

Novel Memories for Sustainable ICT

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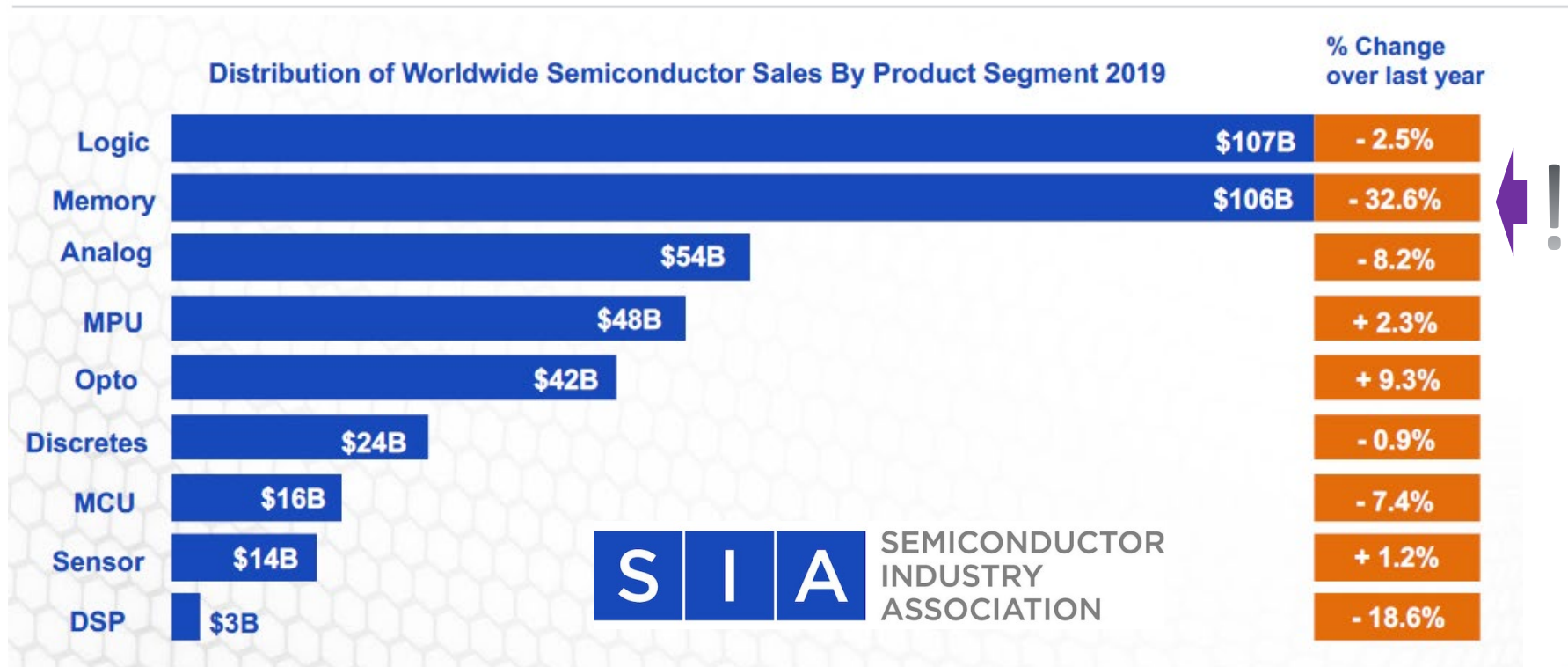
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Why memories?

- Whilst a holistic approach to sustainable ICT involves hardware, software and usage, ICT is underpinned by hardware
- When considering hardware, the conversation (around Moore's law) is typically dominated by processors (feature size/node, # transistors, speed *etc.*)
- Processors are utterly dominated by Si CMOS, whose position seems unassailable (economic as well as technical barriers)
- This is not the case for memories, which are also important
- For example, refresh of 32 Gb DRAM contributes 20% to power consumption and degrades system performance by 30% [Bhati *et al.*, IEEE Trans on Computers **65**, 108 (2016)]

Semiconductor Market (2019)

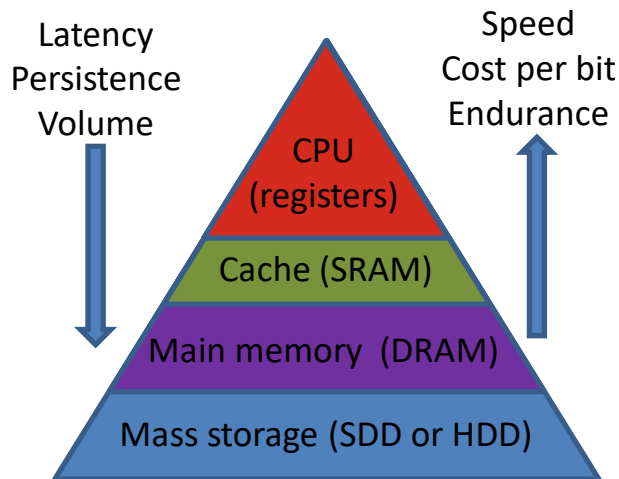


With memories one size **does not** fit all (presently)

There are **four** different types of 'conventional' memory

- SRAM (very fast, very expensive, close to the processor)
- **DRAM** (fast, middle price, volatile, main memory)
- **NAND flash** (slow, cheap, (mass) storage, *e.g.* SSD)
- NOR flash (RAM version of flash, niche applications)

Memory hierarchy



These are all Si based, but only SRAM is fundamentally CMOS based

There are also so-called ‘emerging memories’

- There are very many novel memory concepts, but the main ones are
 - PCRAM: Phase-change RAM
 - RRAM: Resistive RAM
 - FeRAM: Ferroelectric RAM
 - (STT)-MRAM: (Spin-torque transfer) magnetic RAM
- **All** emerging memories are non-volatile
- The dream is a non-volatile memory that combines the qualities of DRAM and flash



Universal memory

DRAM

- + Fast
- + High endurance
- + Low voltage
- Volatile
- Destructive read
- Expensive

Flash

- Slow
- Low endurance
- High voltage
- + Non-Volatile
- + Non-destructive read
- + Cheap

Combine
best of both

Universal memory

- + Non-volatile
- + Low voltage (energy)
- + Non-destructive read
- + Fast
- + High endurance
- + Cheap



128 KB Micron MT4C1024 DRAM

\$70bn pa



\$50bn pa

How to have your cake and eat it?

The problem with Universal Memory is that we need to fulfil ***contradictory requirements***

- Long storage time (>10k years at single bit level)
- Ability to quickly (10 ns) write/erase data (add/remove charge)



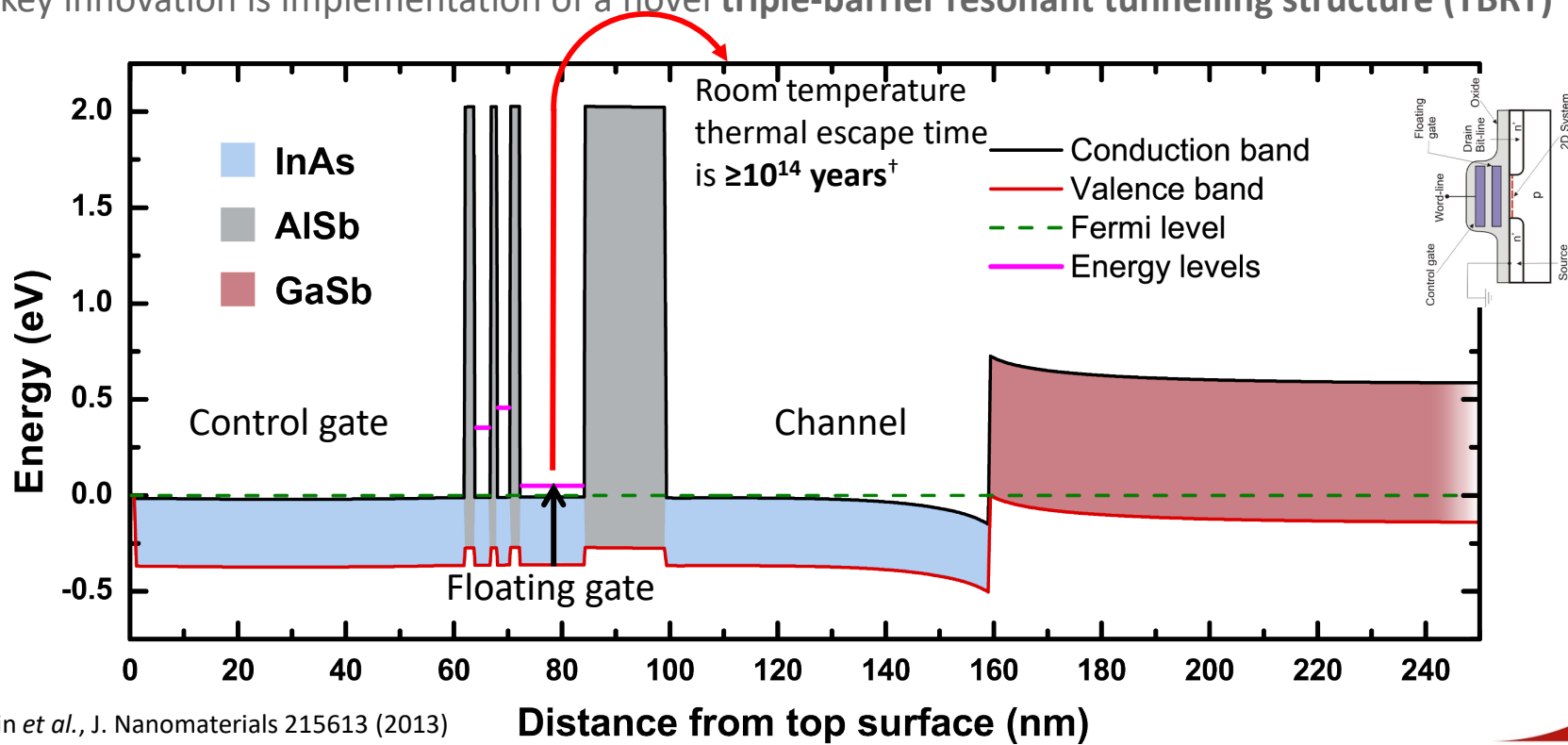
“Now it is generally agreed that the vision of a universal memory is not realistic...

...the need for low energy consumption during writing operations is accomplished by lowering the energy barrier to be overcome when erasing or writing data, which limits the non-volatile retention time of data. ”

H.-S. Wong and S. Salahuddin, Nat. Nano. **10**, 191 (2015)

ULTRARAM™ concept (US 10243086B2)

The key innovation is implementation of a novel **triple-barrier resonant tunnelling structure (TBRT)**



[†]Nowozin *et al.*, J. Nanomaterials 215613 (2013)

Benchmarking

ULTRARAM™ has the potential to outperform DRAM with the **additional advantage** of non-volatility

Technology	NV?	Switching energy	Switching time	Cell size
SRAM	No	1 fJ	~1 ns	$>100F^2$
DRAM	No	1-10 fJ	<10 ns	$6F^2$
Flash (NOR)	Yes	~100 pJ	0.01-100 ms	$10F^2$
Flash (3D NAND)	Yes	~10 fJ	0.1-100 ms	$4F^2$
RRAM	Yes	0.1-10 pJ	10-100 ns	$(4 \text{ to } 12)F^2$
PCRAM	Yes	10-100 pJ	50-400 ns	$(4 \text{ to } 30)F^2$
STT-MRAM	Yes	~0.1 pJ	10-50 ns	$(6 \text{ to } 50)F^2$
ULTRARAM™	Yes	~10 aJ	<1 ns	$<4F^2$

Summary of topic challenge

- Hardware underpins all of ICT, so must be crucial to sustainability
- Whilst the use of Si-CMOS processors looks unassailable, this is not the case for memory
- There are already four types of conventional memory, only one of which (SRAM) is CMOS-based
- There also (at least) four types of emerging memory, with Optane™ (PCRAM) available in the shops
- The vision is of a memory that has the performance of DRAM with non-volatility of flash
- ULTRARAM™ is a novel memory concept that promises to *outperform* DRAM at lower cost *with* the substantial advantages of non-volatility

