



SiNANO-ICOS-INPACE Workshop

"Emerging technologies in Advanced Computation, Advanced Functionalities, Ground-breaking Technologies: Impact on International Cooperation"

Emerging semiconductors meet new applications: security, multi-valued computing, and hazard monitoring

Hocheon Yoo

Gachon University, South Korea

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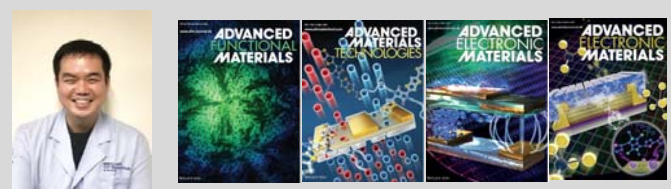
Leuven, September 9, 2024



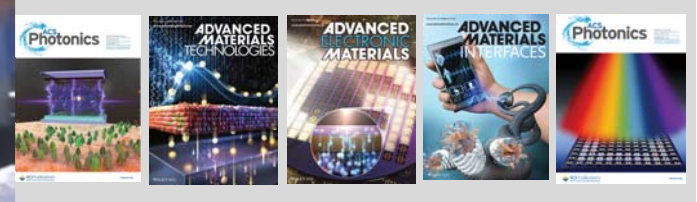
Outline

- Introduction
- Results and discussion
 - Multi-valued Computing
 - Security
 - Unconventional Electronics
- Summary
- Q&A

Introduction



Postdoc, Northwestern Univ. (2019)
 Ph.D., POSTECH (2018)
 Visiting scholar, Holst Centre, Netherland (2015)
 B.S., Hanyang Univ. (2014)



1st Place, (2022,2023,2024)
 Award for Research Excellence, (2022,2023)
 1st Winner, (2021)
 Winner in Teaching Award, (2021, 2023)



The SDC Research Lab develops a wide range of a material-device-process co-innovation app

Gachon Academic Top 1 (2022,203)
 Gachon one of largest Lab (2022)

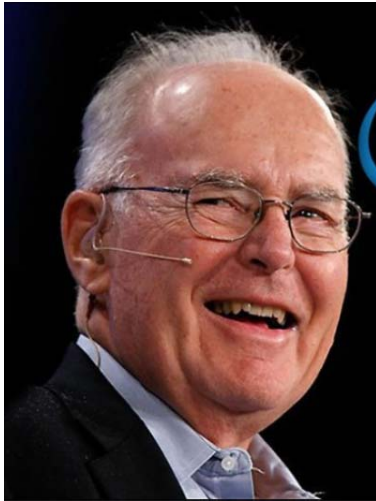


ESS... in Advanced Computation, Advanced Functionalities, Ground-breaking Technologies: Impact on International Cooperation

Introduction



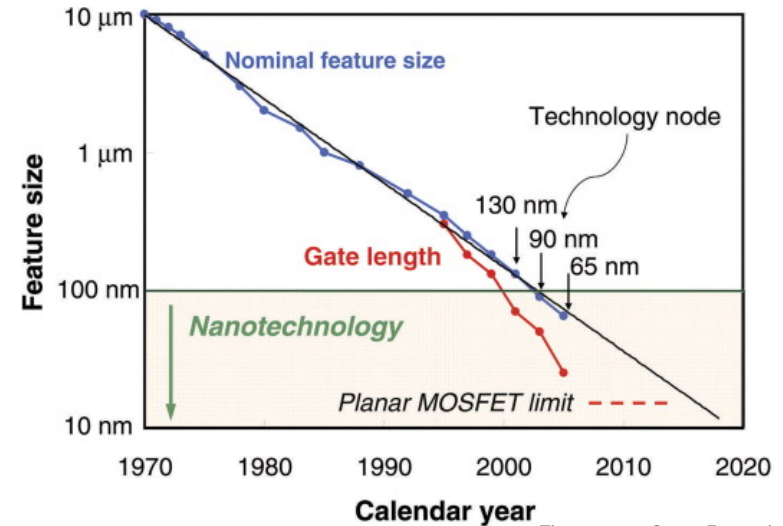
Background



Gordon Moore



Robert Dennard

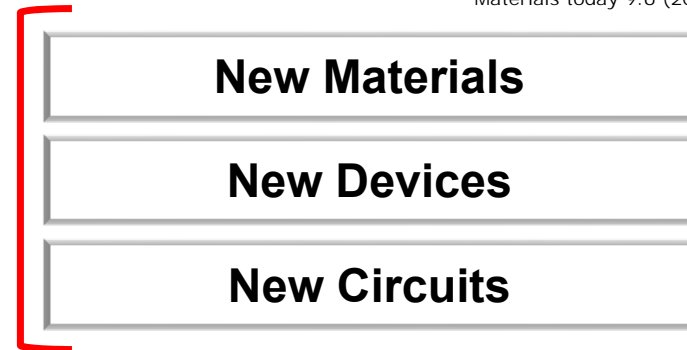


Thompson, Scott E., and Srivatsan Parthasarathy. Materials today 9.6 (2006): 20-25.

😊 Lower power consumption

😊 Higher operating frequency

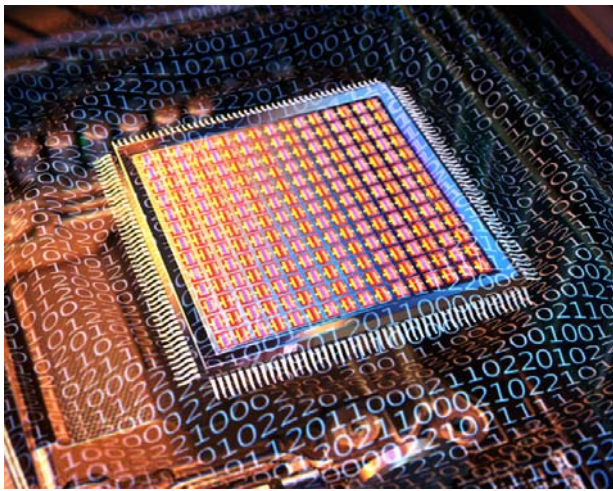
☹️ **Scaling limit** →



Results and discussion

□ *Multi-valued Computing*

Multi-valued Logic



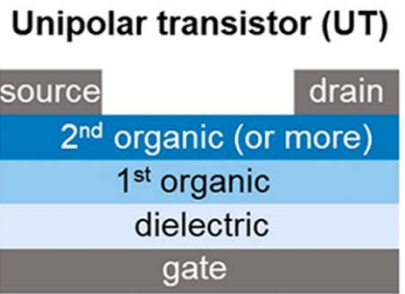
Security Devices



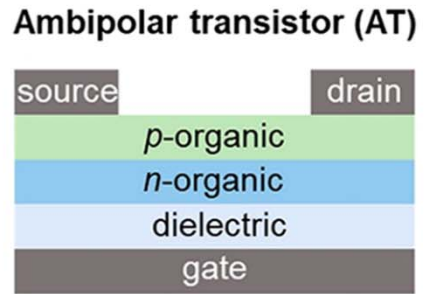
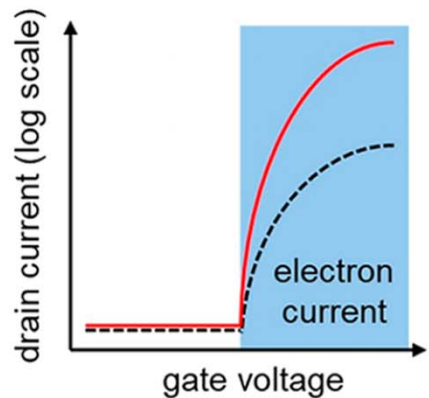
Unconventional electronic devices



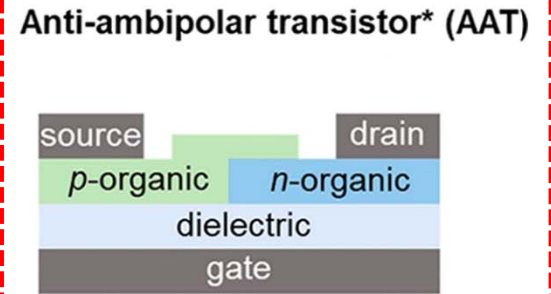
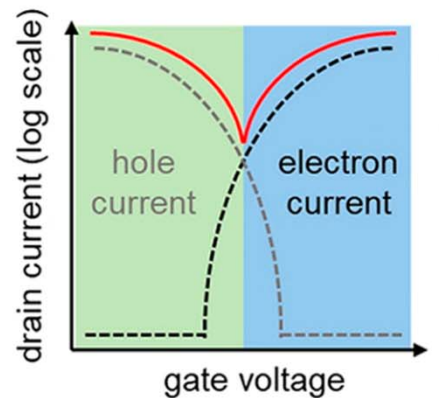
Multi-valued Logic



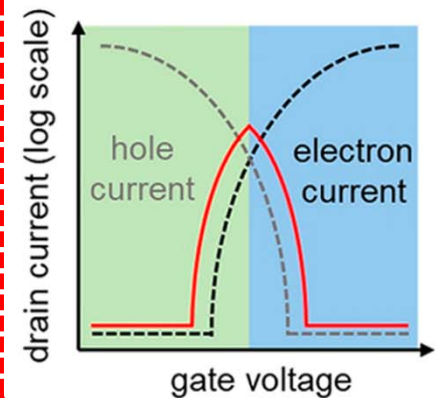
*Quantum confinement,
carrier-density control*



*Majority charge-carrier
injection & transport*



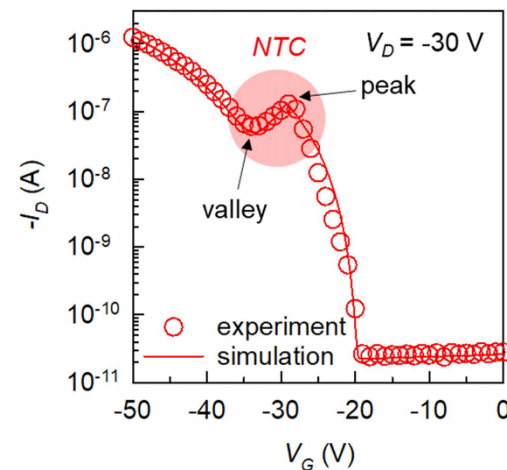
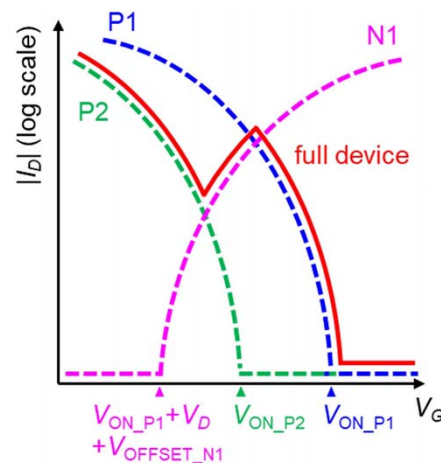
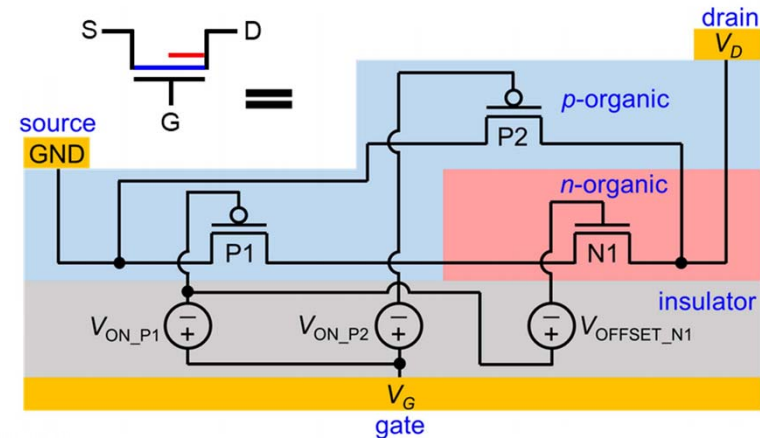
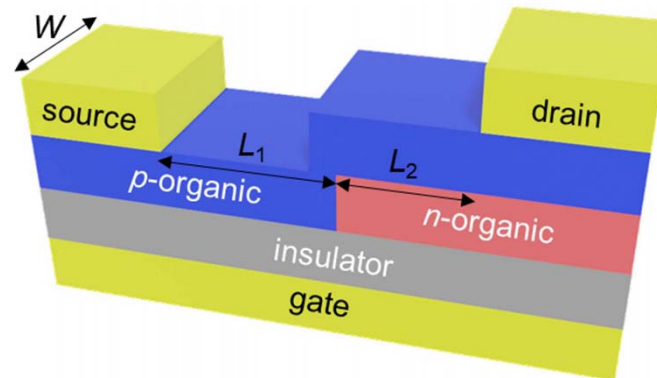
*Gate-induced change
of effective channel*



*also called negative-transconductance transistor

Chang-Hyun Kim et al., ACS Applied Electronic Materials (2022).

Multi-valued Logic



Peak/valley current

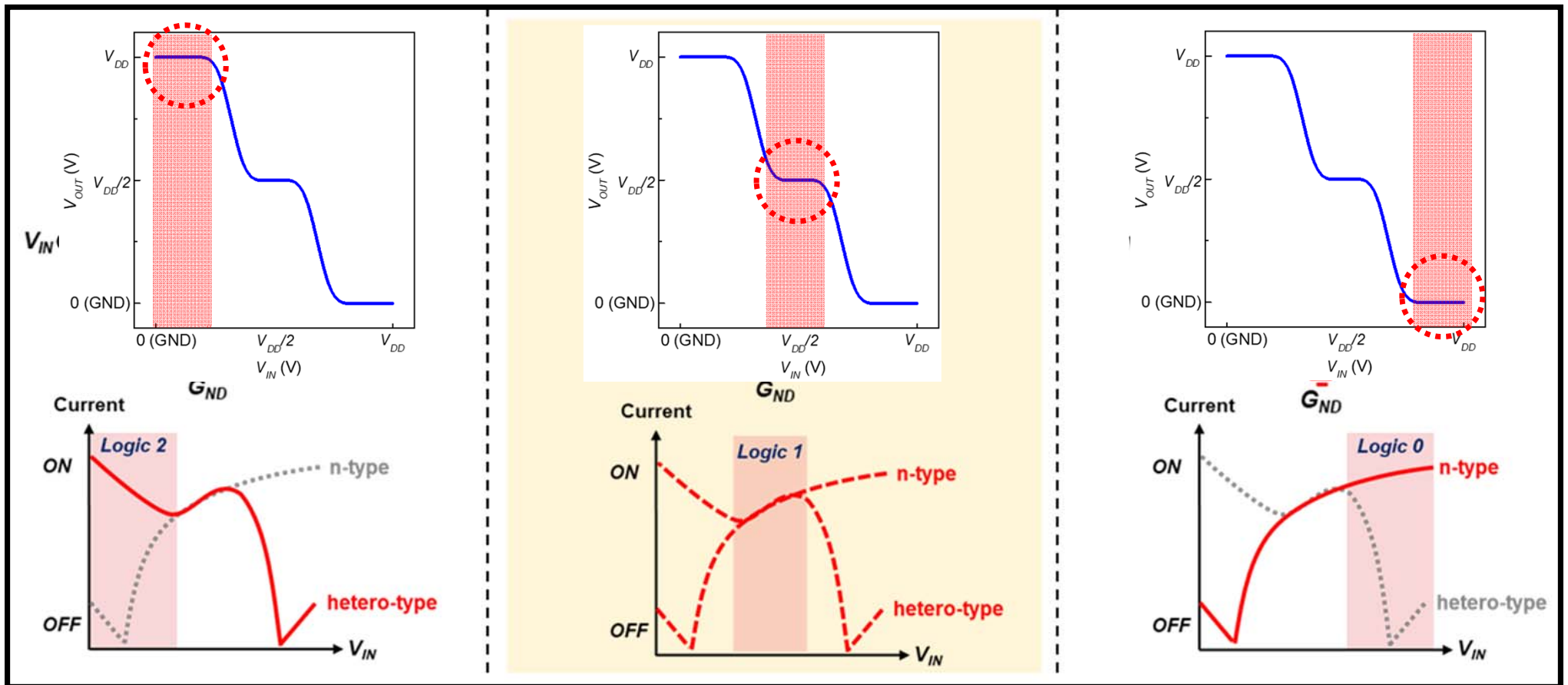
NTC region

Well-defined off-current

Well-defined on-current

Hocheon Yoo, Chang-Hyun Kim *et al.*, *IEEE TED* (2022).

Multi-valued Logic



Multi-valued Logic

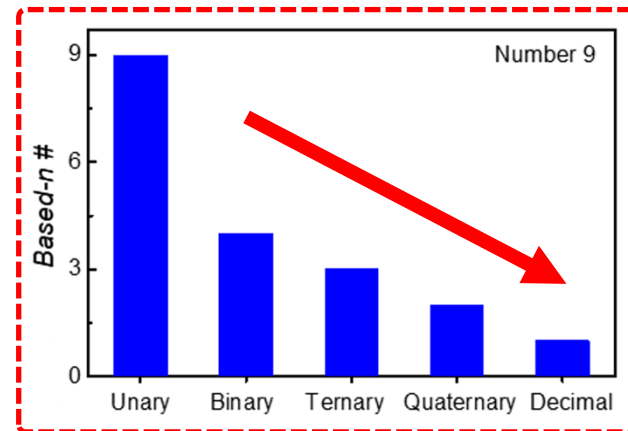
Binary



Ternary



Decimal	1	2	3	4	5	6	7	8	9
Binary	1	10	11	100	101	110	111	1000	1001
Ternary	1	2	10	11	12	20	21	22	100
Quaternary	1	2	3	10	11	12	13	20	21

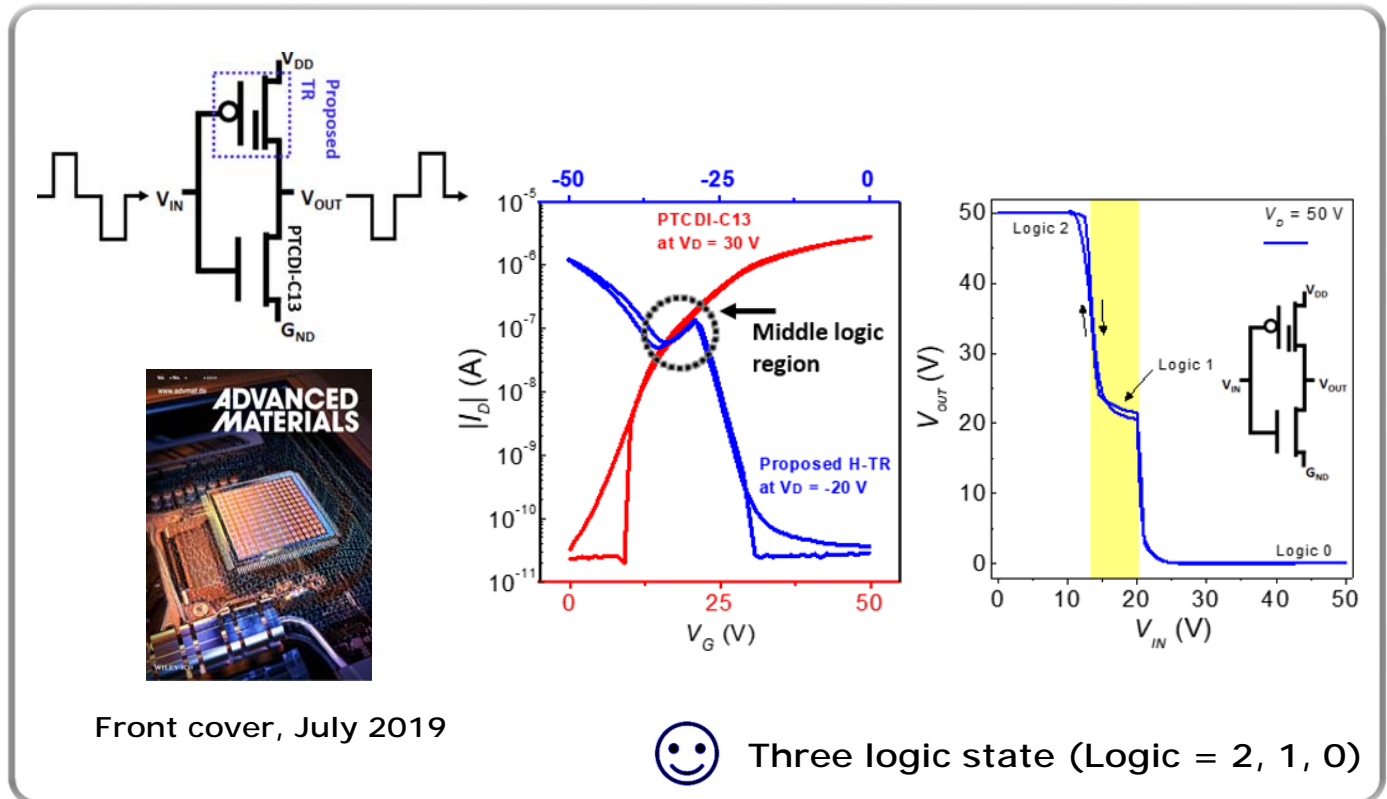


Hocheon Yoo, Chang-Hyun Kim, *Journal of Materials Chemistry C*, 2021

Multi-valued Logic

Logic = 2 (V_{DD}) \rightarrow Logic = 1 ($V_{DD}/2$) \rightarrow Logic = 0 (G_{ND})

DC
characteristic



Transient
characteristic

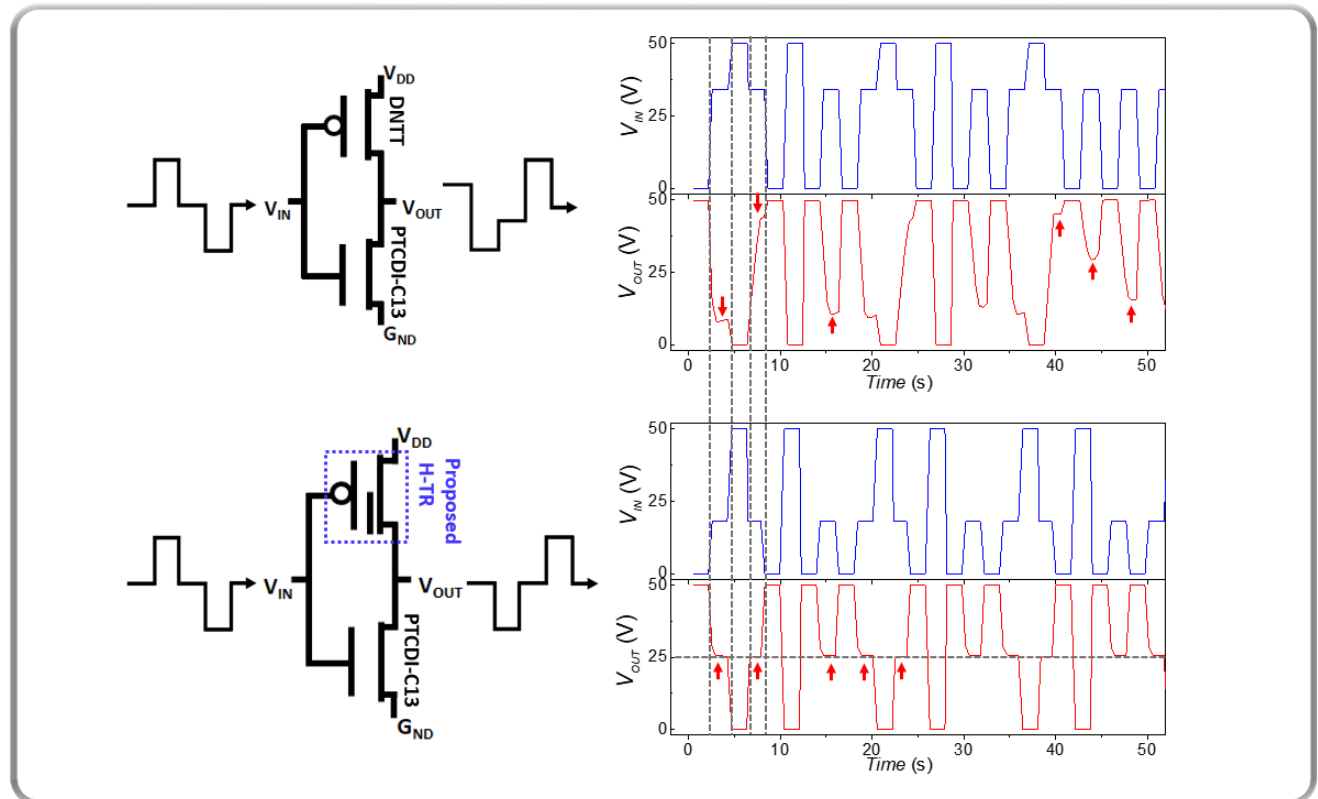
Hocheon Yoo et al., *Advanced Materials* (2019) 1808265

Multi-valued Logic

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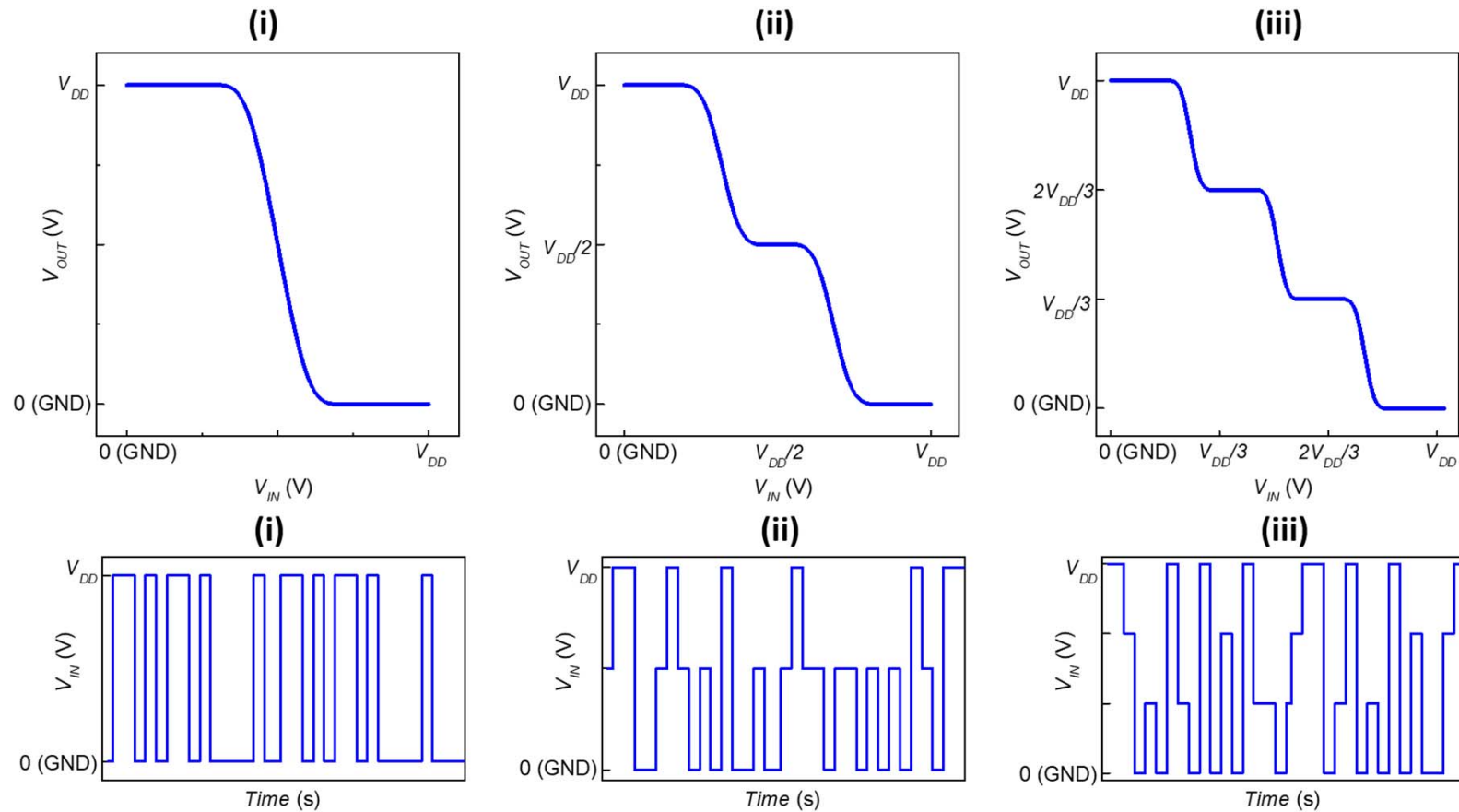
DC
characteristic

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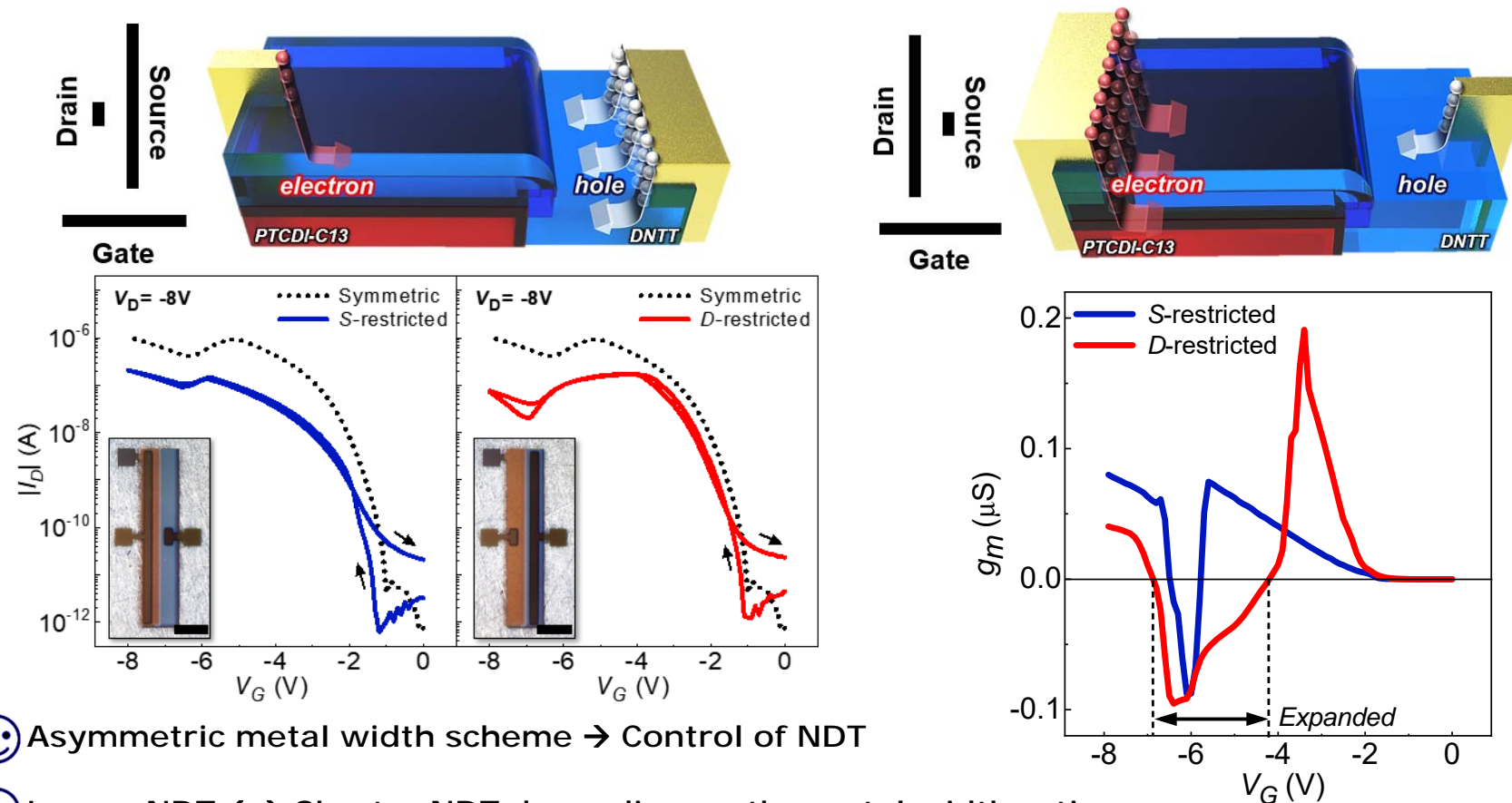
Hocheon Yoo et al., *Advanced Materials* (2019) 1808265

Multi-valued Logic



Hocheon Yoo et al., *Advanced Materials* (2019) 1808265

NDT ternary circuits

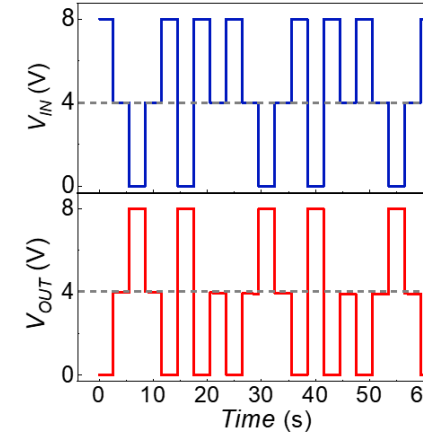
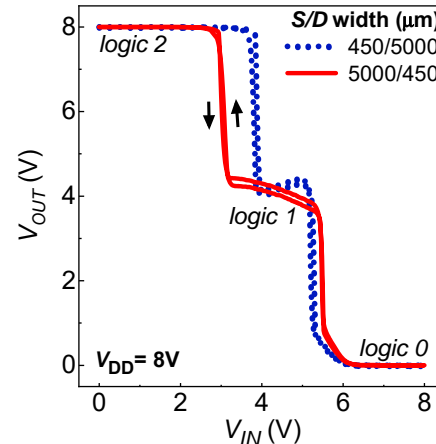
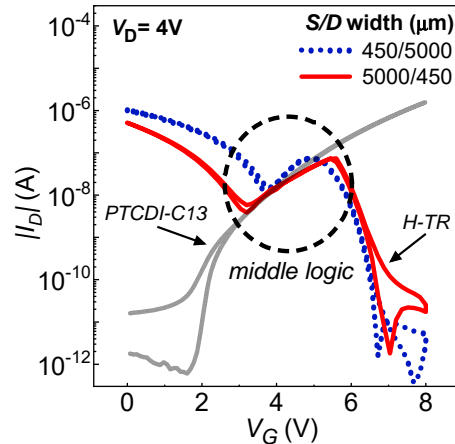
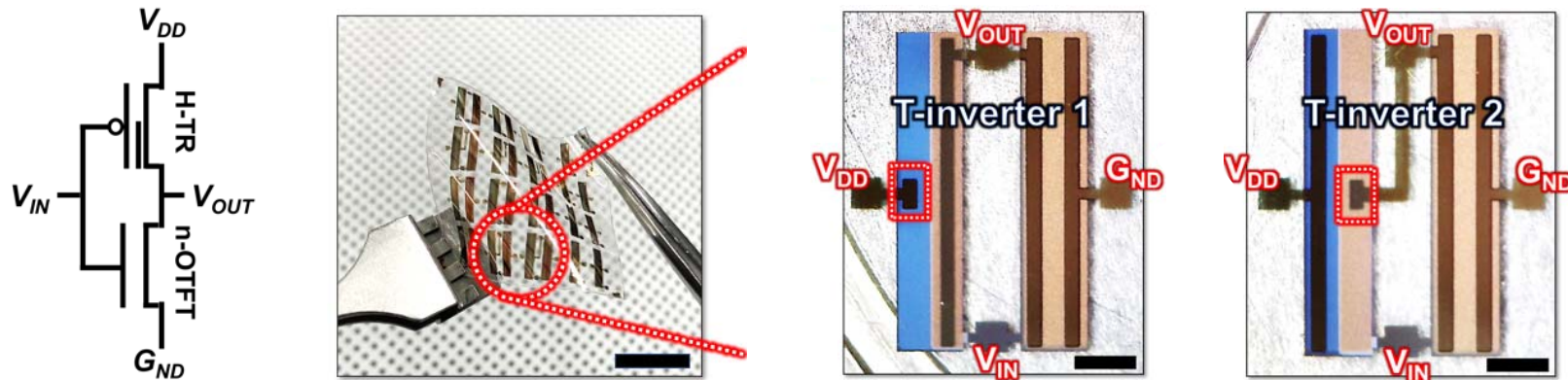


☺ Asymmetric metal width scheme → Control of NDT

☺ Larger NDT ↔ Shorter NDT depending on the metal width ratio

Chungryul Lee, Hocheon Yoo *et al.*, *Small* (2021)

NDT ternary circuit

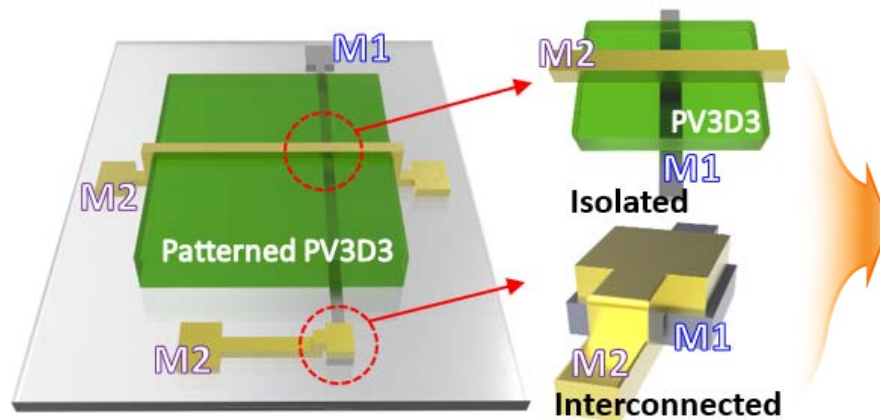


😊 Flexible ternary circuits using asymmetric metal width transistors

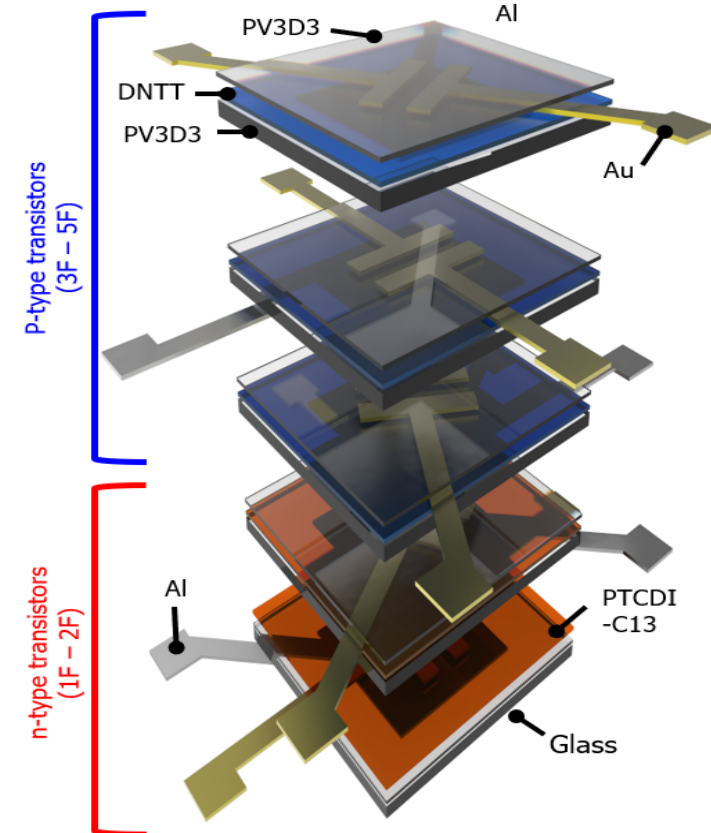
Chungryul Lee, Hocheon Yoo *et al.*, *Small* (2021)

Via-Hole-Less Metal Interconnects

Via-hole-less integration scheme

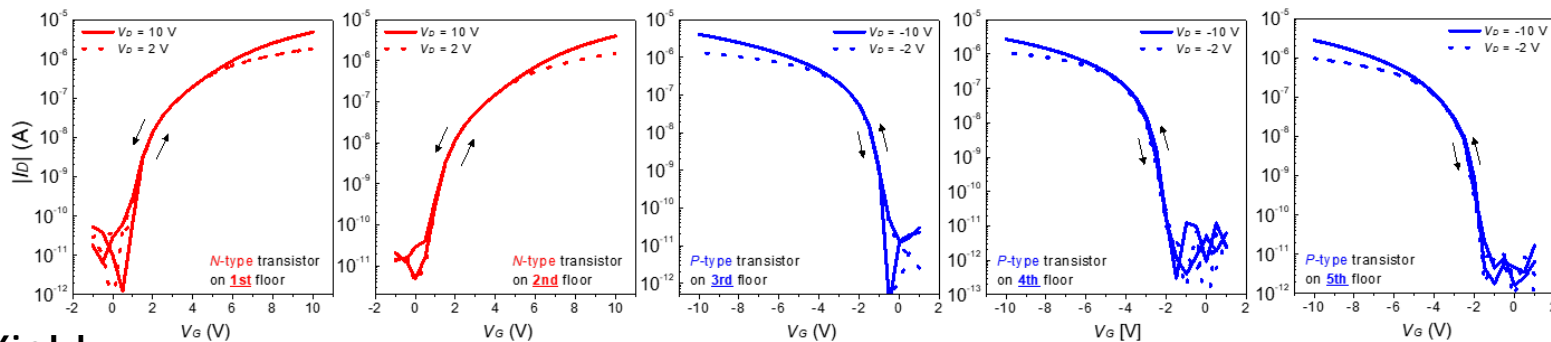
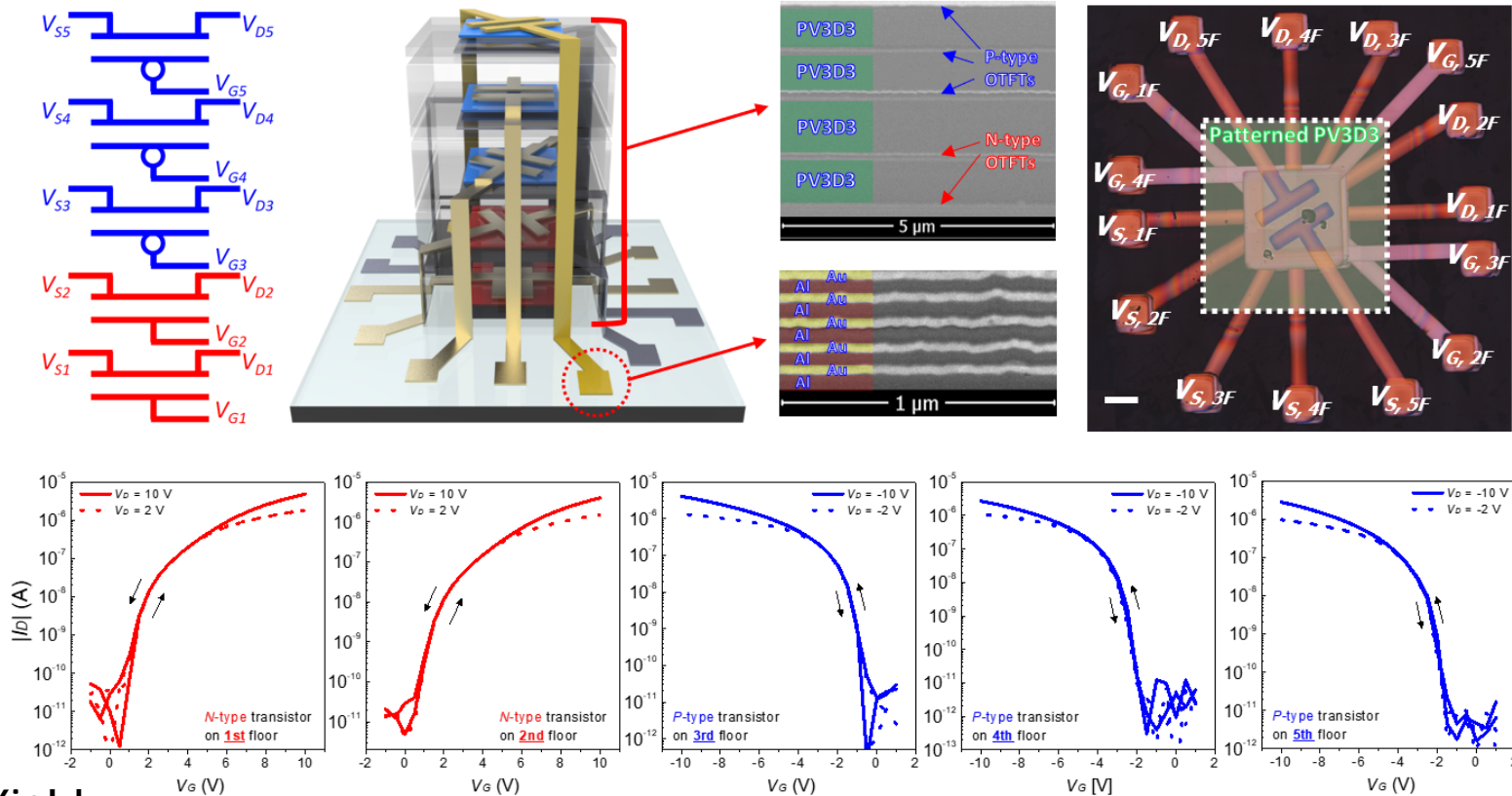


- ☺ Etching-free multilevel metal interconnect
- ☺ Solvent-free multilevel metal interconnect
- ☺ Simultaneous interconnection formation



Hocheon Yoo, Hongkeun Park *et al.*, *IEEE Electron Device Letters* In progress
Hocheon Yoo, Hongkeun Park *et al.*, *Nature Communications* (2019) 10, 2424.

Via-Hole-Less Metal Interconnects



😊 100% Yield

😊 5-time higher density of devices

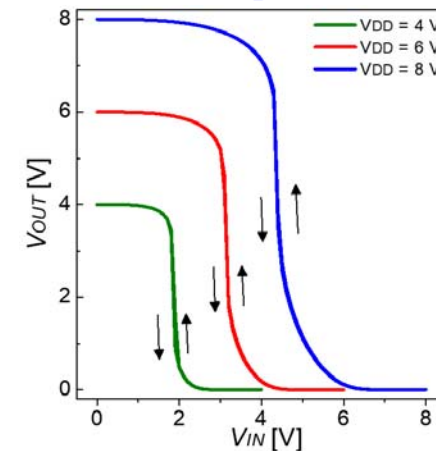
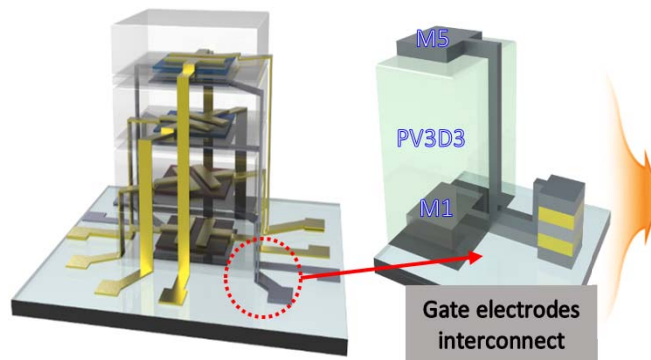
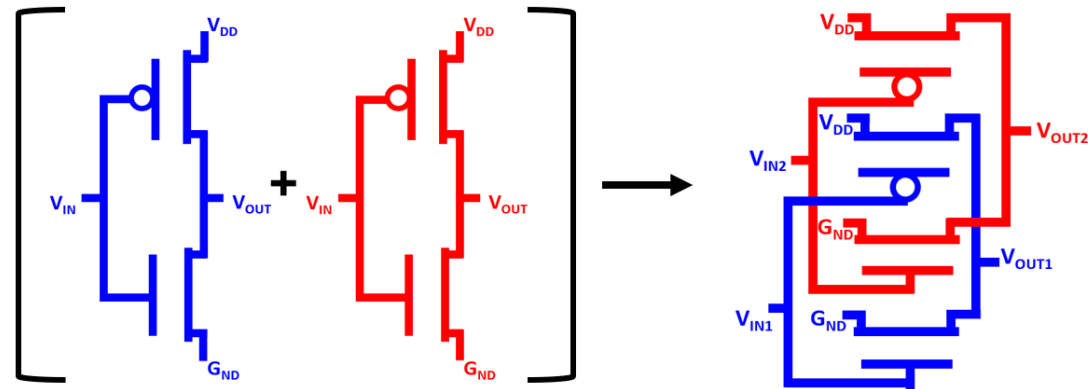
Highlighted in *Nature Research Device & Materials Engineering Community*

Via-Hole-Less Metal Interconnects

3D-Integrated Inverter Circuit

3D-Integrated NAND/NOR Circuit

Exclusive OR Circuit



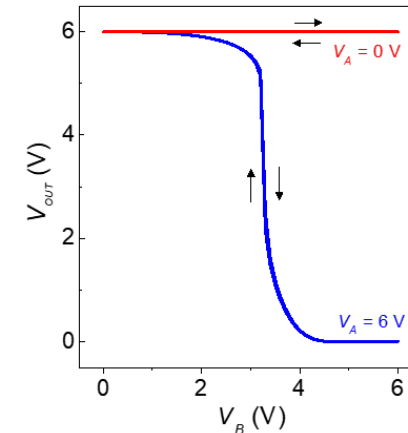
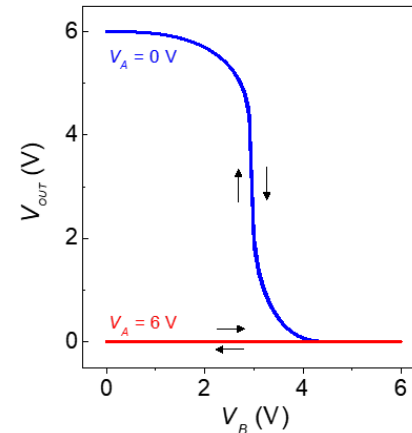
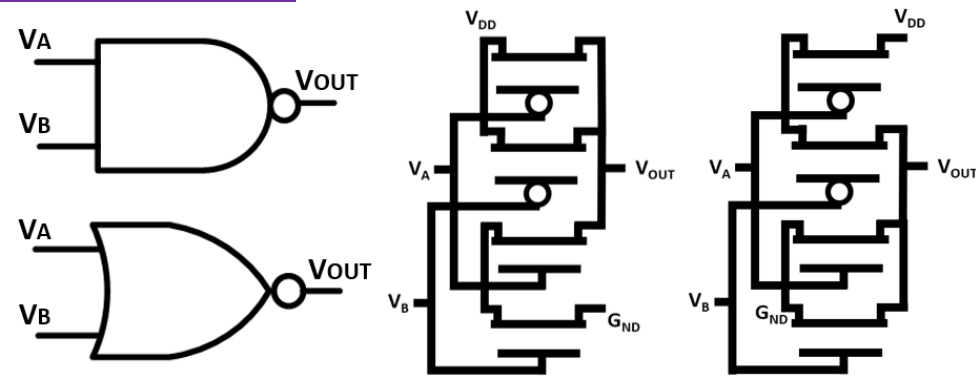
Hocheon Yoo, Hongkeun Park *et al.*, *Nature Communications* (2019) 10, 2424. Highlighted in *Nature Research Device & Materials Engineering Community*

Via-Hole-Less Metal Interconnects

3D-Integrated
Inverter Circuit

3D-Integrated
NAND/NOR Circuit

Exclusive OR
Circuit



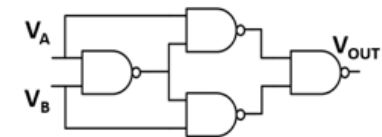
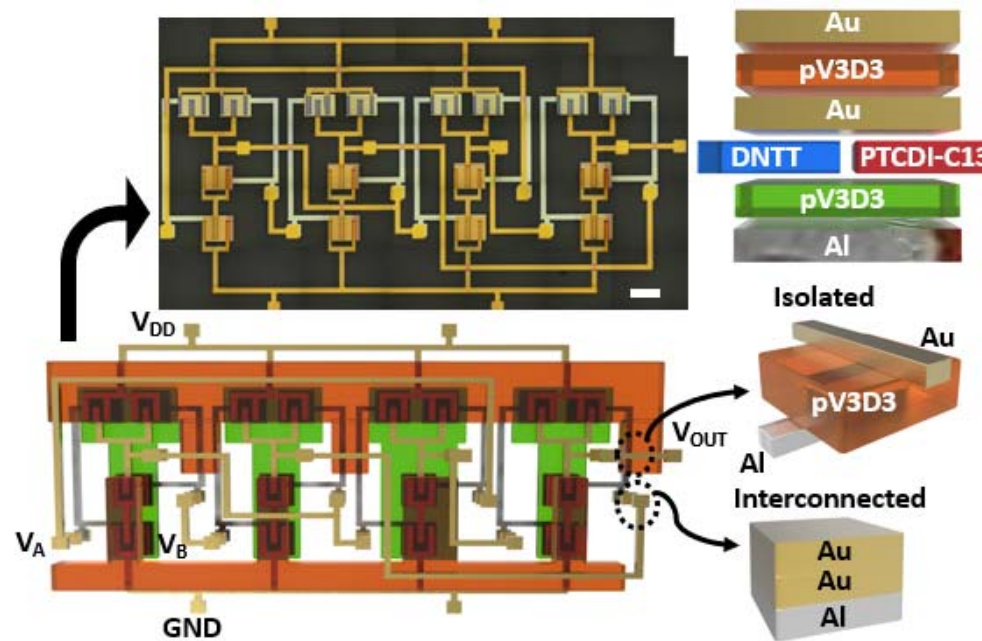
Hocheon Yoo, Hongkeun Park *et al.*, *Nature Communications* (2019) 10, 2424.
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Via-Hole-Less Metal Interconnects

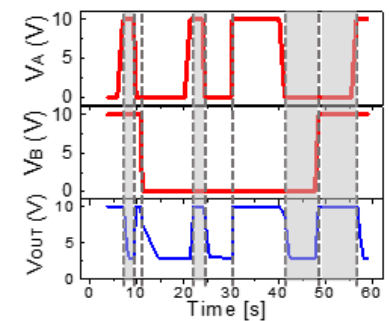
3D-Integrated
Inverter Circuit

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NAND/NOR Circuit

Exclusive OR
Circuit

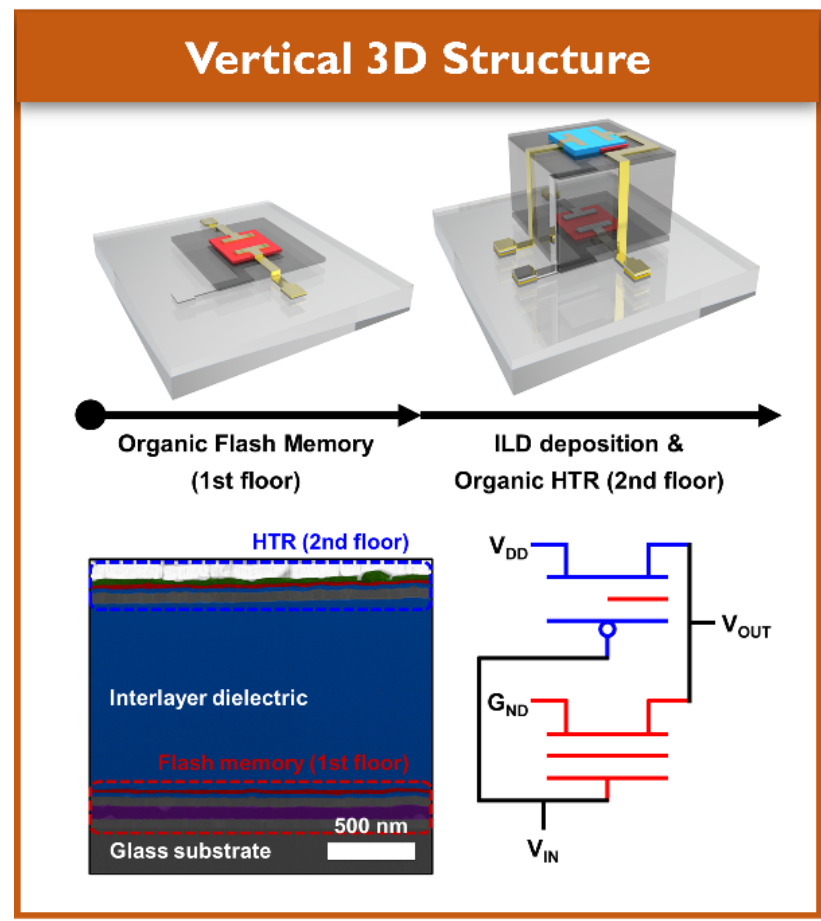


V_A	1	1	0	0
V_B	1	0	0	1
V_{OUT}	0	1	0	1



Hocheon Yoo, Hongkeun Park *et al.*, *IEEE Electron Device Letters*

NDT ternary circuits



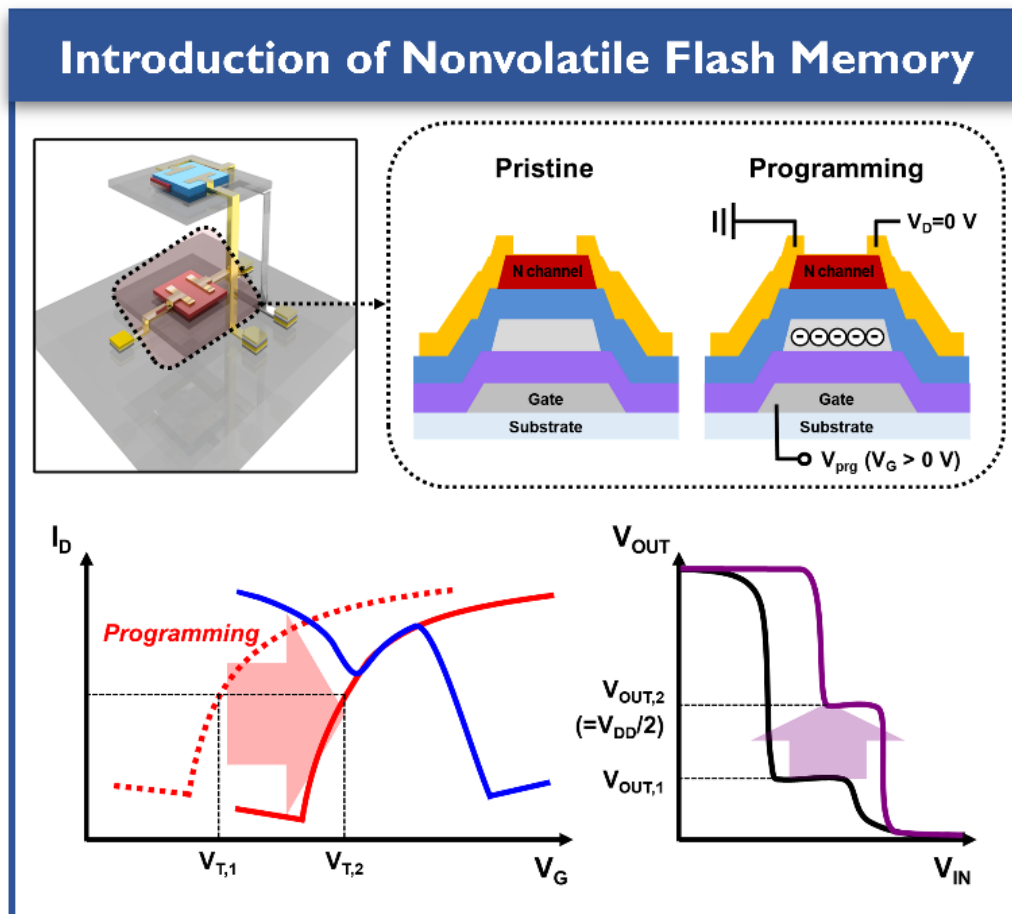
Vertically-Integrated MVL

Controllable MVL operation

MVL depending on memory states

Junhwan Choi, Hocheon Yoo et al., Nature Communications (2022)

NDT ternary circuits



Vertically-Integrated MVL

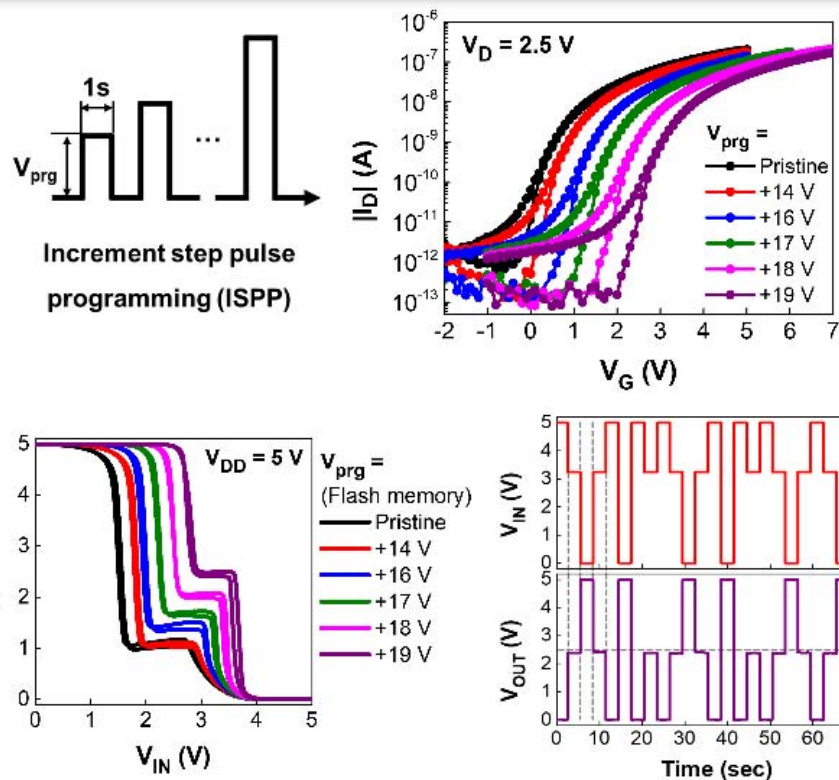
Controllable MVL operation

MVL depending on memory states

Junhwan Choi, Hocheon Yoo *et al.*, *Nature Communications* (2022)

NDT ternary circuits

Controllable Intermediate Logic State



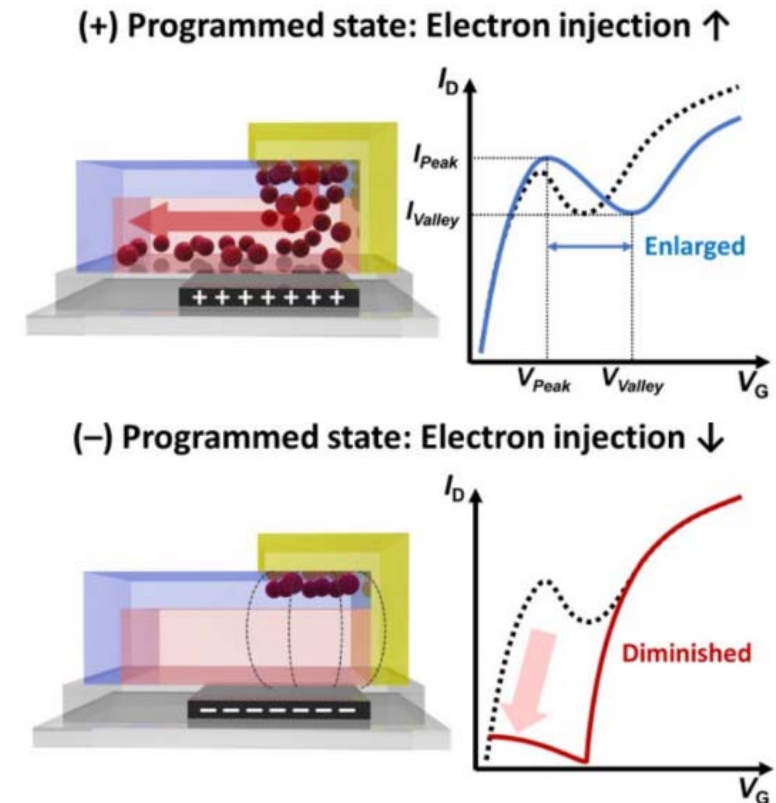
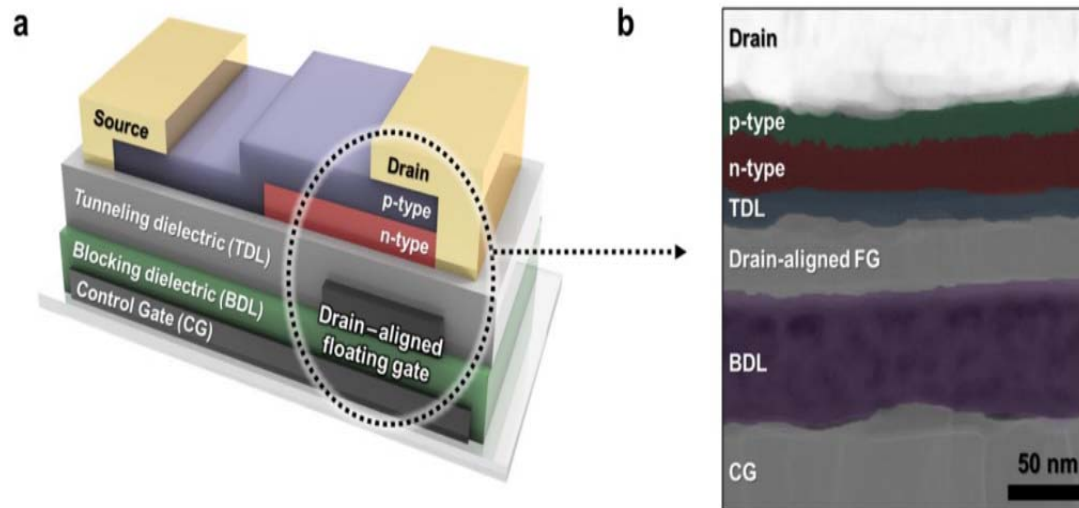
Vertically-Integrated MVL

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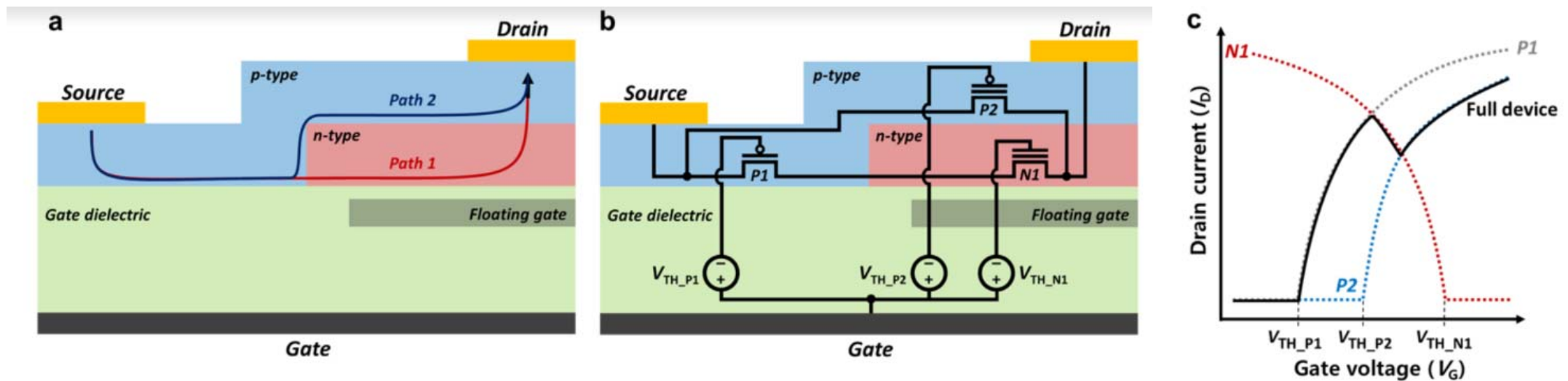
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NDT ternary circuits



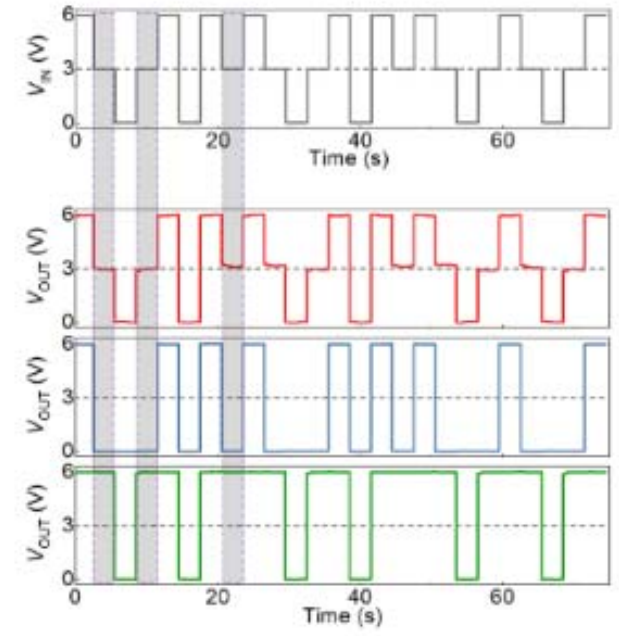
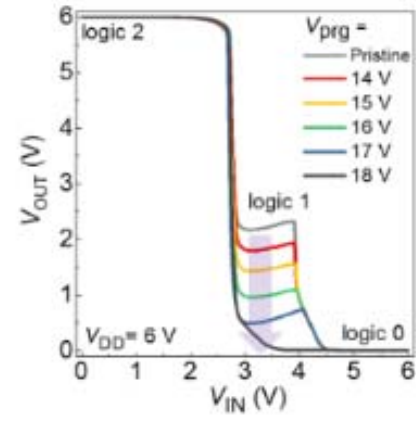
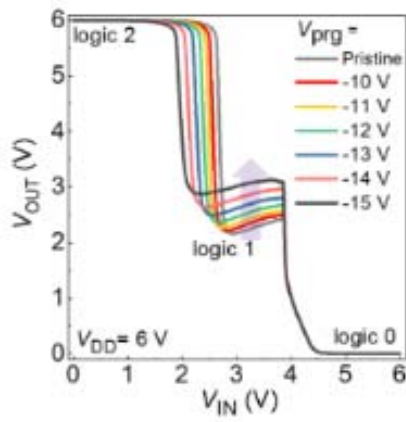
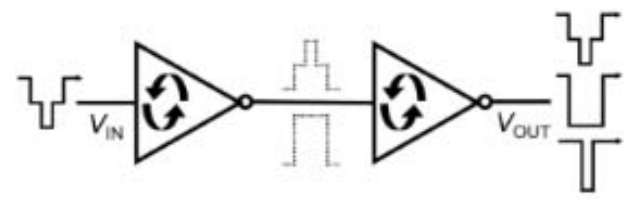
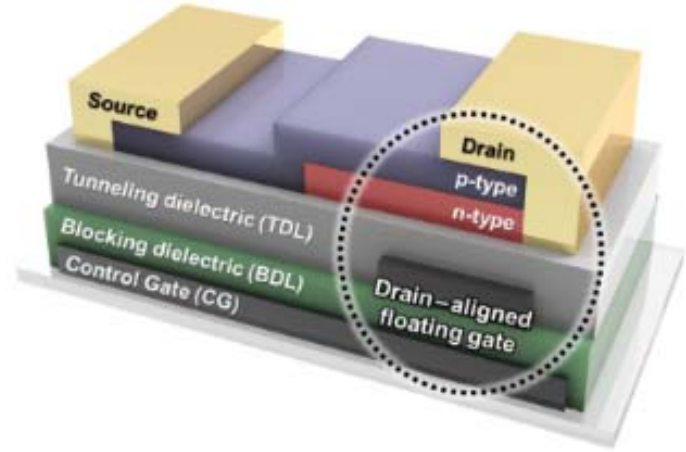
Nature Communications 14.1 (2023): 3757.

NDT ternary circuits



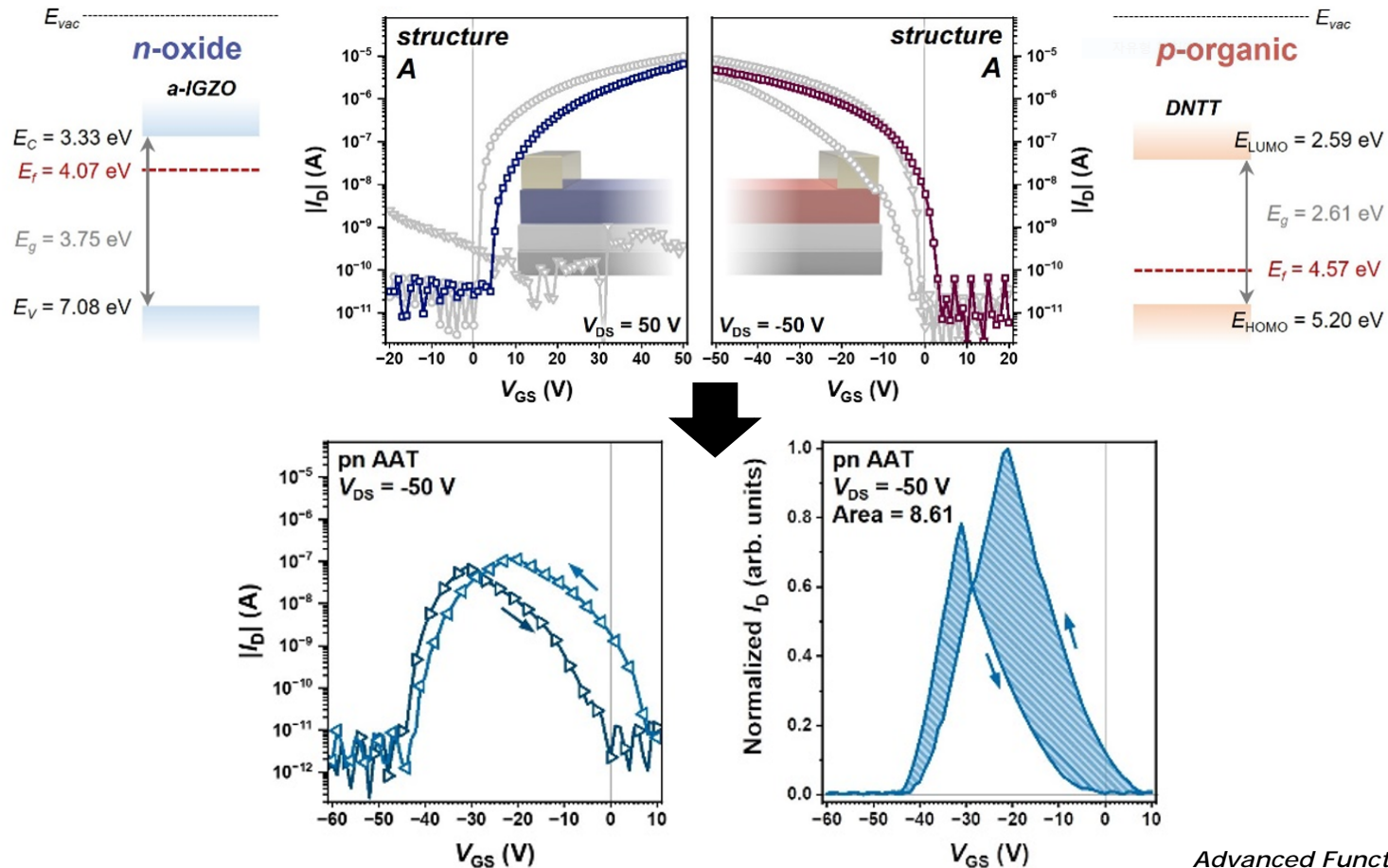
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NDT ternary circuits



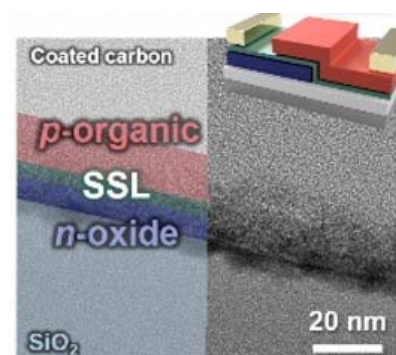
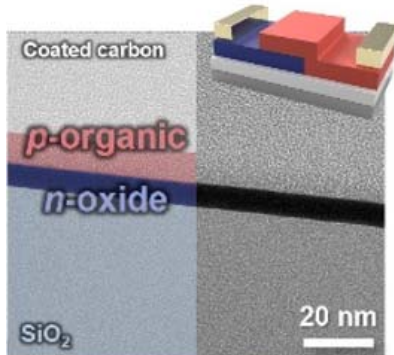
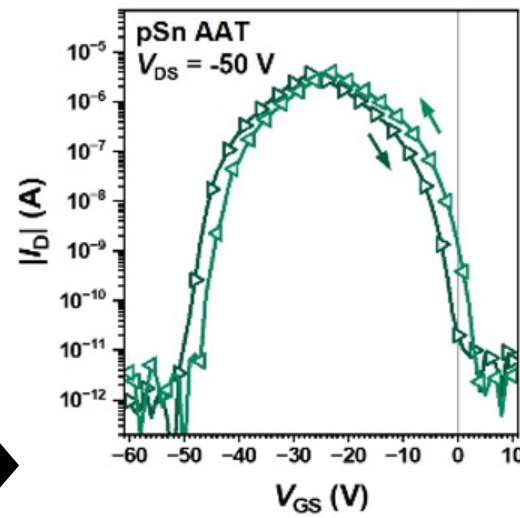
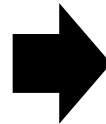
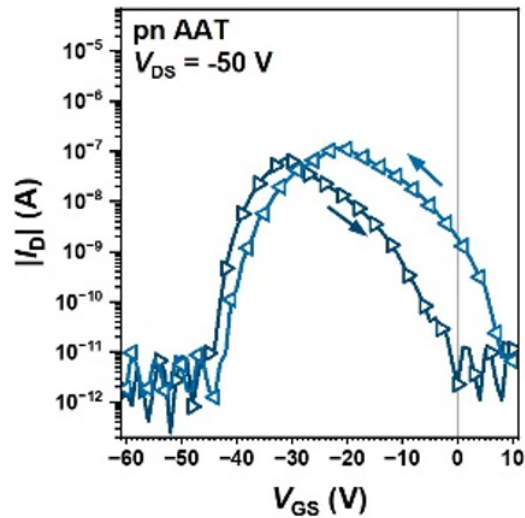
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Anti-ambipolar transistors



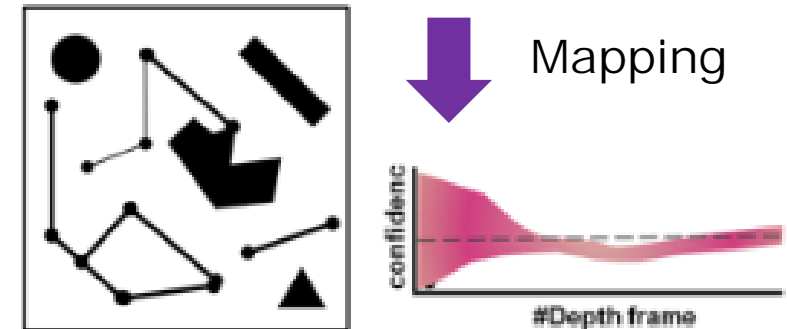
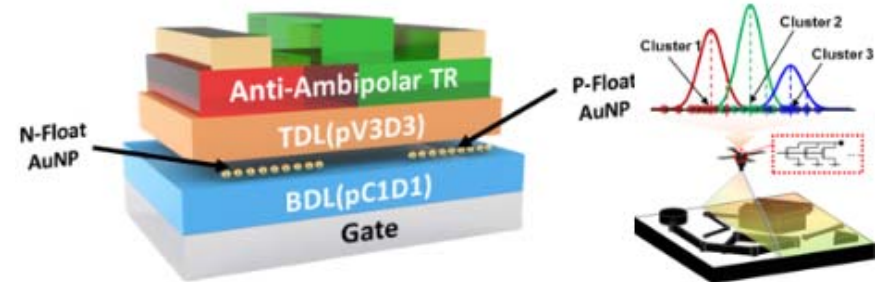
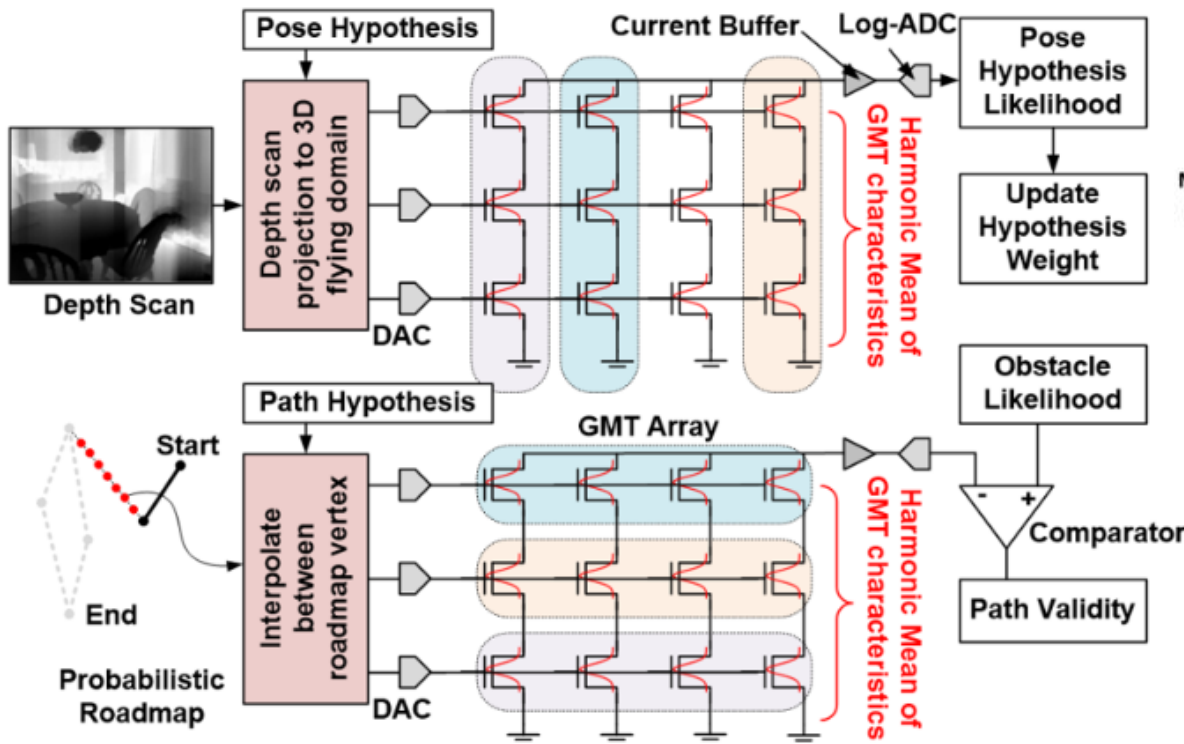
Advanced Functional Materials (2024)

Anti-ambipolar transistors



Advanced Functional Materials (2024)

Probabilistic Reasoning with Gaussian Transistors

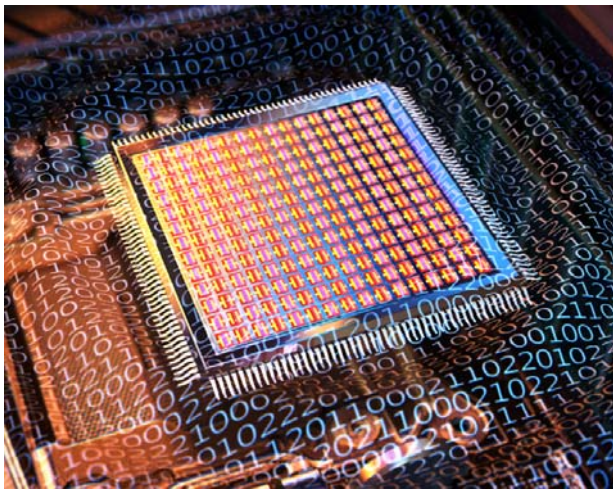


Nature Communications (2024)

Results and discussion

□ Security Devices

Multi-valued Logic



Security Devices



Unconventional Electronic Devices



Physically Unclonable Functions

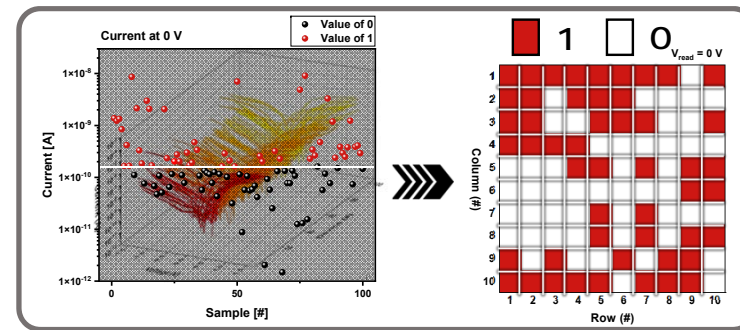
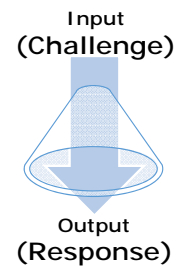
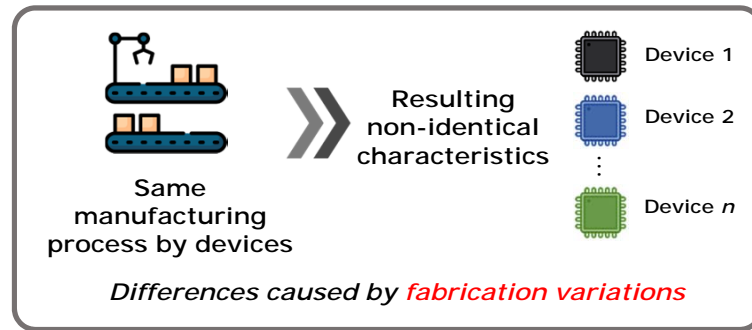


Physically Unclonable Functions

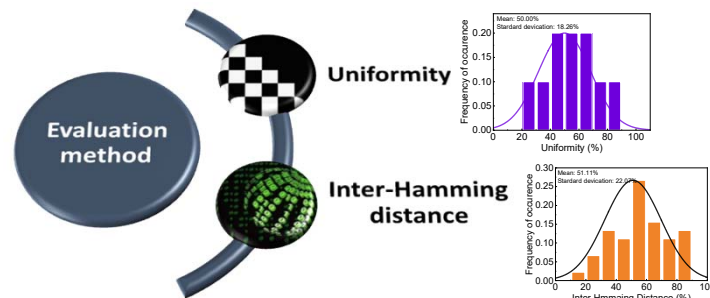


"The only function that cannot be replicated."

"Digital uniquely identifying fingerprints"

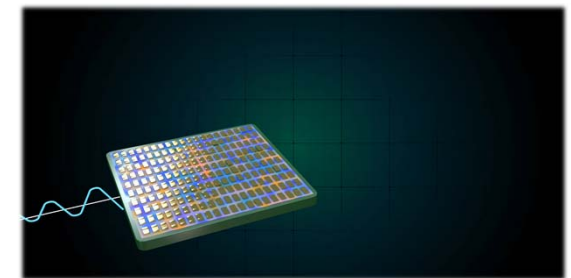
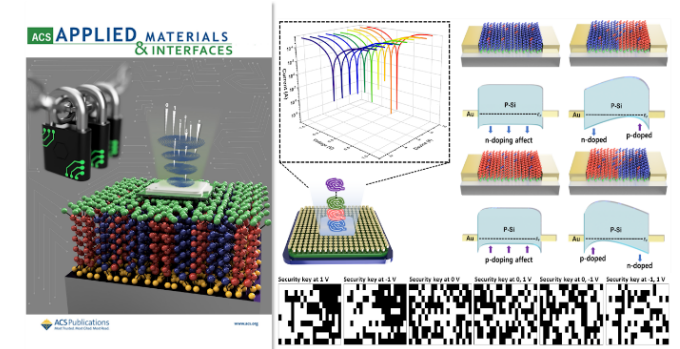
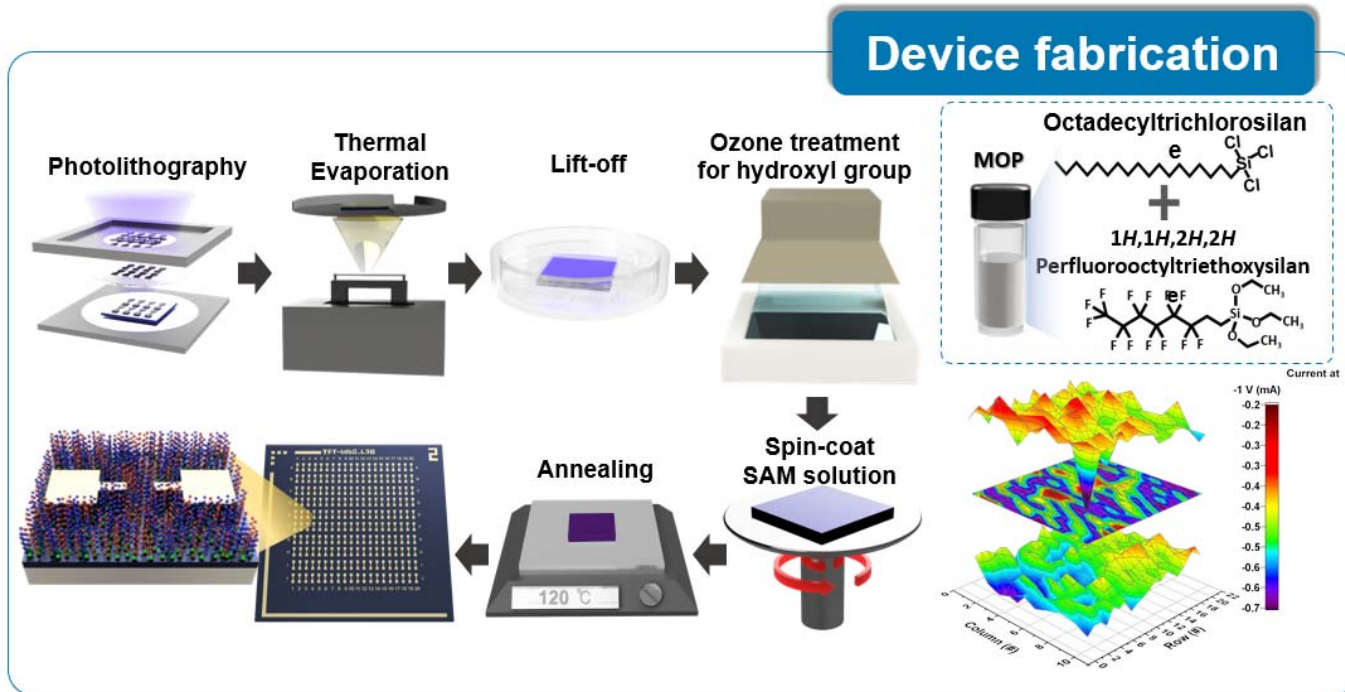


32



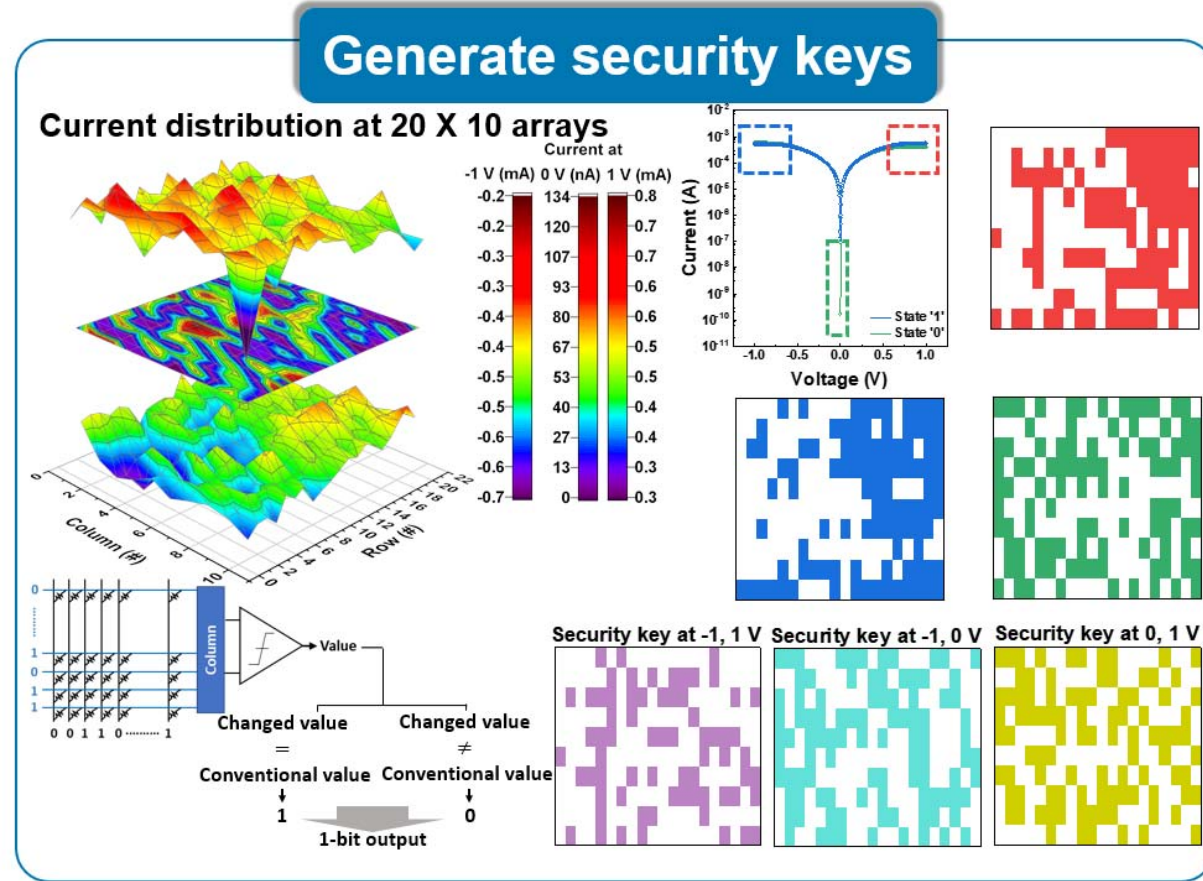
Indicator	Property	Ideal value
Uniformity	Each ratio of 0 and 1 in a dichotomously divided state	50 %
Inter-Hamming distance (HD)	Evaluation of unequal outputs for equal inputs of each device	50 %

Physically Unclonable Functions



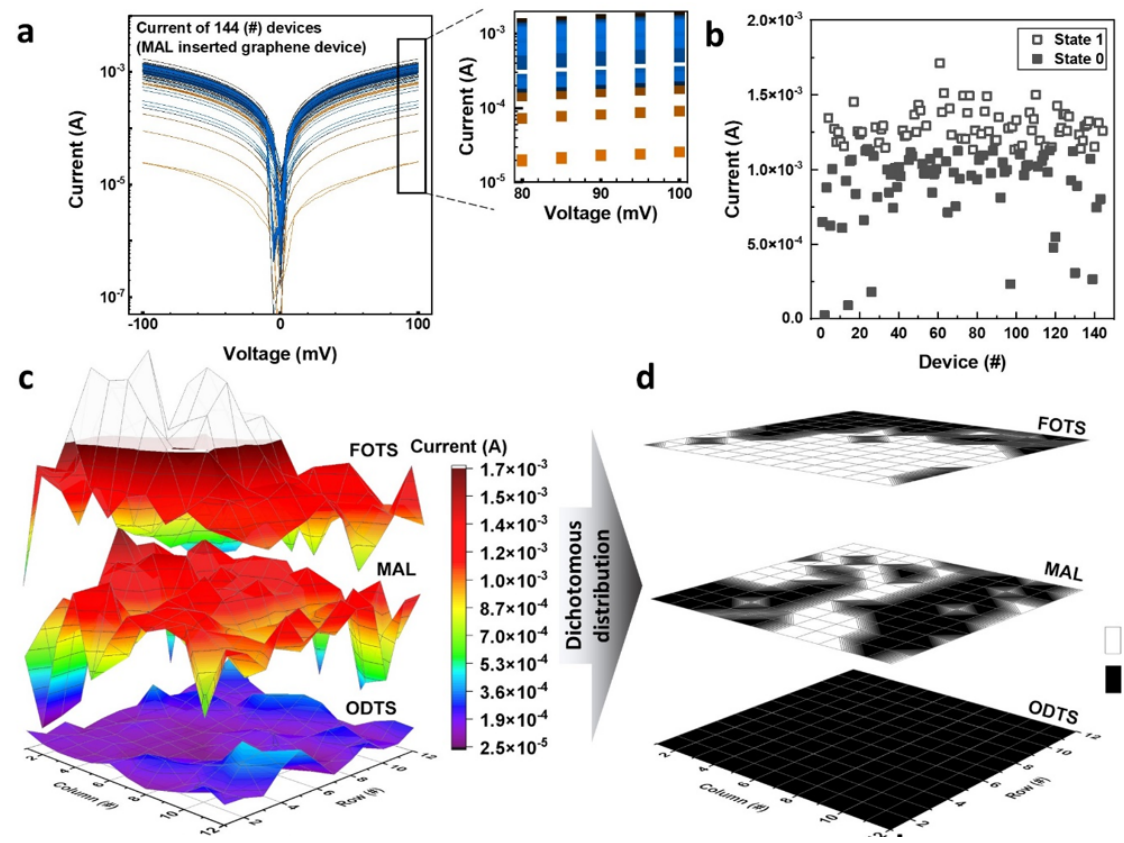
Subin Lee, ACS Applied Materials & Interfaces (2022)

Physically Unclonable Functions



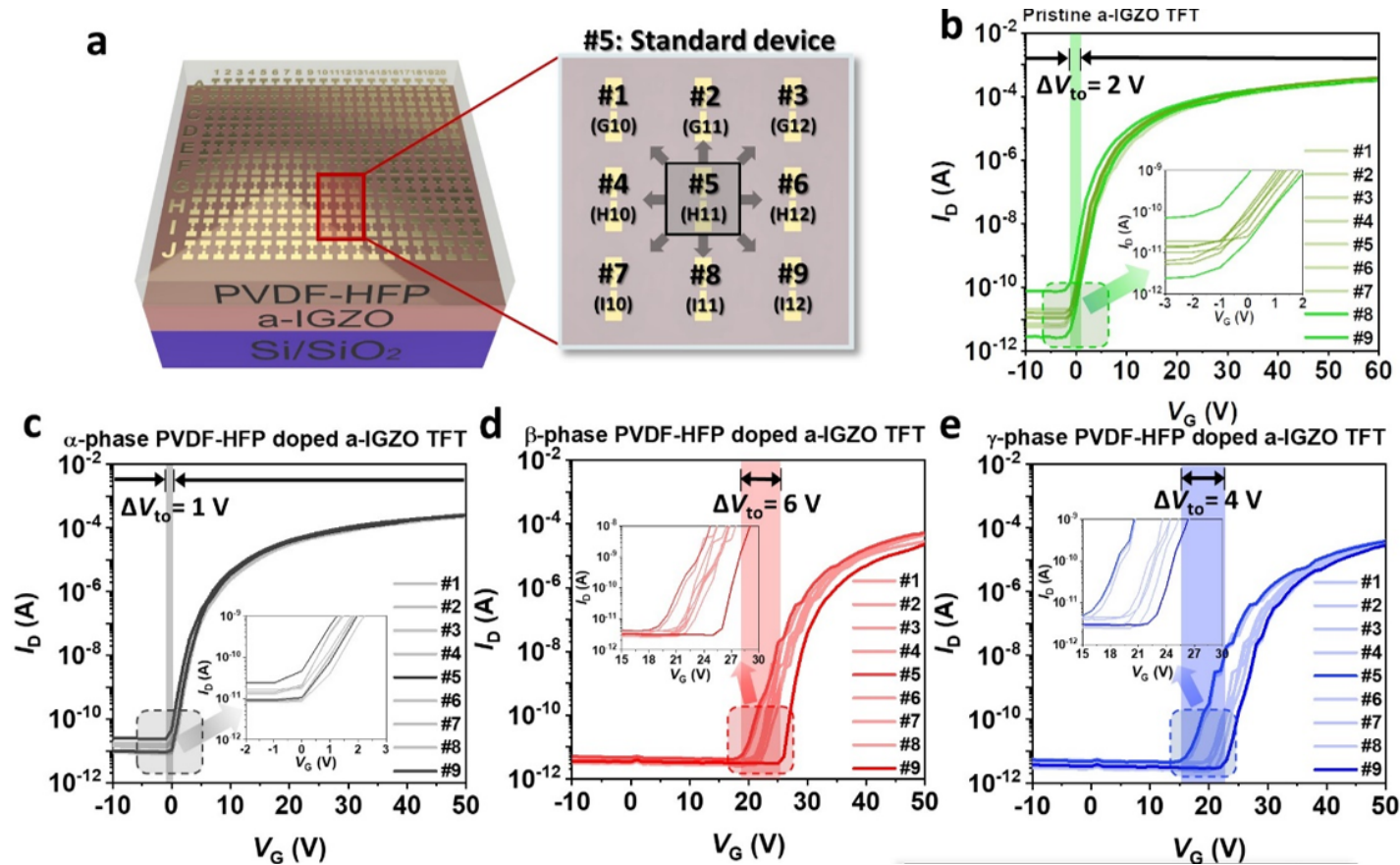
Subin Lee, ACS Applied Materials & Interfaces (2022)

Physically Unclonable Functions



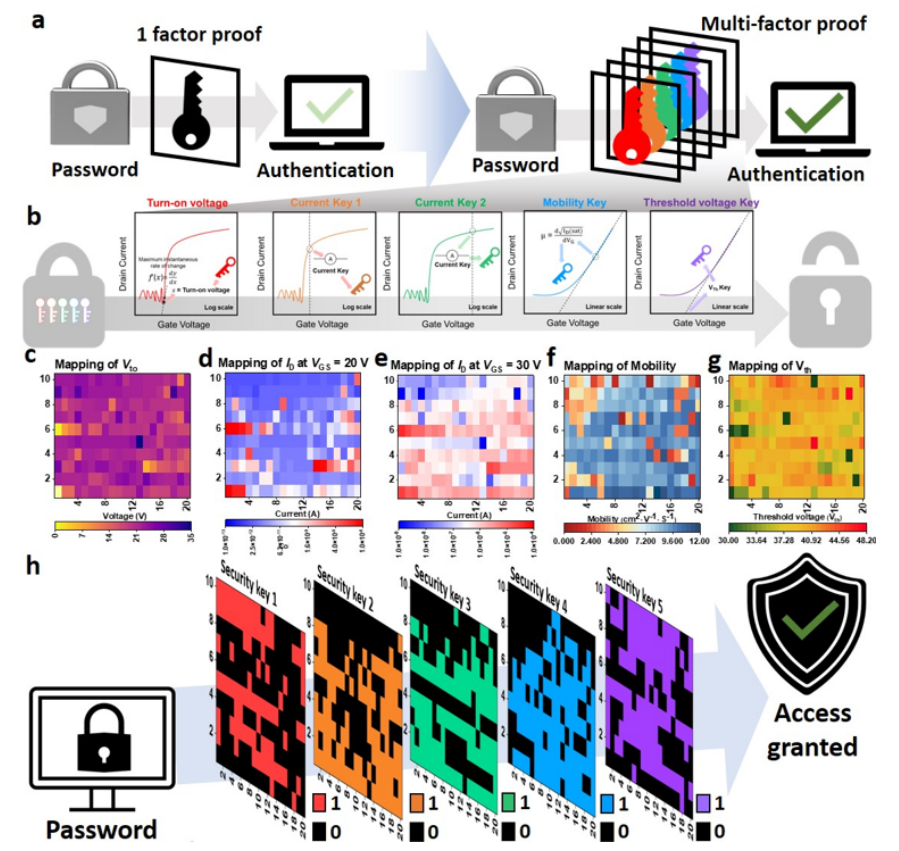
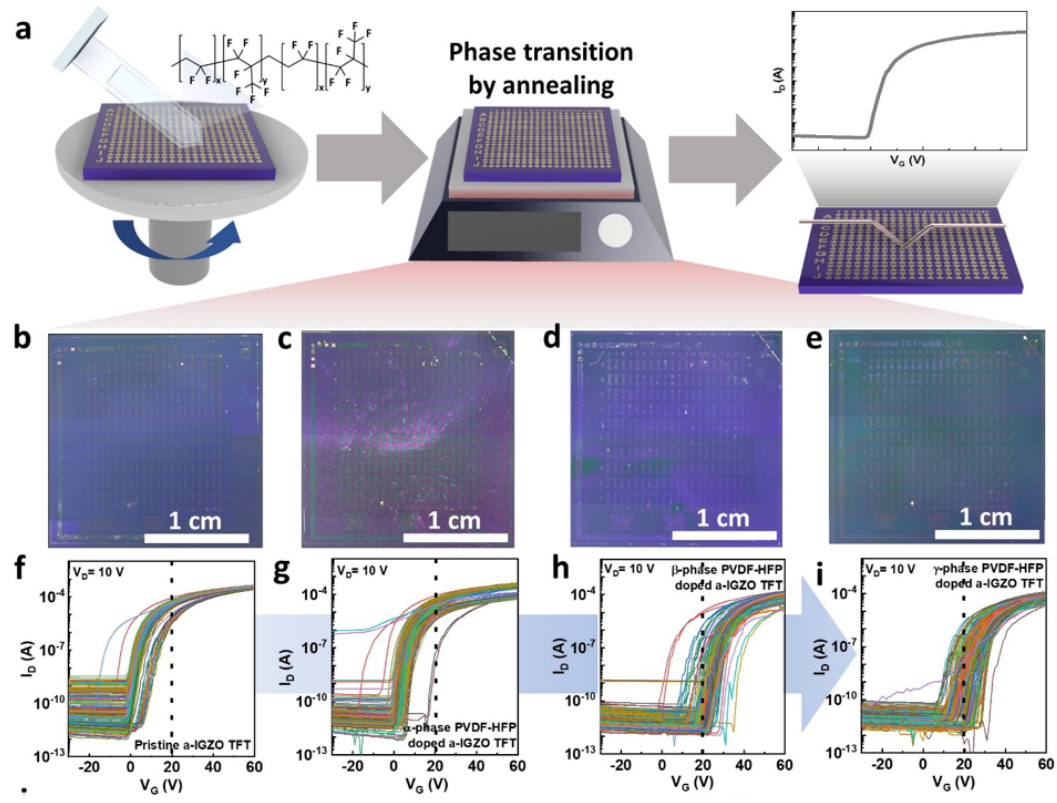
Subin Lee, ACS Applied Materials & Interfaces (2022)

Physically Unclonable Functions



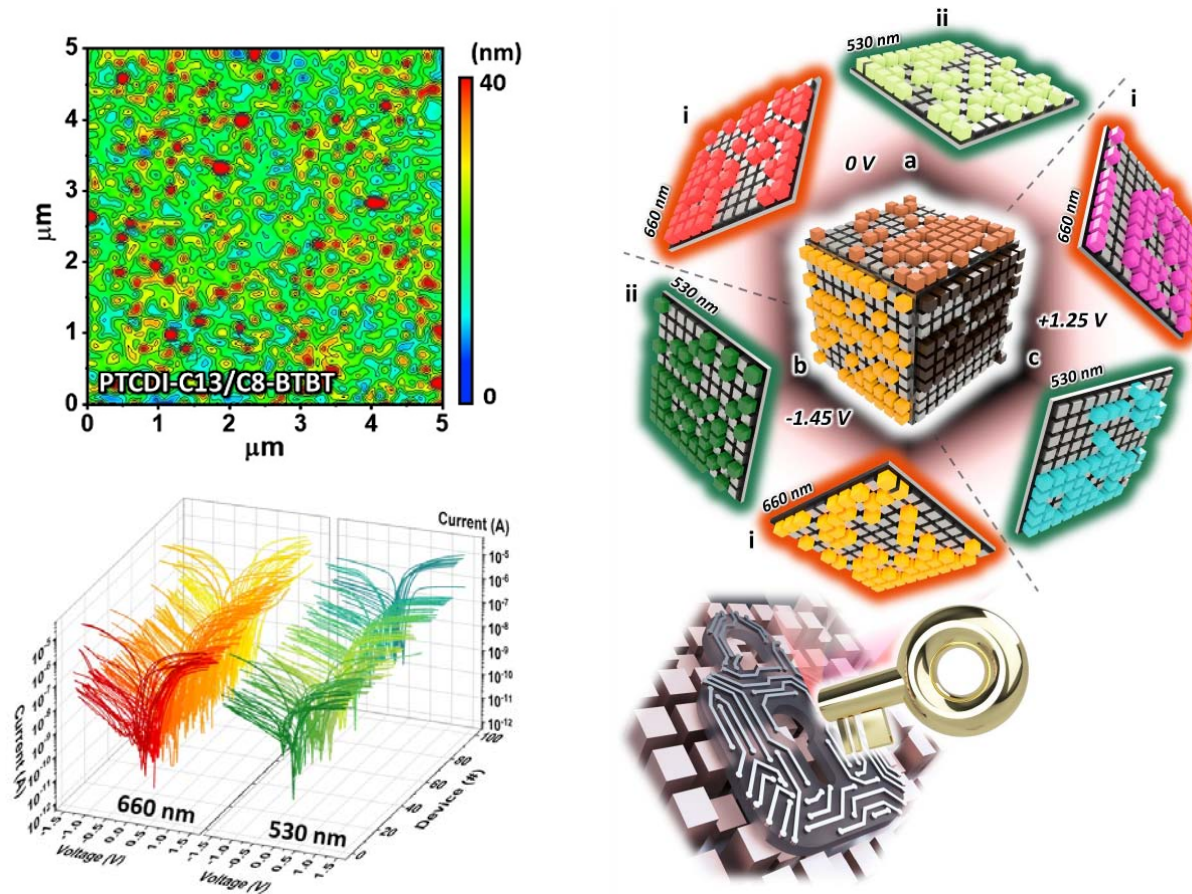
Advanced Science (2024)

Physically Unclonable Functions



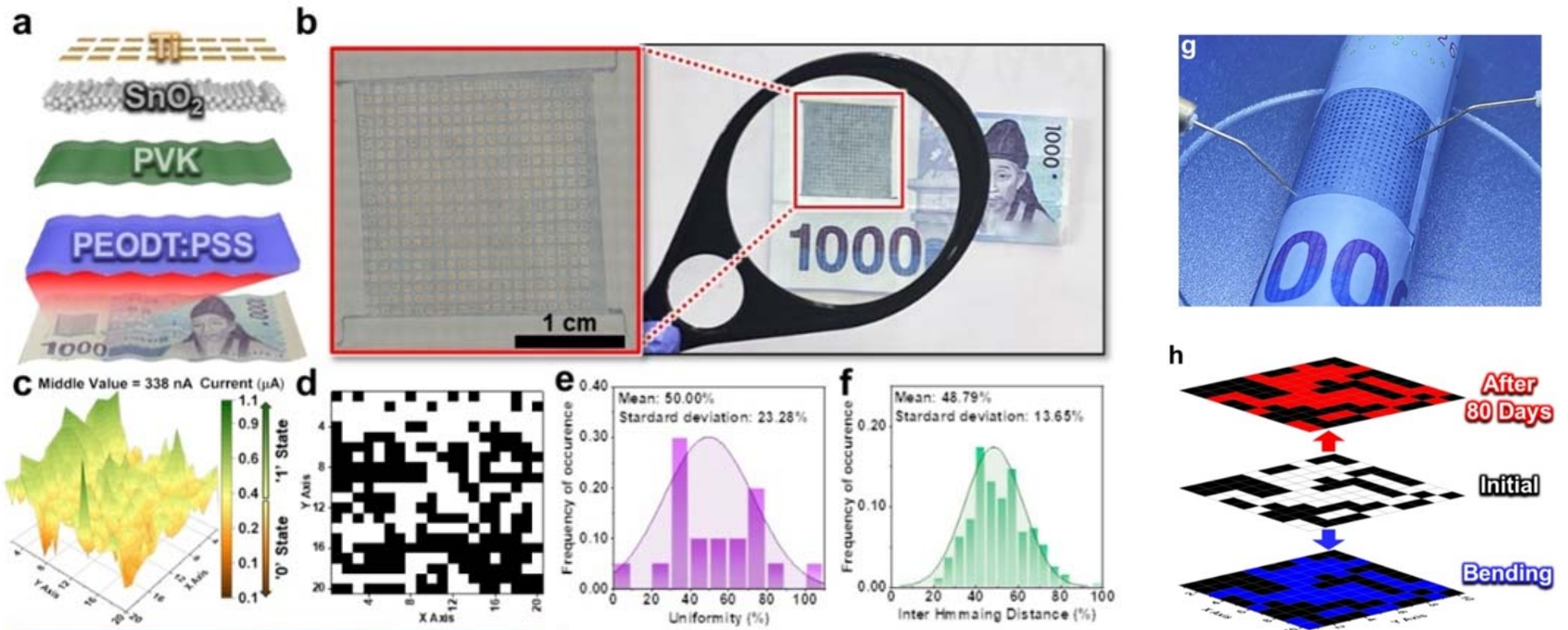
Advanced Science (2024)

Physically Unclonable Functions



Advanced Science (2024)

Unconventional electronics devices

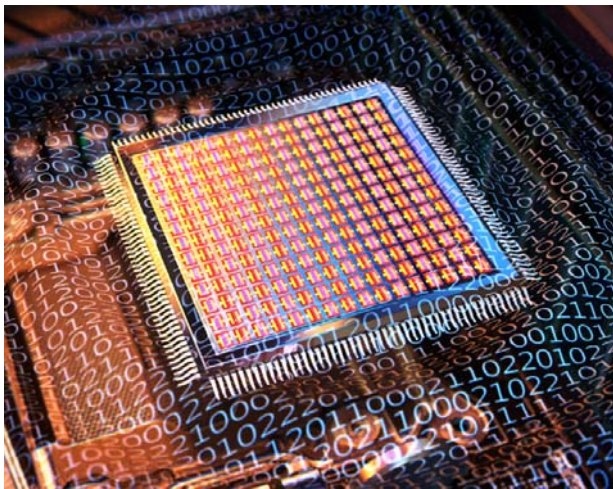


Advanced Materials (2024)

Results and discussion

□ *Unconventional Electronic Devices*

Multi-valued Logic



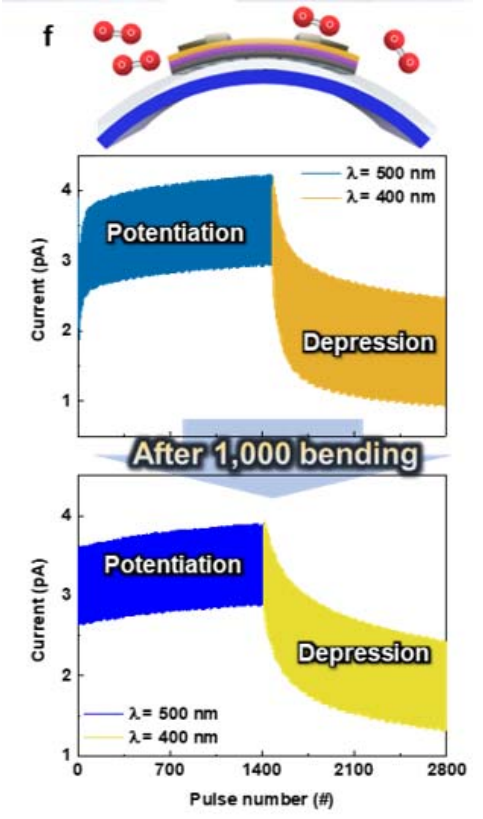
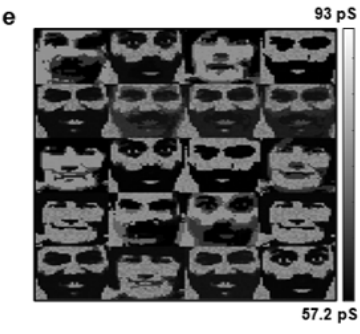
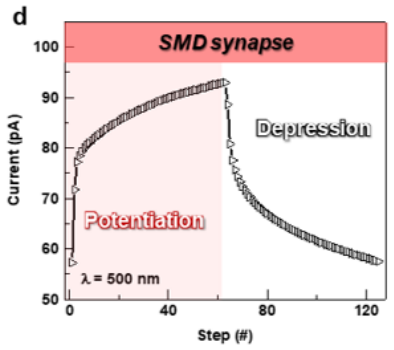
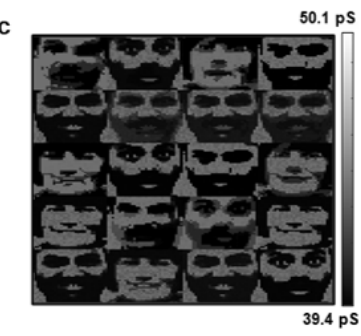
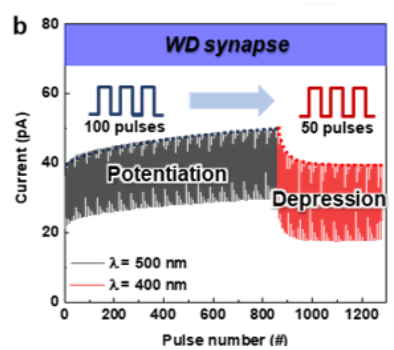
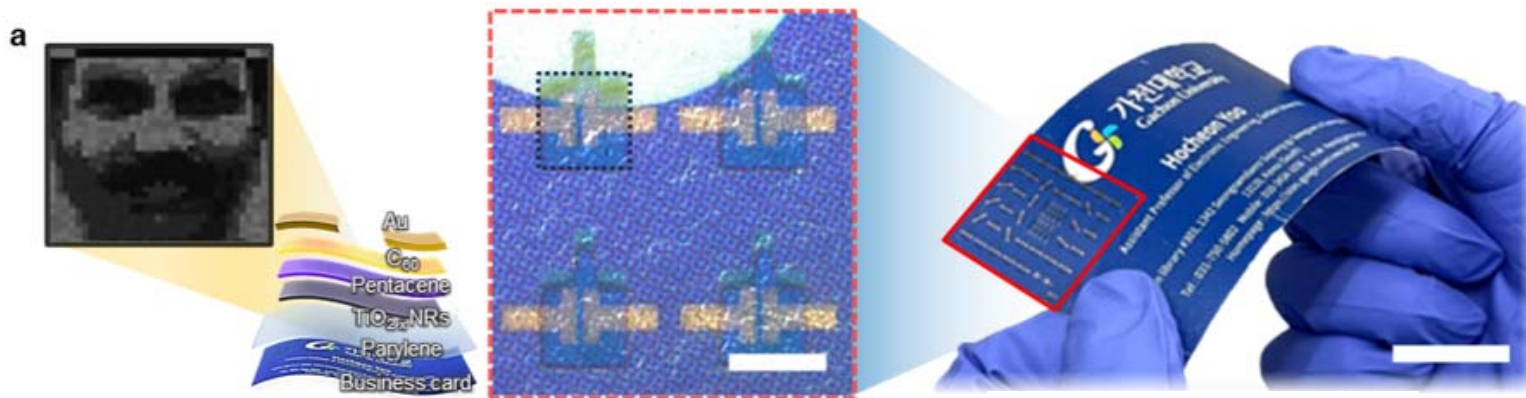
Security Devices



Unconventional Electronic Devices

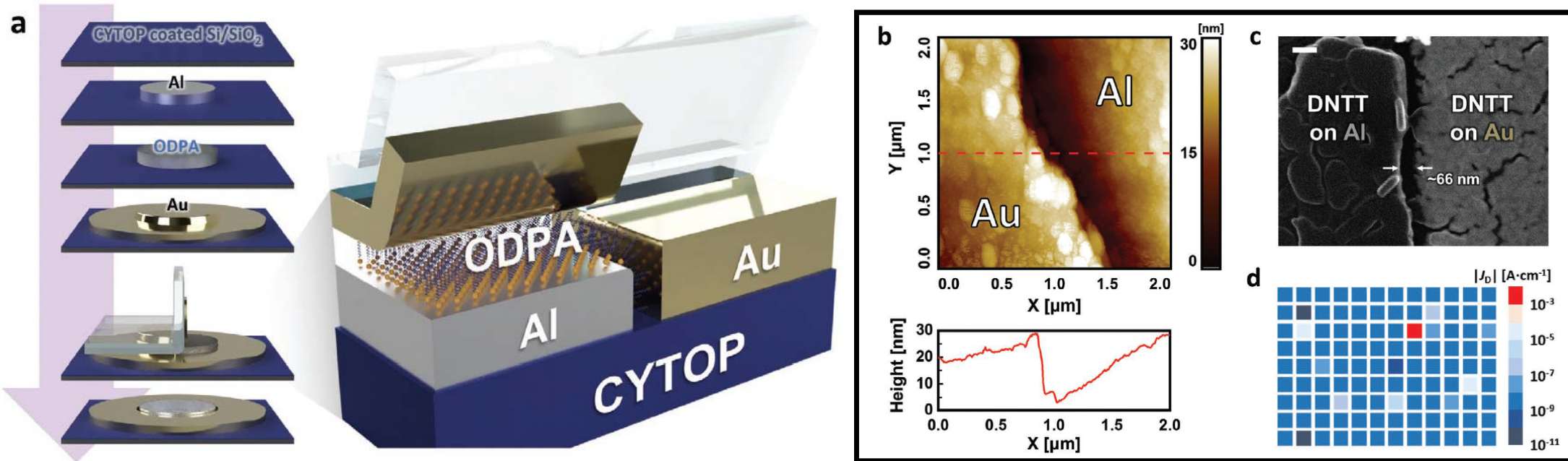


Unconventional electronics devices



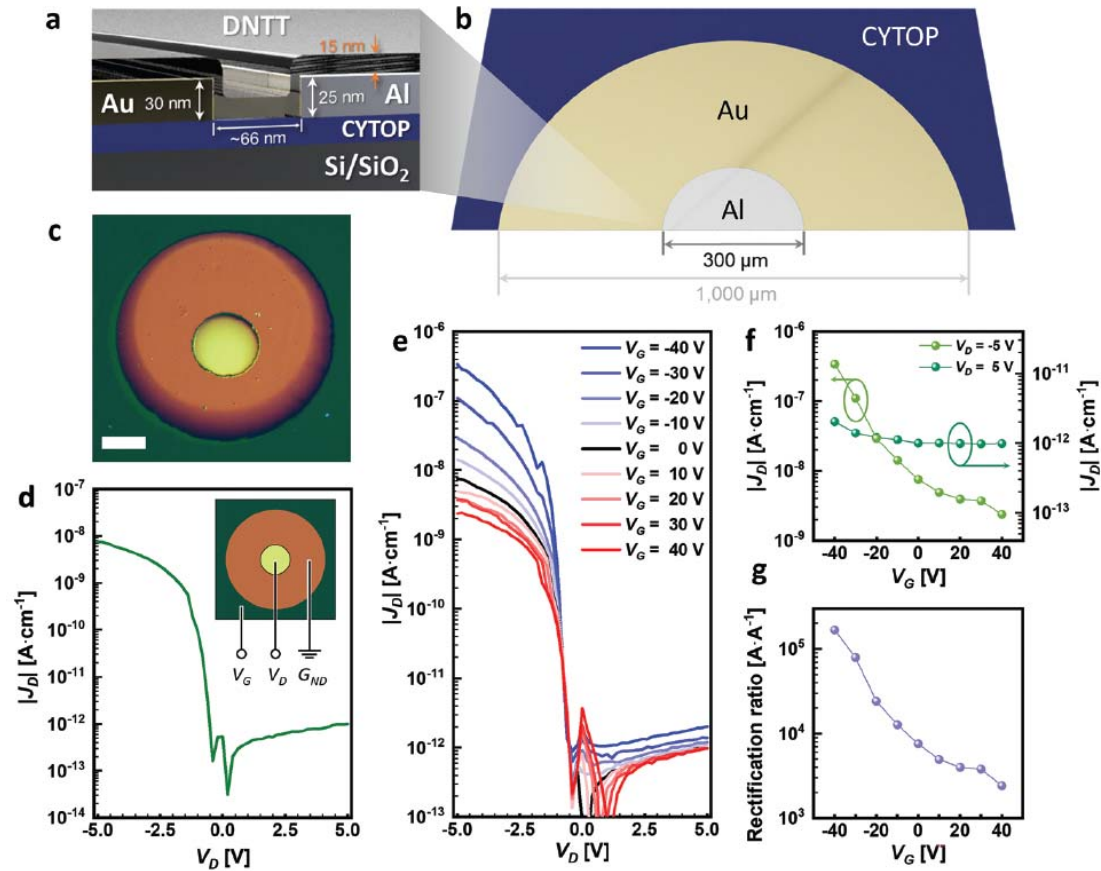
Unpublished results

Nanopattern by adhesion litho (tape)



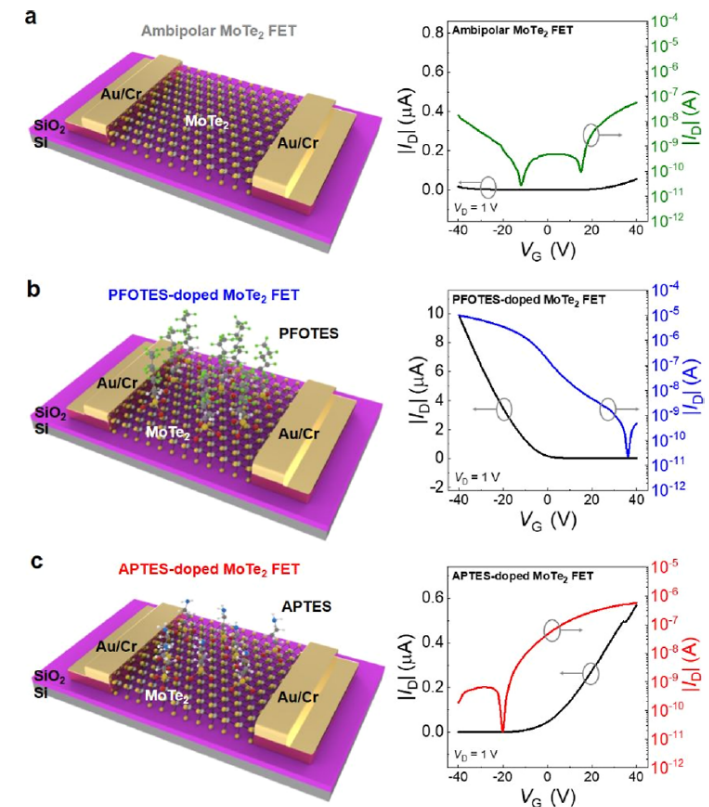
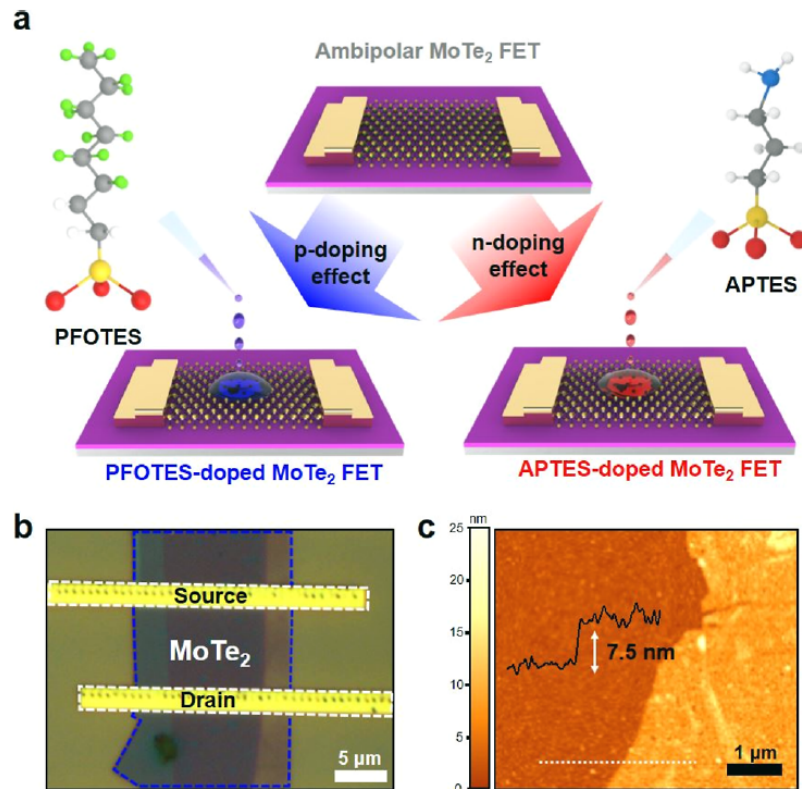
Minseo Kim, Small (2023)

Nanopattern by adhesion litho (tape)



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Nanopattern by adhesion litho (tape)



Dong Hyun Lee et al. ACS AMI (2023)

Thank you very much for your attention!



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