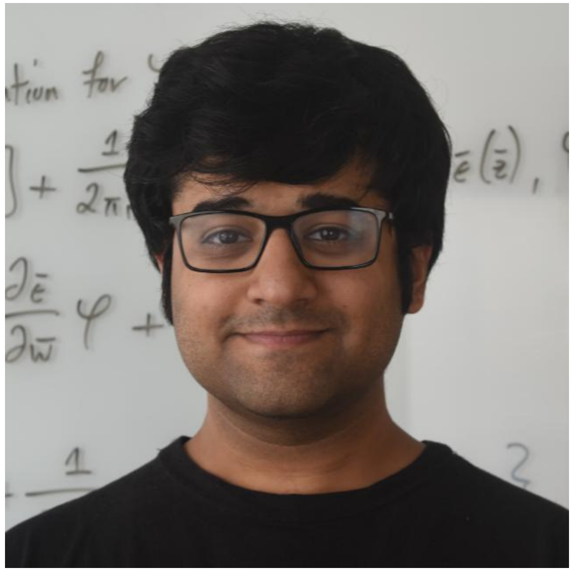
Interplay of Negative Quantum and Ferroelectric Capacitances for Low-Power Transistor Operations



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Presented at the 2021 Virtual MRS Spring Meeting
Date: 19 April 2021

Outline

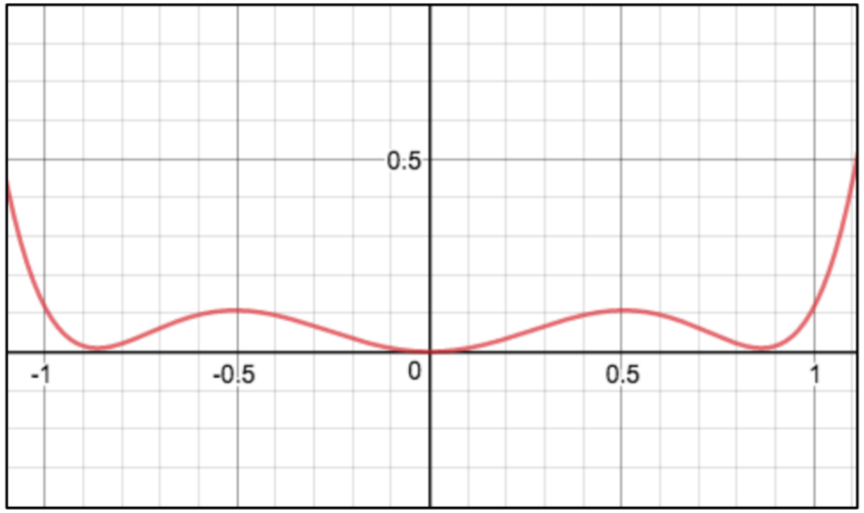
- Ferroelectric negative capacitance (NC) FET model: motivation and role of quantum capacitance.
- Physical origin of quantum capacitance.
- Consequences of negative channel quantum capacitance in NC-FETs.
- Negative capacitance in FET channels: physical considerations.

Ferroelectric Negative Capacitance (NC) FETs

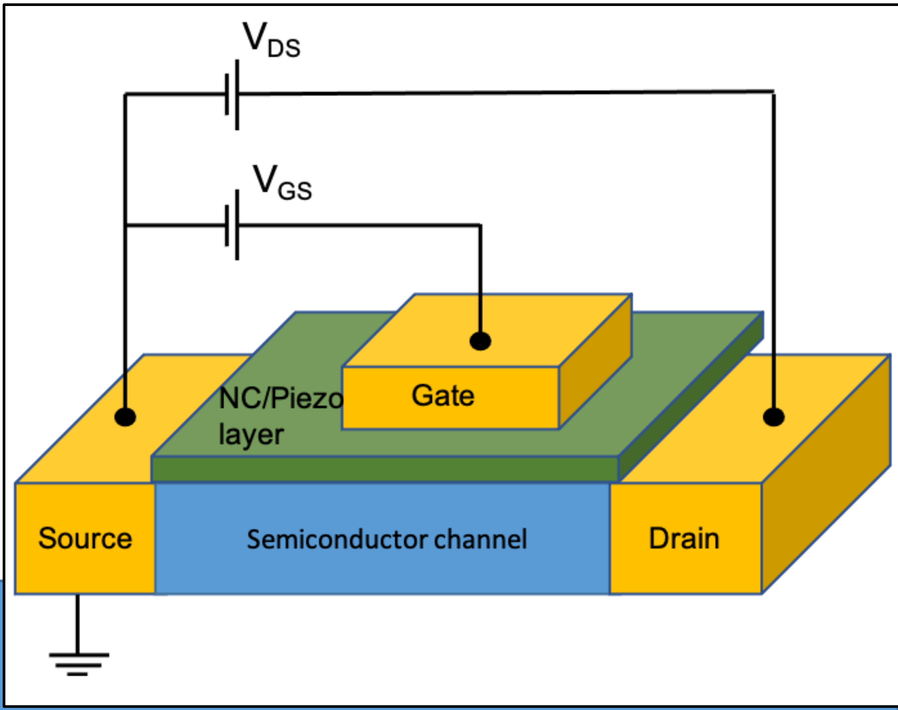
- Landau-Ginzburg-Devonshire theory of piezoelectrics[1]: phase transition induced by applied electric field.

$$G = \alpha|\vec{P}|^2/2 + \beta|\vec{P}|^4/4 + \gamma|\vec{P}|^6/6 + |\vec{E}| \cdot |\vec{P}|$$

  - $\alpha < 0$: Piezoelectric. $\mathrm{d}G/\mathrm{d}|\vec{P}| = 0$ gives stability condition: $|\vec{E}| = \alpha|\vec{P}| + \beta|\vec{P}|^3 + \gamma|\vec{P}|^5$. $\mathrm{d}|\vec{E}|/\mathrm{d}|\vec{P}| < 0$ region gives NC.



- NC for voltage amplification[2]: use stabilized NC layer.
  - NC region is in unstable equilibrium. (Anderson-Higgs-like.) Stabilize by placing positive capaciting layer in series.
  - Total positive cap. w/ NC enhancement. Gate voltage amp.
  - Can help with *e.g.*, supply/wire thermal noise voltage mismatch.



[1] – S. Sivasubramanian, A. Widom, and Y. N. Srivastava, Ferroelectrics 300, *1*, 501 (2003).
[2] – S. Salahuddin and S. Datta, Nano Lett. 8, *2*, 405–410 (2008). 2nd image modified from here.

Quantum Capacitance Analysis of NCFET Design

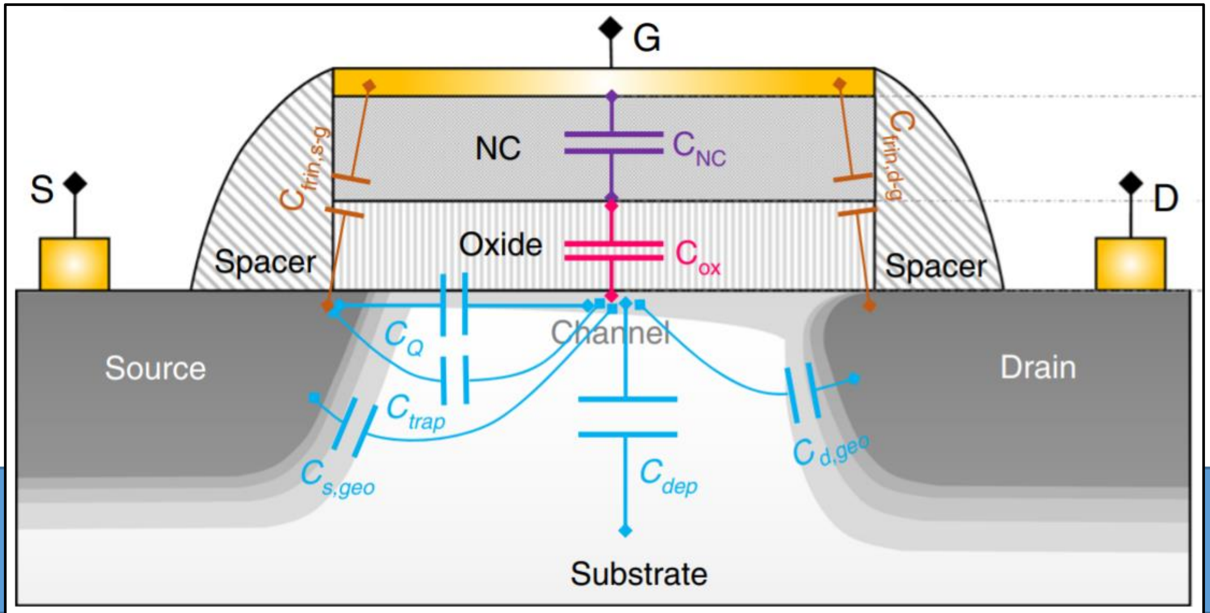
- Generic model[3]: limited benefits from NC.
  - Body factor < voltage gain: sub-60 mV subthreshold swing.
  - $|C_{\mathrm{NC}}| <$ remaining terms: unstable LGD state.
  - $C_{\mathrm{div},<V_{\mathrm{th}}}$ moderate to large: large $|C_{\mathrm{NC}}|$.
    - Large NC material dielectric constant: thick layers.
- Generic NCFET models[3]: quantum capacitance dominates design space.
  - Increasing values of C_{q} yield *smaller* range of hysteresis-free minimum subthreshold swing.

$$C_{\mathrm{div}} \coloneqq C_{\mathrm{q}} + C_{\mathrm{trap}} + C_{\mathrm{dep}} + C_{\mathrm{s,geo}} + C_{\mathrm{d,geo}}$$

$$C_{\mathrm{div},<V_{\mathrm{th}}} \coloneqq C_{\mathrm{trap}} + C_{\mathrm{dep}} + C_{\mathrm{s,geo}} + C_{\mathrm{d,geo}}$$

$$SS = 60\left(1 + \frac{C_{\mathrm{div},<V_{\mathrm{th}}}}{C_{\mathrm{Ox}}}\right)\left(1 - \frac{C_{\mathrm{div},<V_{\mathrm{th}}}\,C_{\mathrm{Ox}}}{|C_{\mathrm{NC}}|\left(C_{\mathrm{div},<V_{\mathrm{th}}} + C_{\mathrm{Ox}}\right)}\right)$$

$$SS_{\mathrm{min}} = \frac{60C_{\mathrm{q}}}{C_{\mathrm{q}} + C_{\mathrm{div},<V_{\mathrm{Th}}}}$$



[3] – W. Cao and S. Banerjee, Nat. Comm. 11, 196 (2020).
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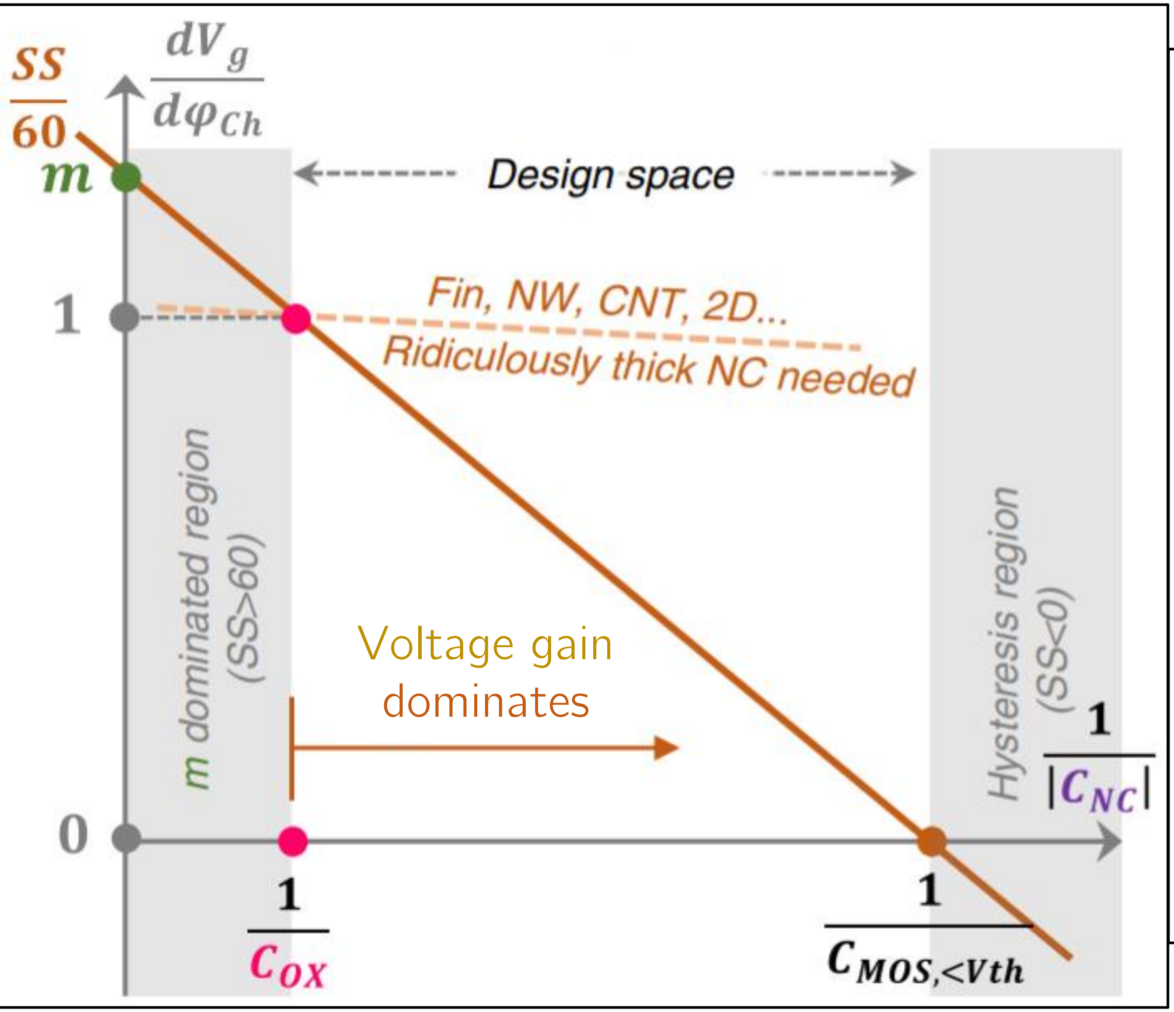
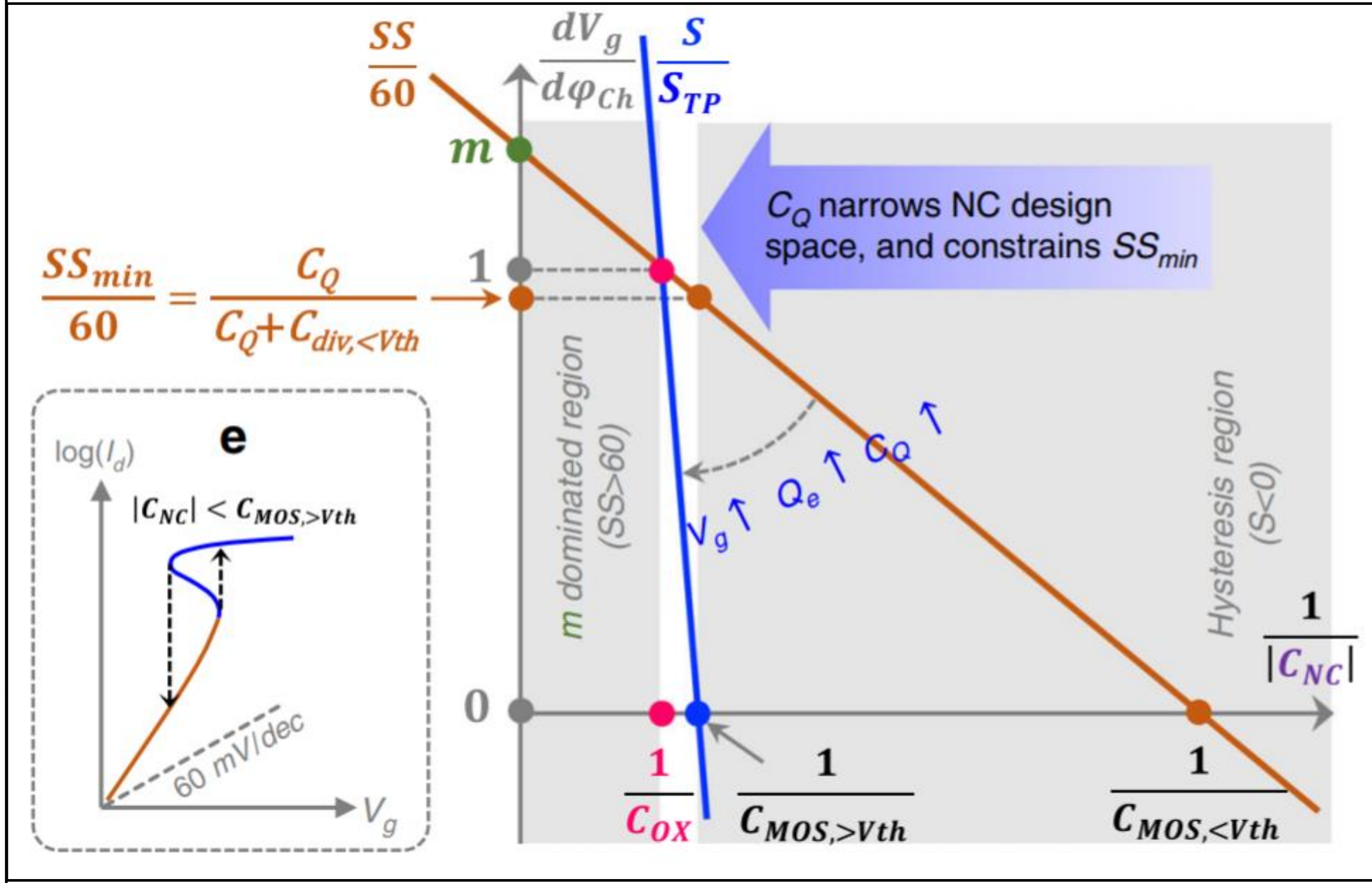

SS/60
dVg/dφCh
m
1
0
Design space
Fin, NW, CNT, 2D...
Ridiculously thick NC needed
m dominated region (SS>60)
Hysteresis region (SS<0)
Voltage gain dominates
1/COX
1/CMOS,<Vth
1/|CNC|


SS/60
dVg/dφCh
S/STP
m
1
0
CQ narrows NC design space, and constrains SSmin
SSmin/60 = CQ/(CQ+Cdiv,<Vth)
e
log(Id)
|CNC| < CMOS,>Vth
60 mV/dec
Vg
m dominated region (SS>60)
Hysteresis region (S<0)
Vg ↑ Qe ↑ CQ ↑
1/COX
1/CMOS,>Vth
1/CMOS,<Vth
1/|CNC|

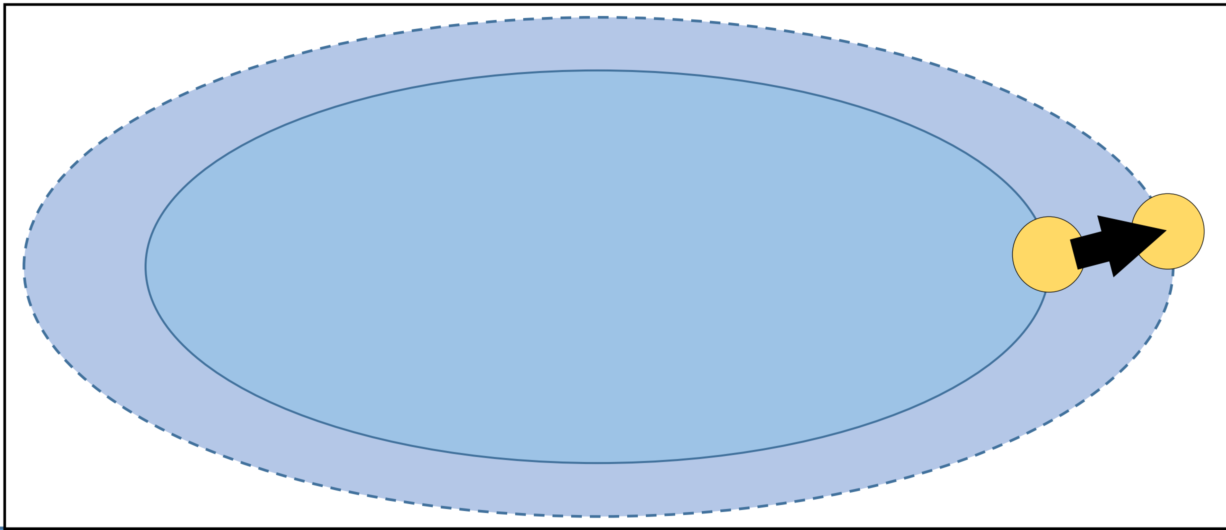
Role of Quantum Capacitance

- Quantum capacitance[4]: change in capacitance due to quantum properties of electron gas.
  - Hartree-Fock approx.: all e⁻ live in single-particle potential (Hartree energy) E_H due to other e⁻.
  - Fock energy $E_{F,i}$: spin-statistics (exchange) energy.
  - Correlation energy $E_{C,i}$: beyond HF approx.
  - External energy $E_{\mathrm{ext},i}$.
- Corresponds to isothermal compressibility of electron gas in electron liquid theory.
  - Change in # of particles due to change in chemical potential.

$$E_F = E_H + \sum_i T_i + \sum_i E_{F,i} + \sum_i E_{C,i} + \sum_i E_{\mathrm{ext},i}$$

$$\frac{1}{C} = \frac{1}{C_{\mathrm{geo},i}} + \sum_i \frac{1}{C_{\mathrm{kin},i}} + \sum_i \frac{1}{C_{\mathrm{exc},i}} + \sum_i \frac{1}{C_{C,i}} + \sum_i \frac{1}{C_{\mathrm{ext},i}}$$

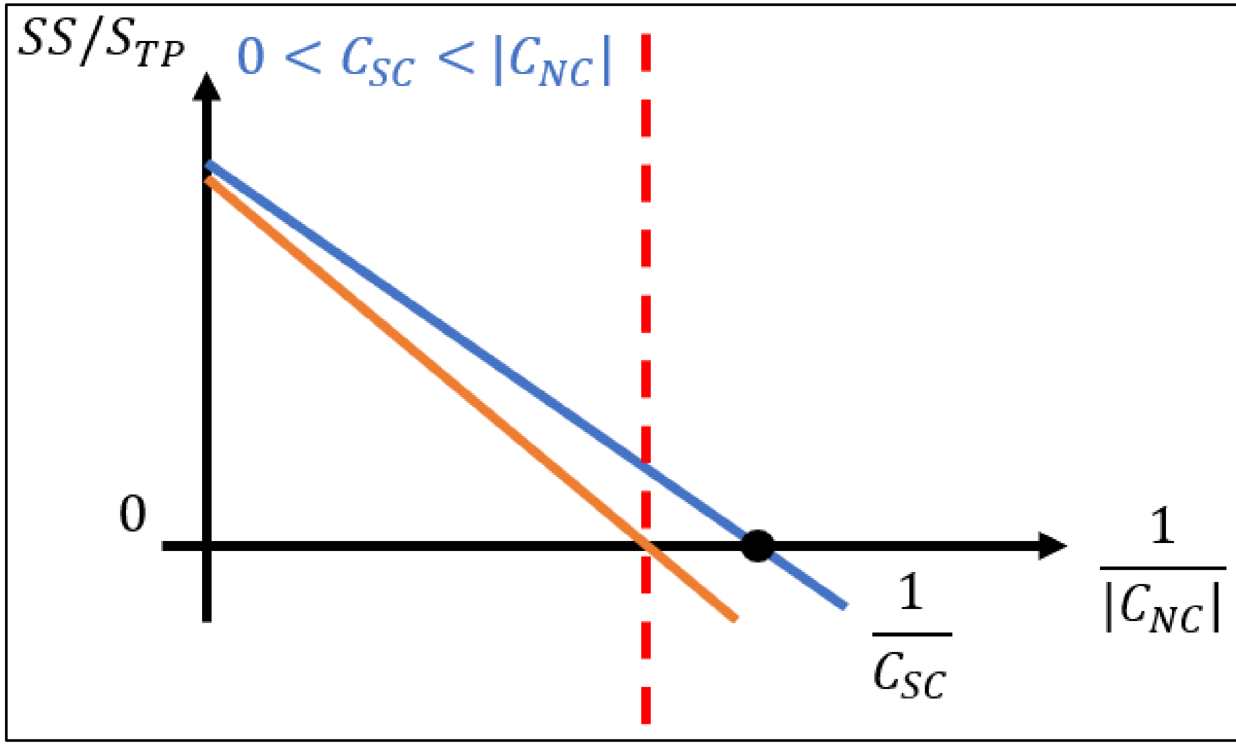
$$C_{\mathrm{q}} = Aq^2 \left(\frac{\delta n}{\delta \mu}\right)_{T,V} = \frac{Aq^2 \kappa_T}{n^2}$$



Negative Quantum Capacitance and Consequences

- Low density e⁻ gas $(3/4\pi n)^{1/3} > 5.25\,a_0$ exhibits[5–7] *negative* compressibility: negative C_q.
  - Observed[8,9] e.g. in high-mobility silicon MOSFETs.
  - Highly unclear: charge density wave[5]? Excitons[6]? Instantons around perturbatively divergent series of phonon modes[7]?
- $C_q < 0$ in channel with or without stabilizer.
  - For $C_\mathrm{NC} < 0$ and $C_\mathrm{SC} \geq 0$ but small, negative C_q reduces total $C_\mathrm{div} = C_\mathrm{q} + C_\mathrm{trap} + C_\mathrm{dep} + C_\mathrm{geo}$.

    As long as $0 < C_\mathrm{div} < |C_\mathrm{NC}|$, design window enhanced.
  - Other cases of C_NC, C_q, and C_NC : same C_q dependence as earlier.



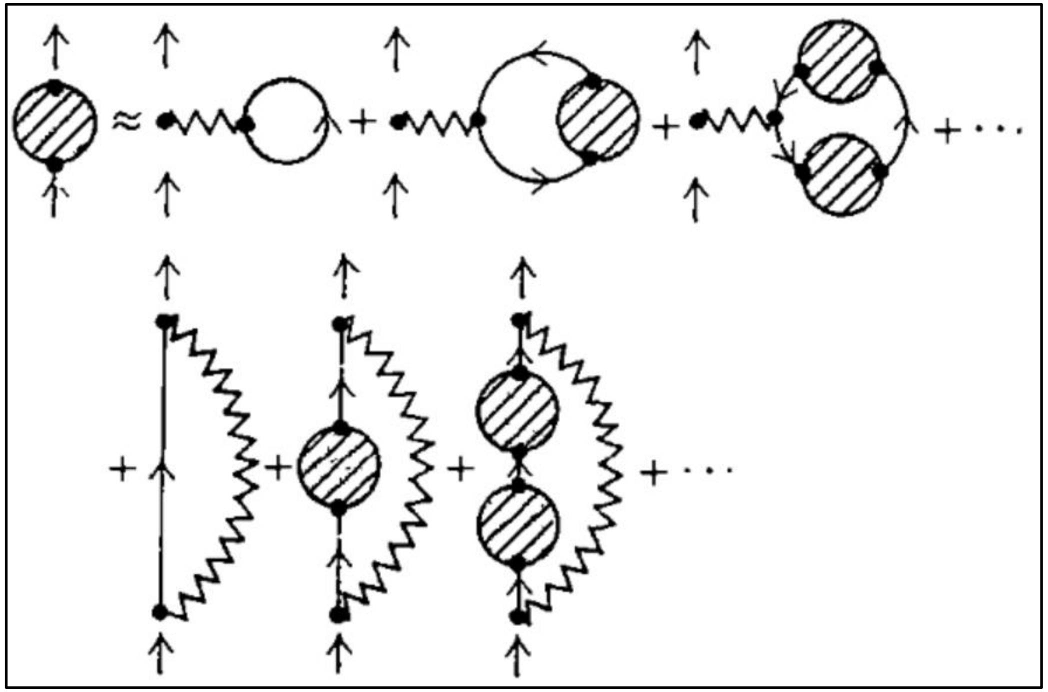
[5] – A. Schakel, Phys. Rev. B 64, 345101 (2001).
[6] – Y. Takada, Phys. Rev. B 94, 245106 (2016).
[7] – T. Banks and B. Zhang, Ann. Phys. 412, 168019 (2020).
[8] – S. Kravchenko *et al.*, Phys. Rev. B 50, 8039 (1994).
[9] – P. Tsipas et al., Adv. Elec. Mat. 2, 1500297 (2016).

Electron Gas Model and Extensions

- Model of NC-FET relies on noninteracting 2D electron gas in channel. Extensions:
  - Simplest: noninteracting 3D electron gas.
    - Evaluating by examining complete FD integral minus Sommerfeld terms.
  - Systematic treatment of $C_\mathrm{q} < 0$ in channel:
    - Diagrammatic HF approx[5,6], apply to polarization insertion.
    - Exact renormalization group technique[7].
  - Single expression for C_q above and below threshold as function of electron density.
  - Negative quantum compressibility in metal.

$$S = \frac{\mathrm{d}V_\mathrm{g}}{\mathrm{d}\ln I_\mathrm{d}}$$

$$S = I_\mathrm{d} \frac{\mathrm{d}V_\mathrm{g}}{\mathrm{d}\varphi_\mathrm{ch}} \frac{\mathrm{d}}{\mathrm{d}\mu}\left[Wvq \sum_i \int_0^\infty \mathrm{d}\varepsilon \sqrt{\varepsilon}\, f_\mathrm{FD} - \int_0^{E_{c,i}} \mathrm{d}\varepsilon \sqrt{\varepsilon}\, f_\mathrm{FD} \right]$$



[5] – A. Schakel, Phys. Rev. B 64, 345101 (2001).
[6] – Y. Takada, Phys. Rev. B 94, 245106 (2016).
[7] – T. Banks and B. Zhang, Ann. Phys. 412, 168019 (2020).
[7] – T. Banks and B. Zhang, Ann. Phys. 412, 168019 (2020).
Image from A. Fetter and J. Walecka, *Quantum Theory of Many-Particle Systems*

Summary and Next Steps

- NC layers provide restricted benefits to NC-FET voltage amplification.
- Channel quantum capacitance serves as primary influencer of NC-FET behaviour.
  - Small positive C_{q} in positive-capacitance-loaded FETs can help enhance design space.
  - Effect of removing positive capacitance load (stabilization directly via channel) is largely same.
  - For $C_{\mathrm{q}} < 0$, quantum capacitance *enhances* design window.
- Significant room to expand in fundamental models of negative capacitance (= negative compressibility) in electron channels.
  - Nature of negative compressibility still highly unclear. Designing negative quantum capacitance FET will require deep investigation into nature of low-density electron gases.

Acknowledgements

- Petr Moroshkin (Brown University)
- Akshay Nagar (Brown University)
- Michael P. Frank (Sandia National Laboratories)
- Silverio Johnson (Brown University)
- Hannah Watson (University of Queensland)
- Materials Research Society
- You, for your attention! Thank you!

This work is supported in part by the Advanced Simulation and Computing (ASC) program at the U.S. Department of Energy's National Nuclear Security Administration (NNSA), and in part under ARO W911NF-14-2-0075, ARO BAA W911NF-19-S-0007, and AFOSR FA9550-19-1-0355. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for NNSA under contract DE-NA0003525. Approved for public release, [SAND Number]. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.