eMRAM Tutorial

Essential Elements and Notable Challenges

August 6, 2018

Dave Eggleston

Intuitive Cognition Consulting

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eMRAM Tutorial Outline

- Hydrogen
  - Markets & Tech comparison
- Metals
  - 9 Essential Elements
- Noble Gases
  - Musings, Speculations & Prognostications

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Market Forecast & Technology Comparison

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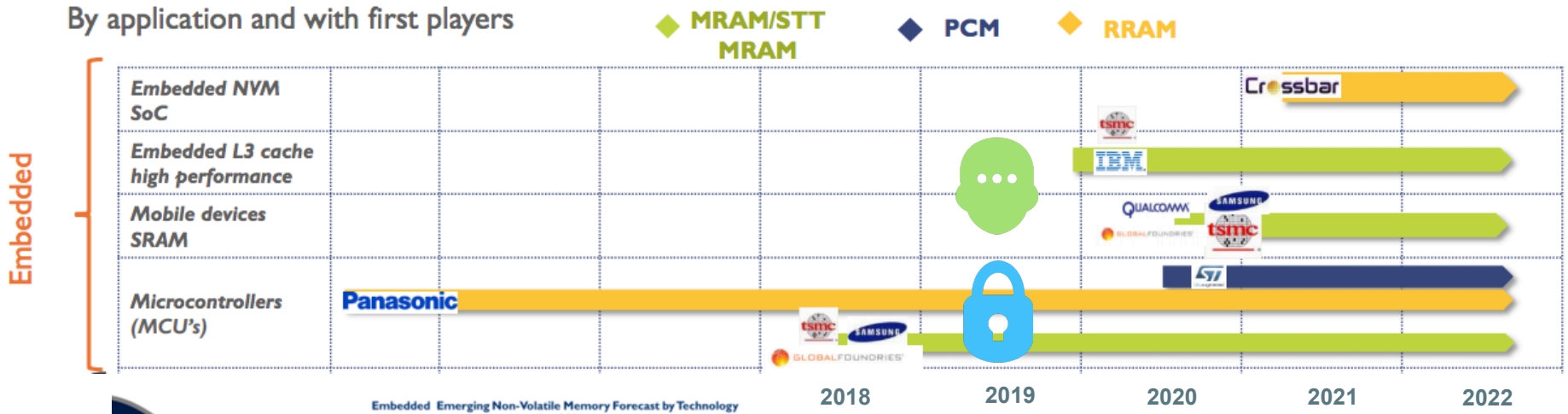
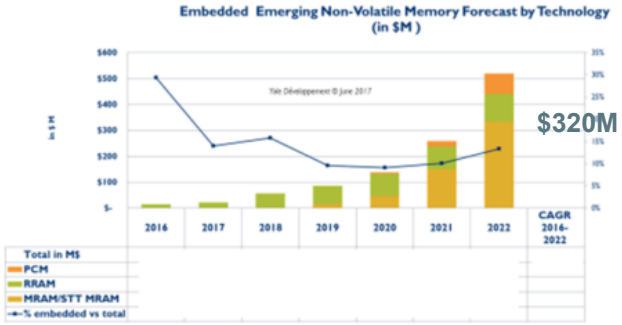
eMRAM Market Forecast

EMERGING NVM – TIME-TO-MARKET



STTMRAM will dominate embedded market thanks to adoption by major foundries and in several applications for eflash and SRAM substitution



Source: Yole' Developpement, Emerging Non-Volatile Memory report, 2017

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eMRAM Market Forecast

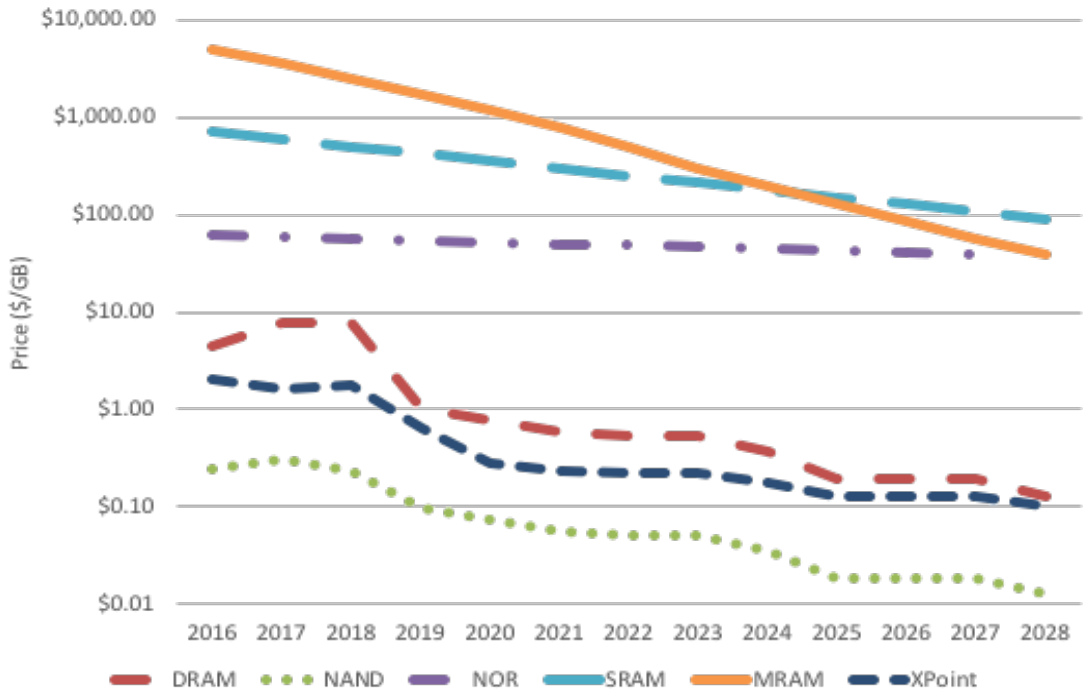
eMRAM will grow from $0 in 2018 to $300M+ in 2022
eMRAM "will dominate the embedded market"

Source: Yole' Developpement

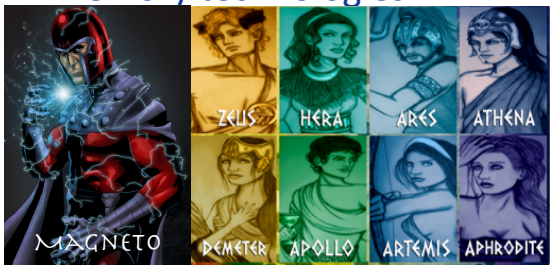
Source: Yole' Developpement, Emerging Non-Volatile Memory report, 2017

eMRAM Market Forecast

BASELINE $/GB FOR MEMORY TECHNOLOGIES FROM 2016 THROUGH 2028



- MRAM and STT-RAM baseline revenues are expected to increase from about $36M in 2017 to $3.3B by 2028.
- Much of this revenue gain will be at the expense of SRAM, NOR flash and some DRAM, although STT-RAM is developing its own special place in the pantheon of shipping memory technologies.



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eMRAM Market Forecast

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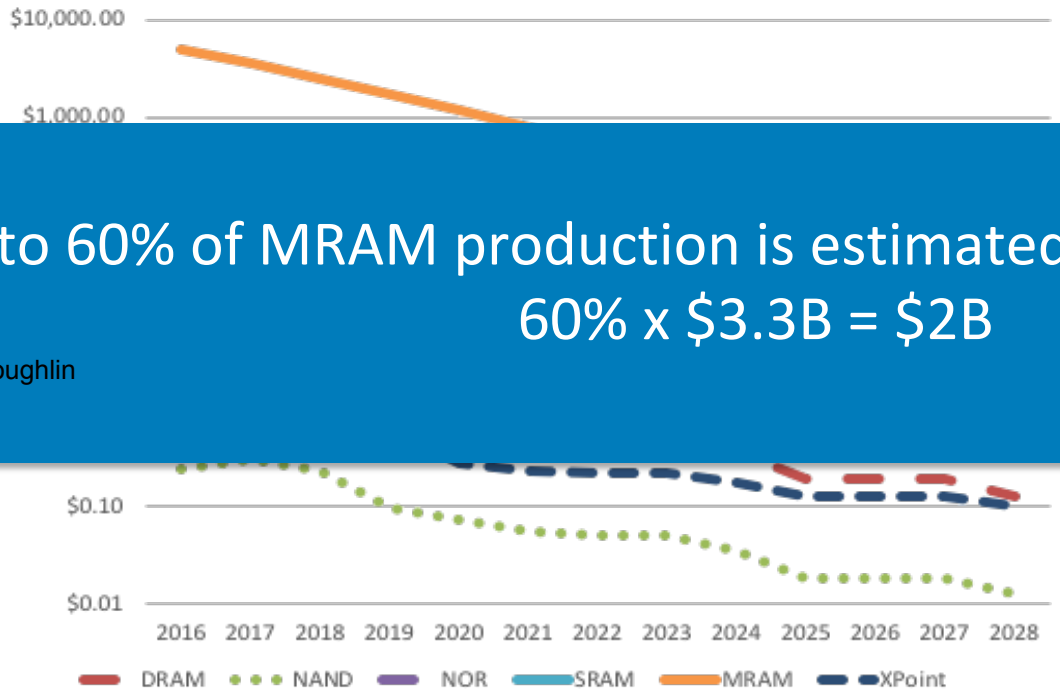


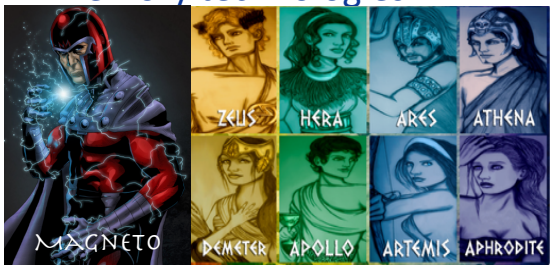
- MRAM and STT-RAM baseline revenues are expected to increase from about $36M in 2017

"Close to 60% of MRAM production is estimated to be eMRAM by 2028"

60% x $3.3B = $2B

Source: Tom Coughlin

pantheon of shipping memory technologies.



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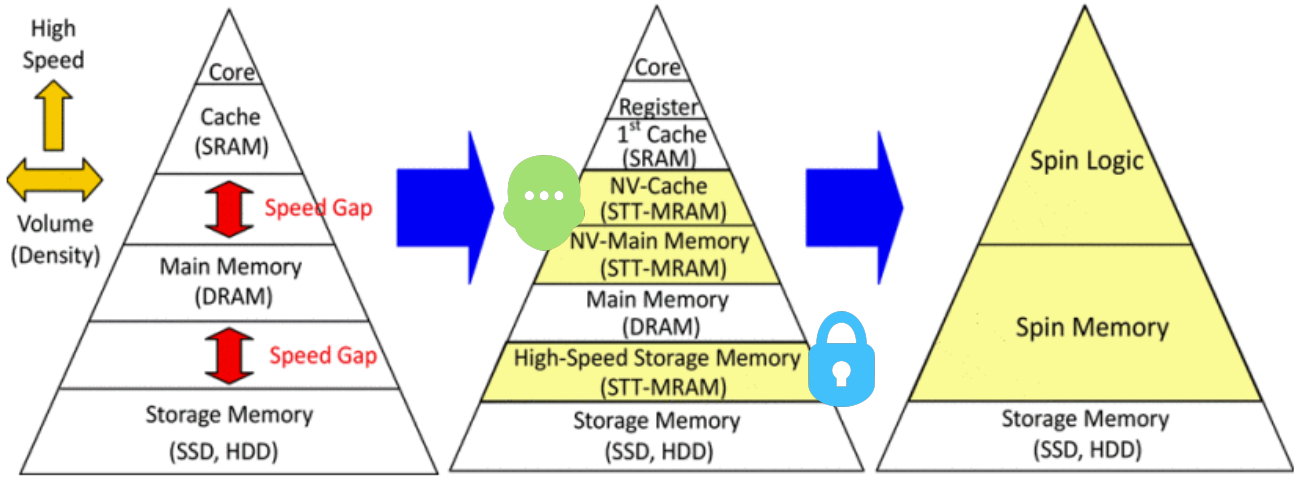
STT-MRAM in the Hierarchy

Restructuring of Memory Hierarchy in Computing System with Spintronics-Based Technologies

Tetsuo Endoh[1, 2, 3], Takashi Ohsawa[1], Hiroki Koike[1], Takahiro Hanyu[1, 2], and Hideo Ohno[1, 2]
[1]Center for Spintronics Integrated Systems, Tohoku University;
[2]Research Institute of Electrical Communication, Tohoku University; [3]Center for Interdisciplinary Research, Tohoku University
Aramaki Aza-Aoba 6-3, Aoba-ku, Sendai, Japan 980-8578, Phone/Fax: +81-22-795-4401, E-mail: endoh@riec.tohoku.ac.jp

2012 Symposium on VLSI Technology Digest of Technical Papers



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eMRAM Technology Comparison

		SRAM	eFlash	eMRAM	RRAM	PCM	FeFET	CNT
Power	Stdby	High	Very low	Low	Very low	Low	Very low	???
	Read	High	Low	High	Low	Low	Low	???
	Write	High	Very high	High	Med	High	Very low	???
Performance	Read	<1 nsec	10 nsec	10-25 nsec	20 nsec	10 nsec	20 nsec	nsec?
	Write	<1 nsec	10 usec	10-200 nsec	1 usec	1 usec	20 nsec	nsec?
	Endurance	Unlimited	100K	1M-100M	1M	1M	10-100K	???
Area	Bitcell	$250F^2$	$30F^2$	$30F^2$ - $80F^2$	$10F^2$	$8F^2$	$10F^2$	$??F^2$
Cost	Wafer cost adder	Free	≈ 30%	≈ 25%	≈ 15%	???	≈ 10%	???
Availability	Foundries	Wide	Wide	Several	Several	Sole	Sole	Sole

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	Read	High	Low	**High**	Low	Low	Low	???
	Write	High	Very high	**High**	Med	High	Very low	???
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eMRAM Comparison Takeaways

Strengths		Weaknesses	
Low stdby power	vs. SRAM	High power	vs. RRAM
Write speed	vs. eFlash	Read speed	vs. eFlash
Endurance	vs. eFlash	Bitcell size	vs. SRAM\
Wafer cost adder	vs. eFlash		
Foundry availability	vs. options		

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eFlash

Code Retention

Tune-ability of eMRAM

SRAM

Working Memory

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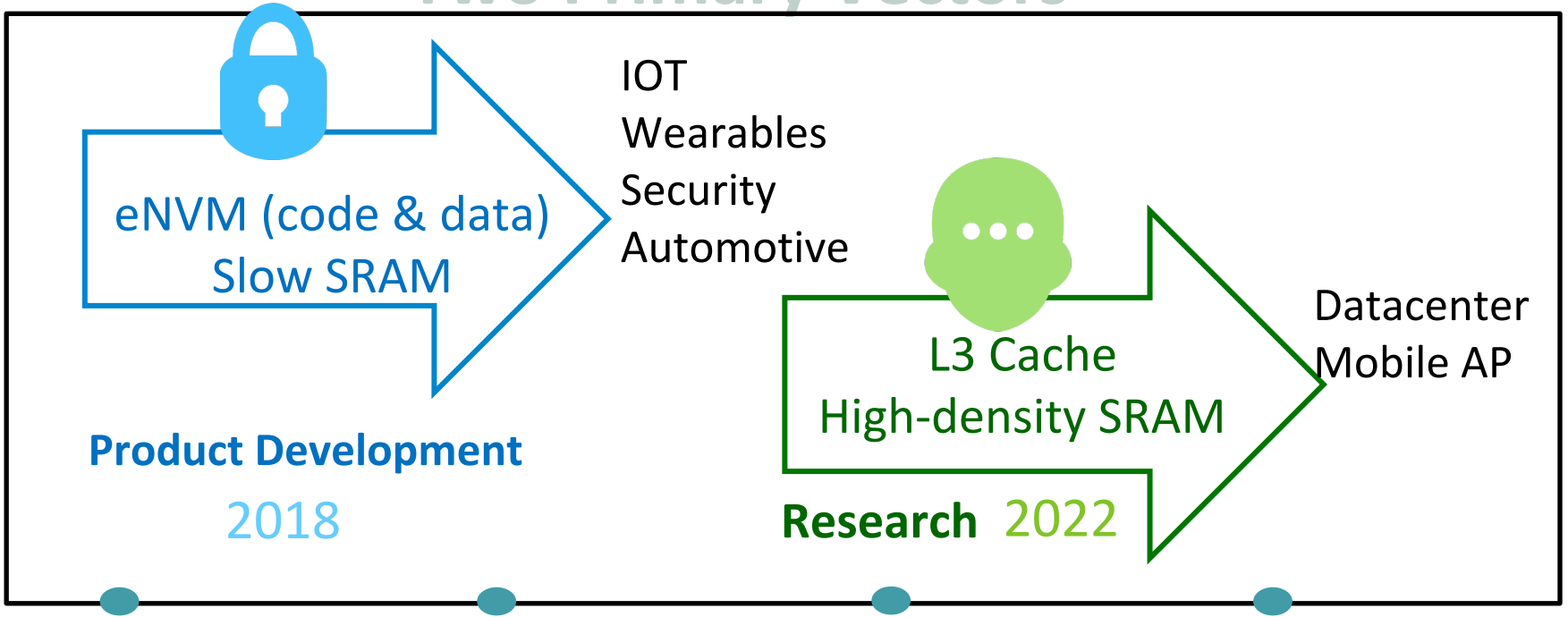
Two Primary Vectors



Source: S. Kang, Qualcomm, 2017 CIES MRAM Forum

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eMRAM Market & Technology Summary

Usage	Code	Working Memory
Application	MCU, IoT, Auto	Datacenter, Mobile AP
Feature	Data Retention	Speed
Node	28/22nm	7/5nm
Year	2018	2022
Revenue	$0 (2018) to $300M (2022) to $2B (2028)	

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9 Essential Elements for eMRAM Success

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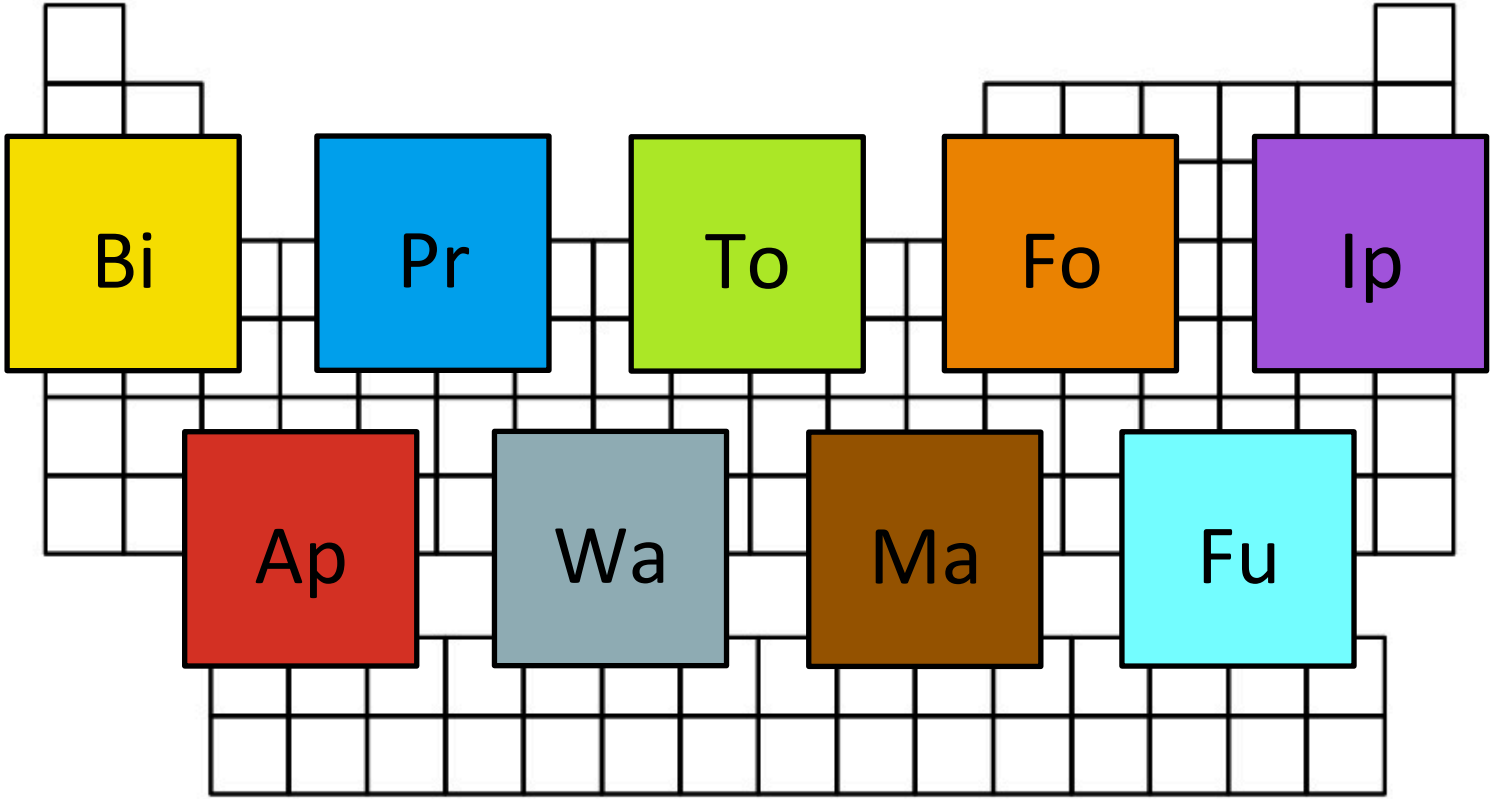
9 Essential Elements for eMRAM Success



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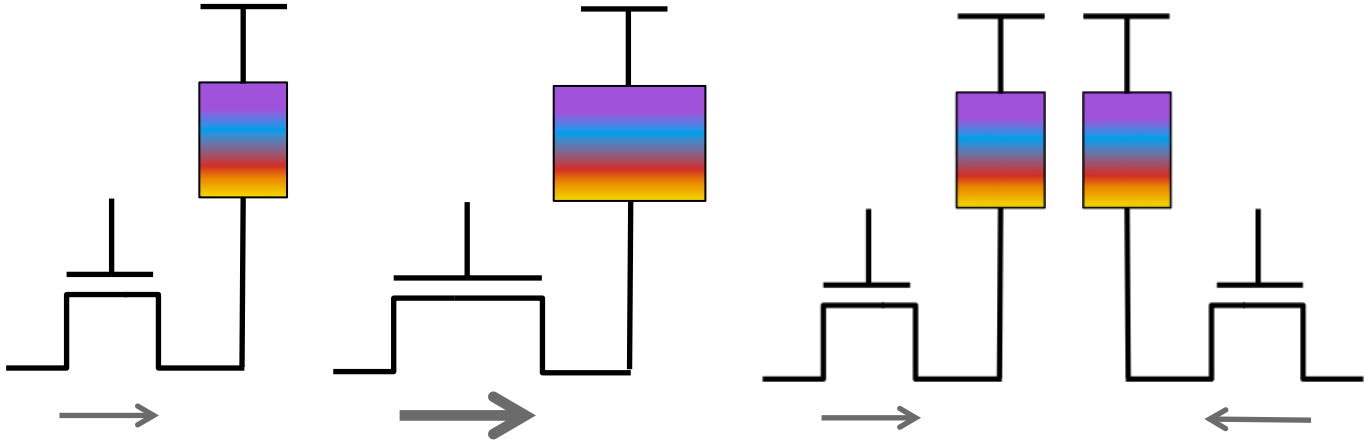
Essential Element: Bi (Bitcell)

Bi
(Bitcell)



1T-1MTJ

+ **Smallest cell size**
+ Fastest write
− Smallest memory window
− Read reliability issues
− Tricky sense amp
− **Poor data retention**

1T-1MTJ Plus

+ **Great data retention, reflow**
+ Solid read
− Slower write
− Write probability issues
− **30%+ bigger cell size vs. 1T-1MTJ**

2T-2MTJ

+ 2x memory window vs. 1T-1MTJ
+ **2x faster read vs. 1T-1MTJ**
+ Simpler sense amp
− Tricky write
− **2x bigger cell size vs. 1T-1MTJ**

Bi
Pr
To
Fo
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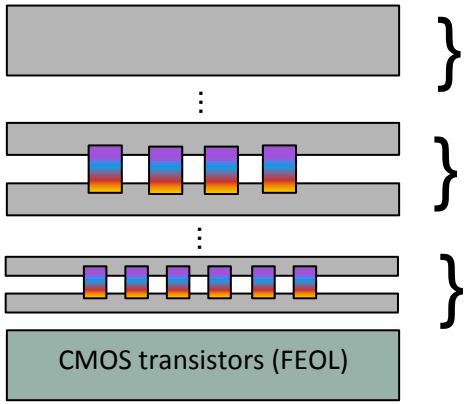
Essential Element: Pr (Process integration)

Pr
(Process)

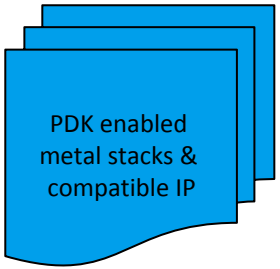
1. Where to place the MTJ in the metal stack?



+ Enough height for MTJ
– Larger bitcell and T routing

+ Smallest cell size
– Not enough height for MTJ

2. Are Logic IP and eMRAM IP metal stack compatible?



+ YES; minimum metal layer cost adder to base logic wafer

– NO; adds metal layer cost and complexity

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Essential Element: Pr (Process integration)

Pr
(Process)

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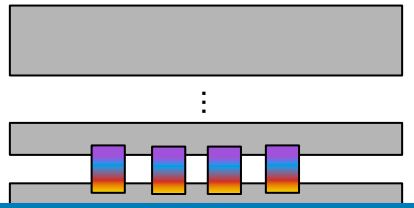

Thick metal layers

Intermediate metal layers

+ Enough height for MTJ
– Larger bitcell and T routing

It is critical to balance the MTJ process integration requirements versus the PDK/Design IP requirements.

Not all metal stacks support eMRAM!

PDK enabled metal stacks & compatible IP

+ YES; minimum metal layer cost adder to base logic wafer

– NO; adds metal layer cost and complexity

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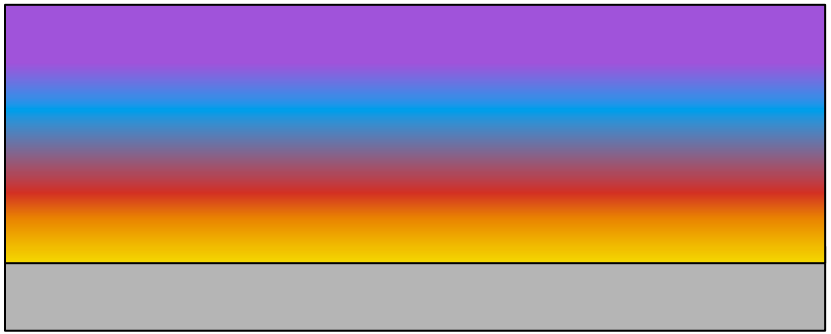
Essential Element: To (Tools)

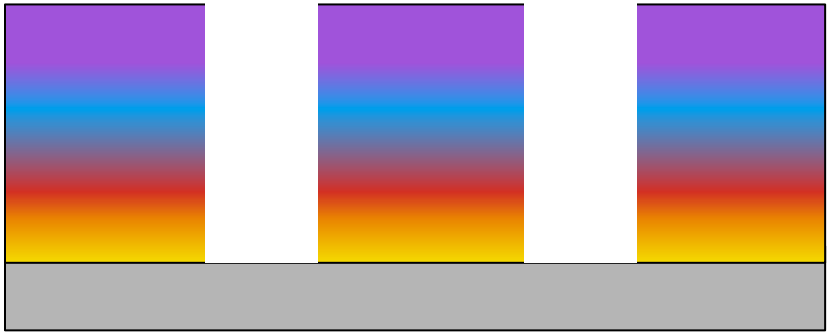
To
(Tools)



MTJ is first fabricated by deposition of

> 20 unique

molecular layers!



MTJ is then fabricated by etch back of these > 20 unique molecular layers… without causing sidewall damage or having re-deposition

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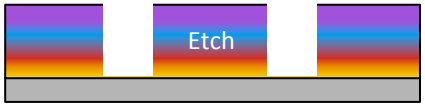
Essential Element: To (Tools)

+ **Custom MTJ tools available from major tool vendors**



– **Custom MTJ tools add depreciation cost and take up considerable fab floor space**

TEL TOKYO ELECTRON

APPLIED MATERIALS®

TEL TOKYO ELECTRON

HITACHI

Canon

Lam RESEARCH

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MRAM DEVELOPER DAY

Essential Element: Fo (Foundry)

Fo
(Foundry)

Ranking	Company	Revenue (in US$ Million)			2017 Market share
		2016	2017 (estimated)	YoY Growth	
1	TSMC	29,437	32,040	8.8%	55.9%
2	GLOBALFOUNDRIES	4,999	5,407	8.2%	9.4%
3	UMC	4,587	4,898	6.8%	8.5%
4	Samsung	4,284	4,398	2.7%	7.7%

Top 4 foundries cover 80% of market

Source: Trendforce, Nov 2017

tsmc		UMC	SAMSUNG
TDK	EVERSPIN TECHNOLOGIES	?	IBM
2018/28 & 22nm 1T-1MTJ **Plus**/MCU	2018/22nm 1T-1MTJ **Plus**/MCU	?	2018/28nm 1T-1MTJ/**MPU**

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Essential Element: Ip (Design IP)

Ip
(Design IP)

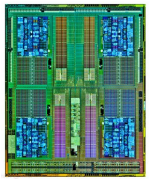
PDK

eMRAM
Design Kit

Foundry
eMRAM IP

Off-the-Shelf Design
Automation Tools

Do-it-Yourself



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Essential Element: Ip (Design IP)

Ip
(Design IP)

PDK

eMRAM
Design Kit

Foundry
eMRAM IP

3rd party
eMRAM IP

arm

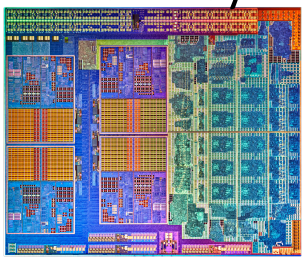
SAMSUNG

Off-the-Shelf Design
Automation Tools

3rd party
eMRAM
Compiler

RAM Design
ation Tools

Turnkey



ARM & Samsung Test First eMRAM Compiler, New Process Nodes

Source: AndroidHeadlines, June 22, 2018

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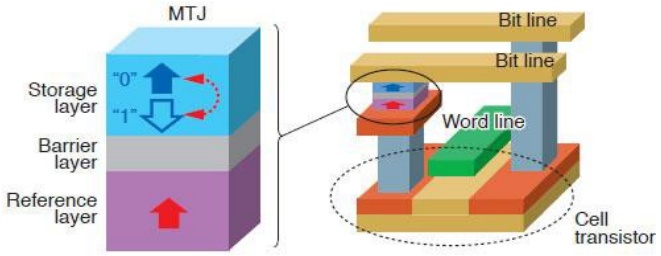
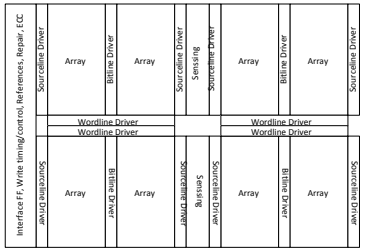
Numem's IP Solutions: from Planning to Production

- Best-in-Class embedded MRAM/ReRAM
  - Standard memory IP blocks
  - Custom memory IP bocks
- MRAM Design Automation SW Tools
- Turnkey test chips and testing
  - Complete memory test chip design, tape out and testing
- Test Board/Subsystem Design



STT-MRAM BITCELL



Numem
MRAM IP Core

numem

MRAM Developer Day Sponsor and Exhibitor (visit booth 4)

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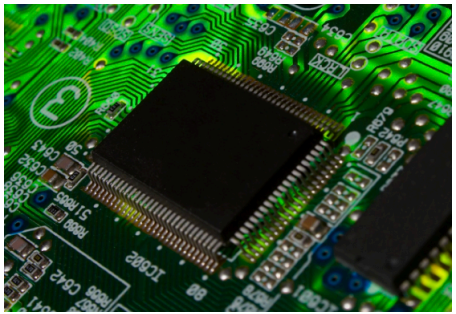
Essential Element: Ap (Application)

Ap
(Application)

Usage	Code
Feature	Data Retention
Node	28/22nm
Year	2018



MCU

$25B per year

Requires eNVM

Smart card

$12B per year

Requires eNVM

eMRAM loses data in the presence of a high magnetic field.

Smart card market is not a suitable eMRAM application!

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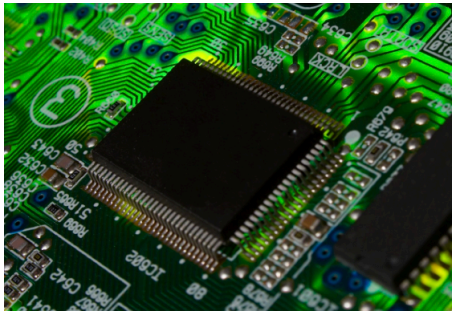
Essential Element: Ap (Application)



MCU

32b $12B = 12B units/year

Industrial

IoT

Automotive

These are the 28/22nm eMRAM target applications!

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Essential Element: Wa (Wafer cost)

Wa
(Wafer cost)

Base logic process (ex.)	40 mask layers	
eNVM	eFlash	eMRAM
eNVM mask adder	+12 mask layers (1)	+3 mask layers
Hypothetical cost adder (simple mask adder analysis)	+30% 12 ÷ 40 = 30%	(2) 7%
Custom fab tools	None	MTJ Dep and Etch
Realistic cost adder	40%+	+25% (3)

Notes: (1) eFlash mask adder expected to increase to +15 to +20 at 28/22/14nm, to a 40%+ cost adder
(2) Incorrectly assumes that all mask layers have the same cost, and ignores other costs
(3) eMRAM cost adder is expected to decrease as custom fab tool depreciation decreases

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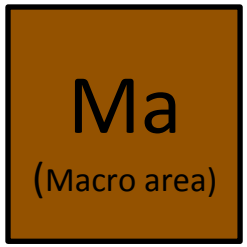
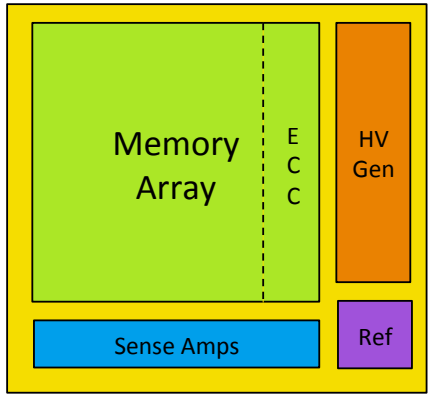
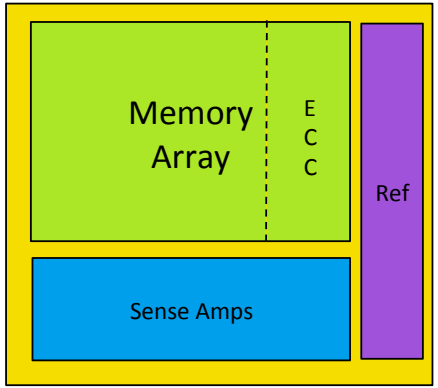
Essential Element: Ma (Macro area)





eFlash macro



eMRAM macro

Memory Array & ECC	Bitcell smaller, but much more ECC needed for read reliability
Sense Amps	Small memory window requires bigger sense amps, plus 2x wider bus since read speed 2x slower
Reference & HV Analog	No HV generator needed, but sense amps needs highly accurate references

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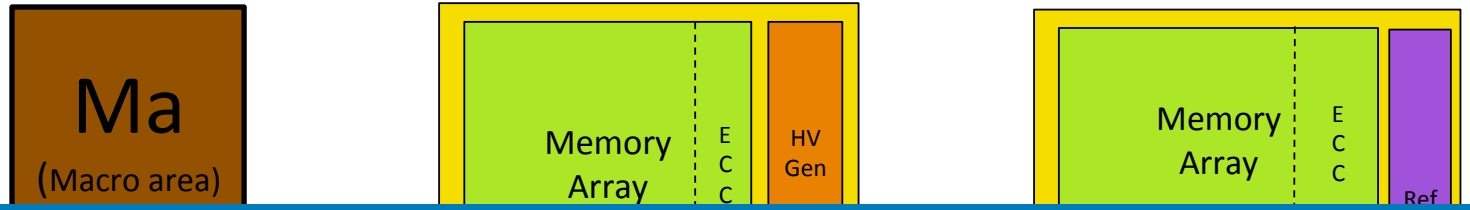
Essential Element: Ma (Macro area)



The small memory window of eMRAM shows up in macro area.
ECC, sense amps, and reference analog are all larger than eFlash.
Increasing eMRAM memory window will result in smaller macros.

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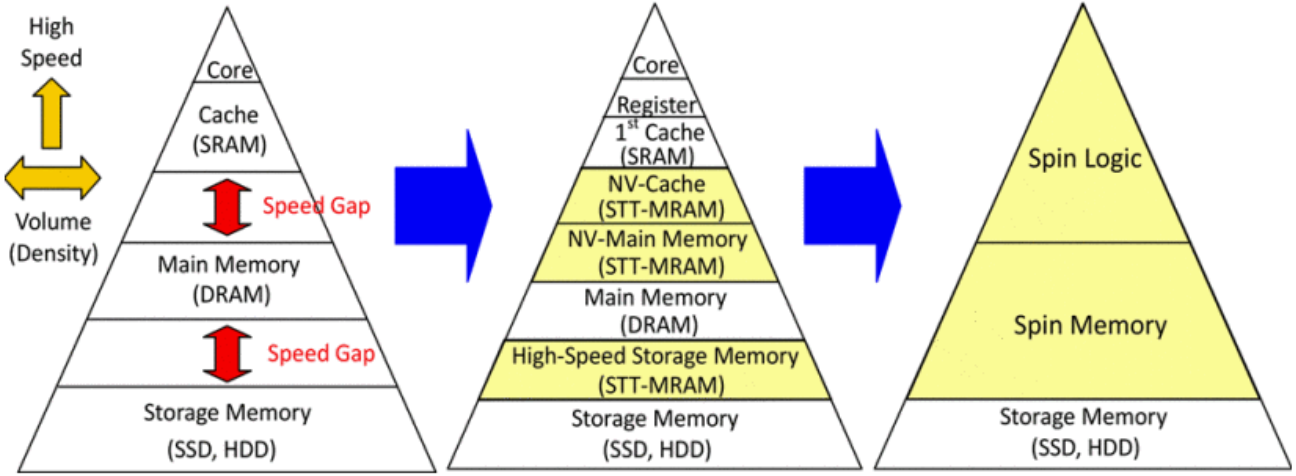
Essential Element: Fu (Future)

Fu
(Future)



Motivation (2012): Speed

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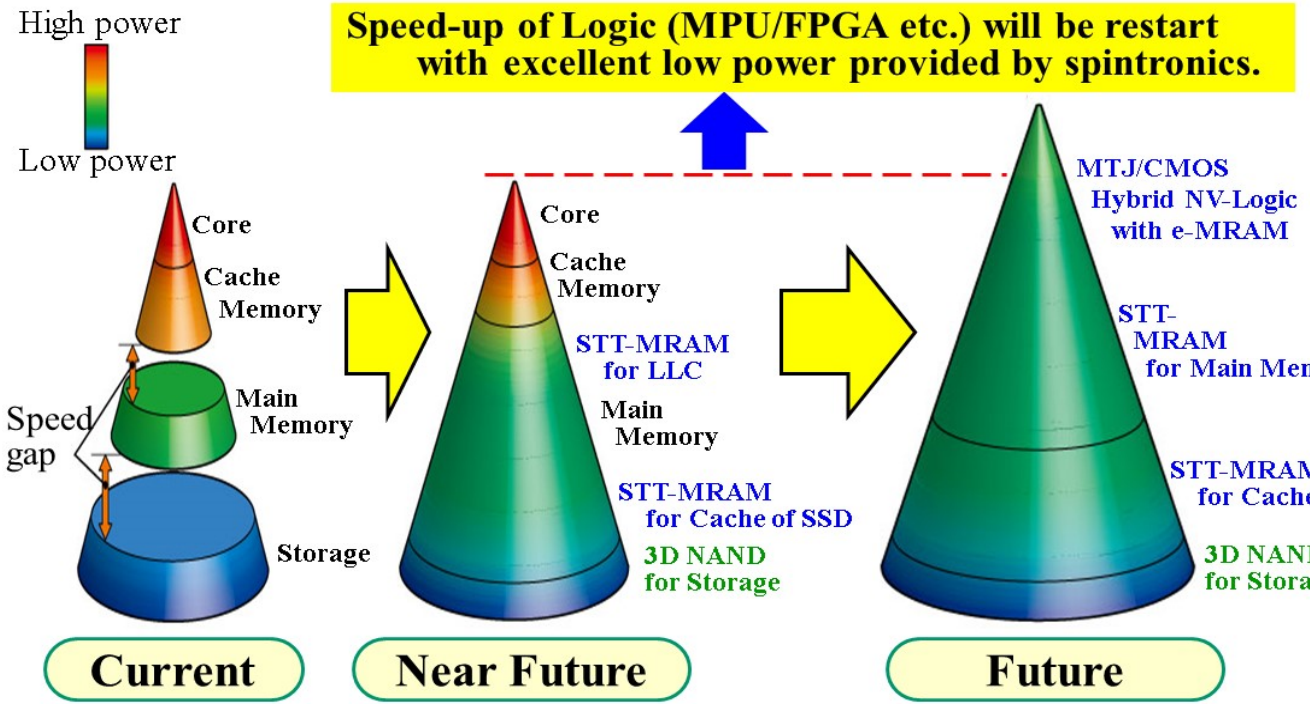
Paradigm Shift of VLSI by eNVM and NV-Logic with CMOS/MTJ Hybrid Technology & 3D-CMOS technology



Motivation (2016):
Speed and Low Power

1 STT bitcell limitations

2 AI architecture

T. Endoh et al., IEEE Journal on Emerging and Selected Topics in Circuits and Systems, Vol. 6, (2016).
T. Endoh MMM2016, T. Endoh SEMICON China2017, T. Endoh ISCAS 2018

Essential Element: Fu (Future)

Fu
(Future)

1

STT bitcell limitations:

- Small memory window (Read, ECC, Sense amps, Macro area)
- High write current (T size)
- Large bitcell size

STT requires innovation; is there a next gen STT? New MTJ materials?
Or will SOT or VCM provide the needed innovation?

2

AI architectures:

- Current datacenter solution: GPU + lots of power-hungry SRAM
- Future edge solution: Non von-Neumann architecture
- Prof. Endoh: “Brain inspired VLSI’s based on hybrid CMOS/MTJ tech”

Will new AI architectures drive rapid eMRAM adoption?

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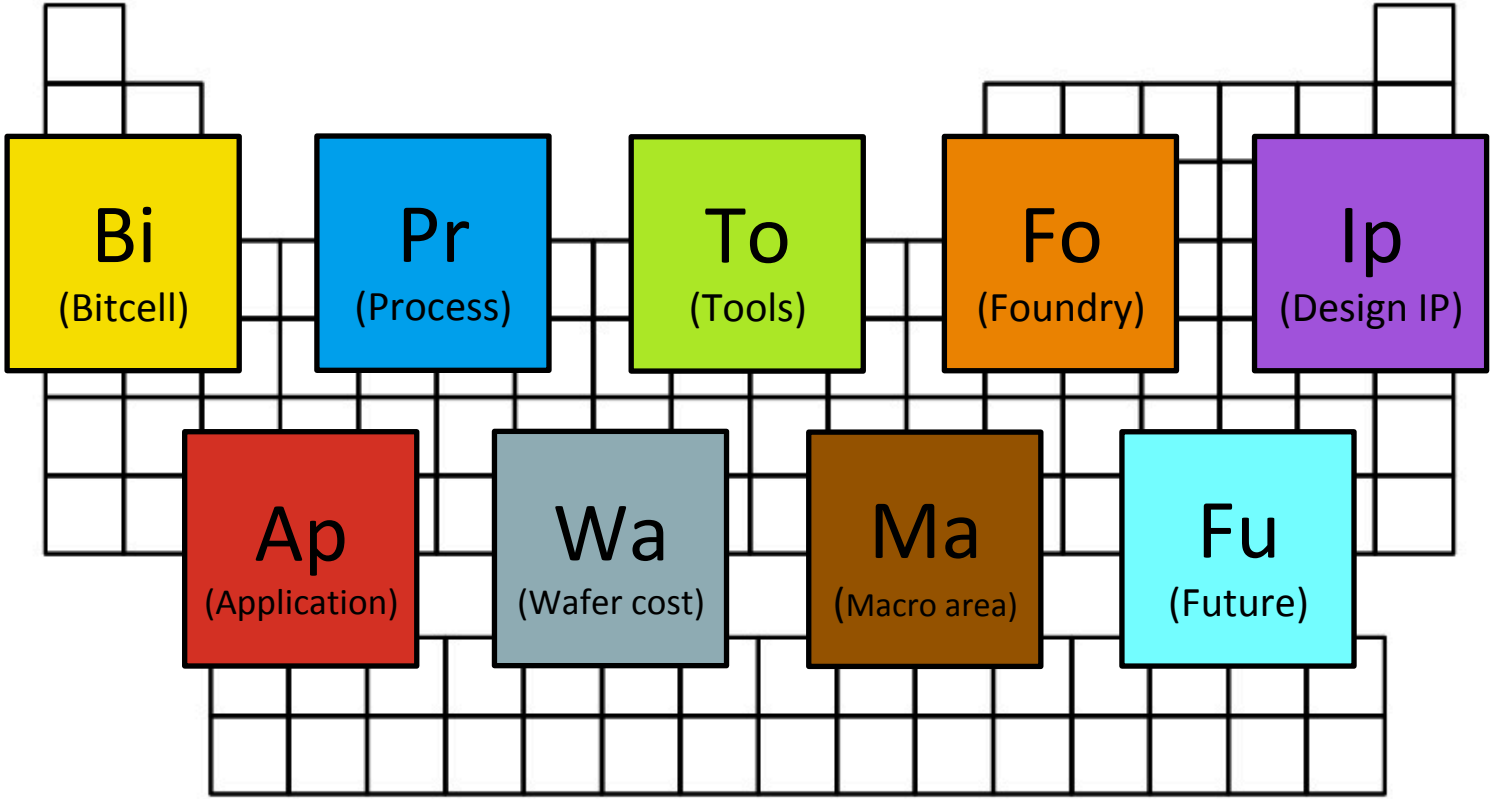
9 Essential Elements for eMRAM Success



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Musings, Speculations & Prognostications

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Musings, Speculations & Prognostications

- eMRAM must succeed in 2018-2020 in code storage application; seize the IoT and MCU opportunities.
- Working memory application (SRAM) requires faster, smaller eMRAM than STT can deliver today; more innovation is required. (Next STT?, SOT? VCM?)
- AI architectures require holistic logic/memory solutions for speed (datacenter training), and low power (edge inference). Opportunity! Tailor eMRAM + CMOS tech and design IP to fit these emerging AI architectures.

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FMS sessions

Don’t miss the following Open (FREE!) sessions:

- Wed Aug 8, 3:20pm NEWM-202A-1 RRAM
- Wed Aug 8, 4:40pm NEWM-202B-1 MRAM
- Thu Aug 9, 8:30am NEWM-301A-1 Life Beyond Flash

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Acknowledgements!

Many thanks to the following friends for the assistance sharing presentation material and guidance:

- Tom Coughlin, Coughlin Associates
- Jack Guedj & Nilesh Gharia, Numem
- Seung Kang, Qualcomm
- Mark Webb, MKW Ventures
- Tetsuo Endoh, Tohoku University and CIES

Defintion:

"Intuitive Cognition is such that when some things are cognized… it is known if the thing inheres or does not inhere… unless that cognition is flawed".

[William of Ockham, Opera Theologica I, p. 31]

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