Flexible Nonvolatile Memory

Snehil Verma
14700

Overview

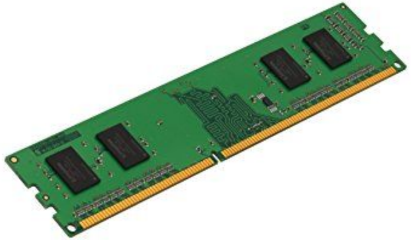
1. Motivation
2. Materials used for designing NVM
3. Approaches for Making Flexible Devices
4. NVM Operational Principles and Architectures
5. Performance numbers
6. References

Motivation

With the advent of healthcare technology, IoT, and big data applications, the need for memory with the following characteristics increased:

- Ultra-dense
- Ultra-low-power
- Robustness to environmental variations (reliability)

IoT -> Fully flexible electronic system



- Processing units - CPU
- The main memory - RAM
- Storage - NVM

Reference: Google Images

Requirements

In order to replace traditional mechanical hard disks with solid-state storage devices, a fully flexible electronic system will need two basic devices:

- Transistors: Used for logic operations and gating memory arrays
- Nonvolatile memory: Required for storing information in the main memory and cache storage.

Overview: Mainstream Design Approaches

All-organic systems

Both devices and substrates are made up of organic materials.

Hybrid systems

Inorganic electronic devices are transferred onto an organic substrate

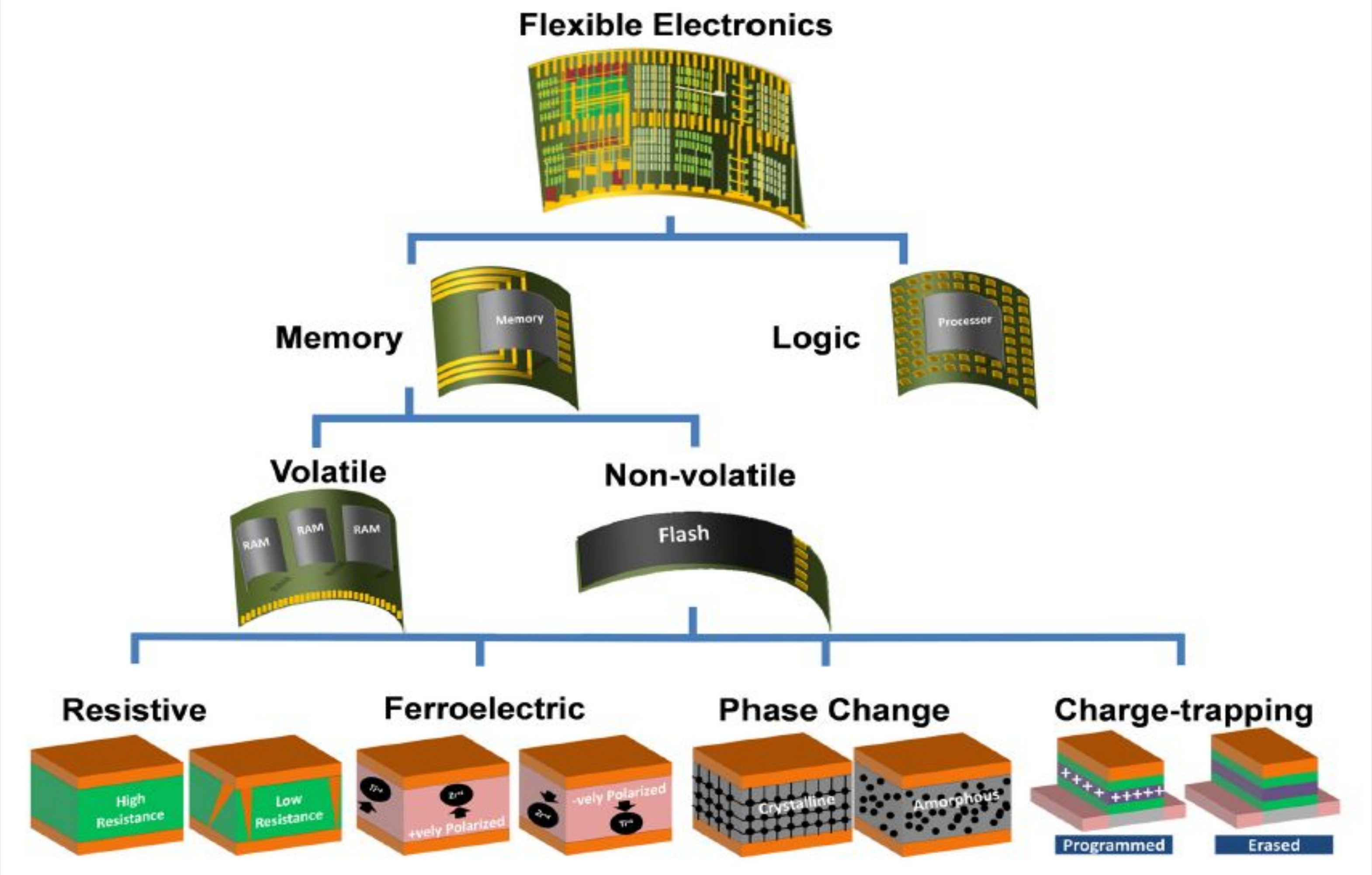
SOI substrate

Use silicon-on-insulator (SOI) substrates, and controlled spalling technology to peel-off thin semiconductor layers.

Overview: Emerging NVM

- Resistive RAM (ReRAM)
- Flash memory (floating gate and charge trapping)
- Phase change RAM (PCRAM)
- Ferroelectric RAM (FeRAM)

Benefits of fast switching, low-operation voltage, and ultra-large-scale-integration (ULSI) densities.



Flexible Electronics
Memory
Memory
Logic
Processor
Volatile
RAM
RAM
RAM
Non-volatile
Flash
Resistive
High Resistance
Low Resistance
Ferroelectric
+vely Polarized
-vely Polarized
Phase Change
Crystalline
Amorphous
Charge-trapping
Programmed
Erased

Reference: [5]

Materials used for designing NVM

0-dimensional

- Gold nanoparticles (NPs)
- Black phosphorus quantum dots (QDs)
- Silicon QDs

1-dimensional

- ZnO nanowires
- Si nanowires
- Carbon nanotubes (CNTs)

2-dimensional

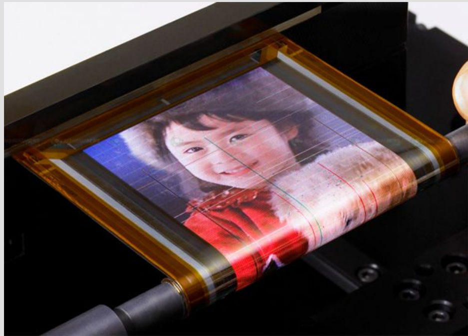
- Graphene
- Graphene oxide
- MoS_2
- ZnO
- Hydrated tungsten trioxide ($WO_3.H_2O$) nano-sheet

Reference: [5]

Samsung

Semiconductor Industry:
Artificial Skin, Display

Sony



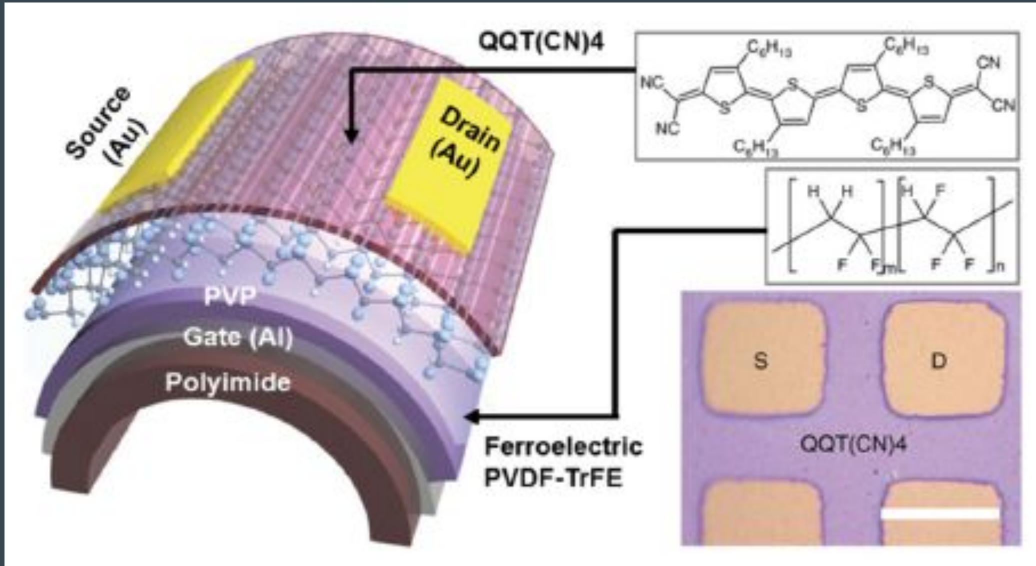
Reference: Google Images

Approaches for Making Flexible Devices

All-Organic Approach

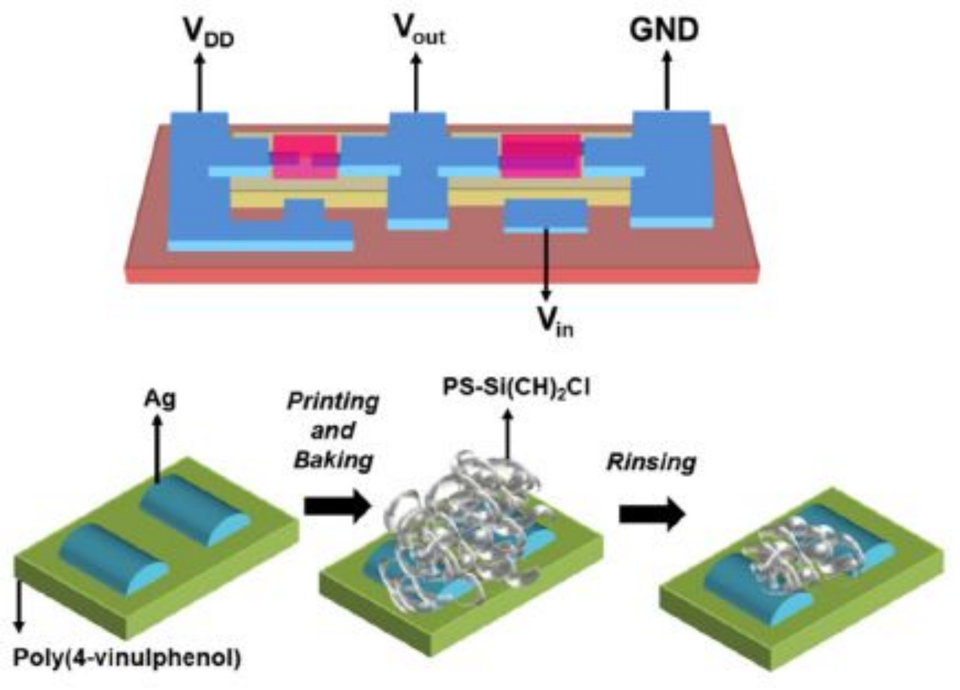
- Polymeric semiconductors as channel materials.
- Polymeric ferroelectrics for nonvolatile storage.
- Thick, durable insulating polymers to support the flexible substrate.

All-organic deposited NVM



Reference: [1]

All-Organic Approach



Inkjet-printed organic inverter on a plastic substrate

Reference: [2]

All-Organic Approach

Challenges

Performance:

- The highest reported mobility more than 20 times lower than silicon (exception of 43 $cm^2/V.s$ peak hole saturation mobility reported by Yongbo Yuan et al. [3]).
- Reliability
- Thermal stability [4]

Advantages

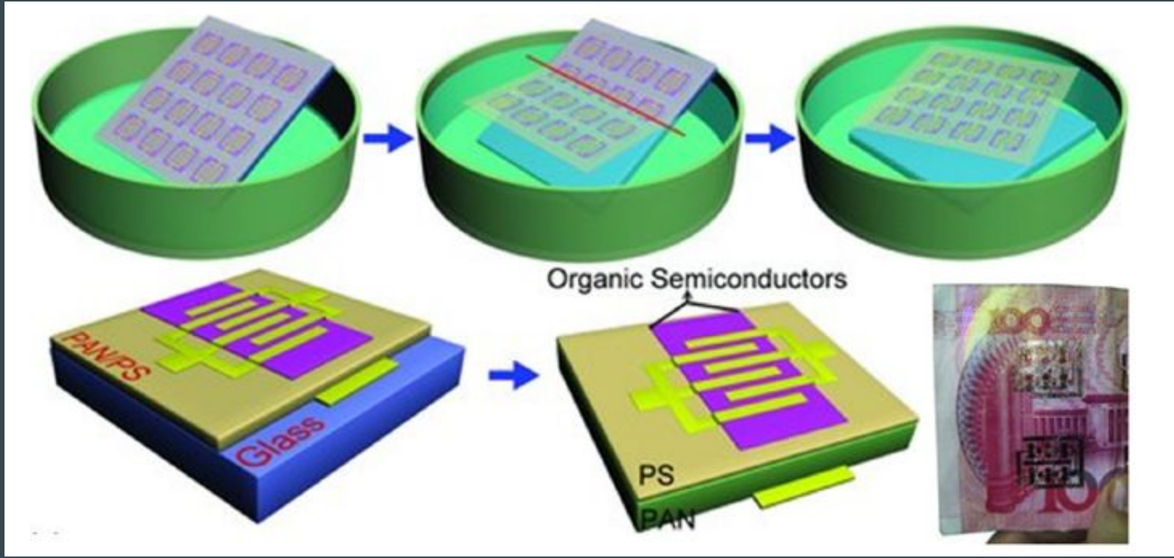
- Low cost
- Flexibility - AMOLED display

Hybrid Systems Approach

Use both organic and inorganic materials.

- More versatile.

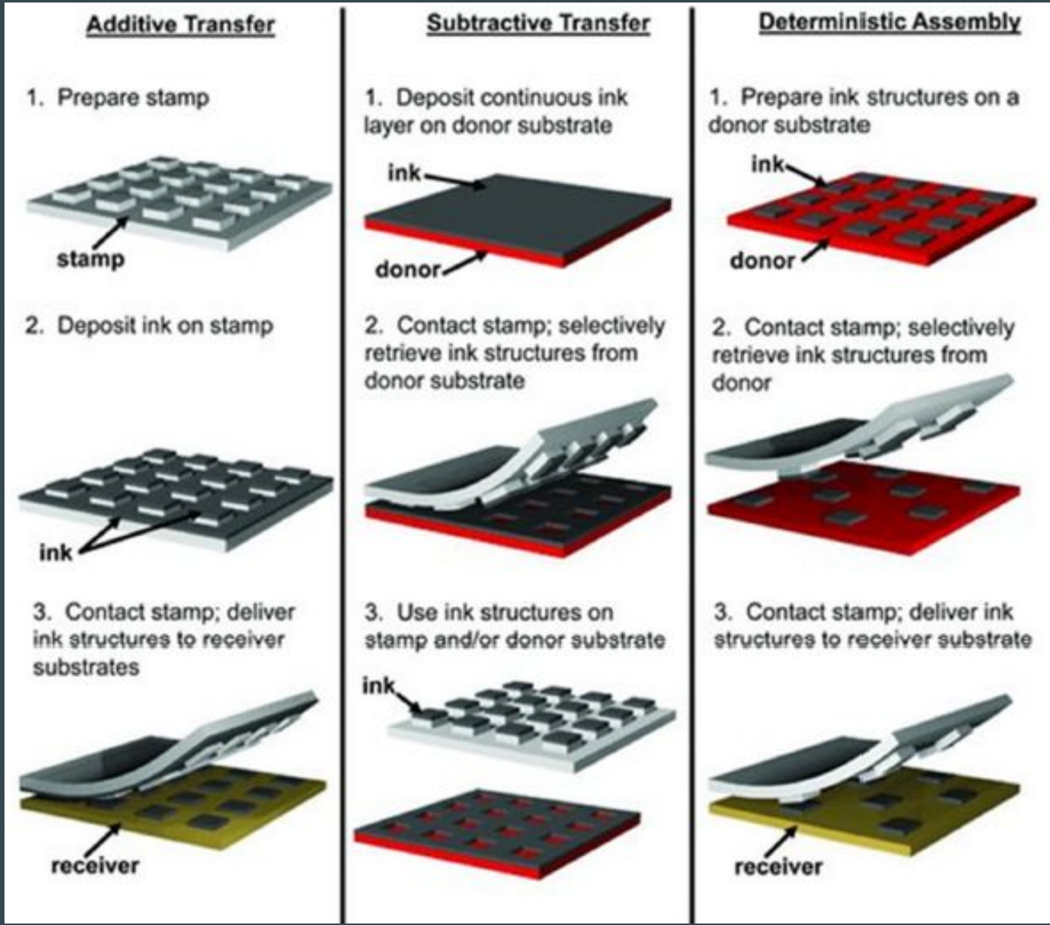
Generic transfer technique, where devices are fabricated on a specific rigid substrate and then transferred to one that is flexible



Reference: [6]

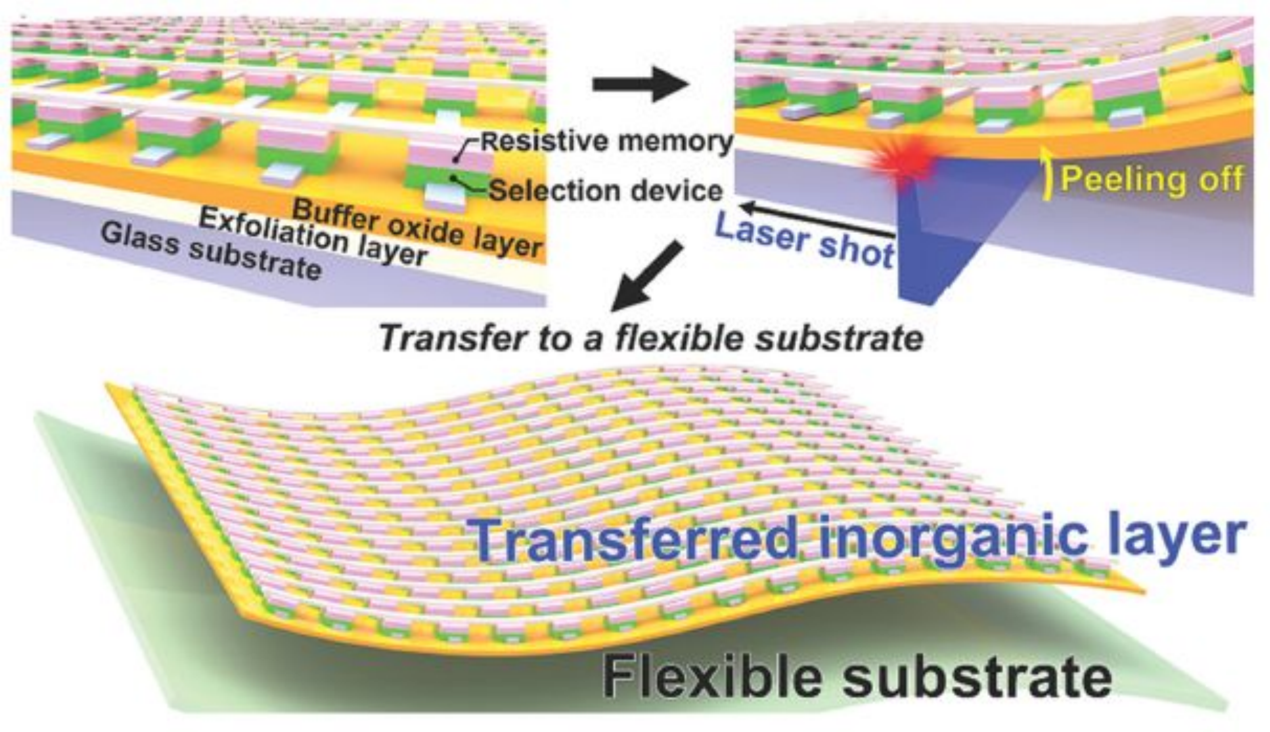
Hybrid Systems Approach

Three modes of transfer printing



Reference: [7]

Hybrid Systems Approach



Fabricating flexible crossbar-structured memory on a plastic substrate via the laser lift-off transfer method

Reference: [8]

Hybrid Systems Approach

Challenges

- Extra non-conventional transfer steps.
- Low yield

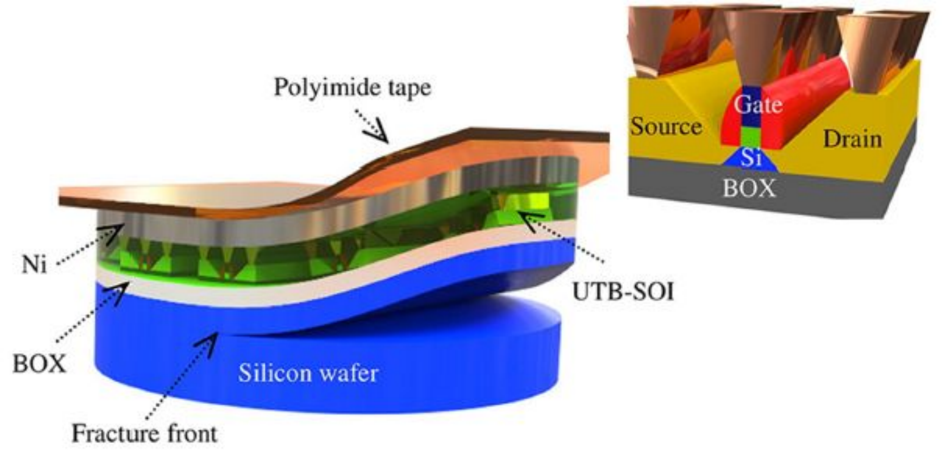
Advantages

- High performance

Spalling Technology

Use stressor layers to initiate fracture-modes in SOI and semiconductor substrates.

- Deposit a Ni stressor layer that is abruptly discontinued near one edge of the wafer where a crack in the mono-crystalline silicon (Si) is to be initiated by applying a force [9, 10].
- Before the force is applied, polyimide tape is added to support the flexible peeled layer bearing ultra-thin body devices.



Reference: [11]

Spalling Technology

Challenges

- Extra deposition and complex tuning of a stressor material with a specific thickness followed by etching are required
- Once the crack has been initiated, the peeling-off process requires high dexterity that is not suitable for mass production

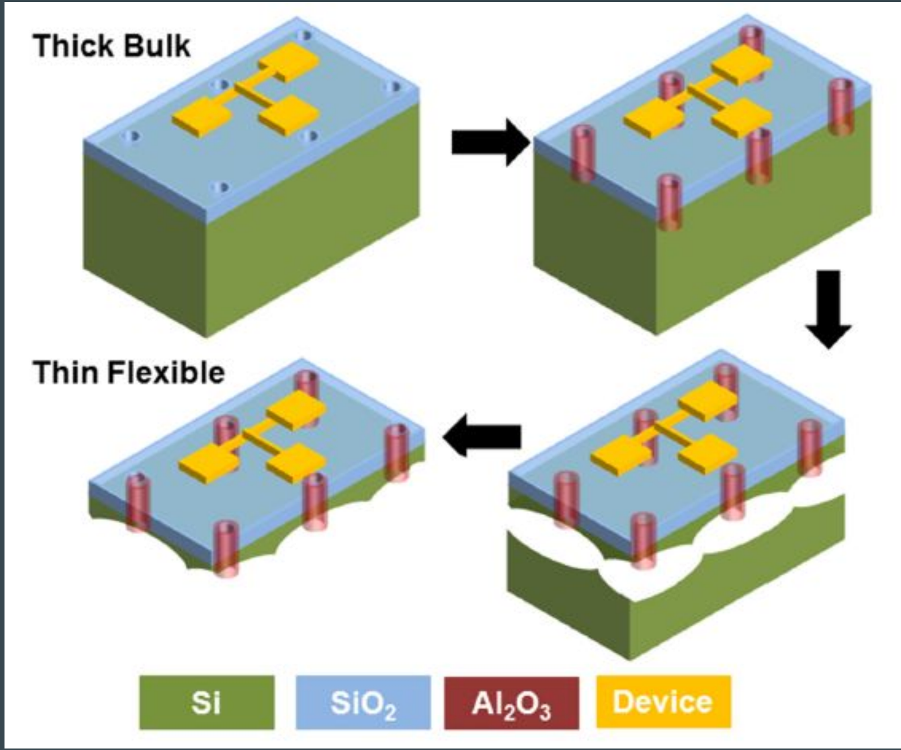
Complementary Transfer-free Inorganic Approach

Inverse proportionality between the material's thickness and flexibility.

- High performance
- Reliability
- ULSI density
- Low cost

$$\textit{Flexibility} \propto t^{-3}$$

Complementary Transfer-free Inorganic Approach

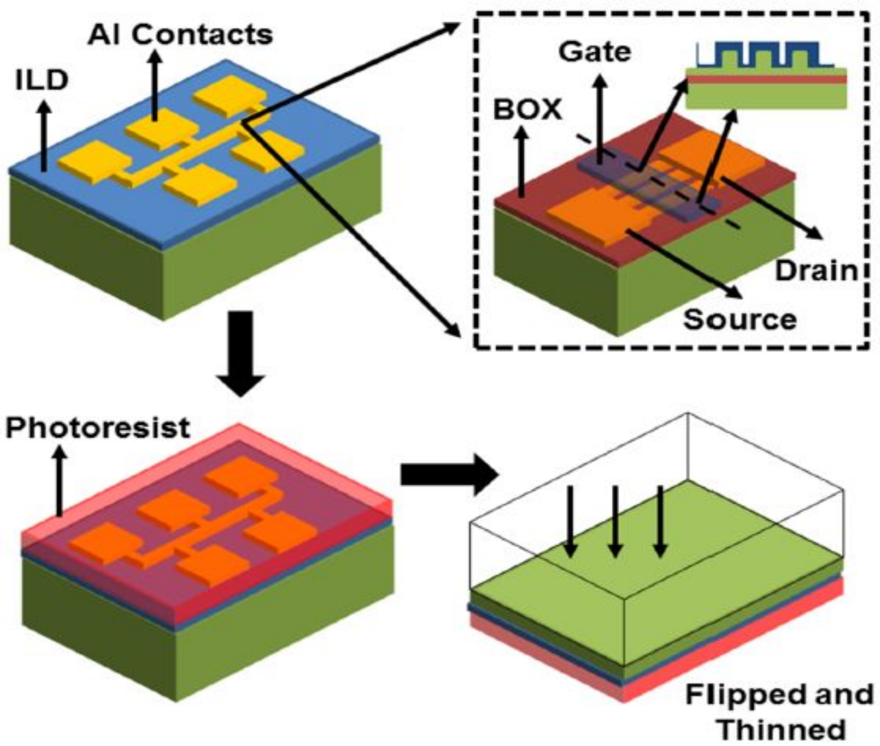


Silicon-flexing technique (Device first approach)

Reference: [12]

Complementary Transfer-free Inorganic Approach

Soft-etch back approach



Reference: [13]

Fracture Strength

Most common method: three-point bending test.

- Based on the application's required bending radius, the thickness of the flexible silicon substrate must be adjusted such that the applied stress is lower than the fracture stress.
- Eg. : the minimum bending radius that would cause fracture stress for a 50-µm thick flexible silicon substrate is ~ 3 mm

NVM Operational Principles and Architectures

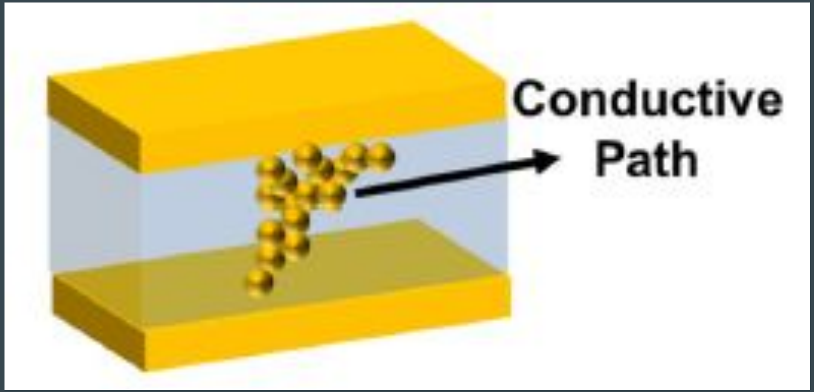
NVM Operational Principles

- Capable of storing information over long periods of time (~10 years is the industry standard)
- Retain information even when no power is supplied.

Leading Flexible NVM technologies

Resistive RAM: ReRAM (Memristor)

- A resistive oxide is sandwiched between two metallic layers.
- The resistance of the oxide changes with applied “set” and “reset” voltage pulses.

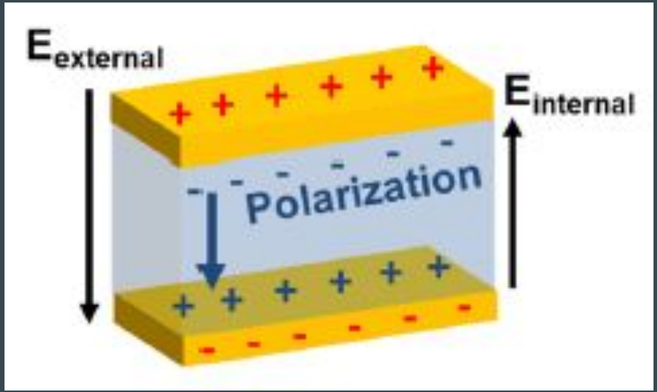


Reference: [14, 15]

Leading Flexible NVM technologies

Ferroelectric RAM: FeRAM

- A ferroelectric material has two possible polarization states inherent from its crystalline structure.
- Applying write/erase voltage pulse switches for positive to negative polarization states.

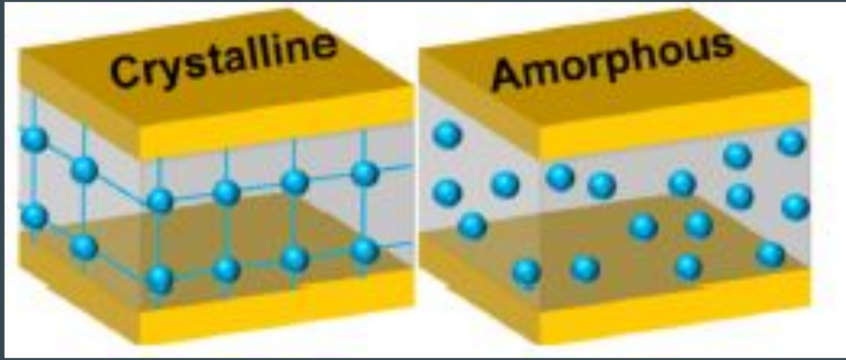


Reference: [16]

Leading Flexible NVM technologies

Phase change RAM: PCRAM

- Current or laser pulses are applied to change the phase of a material from crystalline (low resistance) to amorphous (high resistance) and vice versa at a localized space, which changes the material's electrical and optical properties.



Reference: [17,18]

Leading Flexible NVM technologies

Flash memory (floating gate (FG))

- Similar structure as a field effect transistor (FET), except that its gate dielectric is split into three layers.
  - Tunneling oxide
  - Embedded conductor layer - floating gate
  - Blocking oxide
- When a programming voltage is applied, carriers tunnel from the channel to the floating gate.

Reference: [19]

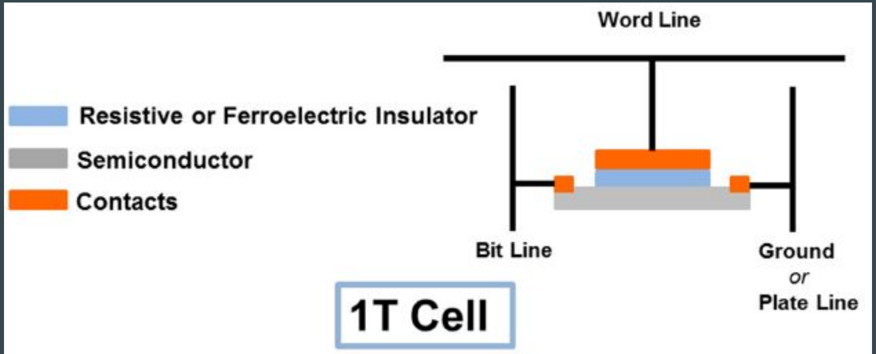
Leading Flexible NVM technologies

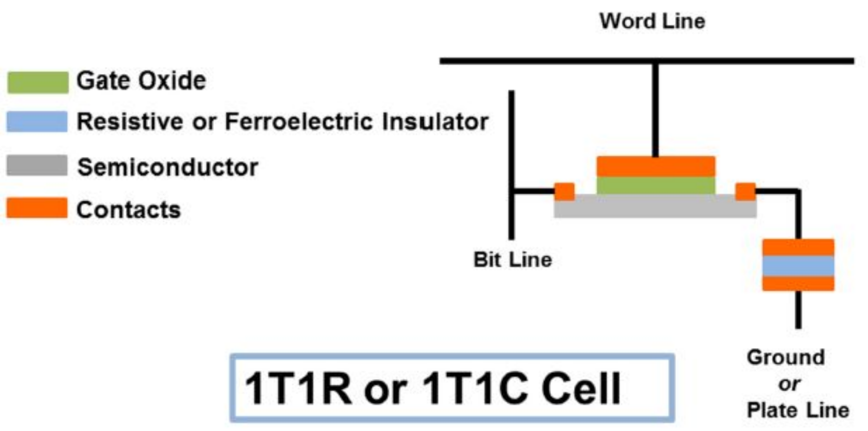
Flash memory (charge trapping (CT))

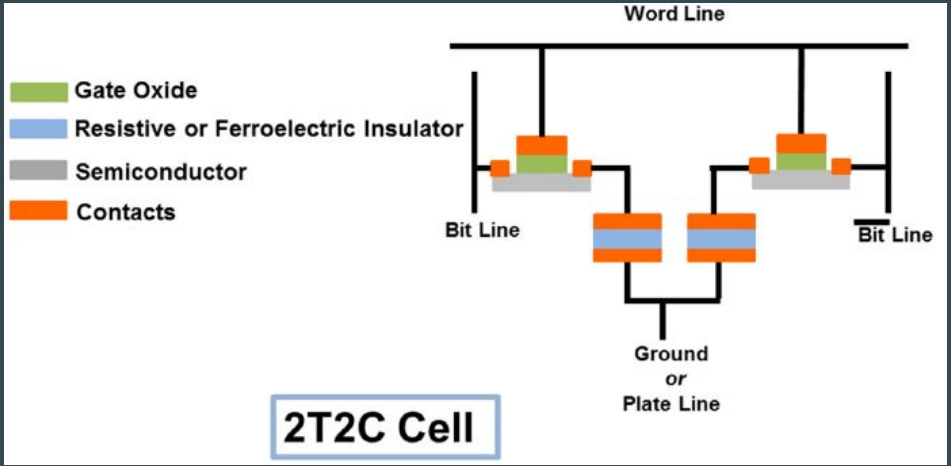
- The charge trap flash replaces the floating gate (a conductor layer) with an insulating layer.

Reference: [20]

NVM Architectures: Memory Cell design

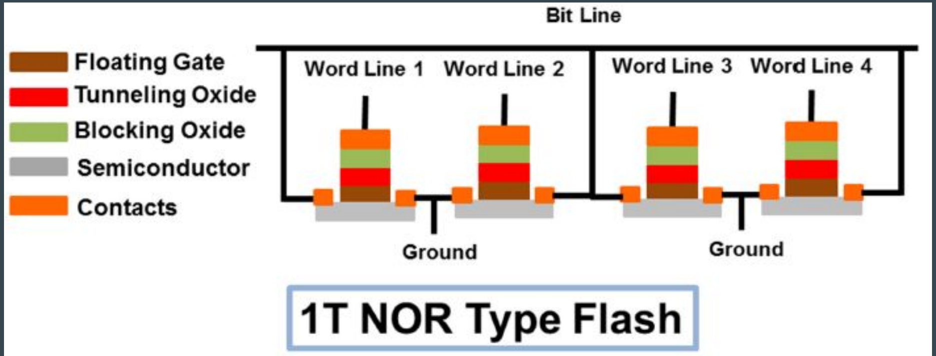


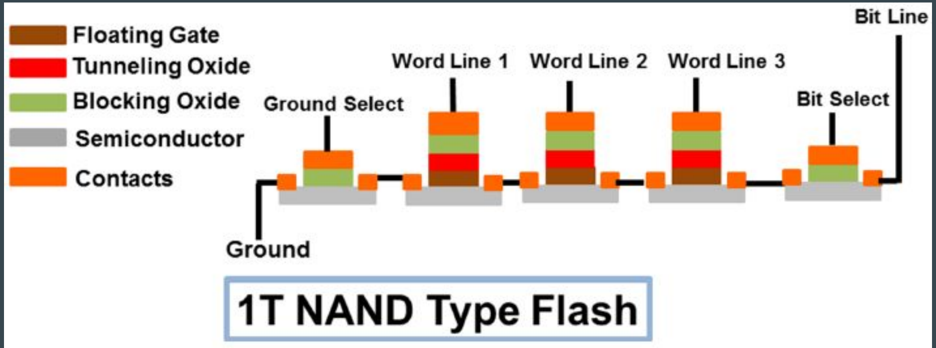


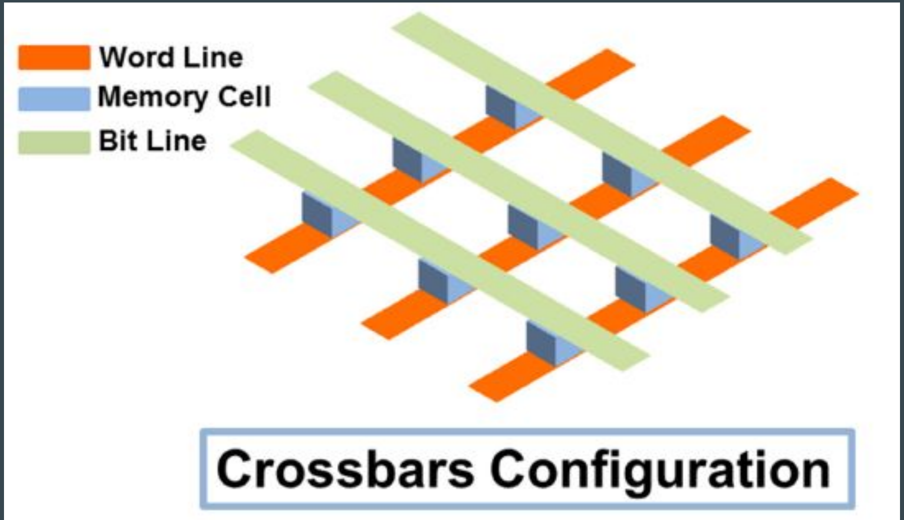


Reference: [5]

NVM Architectures: Major arrangements

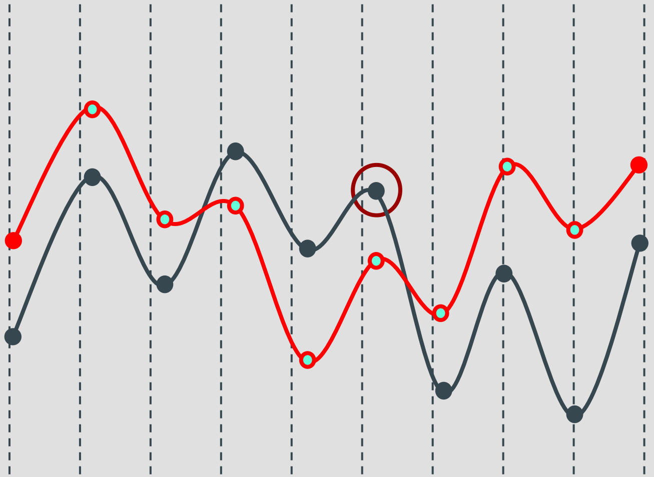






Reference: [5]

Idea of Numbers:
Flexible NVM Technologies



Figures of Merit

- Form Factor (F^2)
- Density
- Cost ($/bit)
- Endurance
- Retention
- Operation voltage
- Speed
- Memory window

Flexible ReRAM

- Report for 10 nm × 10 nm ReRAMs [14].
- S. Jo et al. experimentally demonstrated that CMOS neurons and memristor synapses in a crossbar configuration can support synaptic functions [15].
- Interesting work using inorganic flexible substrate (Al foil) with organic cellulose nanofiber paper enabled achieving the lowest reported bending radius for ReRAM (0.35 mm) and lowest operating voltage (±0.5 V) [21].

Flexible FeRAM

- In general, FeRAMs have superior endurance and low variability, which represent critical challenges for state-of-the-art redox memristive memories [22].
- Rigid ferroelectric random access memories (FeRAM) have already made a great leap by their introduction to the market; hence, it is a relatively mature technology compared to other emerging NVM technologies.
- Commonly used ferroelectric material in FeRAM is lead zirconium titanate ($Pb_{1.1}Zr_{0.48}Ti_{0.52}O_3$—PZT).
  - high switching speed ~ ps for material switching and 70ns for actual arrays (parasitic capacitances)
  - low cost per bit
  - low operation voltage - 1.5V
  - Read/Write Cycles > 10^{15}
  - Retention > 10 years at 85 °C

Reference: [5]

Flexible PCRAM

- In general, PCRAMs have high switching transition speed. Eg.: Flexible PCRAM on polyimide required a 30 ns pulse to switch.
- Highly localized regions of phase change that enables ultra-high integration densities. Hong et al. reported phase-change nano-pillar devices with the potential of reaching up to tera bit/squared inch densities on flexible substrates.
- Yoon et al. demonstrated a 176 Gbit/square inch PCRAM, the highest reported density on a flexible substrate.
- The highest reported bending cycles endurance (1000 bending cycles) and yield (66%) for flexible PCRAM was reported by Mun et al., in 2015.

Reference: [5]

Flexible Flash

- Most mature NVM technology in today's market.
- Current flexible flash memories have reported operation voltages ranging from ±5 to ±90 V with minimum channel length dimensions of 2-μm [19].
- Nonetheless, good bendability has been achieved up to 5 mm for 2000 bending cycles, an endurance of 100,000 cycles, and a retention ability of 10^6 s.

Reference: [5]

Comparison of the Best

	Flexible ReRAM	Flexible FeRAM	Flexible PCRAM	Flexible Flash
Form Factor (F^2)	2	1	--	2
Cell Dimensions (μm)	10 × 20 channel	20 × 20	0.035 diameter	2 channel length
Endurance (cycles)	10^6	10^9	100	10^5
Retention (s)	5×10^6	10^5	10^4	10^6
Operation voltage (V)	−0.5	−3	1.8	−5 to +5
Speed (ns)	50	500	30	100
Memory window (V)	4	35	--	15

Reference: [5]

Future Prospects?

Thank You

Questions?

References

1. https://www.nature.com/articles/ncomms4583
2. https://onlinelibrary.wiley.com/doi/epdf/10.1002/adma.201301040
3. https://www.nature.com/articles/ncomms4005
4. https://www.sciencedirect.com/science/article/pii/S0003267004010189
5. http://www.mdpi.com/2079-9292/4/3/424/htm
6. https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201300675
7. https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201201386
8. https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201402472
9. https://aip.scitation.org/doi/pdf/10.1063/1.2952044
10. https://aip.scitation.org/doi/abs/10.1063/1.326575
11. https://pubs.acs.org/doi/abs/10.1021/nl304310x

References

12. https://ieeexplore.ieee.org/document/6587134/
13. https://pubs.acs.org/doi/abs/10.1021/nn5041608
14. https://ieeexplore.ieee.org/document/6131652/
15. https://pubs.acs.org/doi/abs/10.1021/nl904092h
16. https://aip.scitation.org/doi/10.1063/1.1392970
17. https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201004255
18. http://iopscience.iop.org/article/10.1088/0957-4484/23/25/255301
19. https://ieeexplore.ieee.org/abstract/document/6294439/
20. https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.200800340
21. https://www.nature.com/articles/srep05532
22. https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.200900375