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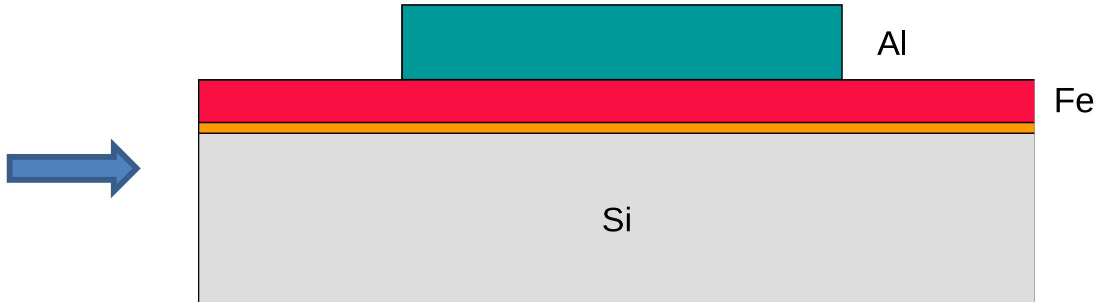
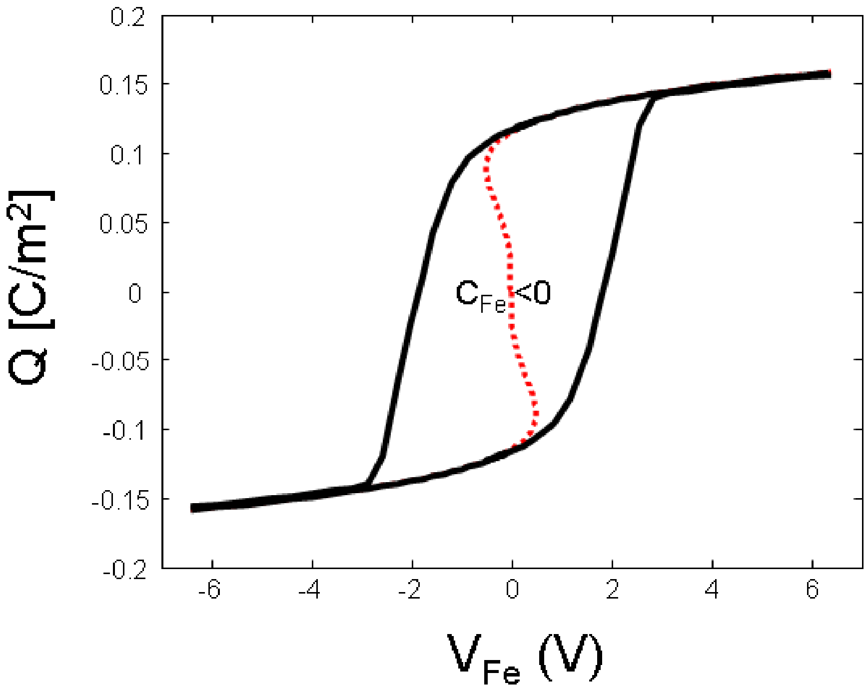
In 2008, Salahuddin and Datta proposed that a ferroelectric material operating in the **negative capacitance** (NC) region could act as a **step-up converter** of the surface potential in a MOS structure, opening a new route for the realization of transistors with **steeper subthreshold** characteristics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

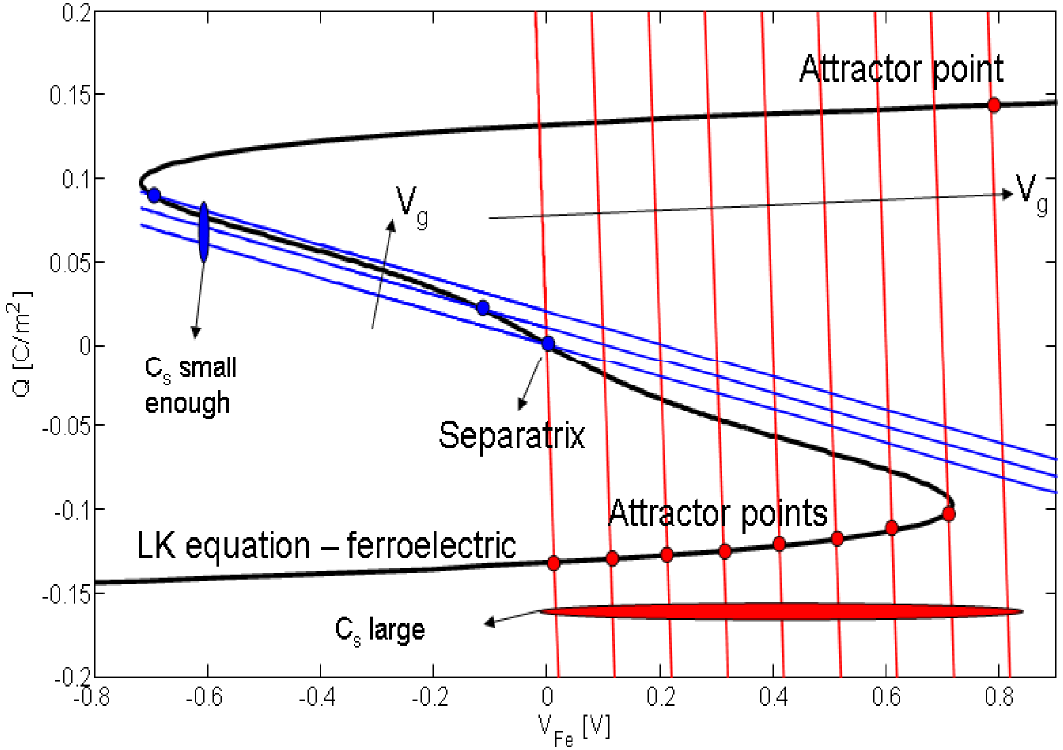
In this presentation, a comprehensive physics-based surface potential and a drain current model for the NC field-effect transistor are reported. The model is aimed to evaluate the potentiality of such transistors for low-power switching applications. This paper also sheds light on how operation in the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

Main idea

Replace the conventional dielectric gate insulator by a ferroelectric oxide

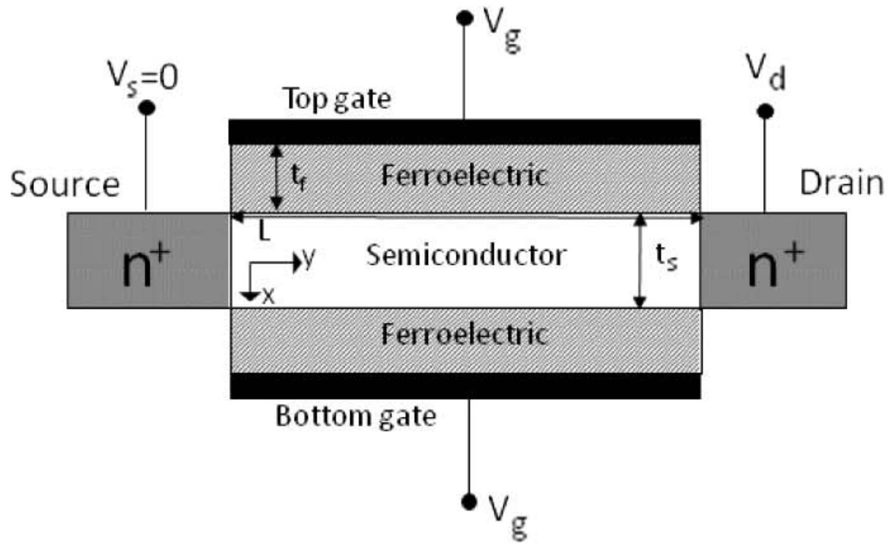


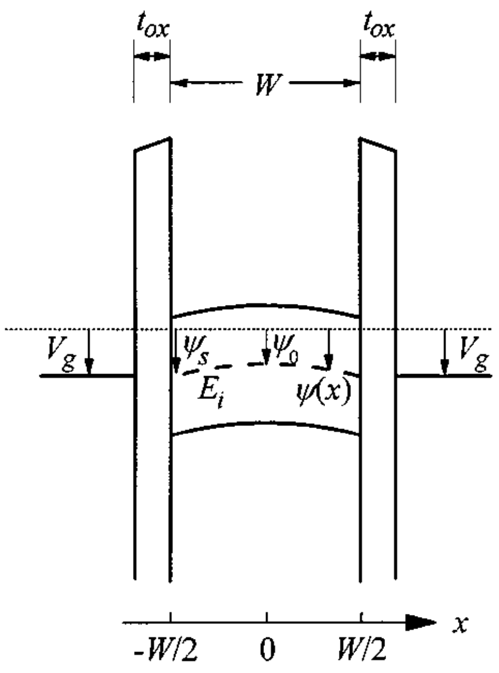




The Negative Capacitance (NC) region is unstable, but it could be accessed if the semiconductor capacitance (C_s) is small with regard to the ferroelectric capacitance (C_{fe})

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(β) into LGD equation:

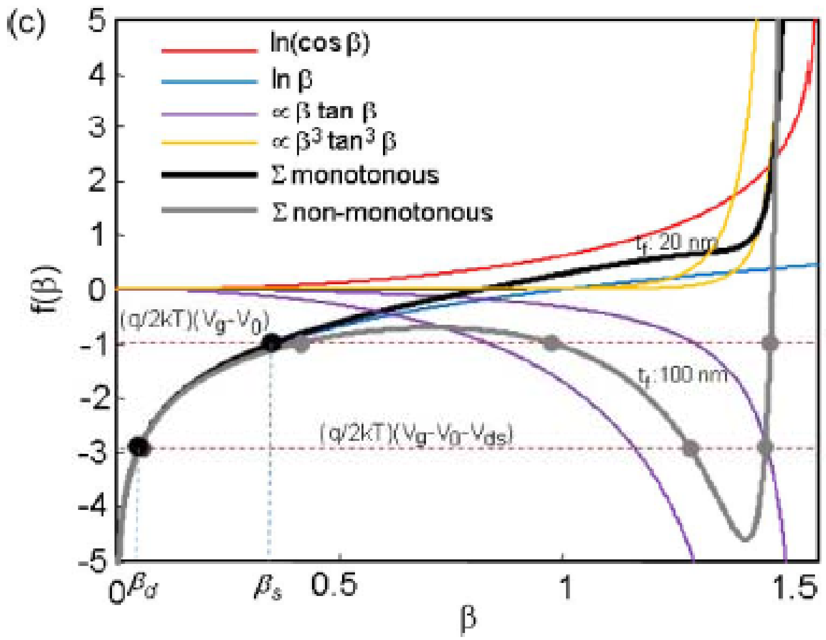
$$f(\beta) = \ln(\beta) - \ln(\cos\beta) + a_0(2C_s)\beta\tan\beta + b_0(2C_s)^3\left(\frac{4kT}{q}\right)^2\beta^3\tan^3\beta + c_0(2C_s)^5\left(\frac{4kT}{q}\right)^4\beta^5\tan^5\beta$$

where f(β)=

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

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

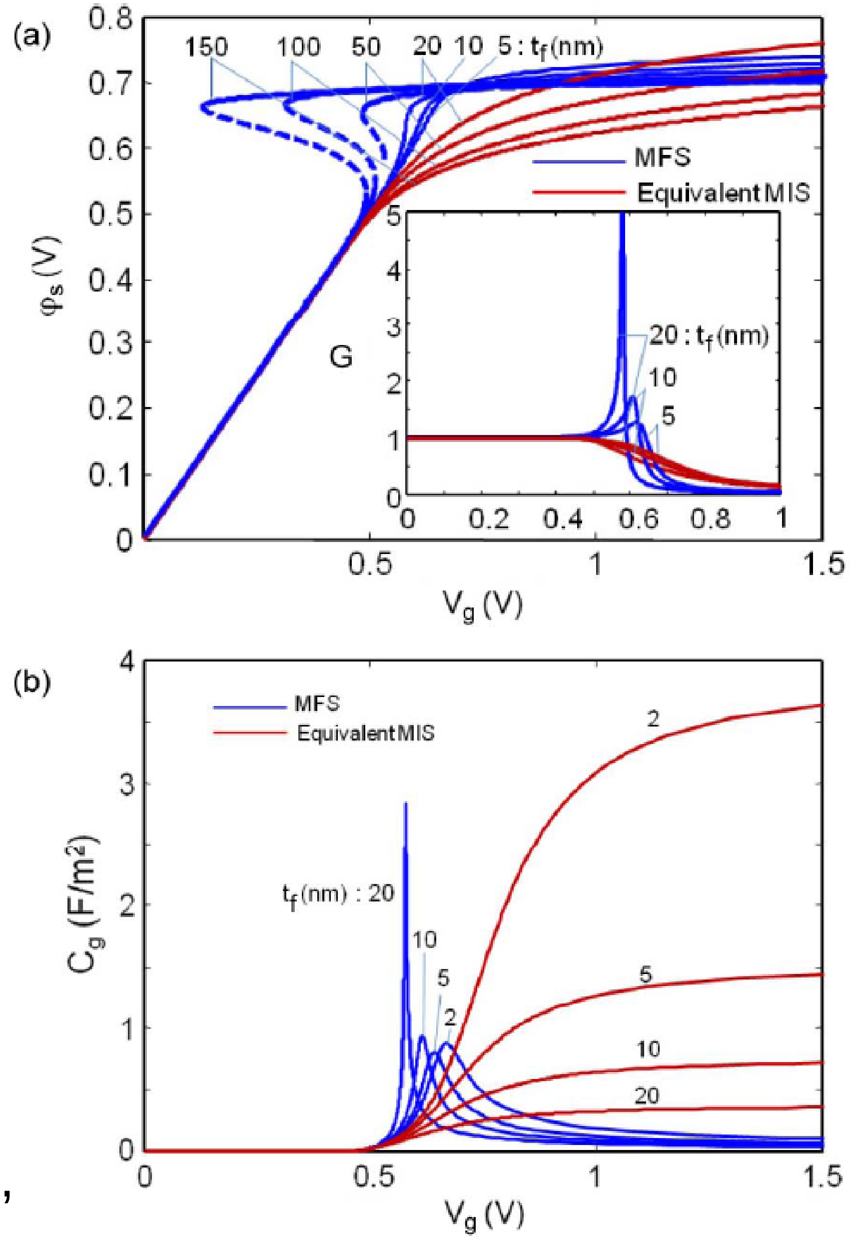
Note that V=0 at the source contact and V=Vds at the drain contact



Determination of β can be geometrically interpreted as the intersection of f(β) with the load line (q/2kT)(V_g-Δφ-V)

If f(β) 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

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Drain current model

The functional dependence of V(y) and β(y) is determined by the current continuity equation, which relies on the drift-diffusion current I_{ds}=μWQdV/dy=constant, which is independent of V and y.

Integrating I_{ds}dy from source to drain and expressing dV/dy as (dV/dβ)/(dβ/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(β): $\frac{q(V_g - \Delta\varphi - V)}{2kT} - \ln\left(\frac{2}{t_s}\sqrt{\frac{2\varepsilon_s kT}{q^2 n_i}}\right)$

with V=0 and V=Vds at the source and drain contact, respectively.

Integration can be analytically performed yielding:

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

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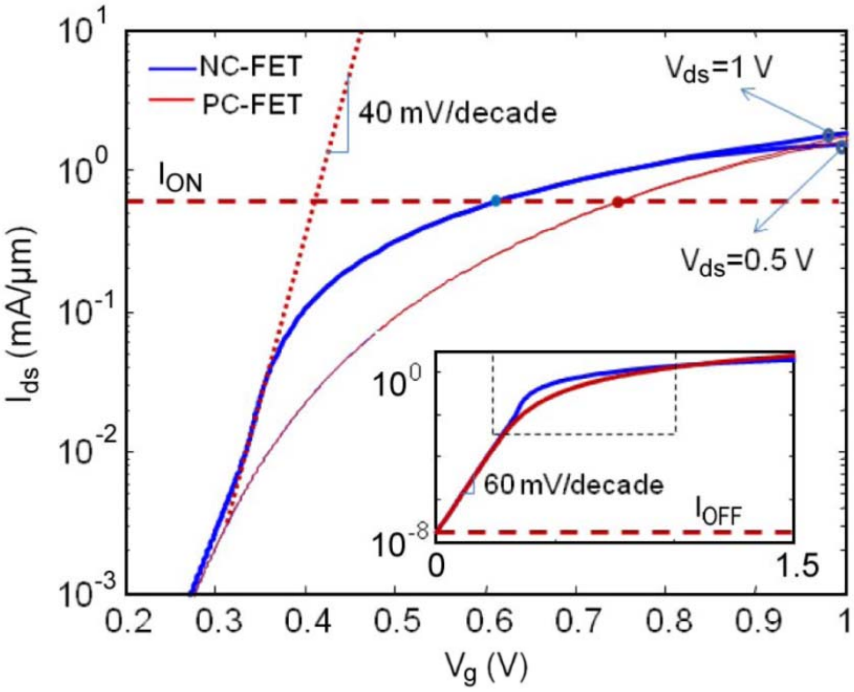
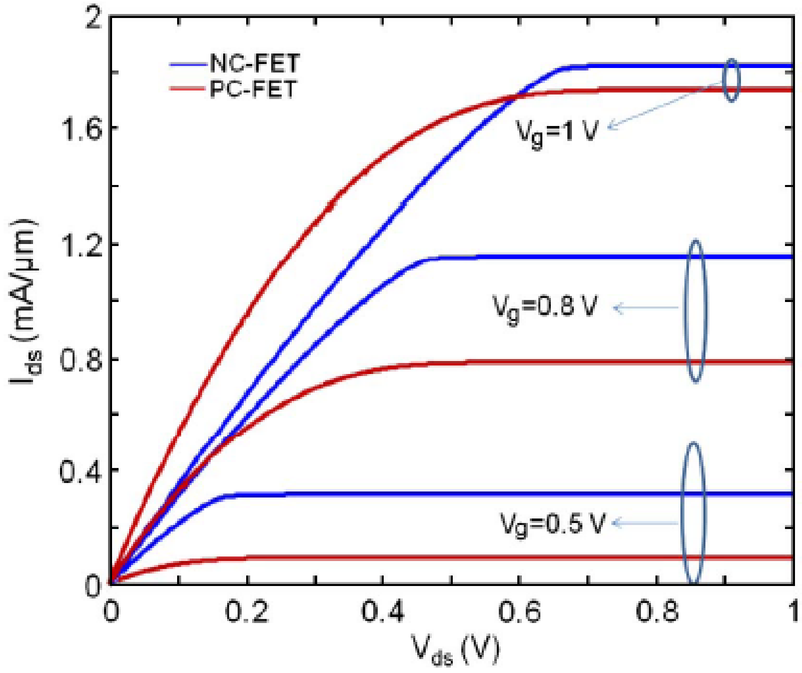
Drain current model





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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=-1.3·10^8, b=1.3·10^{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 Vg 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.