

Workshop on Simulation and Characterization of Steep-Slope
Switches (SSS)

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Modeling of the negative capacitance field-effect transistor

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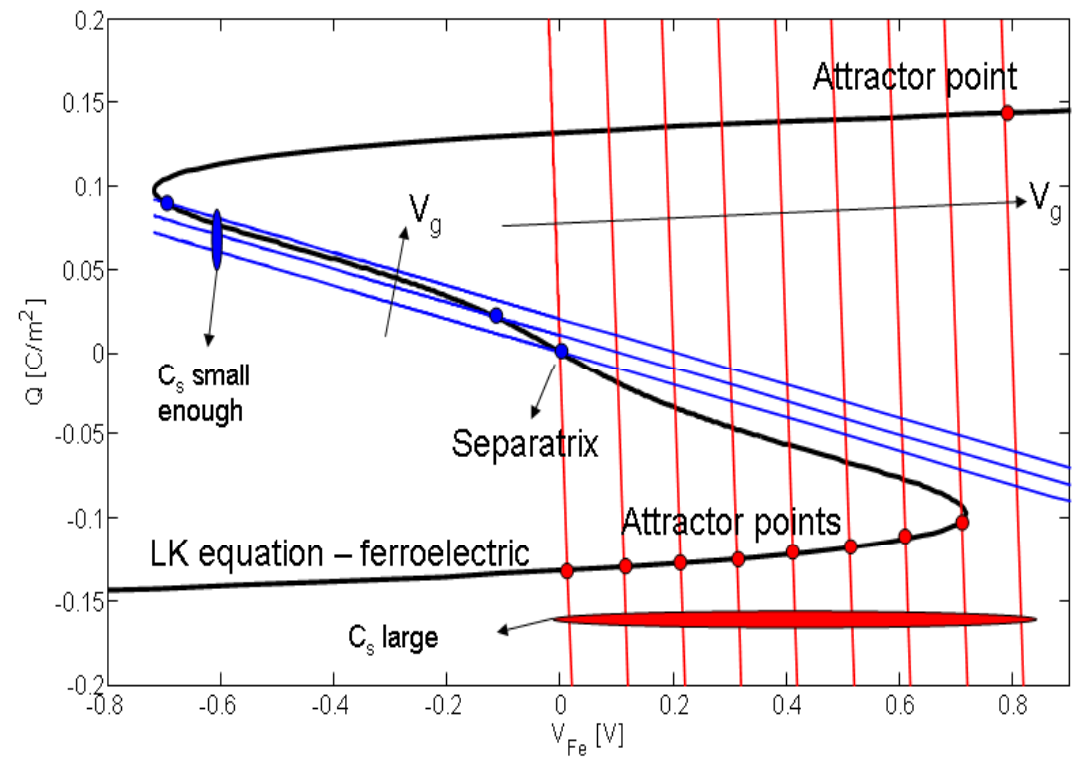
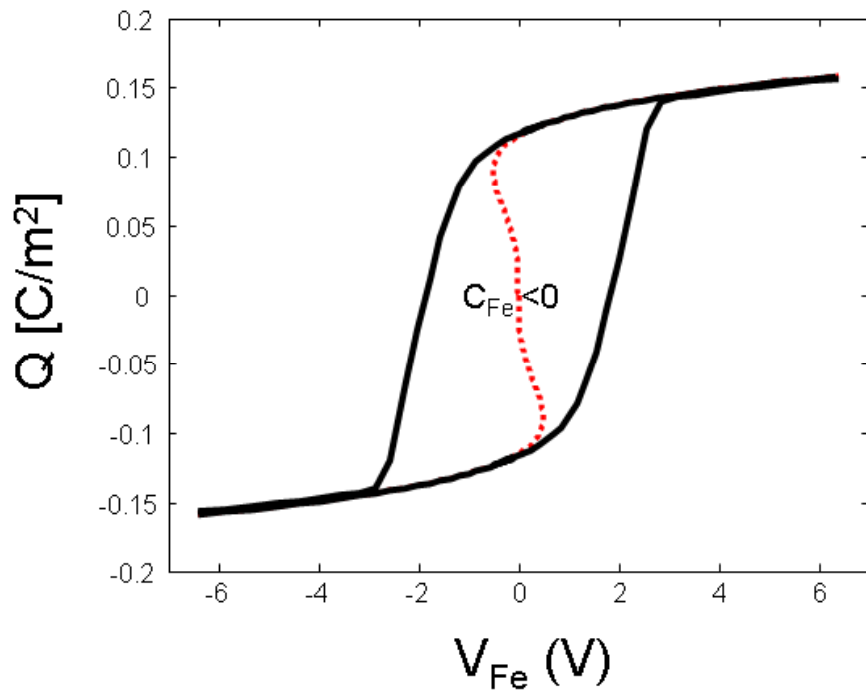
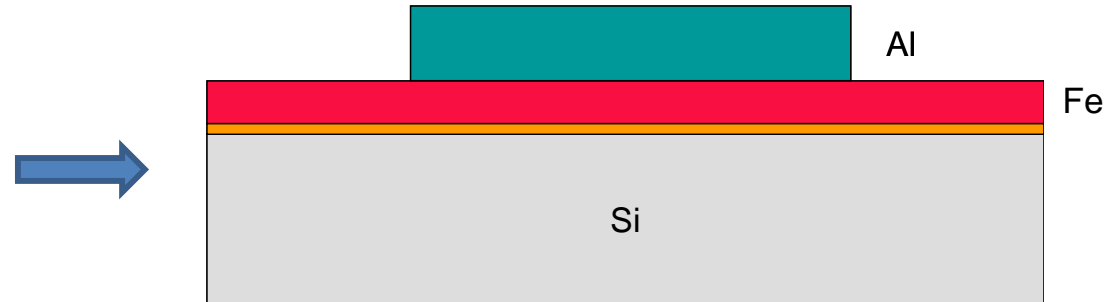
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In 2008, Salahuddin and Datta proposed that a ferroelectric material operating in the **negative capacitance** (NC) region could act as a **step-up converter** of the surface potential in a MOS structure, opening a new route for the realization of transistors with **steeper subthreshold** characteristics ($S < 60$ *mV/dec*).

In this presentation, a comprehensive physics-based surface potential and a drain current model for the NC field-effect transistor are reported. The model is aimed to evaluate the potentiality of such transistors for low-power switching applications. This paper also sheds light on how operation in the NC region can be experimentally detected.

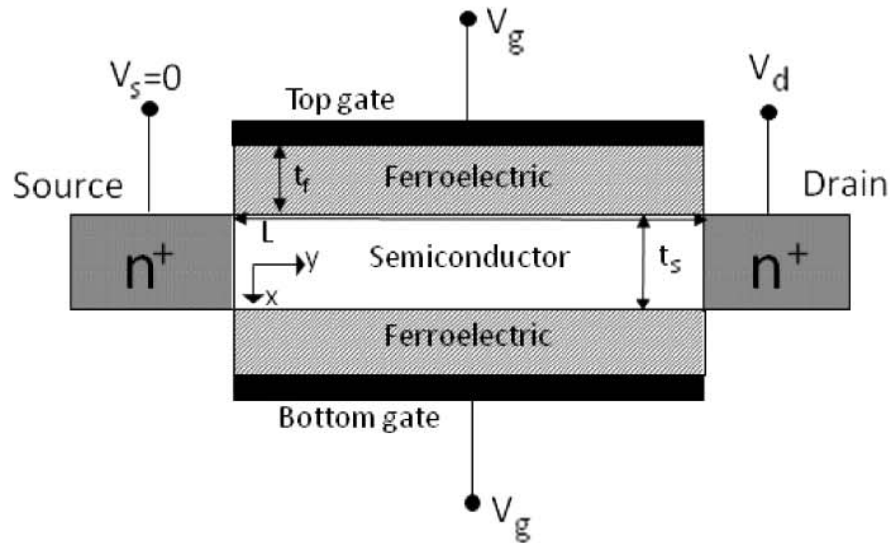
Main idea

Replace the conventional dielectric gate insulator by a **ferroelectric oxide**



The Negative Capacitance (NC) region is unstable, but it could be accessed if the semiconductor capacitance (C_s) is small with regard to the ferroelectric capacitance (C_{fe})

Surface potential model



Electrostatic potential in the semiconductor for a double-gate structure:

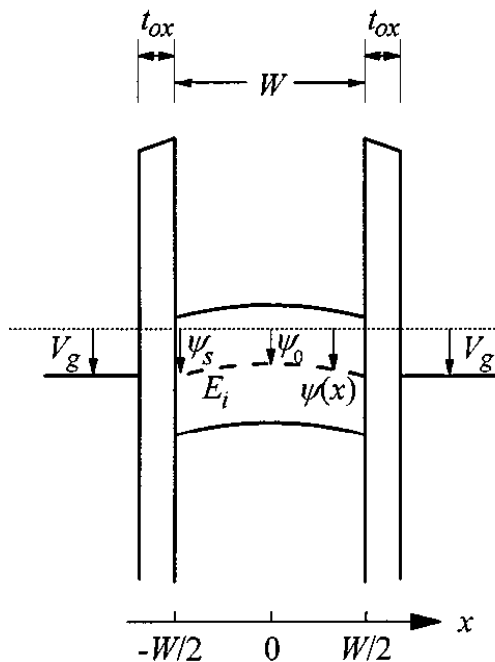
$$\varphi(x) = V - \frac{2kT}{q} \ln \left[\frac{t_s}{2\beta} \sqrt{\frac{q^2 n_i}{2\varepsilon_s kT}} \cos \left(\frac{2\beta x}{t_s} \right) \right]$$

Landau-Ginzburg-Devonshire (LGD) theory gives the constitutive equation for the ferroelectric

$$V_g - \Delta\phi - \varphi_s = a_0 Q + b_0 Q^3 + c_0 Q^5$$

Gauss' law

$$Q = 2\varepsilon_s (d\varphi(t_s/2)/dx) = 2\varepsilon_s (2kT/q) (2\beta/t_s) \tan\beta$$



Surface potential model

Inserting $Q(\beta)$ into LGD equation:

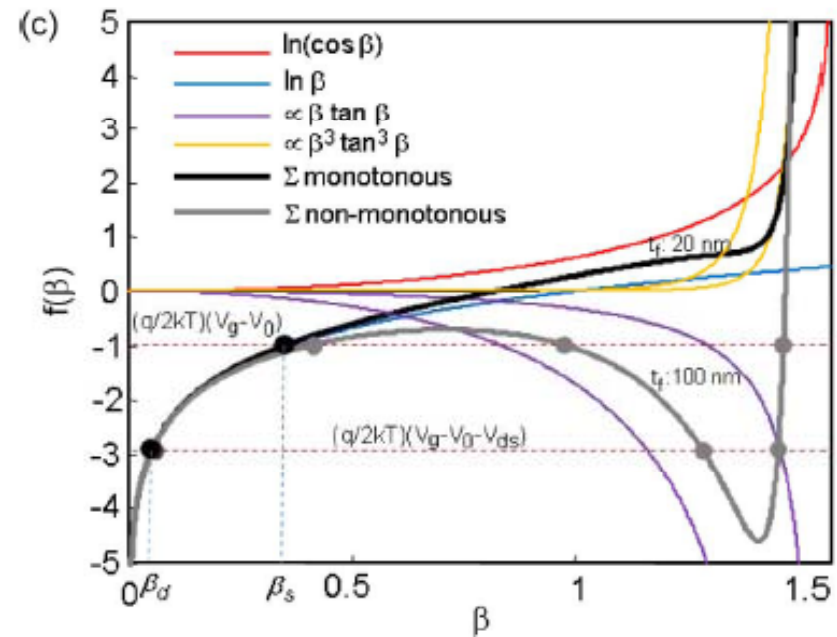
$$f(\beta) = \ln(\beta) - \ln(\cos \beta) + a_0(2C_s)\beta \tan \beta + b_0(2C_s)^3 \left(\frac{4kT}{q}\right)^2 \beta^3 \tan^3 \beta + c_0(2C_s)^5 \left(\frac{4kT}{q}\right)^4 \beta^5 \tan^5 \beta$$

where $f(\beta) =$

$$\frac{q(V_g - \Delta\varphi - V)}{2kT} - \ln\left(\frac{2}{t_s} \sqrt{\frac{2\varepsilon_s kT}{q^2 n_i}}\right)$$

For a given V_g , β can be solved from the above equation as a function of the quasi-Fermi level V .

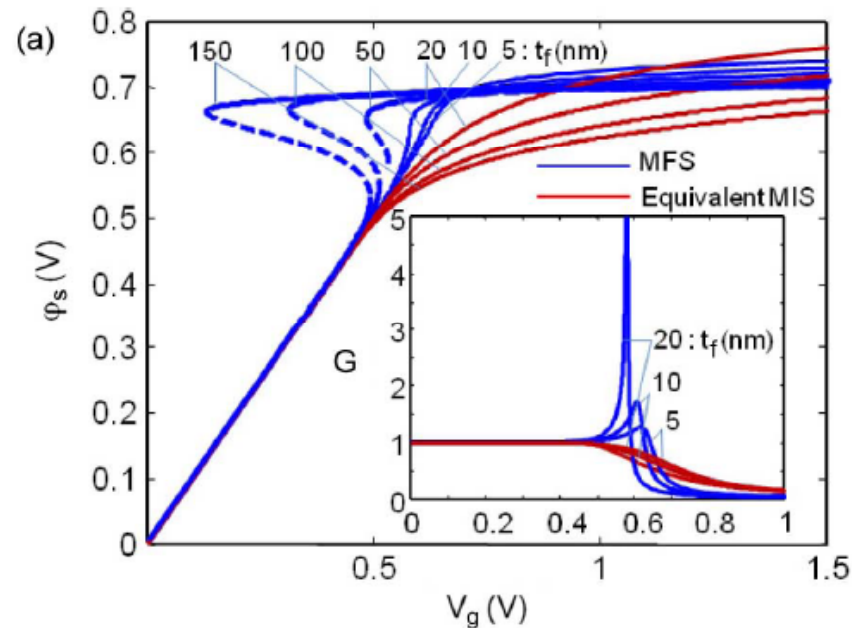
Note that $V=0$ at the source contact and $V=V_{ds}$ at the drain contact



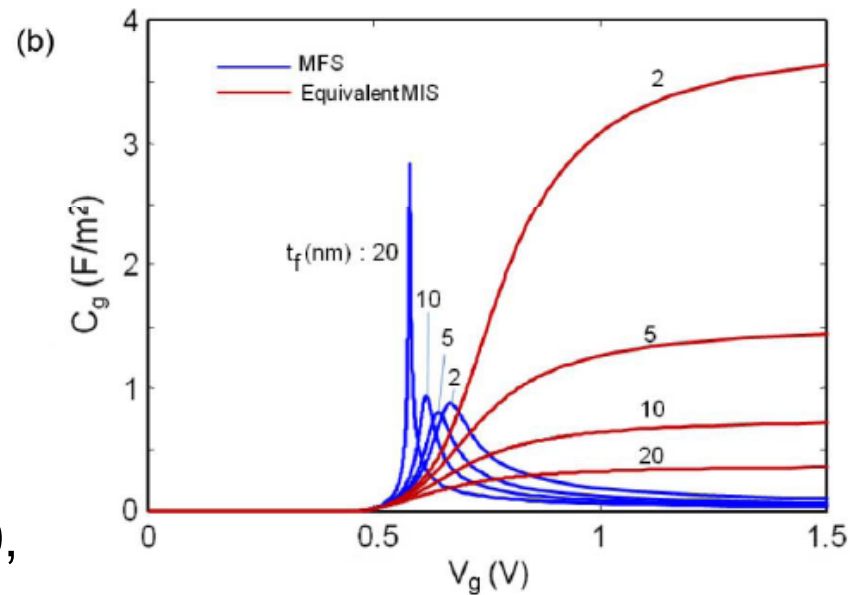
Determination of β can be geometrically interpreted as the intersection of $f(\beta)$ with the load line $(q/2kT)(V_g - \Delta\varphi - V)$

If $f(\beta)$ non-monotonous an **hysteretic behavior** arises. Combination of device geometry and ferroelectric materials leading to hysteresis should be avoided for conventional CMOS-like operation

Surface potential model



Surface potential amplification



The signature of operation in the NC region is a single-valued and peaked C_g - V_g characteristic, where a sharp peak is indicative of a large gain

Drain current model

The functional dependence of $V(y)$ and $\beta(y)$ is determined by the current continuity equation, which relies on the drift-diffusion current $I_{ds} = \mu W Q dV/dy = \text{constant}$, which is independent of V and y .

Integrating $I_{ds} dy$ from source to drain and expressing dV/dy as $(dV/d\beta)/(d\beta/dy)$, the current reads:

$$I_{ds} = \mu \frac{W}{L} \int_0^{V_{ds}} Q(V) dV = \mu \frac{W}{L} \int_{\beta_s}^{\beta_d} Q(\beta) \frac{dV}{d\beta} d\beta$$

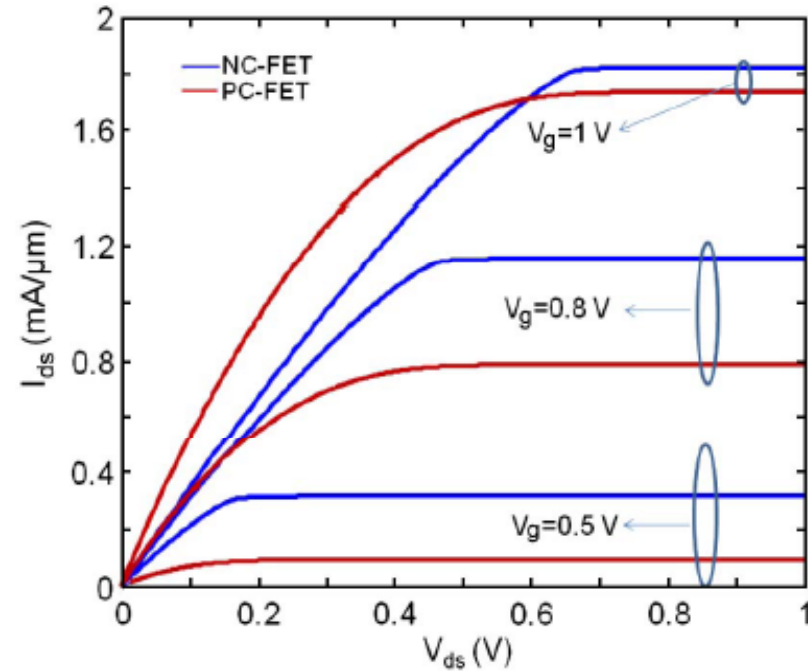
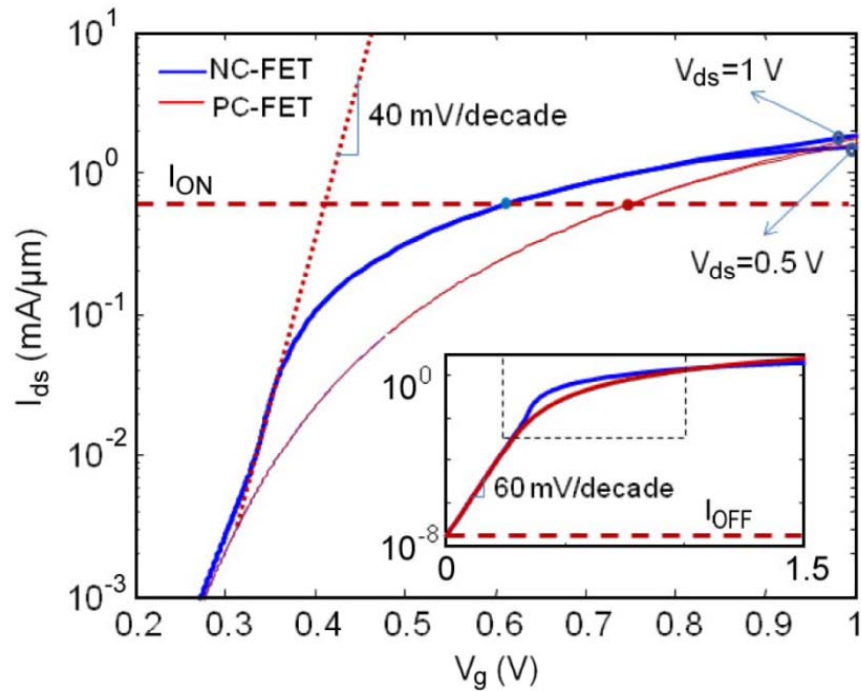
where β_s and β_d are the solutions of $f(\beta) = \frac{q(V_g - \Delta\varphi - V)}{2kT} - \ln \left(\frac{2}{t_s} \sqrt{\frac{2\varepsilon_s kT}{q^2 n_i}} \right)$ with $V=0$ and $V=V_{ds}$ at the source and drain contact, respectively.

Integration can be analytically performed yielding:

$$I_{ds} = \mu \frac{4C_s W}{L} \left(\frac{2kT}{q} \right)^2 \times \left[\beta \tan \beta - \frac{\beta^2}{2} + a_0 C_s \beta^2 \tan^2 \beta + 3b_0 (2C_s)^3 \left(\frac{2kT}{q} \right)^2 \beta^4 \tan^4 \beta + \frac{5}{6} c_0 (2C_s)^5 \left(\frac{4kT}{q} \right)^4 \beta^6 \tan^6 \beta \right] \Bigg|_{\beta_d}^{\beta_s}$$

D. Jiménez et al. TED October 2010,
in press

Drain current model



D. Jiménez et al. TED October 2010, in press

Improvement of the subthreshold slope as a result of operation in the NC region. Strontium Barium Titanate (SBT) has been assumed as the ferroelectric oxide, characterized by the Landau parameters $a = -1.3 \cdot 10^8$, $b = 1.3 \cdot 10^{10}$, $c = 0$ (SI units)

Conclusions

- We have presented a physics-based analytical surface potential model and drain current model derived from the LGD theory, Poisson's equation, and the current continuity equation.
- An SBT ferroelectric has been considered to quantitatively illustrate the model outcomes, but an improved performance can be achieved in terms of gain and V_g range using properly engineered ferroelectric materials.
- It has been shown how the **signature of NC** should manifest in experiments.
- The formulation of the model is general also describing the hysteretic behavior and is therefore useful for **ferroelectric FETs** as the building block of nonvolatile memories.