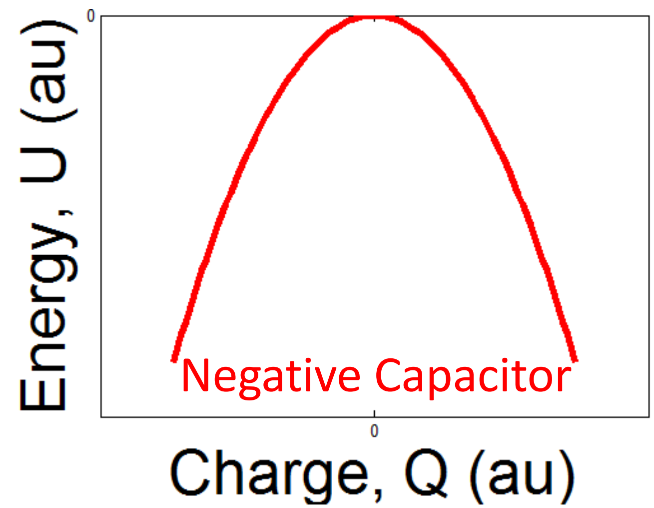
Q-*V* Characteristics

Q-*U* Characteristics (Energy Landscape)









C is inverse of radius of curvature of energy landscape

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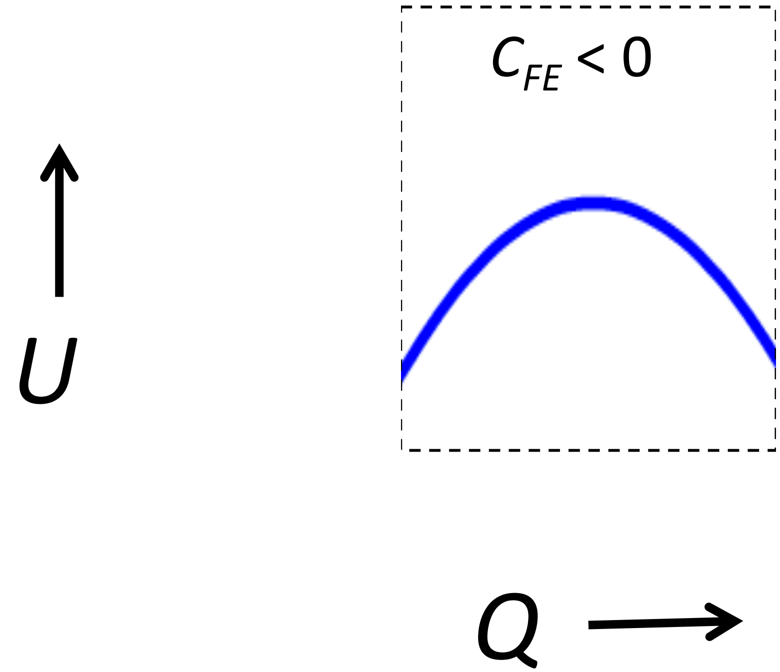
How to get Negative Capacitance Material



Landau Theory of Ferroelectrics

Free energy of a ferroelectric

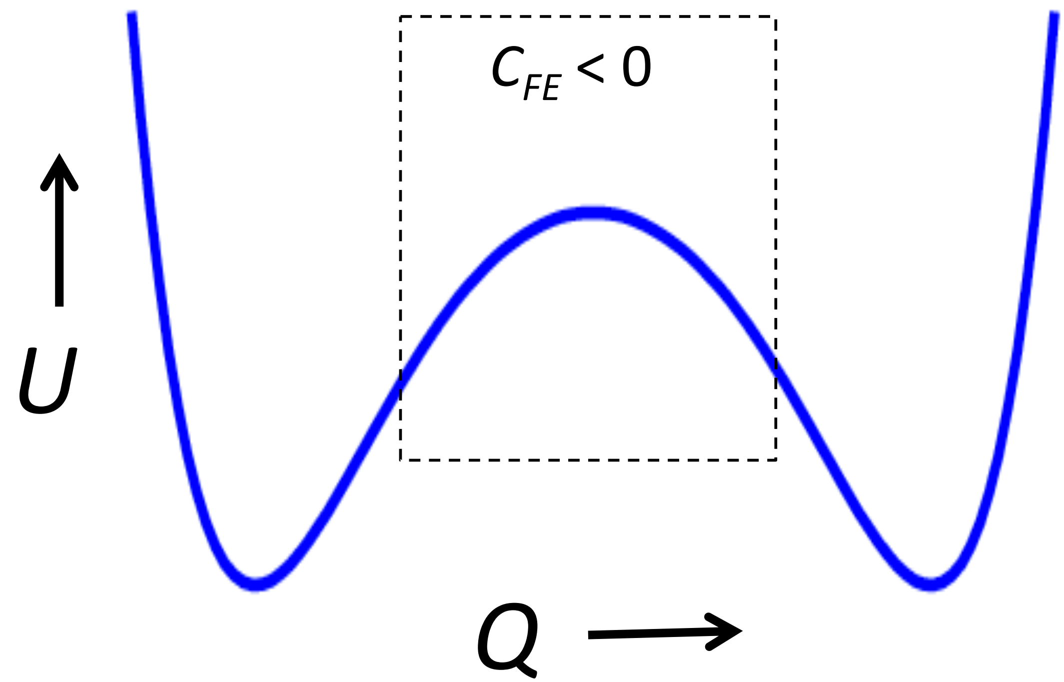
$$U = \alpha Q^2 + \beta Q^4 + \gamma Q^6 ; \alpha < 0$$

α, β, γ = Anisotropy Constants
Q = Charge

According to the Landau theory of ferroelectric, ferroelectric oxides could give an effective negative capacitance

Landau & Khalatnikov. Dokl. Akad. Nauk 96, 85 469472 (1954).

How to get Negative Capacitance Material



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Landau & Khalatnikov. Dokl. Akad. Nauk 96, 85 469472 (1954).

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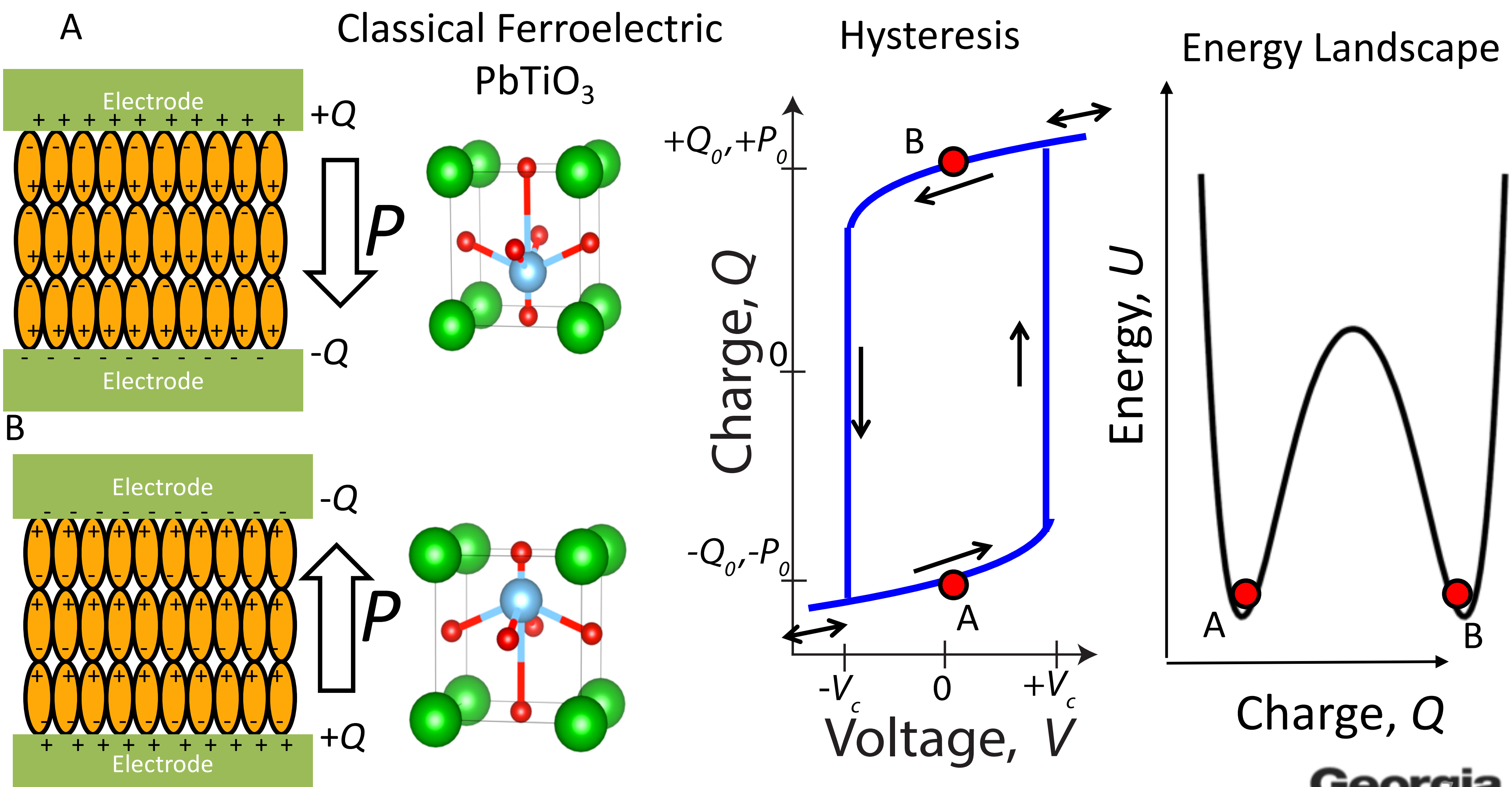
Ferroelectric Oxides

A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercivity voltage .



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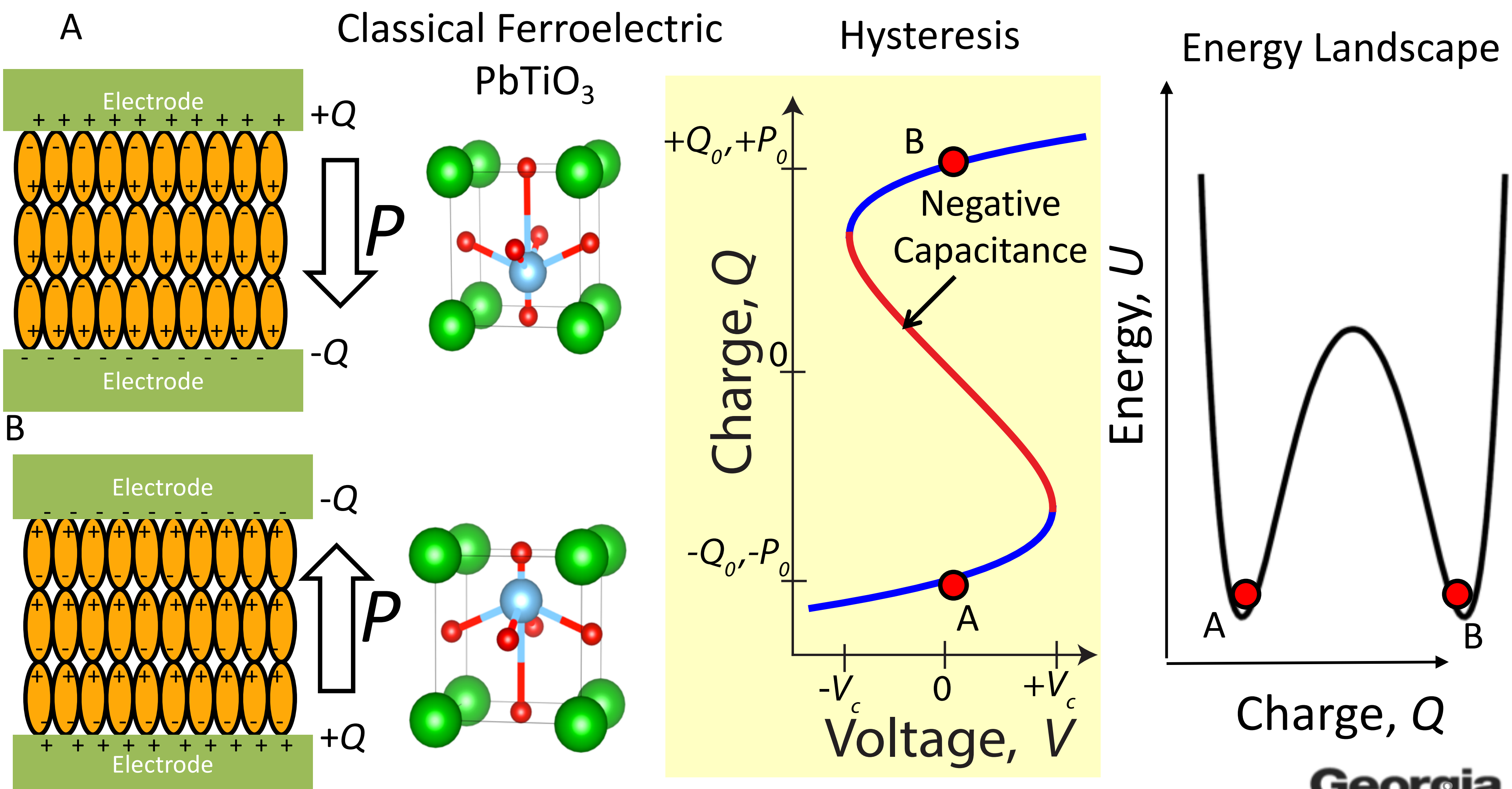
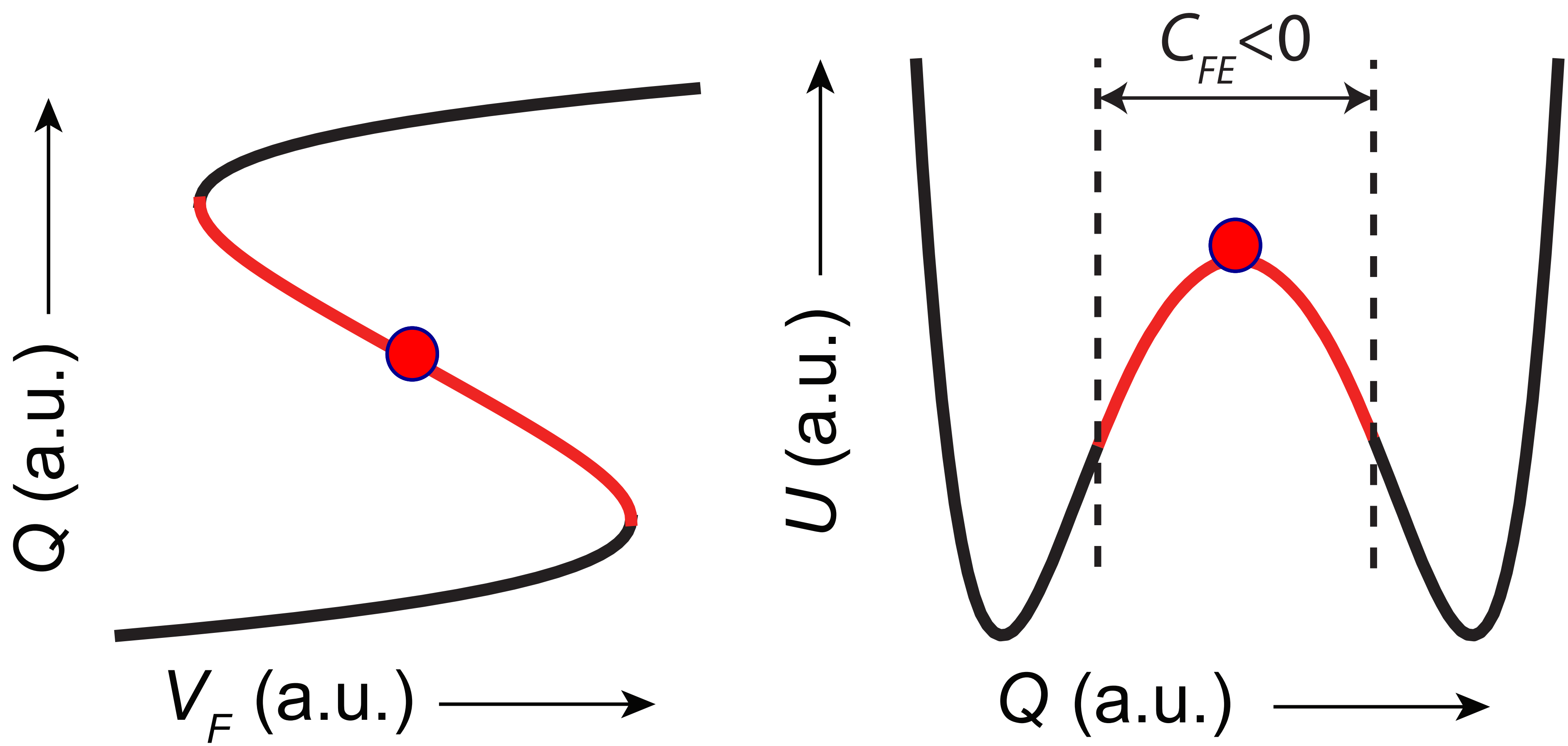
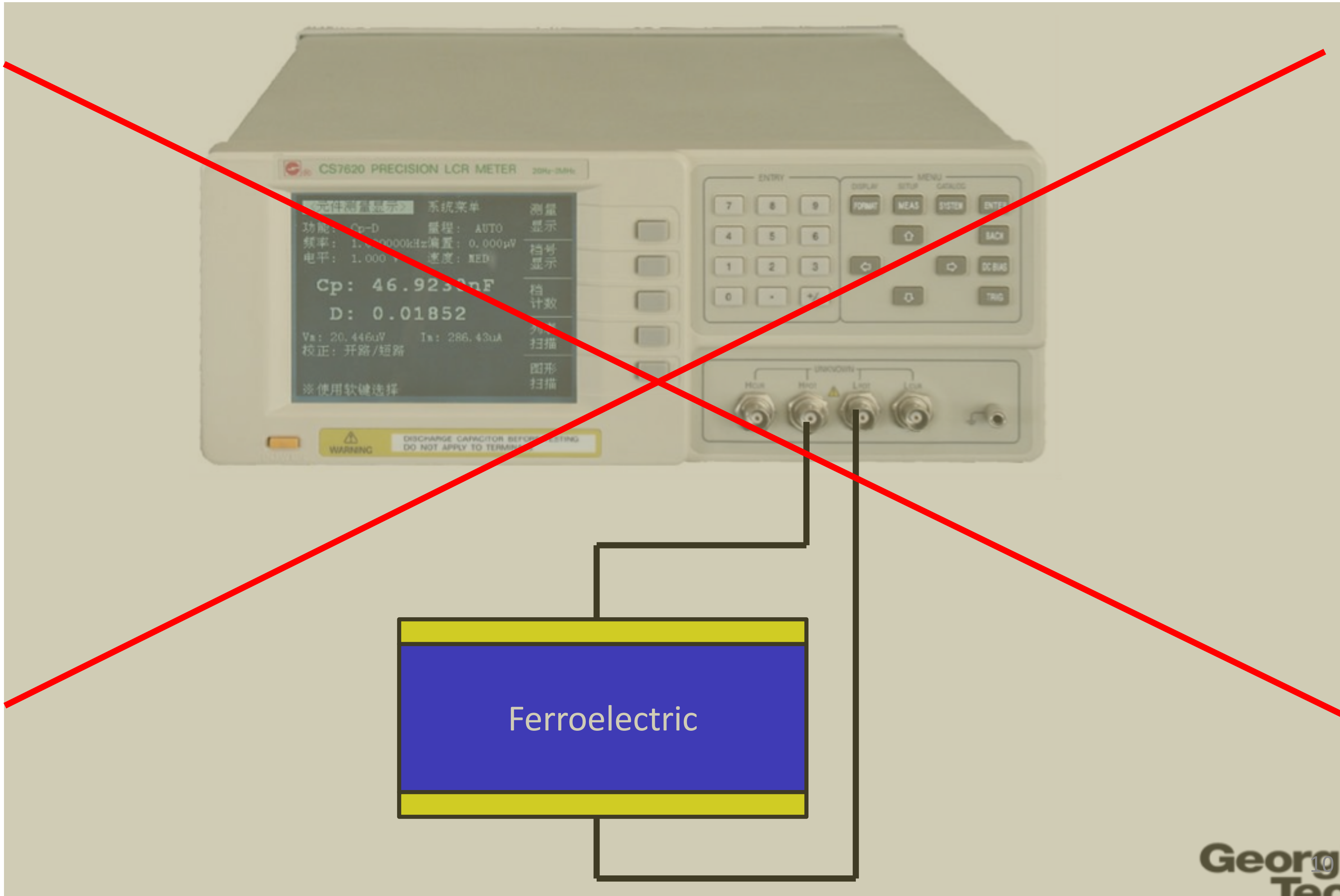


Why is it difficult to measure?

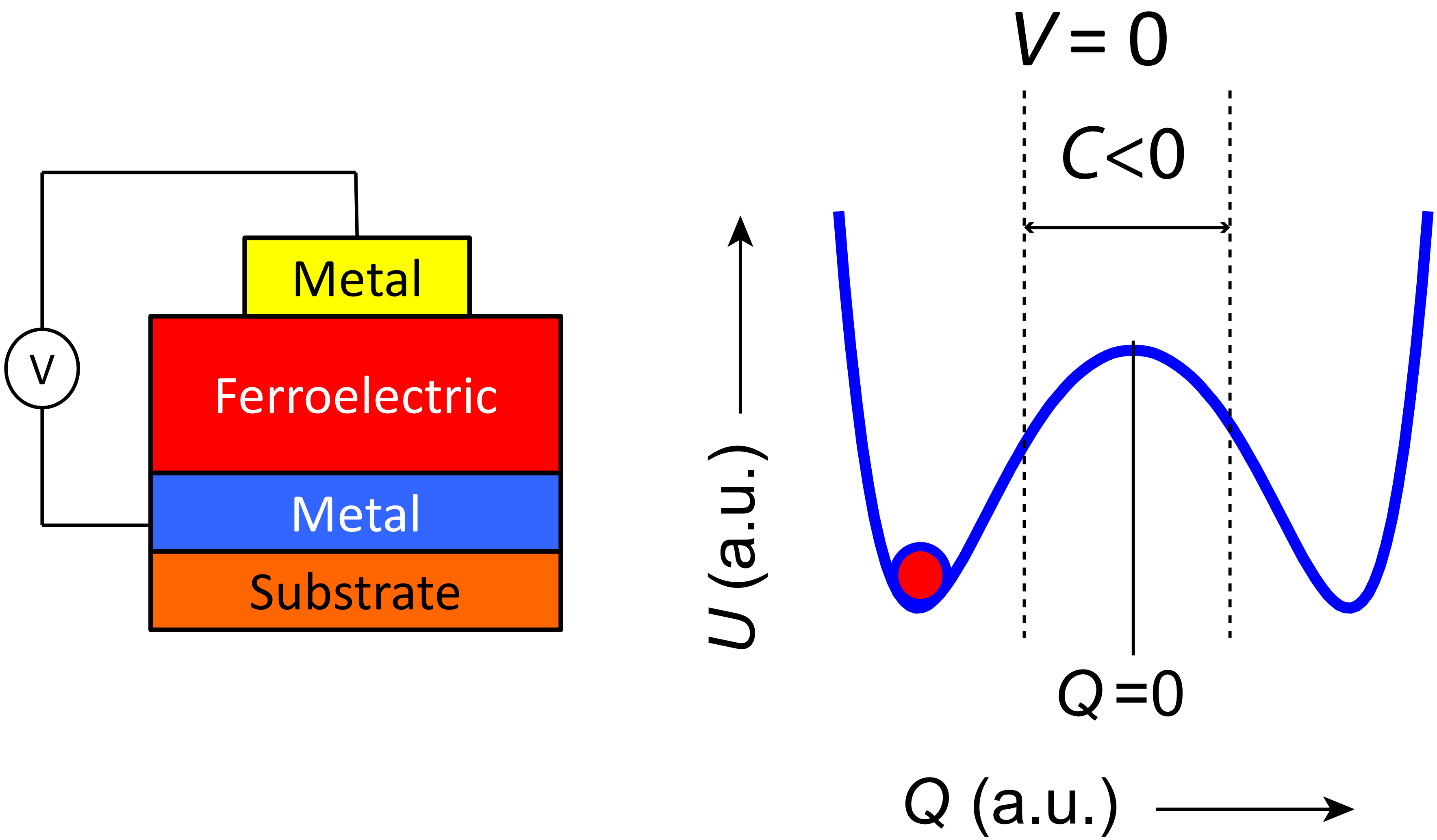


Ferroelectric Negative Capacitance is unstable and cannot be accessed in a time independent equilibrium measurement.

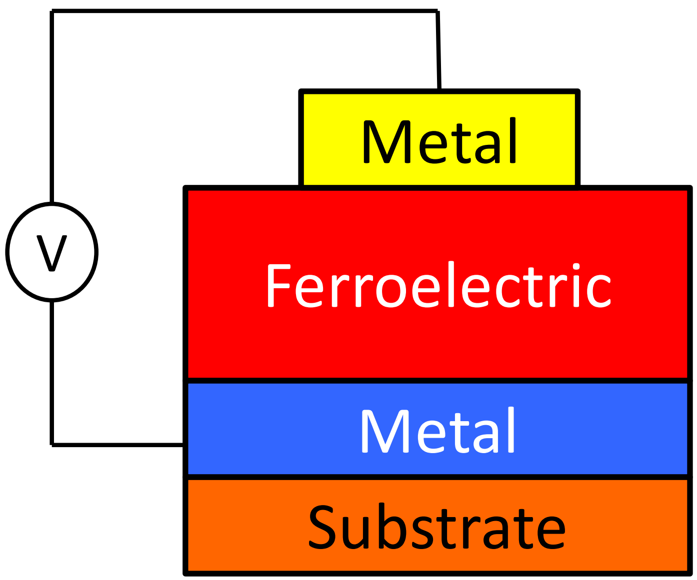
Why is it difficult to measure?

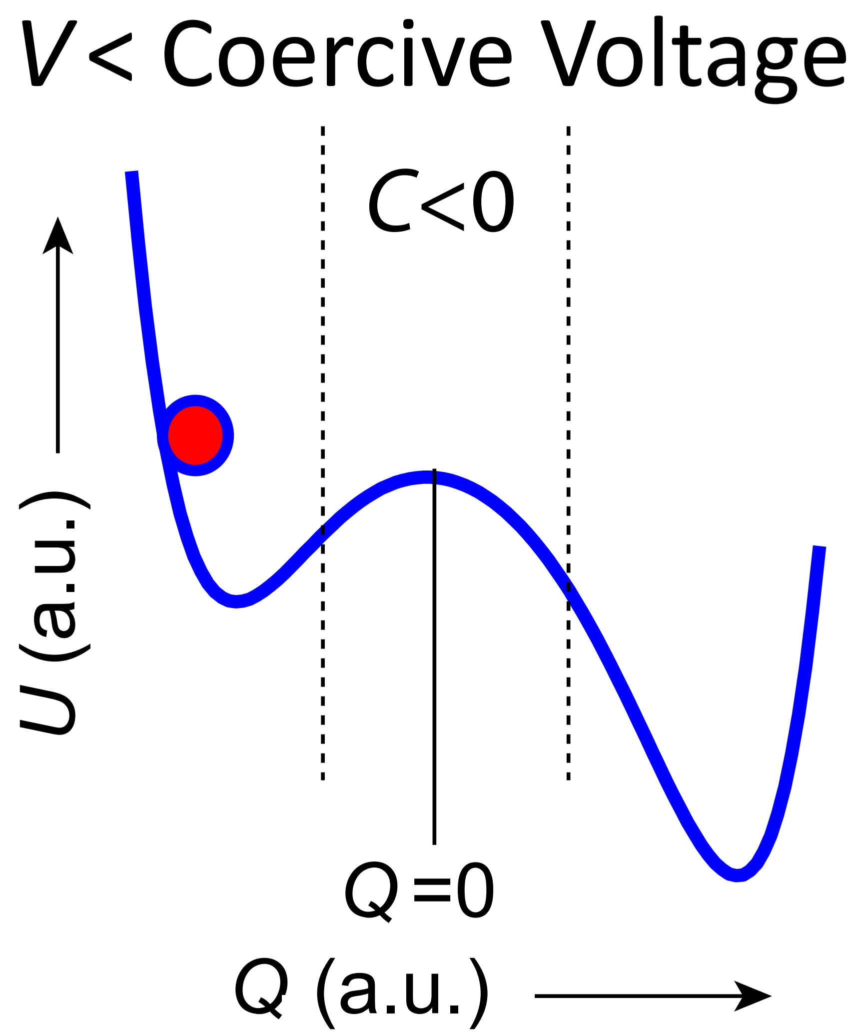


Direct Measurement of Negative Capacitance



Direct Measurement of Negative Capacitance





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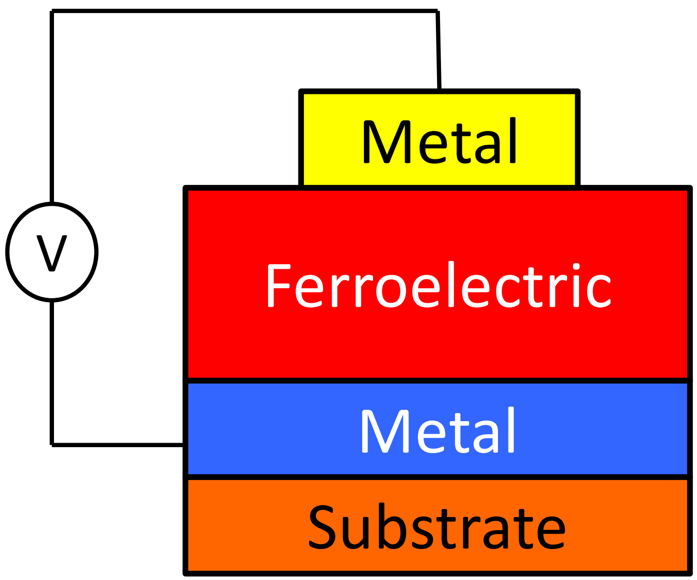
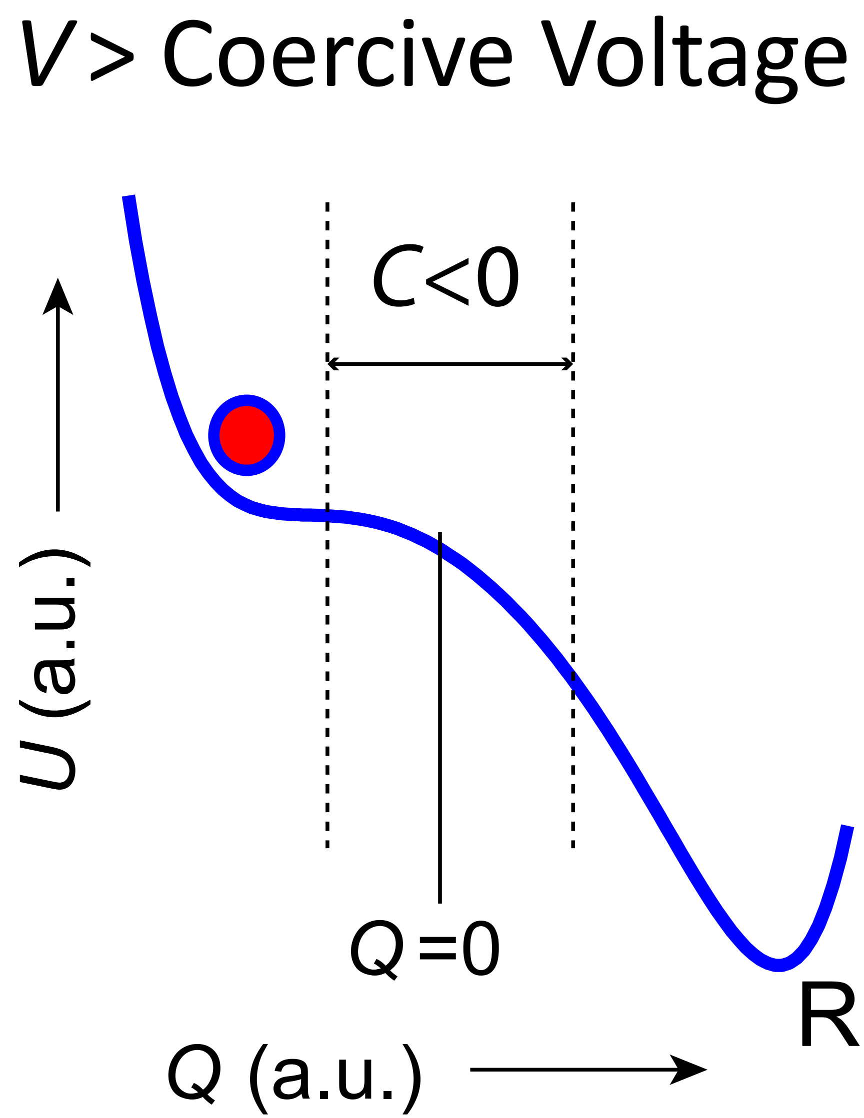
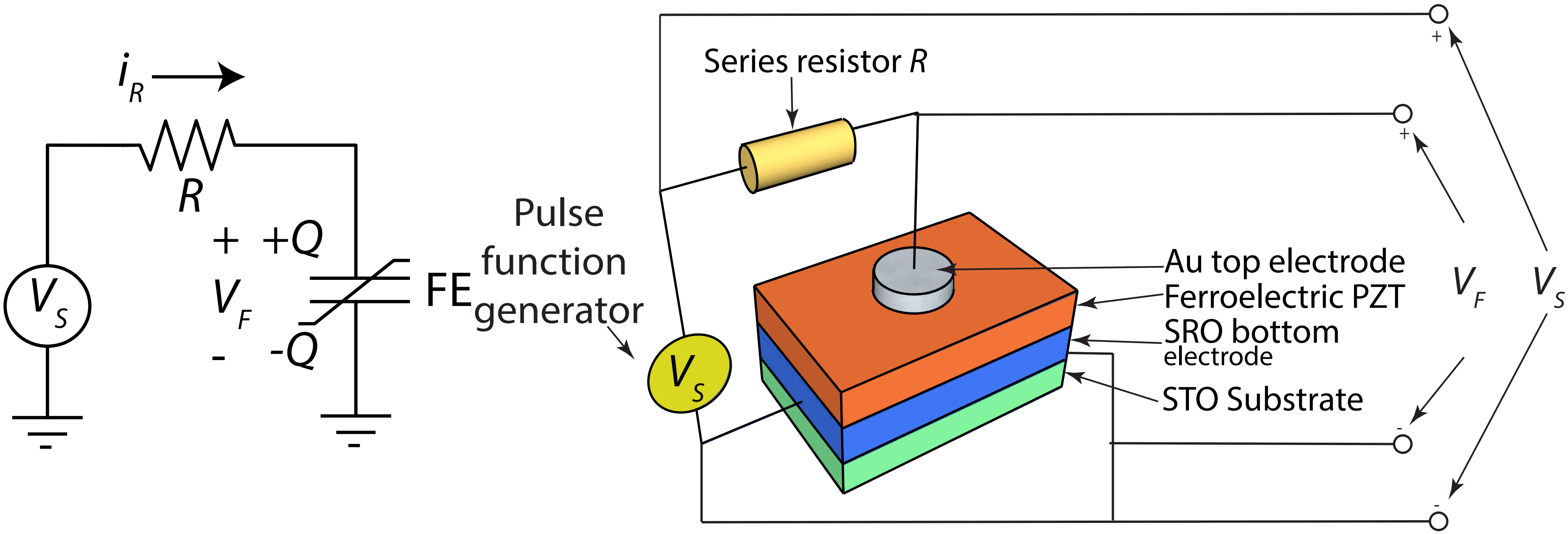
Direct Measurement of Negative Capacitance



A ferroelectric capacitor goes through the unstable negative capacitance states during switching.

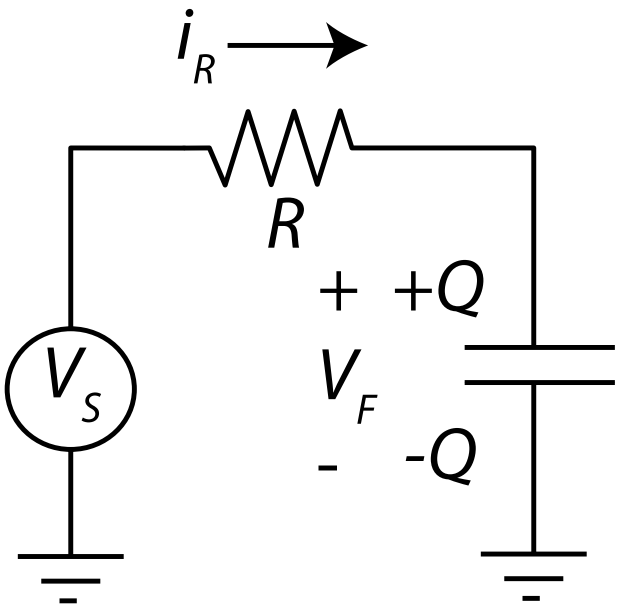


Direct Measurement of Negative Capacitance



A ferroelectric capacitor connected in series with an external resistor.

What happens in an *R-C* Series circuit?

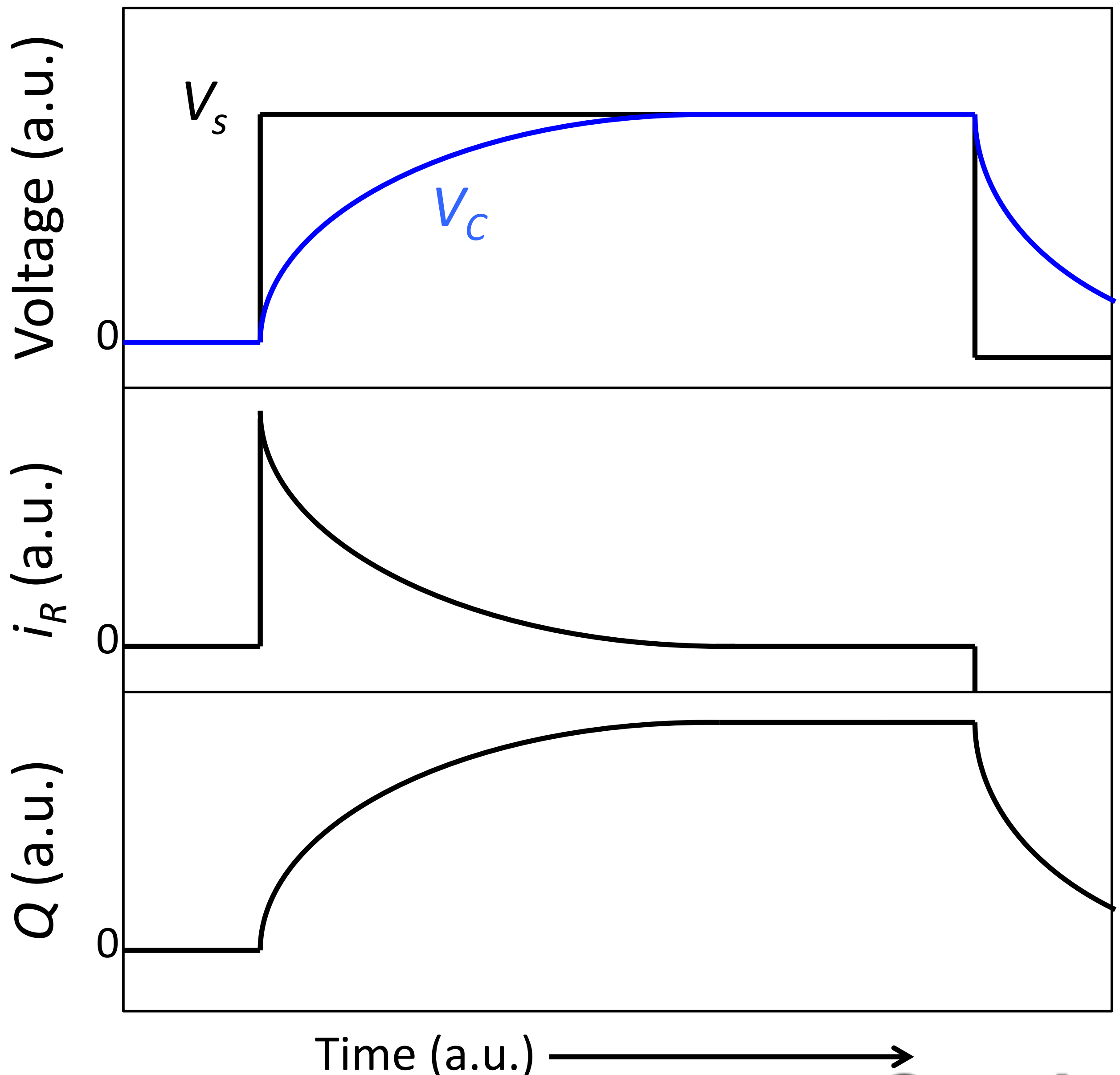


Voltage: $V_C = V_S(1-e^{-t/RC})$

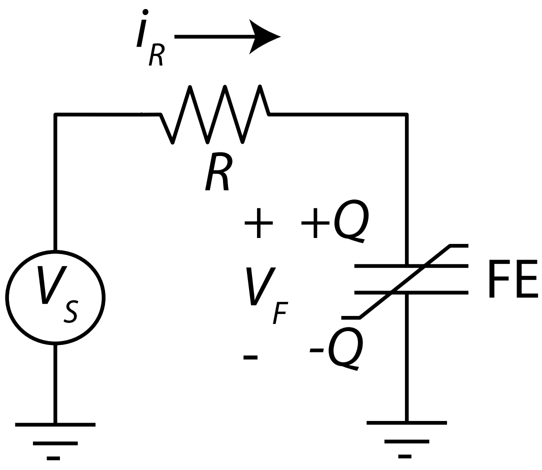
Current: $i_R = V_S e^{-t/RC}/R$

Charge: $Q = CV_S(1-e^{-t/RC})$

At any time t,
$dQ/dV_C = C > 0$.

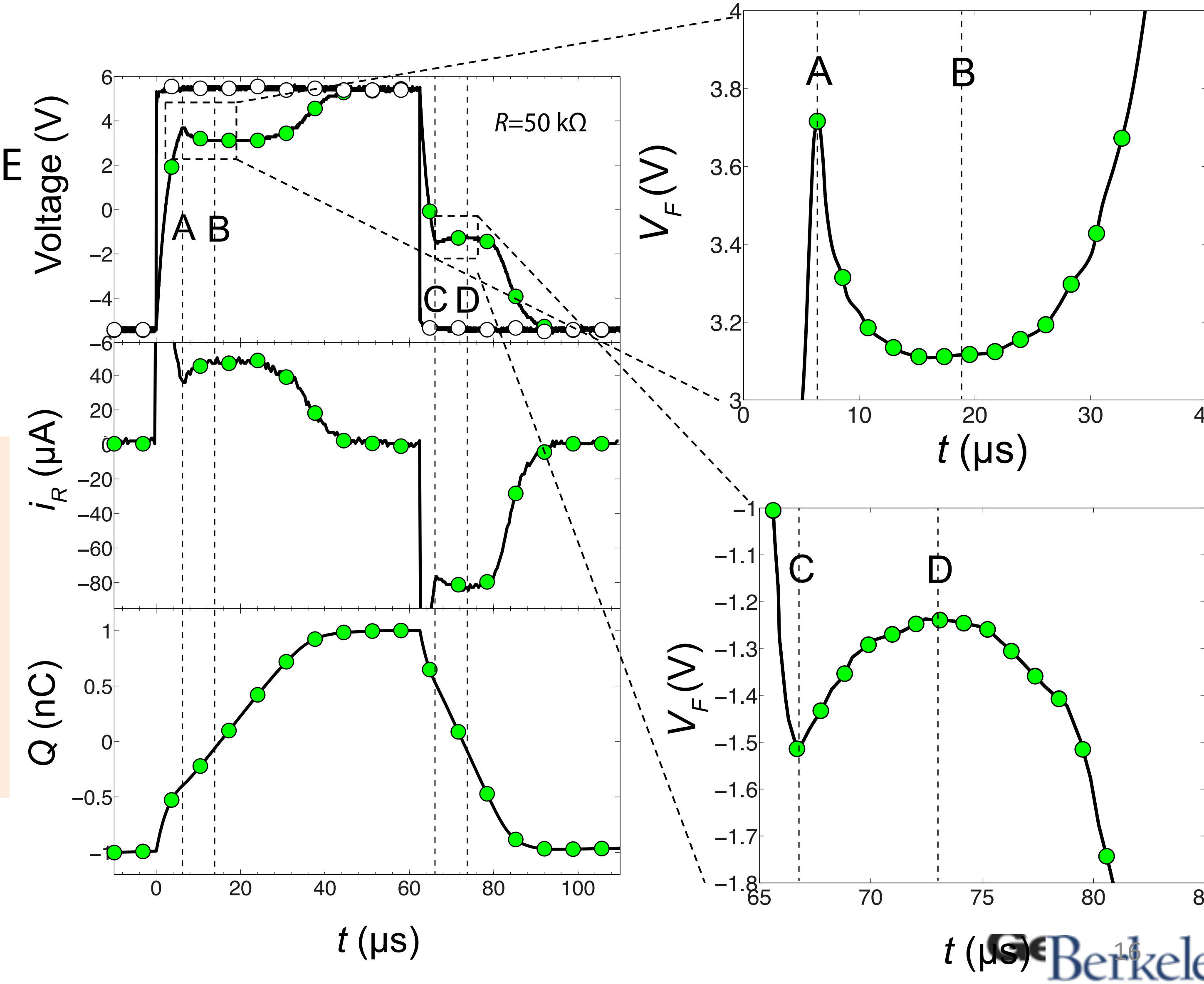


Direct Measurement of Negative Capacitance



60 nm $Pb(Zr_{0.2}Ti_{0.8})O_3$) (Coercive voltage=~2.5 V)

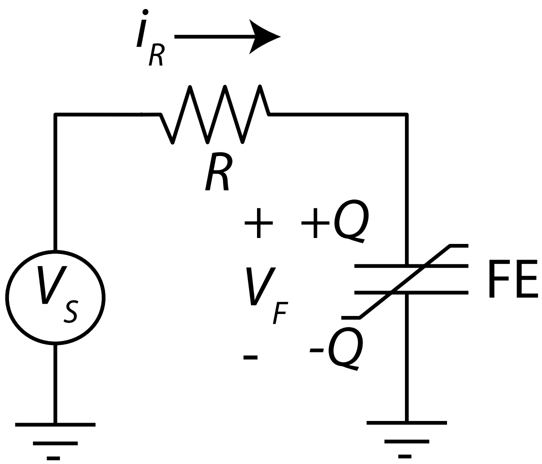
V_s: -5.4 V → +5.4 V → -5.4 V



During AB & CD, dQ & dV_F has opposite signs indicating dQ/dV_F<0.

Khan et al. Nature Mater. 14, 182 (2015)

Direct Measurement of Negative Capacitance



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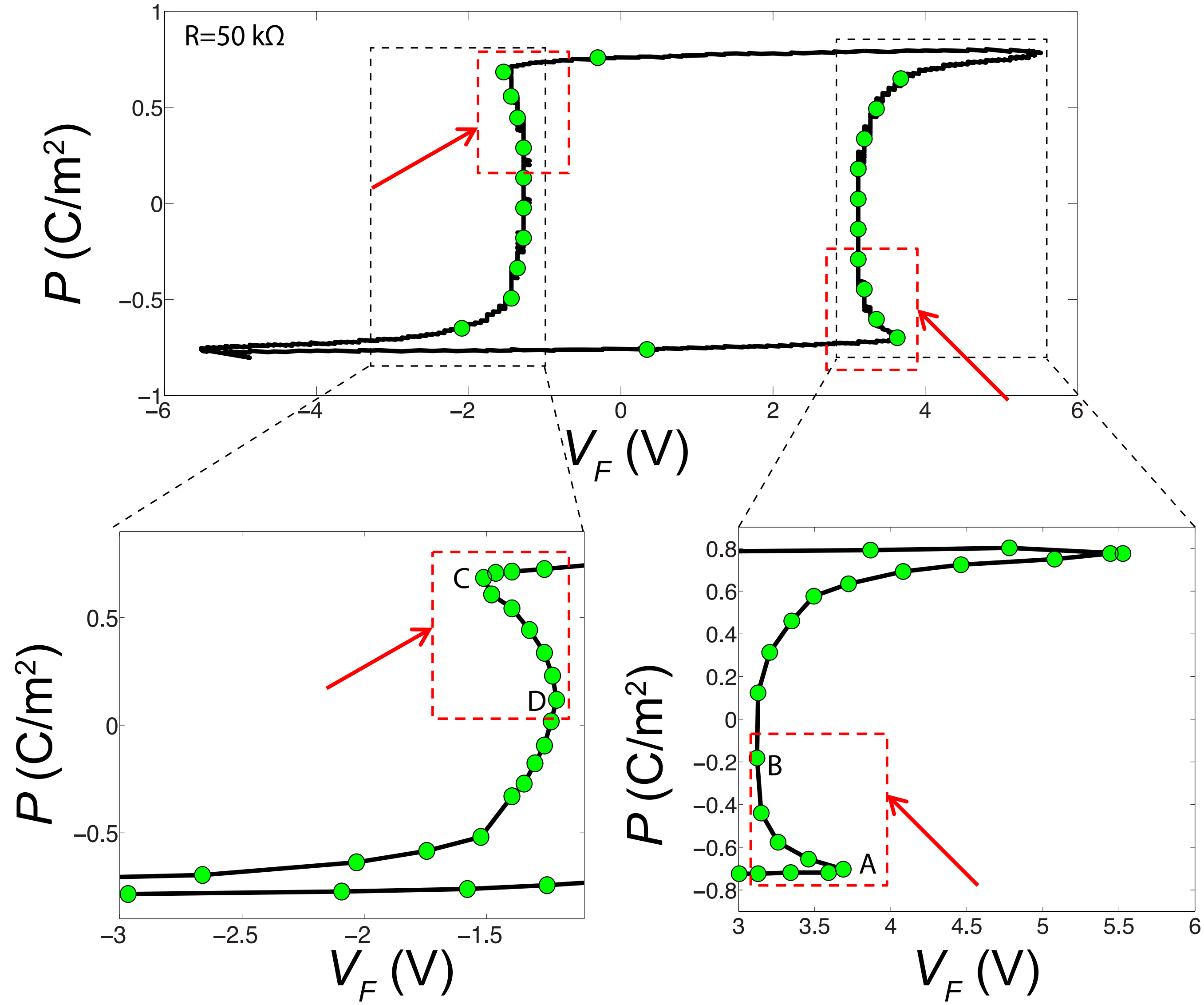
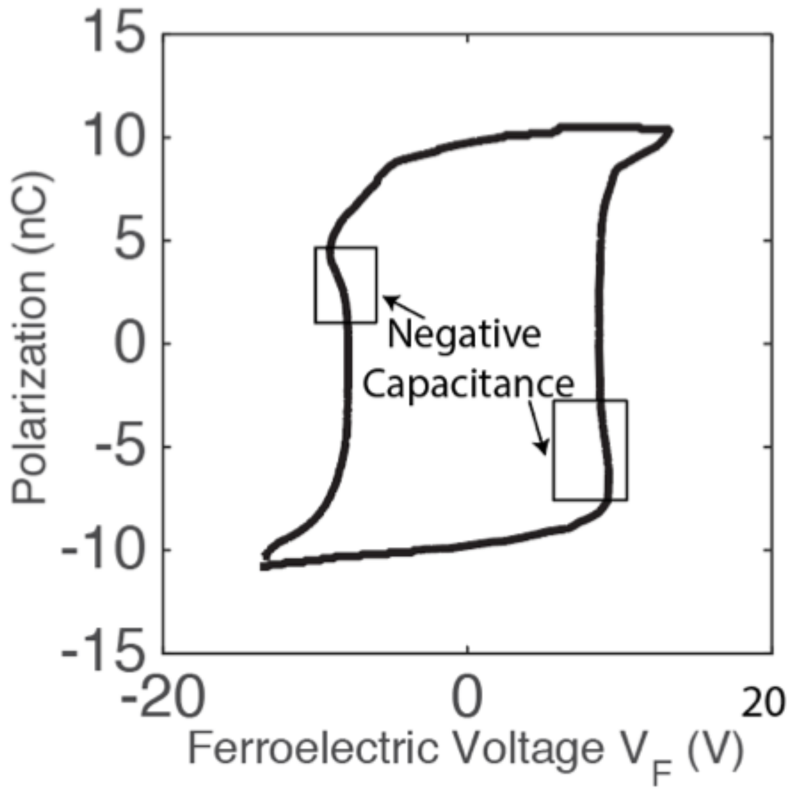


A negative dQ/dV_F directly observed in an isolated ferroelectric.

Khan et al. Nature Mater. 14, 182 (2015)

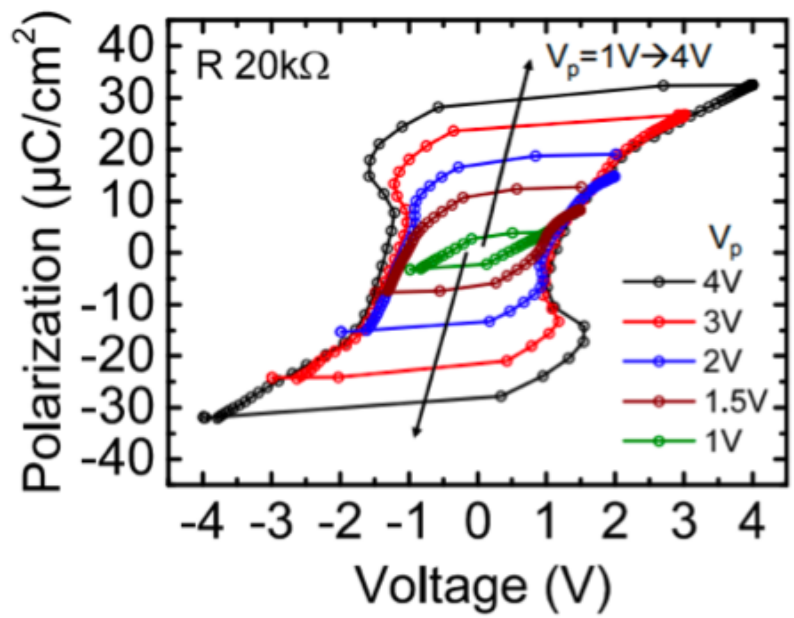
Negative Cap. in Doped HfO_2 Ferroelectrics

Ferroelectric Gd-doped HfO_2 (27 nm)



Hoffmann et al. Direct Observation of Negative Capacitance in Polycrystalline Ferroelectric HfO_2. Advanced Functional Materials 2016.

Ferroelectric HfZrO$_2$ (10 nm)



Kobayashi et al. Experimental study on polarization-limited operation speed of negative capacitance FET with ferroelectric HfO_2. IEDM 2016

Negative capacitance is a general phenomenon in ferroelectrics!

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Negative Capacitance in 1956!

Landauer et al. Polarization reversal in the Barium Titanate hysteresis loops.
J. Appl. Phys. 27, 752 (1956)

Merz. Switching time in BaTiO3 and its dependence on its crystal thickness. **J. Appl. Phys.** 27, 938 (1956)

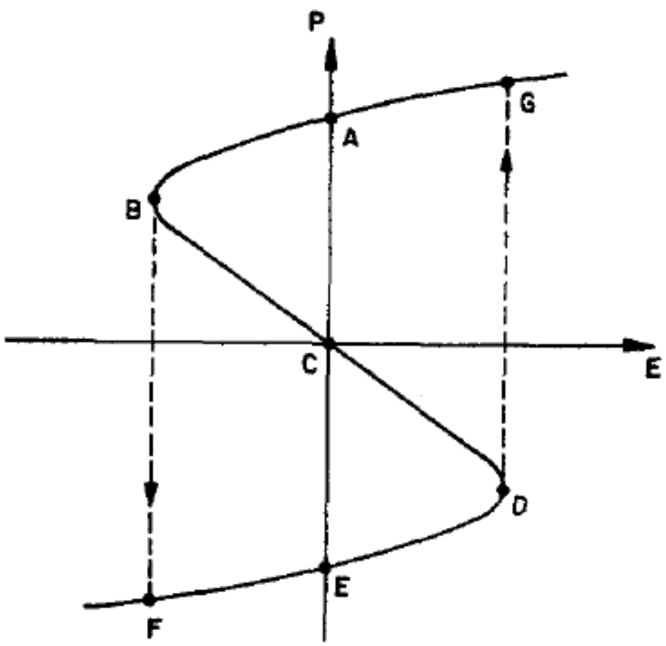


FIG. 1. Plot of polarization against field, at room temperature, as given by Devonshire's theory. P = polarization, E = field. Direction of field and polarization are taken to be the same, and parallel to the "c" axis of a single domain crystal. The solid line $GABCDEF$ gives the theoretical relationship.

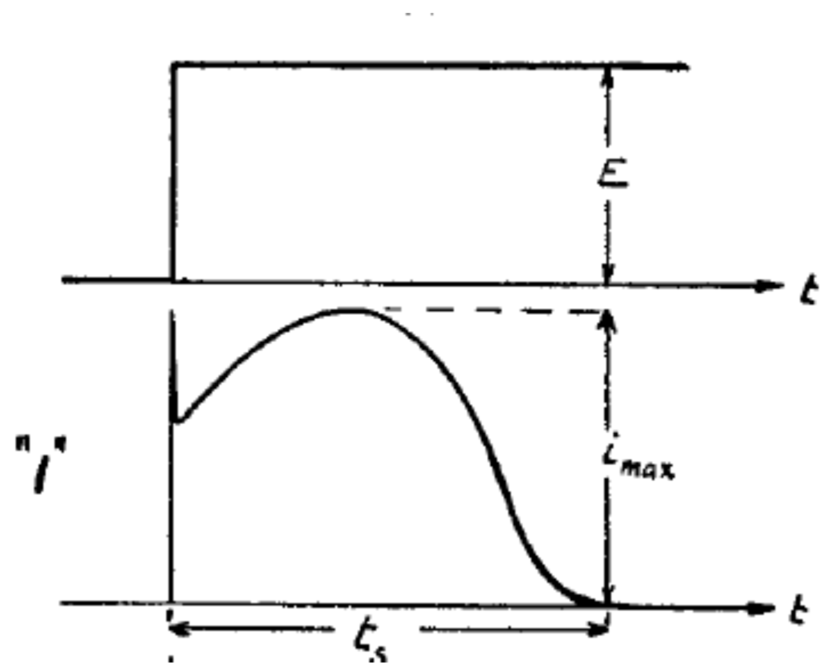
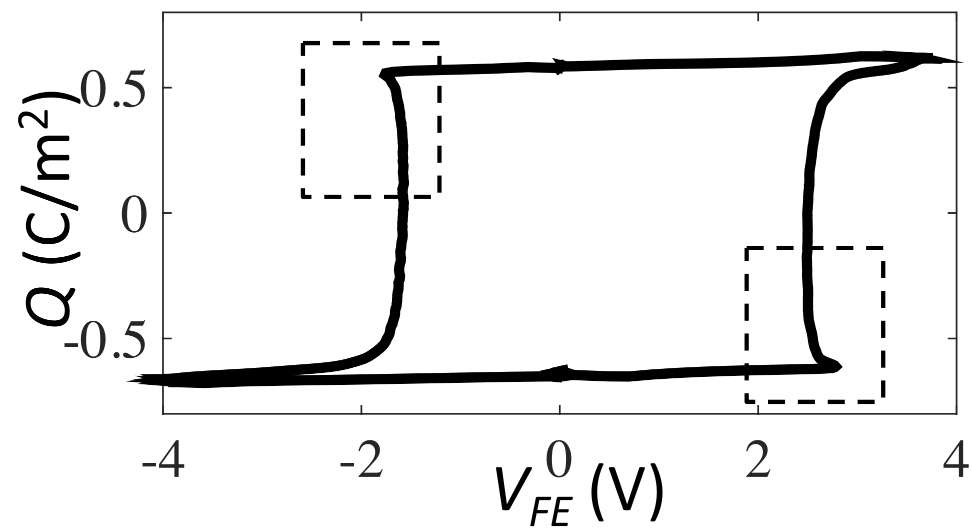


FIG. 1. Pulsing field and pulsing current *versus* time.

What's next?

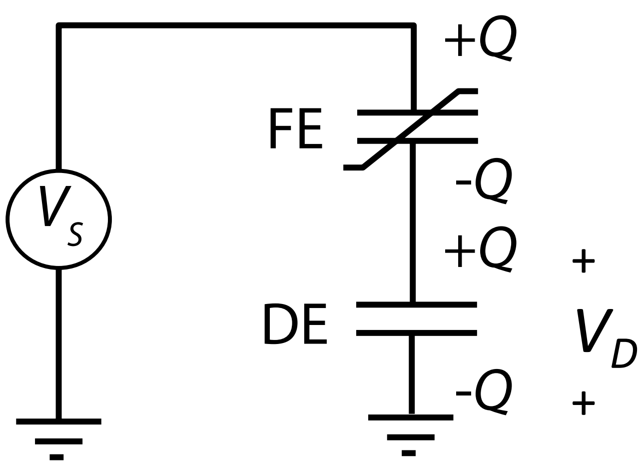
Now that negative capacitance has been detected…

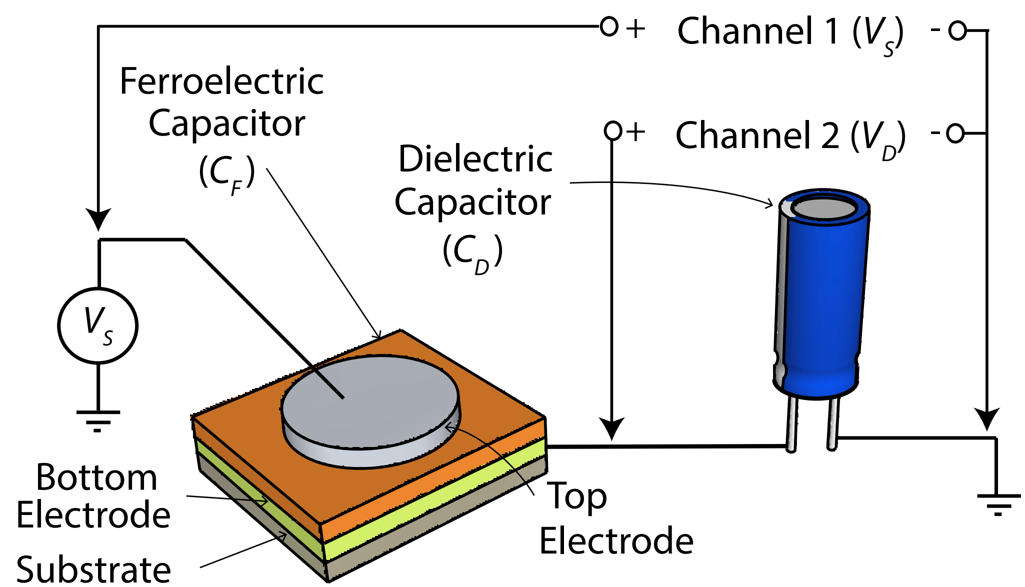


How to achieve voltage amplification from negative capacitance?

How to stabilize negative capacitance?

Ferroelectric+Dielectric Capacitor

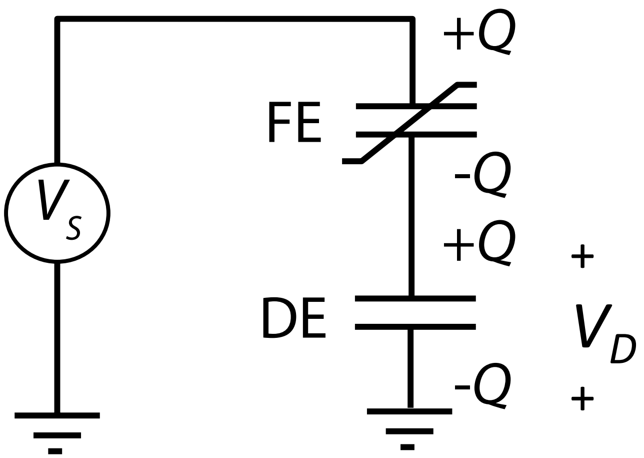


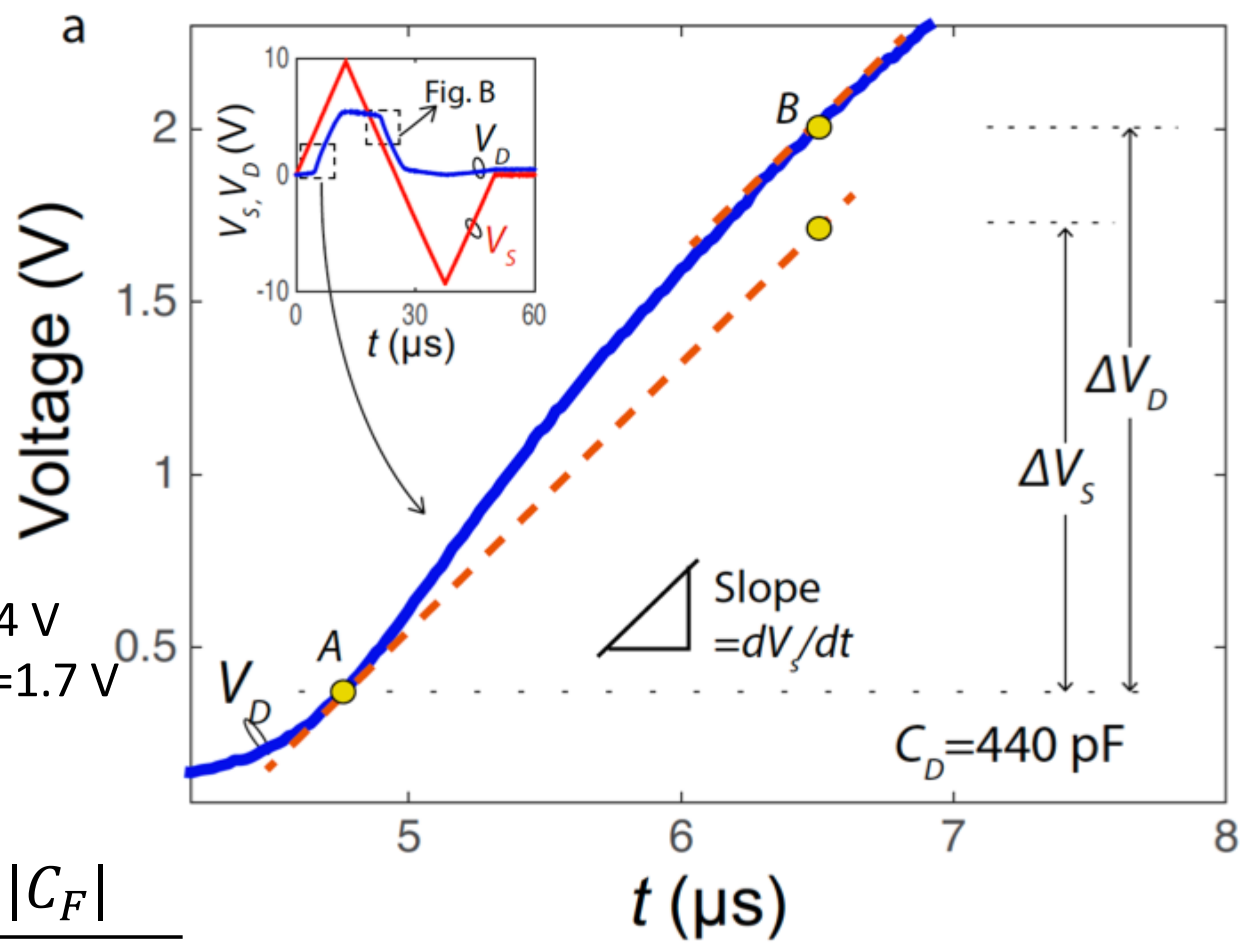


Voltage amplification: $$\frac{dV_D}{dV_S} = \frac{C_F}{C_F + C_D} = \frac{|C_F|}{|C_F| - C_D}$$

If $C_F < 0$ $|C_F| > C_D$, $\boxed{\frac{dV_D}{dV_S} > 1}$

Ferroelectric+Dielectric Capacitor





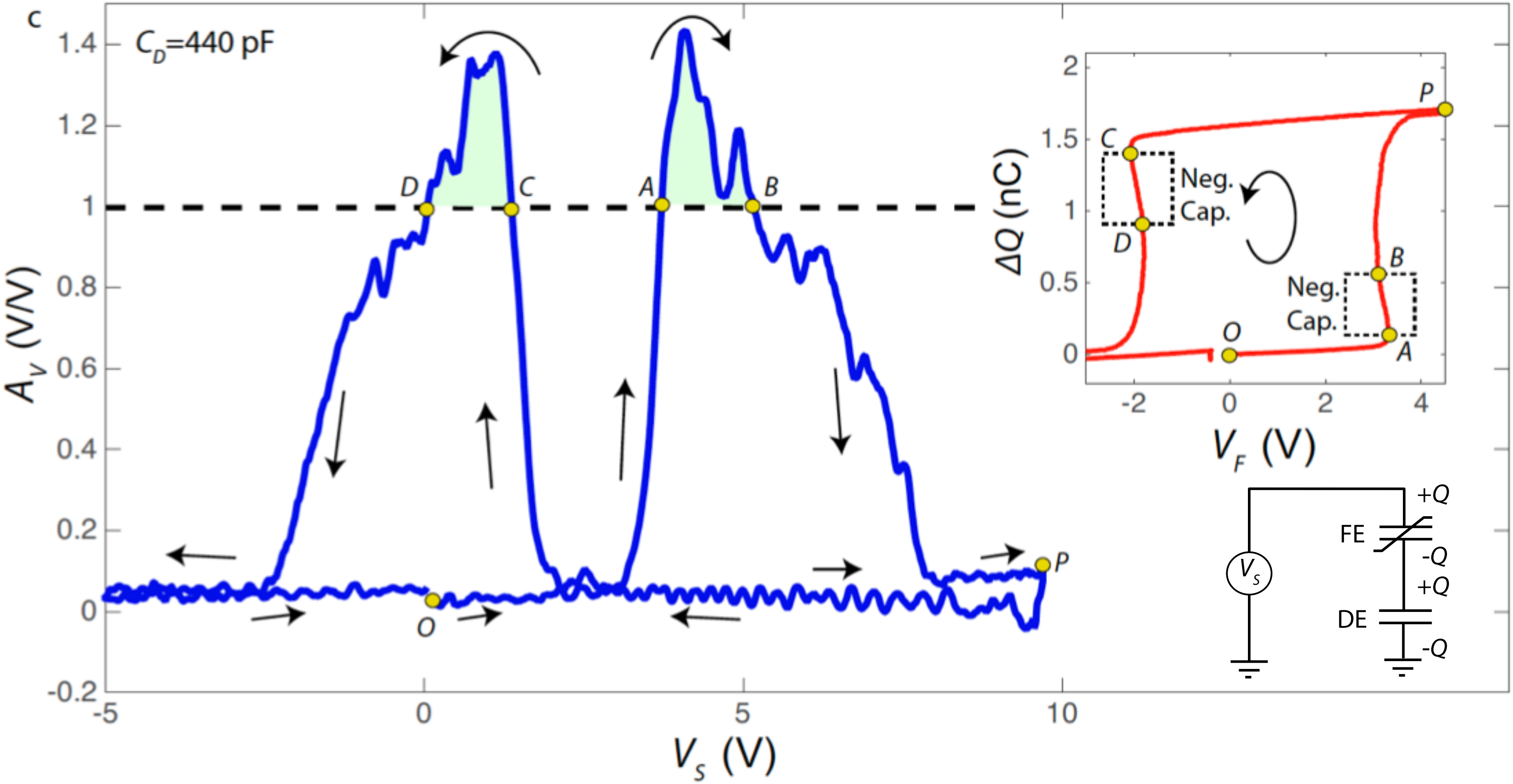
Change in source voltage ΔV_S=1.4 V
Change in dielectric voltage ΔV_D=1.7 V

$$\frac{\Delta V_D}{\Delta V_S} = \frac{1.7\ V}{1.4\ V} \approx 1.21 = \frac{|C_F|}{|C_F| - C_D}$$

Voltage amplification in a FE-DE series network experimentally observed!

Khan et al. Appl. Phys. Lett. 111, 253501 (2017)

Ferroelectric+Dielectric Capacitor

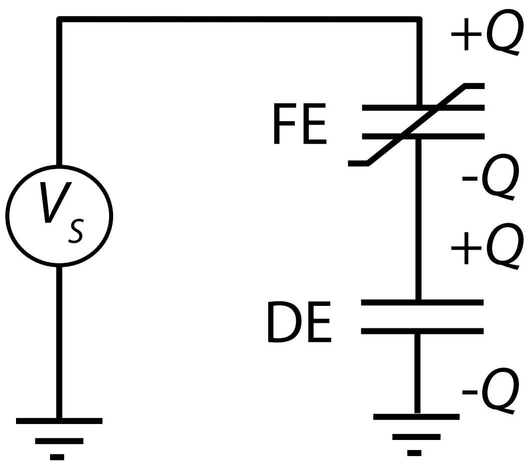


Khan et al. Appl. Phys. Lett. 111, 253501 (2017)

Voltage amplification in a FE-DE series network experimentally observed!

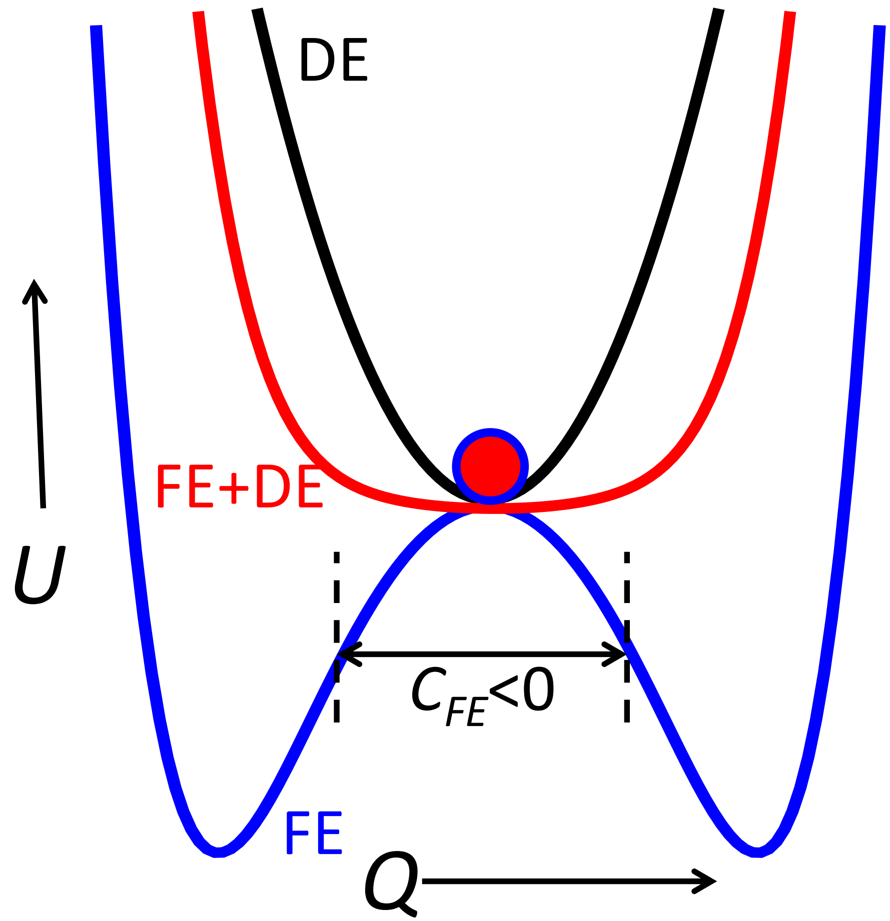
Capacitance Enhancement due to Neg. Cap

Ferroelectric-Dielectric Series Combination



$$C = \left[\frac{d^2U}{dQ^2}\right]^{-1}$$

Energy Landscapes

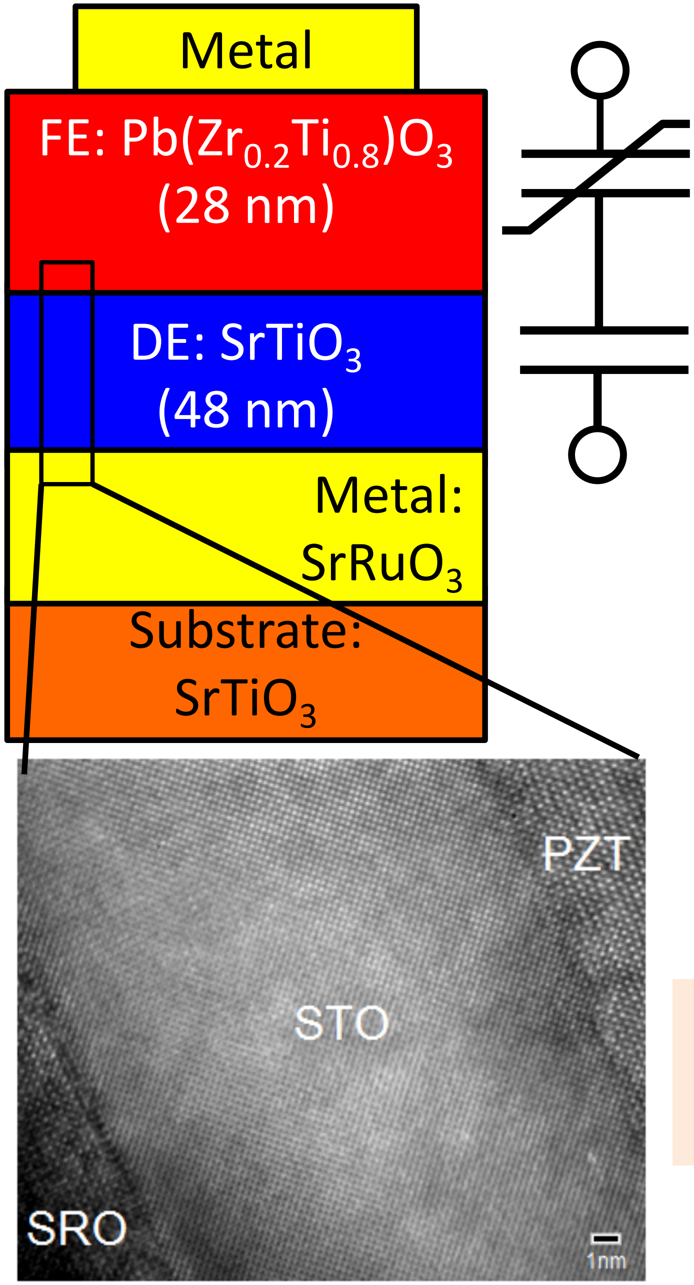


Equivalent Capacitance $$C_{FE+DE} = \left[\frac{1}{C_{FE}} + \frac{1}{C_{DE}}\right]^{-1}$$

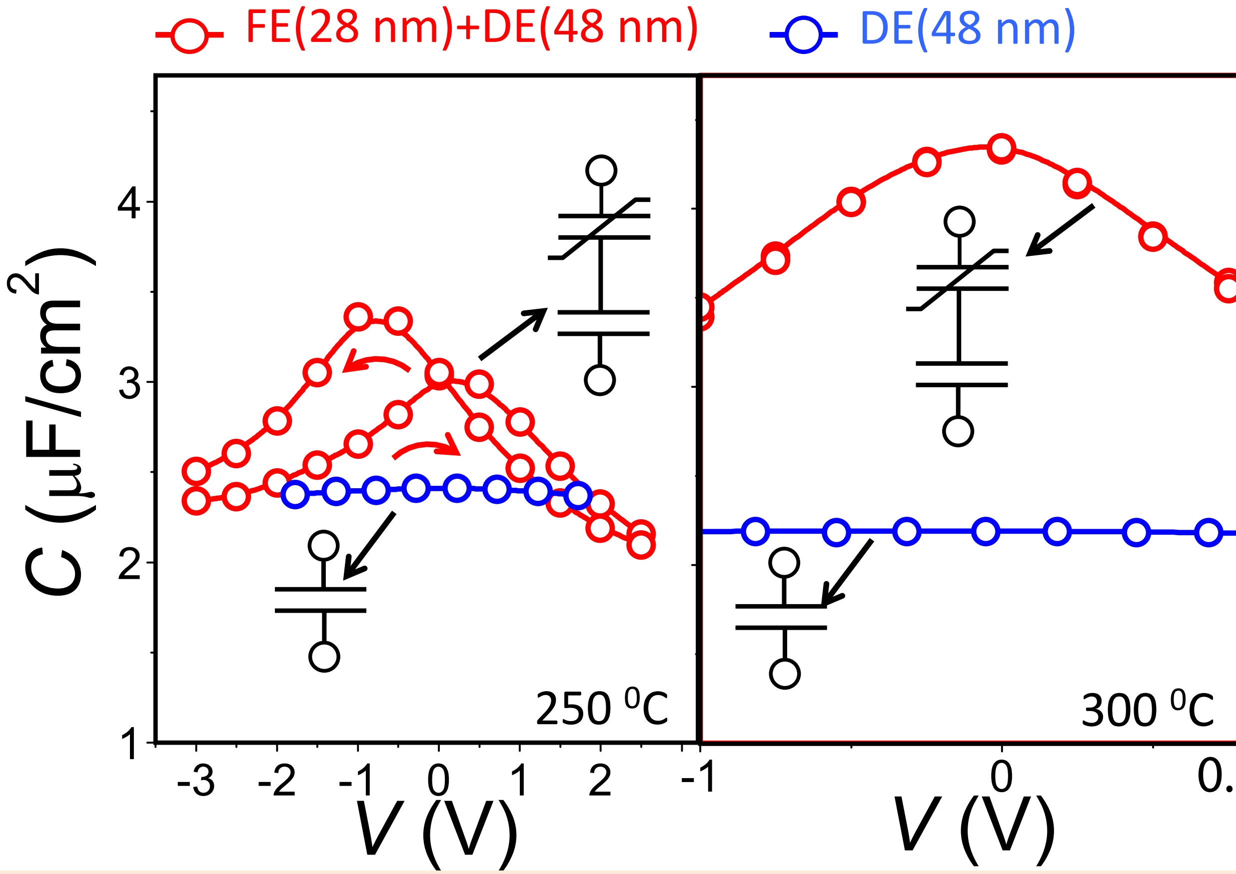
$C_{FE+DE} > C_{DE}$ If $C_{FE} < 0$

Enhancement of capacitance in a FE-DE Series combination!

Capacitance Enhancement due to Neg. Cap.



C-V Characteristics

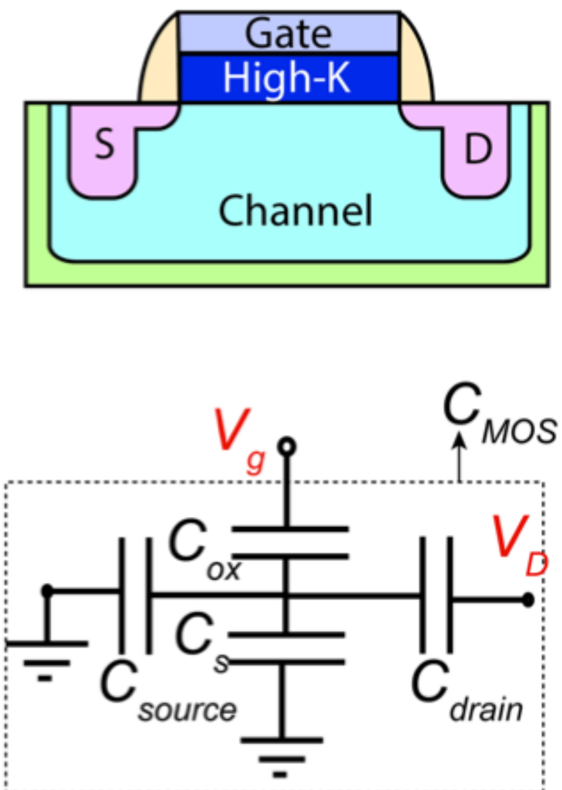


Capacitance Enhancement in a FE-DE heterostructure experimentally observed!

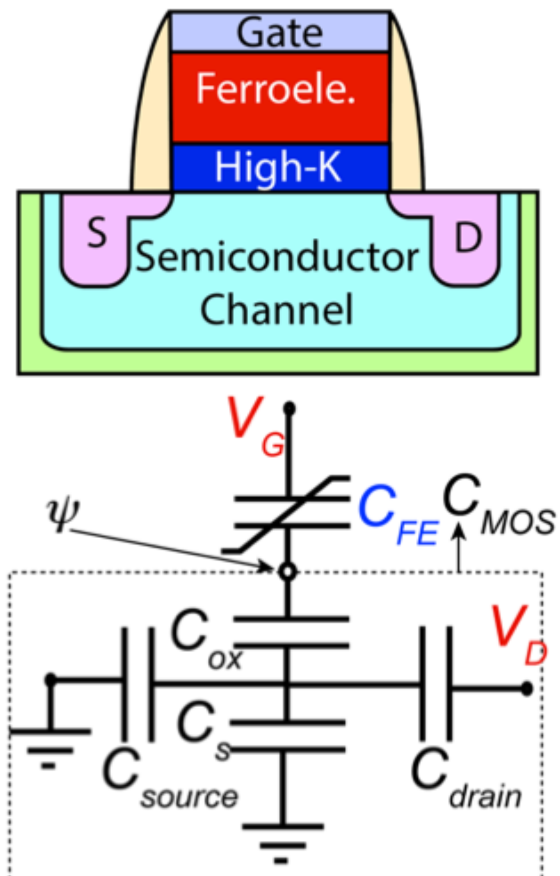
Khan et al. Appl. Phys. Lett. 100, 113501 (2011)
(cover article, most downloaded Aug/Sep 2011).
Gao, Khan et al. Nano Lett. 14, 5814 (2014)

Physics of Negative Capacitance FET

Baseline FET



NCFET



Amplification Factor

$$\frac{d\psi}{dV_G} = \frac{C_{FE}}{C_{FE} + C_{MOS}} = \frac{|C_{FE}|}{|C_{FE}| - C_{MOS}}$$

Modified Body Factor

$$m^o = \frac{dV_G}{d\psi} = 1 - \frac{C_{MOS}}{|C_{FE}|}$$

Subthreshold Swing

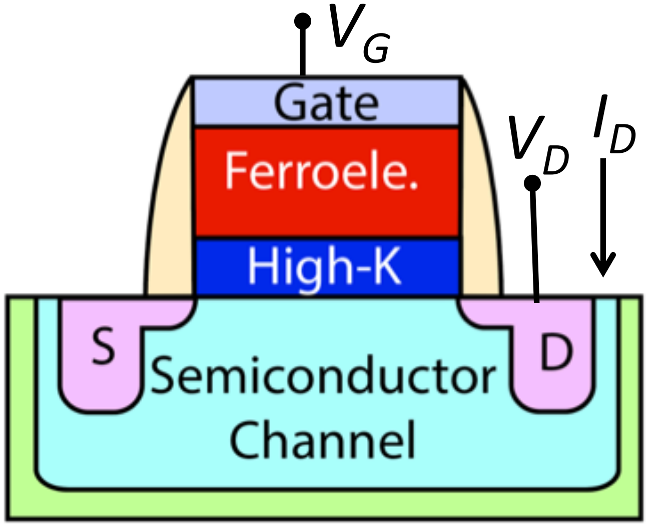
$$S^{NC} = S^{original} \times \left(1 - \frac{C_{MOS}}{|C_{FE}|}\right)$$

Ideal Switch: ~0 mV/decade $\Leftarrow$
$|C_{FE}| \approx C_{MOS}, |C_{FE}| > C_{MOS}$

Condition	Characteristics	Mode
$C_{FE}<0$, $\lvert C_{FE}\rvert>C_{MOS}$	$0<m^o<1$, $S^{NC}<S^{original}$	Logic
$C_{FE}<0$, $\lvert C_{FE}\rvert<C_{MOS}$	$m^o<0$, $S^{NC}<0$	Memory

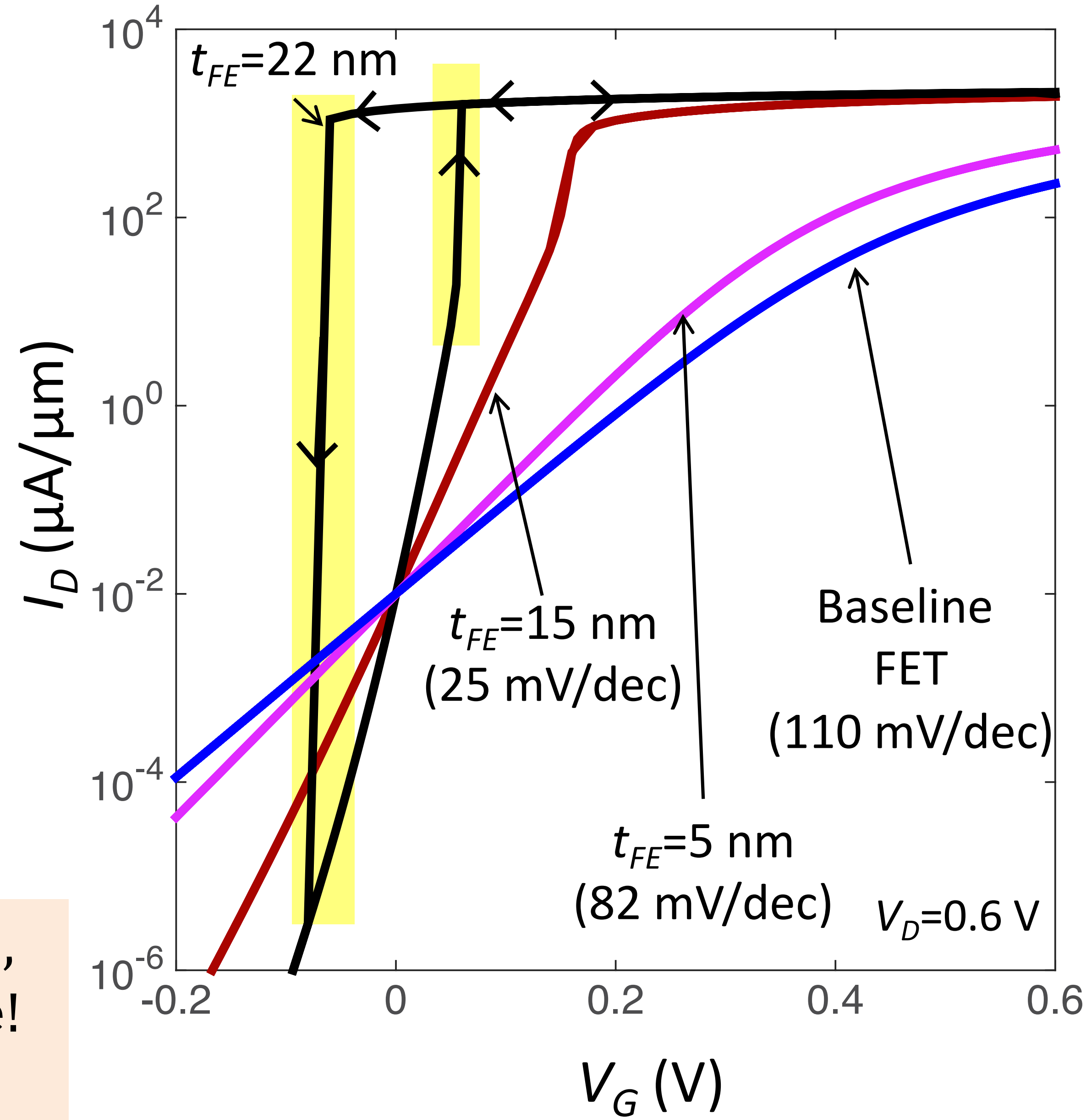
Khan et al. IEDM 2011

Physics of Negative Capacitance FET



Ferroelectric Capacitance $|C_{FE}| = \sim \frac{P_o}{E_{FE} t_{FE}}$

Intel 45 nm node, MIT MVS Model
Collaboration with
Dimitri Antoniadis, MIT



Below a critical FE thickness, NCFET is a steep logic device! Above that it's a memory device!

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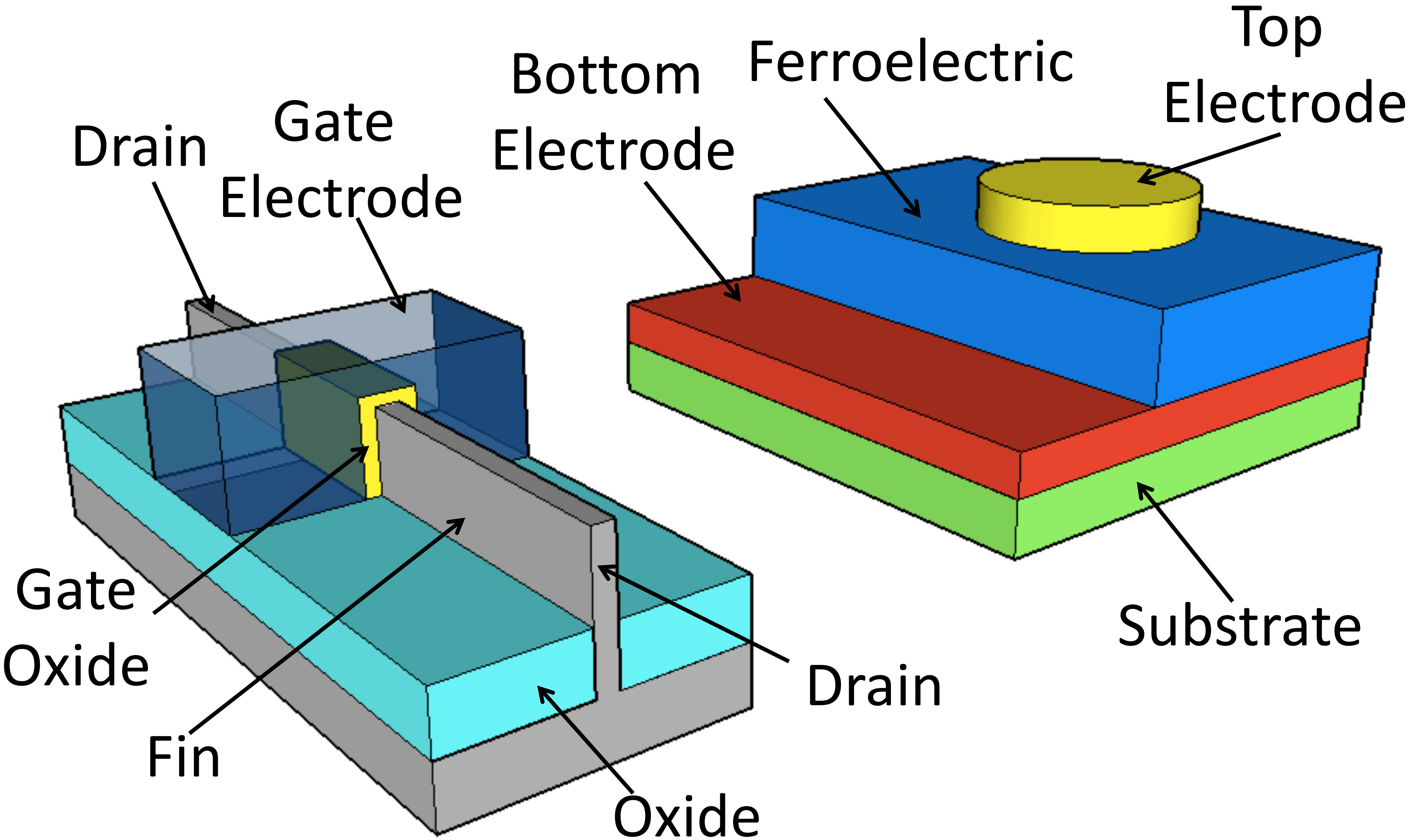
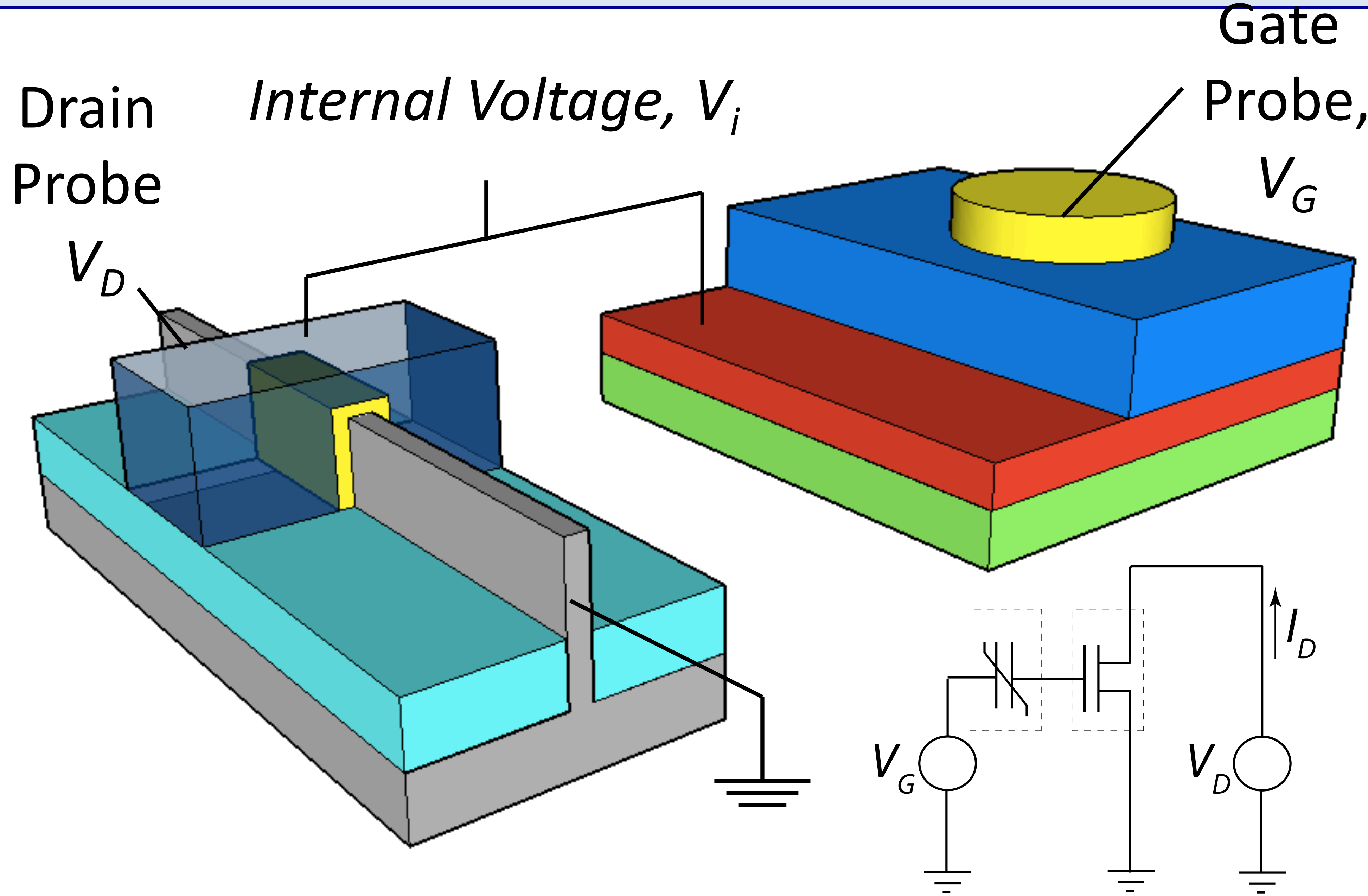
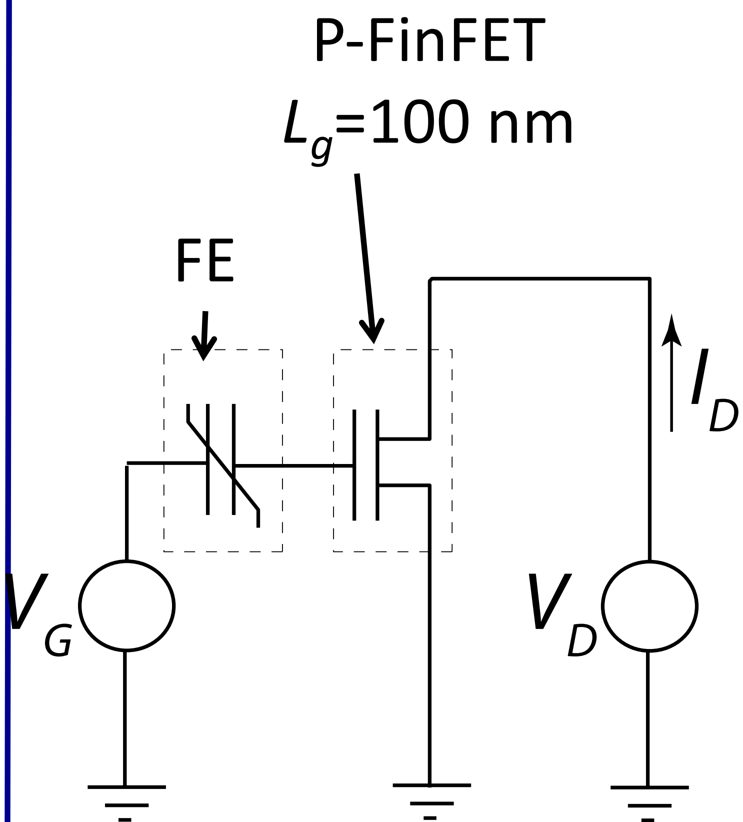
Externally Connected NC-FET

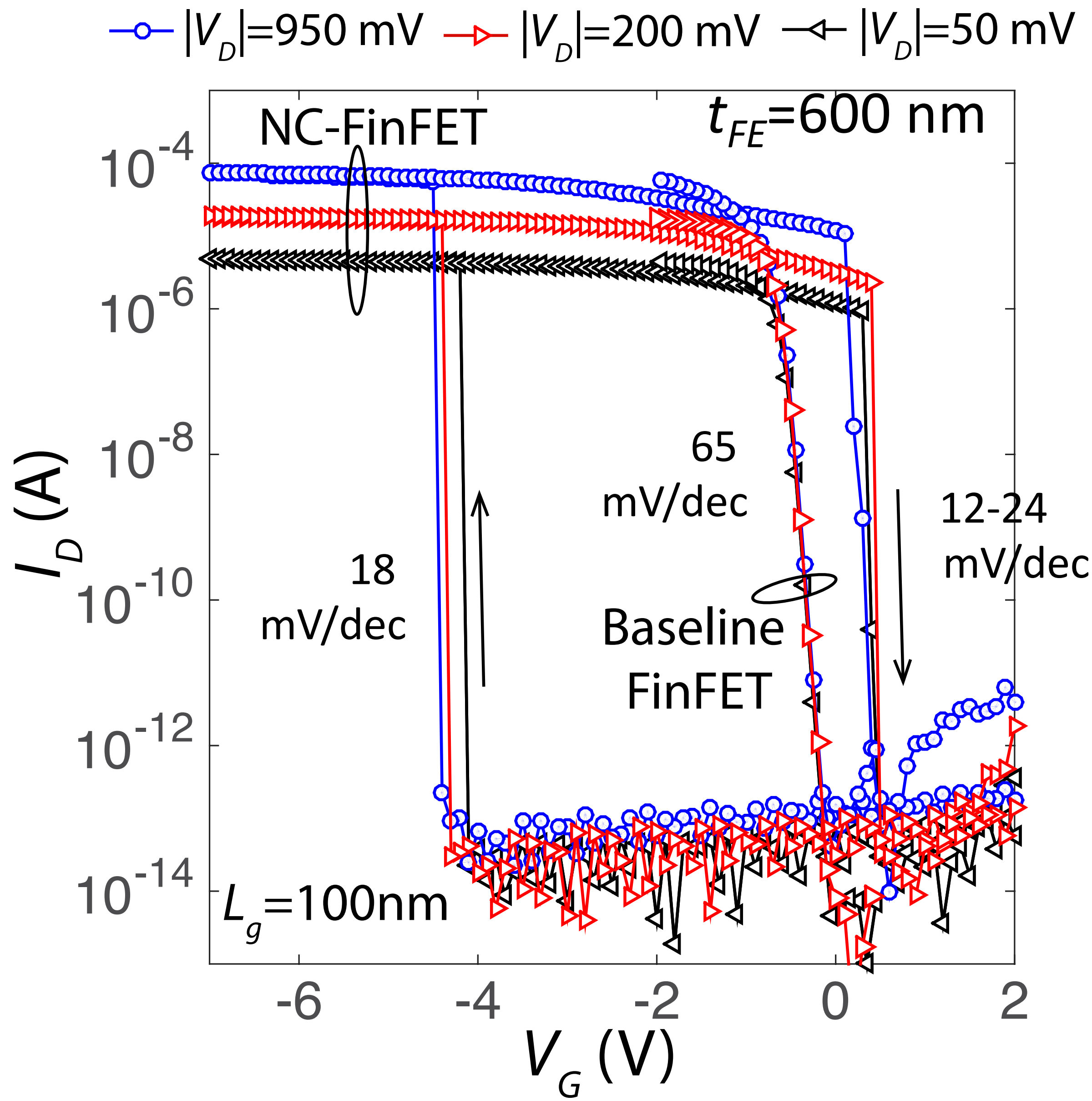


Externally Connected NC-FET



Externally Connected NC-FET

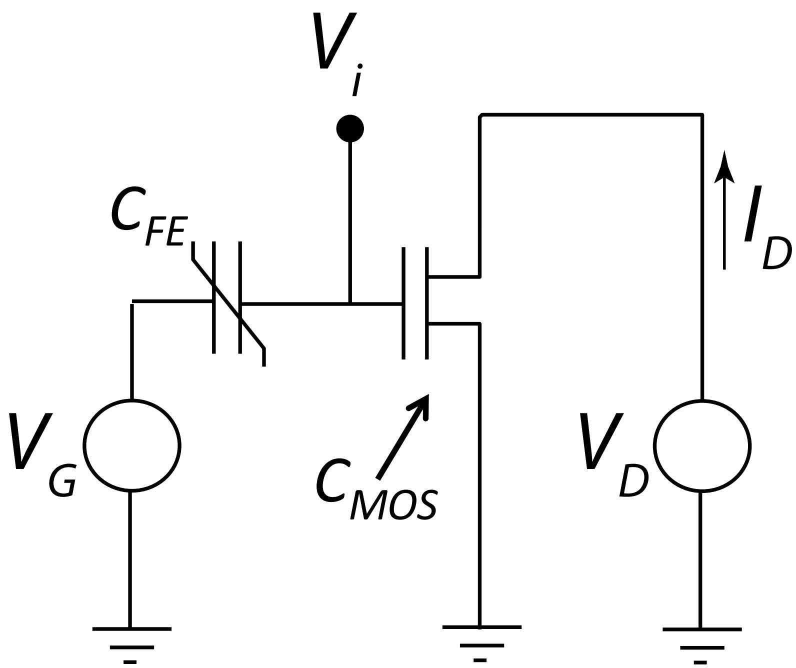




FinFET L_G=100 nm
Fin width=35 nm
Fin height=25 nm
EOT=1.4 nm

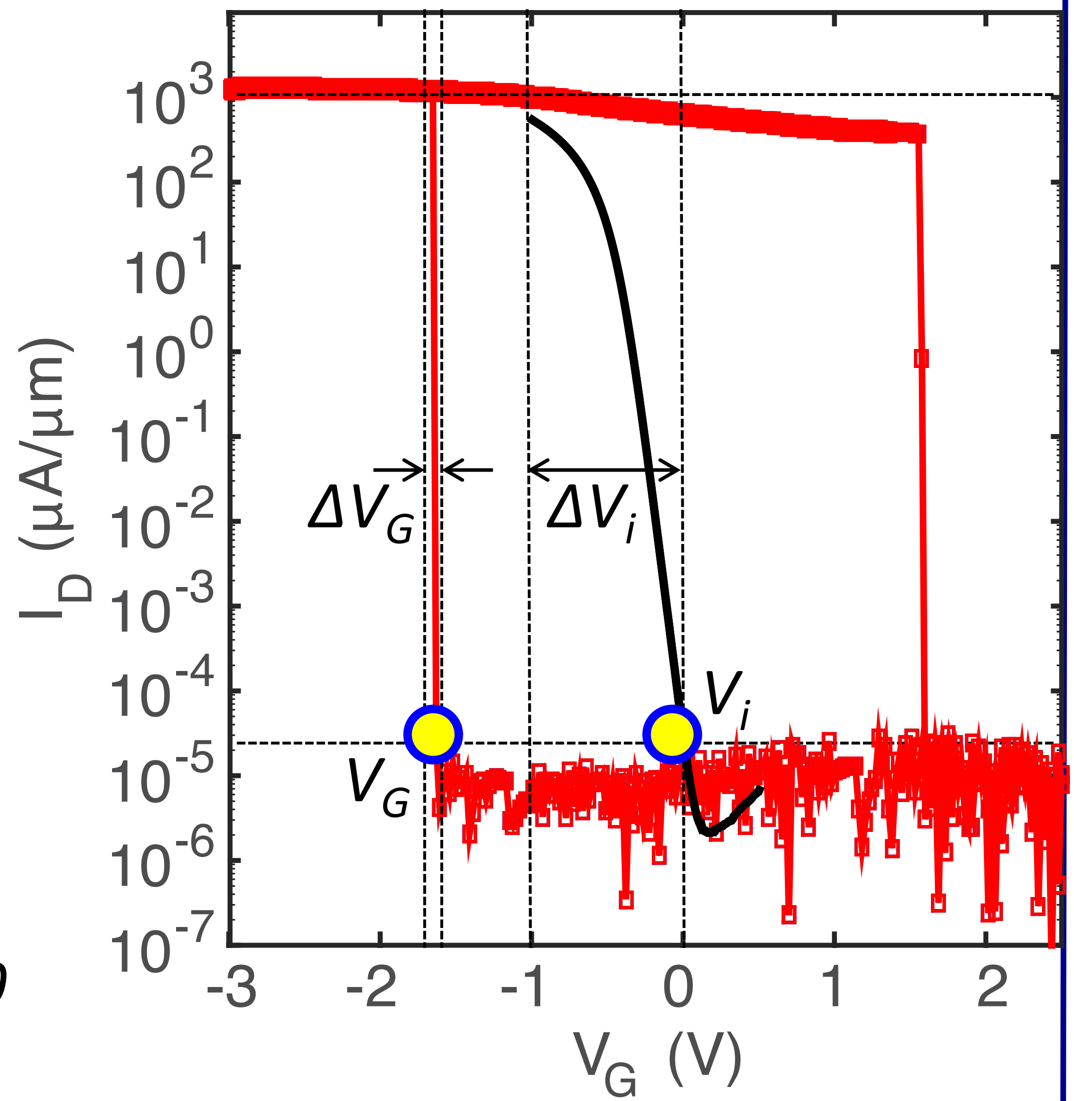
Khan et al. IEEE EDL 37, 111 (2016)

Negative Capacitance Transistors: Experiment



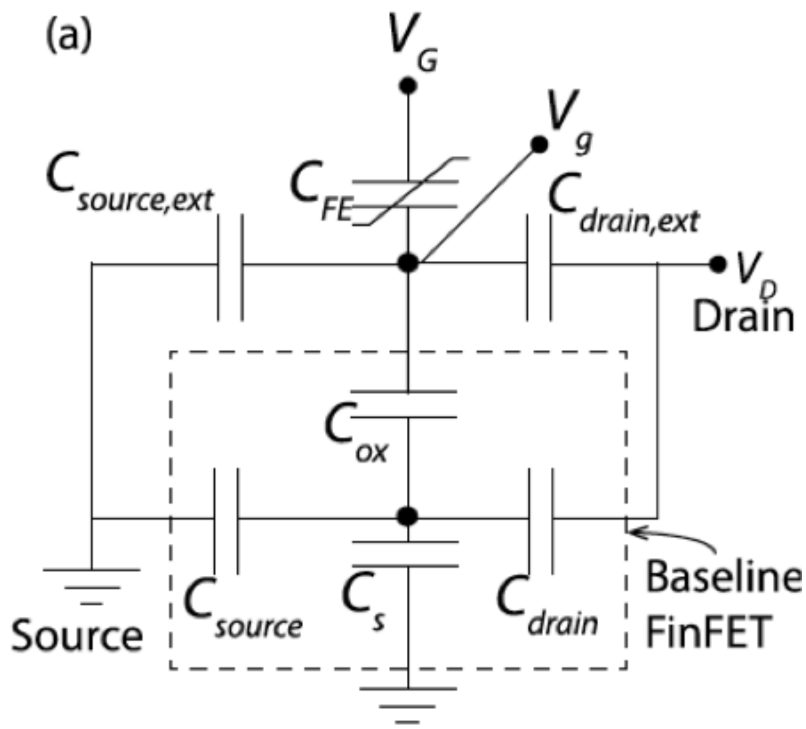
$$\frac{\Delta V_i}{\Delta V_G} > 1$$

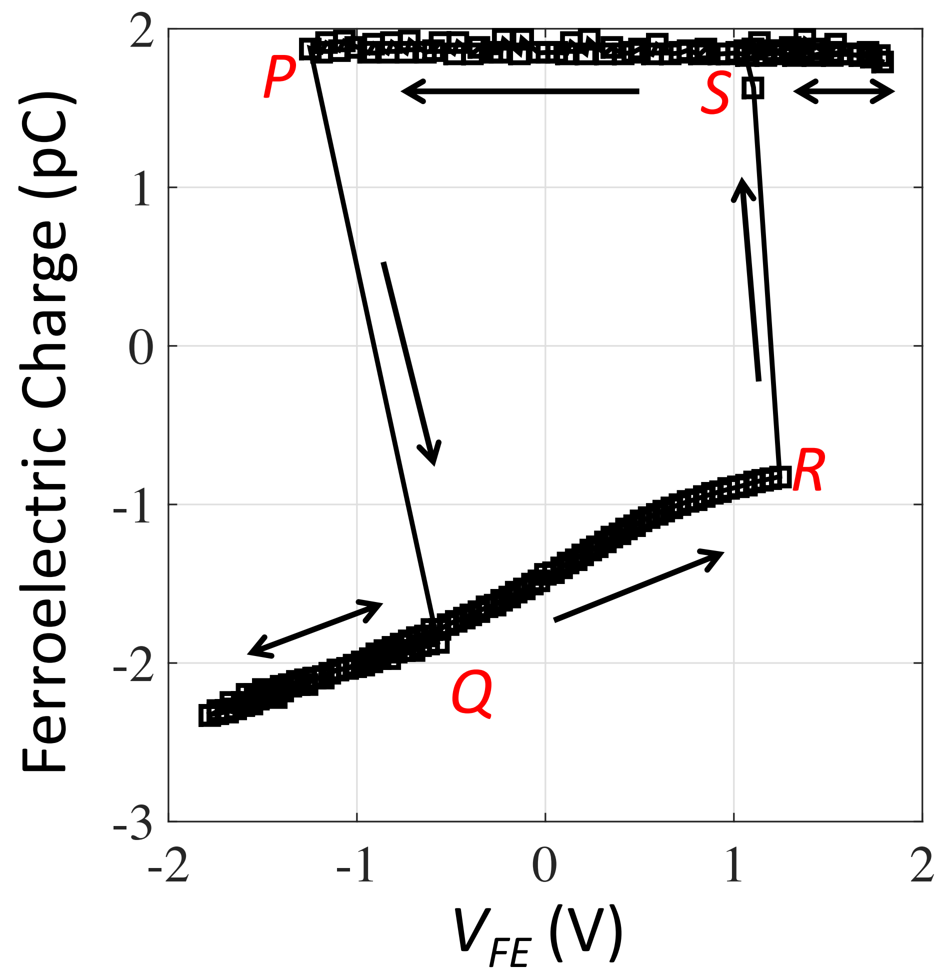
$$\frac{\Delta V_i}{\Delta V_G} = \frac{C_{FE}}{C_{MOS}+C_{FE}} > 1 \text{ only if } C_{FE}<0$$



Sharp switching occurs due to ferroelectric negative capacitance!

Externally Connected NC-FET





Sharp switching occurs due to ferroelectric negative capacitance!

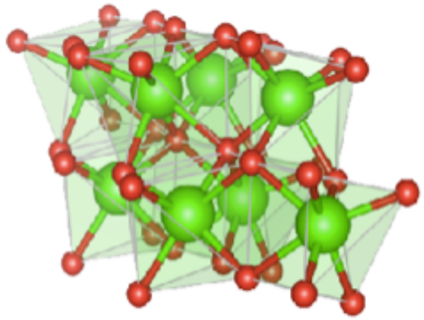
Negative Capacitance Regions: PQ and RS

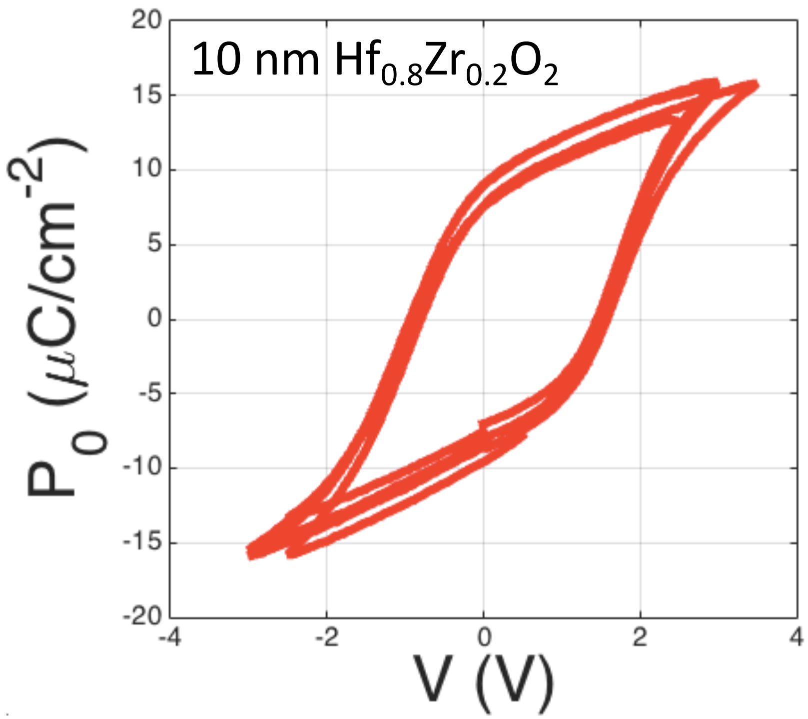
Khan et al. IEEE EDL 37, 111 (2016)

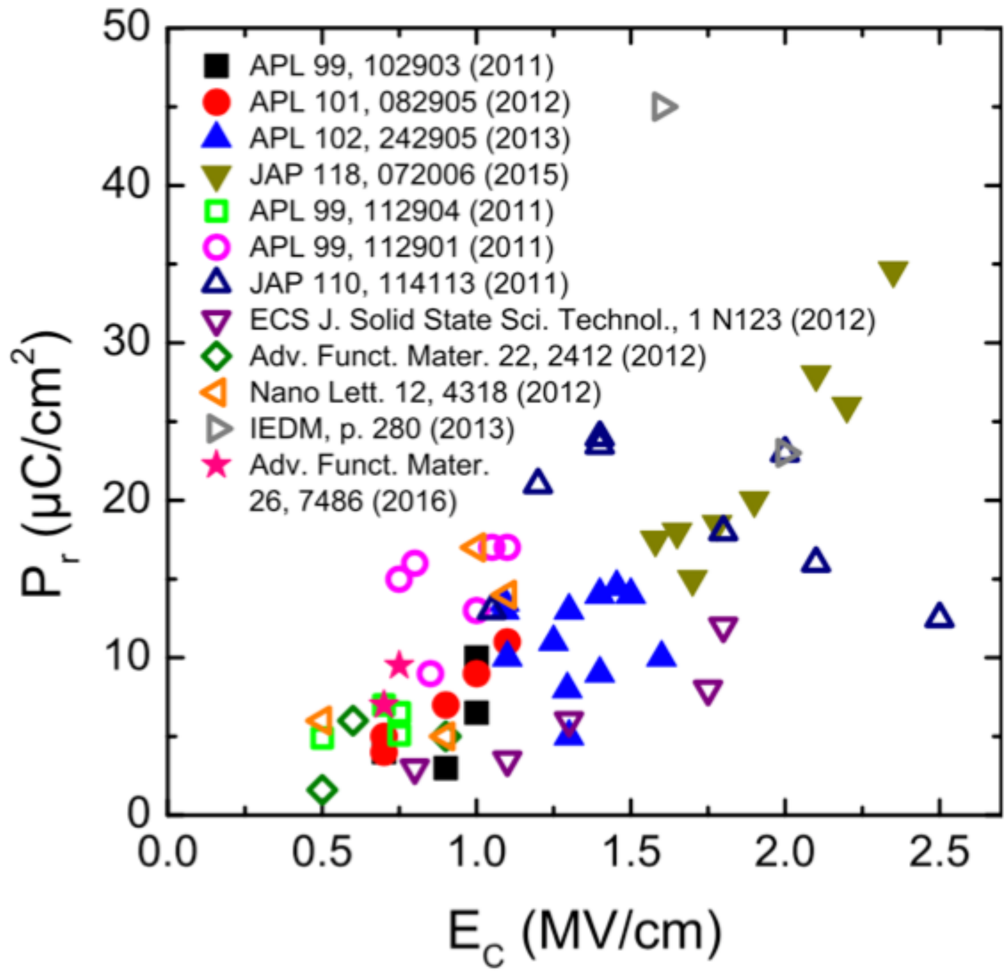
Why is NCFET realistic now?

HfO_2 and ZrO_2 based Ferroelectrics

Orthorhombic Ferroelectric Phase



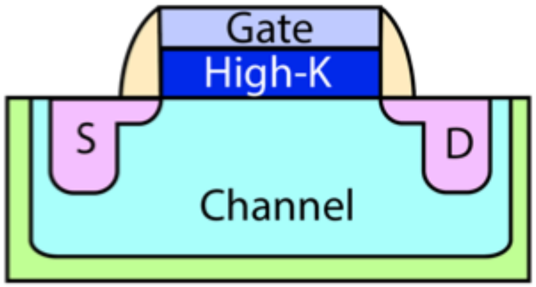




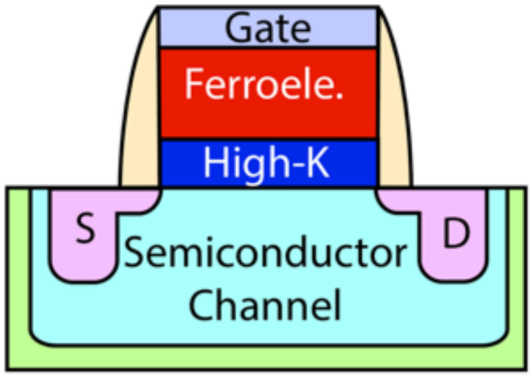
A very wide range of negative capacitance possible in HfO_2 and ZrO_2 based ferroelectrics!

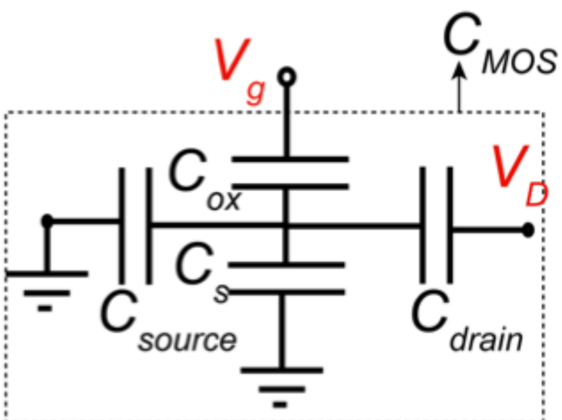
Physics of Negative Capacitance FET

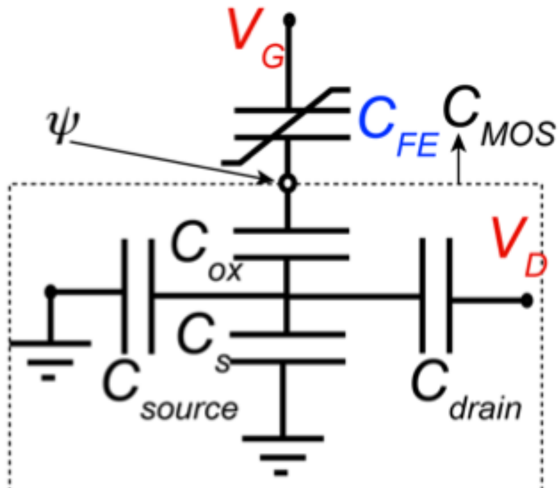
Baseline FET



NCFET







Amplification Factor

$$\frac{d\psi}{dV_G} = \frac{C_{FE}}{C_{FE} + C_{MOS}} = \frac{|C_{FE}|}{|C_{FE}| - C_{MOS}}$$

Modified Body Factor

$$m^o = \frac{dV_G}{d\psi} = 1 - \frac{C_{MOS}}{|C_{FE}|}$$

Subthreshold Swing

$$S^{NC} = S^{original} \times \left(1 - \frac{C_{MOS}}{|C_{FE}|}\right)$$

Ideal Switch: ~0 mV/decade ⇐
$|C_{FE}| \approx C_{MOS}, |C_{FE}| > C_{MOS}$

Condition	Characteristics	Mode
$C_{FE}<0$, $\lvert C_{FE}\rvert > C_{MOS}$	$0<m^o<1$, $S^{NC}<S^{original}$	Logic
$C_{FE}<0$, $\lvert C_{FE}\rvert < C_{MOS}$	$m^o<0$, $S^{NC}<0$	Memory

Khan et al. IEDM 2011

Georgia Tech

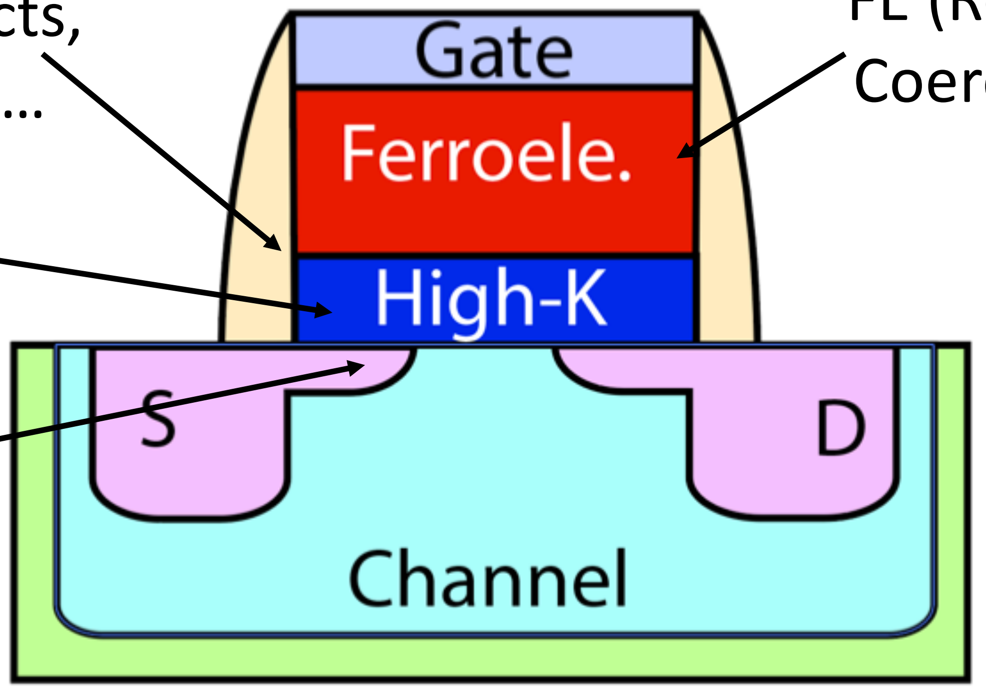
What determines NCFET behavior?

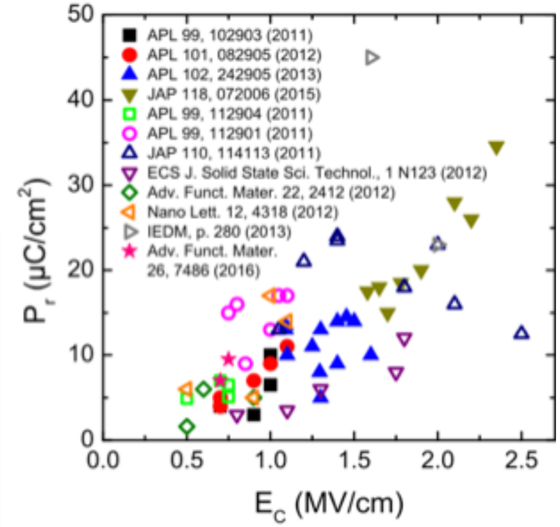
Interface defects,
Fixed charge…

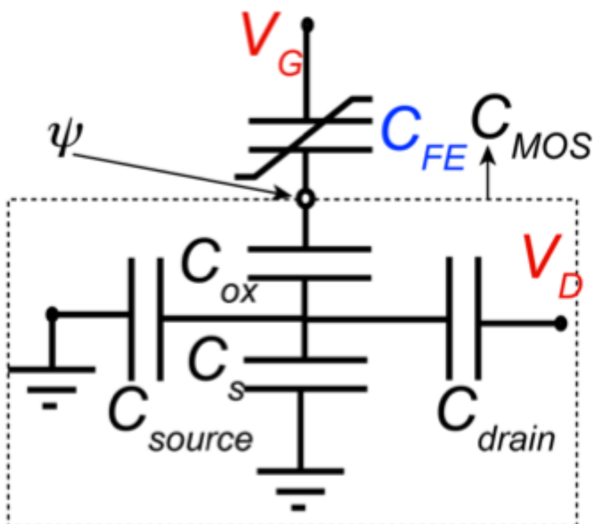
High K
Thickness

Overlaps

FE (Remnant Polarization,
Coercive field, Thickness)

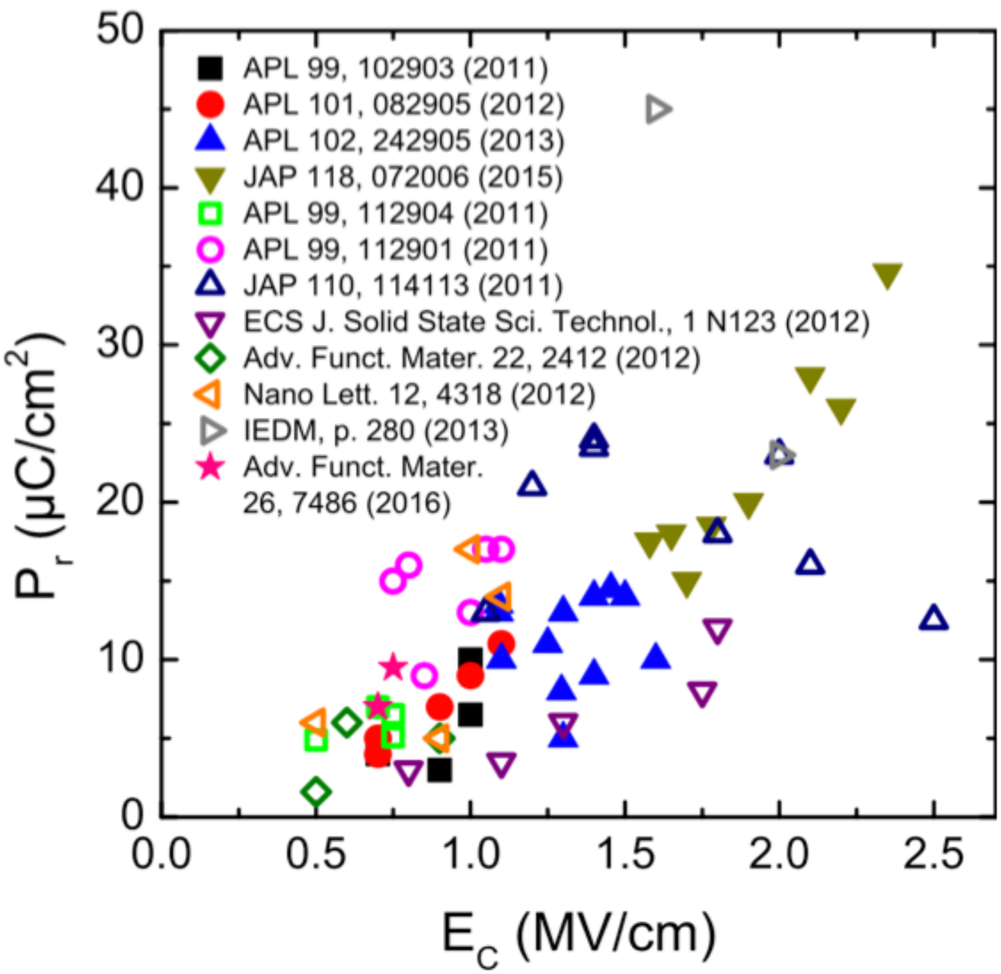


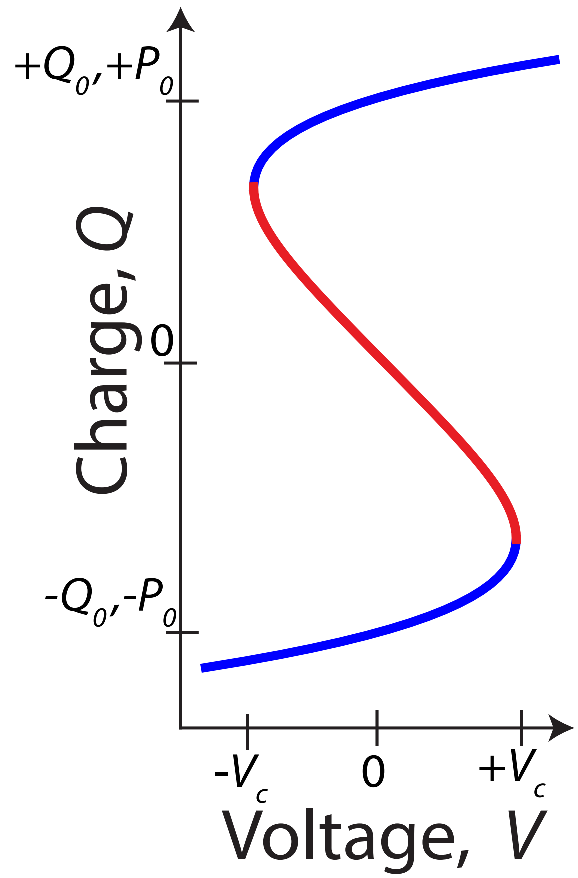




There are many NCFET device design parameters!
Unless designed properly, the NCFET can get screwed up!

Ferroelectric Negative Capacitance

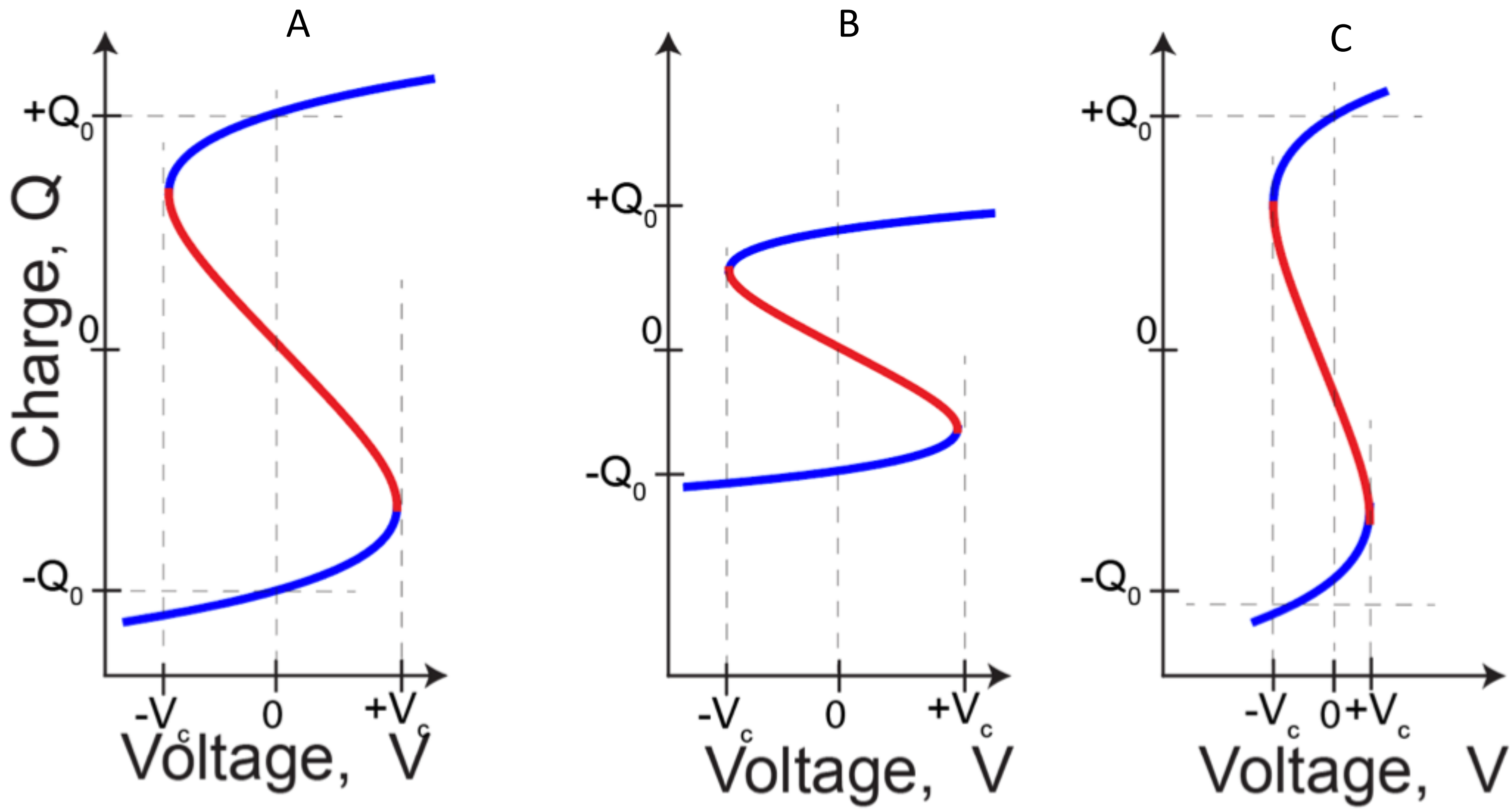




$$C_{FE} = \frac{dQ}{dV} \approx -\frac{Q_0}{V_c}$$

There are plenty of materials to try out!

Ferroelectric Negative Capacitance

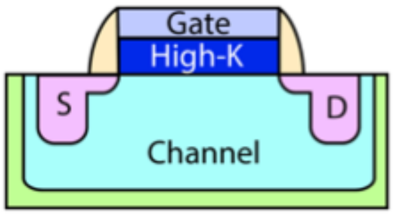


$|C_{FE,A}|$ $|C_{FE,B}|<|C_{FE,A}|$ $|C_{FE,C}|>|C_{FE,A}|$

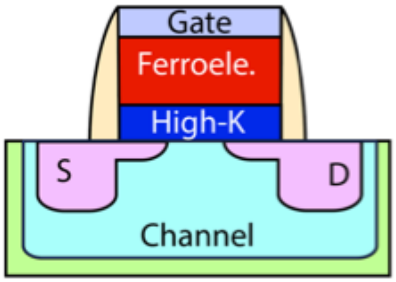
$$C_{FE}=\frac{dQ}{dV}\approx-\frac{Q_0}{V_c}$$

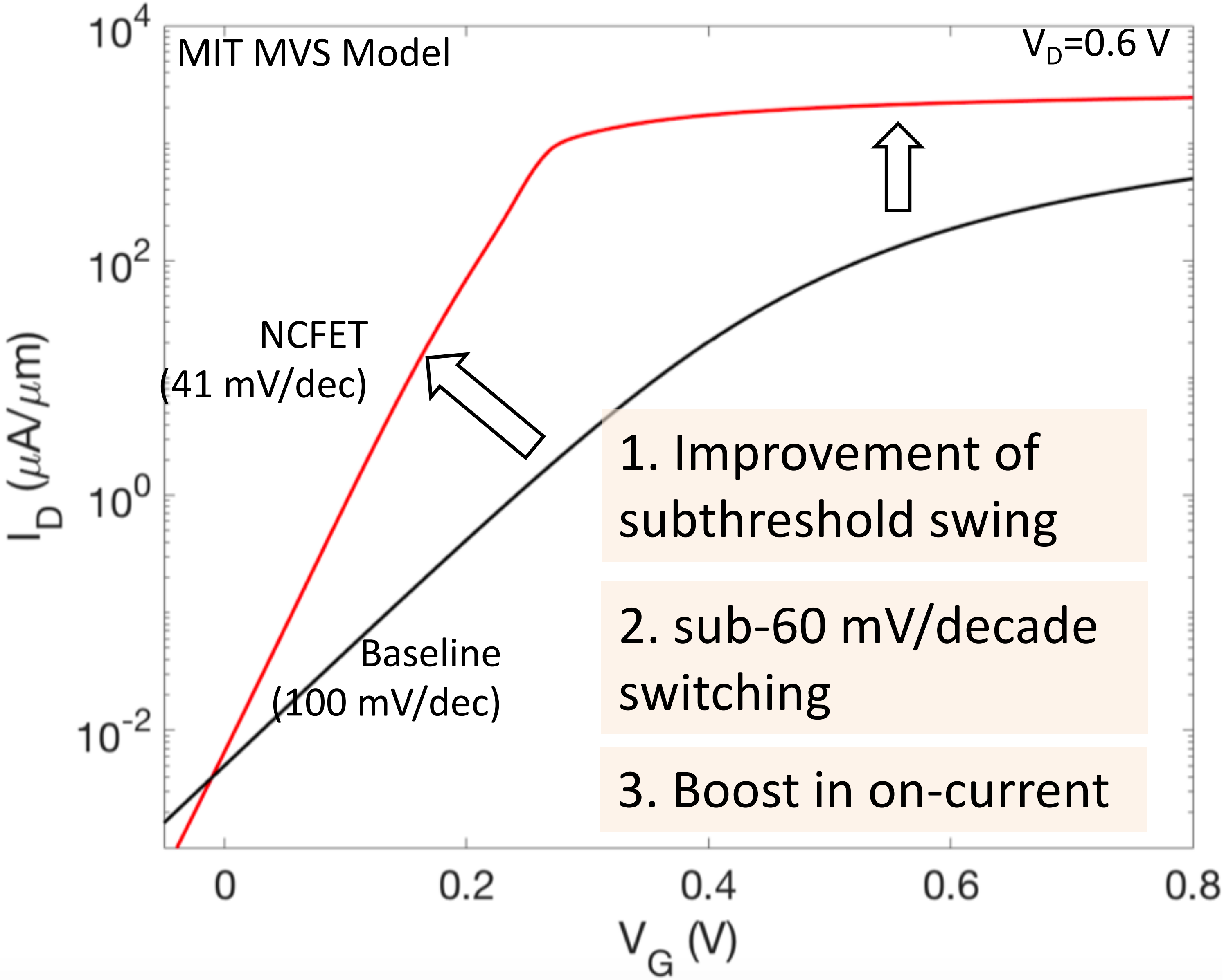
NCFET Expectation

Baseline FET
(Intel 45 nm)

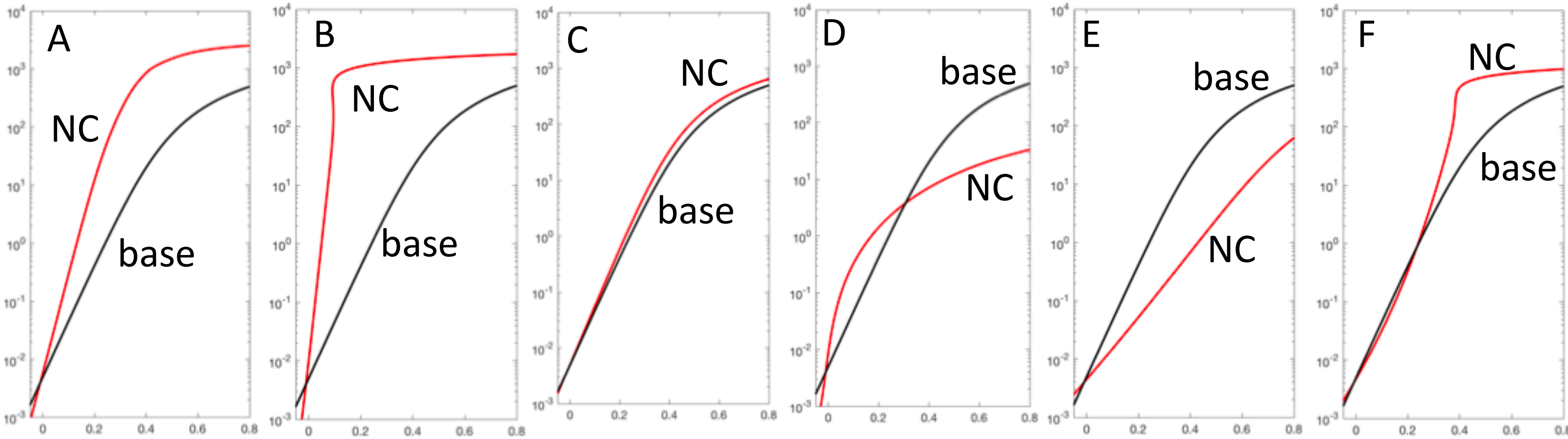


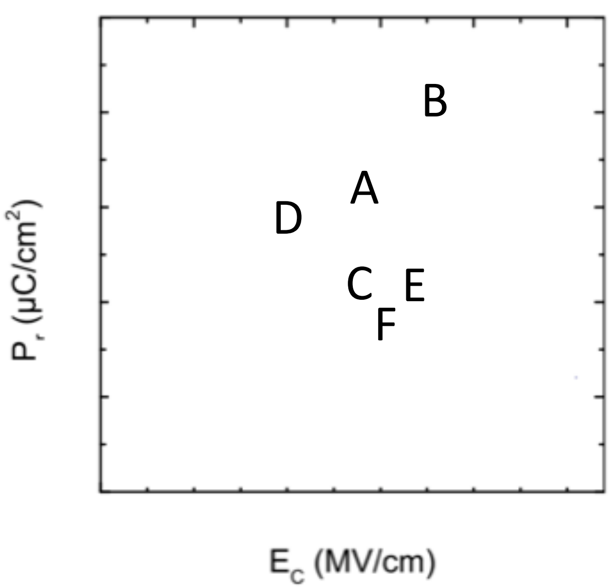
NCFET
(Baseline+FE)





Zoo of NCFET behavior (from best to worst)





A: SS↓↓ (<60 mV/dec) I_{on}↑↑

B: SS↓↓ (<<60 mV/dec), I_{on}↑↑↑

C: SS↓ (~60 mV/dec) I_{on}↑

D: SS↓↓ (<<60 mV/dec) I_{on}↓

E: SS↑↑ (>>60 mV/dec) I_{on}↓↓

F: SS ↑ (>60 mV/dec) I_{on}↑↑

Summary of NCFET

The physics of negative capacitance has been demonstrated consistently in multiple material systems and in different experimental configurations.

Steep switching characteristics and boost in on-current due to negative capacitance has been demonstration!

It is high time that industry and academia joined forces to make NCFET a technological reality!

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THANKS

Negative Capacitance:

What do we know and
What do we need to know?

QUESTIONS
&
COMMENTS