Marco Boccarossa

Advanced Design Strategies and Material Integration for Enhancing Performance and Energy Efficiency in SiC MOSFETs

Tutor:
Prof. Andrea Irace

co-Tutor:
Prof. Luca Maresca

Cycle: XXXVII

Year: Third

Candidate’s information

- MSc degree in **Electronics Engineering** – 26th Oct 2021
- **OptoPowerLab** (OPL) - DIETI
- PhD start and end dates: 01/11/2021 – 31/10/2024
- Scholarship funded by **DIETI Department**
- Abroad research: **University of Warwick** (UK) 09/03/24 – 09/08/24
- **Collaborations:** Vishay Semiconductor, Università Ca’ Foscari Venezia, University of Warwick, Hitachi Energy

VISHAY®

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WARWICK
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Hitachi Energy

Summary of study activities

PhD Year	Courses	Seminars	Research	Tutoring / Supplementary Teaching
1st	21	5.8	33.2	/
2nd	11	5.6	43.4	/
3rd	4	0.2	55.8	/

PhD Schools:

- Summer School of Information Engineering (SSIE) 2022: GaN and related Materials, Bressanone (BZ)
- China-Italy Joint Laboratory on Advanced Manufacturing (CI-LAM) 2022, Bergamo
- Società Italiana di Elettronica (SIE) 2023: How Electronics drives global innovations, Messina

Other relevant courses and seminars:

- Numerical Methods for Thermal analysis, Modeling, and Simulation: Application to electronic Devices and Systems, Dr. A. P. Catalano *(ad hoc course)*
- Gallium Nitride: the new disruptive power technology, STMicroelectronics *(seminar)*
- Ensuring Electronic Reliability Against CERN's Radiation Environment, CERN (seminar)

Attended Conferences

- WiPDA 2022
- ISPSD 2023
- ISPS 2023
- SIE 2023
- ICSCRM 2023
- ISPSD 2024

WiPDA-Europe
2022 United Kingdom

ISPSD
2023

SIE 2023
SOCIETÀ ITALIANA DI ELETTRONICA

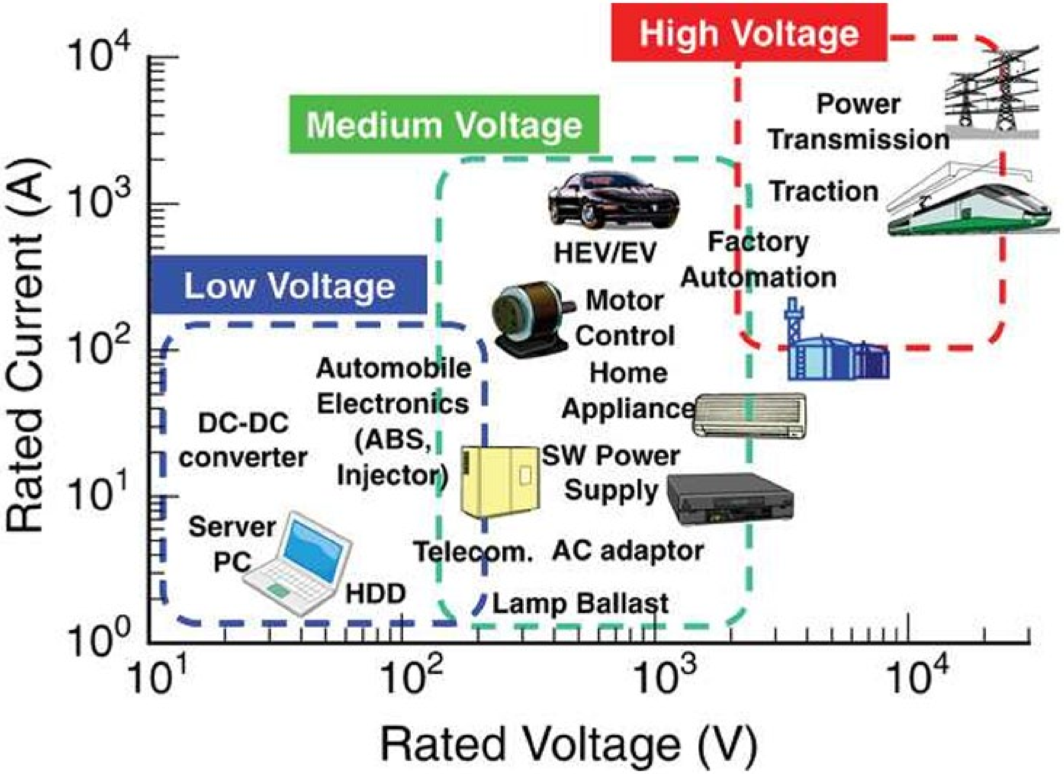
ICSCRM2023
INTERNATIONAL CONFERENCE ON SILICON CARBIDE AND RELATED MATERIALS
SORRENTO, ITALY
17-22 SEPTEMBER 2023

BREMEN | GERMANY
ISPSD
2-6 June 2024

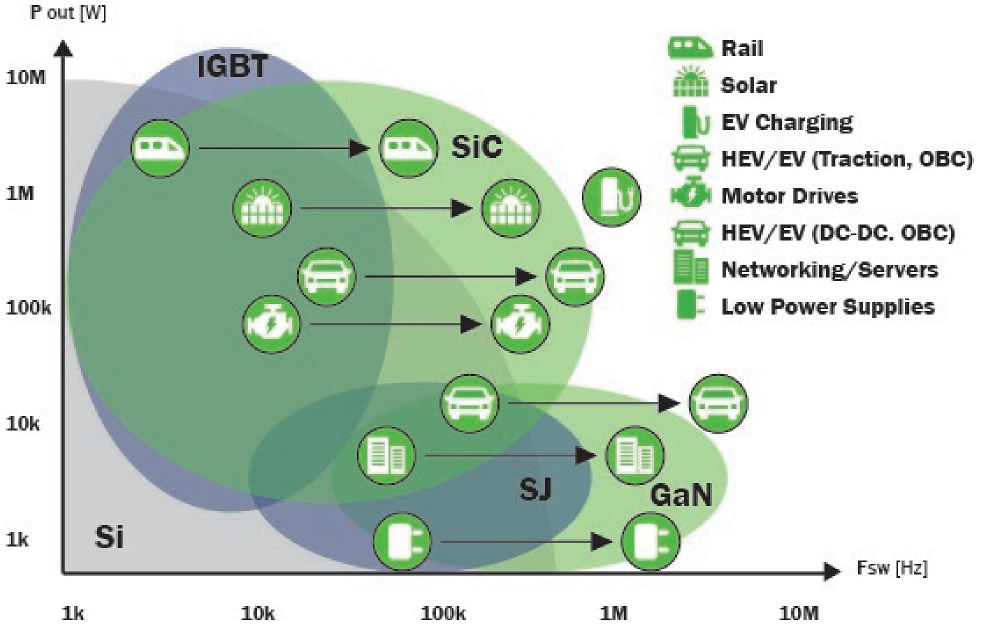
Research area (1/2)

Power Electronics focuses on the control, conversion, and management of the power coming from the power supply to provide the conditioned one required by the load.

A crucial role in power electronics is played by **semiconductor power devices**, which act essentially as switch and controllers within the circuits.



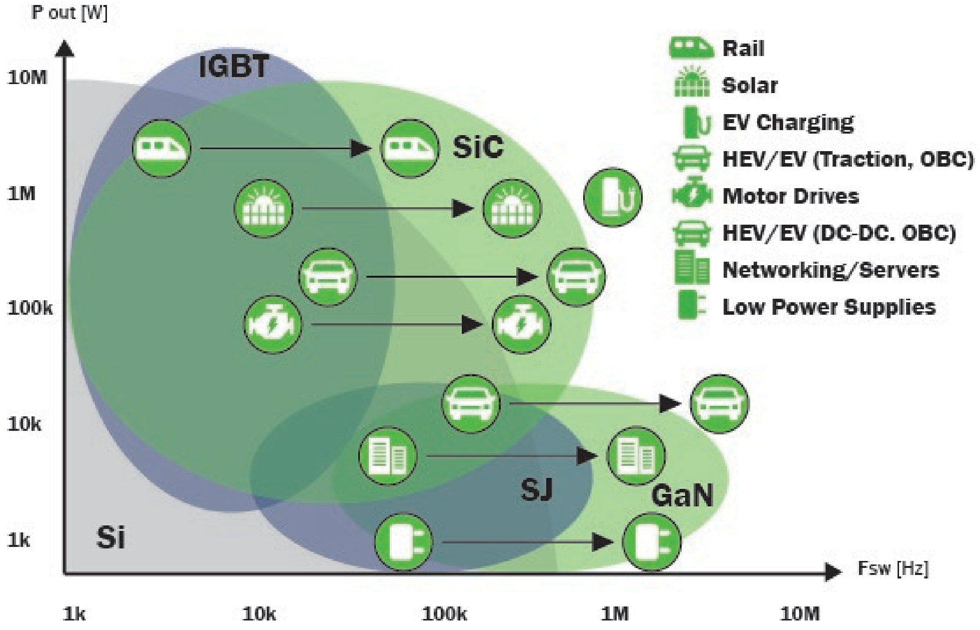
Research area (2/2)



- **Silicon-based** semiconductor devices (e.g., MOSFETs, IGBTs) have long **dominated the field** due to their low cost and mature technology.

- **Demanding for higher efficency**, power density and improved thermal perfomance has led to the exploration of new materials to **overcome silicon limitations**.

Research area (2/2)



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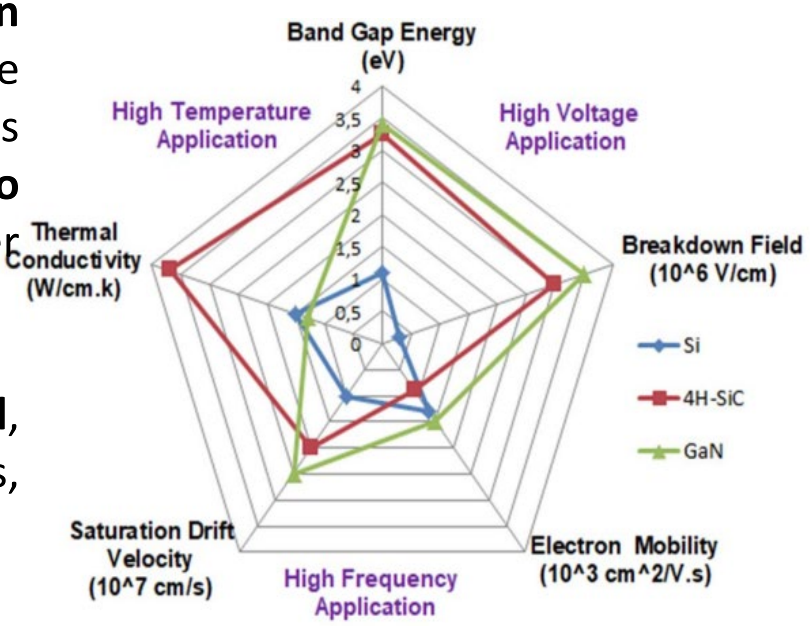
- **Demanding for higher efficency**, power density and improved thermal perfomance has led to the exploration of new materials to **overcome silicon limitations**.

- Wide-bandgap (WBG) materials, such as **Silicon Carbide** (SiC) and Gallium Oxide (GaN) have become increasingly important in power electronics thanks to their **superior properties compared to silicon**, such as as the ability to operate at higher voltages, temperatures, and frequencies.

- **Ideal for applications where efficiency is critical**, such as electric vehicles, renewable energy systems, and high-frequency power converters.



Research results

- SiC diodes
  - Active and termination design
  - MPS diodes simulations strategy[P1, P2]
  - Compact modeling for snapback mechanism [P6, P8]
- *SiC Gate-All-Aroung (GAA) MOSFETs*
  - *Performance analysis [P7, P12]*

*** Covered by the thesis**

- *Semi-superjunction MOSFETs*
  - *Easy fabrication method [P14, P16]*
- *Multidimensional MOSFETs cells*
  - *Improved perfomance [P13]*
- *<<Ferro-Power>> MOSFETs [P4, P5, P10, P11, P15]*
  - *Improved Short-circuit (SC) capability through ferroelectric materials*

Research products (1/4)

[P1]	**M. Boccarossa**, A. Borghese, L. Maresca, M. Riccio, G. Breglio, A. Irace, *TCAD Analysis of the Impact of the Metal-Semiconductor Junction Properties on the Forward Characteristics of MPS/JBS SiC Diodes*, **IEEE Workshop on Wide Bandgap Power Devices and Applications in Europe (WiPDA Europe),** Coventry, United Kingdom, 2022, pp. 1-5, doi: 10.1109/WiPDAEurope55971.2022.9936079.
[P2]	**M. Boccarossa**, A. Borghese, L. Maresca, M. Riccio, G. Breglio, and A. Irace, *Numerical Analysis of the Schottky Contact Properties on the Forward Conduction of MPS/JBS SiC Diodes,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Davos, Switzerland, Sep. 2022, https://doi.org/10.4028/p-mlkxy8.
[P3]	A. Borghese, **M. Boccarossa**, M. Riccio, L. Maresca, G. Breglio and A. Irace, *Short-circuit and Avalanche Robustness of SiC Power MOSFETs for Aerospace Power Converters,* **IEEE Aerospace Conference (AEROCONF),** Big Sky, MT, USA, 2023, pp. 1-8, doi: 10.1109/AERO55745.2023.10115580.
[P4]	**M. Boccarossa**, L. Maresca, A. Borghese, M. Riccio, G. Breglio, A. Irace, G. A. Salvatore, *Short-Circuit Rugged 1.2 kV SiC MOSFET with a Non-Linear Dielectric Gate Stack,* **IEEE 35th International Symposium on Power Semiconductor Devices and ICs (ISPSD),** Hong Kong, 2023, pp. 354-357, doi: 10.1109/ISPSD57135.2023.10147604.
[P5]	**M. Boccarossa**, L. Maresca, A. Borghese, M. Riccio, G. Breglio, A. Irace, and G. A. Salvatore, *Threshold Voltage Temperature Dependence for a 1.2 kV SiC MOSFET with Non-Linear Gate Stack*, **International Seminar on Power Semiconductors (ISPS),** Czech Technical University in Prague, Czech Republic, 2023.

Research products (2/4)

[P6]	V. d'Alessandro, V. Terracciano, A. Borghese, **M. Boccarossa**, and A. Irace, *A Simple Electrothermal Compact Model for SiC MPS Diodes Including the Snapback Mechanism,* **29th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC),** Budapest, Hungary, 2023, pp. 1-5, doi: 10.1109/THERMINIC60375.2023.10325871.
[P7]	L. Maresca, V. Terracciano, A. Borghese, **M. Boccarossa**, M. Riccio, G. Breglio, A. Mihaila, G. Romano, S. Wirths, L. Knoll, and A. Irace, *SiC GAA MOSFET Concept for High Power Electronics Performance Evaluation through Advanced TCAD Simulations,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Sorrento (NA), Italy, Sep. 2023, https://doi.org/10.4028/p-lhRi4M.
[P8]	V. Terracciano, A. Borghese, **M. Boccarossa**, V. d'Alessandro, and A. Irace, *A Geometry-Scalable Physically-Based SPICE Compact Model for SiC MPS Diodes Including the Snapback Mechanism,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Sorrento (NA), Italy, Sep. 2023, https://doi.org/10.4028/p-b9ImzL.
[P9]	A. Borghese, S. Angora, **M. Boccarossa**, M. Riccio, L. Maresca, V. R. Marrazzo, G. Breglio, and A. *Irace, Analysis of Electrothermal Imbalance of Hard-Switched Parallel SiC MOSFETs through Infrared Thermography,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Sorrento (NA), Italy, Sep. 2023, https://doi.org/10.4028/p-2uwgqf.

Research products (3/4)

[P10]	**M. Boccarossa**, L. Maresca, A. Borghese, M. Riccio, G. Breglio, A. Irace, and G. A. Salvatore, *Non-Linear Gate Stack Effect on the Short Circuit Performance of a 1.2-kV SiC MOSFET,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Sorrento (NA), Italy, Sep. 2023, https://doi.org/10.4028/p-50ZNaN.
[P11]	**M. Boccarossa**, L. Maresca, A. Borghese, M. Riccio, G. Breglio, A. Irace, G. A. Salvatore, *Substantial Improvement of the Short-circuit Capability of a 1.2 kV SiC MOSFET by a HfO2/SiO2 Ferroelectric Gate Stack,* **36th International Symposium on Power Semiconductor Devices and ICs (ISPSD),** Bremen, Germany, Jun. 2024, pp. 88-91, DOI: 10.1109/ISPSD59661.2024.10579678.
[P12]	L. Maresca, V. Terracciano, A. Borghese, **M. Boccarossa**, M. Riccio, G. Breglio, S. Wirths, and A. Irace, *Evaluation of Switching Performances and Short Circuit Capability of a 1.2 kV SiC GAA MOSFET through TCAD Simulations,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Raleigh (NC), USA, Oct. 2024.
[P13]	C. Scognamillo, A. Borghese, K. Melnyk, I. Nistor, V. d'Alessandro, **M. Boccarossa**, V. Terracciano, M. Riccio, A. P. Catalano, G. Breglio, N. Lophitis, M. Antoniou, M. T. Rahimo, A. Irace, and Luca Maresca, *Out-of-SOA Performance of 3.3 kV SiC MOSFETs: Comparison between Planar and Quasi-Planar Trench,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Raleigh (NC), USA, Oct. 2024.

Research products (4/4)

[P14]	K. Melnyk, **M. Boccarossa**, A. B. Renz, Q. Cao, P. M. Gammon, V. A. Shah, L. Maresca, A. Irace, and M. Antoniou, *Cost-Effective Design and Optimization of a 3300-V Semi-Superjunction 4H-SiC MOSFET Device,* **International Conference on Silicon Carbide and Related Materials (ICSCRM),** Raleigh (NC), USA, Oct. 2024.
[P15]	**M. Boccarossa**, L. Maresca, A. Borghese, M. Riccio, G. Breglio, A. Irace, and G. A. Salvatore, *The Ferro-Power MOSFET: Enhancing Short-circuit Robustness in Power Switches with a Ferroelectric Gate Stack,* **IEEE Journal of Emerging and Selected Topics in Power Electronics** *(Under review)*
[P16]	**M. Boccarossa**, K. Melnyk, A. B. Renz, P. M. Gammon, V. Kotagama, V. A. Shah, L. Maresca, A. Irace, and M. Antoniou, *The 3.3 kV SiC Semi-superjunction MOSFET with Trench Sidewall Implantations,* **IEEE Transactions on Electron Devices** *(Under review)*

PhD thesis overview

- Problem

  Short-circuit (SC) weakness of SiC MOSFETs

- Objective

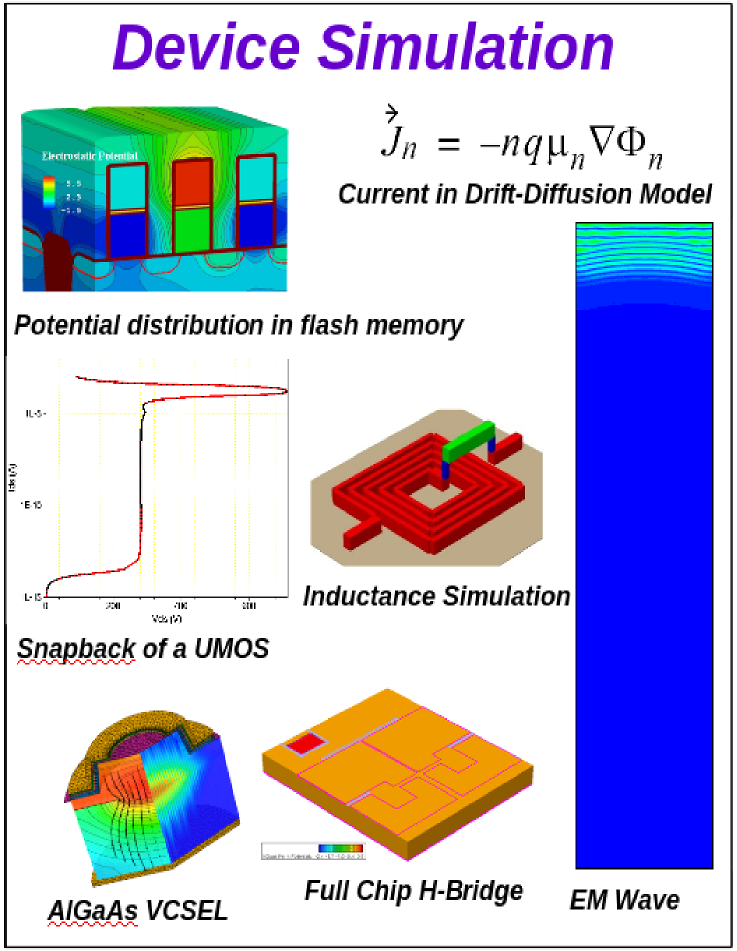
  Improve SC capability of SiC MOSFETs through ferroelectric materials

- Methodology

  TCAD simulations benchmarked on standard MOSFETs perfomance

TCAD simulations

Technology Computer Aided Design



Device Simulation

$$\vec{J}_n = -nq\mu_n\nabla\Phi_n$$

Current in Drift-Diffusion Model

Potential distribution in flash memory

Snapback of a UMOS

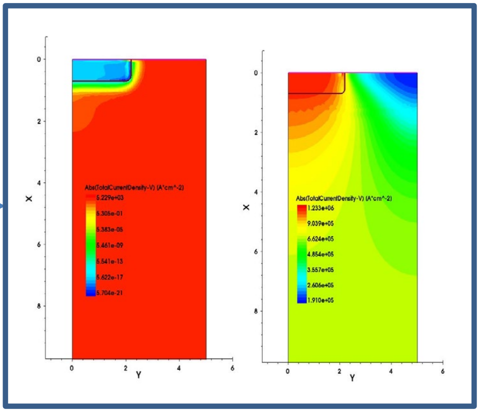
Inductance Simulation

AlGaAs VCSEL

Full Chip H-Bridge

EM Wave

- Predicts the behavior of the device before its physical fabrication
- Reduces development time and costs
- Allows to study the internal phenomena into the device

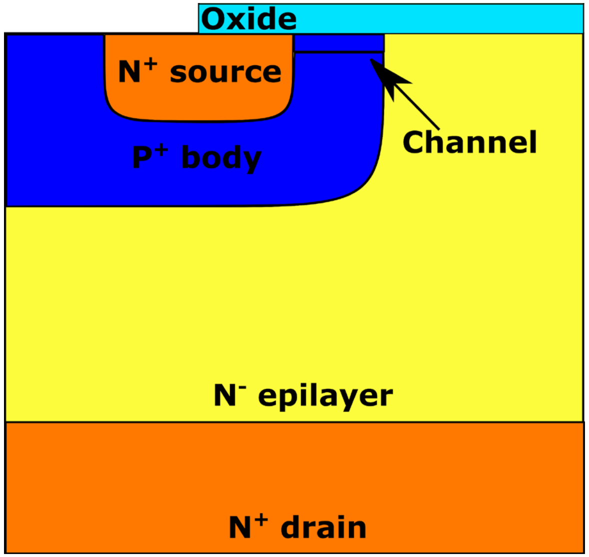


Current distributions inside the device

Sentaurus TCAD

SYNOPSYS

Silicon Carbide MOSFETs



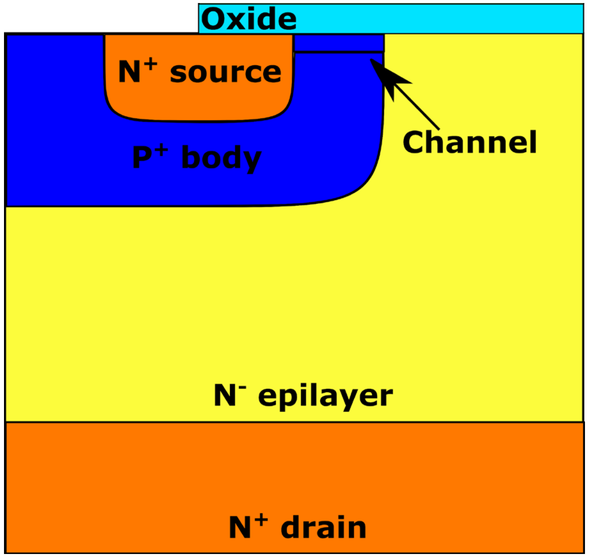
Pros:

- High breakdown voltage
- High switching speed
- Low on-resistance
- High temperature operation

Cons:

- Realibility problems ➔ **Short-circuit capability**

Silicon Carbide MOSFETs



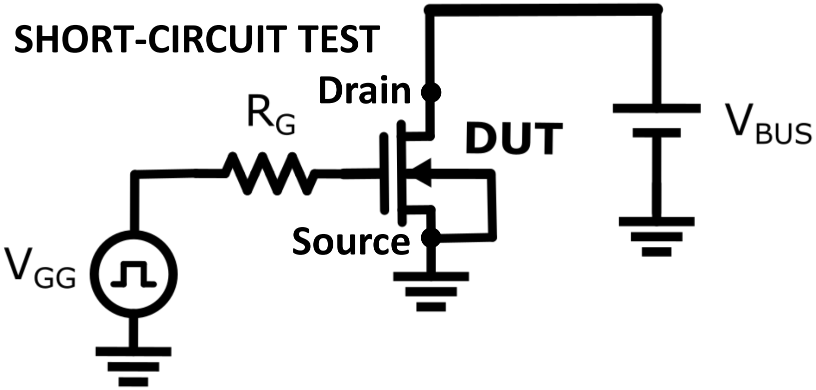
Pros:

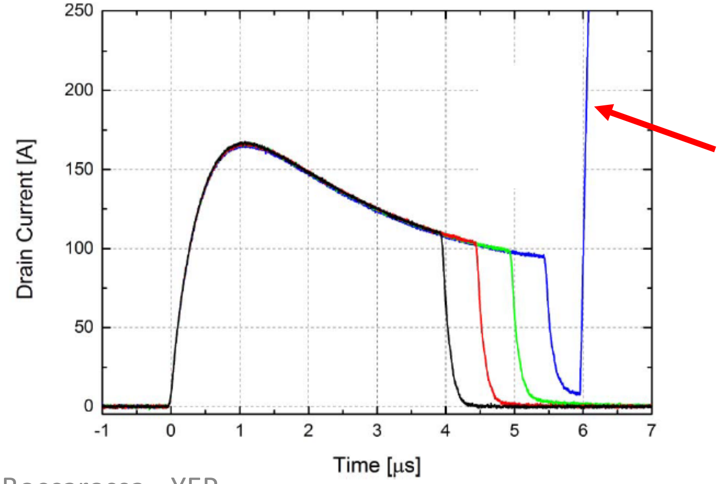
- High breakdown voltage
- High switching speed
- Low on-resistance
- High temperature operation

Cons:

- Realibility problems ➔ **Short-circuit capability**

A possible short-circuit event occurs when the device switches on with the supply voltage applied between drain and source terminals.

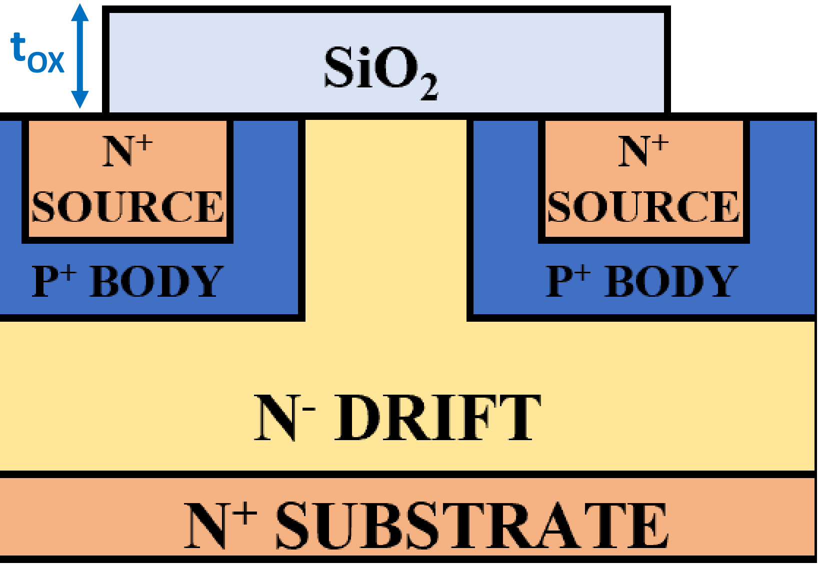

SHORT-CIRCUIT TEST



FAILURE DUE TO THERMAL RUNAWAY

MOSFET operation

Standard MOSFET elementary cell



MOSFET operation

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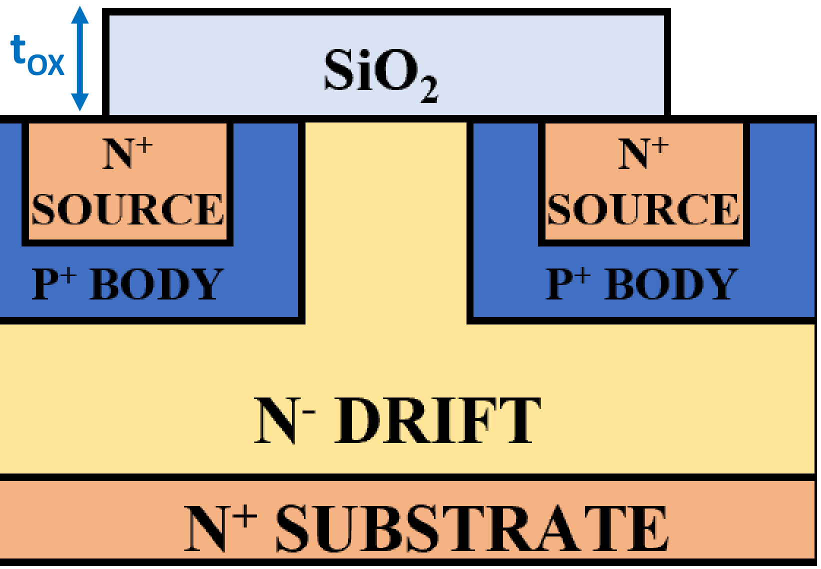
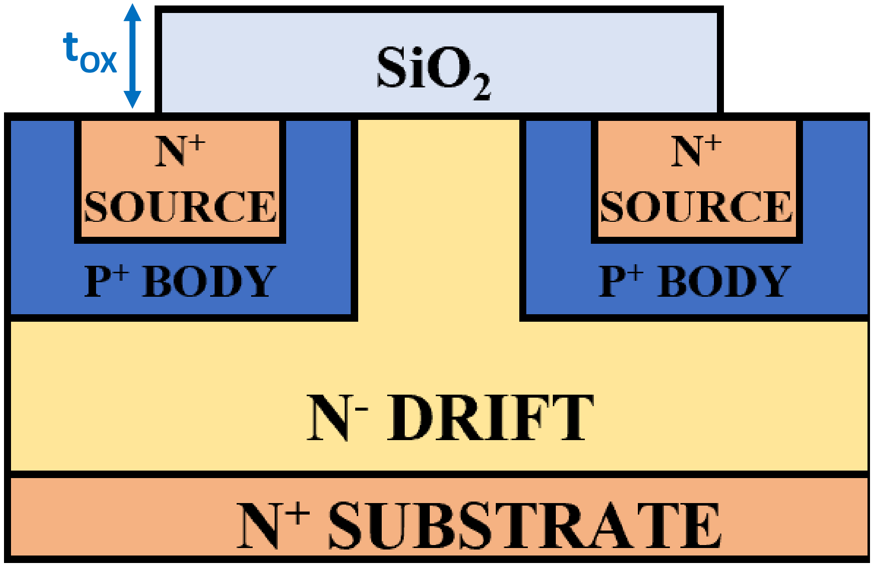


MOSFET Drain Current

$$I_D \propto \mu(T) C_{OX} \left(V_{GS} - V_{TH}(T)\right)^2$$

MOSFET operation

Standard MOSFET elementary cell



MOSFET Drain Current

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Temperature-dependent parameters

MOSFET operation

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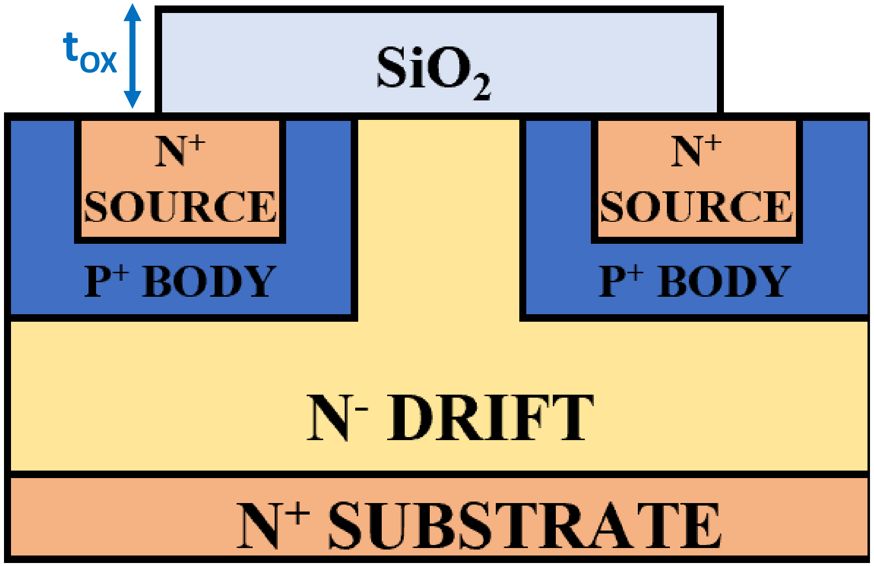

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Temperature-dependent parameters

$$C_{OX} = \frac{\varepsilon_{ox}}{t_{ox}} \Longrightarrow$$ Constant with temperature

MOSFET operation

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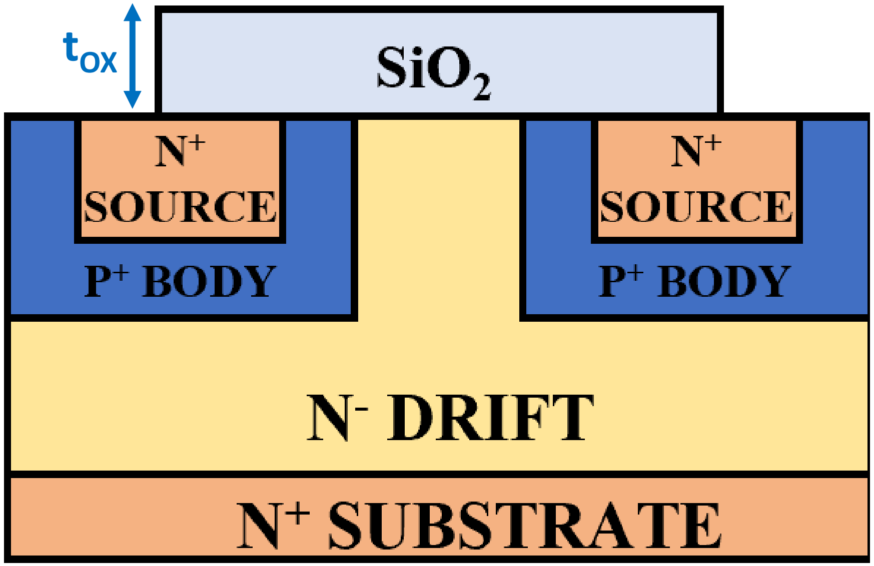

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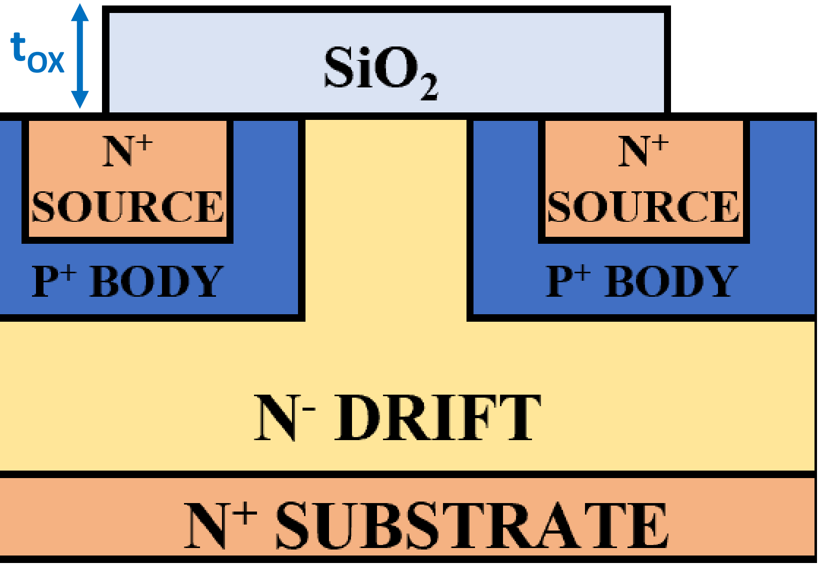
- The **increasing temperature** during SC events can trigger a positive feedback with the current, potentially leading to failure due to thermal runaway.

MOSFET operation

Standard MOSFET elementary cell



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Temperature-dependent parameters

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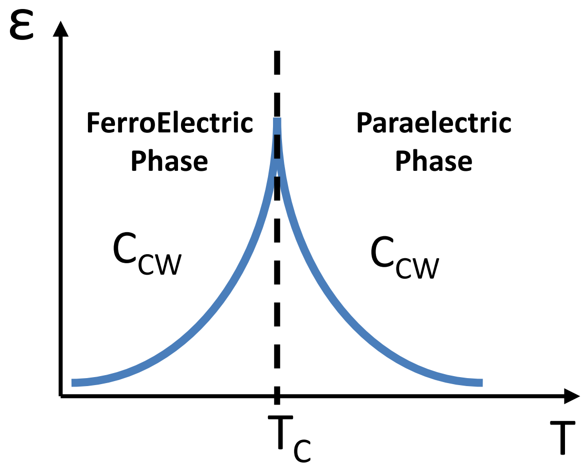
- The **increasing temperature** during SC events can trigger a positive feedback with the current, potentially leading to failure due to thermal runaway.

- Is there a way to limit the current conducted during SC?

Ferroelectric materials

- Ferroelectric materials are chaterized by a spontaneus polarization.



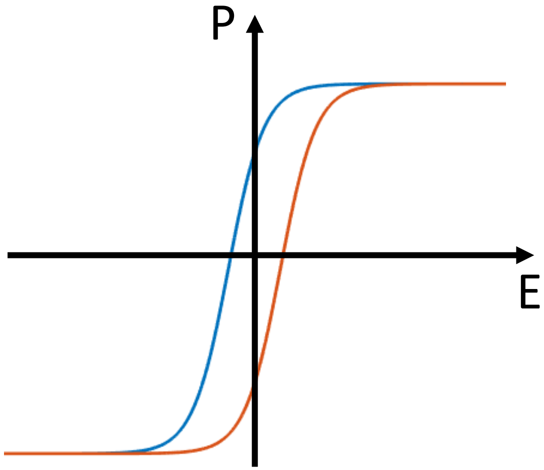
Ferroelectric materials

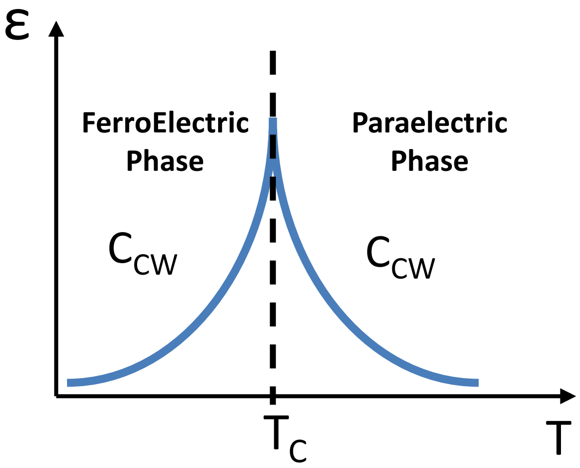
- Ferroelectric materials are chaterized by a spontaneus polarization.

1) Landau's theory:

Describes the dependence of the **polarization** on **electric field** and **temperature**

$$F = \frac{\alpha}{2}P^2 + \frac{\beta}{4}P^4$$





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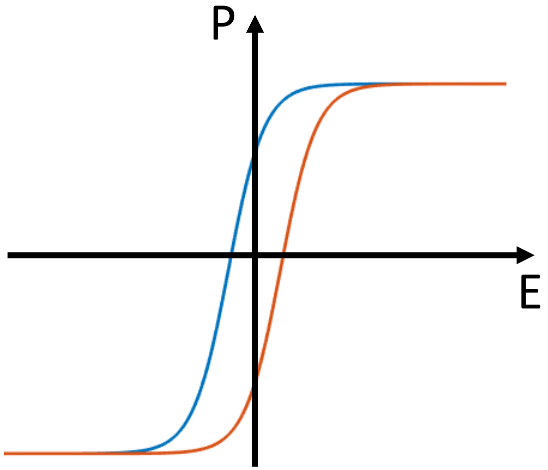


1) Landau's theory:

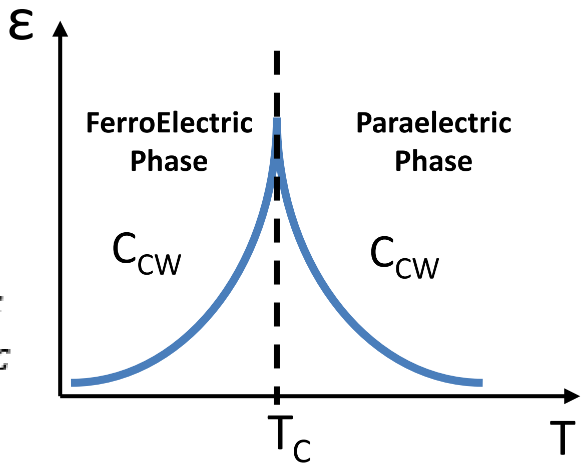
Describes the dependence of the **polarization** on **electric field** and **temperature**

$$F = \frac{\alpha}{2}P^2 + \frac{\beta}{4}P^4$$

2) Curie-Weiss law:

Describes the dependence of the **dielectric constant** on **temperature**

$$\varepsilon = \lambda \frac{C_{CW}}{T - T_C} \quad with \begin{cases} \lambda = -1 & for\, T < T_C \\ \lambda = 1 & for\, T > T_C \end{cases}$$



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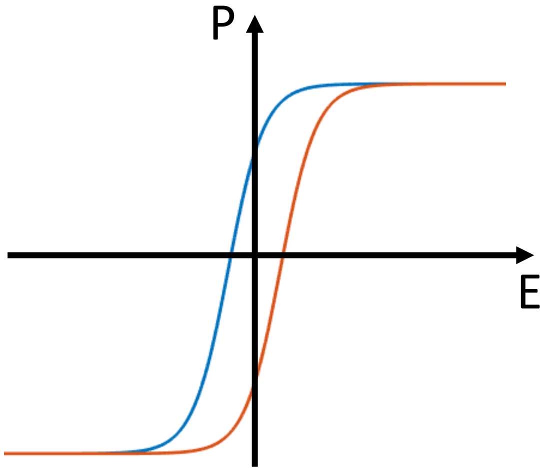

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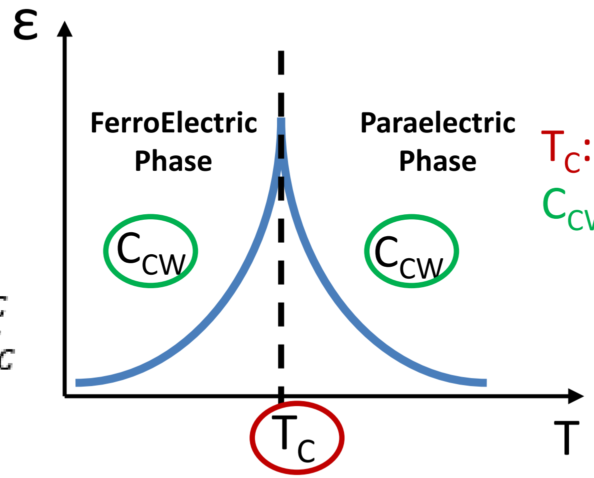
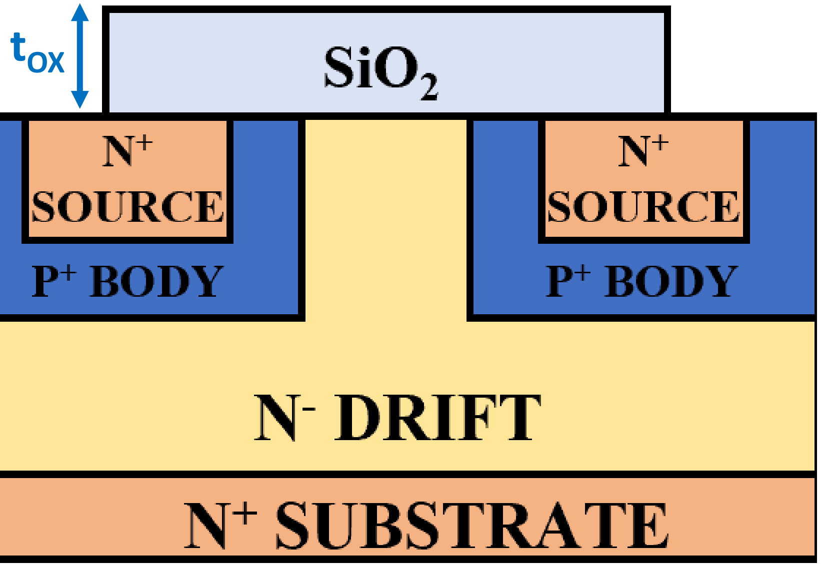


T_C: Curie Temperature

C_{CW}: Curie Constant

<<Ferro-Power>> MOSFET

Standard MOSFET elementary cell



MOSFET Drain Current

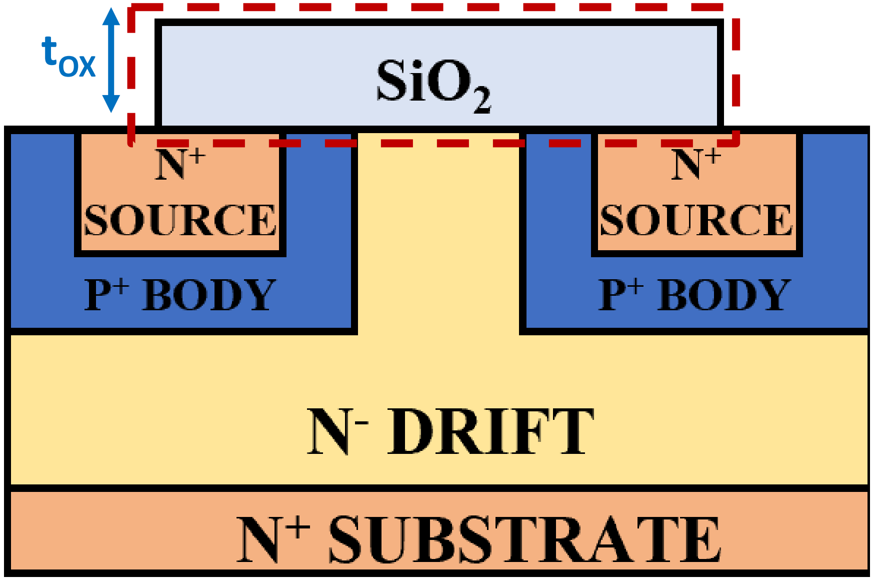
$$I_D \propto \mu(T) C_{OX} (V_{GS} - V_{TH}(T))^2$$

Temperature-dependent parameters

$$C_{OX} = \frac{\varepsilon_{ox}}{t_{ox}} \Rightarrow$$ Constant with temperature

<<Ferro-Power>> MOSFET

Standard MOSFET elementary cell



MOSFET Drain Current

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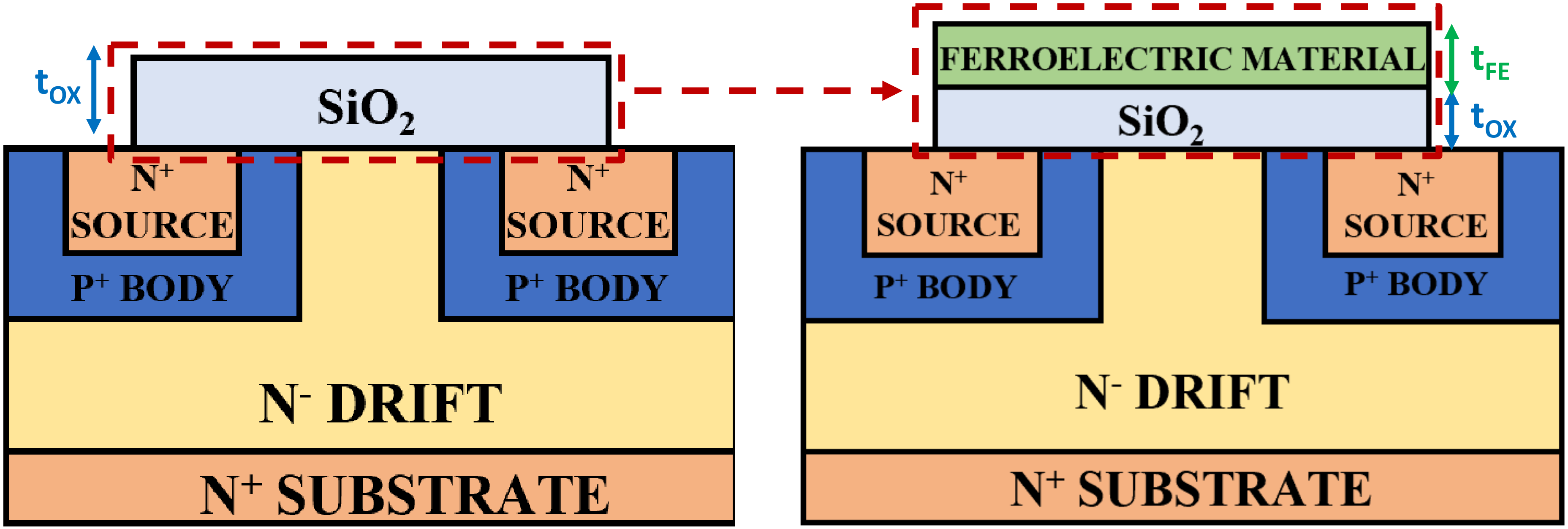
<<Ferro-Power>> MOSFET

Standard MOSFET elementary cell **«Ferro-Power» MOSFET elementary cell**



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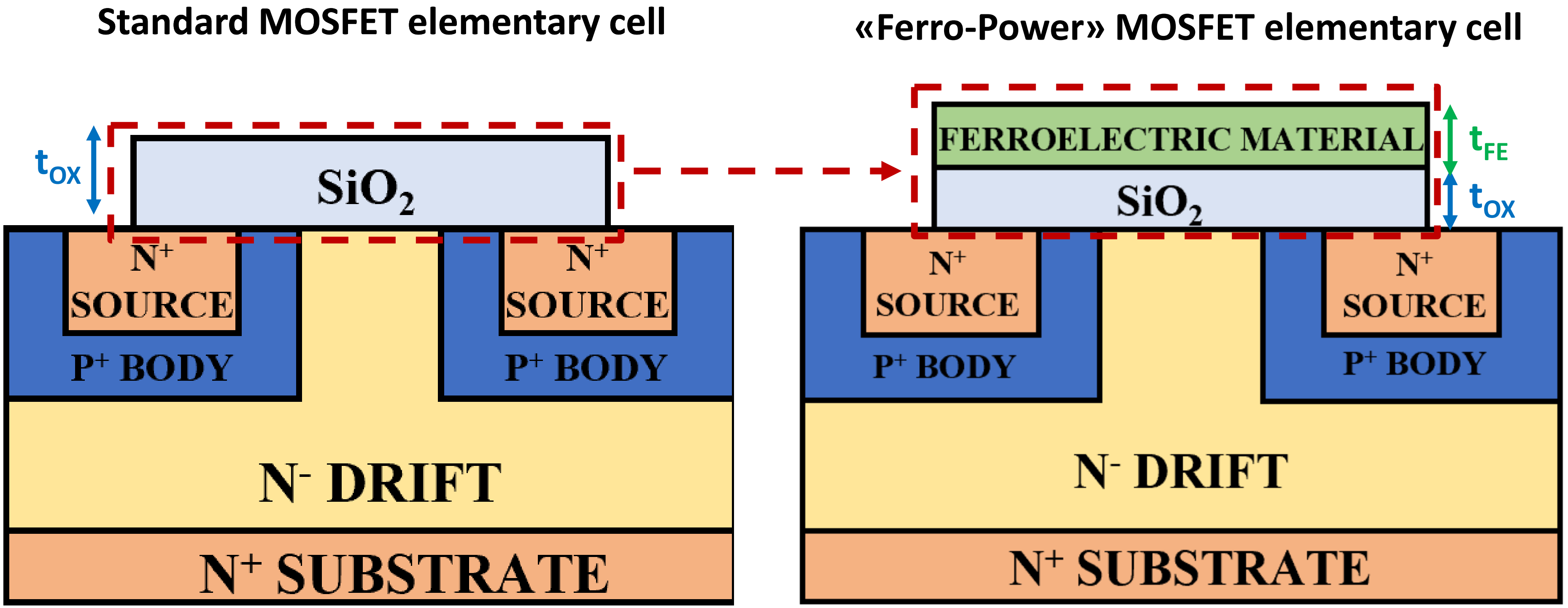
<<Ferro-Power>> MOSFET



MOSFET Drain Current

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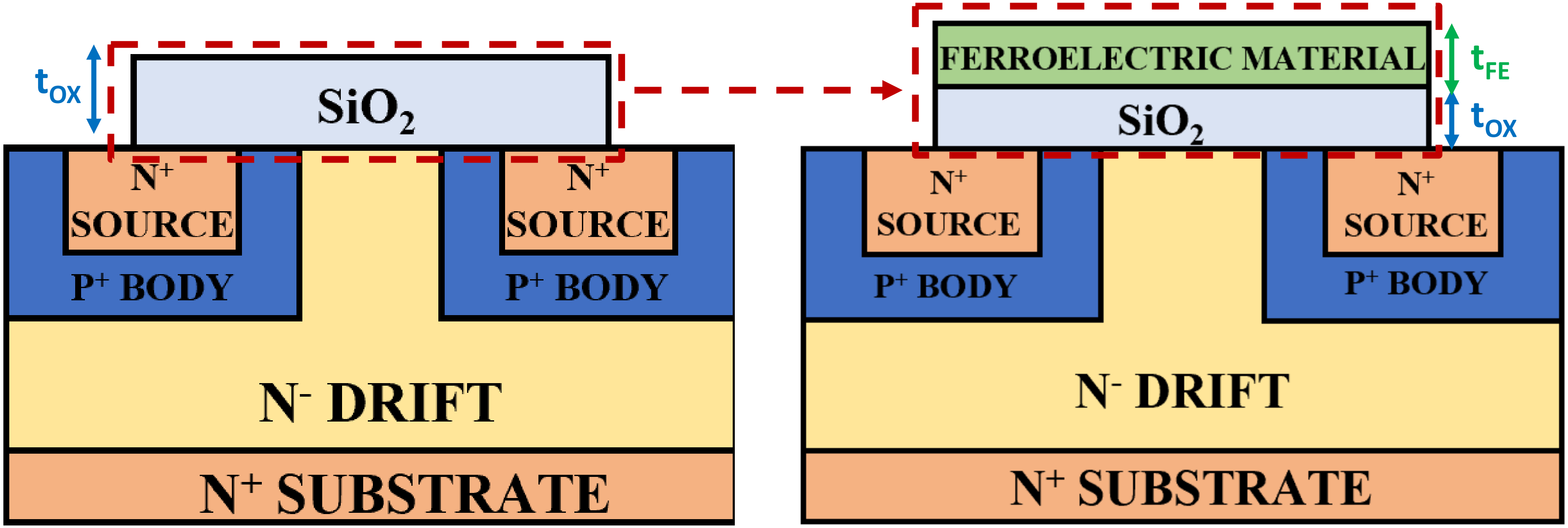
Ferro-Power MOSFET Drain Current

$$I_D \propto \mu_n(T) C_{STACK}(T) (V_{GS} - V_{TH}(T))^2$$

<<Ferro-Power>> MOSFET

Standard MOSFET elementary cell | **«Ferro-Power» MOSFET elementary cell**



MOSFET Drain Current

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Temperature-dependent parameters

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Ferro-Power MOSFET Drain Current

$$I_D \propto \mu_n(T) C_{STACK}(T) \left(V_{GS} - V_{TH}(T)\right)^2$$

$$\left.\begin{aligned} C_{STACK}(T) &= \frac{C_{FE}(T) C_{OX}}{C_{FE}(T) + C_{OX}} \\ C_{FE}(T) &= \lambda \frac{C_{CW}}{T - T_C} \cdot \frac{1}{t_{FE}} \end{aligned}\right\}$$ Temperature dependent

Ferroelectrics in litterature

Ferroelectric are currently used only in **low-power electronics**

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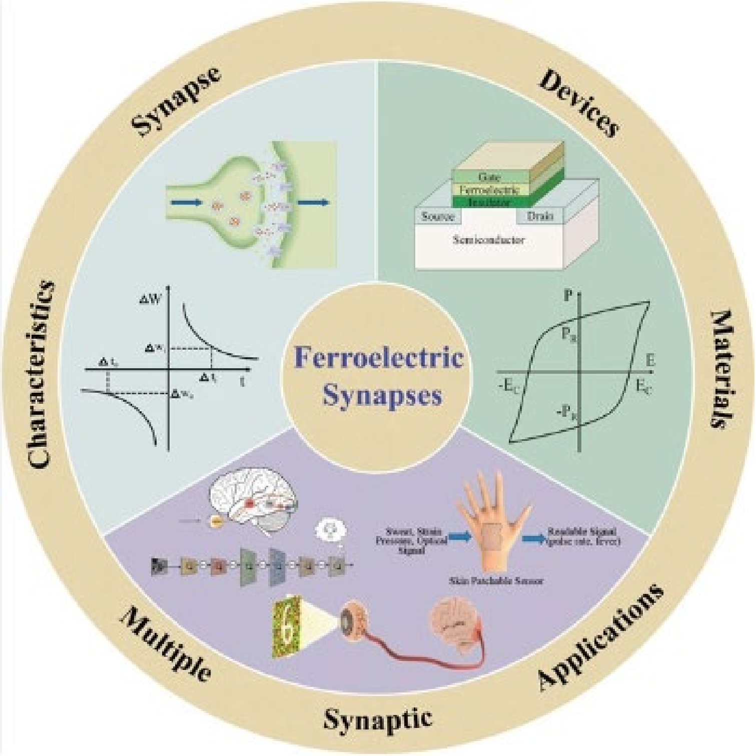
- **NEUROMORPHIC SYNAPSE**



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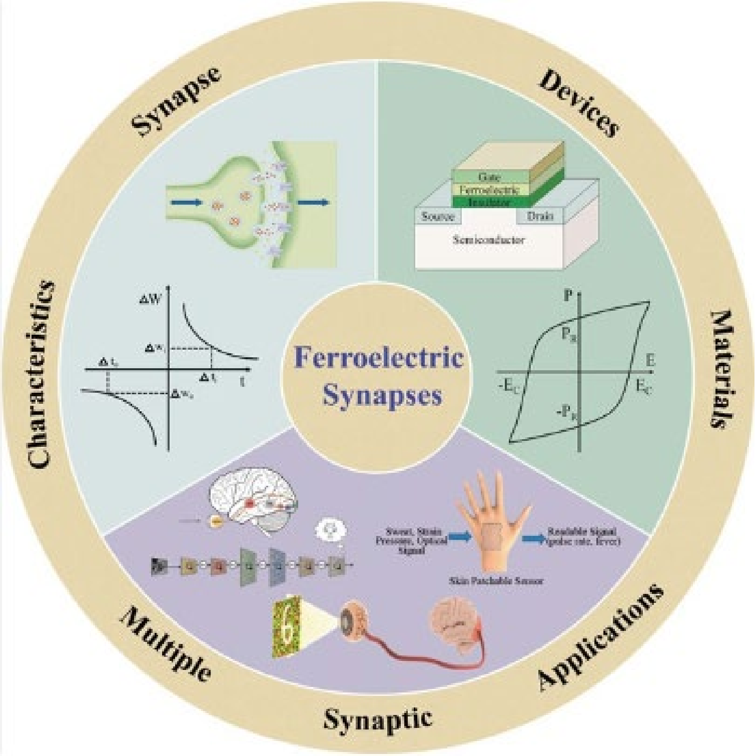
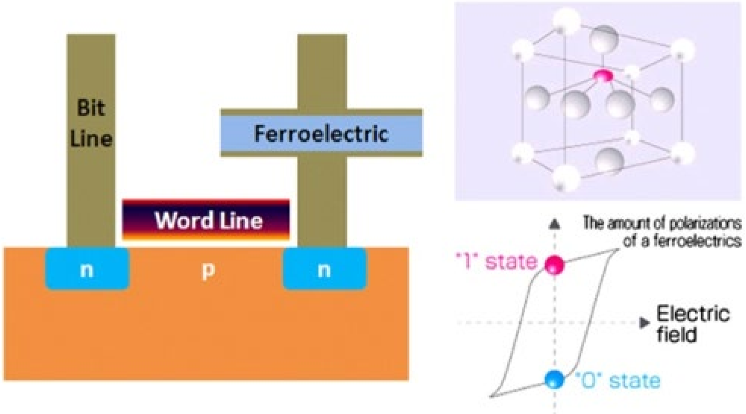


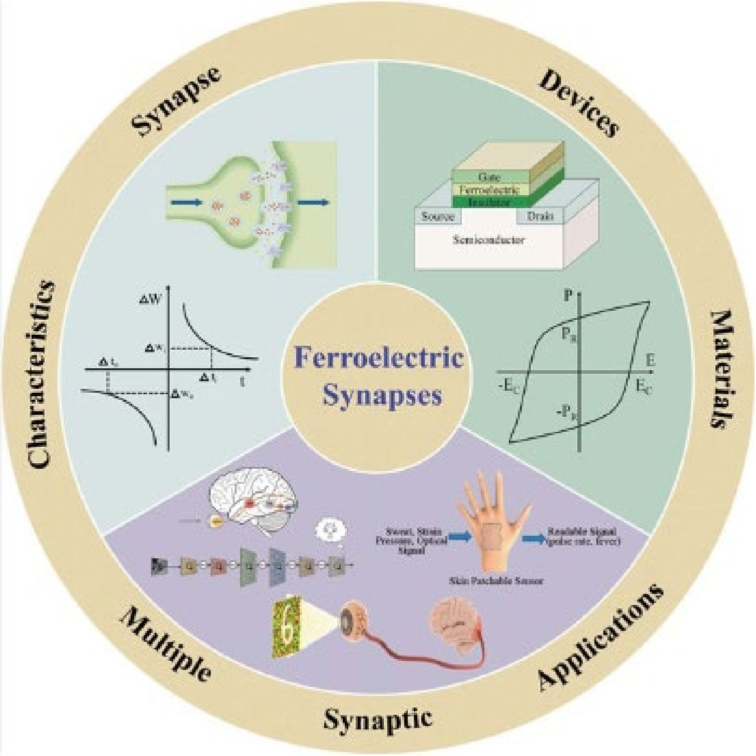
- **NON-VOLATILE FE-RAM**



Ferroelectrics in litterature

Ferroelectric are currently widely used in **low-power electronics**

- **NEUROMORPHIC SYNAPSE**



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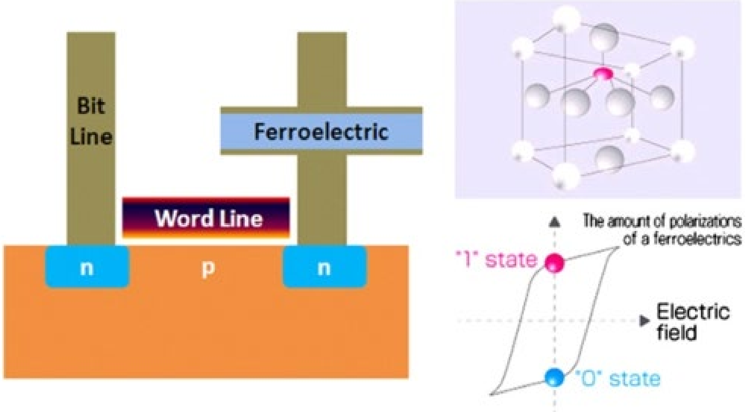
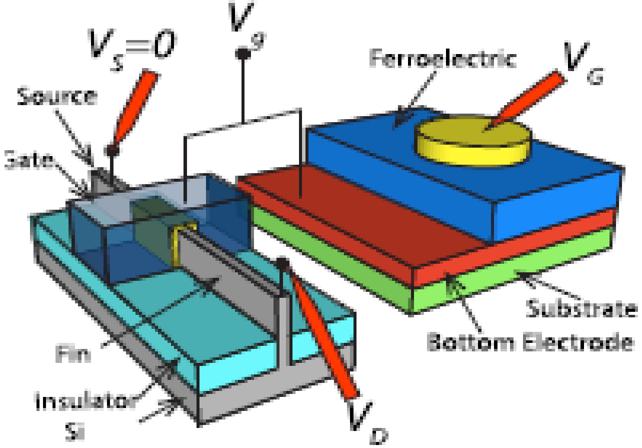
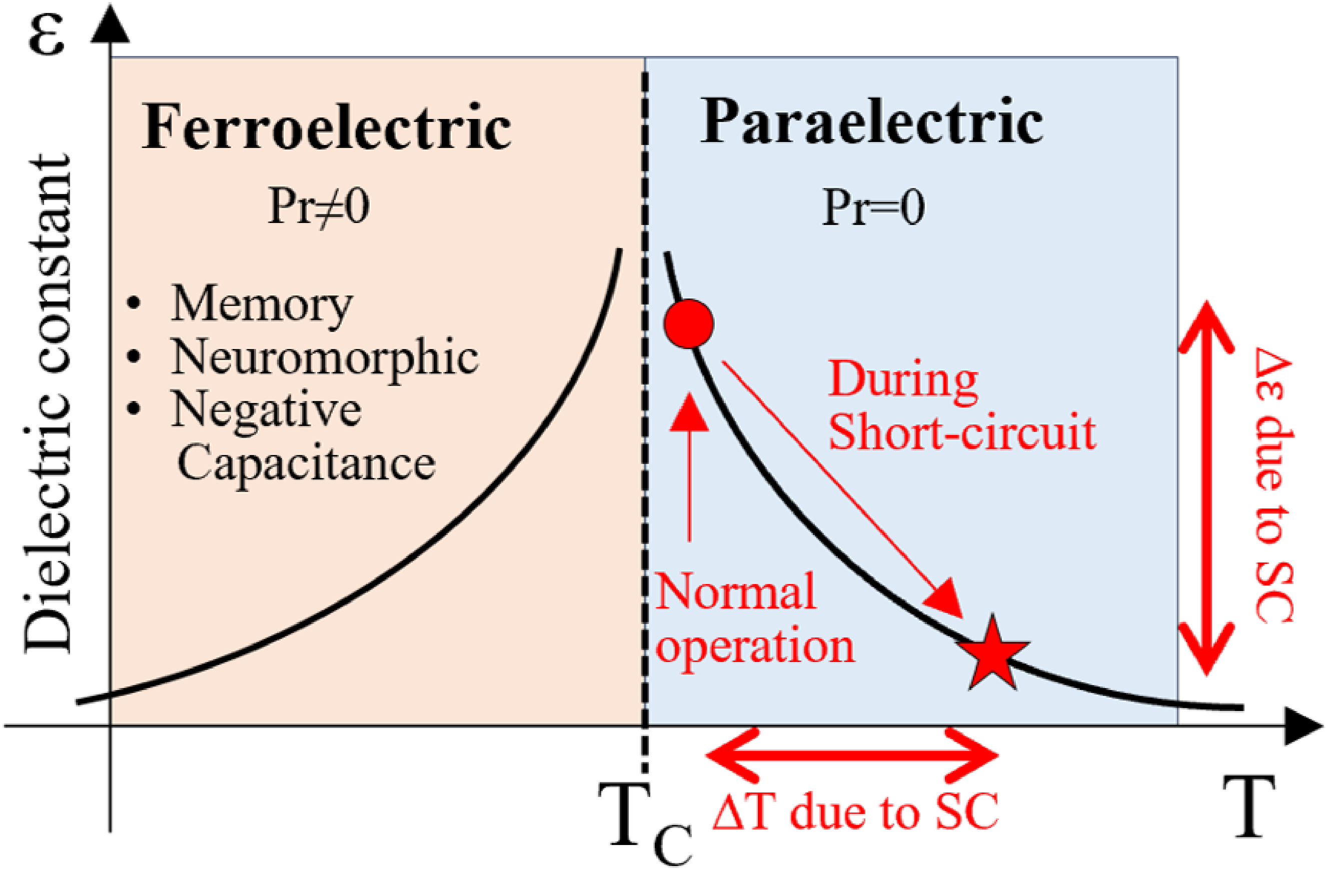


- **NEGATIVE-CAPACITANCE SWITCH**



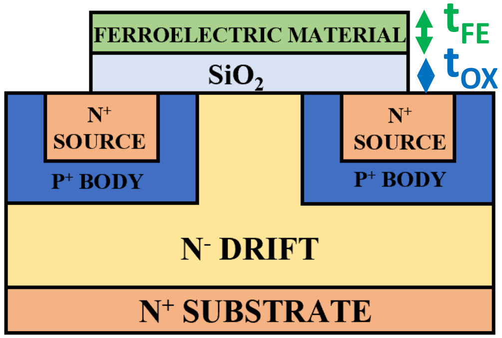
Working Principle

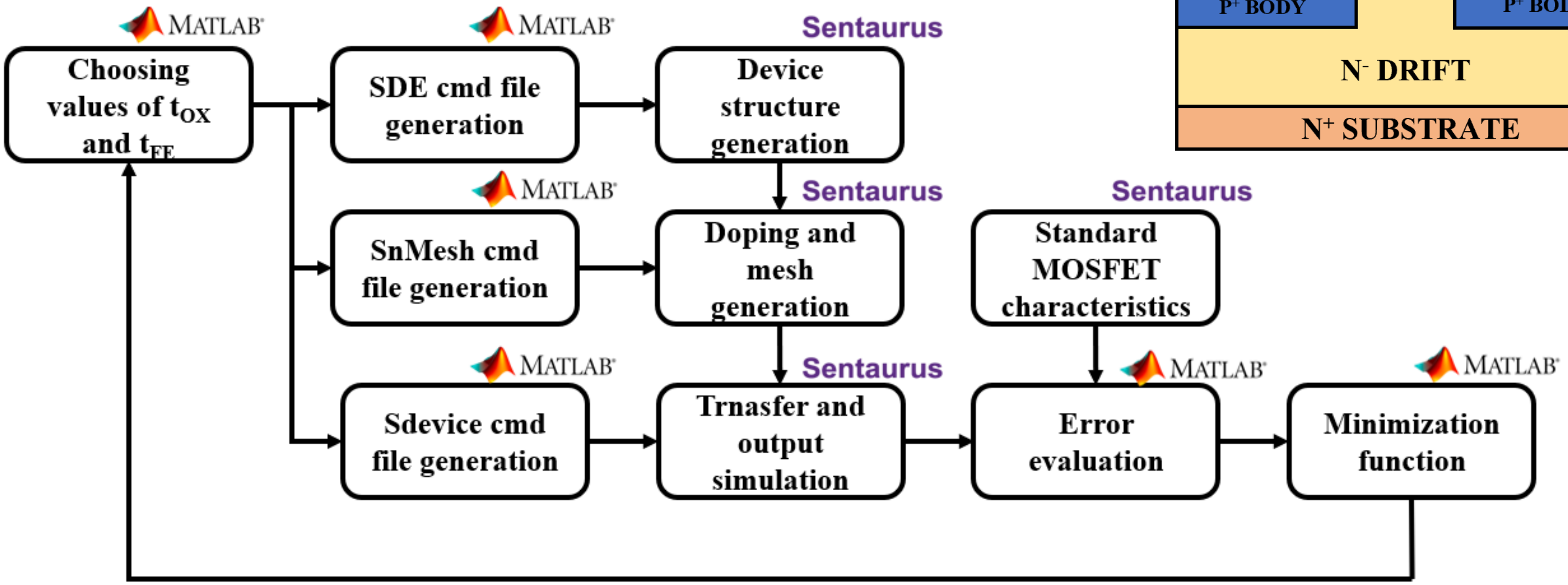


Automatic calibration routine

- An automatic calibration that interfaces Sentaurus and MATLAB gives the values of t_{OX} and t_{FE} that matches the static and dynamic characteristics of the reference device.

T_C=193 K
C_{CW}=3447 K





MATLAB
Choosing values of t_{OX} and t_{FE}

MATLAB
SDE cmd file generation

Sentaurus
Device structure generation

MATLAB
SnMesh cmd file generation

Sentaurus
Doping and mesh generation

Sentaurus
Standard MOSFET characteristics

MATLAB
Sdevice cmd file generation

Sentaurus
Trnasfer and output simulation

MATLAB
Error evaluation

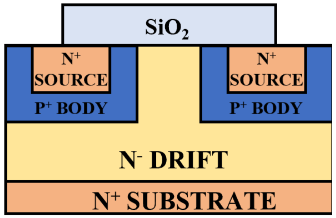
MATLAB
Minimization function

Standard operation

- The Ferro-Power device has the same staticand dynamic perfomance of the standard one.

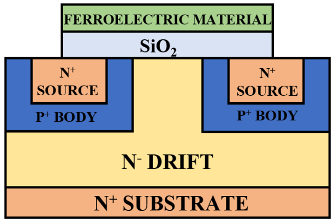
1.2 kV MOSFET

Standard MOSFET (dotted lines)



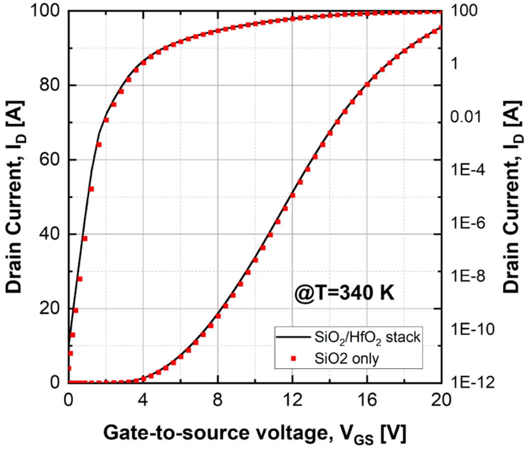
t_{OX}=50 nm

Ferro-Power MOSFET (solid lines)

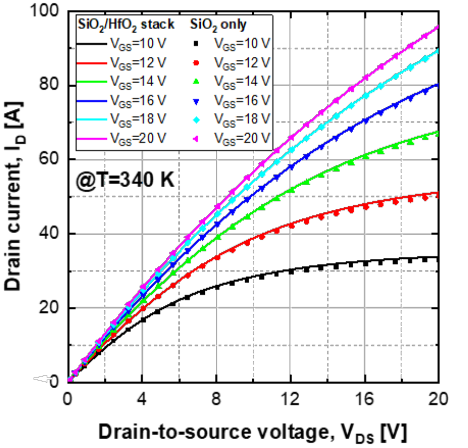


t_{OX}=30 nm t_{FE}=120 nm

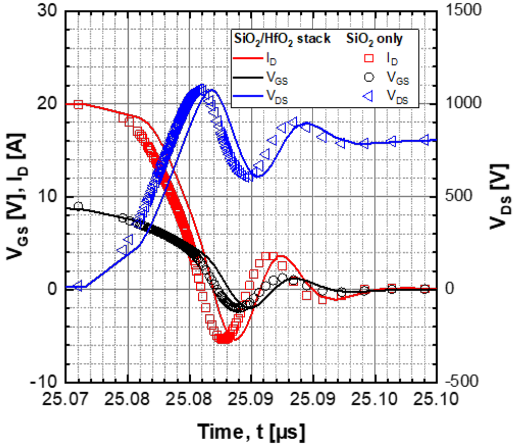
TRANSFER CHARACTERISTICS



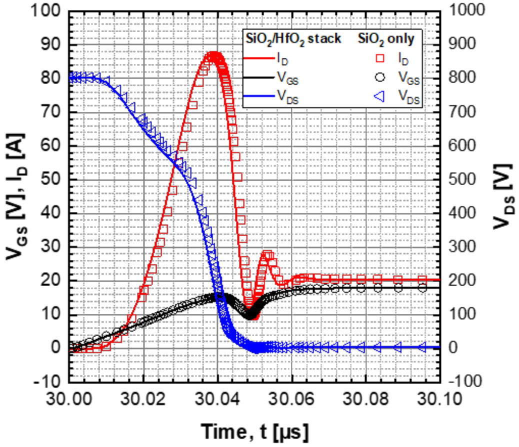
OUTPUT CHARACTERISTICS



TURN-OFF WAVEFORMS

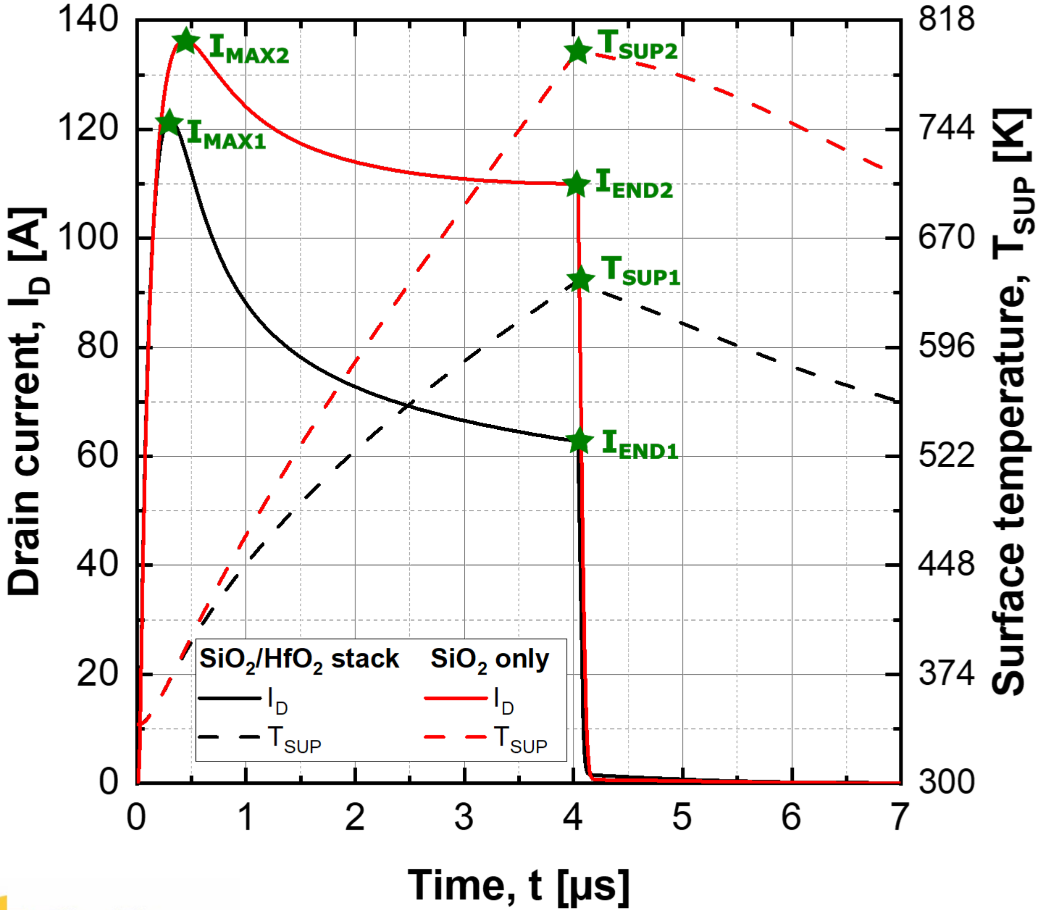


TURN-ON WAVEFORMS



Short-circuit capability

- The SC capability is improved without affecting the perfomance during normal operation.



Test conditions:

V_{DD}=800 V

T_{ON}=4 µ s

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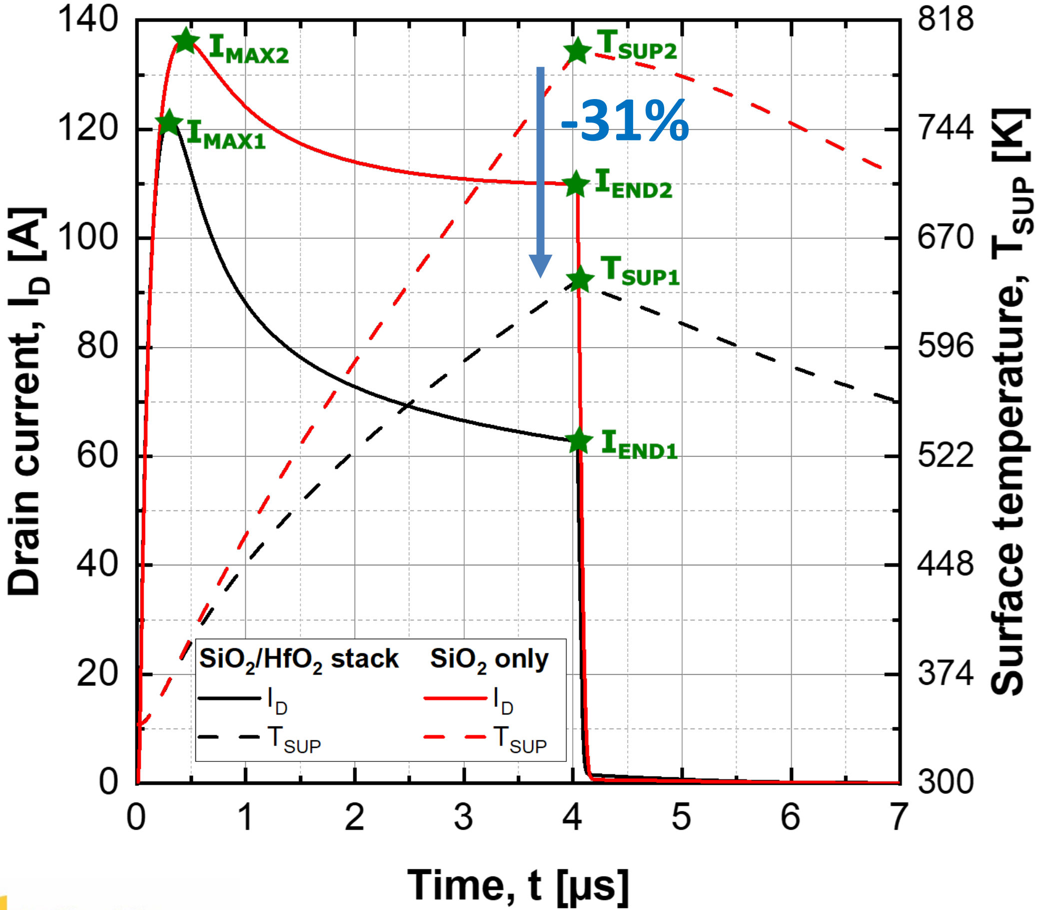

	Standard	Ferro-Power	Percentage variation
T_{SUP}	795 K	640 K	-31%
I_{MAX}	136 A	121 A	-11%
I_{END}	110 A	63 A	-42%

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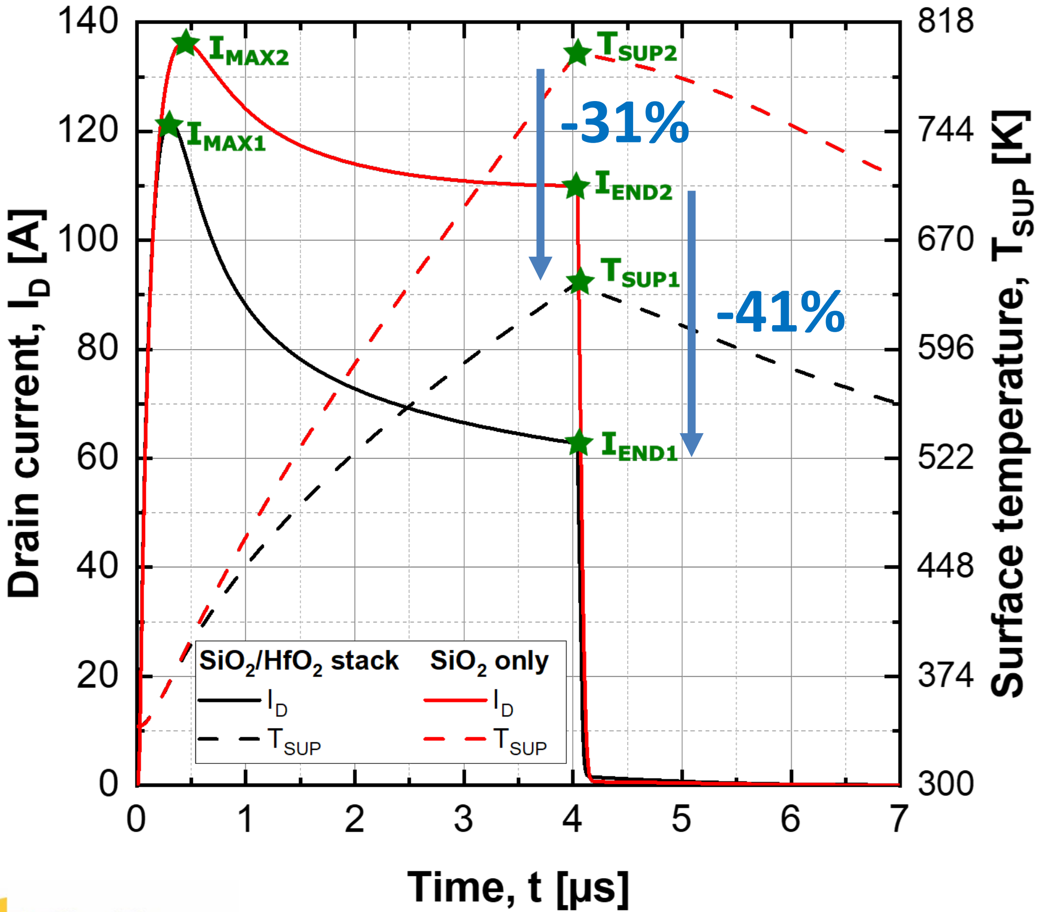

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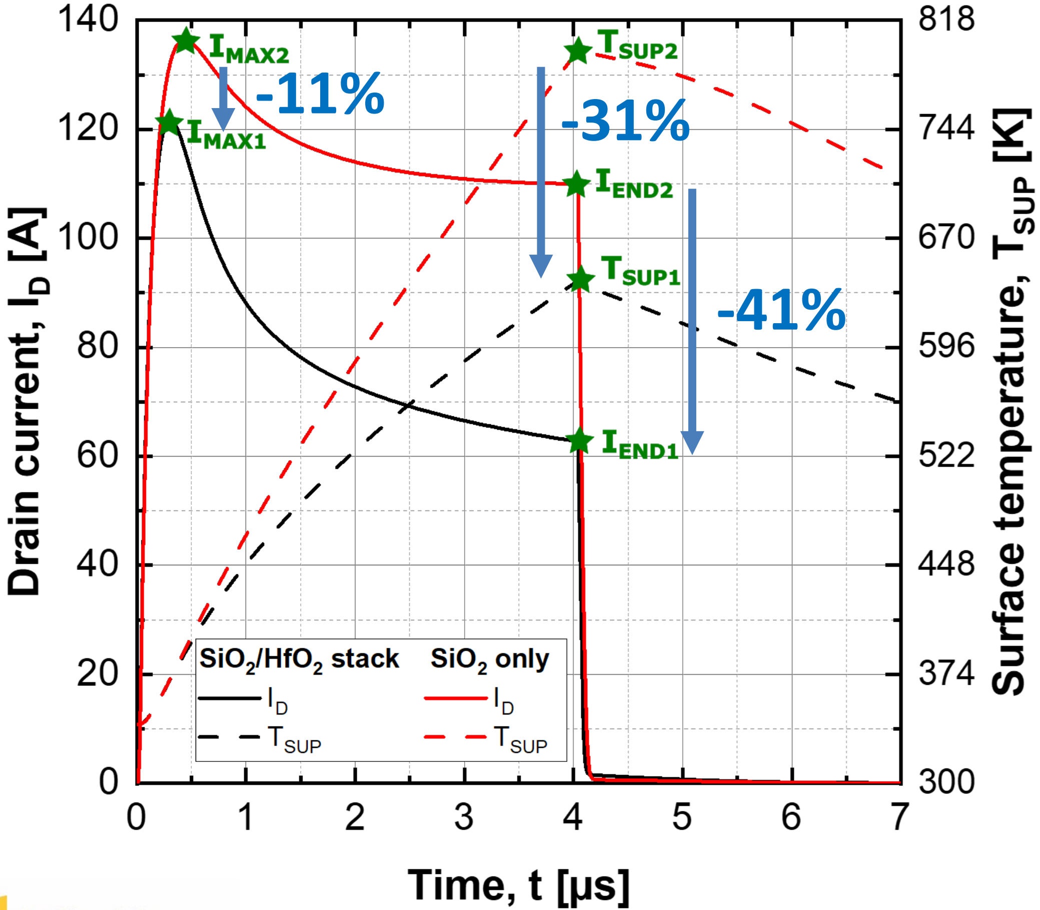

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Conclusions

- Innovative approach to use ferroelectric material in power electronics.
- Same perfomance of the standard device during normal operation.
- Improved Short-circuit capability.

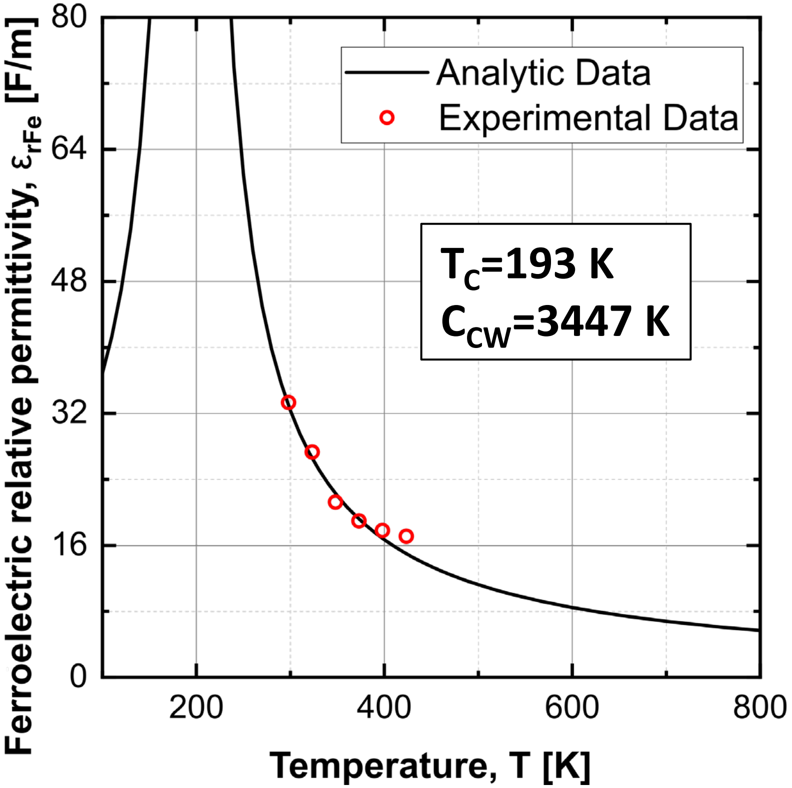
Thank you for your attention!

Modeling of the ferroelectric material

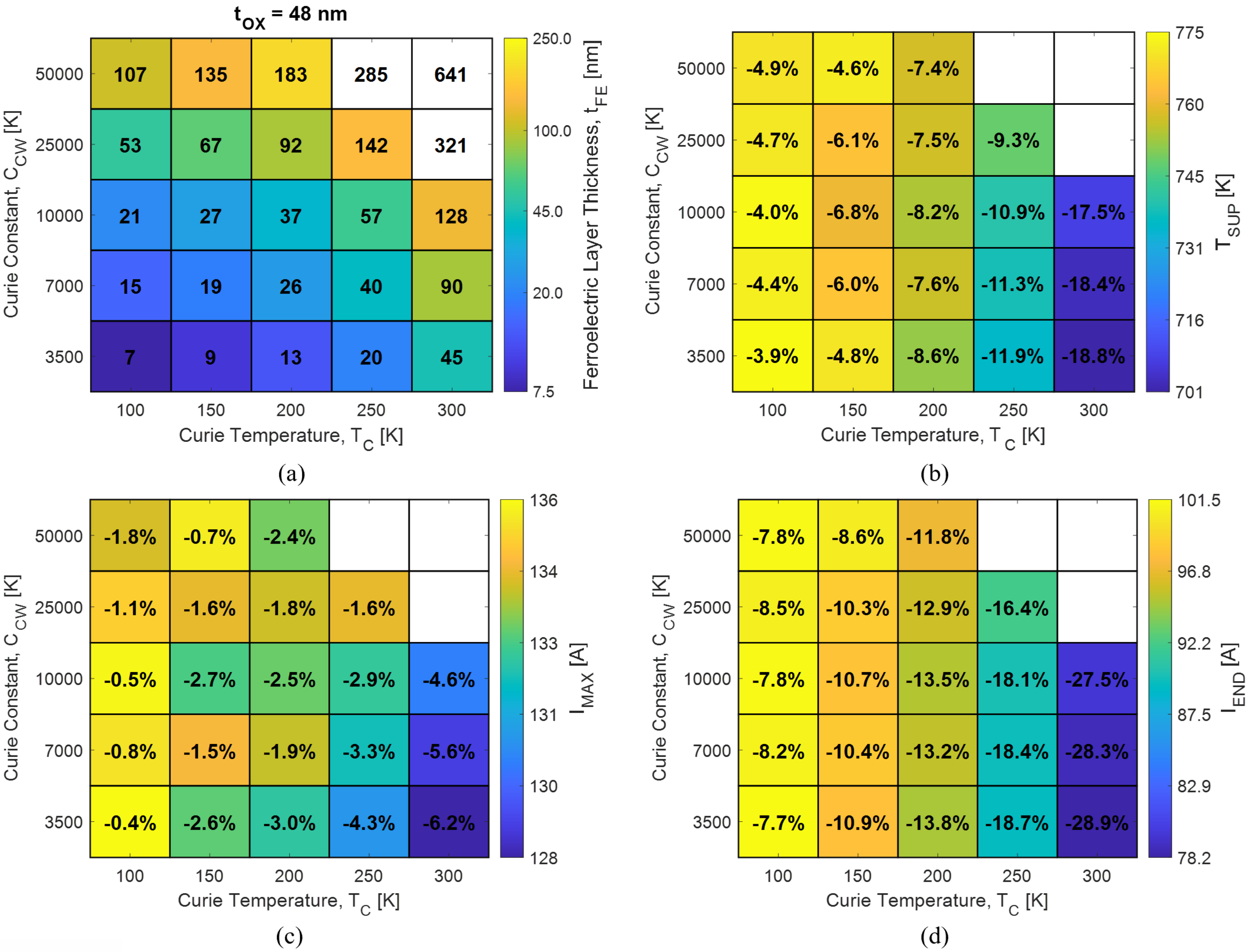
- As a case study, Hafnium Oxide (HfO_2) was chosen as ferroelectric material.

- Plain HfO_2 is widely used as **high-k dielectric**.
- Can be made ferroelectric **by doping**.
- **Ferroelectric parameters** (T_C and C_{CW}) **can be tuned** from dopant species, doping concentration, fabrication process.

CASE STUDY



Design Optimization



	100	150	200	250	300
50000	107	135	183	285	641
25000	53	67	92	142	321
10000	21	27	37	57	128
7000	15	19	26	40	90
3500	7	9	13	20	45

(a)

	100	150	200	250	300
50000	-4.9%	-4.6%	-7.4%		
25000	-4.7%	-6.1%	-7.5%	-9.3%	
10000	-4.0%	-6.8%	-8.2%	-10.9%	-17.5%
7000	-4.4%	-6.0%	-7.6%	-11.3%	-18.4%
3500	-3.9%	-4.8%	-8.6%	-11.9%	-18.8%

(b)

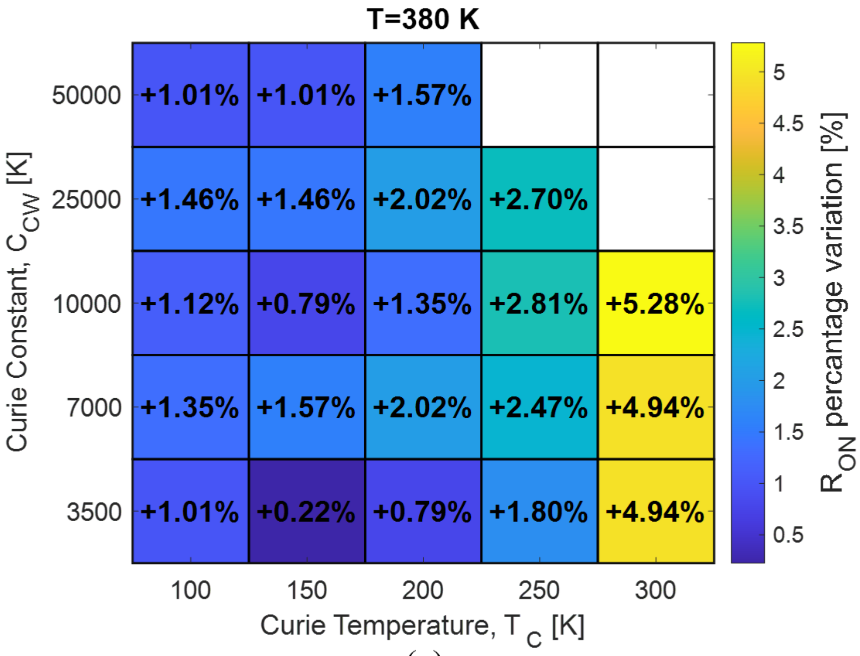
	100	150	200	250	300
50000	-1.8%	-0.7%	-2.4%		
25000	-1.1%	-1.6%	-1.8%	-1.6%	
10000	-0.5%	-2.7%	-2.5%	-2.9%	-4.6%
7000	-0.8%	-1.5%	-1.9%	-3.3%	-5.6%
3500	-0.4%	-2.6%	-3.0%	-4.3%	-6.2%

(c)

	100	150	200	250	300
50000	-7.8%	-8.6%	-11.8%		
25000	-8.5%	-10.3%	-12.9%	-16.4%	
10000	-7.8%	-10.7%	-13.5%	-18.1%	-27.5%
7000	-8.2%	-10.4%	-13.2%	-18.4%	-28.3%
3500	-7.7%	-10.9%	-13.8%	-18.7%	-28.9%

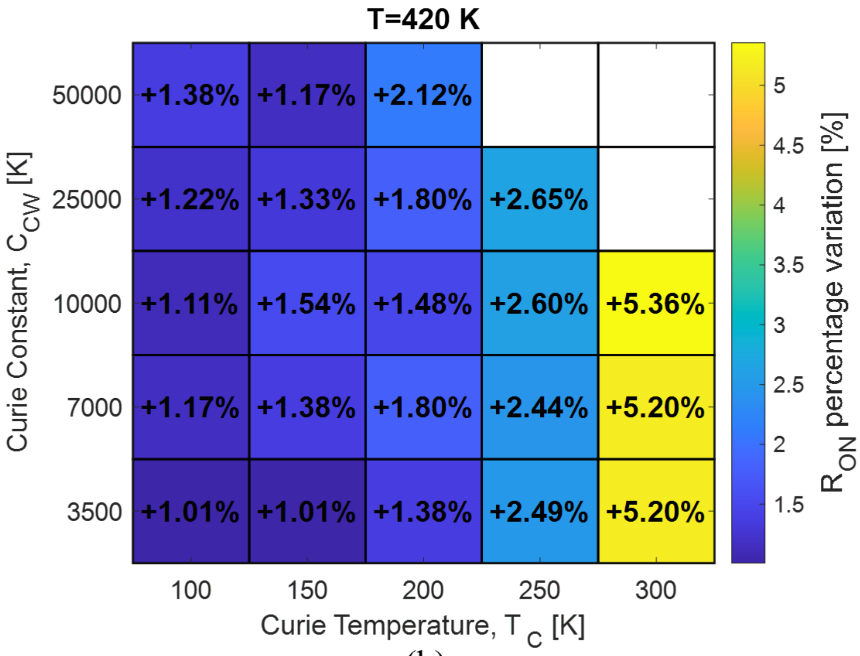
(d)

On-state resistance



Curie Constant, C_{CW} [K] \ Curie Temperature, T_C [K]	100	150	200	250	300
50000	+1.01%	+1.01%	+1.57%		
25000	+1.46%	+1.46%	+2.02%	+2.70%	
10000	+1.12%	+0.79%	+1.35%	+2.81%	+5.28%
7000	+1.35%	+1.57%	+2.02%	+2.47%	+4.94%
3500	+1.01%	+0.22%	+0.79%	+1.80%	+4.94%

(a)



Curie Constant, C_{CW} [K] \ Curie Temperature, T_C [K]	100	150	200	250	300
50000	+1.38%	+1.17%	+2.12%		
25000	+1.22%	+1.33%	+1.80%	+2.65%	
10000	+1.11%	+1.54%	+1.48%	+2.60%	+5.36%
7000	+1.17%	+1.38%	+1.80%	+2.44%	+5.20%
3500	+1.01%	+1.01%	+1.38%	+2.49%	+5.20%

(b)