

Van der Waals ferroelectric heterostructures for in-memory computing and beyond Moore electronics

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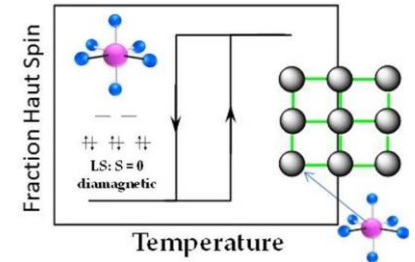
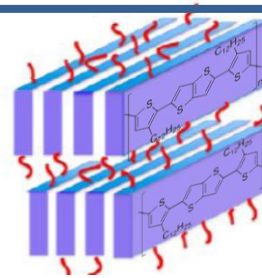
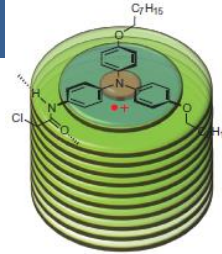
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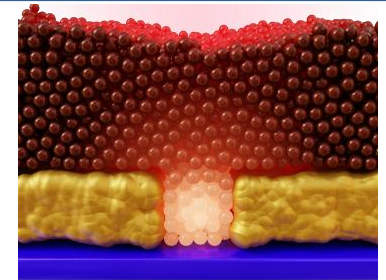
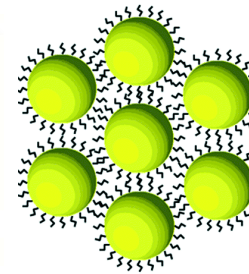
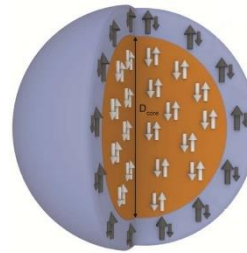
I. Organic and molecular electronics

*Supramolecular systems.
Molecular switch (Spin crossover)*



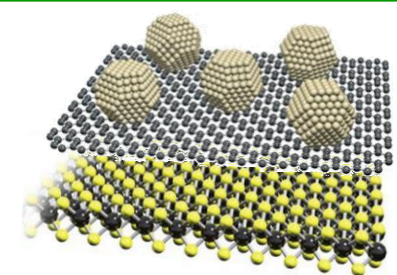
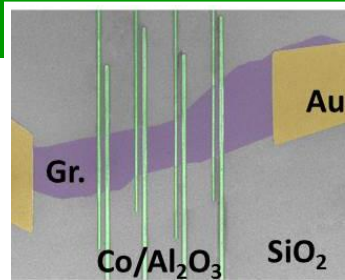
II. Nanocrystals & hybrids

*Magnetic nanocrystals
Quantum dots*



III. 2D materials & heterostructures

*Graphene, h-BN
2D ferroelectrics, semiconductors,
Heterostructures ...*



Basic Science

*Quant. transport :QHE, CB, Q. Interf
Spin transport (proximity, spin filtering)
Photoconduction*

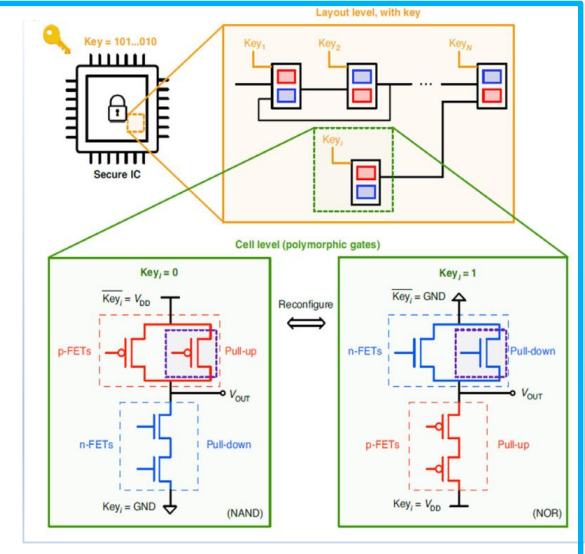
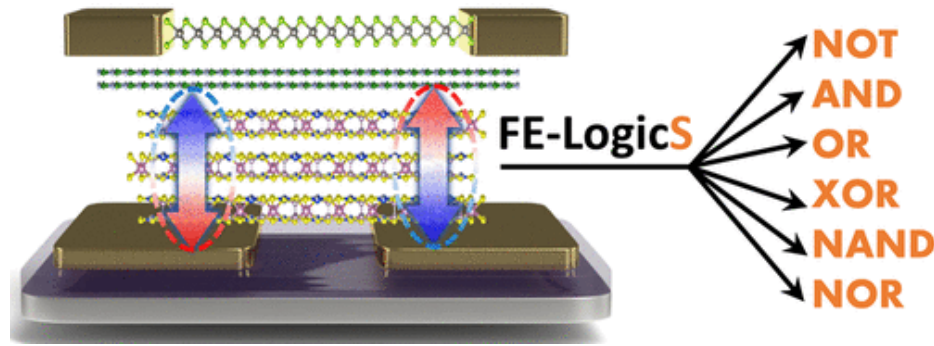
Applied science

*Nanoelectronics FET, SET, artificial synapse
Spintronics Magnetic tunnel junct°, memory
Optoelectronics Photodetector, optical memory*

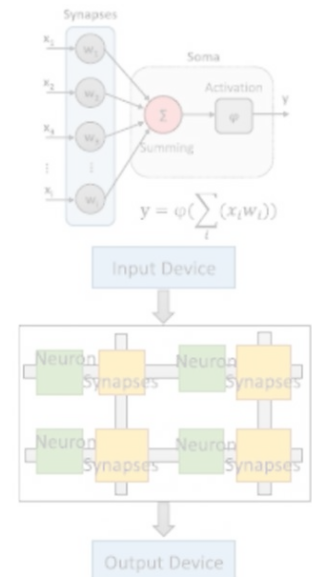
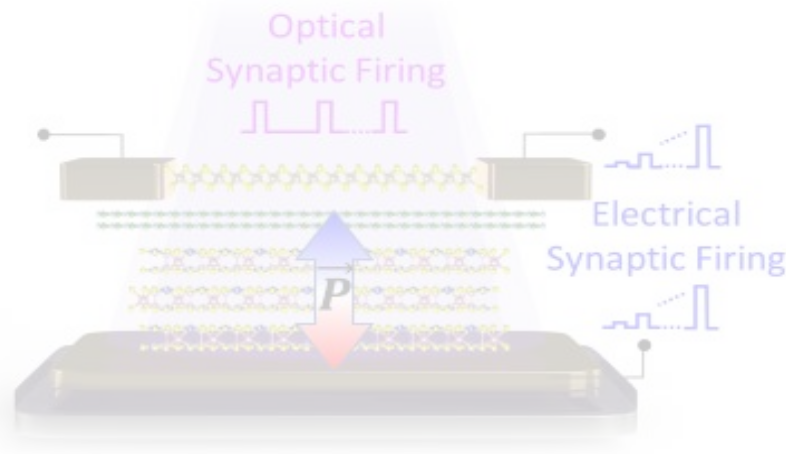
Outline

Van der Waals heterostructure for “beyond CMOS” strategy

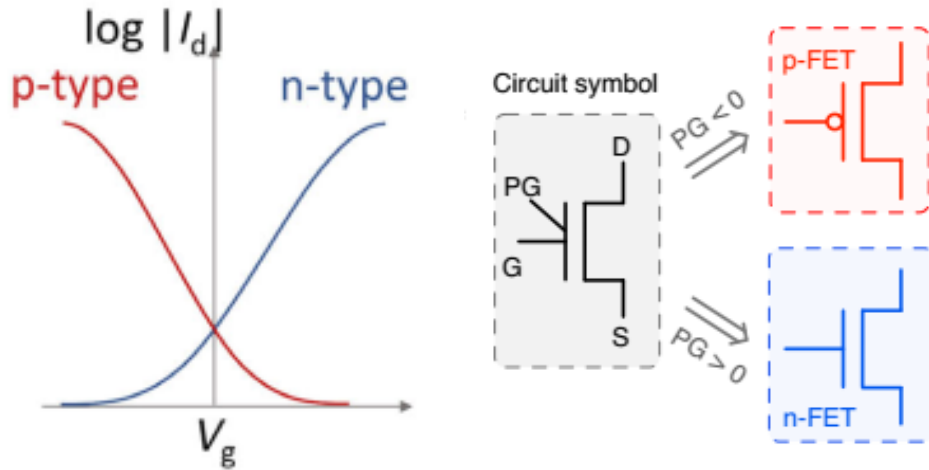
- **Reconfigurable electronics**



- **non-Von Neumann Computing : artificial synapse**

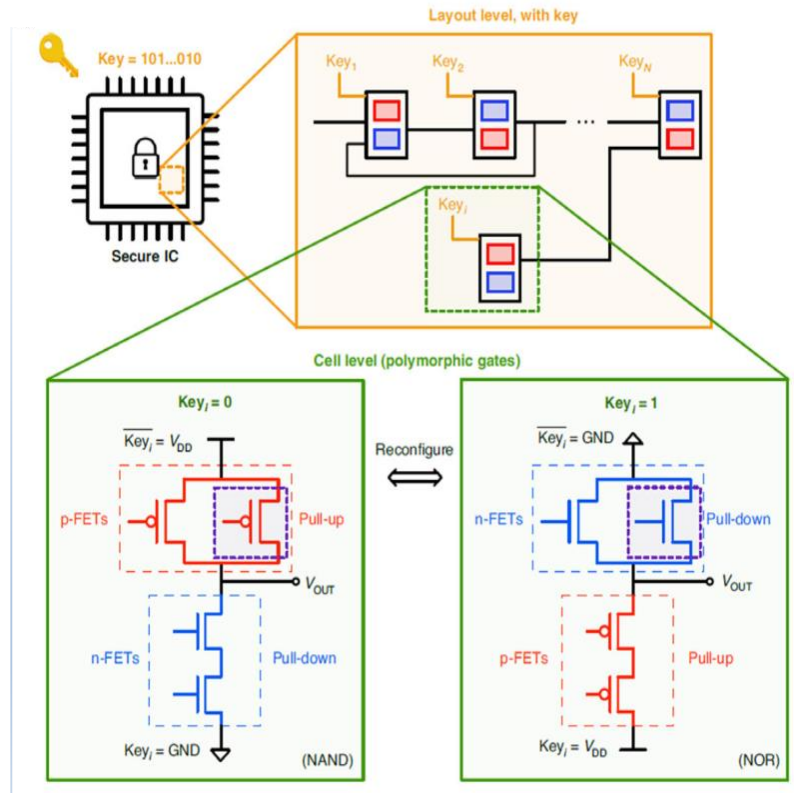


Reconfigurable electronics



Motivations :

- MOSFET with tunable polarity (n, p).
- new circuit topologies :
 - better scalability, power efficiency
 - hardware security
 - multi-functionality



Materials requirements :

- ♠ excellent **electrical tunability**
- ♠ **ambipolar** ($E_g < 1.4$ eV)
- ♠ **multiple gates** integrat°.
- ✓ **2D materials**

Our goal :

- Potential of 2D material of Reconf. Elec. ?
 - Ferroelectric reconfigurable devices ?
 - new logic concept
 - « 2-in-1 » in memory computing
- Ferroelectric + Semiconductor 2D materials

Review : W Fei, et al., InfoMat 2022, 4, e12355

Example : Wu, P., et al. Nature Elec. 2021, 4, 45 (Purdue Univ.)

Ferroelectric devices in a nutshell

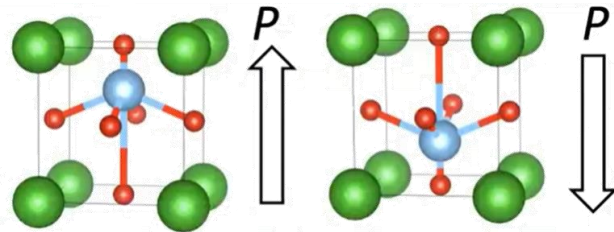
Ferroelectric materials (i) Insulator with spontaneous polarization P ; (ii) P can be reversed by an electric field.

Broken inversion symmetry

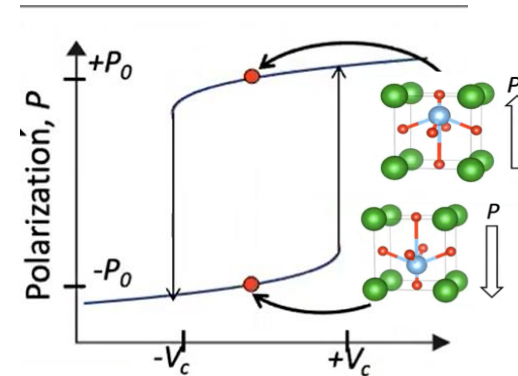
→ stable electric dipole

→ 2 configurations +/- P

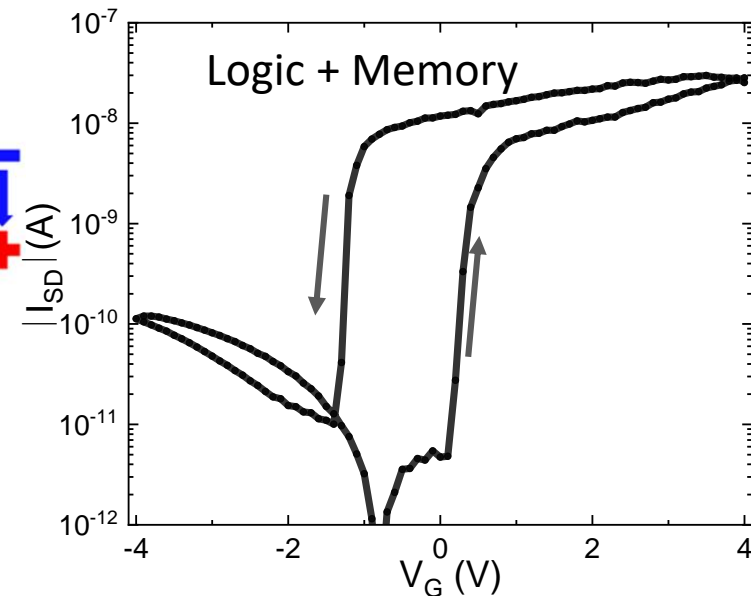
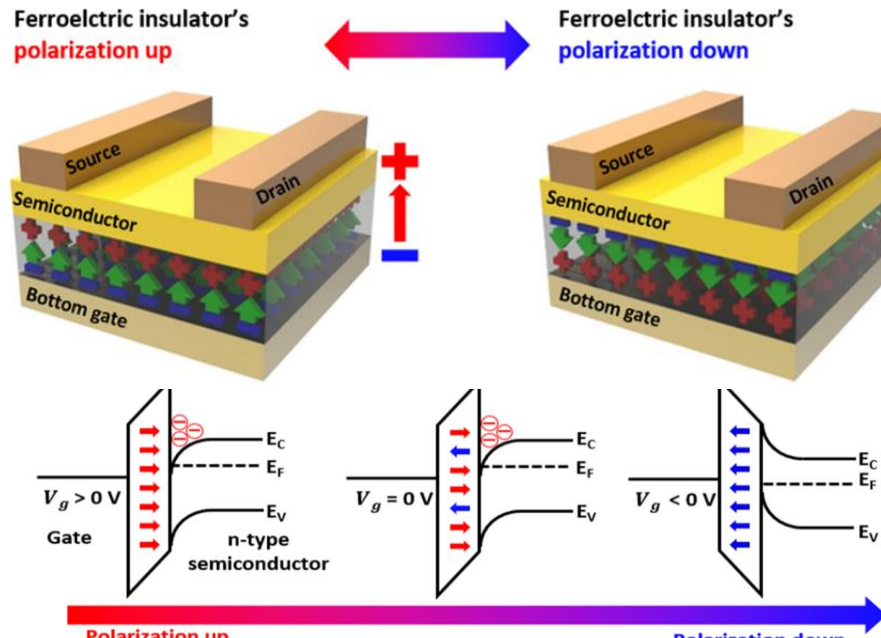
Ex : PbTiO_3 , BaTiO_3 , HfO_2



→ Can be switched by E field.

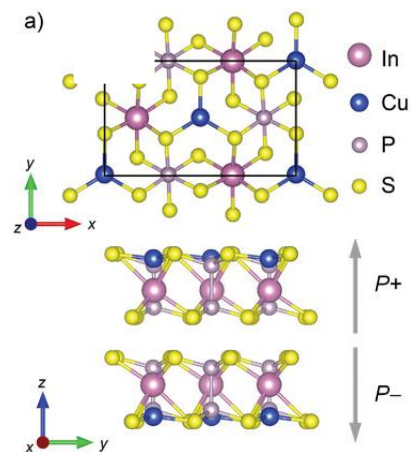
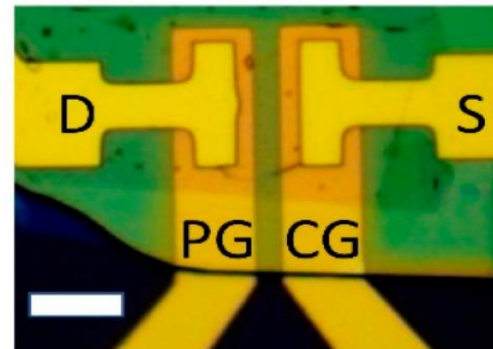
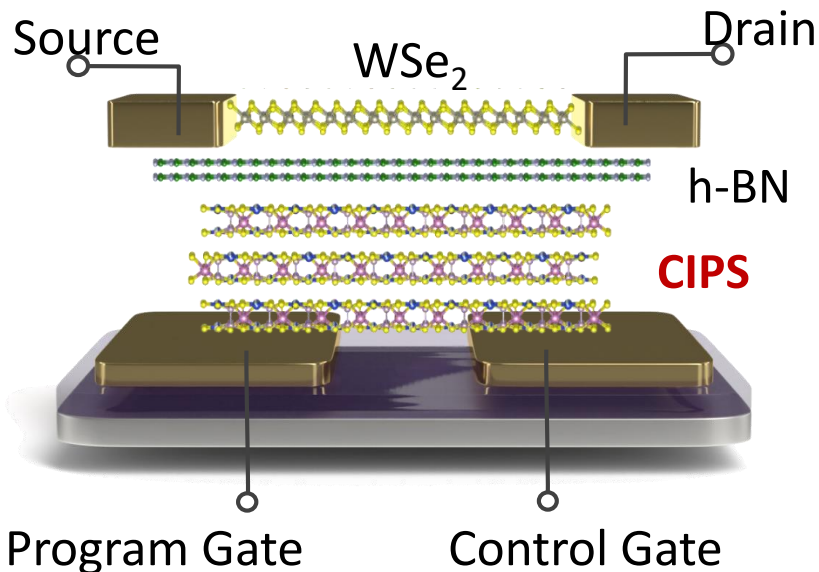


Ferroelectric Field Effect Transistor → logic, in-memory computing, energy harvesting, A.I. ...



Reconfigurable Ferroelectric Devices

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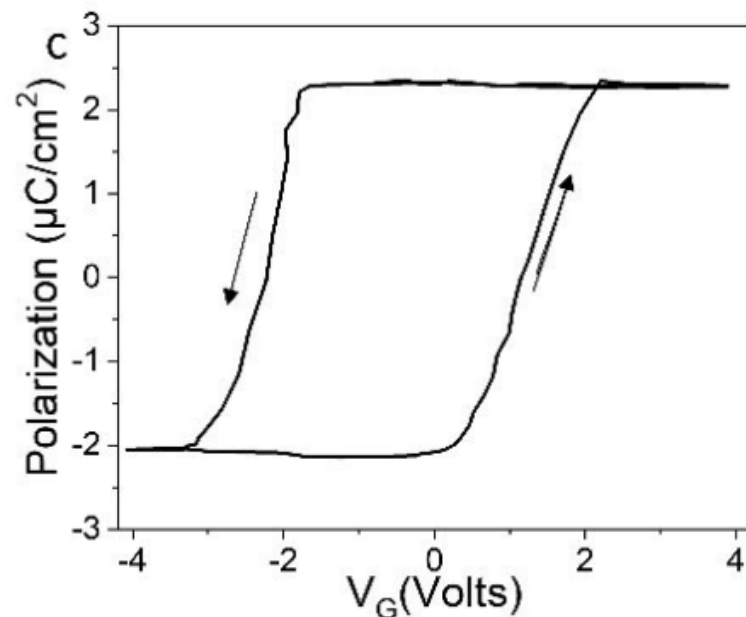


Ferroelectric CuInP₂S₆:

Insulator : 2.9 eV gap

Critical temp. ~ 320 K

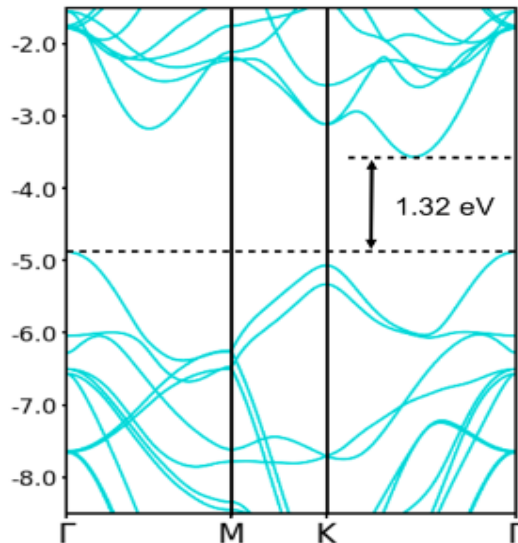
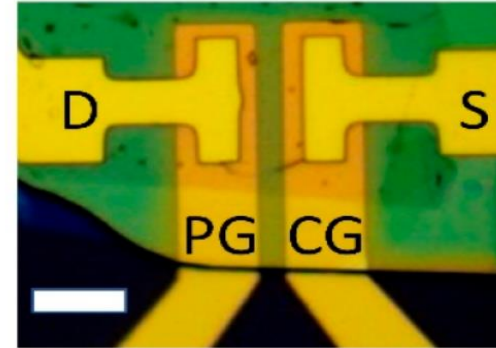
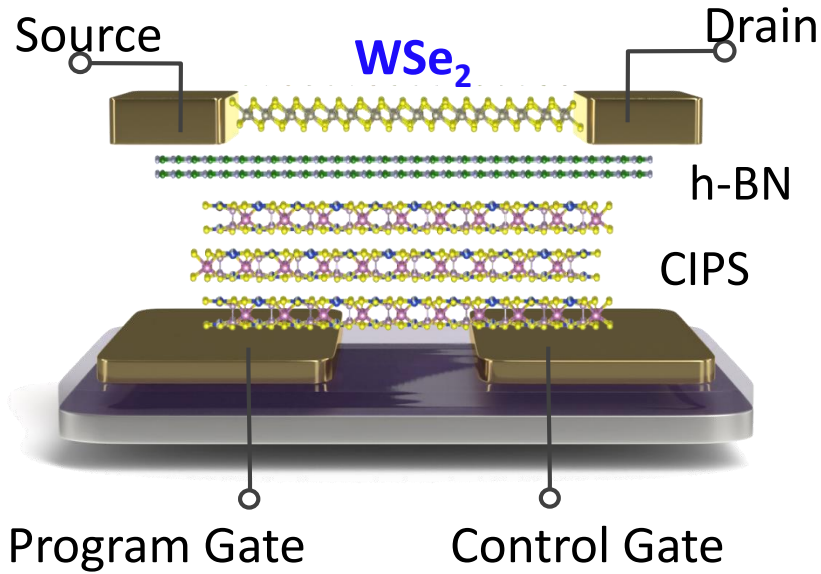
Robust FE down to 1 U.C. (~ 4nm)



Nature Communications 2016, 12357
Nature Materials 2020, 43–48

Reconfigurable Ferroelectric Devices

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ACS Nano 2021, 15, 4, 7279

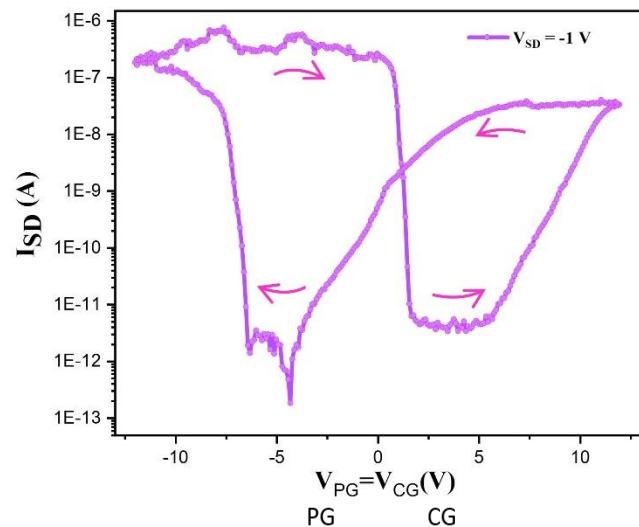
WSe_2

Semiconductor : 1.2-1.3 eV gap
Ambipolar functionality
Stable in air

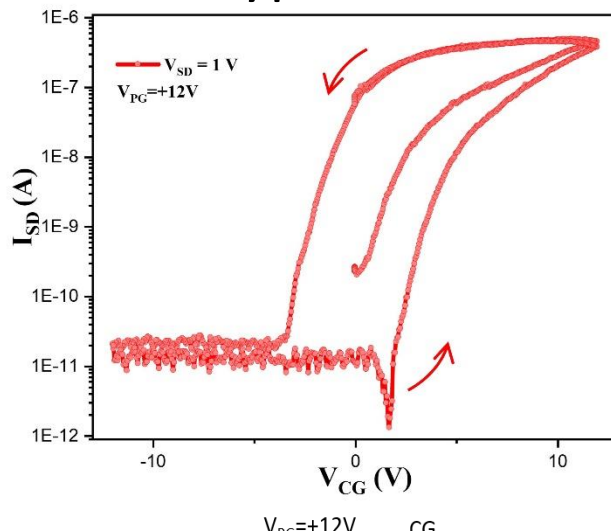
Reconfigurable FeFET functionality

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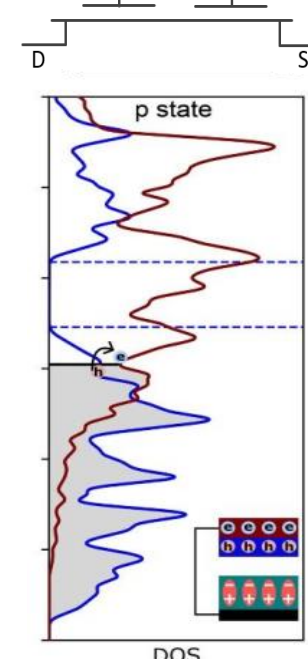
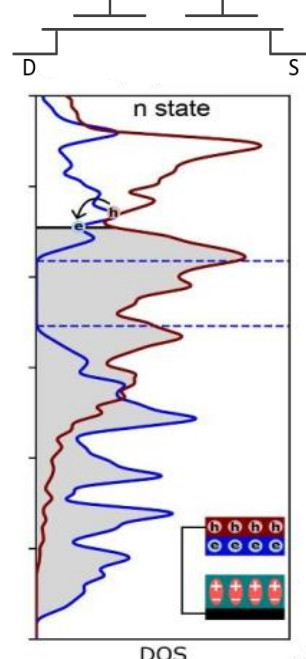
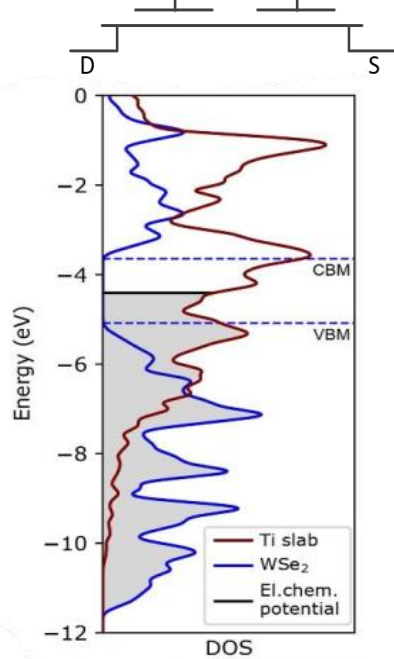
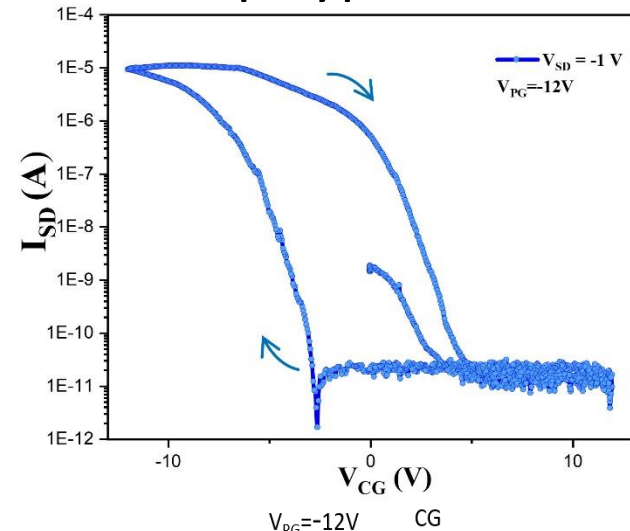
Ambipolar FeFET

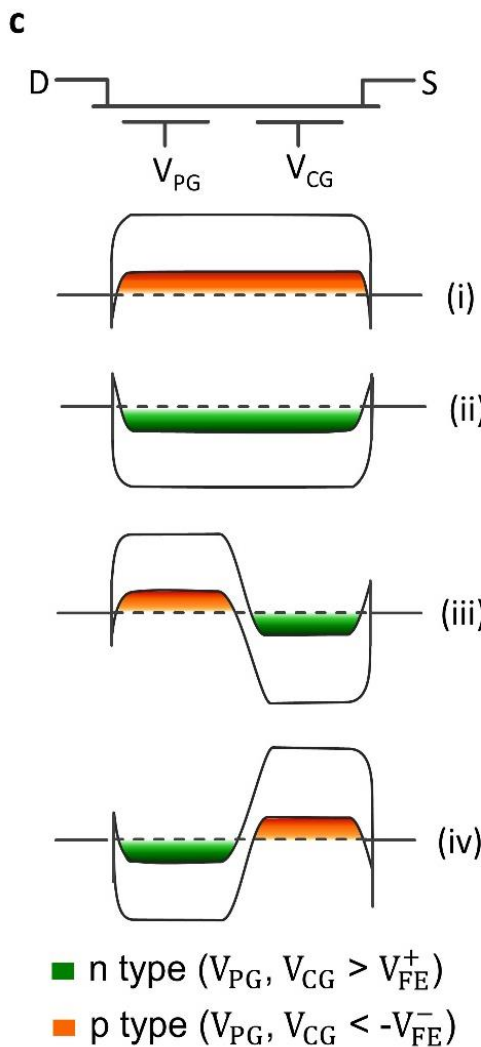
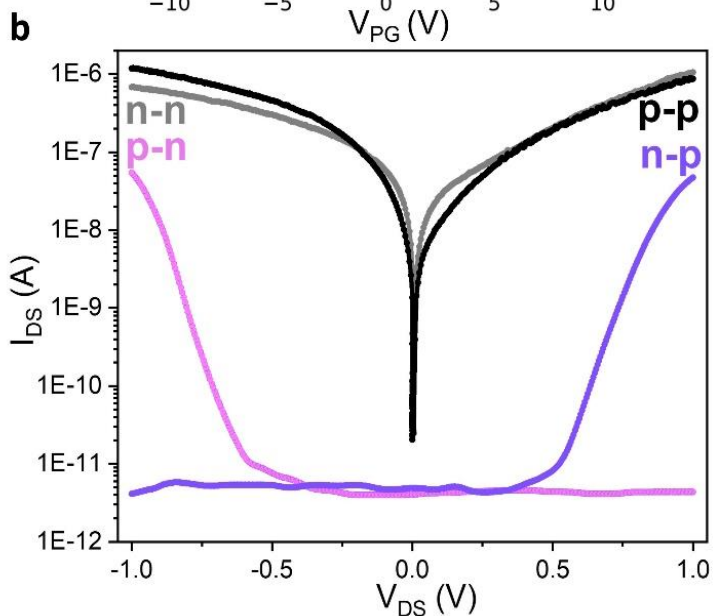
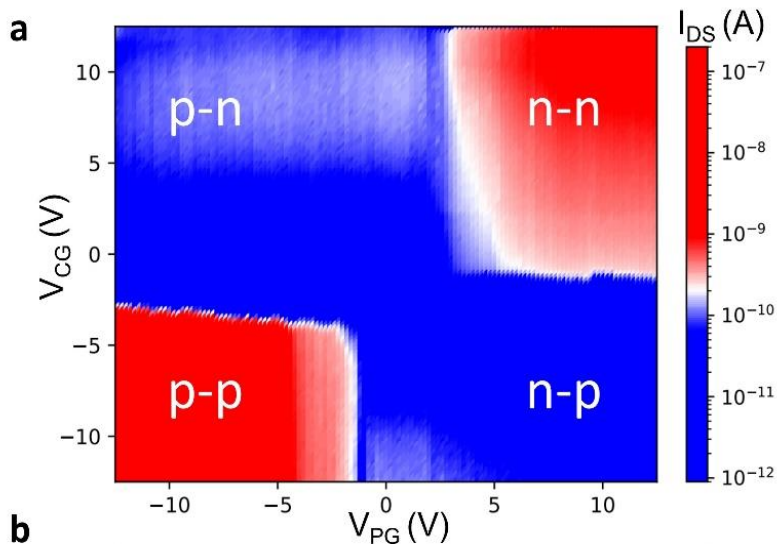


n-type FeFET



p-type FeFET



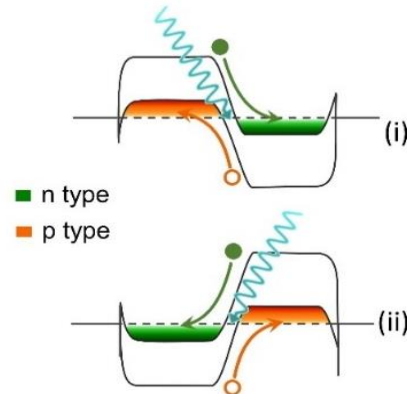
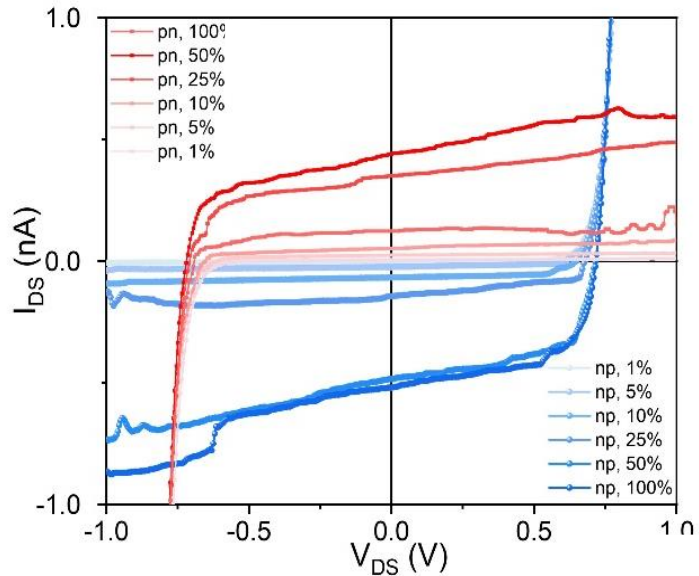


Tunable Homojunction :

- 4 states :
p-p, n-n, p-n, and n-p states
- Large rectification ratio
 $RR > 10^4$

Photodiode functionality

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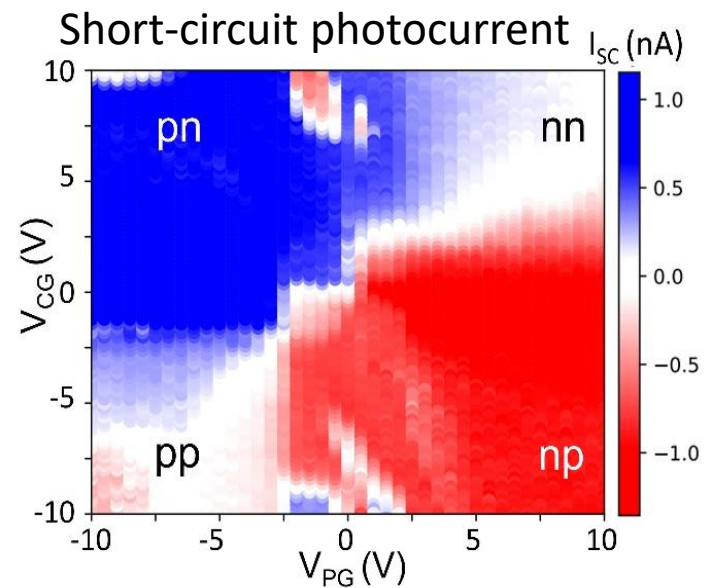
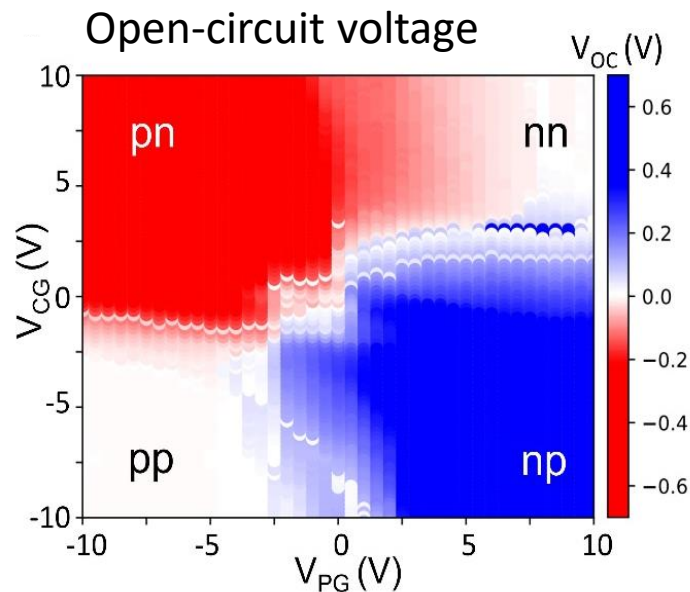


Diode modes

→ Built in electric field

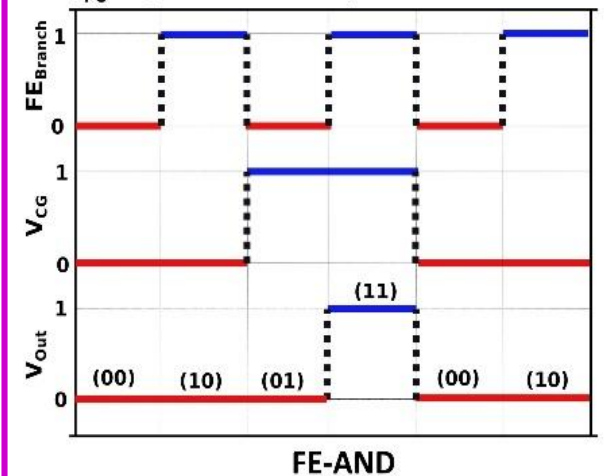
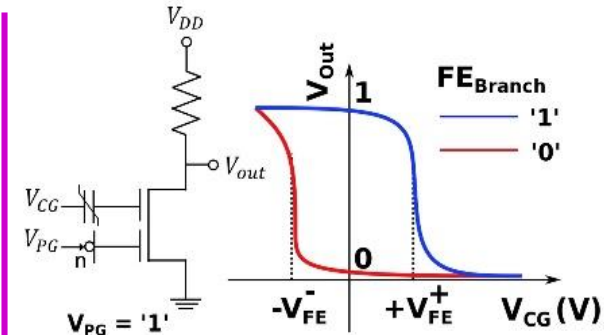
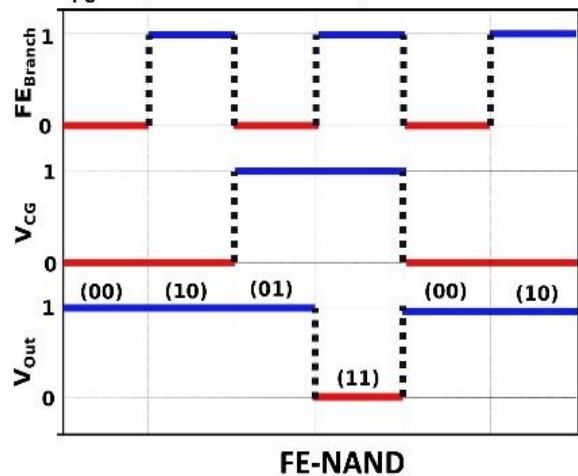
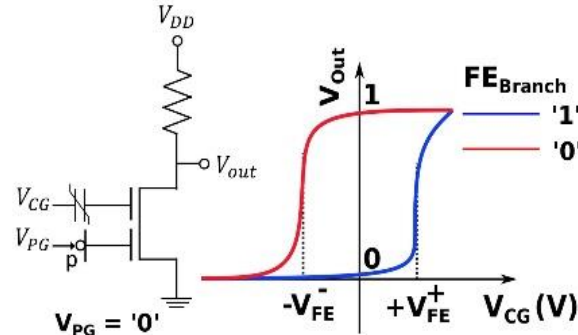
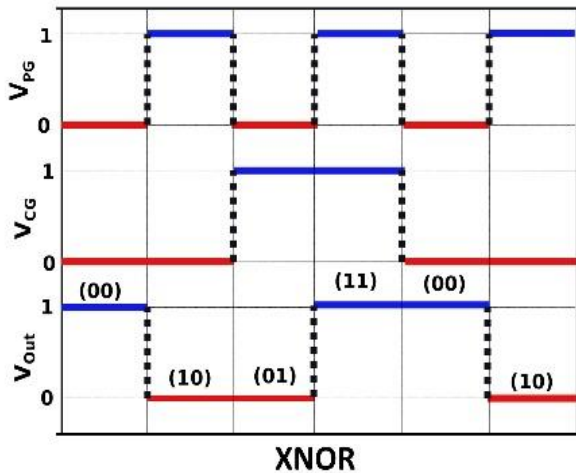
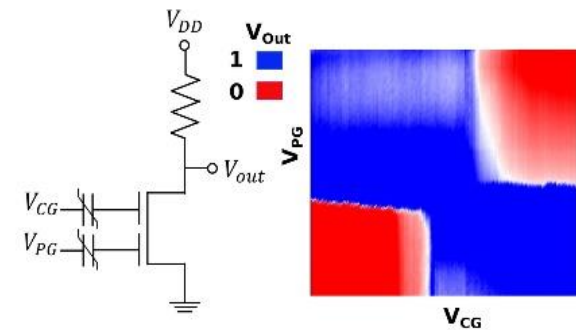
→ **Photovoltaic effect**

→ Consistent I_{SC} & V_{OC} polarity sign switching.



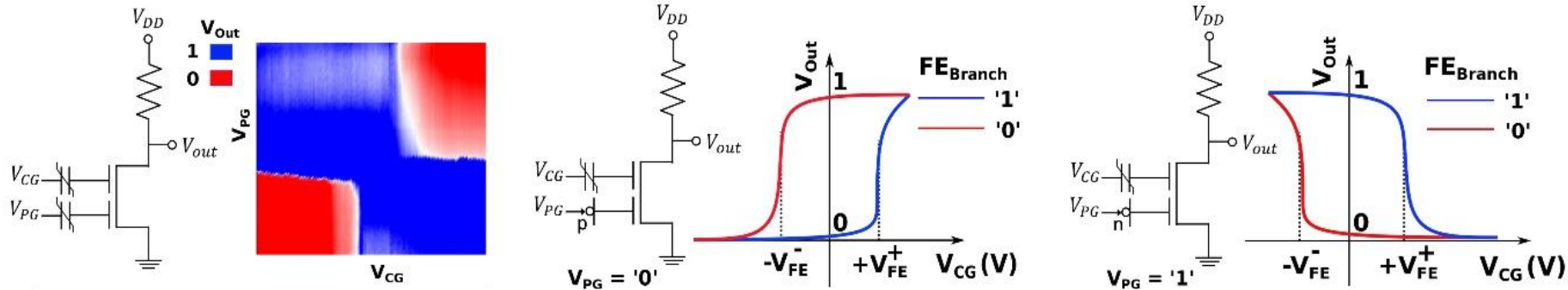
Polymorphic & reconfigurable Logic: Offers versatile logic options for custom operations.

- **Electronic Mode:** V_{CG} and V_{PG} as logic parameters.
- **Ferroelectric Modes:** Ferroelectric state & Gate Voltages as logic parameters.

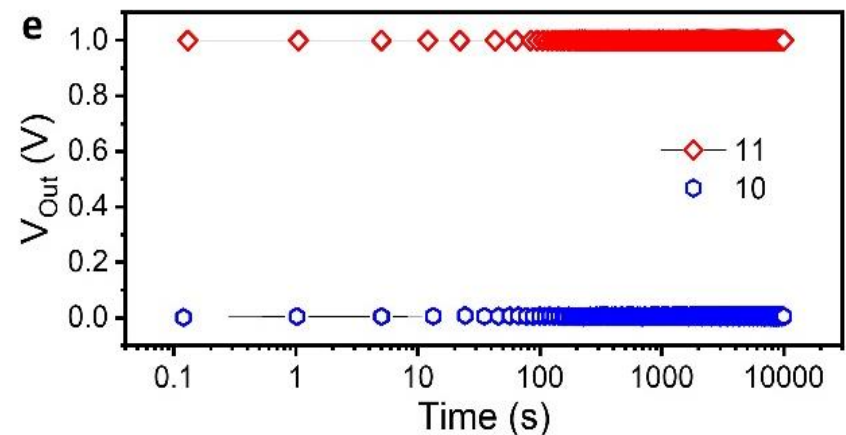
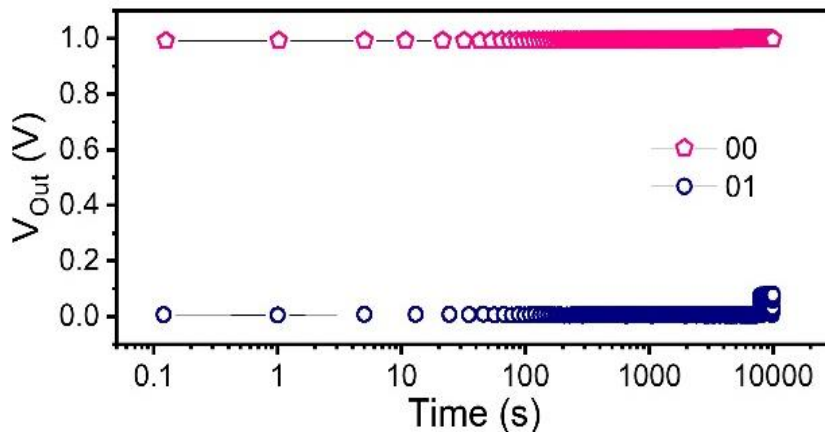


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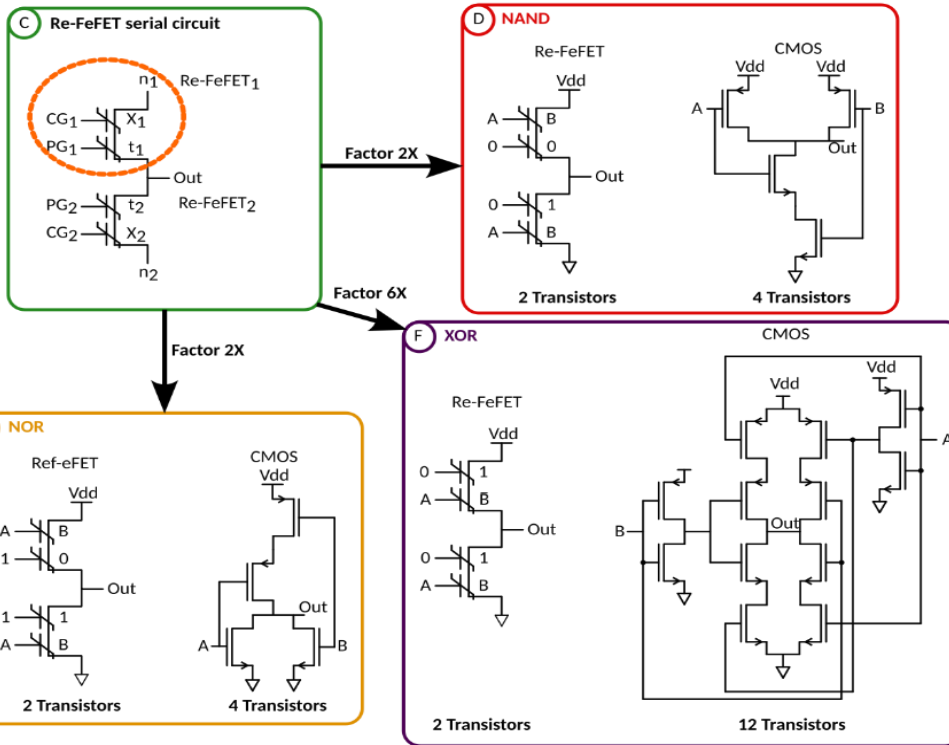
Non-volatile logics: Long Retention time \rightarrow Integrated Processing and Storage for in-memory computing



Circuit design exploration

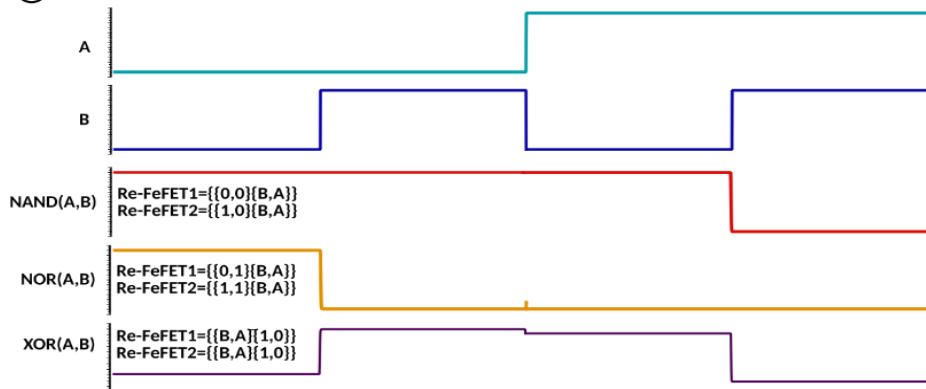
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Cédric Marchand & Ian O'Connor, EC Lyon



- **Circuit Design:**
Two series-connected Re-FeFETs.
FE states + Gate Voltages as logic parameters
- **Logic Functions :**
6 logics with one single device !
NAND, NOR, NOT, OR, AND, XOR
- **Compact Logic Gates:**
Up to 6x fewer transistors unit *Versus* CMOS.

G Cadence simulation of the equivalent circuit for the 2-input NAND, NOR, and XOR



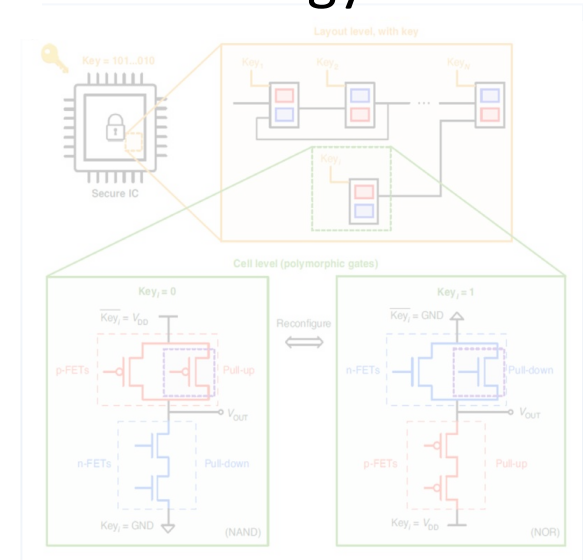
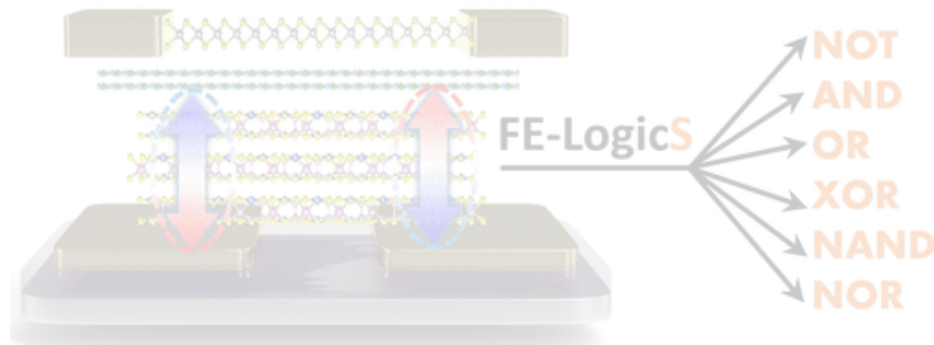
B Re-FeFET serial circuit configuration for elementary logic gates implementation

Operation	$Re-FeFET_1$				$Re-FeFET_2$			
	t_1	PG_1	X_1	CG_1	t_2	PG_2	X_2	CG_2
NOT	0	1	0	A	1	1	0	A
NAND	0	0	B	A	1	0	B	A
OR	0	0	\bar{B}	\bar{A}	1	0	\bar{B}	\bar{A}
NOR	0	1	B	A	1	1	B	A
AND	0	1	\bar{B}	\bar{A}	1	1	\bar{B}	\bar{A}
XOR	\bar{B}	A	1	0	B	A	1	0

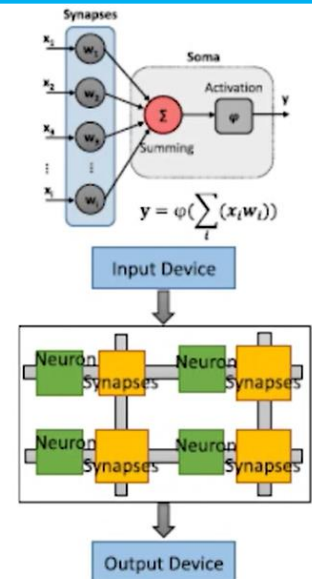
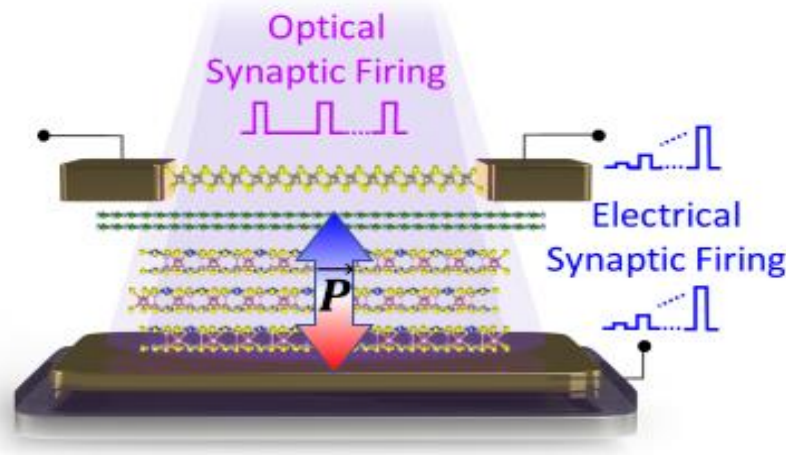
Outline

Van der Waals heterostructure for “beyond CMOS” strategy

- *Reconfigurable electronics*



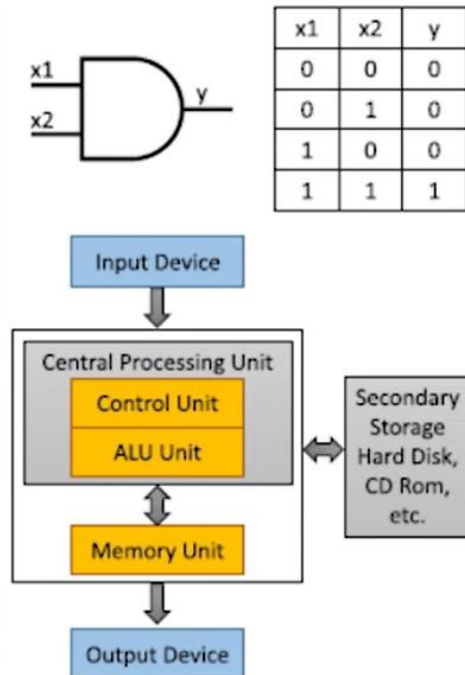
- *non-Von Neumann Computing : artificial synapse*



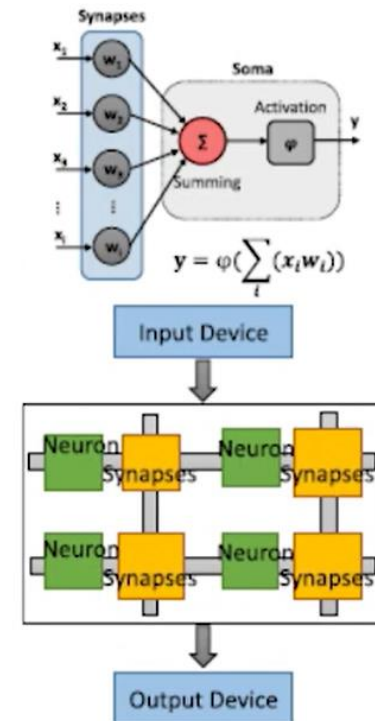
Energy band-profile control towards Reconfigurable Electronics

- **non-Von Neumann Computing** : circumvent latency bottleneck in *memory* ↔ *processing*

Von Neumann architecture



Neuromorphic architecture

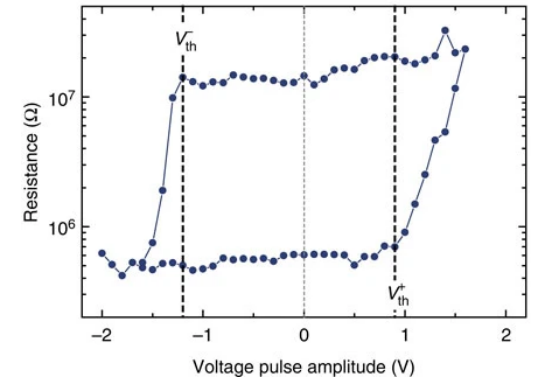
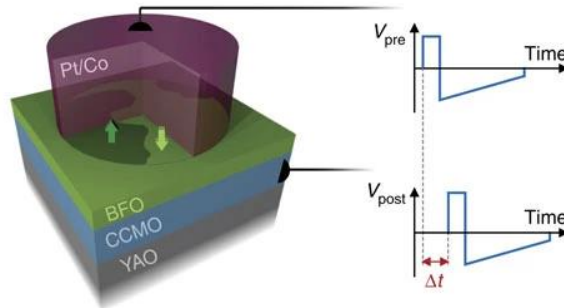
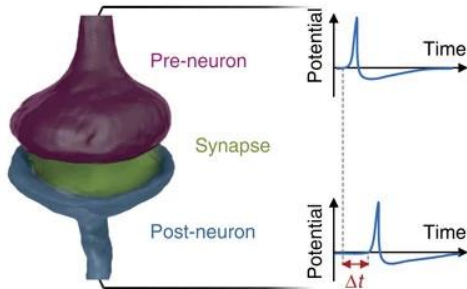


- Calculations and data storing needs : fast and low power consuming.
- Ex : Google's AI processor consume power ~ 100 kW;
Human brain takes only 20 W.

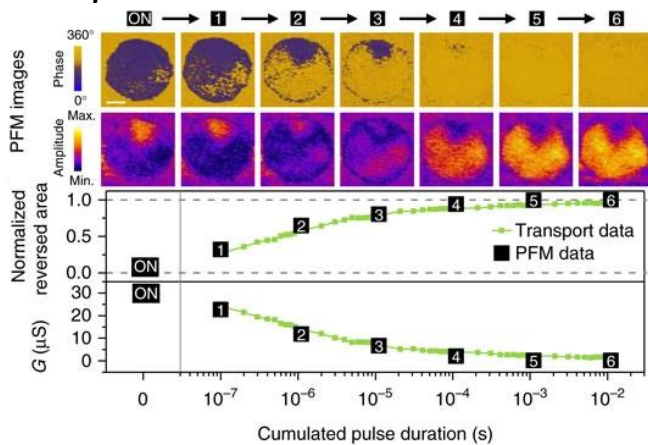
Ferroelectric Artificial Synapse

Learning through ferroelectric domain dynamics in solid-state synapses

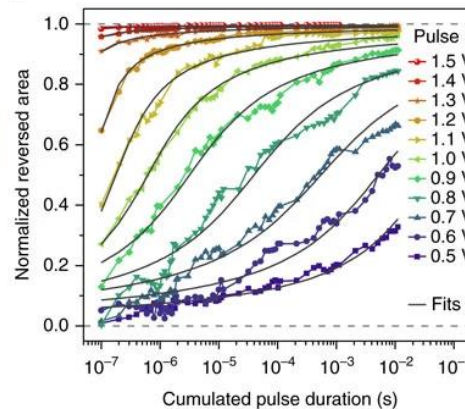
Sören Boyn^{1,†}, Julie Grollier¹, Gwendal Lecerf², Bin Xu³, Nicolas Locatelli⁴, Stéphane Fusil¹, Stéphanie Girod^{1,†}, Cécile Carrétéro¹, Karin Garcia¹, Stéphane Xavier⁵, Jean Tomas², Laurent Bellaïche³, Manuel Bibes¹, Agnès Barthélémy¹, Sylvain Saïghi² & Vincent Garcia¹ [Nature Comm. 2017, 8, 14736.](#)



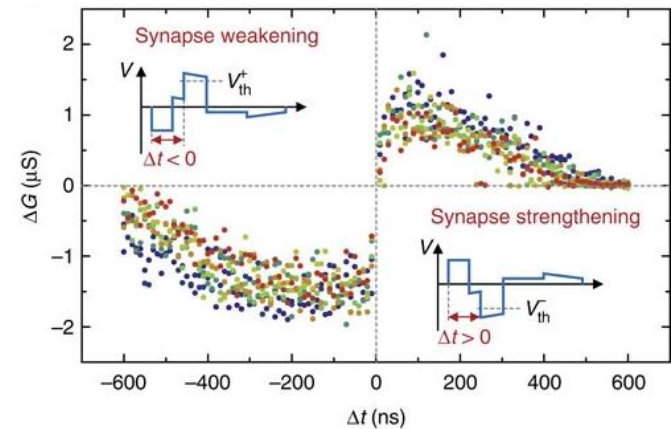
Multiple FE domains → Multi states

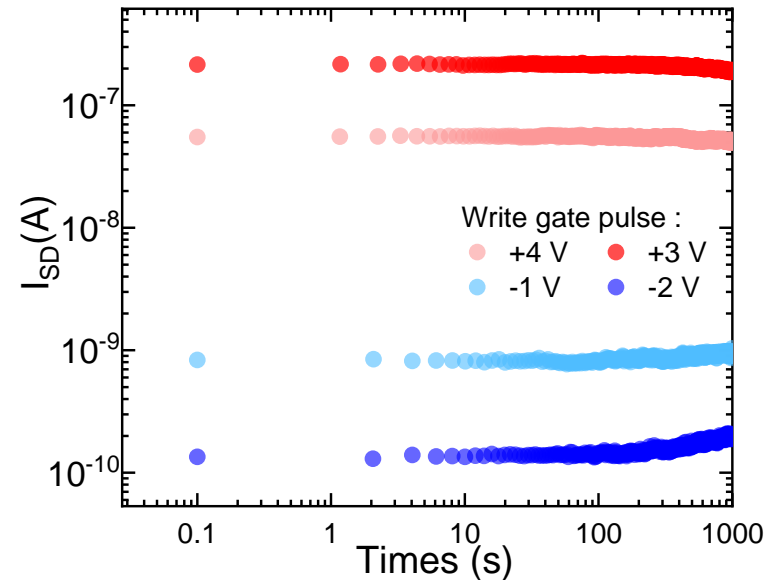
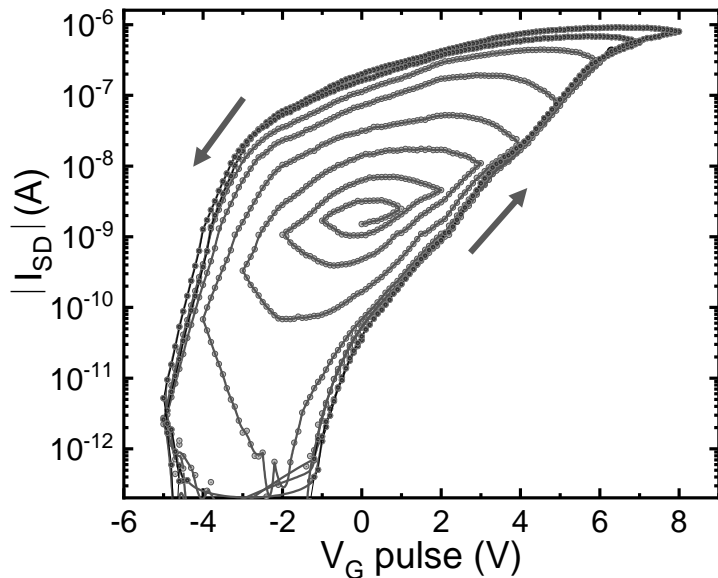
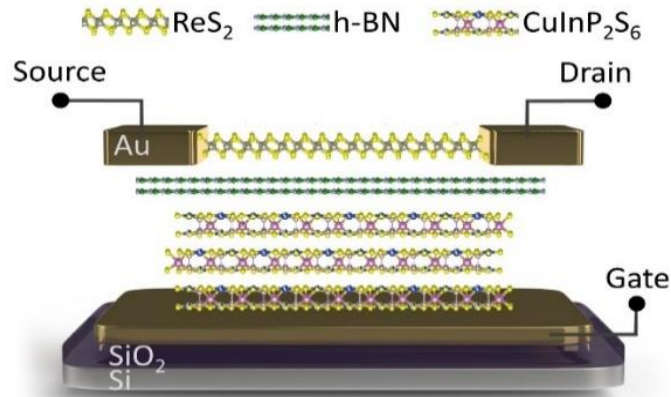


Synaptic plasticity

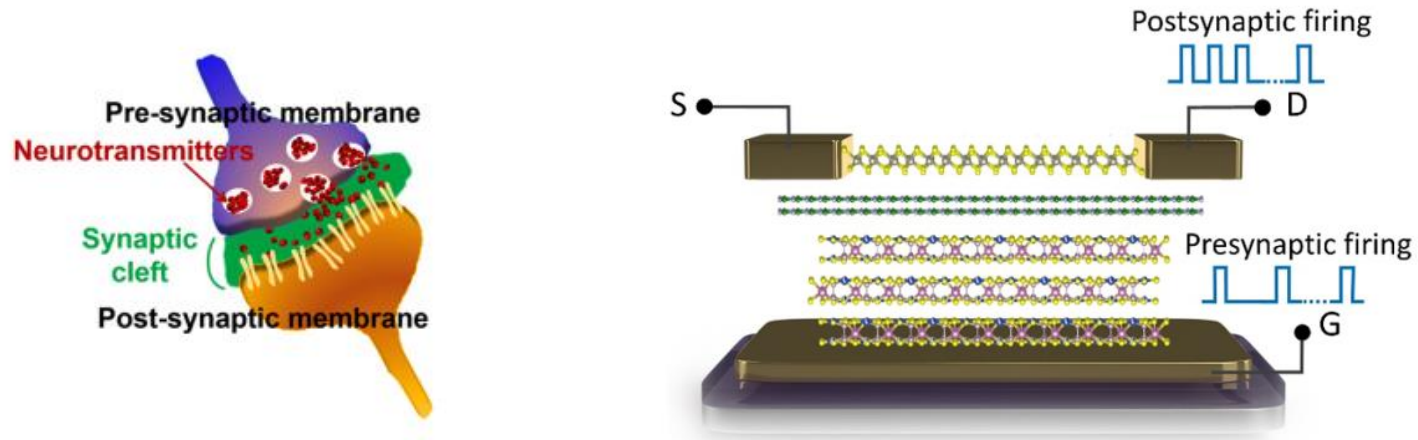


Hebb's rule



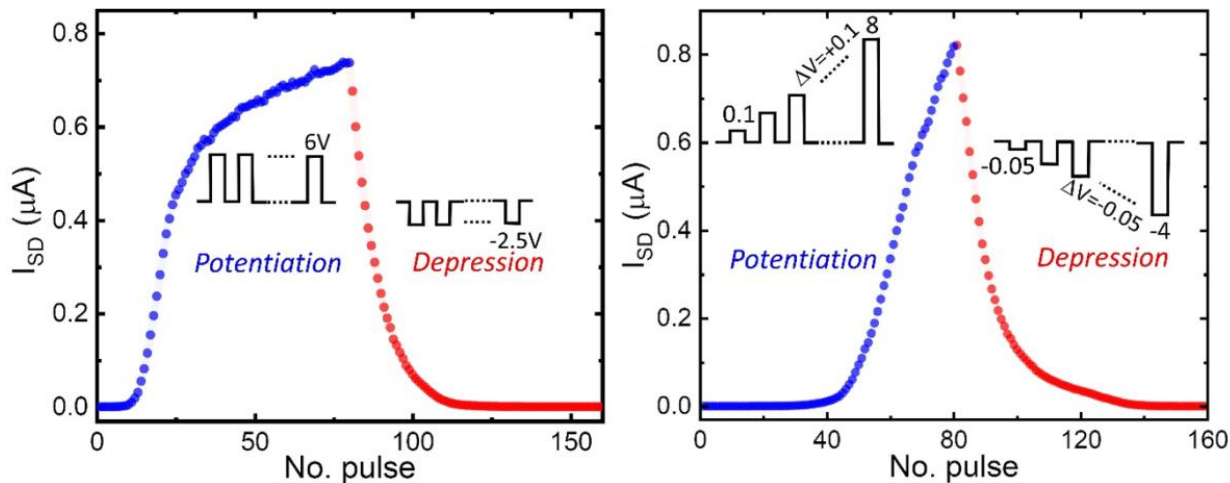


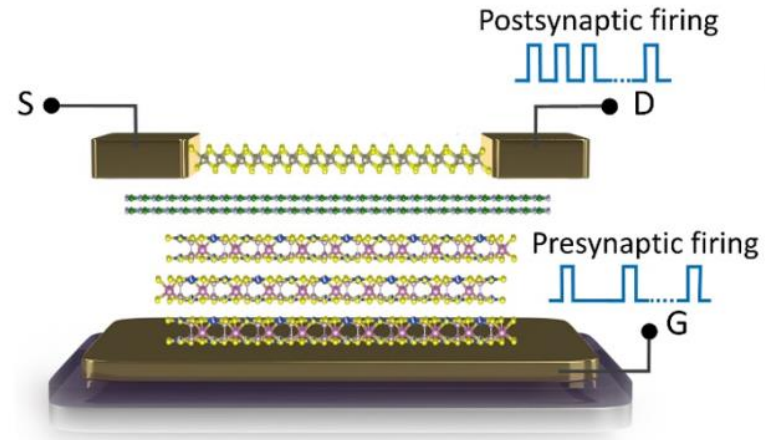
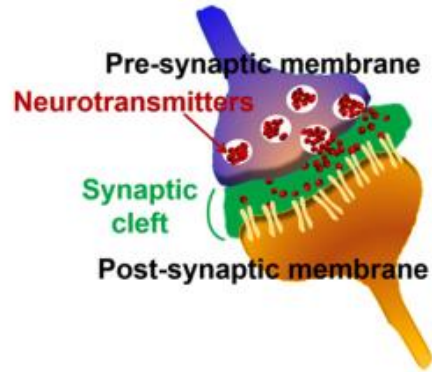
- **Multiple states** via exploring the space of ferroelectric multi-domains multi-states
- **Remanence life time** $\tau \sim 10\ 000$ seconds



Emulating synaptic features : Long Term Potentiation/Depression

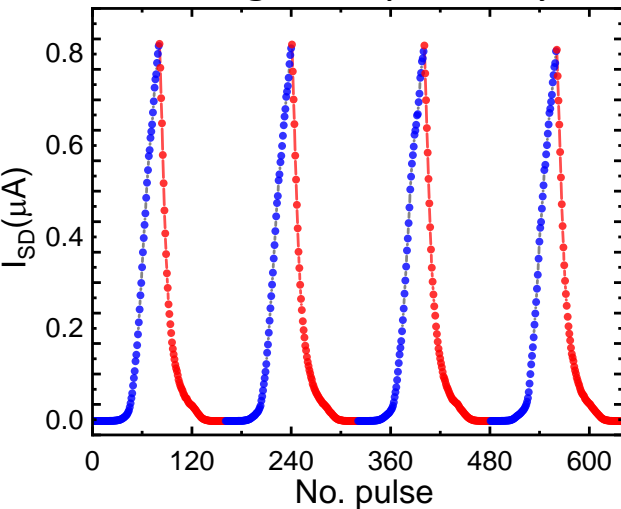
Writing/Erasing multiple states & Pulse shape modulated plasticity



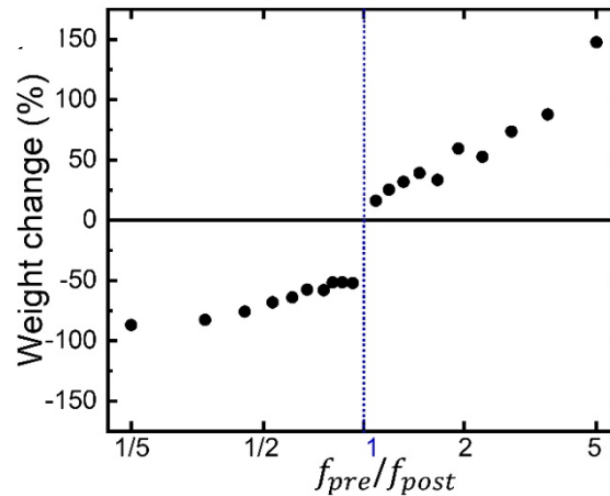


Emulating synaptic plasticity

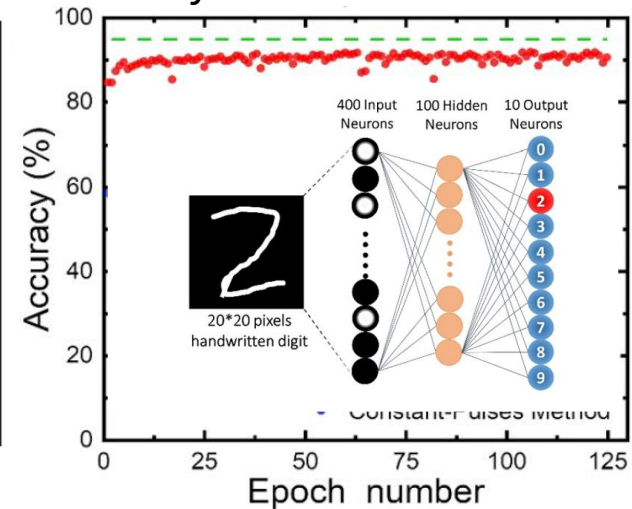
Long term plasticity



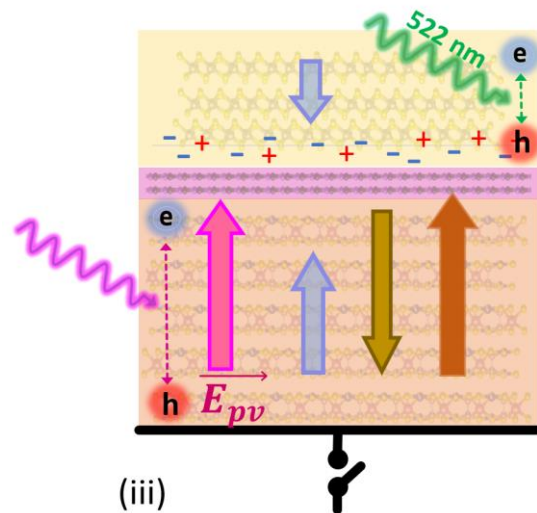
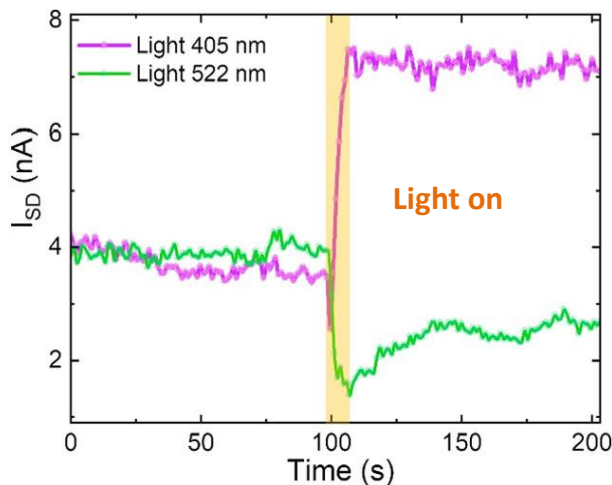
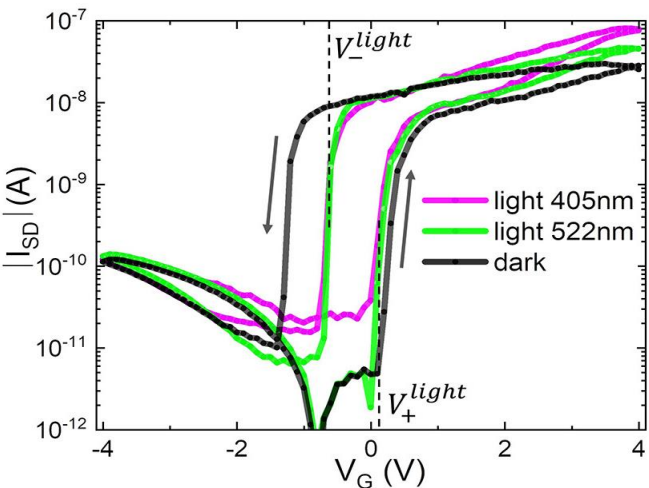
Hebb's rule



Artificial Neural Network

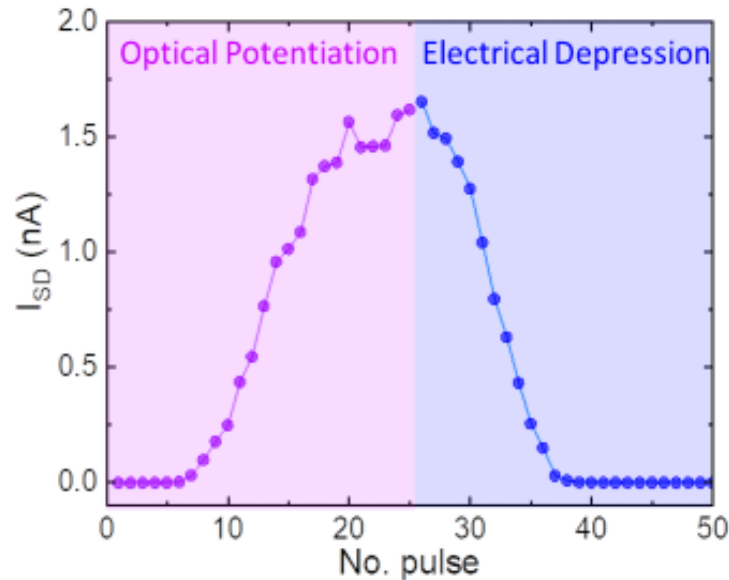
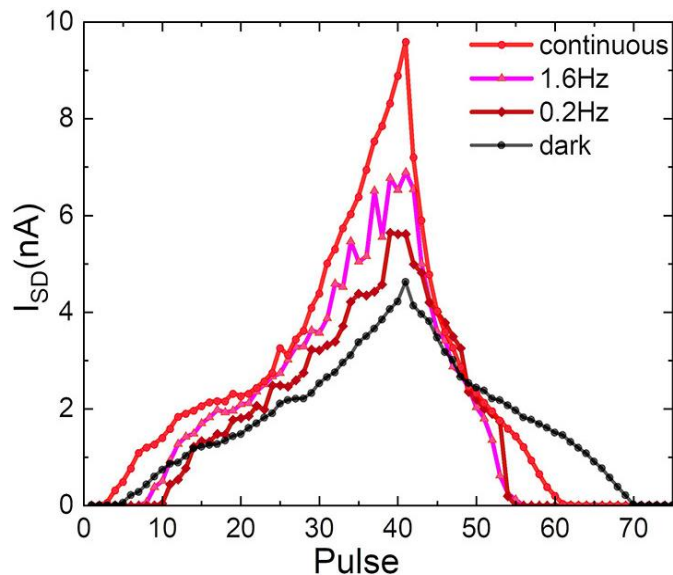


Optical control of Ferroelectricity



Assisted Optoelectrical Synapse

& Stimulated Optoelectrical Synapse

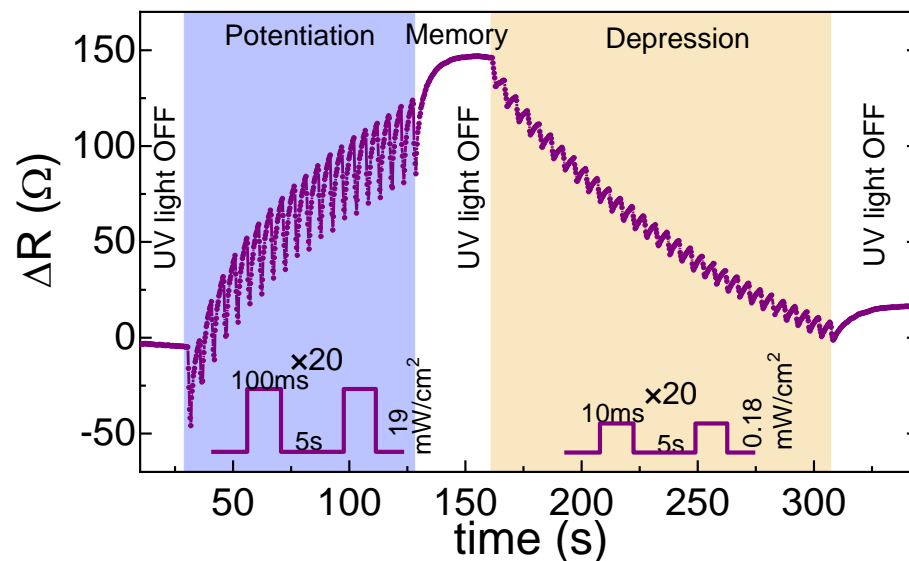
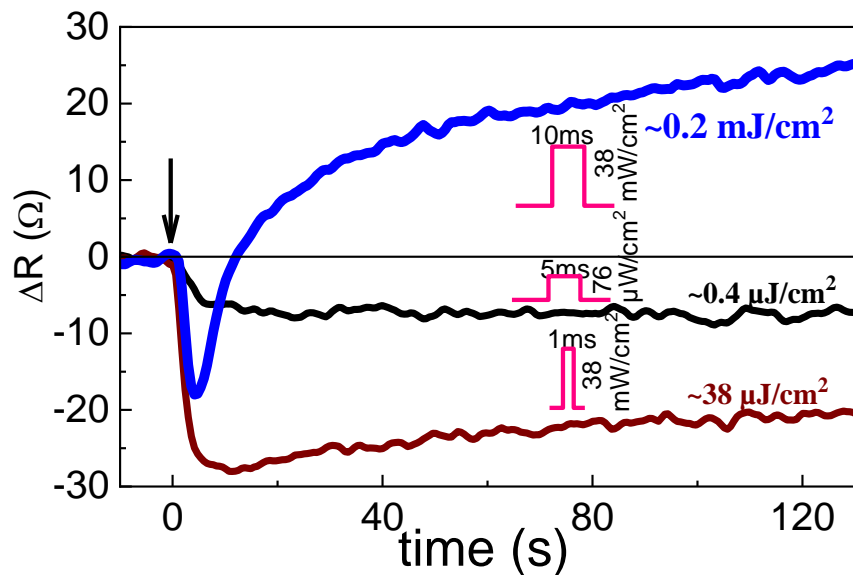
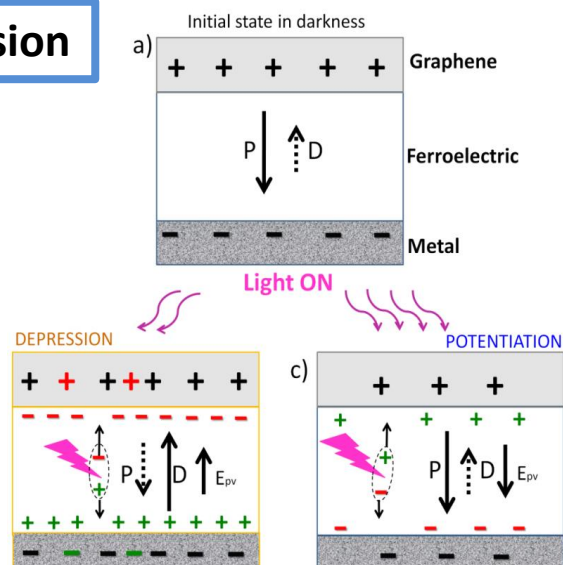
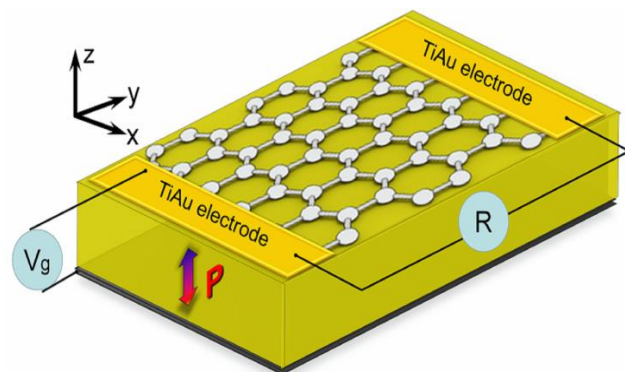


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doi:10.1021/acsaami.3c10010

Bohdan Kundys - Poster Session



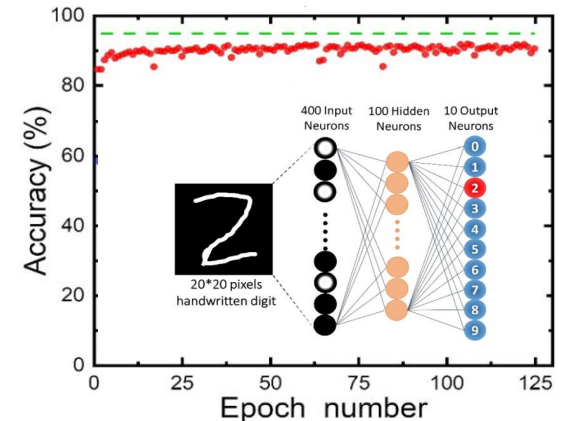
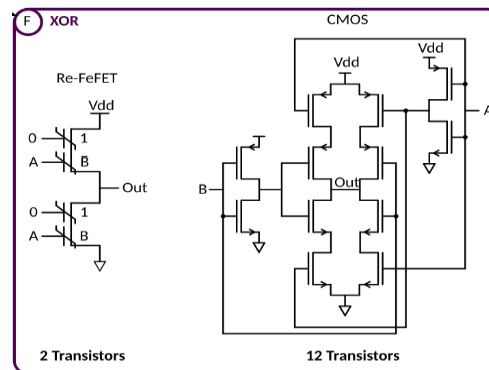
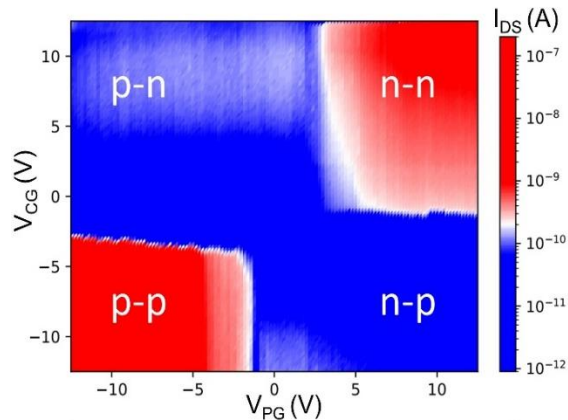
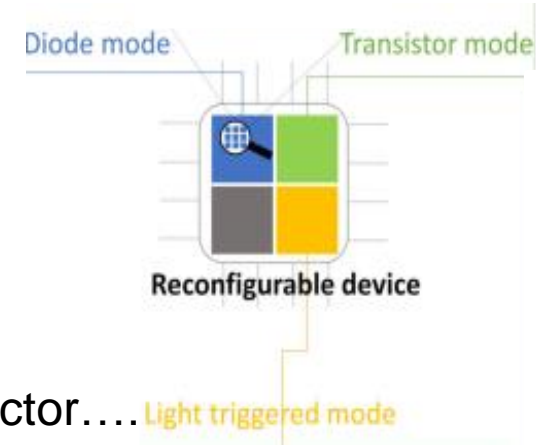
CONCLUSION

Van der Waals heterostructures :

- ✓ *Versatile platform*, crossroads of several fields
- ✓ *Heterogeneous electronics (More than Moore)*
Silicon & nanomaterials compatible
Wide class of materials : ferroelectric, insulator, semiconductor....

✓ *Beyond-CMOS strategies:*

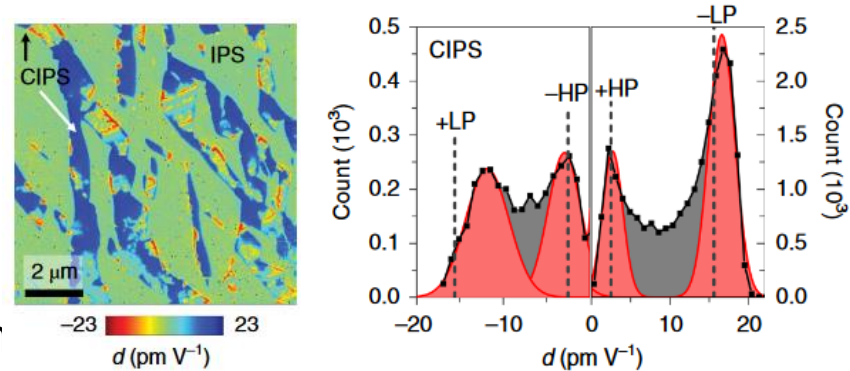
- (i) Reconfigurable Ferroelectric Logics
- (ii) New circuit topology : reconfig. + memory + optoelectronics
- (iii) Neuromorphic devices : electrical, optoelectrical synapses



CONCLUSION

Perspectives :

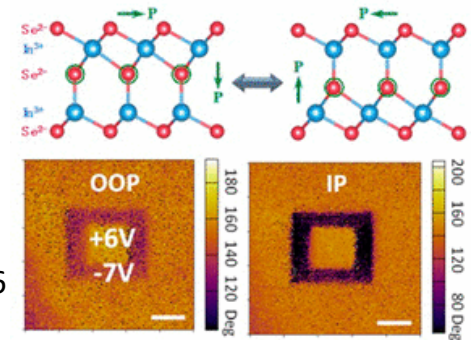
- ✓ *Ferroelectric basic understanding* :
FE domains switching dynamics
Quadrupole-well states control
Interfacial FE tuning (charge transfert, strair



J.A. Brehm et al., *Nature Materials* 2020, 19, 43

- ✓ *Ferroelectric semiconductors (In₂Se₃, InSe)*
Intercorrelated In-Plane and Out-of-Plane Ferroelectricity
Interwinned ferroelectricity & semiconductor transport

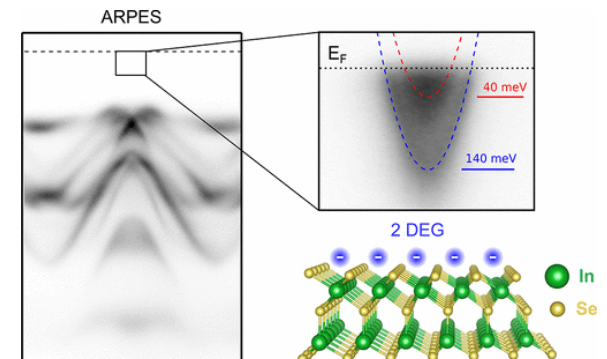
C. Cui et al. *Nano Lett.* 2018, 18, 2, 1253
M. Si et al. *Nature Elec.* 2019, 2, 580–586



- ✓ *2D gaz & ferroelectricity : (2H- α -In₂Se₃)*
Quantum confinement at the surface of FE 2D layer

G. Kremer et al. *ACS Nano* 2023, 17, 19, 18924–18931
(coll^o with A. Ouerghi group C2N & M.L. Della Roca group MPQ)

- ✓ *2D interfaced with oxide & quantum materials*
New effects/functionality, interfacial coupling, ...



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Merci !

