HfO_2 – the swiss army knife of semiconductor devices

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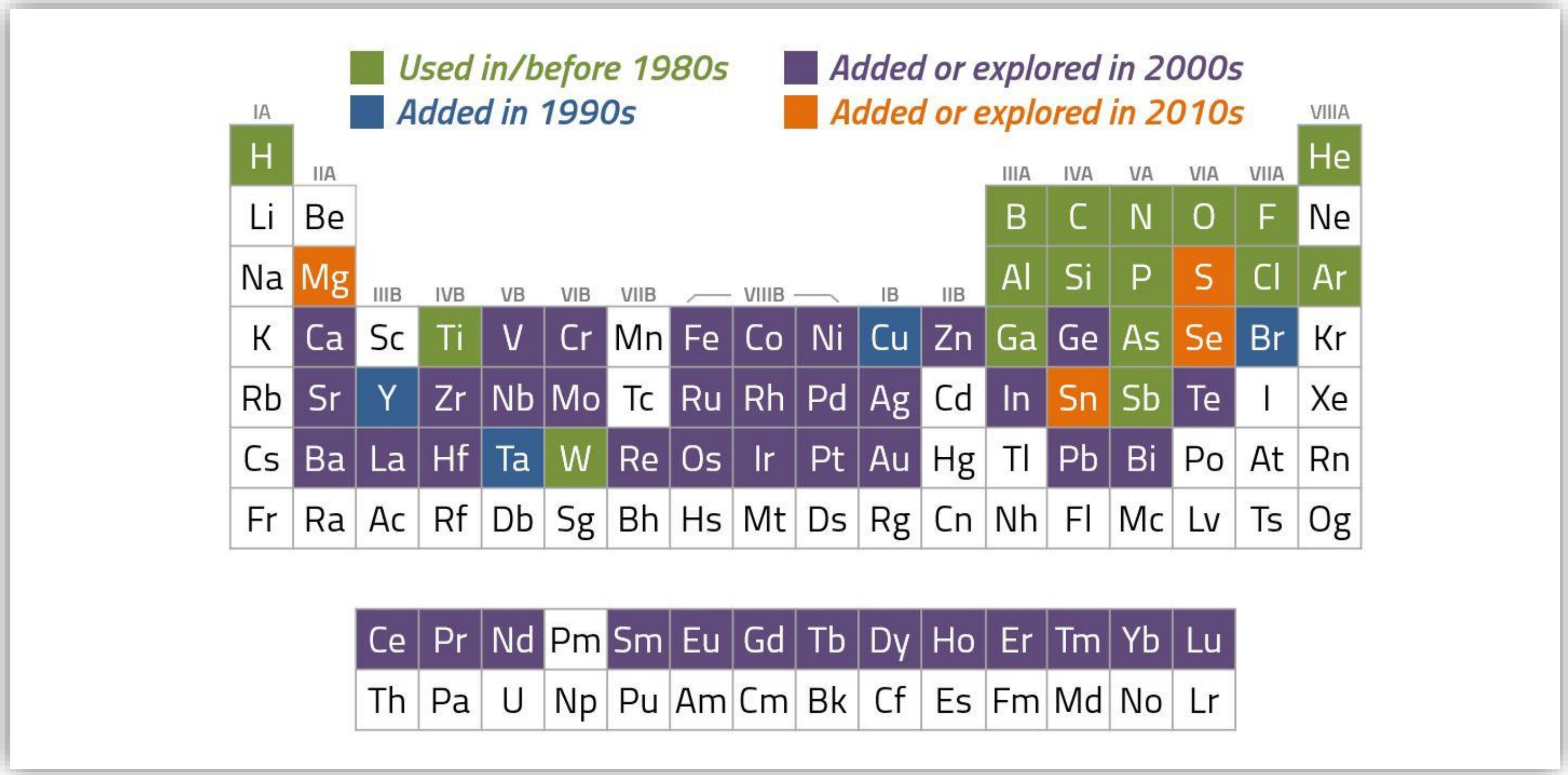
Introduction

Elements used in Silicon Semiconductor device fabrication over time



- Till the 1980s only a very limited number of Elements were used in semiconductor fabrication
- A wave of new materials was introduced since the 2000s
- The development is still going on with new material intros coming up continuously
- The technology base remains the same

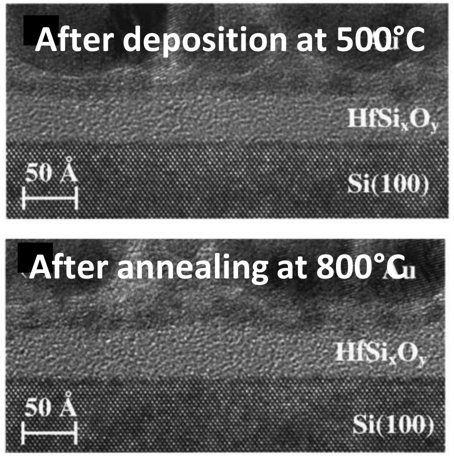
Introduction

Properties of different dielectrics

Gate dielectric Material	Dielectric constant (k)	Energy bandgap Eg (eV)	Conduction band offset ΔEc (eV)	Valence band offset ΔEc(eV)
SiO_2	3.9	9	3.5	4.4
Al_2O_3	8	8.8	3	4.7
TiO_2	80	3.5	1.1	1.3
ZrO_2	25	5.8	1.4	3.3
HfO_2	25	5.8	1.4	3.3

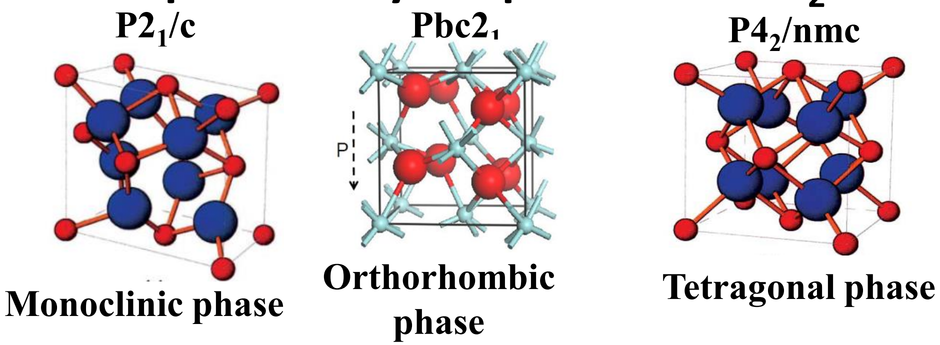
- Dielectrics play an increasing role also for new fundtionalities
- HfO_2 has a reasonable high k-value and a large enough bandgap
- HfO_2 is thermally stable on silicon
- HfO_2 has an interesting polymorphism

Thermal stability of HfO_2 on Silicon



G. D. Wilk and R. M. Wallace, APL 1999

Important crystal phases in HfO_2

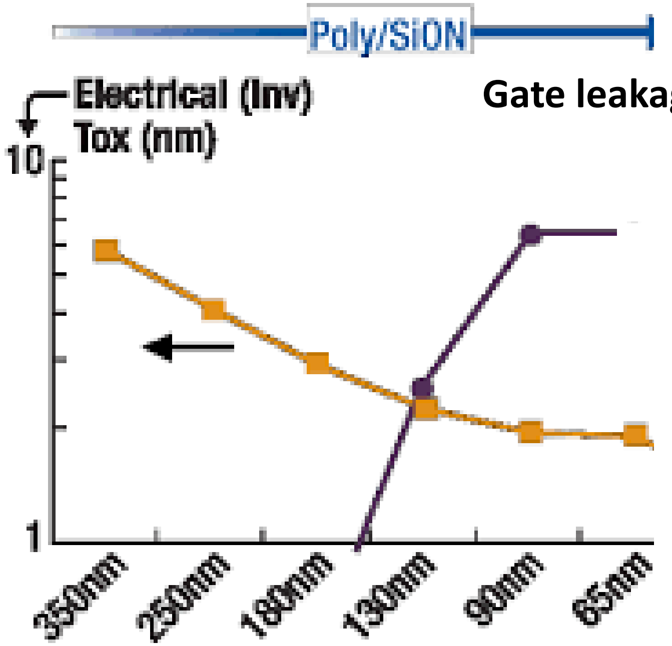


T.S. Böscke et al. Appl. Phys. Lett. 99, 102903 (2011)
T.S. Böscke et al. Appl. Phys. Lett. 99, 12000 (2011)

Transistor Gate Oxide

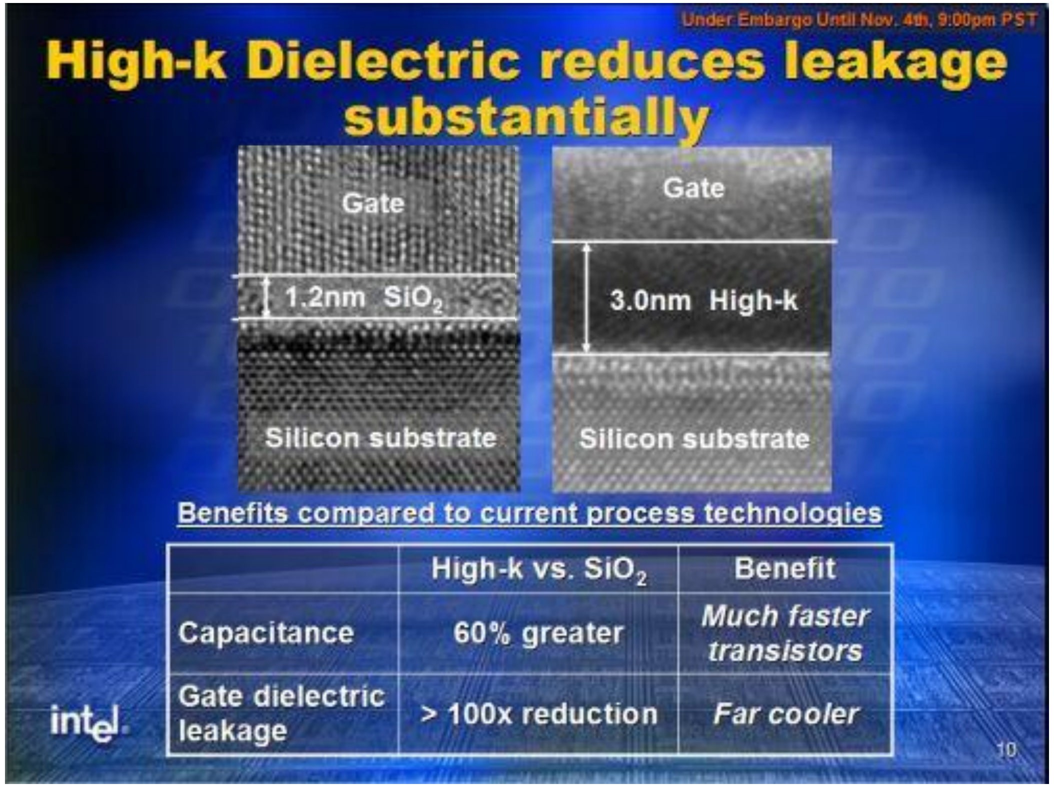
Transistor Gate Oxide

Gate oxide thickness scaling and gate leakage current



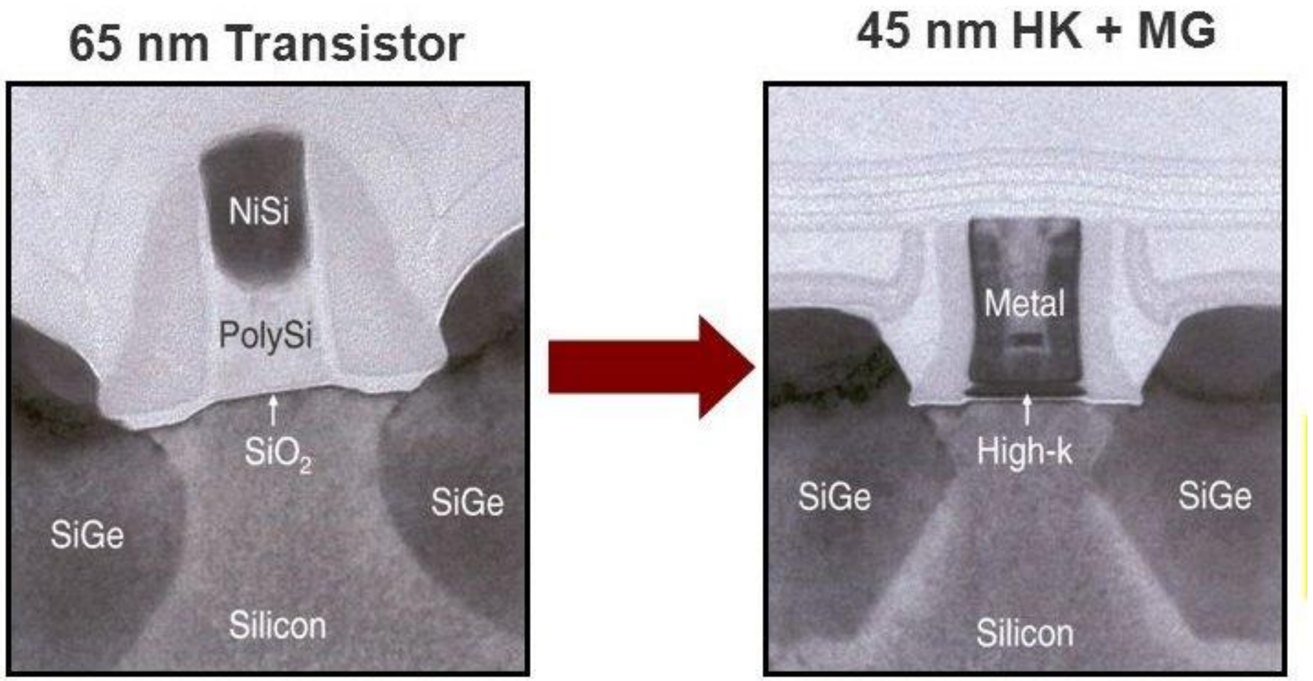
Gate stack

Poly - SiO_2 Metal - HfO_2



- SiO_2 reached its scaling limit at 65nm/40nm due to excessive leakage
- HfO_2 allows for a thicker layer getting out of the tunneling regime again

Transistor Gate Oxide



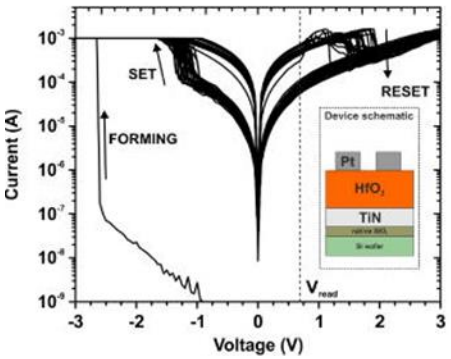
Changing the gate oxide of the transistor was like an open heart surgery!

- Together with the HfO_2 also metal gates were introduced
- While SiO_2 is thermally grown HfO_2 is deposited (e.g. by ALD) and therefore can be applied to different channel materials as well

RRAM / Memristor

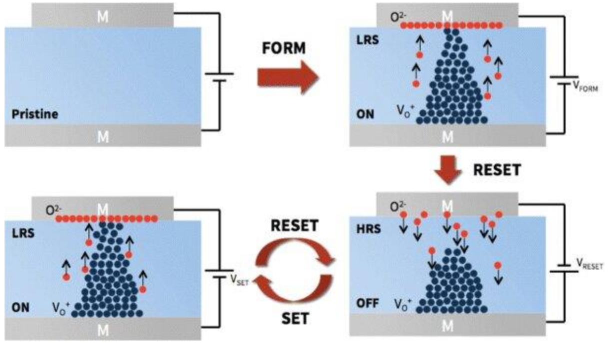
RRAM / Memristor

Switching curves of HfO_2 based RRAM / Memristor



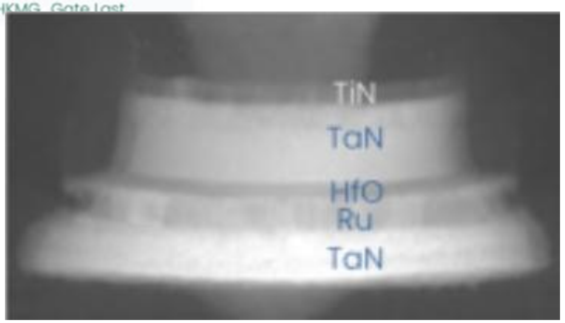
B. Max et al., APL 2018

Switching mechanism of VCM Memristor



Commercial RRAM devices

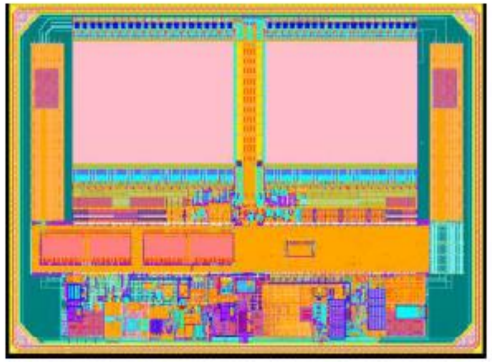
ReRAM Tech/Foundry	Fujitsu 40 nm eReRAM	TSMC 40 nm eReRAM	TSMC 22 nm eReRAM
Product Examples	Fujitsu MB85AS12MTPW-EAERE1	STMicroelectronics STWLC38JRM Wireless Power Receiver	Nordic nRF54L15 Bluetooth 5.4 SoC (Fanstel EV-BM15 Evaluation Kit)
Foundry CMOS Platform	Fujitsu (UMC) 40 nm	TSMC 40BCD	TSMC 22ULL
Die ID	Fujitsu MB85AS12MT	STMicroelectronics US0BAC	Nordic TMRC83
Die Size (Seal)	5.668 mm²	6.716 mm²	5.123 mm²
ReRAM Memory / Die	12 Mb	256 Kb	12 Mb
Cell Size	0.0625 μm²	0.0849 μm²	0.0432 μm²
Pitch (WL/BL) measured	167 nm / 250 nm	162 nm / 262 nm	116 nm / 186 nm
ReRAM Location	on M2	on M3	on M3
Capping Layer	TaO	SiCN/SiON/TaO	SiCN/SiON
Top Electrode	TaN/Ir	TaN	TiN / TaN
ReRAM Materials	TaO	HfO	HfO
Bottom Electrode	TaN	Ru / TaN	Ru / TaN
# Metals	6 (5Cu+1Al)	7 (6Cu+1Al)	9 (8Cu + 1Al)
Cell Gate Process	NiSi/Poly-Si Gate	NiSi/Poly-Si Gate	HKMG, Gate last



Tech Insigths 2024

RRAM / Memristor

Infineon 28nm RRAM demonstrator



Infineon press release on RRAM for automotive

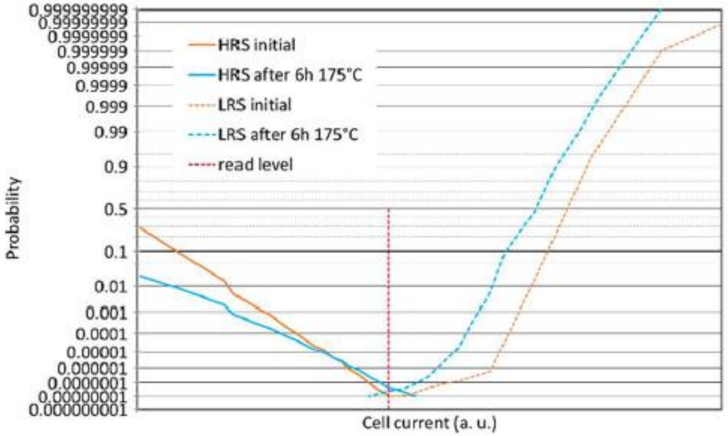
Infineon and TSMC to introduce RRAM technology for automotive AURIX™ TC4x product family

Nov 25, 2022 | Market News

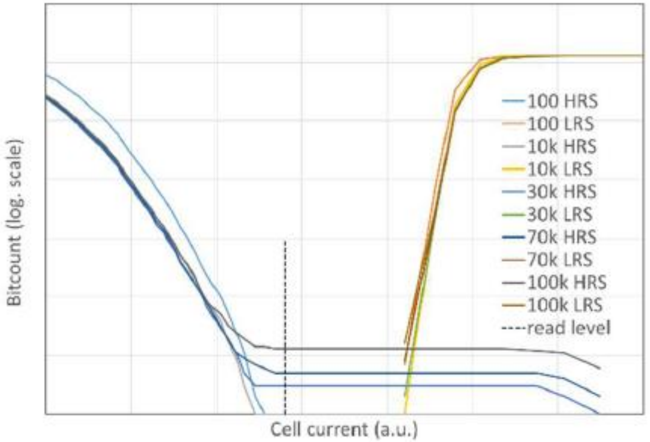
f in X

Munich, Germany – 25 November, 2022 – Infineon Technologies AG (FSE: IFX / OTCQX: IFNNY) and TSMC today announced the companies are preparing to introduce TSMC's Resistive RAM (RRAM) Non-Volatile Memory (NVM) technology into Infineon's next generation AURIX™ microcontrollers (MCU).

28nm RRAM retention



28nm RRAM cell distribution during cycling



C. Peters et.al., IMW 2022

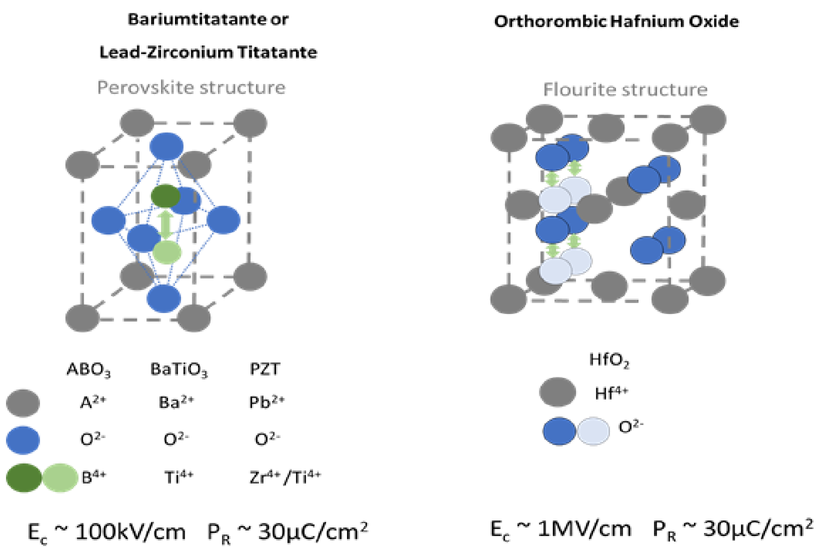
Ferroelectric Devices

Ferroelectric hafnium oxide is the biggest semiconductor innovation from Germany from the last decades

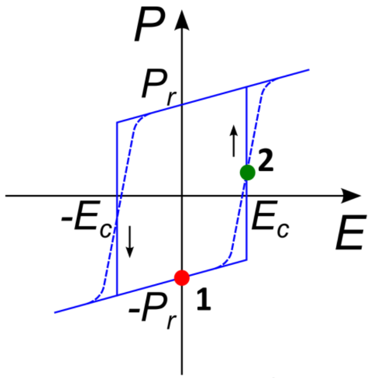
Victor Zhirnov, SRC

Ferroelectric Devices

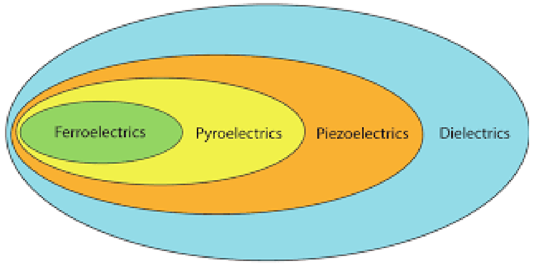
Ferroelectric perovskite crystal



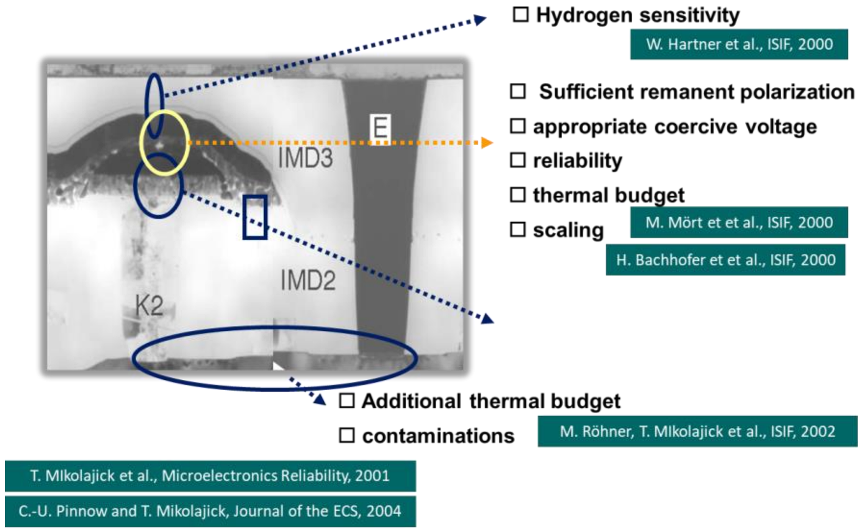
Hysteresis



Ferroelectrics as subgroup of dielectrics



Issues with perovskite integration

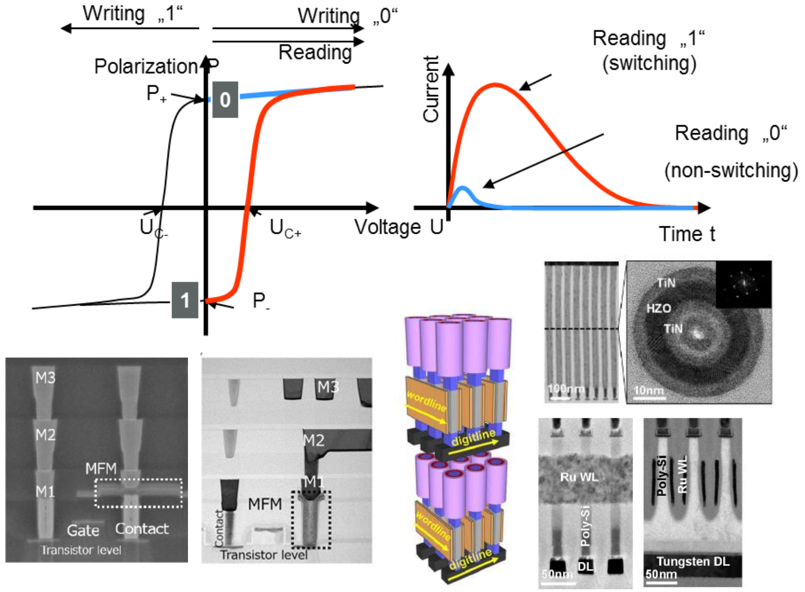


- Ferroelectrics have two stable polarization states that can be switched by applying an electric field → **no inefficiency** during writing → **lowest write energy** of known nonvolatile concepts
- Ferroelectricity inHfO2 solves the integration problems ofcomplex ferroelectric oxides
- The effect was discovered in 2006 at Qimonda
- Basic patent applications have been acquired by NaMLab and licensed to FMC

FMC The Ferroelectric Memory Company

Ferroelectric Devices

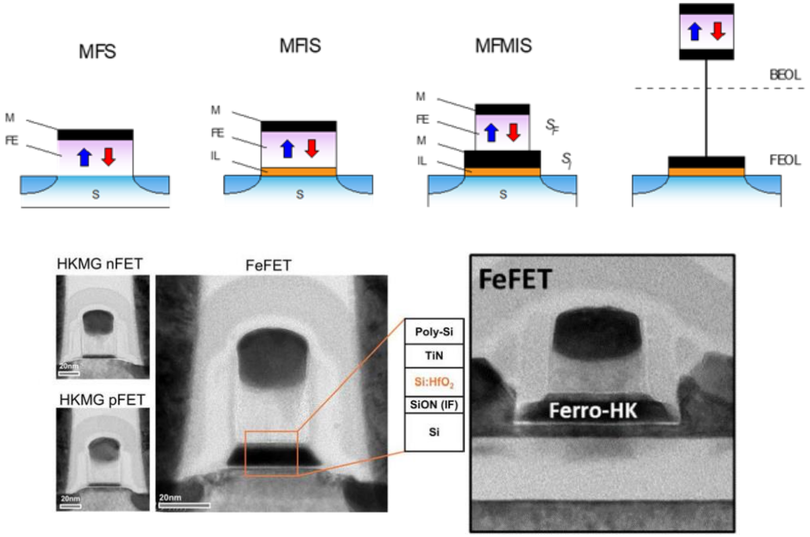
Readout by switched charge: FeRAM (DRAM like)



J. Okuno et al., VLSI 2020, IEDM 2023

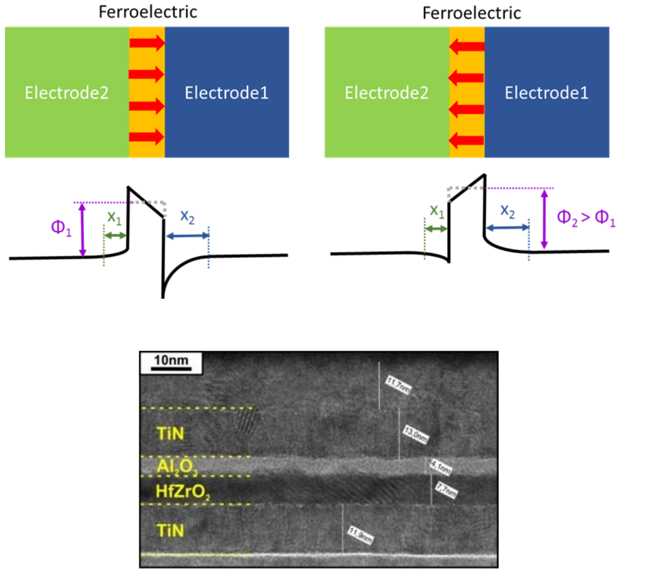
N. Ramaswamy et al., IEDM 2023

Readout by coupling to transistor channel: FeFET (Flash like)



H. Mulasomanovic et al., Nanotechnology 2021

Readout by resistance change: FTJ (RRAM like)



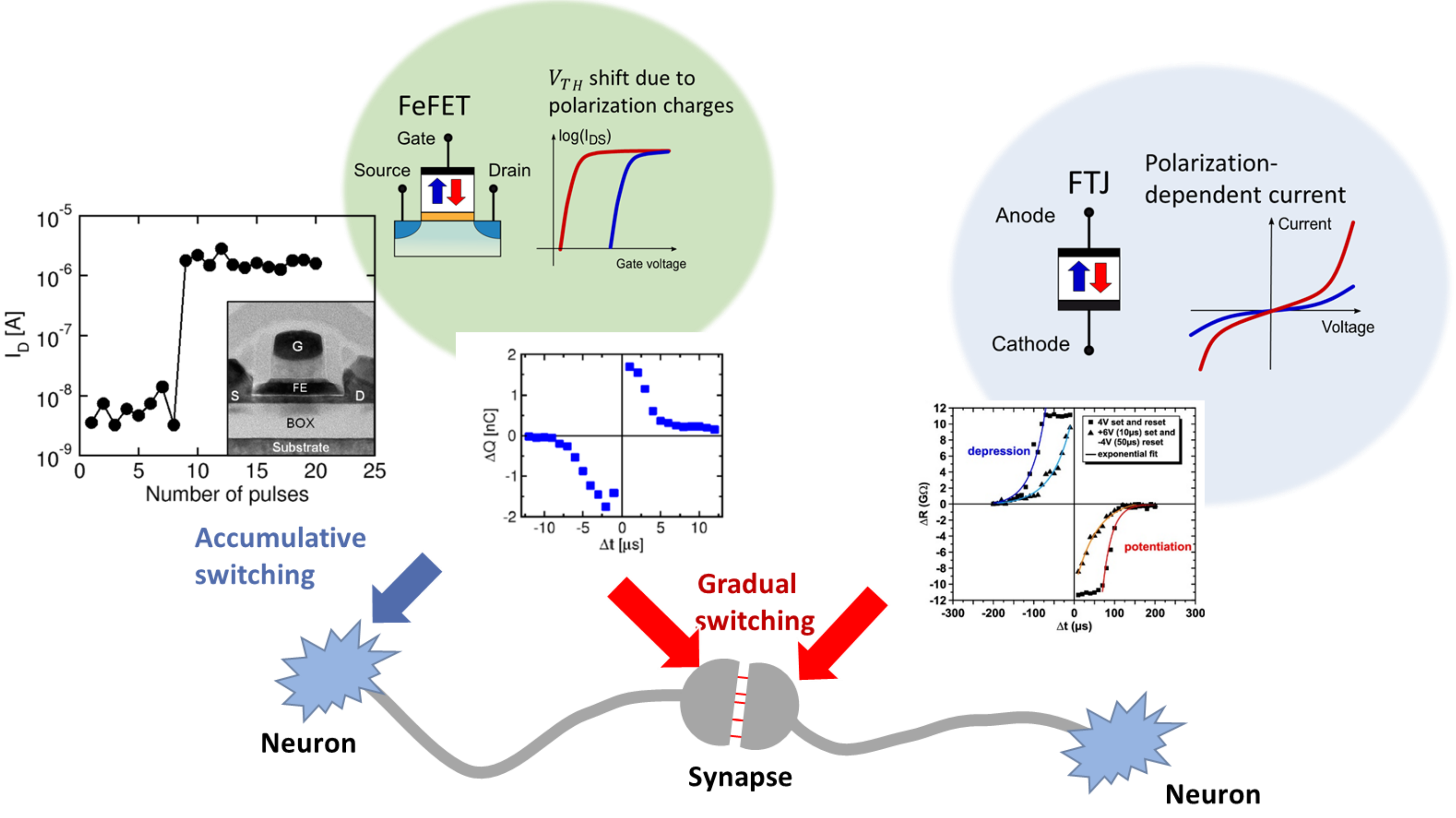
E. Y. Tsymbal and H. Kohlstedt, Science 2006

B. Max et al., JEDS 2019

- Ferroelectric materials enable three fundamentally different types of memory devices
- New possibilities for in-memory computing and neuromorphic computing

Ferroelectric Devices

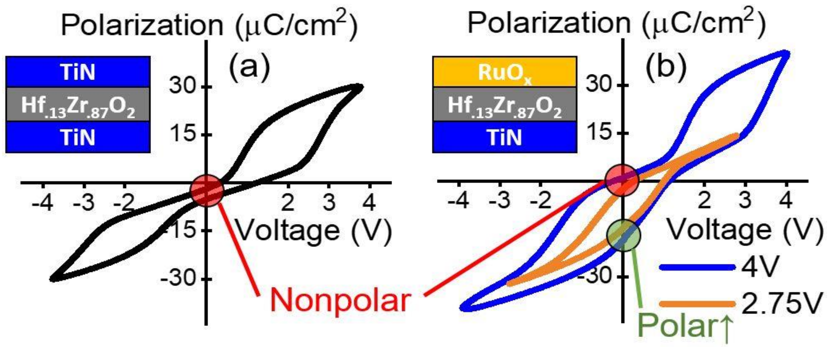
Realization of neuromorphic primitives using ferroelectric devices



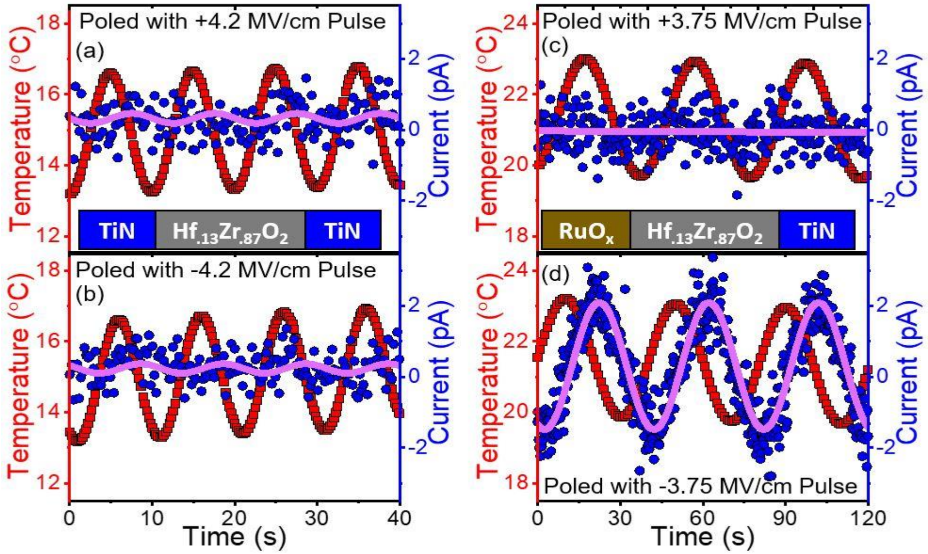
- For neuromorphic computing neurons and synapses era required
- Both FeFETs and FTJs cam be used to realize neurotic and synaptic functions

Ferroelectric Devices

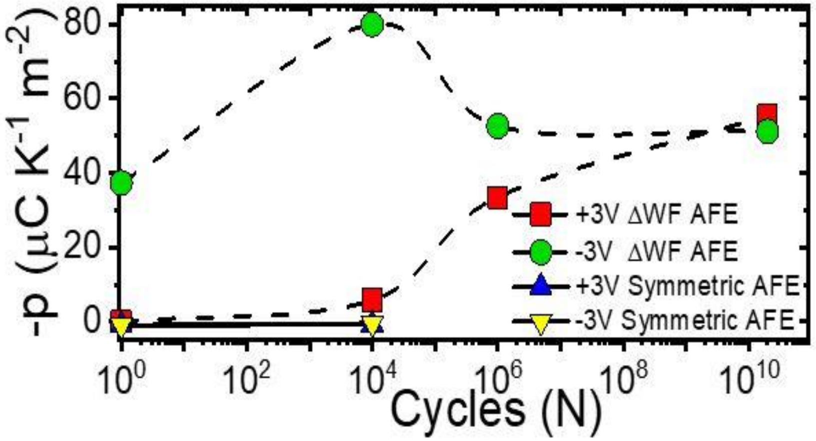
Antiferroelectric Hysteresis without (a) and with (b) internal bias field



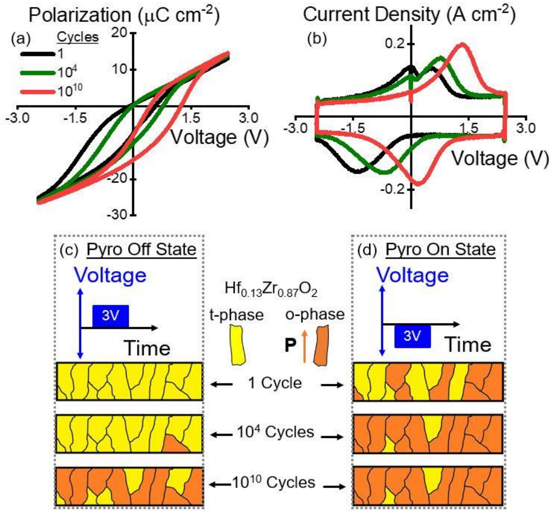
Antiferroelectric Hysteresis without (left) and with (right) internal bias field after poling



Pyroelectric coefficient of symmetric and unsymmetric samples



Field cycling model



- Antiferroelectric hysteresis can be shifted to show a window at 0V
- He shifted hysteresis can be switched between a polar and a non-polar state
- Pyroelectric response can be switches on and off accordingly

P.D. Lomenzo et al., Transducerss 2023

P.D. Lomenzo et al., IEEE Sensors 2024

To be continued…

Thank you

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Europäische Union

Europa fördert Sachsen.

EFRE

Europäischer Fonds für regionale Entwicklung

Freistaat Sachsen