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Modelling and Simulation of Ferroelectric-based Negative Capacitance Devices

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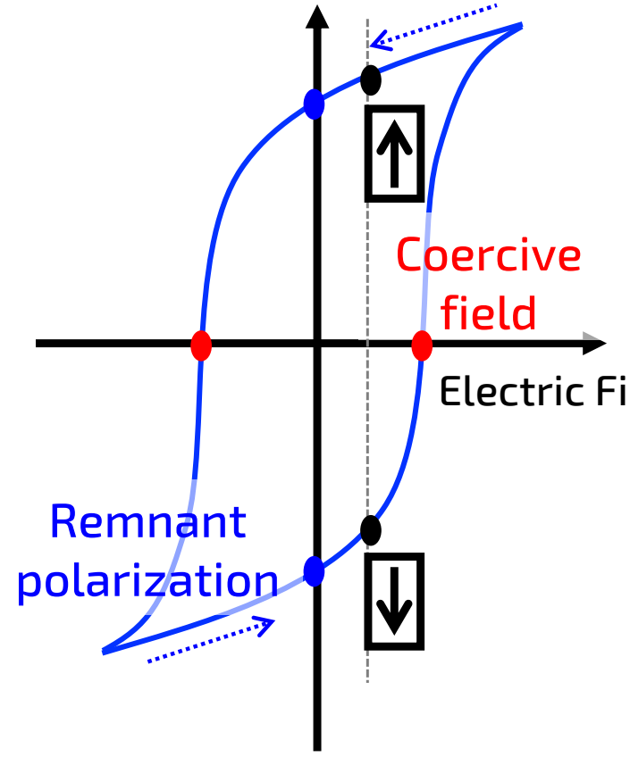
Background

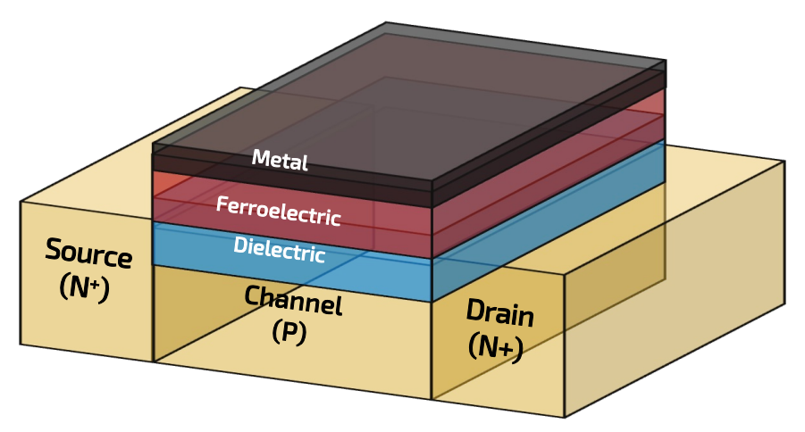
Field-Effect Transistor (FET)

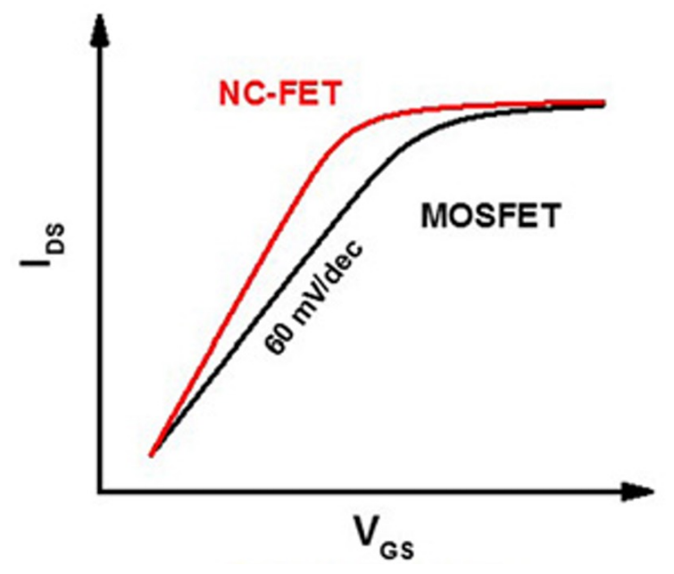
The FET is a device used to amplify or switch electrical signals. The motivation to scale down the size of the FET has been crucial for producing high performing integrated circuits by increasing the overall density of transistors that can fit on a single chip for logic and memory applications [1]. However, classical transistor technology is limited by both undesirable scaling effects and the classical switching limit which inhibits the switching performance of these transistors for ultra-low-power electronics. Hence, there is a clear incentive to find alternative transistor technologies.

Negative Capacitance (NC) FET



By integrating a ferroelectric (FE) material in the conventional FET structure, it is possible to achieve steep switching characteristics beyond the classical limit.

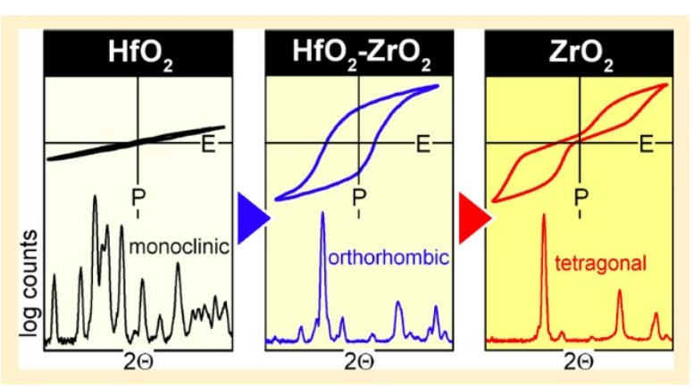




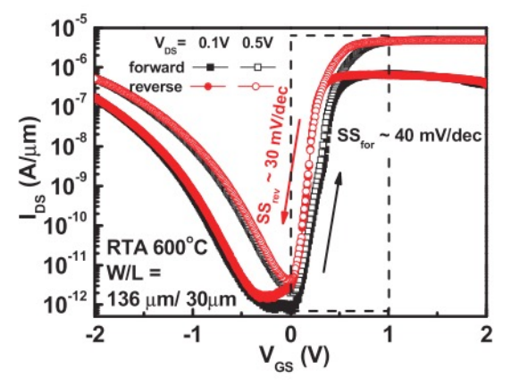
[2]

FE materials exhibit a hysteretic response to an applied electric field due to polarization switching. Unique to FE materials is the ability to internally amplify the voltage when used along with dielectric materials – a phenomenon known as negative capacitance [2].

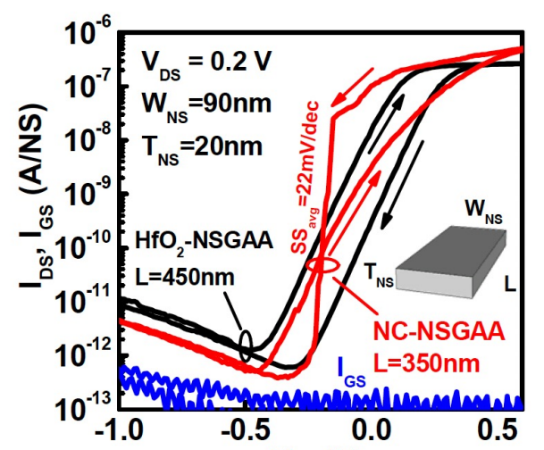
Experimental Demonstration



FE hysteresis in HZO films [3]



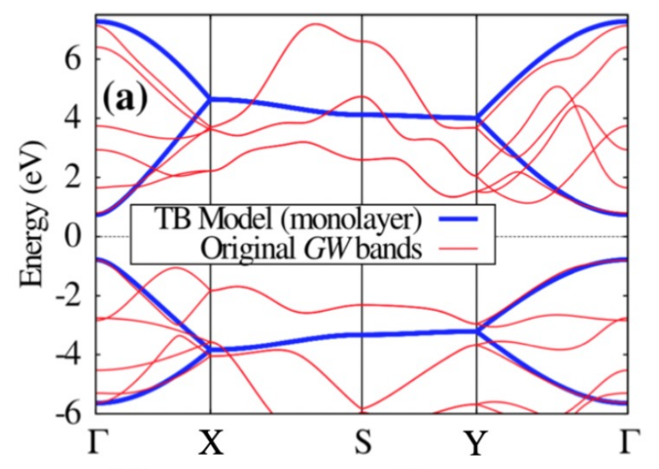
5 nm thick $Hf_{0.5}Zr_{0.5}O_2$ [4]



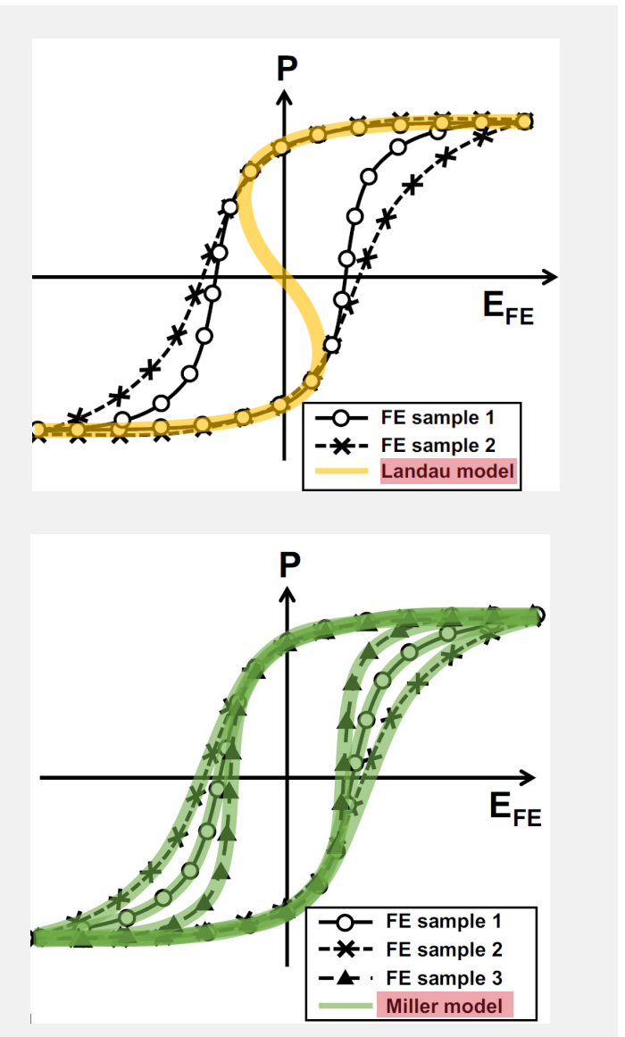
HfO_2 vs. HZO-GAAFET [5]

Methodology

Material Level

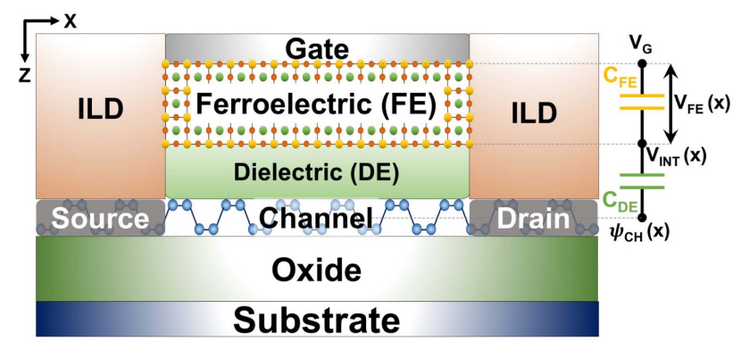


For the electronic states of the active channel material, density functional theory simulations are used. Tight-binding like Hamiltonians are generated as an input to our device simulator. FE material is modelled using Miller Model (MM) instead of the conventionally used Landau model to accurately capture hysteresis.



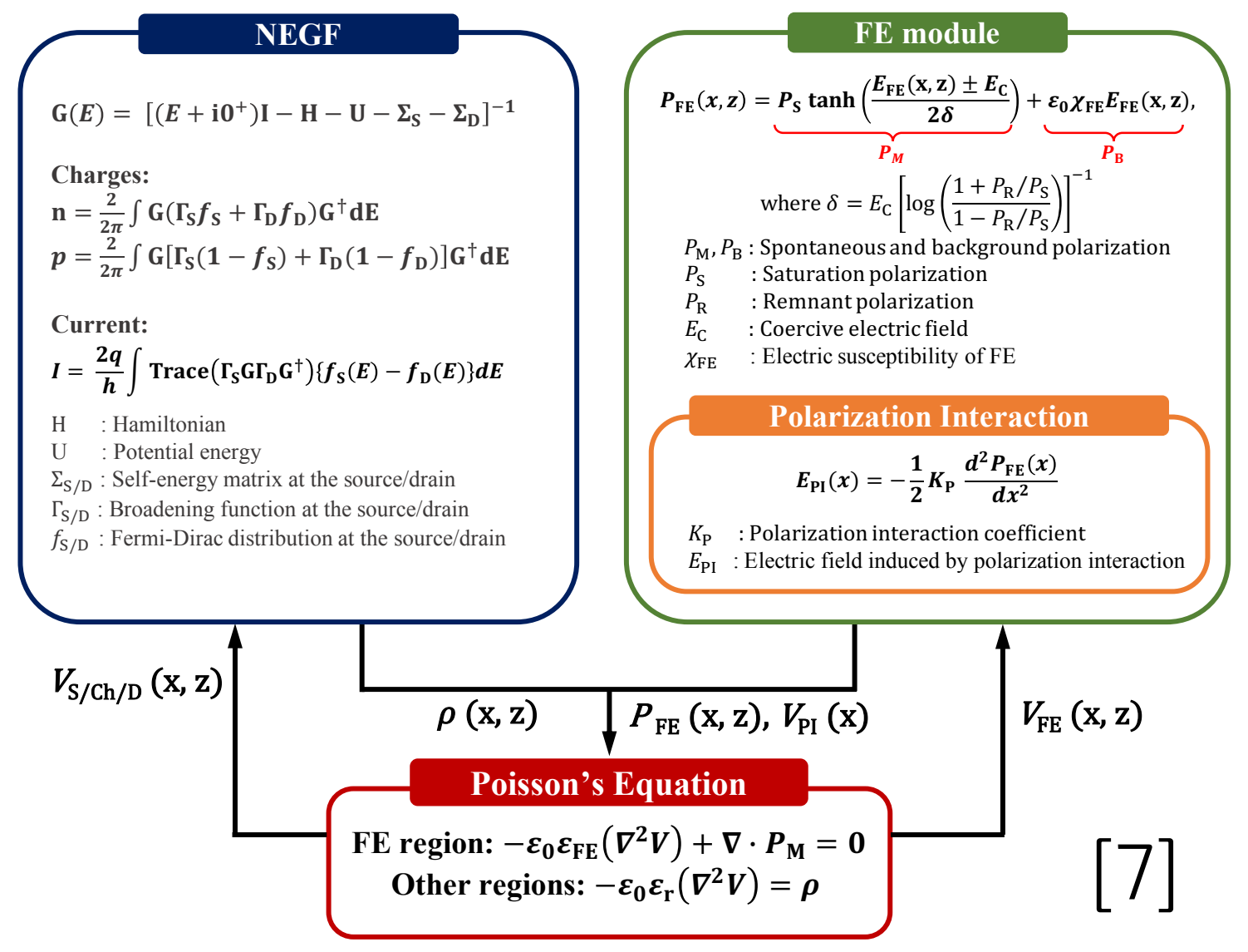
[6]

Device Level



[7]

The quantum transport simulator iterates along with Poisson's and FE modules until the system self-consistently converges.



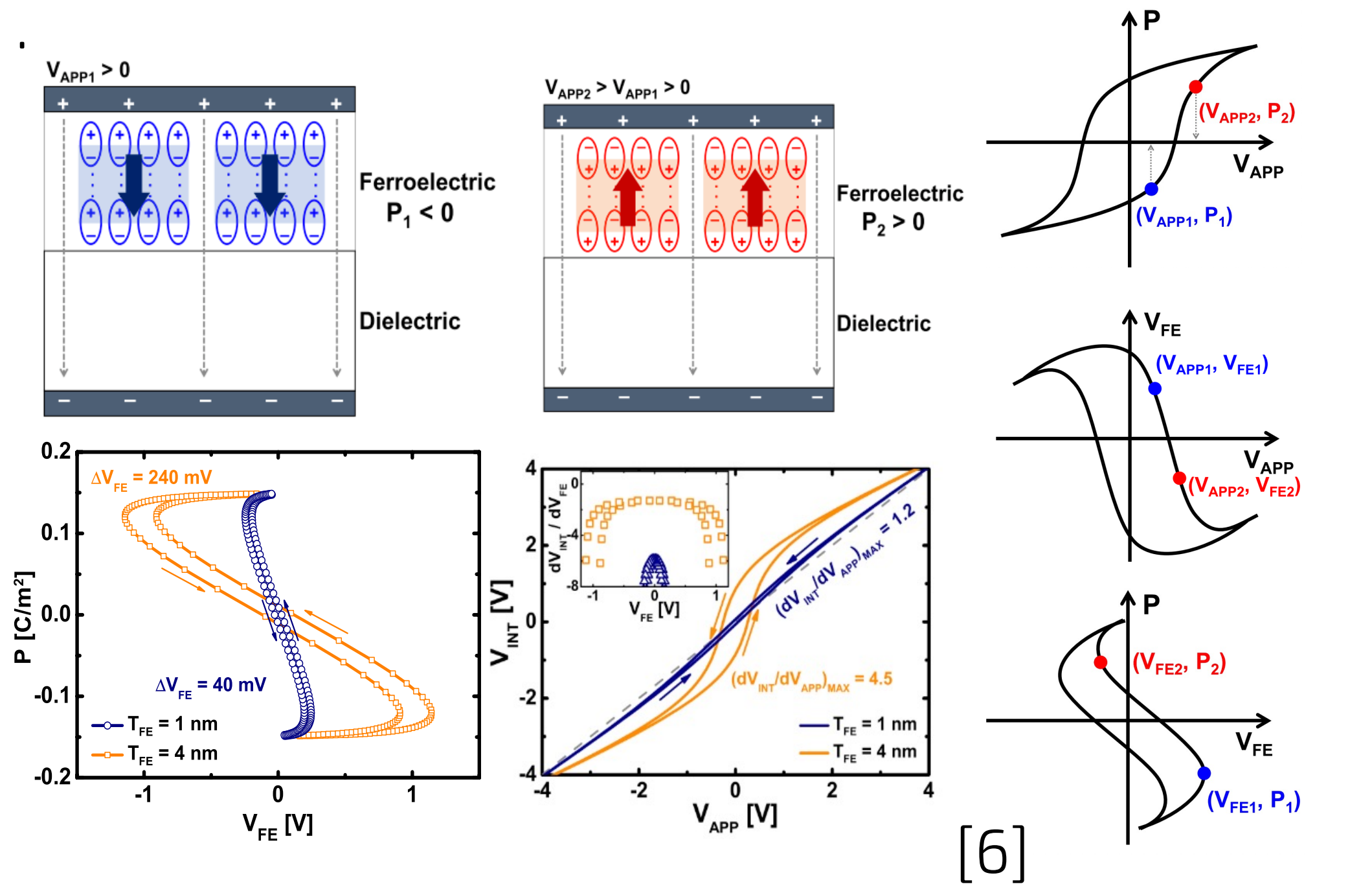
[7]

Polarization interactions are included considering the variation of polarization along channel under bias.

Results

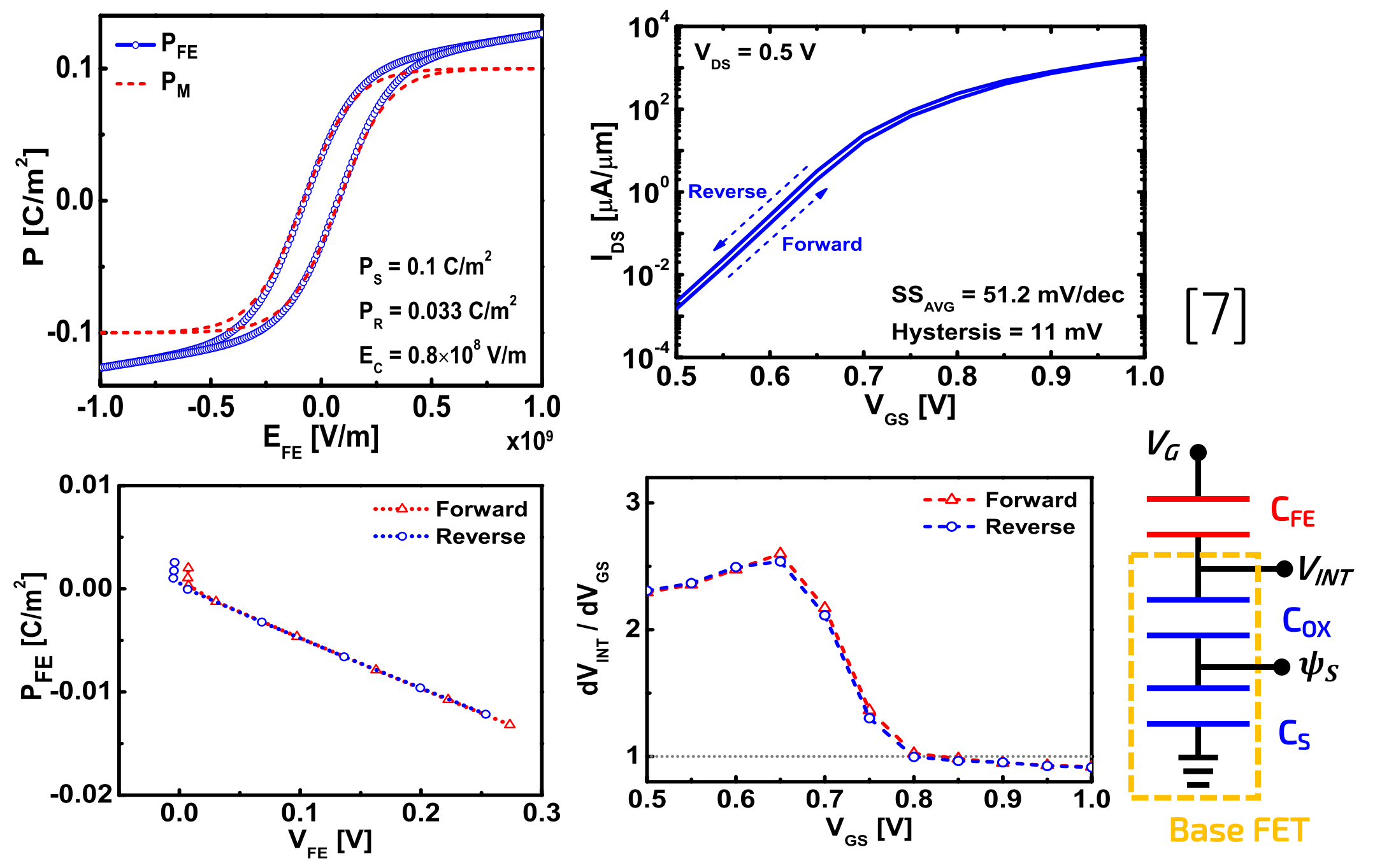
FE-DE Structure

We simulate a FE-DE structure to understand the fundamental physics of polarization switching in FE on dielectric material using MM.



[6]

NCFET Nominal Device Results

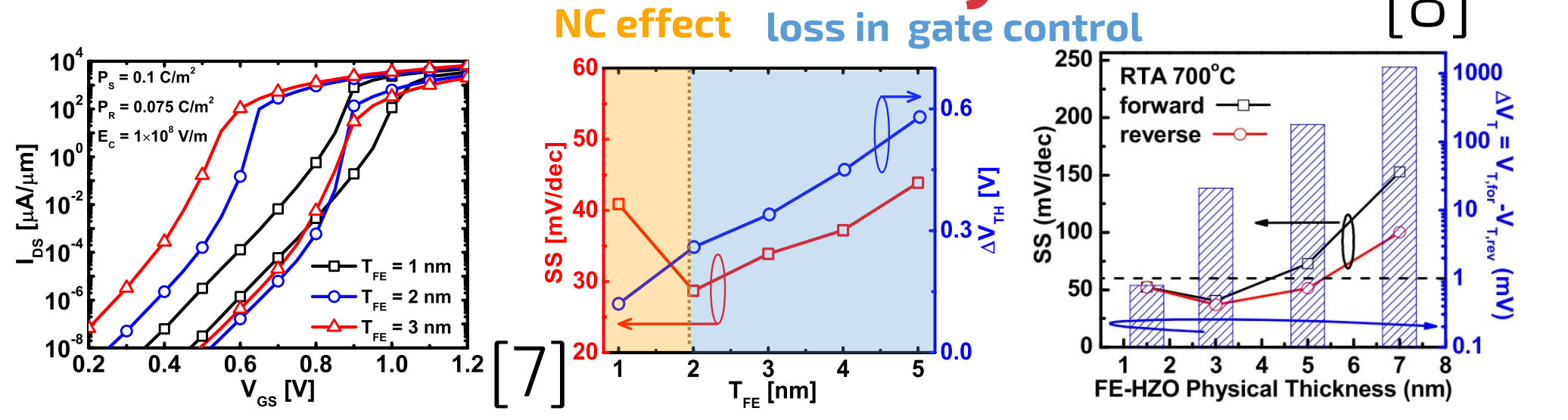


[7]

NC effect is achieved when internal voltage (V_{INT}) is amplified under polarization switching resulting in sub-60 mV/dec subthreshold swing.

$$SS = \frac{dV_{GS}}{dV_{INT}} \times \frac{dV_{INT}}{d\psi_S} \times \frac{d\psi_S}{dlog_{10}(I_{DS})}$$

FE film thickness study



[8]

Conclusions

1. By simulating FE-DE, we have shown the physical origin of the NC effect.
2. Our rigorous NCFET device simulation proposes device structures that can achieve steep-switching and hysteresis free characteristics for different target applications.
3. FE film thickness study reveals a critical thickness confirming experimental results.

References

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