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September 18, 2017

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Moore's Law Scaling Realities for Storage Components: LTO TAPE, HDD and NAND

TOPICS

- Moore's law for integrated circuits
- Moore's law scaling applied to *storage: bit areal density* and cost per bit
- Bit areal density and $/gigabits trends for TAPE, HDD, and NAND (3 and 8 yr periods)
- Cost scaling deviations and other problems
- Summary

What is Moore’s law?

- 1965: Gordon Moore observed that the number of transistors, resistors and capacitors in an integrated circuit (IC) had been increasing *exponentially (2x per year);* this implied that the unit cost of the transistors, etc., that could be crammed into an IC was decreasing *exponentially*

- 1975: Moore refined his observation and made projection that IC complexity would *double every 2 years* (with IC cost remaining static) - this became known as ‘Moore’s Law’

- The implication of this is the unit cost of the transistors, etc., will decrease 2x every 2 years

- There is a close parallel to this for digital data storage

Bits, areal density and scaling

- In storage architectures, dimensions of the bits (the 1’s and 0’s) determine bit areal density
- Thus, bits are analogous to transistors, resistors, etc., and the aggregate area of the all the bits, to an IC

- For NAND, bit dimensions are photo lithographically defined (more akin to the paradigm behind Moore’s law)
  - *Scaling means improvements in photo lithography (X and Y) and other IC processes (X, Y and Z)*
- For magnetic storage, the bit dimensions are established during *writing the bits* onto the magnetic medium
  - *Bit width (X) is set by the width of the write head (HDD) or shingling pitch (TAPE, some HDD)*
  - *Bit length (Y) is set by the writing frequency and speed of the magnetic medium under the head*
  - *Scaling means narrower written tracks and shorter bit length*

Moore's exponential law for storage: bit areal density, cost per bit

- In storage technology, bit areal density (D) ideally increases exponentially with an annual growth factor of $(1+ \alpha)$
  - *Year 0:* $D = D_0$
  - *Year N:* $D_N = D_0 \times (1+ \alpha)^N$

- If the cost / unit area of storage is constant, then the cost per bit (C) decreases exponentially with an annual decrease factor of $(1- \beta)$
  - *Year 0:* $C = C_0$
  - *Year N:* $C_N = C_0 \times (1- \beta)^N$

- And the relationship between the 2 factors is:
  - $\beta = \alpha / (1 + \alpha)$

- Thus, an 'ideal' Moore's law IC scaling equivalent for storage components would give:
  - *Bit areal density doubling every 2 years, i.e* $\alpha = 0.41$ *(41% annual increase)*
  - *Cost / unit of media area remaining constant ➔ cost / bit halves every 2 years, i.e* $\beta = 0.29$ *(29% annual decrease)*

But…current storage areal density gains are less than Moore's 41%*

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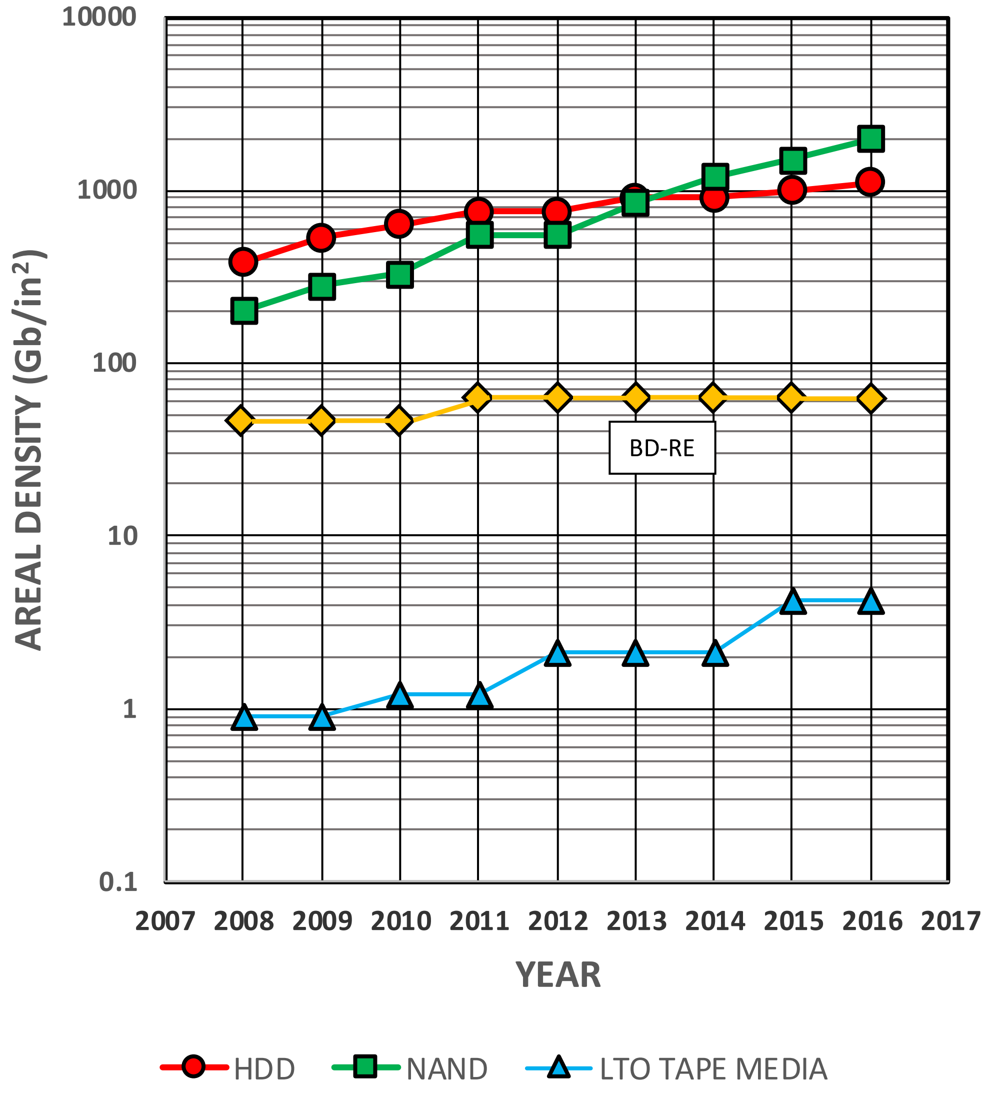


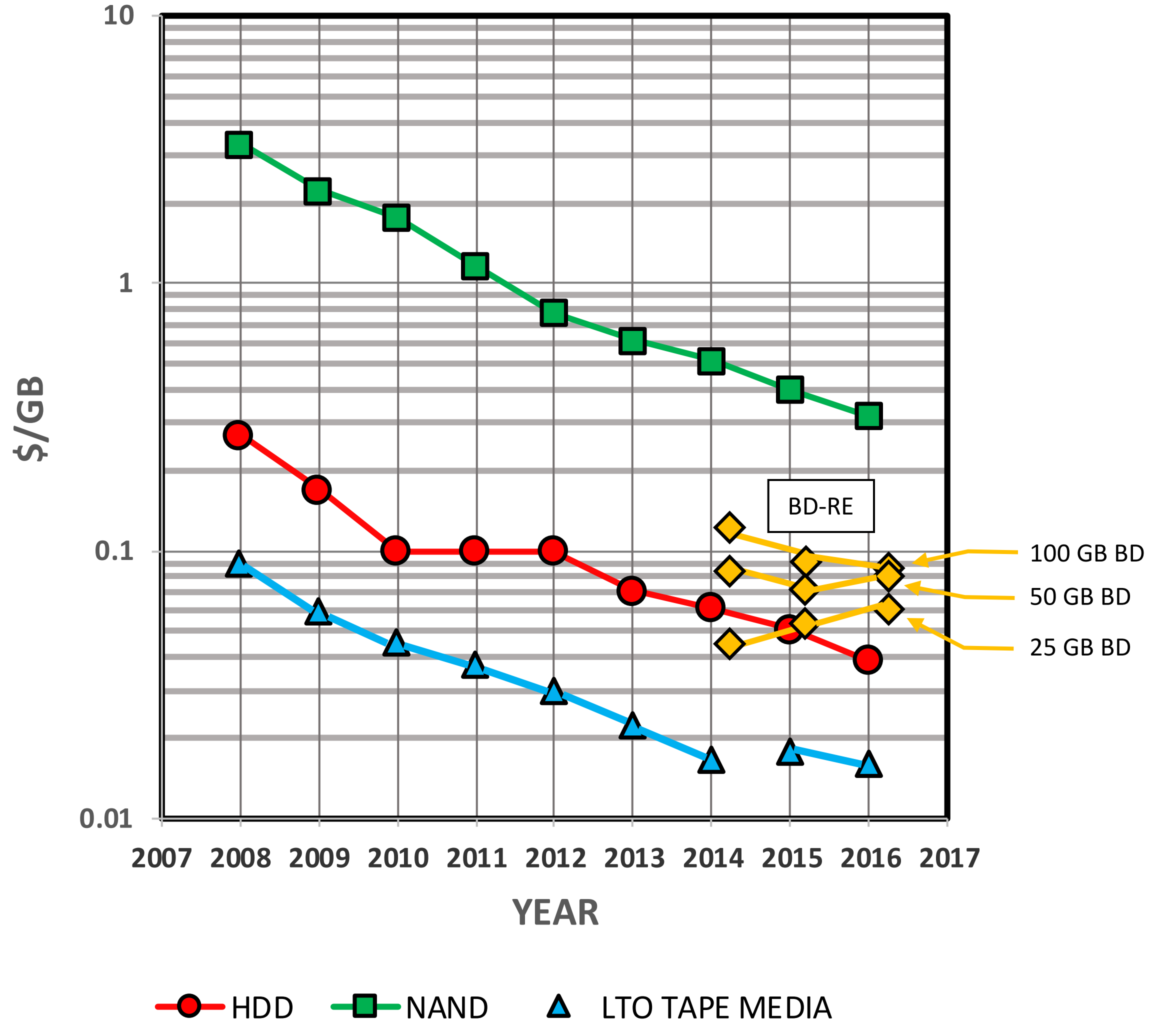
AREAL DENSITY ($Gbit/in^2$)	2008	2015	2016	8 YEAR ANNUAL % Δ	3 YEAR ANNUAL % Δ	1 YEAR ANNUAL % Δ
LTO TAPE MEDIA[1]	0.9	4.1	4.1	21%	25%	0%
HDD	380	1000	1100	14%	7%	10%
NAND	200	1500	2000	33%	33%	33%

1. LTO products on 2 year product cycle, 2017 LTO8 product will increase 1 year and 8 year averages

- NAND increases are closer to Moore's at 33% and show no decrease in this rate
- LTO TAPE MEDIA doubles on ~ 3 year cycle, or 25% annually, and shows no slowing in this rate
- HDD increases are << Moore's scaling; 8 year increases reduced to 14% and show significant slowing in recent time frames
- Blu-ray AD is stable, at most increasing slowly

*In the period 2003 - 2011, HHD density *did* grow at 39% / year

And…currently, reductions in cost per bit are less than Moore's 29%



$/GB	2008	2015	2016	8 YEAR ANNUAL % Δ	3 YEAR ANNUAL % Δ	1 YEAR ANNUAL % Δ
LTO TAPE MEDIA[1]	0.091	0.018	0.016	-19%	-10%	-10%
HDD	0.272	0.051	0.039	-21%	-18%	-23%
NAND	3.330	0.401	0.320	-25%	-20%	-20%

1. Data source change from 2014 to 2015 distorts LTO averages

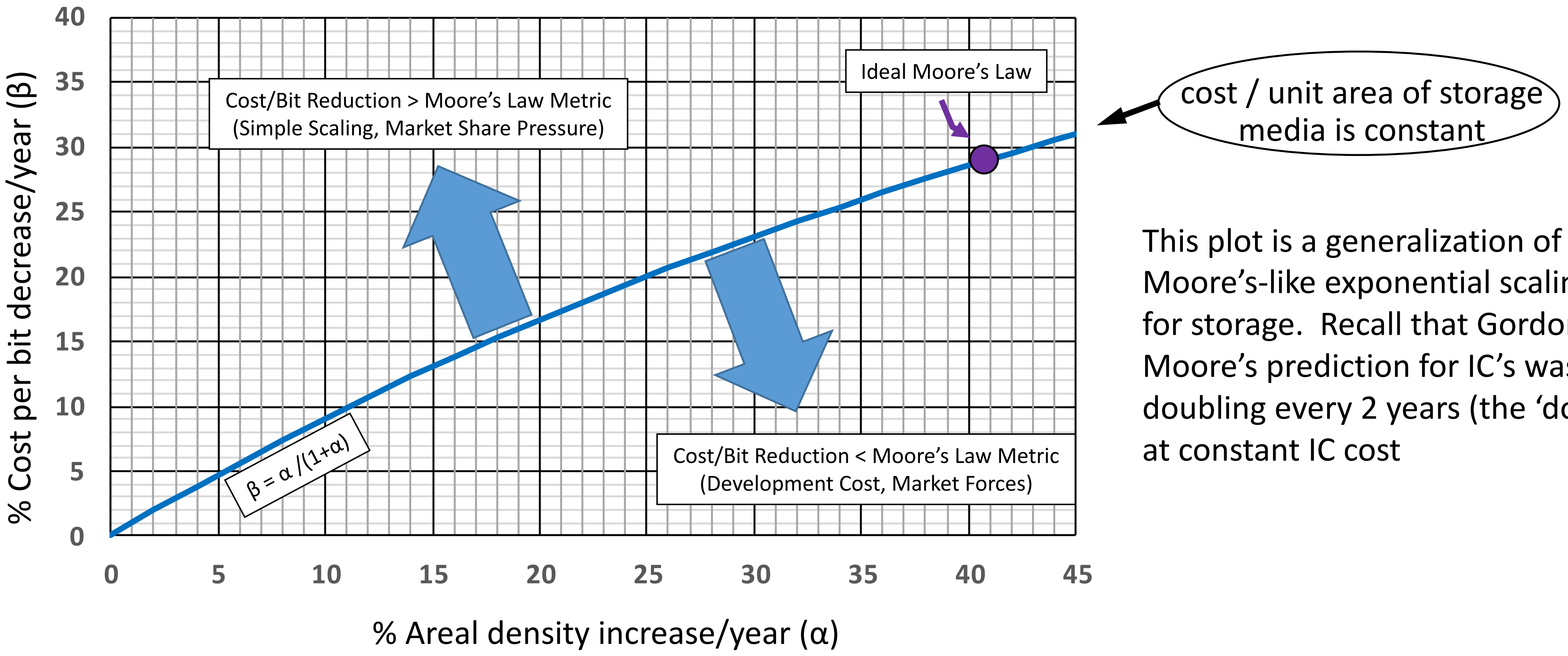
- 29% decreases in cost per bit are not being achieved
- NAND $/GB shows a 3 year average drop of 20%
- HDD $/GB shows a 3 year average drop of 18%
- LTO TAPE MEDIA $/GB (distorted by a change in LTO data sources) shows a 10% drop
- Blu-ray cost per bit is stable, no drop

An important distinction between HDD and TAPE

- Disk cost is unit cost of the HDD brick, which includes platters, heads, electronics, etc.

- Tape cost is for the media cartridge only; drive cost is typically included in automation and is significantly less than the cost of the media

$/GB and areal density ‘dynamics’



This plot is a generalization of Moore’s-like exponential scaling for storage. Recall that Gordon Moore’s prediction for IC’s was a doubling every 2 years (the ‘dot’) at constant IC cost

$/GB and areal density 'dynamics'

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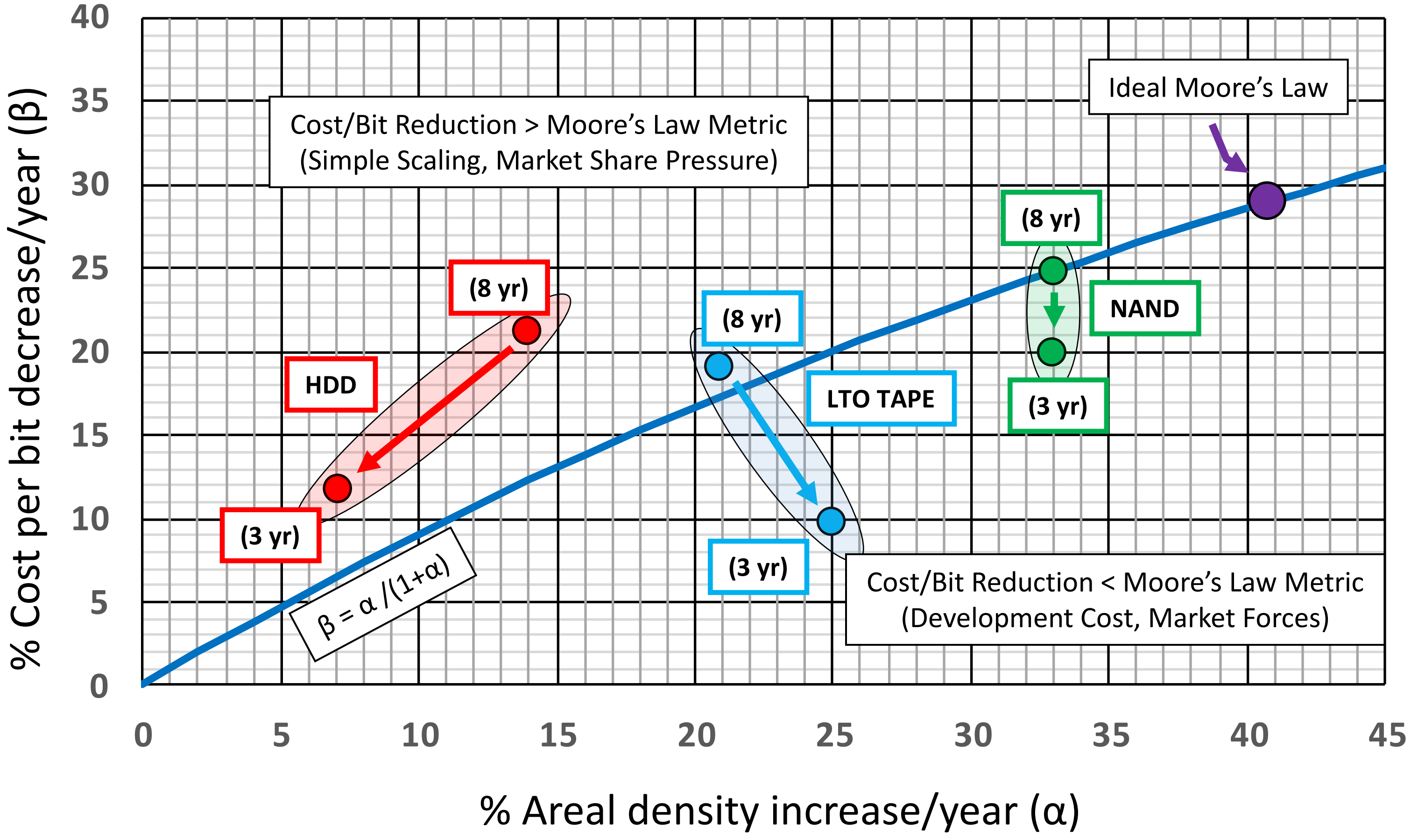

- LTO TAPE, NAND: 8 yr data follow a Moore's law trend, while 3 yr data fall below it, implying (1) market forces and/or (2) greater investment was needed for the gain in density
- HDD: 8 yr and 3 yr data are above the Moore's law trend, implying (1) market force competition and/or (2) the modest areal density gains did not drive up cost
- Observation 1: Historical 8 yr data shows $/bit for all technologies fell between 20% to 25% annually
- Observation 2: Historical 3 yr data shows lower $/bit reductions for all technologies relative to 8 yr data

What are the scaling *REALITIES*

- *Present day* storage component trends are not meeting Moore's law for ICs
  - *Annual density increase is not 41%, but ranges from 10% to 30% (depending on technology)*
  - *Cost per bit decrease is not 29%, but closer to 10% to 20%, (depending on technology)*

- *Critically*, the cost to produce a unit area of storage is NOT remaining constant, but rather *is increasing*
  - *Physics and the required linewidths associated with scaling bit cells are raising development costs*
  - *Marketing forces*

- Further, the landscape of storage component manufacturers is changing
  - *Fewer competitors (both HDD and TAPE)*
  - *Manufacturing capacity constraints (NAND)*
  - *Limited market (Optical)*

And…cost effective bit-scaling is becoming more difficult

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- Feynman famously stated in 1959 (the year the first integrated circuits were built), ‘there is plenty of room at the bottom,’ i.e. you can always make things smaller
  - *1959 minimum features ~ 1500 um*
  - *2017 minimum features ~ 0.015 um*
  - *In 60 years linewidths fell by ~10^5 and cell areas fell by ~ 10^{10}*
  - *2017 NAND chips (12 mm x 12 mm) contain 256 x 10^9 bits, while chips in 1960 contained 1 to 5 bits [1]*

- Thus, for ~ 50 years, the Moore’s law ‘contract’ had been: reduce component cost per bit by finding ‘room at the bottom’ with smaller bit cell devices at the same cost per unit total storage area

- In the last 5 years, the ‘art’ of making bit cells smaller, though, has increased the cost of a unit area of storage

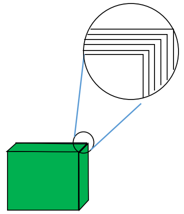
[1] Jack S. Kilby, Miniaturized Electronic Circuits, United States Patent Office, US Patent 3,138,743, filed 6 February 1959, issued 23 June 1964

Bit cell dimensions

- TAPE: <u>room at the bottom</u>, so continue scaling (Moore's law)
- HDD: <u>no room at the bottom</u>, so add more platters (not Moore's law)
- OPTICAL: <u>some room at the bottom</u>, limited by λ, so add more layers (not Moore's law)
- NAND: <u>no room at the bottom</u>, so add more layers at the media level, but process layers simultaneously (close to Moore's law)

<u>NAND 3D TLC</u>
40 layers
3 bit/cell
84 nm x 84 nm
3000 Gbit/in ^{2}

40 layers, or more

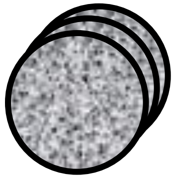


7TB 12” wafer
440 12 mm x 12 mm dies / ~ 256 Gb/die

<u>HDD</u>
58 nm x 11 nm
1000 Gbit/in ^{2}

10TB 3.5” drive
7-8 platters / ~ 1.4TB/platter

<u>OPTICAL BD-XL</u>
3 layer
land recording
180 nm diameter
75 Gbit/in ^{2}



1.2TB cartridge
12 platters / ~ 0.1 TB/platter

<u>LTO TAPE</u>
~3200 nm x 47 nm
4 Gbit/in ^{2}

6TB Cartridge, 1000 m tape length

<u>ENTERPRISE TAPE</u>
1350 nm x 47 nm
9 Gbit/in ^{2}

15TB cartridge, 1100 m tape length

NAND

NAND 3D TLC
40 layers
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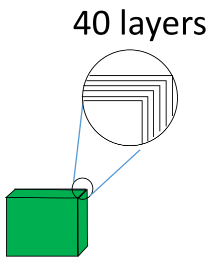


7TB 12” wafer
440 12mm x 12mm dies
~ 256 Gb/die

- *Areal Density Strategy* is adding more layers
- Cost / bit reductions are maintained provided all layers are processed in a single step to form individual stacked bit cells
- Continued scaling and Moore’s law are limited by ability to continually double number of layers
- Density increase of 4X to ~ 128 layers and 4 bits per cell are in the offing
- Cost per bit decrease of 4X less likely since ‘tiered’ processing of layers is required, i.e. process the first 64 layers and then the second 64 layers, etc.

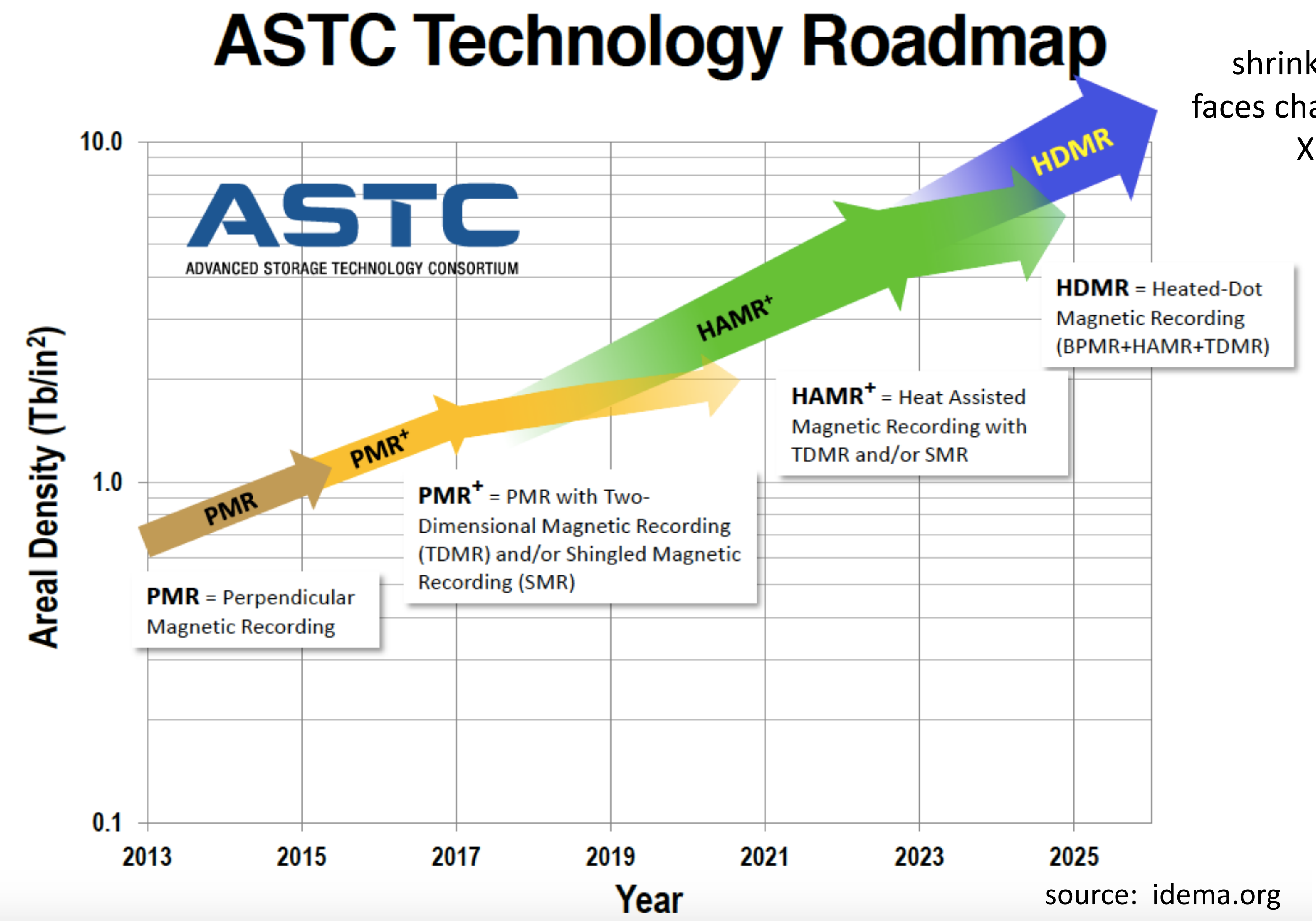
HDD

HDD
58 nm x 11 nm
1000 Gbit/in ^{2}

10TB 3.5" Drive
7-8 platters / ~ 1.4TB/platter

- *Volumetric strategy* is adding more disk platters, with minimal increase in aerial density
- Cost / bit in transitioning from 4 TB to 10 TB capacity was managed by moving from 4 to 7 or 8 platters, but this meant increasing the manufacturing area for components (heads and disk surfaces)
- Scaling and hence Moore's law gains are limited by ability to continually double number of platters
- Density increase of 2X possible but addition of more platters will be difficult
- Cost / bit reductions have limited scaling potential due to difficulty of increasing areal density, e.g. HAMR

HAMR is needed to enable significant HDD bit length scaling



shrinking HDD bit dimensions faces challenges in both directions: X (SMR) and Y (KBPI)

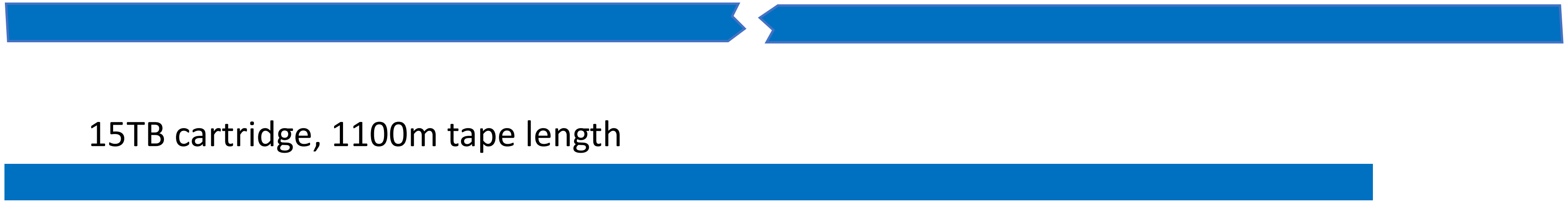
TAPE

6TB cartridge, 1000m tape length

LTO TAPE
3200 nm x 47 nm
4 Gbit/in ^{2}

15TB cartridge, 1100m tape length

Enterprise TAPE
1350 nm x 47 nm
9 Gbit/in ^{2}

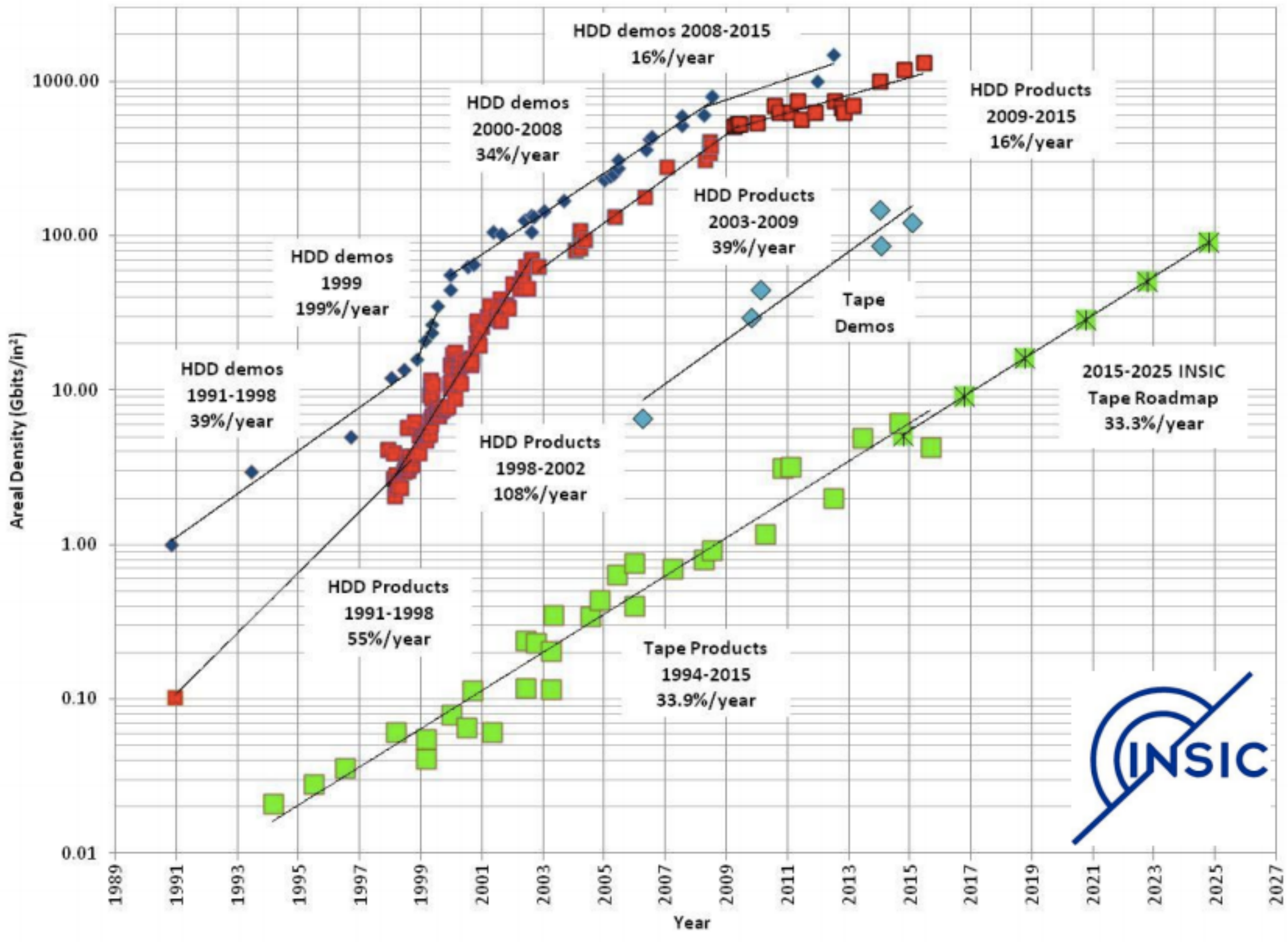


- *Areal Density Strategy* is classical planar scaling, i.e. making the bit cell smaller
- Cost likely is likely to be managed since (1) classical scaling is used, (2) TAPE uses HDD existing technology ('no new physics'), and (3) length scales and media particle sizes will scale for the future
- Cost dynamics may be influenced by market sources
- 4X density increases providing > 40 TB cartridge capacities are only 4 years on the horizon

- The Future

TAPE Demonstration (2017)
103 nm x 31 nm
207 Gbit/in ^{2}

Tape has room to continue bit scaling in both X and Y directions



TAPE scaling requires
'no new physics'

SUMMARY

- Moore's law for ICs (doubling density every 2 years, and cost / bit halving every two years) is not being achieved by LTO TAPE, HDD, NAND (NAND being the closest)

- Bit cell scaling is loosing cost efficiency
  - *Physics, e.g. HAMR*
  - *Processing smaller features - nano technology limits (HDD, NAND)*
  - *Cost-per-bit reductions are trending to less than 20% / year*

- Market forces are now impacting $/GB reductions
  - *3 year and 8 year trends show decrease in $/GB reductions for all technologies*
  - *There is an under-capacity in NAND (not enough factories to meet HDD demand in foreseeable future)*
  - *HDD market has shifted from personal devices to datacenter applications*
  - *There is tape consolidation (1 drive manufacturer, 2 media suppliers)*

APPENDIX

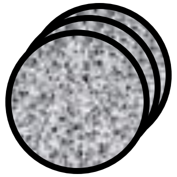
Storage Landscape - 9 Year History

	2008	2009	2010	2011	2012	2013	2014	2015	2016
HDD									
Units (HDD millions)	540	557	652	620	577	551	564	470	425
PB Shipped (PB)	125000	200000	330000	335000	380000	470000	549000	565000	693000
Areal Density (Gb/in^2)	380	530	635	750	750	900	900	1000	1100
Revenue ($ billions)	34.0	34.0	33.0	33.5	37.5	33.4	33.4	28.3	26.8
$/GB Shipped	0.272	0.170	0.100	0.100	0.100	0.071	0.061	0.051	0.039
NAND									
Wafers (12"-millions)	7.3	8.3	9.7	11.3	12.1	13.7	14.8	15.9	17.0
PB Shipped (PB)	3000	5430	10464	18600	28000	39000	62500	83000	120000
Areal Density (Gb/in^2)	200	280	330	550	550	850	1200	1500	2000
Revenue ($ billions)	10.1	12.1	18.5	21.5	22.0	24.0	32.2	33.2	38.7
$/GB Shipped	3.33	2.23	1.77	1.16	0.78	0.615	0.515	0.401	0.320
LTO TAPE MEDIA									
Units (Cart millions)	27.1	24.3	25.0	24.3	23.4	21.6	22.2	19.4	19.4
PB Shipped (PB)	11050	11960	15340	18420	20680	24270	30100	33020	40320
Areal Density (Gb/in^2)	0.9	0.9	1.2	1.2	2.1	2.1	2.1	4.1	4.1[1]
Revenue <SCCG.com> ($ billions) [2]	1.0	0.7	0.7	0.7	0.62	0.54	0.50		
Revenue <LTO.org> ($ billions) [2]								0.59	0.65
$/GB Shipped	0.0905	0.0585	0.0456	0.0380	0.0300	0.0222	0.0166	0.0177	0.0162

1. LTO on 2 year product cycle for areal density
2. LTO data source shifts from SCCG to LTO Consortium in 2015. Data discontinuity for revenue and $/GB in 2014-2015 transition

Optical BD-XL

<u>Optical BD-XL</u>
3 layer
land recording
180 nm diameter
75 Gbit/in ^{2}



1.2TB Cartridge
12 disks
~ 0.1TB/platter

- *<u>Areal Density Strategy</u>* is adding more storage layers on the plastic disk substrate
- Cost per bit likely not well managed, since the patterning or processing of each storage layer is done individually
- A 2-sided 3 + 3 layer disk may have 2X the capacity of the single sided 3 layer disk but at close to 2x the cost of the single sided 3 layer disk.
- Scaling, and hence Moore's law geometric figure of merit gains, are limited by ability to simultaneously process individual layers
- Land and groove recording will likely increase density by 1.5X at the expense of error rate
- Cost per bit reductions have limited potential with land and groove recording, providing the potential for only a one time 30% reduction in cost per bit