Negative Capacitance:
What do we know and What do we need to know?

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Negative Capacitance:

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

Disclaimer:

1. **The physics of negative capacitance devices!**
2. **The talk is material agnostic! No discussion of growth and fabrication!**
3. **Focuses on ”new-yet-easy-and-simple” measurements techniques only!**
4. **Focuses on what and how we can learn more!**

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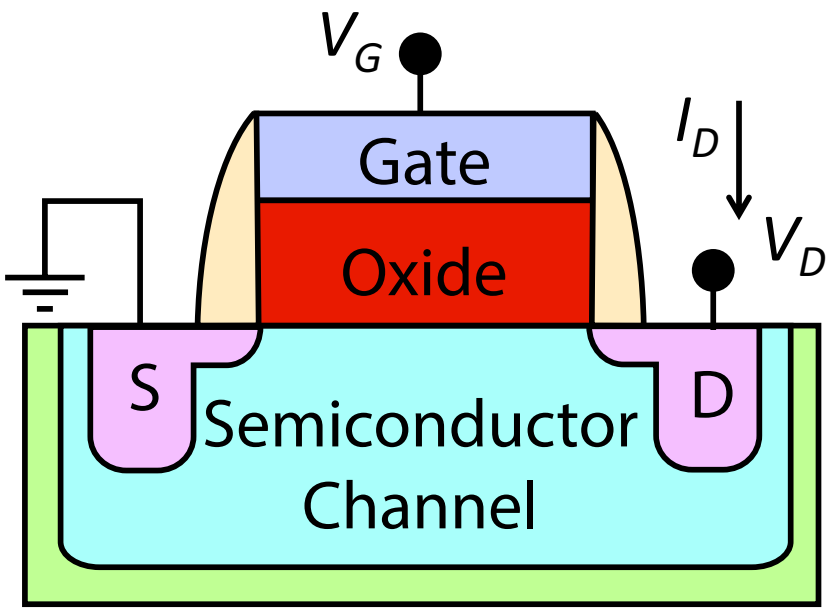
The Negative Capacitance Approach

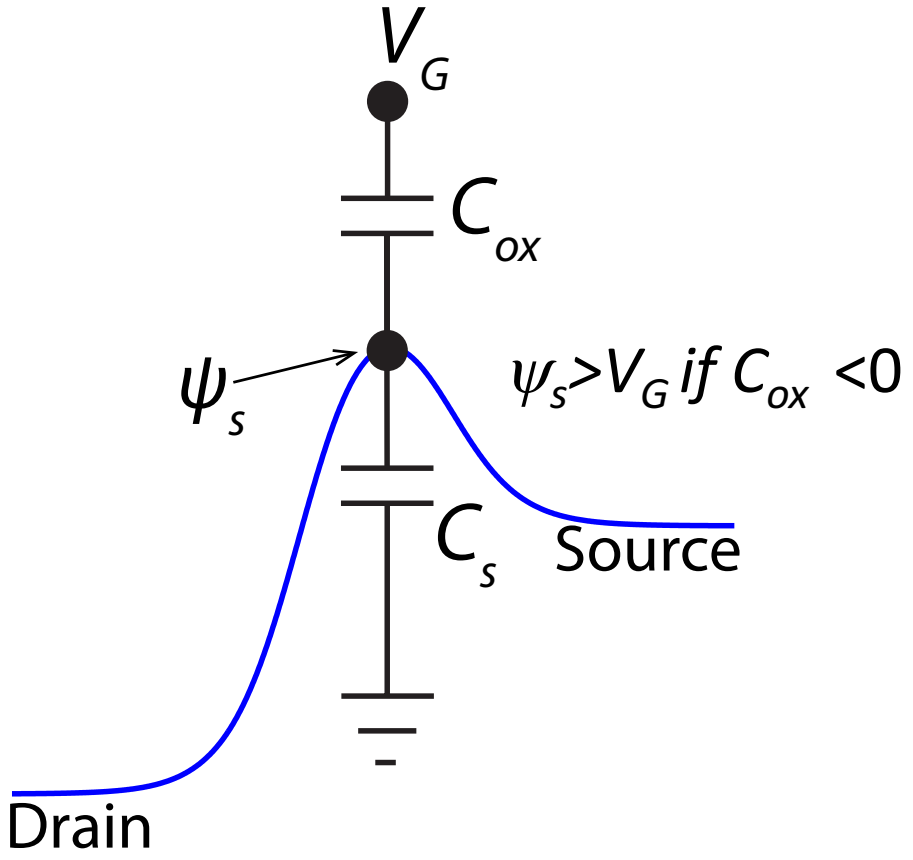


Subthreshold Swing

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

Body Factor

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



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

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

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

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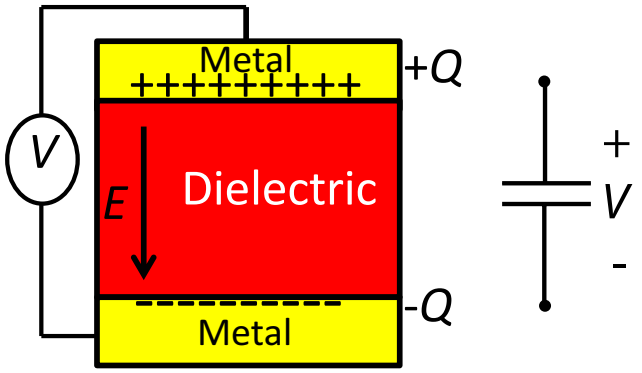
Capacitance: Positive and Negative

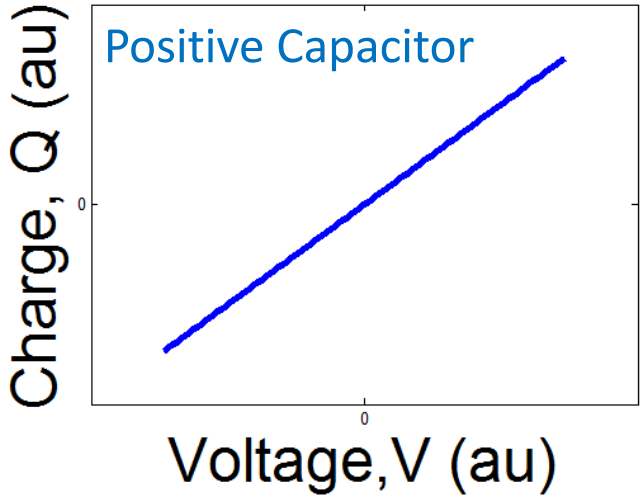


Capacitance $C = \frac{dQ}{dV}$

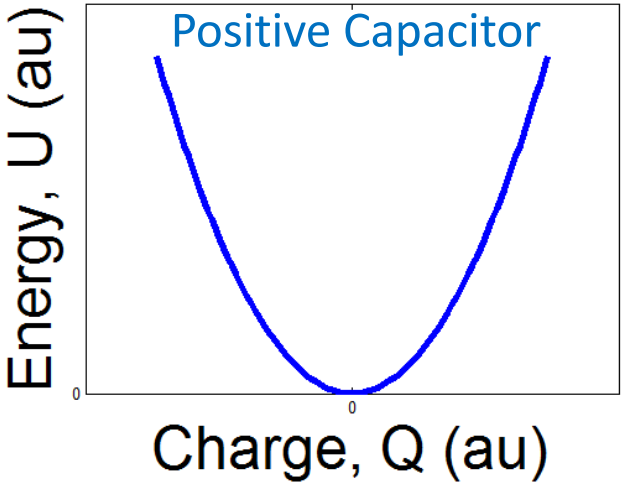
Stored Energy $U = \frac{Q^2}{2C}$

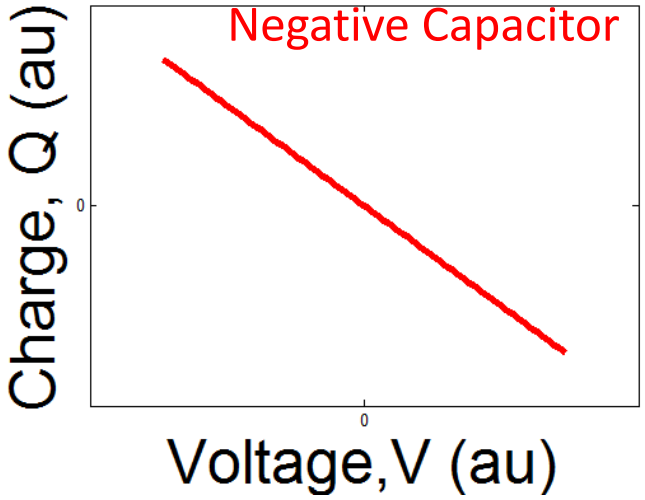
$$C = \left[\frac{d^2U}{dQ^2}\right]^{-1}$$

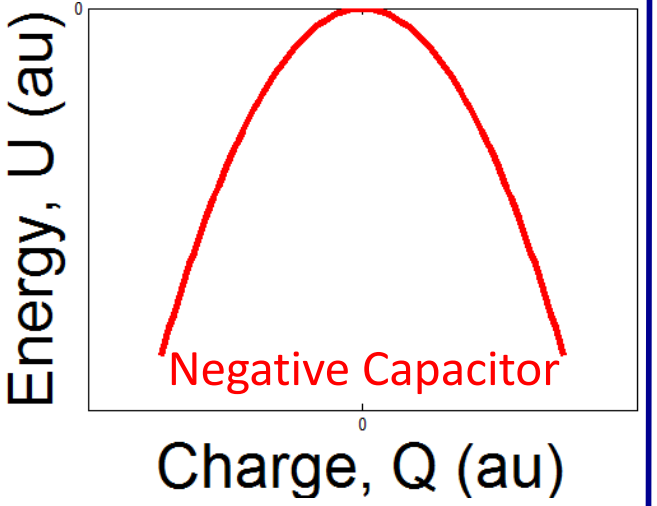
Q-V Characteristics



Q-U Characteristics (Energy Landscape)







C is inverse of radius of curvature of energy landscape

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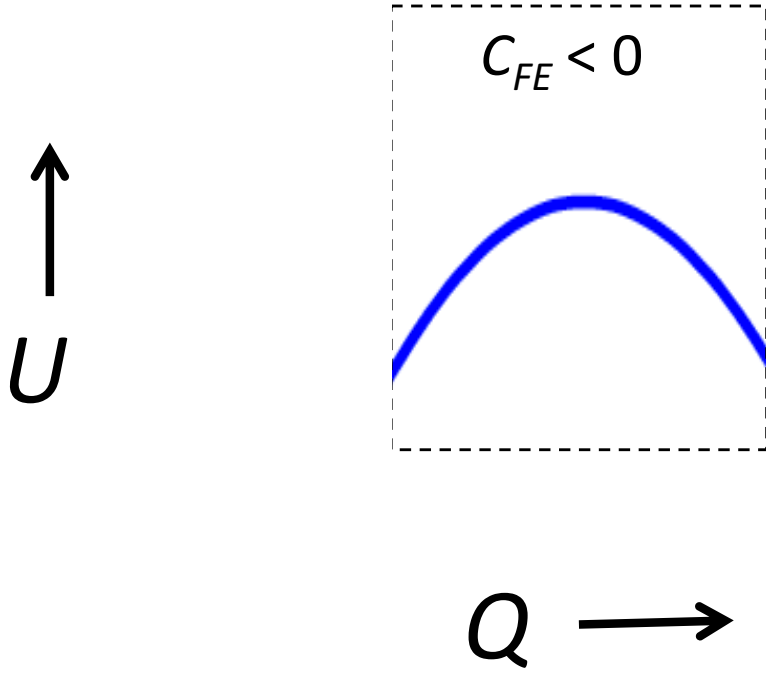
How to get Negative Capacitance Material



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).

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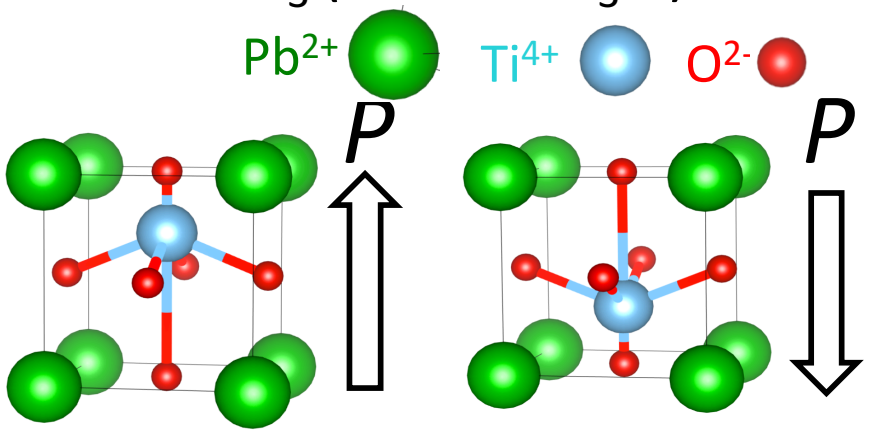
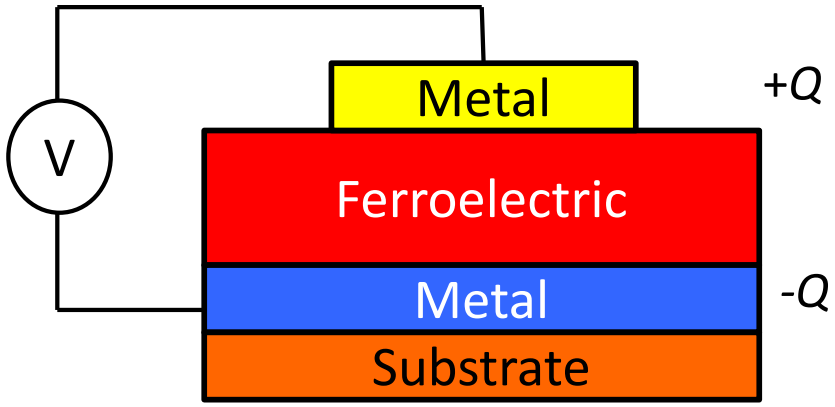
Ferroelectric Oxides

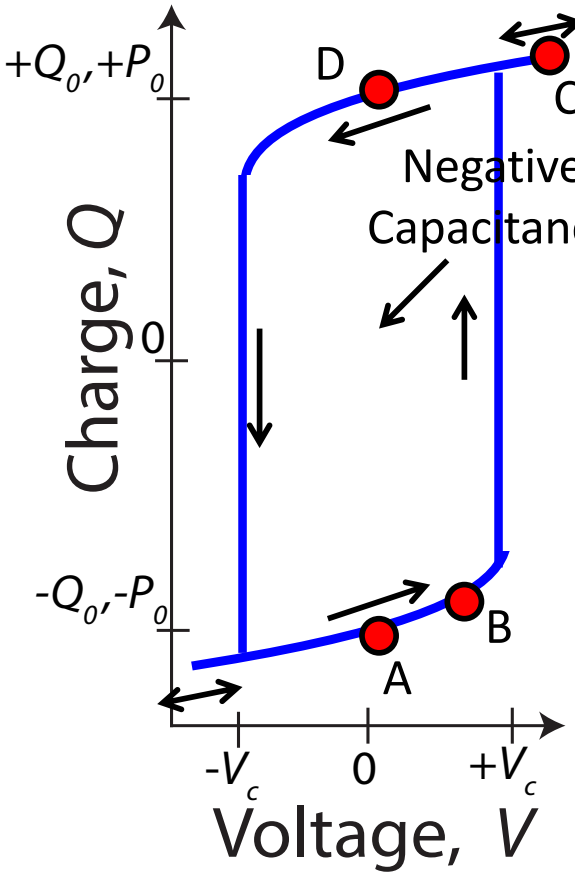
Classical Ferroelectric

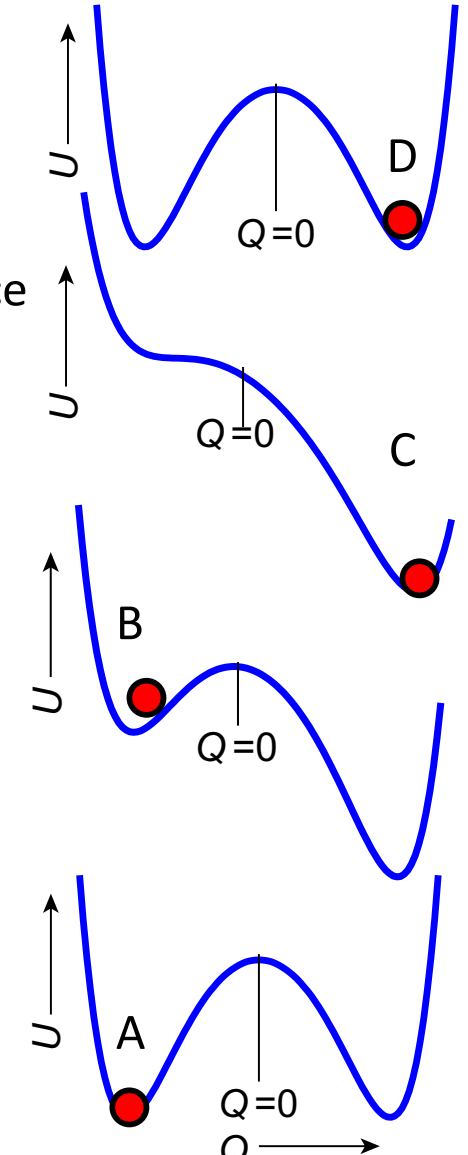
$PbTiO_3$ ($Pb^{2+}Ti^{4+}O_3^{6-}$)





Charge Voltage Characteristics





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

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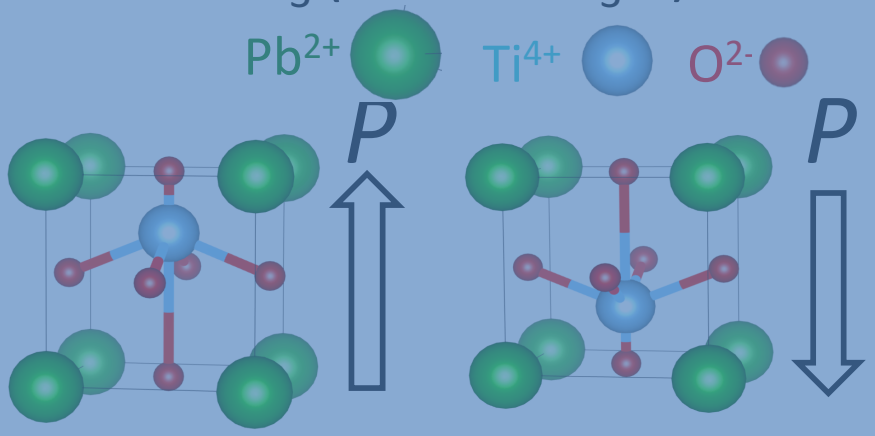
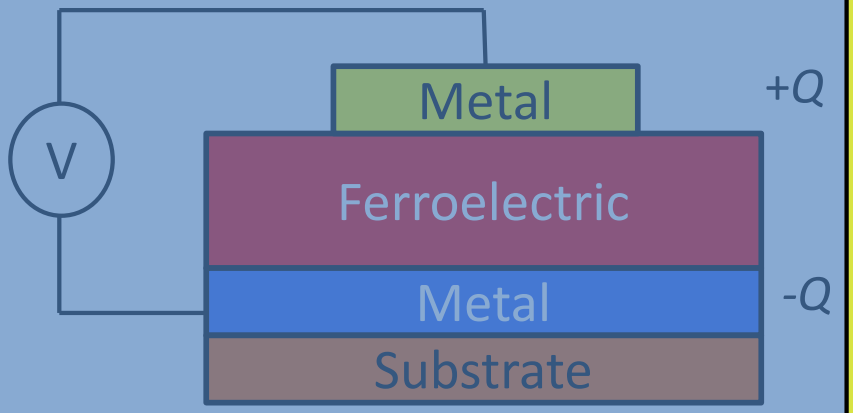
Ferroelectric Oxides

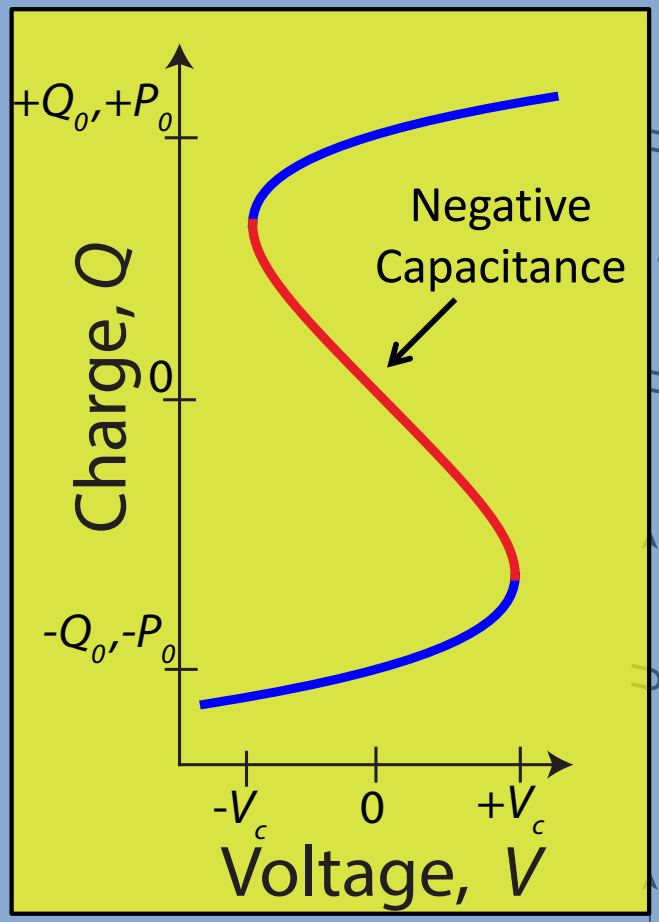
Classical Ferroelectric

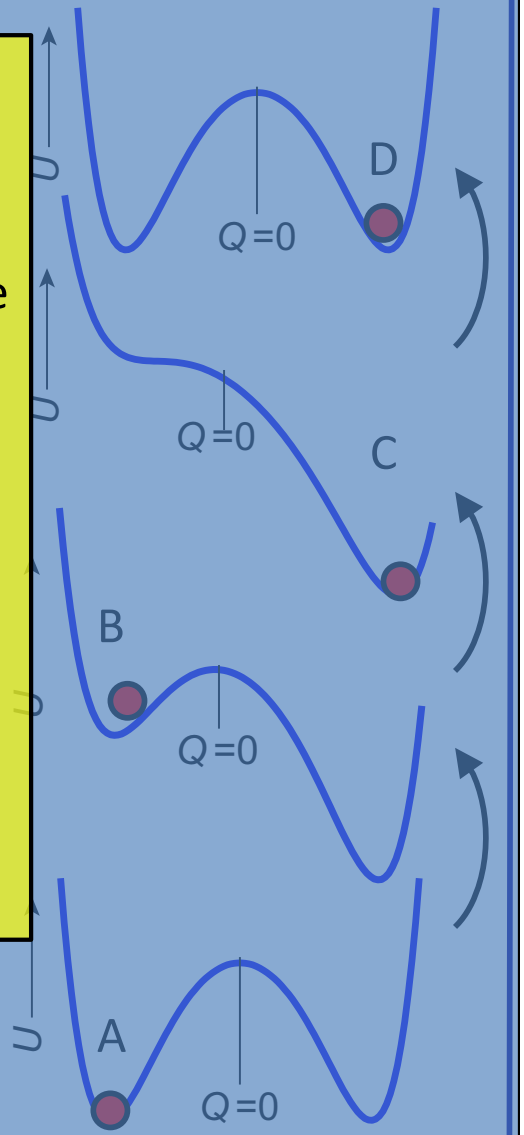
$PbTiO_3$ ($Pb^{2+}Ti^{4+}O_3^{6-}$)





Charge Voltage Characteristics





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

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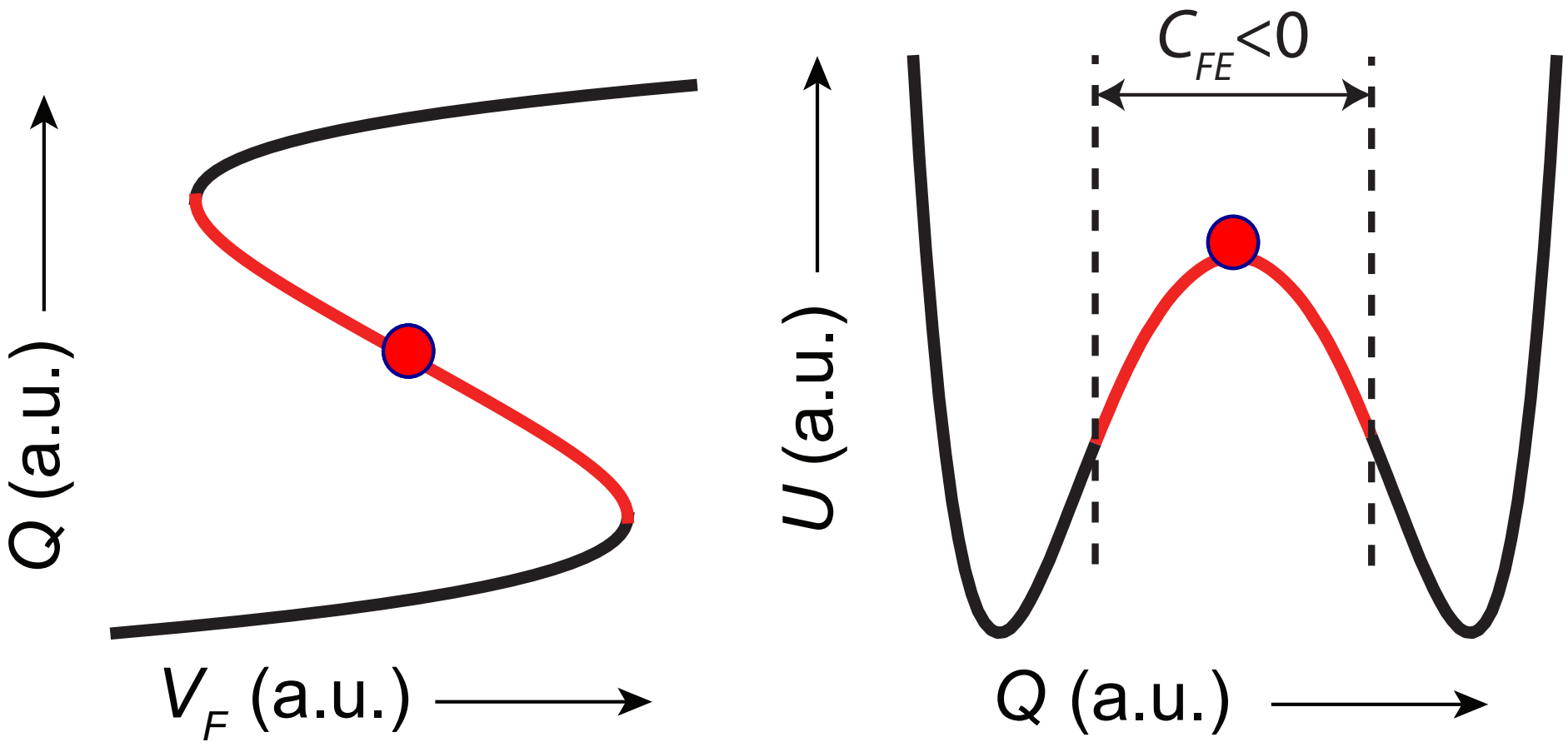
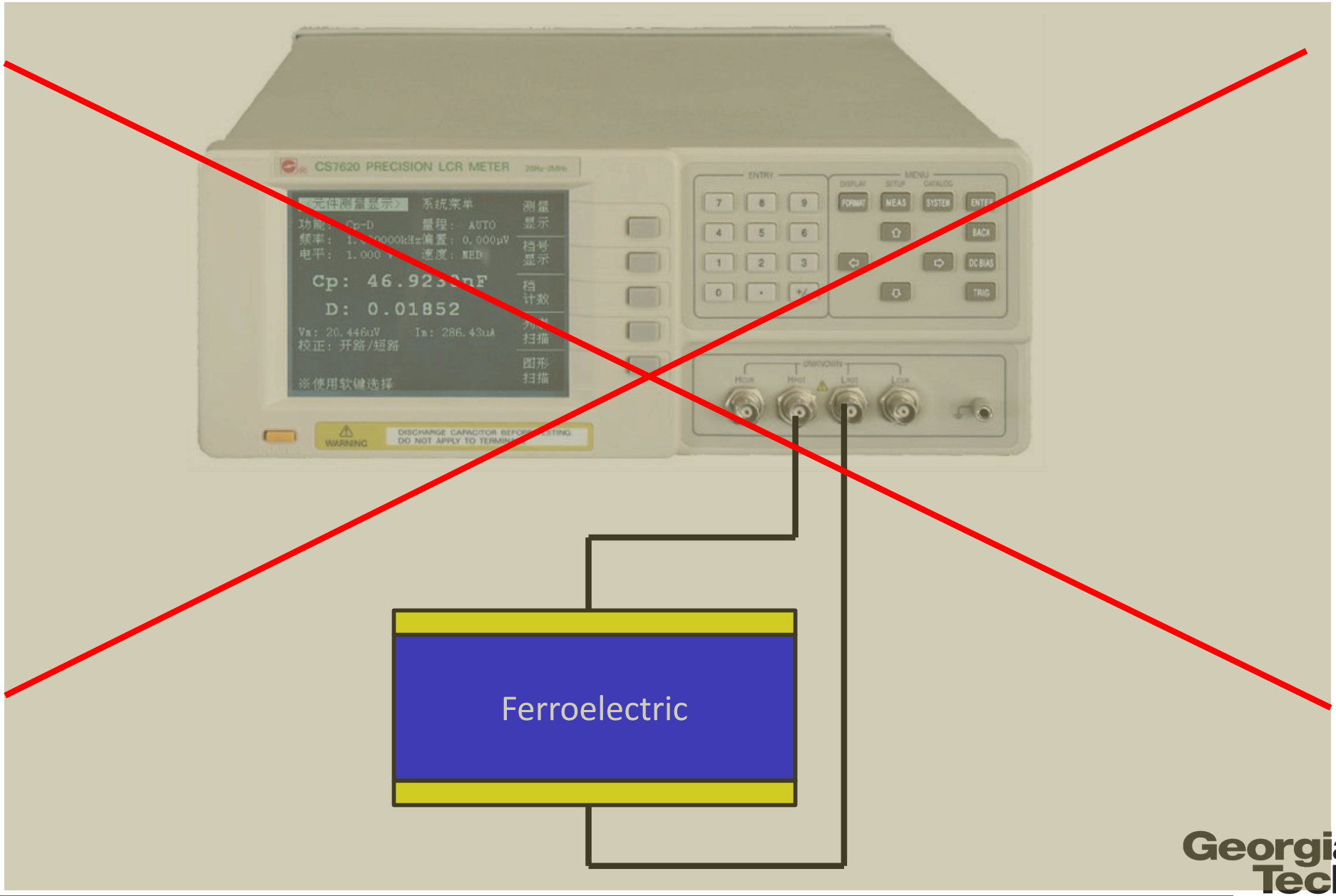
Why is it difficult to measure?

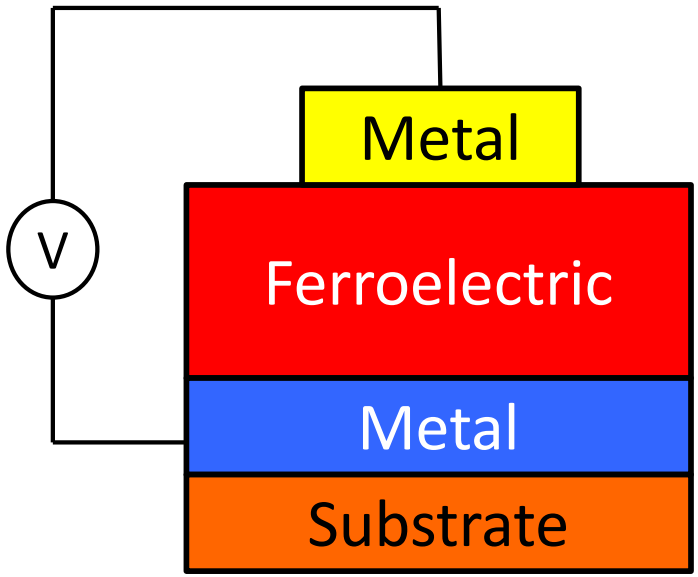


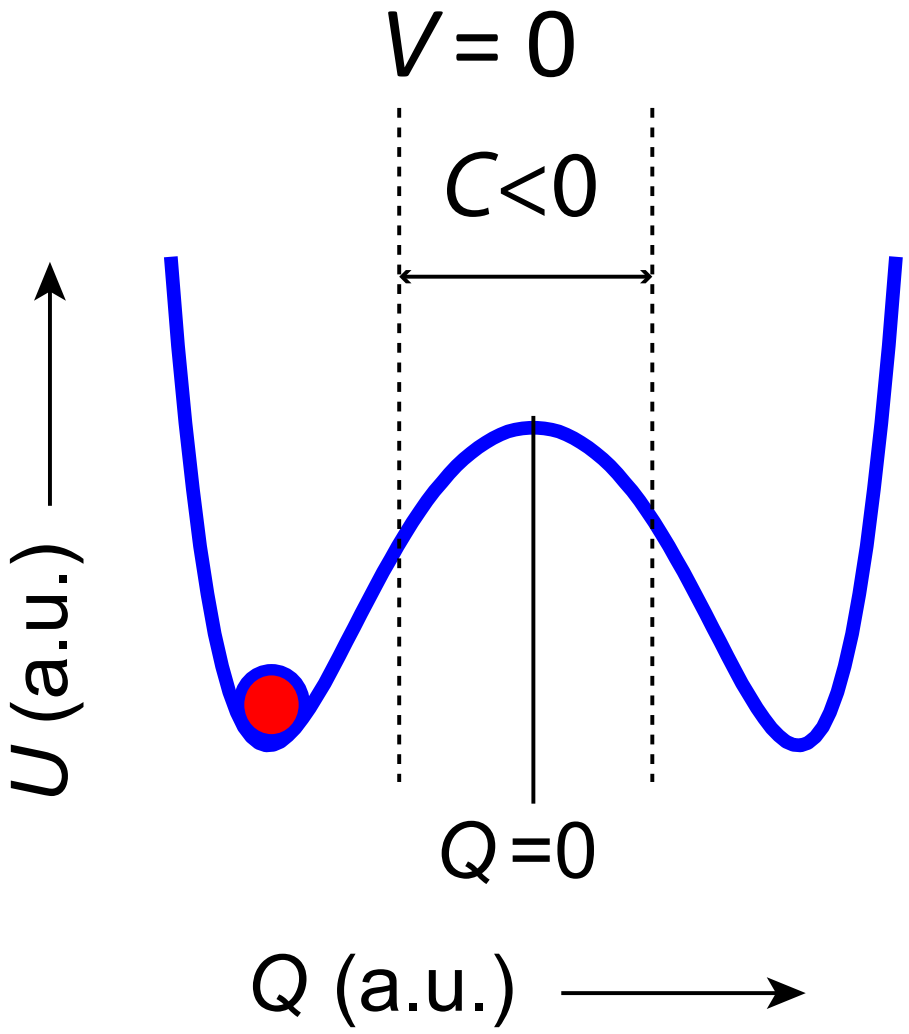
Ferroelectric Negative Capacitance is unstable and cannot be accessed in a time independent equilibrium measurement.

Why is it difficult to measure?



Direct Measurement of Negative Capacitance





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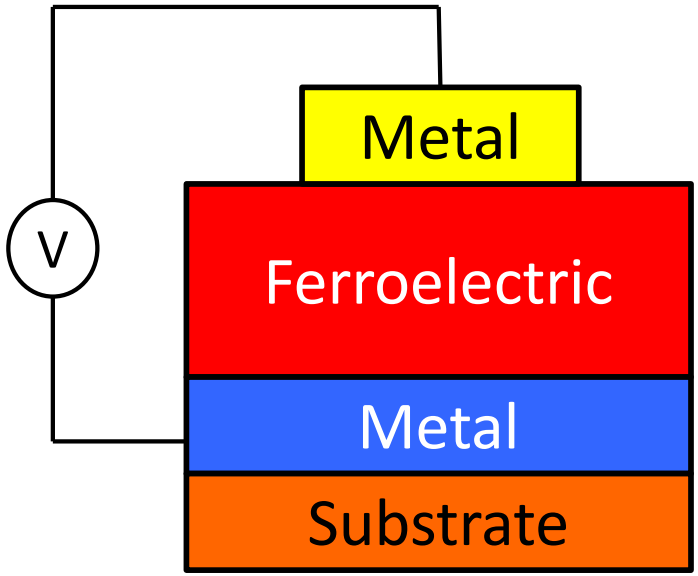
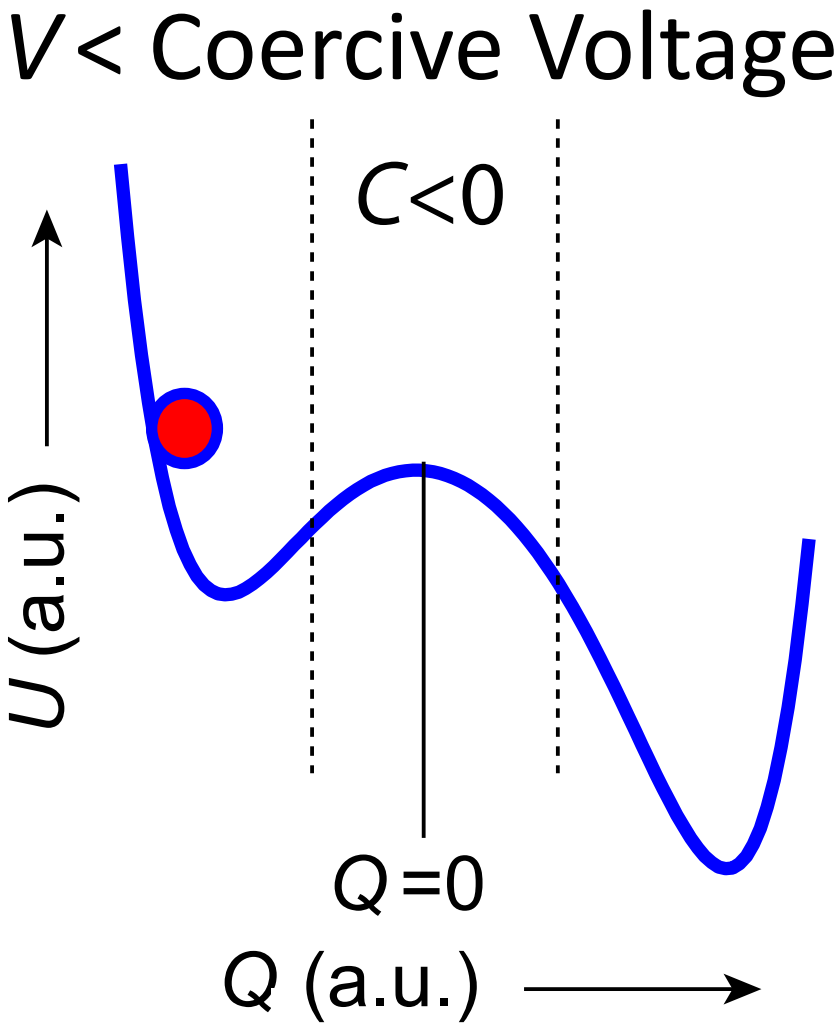
Direct Measurement of Negative Capacitance





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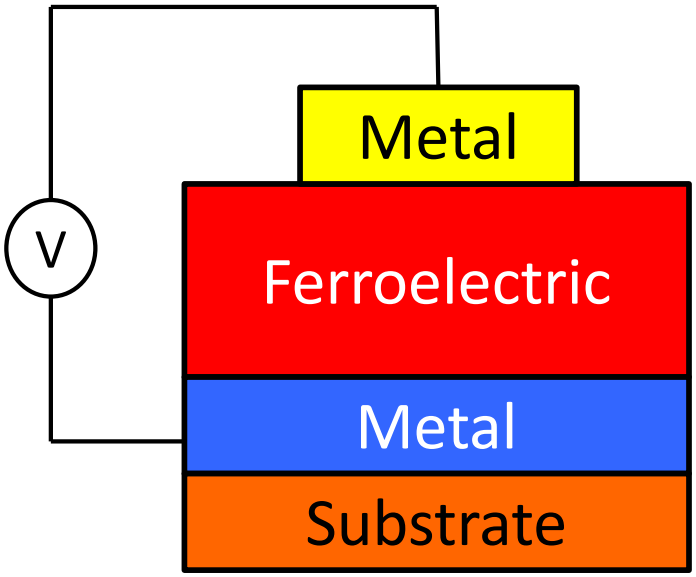
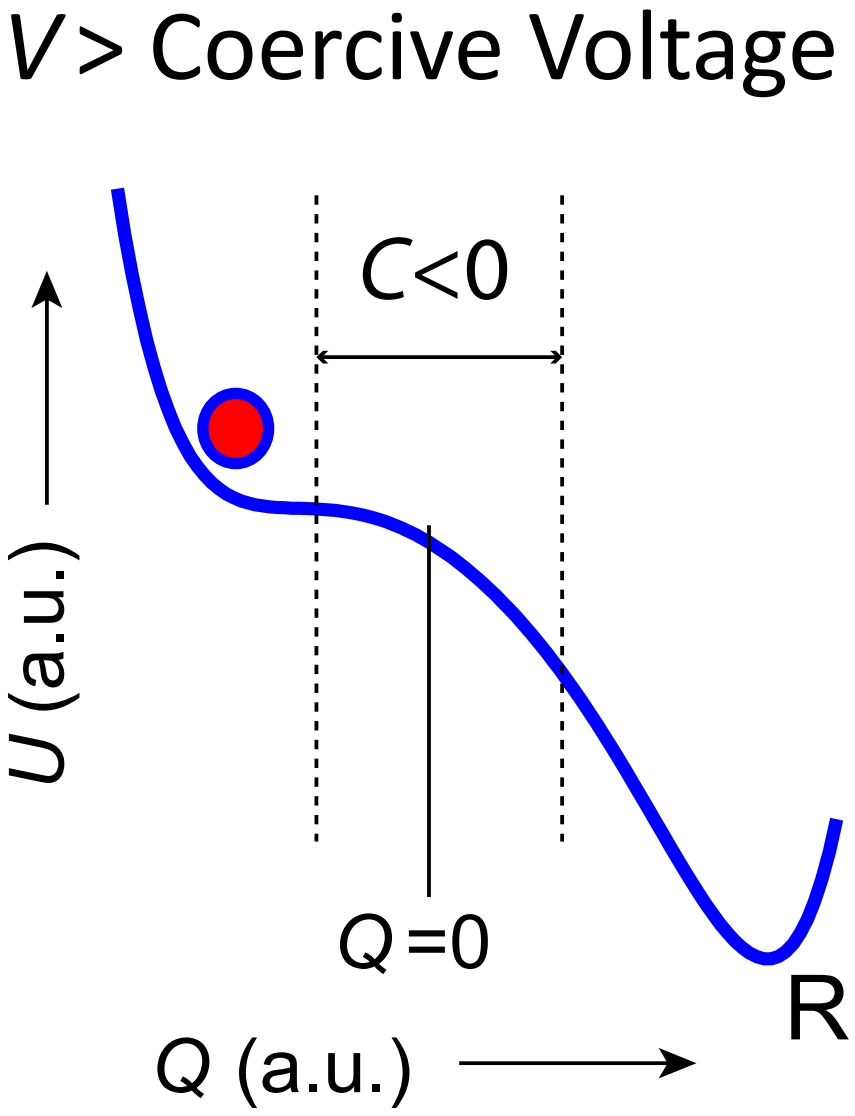
Direct Measurement of Negative Capacitance



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



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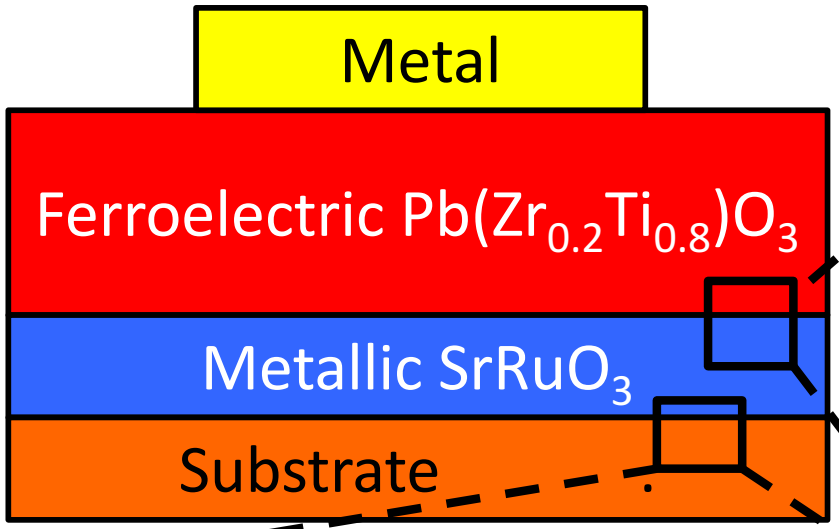
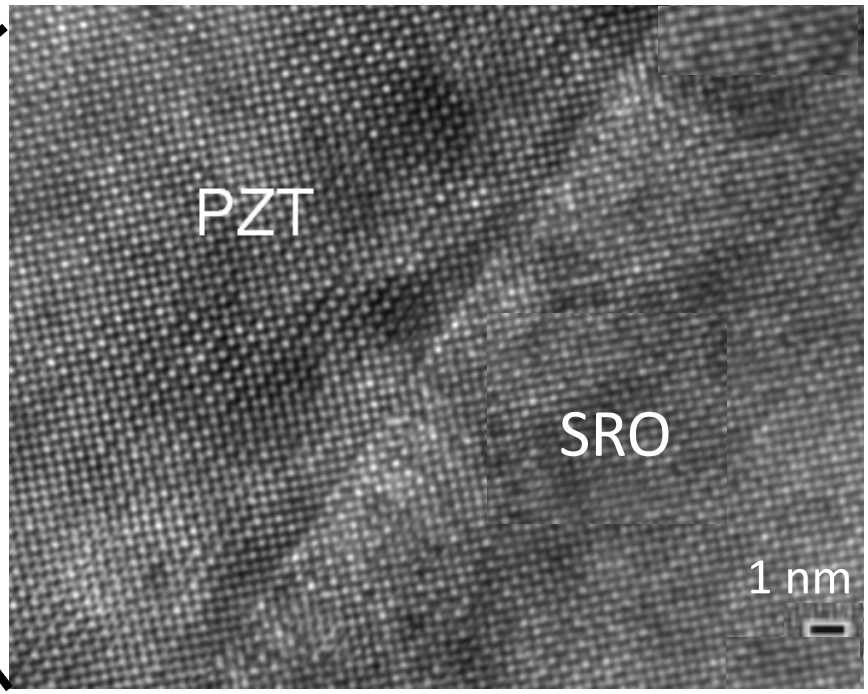
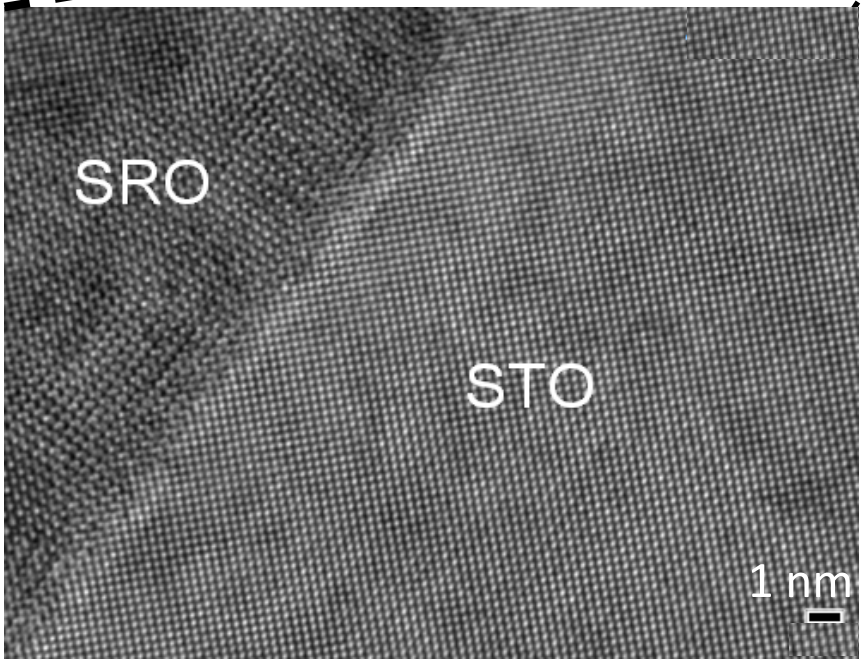
Ferroelectric $Pb(Zr_{0.2}Ti_{0.8})O_3$







Courtesy: Pan group, U. Mich.

Excellent epitaxial quality!

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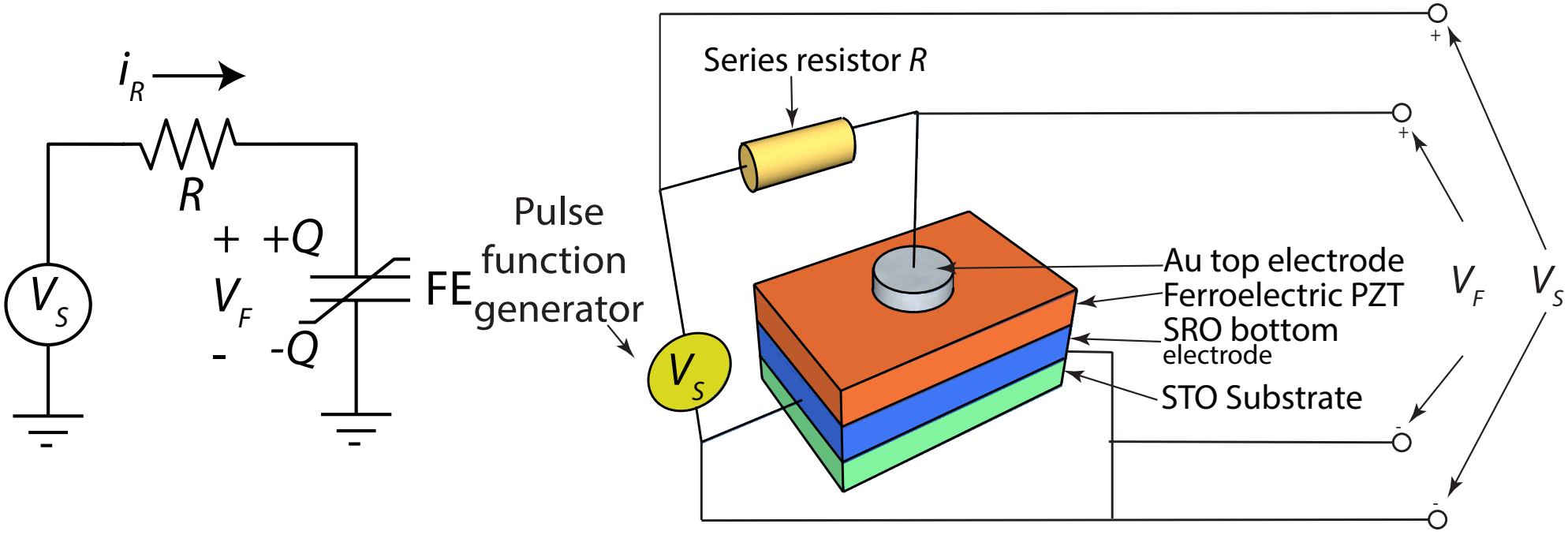
Direct Measurement of Negative Capacitance



A ferroelectric capacitor connected in series with an external resistor.

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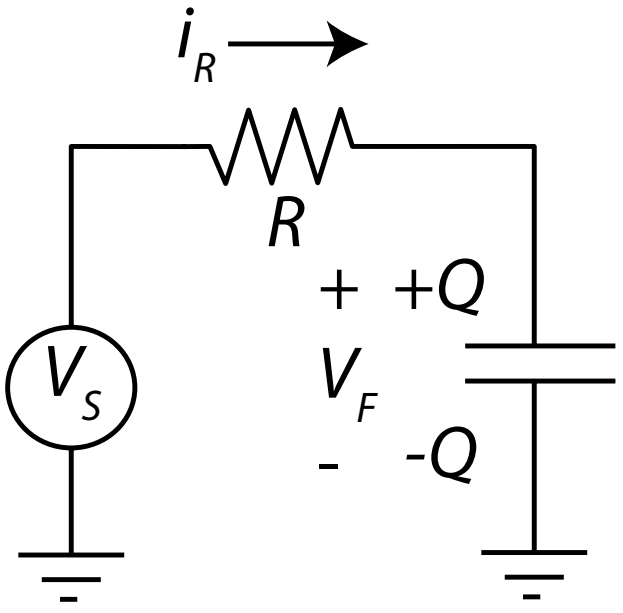
What happens in an *R-C* Series circuit?

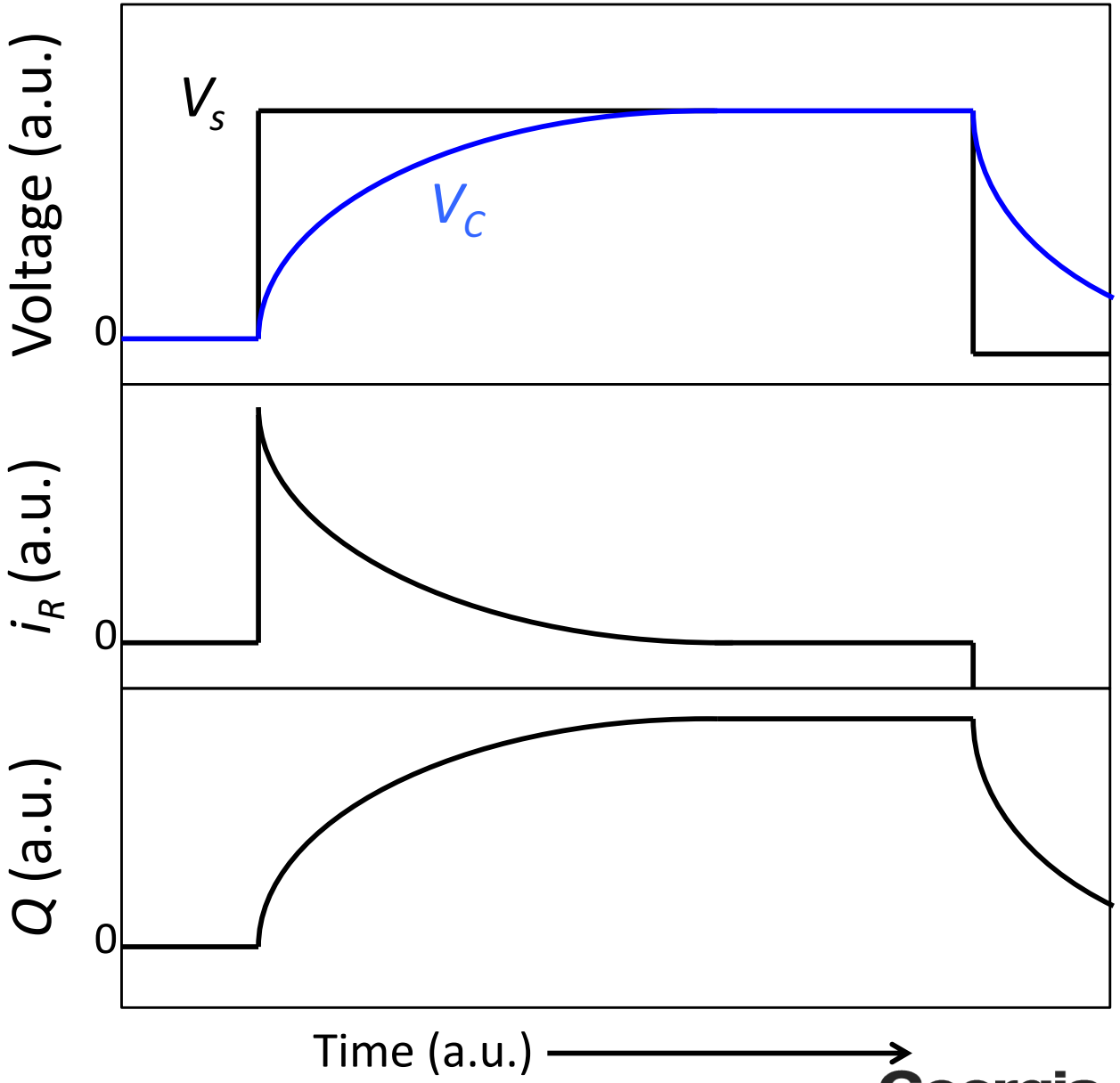


Voltage: $V_C = V_S(1-e^{-t/RC})$

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

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

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



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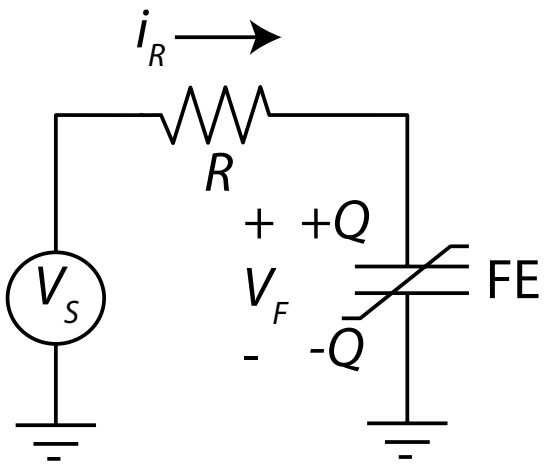
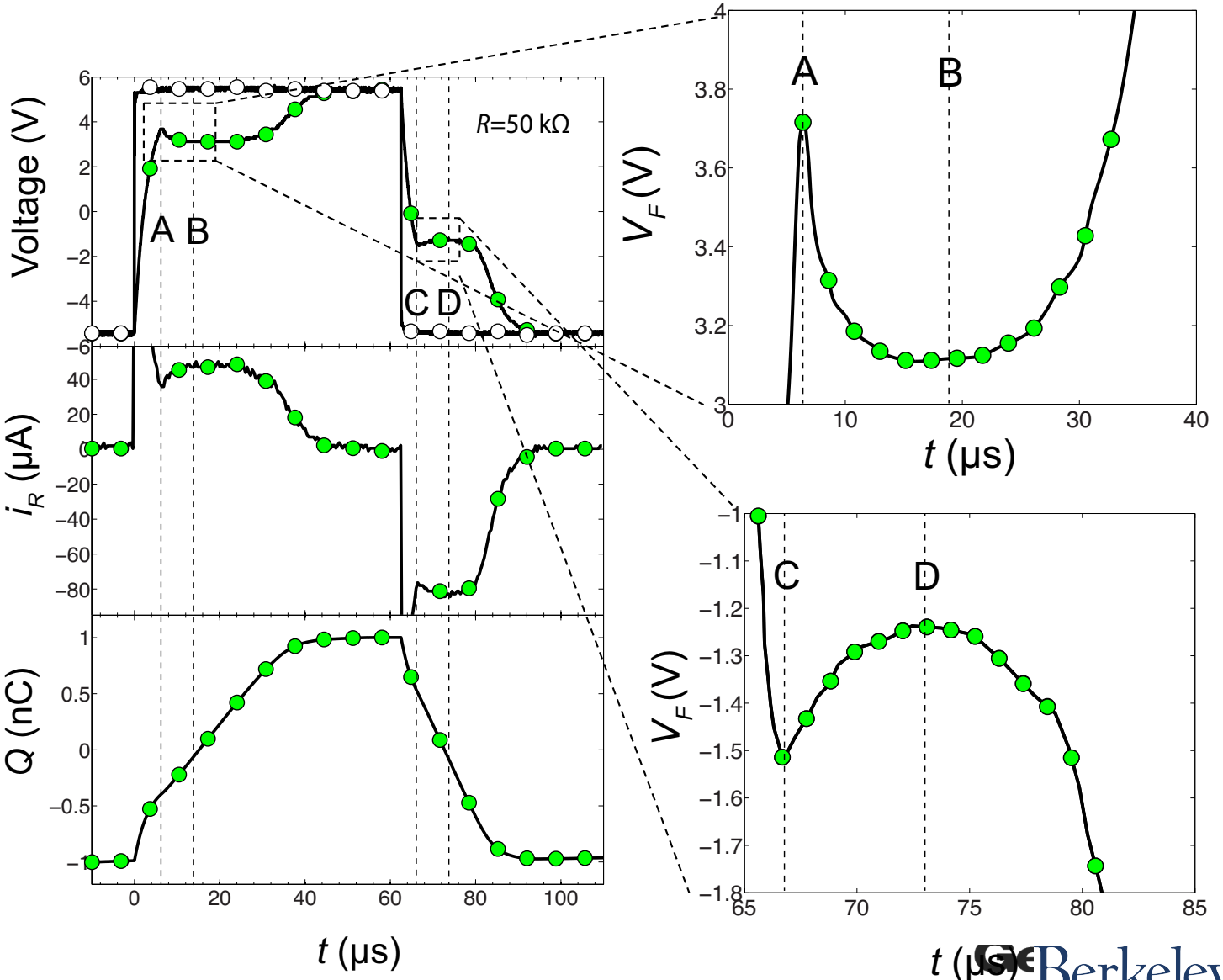
Direct Measurement of Negative Capacitance

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



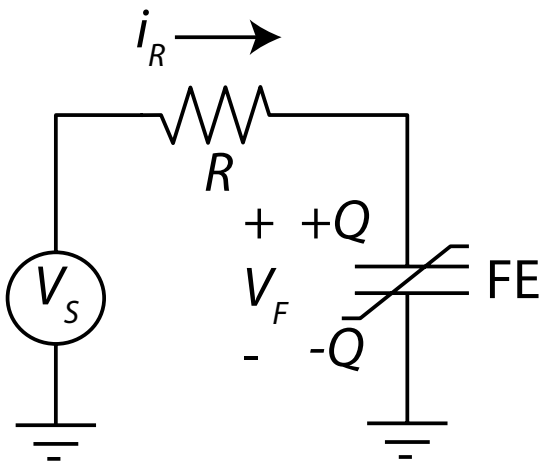


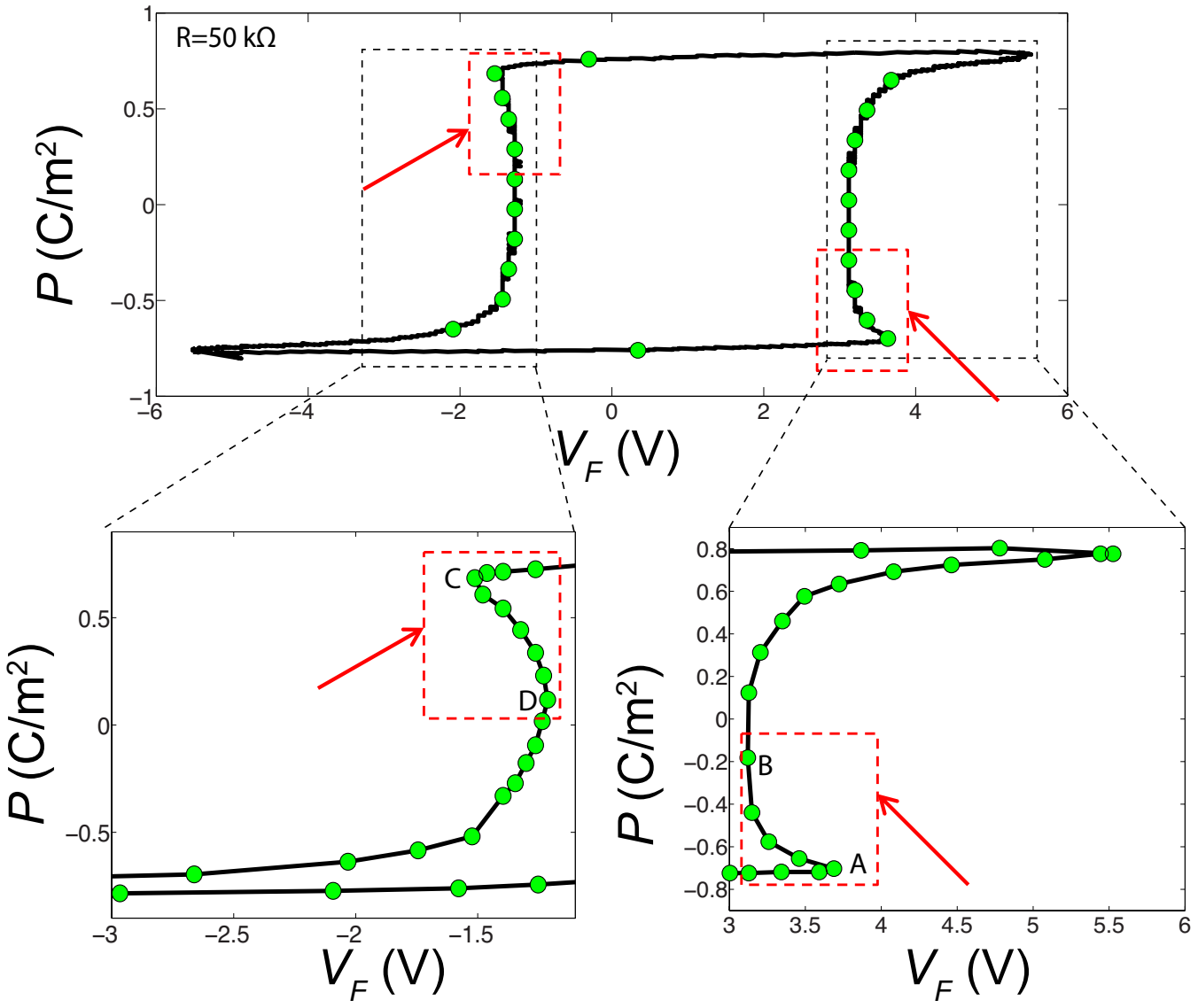
During AB & CD, dQ & dV_F has opposite signs indicating $dQ/dV_F < 0$.

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

Direct Measurement of Negative Capacitance

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



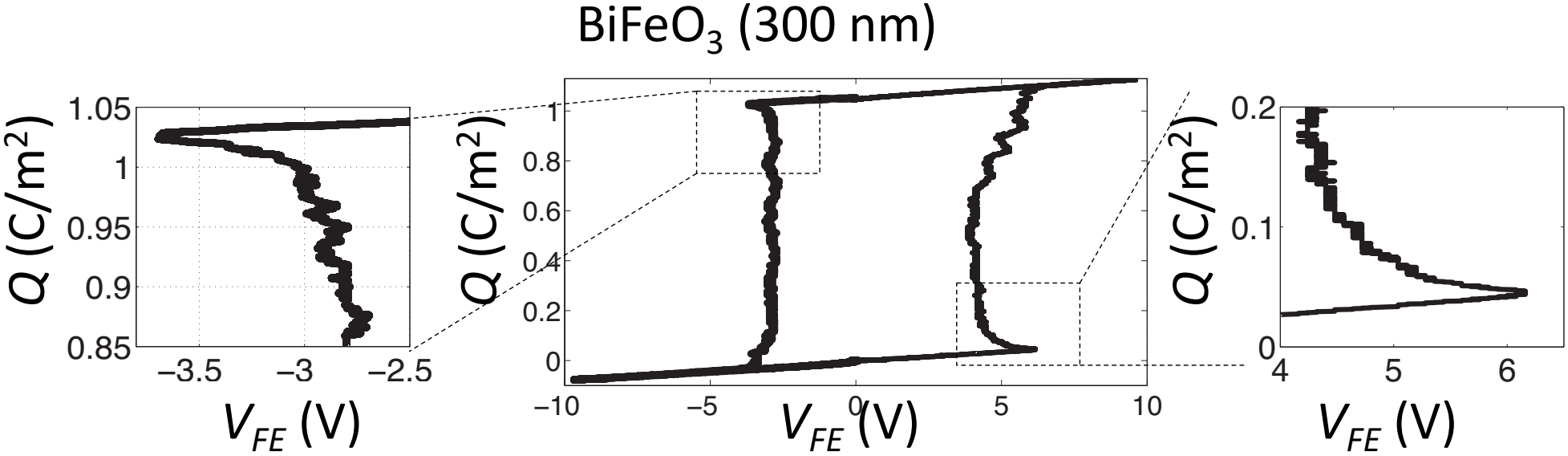


A negative dQ/dV_F directly observed in an isolated ferroelectric.

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

Negative Capacitance in Ferroelectrics

Negative Capacitance is a general phenomenon in ferroelectrics!



Doped HfO2:

- Hoffmann et al. Direct Observation of Negative Capacitance in Polycrystalline Ferroelectric HfO_2. Advanced Functional Materials 2016.
- Kobayashi et al. Experimental study on polarization-limited operation speed of negative capacitance FET with ferroelectric HfO_2. IEDM 2016

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Perspective

Nature Nanotech. 3, 77 (2008)

NEWS & VIEWS

NANOELECTRONICS

Negative capacitance to the rescue?

Victor V. Zhirnov* and Ralph K. Cavin
are at the Semiconductor Research Corporation, Research Triangle Park, North Carolina 27709, USA.
*e-mail: Victor.Zhirnov@src.org

At this point the proposed negative capacitance mechanism has not been observed in experiments, and it remains

Nature Materials 14, 137 (2015)

news & views

FERROELECTRICS

Negative capacitance detected

The experimental detection of negative capacitance in ferroelectrics rekindles hopes that the phenomenon could be used to further push the miniaturization of conventional transistors.

Gustau Catalan, David Jiménez and Alexei Gruverman

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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)

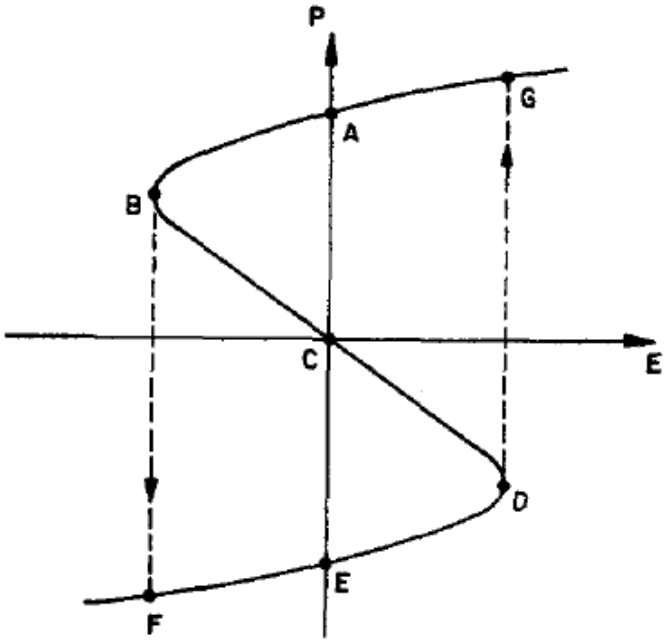

FIG. 1. Plot of polarization against field, at room temperature, as given by Devonshire's theory. P = polarization, E = field. Direction of field and polarization are taken to be the same, and parallel to the "c" axis of a single domain crystal. The solid line $GABCDEF$ gives the theoretical relationship.

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

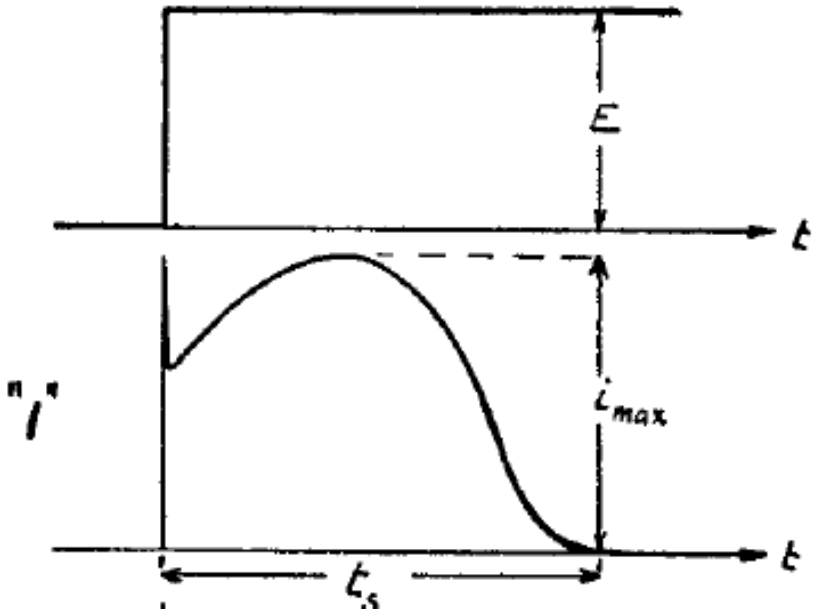

FIG. 1. Pulsing field and pulsing current *versus* time.

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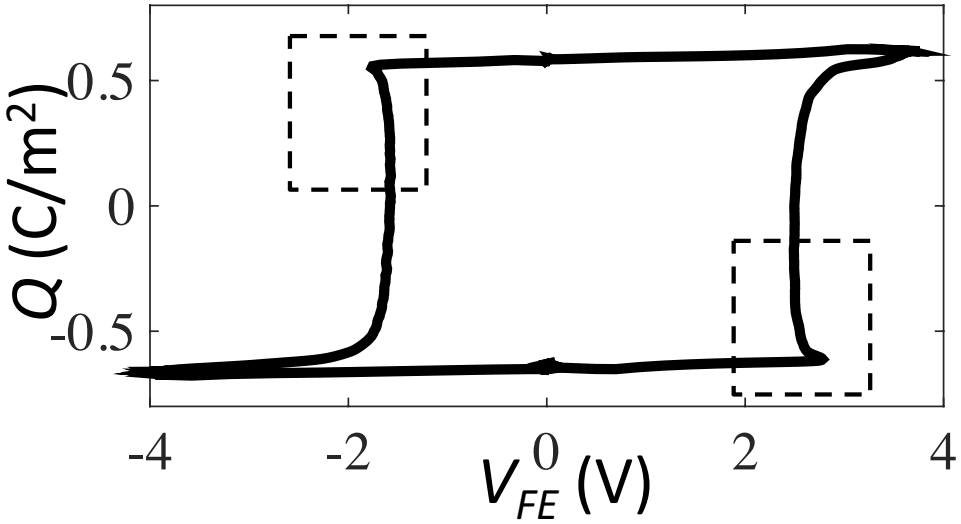
What's next?

Now that negative capacitance has been detected…



1. Can we see capacitance enhancement?

2. Can we see sub-60 mV/decade of subthreshold swing?

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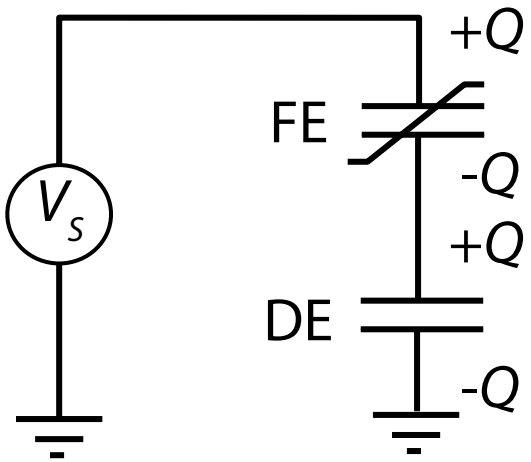
Breaking the Circuit Laws using Neg. Cap.

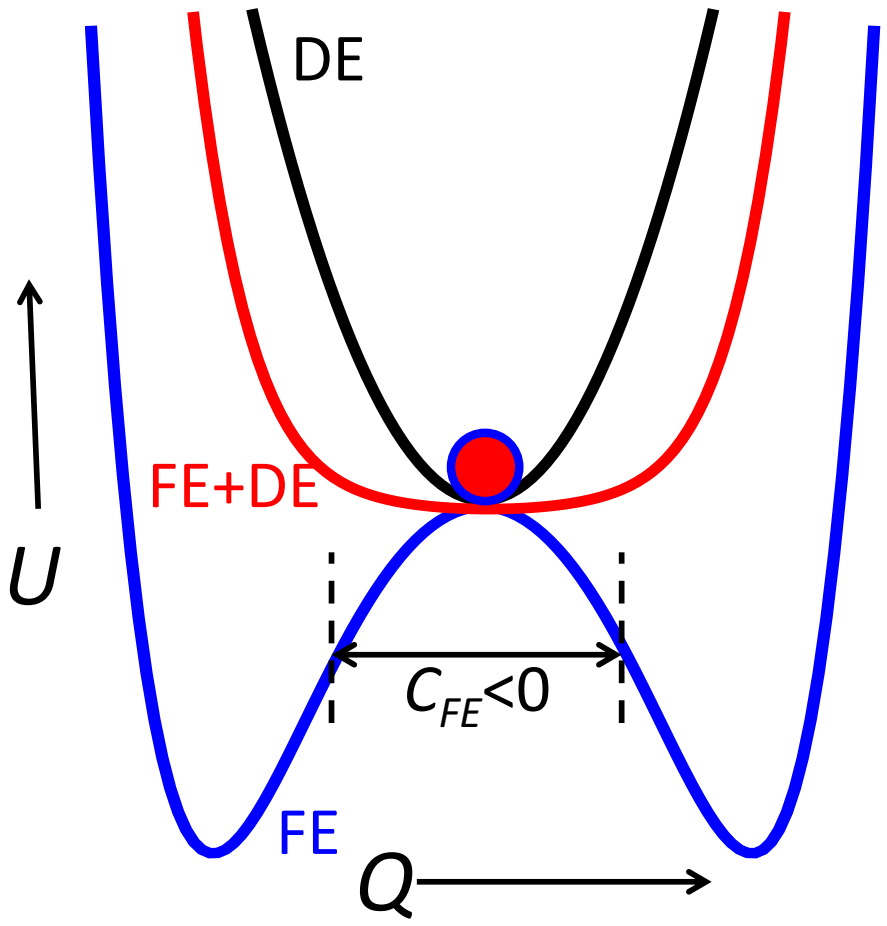
Ferroelectric-Dielectric Series Combination



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

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

Energy Landscapes



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

Enhancement of capacitance in a FE-DE Series combination!

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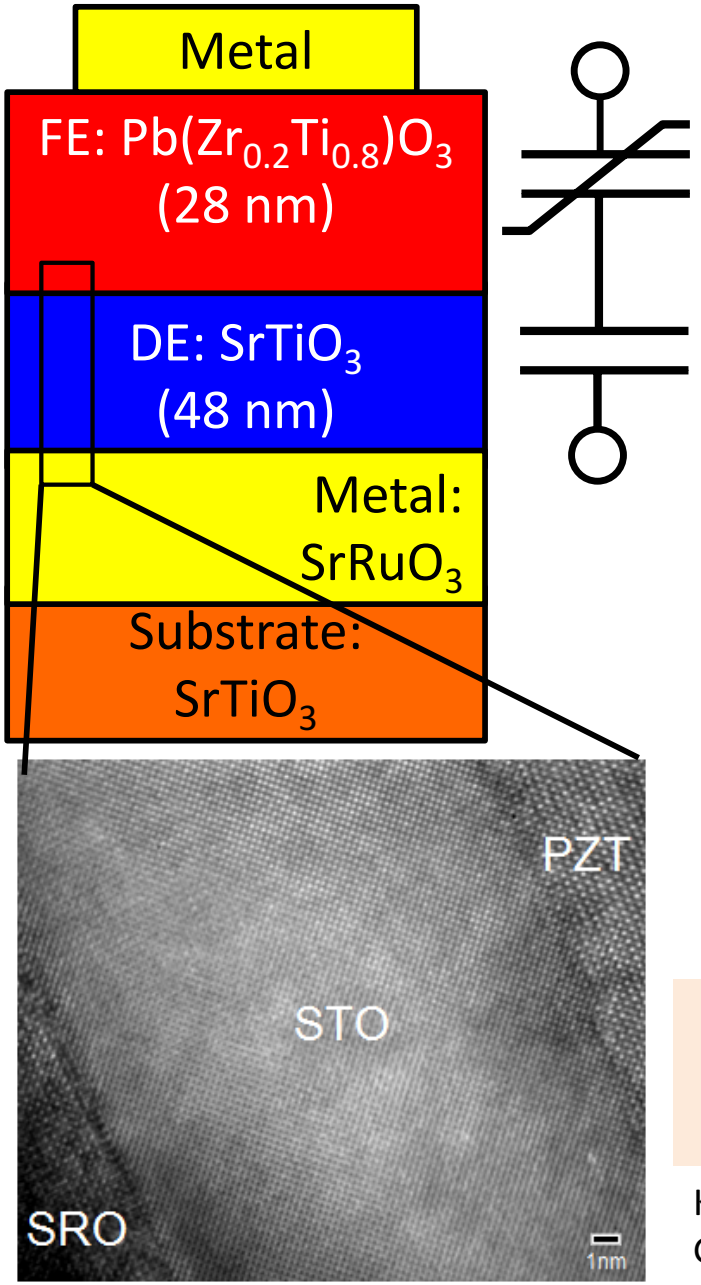
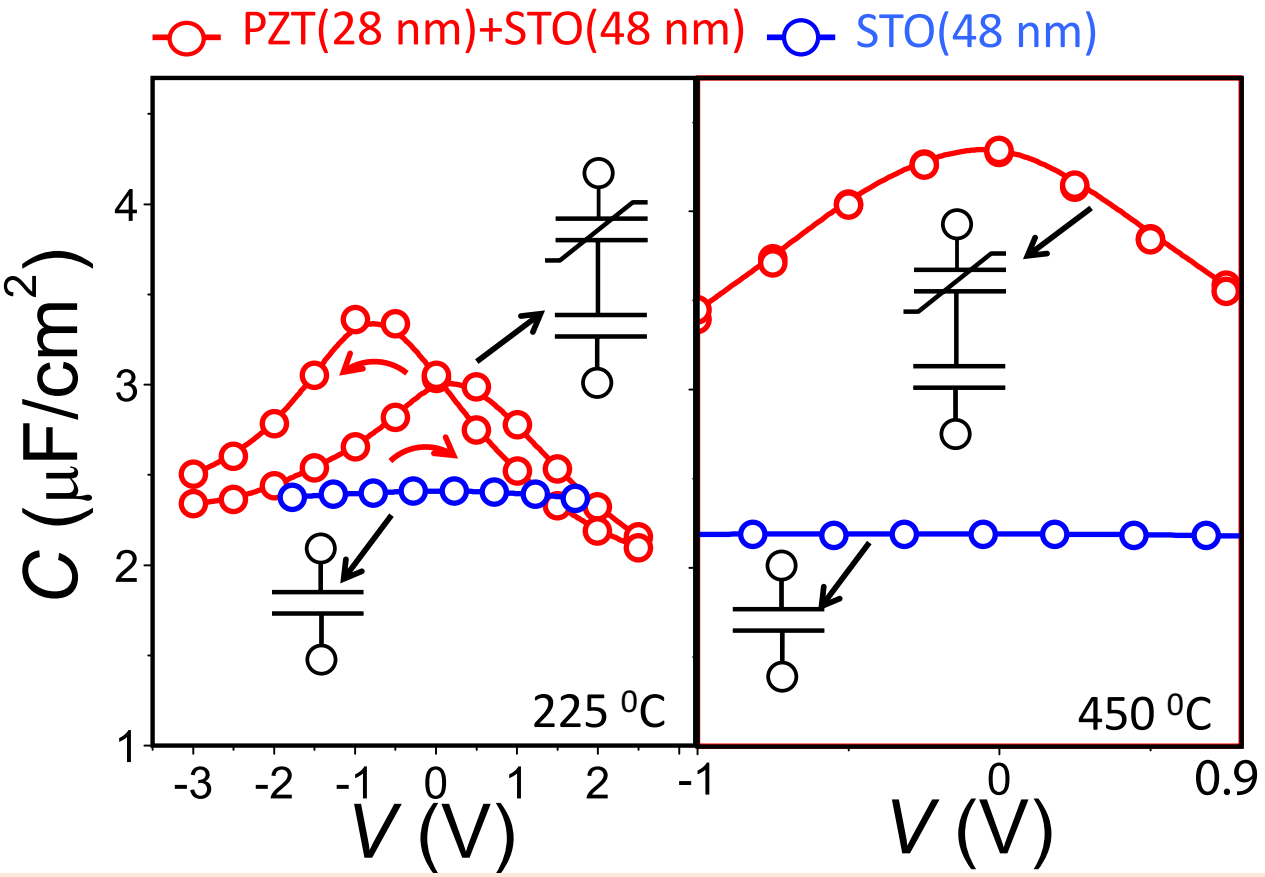
Breaking the Circuit Laws using Neg. Cap.



C-V Characteristics



Capacitance Enhancement in a FE-DE heterostructure experimentally observed!

Khan et al. Appl. Phys. Lett. 100, 113501 (2011)
Gao, Khan et al. Nano Lett. 14, 5814 (2014)
Appleby et al. Nano Lett. (2014)

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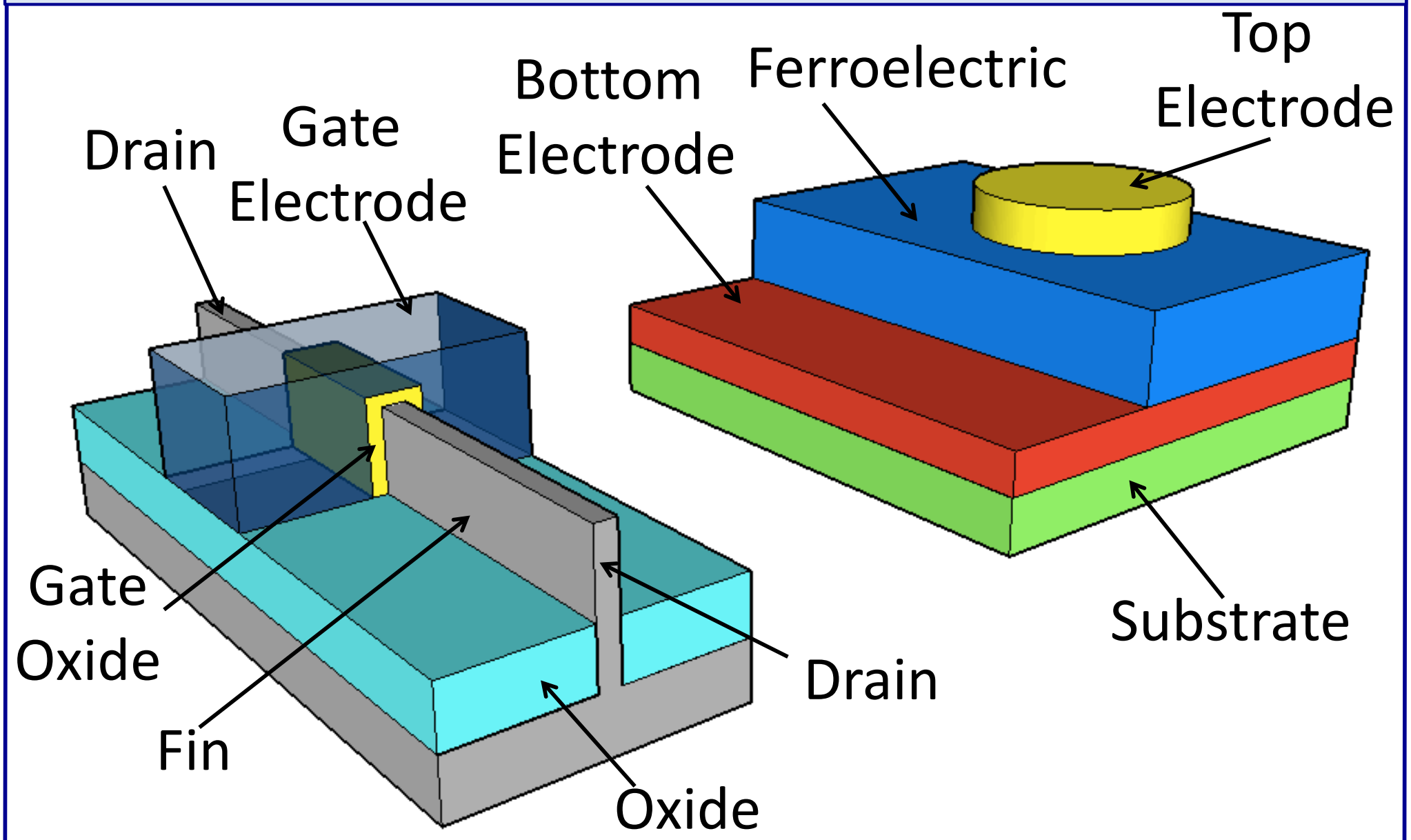
Externally Connected NC-FET



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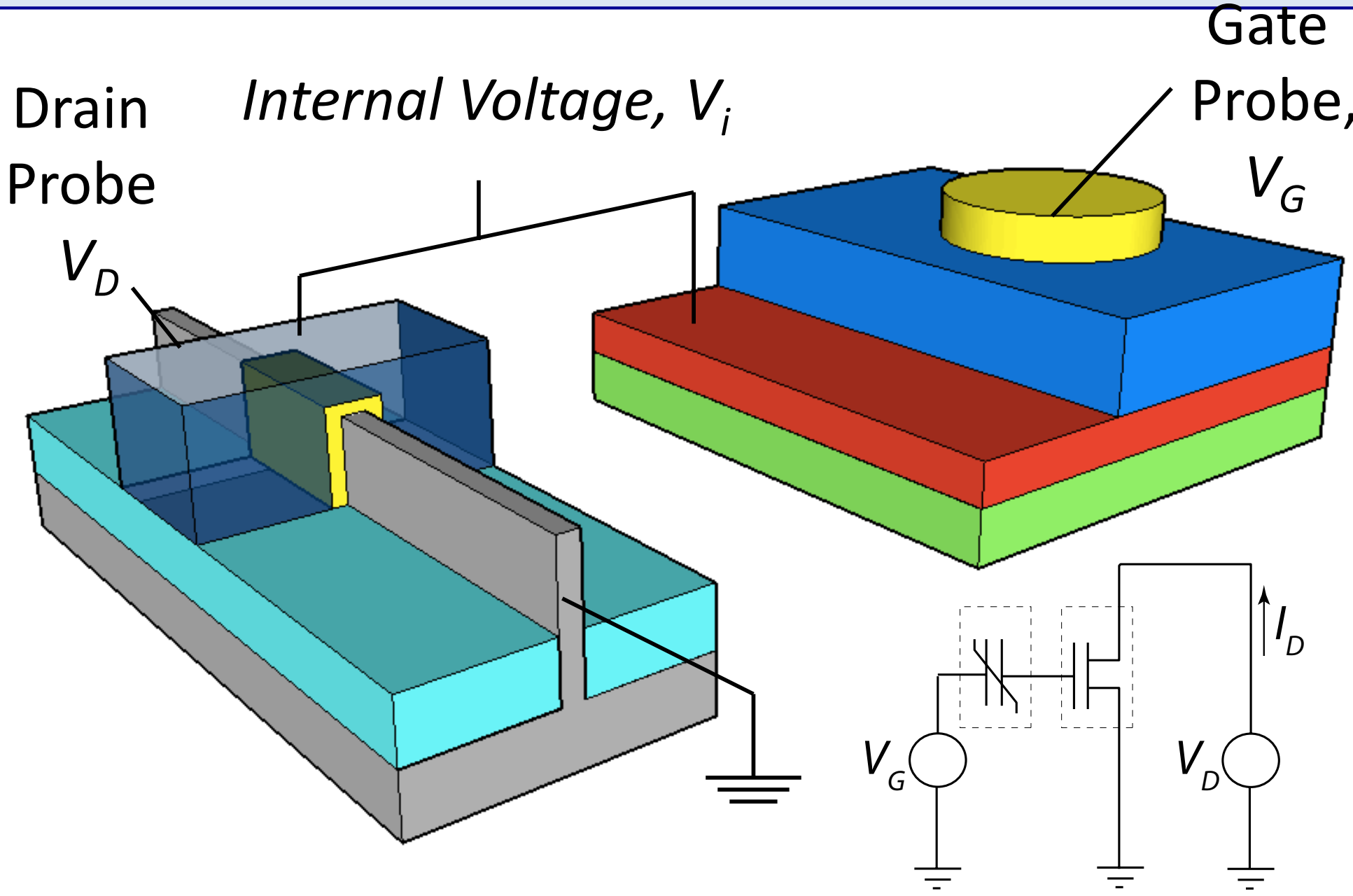
Externally Connected NC-FET



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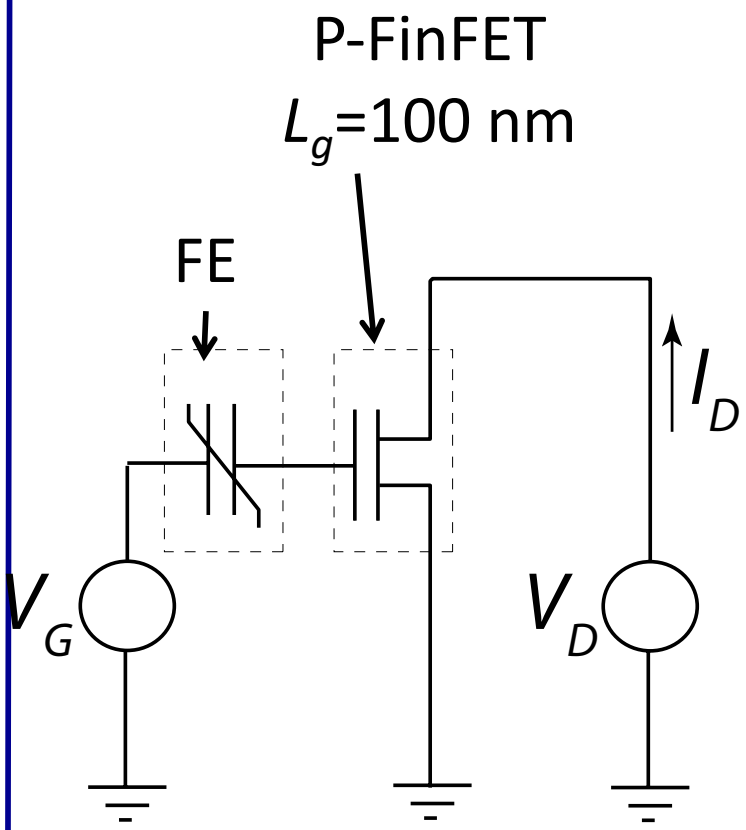
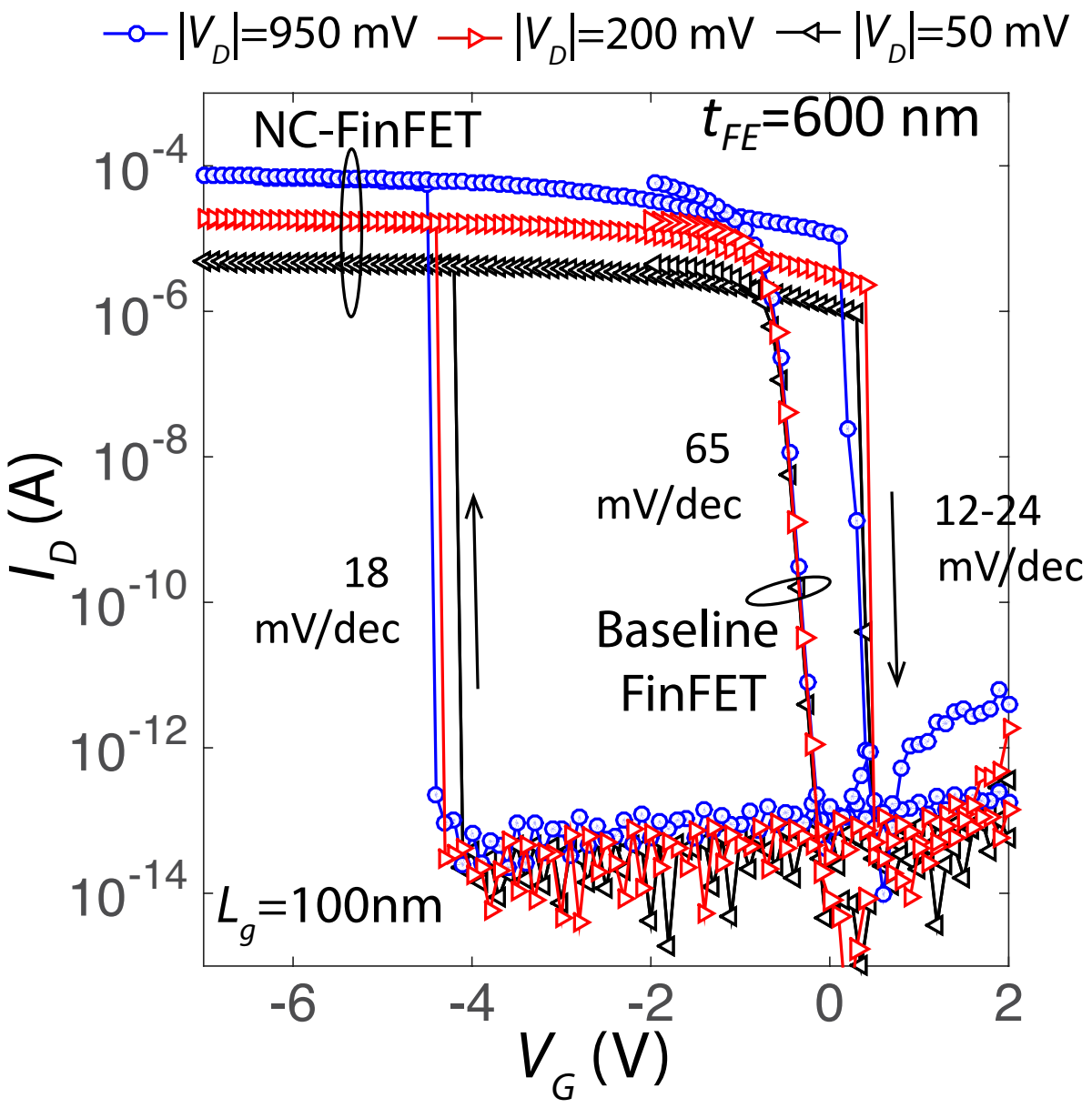
Externally Connected NC-FET





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)

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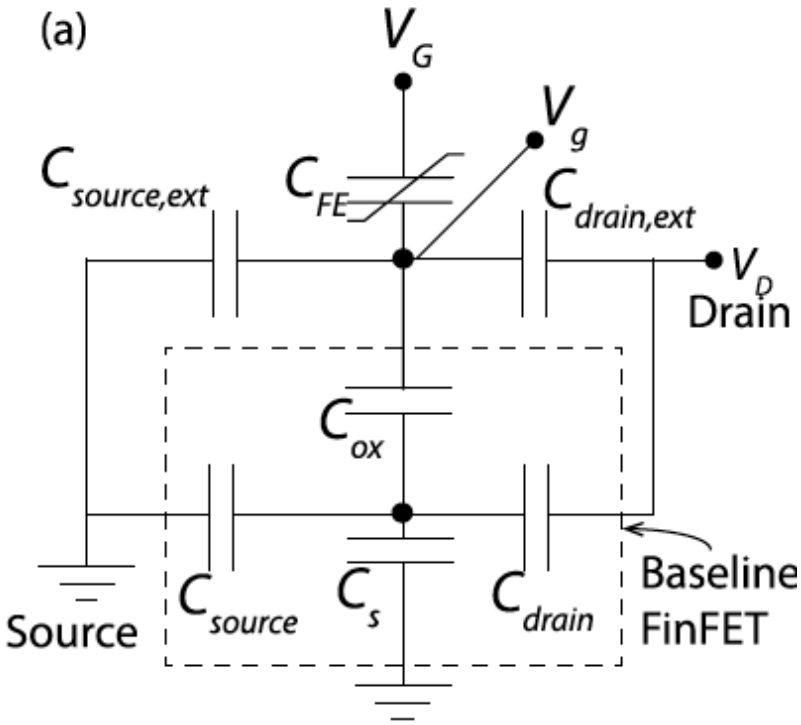
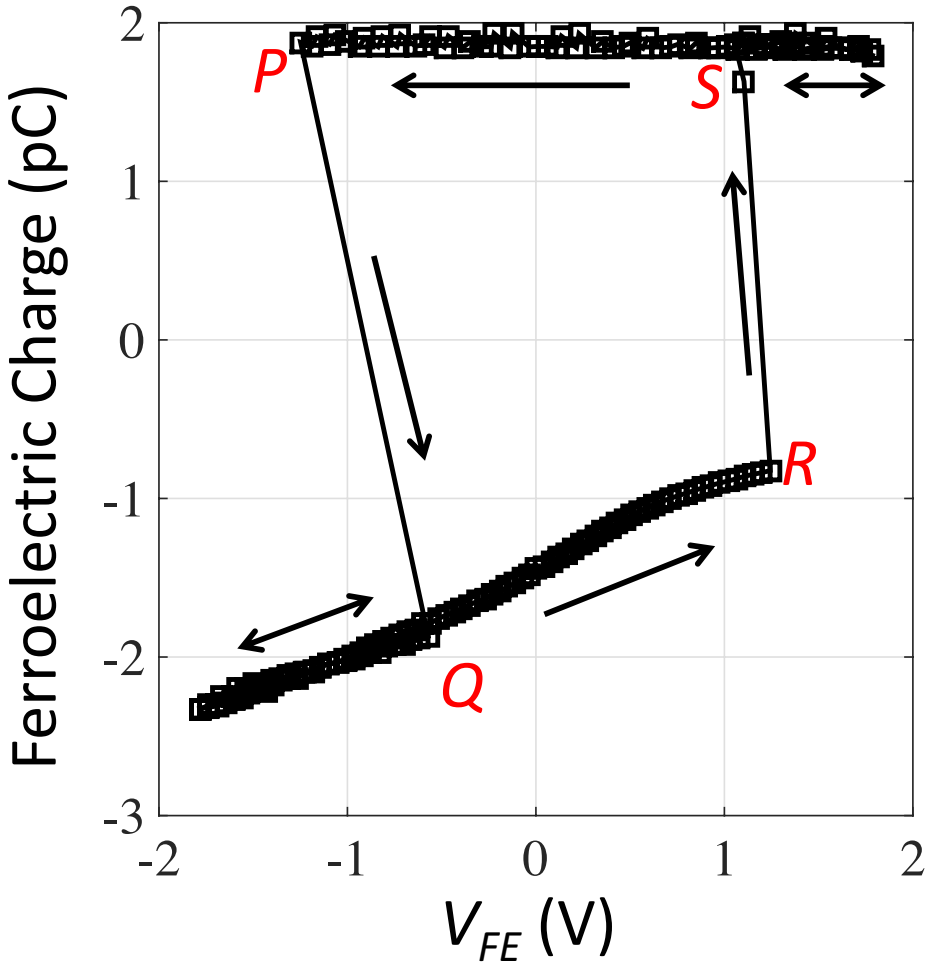
Externally Connected NC-FET



Sharp switching occurs due to ferroelectric negative capacitance!



Negative Capacitance Regions: PQ and RS

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

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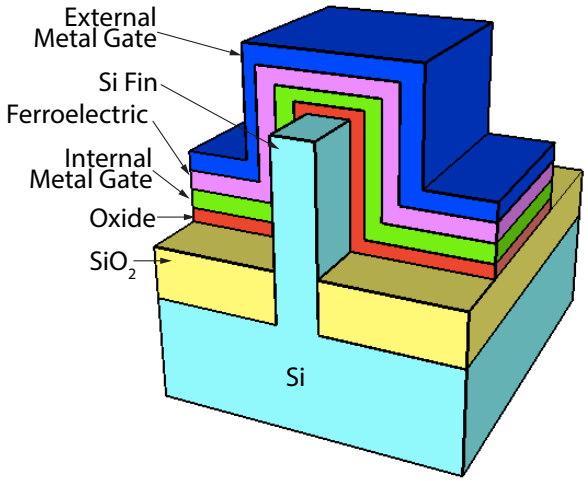
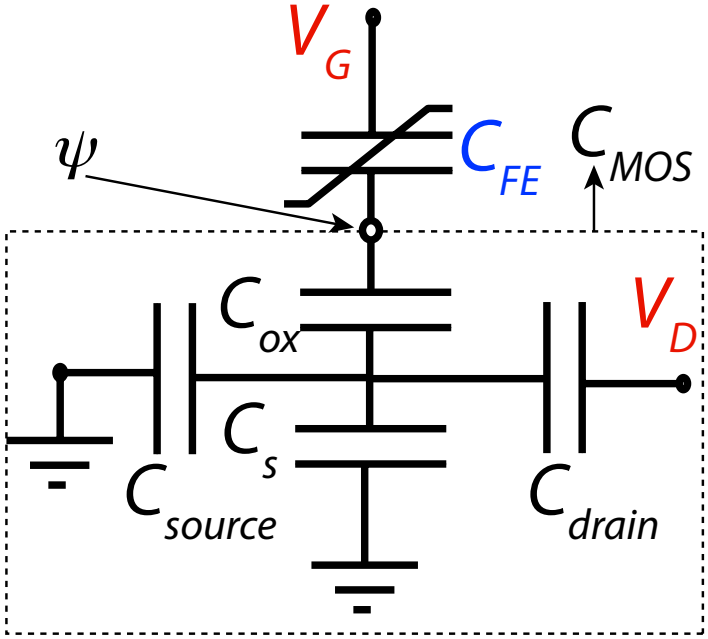
Physics of Negative Capacitance FET

14 nm FinFET Node





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

Subthreshold Swing $S = S^{baseline} \times m^o < S^{baseline}$

Input gate capacitance $C_G = \frac{C_{G,baseline}}{m} > C_{G,baseline}$

Power $P = \alpha C_L V_{DD}^2 f$

Where does the power benefits come from?

$C_L \uparrow V_{DD} \downarrow\downarrow P \downarrow\downarrow$

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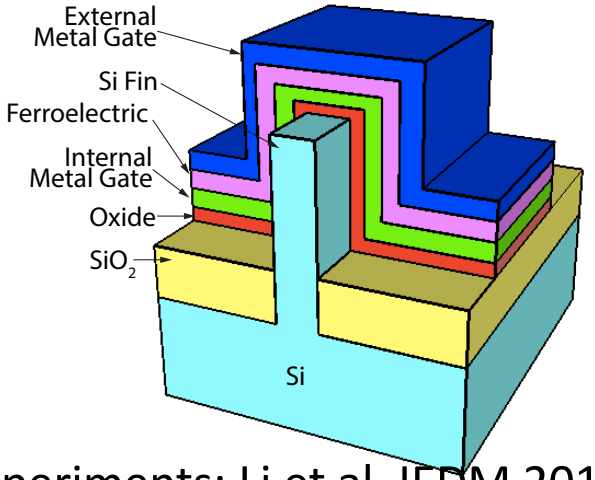
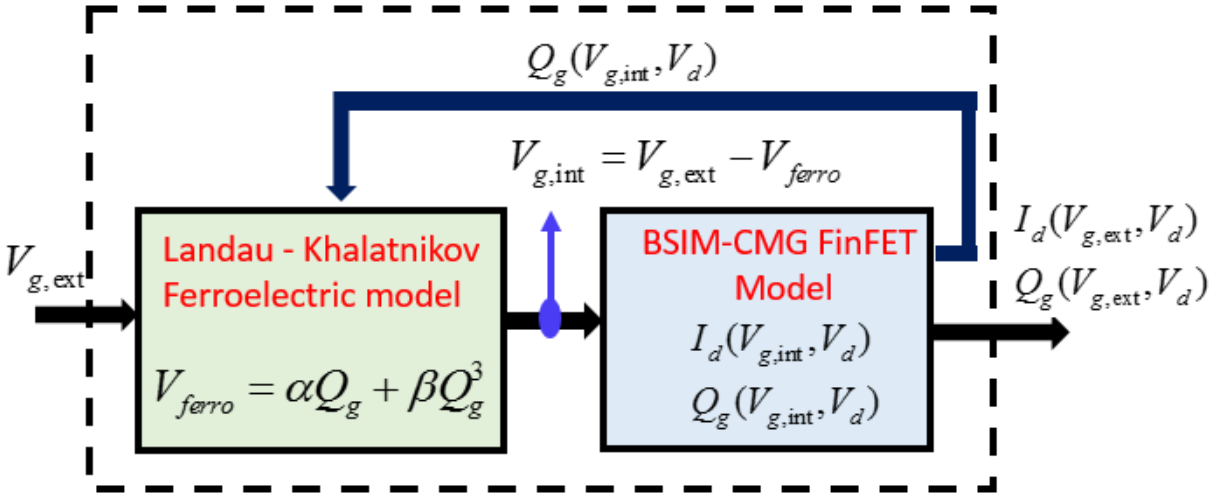
Performance Projection of NCFETs

14 nm FinFET Node

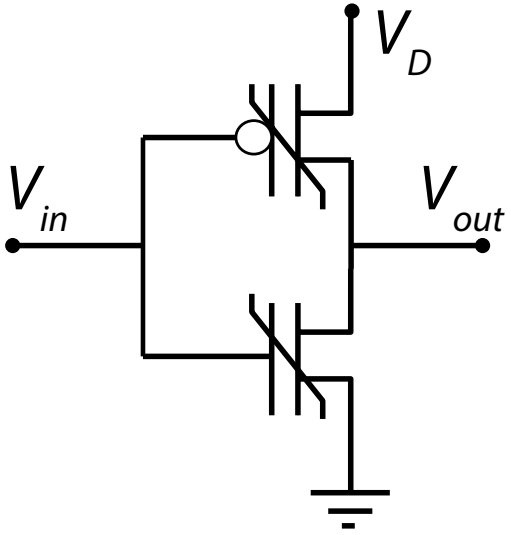


Experiments: Li et al. IEDM 2015

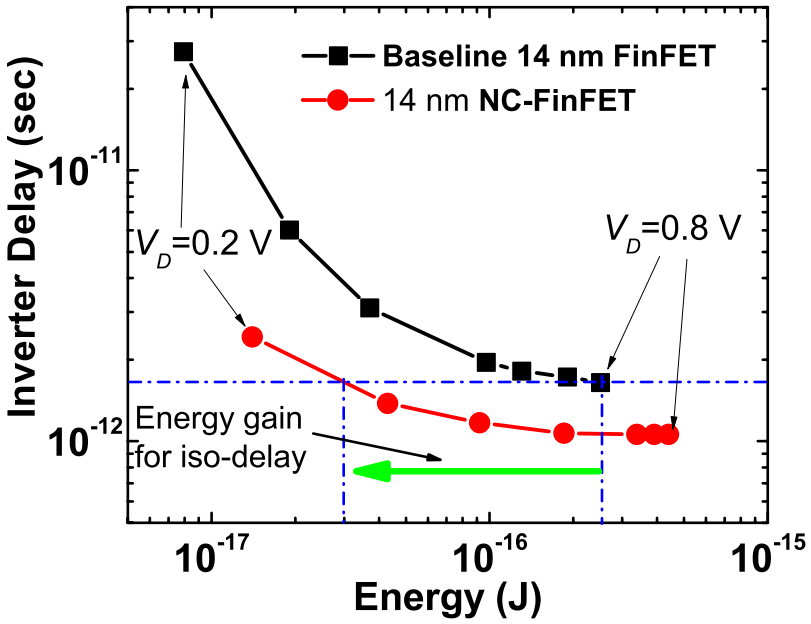
Compact Model



Inverter



Energy-Delay Curve



Significant reduction of energy-delay product is possible with negative capacitance

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What do we need to know?

1. **Domains:** What role do domain mechanisms play for negative capacitance?
    - We do not have a good model for negative capacitance in the presence of domain mechanisms.

2. **Speed:** What the fundamental time scale for negative capacitance mechanisms?
    - Sub-ps?

3. **NCFET Designs:** How to design an NCFET? ~0 mV/decade swing?
    - Internal metal gate: no!
    - Make $|C_{FE}|=C_{MOS,}$ Parasitic capacitances help!

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THANKS

Negative Capacitance:

What do we know and

What do we need to know?

QUESTIONS

&

COMMENTS

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