A Tutorial Introduction to Negative Capacitor Field Effect Transistors: Perspective on The Road Ahead

Muhammad A. Alam
alam@purdue.edu

Acknowledgment

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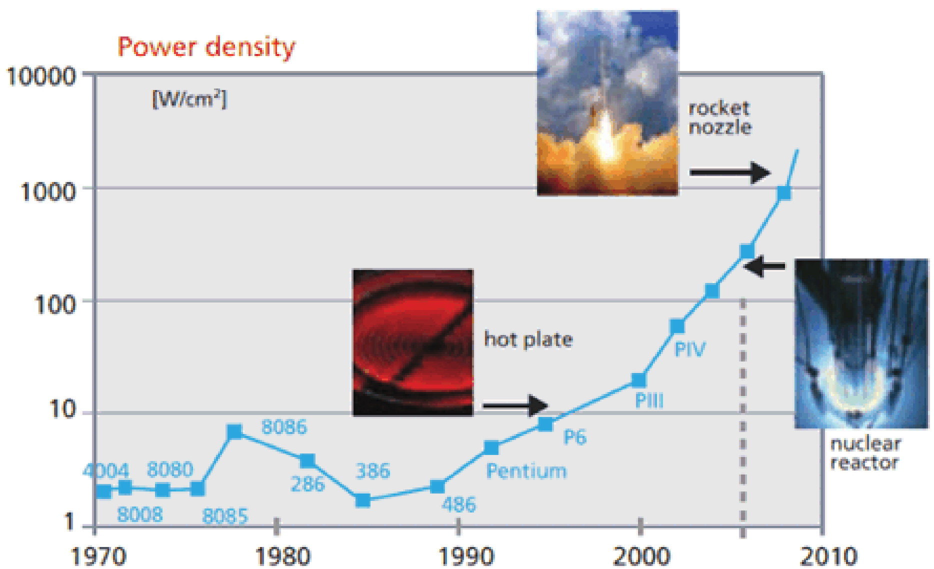
Outline

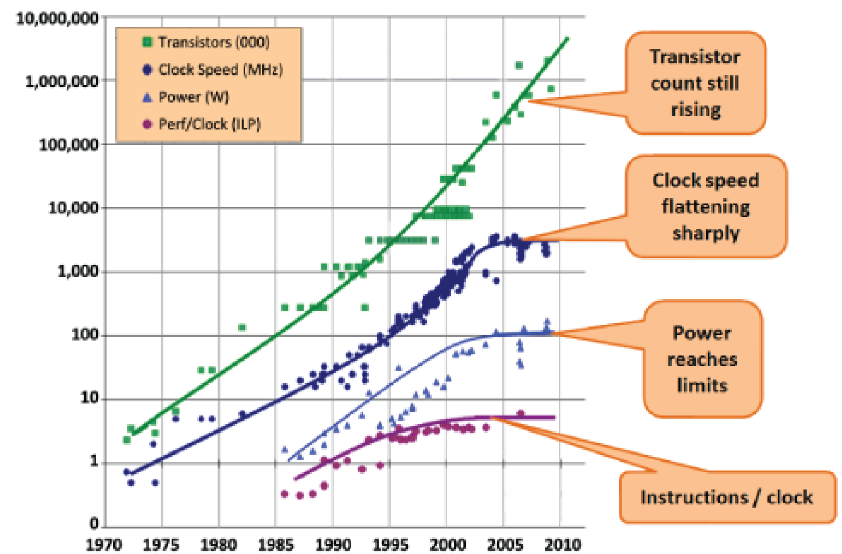
- Motivation: Self-heating in Transistors
- The physics of Classical and Landau-FET
- Physics of FE-based Landau Transistors
- Strategies of Improving FE-Transistors
- Speed, Reliability, and Fake Amplifcation
- Conclusions

Motivation: Power dissipation

A scary prospect …



… the community listened

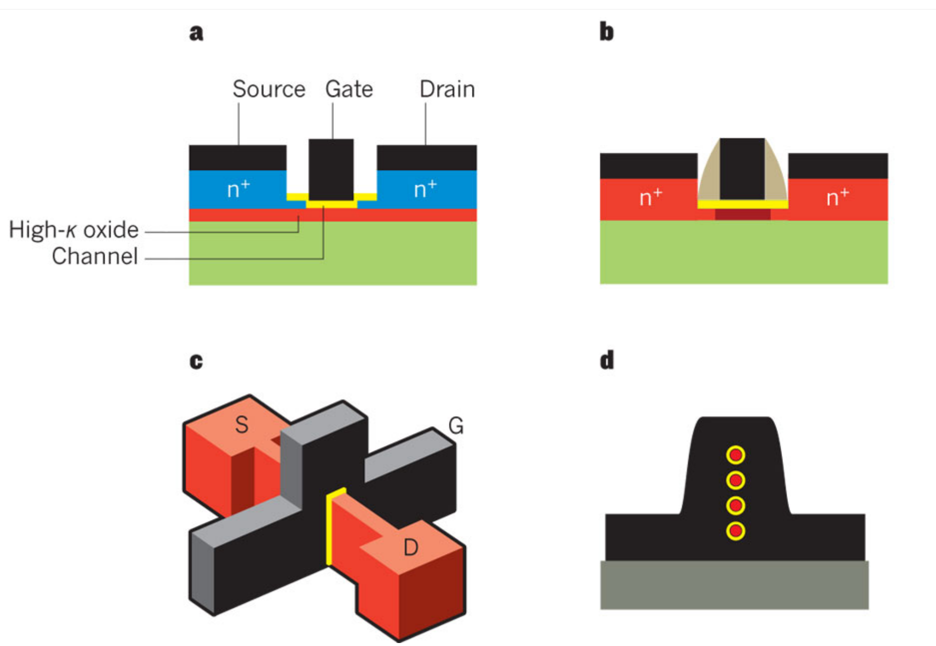


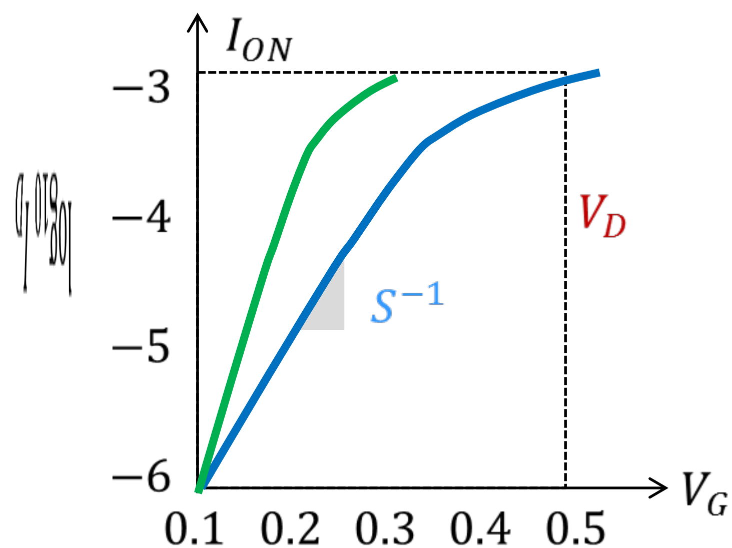
… but can we live happily ever after?

Power vs. self-heating

$$\Delta T \equiv T - T_a = P \times R_{th} \propto V_D^2 R_{th}$$

$$V_D > S \times \log(I_{ON}/I_{OFF})$$





Outline

- Motivation: Self-heating in Transistors
- The physics of Classical Transistors
- The meaning of Negative Capacitors
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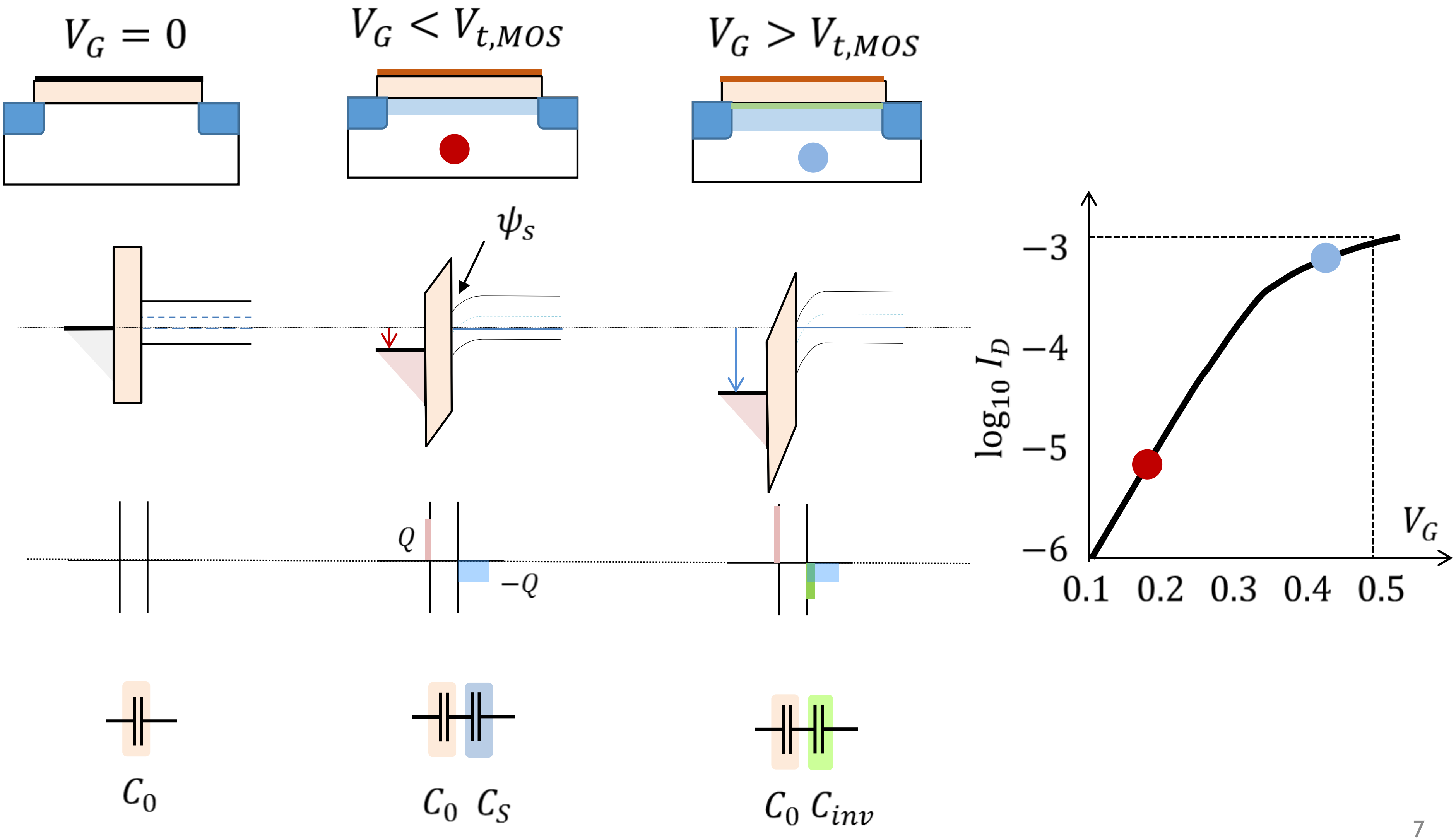
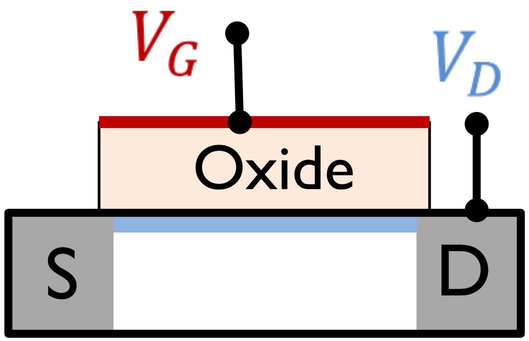
- Strategies of Improving FE-Transistors
- Additional Considerations:
  – Speed, Reliability, Fake amplification
- Conclusions

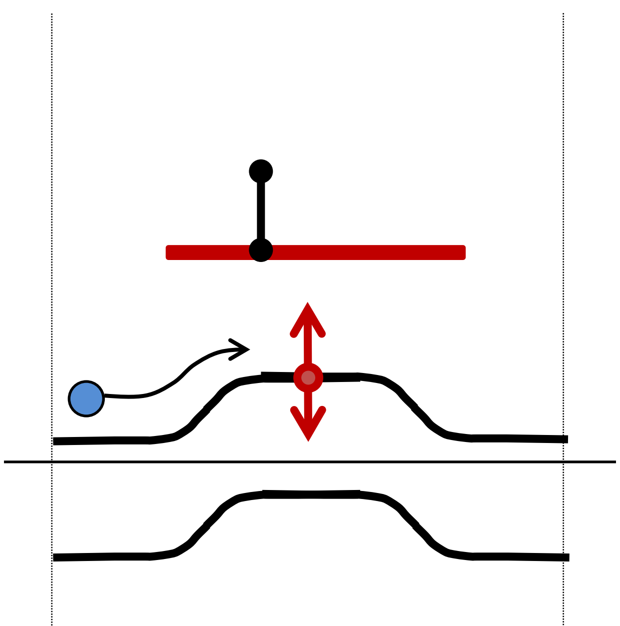
Classical MOSFET: Band diagram

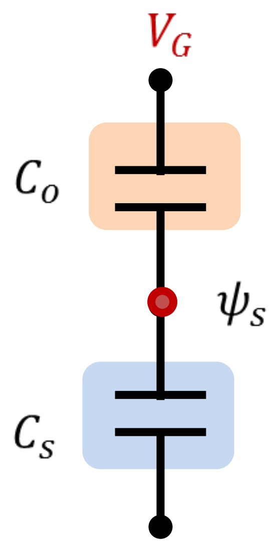


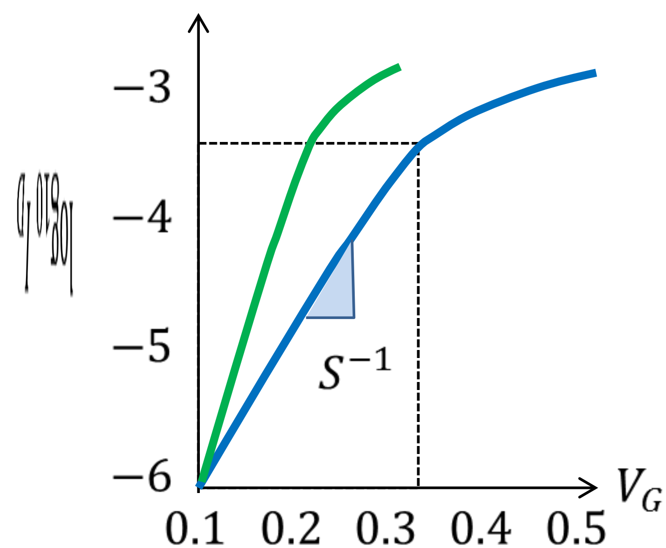
Capacitors control MOSFET Operation



$$S = \left(\frac{d\log I_D}{dV_G}\right)^{-1}$$
$$= \left[\left(\frac{d\psi_s}{dV_G}\right)\left(\frac{d\log I_D}{d\psi_s}\right)\right]^{-1} \equiv m \times n$$







S for *classical* transistors

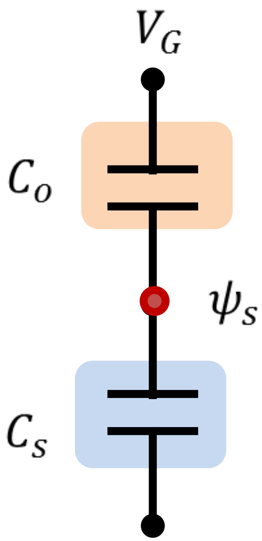
$$S = \left(\frac{d\log I_D}{dV_G}\right)^{-1} = \left[\left(\frac{d\psi_s}{dV_G}\right)\left(\frac{d\log I_D}{d\psi_s}\right)\right]^{-1} = m \times n$$

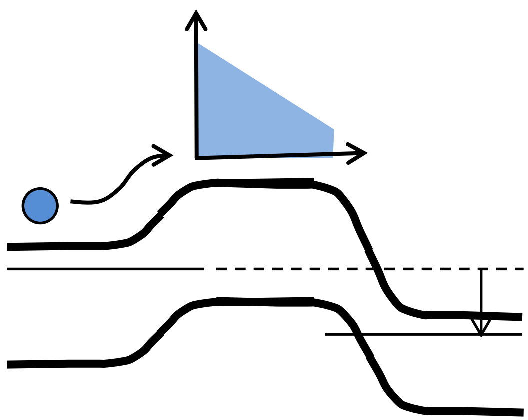
$$I_D = I_0\, e^{\frac{q\psi_s}{kT}}\left(1 - e^{-\frac{qV_D}{kT}}\right) \sim I_0\, e^{\frac{q\psi_s}{kT}} = I_0\, e^{qV_G/mkT}$$

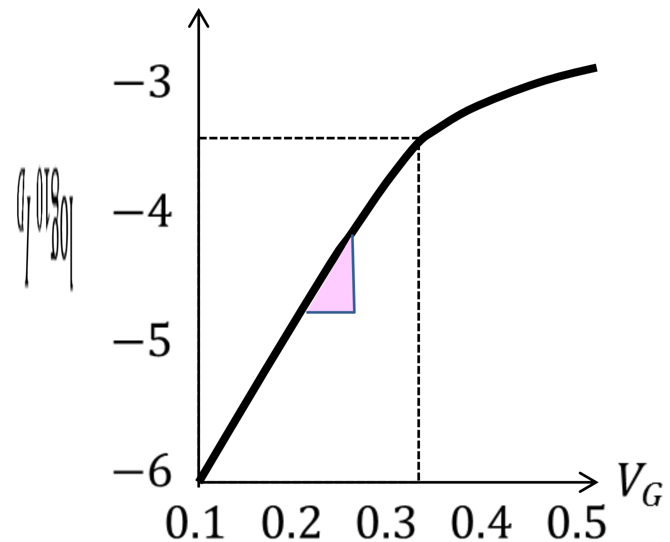
$$m = \frac{dV_G}{d\psi_s} = 1 + \frac{C_s}{C_0}$$

$$n = \frac{2.3k_BT}{q}$$

$$S = m \times n$$

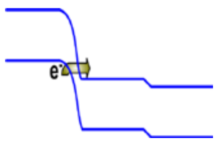


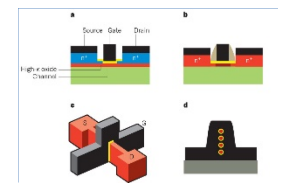




Phase Space of MOSFET

$$S \equiv \left[\left(\frac{d\psi_s}{dV_G}\right)\left(\frac{d\log_{10}(I_{DS})}{d\psi_s}\right)\right]^{-1} = m \times n$$





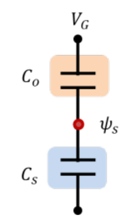
m (vertical axis), n (horizontal axis); 1 marked on the m axis, 60 marked on the n axis.

Tunnel FET
(m>1, n<60)
II-FET, NEM-Relay.
MIT-FET

Boltzmann FET
(m>1, n=60)
SOI, FinFET, DGFET

Super FET
(m<1, n<60)

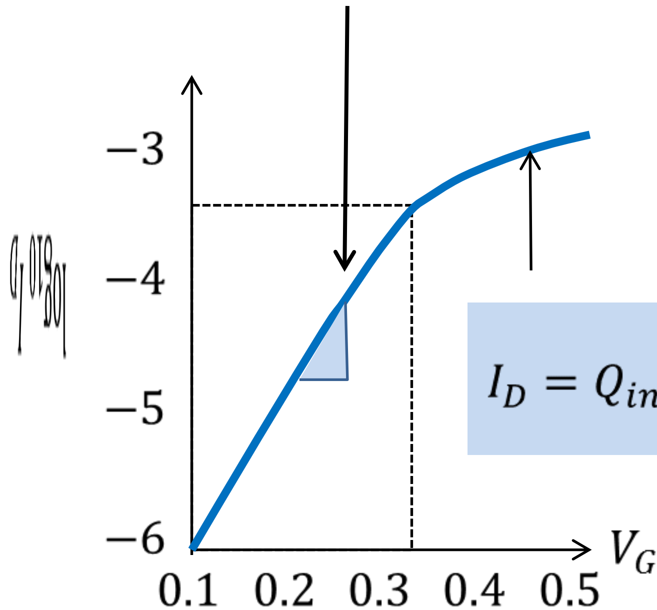
Landau FET
(m <1, n=60)
NEMFET, FEFET, ZFET



Alam, A Tutorial on Landau Transistors, 2015

I-V Characteristics of a MOSFET

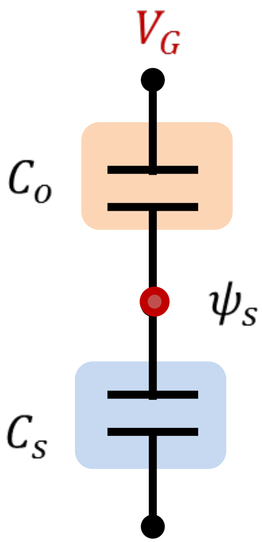
$$I_D = I_0\, e^{\frac{qV_G}{mkT}}\left(1 - e^{-\frac{qV_D}{kT}}\right)$$



$$I_D = Q_{inv} v = \left(W\mu\frac{C_o}{L}\right)\left[\,(V_G - V_t)V_D - \frac{V_D^2}{2}\right]$$

Recall: Capacitor divider rule

$$m = \frac{dV_G}{d\psi_s} = 1 + \frac{C_s}{C_0}$$

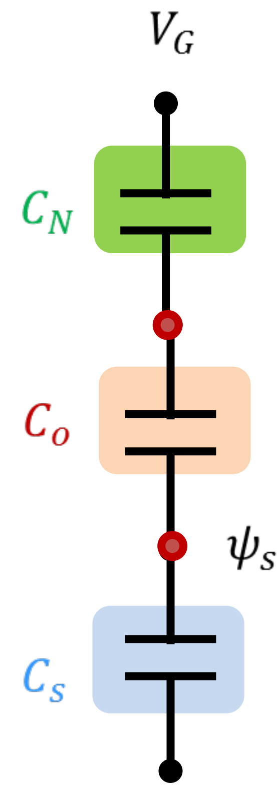


$$Q = V_G\, C_T = \psi_s C_S = C_N V_N$$

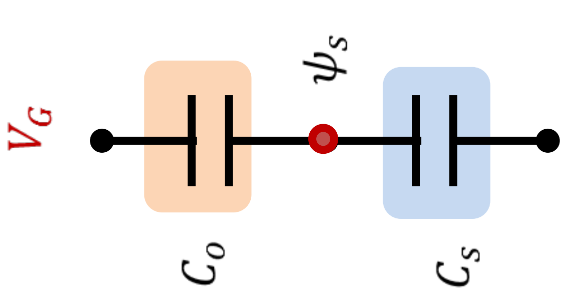
$$\frac{1}{C_T} = \frac{1}{C_S} + \frac{1}{C_0} + \frac{1}{C_N}$$

$$\frac{V_G}{\psi_s} = \frac{C_S}{C_T} = 1 + \frac{C_S}{C_0} + \frac{C_S}{C_N}$$

$$= 1 + \frac{C_{down}}{C_{up}}$$

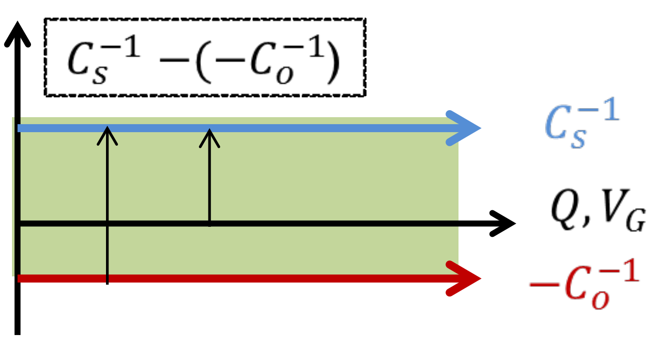


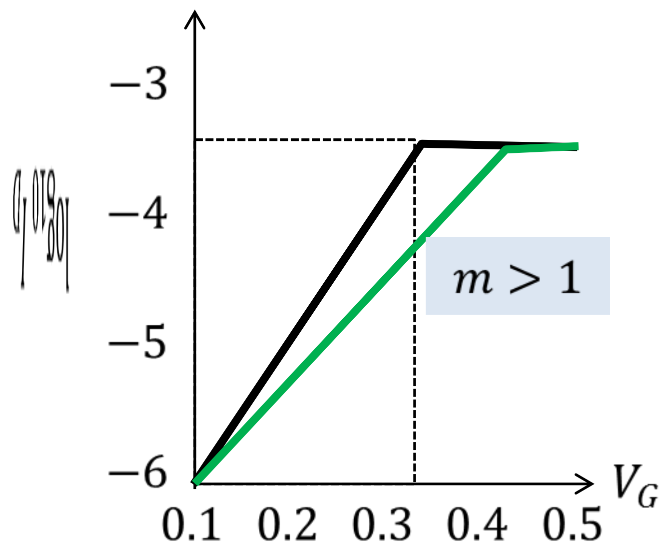
Graphical approach to S: Classical FET



$$m = 1 + \frac{C_s}{C_0} = \frac{C_s^{-1} - (-C_o^{-1})}{C_s^{-1}}$$

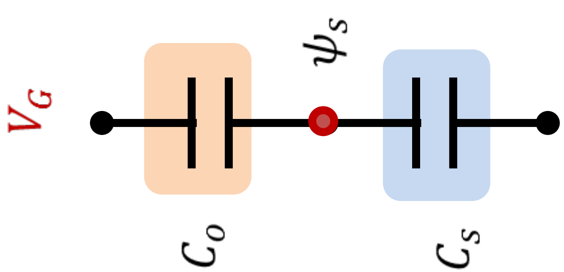
$m > 1$



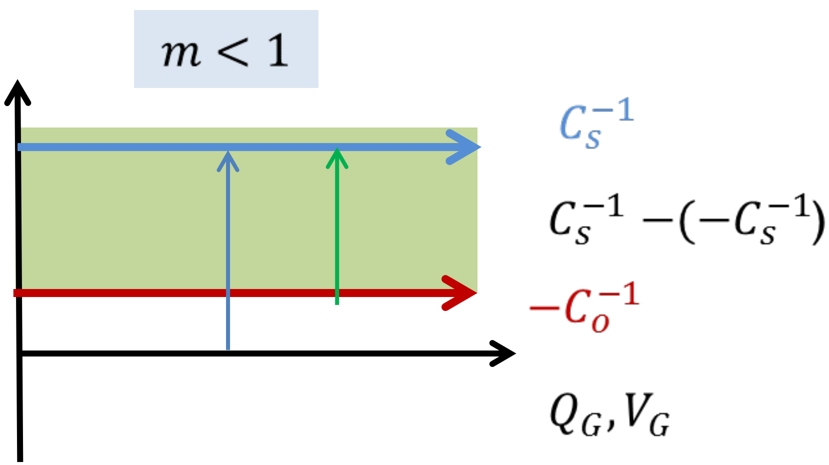


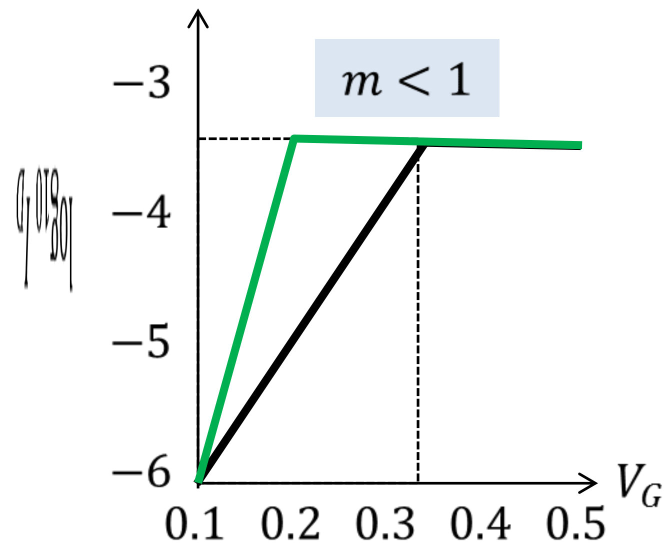
Any value of C_s is allowed.

Graphical approach to S: NC-FET



$$m = 1 + \frac{C_S}{C_0} = \frac{C_S^{-1} - (-\,C_O^{-1})}{C_S^{-1}}$$





Only C_S <C_0 allowed.; $S = 0$ possible with perfect matching.

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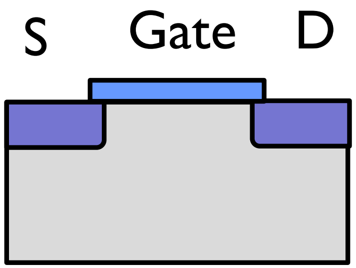
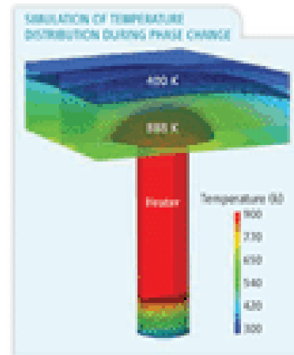
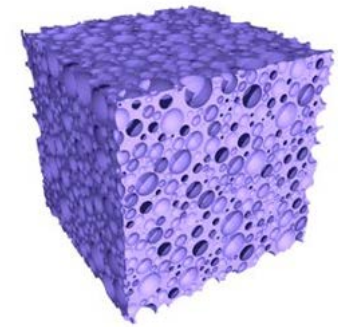
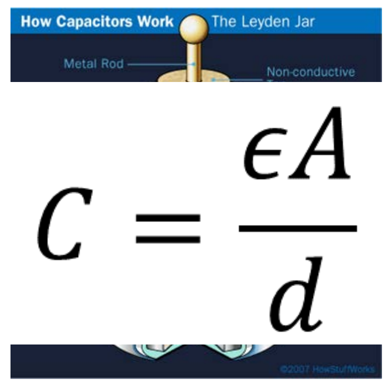
A short history of positive capacitors

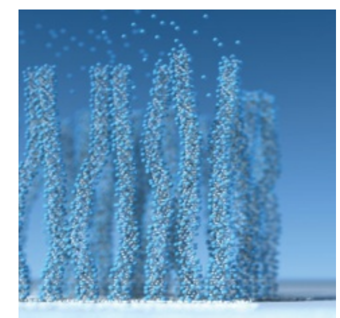


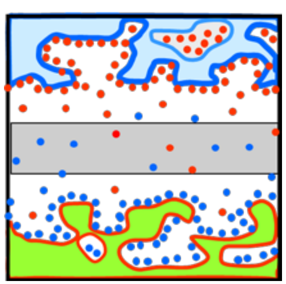


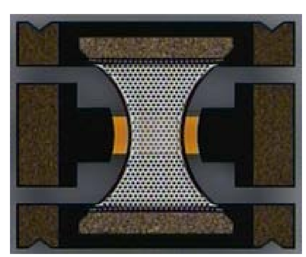




$$C = \frac{\epsilon A}{d}$$

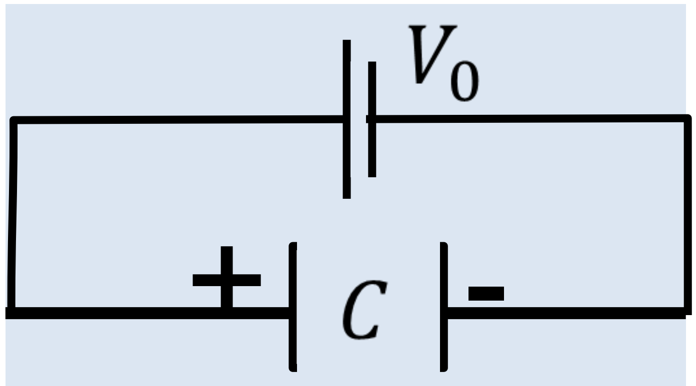




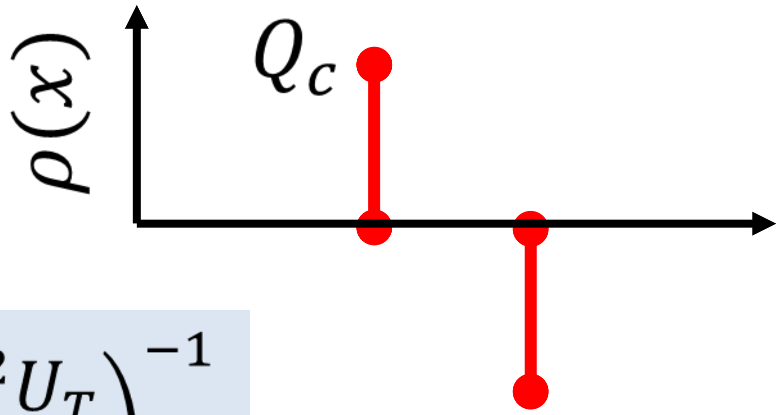


A capacitor minimizes stored energy

$$U_T = \frac{Q^2}{2C} - V_0 Q$$



$$\frac{dU_T}{dQ} = \frac{Q_c}{C} - V_0 = 0$$

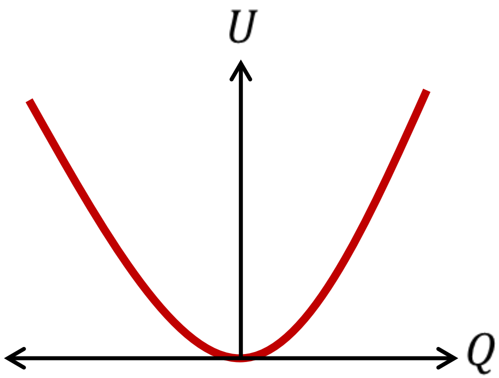


$$Q_c = C\,V_0$$

$$\frac{d^2 U_T}{dQ^2} = \frac{1}{C}$$

$$C \equiv \left(\frac{d^2 U_T}{dQ^2}\right)^{-1}$$

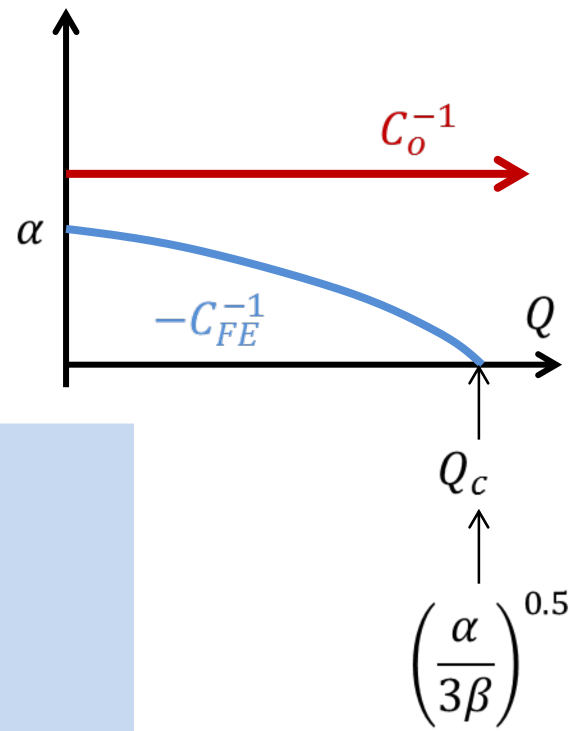
Landscape defines the sign of a capacitor

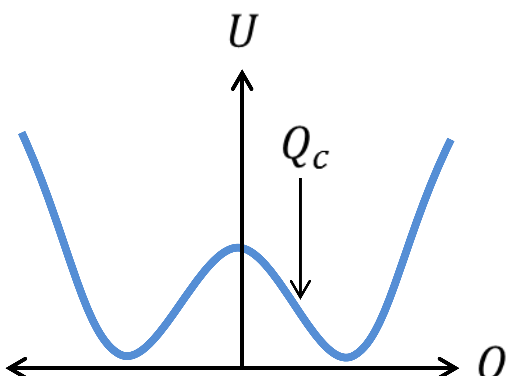


$$U = Q^2/(2C_o)$$

$$V = dU/dQ = Q/C_o$$

$$C \equiv \left(\frac{d^2U}{dQ^2}\right)^{-1} = C_0$$



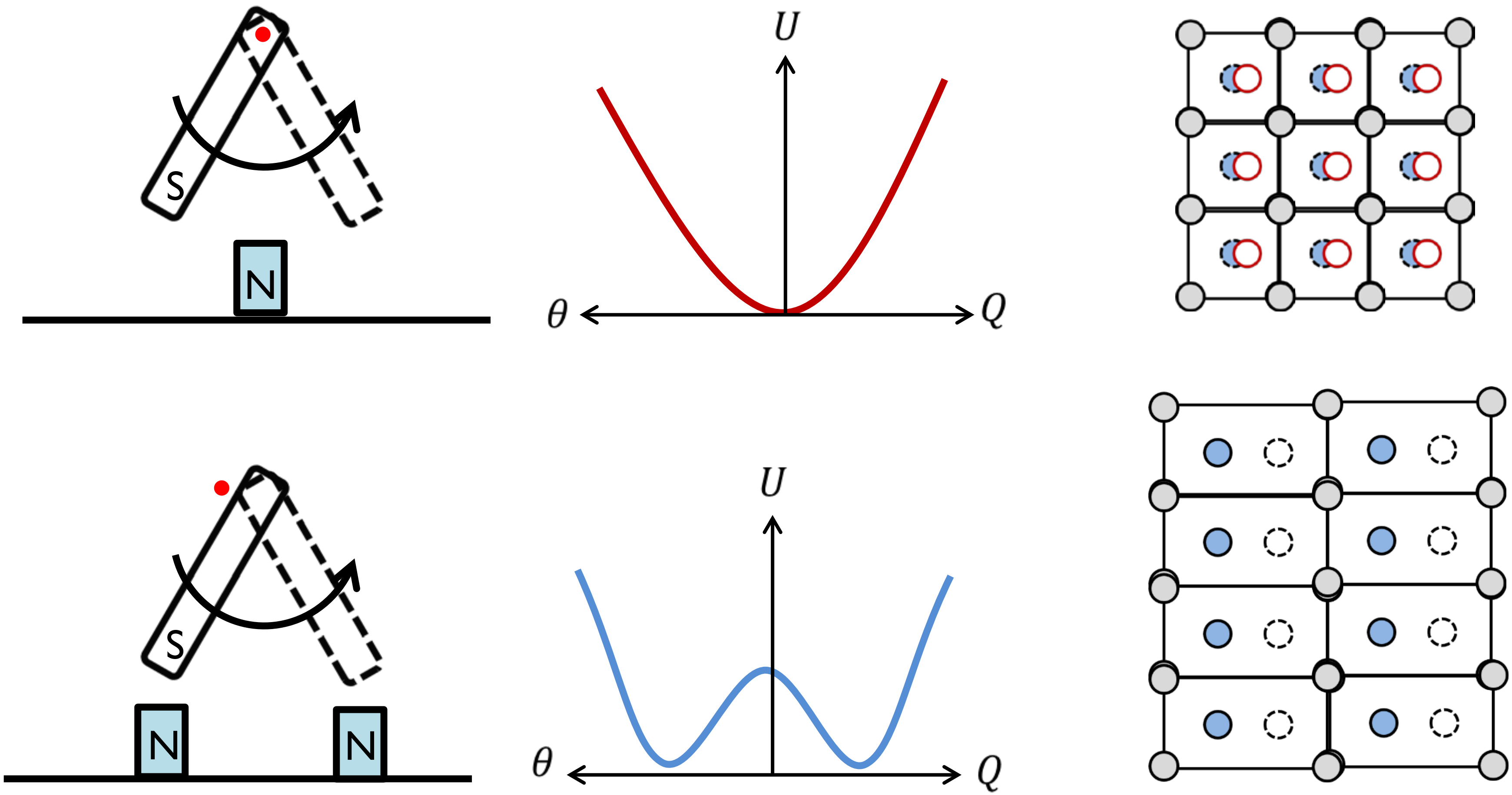


$$U = -(\alpha Q^2/2) + (\beta' Q^4/4)$$

$$V = \frac{dU}{dQ} = -\alpha Q + \beta Q^3$$

$$C^{-1} \equiv \left(\frac{d^2U}{dQ^2}\right) = -\alpha + 3\beta Q^2$$

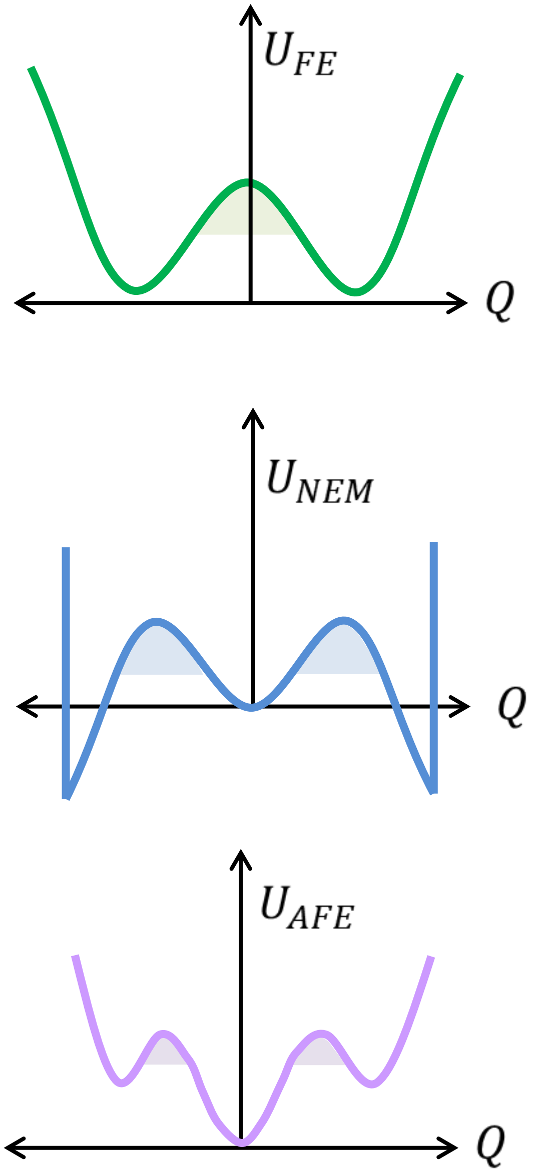
Positive and Negative Capacitors



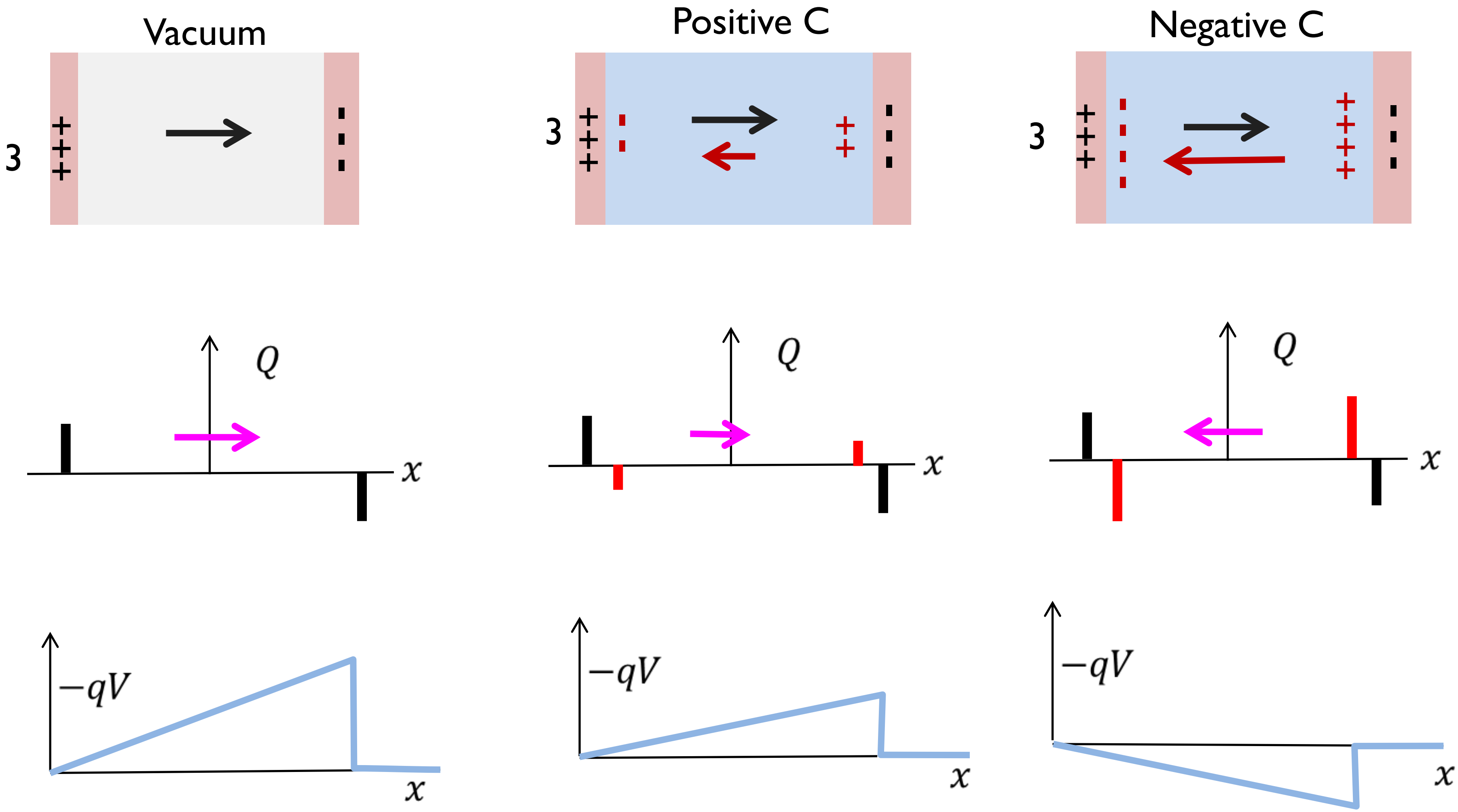
Types of NC

$$C^{-1} = \alpha + \beta Q^2 + \gamma Q^4$$

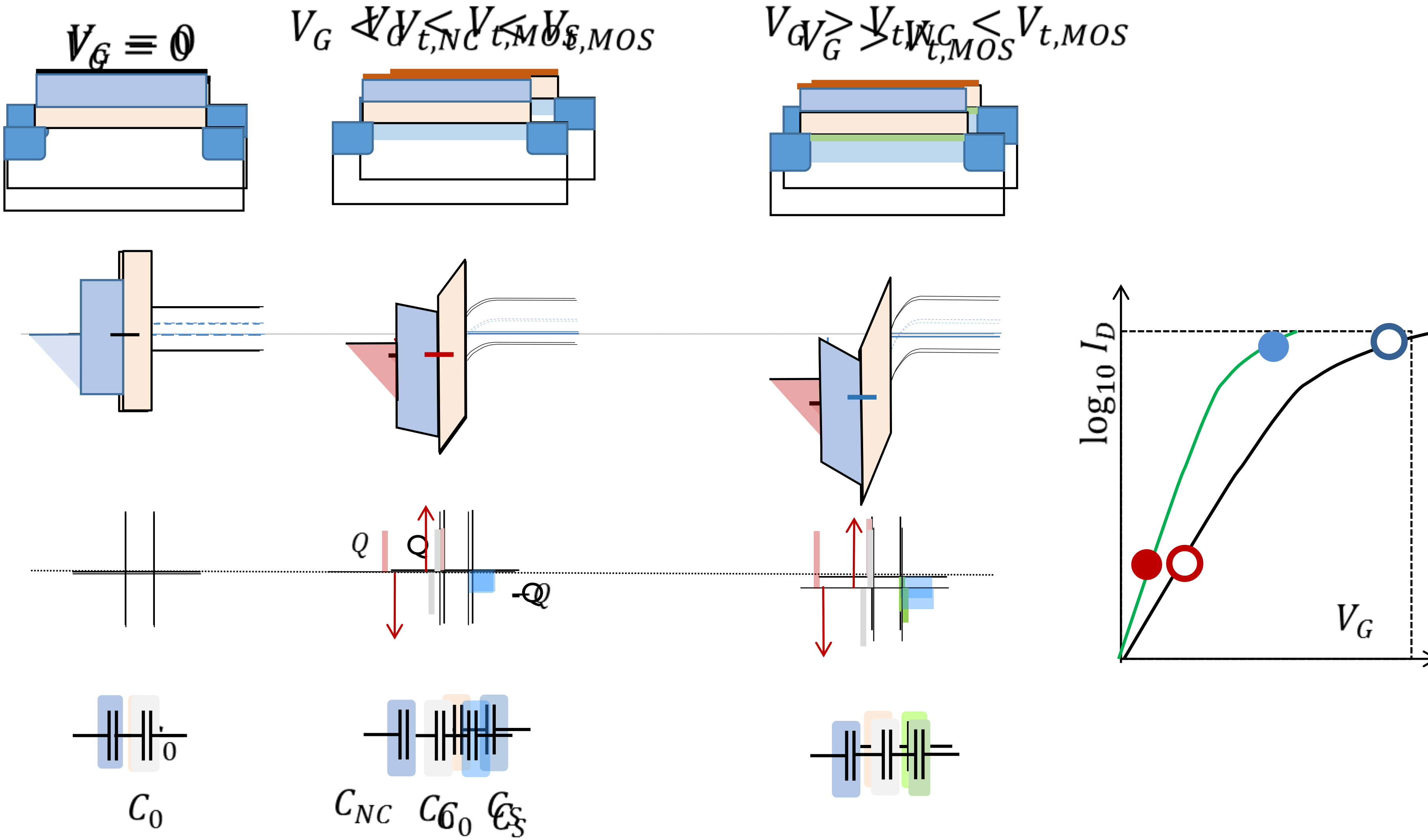
	α	β	γ
Positive	+	+	+
FE-1	−	+	+
FE-2	−	−	+
NEM AFE	+	−	+



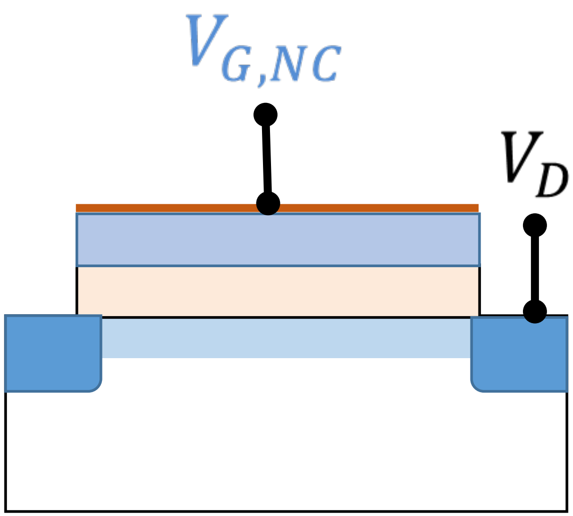
Charge, Field, Potential of Capacitors

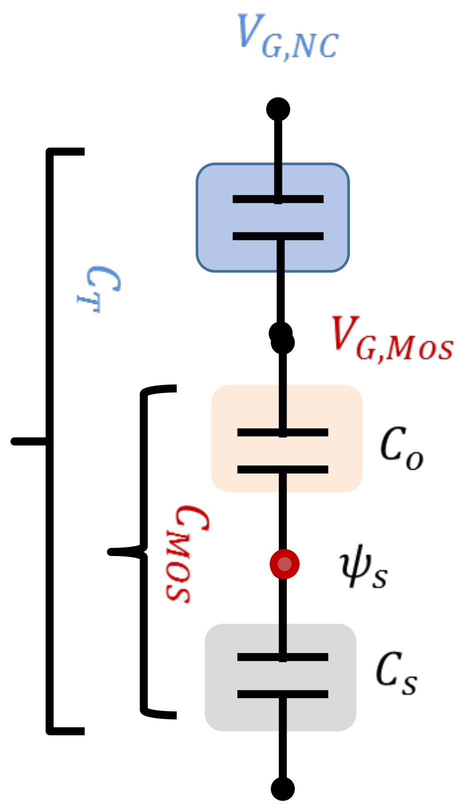


Classical vs. NC-MOSFET



IF we had a constant NC-FET …



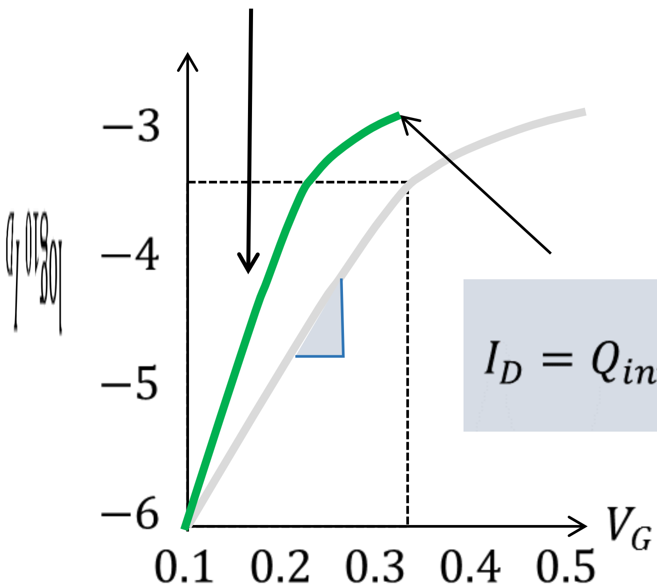


$$\frac{V_{G,NC}}{V_{G,MOS}} = m_i = \frac{C_{MOS}}{C_T}$$

$$\frac{V_{G,NC}}{\psi_S} = m_D = \frac{C_S}{C_T}$$

… I-V would be easily calculated

$$I_D = I_0\, e^{\frac{qV_{G,NC}}{m_D kT}}\left(1 - e^{-\frac{qV_D}{kT}}\right)$$



$$I_D = Q_{inv} v = \left(W\mu\frac{C_o}{L}\right)\left[\left(\frac{V_{G,NC}}{m_i} - V_t\right)V_D - \frac{V_D^2}{2}\right]$$

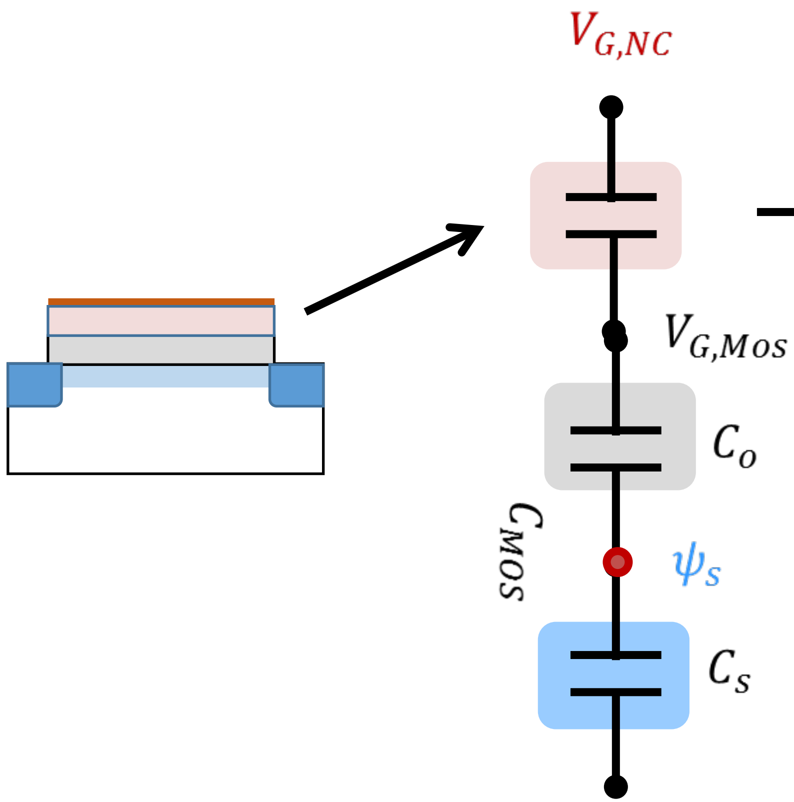
… and all our problems will be solved!

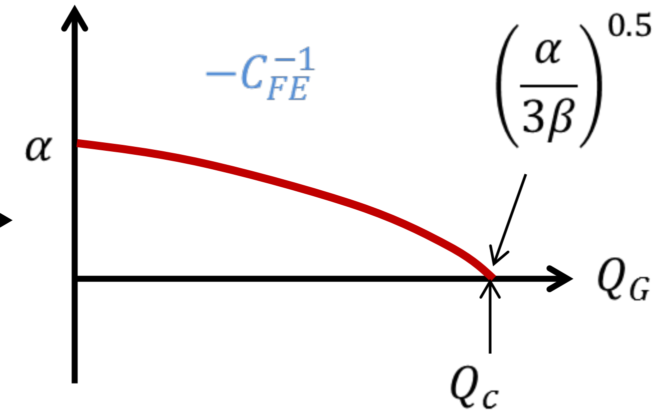
Outline

- Motivation: Self-heating in Transistors
- The physics of Classical and Landau-FET
- Physics of FE-based Landau Transistors
- Three strategies of Improving FE-Transistors
  - NEM-FE, FE-AFE gate stacks, overlap capacitance
- Additional Considerations:
  - Speed, Reliability, Fake amplification
- Conclusions

FE is a voltage dependent NC

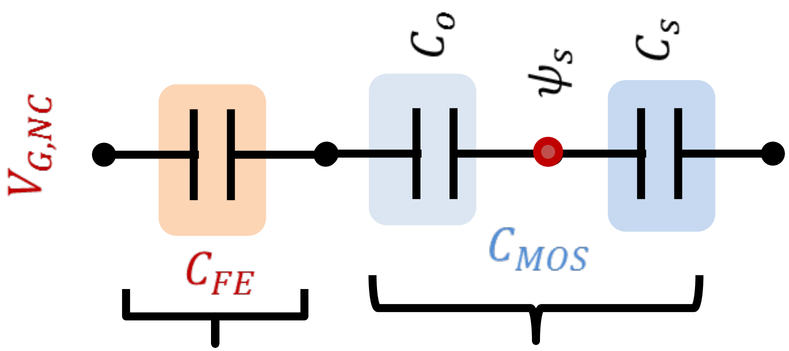
Salahuddin & Datta, NL, 2008



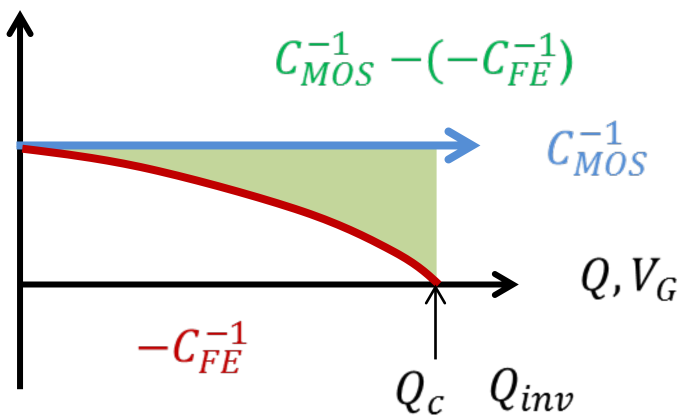


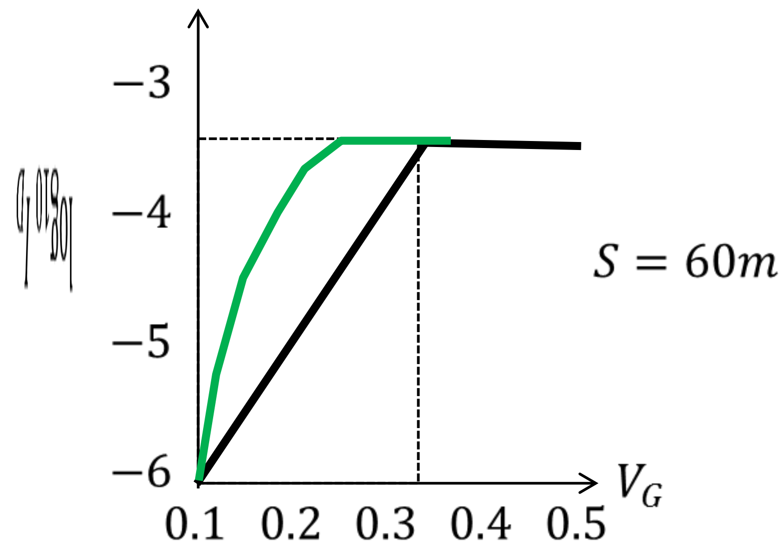
$$C_{FE} \equiv \left(\frac{d^2U}{dQ^2}\right)^{-1} = \frac{1}{-\alpha + 3\beta Q^2}$$

FE-FET improves 0<S<60, but …

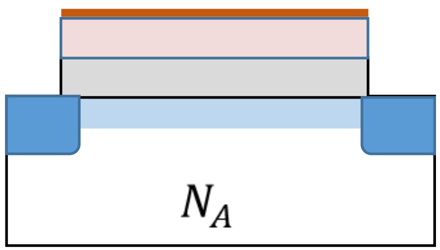


$$m = \frac{C_{MOS}^{-1} - (-\,C_{FE}^{-1})}{C_s^{-1}}$$





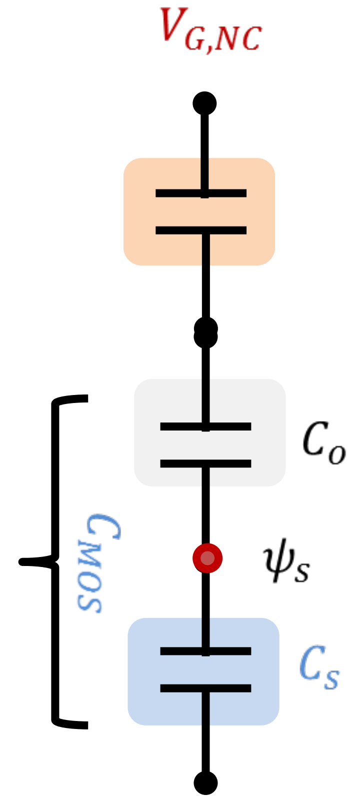
MOS Capacitor is nonlinear as well!



In depletion …

$$\frac{1}{C_{MOS}} = \frac{1}{C_0} + \frac{1}{C_S}$$

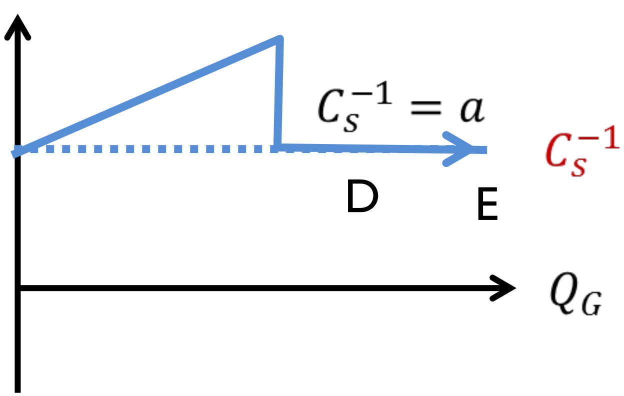
$$= \frac{1}{C_0} + \frac{W}{\kappa\epsilon_0}$$



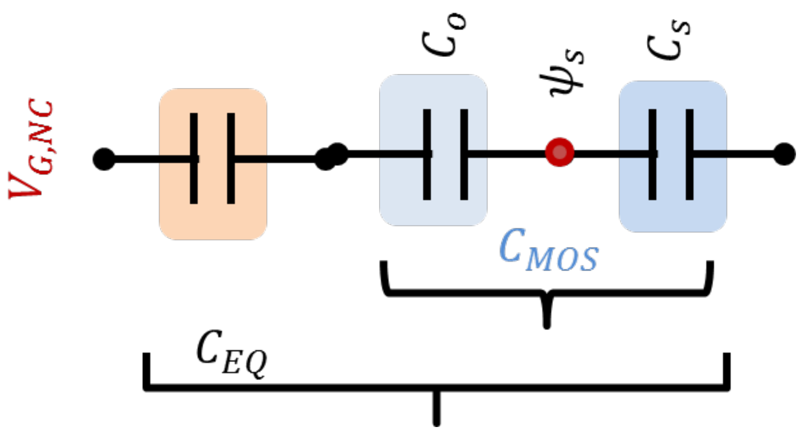
$$C_S^{-1} = a + pQ_G$$

$$Q_G = Q_{dep} = qN_A W$$

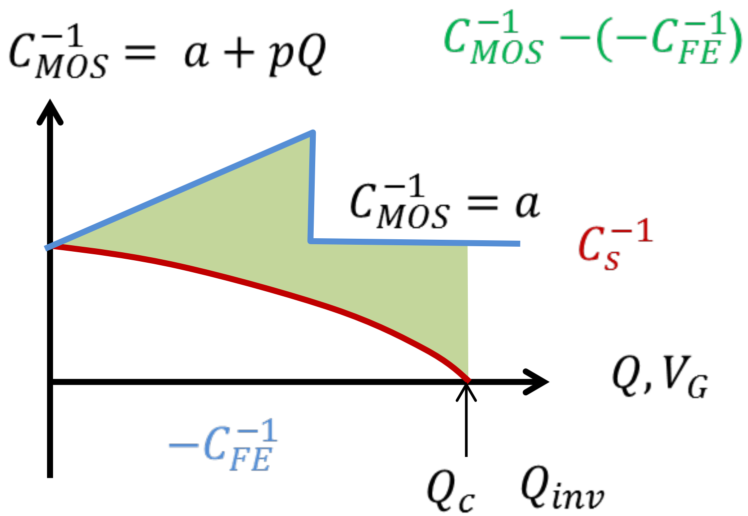
$$\frac{1}{C_{MOS}} = \frac{1}{C_0} + \frac{Q_G}{q\kappa\epsilon_0 N_A}$$

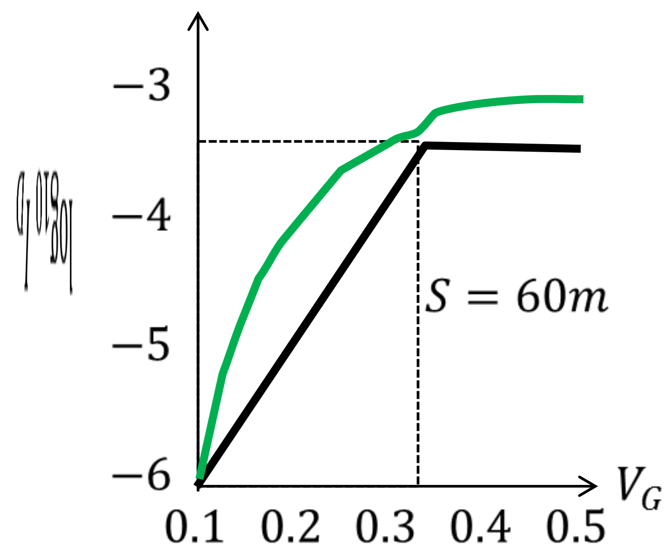


Real FE-FET with 0<S<60



$$m = \frac{\int_{Q_{c1}}^{Q_{c2}} dQ\,[C_S^{-1} + C_0^{-1} - C_{FE}^{-1}]}{\int_{Q_{c1}}^{Q_{c2}} dQ\, C_S^{-1}}$$





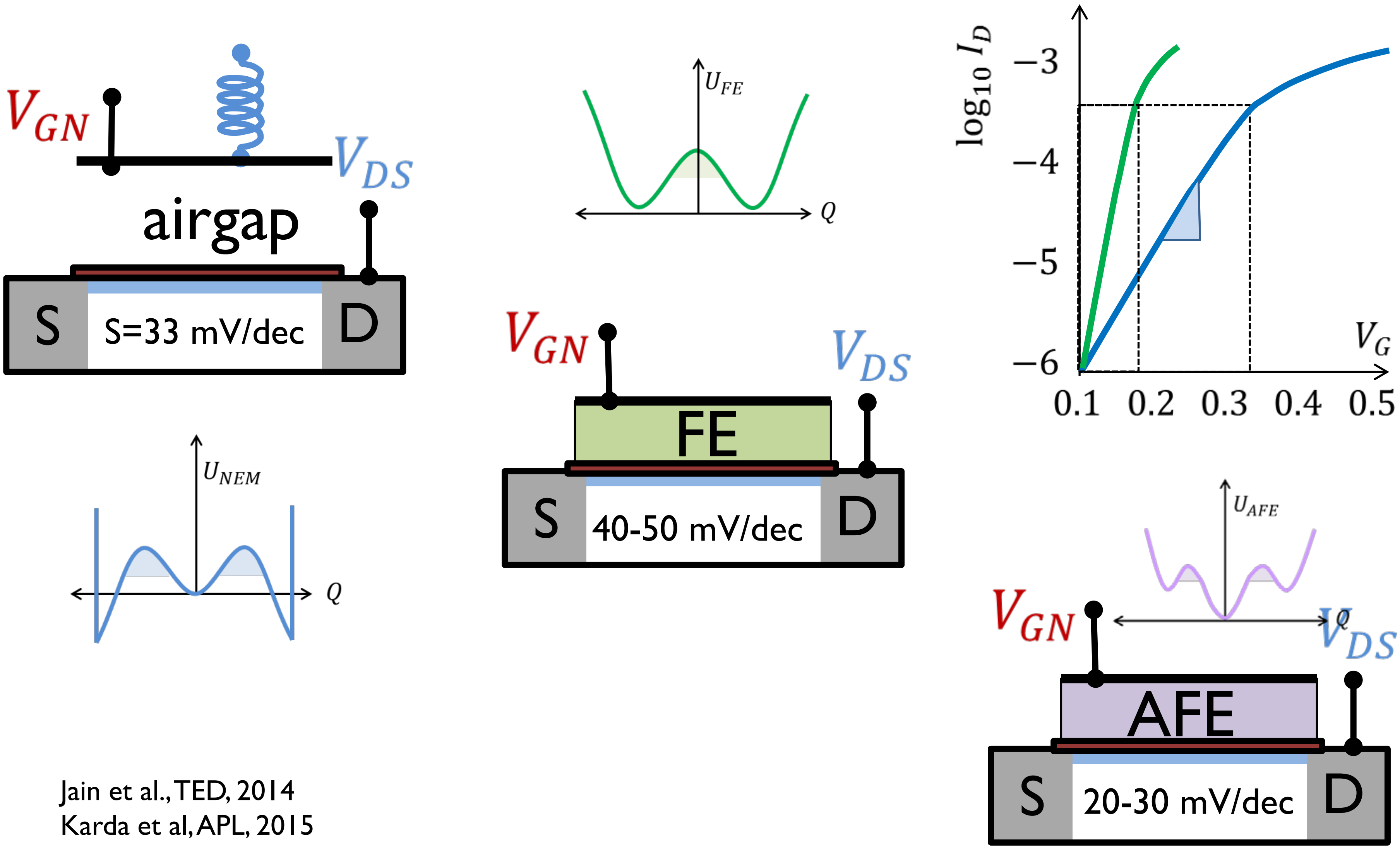
Minimum S for different FE

$$C_{FE}^{-1} = \alpha_0 y_0 + 3\beta_0 y_0 Q^2 + 5\gamma_0 y_0 Q^4$$

Jain et al., TED, 2014
Karda et al, APL, 2015

Parameters	BaTiO3	PZT	SBT	
$\alpha_0 (m/F)$	$-1e7$	$-4.5e7$	$-6.5e7$	
$\beta_0 (m^5 F/coul^2)$	$-8.9e8$	$5.2e8$	$3.75e9$	
$\gamma_0 (m^9 F/coul^4)$	$4.5e10$	$5.9e8$	0	
S_{min}	42	52	52	Bulk-FET
S_{min}	17	20	20	Constant C_S

S improves for all these transistors

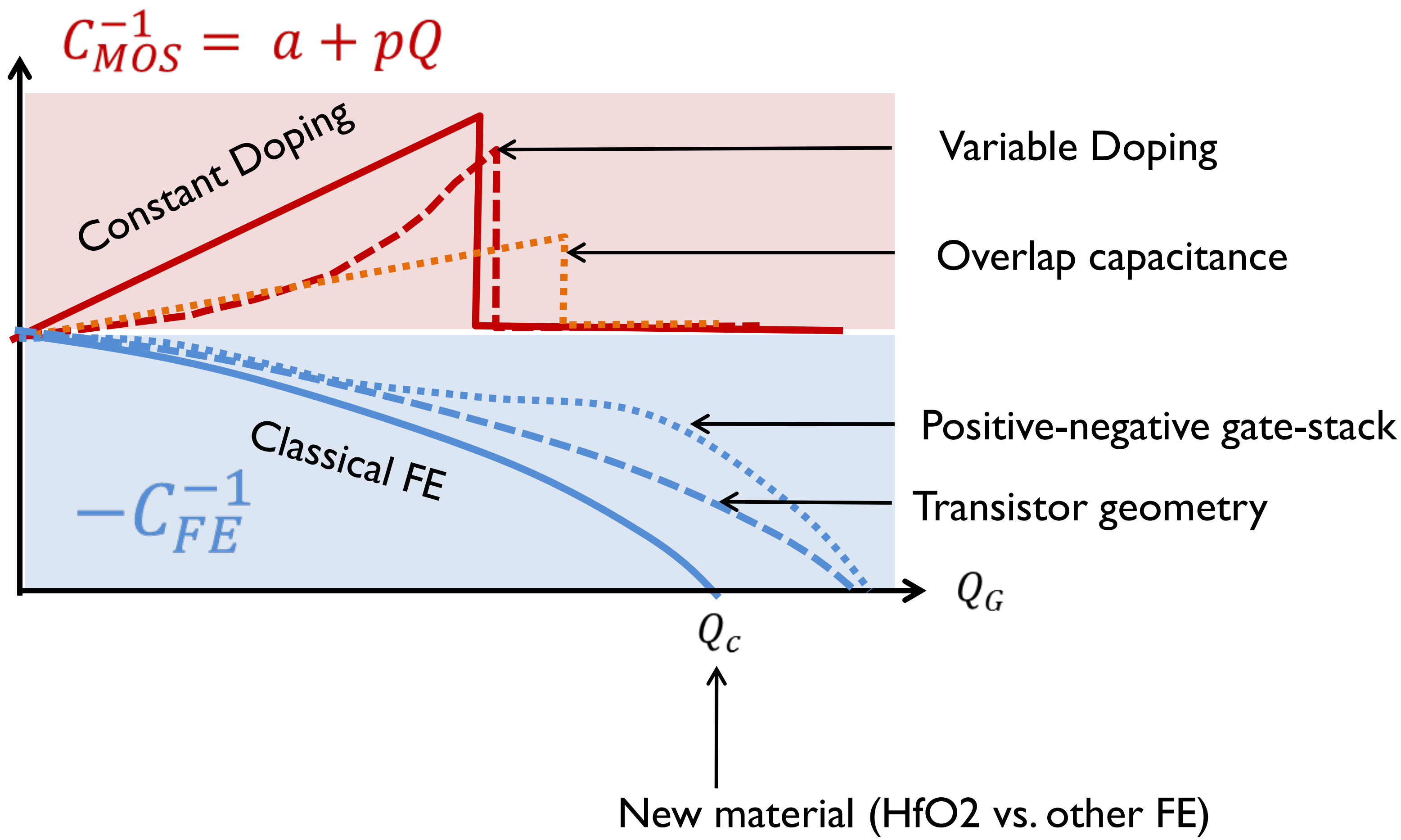


Jain et al., TED, 2014
Karda et al, APL, 2015

Outline

- Motivation: Self-heating in Transistors
- The physics of Classical and Landau-FET
- Physics of FE-based Landau Transistors
- Strategies of Improving FE-Transistors
  - Geometry, Energy Landscape, and FET design
- Additional Considerations:
  - Speed, Reliability, Fake amplification
- Conclusions

Strategies to improve S

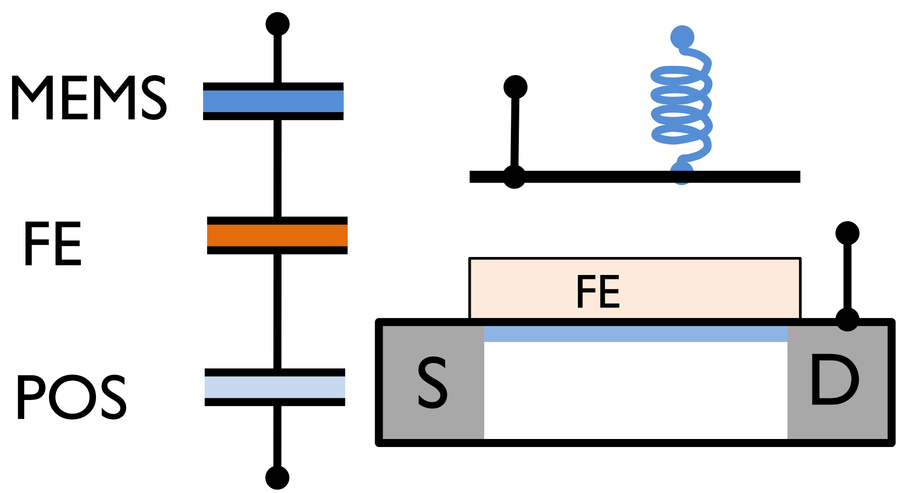


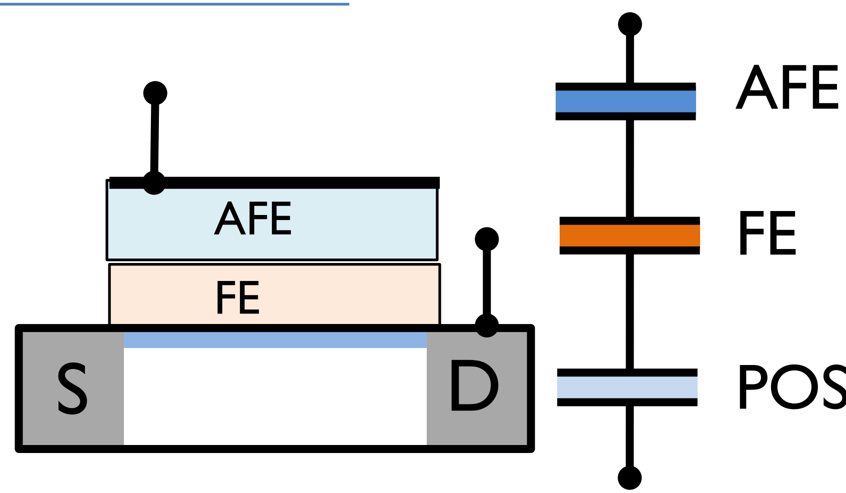
Approach 1: Stack of Negative Capacitor

$$C^{-1} = \alpha + \beta Q^2 + \gamma Q^4$$

	α	β	γ
Positive	+	+	+
FE	-	+	+
NEM	+	-	+
AFE	+	-	+

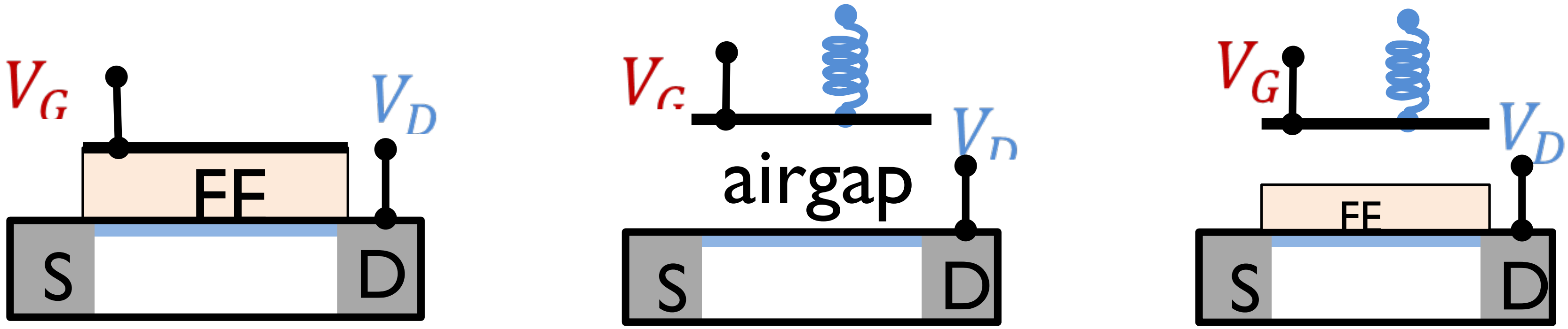
Jain et al., TED 2014
Karda et al, APL, 2015

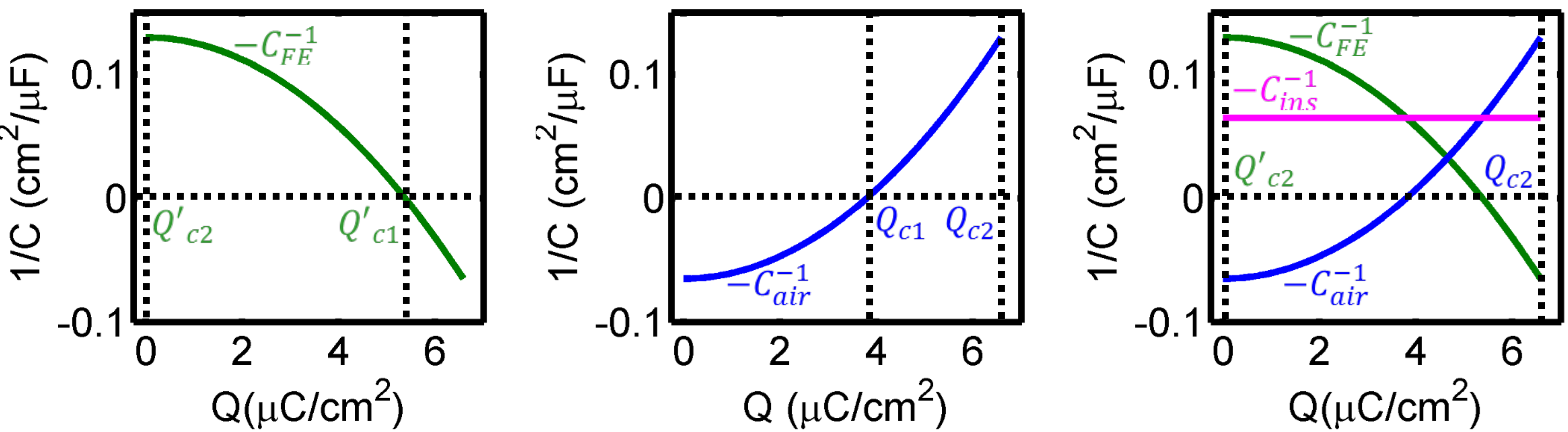




Proposed NEM-FE FET

Jain et al., TED, 2014





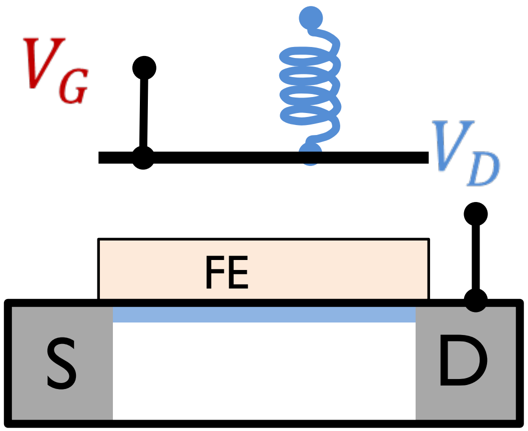
$$C_F^{-1} = -\alpha_F + \beta_F Q^2$$

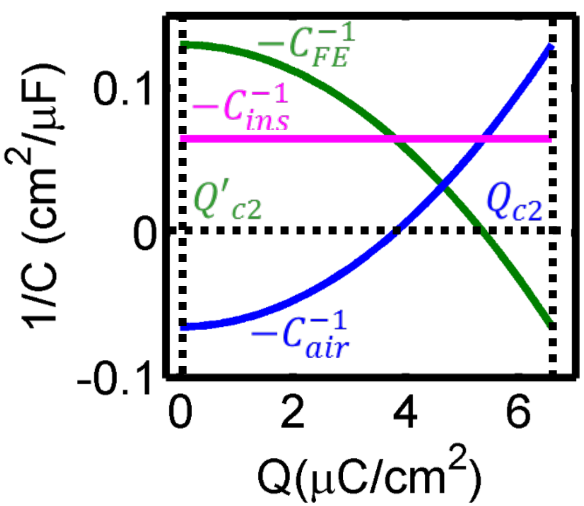
$$C_N^{-1} = \alpha_N - \beta_N Q^2$$

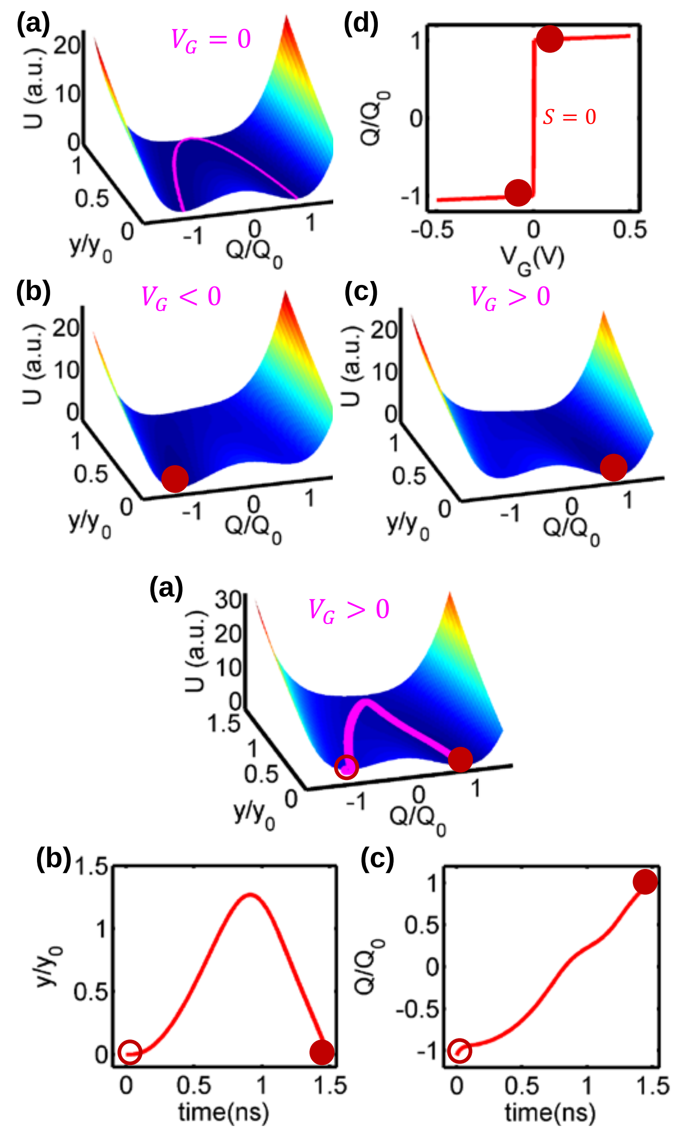
$$C_{ins}^{-1} = \alpha_N - \alpha_F < 0$$

Physics of Zero-subthreshold slope

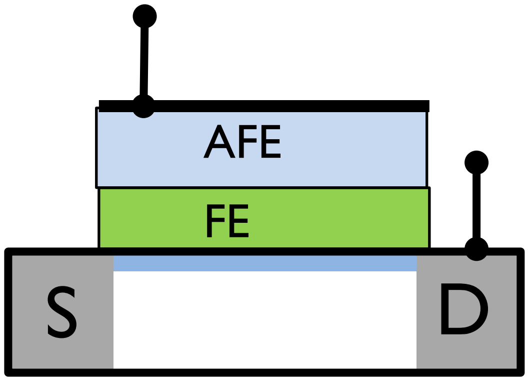
Jain et al., TED, 2014

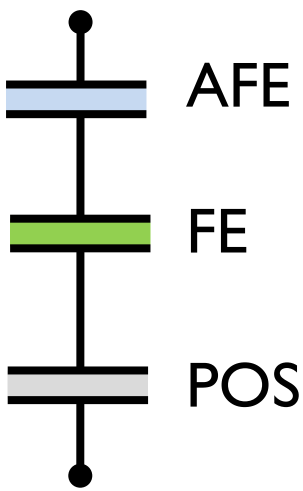


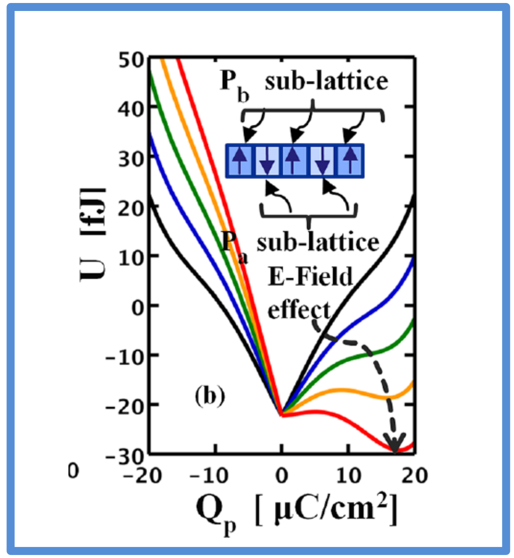


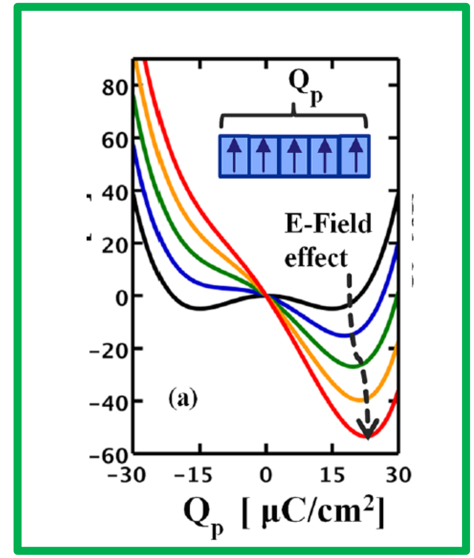


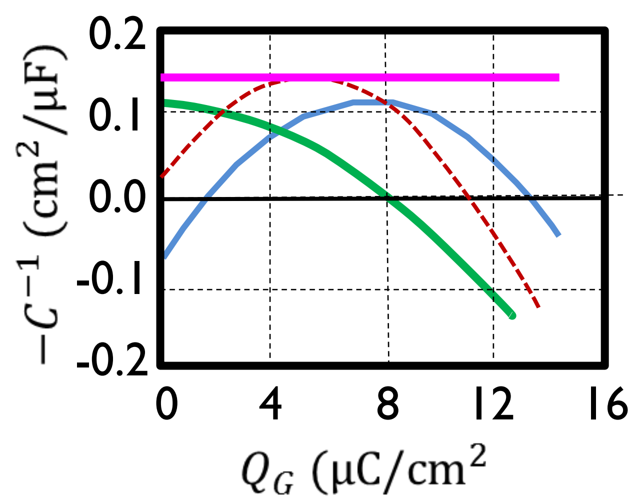
Capacitance of a FE-AFE FET







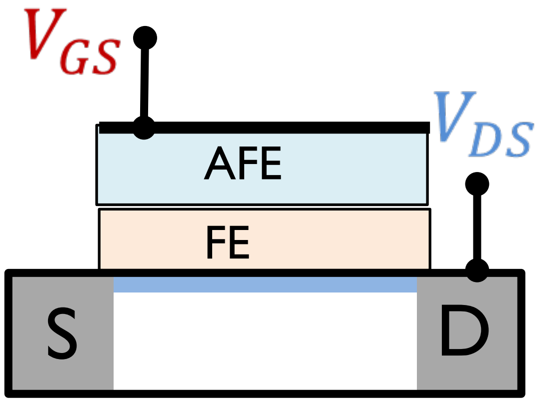


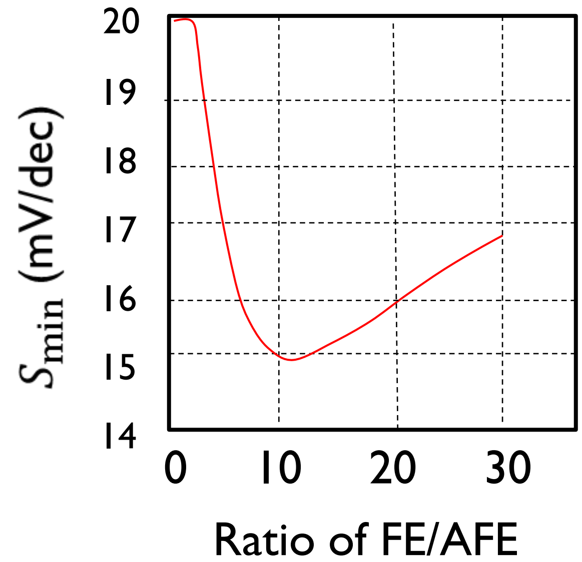


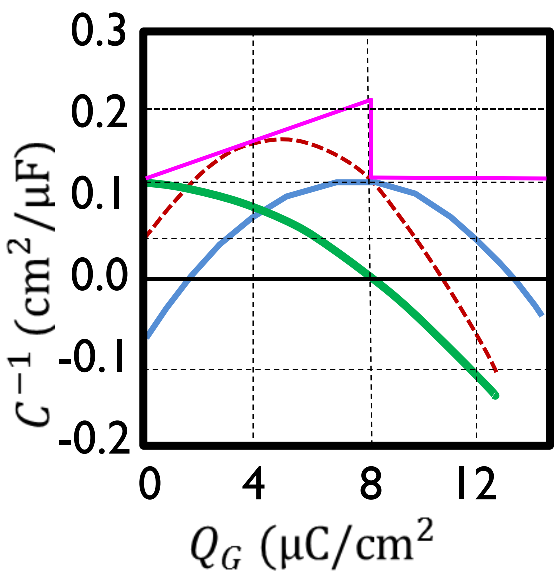
Karda et al. APL, 2015.

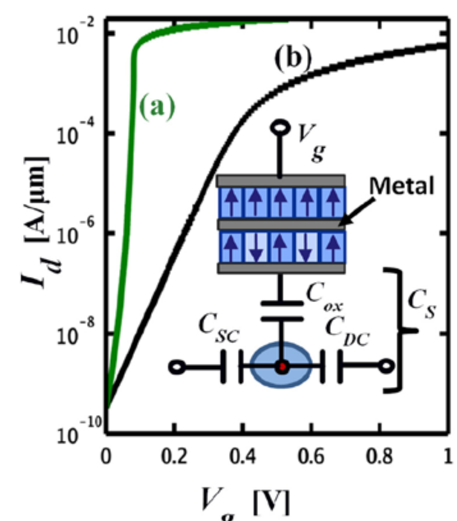
FE-AFE FET

Karda et al. APL, 2015.

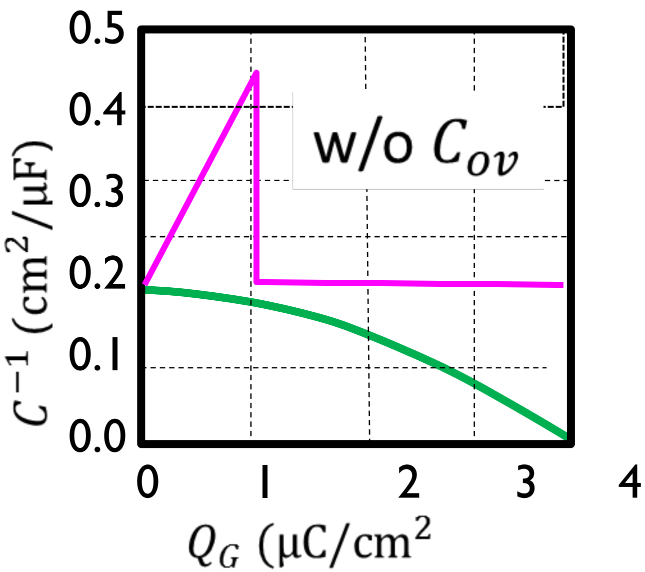


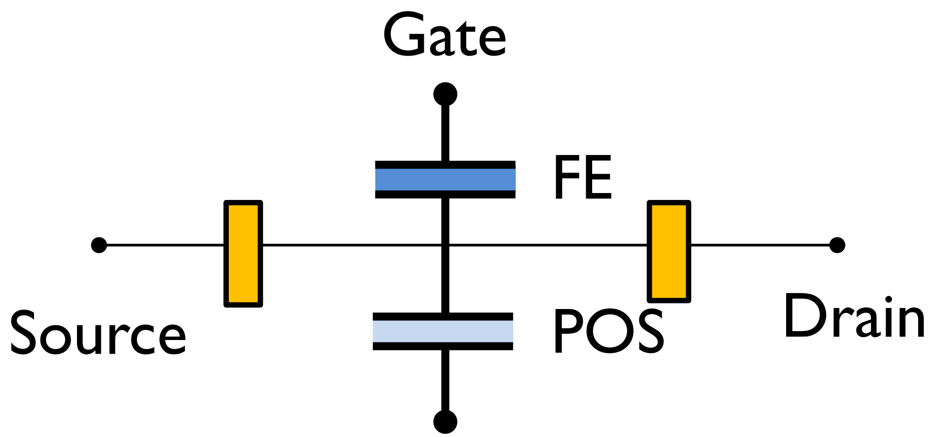


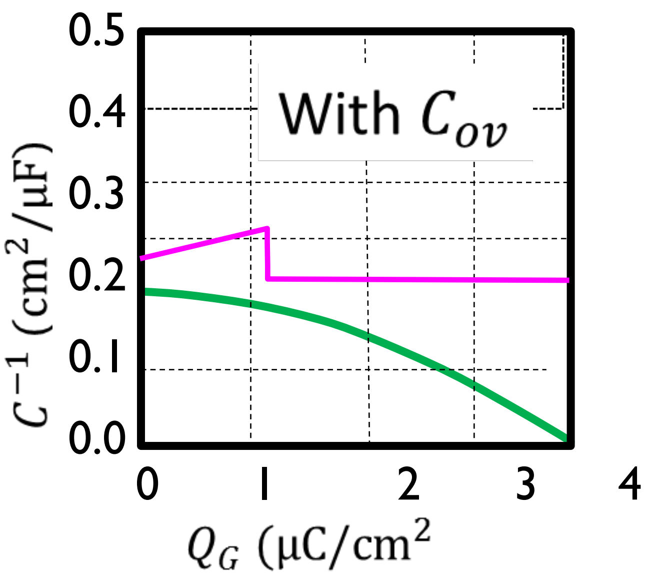


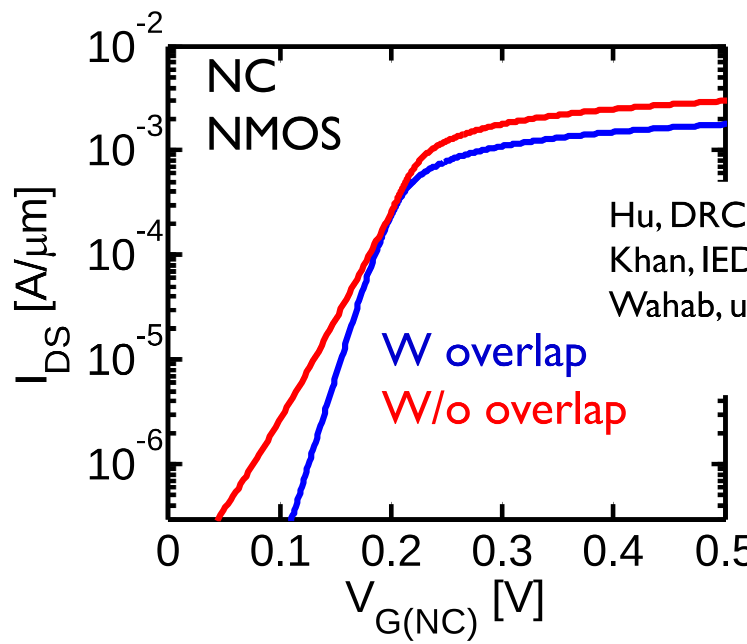


Approach 2: Use Overlap Capacitors



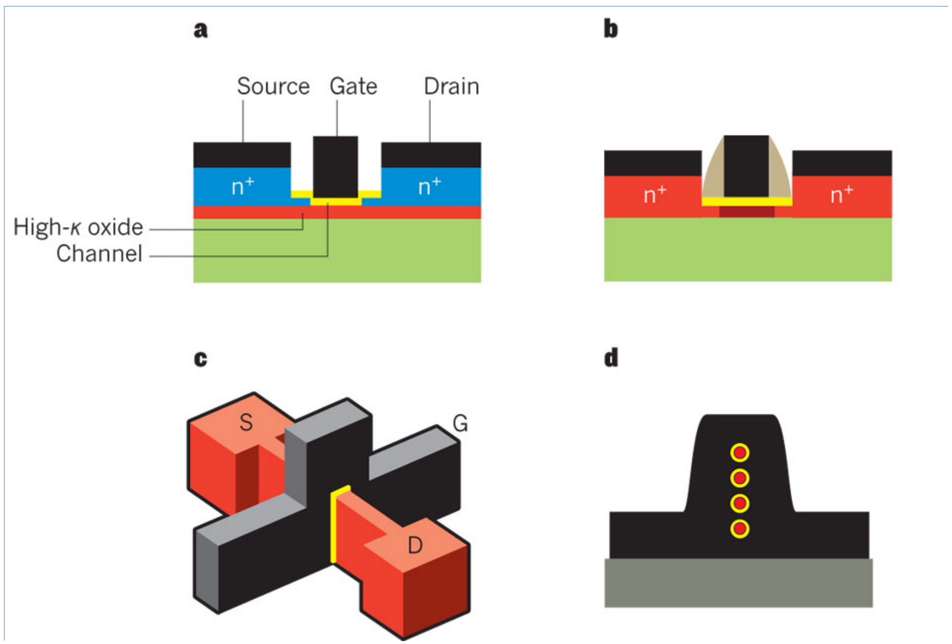


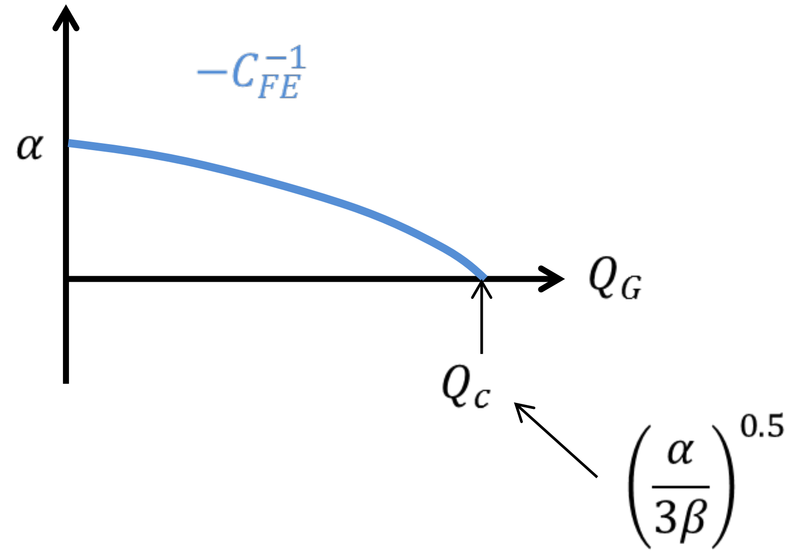


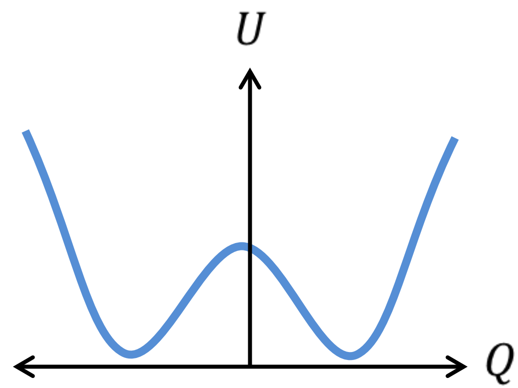


Hu, DRC, 2015
Khan, IEDM, 2011
Wahab, unpublished

Approach 3: Tailor Coefficients by Geometry

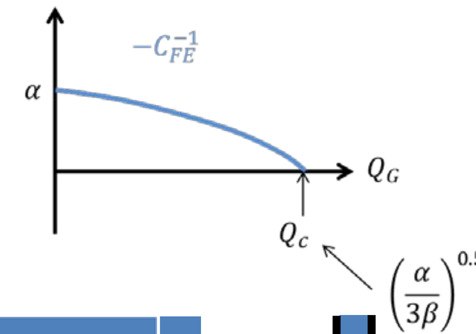




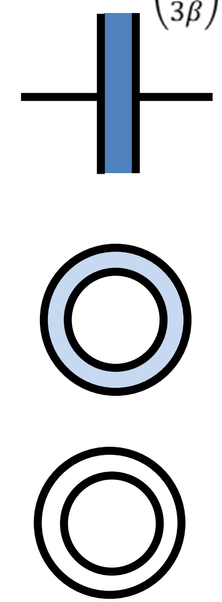


Approach 3: Tailor Coefficients by Geometry

$$C^{-1} = \alpha + 3\beta Q^2$$



Dimension	α	β
2D: Planar	$\frac{\alpha_0 y}{A}$	$\frac{\beta_0 y}{A^3}$
1D: Cylinder	$\frac{\alpha_0}{2\pi L}\log\left(\frac{r_o}{r_i}\right)$	$\frac{\beta_0}{16\pi^3 L^3}\left(\frac{1}{r_i^2} - \frac{1}{r_o^2}\right)$
0D: Sphere	$\frac{\alpha_0}{4\pi}\left(\frac{1}{r_i} - \frac{1}{r_o}\right)$	$\frac{\beta_0}{320\pi^3}\left(\frac{1}{r_i^5} - \frac{1}{r_o^5}\right)$



Induced NC

Capacitor

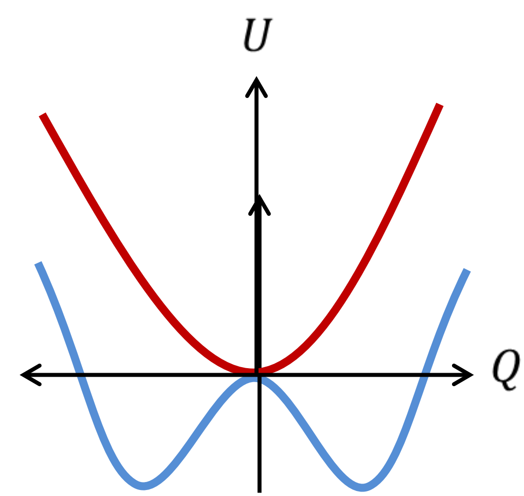
Positive | Negative

FE AFE NEMS

Piezo pH Temp

$$C^{-1} = \alpha + \beta Q^2 + \gamma Q^4$$

	α	β	γ
Positive	+	+	+
FE-1	-	+	+
FE-2	-	-	+
NEM AFE	+	-	+



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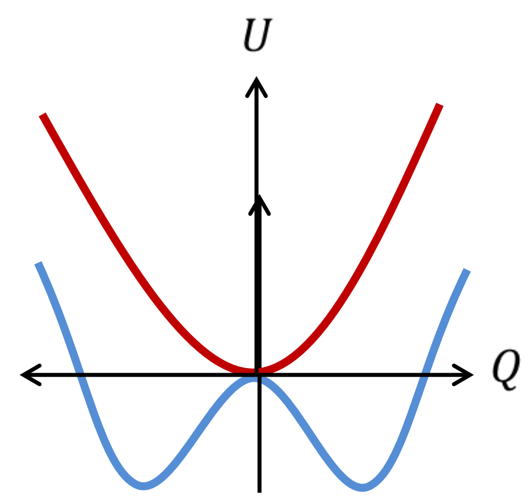
$$C^{-1} = \alpha + \beta Q^2 + \gamma Q^4$$

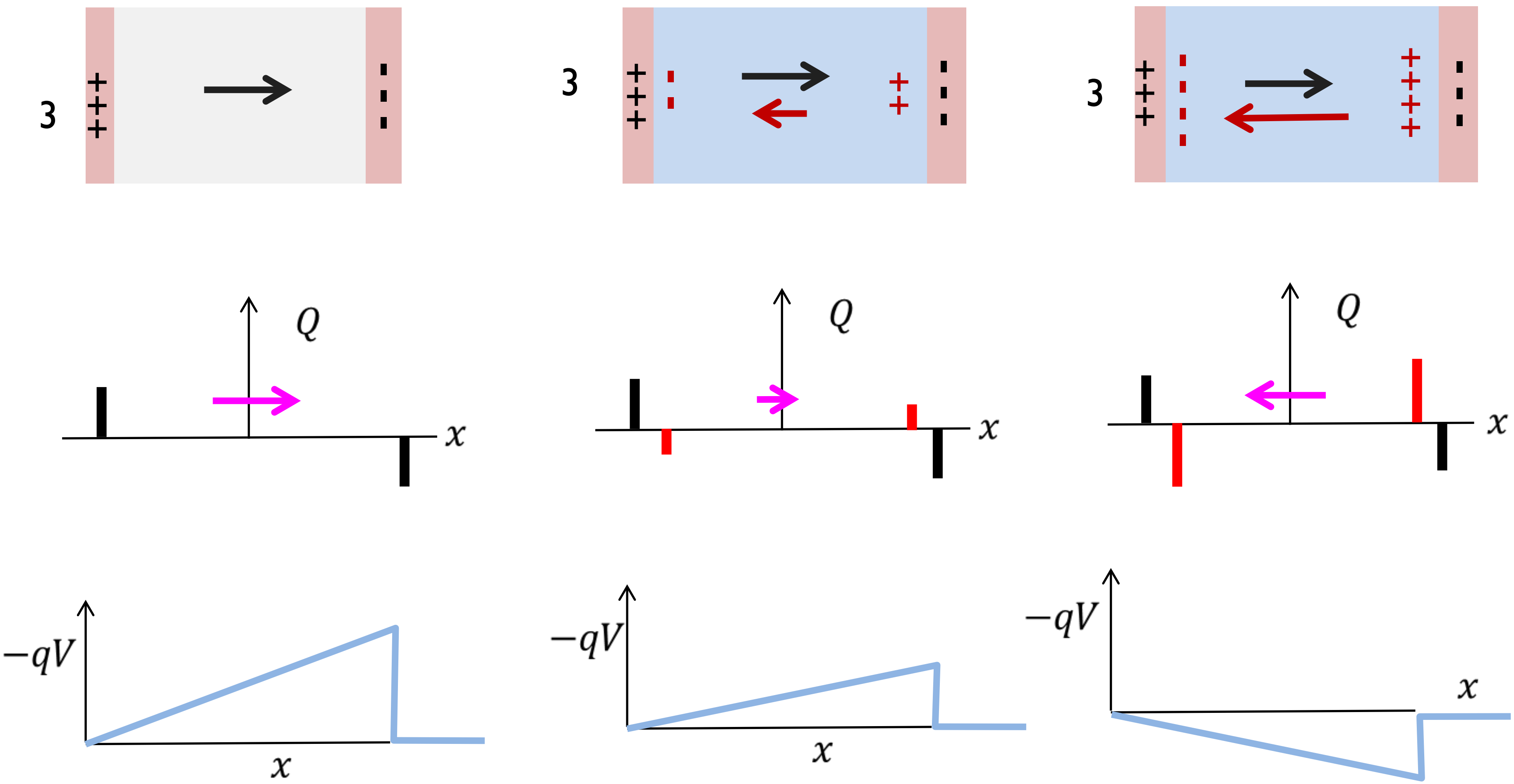
	α	β	γ
Positive	+	+	+
FE-1	-	+	+
FE-2	-	-	+
NEM AFE	+	-	+

Capacitor

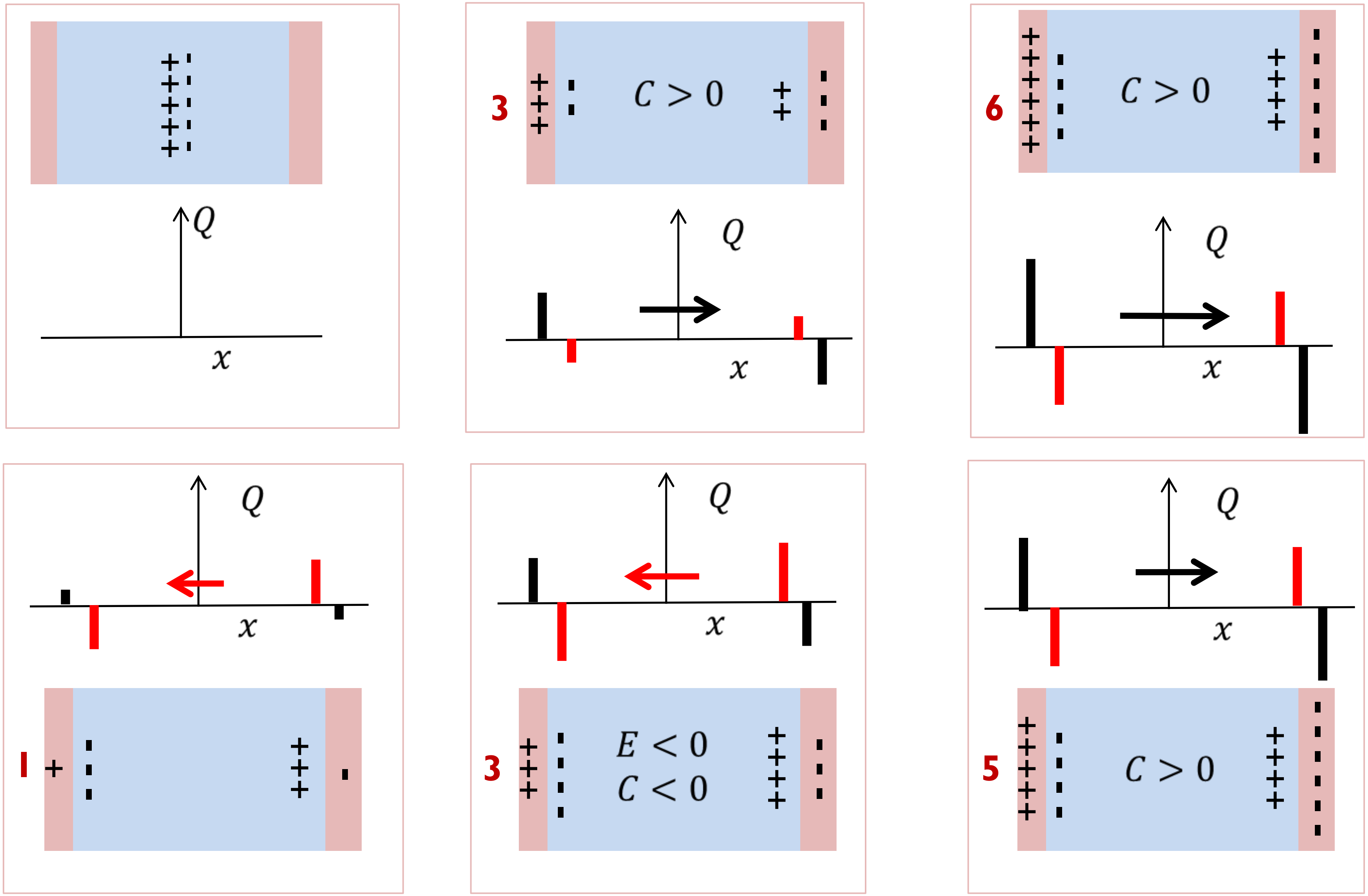
- Positive
- Negative
  - Extrinsic
    - Charging
    - Dispersion
  - Intrinsic
    - FE AFE NEMS
    - Piezo pH Temp



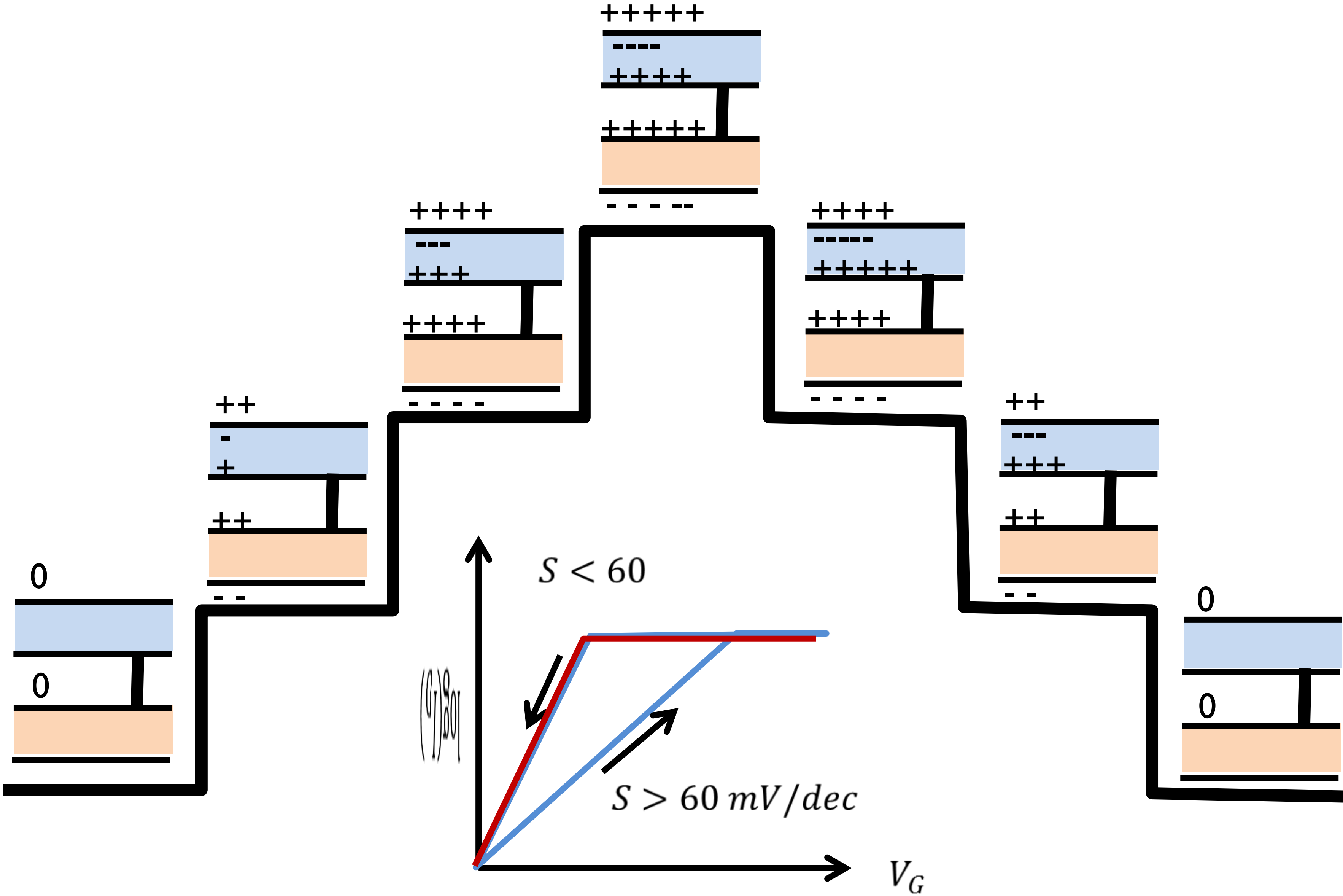
Recall: Essence of Negative Capacitor



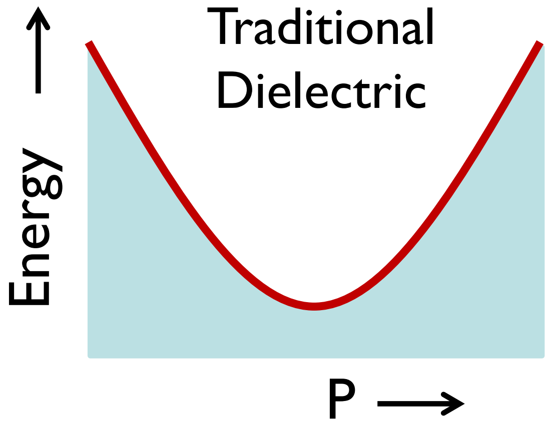
Ion Motion and Transient NC

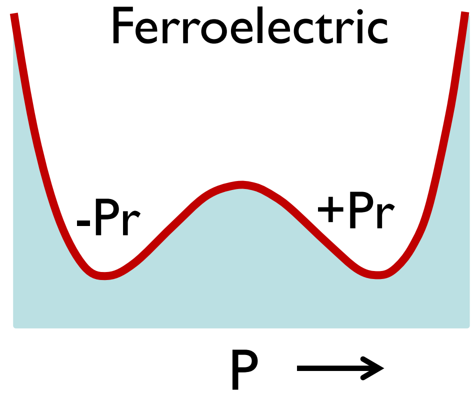


Ion Motion and Transient NC

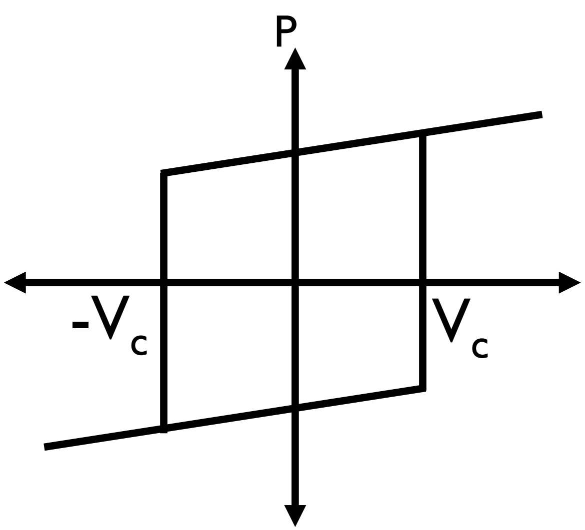


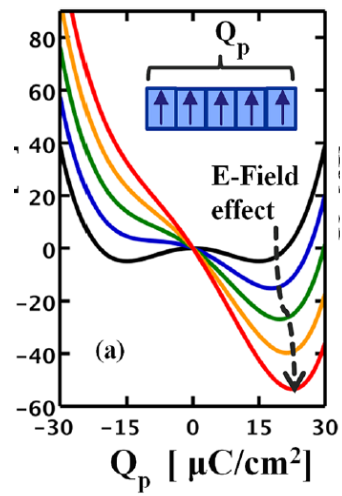
Switching & Reliability of Ferroelectrics

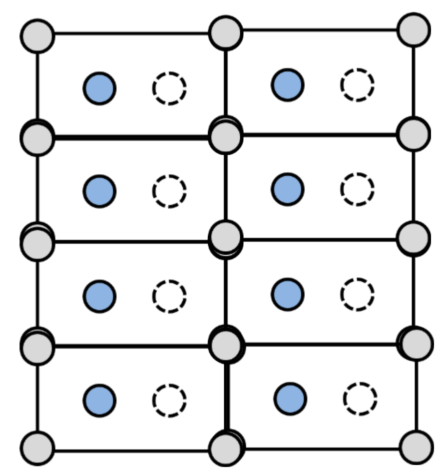




Would transient overshoot reduce lifetime?

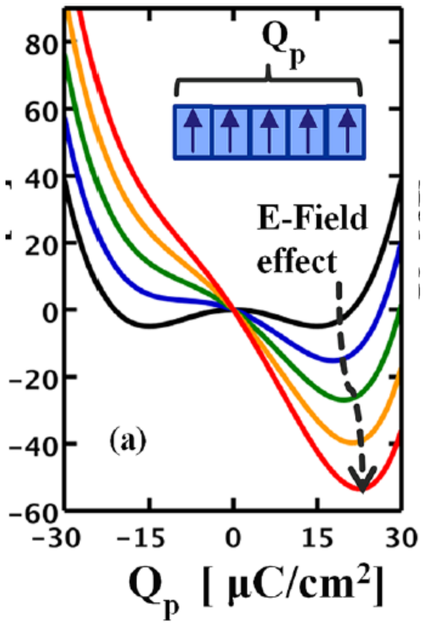


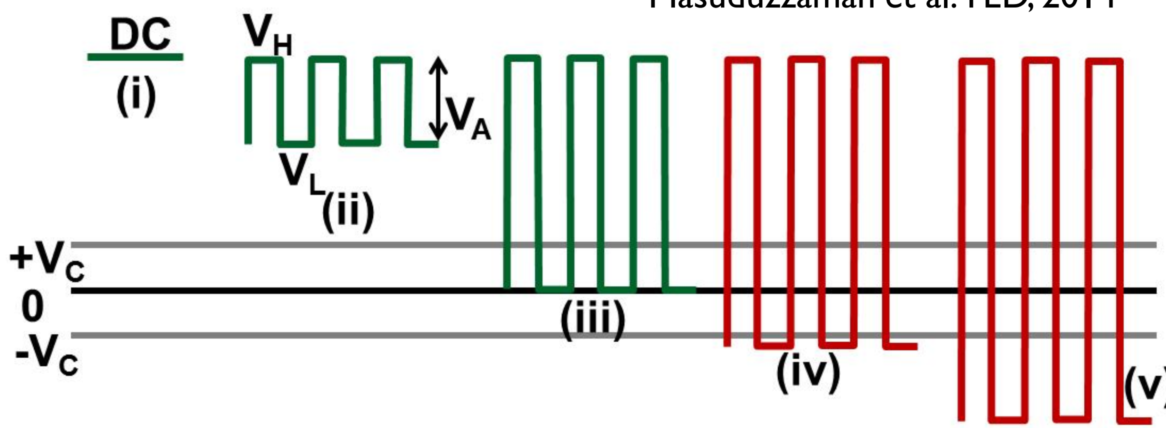


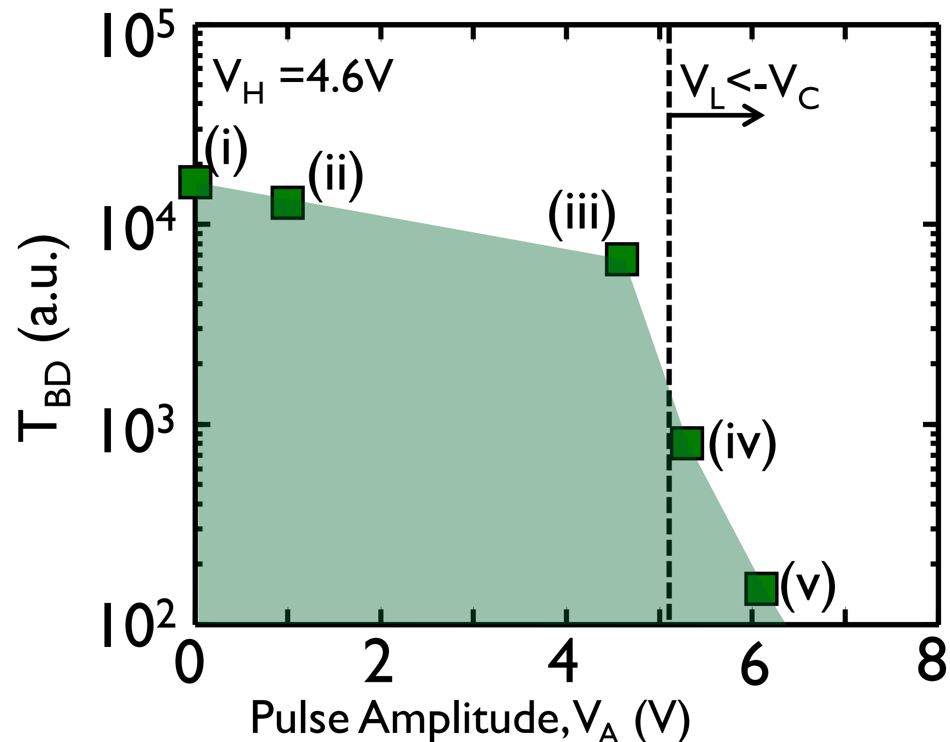


$Pb(Zr,Ti)O_3$

Coercive Voltage Dependence

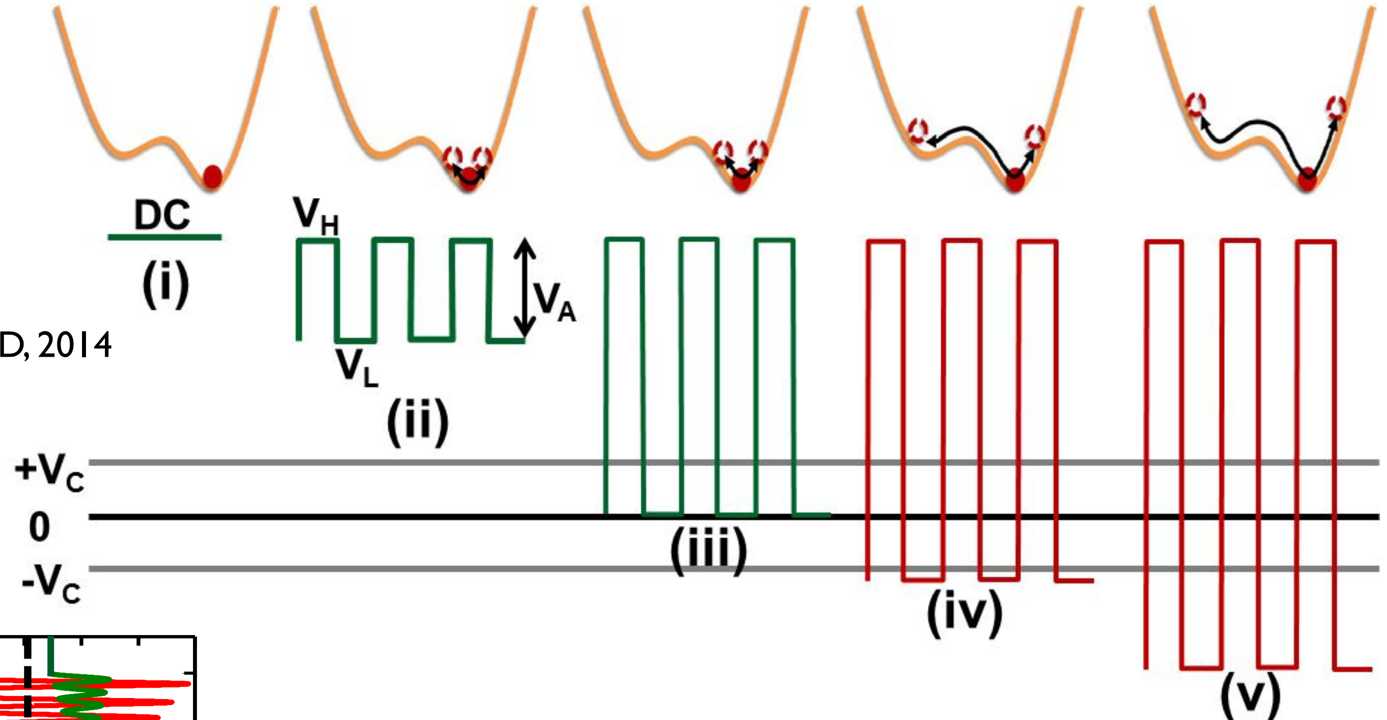




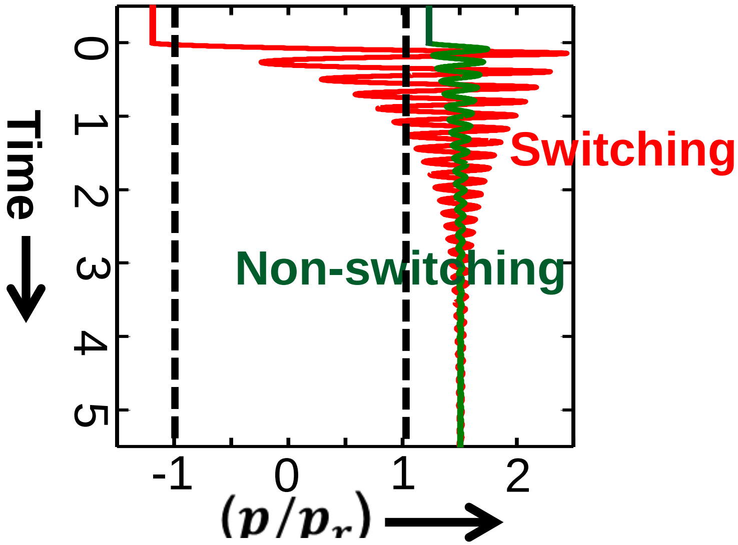


Lifetime decreases sharply as the FE starts switching

Theoretical Model (cont.)

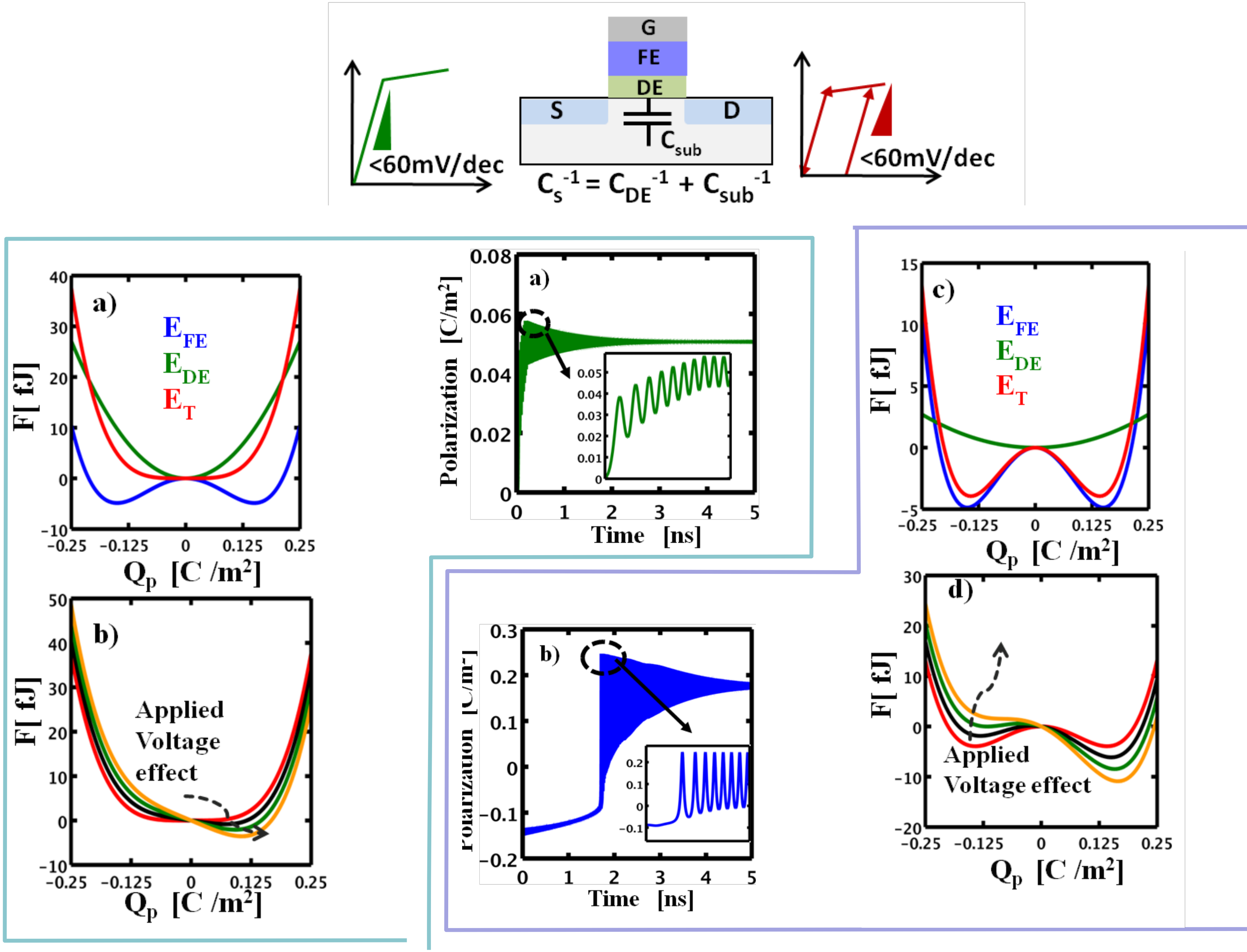


Masuduzzaman et al. TED, 2014
Karda et al. EDL, 2015



The model explains the coercive field and cycle dependence observation

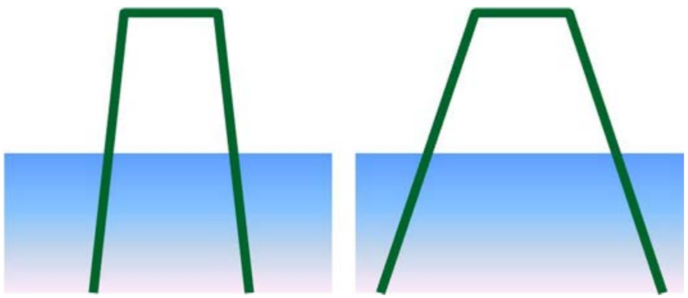
$$M\frac{d^2p_i}{dt^2} + \Gamma\frac{dp_i}{dt} = \mathcal{F}(p_i) + E(t)$$

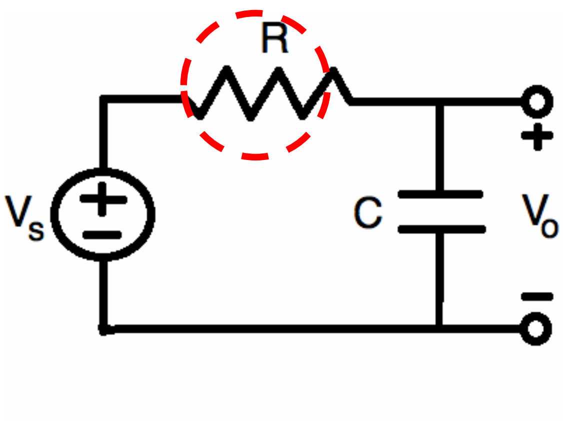


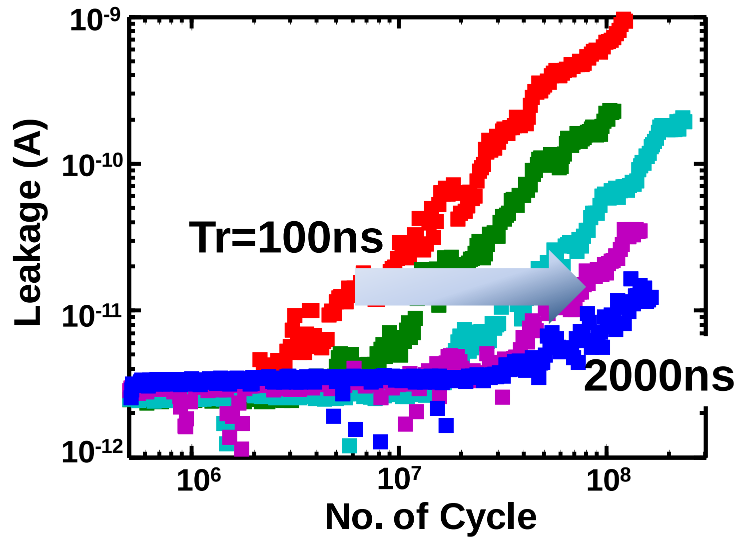
Alam, A Tutorial on Landau Transistors, 2015

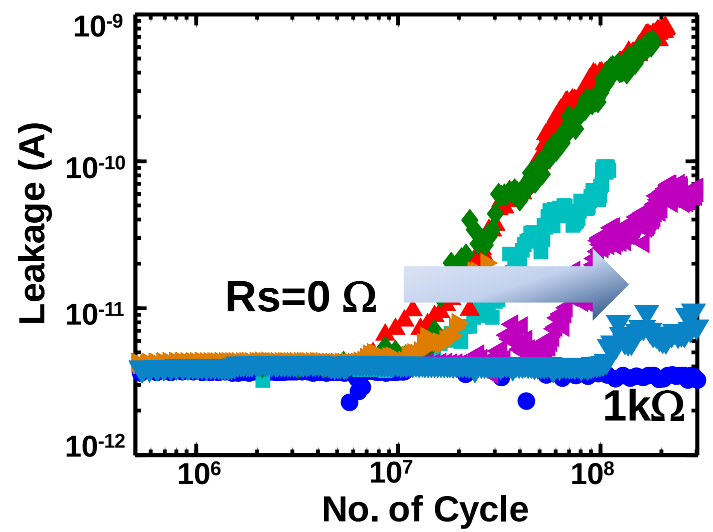
Experimental Verification

Masuduzzaman et al. TED, 2014







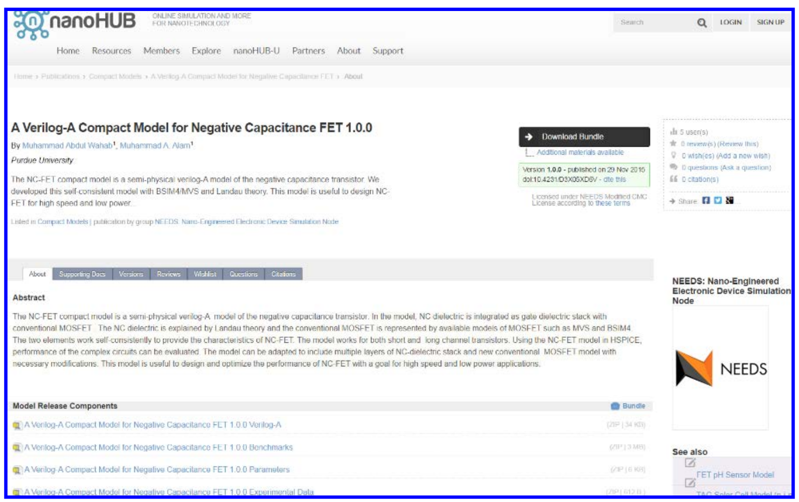


Conclusions

- Negative capacitor-FET promises to lower supply voltage and power dissipation.
- A simple graphical approach and band-diagram interprets NC-FET in terms of classical FET
- There are wide variety of Negative capacitors, all defined by Landau landscape. Combination of capacitors may improve performance.
- Hysteresis, reliability, speed, self-heating are emerging topics. Results are easy to misinterpret.
- Broad variety of new applications: circuits based on positive and negative resistors, inductors, and capacitors

Resources

- A simple code for exercise landaufet.m
- Compact model compatible with BSIM/MVS models posted at nanohub.org/groups/ needs



For Further Reading: NC in Transistors

- **Various types of Single Negative Capacitor Transistors**
- FE-FET: Use of negative capacitance to provide voltage amplification for low power nanoscale devices, S Salahuddin, S Datta, Nano letters 8 (2), 405-410, 2008
- FE-FET: Ferroelectric negative capacitance MOSFET: Capacitance tuning & antiferroelectric operation, AI Khan, CW Yeung, C Hu, S Salahuddin, Electron Devices Meeting (IEDM), 2011 IEEE International, 11.3. 1-11.3. 4, 2011
- FE-FET: Experimental evidence of ferroelectric negative capacitance in nanoscale heterostructures, AI Khan, D Bhowmik, P Yu, SJ Kim, X Pan, R Ramesh, S Salahuddin, Applied Physics Letters 99 (11), 113501, 2011. Negative capacitance in a ferroelectric capacitor, A. I. Khan, K. Chatterjee, B. Wang, S. Drapcho, L. You, Claudy Serrao, S. R. Bakaul, R. Ramesh and S. Salahuddin, Nature Materials 14, 182–186 (2015)
- NEFFET: Three-Terminal Nanoelectromechanical Field Effect Transistor with Abrupt Subthreshold Slope, Ji-Hun Kim†, Zack C.Y. Chen†, Soonshin Kwon‡, and Jie Xiang, Nano Lett., 2014, 14 (3), pp 1687–1691, 2014
- FE-FET, NEMFET: Prospects of hysteresis-free abrupt switching (0 mV/decade) in Landau switches, A Jain, M Alam, Electron Devices, IEEE Transactions on 60 (12), 4269-4276, 2013.
- NEMFET, FEFET: Stability Constraints Define the Minimum Subthreshold Swing of a Negative Capacitance Field-Effect Transistor, A Jain, MA Alam, IEEE Transactions on Electron Devices 61 (7), 2235 – 2242, 2014
- Piezo-FET: A Nanoscale Piezoelectric Transformer for Low-Voltage Transistors, Sapan Agarwal* and Eli Yablonovitch, Nano Lett., 2014, 14 (11), pp 6263–6268 , DOI: 10.1021/nl502578q, 2014
- HfO2-FE: T. S. Böscke , J. Müller , D. Bräuhaus , U. Schröder and U. Böttger "Ferroelectricity in Hafnium Oxide: CMOS compatible ferroelectric field effect transistors", IEDM Tech. Dig., pp.547 -550 2011

For Further Reading: NC in Transistors

- **Various types of Single Negative Capacitor Transistors**

- FE-FET with Quantum Metal: D. Frank et al., "The Quantum Metal Field-Effect Transistors, TED, 2014.
- FE-FET, parasitic Capacitance: 0.2 Volt Adiabatic NC-FinFET with 0.6mA/um Ion and 0.1 nA/um IOFF, C. Hu, S. Salahuddin, C.-I. Lin, and A. Khan, 978-1-4673-8135-2/15, 2015.
- FE-FET, parasitic Capacitance: Abdul Wahab, Generalized NC compact model for BSIM and MVS, to be published, 2016.
- FE-FET Reliability: Reliability and Switching Dynamics of Landau Switches, K. Karda, C. Mouli, and M. A. Alam, to be published, 2016.

- **Various types of NC-FET with Compensated Gate Dielectrics**

- NEM-FE FET: Proposal of a hysteresis-free zero subthreshold swing field-effect transistor, A Jain, M Alam, Electron Devices, IEEE Transactions on 61 (10), 3546-3552, 2014.
- AFE-FE FET: An anti-ferroelectric gated Landau transistor to achieve sub-60 mV/dec switching at low voltage and high speed, K Karda, A Jain, C Mouli, MA Alam, Applied Physics Letters 106 (16), 163501, 2015.
- Piezo-FET: On the possibility of sub 60 mV/decade subthreshold switching in piezoelectric gate barrier transistors, Raj K. Jana*, Gregory L. Snider and Debdeep Jena, physica status solidi (c), Volume 10, Issue 11, pages 1469–1472, November 2013

For Further Reading: NC in Sensors, MEMS, DNA Design

- NEM-Biosensors: Intrinsic low pass filtering improves signal-to-noise ratio in critical-point flexure biosensors, A Jain, MA Alam, Applied Physics Letters 105 (8), 084106, 2014.
- NEM-Biosensors: Flexure-FET biosensor to break the fundamental sensitivity limits of nanobiosensors using nonlinear electromechanical coupling, A Jain, PR Nair, MA Alam, Proceedings of the National Academy of Sciences 109 (24), 9304-9308, 2012.
- NEM-Landscape. Strategies for dynamic soft-landing in capacitive microelectromechanical switches, A Jain, PR Nair, MA Alam, Applied Physics Letters 98 (23), 234104, 2011.
- NEM-FE: Effective Nanometer Airgap of NEMS Devices Using Negative Capacitance of Ferroelectric Materials, M Masuduzzaman, MA Alam, Nano Letters 14 (6), 3160-3165, 2014.
- FE-Reliability: Observation and control of hot atom damage in ferroelectric devices, M Masuduzzaman, D Varghese, JA Rodriguez, S Krishnan, MA Alam, Electron Devices, IEEE Transactions on 61 (10), 3490-3498, 2014.
- DNA-Origami: Direct Design of an Energy Landscape with Bistable DNA Origami Mechanisms, L. Zhou, A. Marras, H.-J. Su and C. E. Castro, NL, 1815, 2015.