2D-Materials based memristors for neuromorphic computing

PEARL
Pervasive Electronics Advanced Research Laboratory

UNIVERSIDAD DE GRANADA

This project has received funding from the EU Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101032701

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Acknowledgement

European Union and Marie Skłodowska-Curie (MSCA) Fellowship

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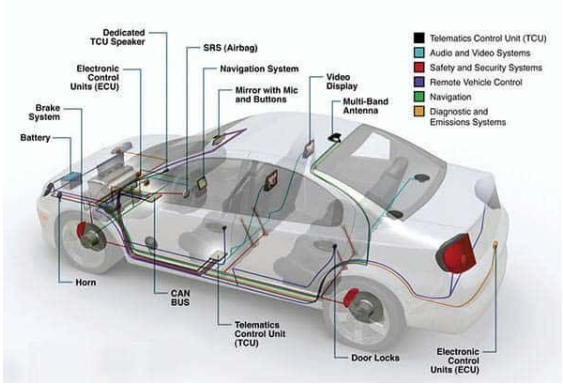
Electronics is everywhere

Hard to imagine a world without it

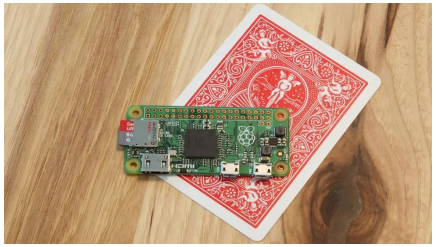


Exponential growth

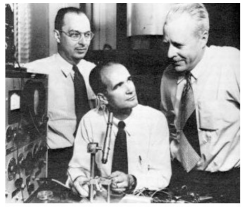
ENIAC

50x30 feet room

https://www.britannica.com/technology/ENIAC



Quad processor @ 1.2 GHz



John Bardeen, Walter Brattain, William Shockley

Nobel - 1965

Jack Kilby and Robert Noyce

Nobel - 2000

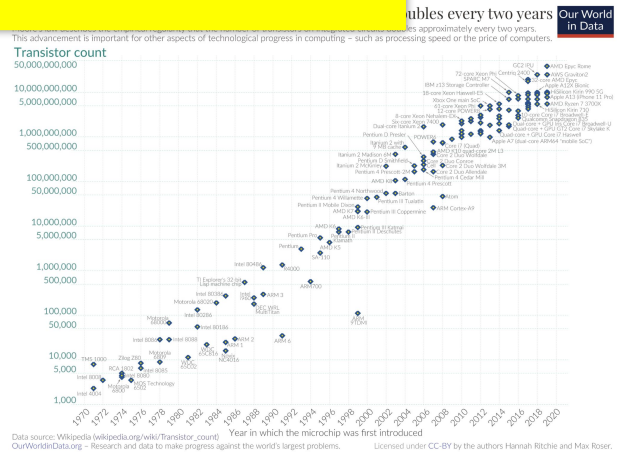
Perfect formula for economic growth !!!

3.75 M HDD

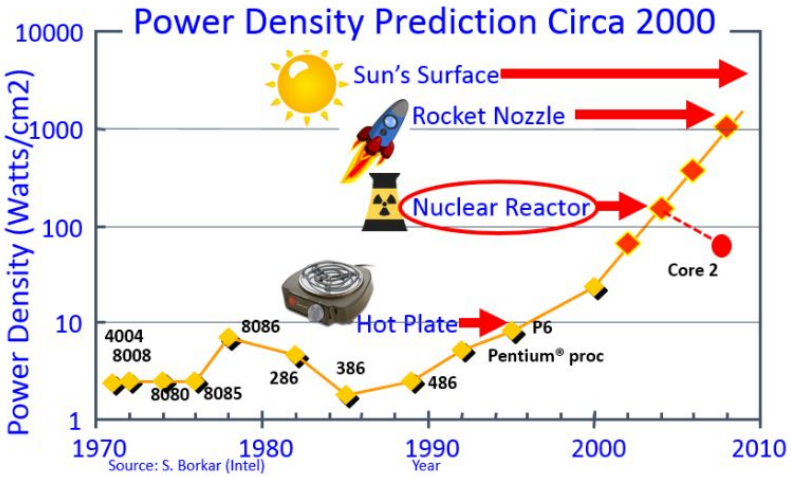
in 1956

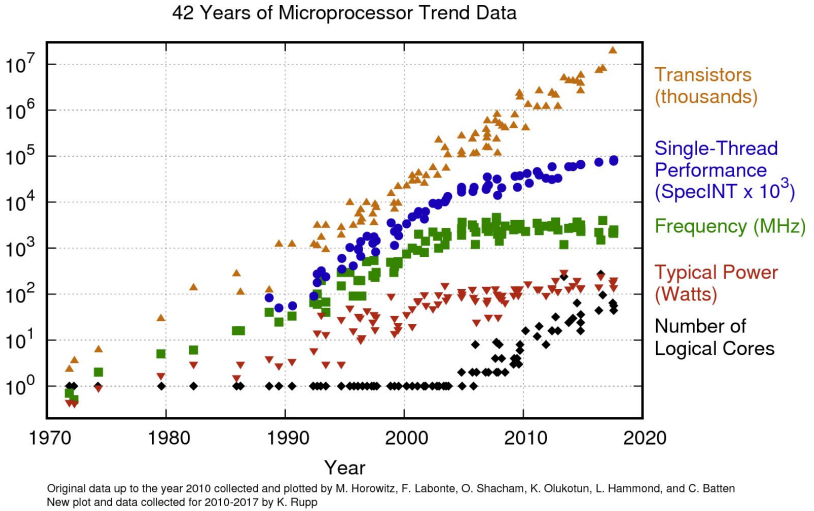
https://www.bbc.com/news/technology-34922561

1TB Solid State drive



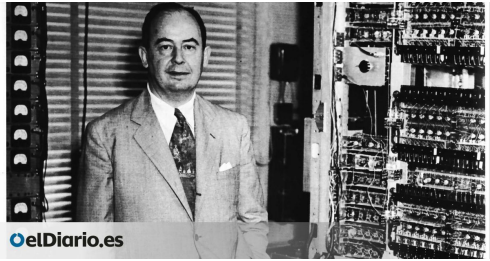
There is no free lunch !!



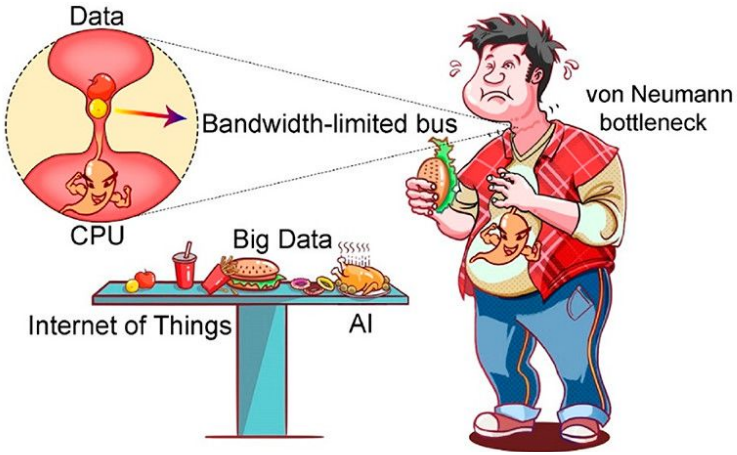


Power density is the limiting factor

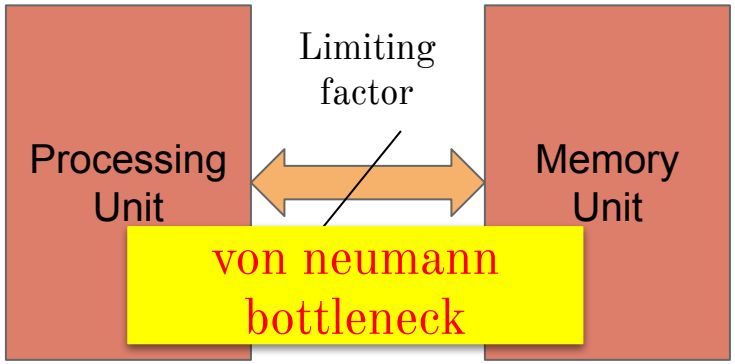
Where does the energy goes ?



John von Neumann



Ziyu Lv, et. al.,Chemical Reviews 2020



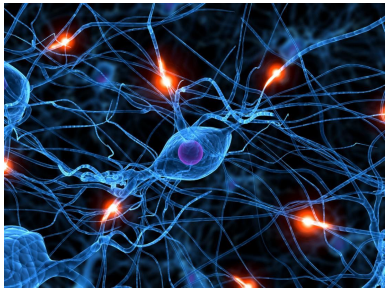
Processing and memory unit are physically separated

Inspiration is right here !!

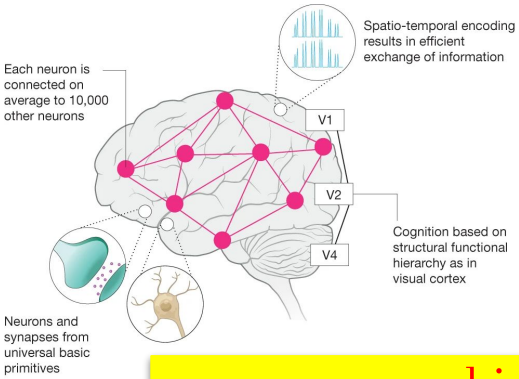
The most power efficient machine

~ 20 W

G. J. Siegel, et. al.
Lippincott-Raven, 1999



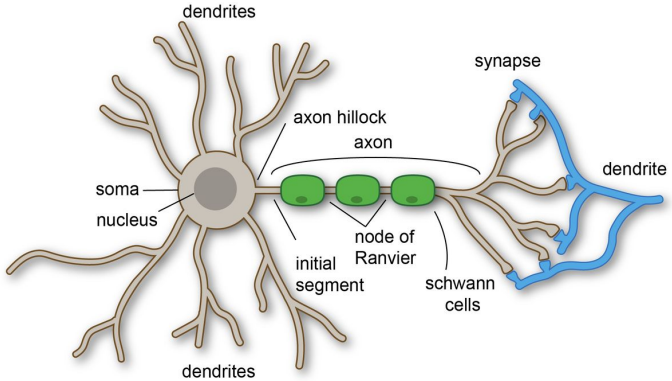
non von Neumann architecture



Roy, K., et. al., *Nature*, 2019

10^{11} neurons

10^{15} synapses



neuromorphic computing

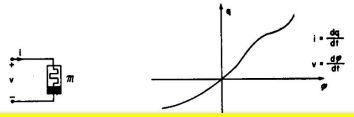
Need electronic equivalent of biological synaps

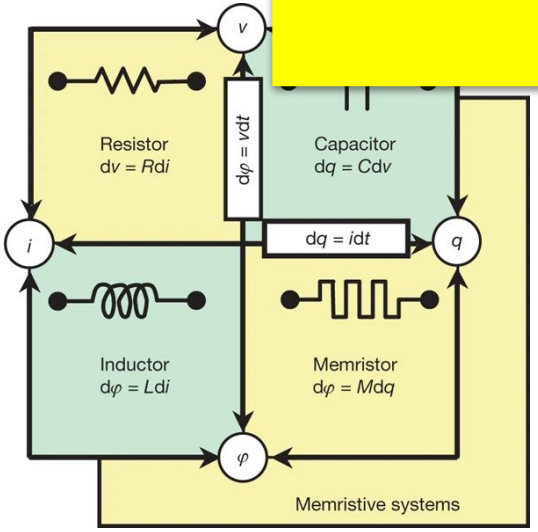
Memristor - an entelechy

IEEE TRANSACTIONS ON CIRCUIT THEORY, VOL. CT-18, NO. 5, SEPTEMBER 1971 507

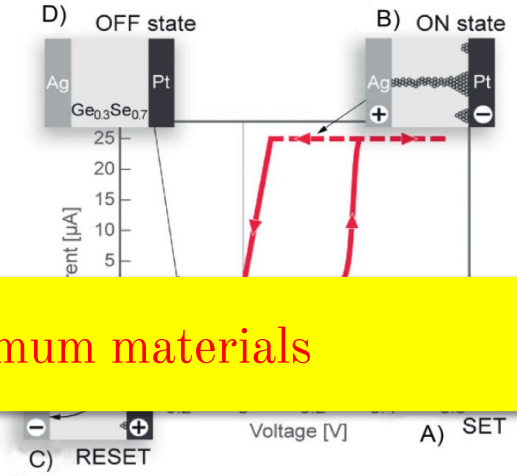
Memristor—The Missing Circuit Element

LEON O. CHUA, SENIOR MEMBER, IEEE



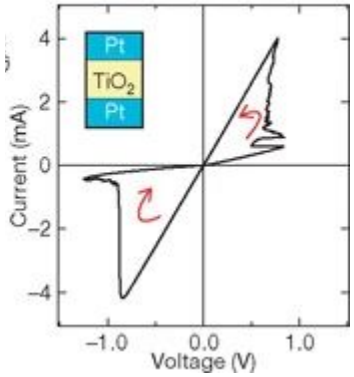


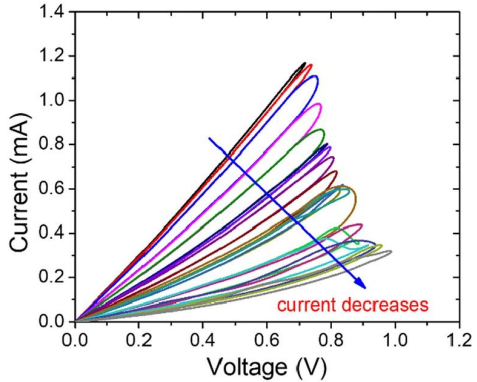
Ongoing hunt for optimum materials



Waser, Rainer, et al., *Advanced materials* 2009.

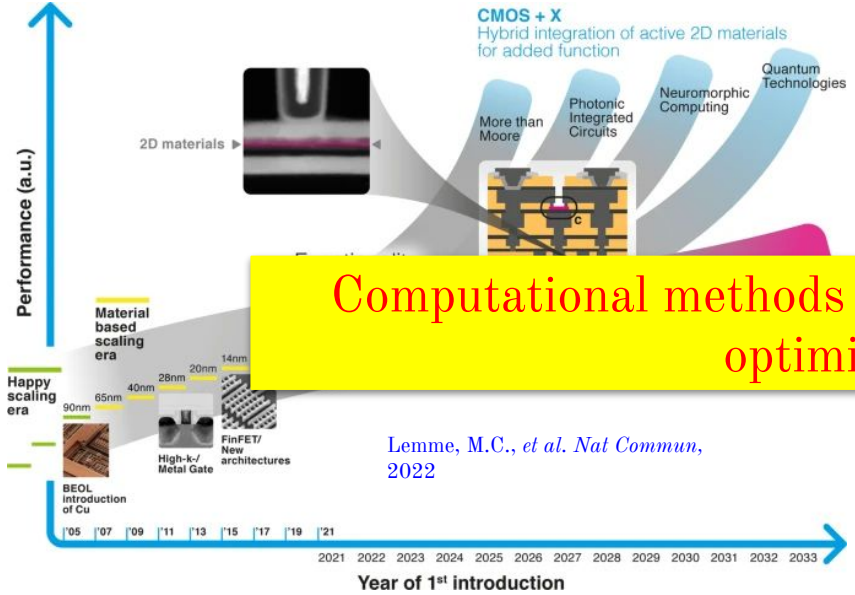
Strukov, D., *et al. Nature* 2008



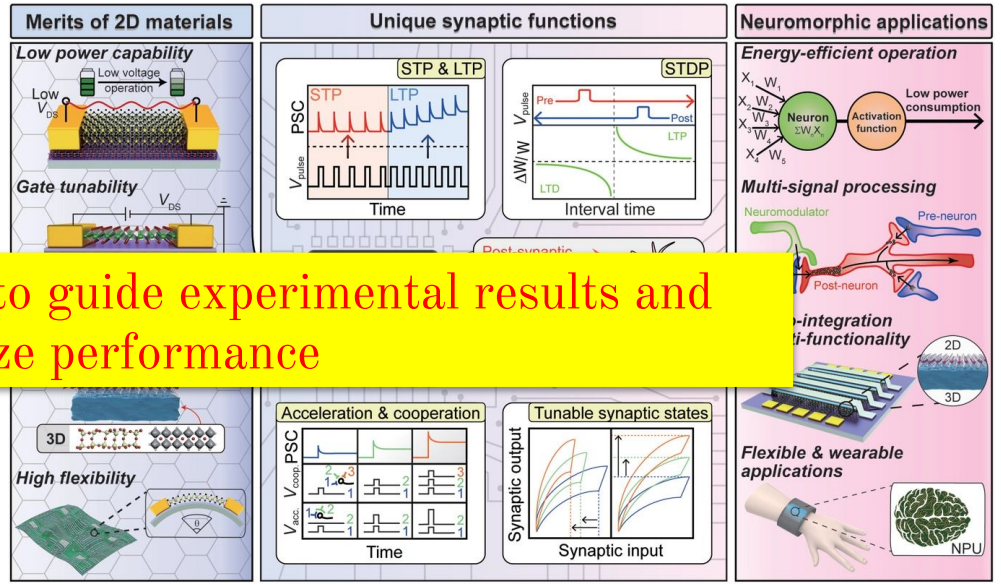


Ismail, M.*et al. Nanoscale Res Lett*, 2022

2D Materials - paradigm shifting discovery



Lemme, M.C., *et al. Nat Commun*, 2022



Huh, Woong,et. al., *Advanced Materials*, 2020.

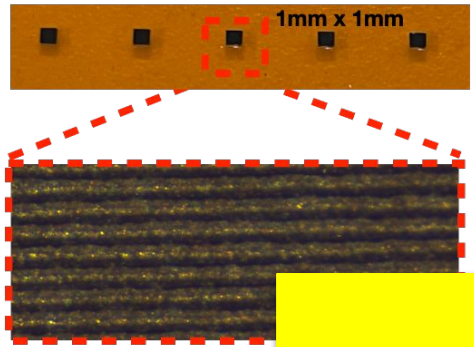
Computational methods to guide experimental results and optimize performance

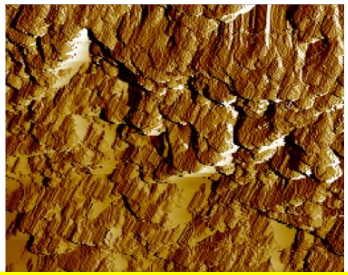
Fundamental challenges remains -

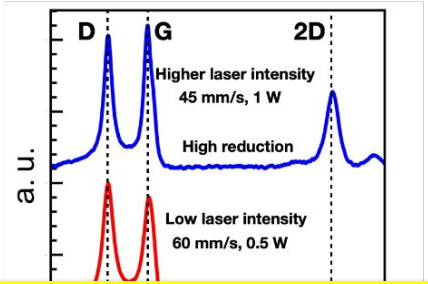
- Large scale fabrication
- Endurance
- Retention time
- Which material and mechanism

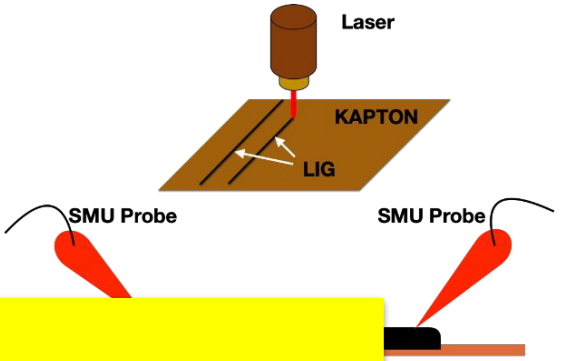
Memristor Fabrication at University of Granada

Laser Induced Graphene

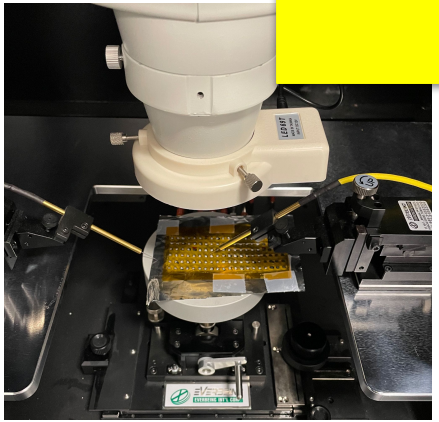




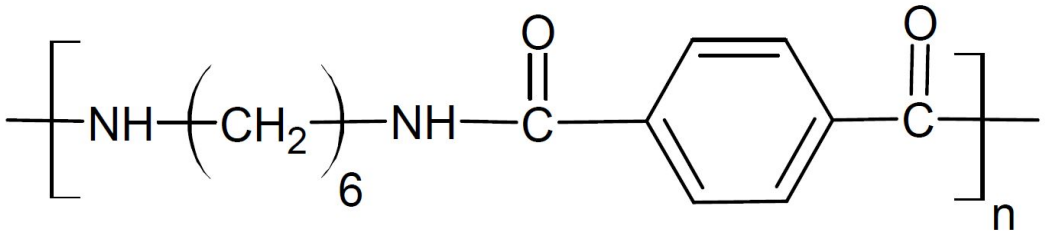




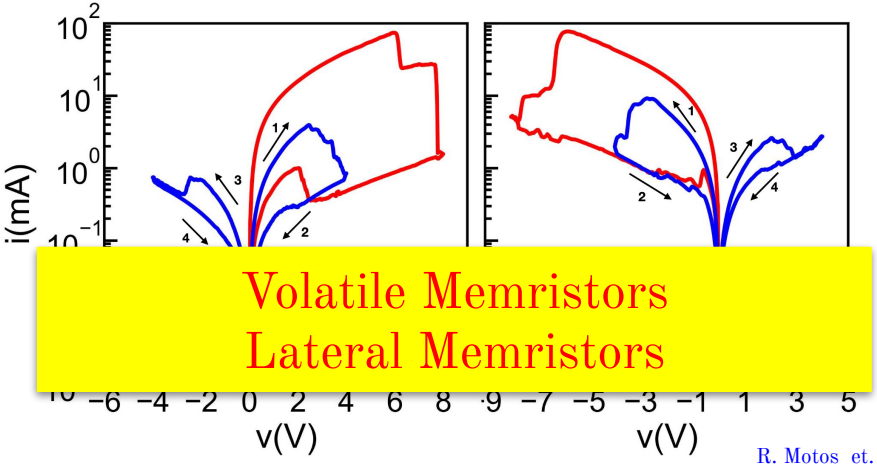
Low Cost Process
Flexible Substrate



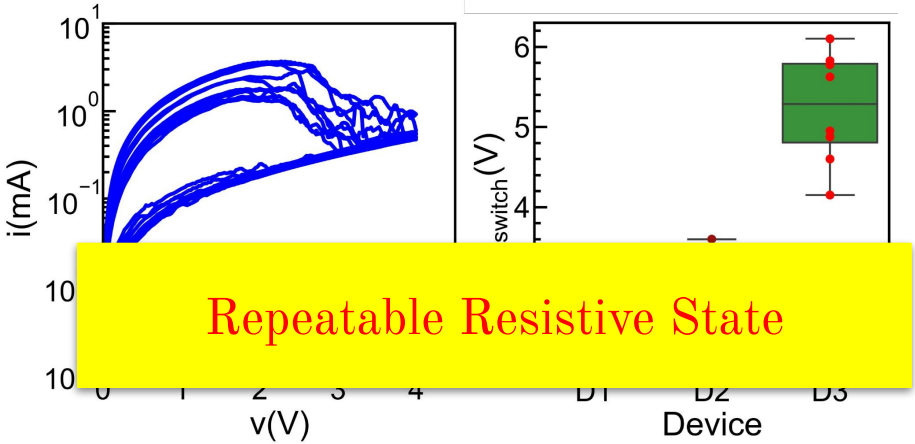
Polyamide



Memristor Fabrication at University of Granada



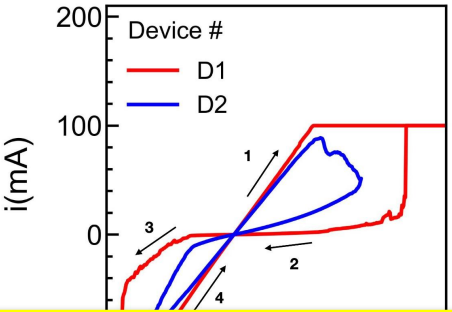
Volatile Memristors
Lateral Memristors



Repeatable Resistive State

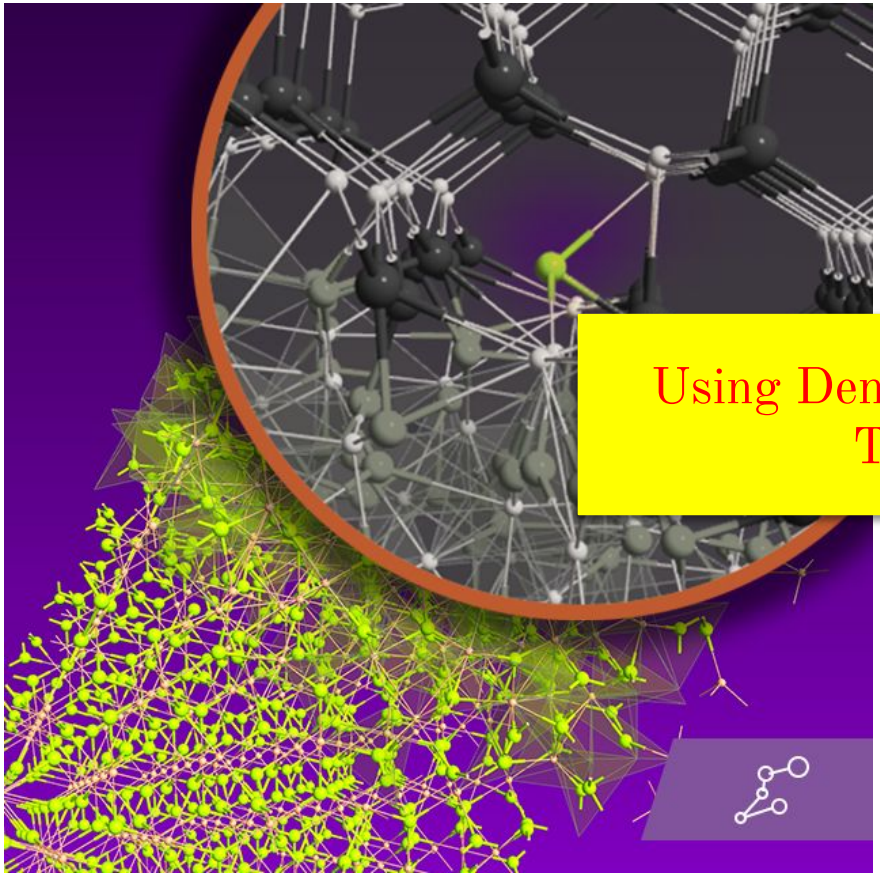
R. Motos et. al., DRC, 2023 (submitted)

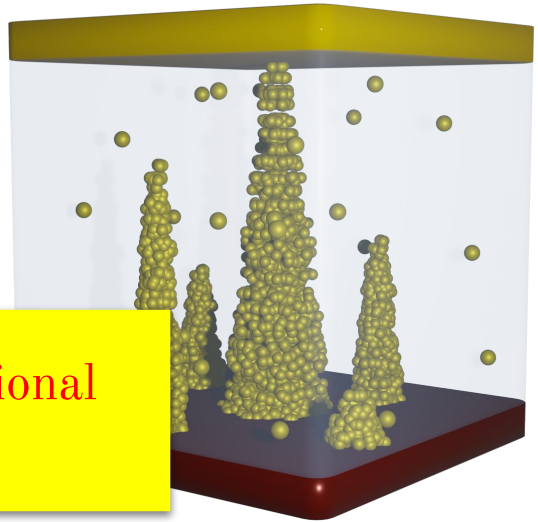
M. Fernandez. et. al., CDE, 2023 (submitted)



Non-Volatile Memristors
Vertical Memristors

Ab initio simulations



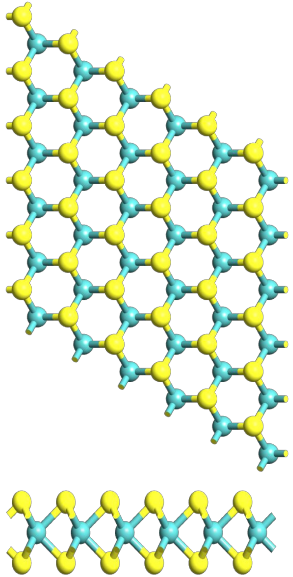


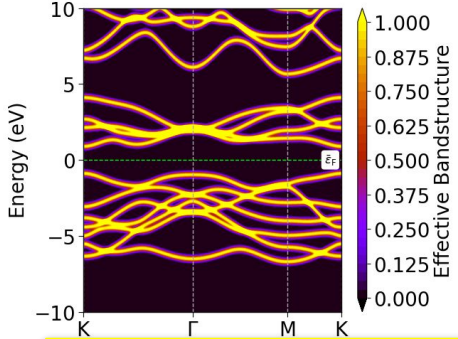
Using Density Functional Theory

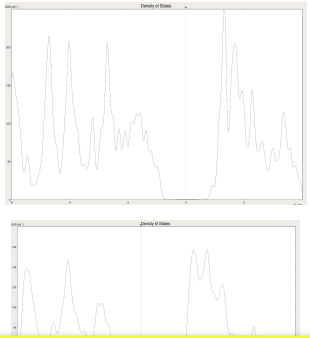
$$\left(-\frac{\hbar^2}{2m}\nabla^2 + v_{\text{eff}}(\mathbf{r})\right)\varphi_i(\mathbf{r}) = \varepsilon_i\varphi_i(\mathbf{r}).$$

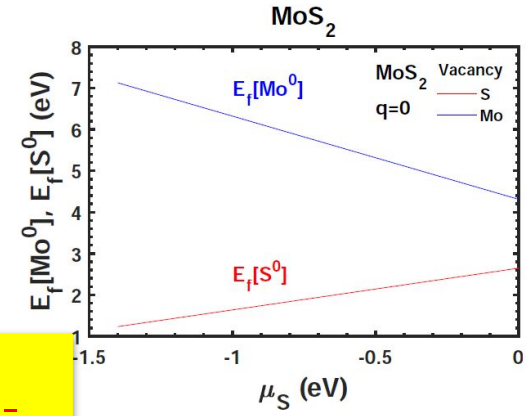
Synopsys, QATK

Ab initio simulations



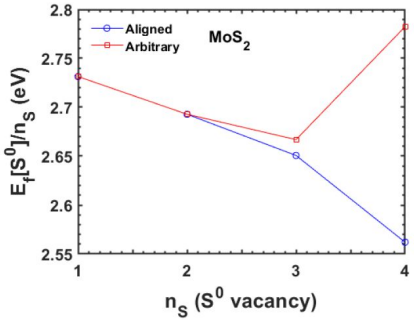






Thermodynamically stable defect - types and position

$$- E_{tot}[bulk] - \sum_i n_i \mu_i + q\,(E_{VBM} + \mu_e) + E_{corr}.$$

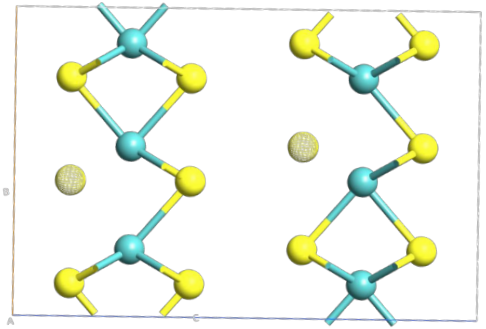


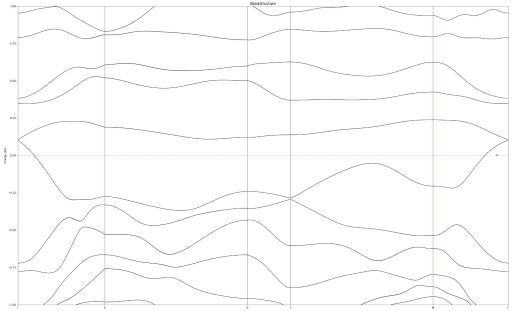
n_S	Aligned (eV)	Arbitrary (eV)
1	2.73	2.73
2	2.69	2.69
3	2.65	2.66
4	2.56	2.78

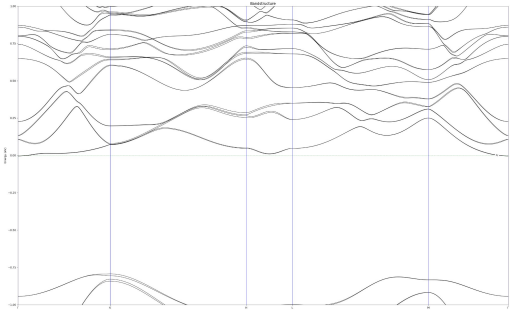
Crystal	Y Vacancy	E_f (eV)
PtS_2	S	1.98
$PtTe_2$	Te	2.00
$PtSe_2$	Se	2.09
WTe_2	Te	2.21
$MoTe_2$	Te	2.39
WSe_2	Se	2.46
$MoSe_2$	Se	2.47
MoS_2	S	2.64
WS_2	S	2.70

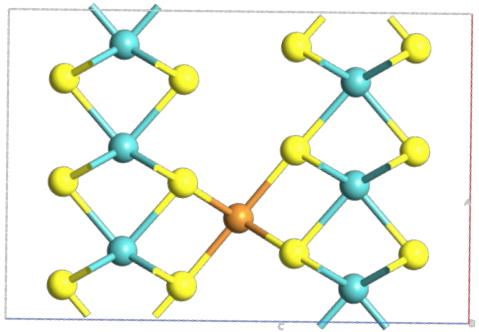
Crystal	X Vacancy	E_f (eV)
WTe_2	W	2.75
$PtTe_2$	Pt	3.22
$MoTe_2$	Mo	3.40
$PtSe_2$	Pt	4.39
PtS_2	Pt	5.23
WSe_2	W	5.33
$MoSe_2$	Mo	5.85
WS_2	W	6.65
MoS_2	S	7.12

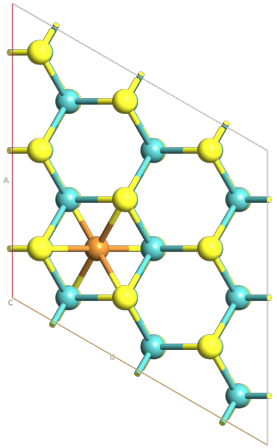
Transport study using NEGF + DFT

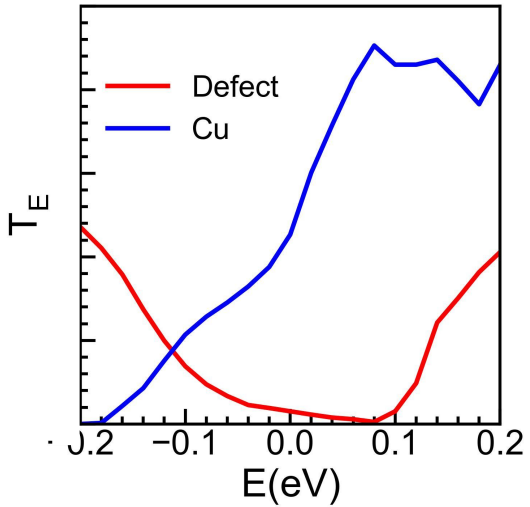




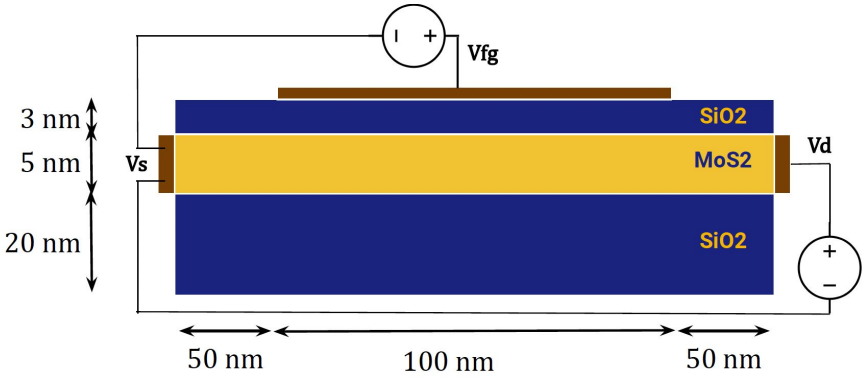


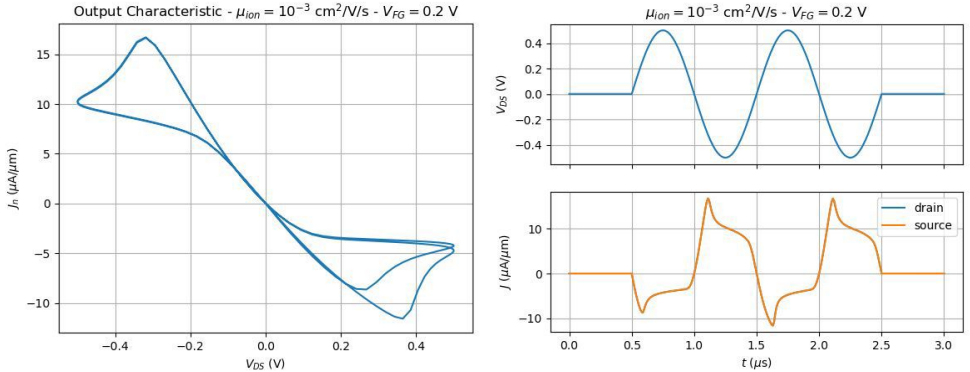






Numerical Simulation





Self-consistent Simulation

$$\vec{\nabla} \cdot (\varepsilon \vec{\nabla} V) = -\rho$$

$$n = \int_{-\infty}^{\infty} g(E+V) f(E+V, E_F) dE$$

$$\vec{\nabla} \cdot \vec{J}_n = \vec{\nabla} \cdot \left(\varepsilon \frac{\partial}{\partial t} \vec{\nabla} V \right) + \sum_i \frac{\partial c_i}{\partial t}$$

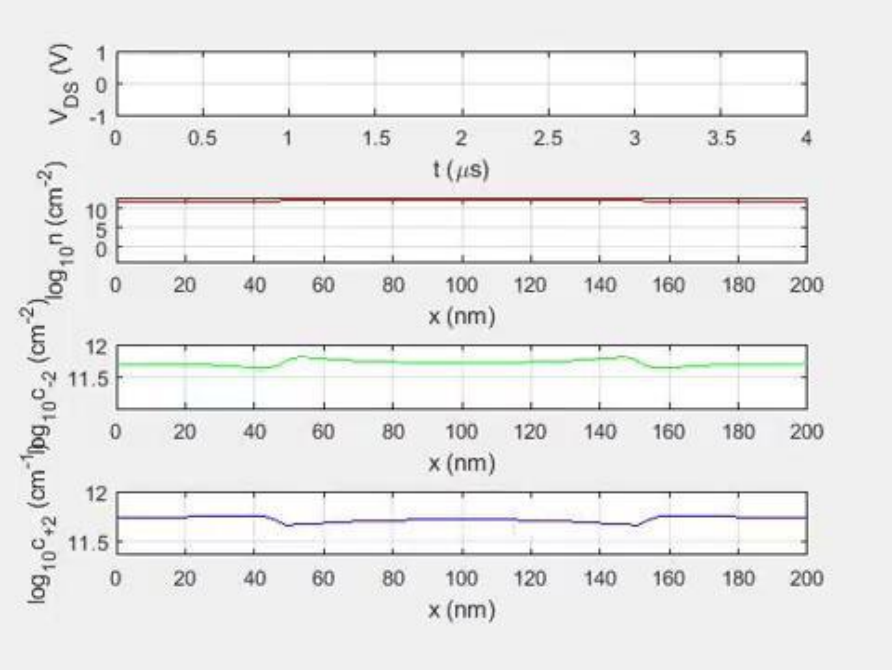
$$\vec{J}_n = q \mu_n n \vec{\nabla} E_{F_n}$$

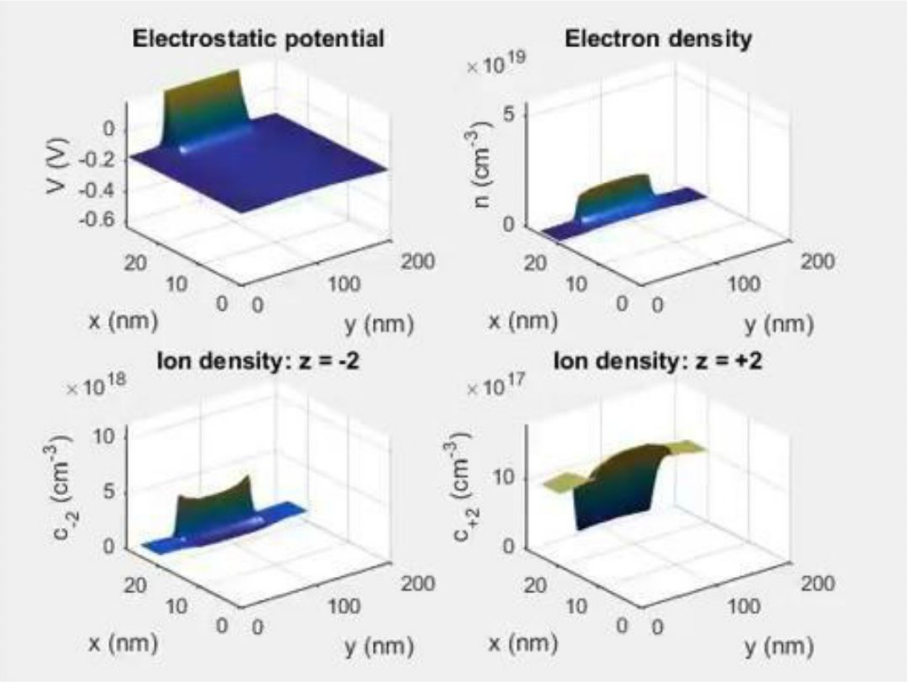
$$\vec{\nabla} \cdot \vec{J}_{c_i} = -\frac{\partial c_i}{\partial t}$$

Nerst-Planck:

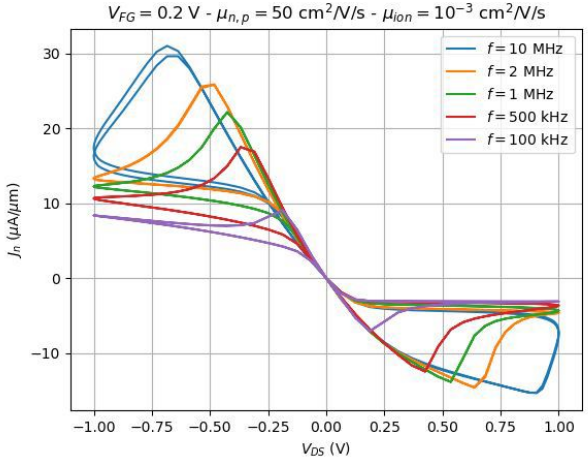
$$\vec{J}_{c_i} = z_i q D_i \left(-\vec{\nabla} c_i - s_i c_i \vec{\nabla} \frac{qV}{k_B T} \right)$$

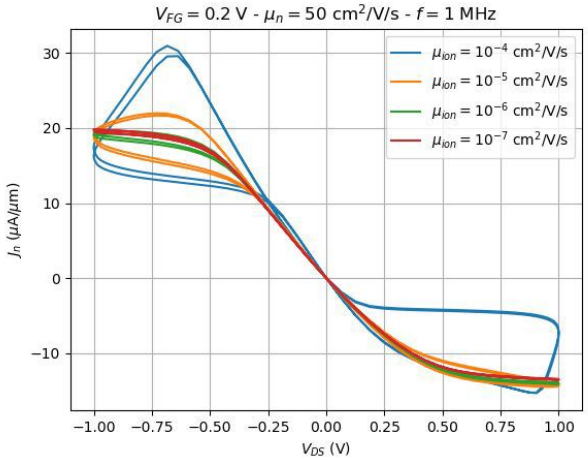
Numerical Simulation

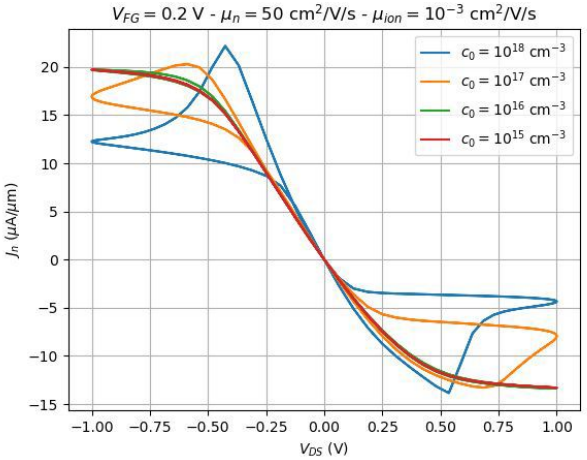


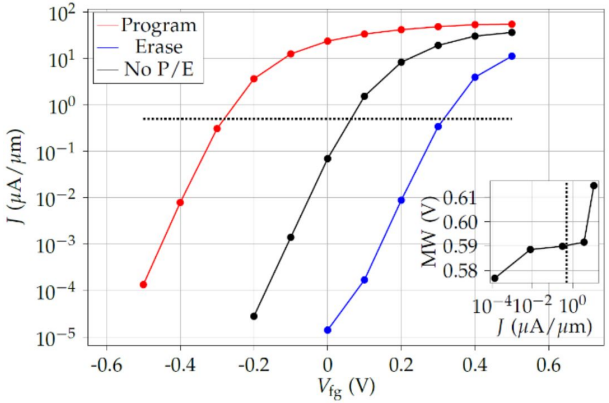


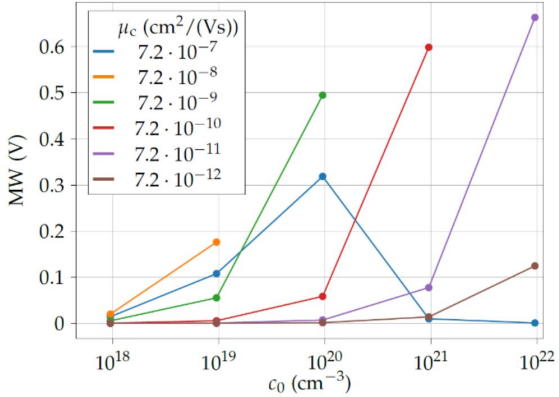
Numerical Simulation





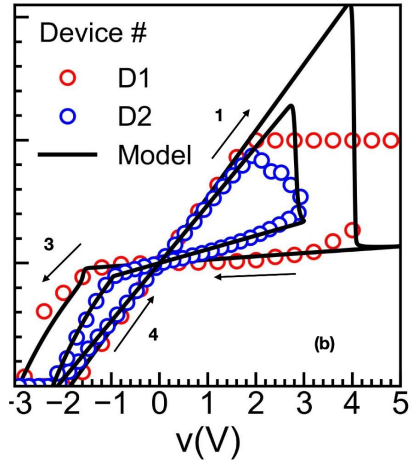


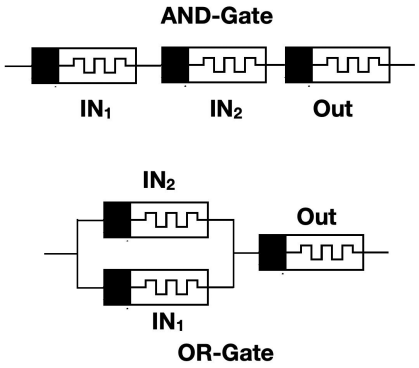


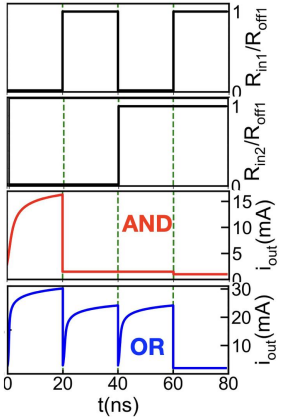


J. Cuesta-Lopez et. al., CDE , 2023 (submitted)

Compact Model / SPICE Model





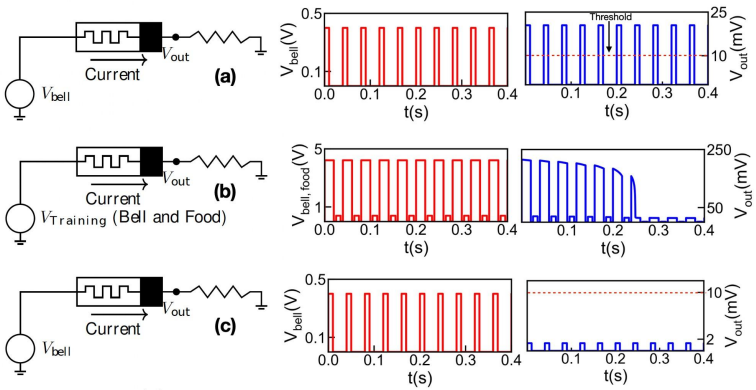


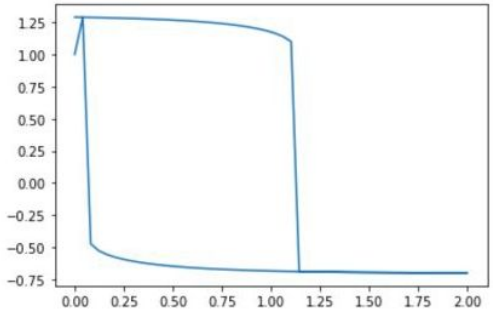
Development of In-house Compact Model

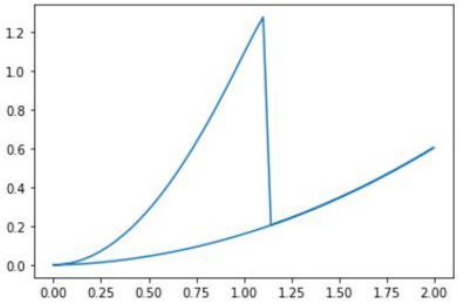
Continuous and cross-compatible

$$I(t) = R * (s(t) + 1) * V^2$$

$$\frac{ds(t)}{dt} = tanh\left(-V(t) + 2s(t)\right) - s(t) + 0.3$$







Thank you

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This project has received funding from the EU Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101032701

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