Ferroelectrics and Negative Capacitance:

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

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FCRP MSD Center

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Ferroelectrics and Negative Capacitance:

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

Disclaimer:

1. **Experimental facts regarding negative capacitance!**
2. **The talk is material agnostic!**
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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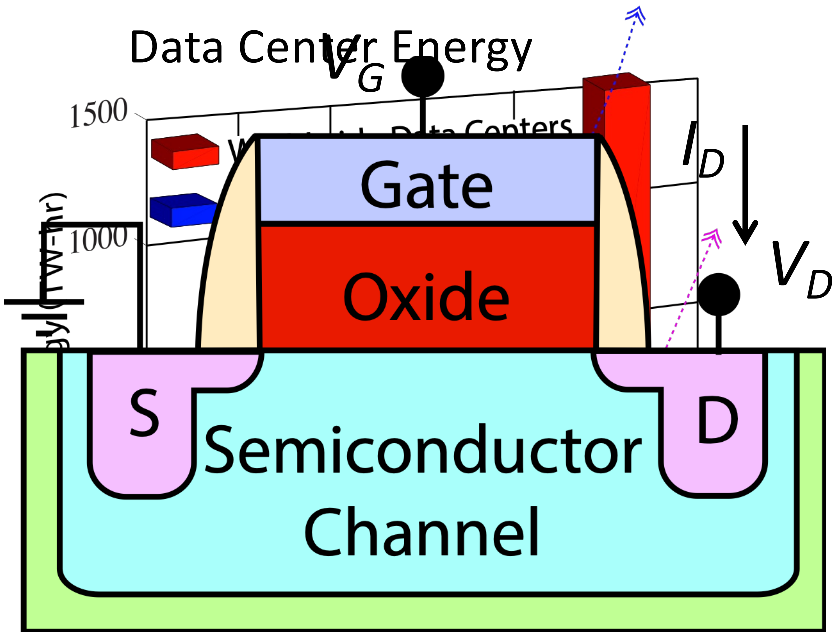
Energy Challenge in Computing



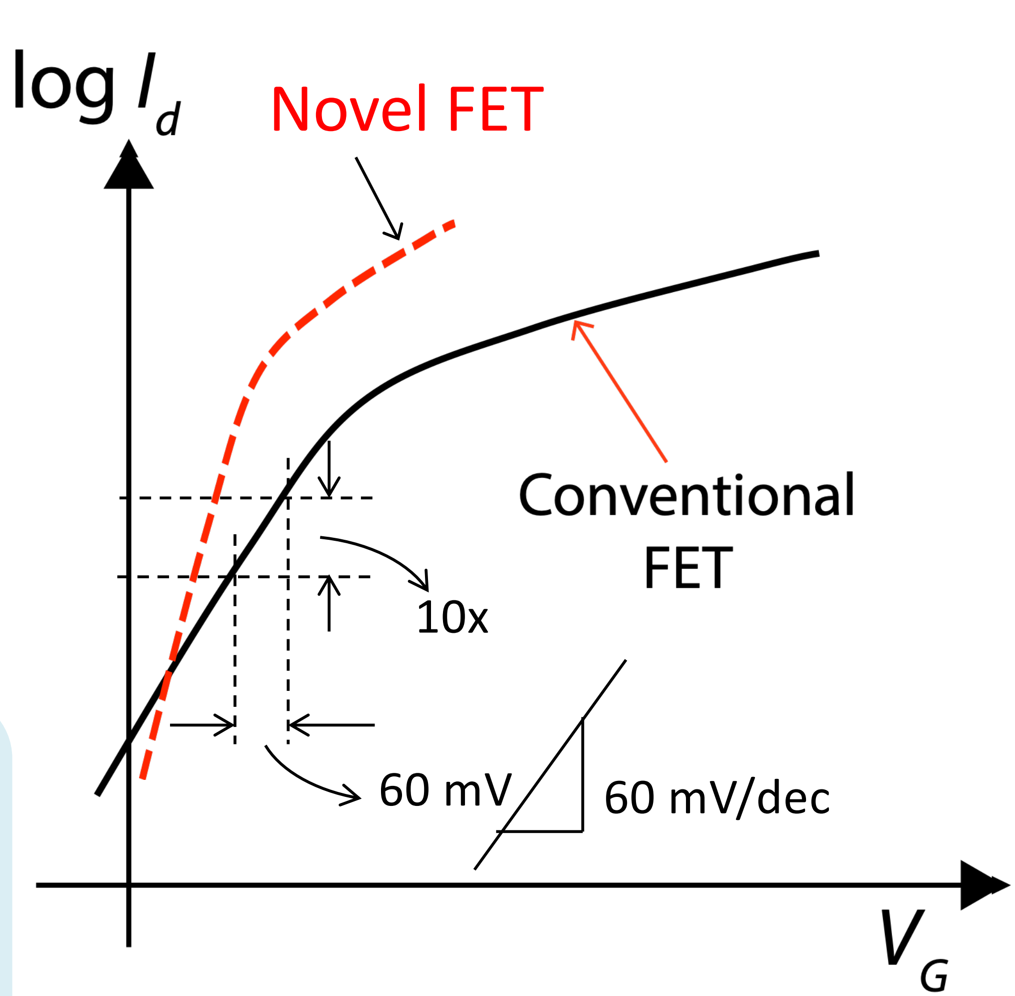
& http://www.alliancetrustinvestments.com/sri-hub/posts/Energy-efficient-data-centres

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

Minimum Subthreshold Swing $S_{\min} = \frac{k_B T}{q}\log_e(10)$

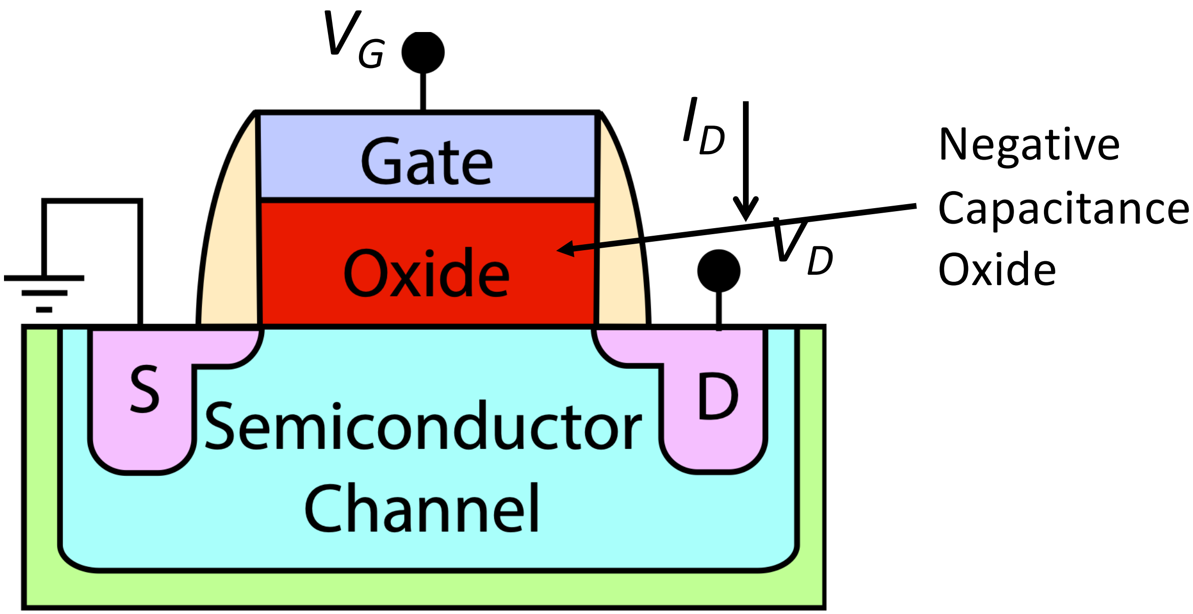
$= 60 mV / dec$

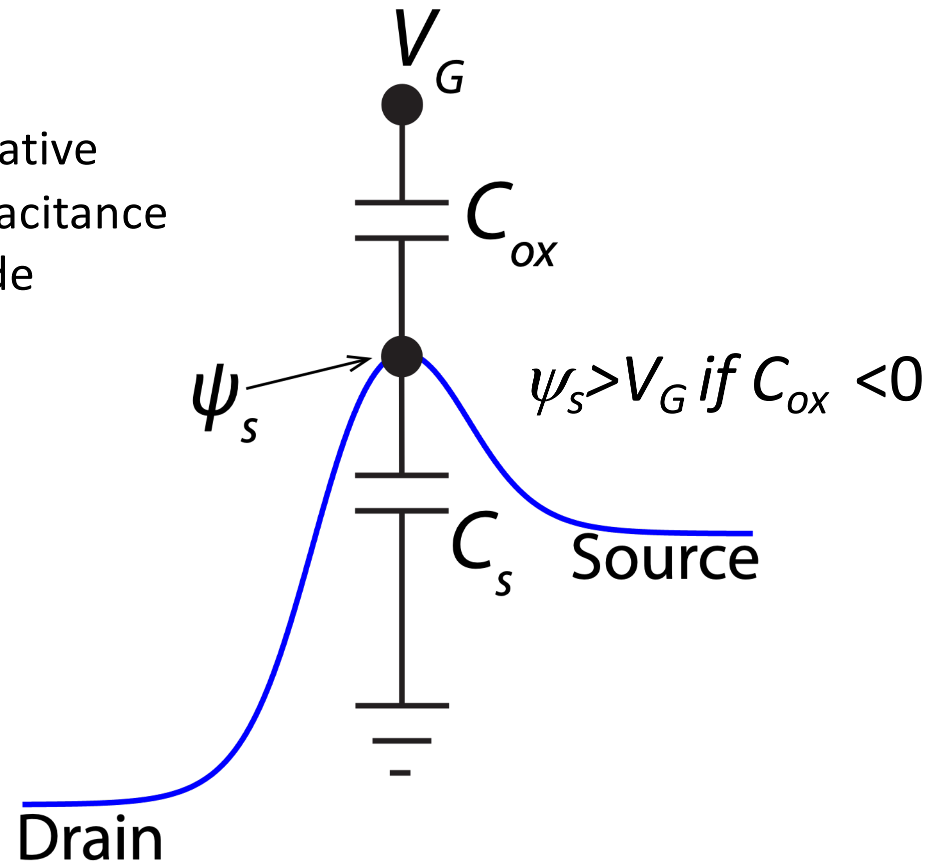
Communications of the ACM 55.1 (2012).



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

The Negative Capacitance Approach





Subthreshold Swing

$$S = \frac{\partial V_G}{\partial(\log_{10} I_D)}$$

$$= \underbrace{\frac{\partial V_G}{\partial \psi_s}}_{\equiv \mathrm{m}} \frac{\partial \psi_s}{\partial(\log_{10} I_D)}$$

$$= m \times 60 \text{ mV/decade}$$

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

Body Factor

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

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

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

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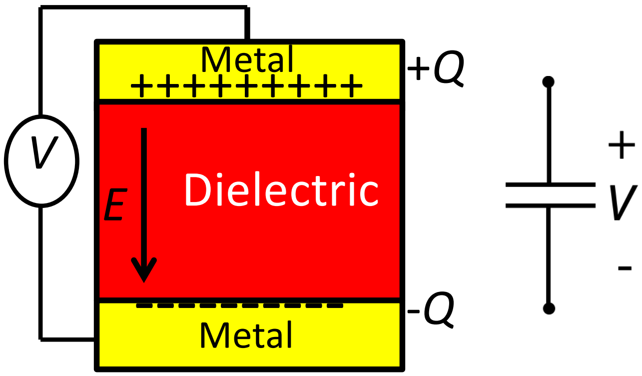
Capacitance: Positive and Negative

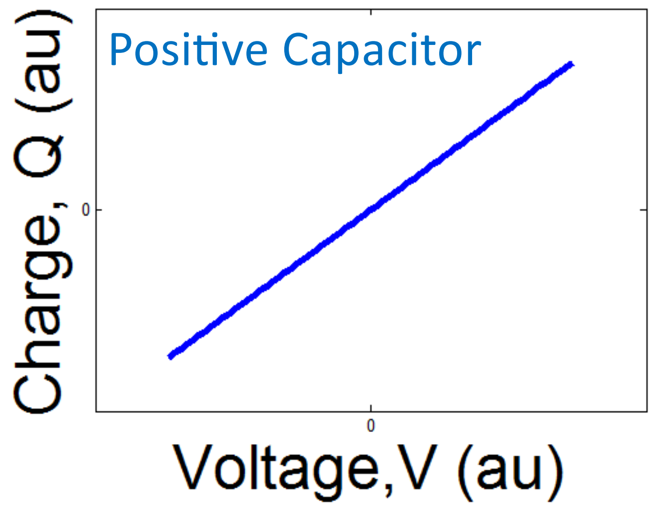


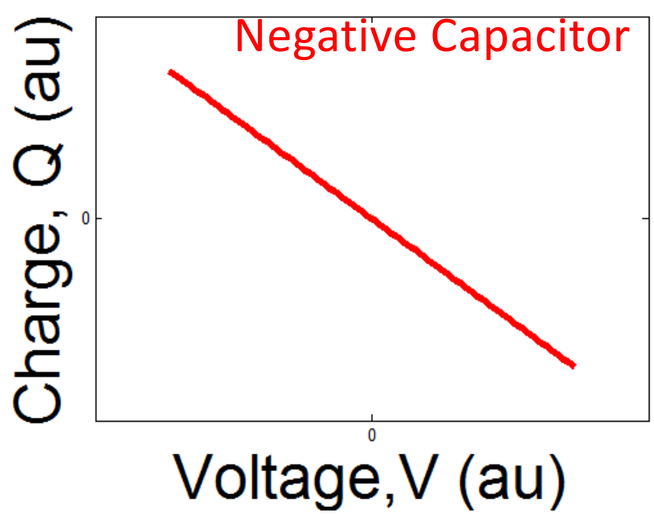
Capacitance $C = \dfrac{dQ}{dV}$

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

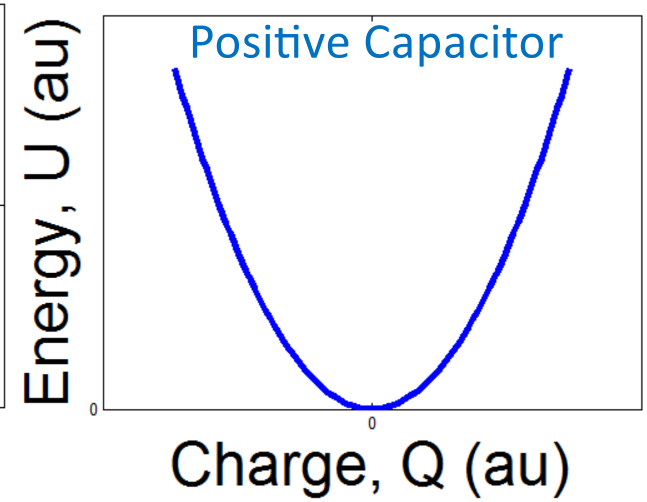
$$C = \left[\frac{d^2U}{dQ^2}\right]^{-1}$$

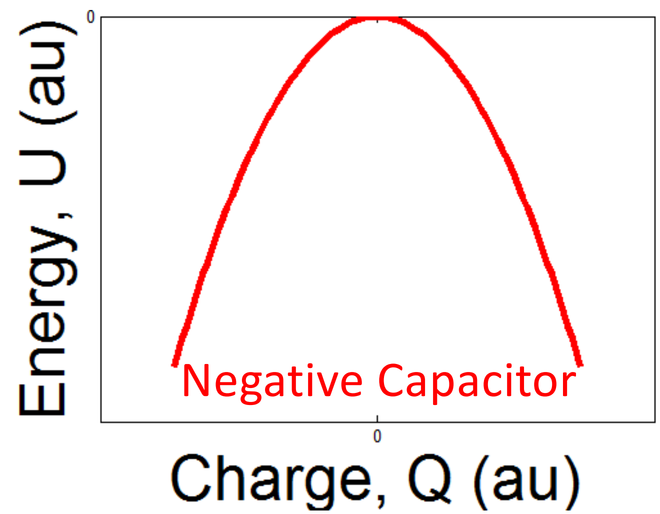
Q-V Characteristics





Q-U Characteristics (Energy Landscape)





C is inverse of radius of curvature of energy landscape

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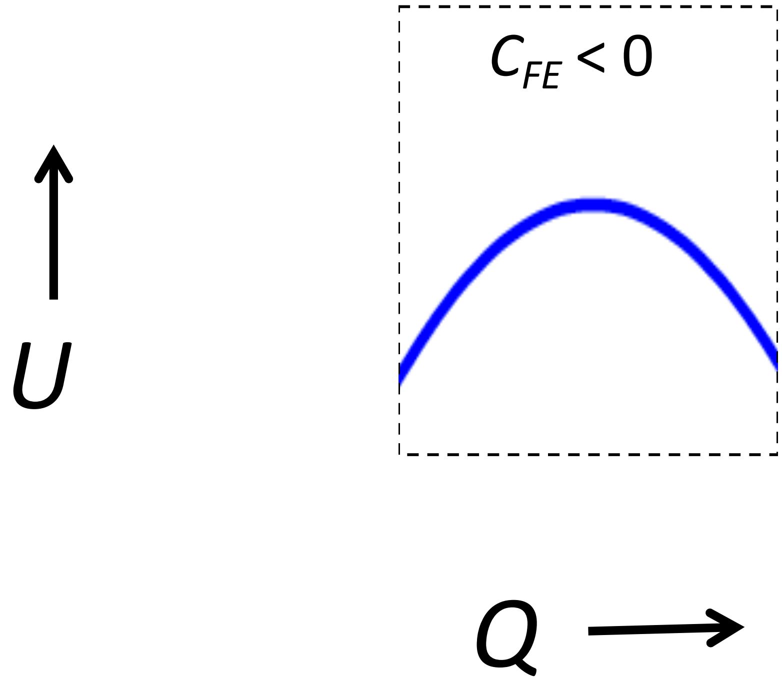
How to get Negative Capacitance Material



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

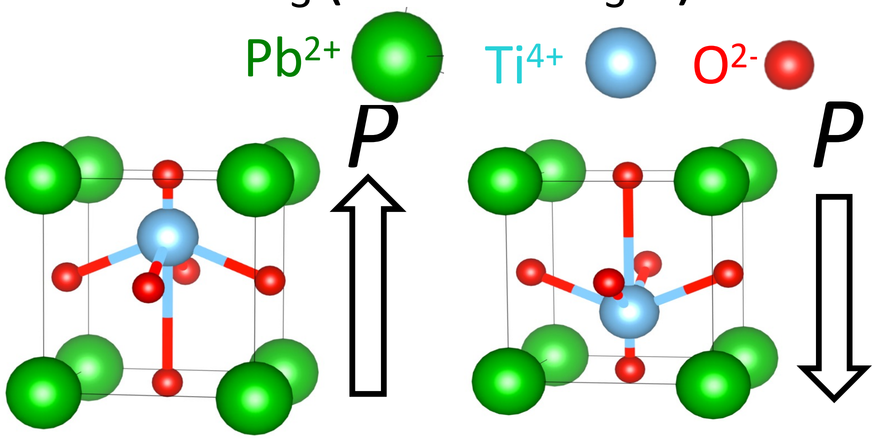
According to the Landau theory of ferroelectric, ferroelectric oxides could give an effective negative capacitance

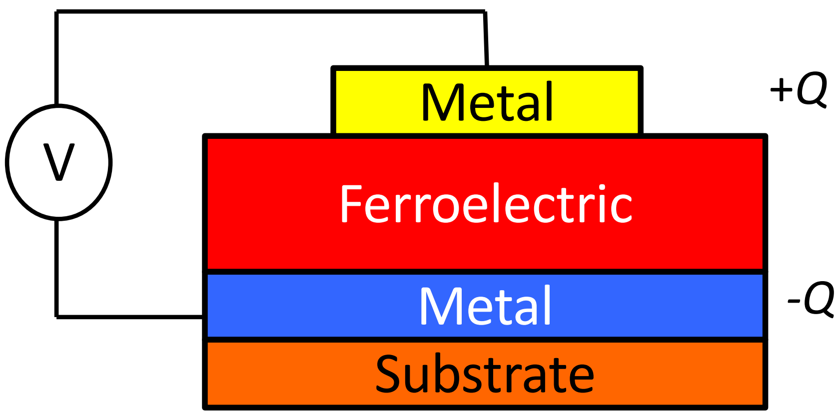
Landau & Khalatnikov. Dokl. Akad. Nauk 96, 85 469472 (1954).

Ferroelectric Oxides

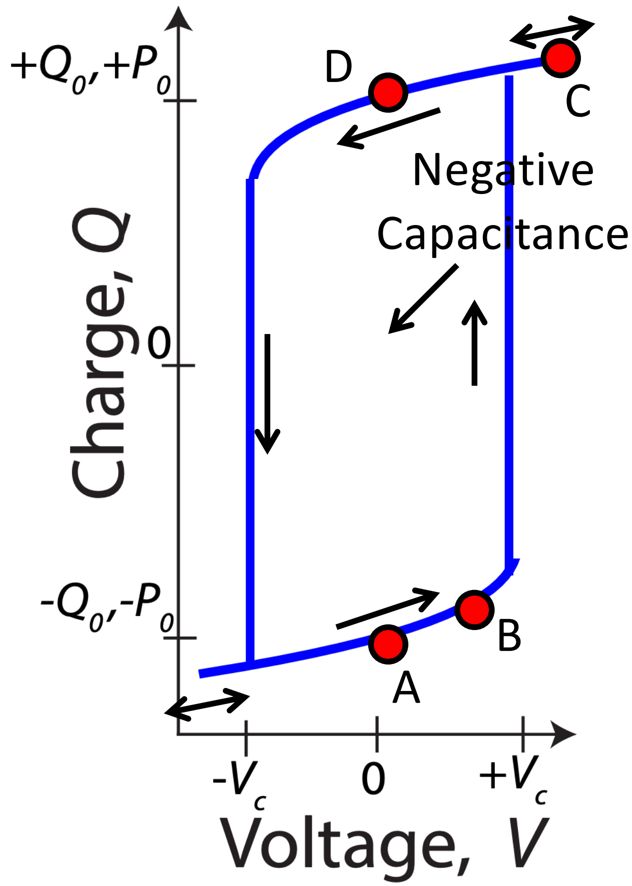
Classical Ferroelectric

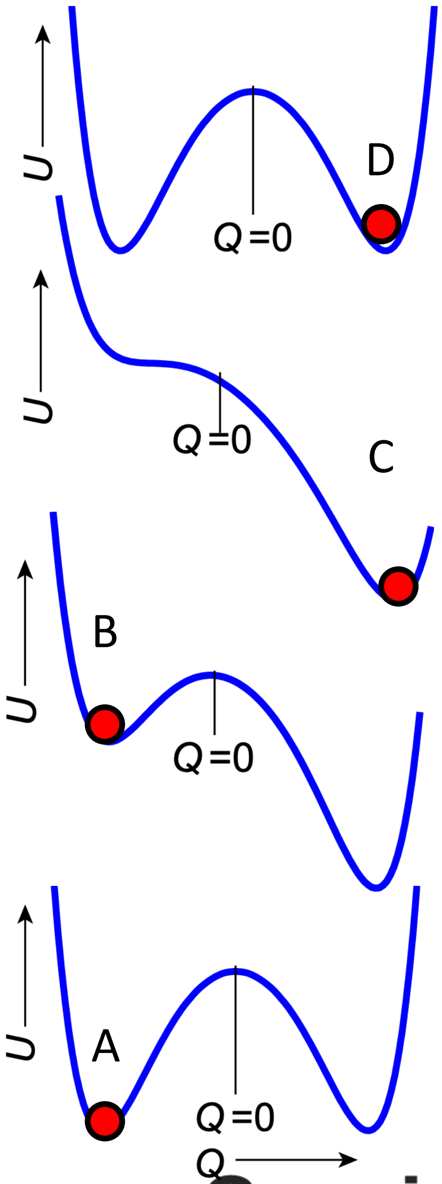
$PbTiO_3$ ($Pb^{2+}Ti^{4+}O_3^{6-}$)





Charge Voltage Characteristics



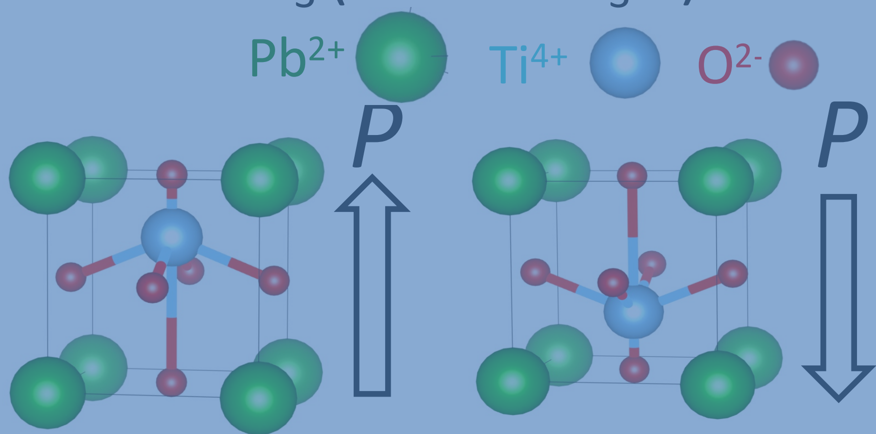


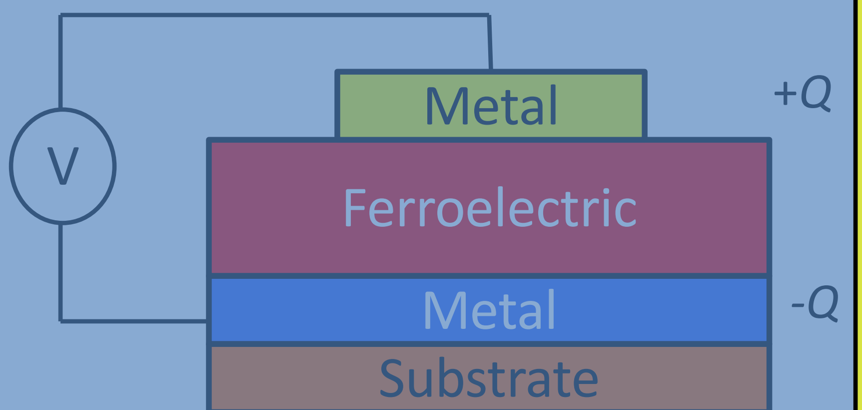
A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercivity voltage .

Ferroelectric Oxides

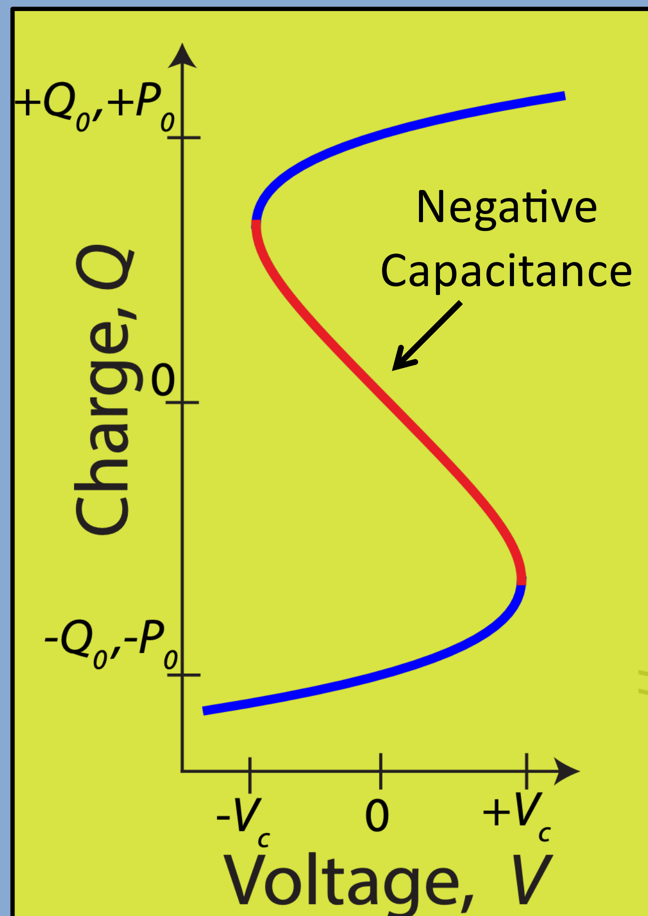
Classical Ferroelectric

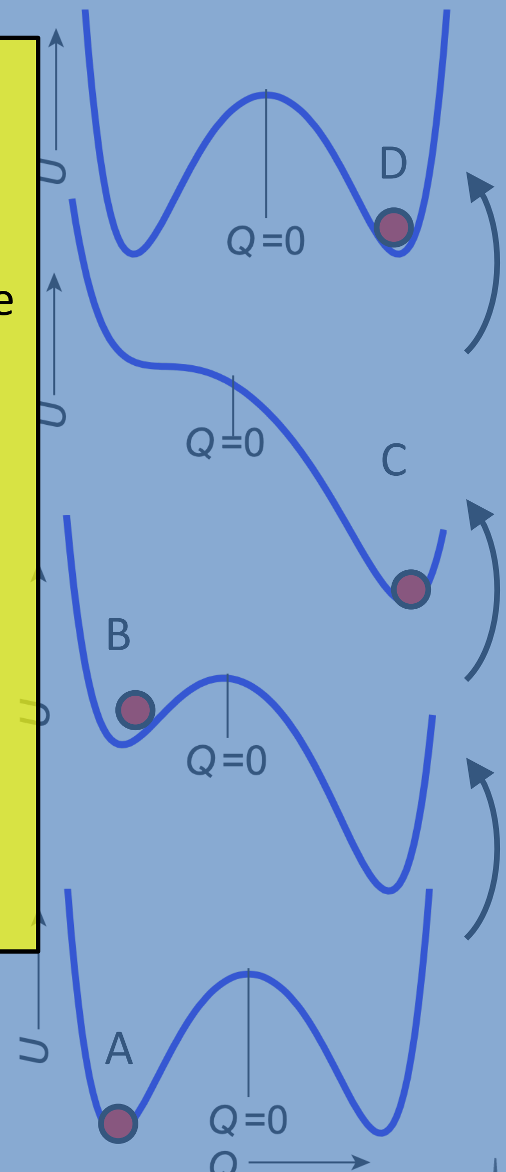
$PbTiO_3$ ($Pb^{2+}Ti^{4+}O_3^{6-}$)





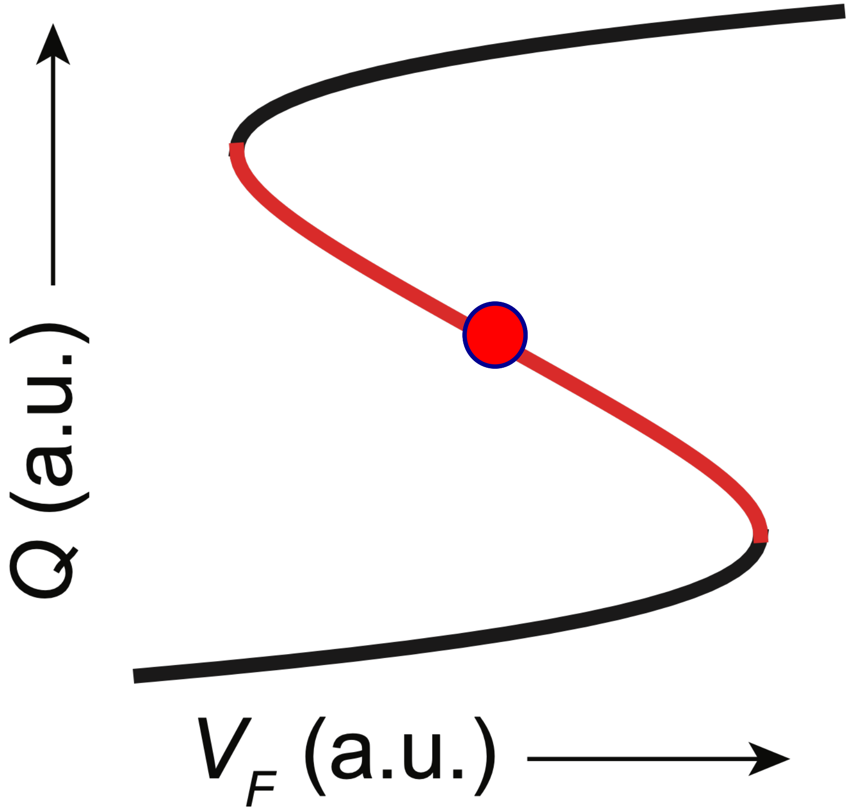
Charge Voltage Characteristics

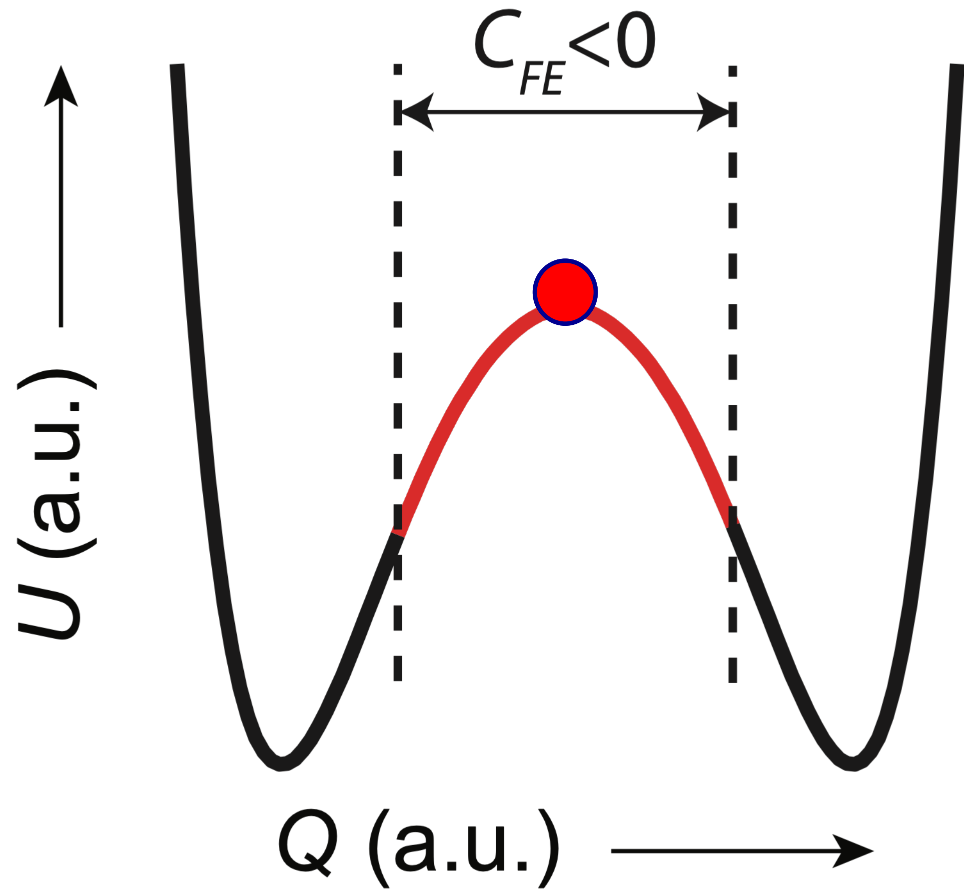




A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercivity voltage .

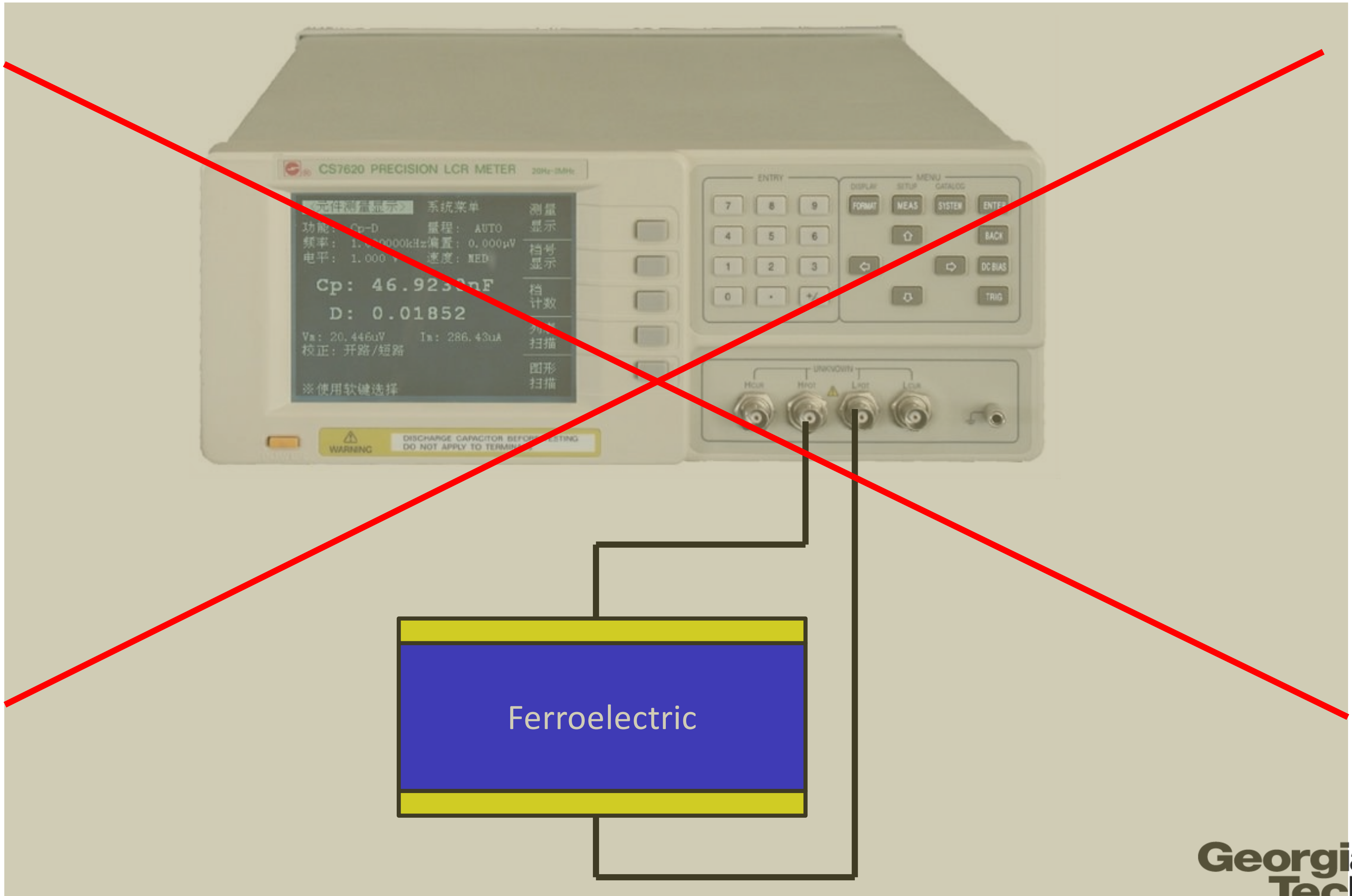
Why is it difficult to measure?



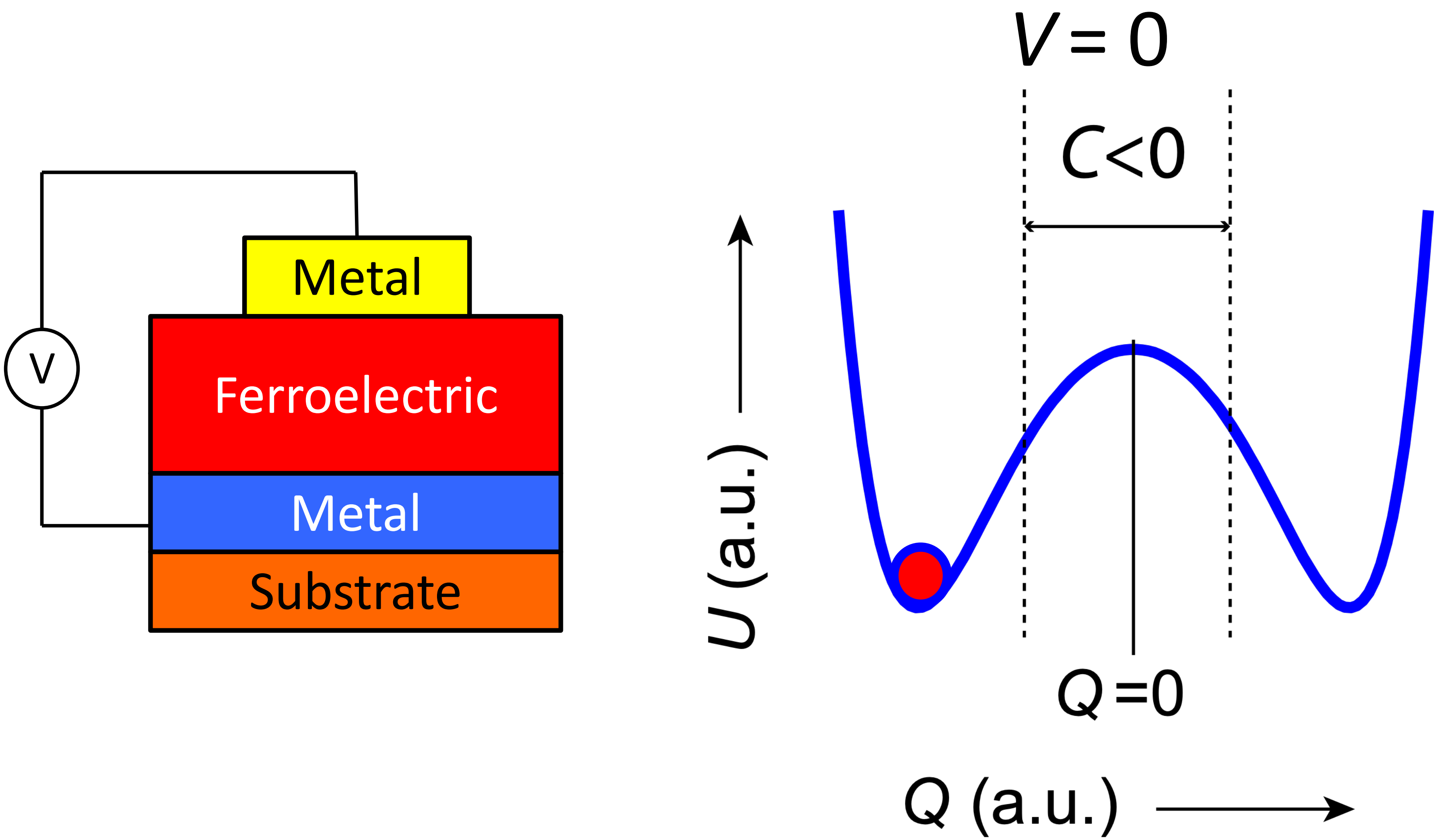


Ferroelectric Negative Capacitance is unstable and cannot be accessed in a time independent equilibrium measurement.

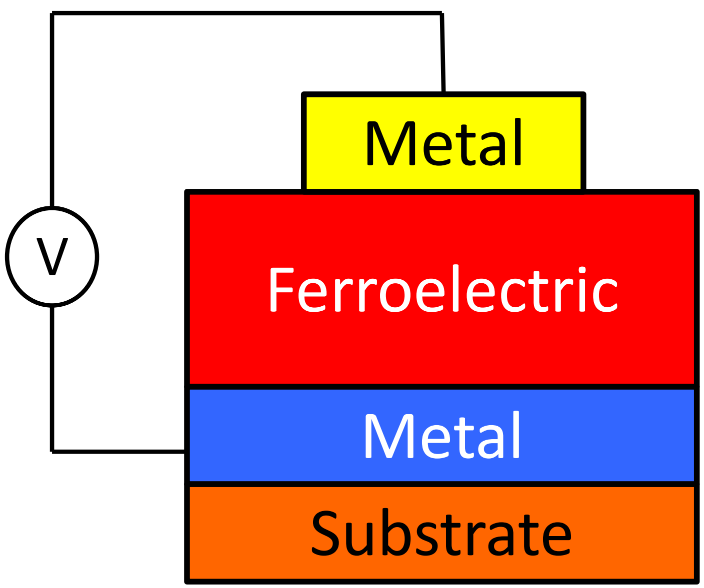
Why is it difficult to measure?



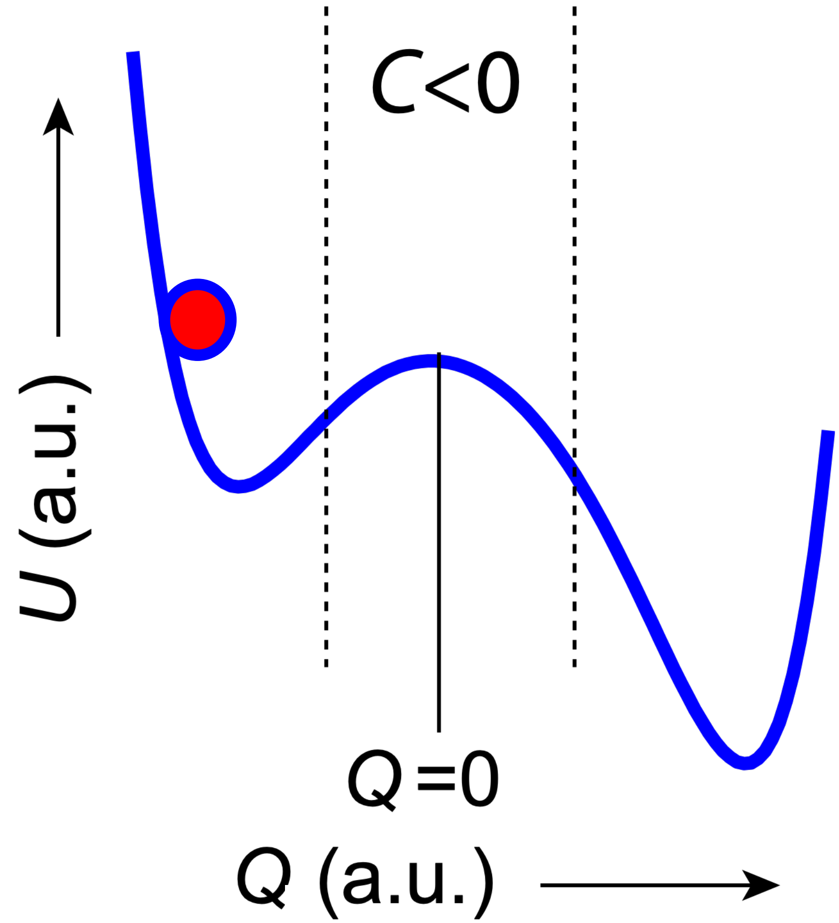
Direct Measurement of Negative Capacitance



Direct Measurement of Negative Capacitance



V < Coercive Voltage



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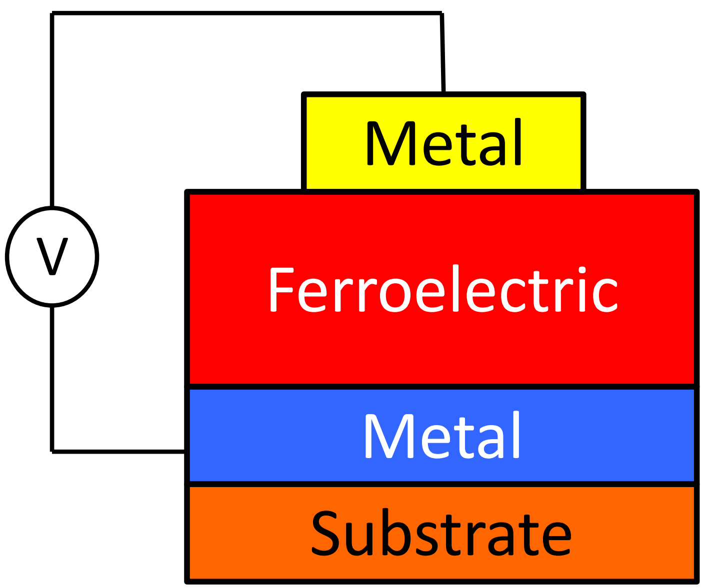
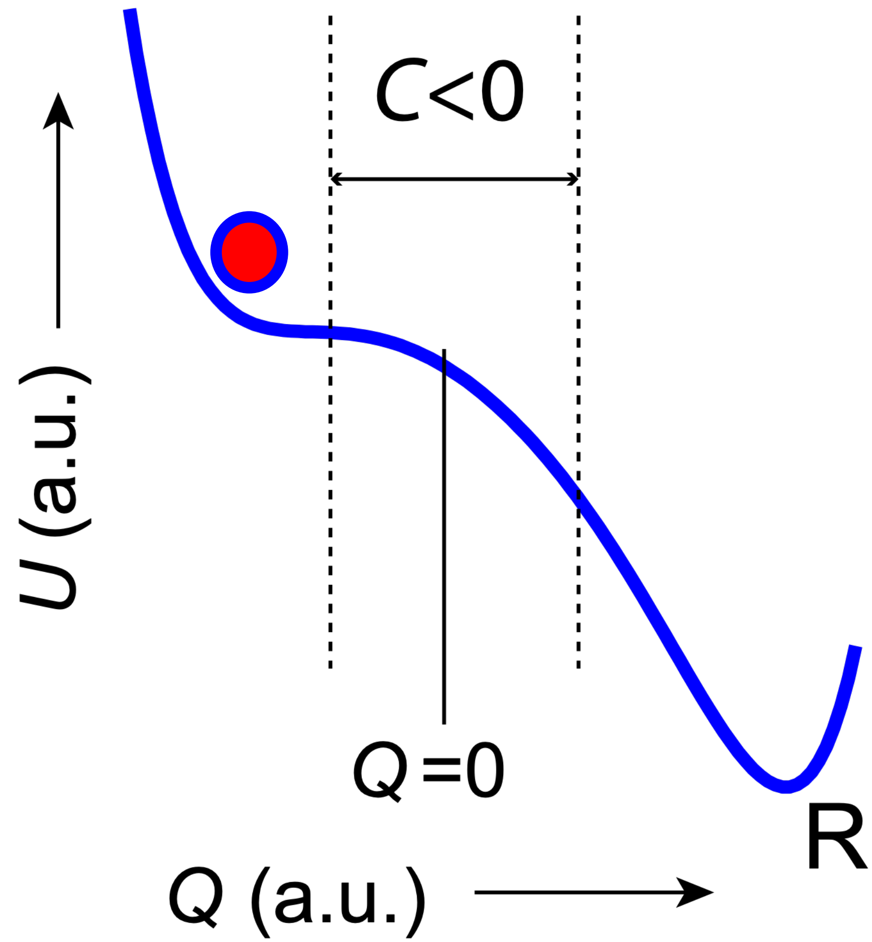
Direct Measurement of Negative Capacitance



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

V > Coercive Voltage



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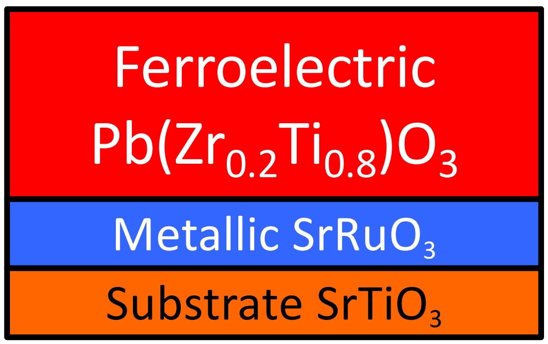
Growth of Ferroelectric Oxides

Experimental Heterostructure



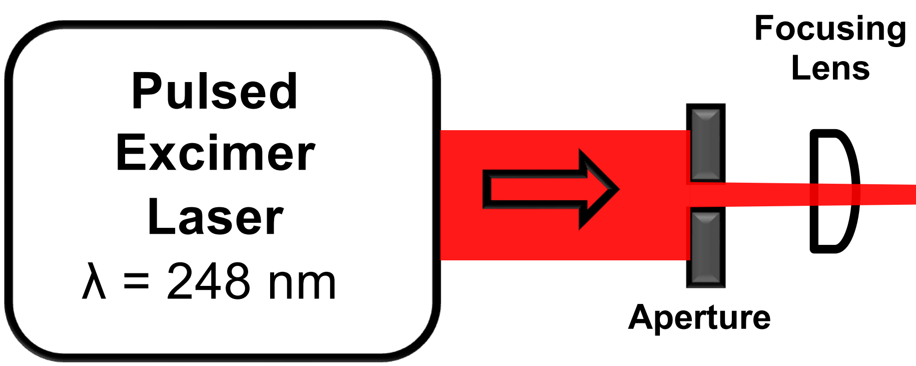
In-plane lattice parameter

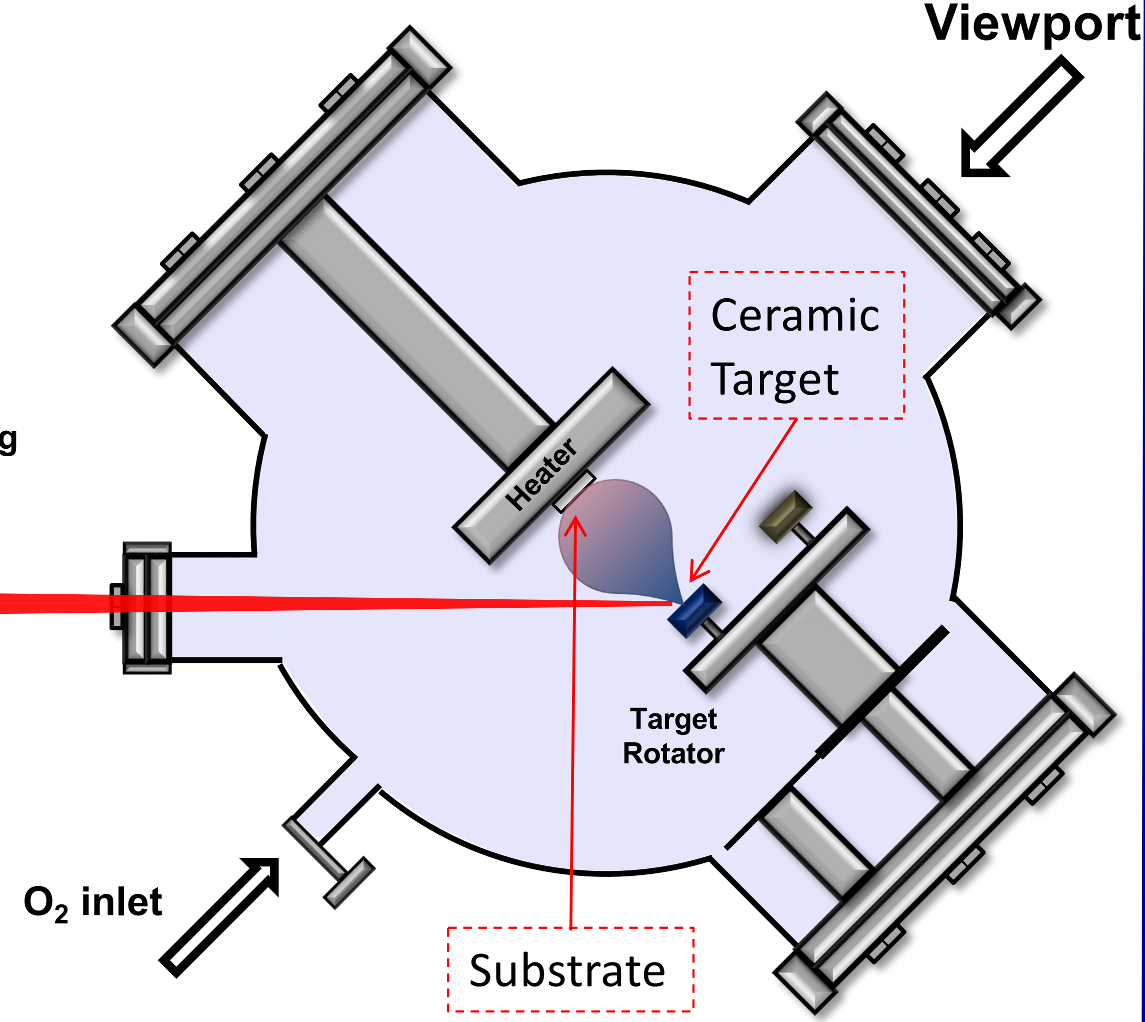
a_{PZT}=0.393 nm

a_{SRO}=0.394 nm

a_{STO}=0.3905 nm

Pulsed laser deposition technique





Typical Growth Conditions:

$SrRuO_3$: 720°C, 100 mTorr, 1.2 J/cm^2, 5-15 Hz

$Pb(Zr_{0.2}Ti_{0.8})O_3$: 630 °C, 100 mTorr, 1-1.5 J/cm^2, 5-15 Hz

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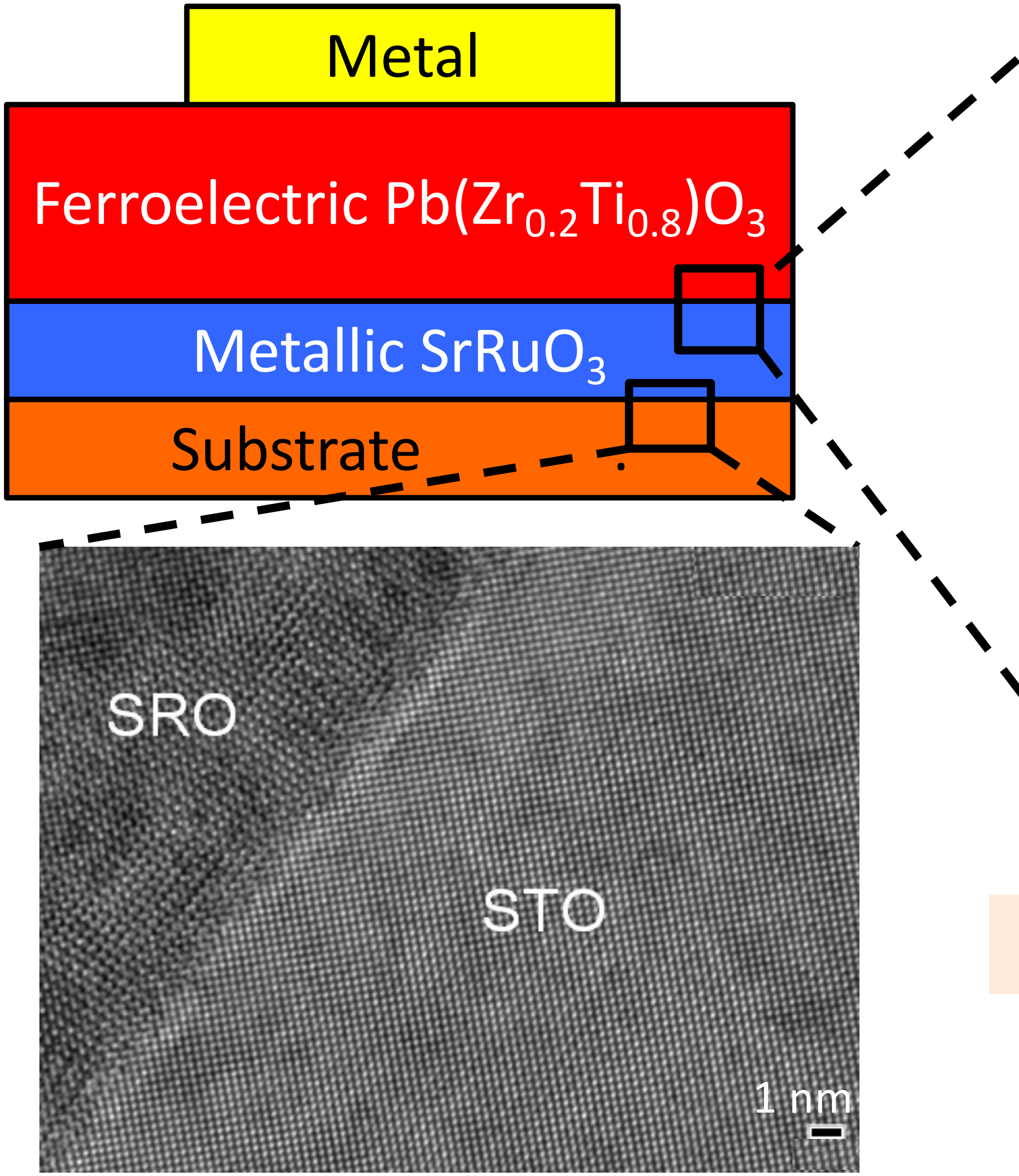
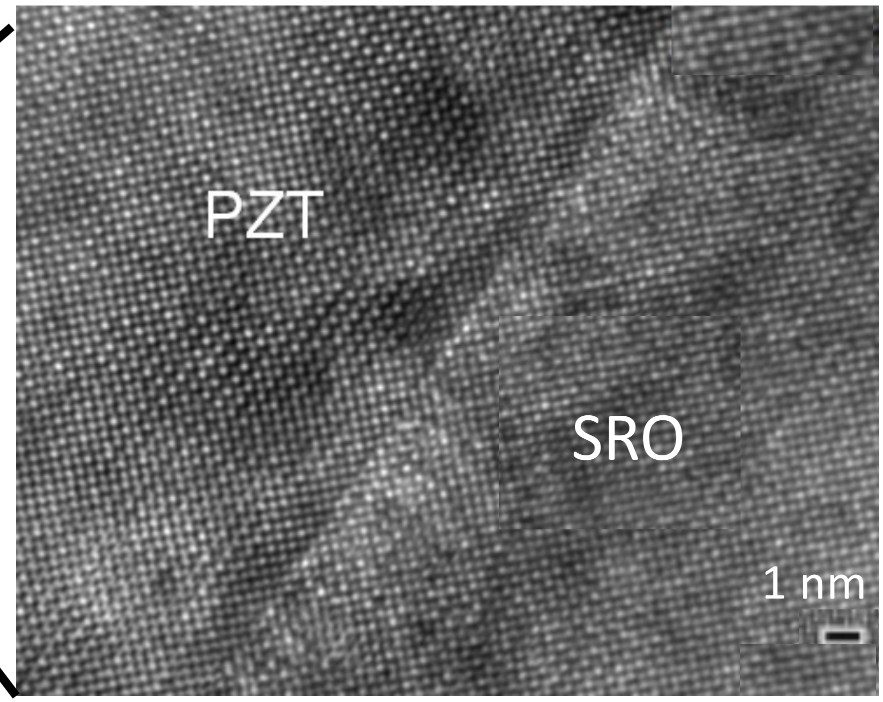
Ferroelectric $Pb(Zr_{0.2}Ti_{0.8})O_3$





Courtesy: Pan group, U. Mich.

Excellent epitaxial quality!

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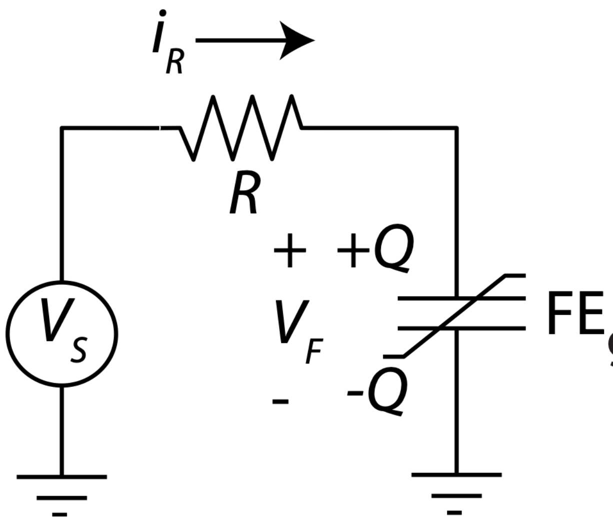
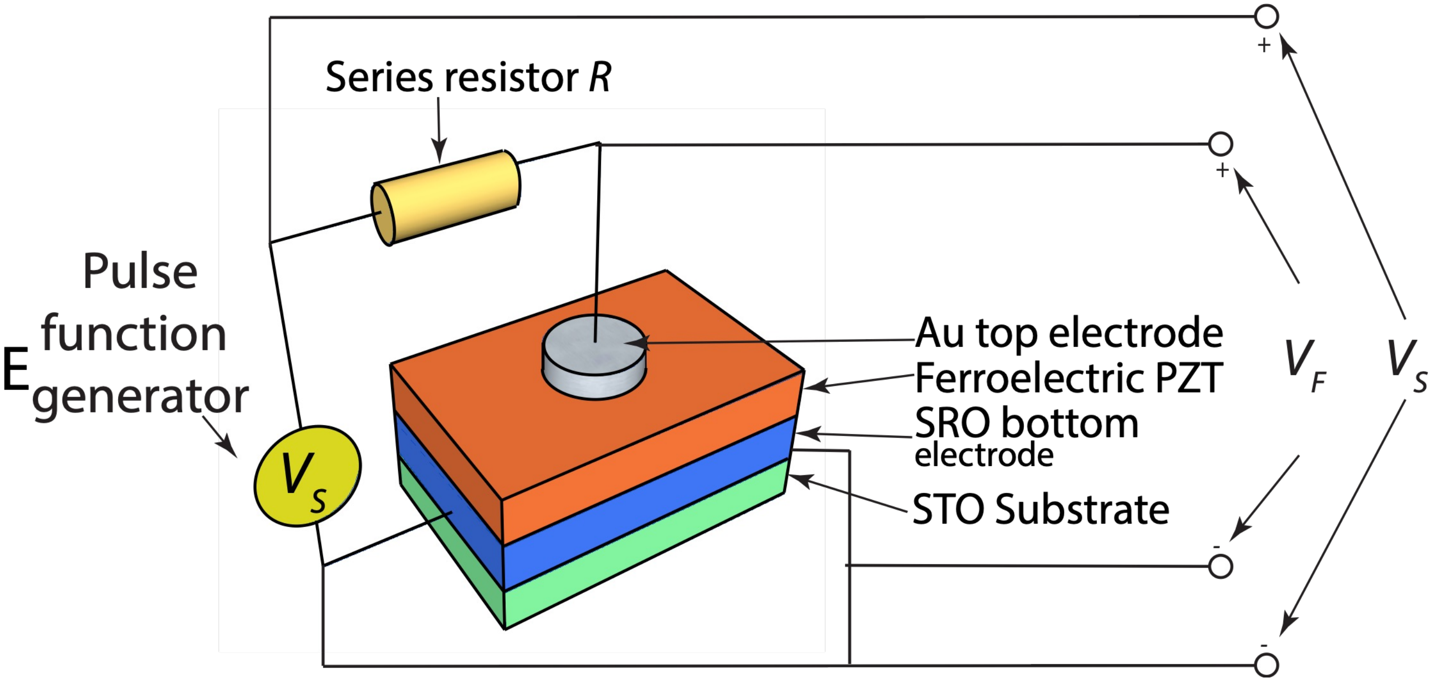
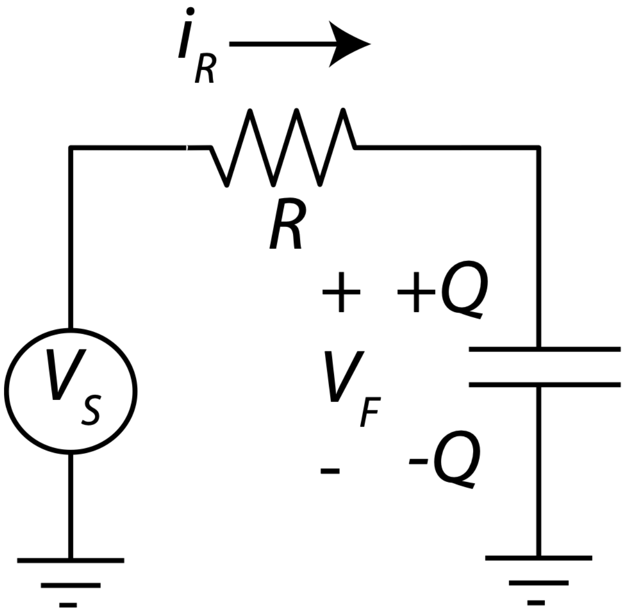
Direct Measurement of Negative Capacitance





A ferroelectric capacitor connected in series with an external resistor.

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

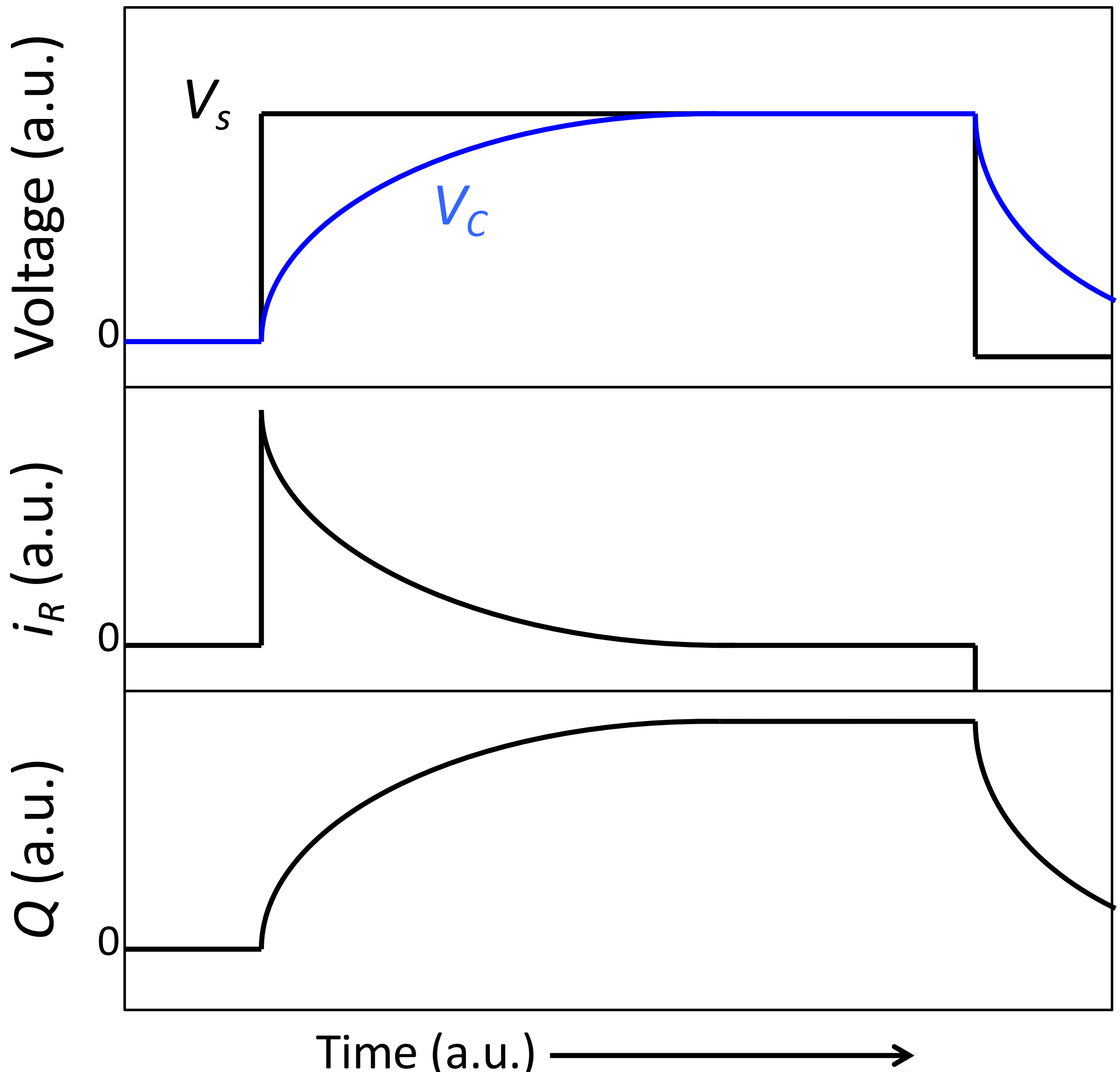


Voltage: $V_C = V_S(1 - e^{-t/RC})$

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

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

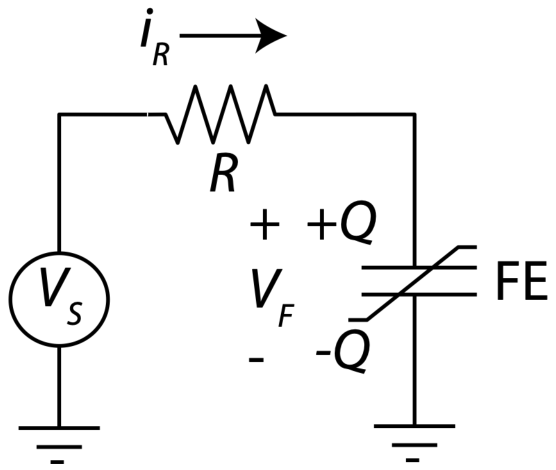
At any time t,
$dQ/dV_C = C > 0$.

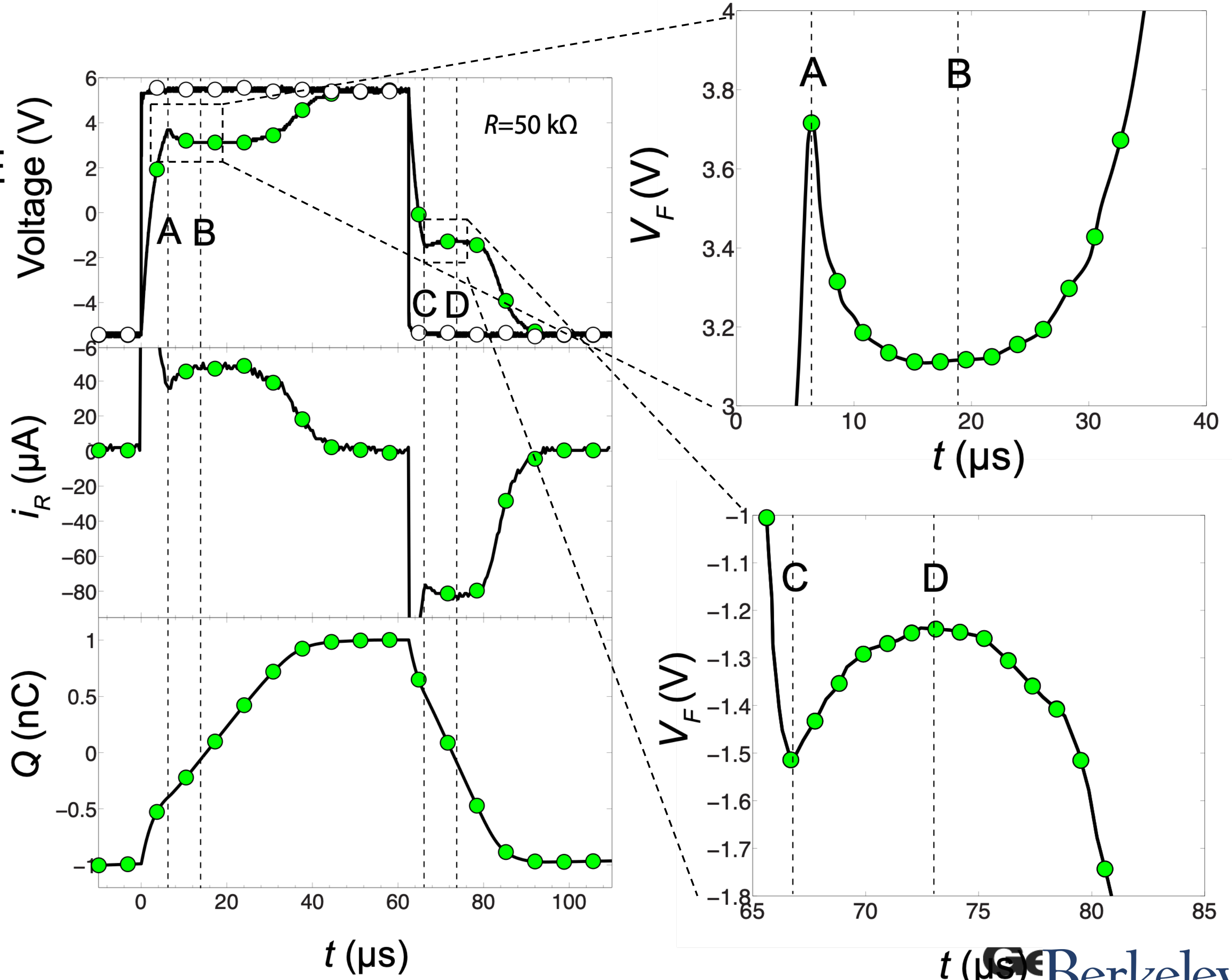


Direct Measurement of Negative Capacitance

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

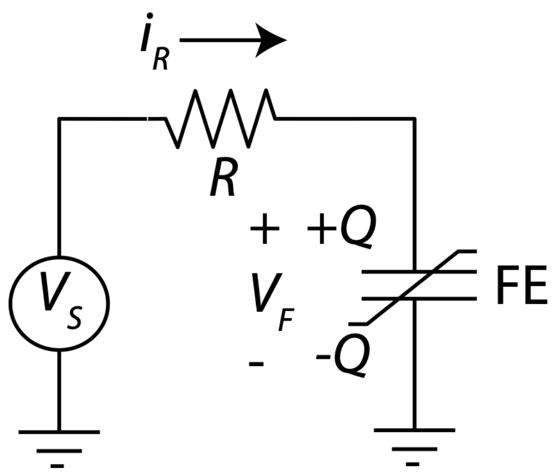




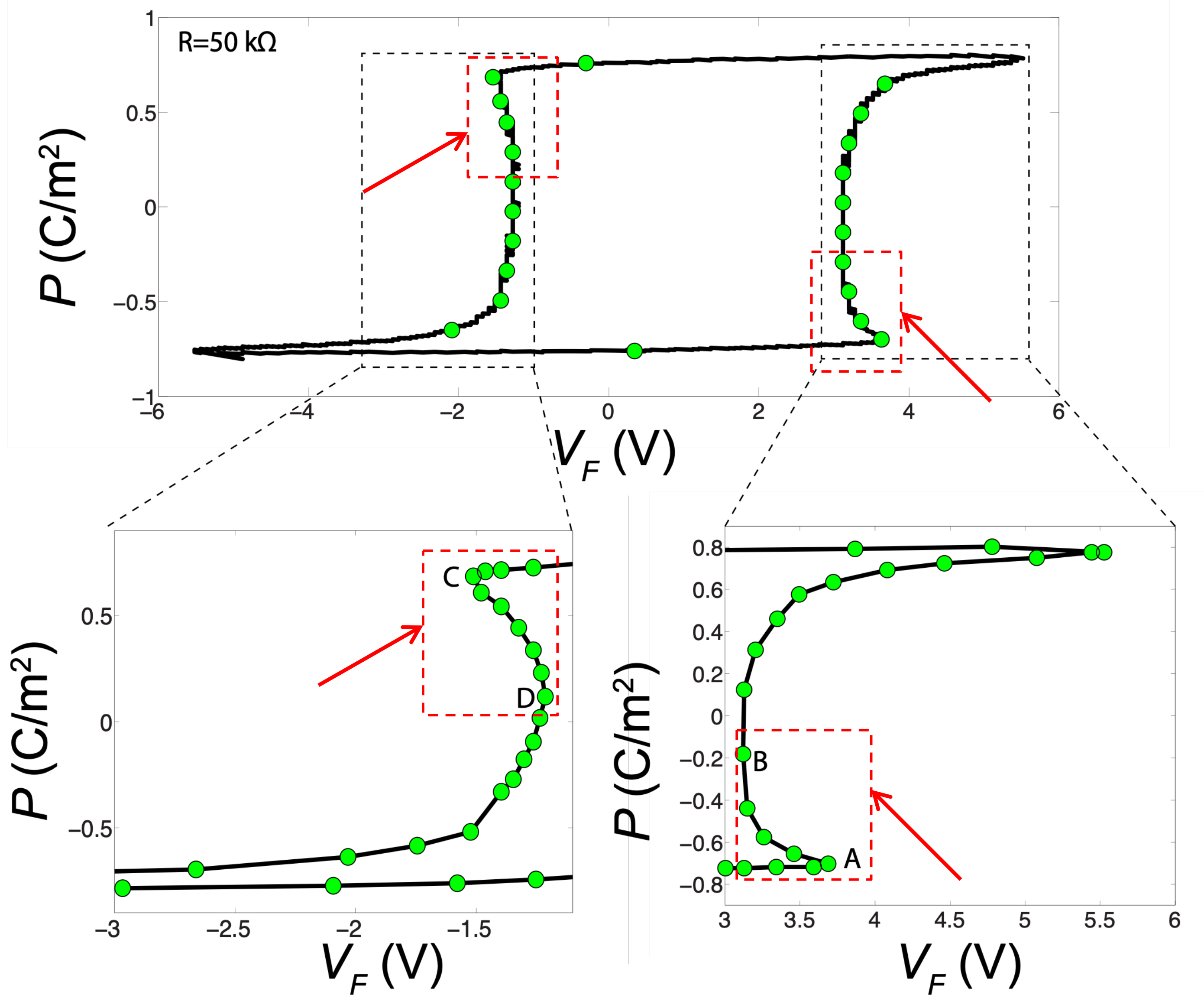
During AB & CD, dQ & dV_F has opposite signs indicating $dQ/dV_F<0$.

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

Direct Measurement of Negative Capacitance



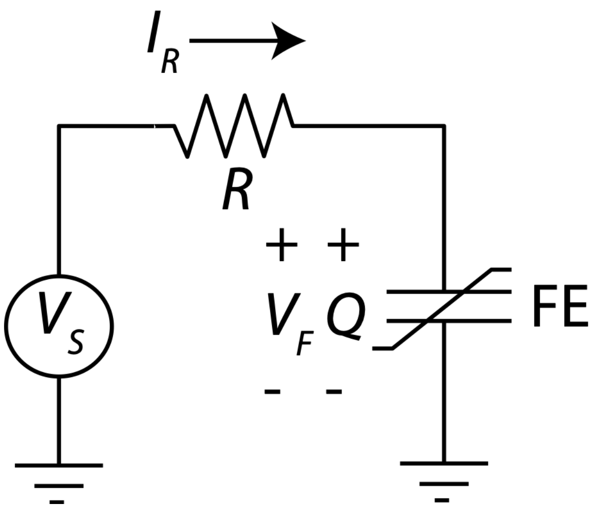
60 nm $Pb(Zr_{0.2}Ti_{0.8})O_3$) (Coercive voltage=~2.5 V)



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

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

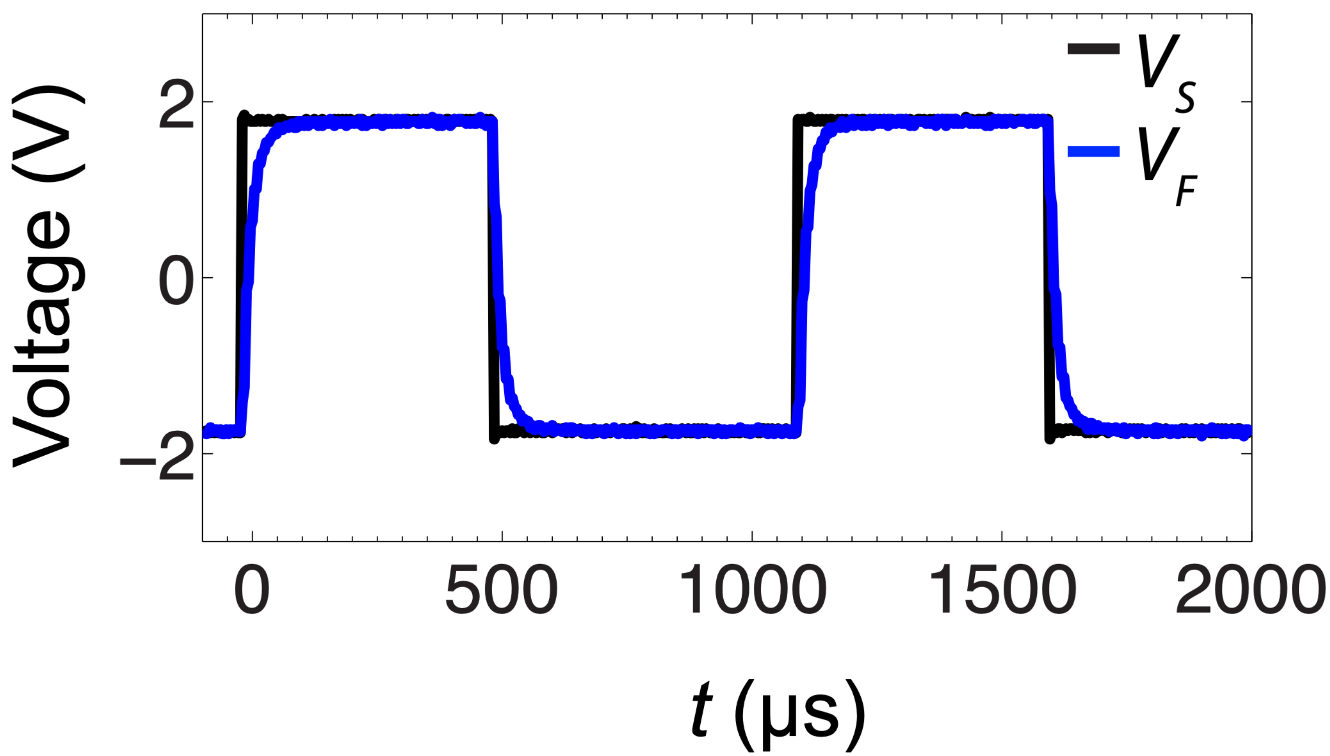
Correlation with ferroelectric switching



No negative capacitance transients are observed when the voltage is smaller than coercive voltage.

Coercive Voltage (~2.5 V)

V_S: -1.8 V→+1.8 V → -1.8 V → +1.8 V



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

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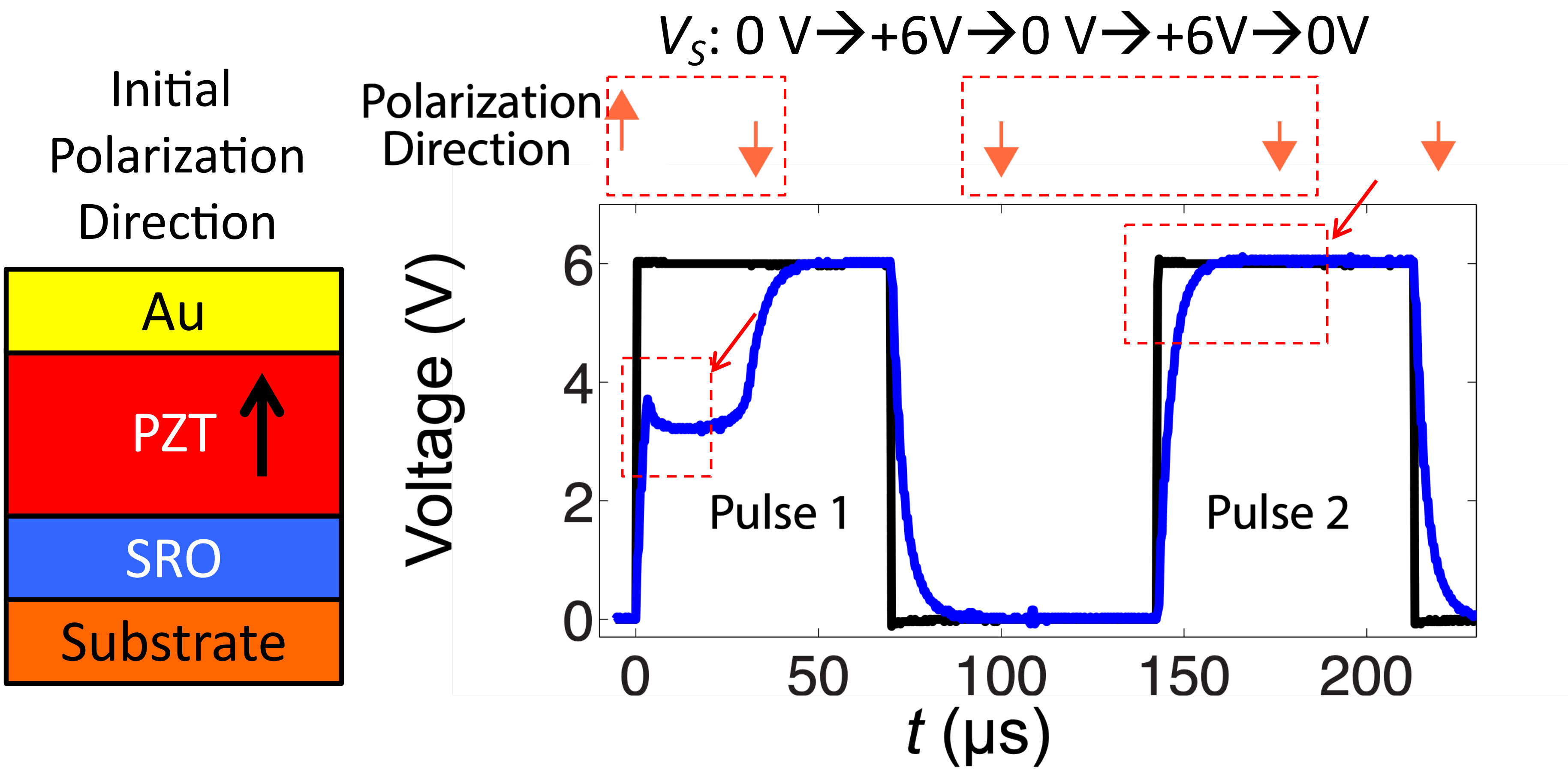
Correlation with ferroelectric switching



No negative capacitance transients are observed when there is no FE switching event.

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

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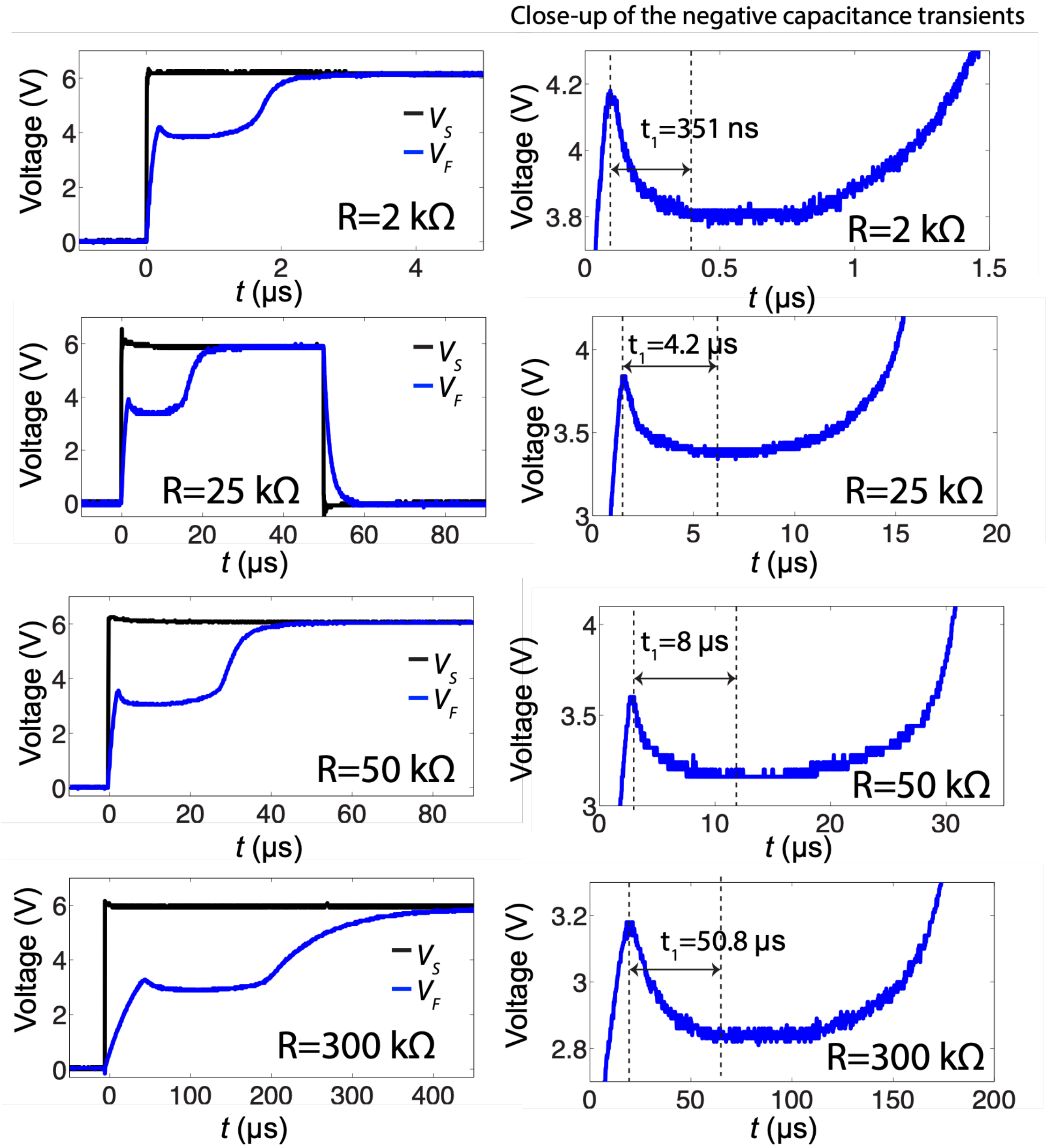
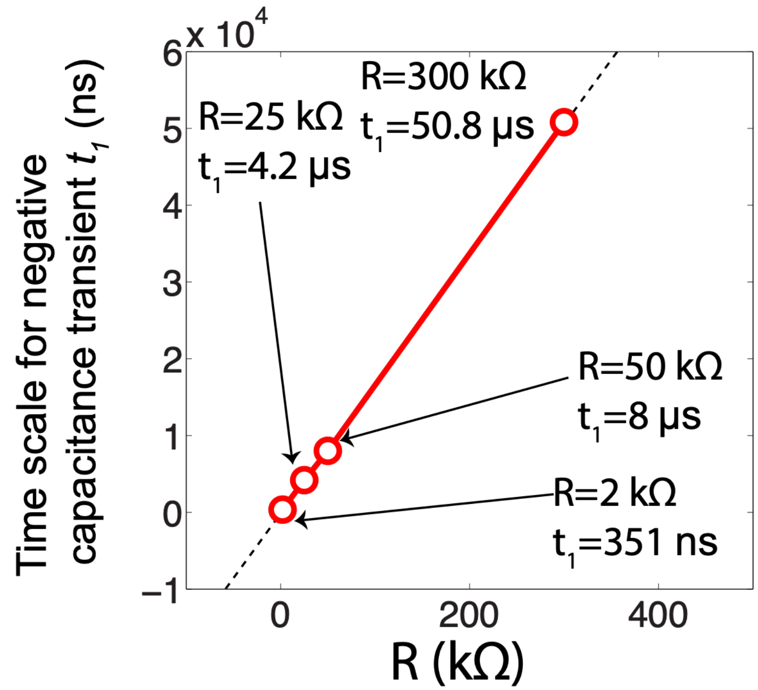
Time scale of transients





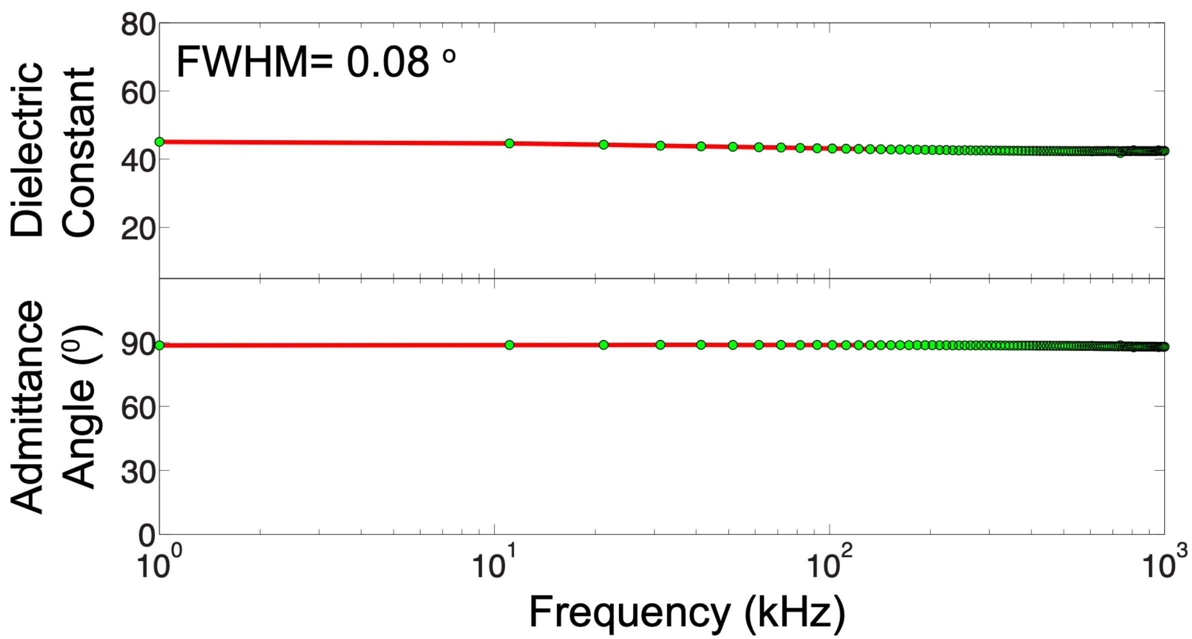
The intrinsic time scale of negative capacitance transient could be very small.

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

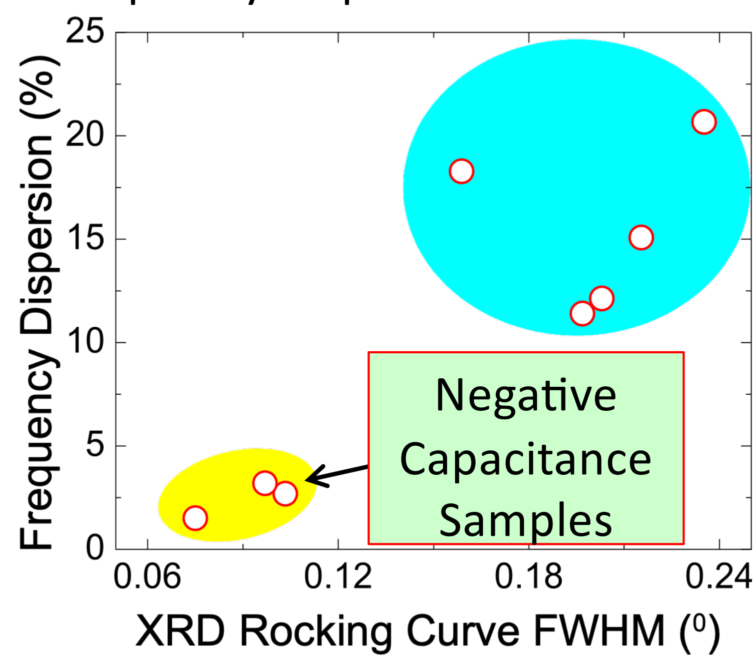
Correlation with Structural Properties

Negative capacitance effect is correlated to the structural quality of the thin film.

Dielectric Frequency Dispersion



Frequency Dispersion vs. FWHM



Frequency Dispersion between 1 kHz and 1 MHz < 2 %

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

Khan et al. Appl. Phys. Lett. 104, 262407 (2014)

High quality materials growth is the key!

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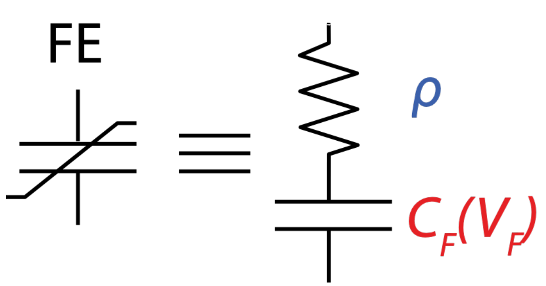
Landau-Khalatnikov model

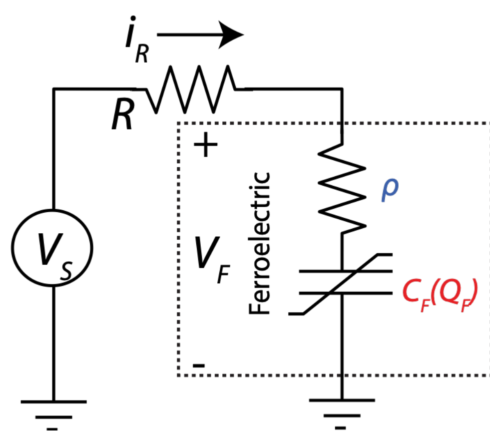
Landau-Khalatnikov Equation: $$\rho \frac{dP}{dt} = -\frac{dU}{dP}$$

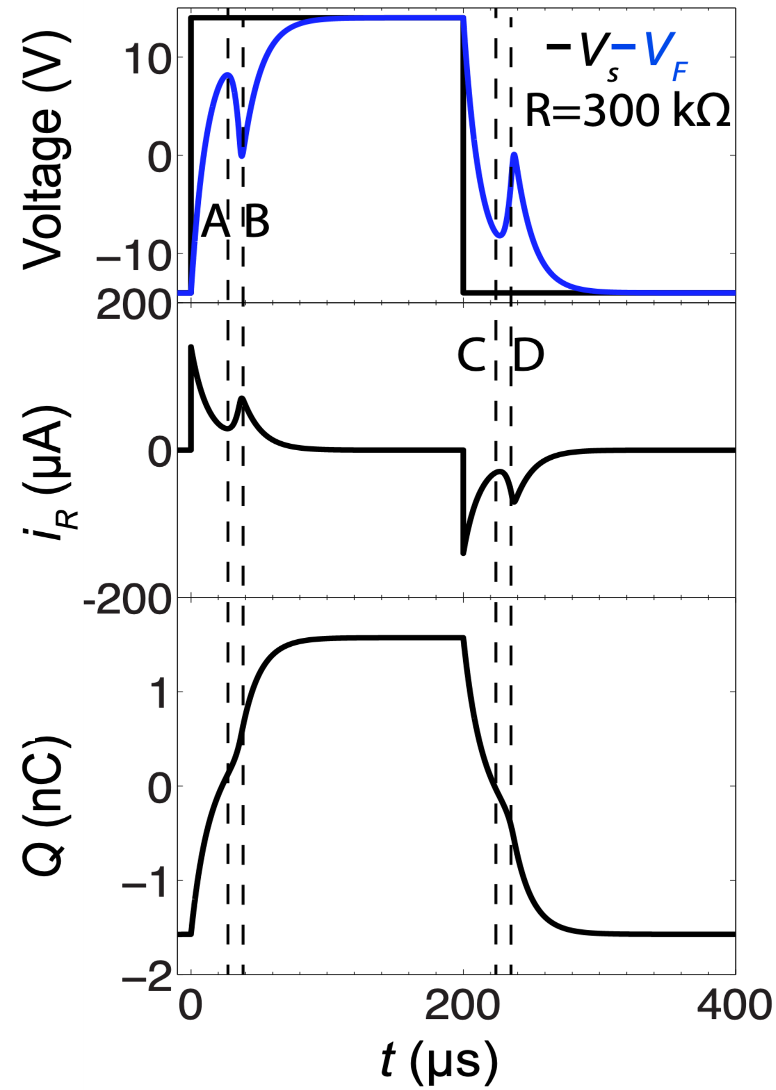
P=Ferroelectric polarization
U=Free energy of the system
ρ= Material dependent parameter

Equivalent Circuit



Simulated Circuit





Qualitative match between simulated and experimental transients.

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

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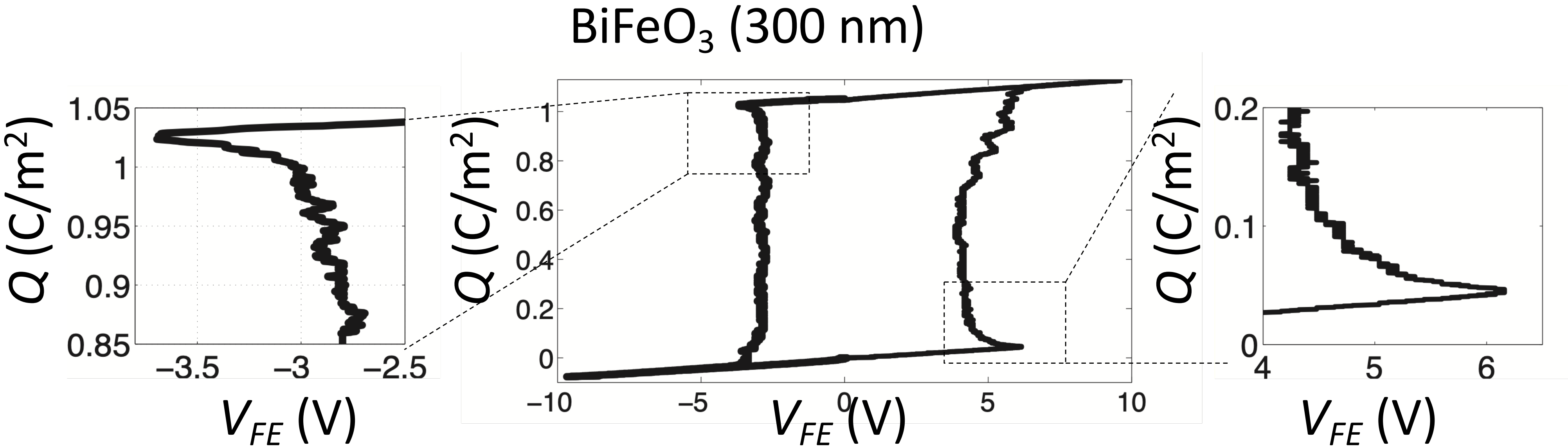
Negative Capacitance in Ferroelectrics

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

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

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)

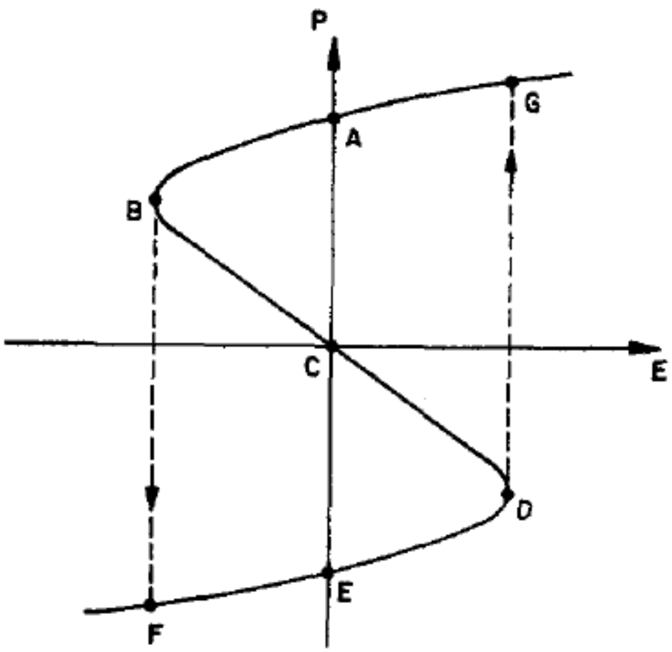


FIG. 1. Plot of polarization against field, at room temperature, as given by Devonshire's theory. P = polarization, E = field. Direction of field and polarization are taken to be the same, and parallel to the "c" axis of a single domain crystal. The solid line $GABCDEF$ gives the theoretical relationship.

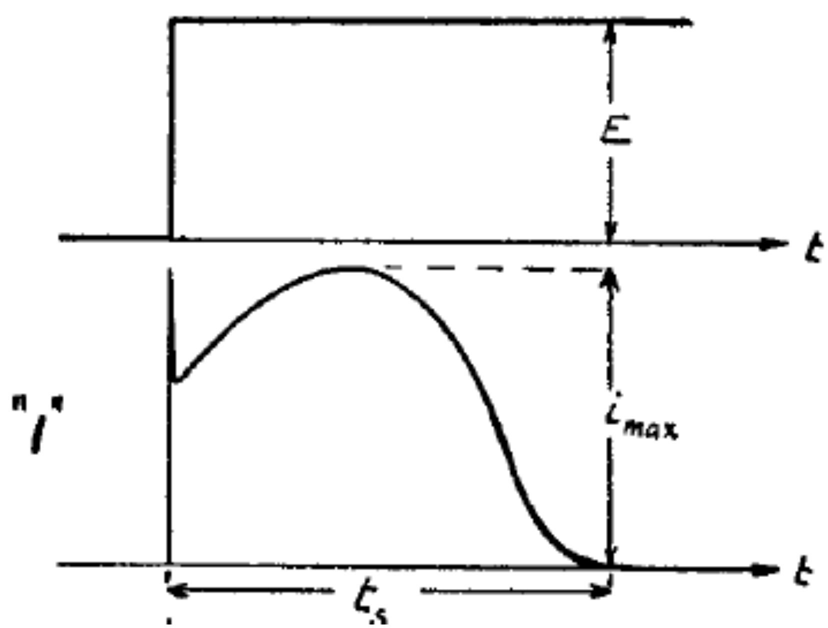


FIG. 1. Pulsing field and pulsing current *versus* time.

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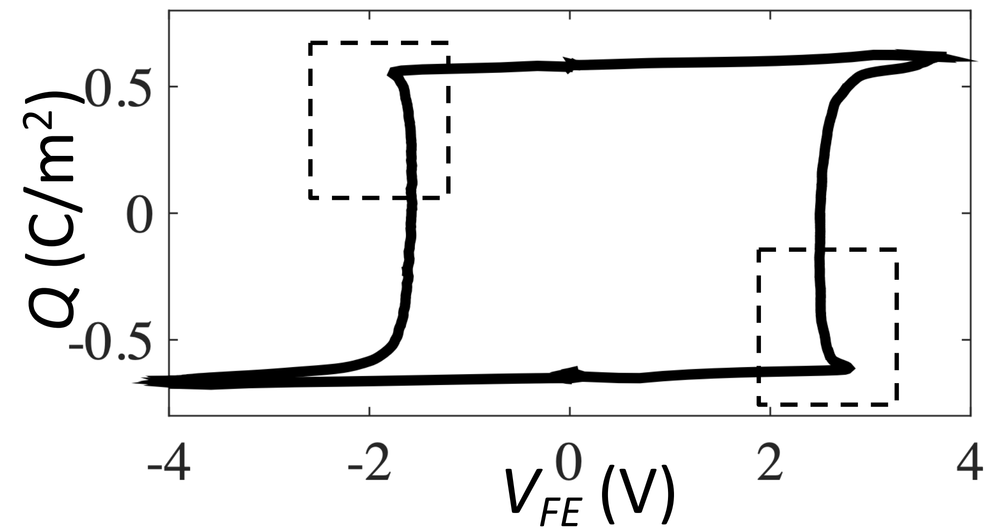
What's next?

Now that negative capacitance has been detected…



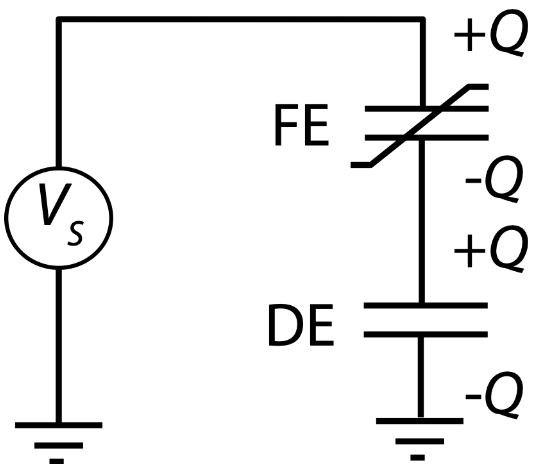
1. Can we stabilize negative capacitance in a ferroelectric?

2. Can we see capacitance enhancement and voltage amplification?

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

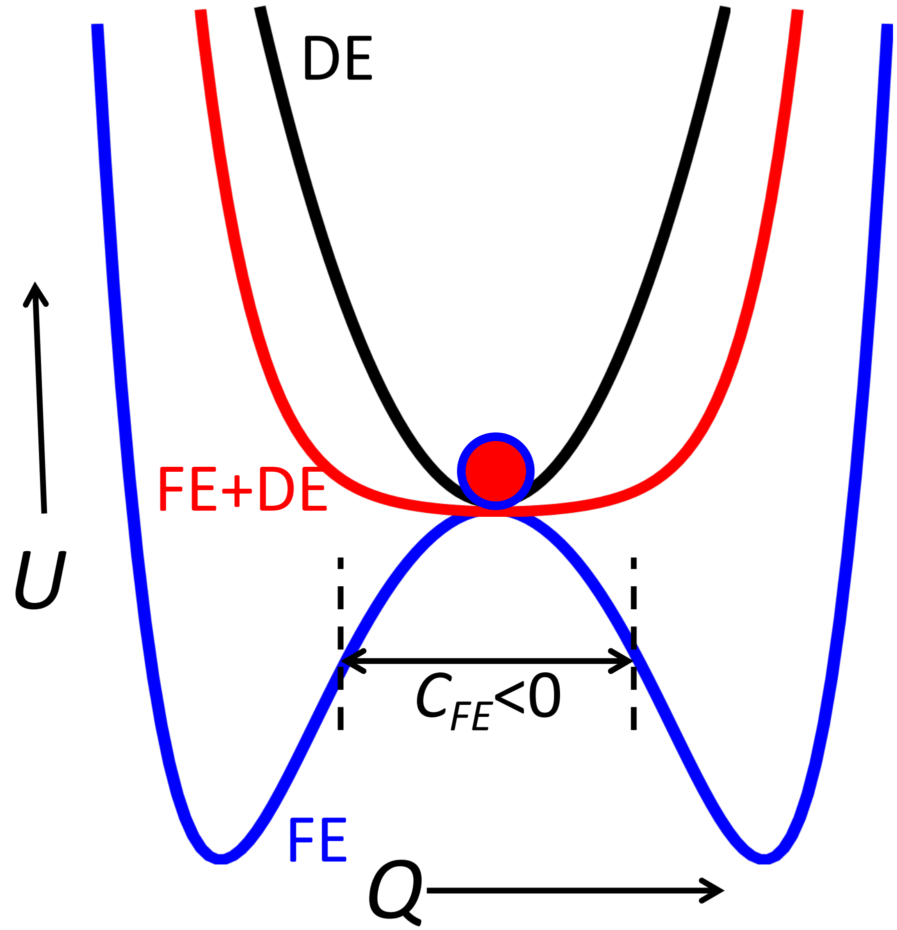
Stabilization of Negative Capacitance

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!

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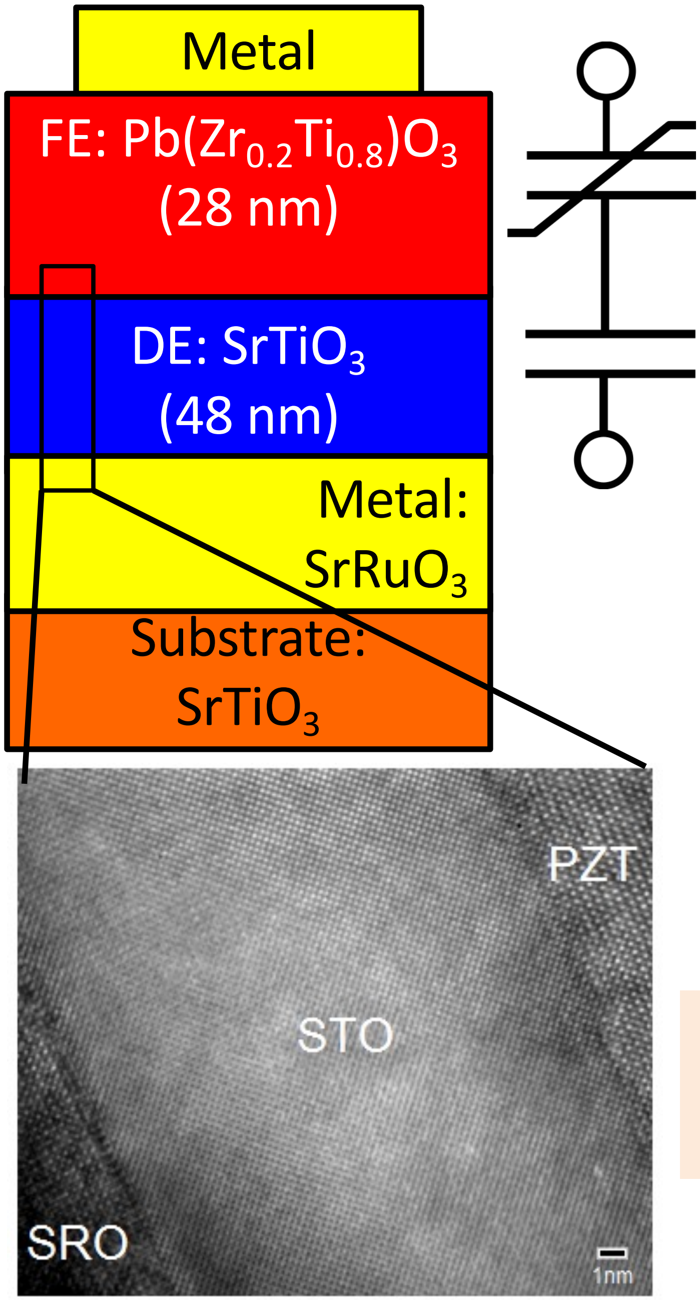
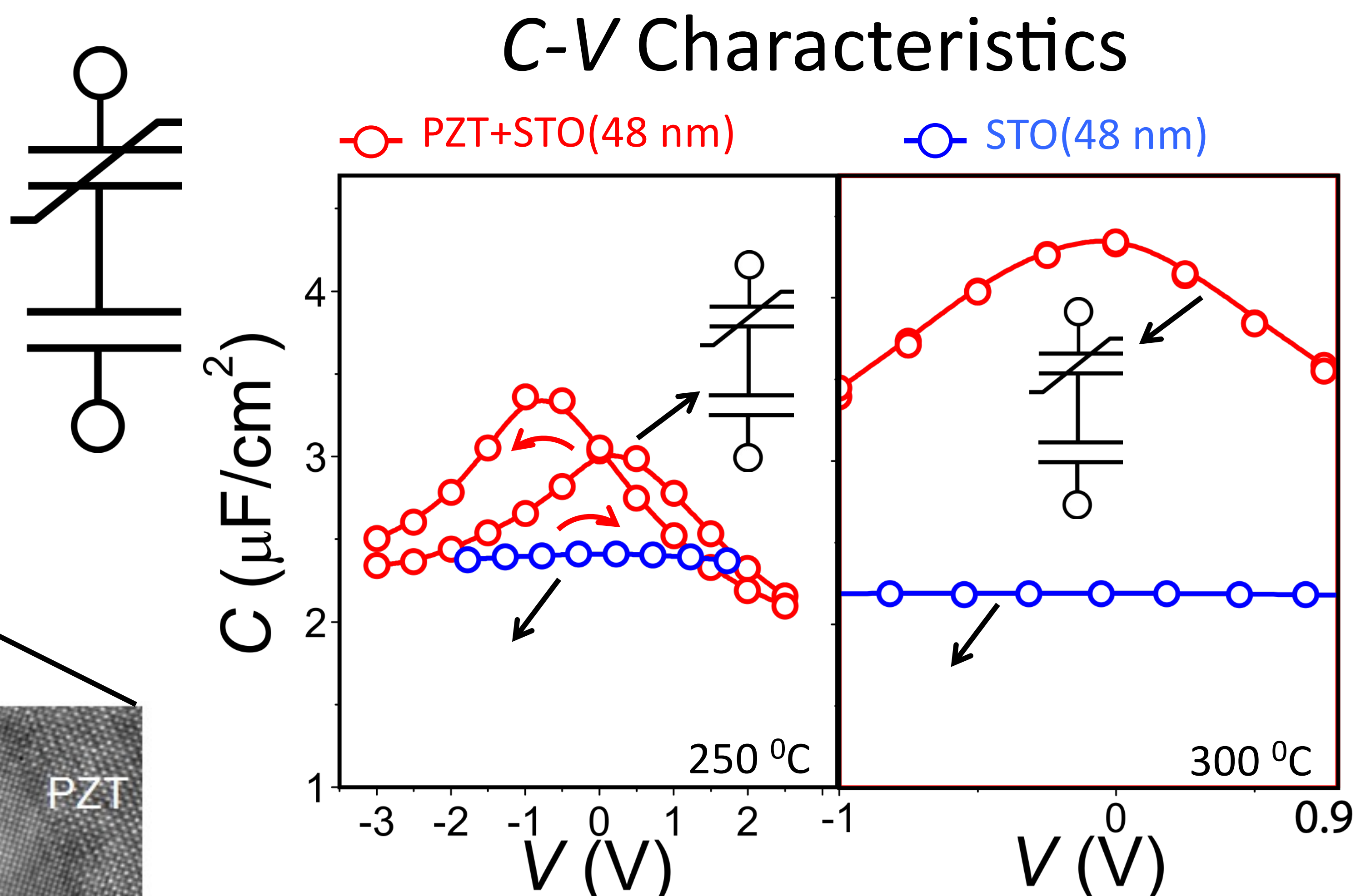
Stabilization of Negative Capacitance





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, Editor's choice)
Gao, Khan et al. Nano Lett. 14, 5814 (2014)

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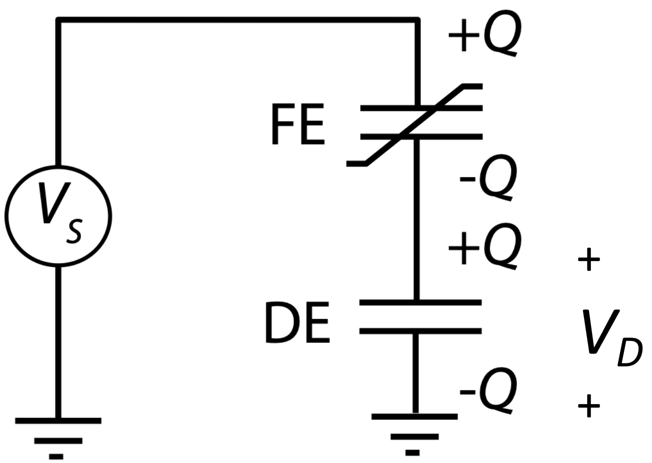
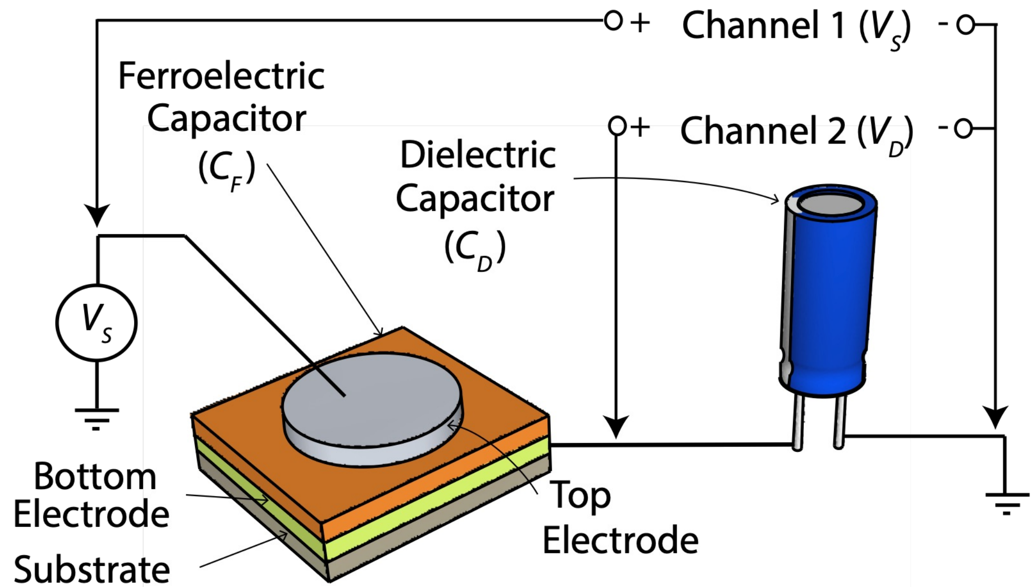
Voltage Amplification in a FE+DE System





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

If $|C_F| > C_D$, $\boxed{\dfrac{dV_D}{dV_S} > 1}$

Voltage amplification can be possible in passive ferroelectric networks!

Khan, Hoffmann et al. (under review)

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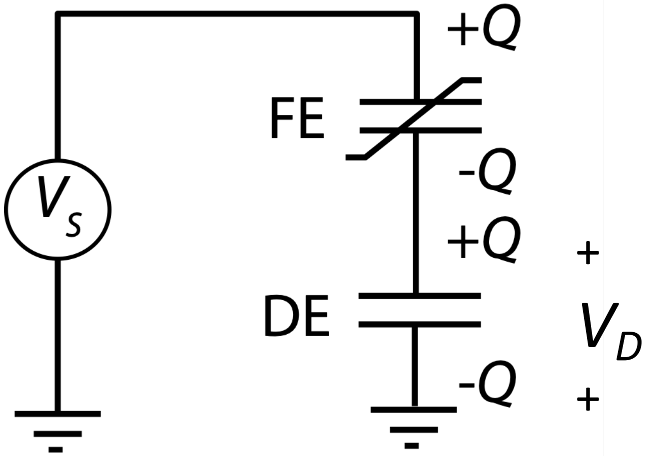
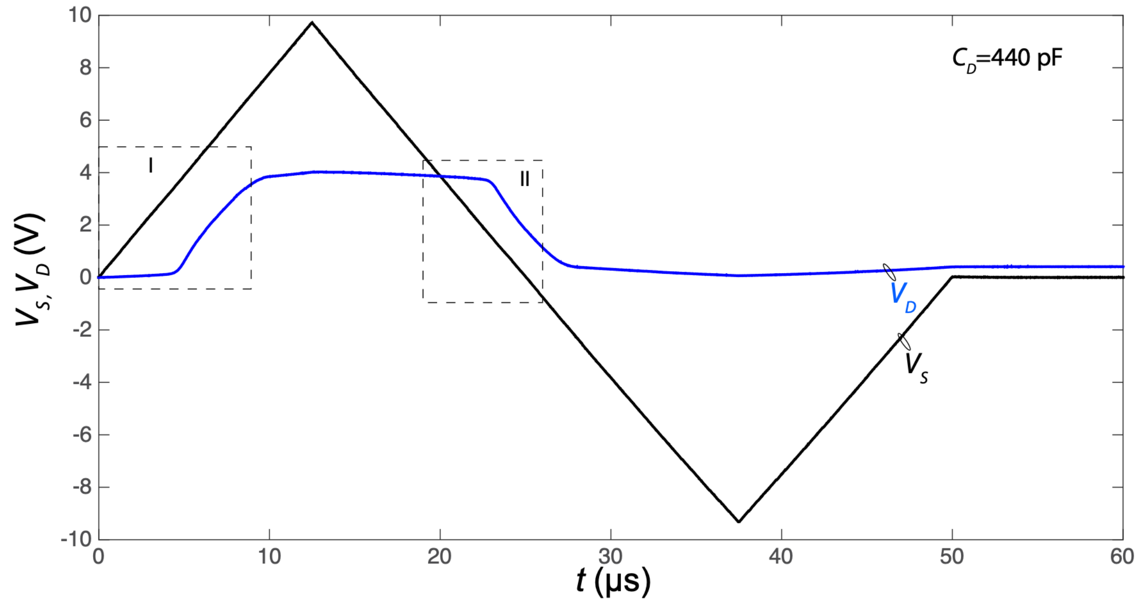
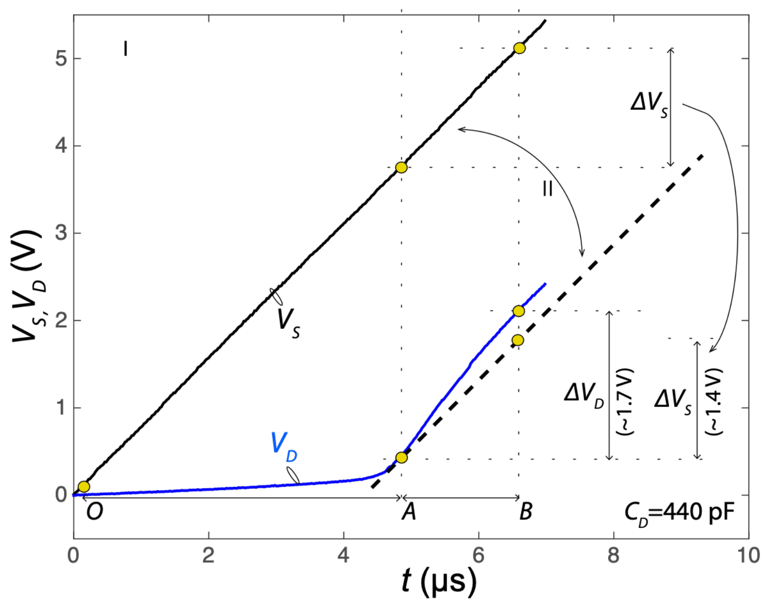
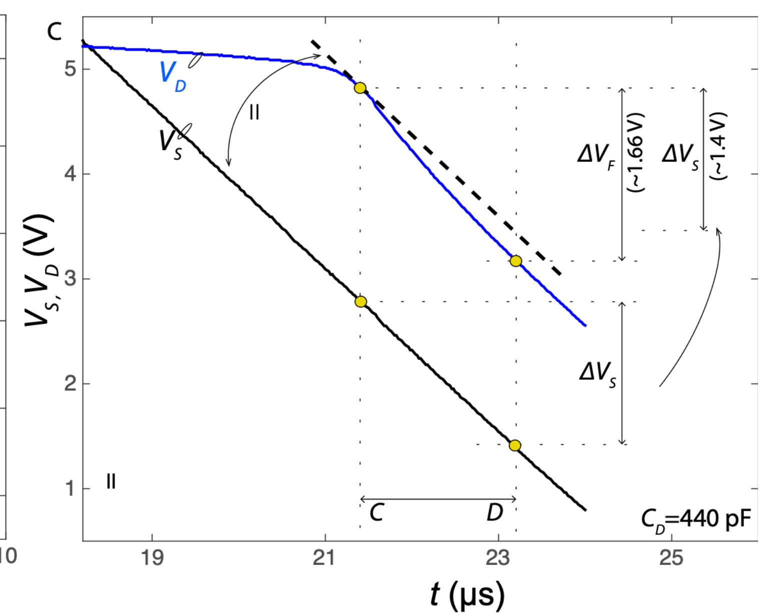
Ferroelectric+Dielectric Capacitor



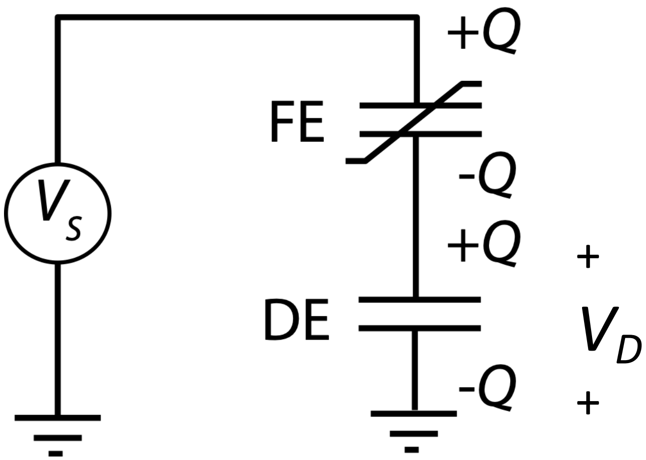




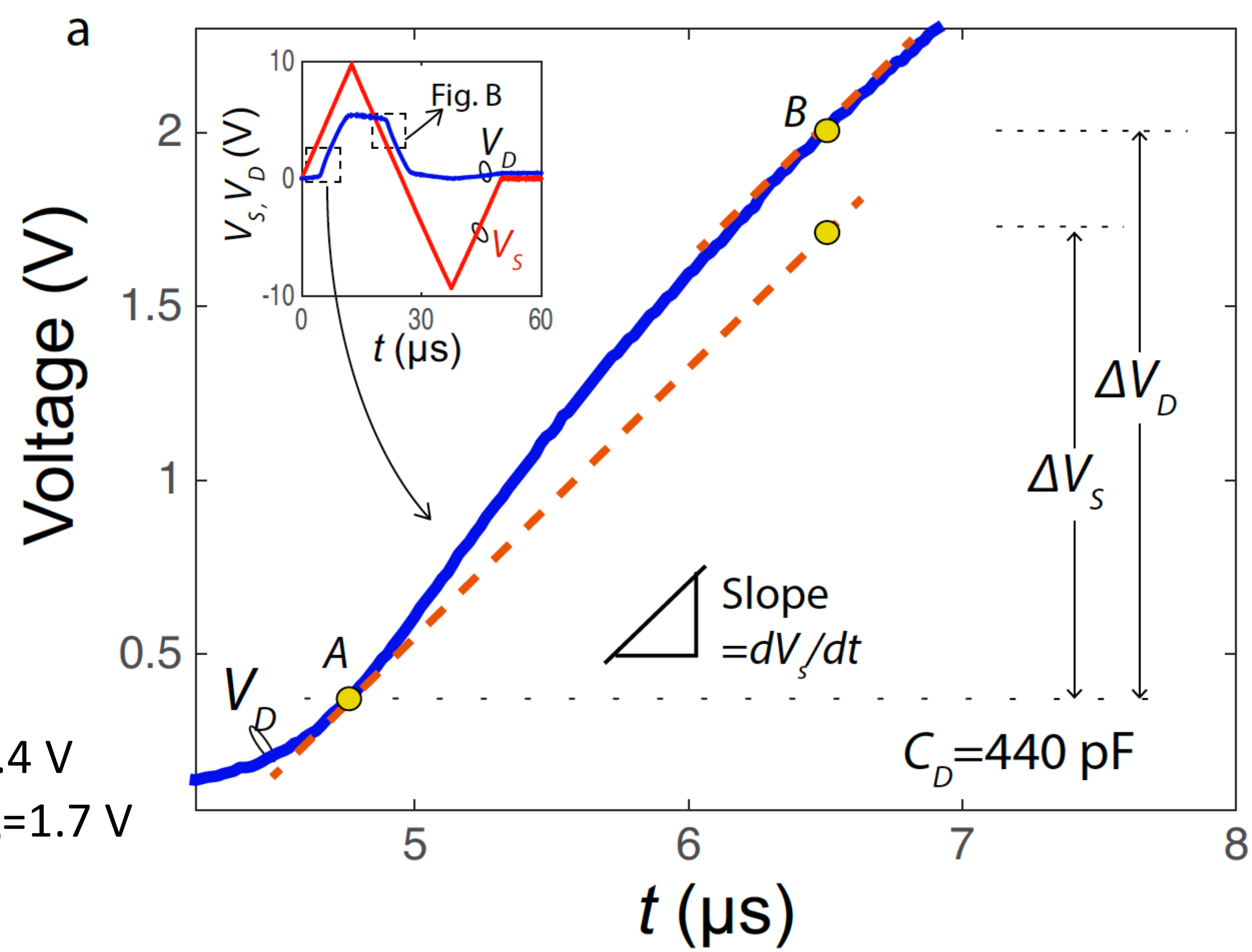


Khan, Hoffmann et al. (under review)

Ferroelectric+Dielectric Capacitor



Khan, Hoffmann et al. (under review)



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!

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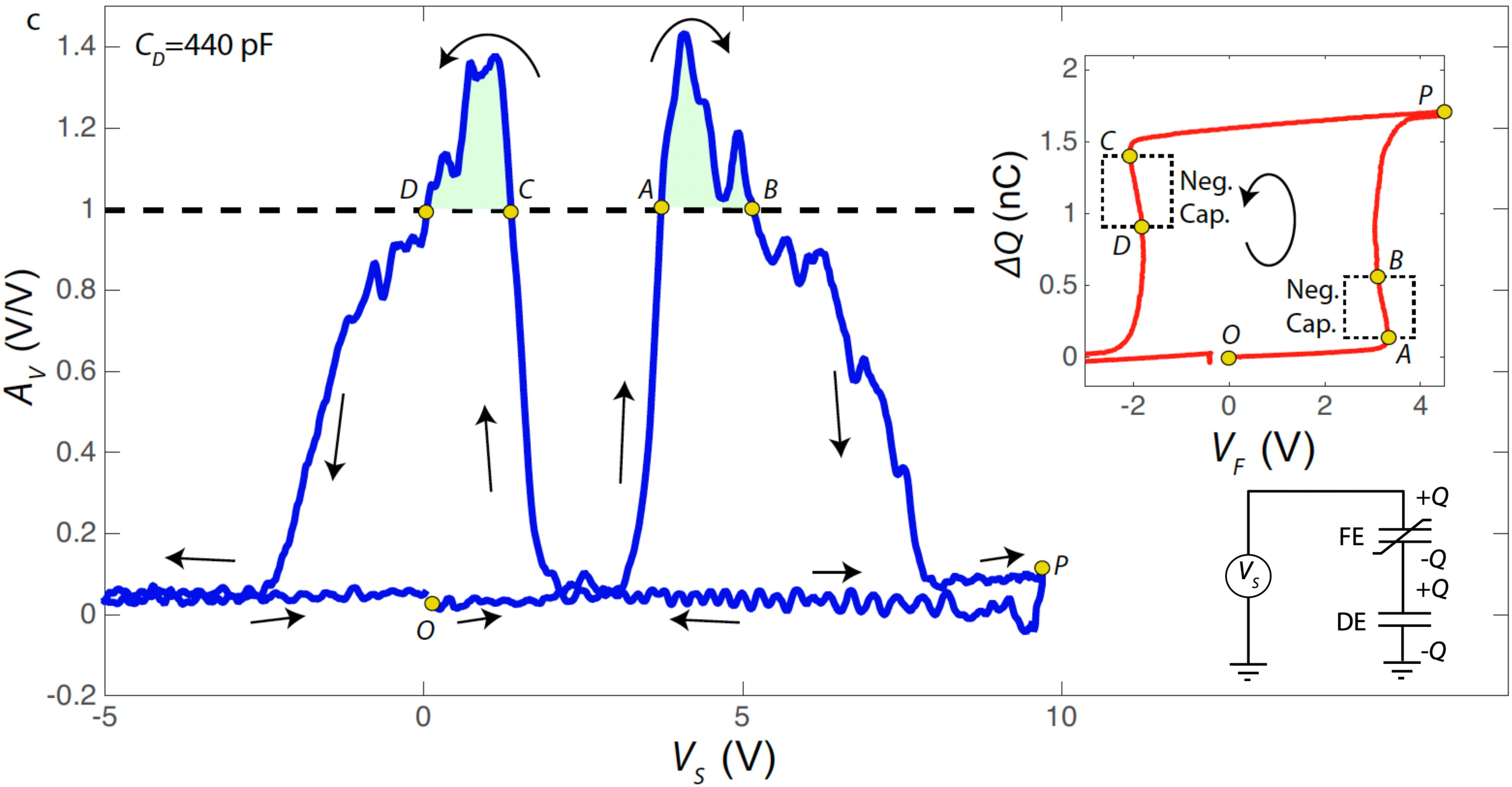
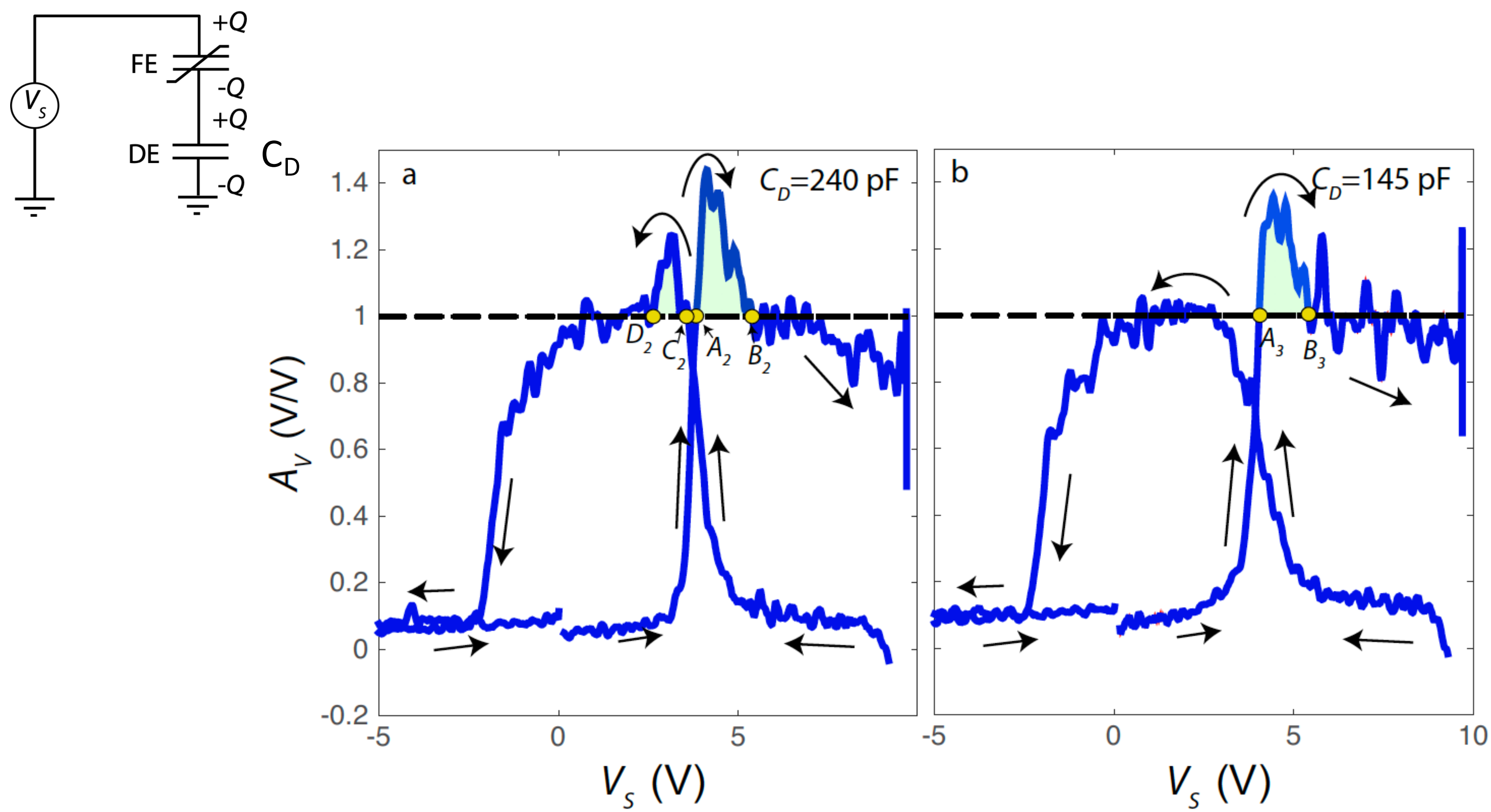
Ferroelectric+Dielectric Capacitor



Khan, Hoffmann et al. (under review)

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

Ferroelectric+Dielectric Capacitor



Khan, Hoffmann et al. (under review)

Voltage amplification reduces in negative voltage sweeps with the reduction of C_D!

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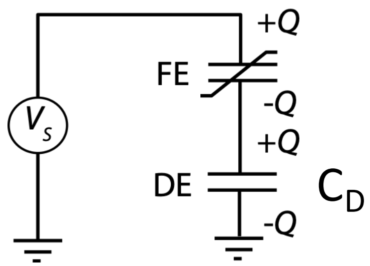
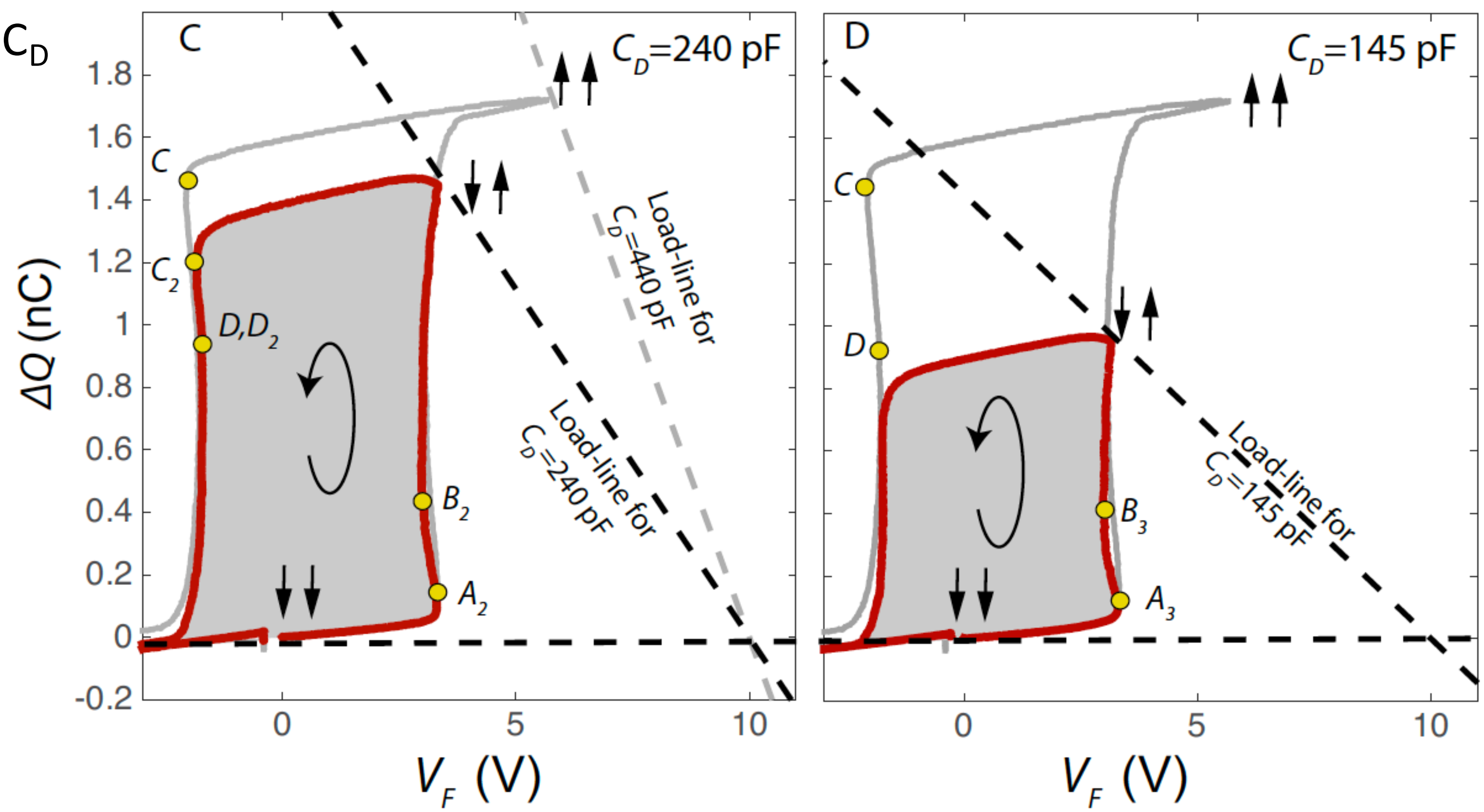
Ferroelectric+Dielectric Capacitor

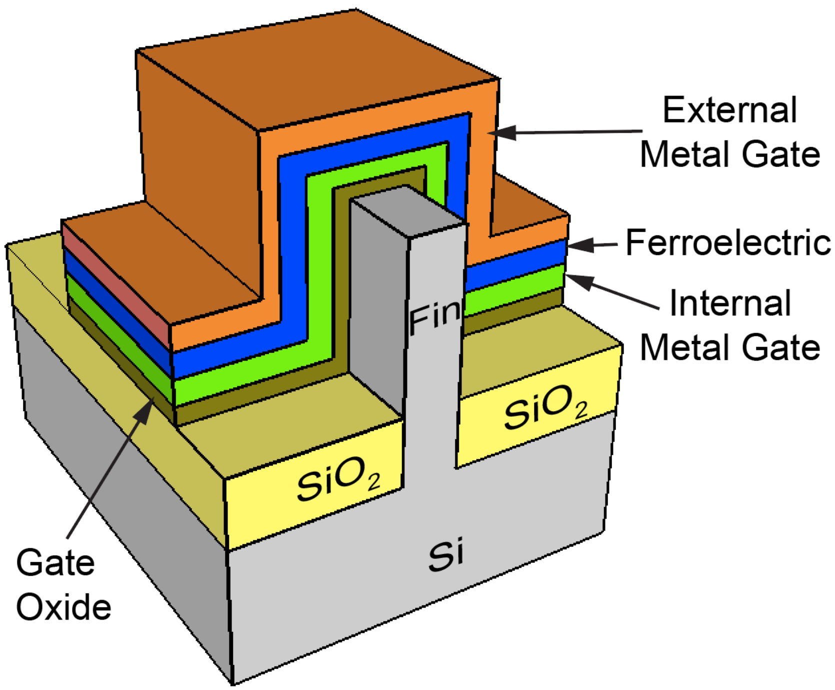




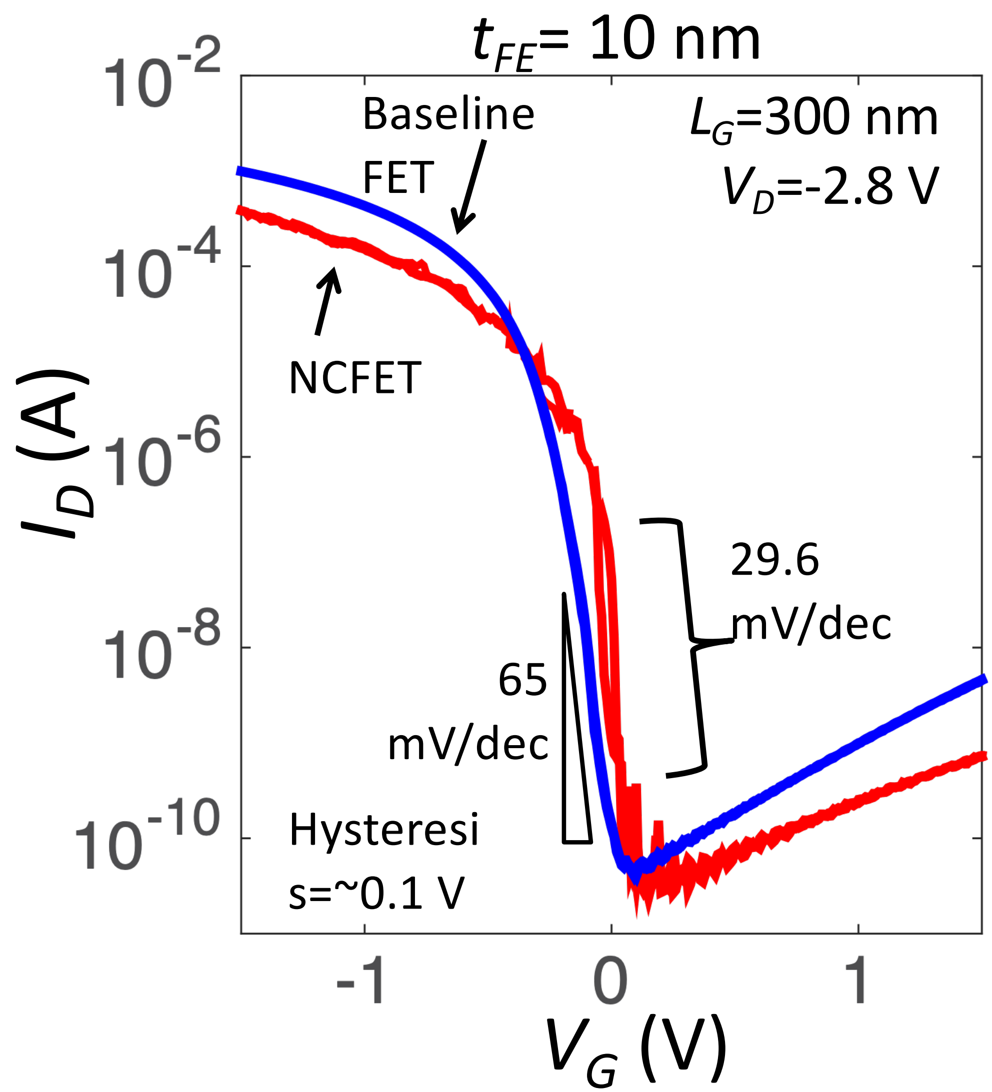
Khan, Hoffmann et al. (under review)

Domain mediated mechanisms are at play! Initial epochs of switching show negative capacitance!

Negative Capacitance Transistor



Khan et al. (unpublished)



Negative capacitance can reduce subthreshold swing below 60 mV/dec!

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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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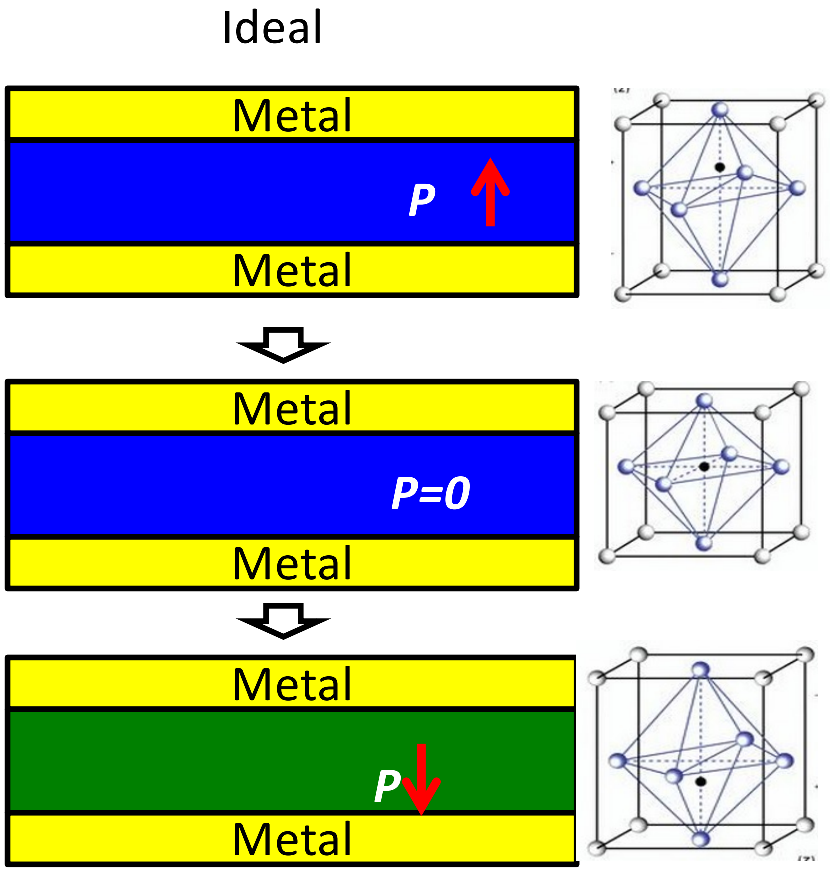
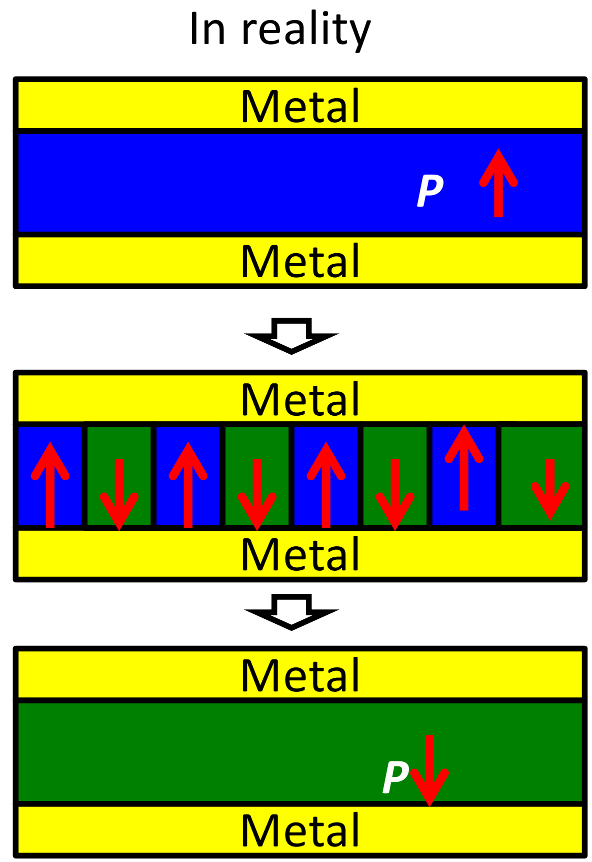
Domain mechanisms



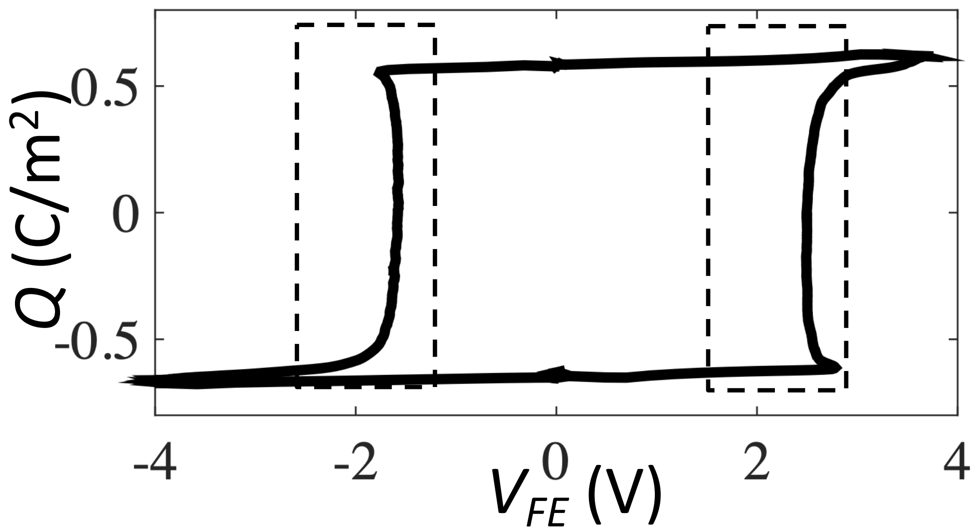


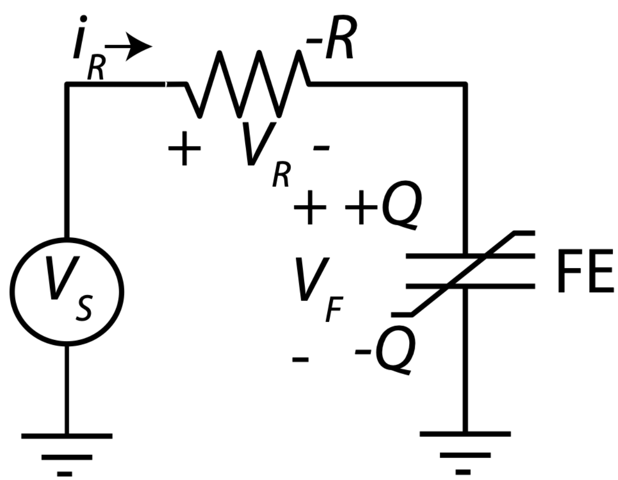
Landau type switching
Single domain switching
Intrinsic switching

We do not have a good model for negative capacitance in the presence of domain mediated mechanism of switching

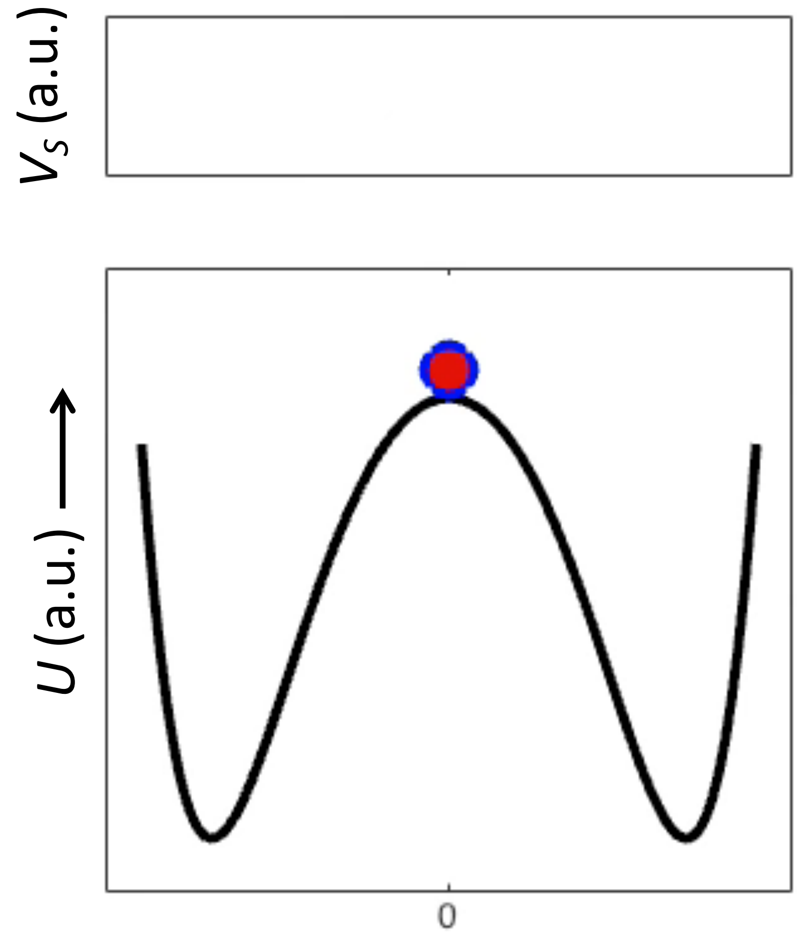
Domain mechanisms

There are lots of physics in the transition edges!





Energy Landscape



THANKS

Ferroelectrics and

Negative Capacitance:

What do we know and

What do we need to know?

QUESTIONS

&

COMMENTS

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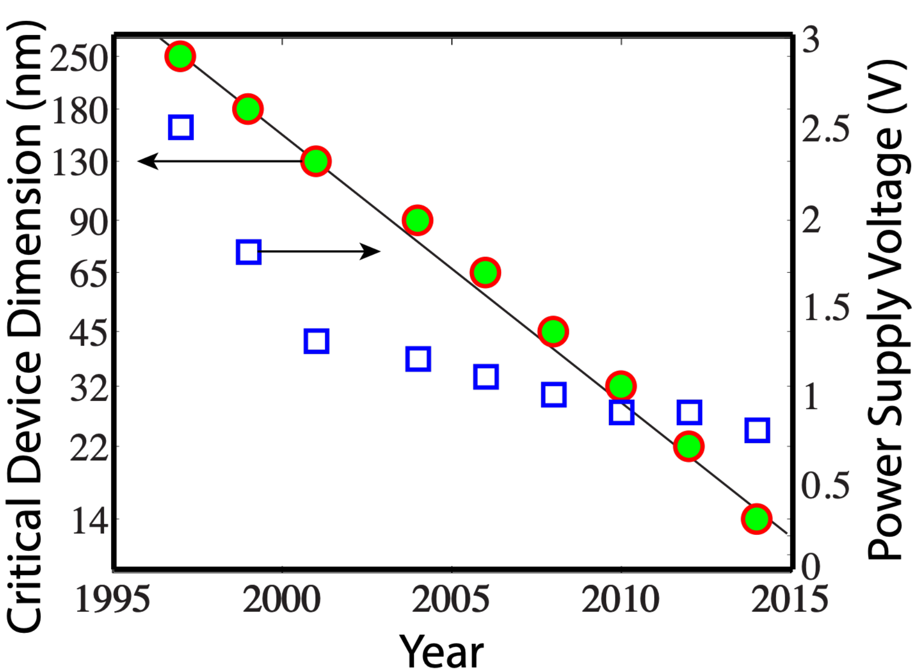
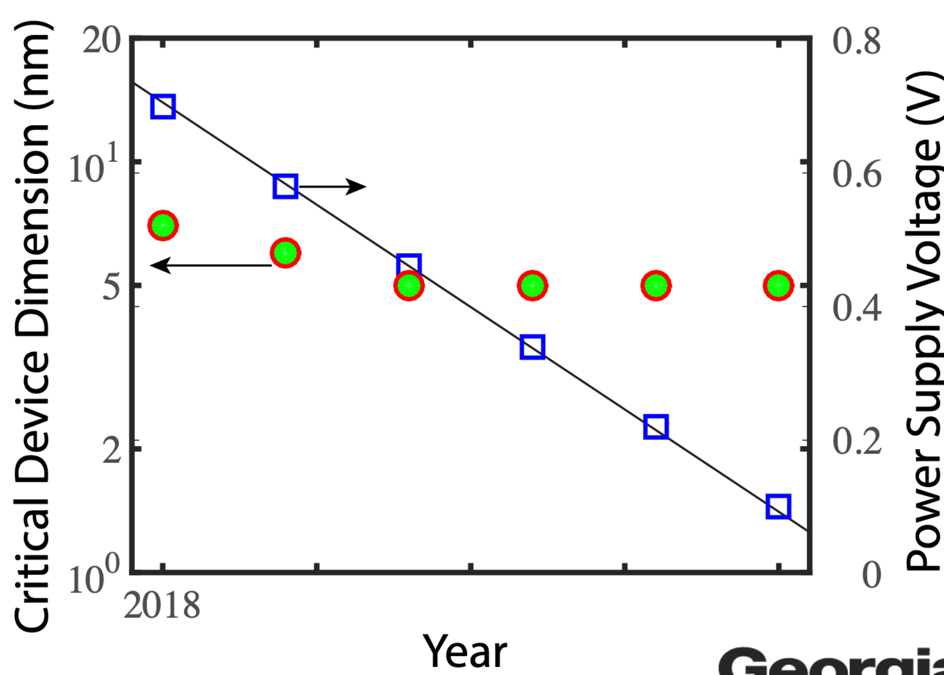
Summary

- **Negative capacitance detected!**
- **Amplification due to negative capacitance demonstrated!**
- **Sub-60 mV/decade subthreshold switching is possible!**

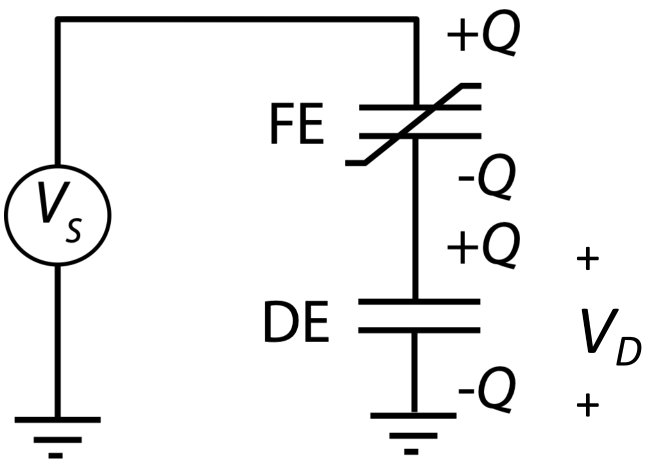
Current CMOS Technology



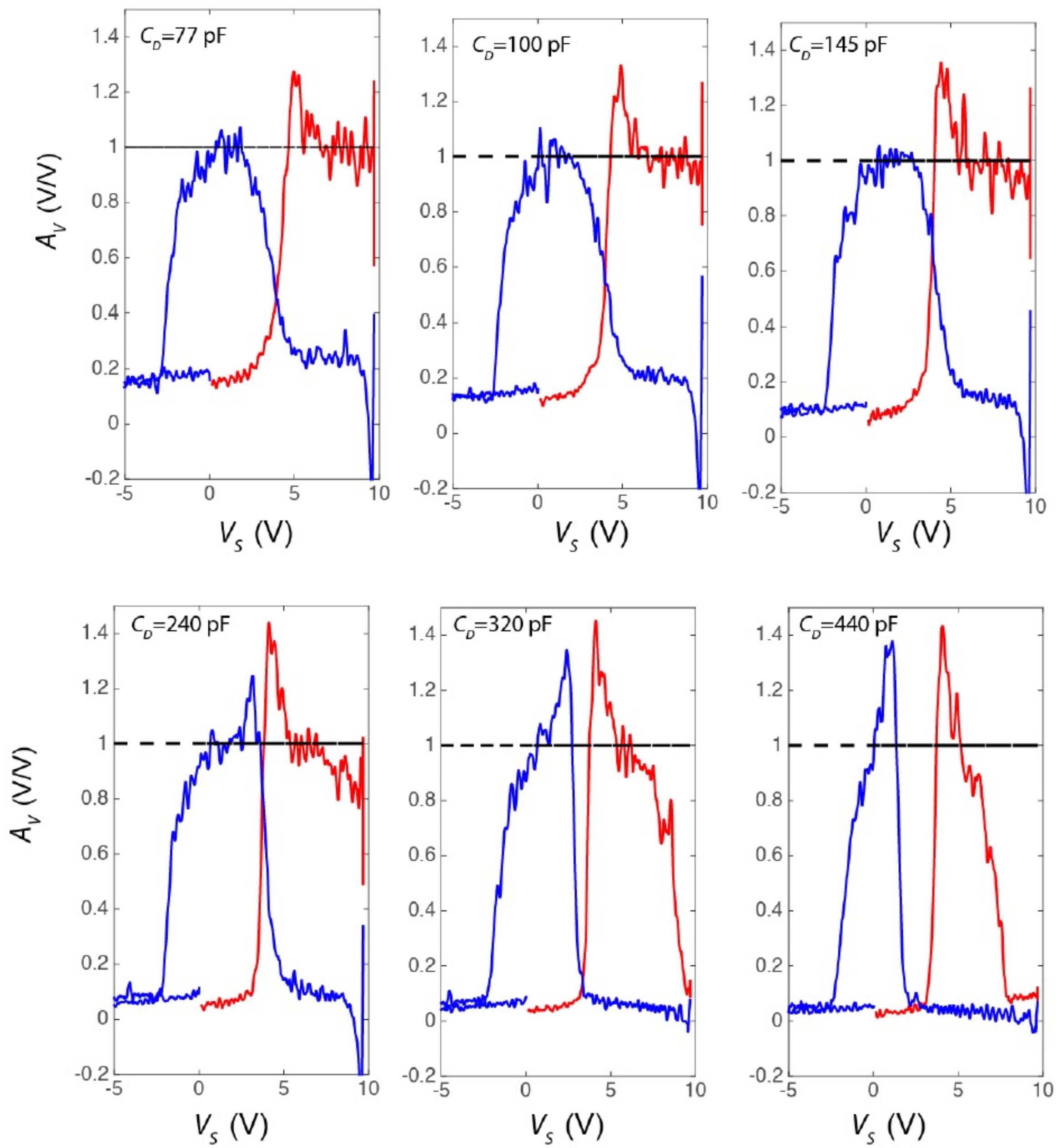
Beyond CMOS Technology



Ferroelectric+Dielectric Capacitor



Khan, Hoffmann et al.
(under review)



Voltage amplification reduces in negative voltage sweeps with the reduction of C_D!

Speed

What is the speed of negative capacitance mechanisms?

1. **10-100 ns in HFO2 FETs**
Müller et al. Nanosecond Polarization Switching and Long Retention in a Novel MFIS-FET Based on Ferroelectric HfO2. IEEE Electron Devices Letters33, 185 (2011).

2. ~220 ps in micron size PZT capacitors:
Li et al. Ultrafast polarization switching in thin-film ferroelectrics. Applied Physics Letters 84, 1175 (2004).

3. ~ps scale atomic displacement in BaTiO3:
Chen et al. Ultrafast terahertz-field-driven ionic response in ferroelectric BaTiO3. Physical Review B 94, 180104(R) (2016).

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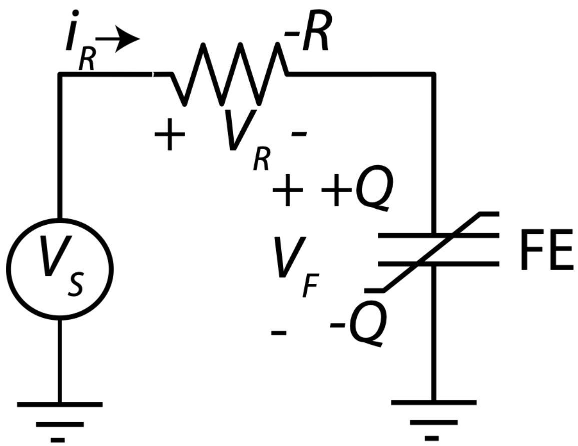
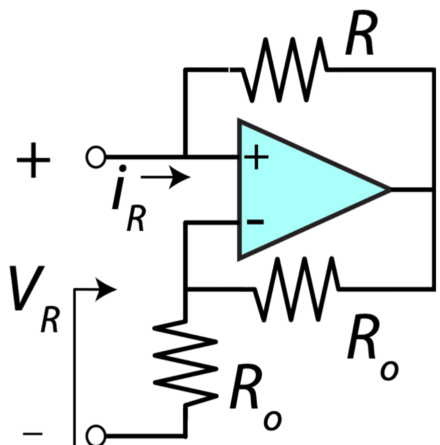
Dynamic Stabilization of an Unstable State

Circuit Diagram



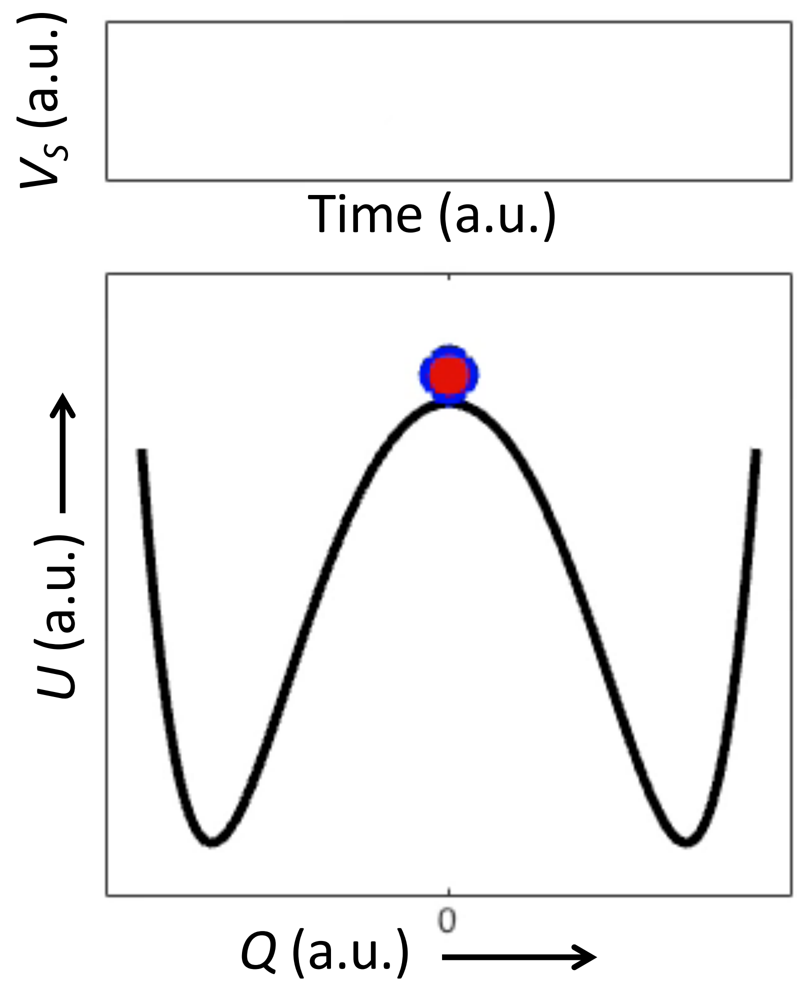
KVL: $V_S = -R\dfrac{dQ}{dt} + V_F(Q)$

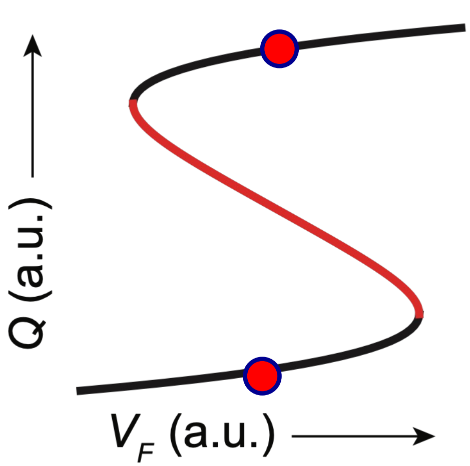
Negative Resistor

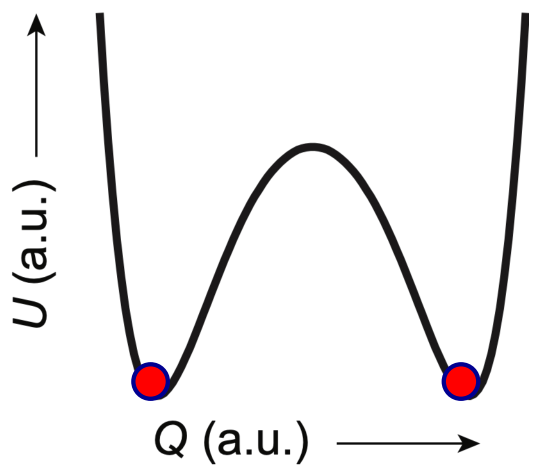


$$R_{in} = \frac{V_R}{i_R} = -R$$

Energy Landscape







New technique for stabilization

Berkeley UNIVERSITY OF CALIFORNIA

How does the physics change?

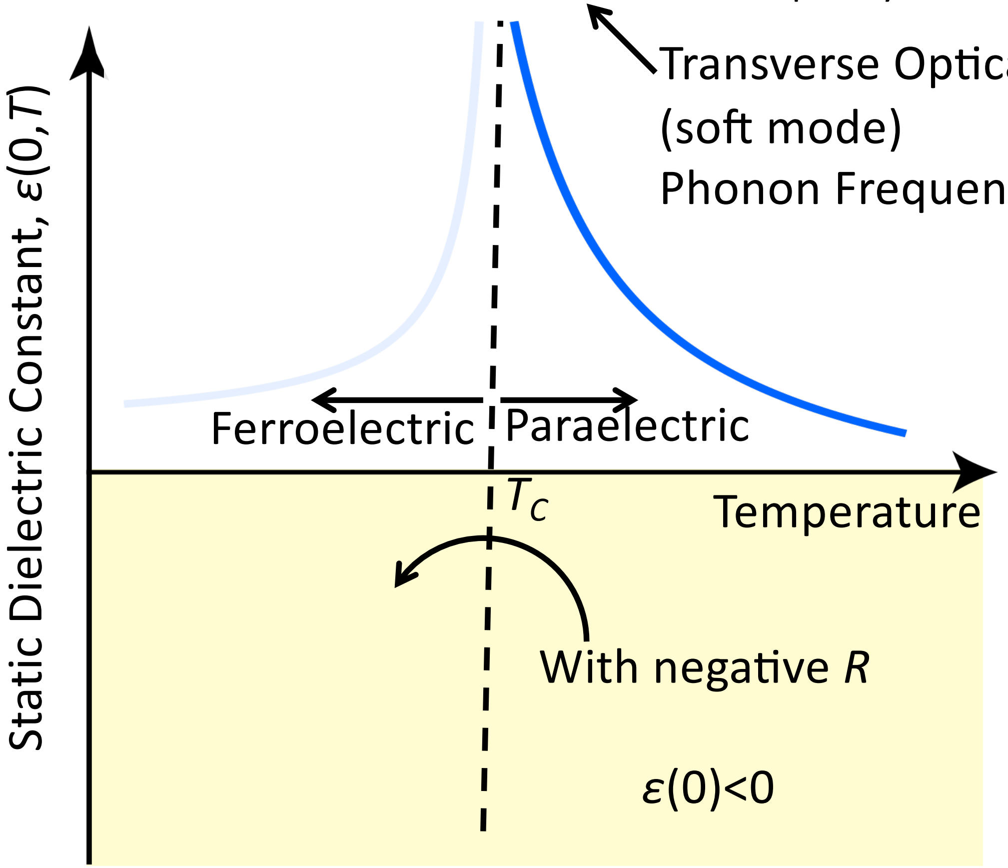
Ferroelectricity occurs due to certain vibration modes called soft mode phonons.

$\varepsilon(0,T)$=Static Dielectric Constant at T

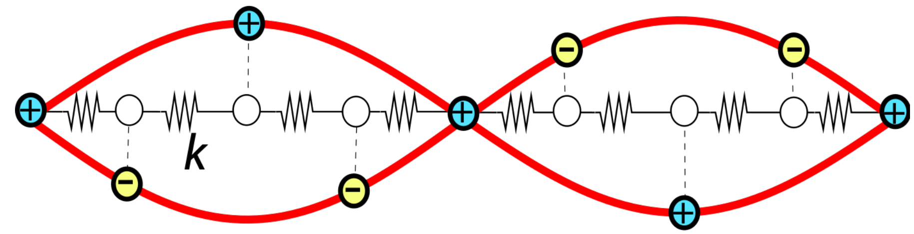
Lydanne-Sachs -Teller Relation $\dfrac{\varepsilon(0,T)}{\varepsilon(\infty)} = \dfrac{\omega_L^2}{\omega_T^2(T)}$

Longitudinal Phonon Frequency

Transverse Optical (soft mode) Phonon Frequency



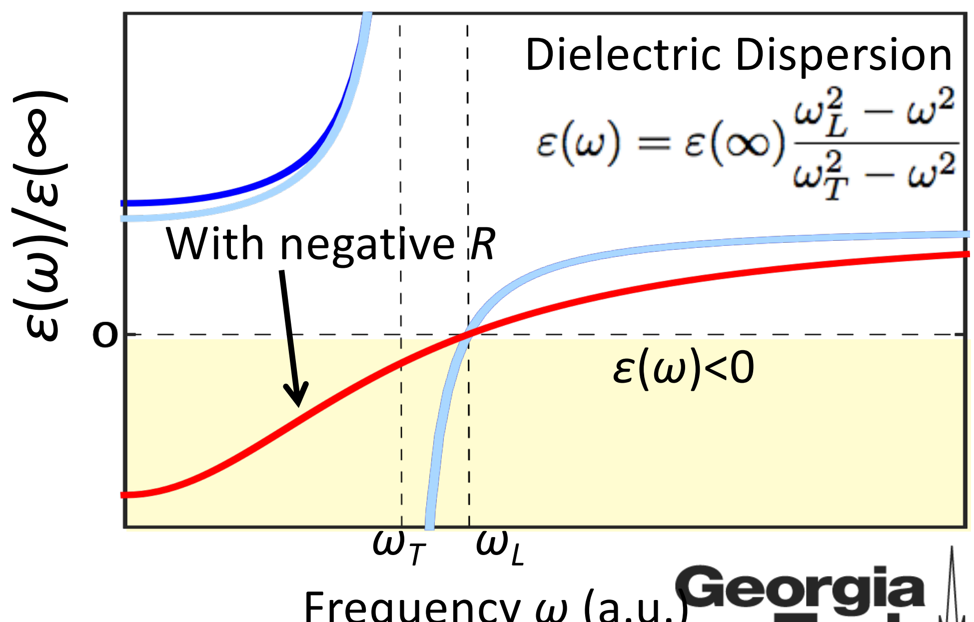
Transverse Optical Phonons



Soft mode theory: Cochran. Adv. Phys 9, 387 (396)

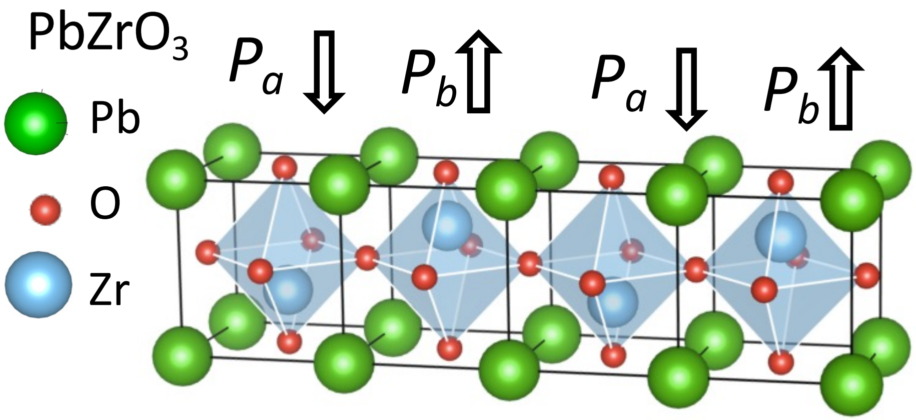
$$\text{If } \varepsilon(0) < 0,\ \omega_T^2 \approx \frac{k}{m_{eq}} < 0 \text{ and, hence, } k < 0$$

Revisit the soft-mode theory of ferroelectrics!

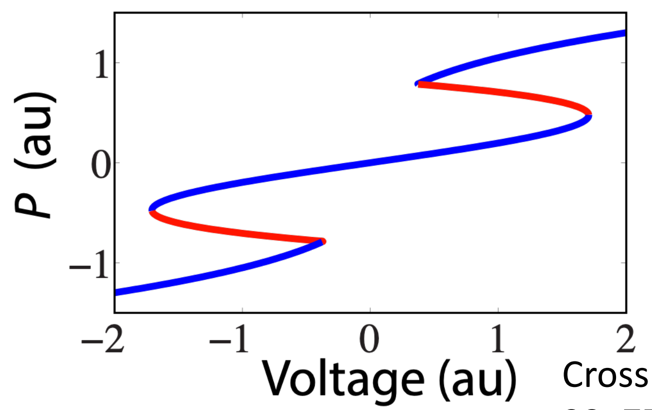


Experiments & Beyond Ferroelectrics

Antiferroelectric Oxides



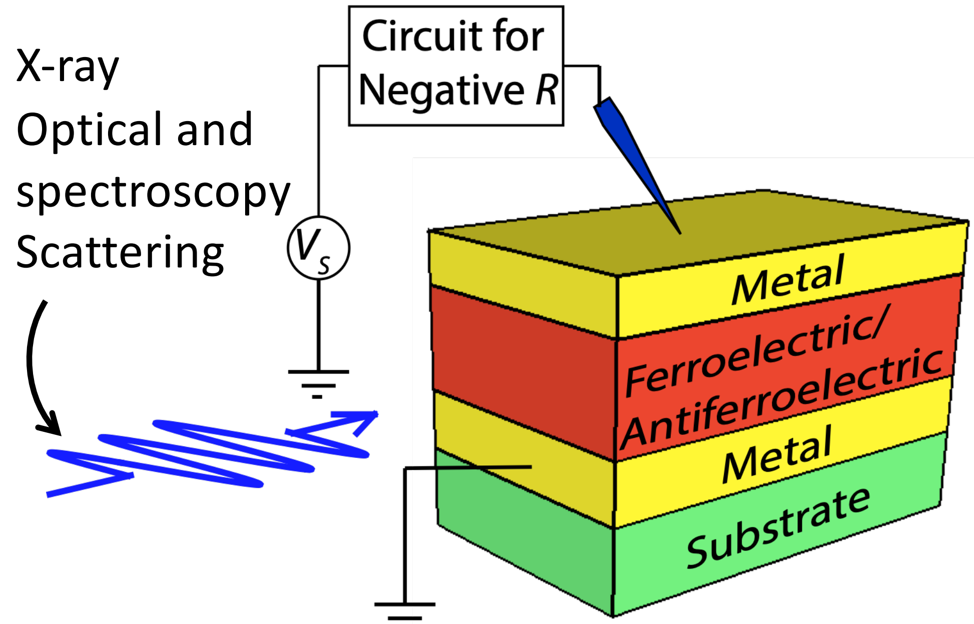
Charge Voltage Characteristics



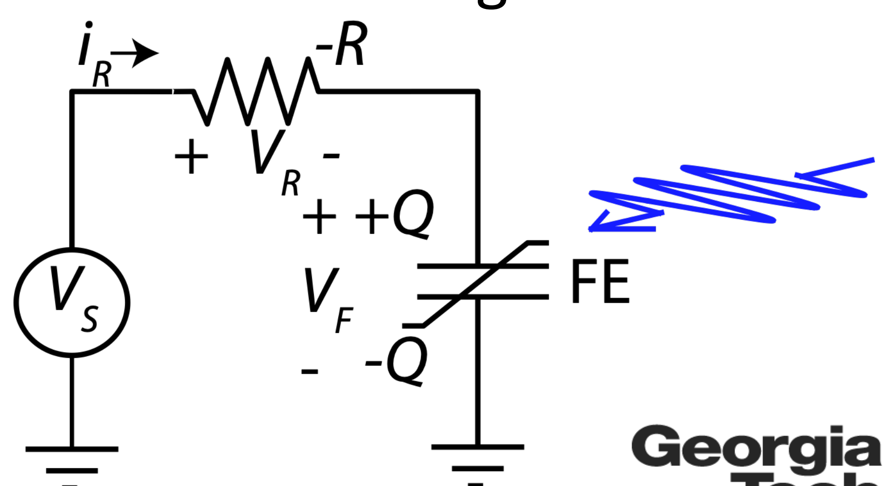
Cross . J. Jap. Soc. Phys. 23, 77 (1967)

- Complex Oxide Antiferroelectrics
  - Pb(Zr$_x$Ti$_{1-x}$)O$_3$ and doped variants
  - BeFeO$_3$ and doped variants
- CMOS Compatible Hf$_x$Zr$_{1-x}$O$_2$

Possible Experimental Setup



Circuit Diagram



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Roadmap to Future

Electronics with Ferroelectrics and Unconventional Oxides

- Technology Development
- Fundamental Science

Materials Growth

- Complex Oxides (Pulsed Laser Deposition)
- Transition Metal Binary Oxide (Atomic Layer Deposition)

Nano-Fabrication

- Heterostructures
- Nanostructures
- Devices

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Chenming Hu, UC Berkeley

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Ian Young, Intel
Zia Karim, Aixtron

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Office of Naval Research

STARNET LEAST

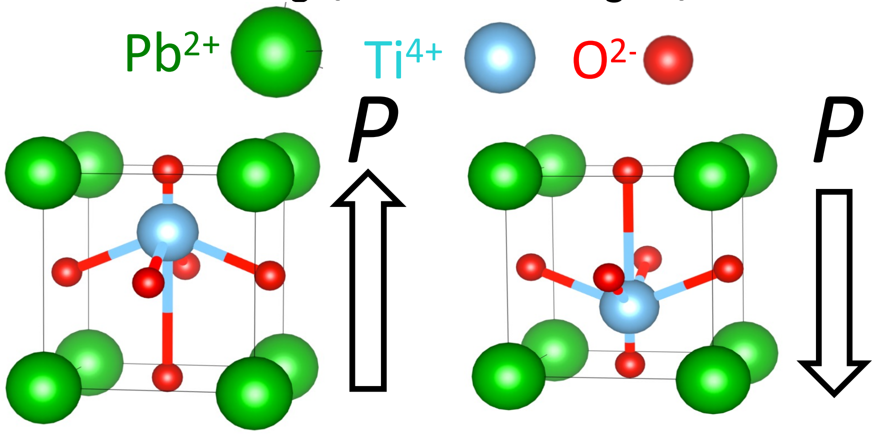
NSF E3S Center

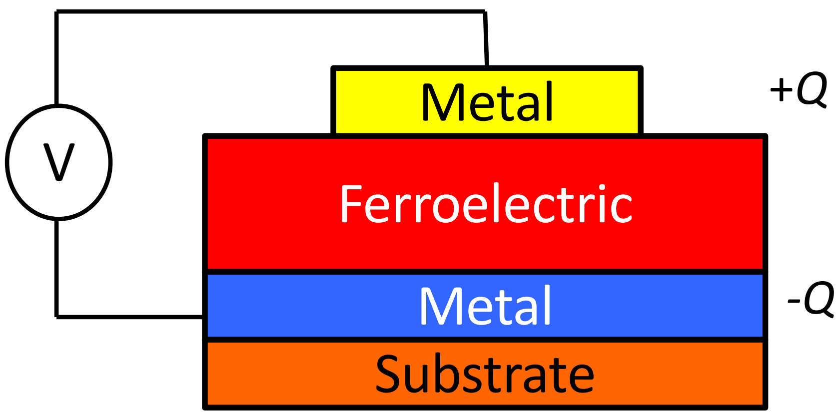
FCRP MSD Center

Ferroelectric Oxides

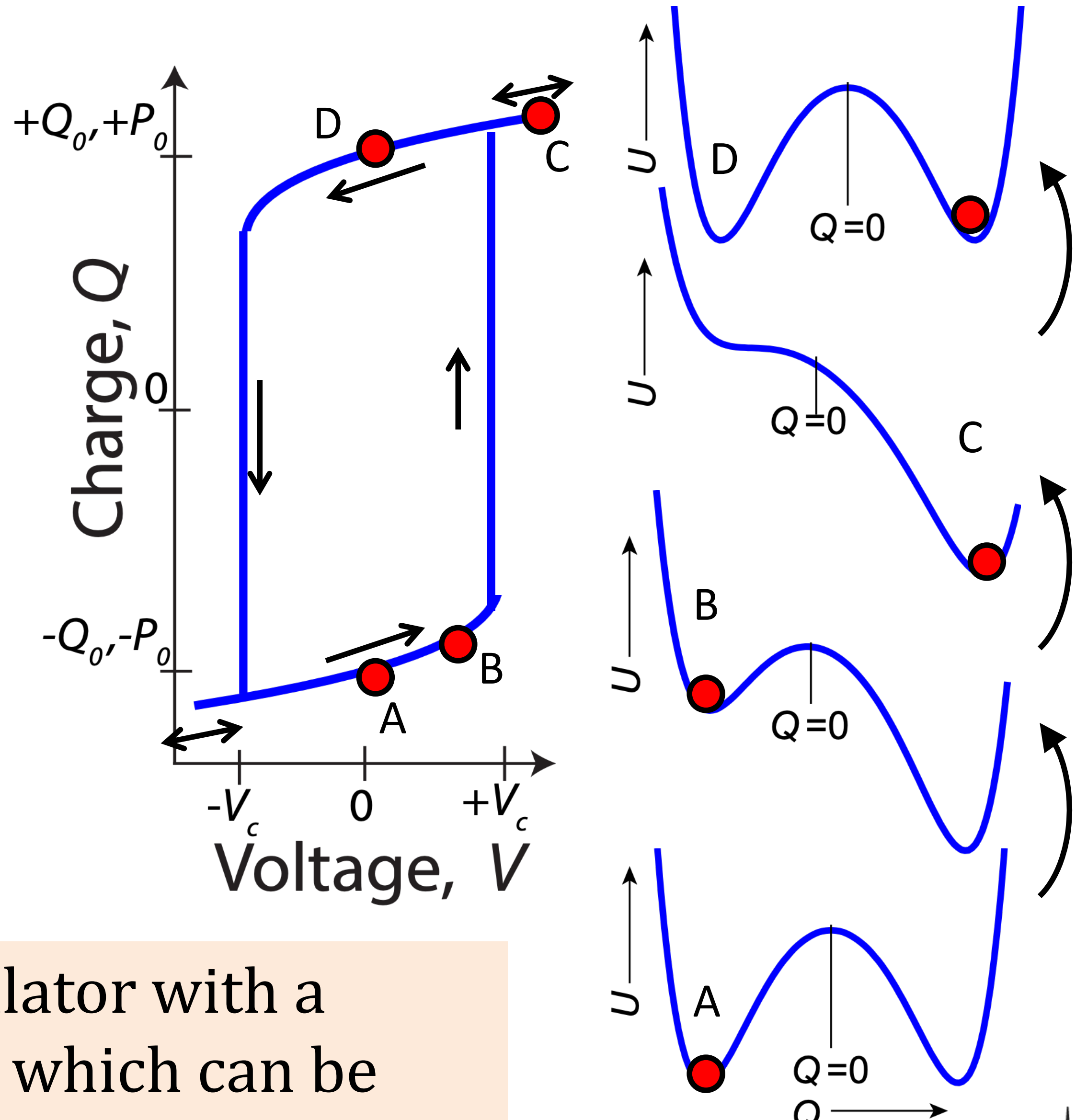
Classical Ferroelectric

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





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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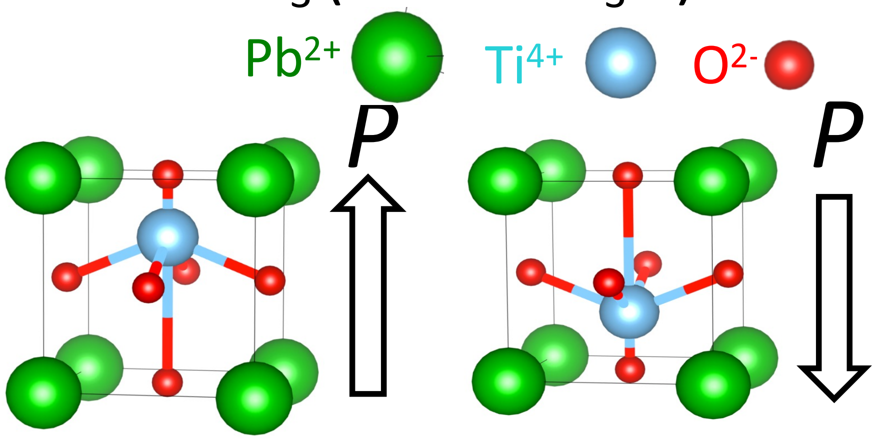
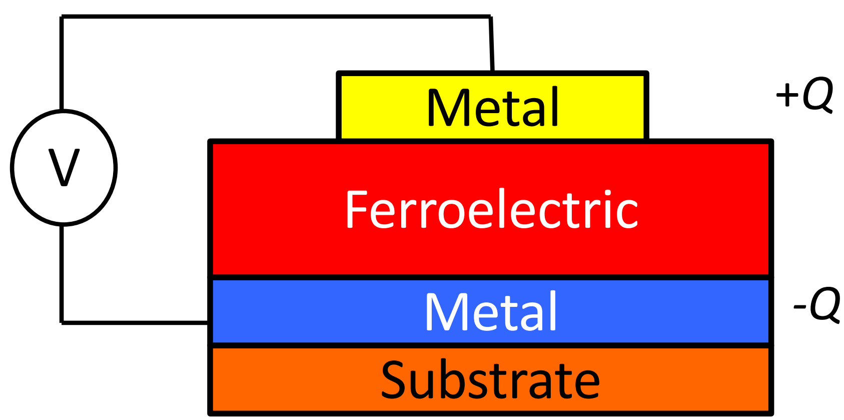
Ferroelectric Oxides

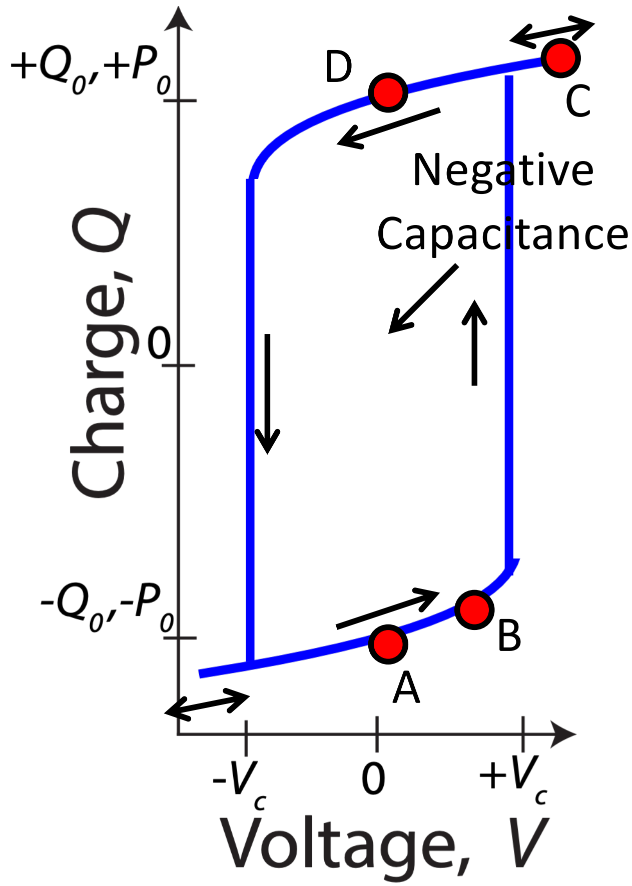
Classical Ferroelectric

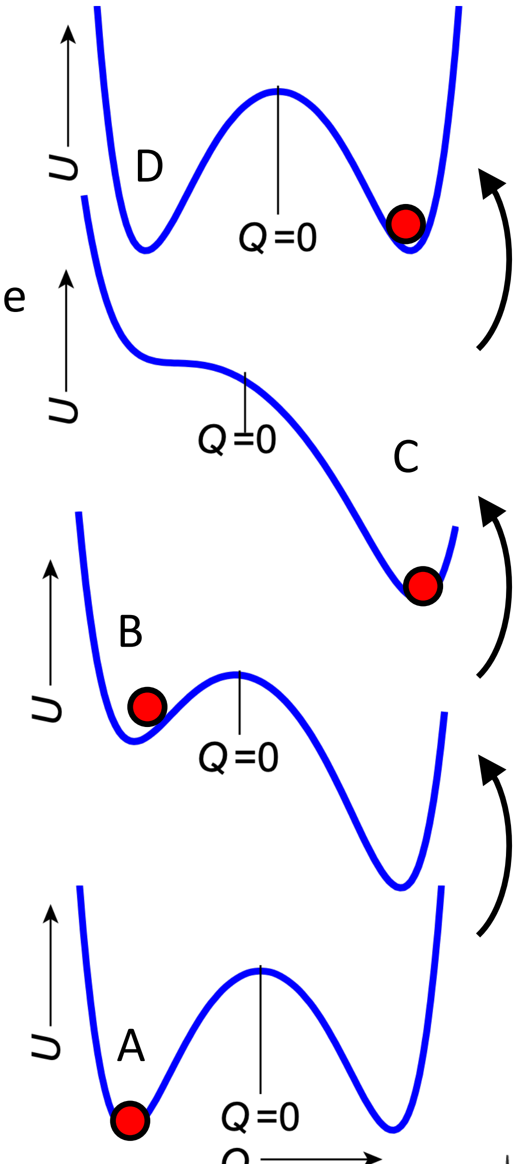
$PbTiO_3$ ($Pb^{2+}Ti^{4+}O_3^{6-}$)





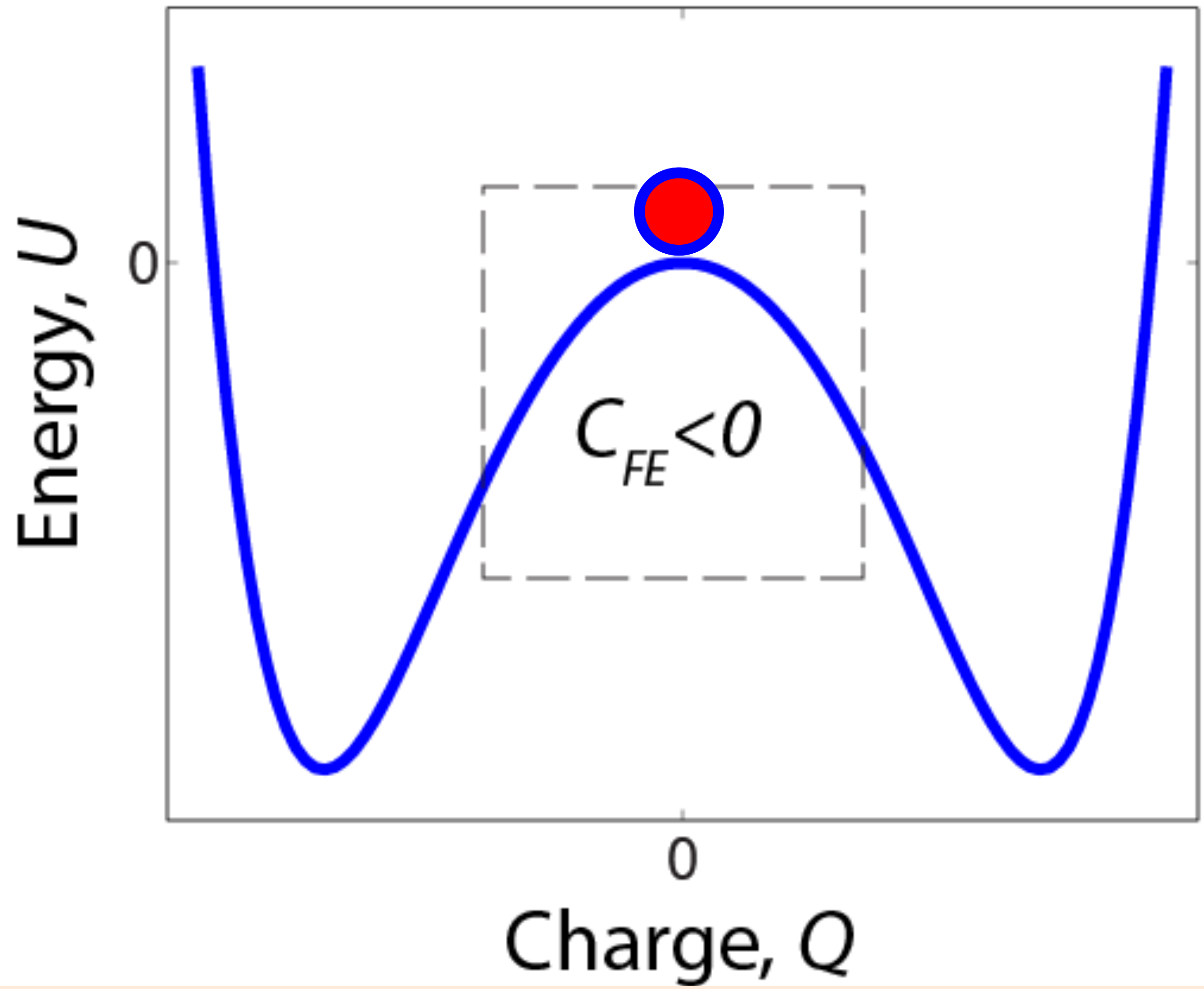
Charge Voltage Characteristics





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

Why is it difficult to measure?



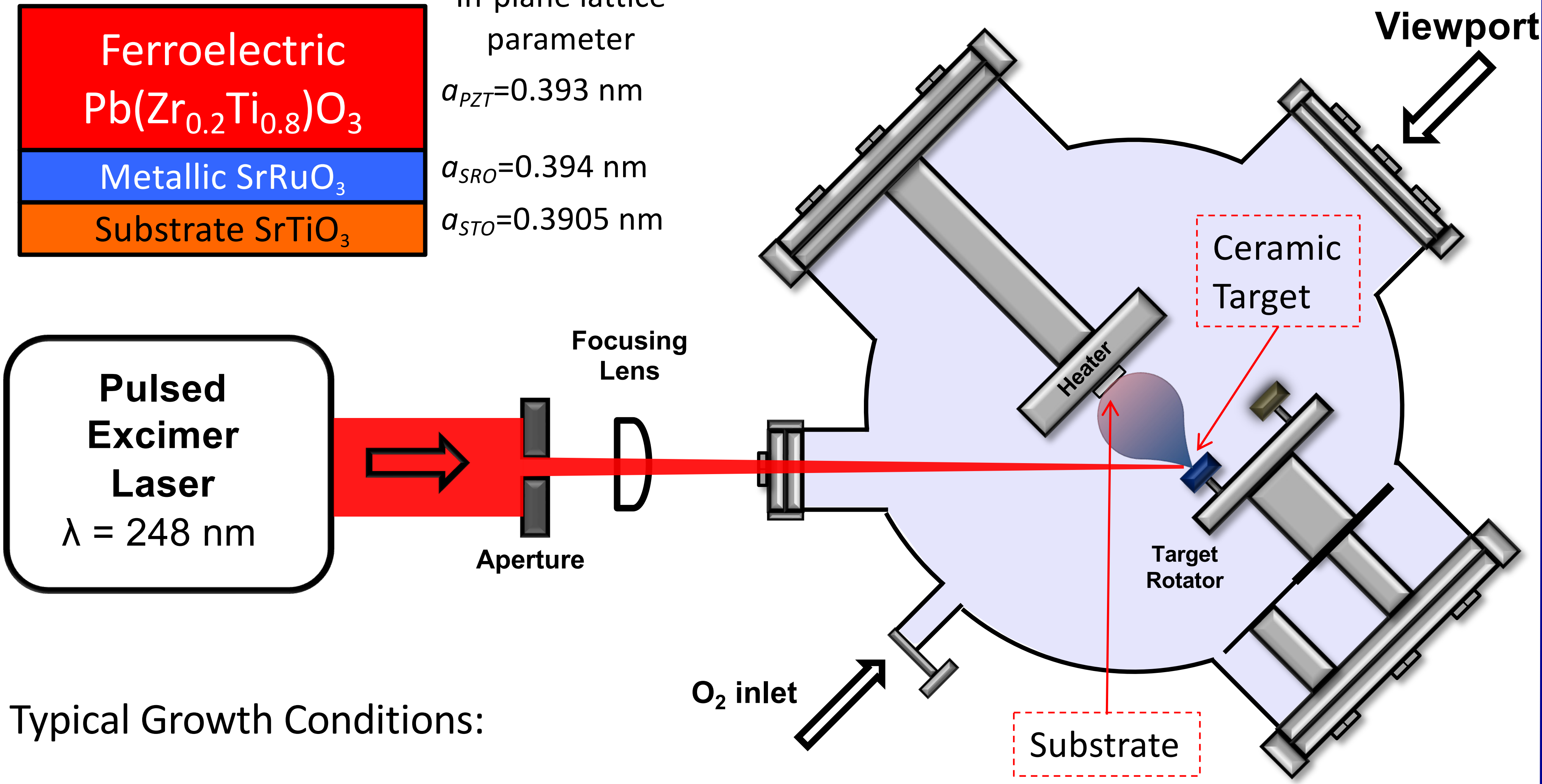
Ferroelectric Negative Capacitance is unstable and cannot be accessed in a time independent equilibrium measurement.

Growth of Ferroelectric Oxides

Experimental Heterostructure

Layer	In-plane lattice parameter
Ferroelectric $Pb(Zr_{0.2}Ti_{0.8})O_3$	a_{PZT}=0.393 nm
Metallic $SrRuO_3$	a_{SRO}=0.394 nm
Substrate $SrTiO_3$	a_{STO}=0.3905 nm

Pulsed laser deposition technique



Typical Growth Conditions:

$SrRuO_3$: 720°C, 100 mTorr, 1.2 J/cm^2, 5-15 Hz

$Pb(Zr_{0.2}Ti_{0.8})O_3$: 630 °C, 100 mTorr, 1-1.5 J/cm^2, 5-15 Hz

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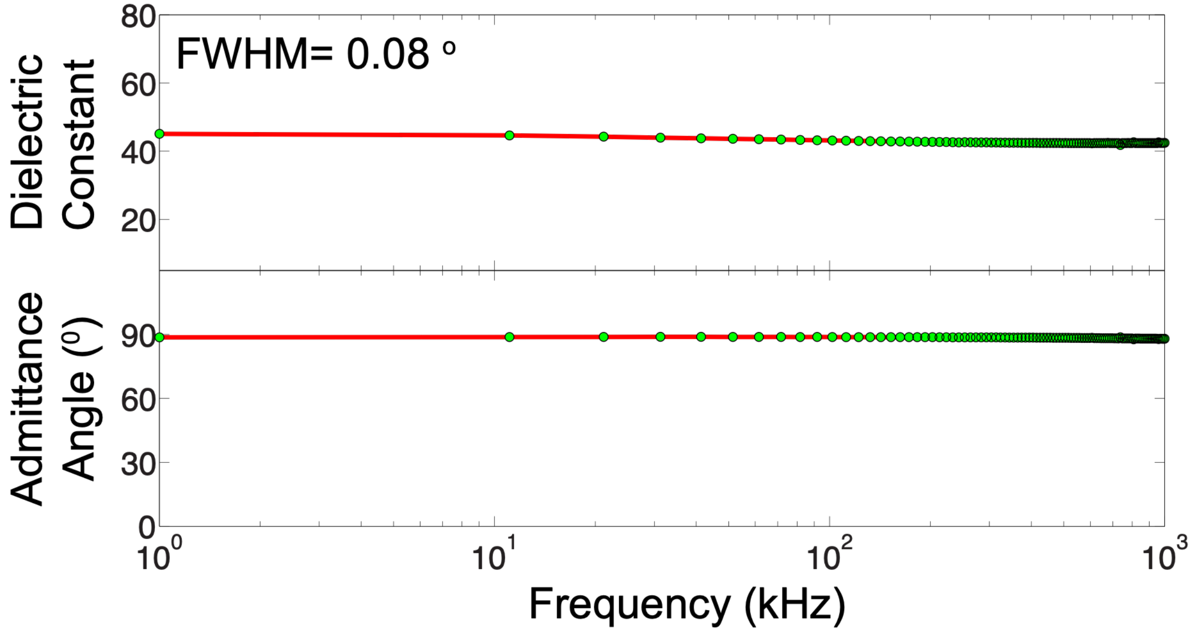
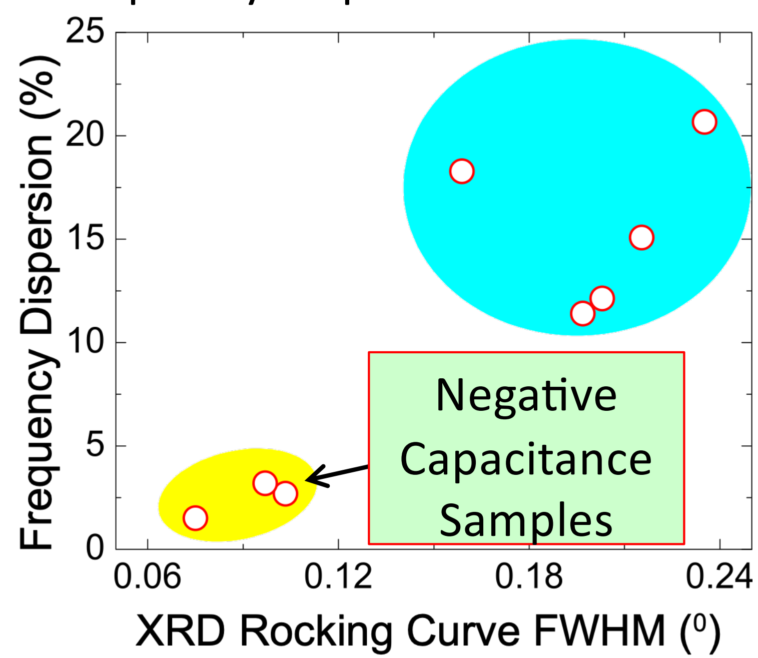
Correlation with Structural Properties

Negative capacitance effect is correlated to the structural quality of the thin film.

Dielectric Frequency Dispersion



Frequency Dispersion vs. FWHM



Frequency Dispersion between 1 kHz and 1 MHz < 2 %

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

Khan et al. Appl. Phys. Lett. 104, 262407 (2014)

High quality materials growth is the key!

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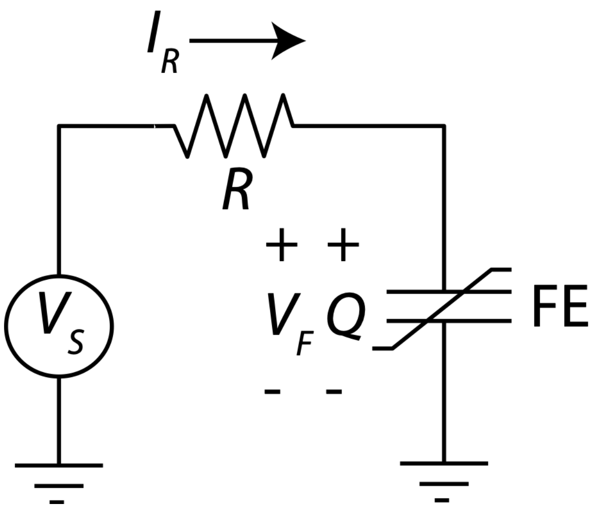
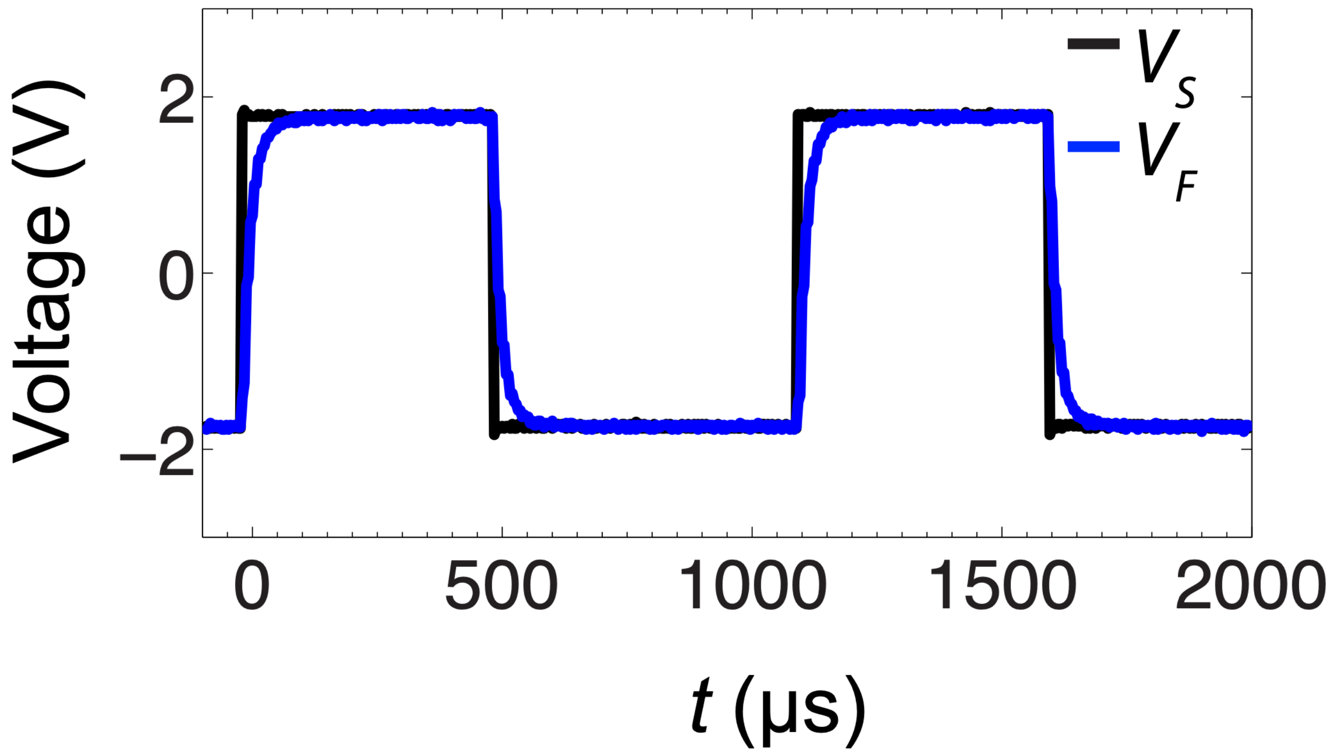
Correlation with ferroelectric switching



Coercive Voltage (~2.5 V)

V_S: -1.8 V→+1.8 V → -1.8 V → +1.8 V



No negative capacitance transients are observed when the voltage is smaller than coercive voltage.

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

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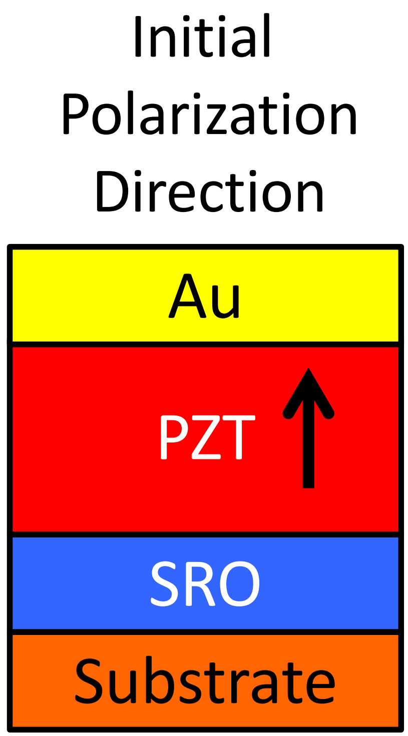
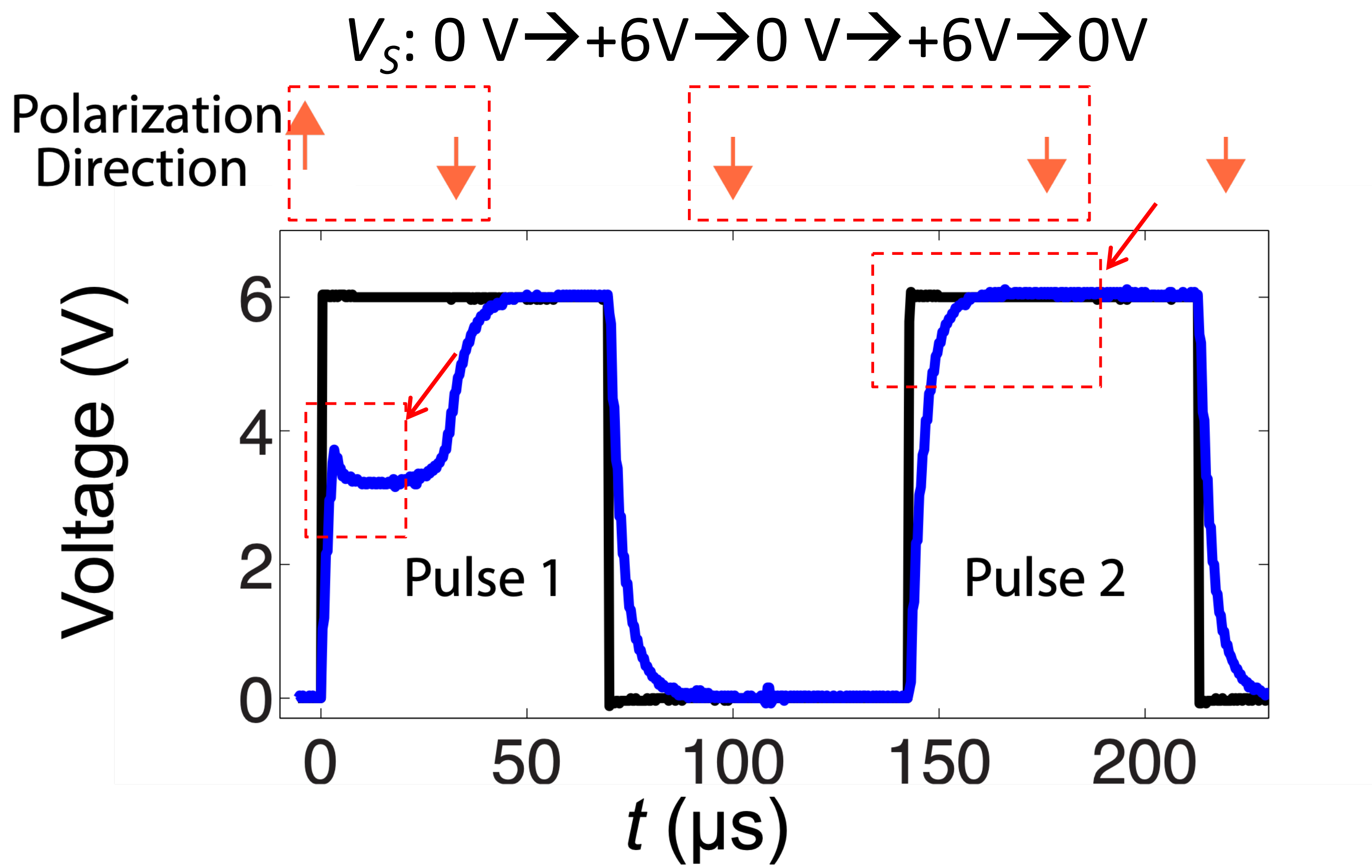
Correlation with ferroelectric switching





No negative capacitance transients are observed when there is no FE switching event.

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

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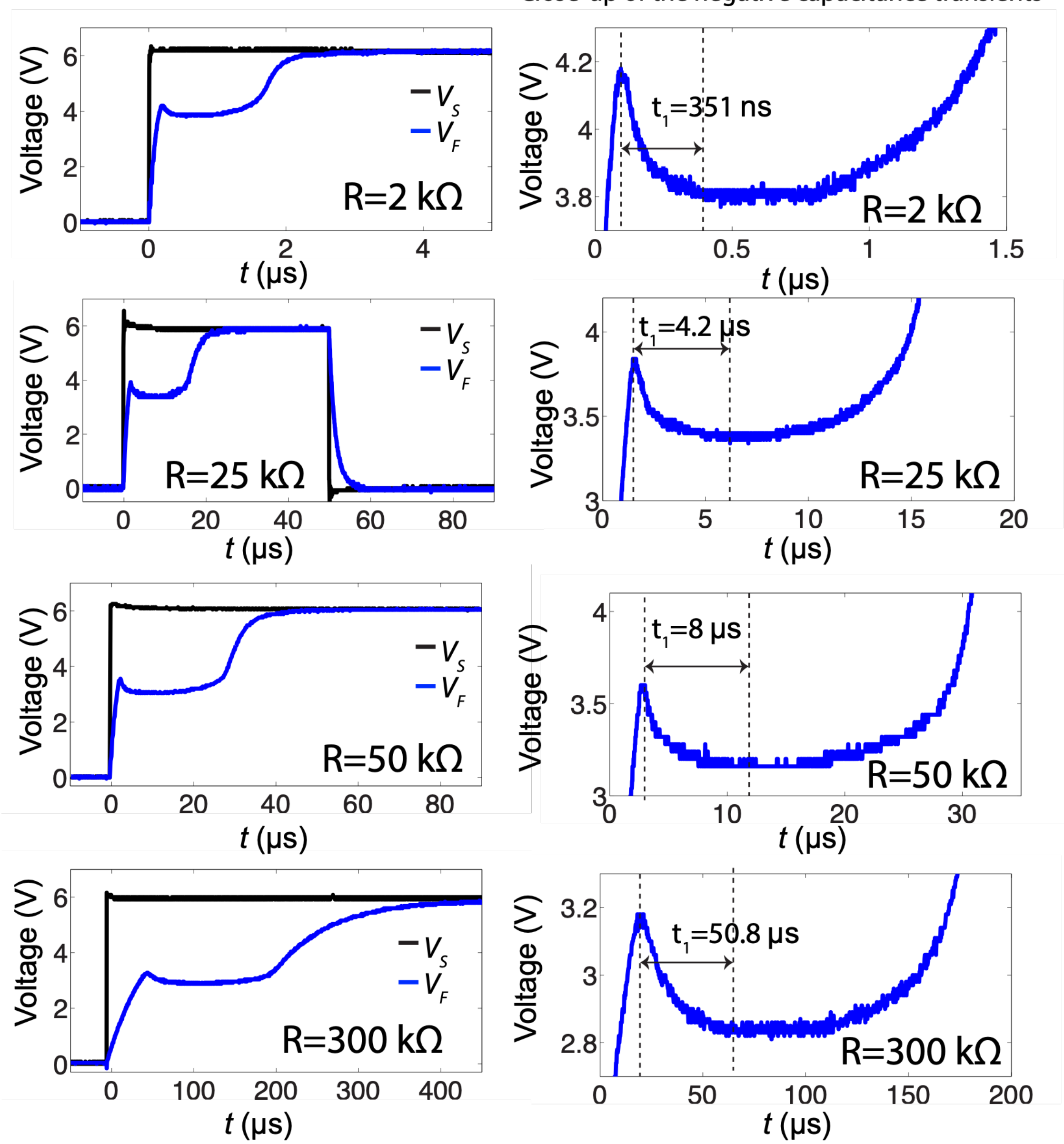
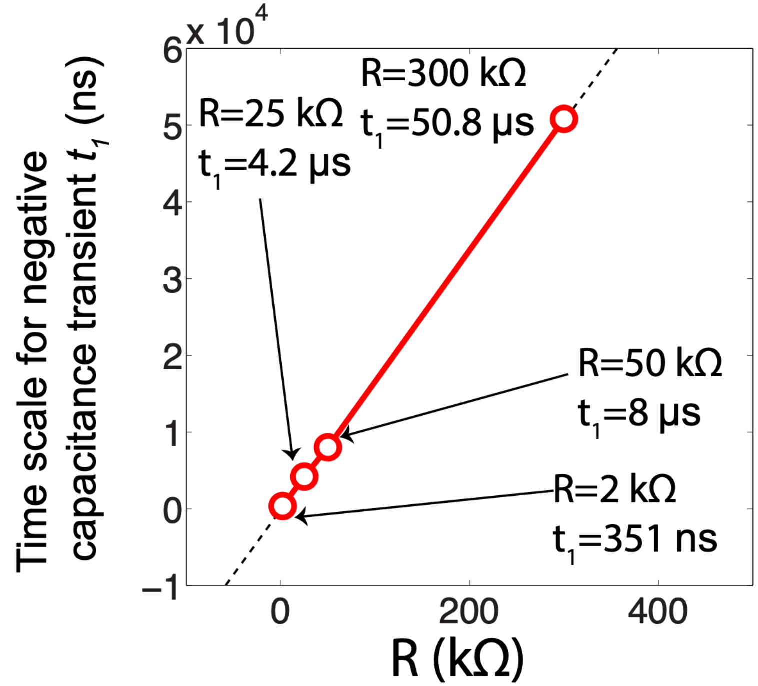
Time scale of transients

Close-up of the negative capacitance transients





The intrinsic time scale of negative capacitance transient could be very small.

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

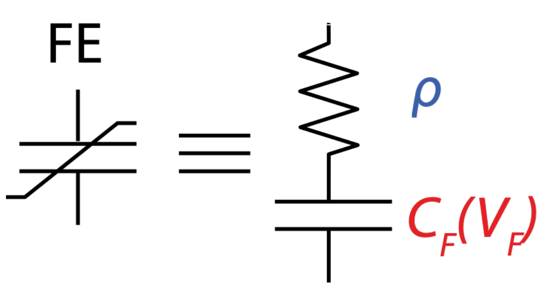
Georgia Tech

Landau-Khalatnikov model

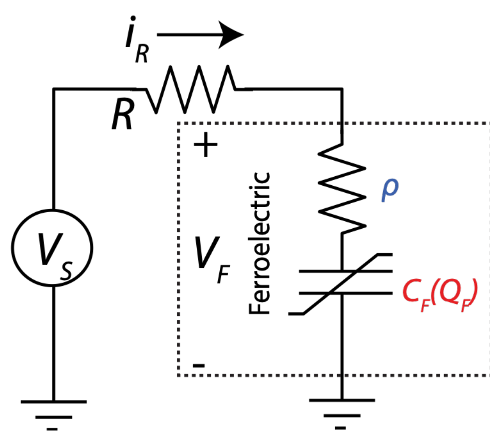
Landau-Khalatnikov Equation: $$\rho \frac{dP}{dt} = -\frac{dU}{dP}$$

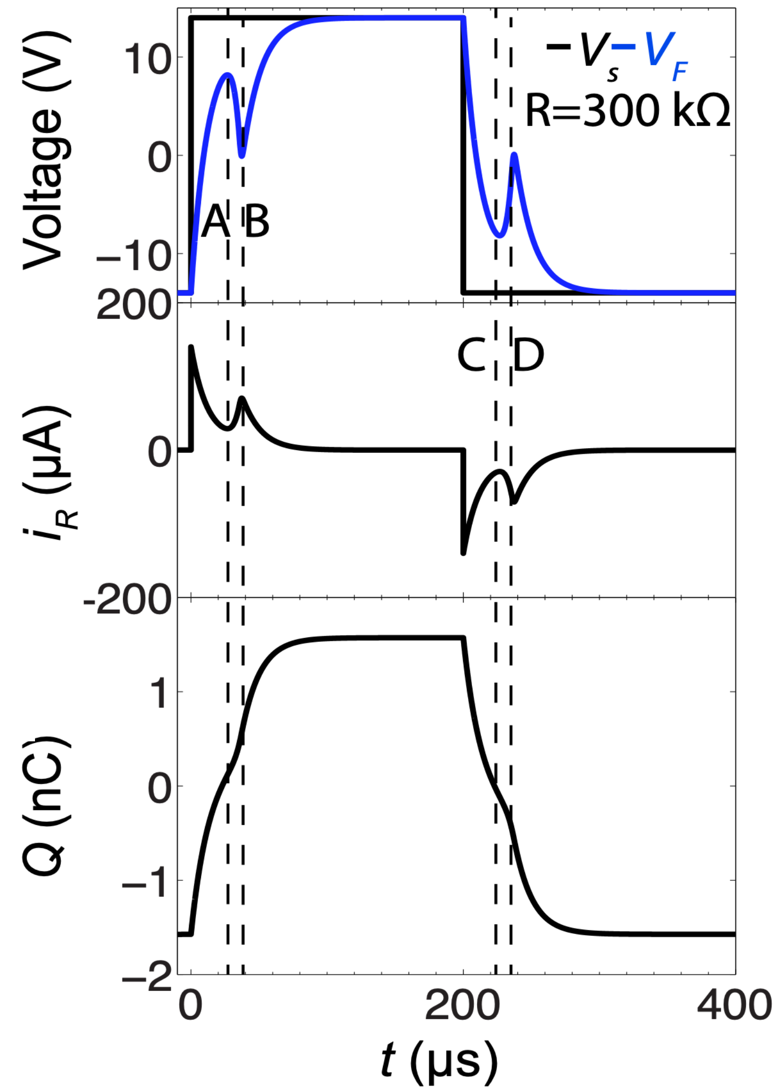
P=Ferroelectric polarization
U=Free energy of the system
ρ= Material dependent parameter

Equivalent Circuit



Simulated Circuit





Qualitative match between simulated and experimental transients.

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

Landau-Khalatnikov model

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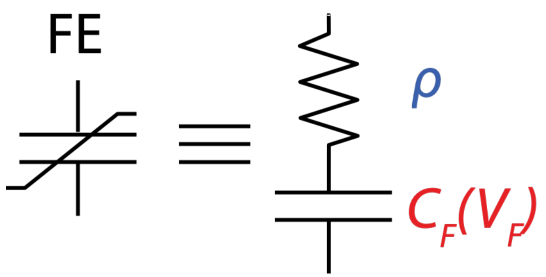
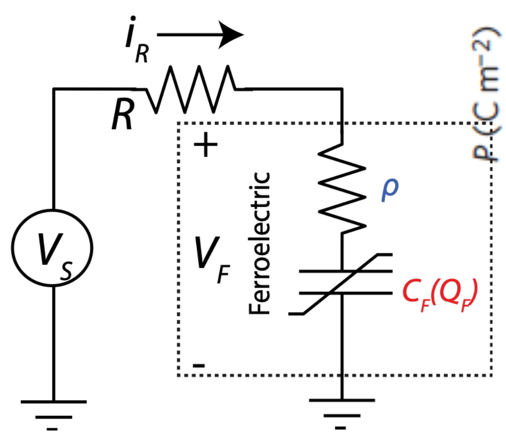
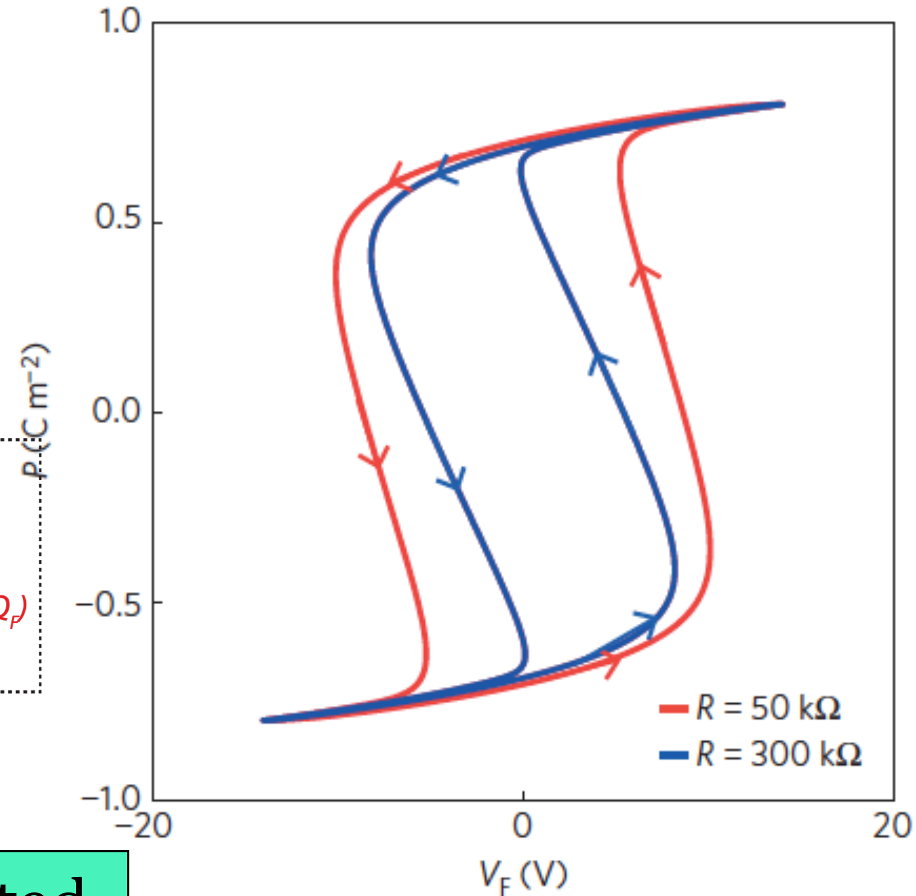
Equivalent Circuit



Simulated Circuit





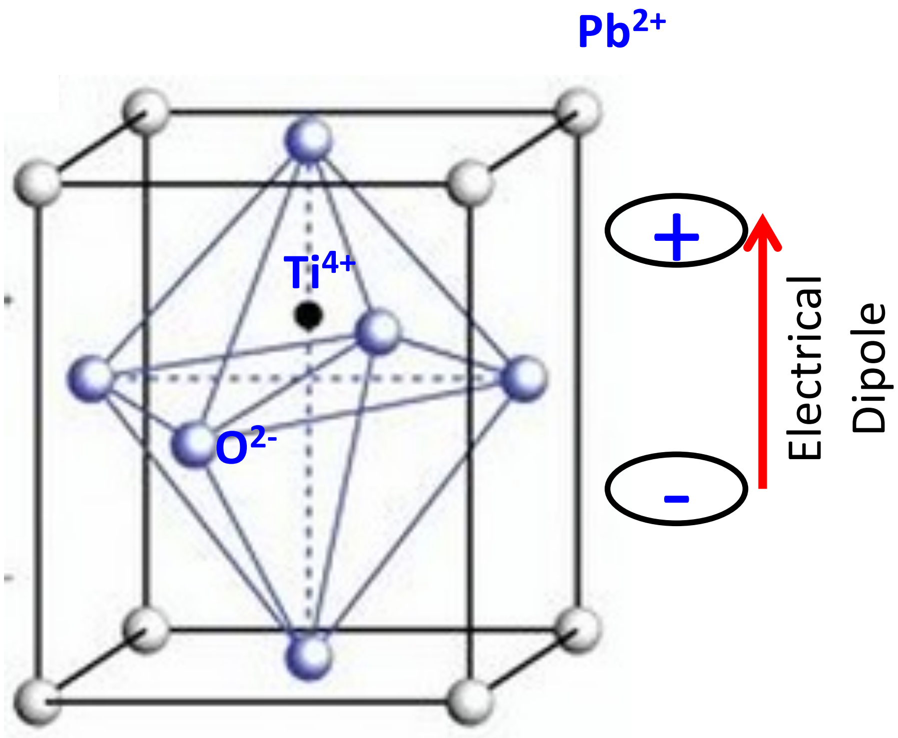
Qualitative match between simulated and experimental transients.

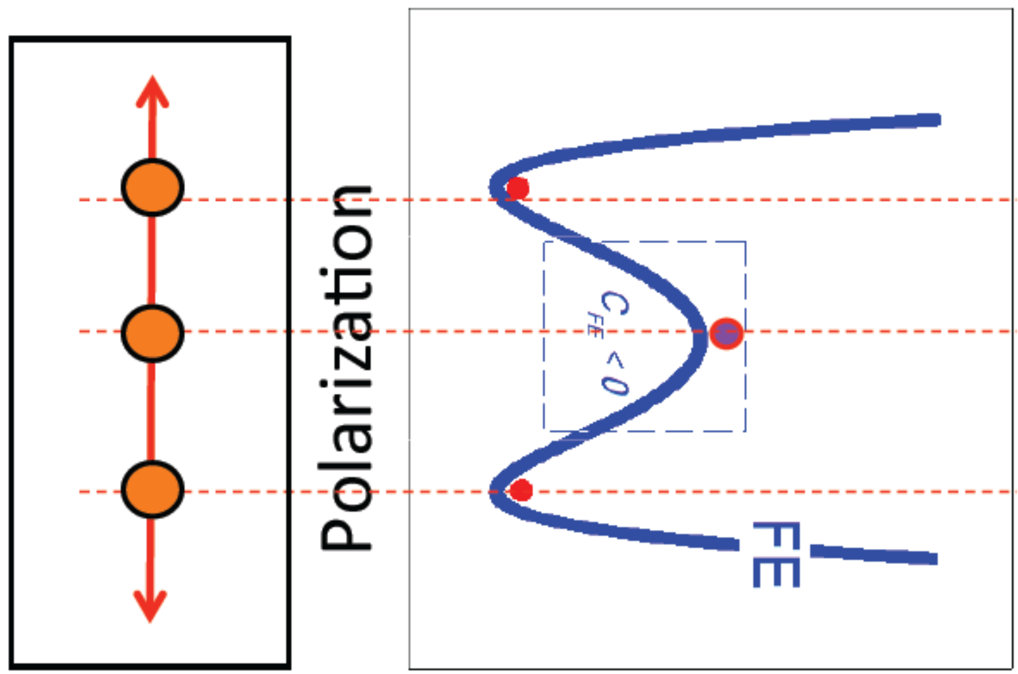
Khan et al. Nature Mater. 14, 182 (2015)

Ferroelectricity and Negative Capacitance

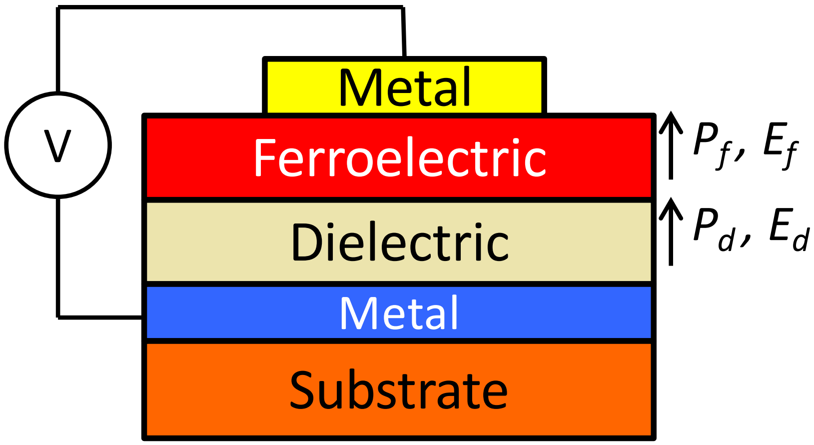
Ferroelectric Unit Cell

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





Temperature Effects on Negative Capacitance



Laudau-Devonshire formalism

$$U_i = \alpha_i P_i^2 + \beta_i P_i^4 + \gamma_i P_i^6 - E_i . P_i$$

$$U_{f+p} = l_f U_f + l_d U_f$$

Self-consistent solution with Poisson's equation.

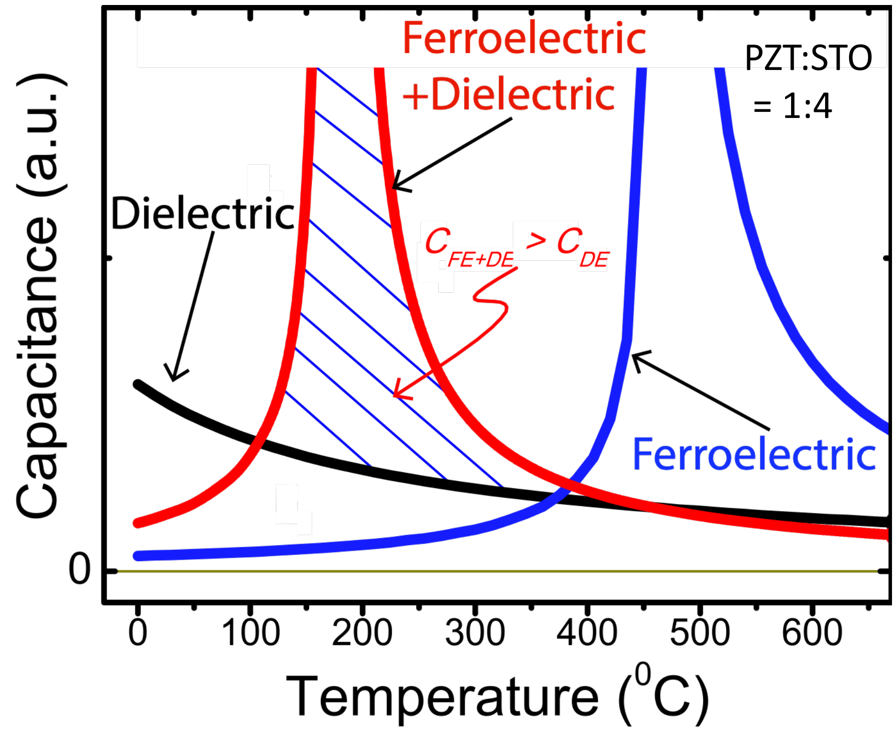
α, β, γ = Landau coefficients

U_i = Free energy on *i*-th layer

E_i = Electric field of *i*-th layer

P_i = Polarization in *i*-th layer

l_i = Thickness of *i*-th layer

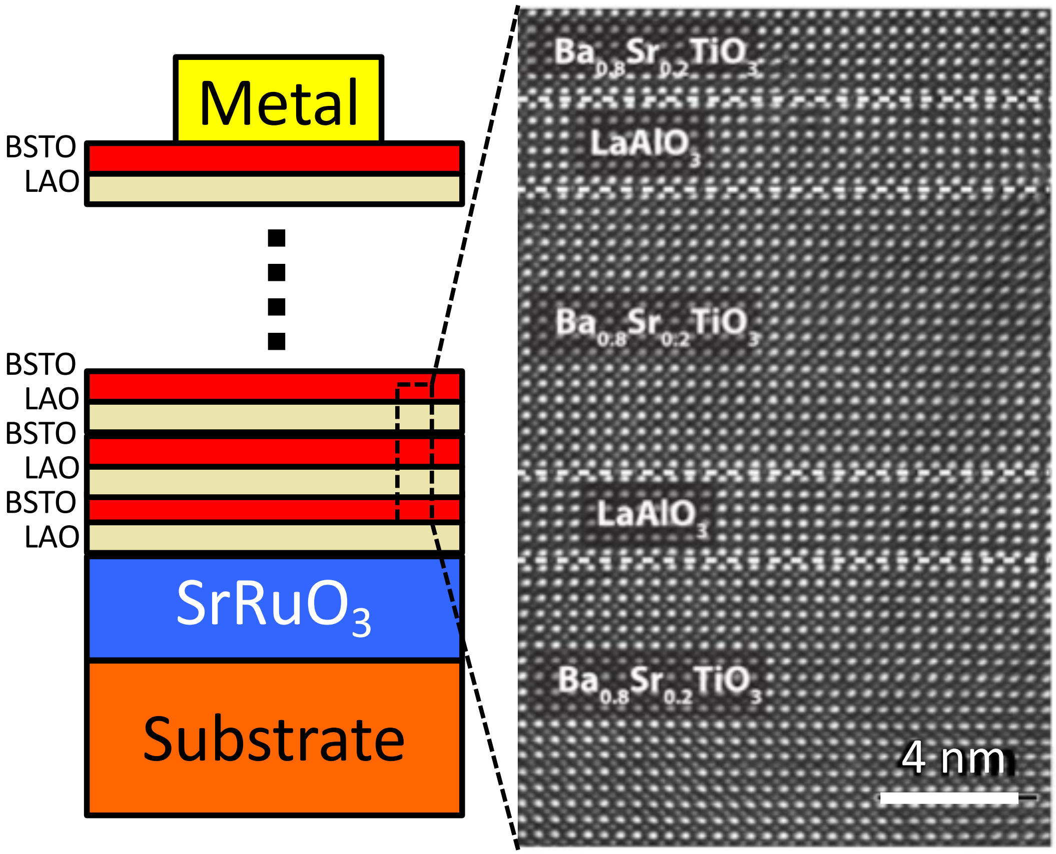


The temperature range of capacitance enhancement depends on the Curie temperature of the ferroelectric!

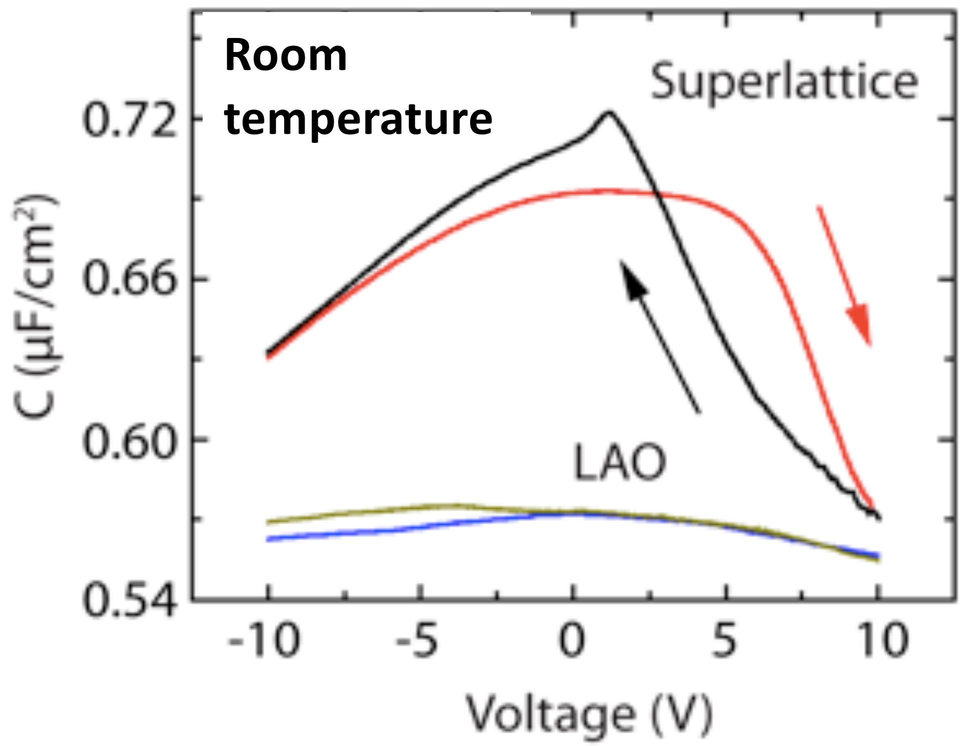
Room temperature capacitance enhancement

Ferroelectric	$(Ba_{0.8}Sr_{0.2})TiO_3$
Dielectric	$LaAlO_3$

$(Ba_{0.8}Sr_{0.2})TiO_3$ bulk Curie Temperature: <110 ^{0}C



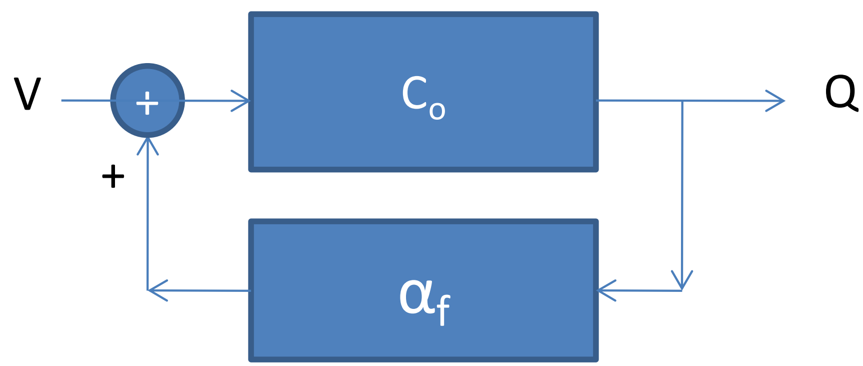
Superlattice: LAO(6 monolayer (ML))/ BSTO(18 ML) repeated 11 times on GSO.



Gao, Khan et al. Nano Lett. 14, 5814 (2014).

Negative Capacitance effect in sub-10 nm ferroelectrics at room temperature

A General Guideline for finding Negative Capacitance in different systems



$$Q = C_0(V + \alpha Q)$$

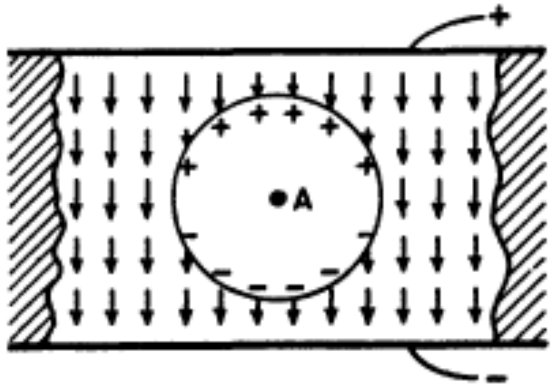
$$\boxed{C = \frac{C_0}{1 - \alpha_f C_0}}$$

$$\boxed{\alpha_f C_0 > 1 \Rightarrow C < 0}$$

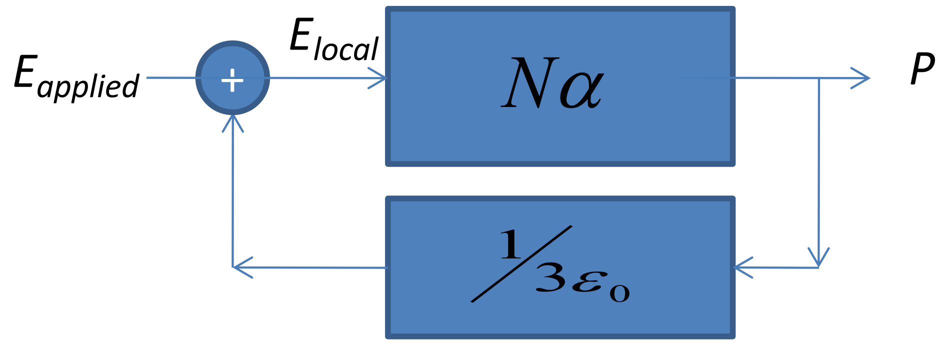
Positive feedback can give rise to Negative Capacitance

Origin of Negative Capacitance (contd)

The Clausius Mossoti Picture of Polar Insulators



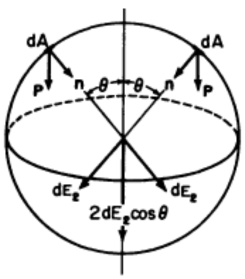
$$E_{local} = E_{applied} + \frac{P}{3\varepsilon_0}, P = N\alpha E_{local}$$



$$E_{local} = E_{applied} + E_{outside} + E_{inside}$$

$$E_{inside} = 0$$

$$E_{outside} = \frac{P}{3\varepsilon_0}$$



$$\boxed{\varepsilon_r = \frac{N\alpha/\varepsilon_0}{1 - N\alpha/3\varepsilon_0}}$$

Origin of Negative Capacitance (contd)

$$\boxed{P = \frac{N\alpha}{1 - N\alpha / 3\varepsilon_0} E_{applied}}$$

$$\alpha = \alpha_o + \frac{\mu^2}{3kT}$$

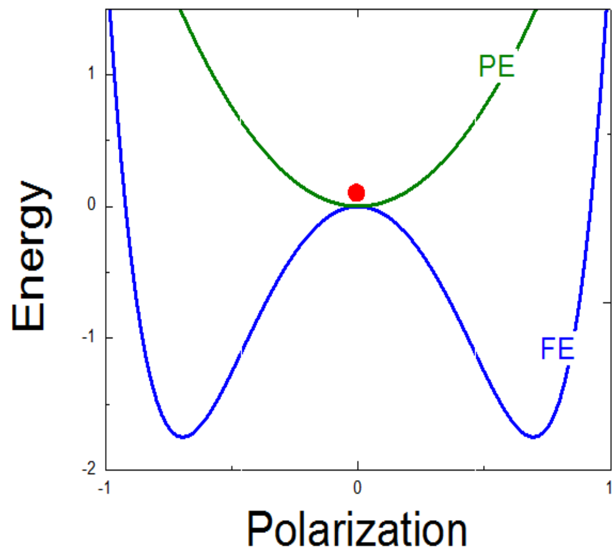
$$\varepsilon_r = \frac{3T_c}{T - T_c}$$ Curie-Weiss Law

$T<T_c$: $\varepsilon_r < 0$

Polar Catastrophe and manifestation Remnant Polarization

Feedback mechanism is well described in the framework of the mean field theory in condensed matter physics.

Landau Model incorporates the feedback mechanisms in the phenomenological energy well description of ferroelectric and paraelectric.



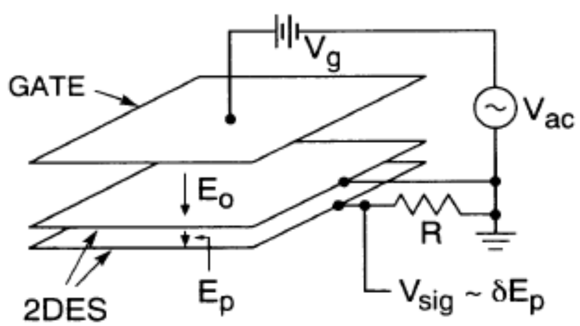
EECS

Is it possible to achieve negative capacitance in non-ferroelectric materials?

A system with bistability/stored energy can provide negative capacitance

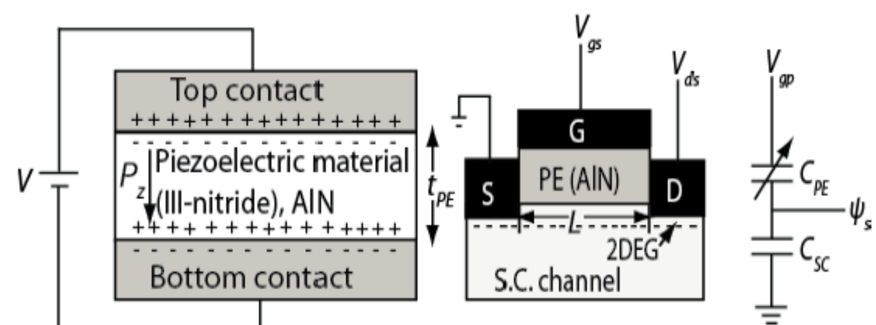
Interaction between two 2D electron gases

Electron-electron interaction; exchange and correlation energies among electrons lower the chemical potential of an electron system as the electron density increases.



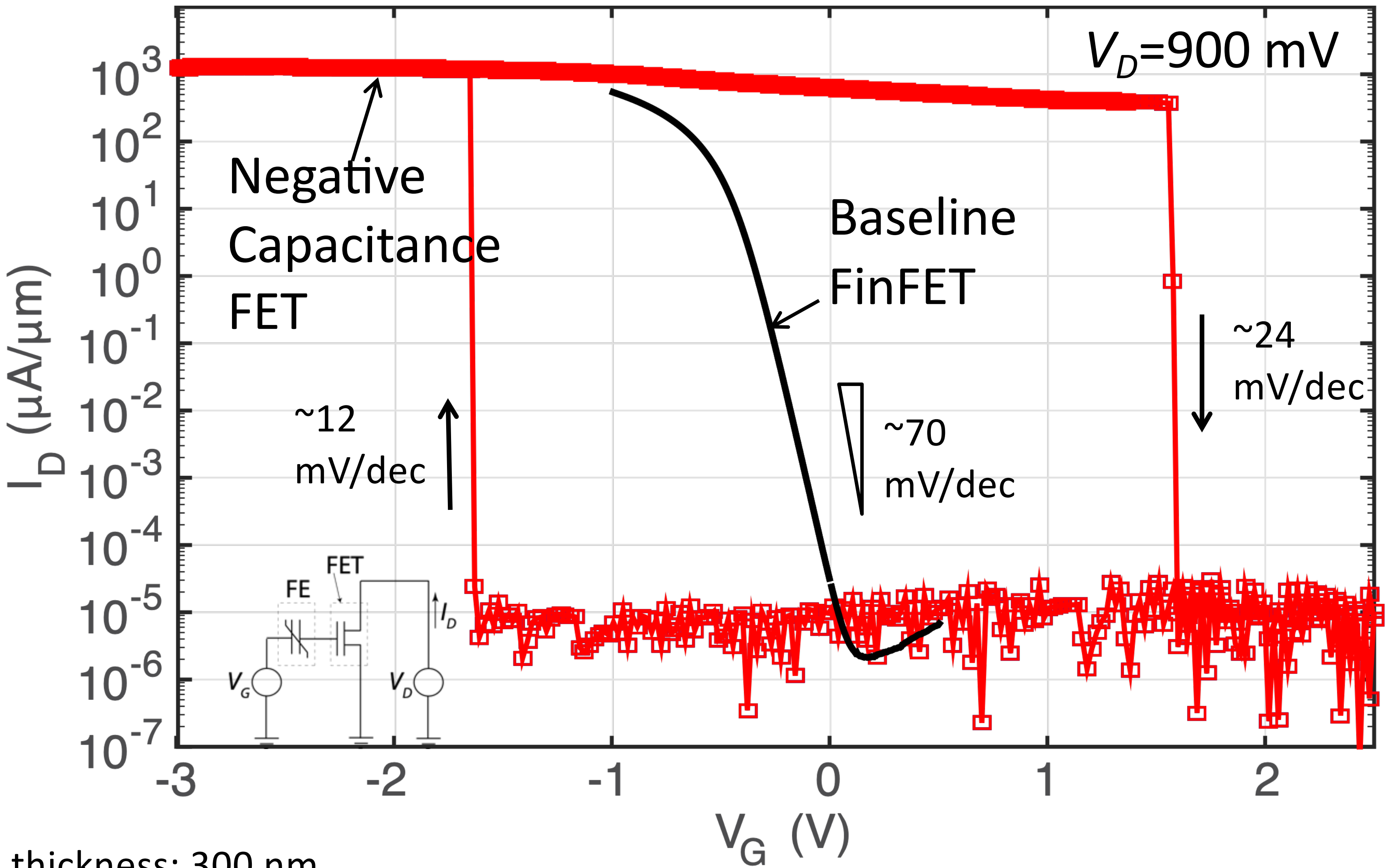
Eisenstein, et al. Phys. Rev. Lett. 68, 674 ('92)
Li et al. Science 332, 825 ('11).

Piezoelectricity



Jana et al. Physica Status Solidi (c) 10, 1469 ('13).
Jana et al. IEDM 2014.
Wong et al. IEDM 2014.

Negative Capacitance Transistors: Experiment



FE thickness: 300 nm

FinFET L_G=100 nm

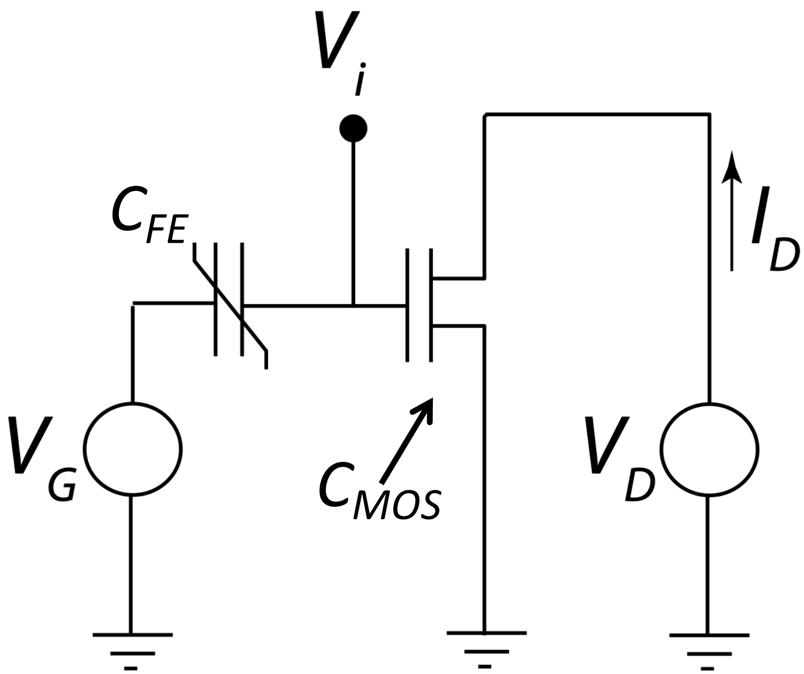
Fin width=35 nm

Fin height=25 nm

EOT=1.4 nm

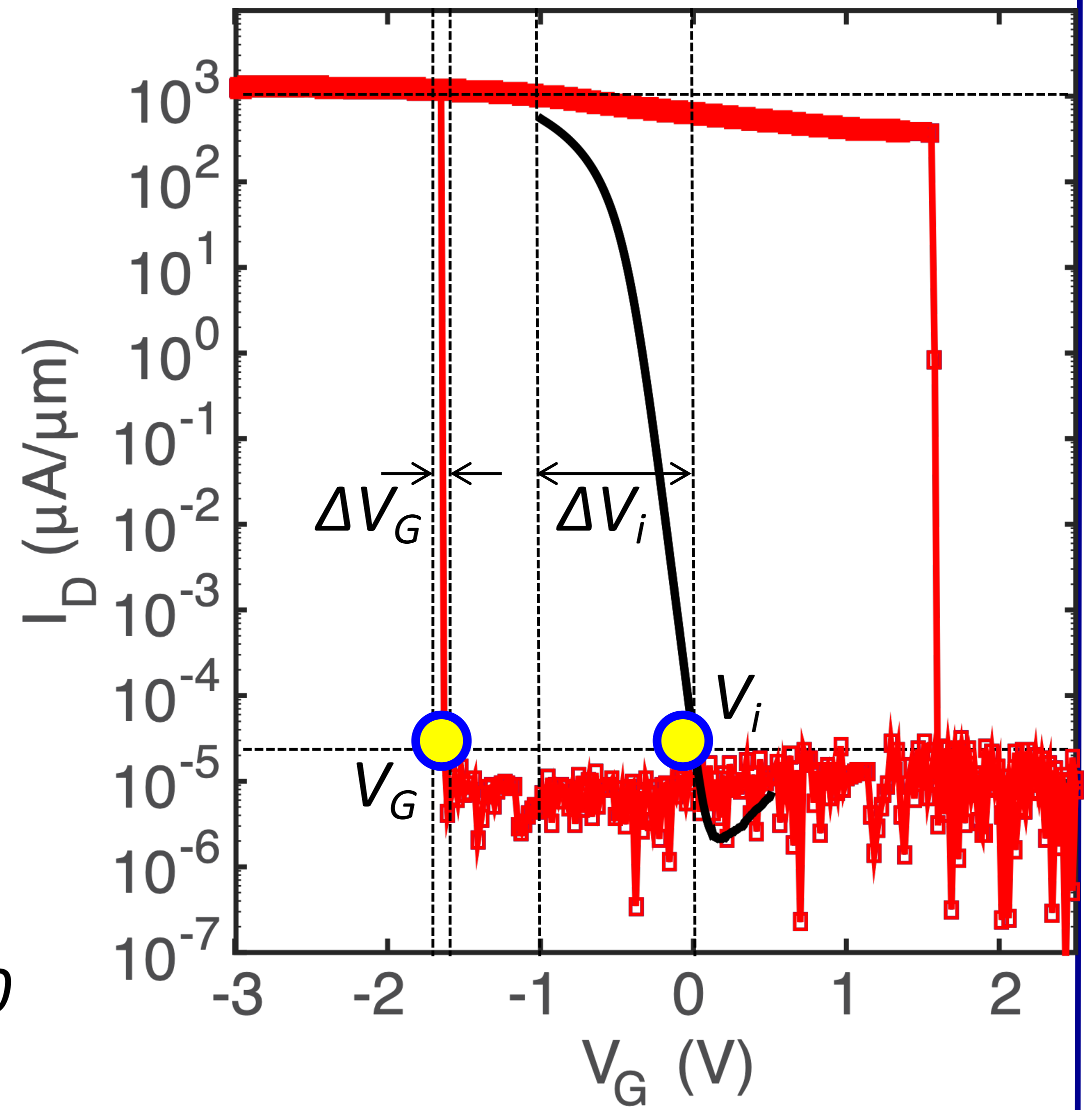
Extremely sharp turn-on & –off (10-20 mV/dec) over 7-8 orders of on-current!

Negative Capacitance Transistors: Experiment



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

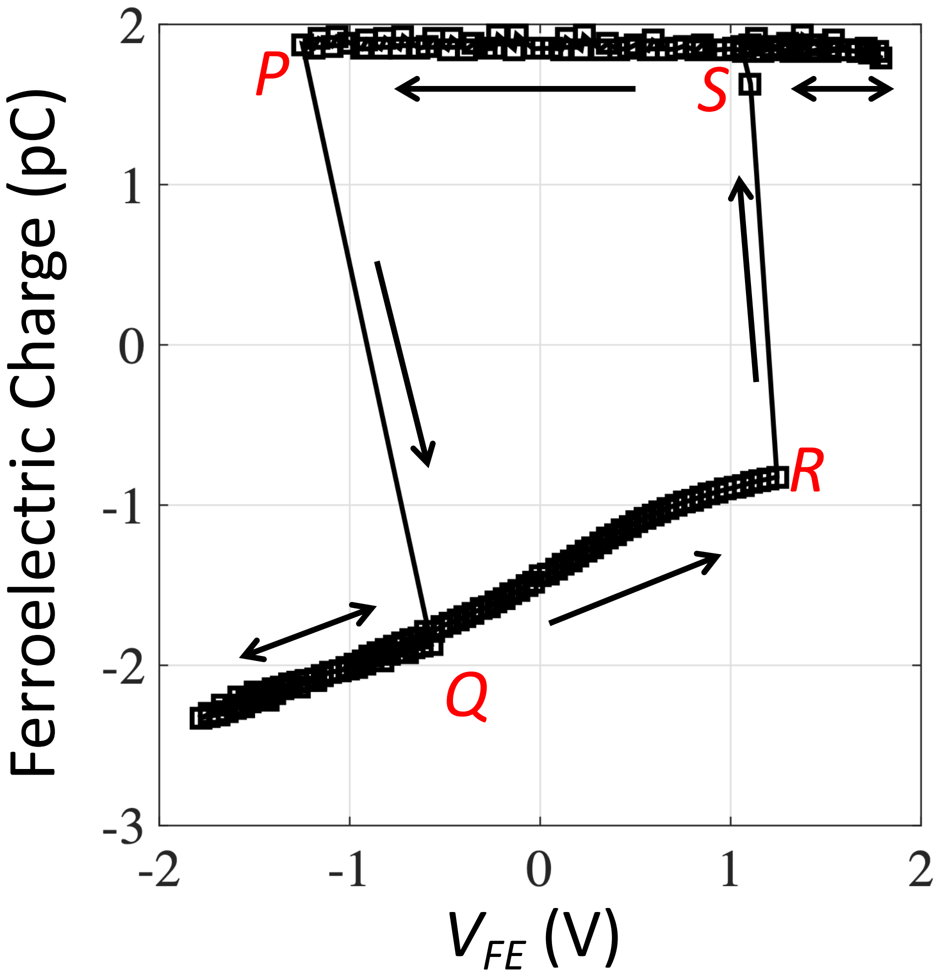
$$\frac{\Delta V_i}{\Delta V_G} = \frac{C_{FE}}{C_{MOS}+C_{FE}} \quad >1 \textit{ only if } C_{FE}<0$$



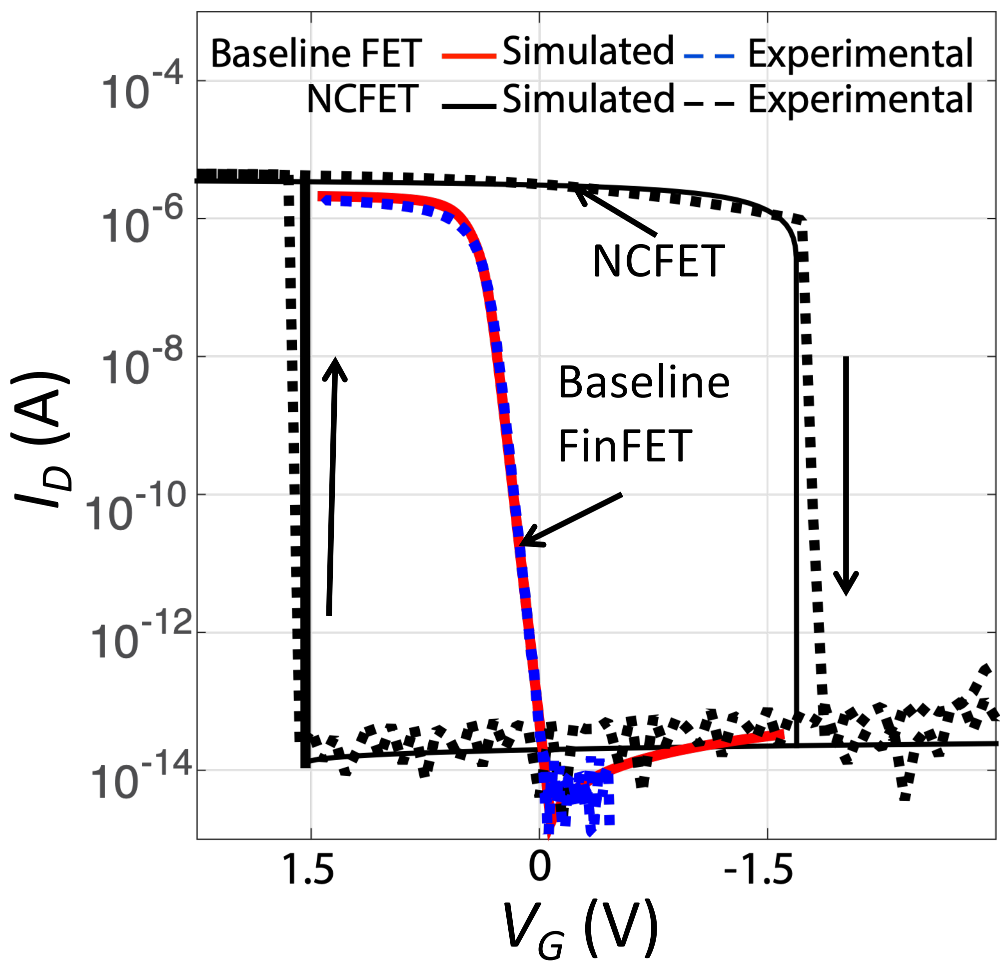
Sharp switching occurs due to ferroelectric negative capacitance!

Negative Capacitance Transistors: Experiment

Hysteresis Loop
extracted from the circuit



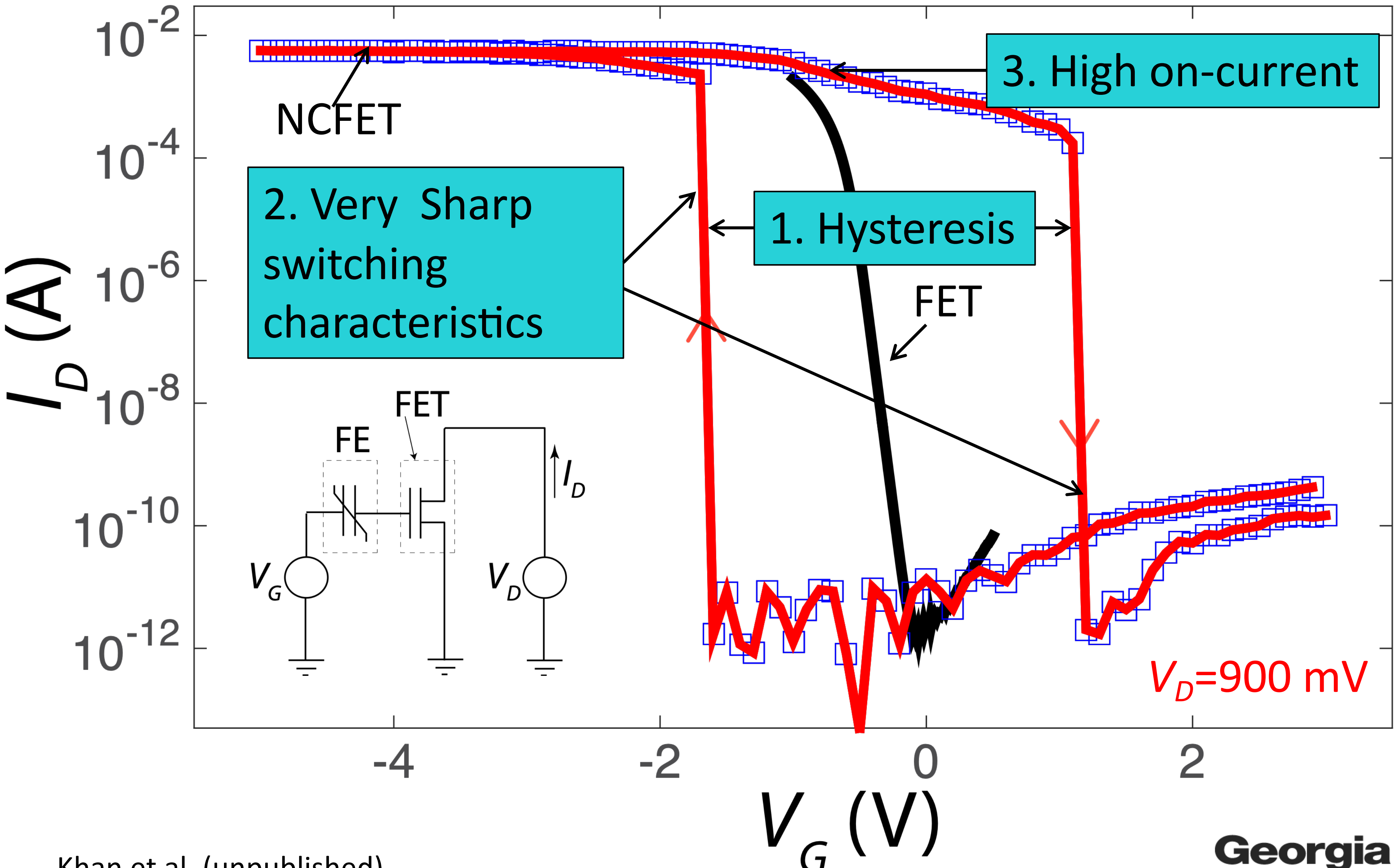
Experiment vs. Simulation



Negative Capacitance
Regions: PQ and RS

Sharp switching occurs due to
ferroelectric negative capacitance!

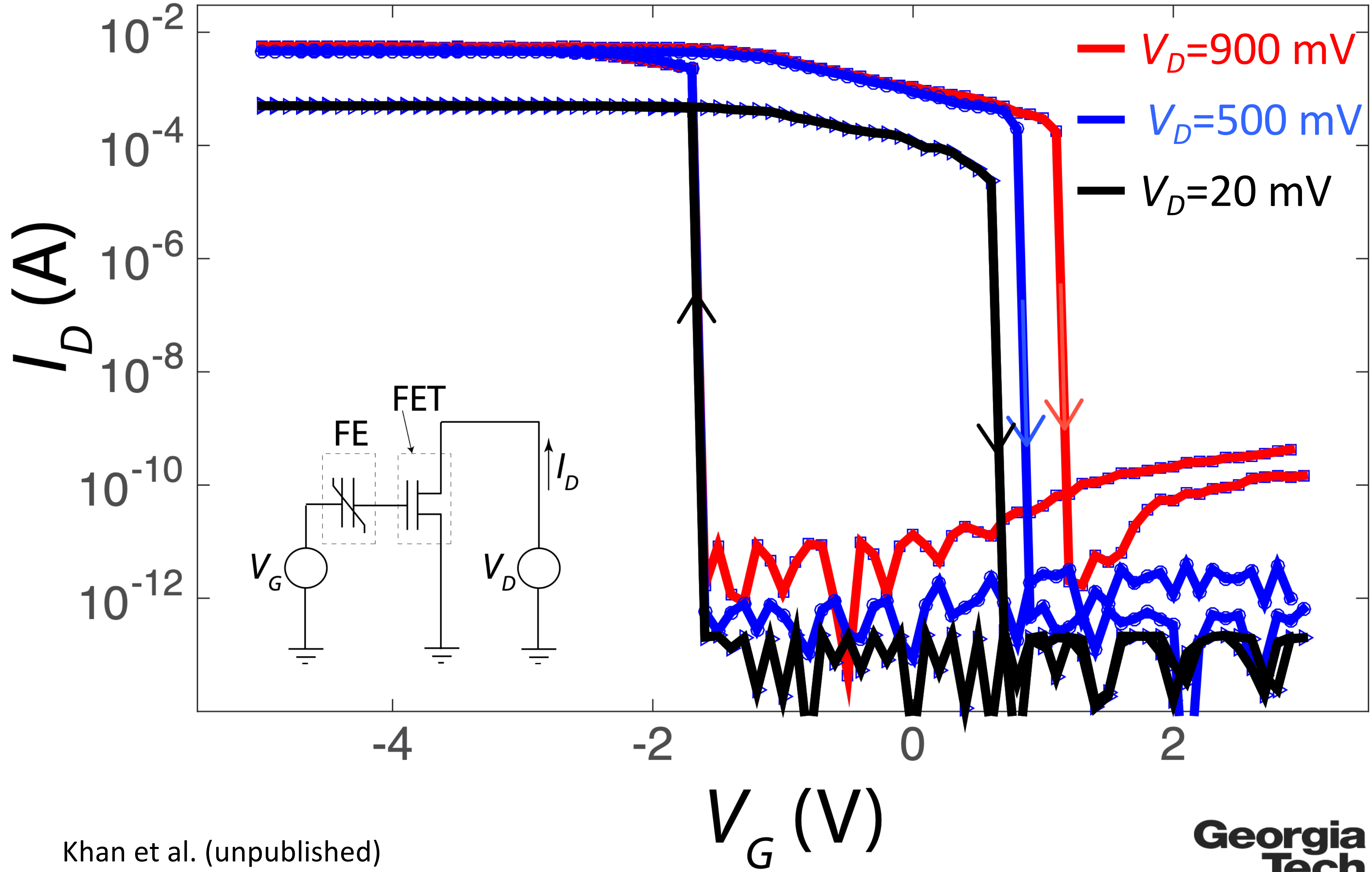
External connection to a ferroelectric



Khan et al. (unpublished)

Georgia Tech

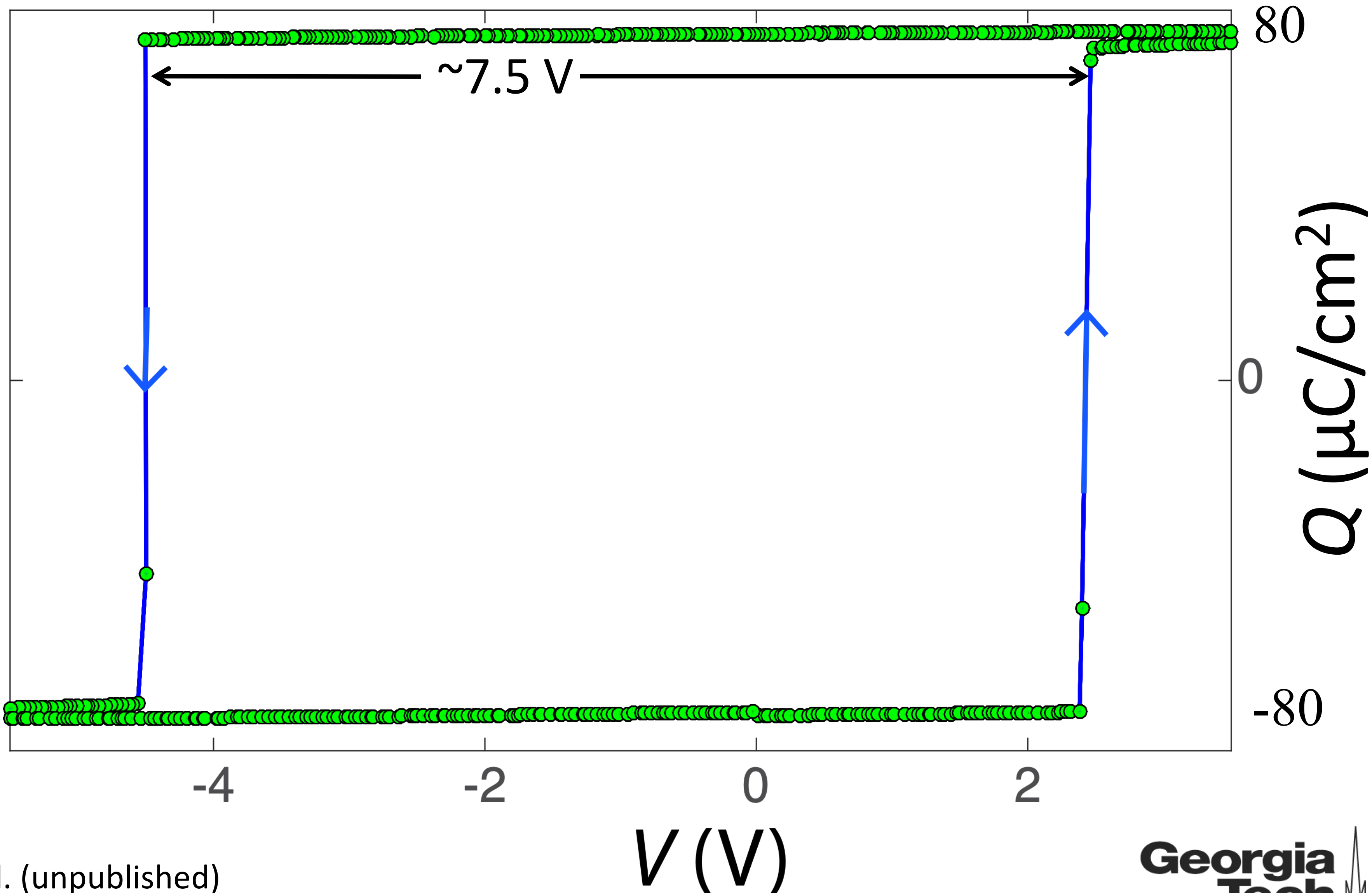
External connection to a ferroelectric



Khan et al. (unpublished)

External connection to a ferroelectric

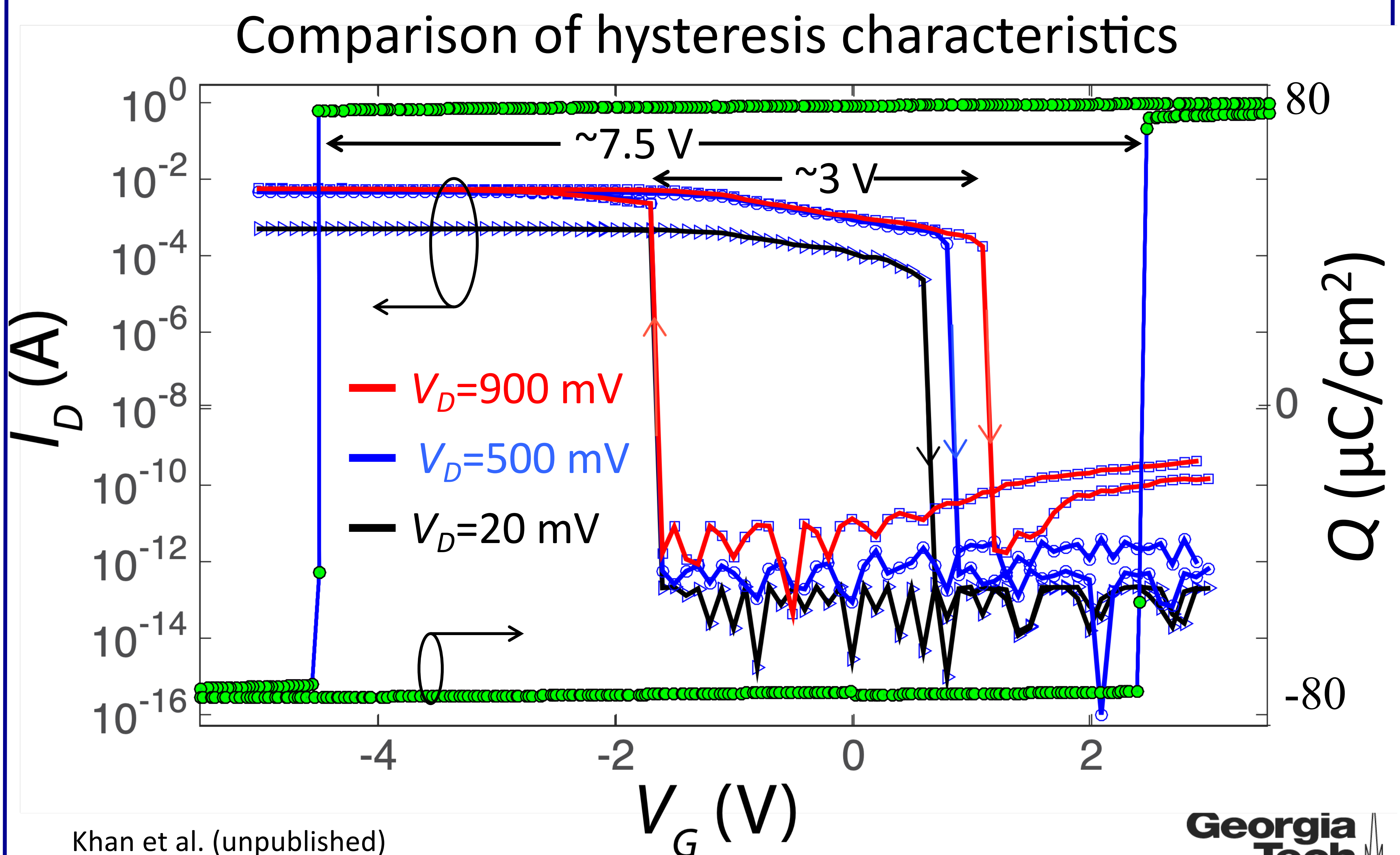
Q-*V* Characteristics of the ferroelectric capacitor



Khan et al. (unpublished)

Georgia Tech

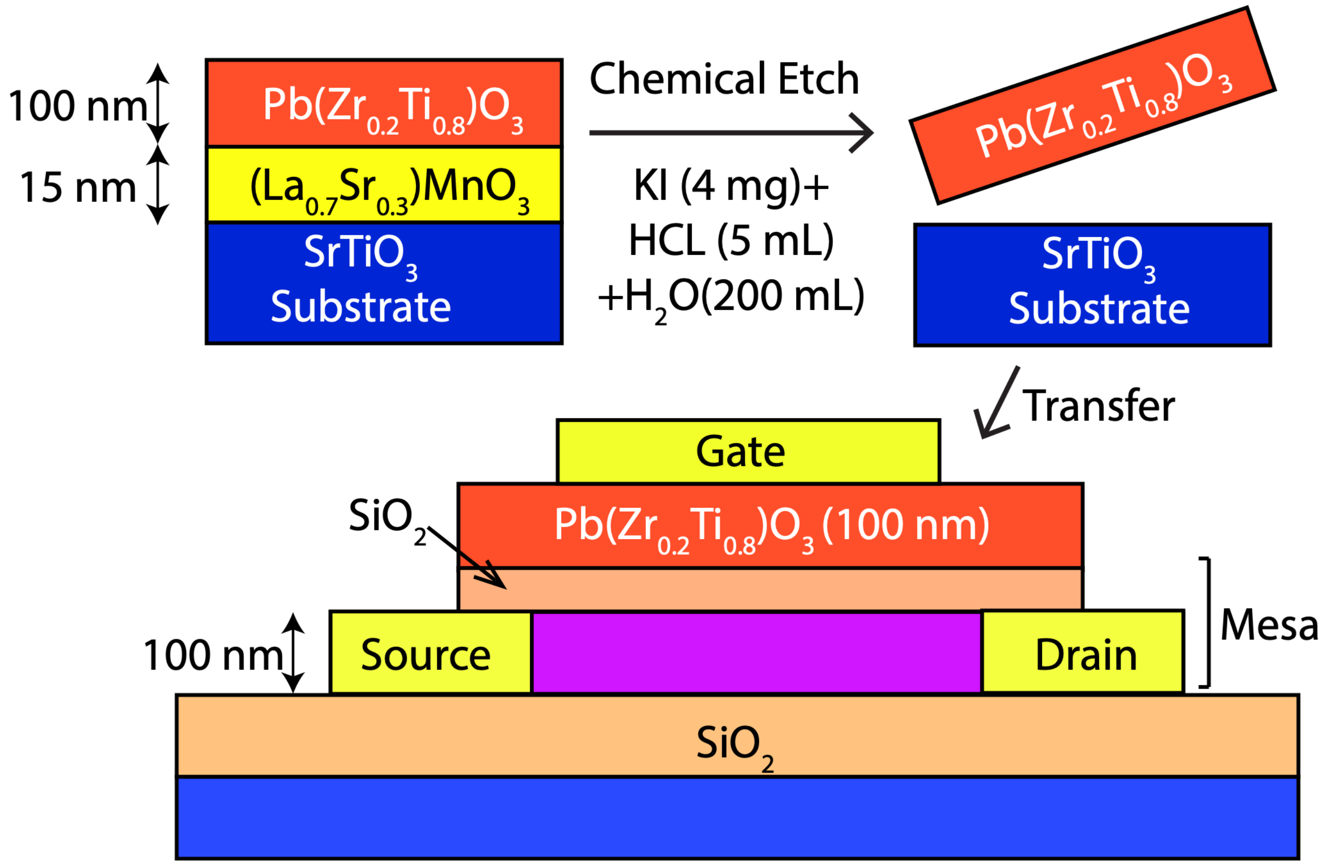
External connection to a ferroelectric



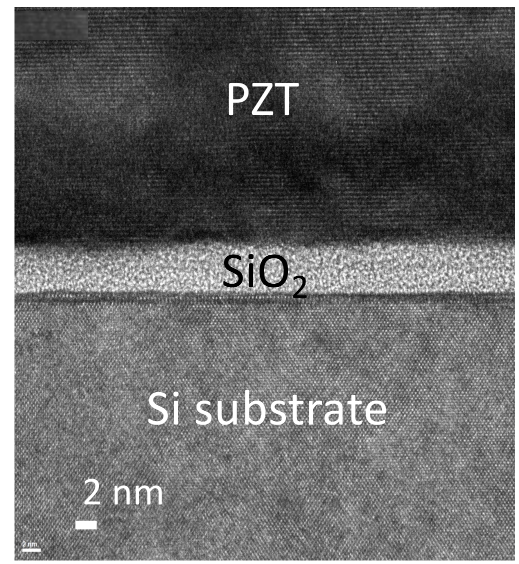
Khan et al. (unpublished)

Fully Integrated Ferroelectric FET

Transfer Technique of Epitaxial Ferroelectric



TEM Image



Bakaul,..,Khan et al. Nature Comm. 7, 10540 (2016)

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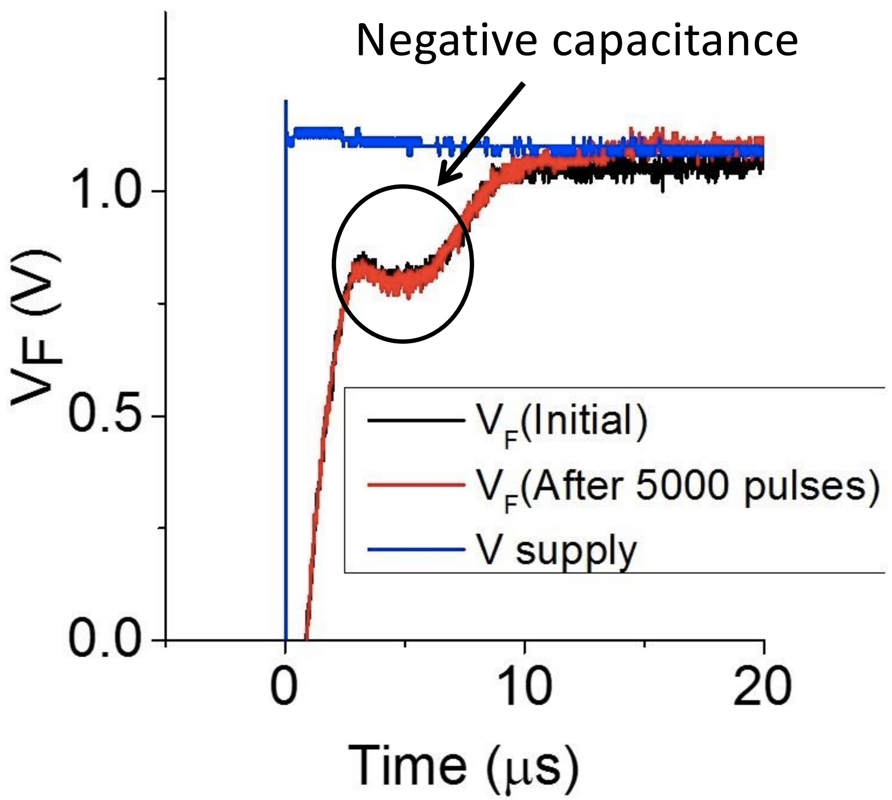
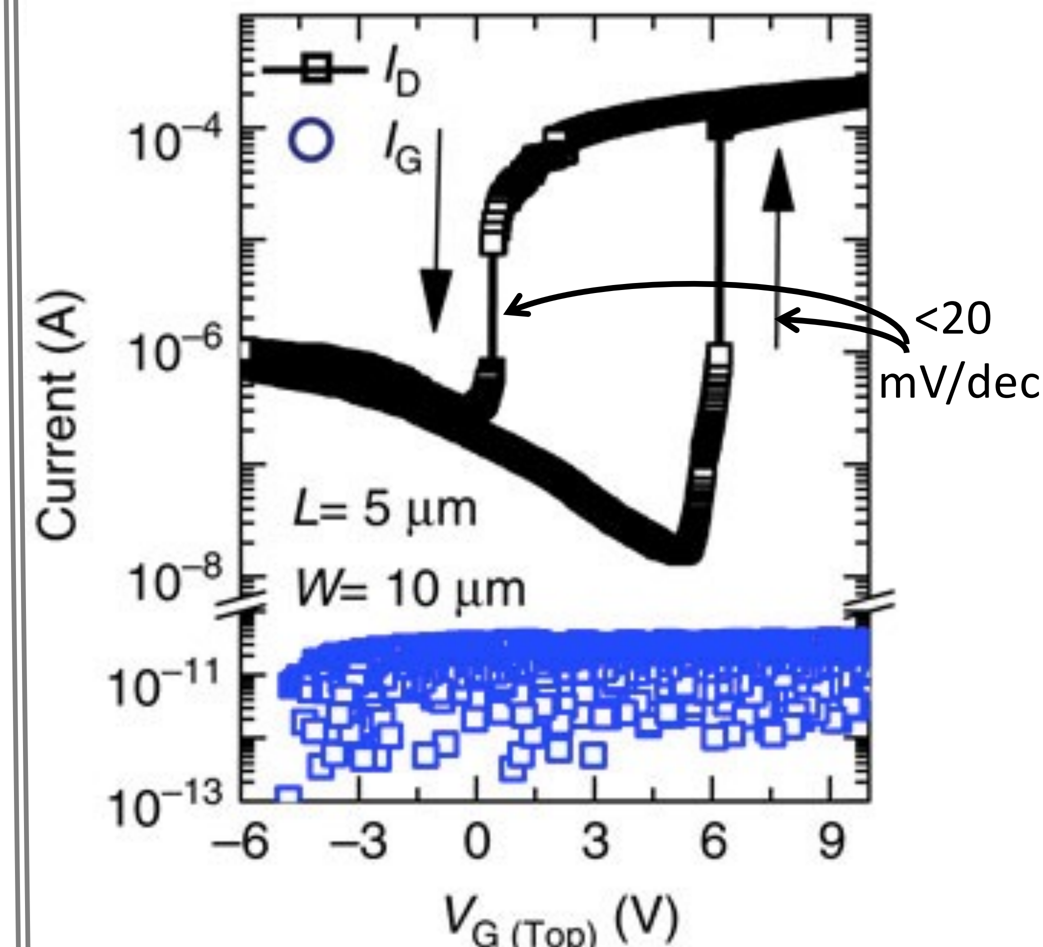
Fully Integrated Ferroelectric FET

Negative Capacitance Transients



Transferred ferroelectric films show negative capacitance transients.

Characteristics of FE-FET



World's First Epitaxial Single Crystal Ferroelectric FET!

Bakaul,..,Khan et al. Nature Comm. 7, 10540 (2016)

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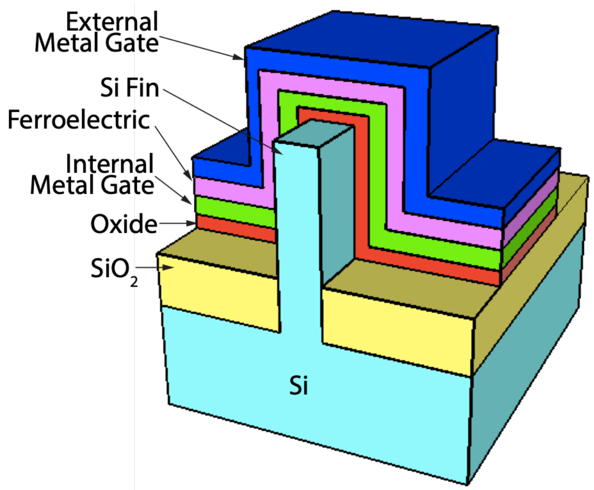
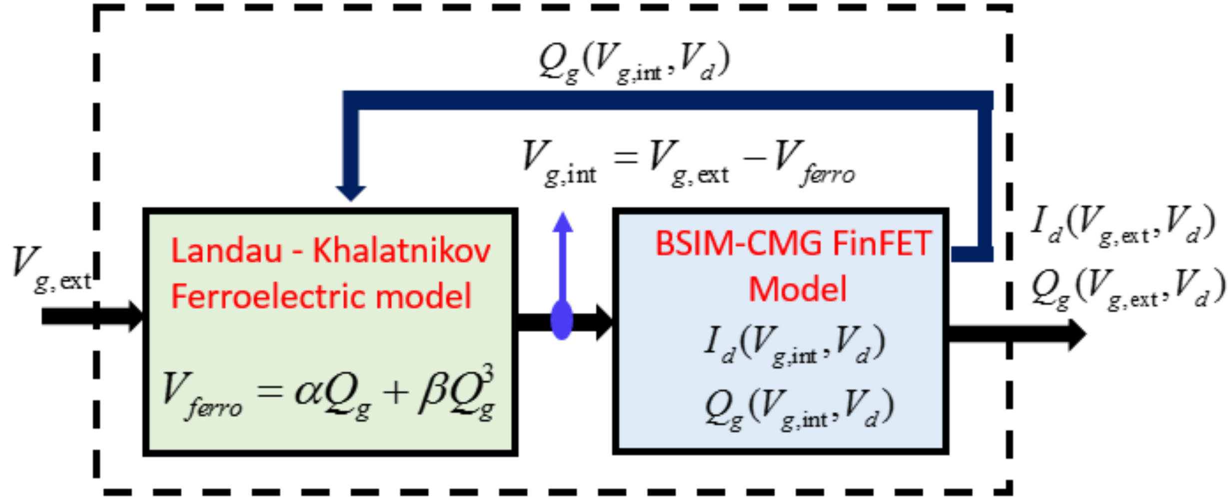
Performance Projection of NCFETs

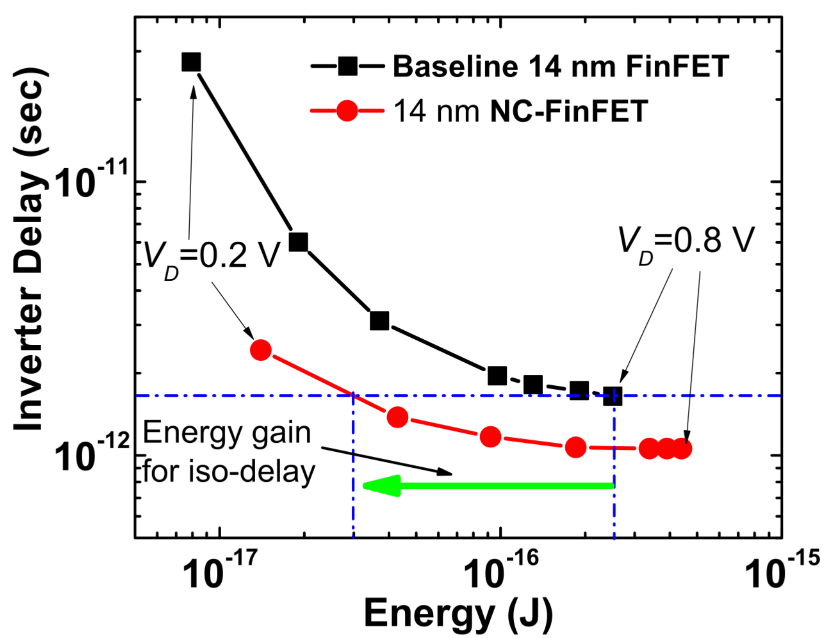
14 nm FinFET Node



Compact Model



Energy-Delay Curve



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

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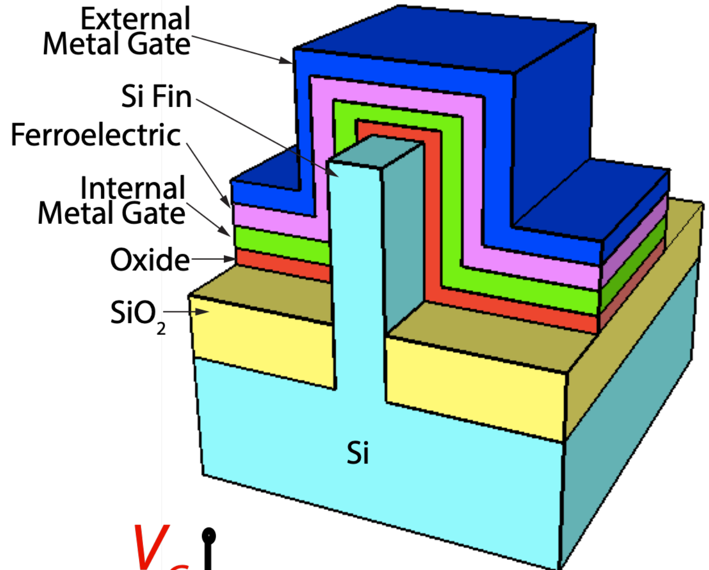
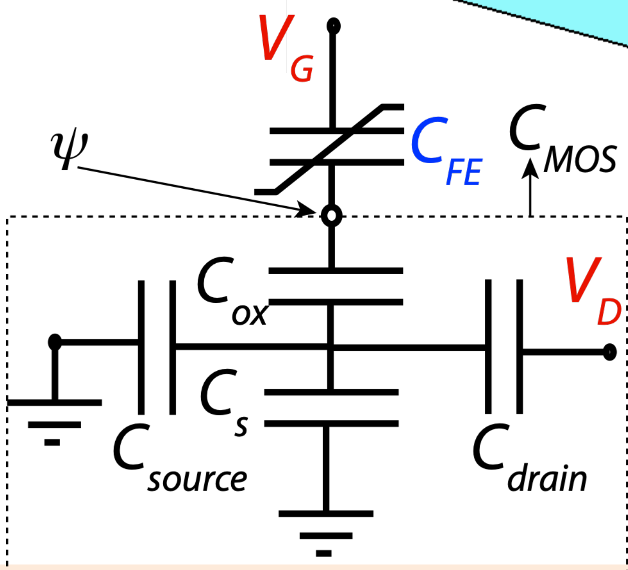
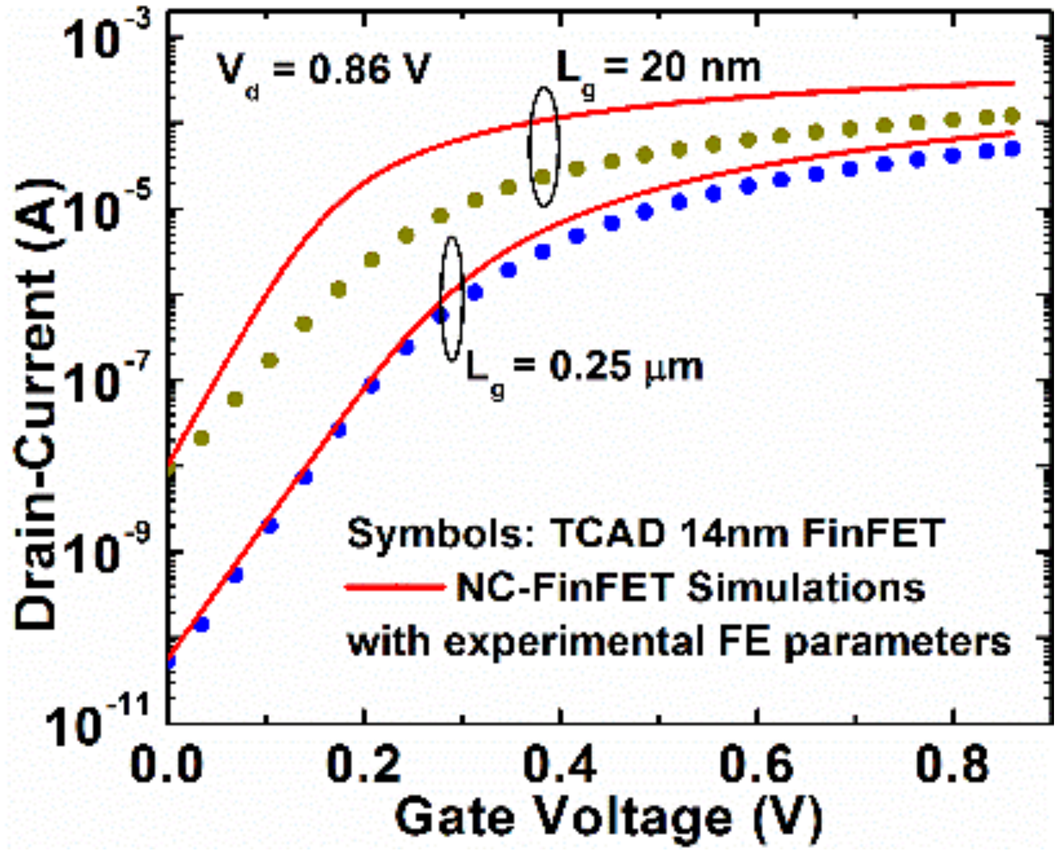
Short L_g Negative Capacitance Transistors







Improvement of Subthreshold Swing is higher in short channel transistors!

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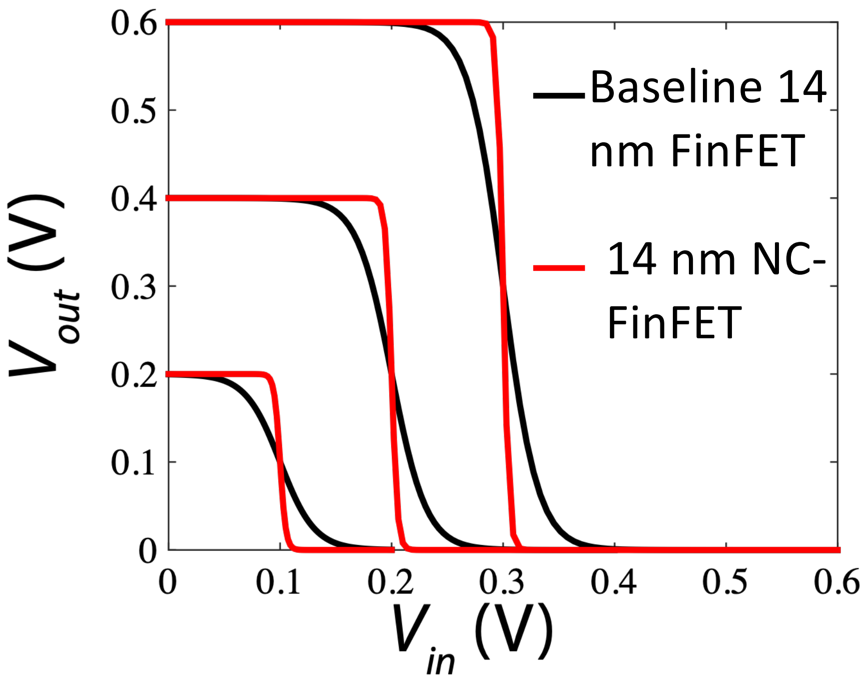
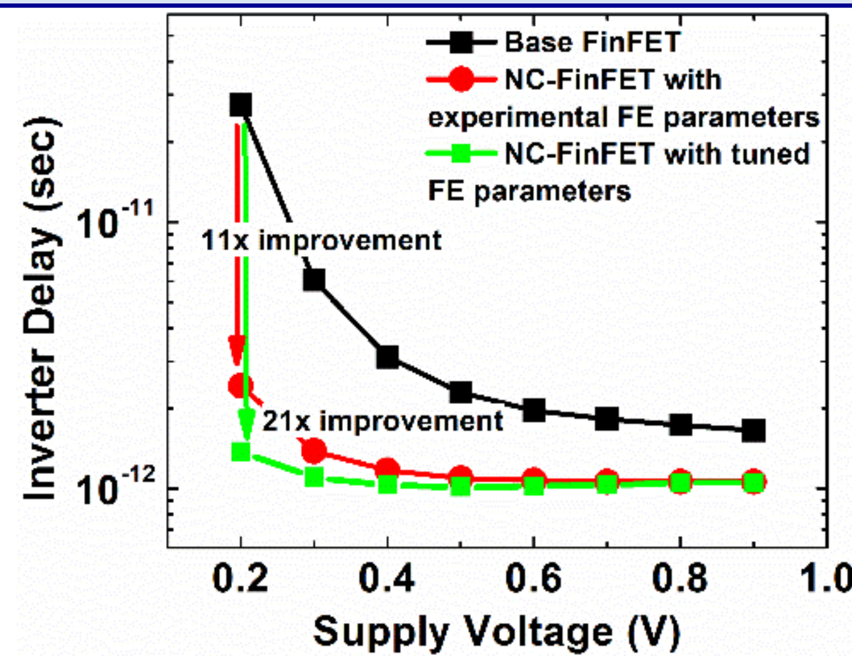
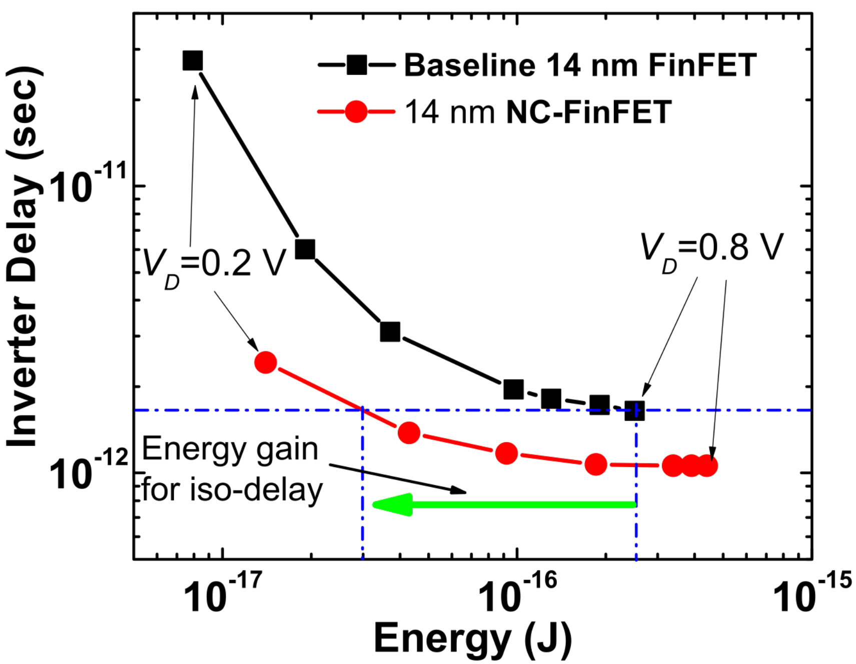
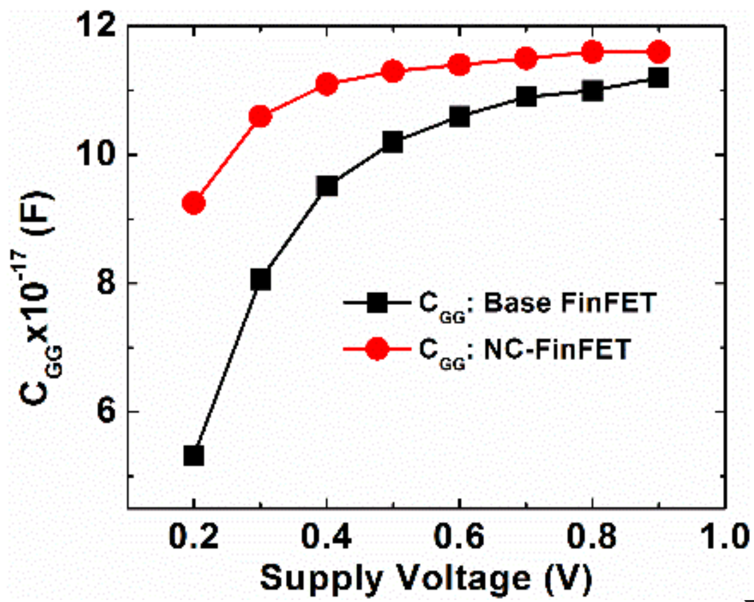
Performance Projection of NCFETs









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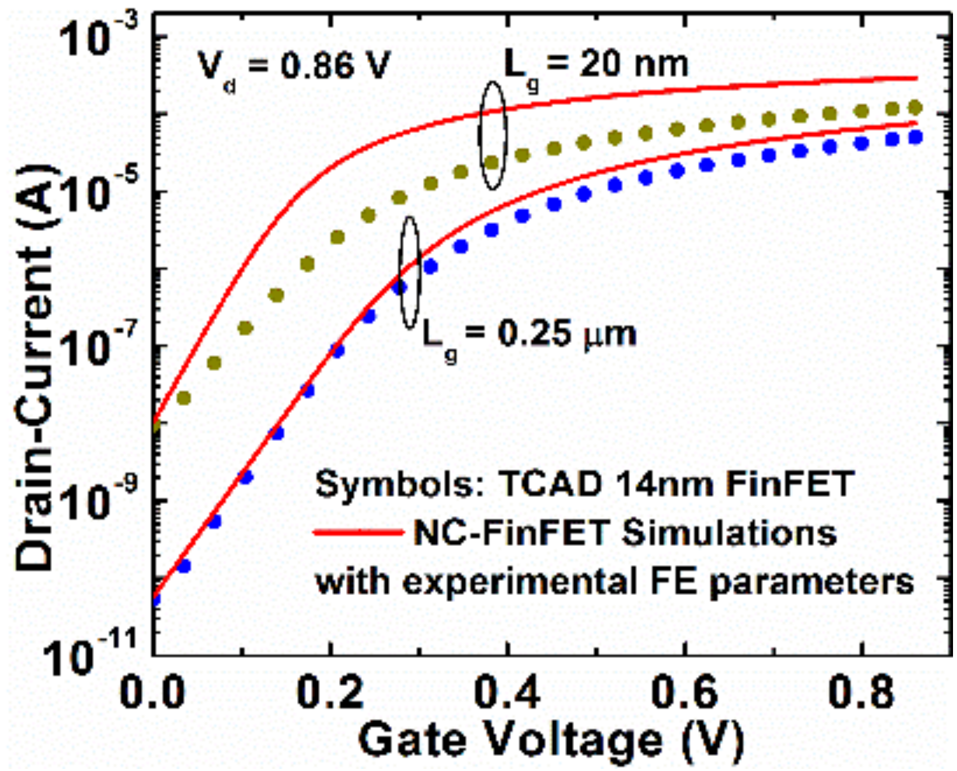
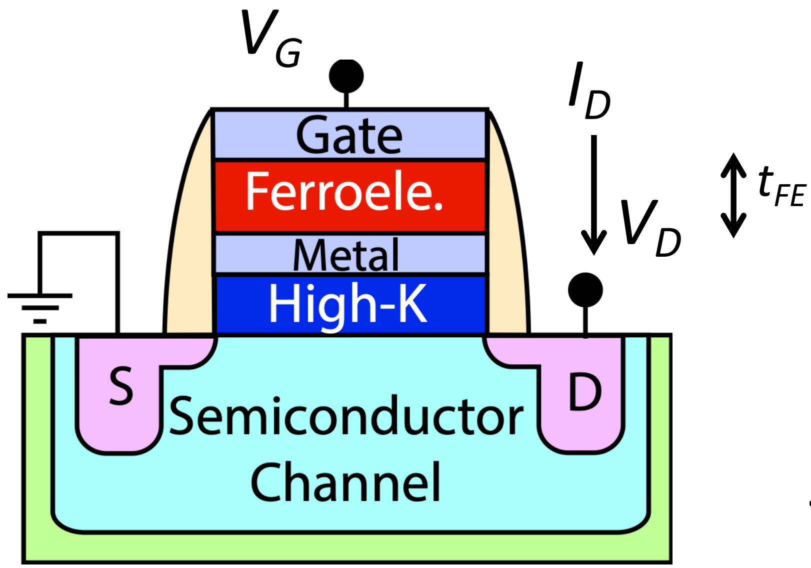
Effects of Channel Length Scaling

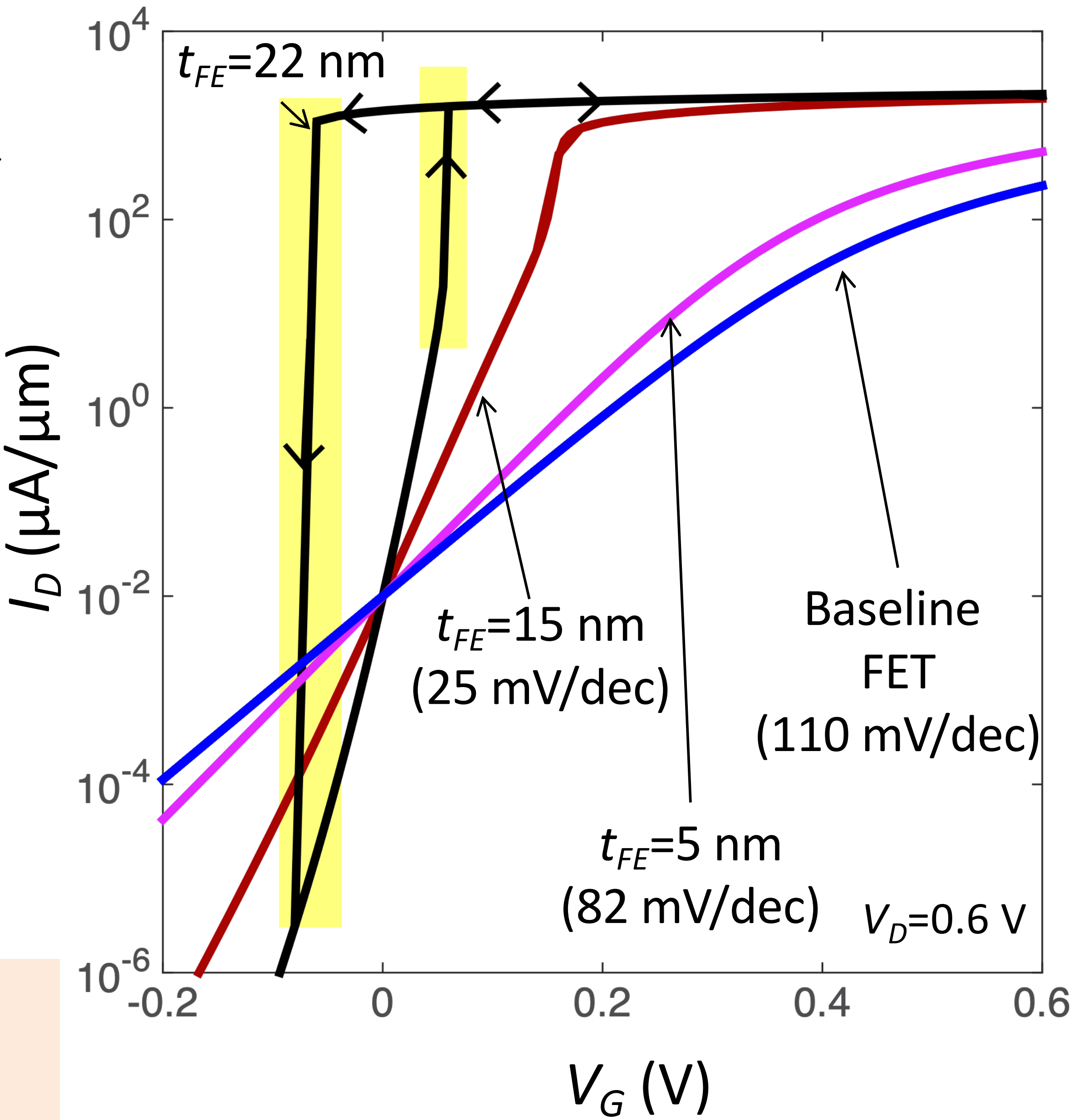


Physics of Negative Capacitance FET



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

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



Capacitance Matching can lead to wide range of behavior in NCFETs!

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Stability Criteria

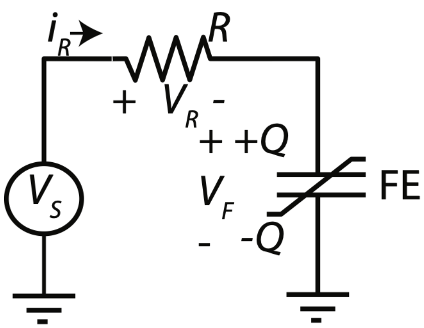
$$V_S = R\frac{dQ}{dt} + V_F(Q)$$

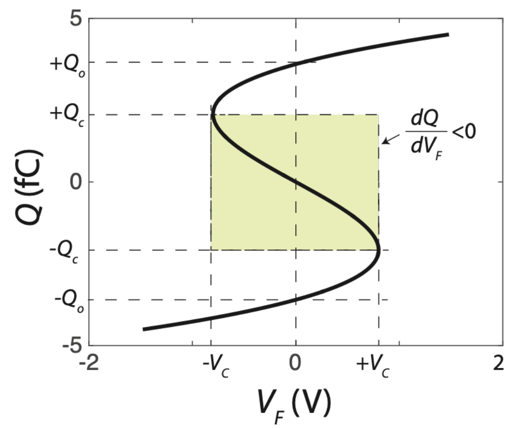
$$\frac{dQ}{dt} = \frac{1}{R}(V_S - (\alpha Q + \beta Q^3))$$

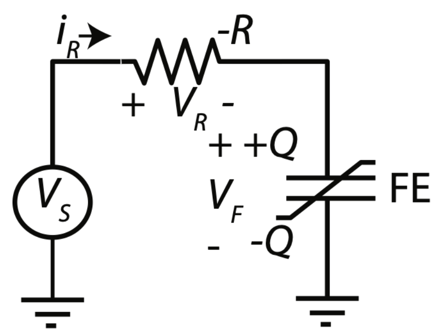
$$V_S = -R\frac{dQ}{dt} + V_F(Q)$$

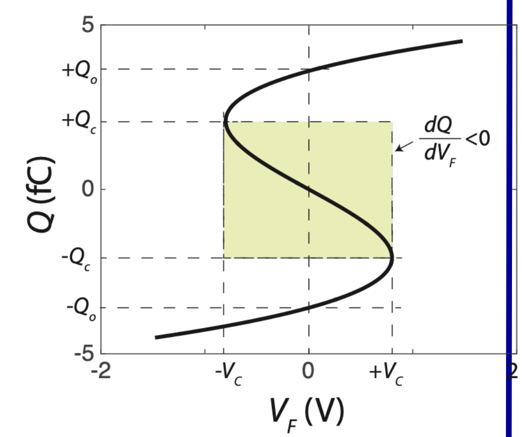
$$\frac{dQ}{dt} = -\frac{1}{R}(V_S - (\alpha Q + \beta Q^3))$$

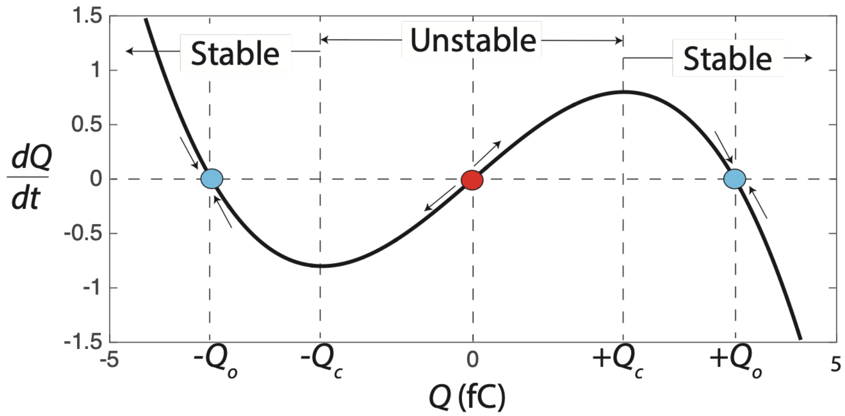
$$V_F = \alpha Q + \beta Q^3$$

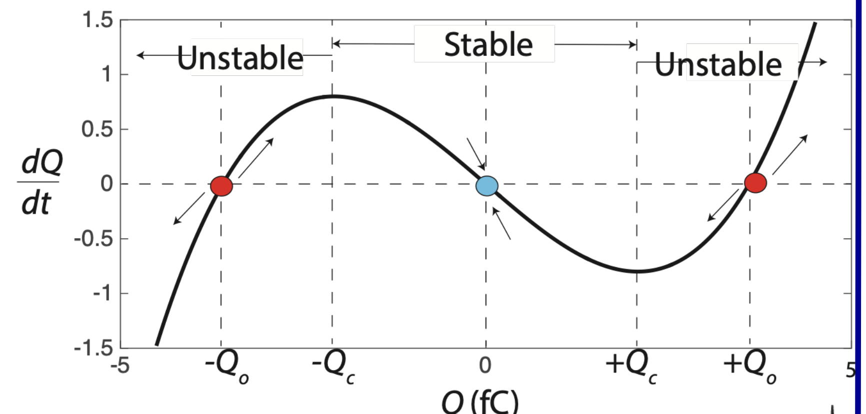






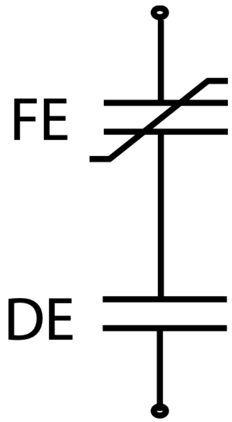






New Applications of Negative Capacitance

DRAM Technology with Negative Capacitance



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

General structure of DRAM capacitor

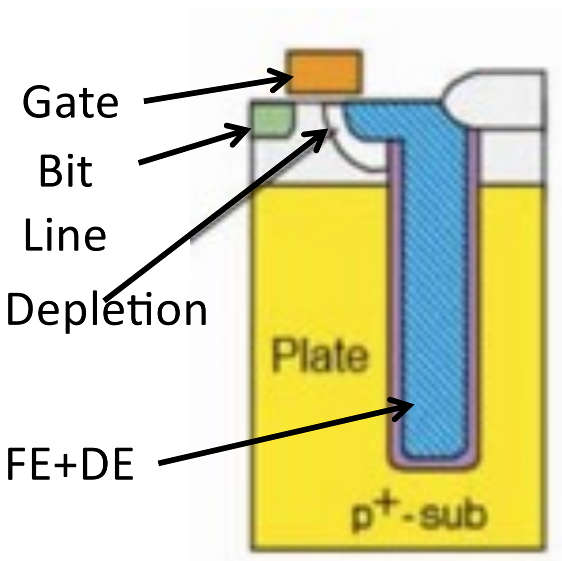
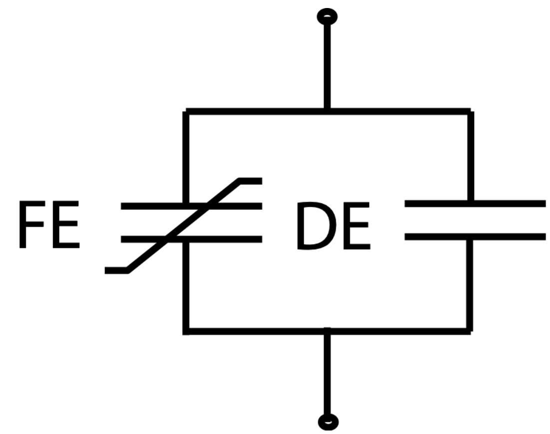


Image source: Kim et al. IEDM 2012

Capacitance Enhancement can help DRAM Scaling

Interconnect Technology with Negative Capacitance



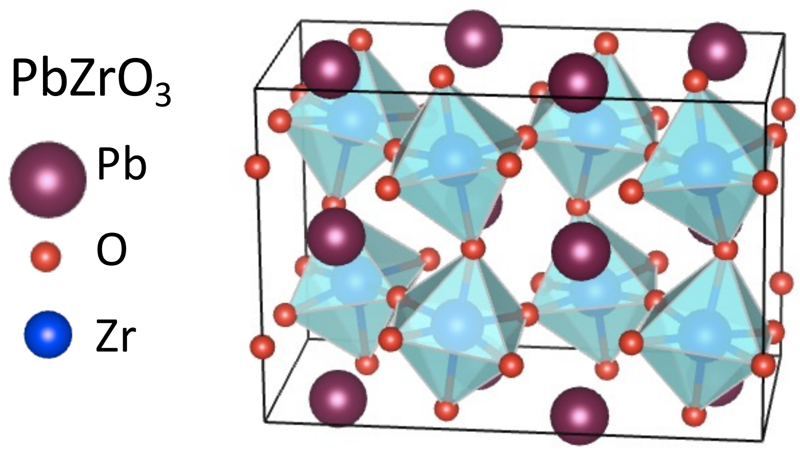
$$C_{eq} = C_{DE} - |C_{FE}|$$

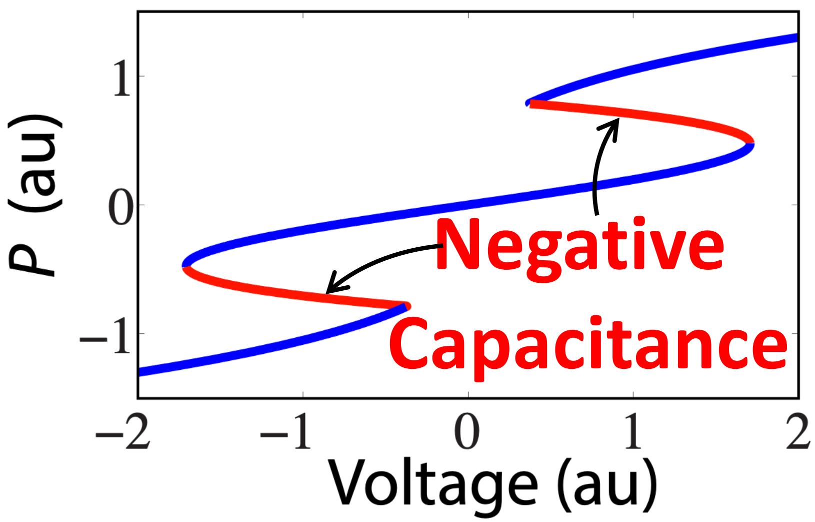
Negative capacitance reduce the capacitance in a parallel combination

Capacitance reduction techniques can lead to better interconnects

Antiferroelectric Negative Capacitance

Antiferroelectrics





Negative capacitance regions marked by **red curves**.

Material Systems

- Complex Oxide Antiferroelectrics
  - $Pb(Zr_xTi_{1-x})O_3$ and doped variants
  - $BeFeO_3$ and doped variants
    Growth: Pulsed laser deposition
- CMOS Compatible $Hf_xZr_{1-x}O_2$
  Growth: Atomic layer deposition, sputtering, pulsed laser deposition

Why Antiferroelectricity?

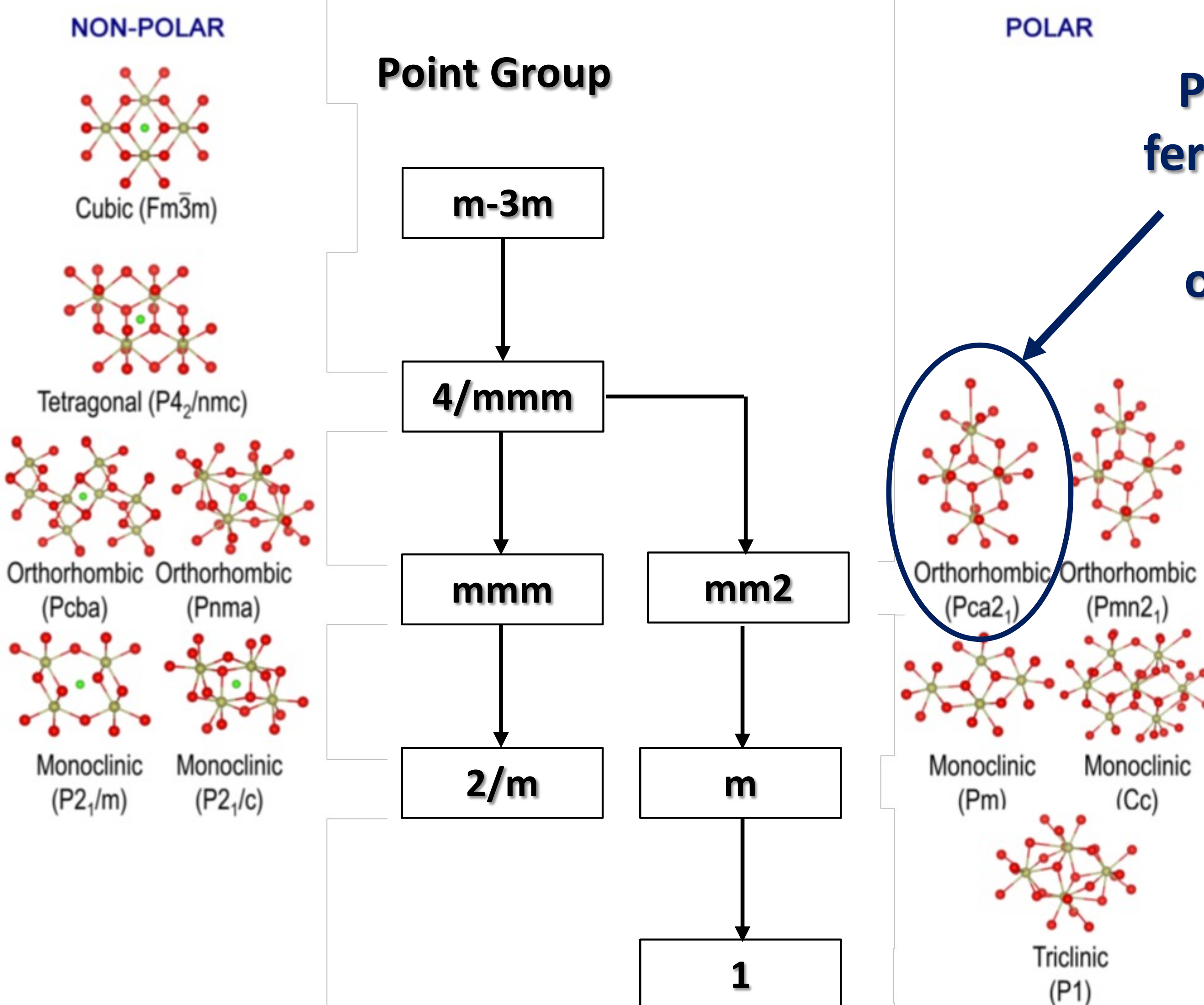
- Better charge matching of the negative capacitance region with that of MOSFET
- Possibility of Intrinsic Switching

Antiferroelectrics may show stronger negative capacitance effects!

Origin of Ferroelectricity in HfO_2

Tetragonal to Cubic @ 2800 K

Monoclinic to Tetragonal @ 2000 K



Polycrystalline ferroelectric films belong to orthorhombic space group $Pca2_1$

Huan *et.al.,* Phys. Rev. B, **90**, 064111 (2014)

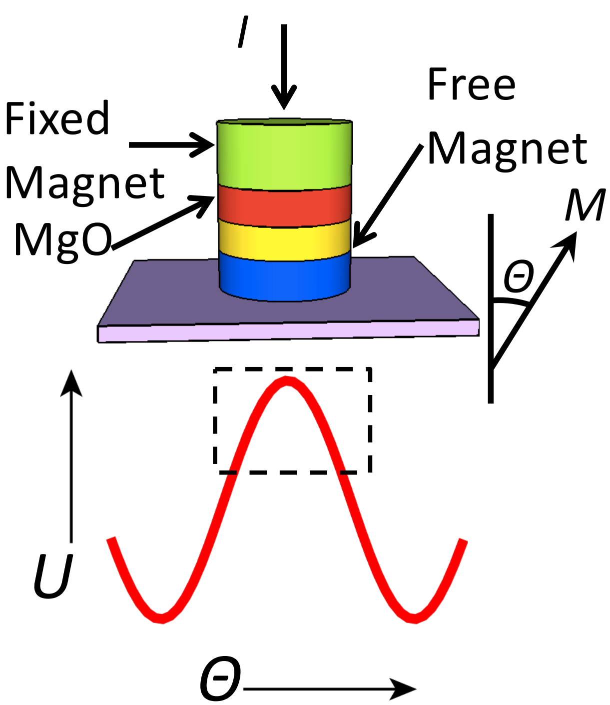
What is there for Physics and Beyond

Static Negative Dielectric Constant is important in the context of Electromagnetism!

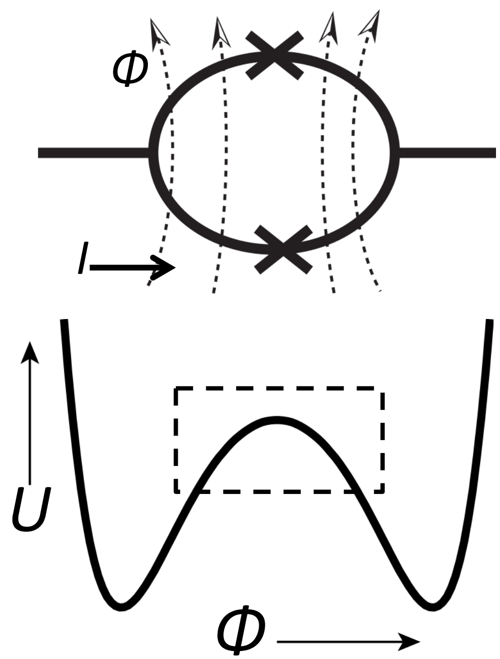
Landau, Liftshitz. Electrodynamics of Continuous Media (Pergamon, NY) 1960.
Pines. The Theory of Quantum Liquids (Benjamin, New York), 1960.

Martin. Phys. Bev. 161, 143 (1967).
Kirzhnits. Sov. Phys. -Usp. 19, 530 (1976).
Dolgov et al. Rev. Mod. Phys. 53, 81 (1981).

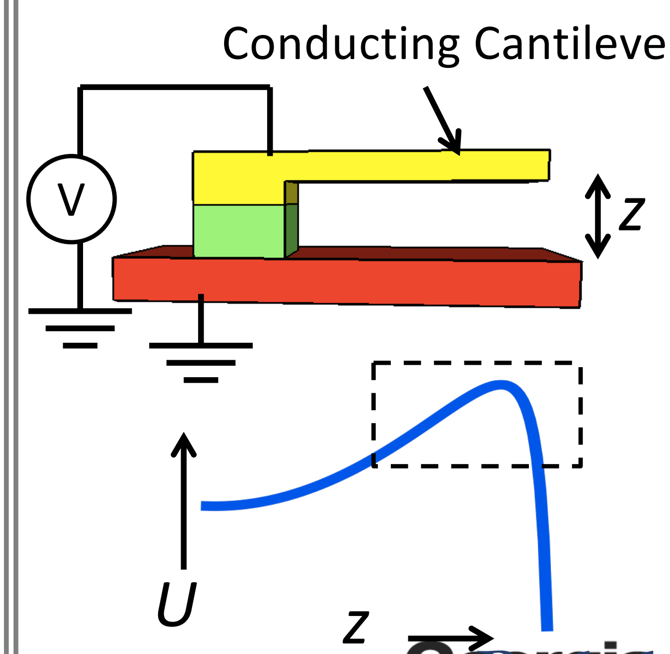
Spintronic Devices



Superconducting Devices

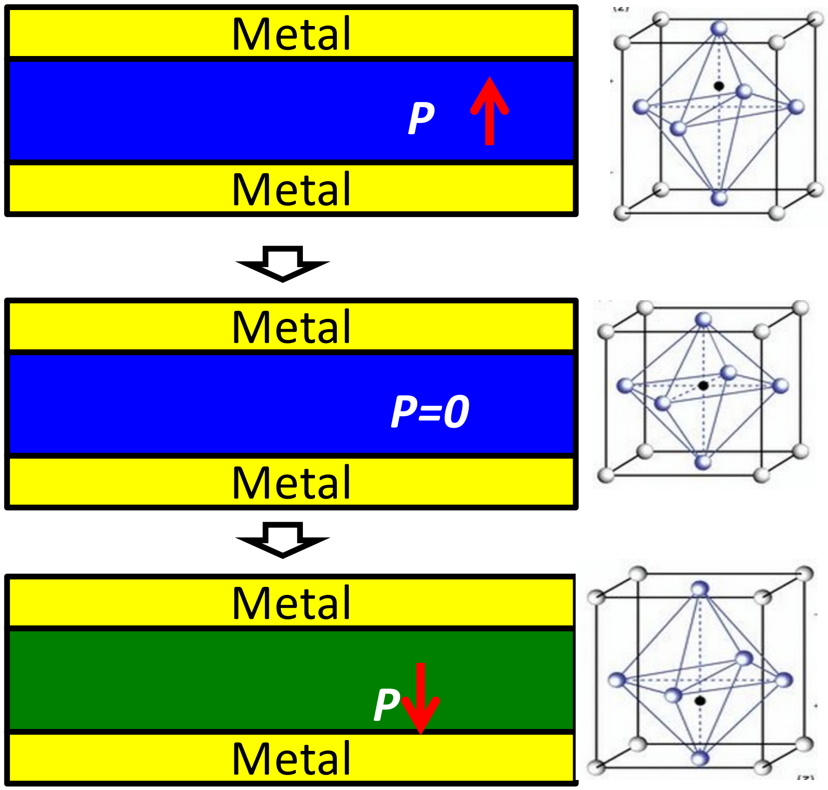


MEMS Devices

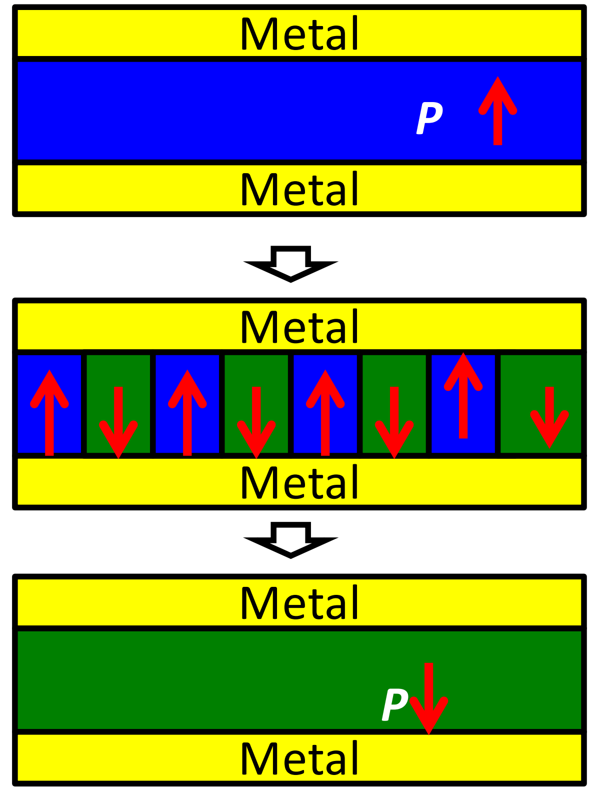


Effects of Domain Mechanisms

Landau-Khalatnikov Dynamics

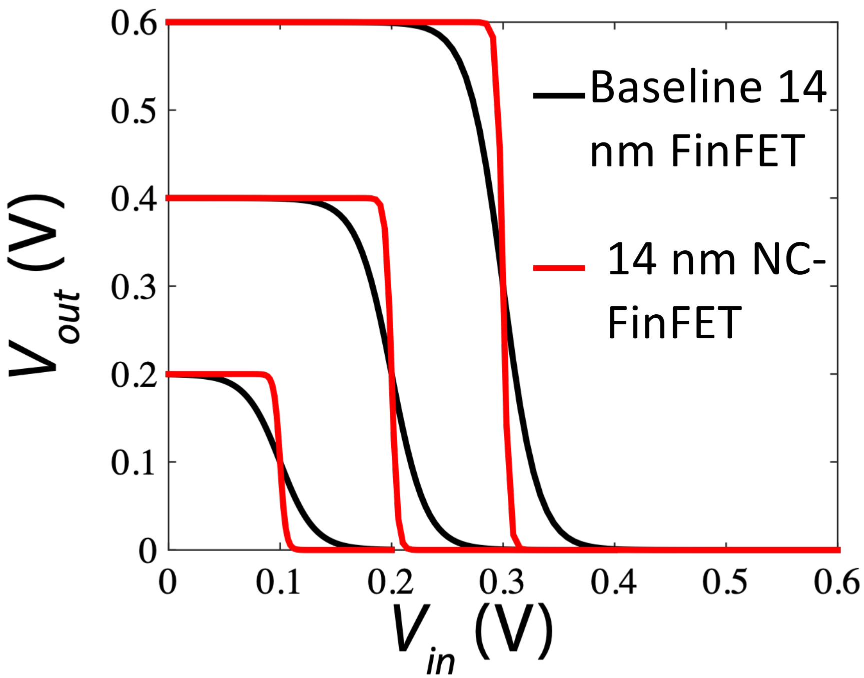


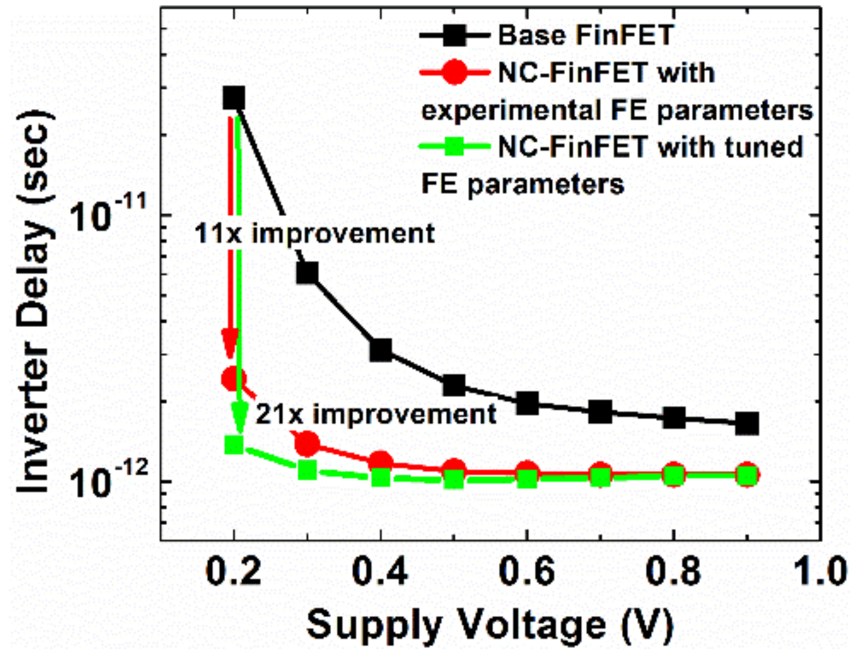
Domain Mediated Dynamics

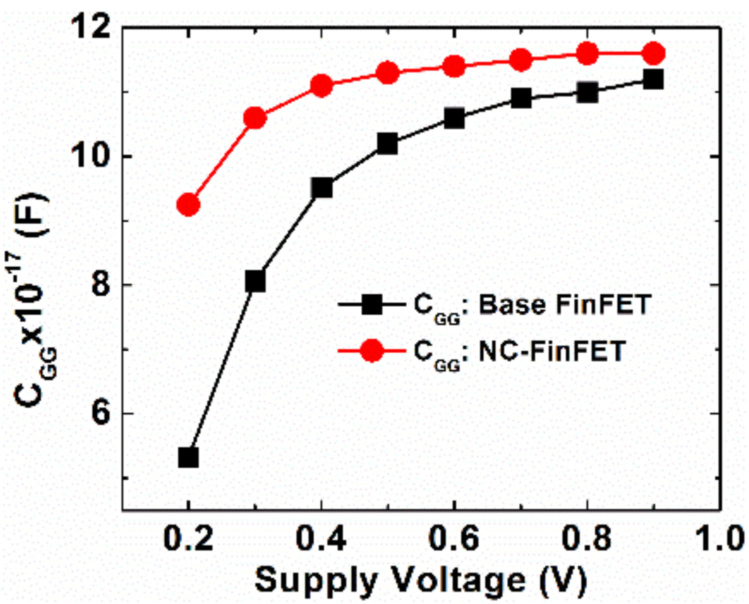


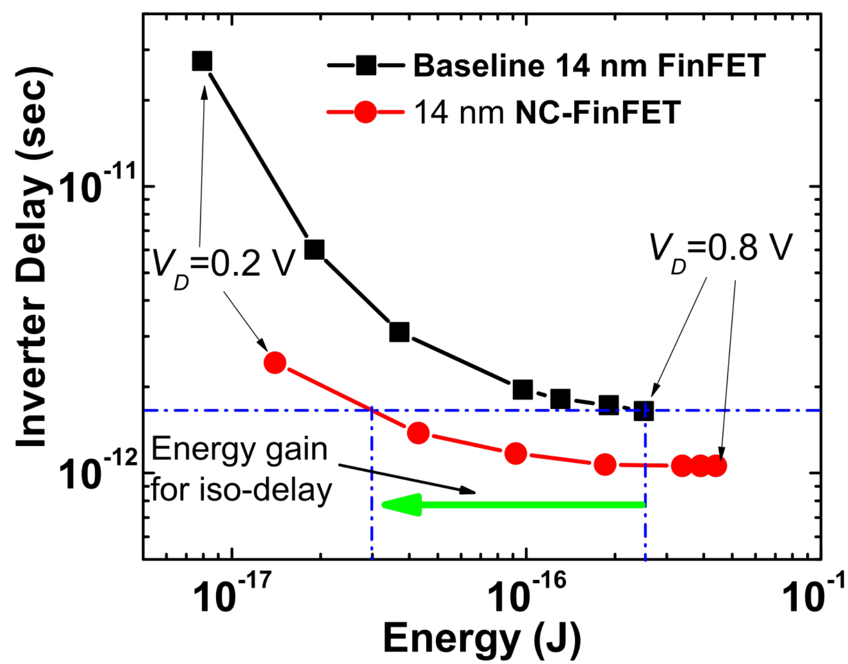
The Negative Capacitance effect is present even though the ferroelectric does not switch in a single domain fashion.

Performance Projection of NCFETs



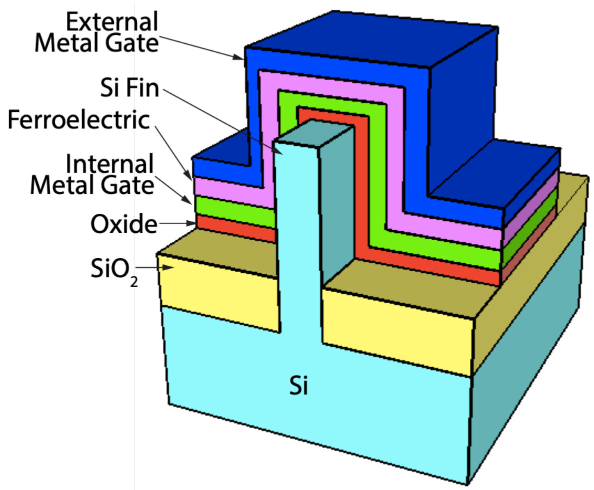




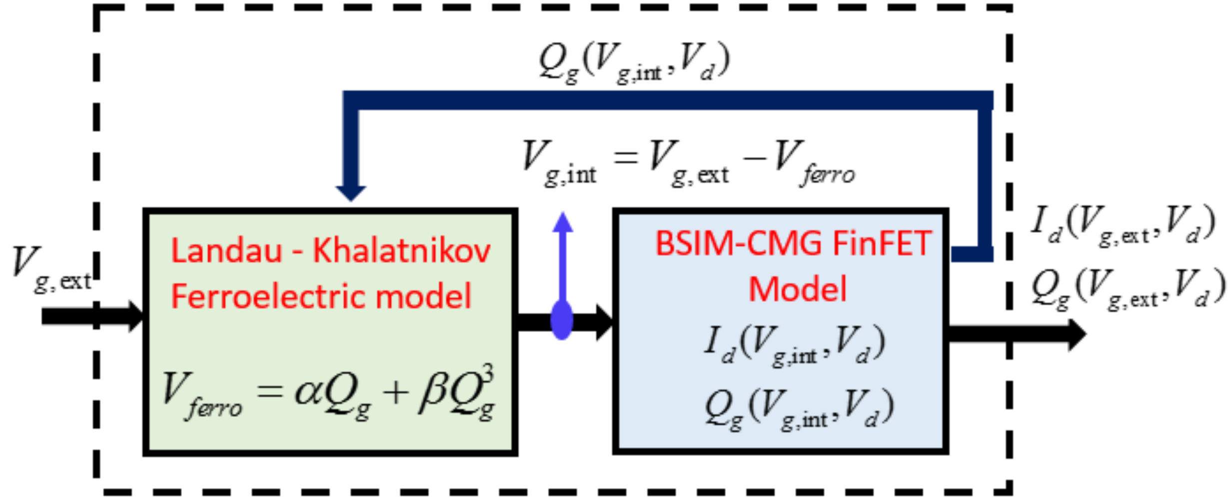


Performance Projection of NCFETs

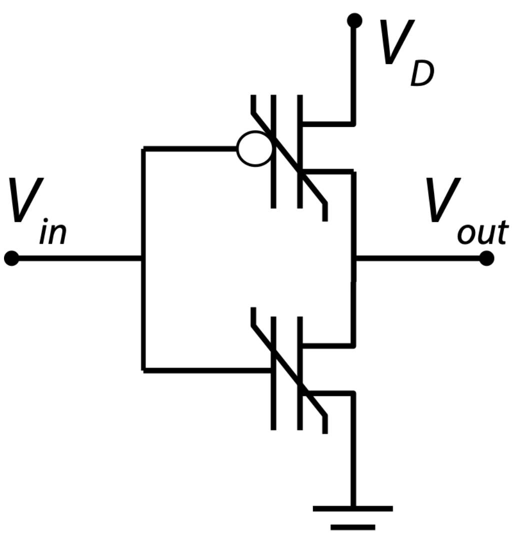
14 nm FinFET Node



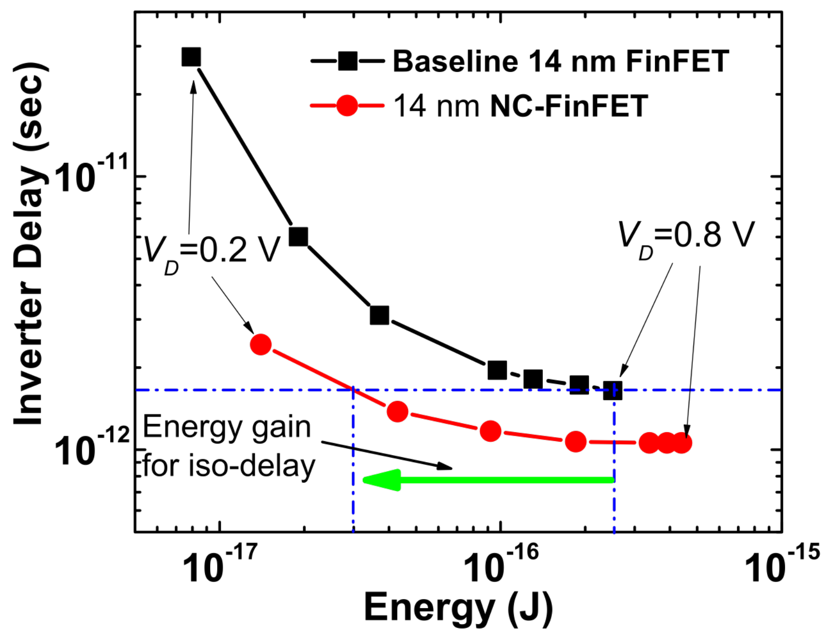
Compact Model



Inverter



Energy-Delay Curve



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

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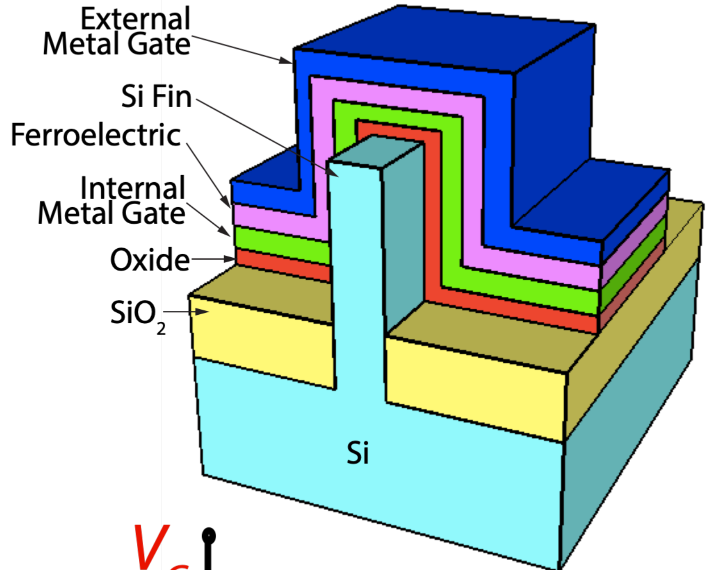
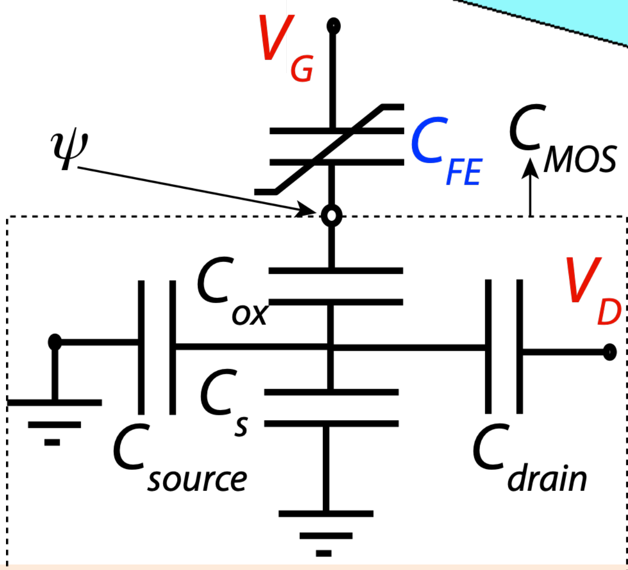
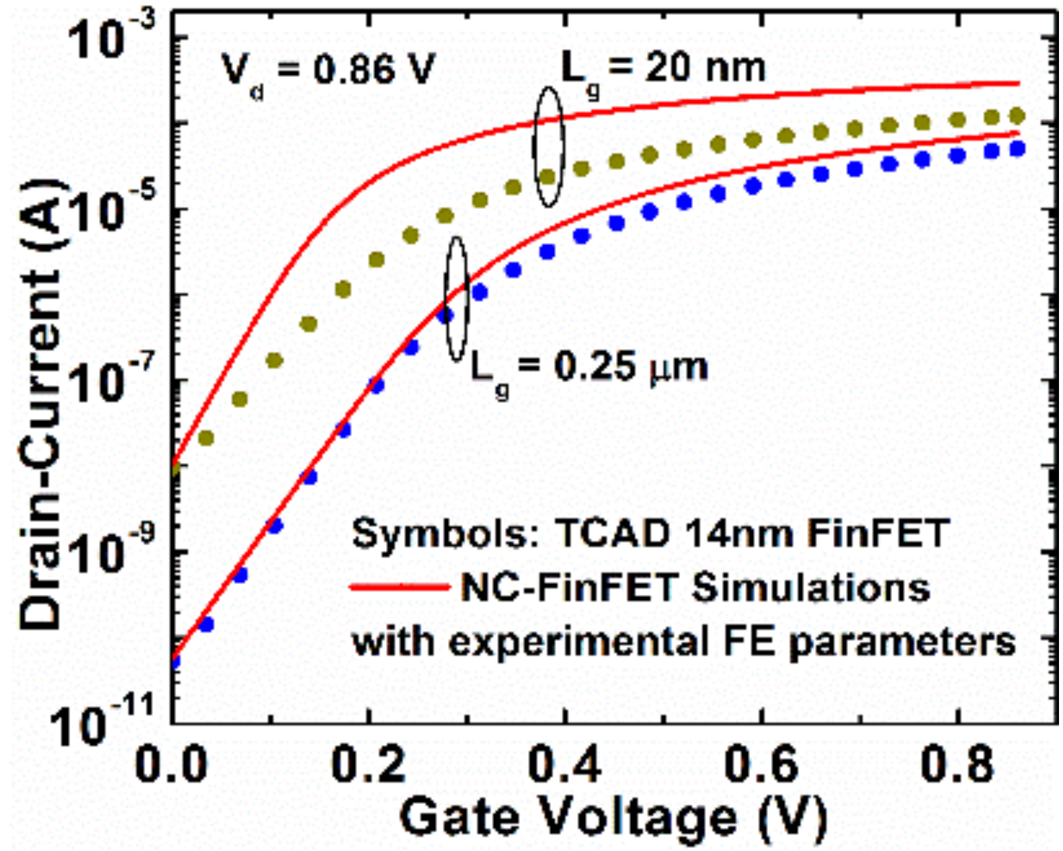
Short L_g Negative Capacitance Transistors







Improvement of Subthreshold Swing is higher in short channel transistors!

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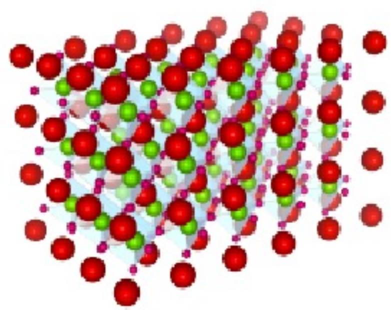
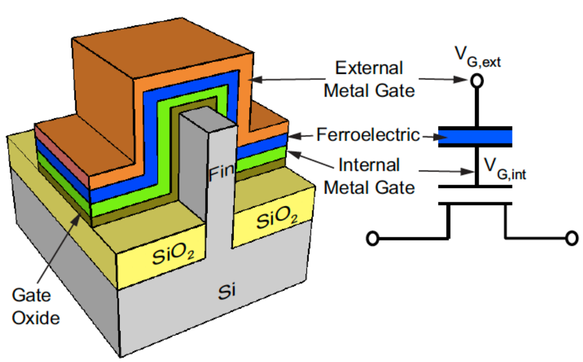
What am I going to do today?

Physics of Negative Capacitance in Materials



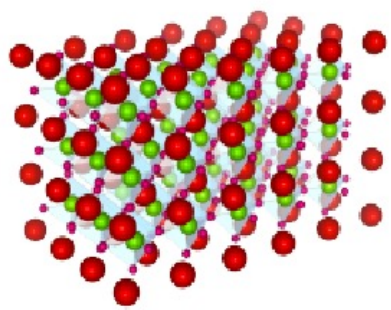
Physics of Negative Capacitance Transistors



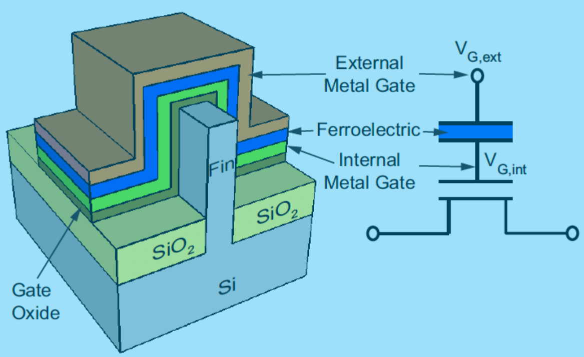
What do we need to know?

What am I going to do today?

Physics of Negative Capacitance in Materials



Physics of Negative Capacitance Transistors



What do we need to know?

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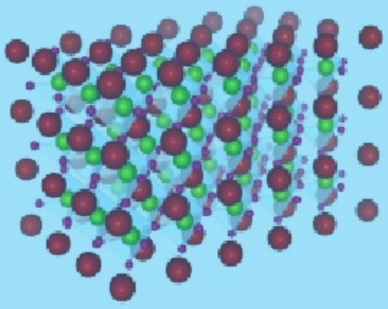
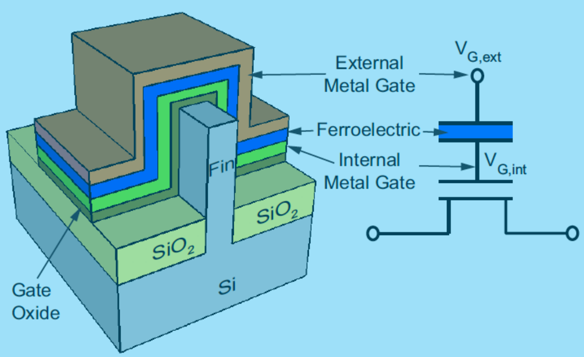
What am I going to do today?

Physics of Negative Capacitance in Materials



Physics of Negative Capacitance Transistors



What do we need to know?

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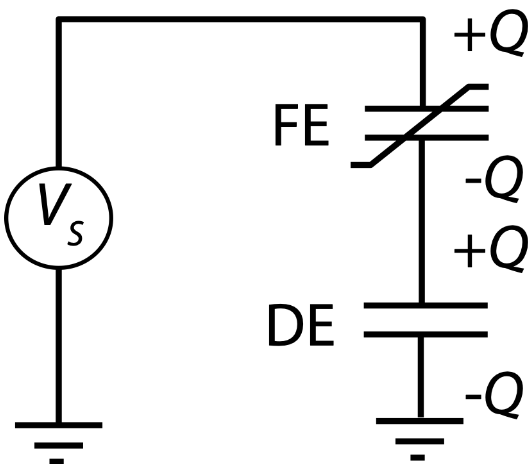
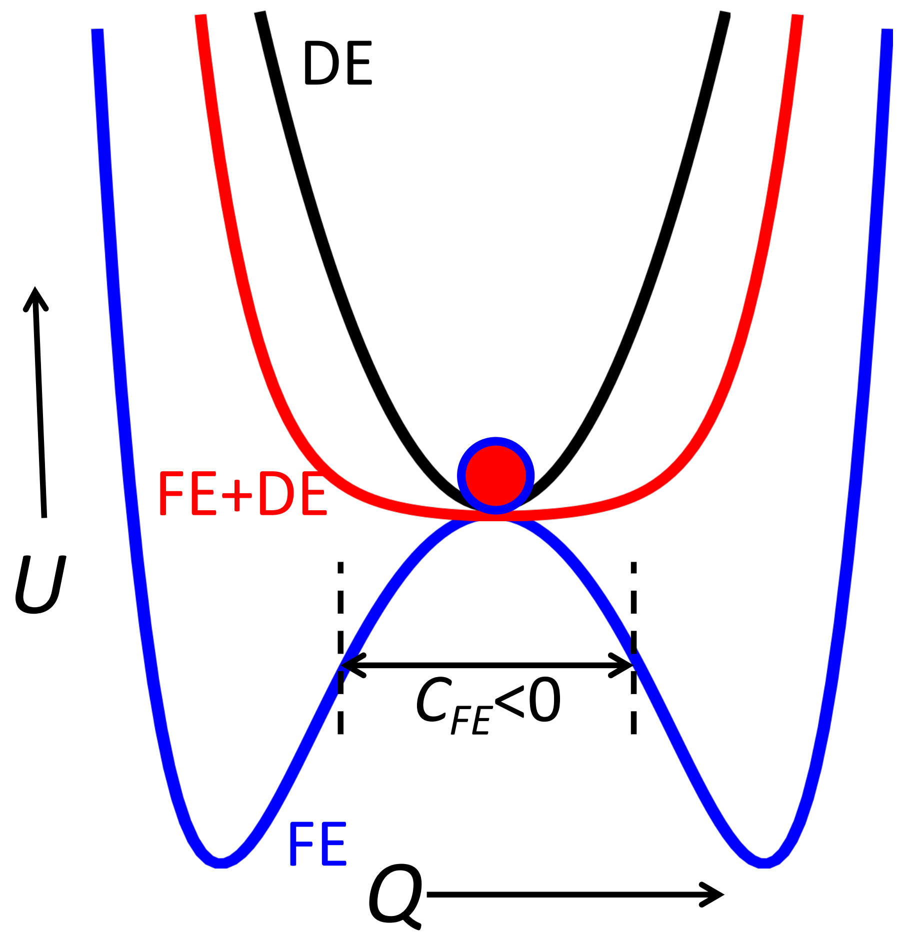
Breaking the Circuit Laws using Neg. Cap.

Ferroelectric-Dielectric
Series Combination



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

Energy Landscapes

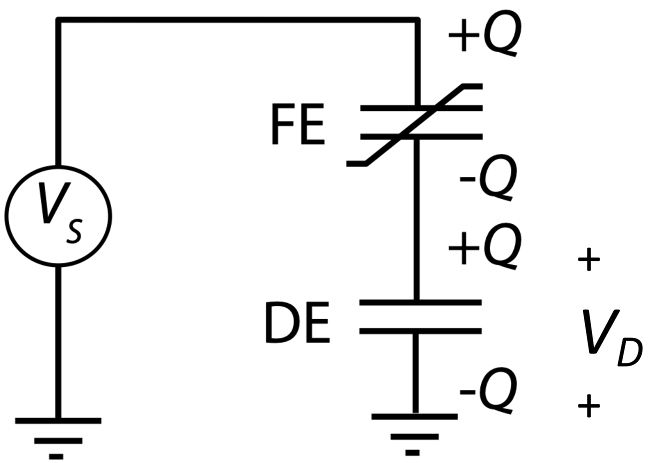


Equivalent Capacitance $$C_{FE+DE} = \left[\frac{1}{C_{FE}} + \frac{1}{C_{DE}}\right]^{-1}$$

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

Enhancement of capacitance in a FE-DE Series combination!

Ferroelectric+Dielectric Capacitor



Voltage amplification: $\dfrac{dV_D}{dV_S} = \dfrac{C_F}{C_F + C_D} = \dfrac{|C_F|}{|C_F| - C_D}$ If $|C_F| > C_D$, $\boxed{\dfrac{dV_D}{dV_S} > 1}$

Equivalent Capacitance $C_{F+D} = [\dfrac{1}{C_D} + \dfrac{1}{C_F}]^{-1}$ If $|C_F| > C_D$, $\boxed{C_{D+F} > C_D}$

Khan, Hoffmann et al. (under review)

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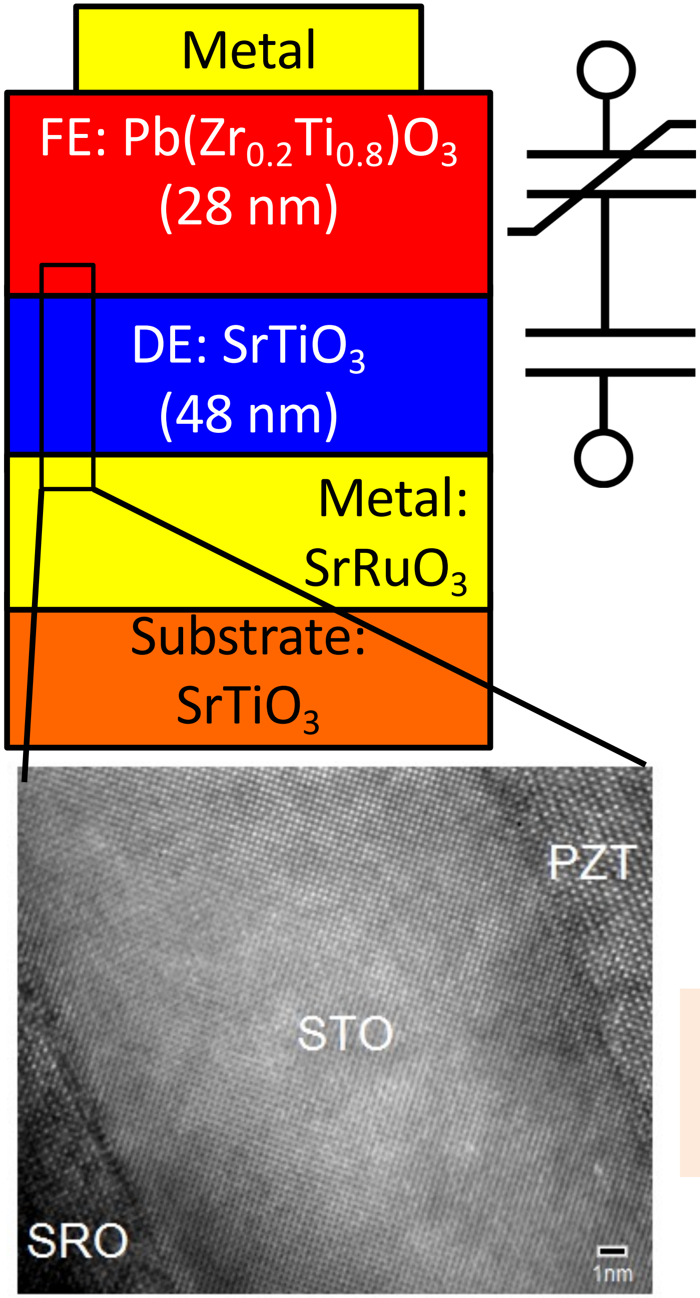
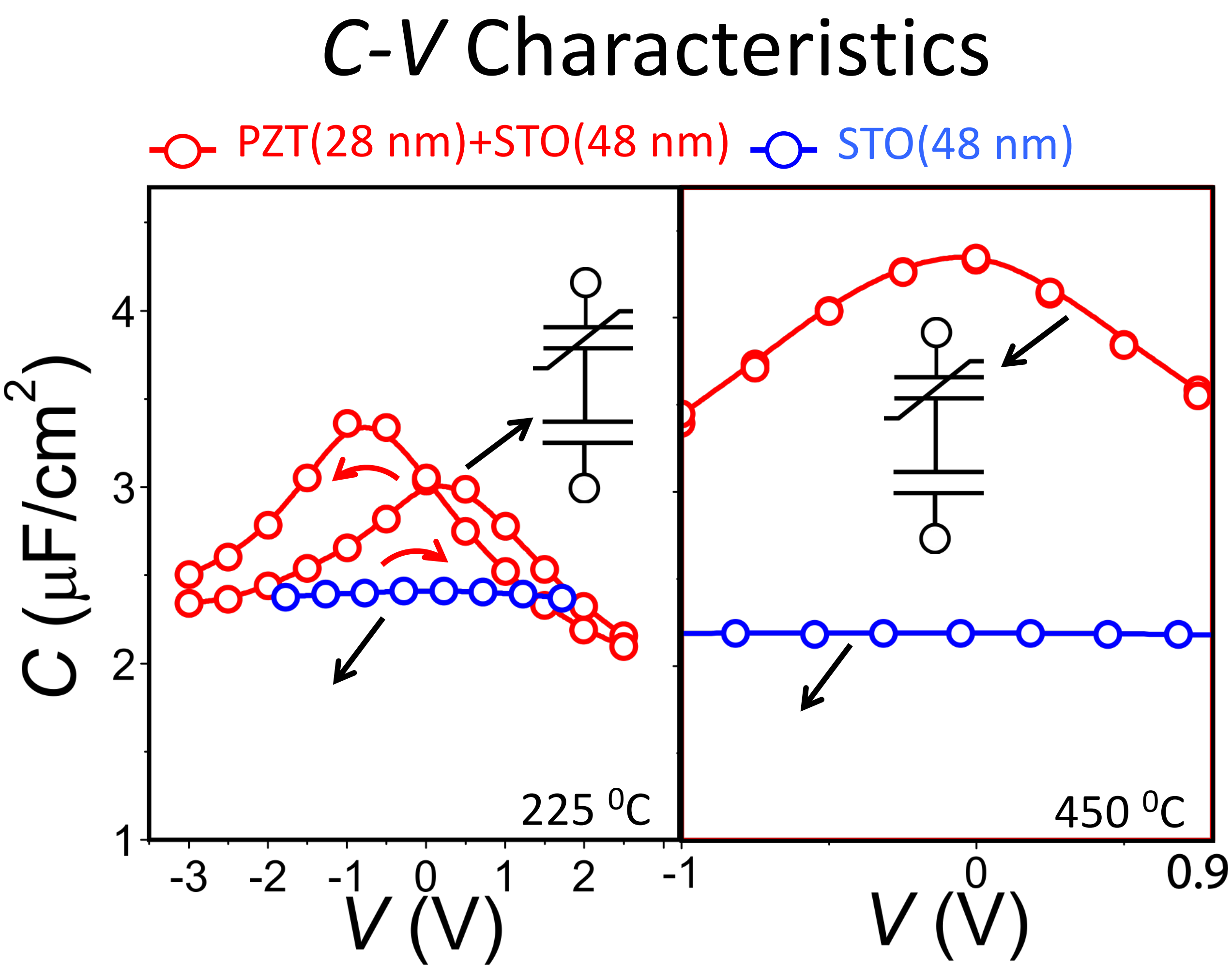
Breaking the Circuit Laws using Neg. Cap.





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)