RRAM Status and Forecast

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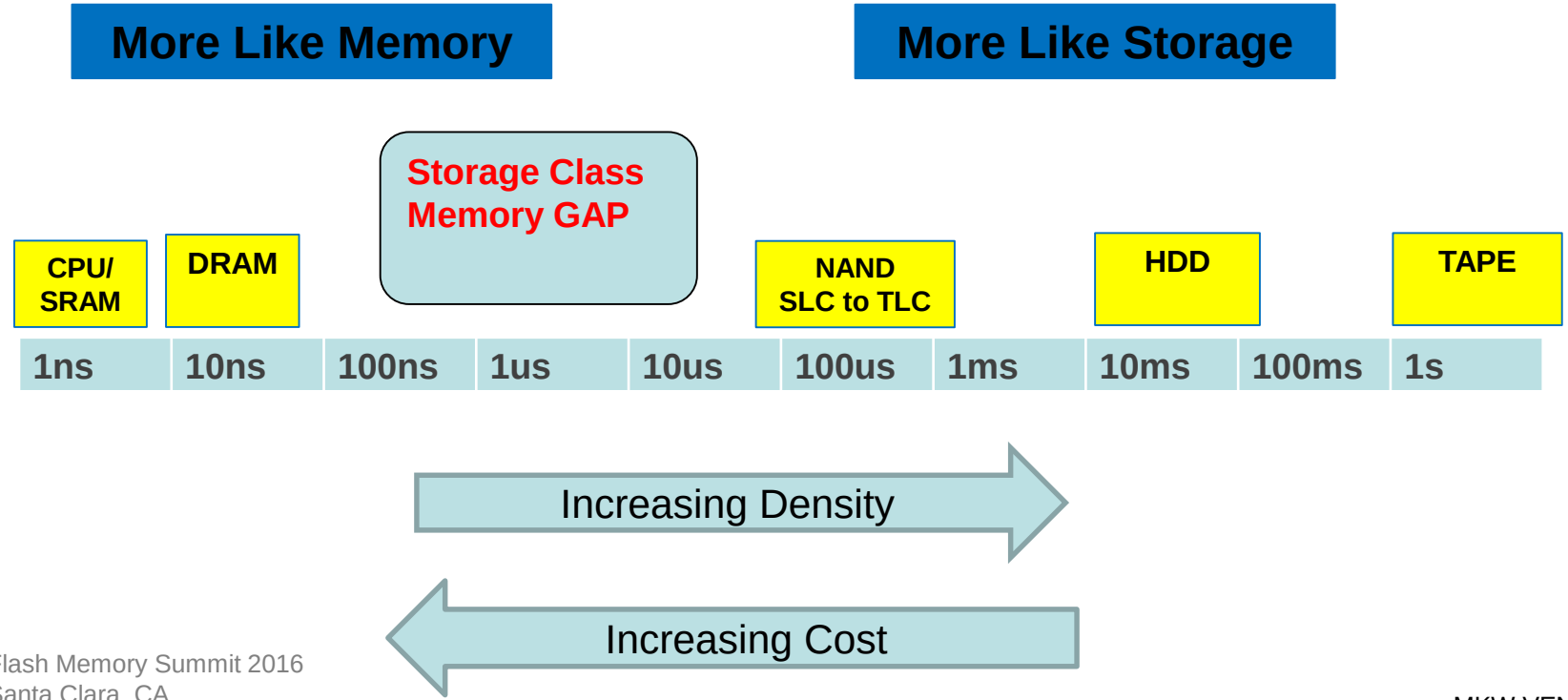
The Latency Spectrum and Gaps



Storage Class Memory

- Storage Class Memory is promising new application for NVM
- Intel/Micron have announced 3D Xpoint as solution
  - Intel support for architecture, software, applications is providing the demand along with the memory
  - Other NVM options can benefit from this lead
- Potential Market for 3DXpoint/RRAM SCM is >$1B in 2018. >$2B in 2020

New NVM Technologies

	Latency	Density	Cost	HVM ready
DRAM	*****	***	***	*****
NAND	*	*****	*****	*****
MRAM	*****	*	*	**
PCM (Micron)	***	****	**	*
3DXP	***	****	****	*
ReRAM	***	****	****	*

RRAM density, Cost, and latency numbers make it ideal to fill SCM gap

Summary of New NVM

- Phase change memory
  - Licensed and researched by nearly every memory company
  - If we assume 3D Xpoint is some variation of PCM, it will ship this year with more revenue in 2017 than all other new NVM combined (301C)
  - Excellent storage class memory in a cross point layout at 128gbit density
- MRAM
  - Very old technology. STT gaining traction and shipping for revenue
  - Fastest NVM… close to DRAM. Max density is 256Mbit.
  - >5 years minimum from matching todays DRAM densities, 12+ from NAND densities
- RRAM (This Talk)
  - Opportunity for highest density and lowest cost
  - Performance is optimal for Storage class memory

What We Know About RRAM

- Lots of technologies and physics
- Papers published show capability for 32Gbit+.
  - Sandisk 32Gb device at 130mm^2 (crosspoint)
  - Micron 16Gb device at 168mm^2 (not crosspoint)
- Revenue products come from embedded applications in Mbit range
  - Unity (Rambus), Adesto, Panasonic
  - These are interesting for physics but not applicable to 90% of FMS topics

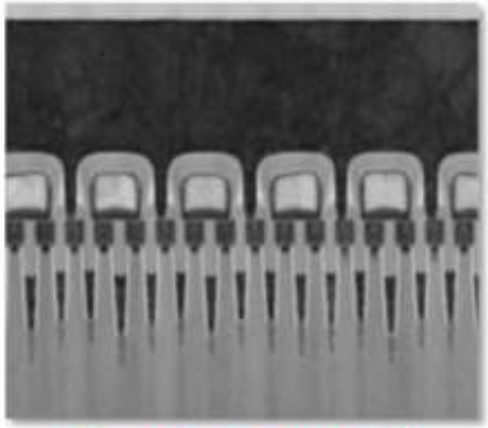
What We Hear in RRAM Presentations

- 1TB on postage stamp in future
- More scalable than NAND
- Crosspoint solutions are lowest cost ($4F^2$)
- New selector elements and leakage suppression tricks
- The question is:
  - Can RRAM become a low cost, storage class solution???

Non-Cross Point Micron ISSCC

- 16Gb in 168mm^2, 27nm, ~0.1Gbit/mm2
- Paper shows complex layout and very tight spacing.
- Modeled cost is higher than DRAM
  - Not cost effective compared to NAND or DRAM
  - What if we shrink to more aggressive node?

Device	COST $/GB
2017 DRAM COST	1X
27nm	1.1x
20nm	0.6x
14nm	0.4x

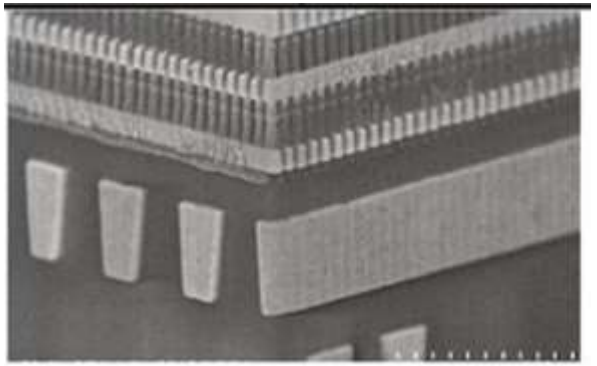


Advanced 27nm RRAM Cell

Sandisk Crosspoint

- 32Gb in 130mm2, 24nm, ~0.2Gbit/mm2
- Cross point is much better and takes advantage of scaling
- Lower cost than DRAM at 24nm… 1/3 the cost at 14nm

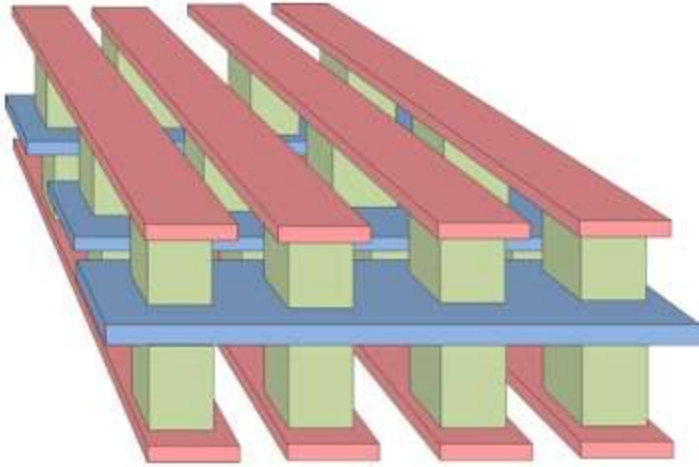
Device	COST $/GB
2017 DRAM COST	1X
24nm	0.6x
14nm	0.3x



Theoretical Crosspoint Array

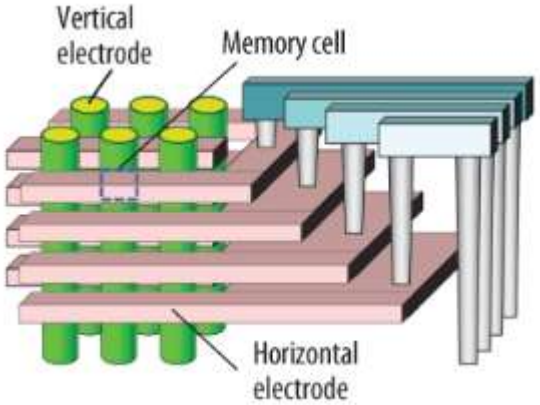
- At higher densities, we get better array efficiency and take advantage of scaling. >1Gb/mm^2
- 2 layer array, 100Gb at 20nm, 200Gb at 14nm
- Result: Significantly Cheaper than DRAM
- Result: 14nm similar to NAND costs

Device	COST $/GB
2017 DRAM COST	1X
20nm	0.2x
14nm	0.15x



Vertical (3D NAND Type Structure)

- A vertical RRAM structured is possible using similar processing to 3D NAND
- Need to embed selector material in similar way as Micron Floating gate
- Cost would potentially be in same range as 3D NAND structure (+/- 20%)
- Issue is physics and maturity of RRAM device
  - NAND was extremely mature when moved to vertical
  - Solution: implement in crosspoint (2018). Migrate when mature to 3D NAND type structure (2021).



Cost Implications and Data

- Costs for published RRAM devices are higher than NAND and close to DRAM pricing
- Cost target required for SCM is possible for RRAM
  - Crosspoint array required
  - 2 layer array, Large density
  - 14nm or below
  - Mature process and yields
- Additional layers, Vertical cells, MLC would allow even lower cost

Summary

- SCM is moving from a concept to high revenue market over next few years
  - 3D Xpoint will create and grow this market demand
- RRAM is a leading candidate to meet SCM requirements for cost
- Model shows a crosspoint RRAM technology with cost below DRAM at 20nm
  - Approaching NAND cost at 14nm
  - NAND like costs with vertical structure in 2021 timeframe