КНИ СТРУКТУРЫ С УЛЬТРАТОНКИМИ СЛОЯМИ ОКСИДОВ ГАФНИЯ И АЛЮМИНИЯ

Попов В.П., Руденко К.В.

Москва, 26 ноября 2018 г.

План

1. Мотивация: UTBB КНИ для двухзатворных FeFETs
2. Перенос слоев Si на окисленный кремний или сапфир методом DeleCut
3. Транспорт носителей заряда в слоях Si на оксиде кремния в КНИ и КНС
4. Транспорт носителей заряда в слоях Si с прослойками ALD high-k HfO2 и Al2O3 в КНИ и КНС
5. Захват заряда и сегнетоэлектричество в BOX HfO_2 после BT термообработки
6. Заключение

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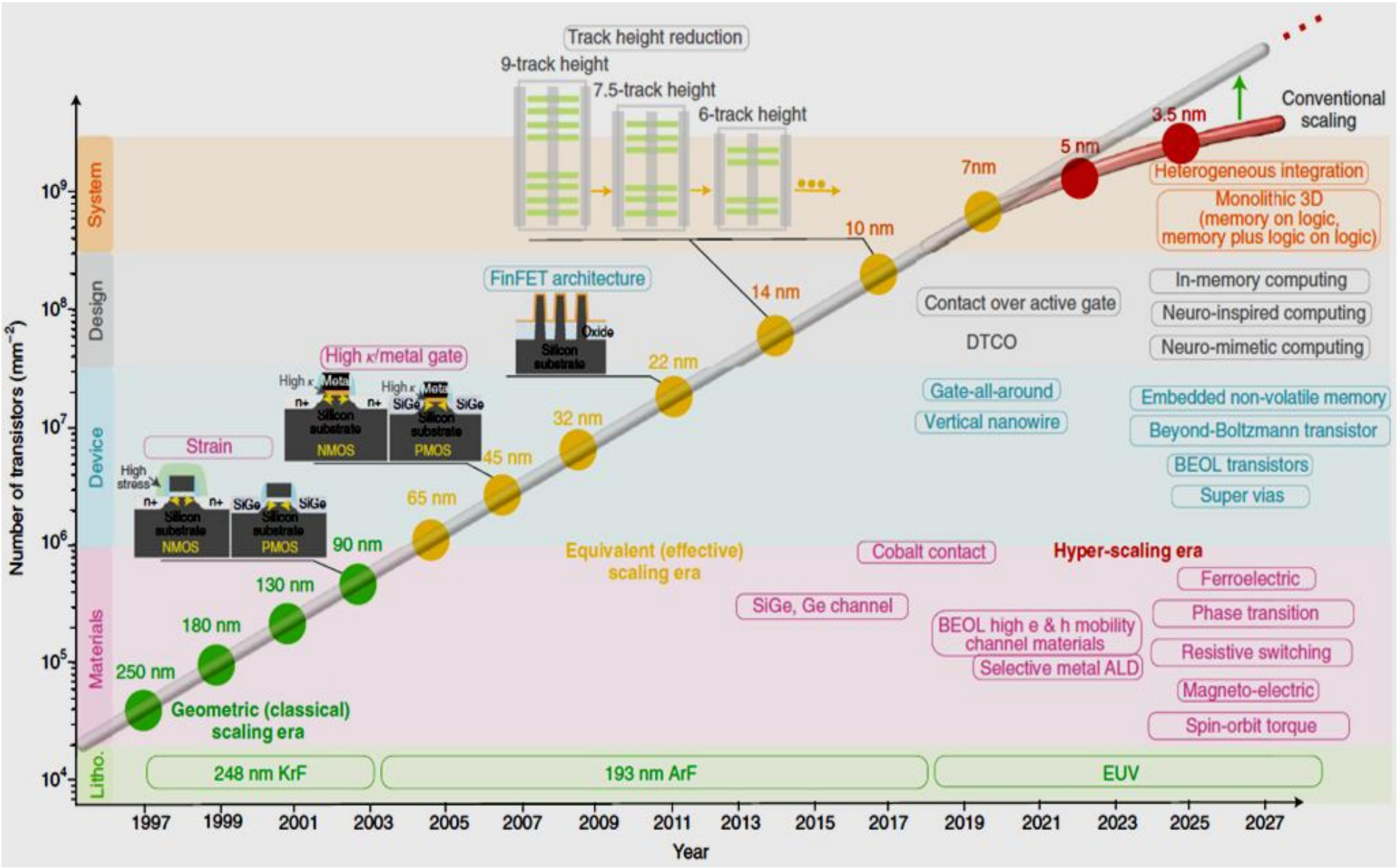
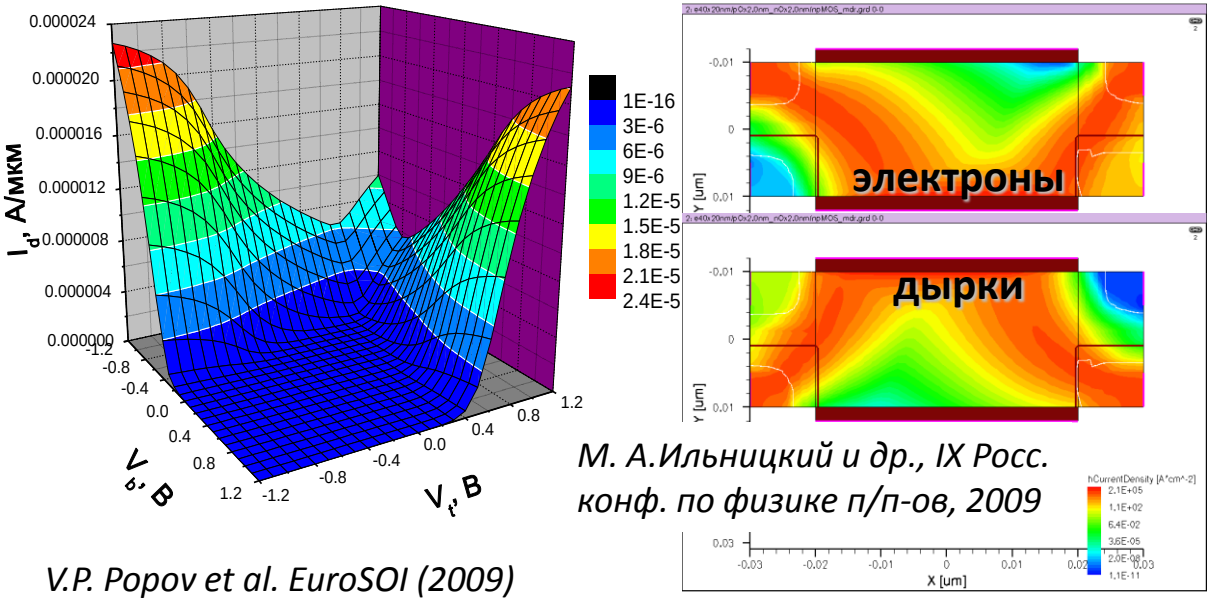
Future work: Impact on hyper scaling landscape



S.Salahuddin, K. Ni, S. Datta. Nat. Electron. **1** (2018) 442–450

Многофункциональные КНИ транзисторы: ISFET, NCFET, FeFET

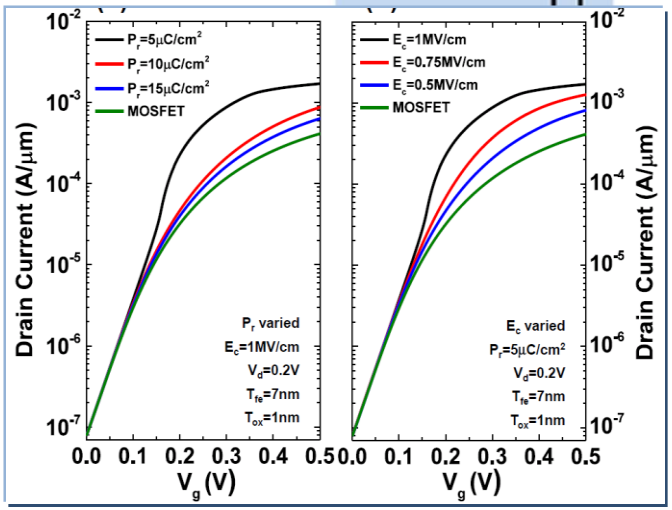
Симметричная и антисимметричная моды 2G FDSOI FET



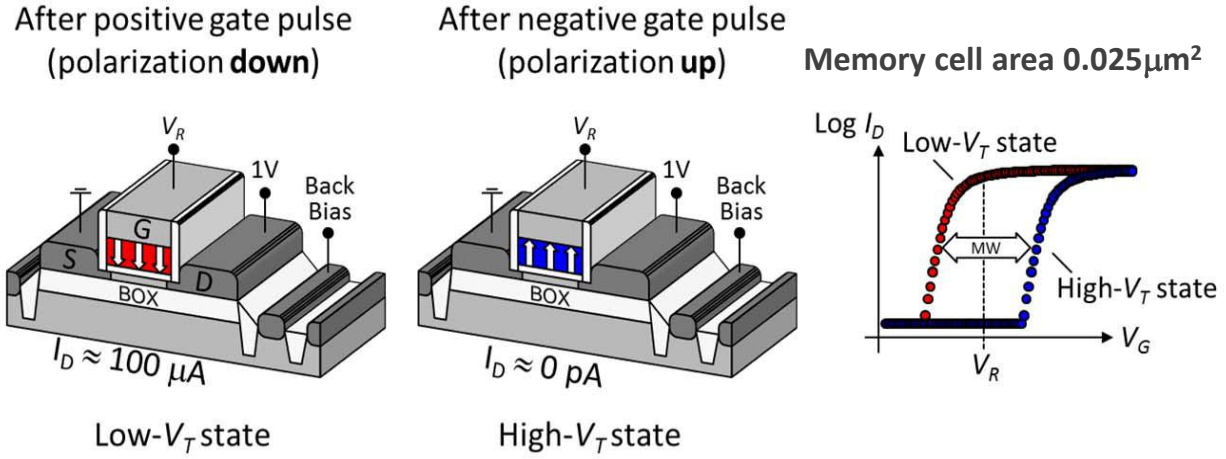
M. А.Ильницкий и др., IX Росс. конф. по физике п/п-ов, 2009

V.P. Popov et al. EuroSOI (2009)

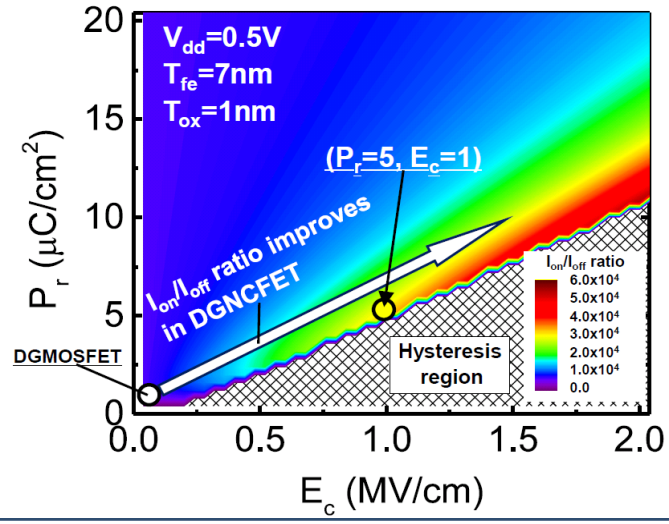
DG NCFET SOI



FeFET SOI



2G NCFET SOI



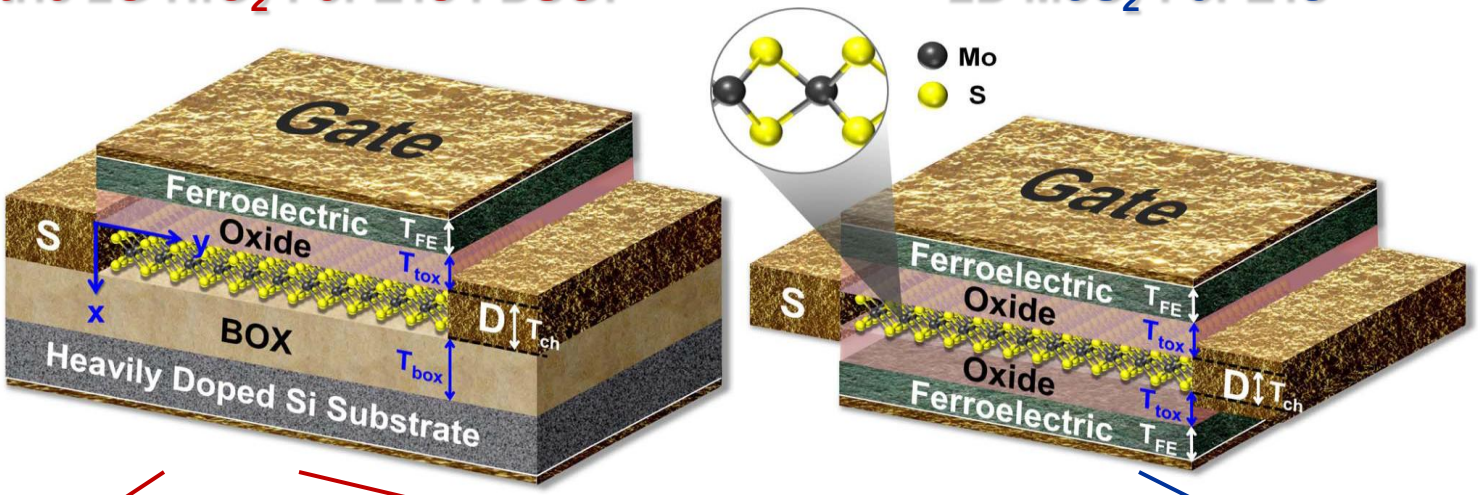
K.Jang *et al. Jpn.J. Appl.Phys. 57 (2018)*

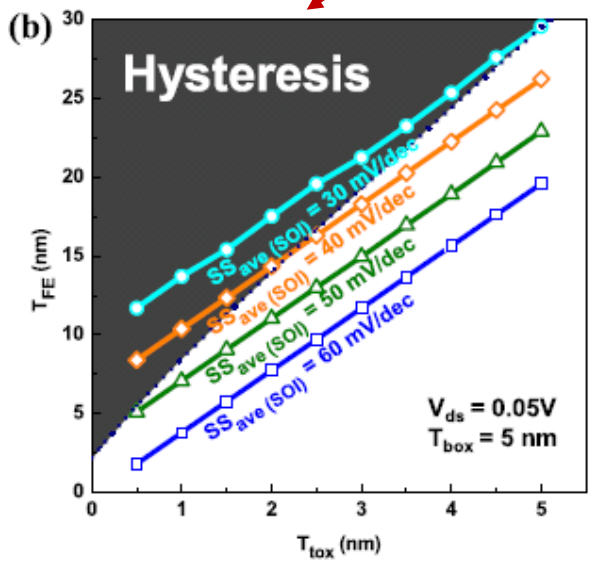
S. Dunkel *et al. IEEE 19.7.1 IEDM17-485 2017*

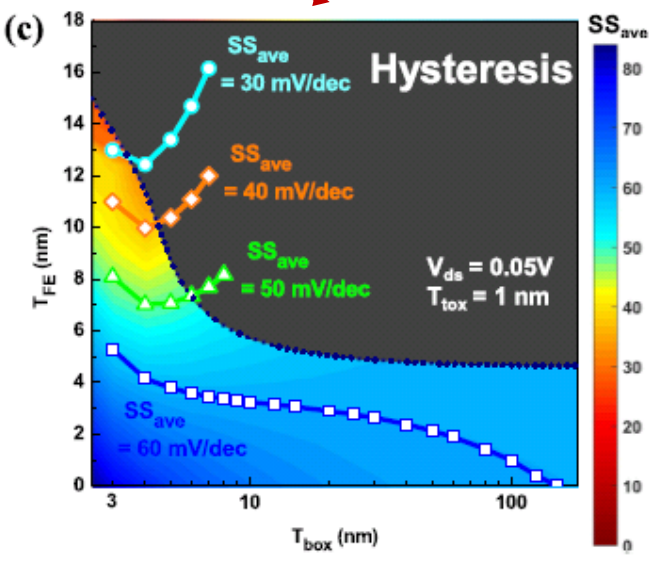
2G FDSOI NCFETs vs. DG 2D MoS_2 NCFETs

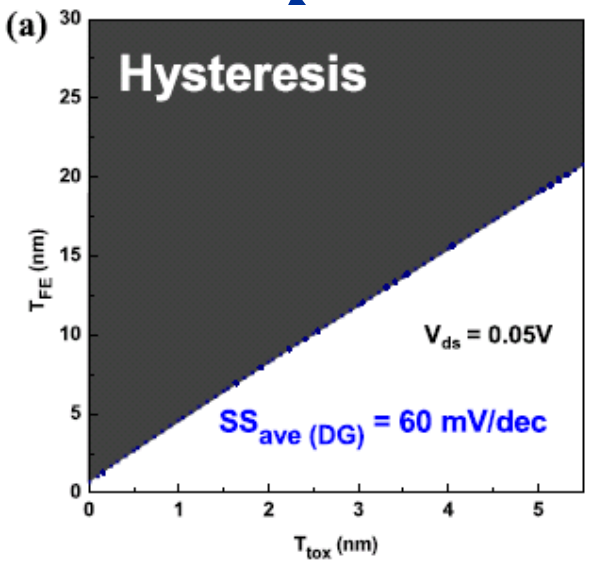
Asimetric 2G HfO_2-FeFETs FDSOI

2D MoS_2-FeFETs





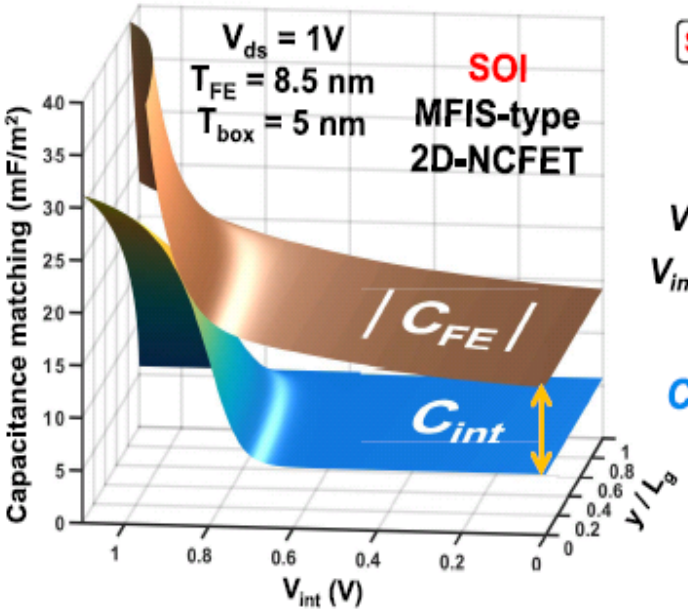


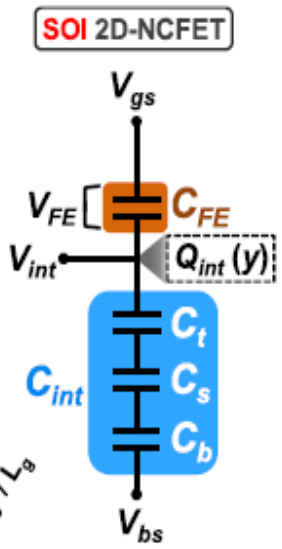


Wei-Xiang You, Pin Su. *IEEE TED, 65 (2018) 4196*

2G FDSOI NCFETs vs. DG MoS_2 NCFETs

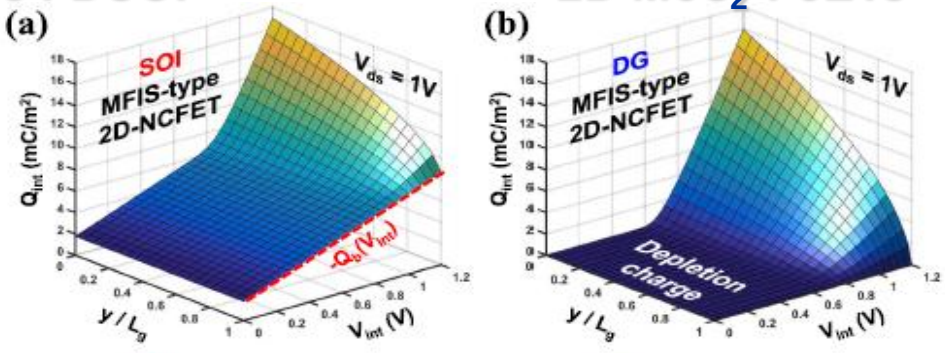
2G HfO_2-FeFETs FDSOI

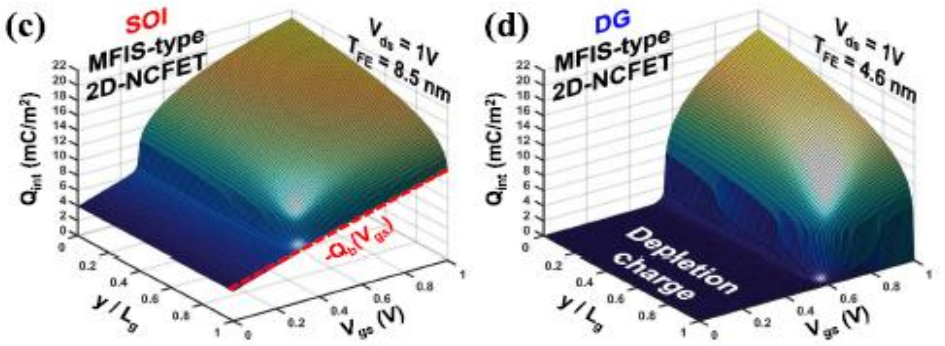


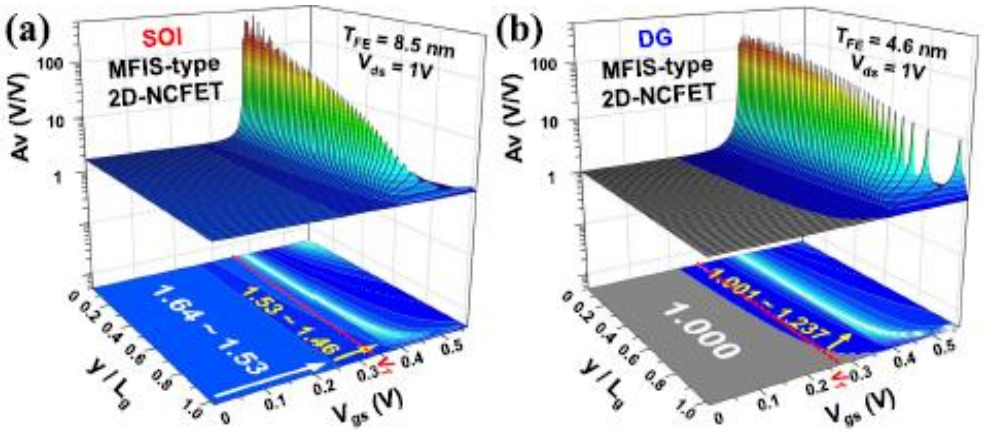


$$SS_{ave}^{NCFET} = SS_{ave}^{MOSFET} \frac{1}{Av} \qquad Av = \frac{\partial V_{int}}{\partial V_{gs}} = \frac{|C_{FE}|}{|C_{FE}| - C_{int}}$$

2D MoS_2-FeETs

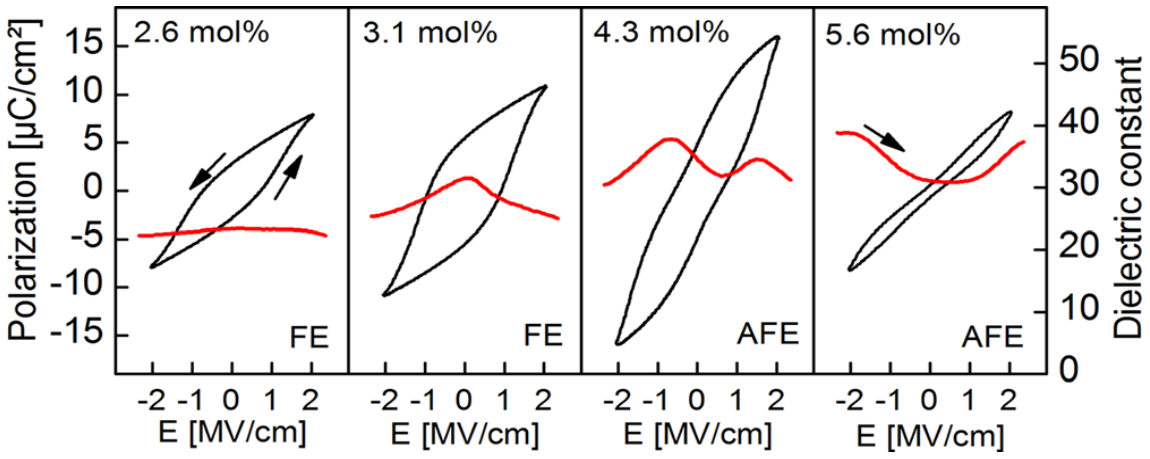






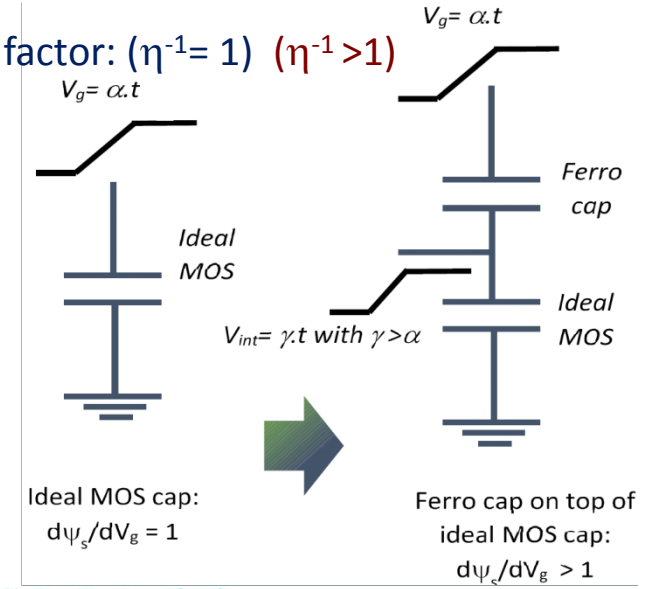
Wei-Xiang You, Pin Su. *IEEE TED, 65 (2018) 4196*

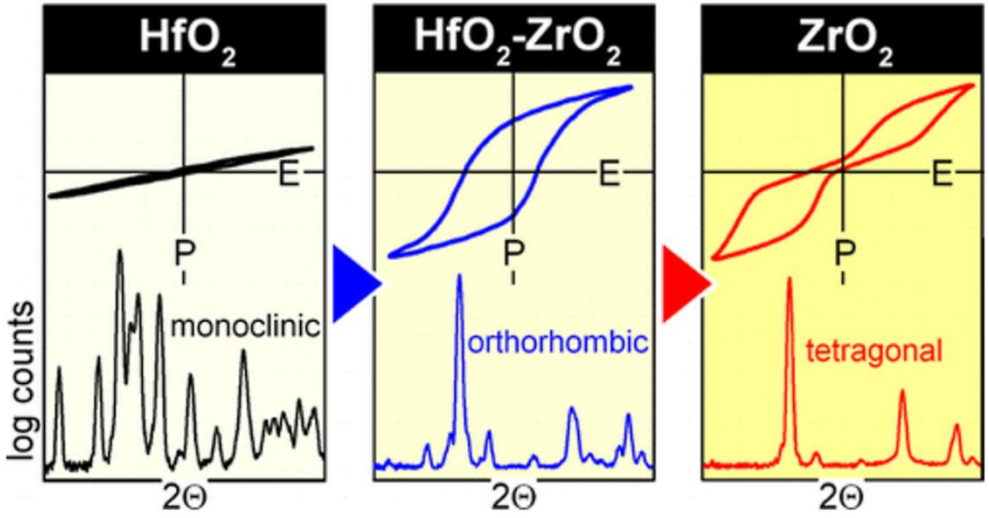
High-k Ferroelectric Hafnia & Dielectric Stacks



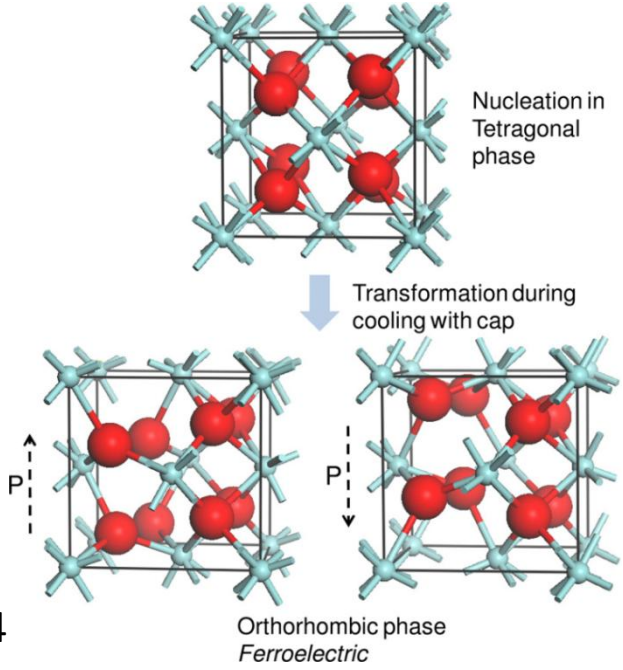
J. Müller *et al., VLSI, 25-26, 2012*

Body factor: (η^{-1}= 1) (η^{-1} >1)



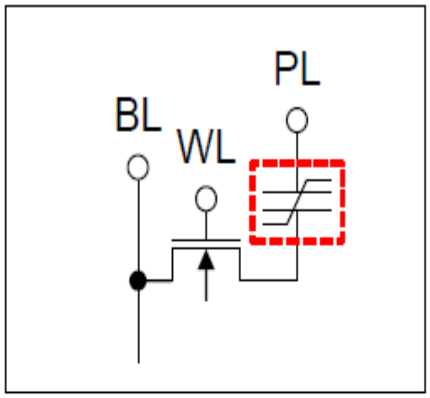


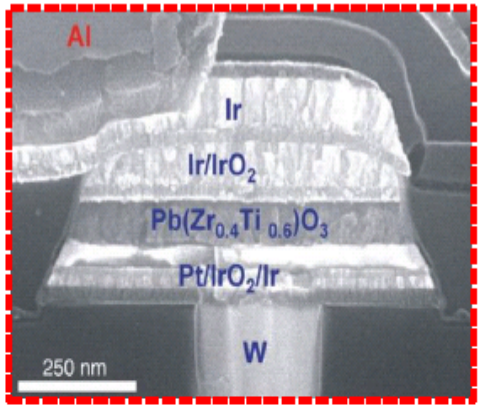
J. Müller *et al., Nano Lett.*, **2012**, *12* (8), pp 4



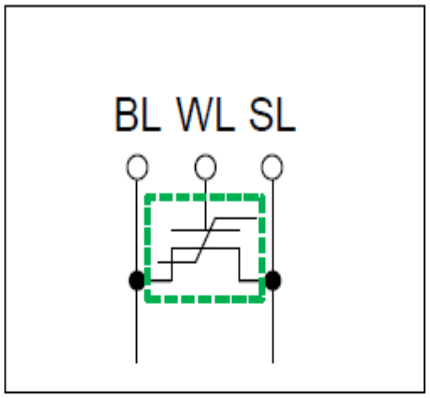
Bo scke *et al. Appl. Phys. Lett.* 99, 102903 (2011)

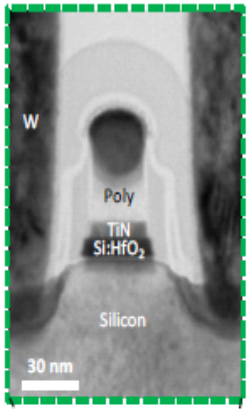
High-k ferroelectric transistors with PZT or hafnia





Source: Science, Vol. 315,, pp. 954-959



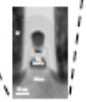


Source: S. Mueller, EMF, 2015.

- 1T-1C memory cell
- Exotic ferroelectric materials (PZT)
- Stuck at 130 nm

+ 1T memory cell
+ Ferroelectric HfO_2
+ In dev. at 22 nm

to actual scale...



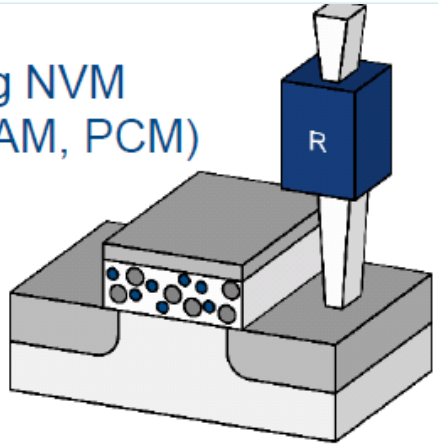
THE enabler for FeFET!

Flash Memory Summit

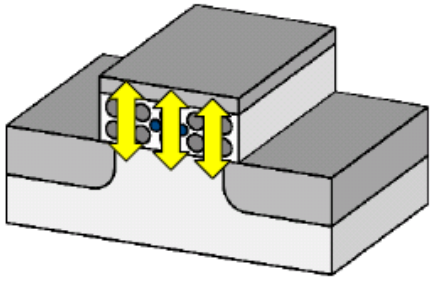
S. Müller (Ferroelectric Memory Co.) *Flash Memory Summit* 2018.

High-k ferroelectric transistors with PZT or hafnia

Emerging NVM
(RRAM, MRAM, PCM)



The FeFET solution



Challenges:

- **Additional memory element R adds cost!**
- Higher power consumption
- Questionable scalability

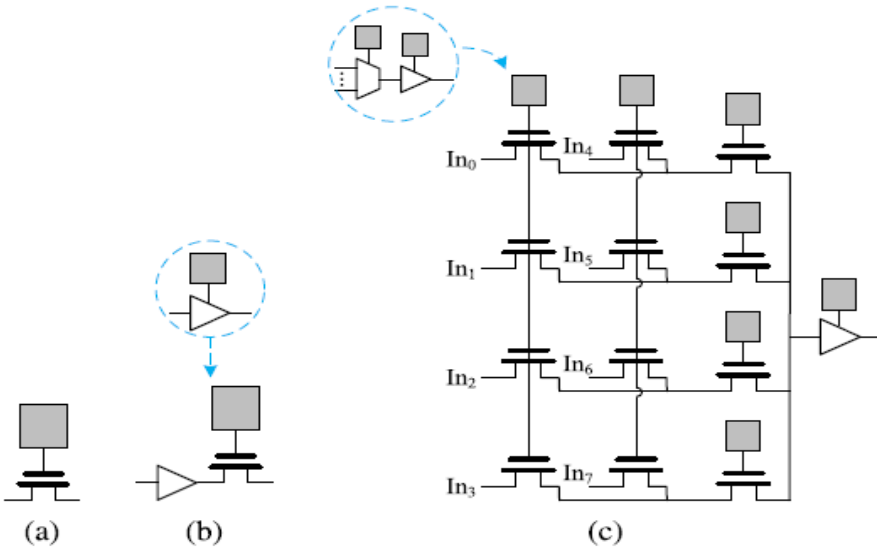
FeFET benefits:

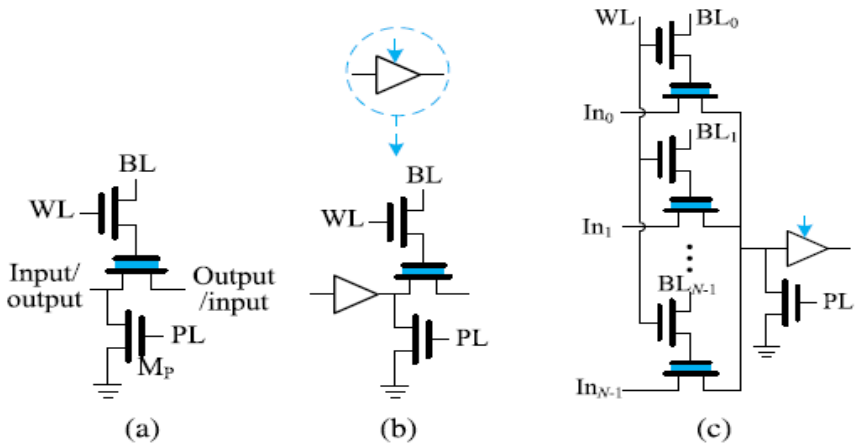
- Reduces manufacturing cost significantly
- Lowers power consumption by 1000x
- Inherently scalable alongside CMOS

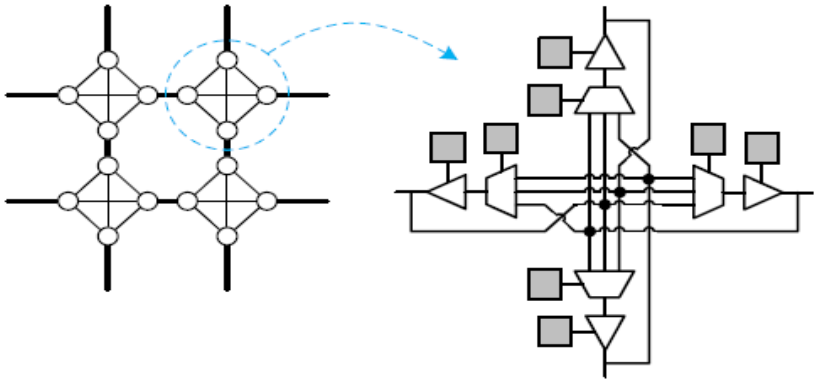
Flash Memory Summit

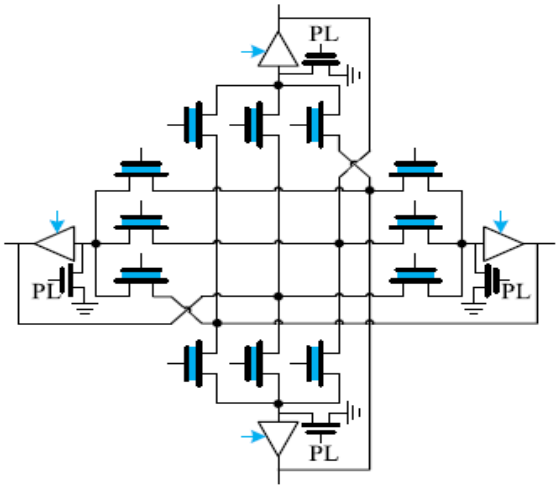
S. Müller (Ferroelectric Memory Co.) *Flash Memory Summit* 2018.

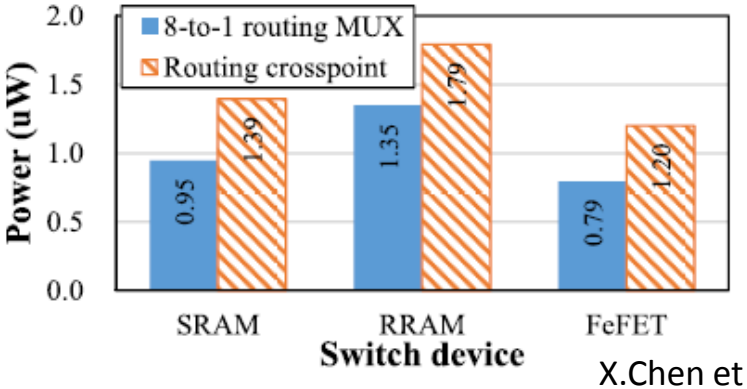
FeFET логические элементы в СОЗУ и ПЛИС

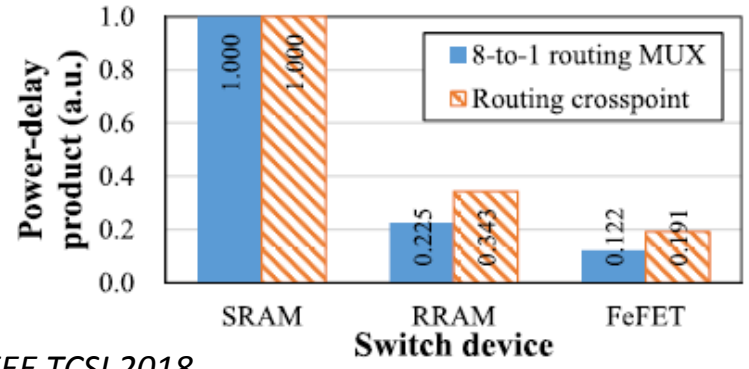






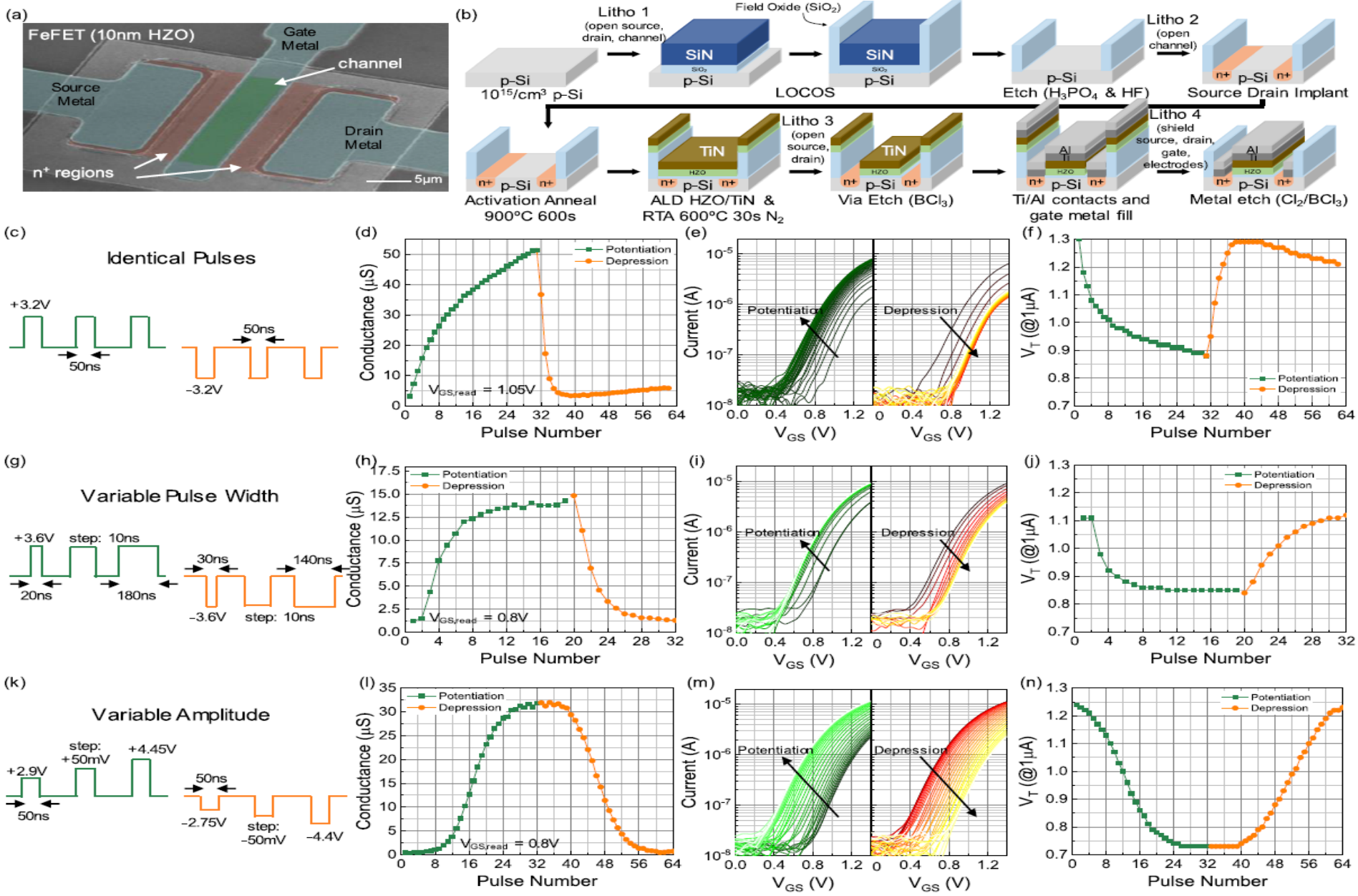






X.Chen et al. *IEEE TCSI 2018*

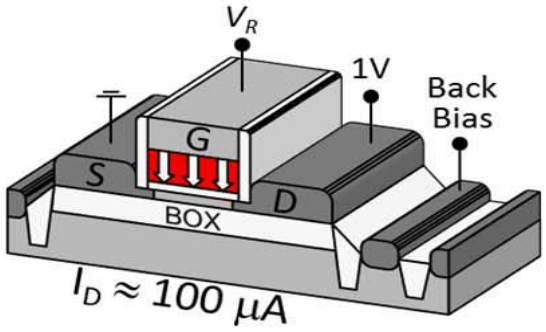
HZO 1T FeFET synapses for Artificial Intellect ICs



M Jerry et al. *J. Phys. D: Appl. Phys. 51 (2018) 434001*

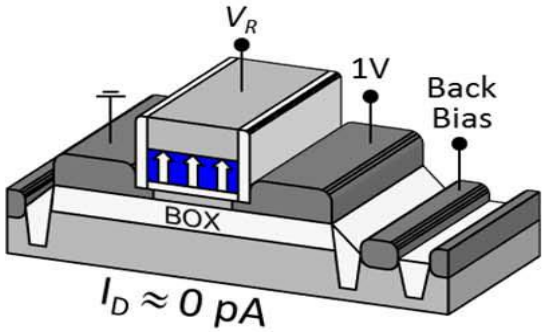
2G HfO_2-FeFETs FDSOI : Embedded Memory (eNWM 32 Mb)

After positive gate pulse (polarization **down**)



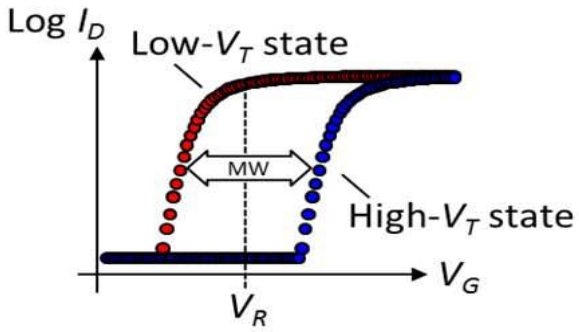
Low-V_T state

After negative gate pulse (polarization **up**)

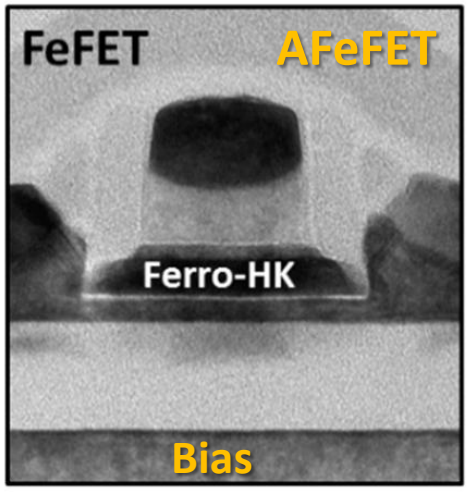


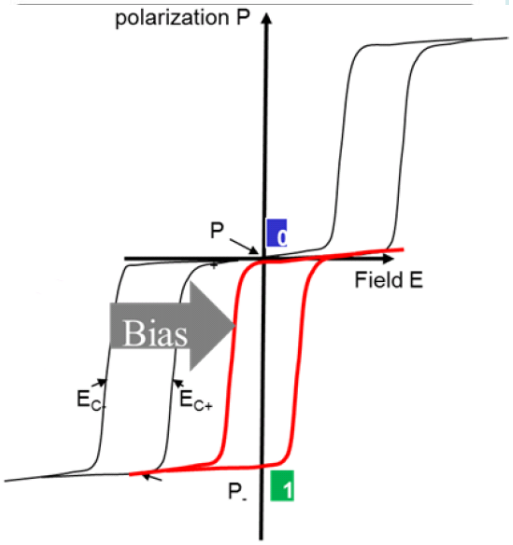
High-V_T state

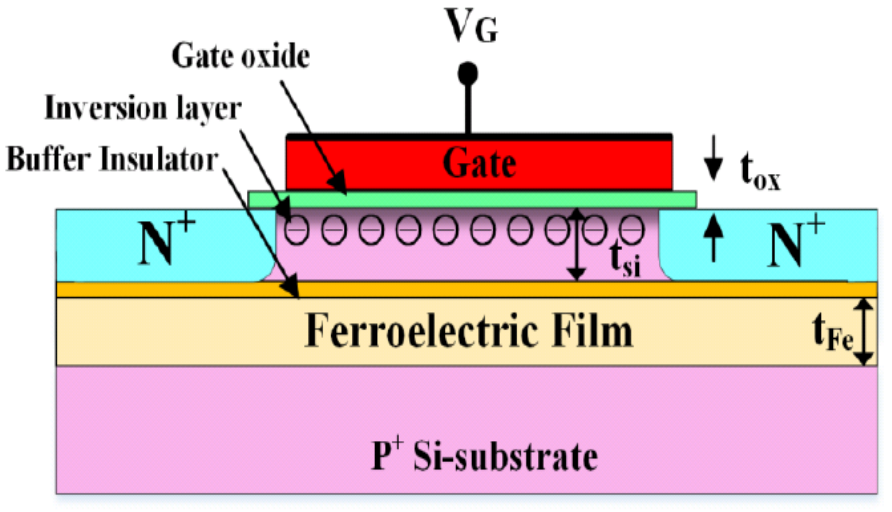
Memory cell area is 0.025µm²



reported FeFETs in literature







publication year

S. Dunkel et al. IEEE 19.7.1 IEDM17-485 2017

Es-Sakhi et al. DOI:10.1109/S3S.2015.7333514

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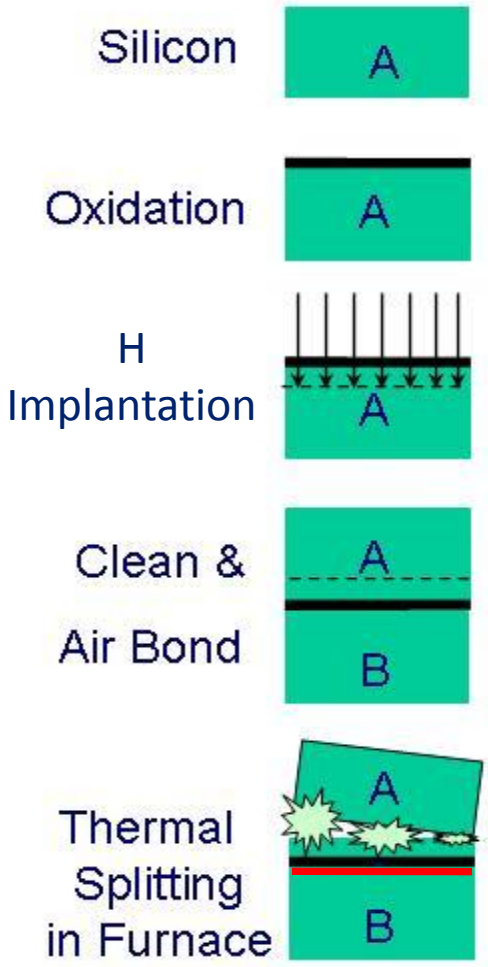
6. Заключение

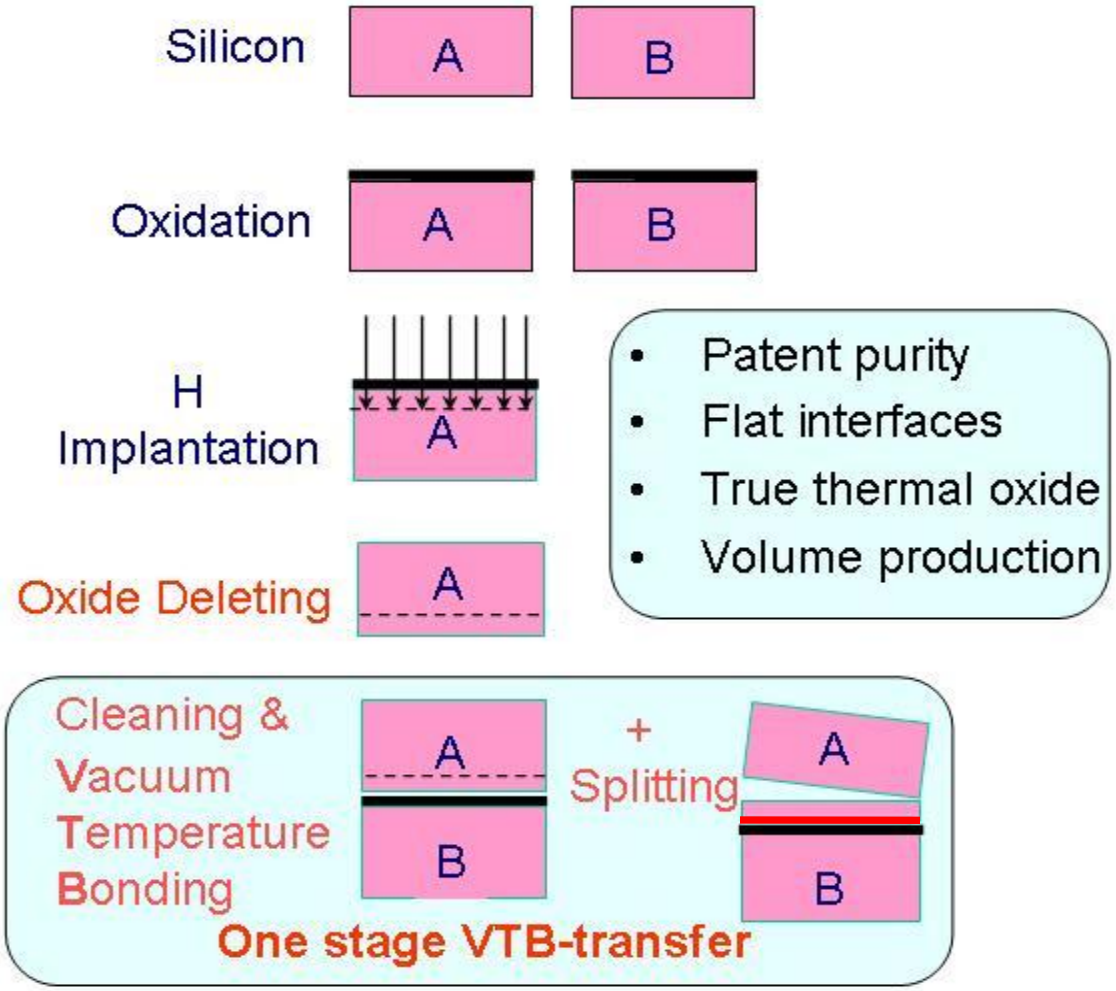
Гетероструктуры КНИ с тонким слоем кремния

Smart Cut® SOI



M. Bruel, Electron. Lett., **31**, 1201 (1995).

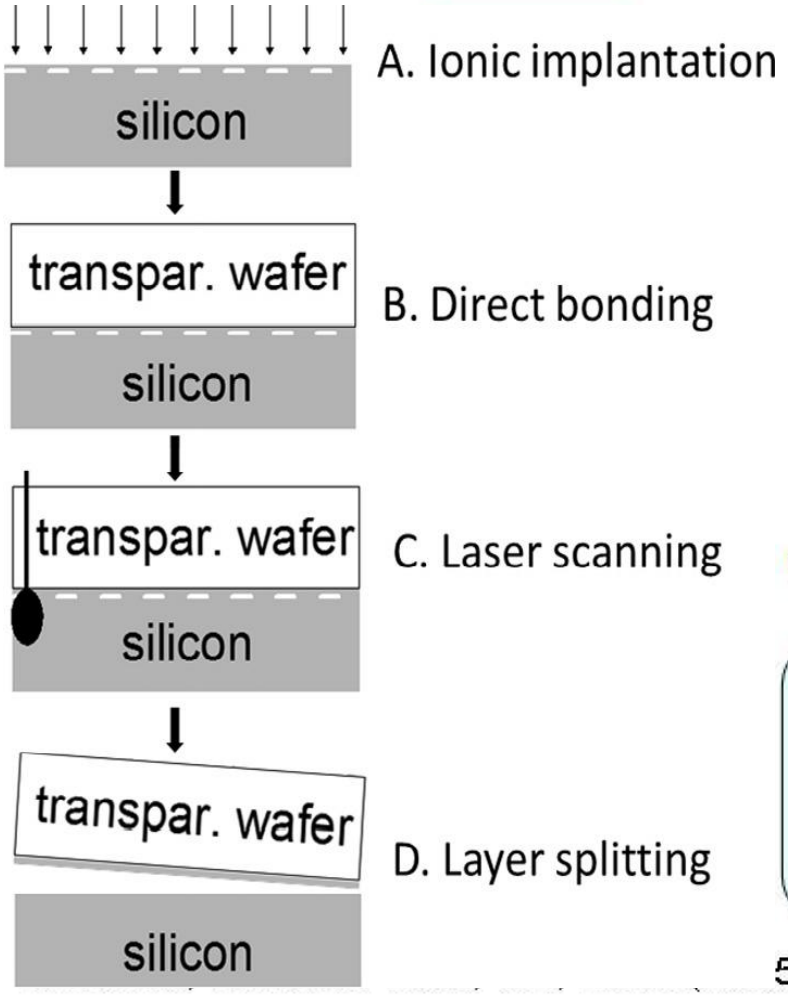
DeleCut SOI



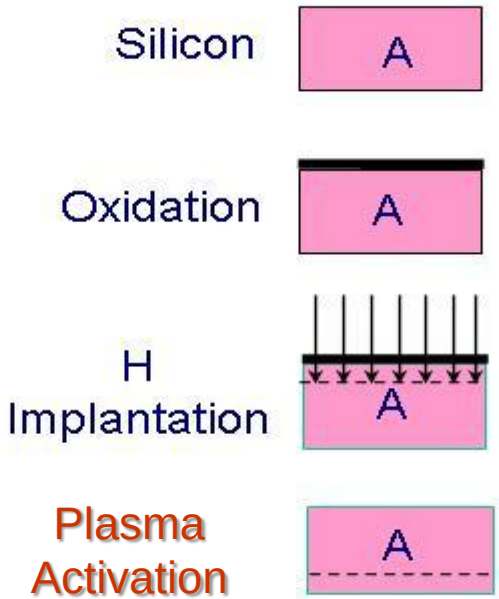
V.P. Popov, I.E. Tyschenko. PCT WO 2004/064137

Гетероструктуры КНС с тонким слоем кремния

Smart Cut® SOS



DeleCut SOS



- Patent purity
- Flat interfaces
- True thermal oxide
- Plasma activation

5) **V.P. Popov et al. Patent RF no.2538352 (2015)**
Priority from 14.06.2013

***R. Meyer et al. Sol.-State Electron. 115 (2016) 225**

**** Только островки в отличие от сплошного слоя в нашем методе.***

Технология UTBB high-k КНИ и КНС структур ИФП СО РАН

Лабораторная (*IMP Halle*) и полупромышленные системы (*Suss BA8/SB8*) для *Ø 200 мм Si*

Σ = 70 м² ISO4,5

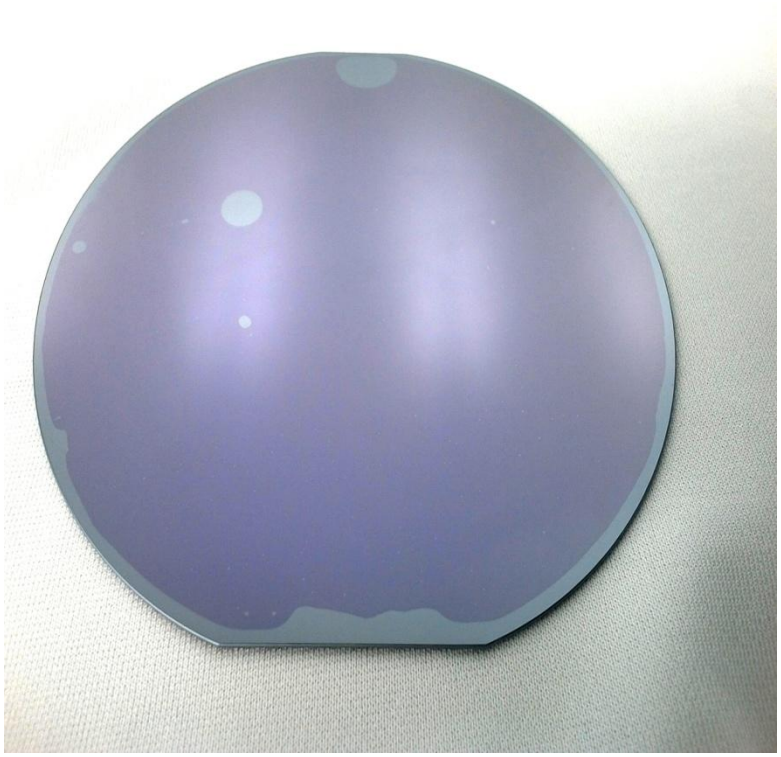
MA8 Mask Aligner с модулем активации DBD (плазма Dielectric Barrier Discharge)

SB8 бондер для КНИ, КНС и п/п гетеропар, оптических и биохимических чипов

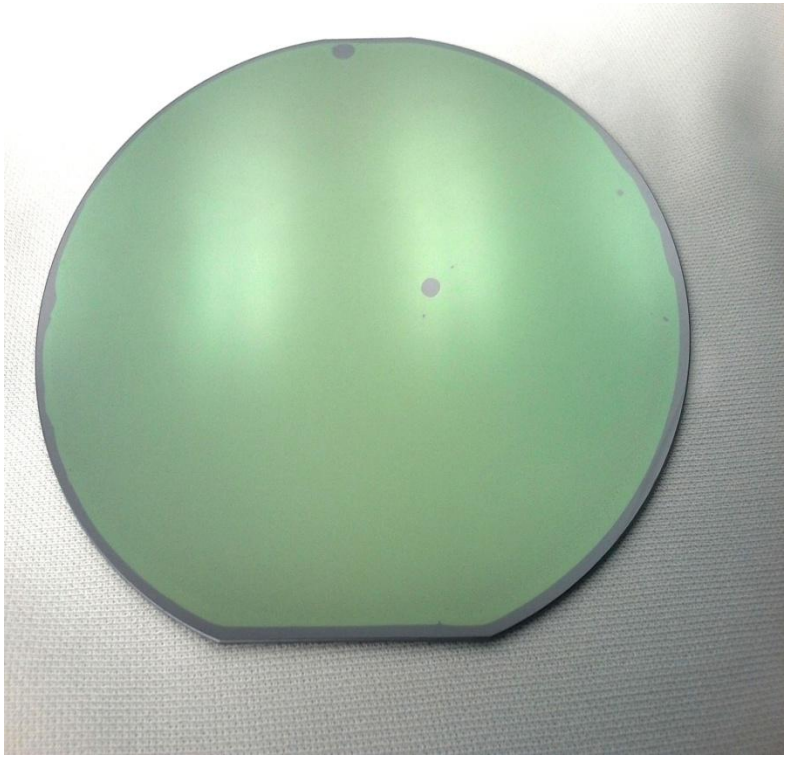
UTBB SOI - КНИ с УТ слоями HfO_2, HfO_2/Al_2O_3, $Al_2O_3/HfO_2/Al_2O_3$

Перенос 0.5 мкм слоев Si с PEALD HfO_2/Al_2O_3 на кремний

SOI: 20 nm HfO_2/Al_2O_3 on (100) Si 500 μm



SOI: 20 nm $Al_2O_3/HfO_2/Al_2O_3$ on (100) Si 500 μm



Дырки в Si из-за пыли в ALD Flex-Al и ЧК при бондинге

Несращивание по краям – из-за пинцета при влажных химобработках

Толщины перенесенного слоя Si – 0.47 мкм

План

1. Мотивация: UTBB КНИ для двухзатворных FeFETs
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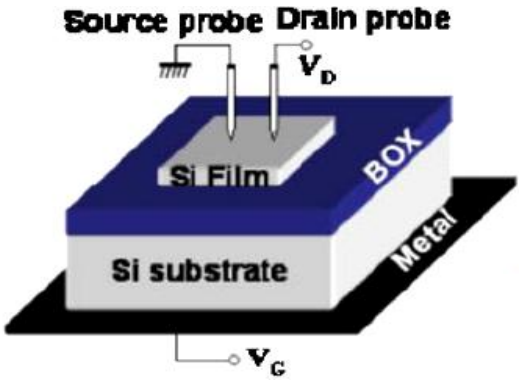
6. Заключение

SOI & SOS pseudo-MOSFETs with HfO_2 interlayers

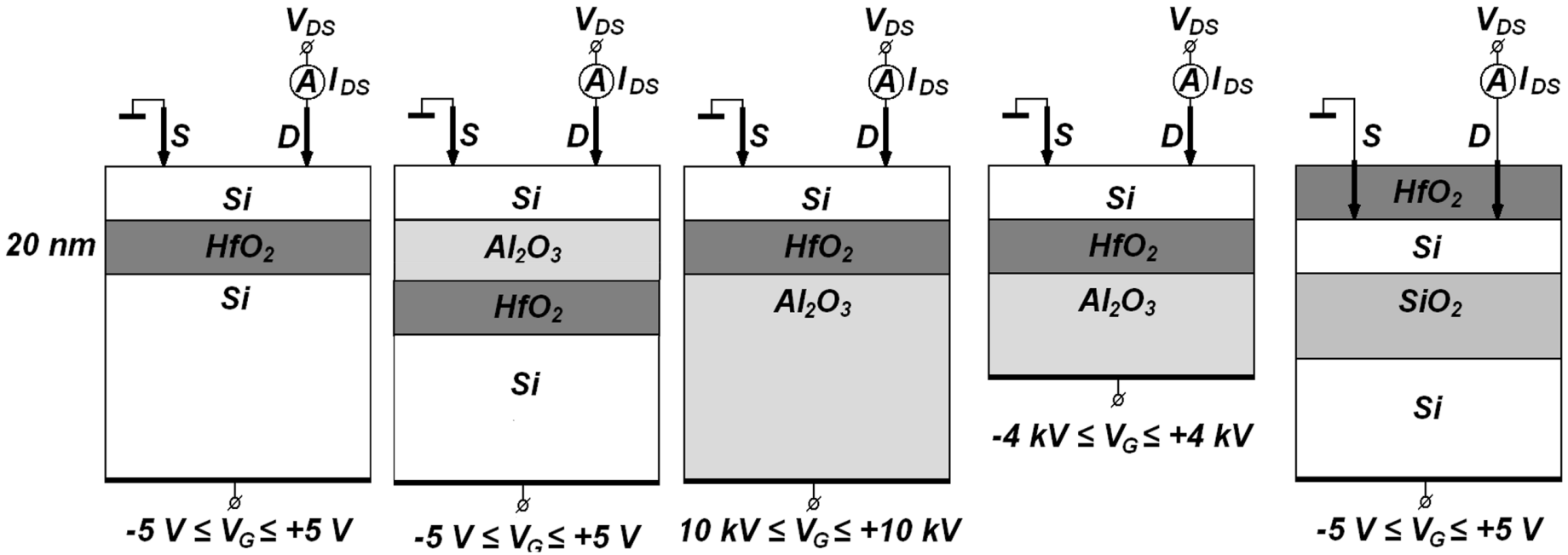


Pseudo-MOSFET Y-Function*:

$$Y = I_{DS}/(dI_{DS})/dV_{BG})^{0,5} = (\mu_{eff} f_g C_{BOX} V_{DS})^{0,5} (V_G - V_{TH/FB})$$

$$V_{Tn} - V_{Tp} \cong 2\Phi_F + \frac{qN_0}{C_{BOX}} t_{Si} + \frac{qD_{it}}{C_{BOX}} 2\Phi_F$$

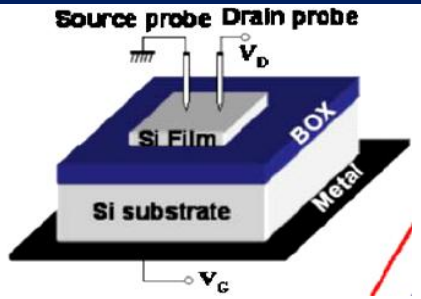
Pseudo-MOSFETs SOI** & SOS samples :



* S. Cristoloveanu, et al. *ECS Trans., 50 (2012) 249*

** M. Alexe *et al. Appl.Phys.Lett., 70 (1997) 3416*

Y-functions for SOS pseudo-MOSFETs with SiO_2 interlayers

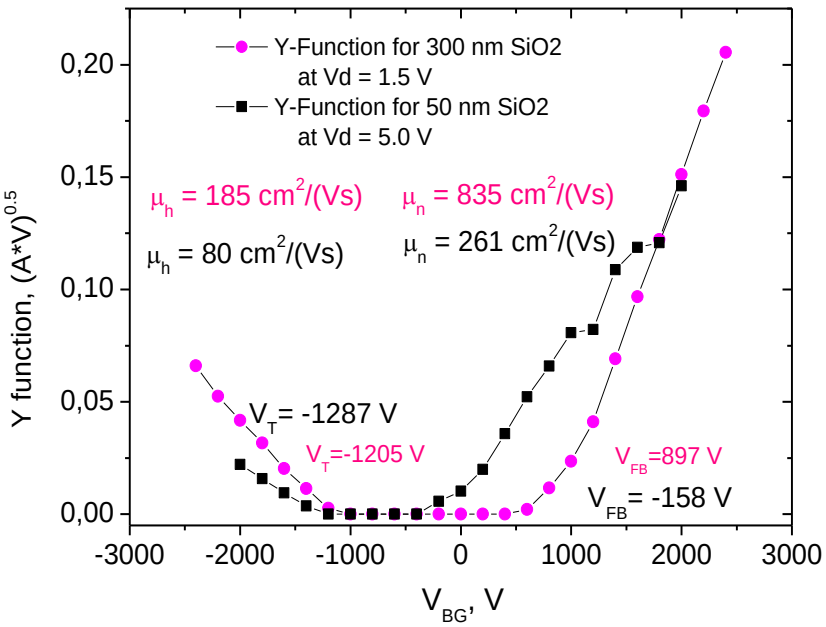


Pseudo-MOSFET:

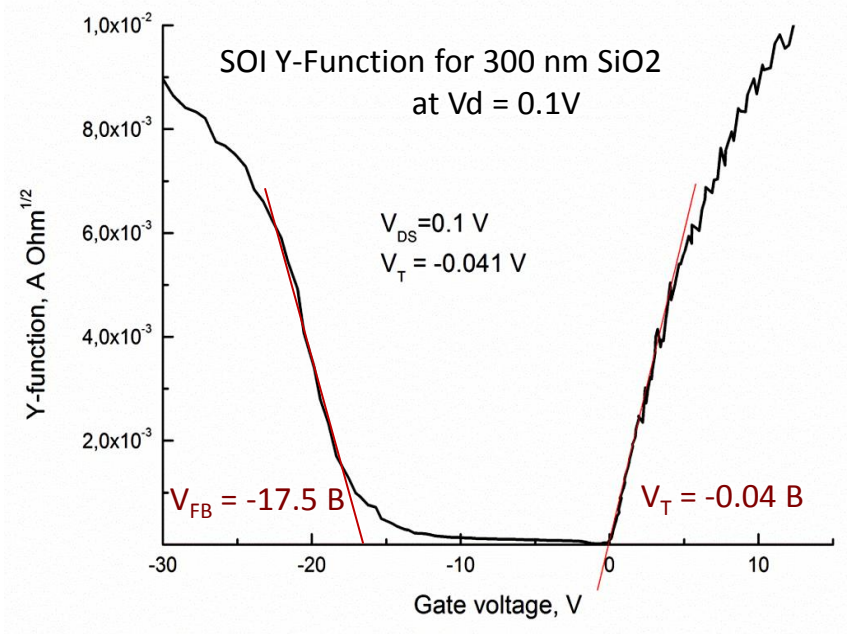
$$Y = I_{DS}/(dI_{DS})/dV_{BG})^{0,5} = (\mu_0 f_g C_{OX} V_{DS})^{0,5} (V_G - V_{TH/FB})$$

$$V_{Tn} - V_{Tp} \cong 2\Phi_F + \frac{qN_0}{C_{sa}} t_{Si} + \frac{qD_{it}}{C_{sa}} 2\Phi_F$$

SOS: 300 nm SiO_2 on (0001)-Al_2O_3 500 μm



SOI: 300 nm SiO_2 on (100)-Si 500 μm



$M_{e,h}$= 835,185 см²/В·с
Q_{OX} = 1.5x10¹¹ см⁻²
$D_{it,e}$ *= 0.8x10¹¹см⁻²эВ⁻¹*
$D_{it,h}$ *= 4.4x10¹¹см⁻²эВ⁻¹*

M_e = 370 см²/В·с
Q_{OX} = 1.3x10¹² см⁻²
$D_{it,e}$ *= 1.0x10¹²см⁻²эВ⁻¹*

V.Popov *et al. EUROSOI-ULIS 2018, IEEE Xplore: 07 May 2018*

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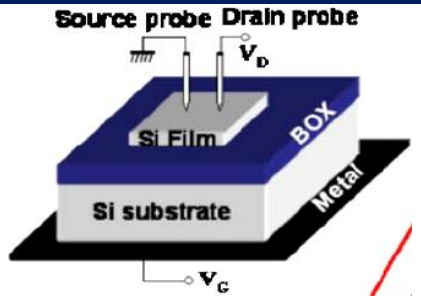
6. Заключение

Y-functions for SOS & SOI pseudo-MOSFETs with HfO_2 interlayers

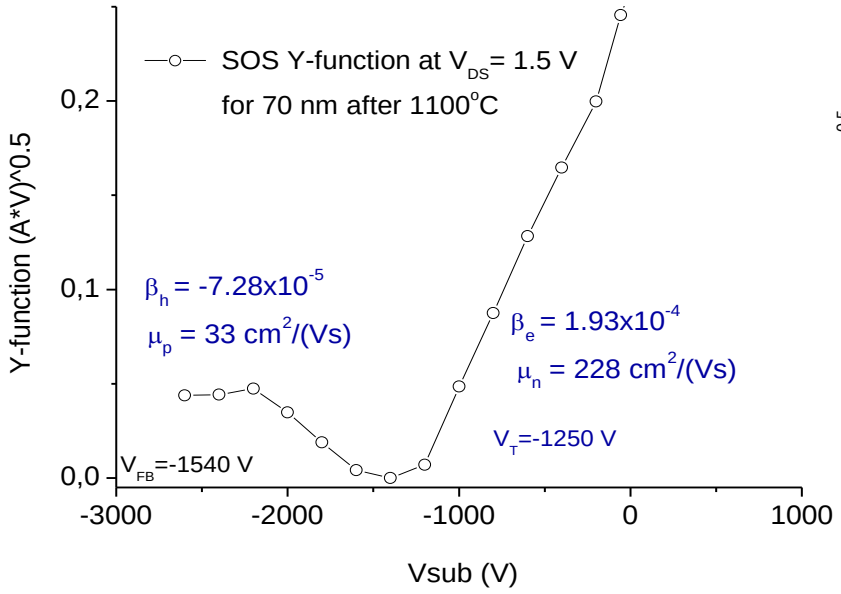


Pseudo-MOSFET:

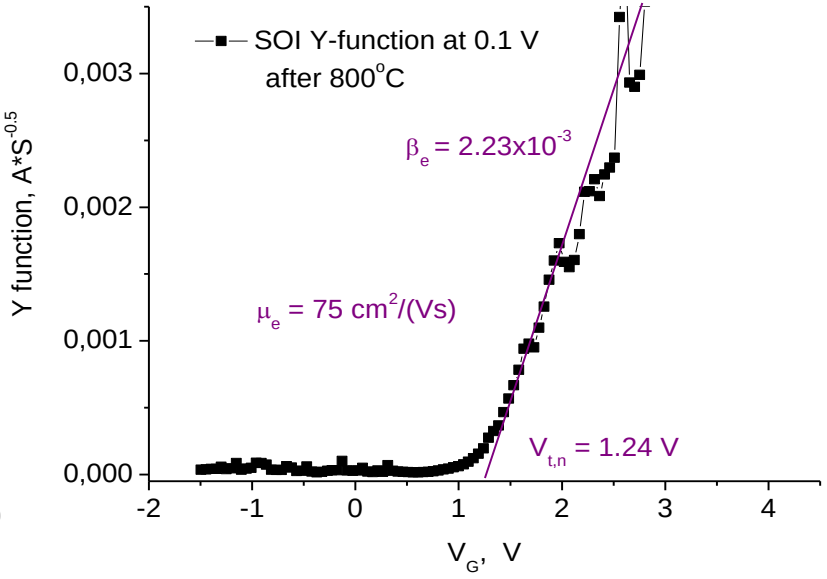
$$Y = I_{DS}/(dI_{DS})/dV_{BG})^{0,5} = (\mu_0 f_g C_{OX} V_{DS})^{0,5} (V_G - V_{TH/FB})$$

$$V_{Tn} - V_{Tp} \cong 2\Phi_F + \frac{qN_0}{C_{sa}} t_{Si} + \frac{qD_{it}}{C_{sa}} 2\Phi_F$$

SOS: 20 nm HfO_2 on c-Al_2O_3 70 μm



SOI: 20 nm HfO_2 on (100) Si 500 μm

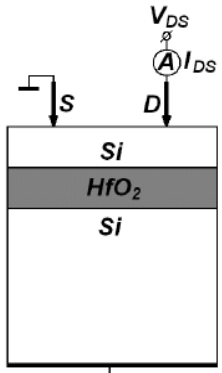


$\mu_{e,h}$ = 230, 33 см^2/Вс,
Q_{OX} = 1.2x10^{12} см$^{-2}$
$D_{it,e}$ = 0.7x10^{12} см$^{-2}$эВ$^{-1}$
$D_{it,h}$ = 2.4x10^{12} см$^{-2}$эВ$^{-1}$

Degradation of transport properties due to the residual defects after 800°C:

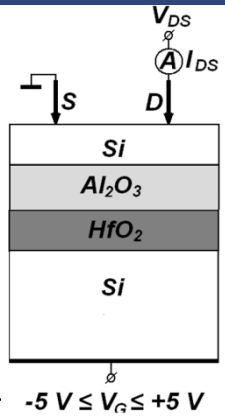
for electrons: $\mu_e = \theta_e^2/(f_G C_{OX} V_{DS})$ ~ 75 cm^2/Vs,

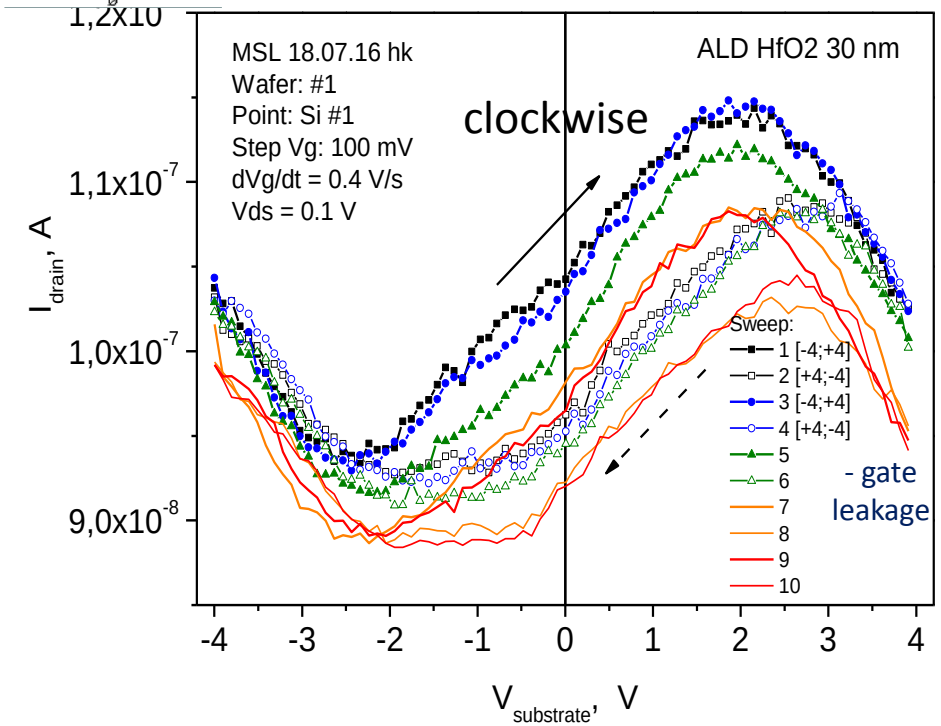
Source-drain curves in SOS & SOI pseudo-MOSFET s



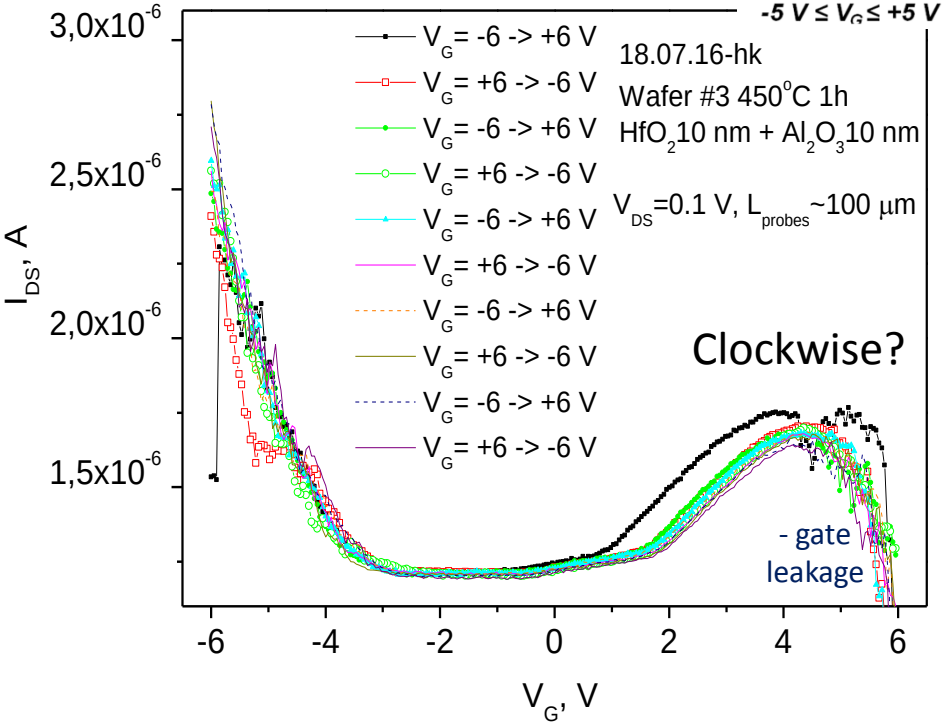
PEALD HfO_2 deposition: t_{HfO2} = 4 to 20 nm at 300°C on Si wafers before bonding
DB + TA at 450 °C

$$1 \approx \frac{\partial \varphi_s}{\partial V_G} = \frac{C_{di}}{C_{di} + C_{sc}} = \frac{|C_{fe}|C_{ox}}{|C_{fe}|C_{ox} + C_{sc}(|C_{fe}| - C_{ox})} \approx 1$$





n-SOI / HfO2 / n-Si



n-SOI/ HfO2 / Al2O3

Hysteresis: IF states – clockwise;

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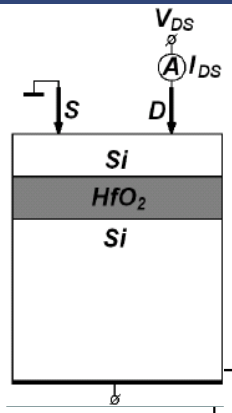
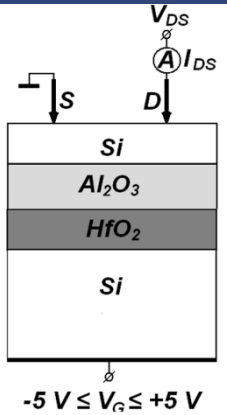
Source-drain curves in SOS & SOI pseudo-MOSFET s

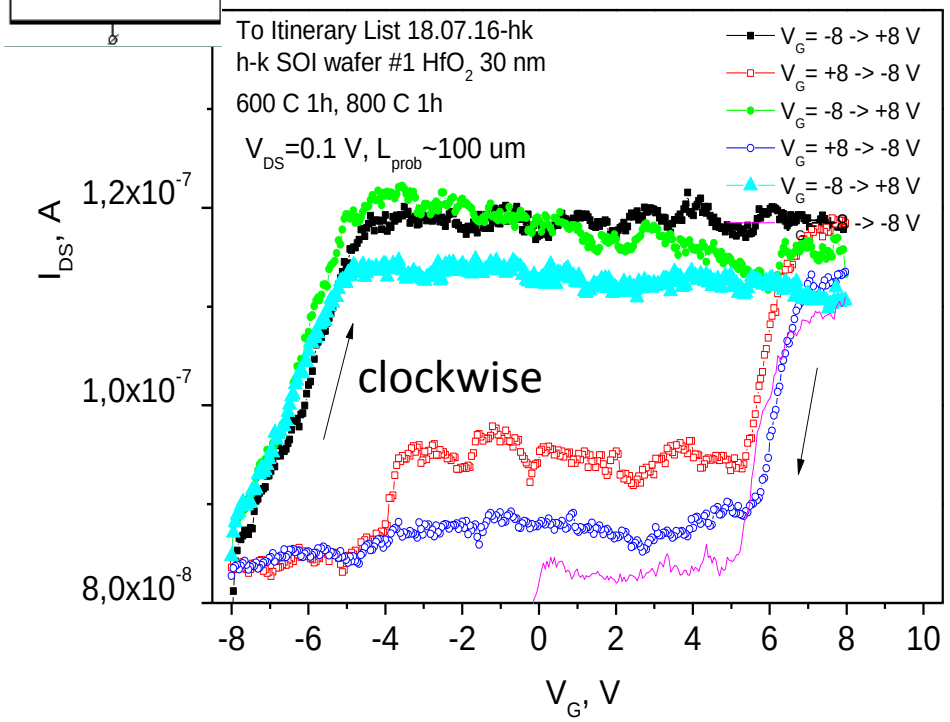


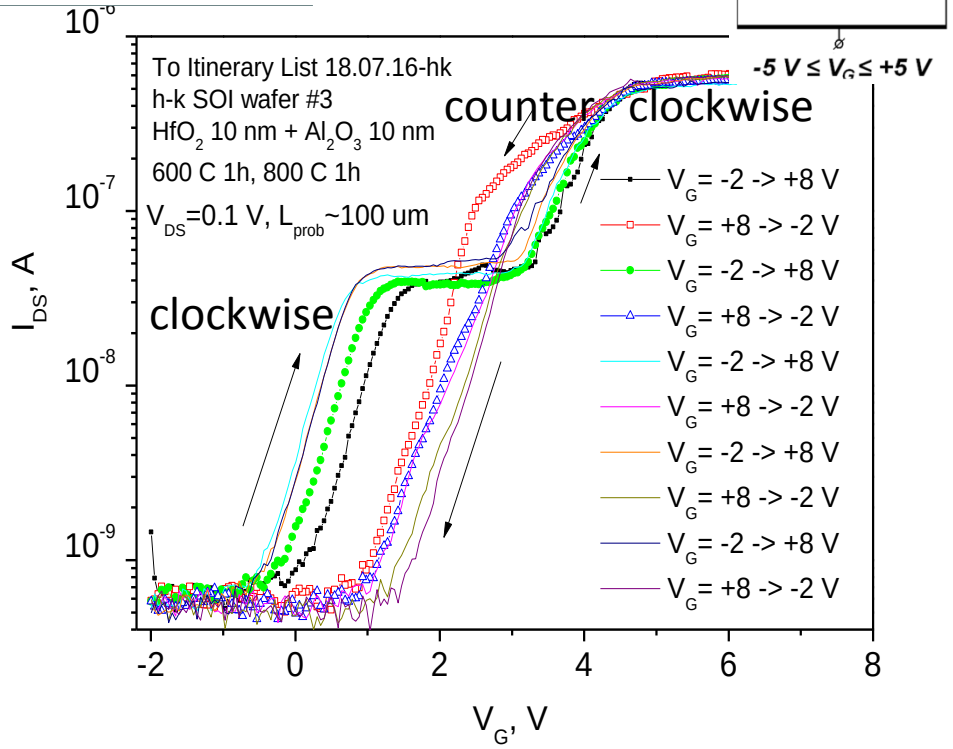
PEALD HfO_2 deposition: t_{HfO2} = 4 to 20 nm at 300°C on Si wafers before bonding

DB + TA at 800 °C



$$1 \approx \frac{\partial \varphi_s}{\partial V_G} = \frac{C_{di}}{C_{di} + C_{sc}} = \frac{|C_{fe}|C_{ox}}{|C_{fe}|C_{ox} + C_{sc}(|C_{fe}| - C_{ox})} \approx 1$$





-5 V ≤ V_G ≤ +5 V

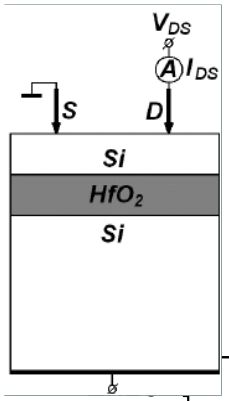
n-SOI / HfO2 / n-Si

n-SOI / HfO2+Al2O3 / n-Si

Hysteresis: IF states – clockwise;

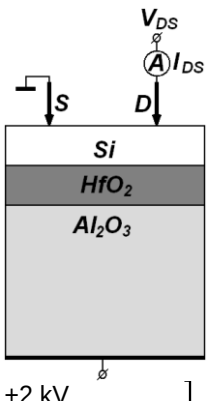
FE polarization - counterclockwise

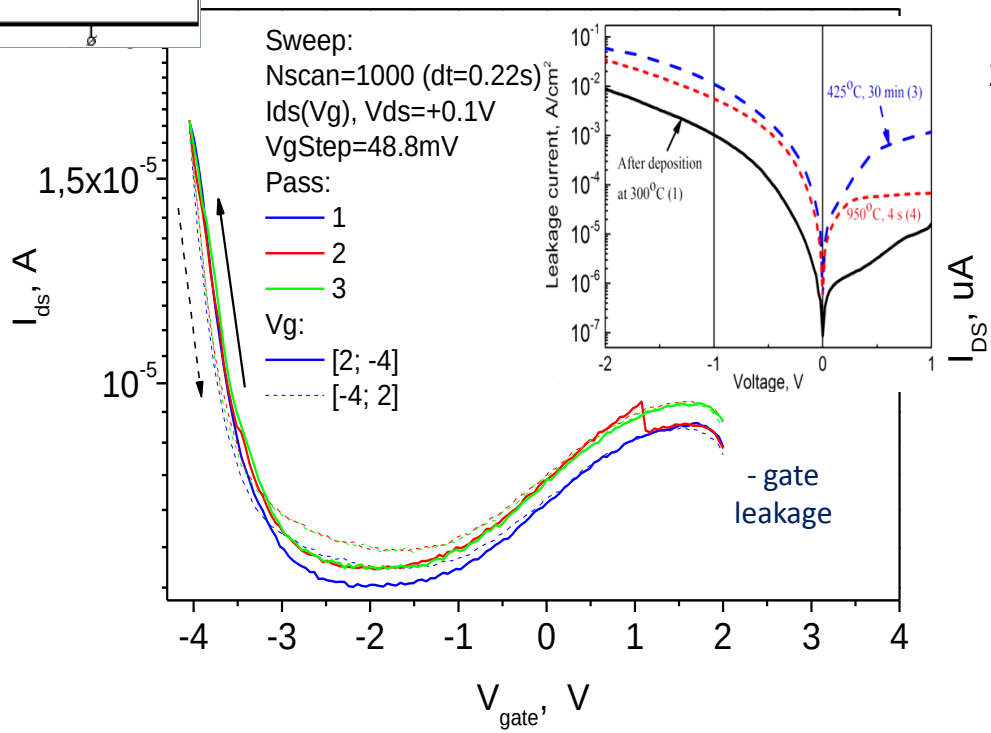
Source-drain curves in SOS & SOI pseudo-MOSFET s

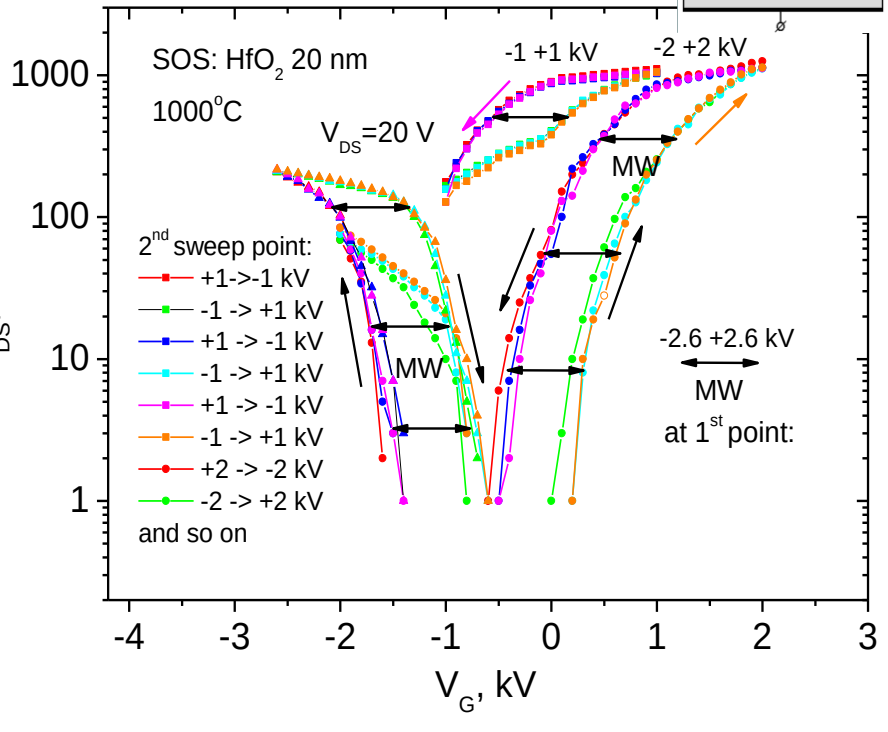


PEALD HfO_2 deposition: t_{HfO2} = 4 to 20 nm at 300°C on Si wafers before bonding
DB + TA at 1000 °C

$$1 \approx \frac{\partial \varphi_s}{\partial V_G} = \frac{C_{di}}{C_{di} + C_{sc}} = \frac{|C_{fe}|C_{ox}}{|C_{fe}|C_{ox} + C_{sc}(|C_{fe}| - C_{ox})} \approx C_{sa}/(C_{sa} + C_{sc}) << 1$$





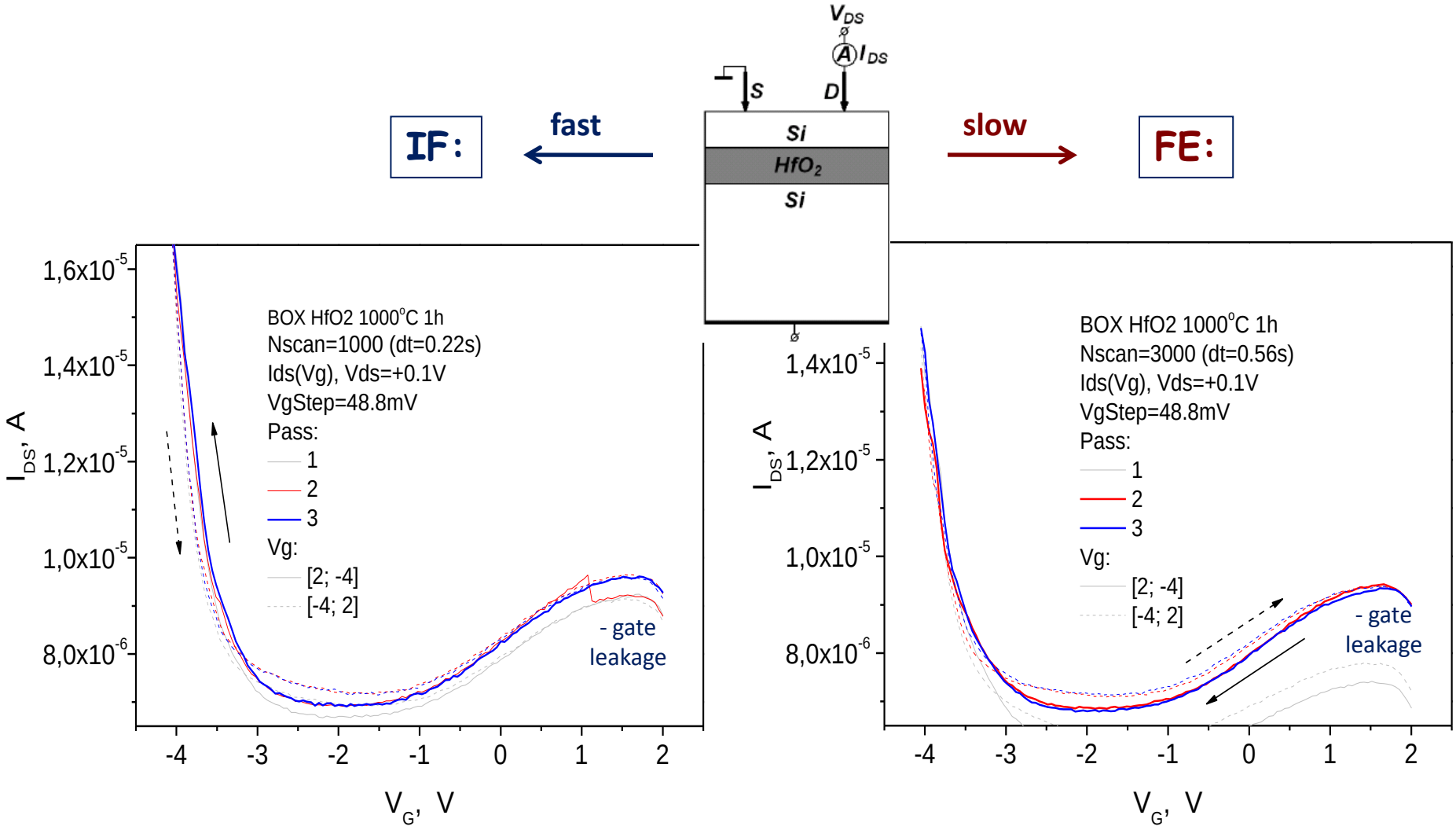


p-SOI / HfO2 / p-Si

n-SOS / HfO2 / c-sapphire

Weak FE hysteresis is due to the increase in IF trap density & positive charge

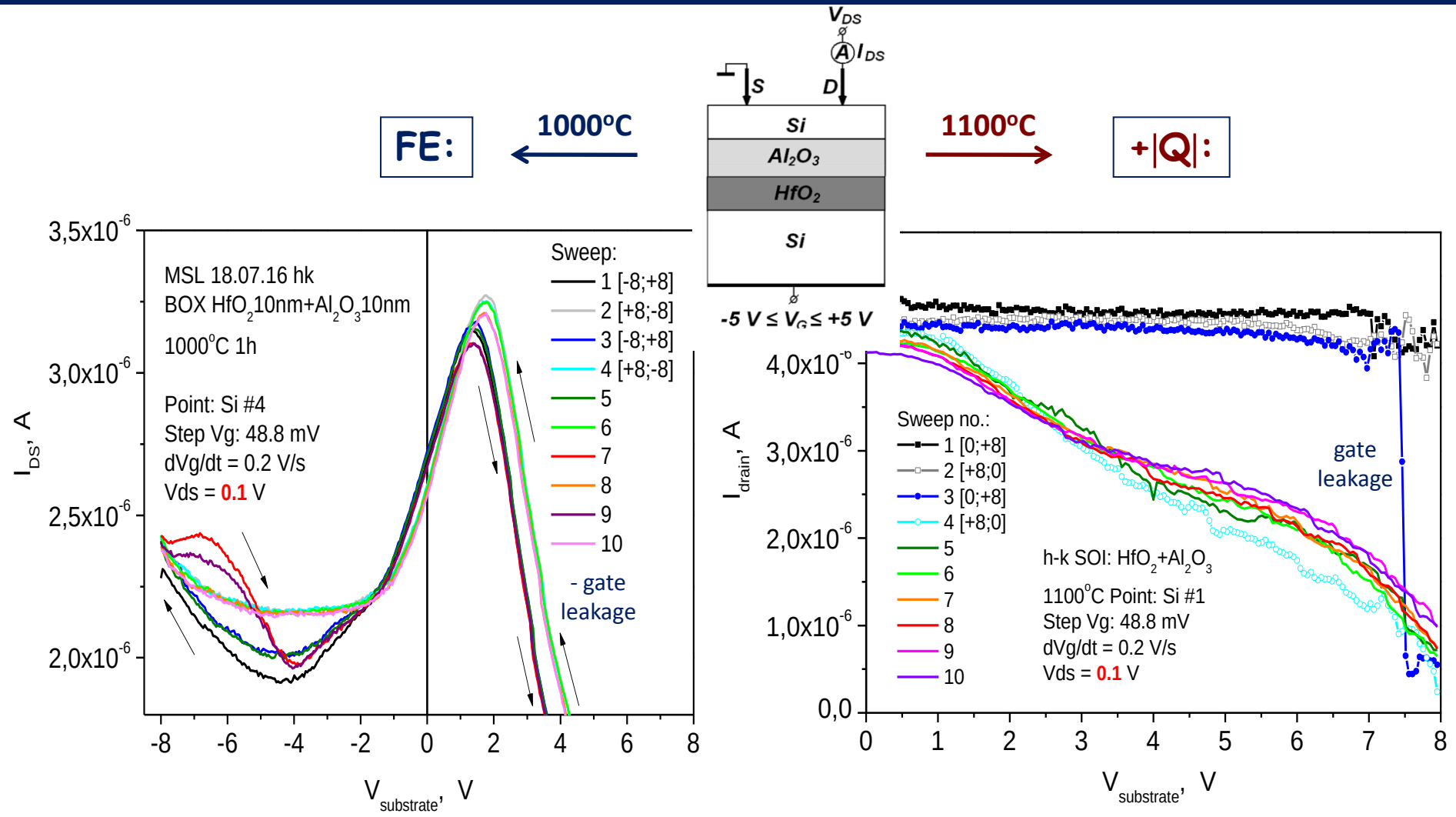
Interface Charge Trapping & Ferroelectricity in SOI: HfO_2+Al_2O_3



Slow IF states are presented at the BOX: HfO_2.

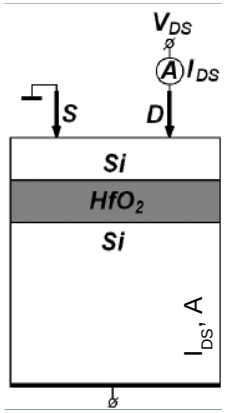
SOI has a strong time dependence for Δt ~ 220 ms due to IFS's !

Interface Charge Trapping & Ferroelectricity in SOI: HfO_2+Al_2O_3

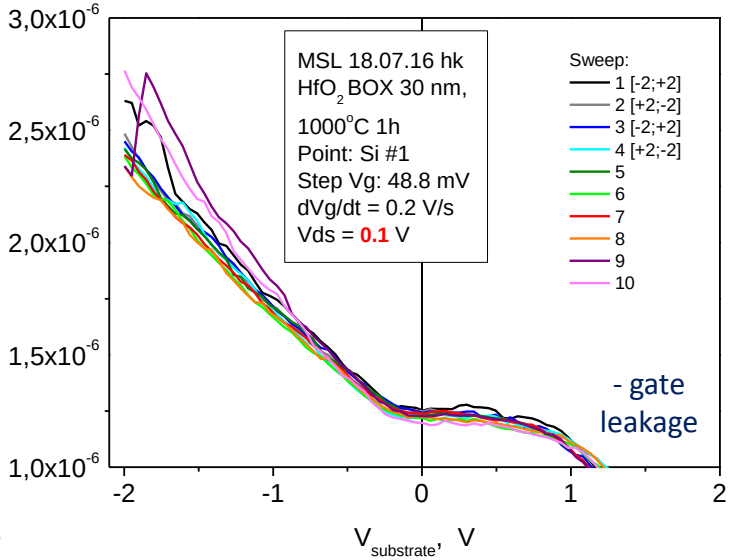


Breakdown & high positive Q is presented at BOX: HfO_2+Al_2O_3 after HT

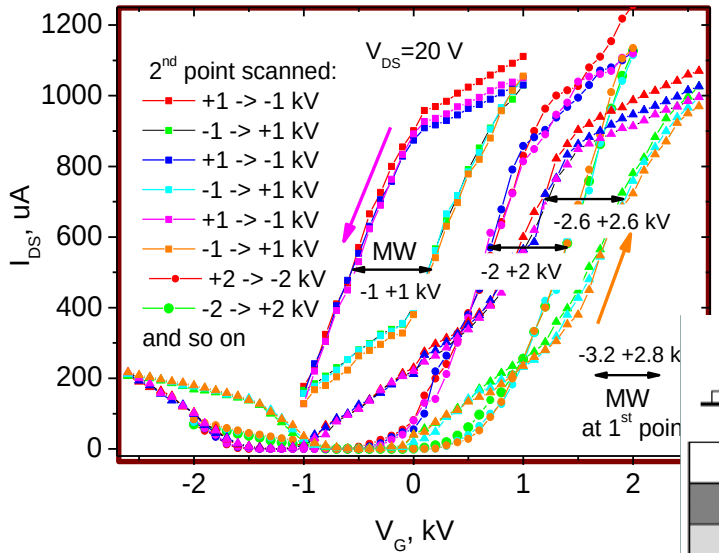
Ferroelectricity in BOX HfO_2 SOI & SOS FeFETs

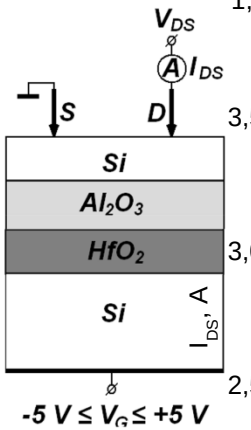


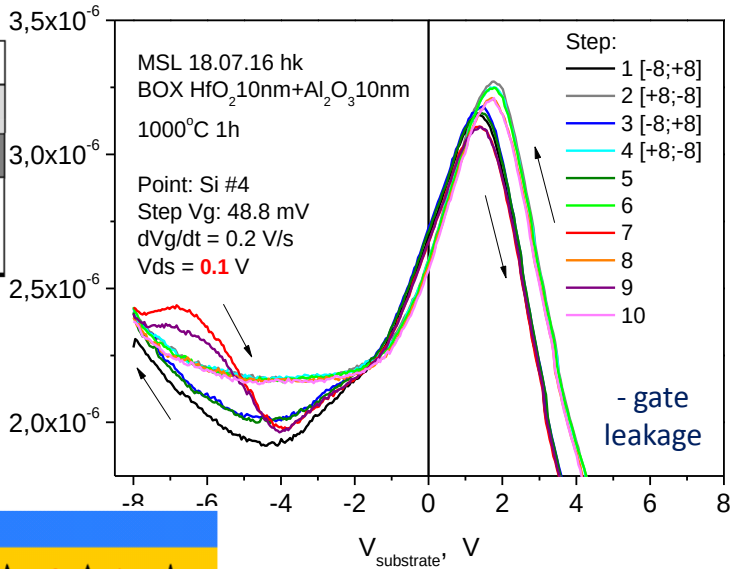
SOI: E_{FE}=(1-2)·10^6 V/cm

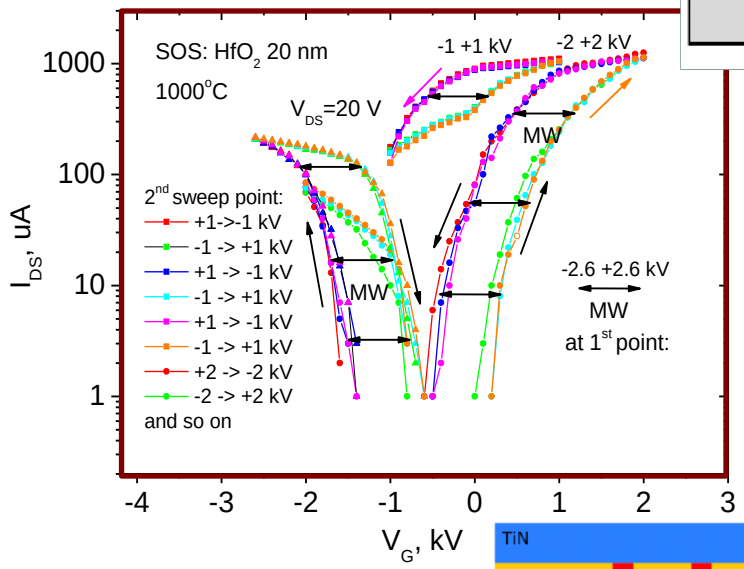


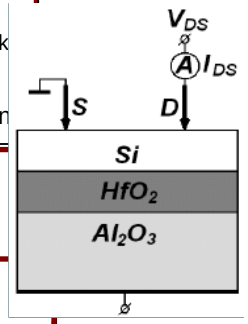
SOS: E_{FE}=(1-3)·10^4 V/cm !

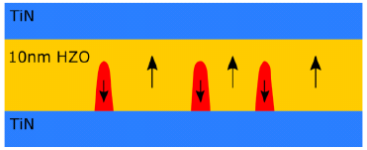




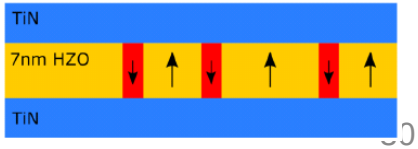






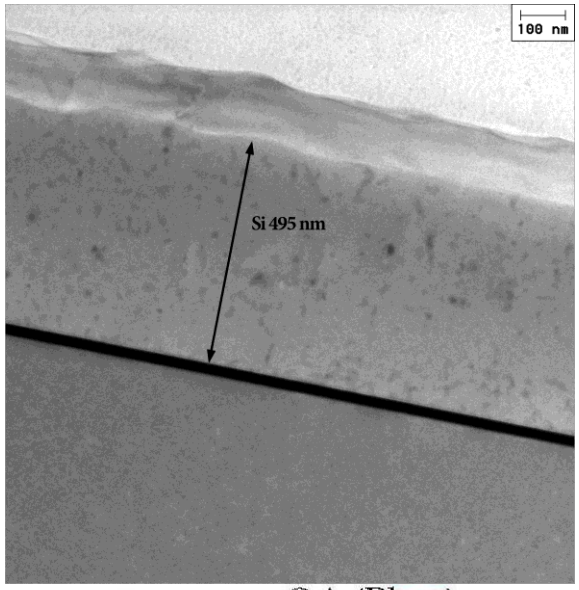


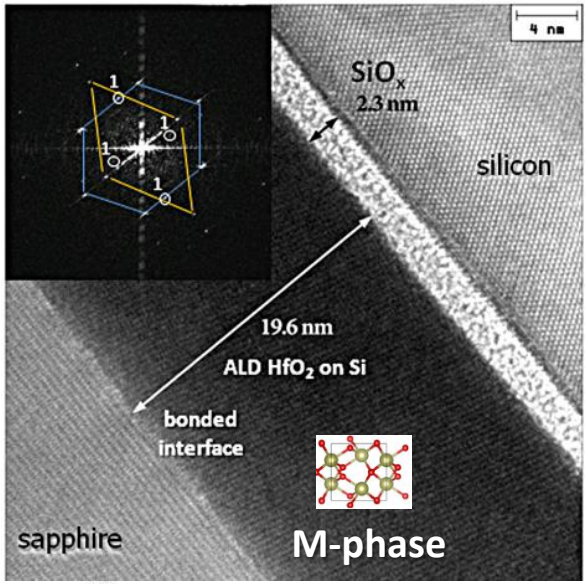
SOI: RTA and /or HfO_2-ZrO_2 (HZO)?

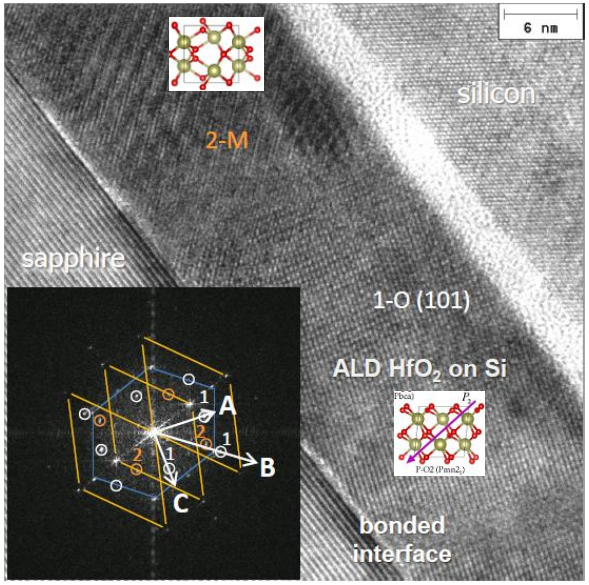


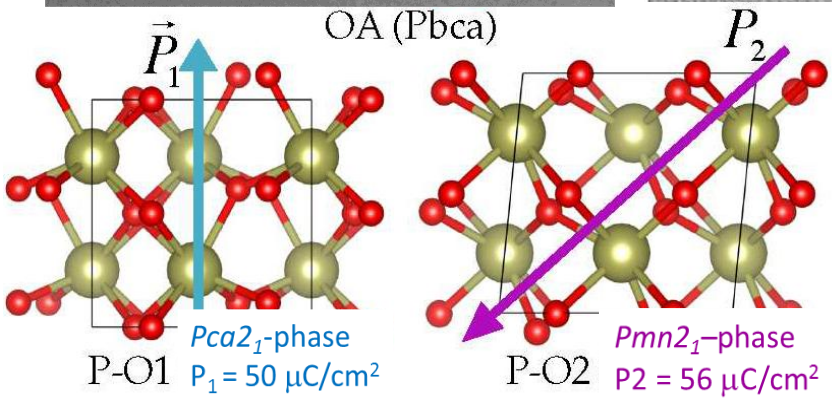
Stolichnov et al. ACS Appl. Mater. Interfaces, 10 (2018) 30514

SOS structures with ALD HfO_2 interlayer









*Batra et al. J. Phys. Chem. C, 2017, 121, 4139

Phase	a(Å)	b(Å)	c(Å)	β(°)	γ(°)
M	**5.15**	**5.20**	**5.33**	**99.7**	**90**
	(5.14[a], 5.12[b])	(5.20[a], 5.17[b])	(5.31[a], 5.29[b])	(99.8[a], 99.2[b])	(90[a], 90[b])
T	**5.08**	**5.08**	**5.23**	**90**	**90**
	(5.08[a], 5.08[c])	(5.08[a], 5.08[c])	(5.28[a], 5.20[c])	(90[a], 90[c])	(90[a], 90[c])
P-O1	**5.06**	**5.09**	**5.27**	**90**	**90**
	(5.01[a], 4.90[c])	(5.08[a], 4.92[c])	(5.29[a], 5.10[c])	(90[a], 90[c])	(90[a], 90[c])
P-O2	**5.13**	**5.13**	**5.18**	**90**	**84.07**
	(5.12[a])	(5.12[a])	(5.18[a])	(90[a])	(83.51[a])
Exp	**5.01**	**5.01**	**5.24**	**90**	**84,5**

[a]Ref 13, [b]Ref 31,[c]Ref 32,[d]Ref 33 from DOI:10.1021@acs.jpcc.6b11972

Заключение

1. Медленные состояния IFS и ловушки заряда, а также сегнетоэлектрическая поляризация P есть после отжига до 1000°C в КНИ и КНС структурах с ALD high-k стеком HfO_2 /Al_2O_3
2. Биаксиальные напряжения в слое HfO_2 КНС структур обеспечивают низкие коэрцетивные поля $E_C \geq 0.01$ МВ/см для сегнетоэлектрического переключения поляризации P в отличие от КНИ ($E_C \geq 1.0$ МВ/см)
3. Для сохранения сегнетоэлектрических свойств ALD high-k стеков HfO_2 /Al_2O_3 при ВТ термообработках необходимы RTA отжиги
4. Сегнетоэлектрические свойства pseudo-MOSFETs открывают новые пути создания FeFET и AFeFET транзисторов для встроенной памяти eNVM
5. КНИ и КНС структуры с high-k межслойными сегнетоэлектриками HZO перспективны для FeRAM на транзисторах FeFET, AFeFET, а также для нейронных сетей с Искуственным Интеллектом

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