A brief introduction about Negative Capacitance

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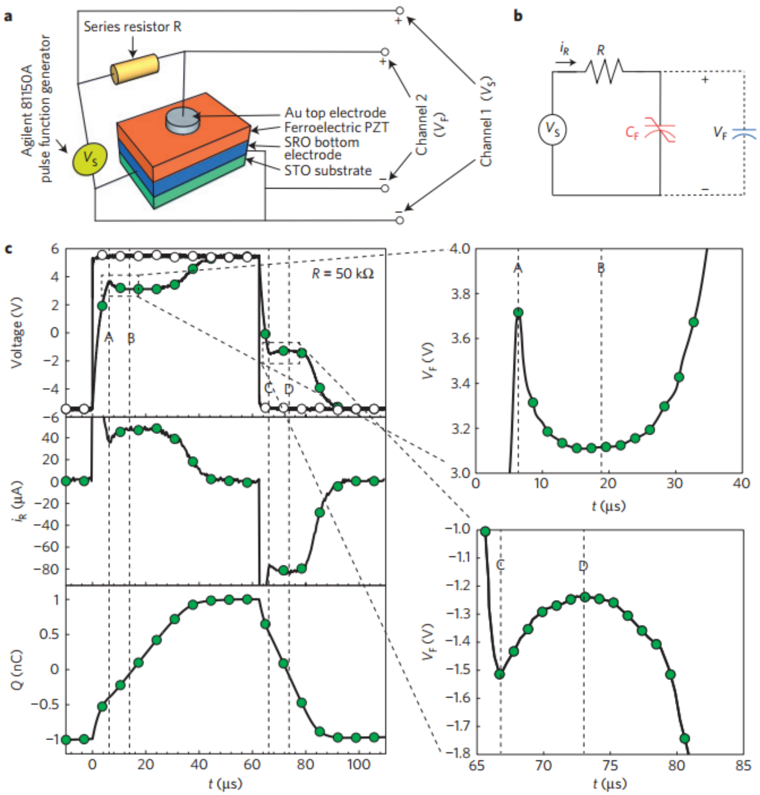
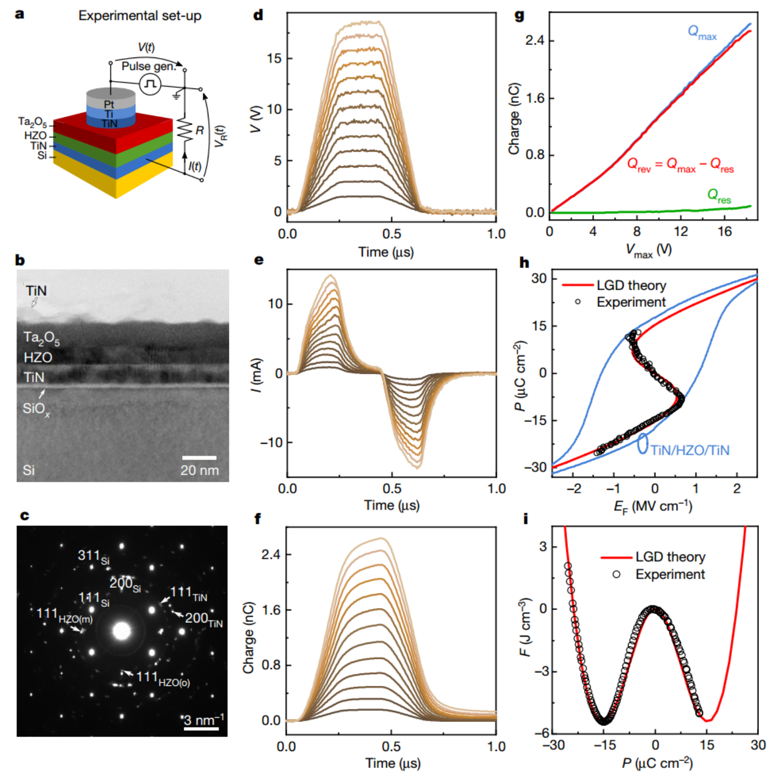
Motivation & Background





[1] Nat. Mater. 14, 182–186 (2015).

[2] Nature 534, 524–528 (2016).

[3] Nano Lett. 14, 3864–3868 (2014).

[4] Nature Reviews Materials, 4, 243-256 (2019).

[5] Nature, 565, 468 (2019).

[6] Nature, 565, 464 (2019).

Outline

What is Negative Capacitance ?

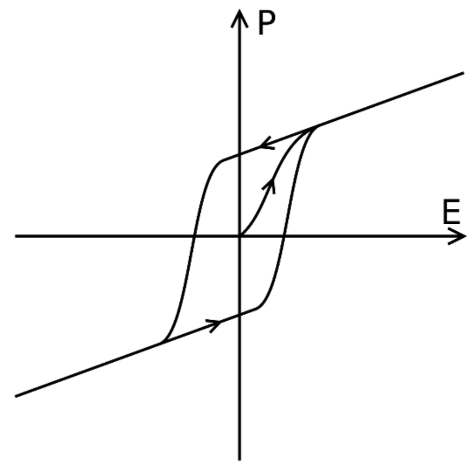
- Ferroelectric Polarization
- Landau Theory
- Types of Negative Capacitance

Why Negative Capacitance ?

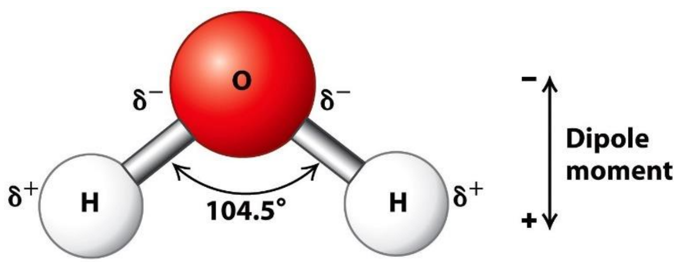
- Its importance in industry

What is Negative Capacitance ?

- **Ferroelectricity** is a characteristic of certain materials that have a **spontaneous electric polarization** that can be reversed by the application of an external electric field.
- A ferroelectric material has a **permanent electric dipole** and is named in analogy to a ferromagnetic material that has a permanent magnetic dipole.

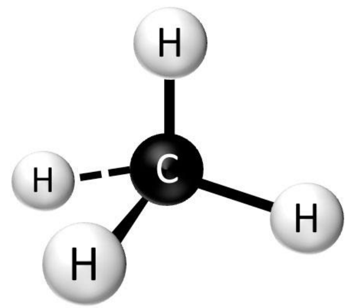


H_2O



asymmetric

CH_4



symmetric

Treated as point charges

$$\vec{p} = \sum_i Q_i \vec{R}_i$$

Large numbers of molecules with their dipoles aligned

$$\vec{p} = \sum_{molecules} \vec{p}_{molecule}$$

The formal definition of a dipole moment

$$\vec{p} = \int dV \rho(\vec{r})\vec{r}$$

where $\rho(\vec{r})$ is the charge density in the molecule - which consists of both the positive nuclear charge and the negative electronic charge density. Provided the molecule is overall neutral, this definition is conveniently independent of the choice of origin[1]

What is Negative Capacitance ?

one-dimensional crystal made up of two atoms of opposite charge

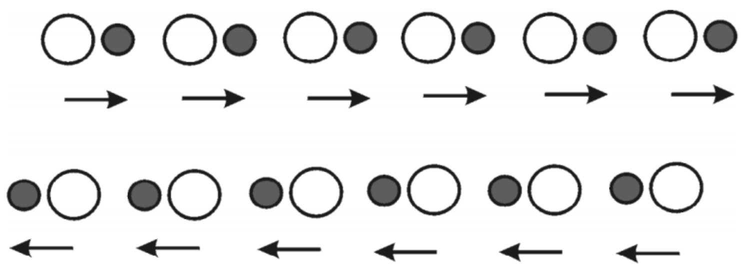


Figure 2: Model (fictitous) crystal

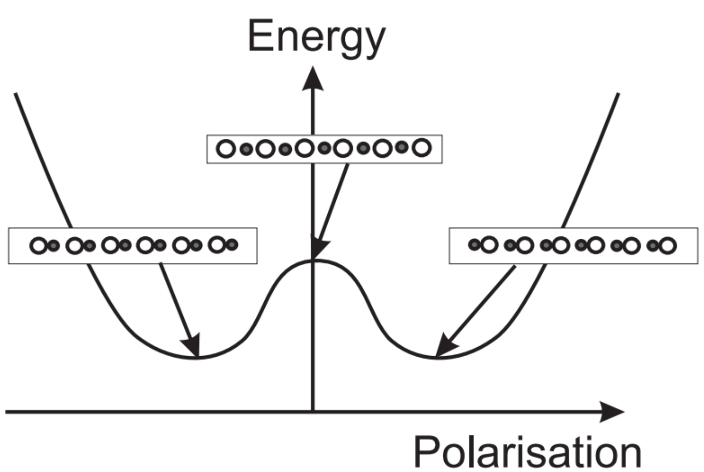


Figure 3: Schematic potential well

- ❑ Given that we know the crystal is stable in either of the two polarized states, there must be **an energy barrier** between the two states, and we can sketch a curve for the energy as a function of the polarization.

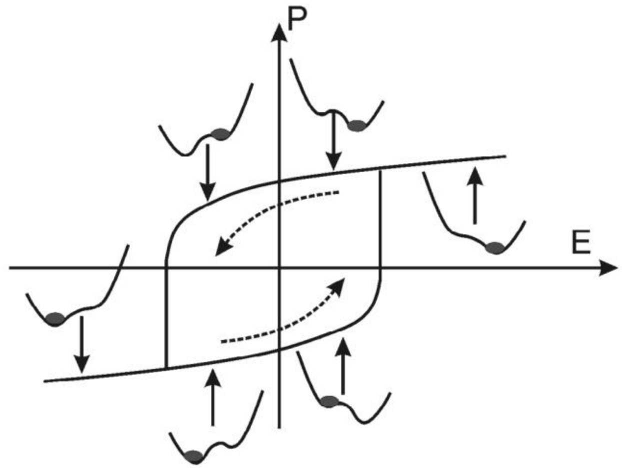


Figure 4: Schematic picture of hysteresis in an idealised ferroelectric

- ❑ In an electric field E ~ the two stable states no longer have the same energy because of the electric polarization energy -$\vec{P} \cdot \vec{E}$

What is Negative Capacitance ?

Landau theory

- Free energy (F) can be expressed as a function of the ten variables (**three components of polarization, six components of the stress tensor, and temperature**)

a simple example, a single **component of the polarization** and ignore the strain field, the origin of energy for the **free unpolarized, unstrained crystal to be zero**,

$$\mathcal{F}_P = \frac{1}{2}aP^2 + \frac{1}{4}bP^4 + \frac{1}{6}cP^6 + ... - EP$$

E is the electric field, and the unknown coefficients a, b, c, etc. are in general temperature-dependent, and may have any sign. **The equilibrium configuration is determined by finding the minima of F.**

$$\frac{\partial \mathcal{F}}{\partial P} = 0$$

ignore the higher order terms $\quad \dfrac{\partial \mathcal{F}}{\partial P} = aP - E = 0$

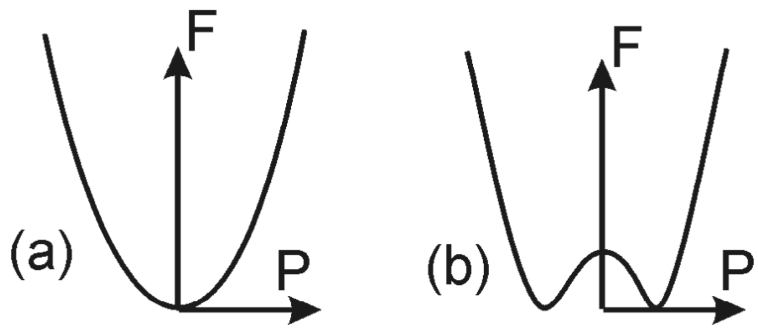
defines the dielectric susceptibility $\quad \chi = \dfrac{P}{E} = \dfrac{1}{a}$

What is Negative Capacitance ?

Landau theory

a ,b, c > 0

a < 0, while b, c > 0



a < 0, while b, c > 0

$$a(T) = a' \times (T - T_0)$$

$T_0 \leq T_C$

a second-order transition

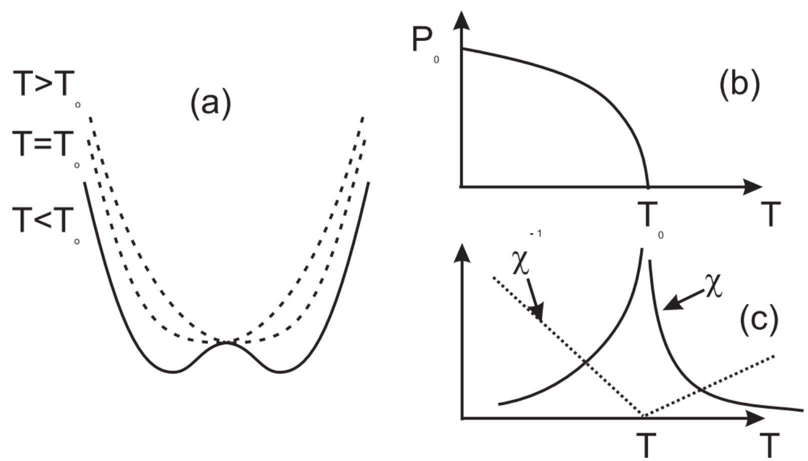


Figure 6: Second order phase transition. (a) Free energy as a function of the polarisation at $T > T_o$, $T = T_o$, and $T < T_o$; (b) Spontaneous polarisation $P_o(T)$ as a function of temperature (c) Inverse of the susceptibility χ, where $\chi = \partial P / \partial E|_{P_o}$ is evaluated at the equilibrium polarisation $P_o(T)$

What is Negative Capacitance ?

Landau theory

- **If a, b< 0 and c>0**

- $T>T_0$ the free energy may have a subsidiary minimum at non-zero P.

- As the temperature decrease, this minimum will drop in energy to below that of the unpolarized state,

a first-order transition

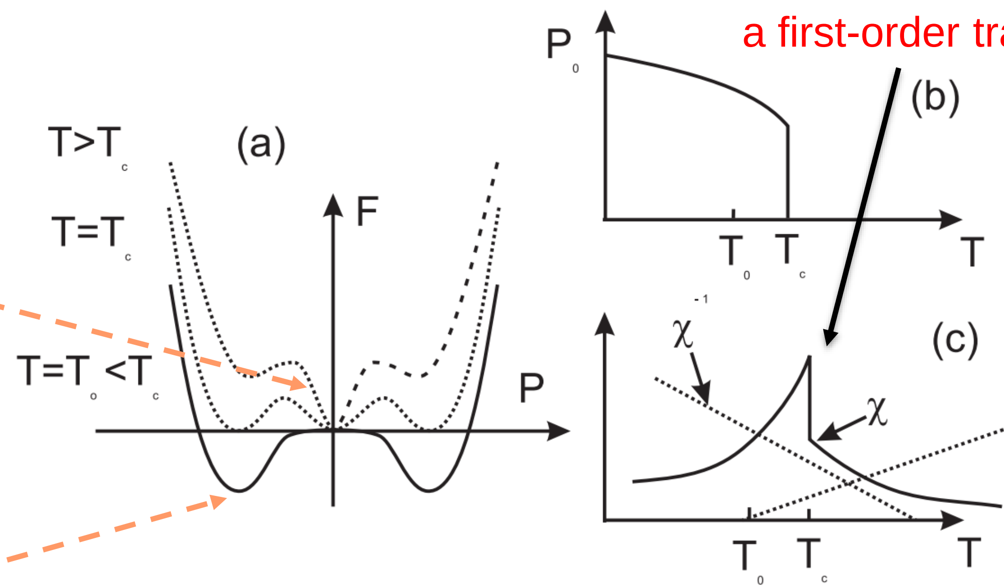


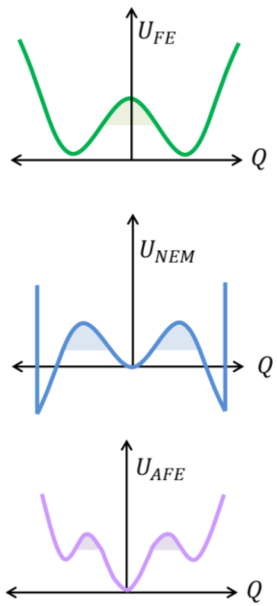
Figure 7: First order phase transition. a) Free energy as a function of the polarisation at $T > T_c$, $T = T_c$, and $T = T_o < T_c$; (b) Spontaneous polarisation $P_o(T)$ as a function of temperature (c) Susceptibility χ.

What is Negative Capacitance ?

Types of NC

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

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



A capacitor minimizes stored energy

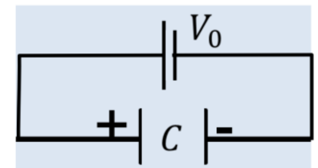
$$U_T = \frac{Q^2}{2C} - V_0 Q$$

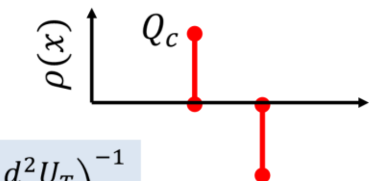
$$\frac{dU_T}{dQ} = \frac{Q_c}{C} - V_0 = 0$$

$$Q_c = C\,V_0$$

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

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

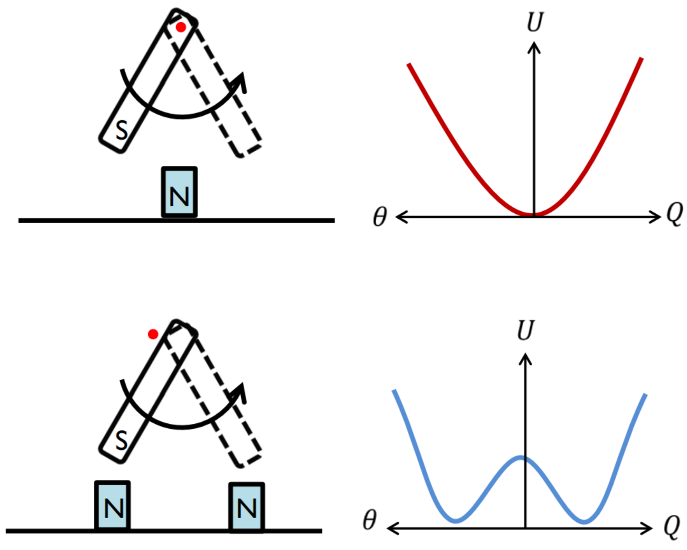


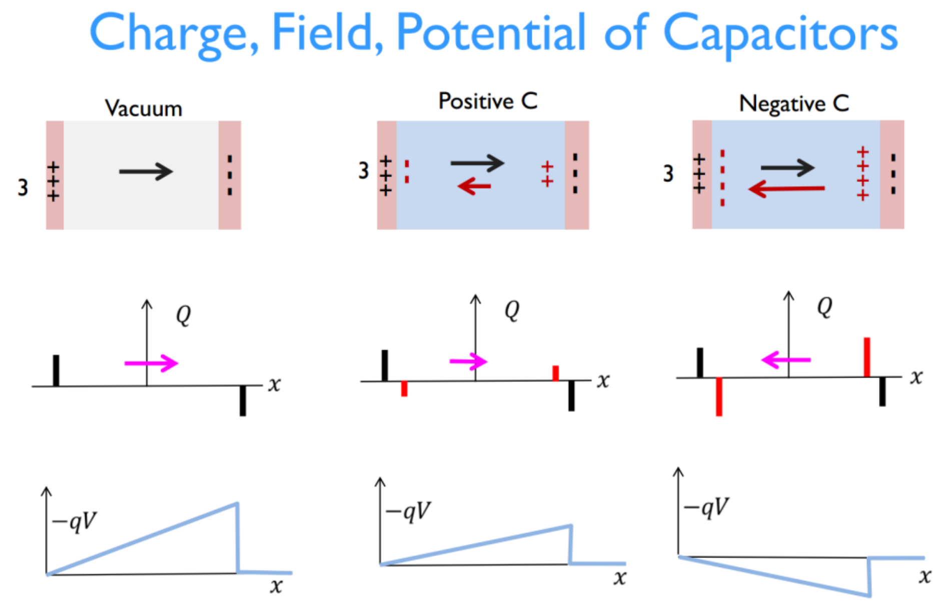


Parameters	BaTiO3	PZT	SBT
$\alpha_0(m/F)$	$-1e7$	$-4.5e7$	$-6.5e7$
$\beta_0(m^5F/coul^2)$	$-8.9e8$	$5.2e8$	$3.75e9$
$\gamma_0(m^9F/coul^4)$	$4.5e10$	$5.9e8$	0

What is Negative Capacitance ?

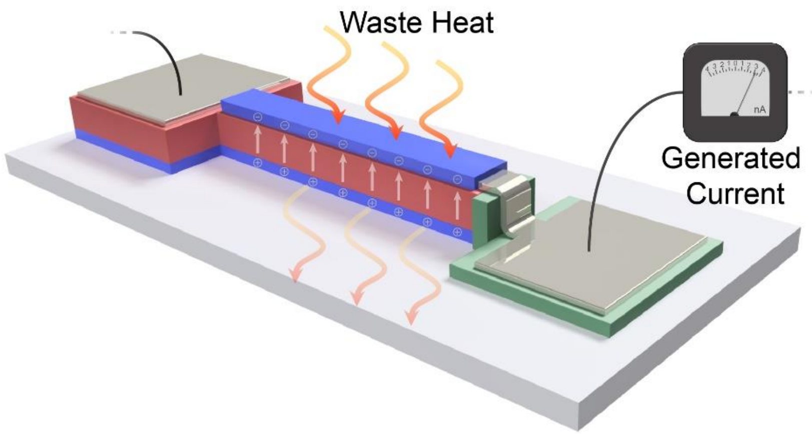
Positive and Negative Capacitance



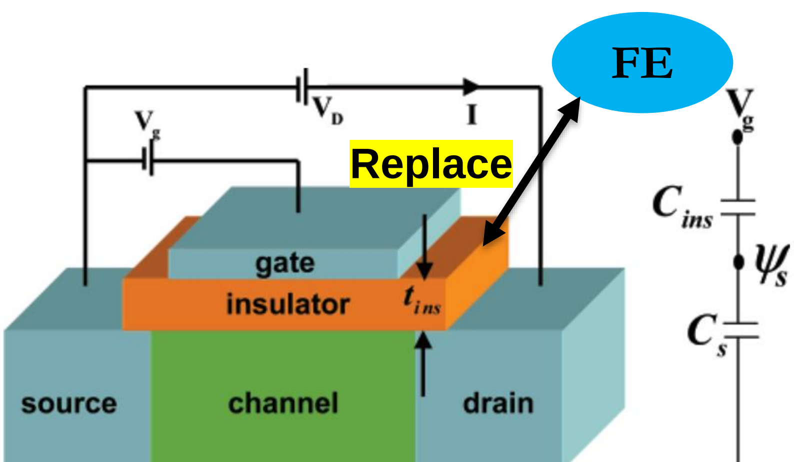


Why Negative Capacitance ?

- The most difficult problem in nanoelectronics is the management of the heat generated during information processing



‘Generate less heat and/or remove it more effectively’



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2008
Vol. 8, No. 2
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Use of Negative Capacitance to Provide Voltage Amplification for Low Power Nanoscale Devices

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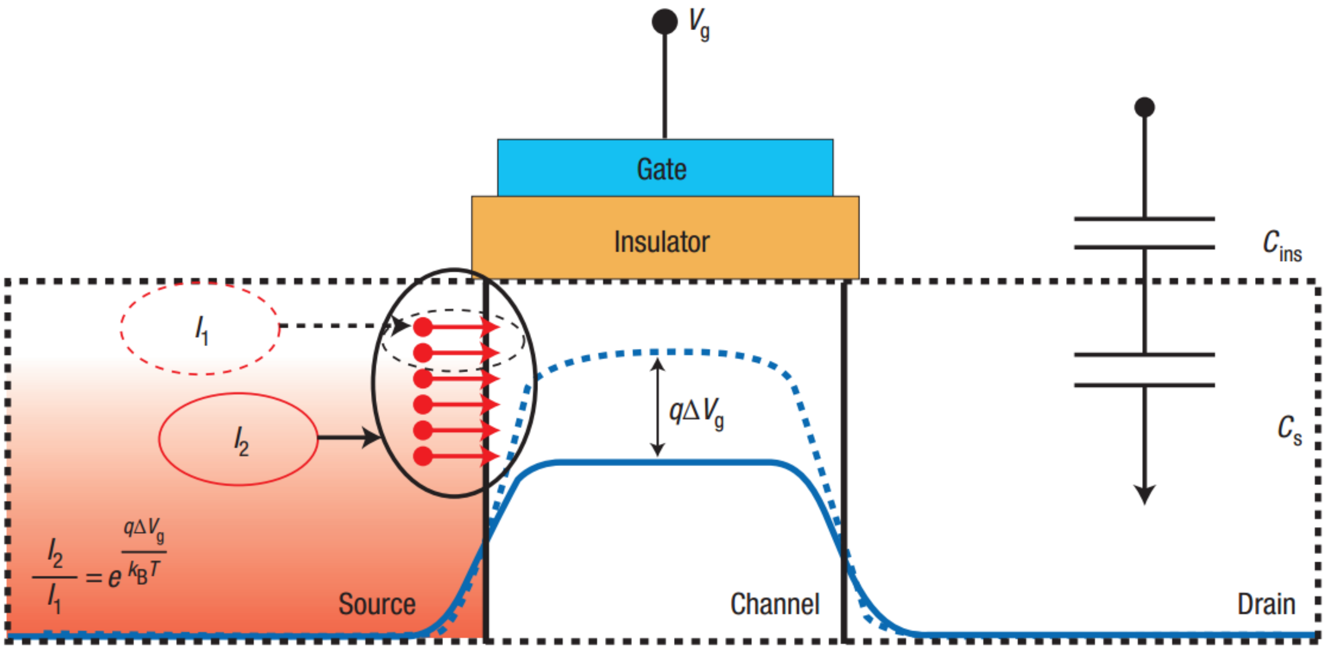
ABSTRACT

It is well-known that conventional field effect transistors (FETs) require a change in the channel potential of at least 60 mV at 300 K to effect a change in the current by a factor of 10, and this minimum subthreshold slope *S* puts a fundamental lower limit on the operating voltage and hence the power dissipation in standard FET-based switches. Here, we suggest that by replacing the standard insulator with a ferroelectric insulator of the right thickness it should be possible to implement a step-up voltage transformer that will amplify the gate voltage thus leading to values of *S* lower than 60 mV/decade and enabling low voltage/low power operation. The voltage transformer action can be understood intuitively as the result of an effective negative capacitance provided by the ferroelectric capacitor that arises from an internal positive feedback that in principle could be obtained from other microscopic mechanisms as well. Unlike other proposals to reduce *S*, this involves no change in the basic physics of the FET and thus does not affect its current drive or impose other restrictions.

Nano Lett., Vol. 8, No. 2, 2008

Why Negative Capacitance ?

Schematic diagram of a field-effect transistor (FET)



"Boltzmann tyranny"

- ❑ Only electrons with energies greater than the barrier height can contribute to the current, which can be controlled by applying a voltage to an external electrode (called the gate) to change the height of the barrier.

Nature nanotechnology 3 ,77, (2008)

- ❑ The electrons follow a Boltzmann distribution, and the current through the channel is proportional to **exp ($q\Delta Vg/k_BT$)**.
- ❑ Vg must be changed by **" k_BT ln10/q = 60 mV"** to change the current by a factor of ten at room temperature.

Why Negative Capacitance ?

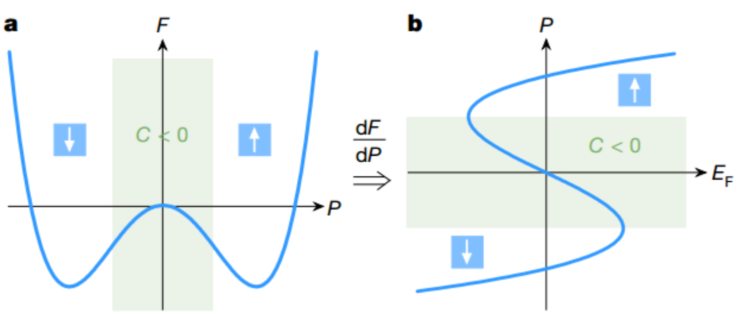
- To achieve the **same charge density** in the channel with **a smaller voltage** at the gate. This in turn translates into **a current increase steeper than 60 mV** per decade (red line). This principle could be exploited to reduce the voltage needed to turn the transistor on.

Voltage Amplifier

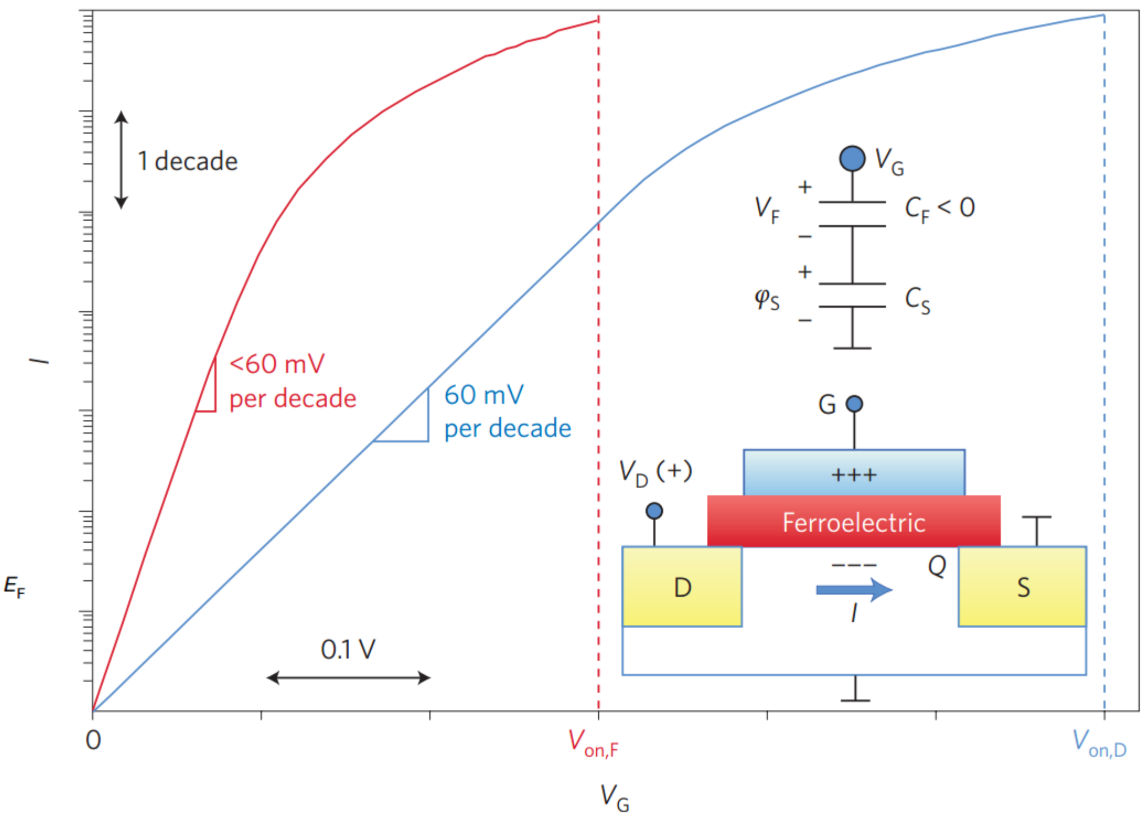
$$V_G = V_F + \varphi_s$$

If $V_F<0$, $V_G < \varphi_s$

$$C_T^{-1} = C_s^{-1} + C_{ins}^{-1}$$



Nature, 565, 464 (2019).



Nature Materials,14, 2, 137-139 (2015)

Why Negative Capacitance ?

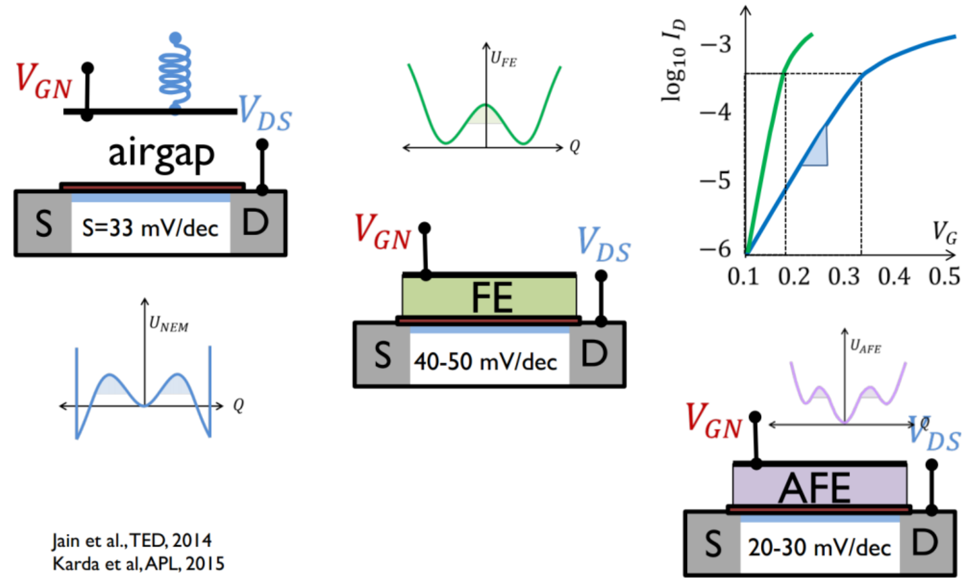
Minimum S for different FE

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

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

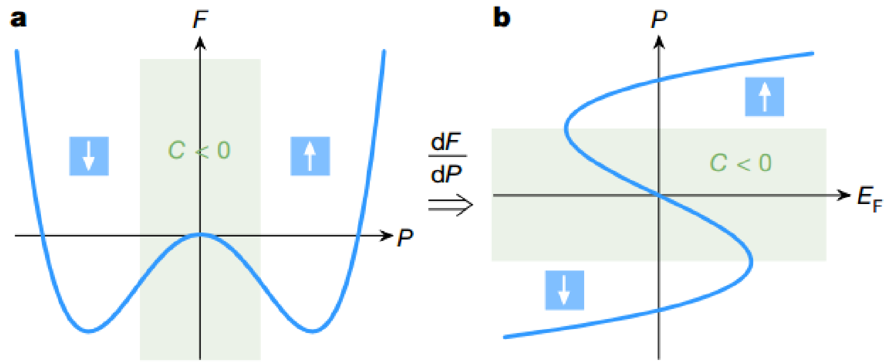
Parameters	BaTiO3	PZT	SBT	
$\alpha_0(m/F)$	$-1e7$	$-4.5e7$	$-6.5e7$	
$\beta_0(m^5F/coul^2)$	$-8.9e8$	$5.2e8$	$3.75e9$	
$\gamma_0(m^9F/coul^4)$	$4.5e10$	$5.9e8$	0	
S_{min}	42	52	52	Bulk-FET
S_{min}	17	20	20	Constant C_s

S improves for all these transistors



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

Summary



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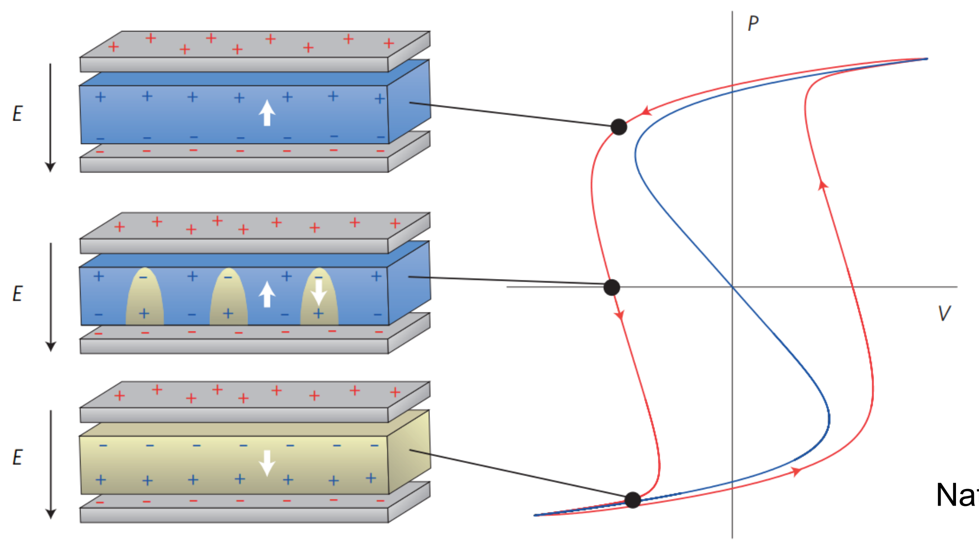

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Thanks for your attention

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