THIC Inc.

The Premier Advanced Recording Technology Forum

Moore's Law and Data Storage

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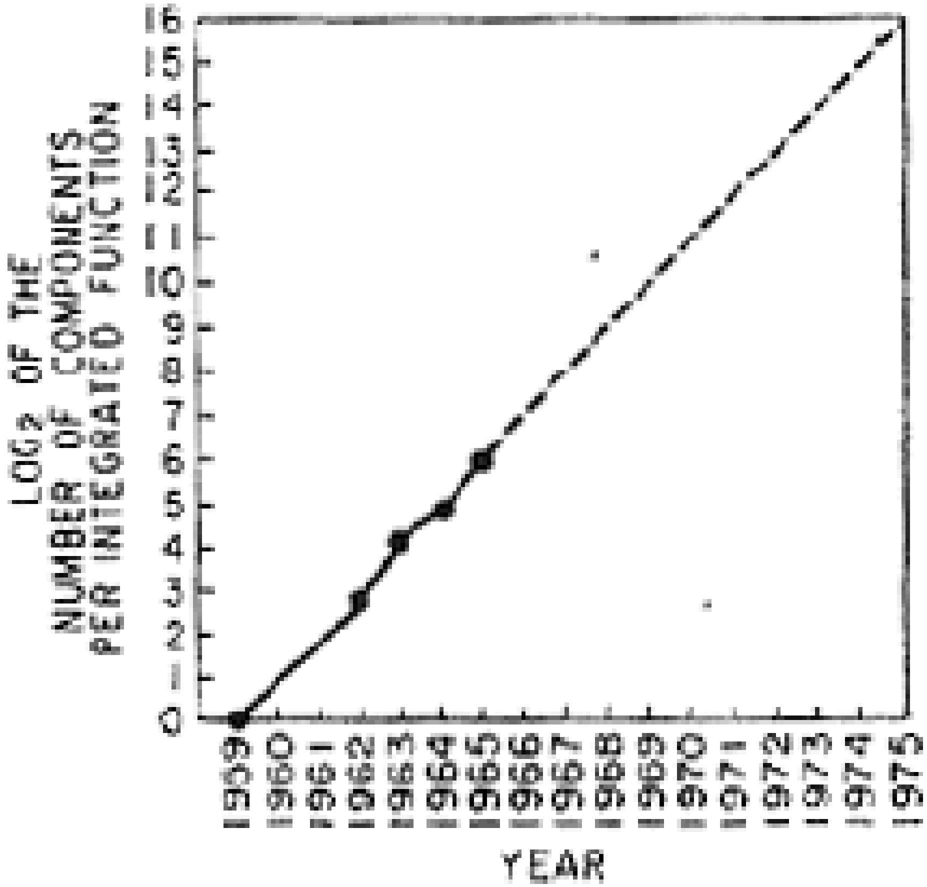
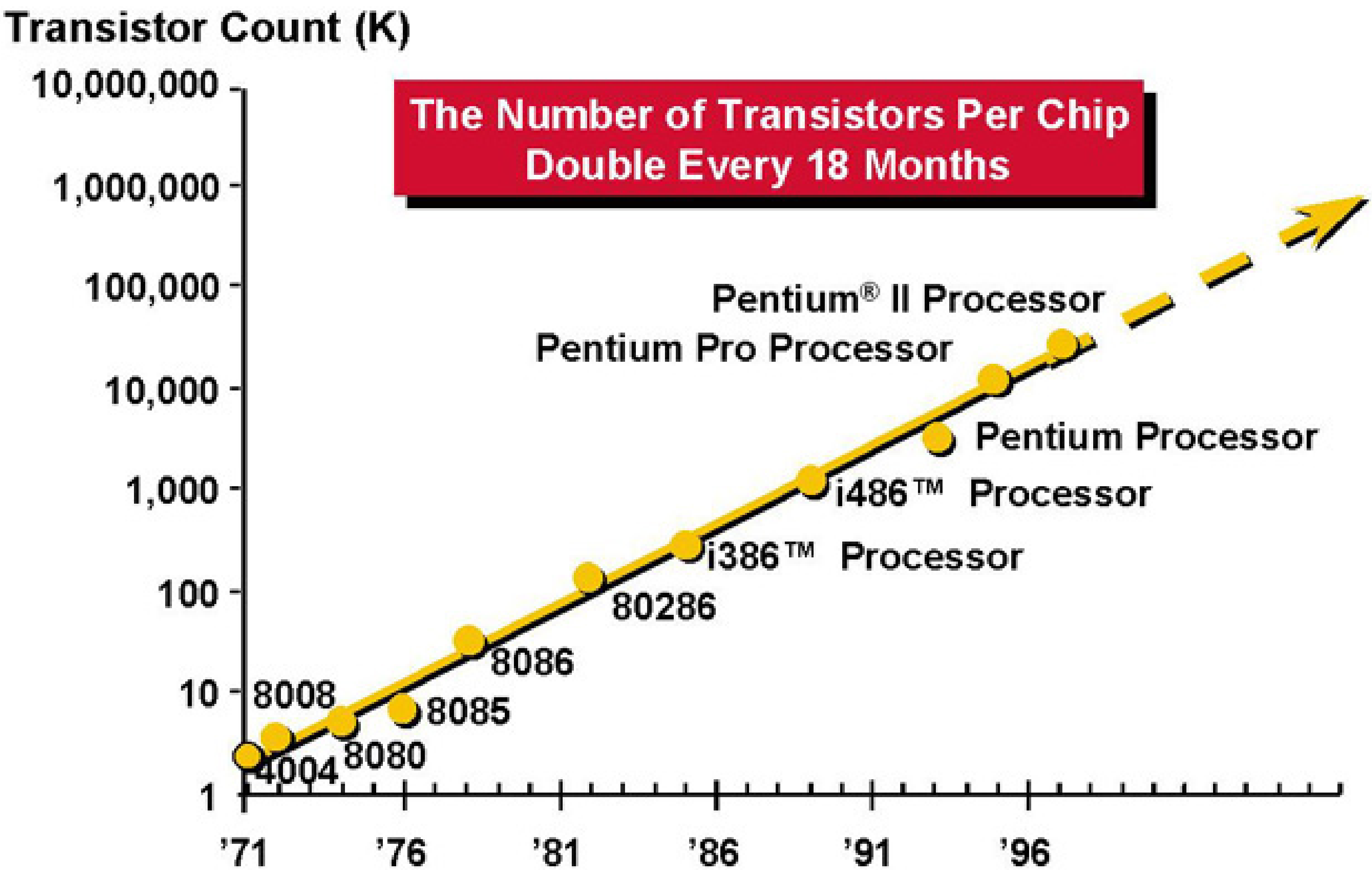
Moore’s Law



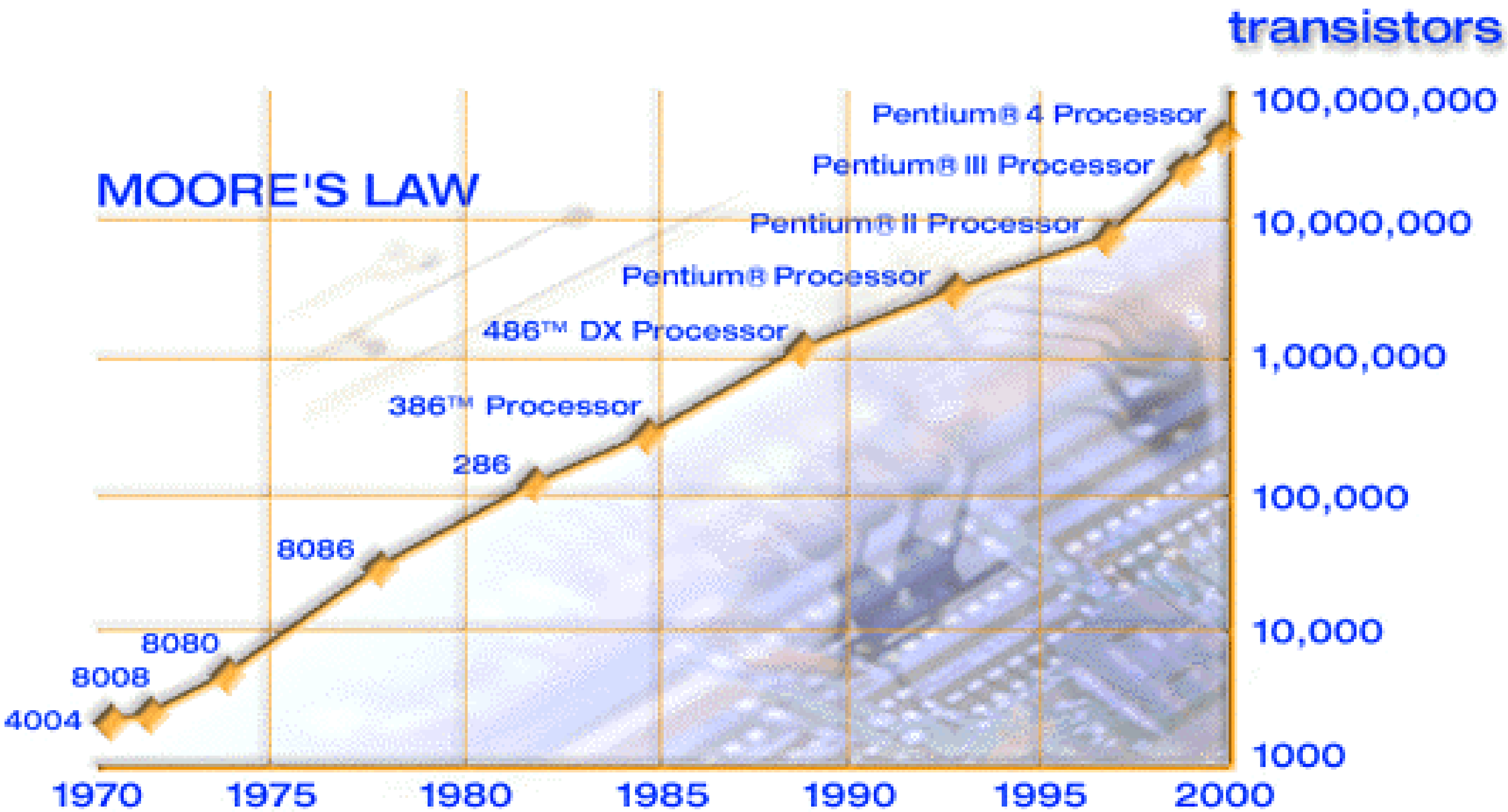
From “Cramming more components onto integrated circuits, by Gordon E. Moore, Electronics, Volume 38, Number 8, April 19, 1965

Moore's Law for IC's



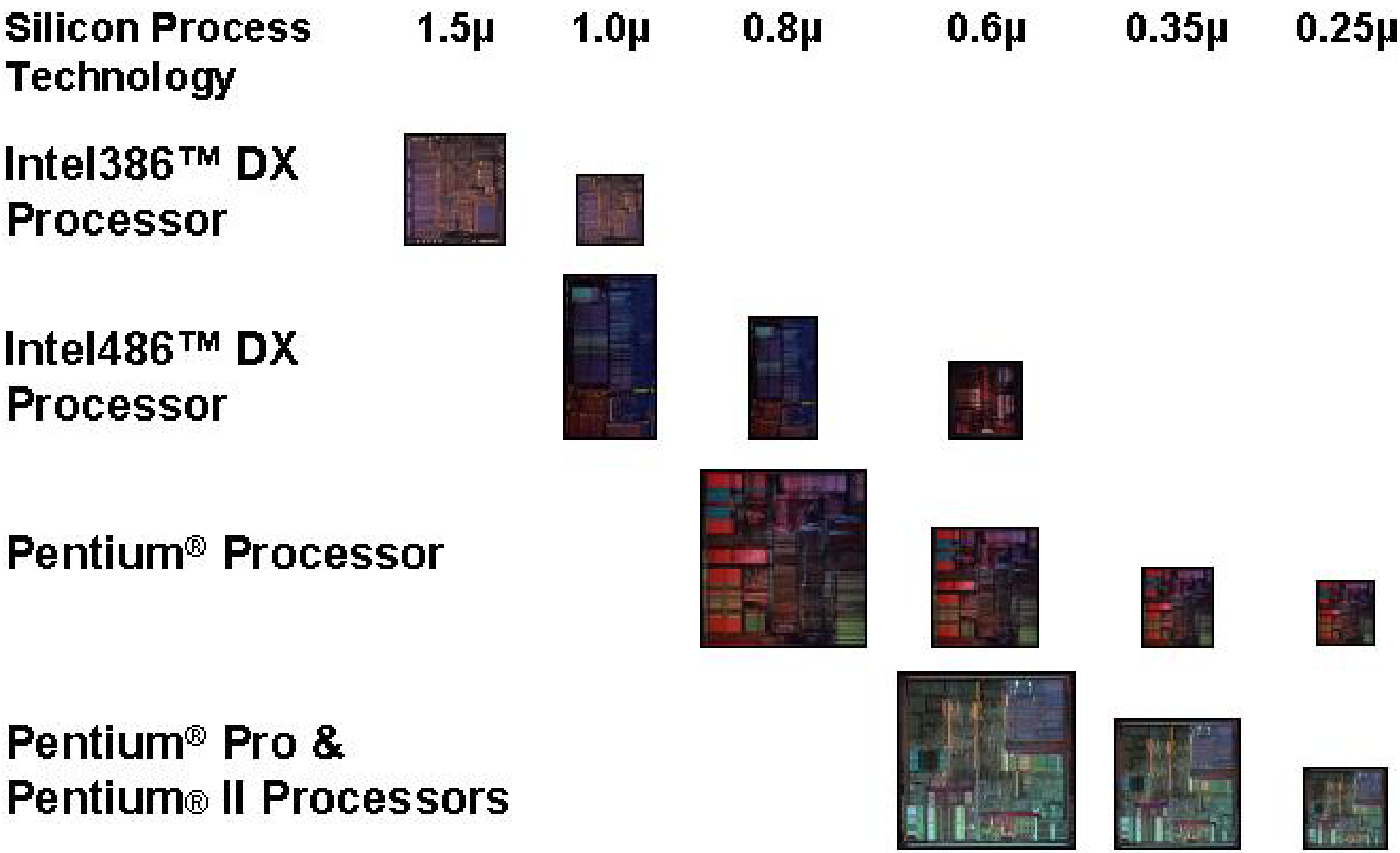
Source: Intel

Moore's Law updated to Pentium 4



Source: Intel

Moore's Law for Intel Processors



Source: Intel

Moore's Law for Storage Devices

- Capacity increase
  - Hard disks: 100% per annum during the last three years (Doubling every 18 months since 1994)
  - Tapes: Doubling every 18 months
- Transfer rate: slower growth. Does not follow Moore's law

  disks: single disks, from 2 to 8 MB/s (1990-2000)

  tapes: from 3 MB/s to 12 MB/s (1990-2000)

  RAID: upto 200 MB/s

2001 INSIC Tape Roadmap

- 10 year roadmap
- Consensus of over 40 researchers
  - Representing virtually every large drive manufacturer, tape media and substrate supplier, manyof the leading research universities
- Primarily focused on linear tape (helical section by Sony)
- Goal to remain competitive with disk ($/MB) and be technically feasible
- Keep the ratio of the capacities of a tape cartridge to a single 3 1/2 inch disk platter constant. (Ratio = 3.3 at time of roadmap)
- Assume
  - Disk capacity growth will be 60% /year
  - Disk data rate growth will be 26%/year

(From Robert Raymond, STK, THIC June 2002)

Magnetic Recording

- 1898, Valdemar Poulsen in Denmark (wire)
- Picked up in the 50's: Ampex (audio and video), IBM (data storage)
- Magnetic Disk since 1957 (IBM RAMAC)
- Inductive write, inductive read till mid-90's
- Magneto-resistive (MR) read -> Giant MR (GMR) -> Colossal MR -> Ballistic MR (BMR)
- MR read heads have proved to be a significant enabler in the pursuit of higher areal densities

Pigments

- Gamma Ferric Oxide
- Co-doped Gamma Ferric Oxide
- CrO_2
- Metal Particle (MP)

Coating Technology

- Traditional methods
- Plating
- Sputtering
- Dual coating

From Round reel to square

Year	Product	bpi*	KB/s	capacity (MB)	tpi
1952	IBM726	100	7.5	1.4	14
1953	IBM727	200	15	5.8	14
1957	IBM729	800	90	23	14
1965	IBM2401	1600	180	46	18
1968	IBM2420	1600	320	46	18
1973	IBM3420	6250	1250	180	18
1984	IBM3480	38000	3000	200	36
1991	IBM3490E	76000	3000	800	72
1995	IBM3590	92000	9000	10000	256

***This is the user bit density in each track; channel code, ECC and other overhead will be reflected in the number of flux transitions per inch, which is not considered here.**

Special thanks to Dr Steve Vogel, IBM Storage Systems Division, Tucson AZ for checking this table, and supplying information to complete it.

P C Hariharan

Areal Density of Magnetic Tape

	1984	1990	1996	2002
Product	3480 (200 MB)	ID-1 (14-96 GB)	DLT-7 (40 GB)	SDLT-320 (160 GB)
TPI	36	655	336	1058
Kbits/in	38.0	50.8	123	190
Mb/in^2	1.36	33.3	41.4	201
$\mu m^2/bit$	474	19.4	15.6	3.2

Further Information will be available in talks by Wayne Imaino/Joe Gordon II (IBM), John Woelbern (SONY)

DLT from Quantum

Year	Product	Transfer Rate (MB/s)	Capacity (GB)	Tracks per Inch (tpi)	Bits per inch (bpi)
1992	2000	1.25	15	256	62500
1994	4000	1.5	20	256	82500
1996	7000	5.0	35	416	86000
1999	8000	6.0	40	416	98000
2001	SuperDLT 220	11.0	110	1058	130000
2002	SuperDLT 320	16.0	160	1058	190000

Areal Density of Hard disk drives

	1970	1980	1990	1999	2000+
Product	3330	3380	Corsair	Micro-drive	Today's Drive
TPI	192	801	2,238	19,000	67,300
Kbits/in	4.04	15.2	58.9	265	522
Mb/in^2	0.776	12.2	131.8	5,035	35,300
$\mu m^2/bit$	830	53	4.9	0.128	0.018

Further Information will be available in talks by Dr. Dmitri Litvinov (Seagate Research)

Optical Recording

- WORM
- Rewritable
- CD
- CD-ROM, -R, -RW
- Calimetrics (multi-level, 3x conventional capacity)
- DVD-ROM
- The +/- wars
- Blu-ray and the next generation wars

Areal Density of Optical Disk

	1982	1998	1999	2000+
Product	CD 650 MB	DVD-RAM 2.6 GB	DVD-RAM 4.7 GB	Next Gen 15~25 GB
TPI	15,875	34,300	41,300	85,000
Kbits/in	30.5	62.1	90.7	120
Mb/in^2	484	2,130	3,745	10,000
$\mu m^2/bit$	1.3	0.303	0.172	0.065

Fell by the wayside?

- Tamarack and the Gigastore (1994)
- Surface-enhanced Raman spectroscopy
- Bacteriorhodopsin
- Terastore Near Field Optical Storage (SIL)

Holography

- Has been in the lab for two decades, but components for a system are now beginning to become available (see: Roadmap from InPhase)
- Two-photon storage, truly three-dimensional

InPhase Recordable/Rewritable Technology Roadmap

	2003	2004	2005	2006	2007
Recordable Specs	100 Gb/in^2 20 MB/s	200 Gb/in^2 40 MB/s	400 Gb/in^2 80 MB/s	800 Gb/in^2 160 MB/s	1600 Gb/in^2 250 MB/s
Drive Configuration	• Angle Mux ~1000 pages • Blue Laser	• Custom SLM, Detector • Grayscale	• 2000 pages by using 2 wavelengths	• Custom laser • 4 λ's	• 8λ's • Or more angles used
Re-Writable Specs			200 Gb/in^2 30 MB/s	400 Gb/in^2 60 MB/s	800 Gb/in^2 120 MB/s
Drive Configuration			• Custom SLM, Detector • Grayscale	• 2000 pages by using 2 wavelengths	•Custom laser • 4λ's

From Presentation by Dr. William Wilson, InPhase, THIC, June 2002, Boulder, CO

Microelectromechanical Systems (MEMS)

- Only system in conformance with Reed's First Law (Don't separate the head from the media)

Microelectromechanical systems (MEMS) come closest to the clay tablet. See recent announcement by IBM Zurich about the Millipede. It is a self-contained read/write system with an areal density of 1 Tb/in^2.

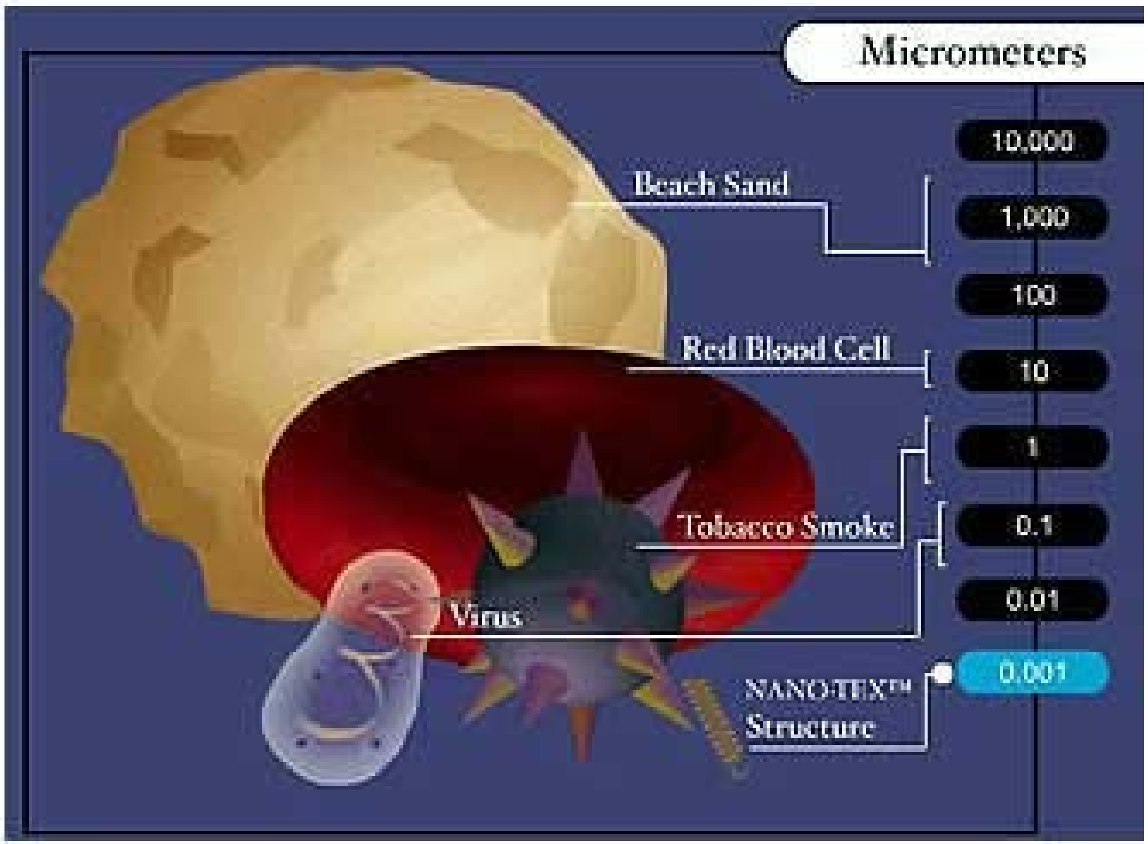
http://mems.sandia.gov/scripts/memscam.asp

500,000 rpm (normal auto at highway speed ~3000 rpm); the maximum rpm observed was 7×10^9 ! An auto engine would accumulate this many revolutions if it was driven to the moon and back 6 times.

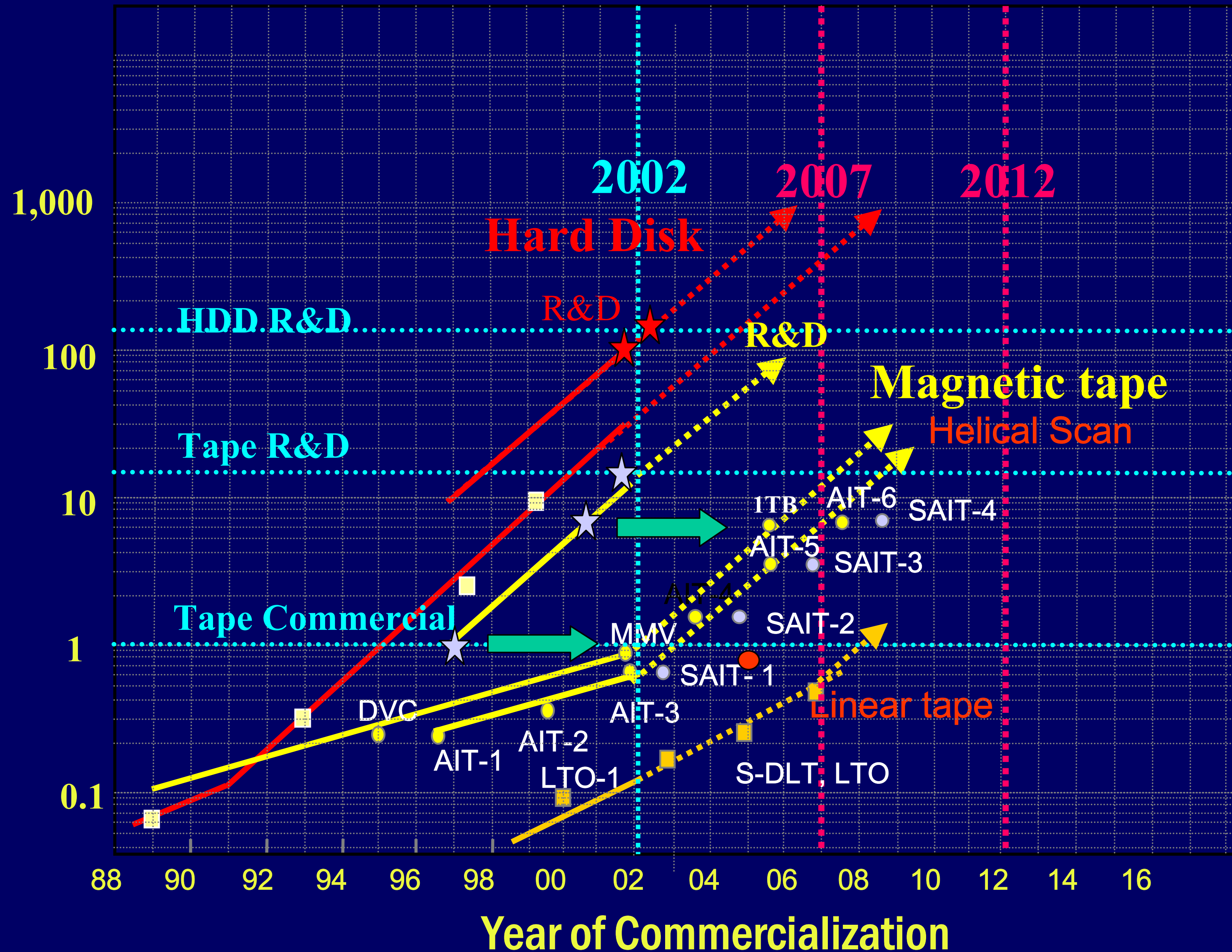
High performance disk drives: 10,000 or 15,000 rpm

MEMS (continued)

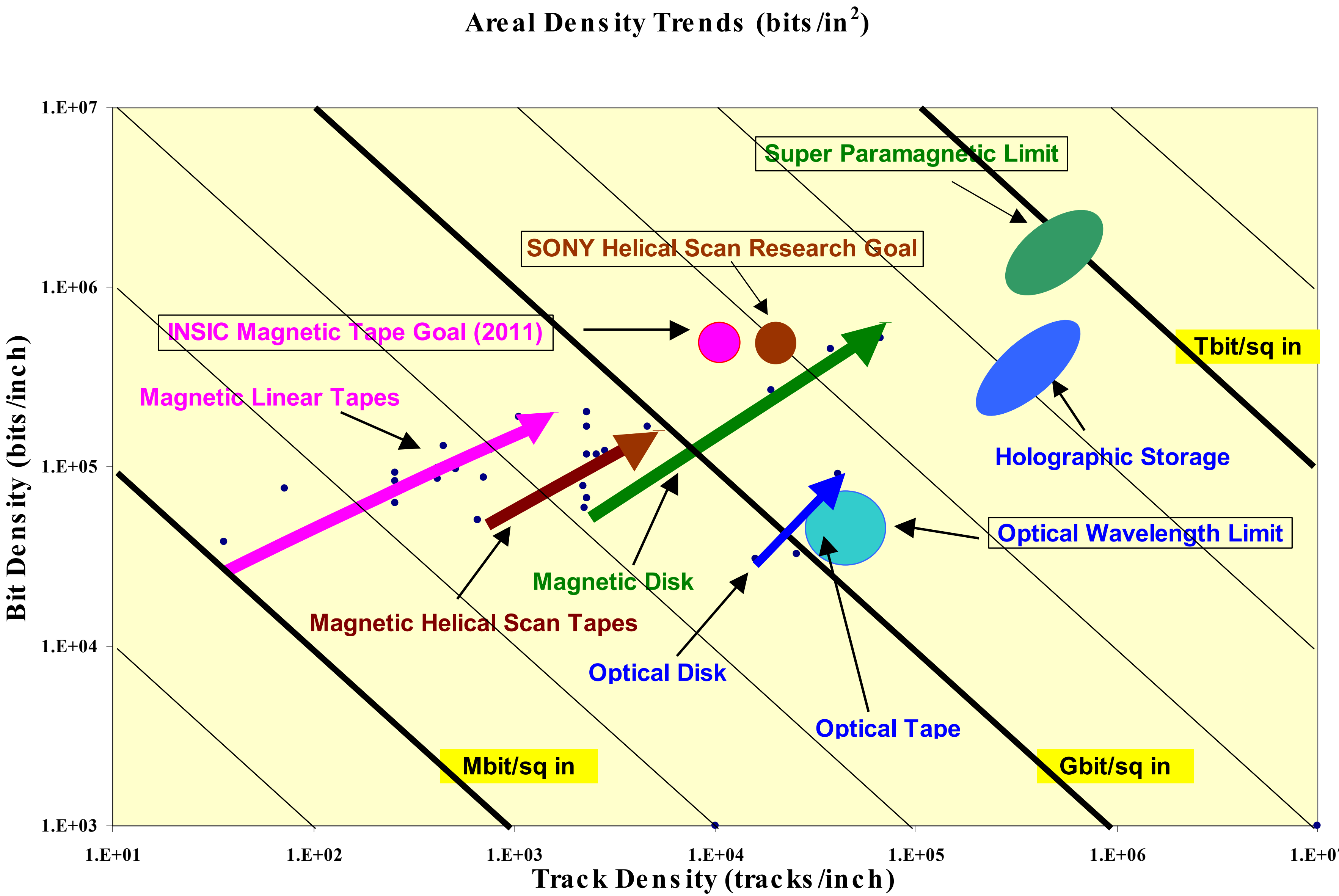
- Linear dimensions a thousand times larger than those of nanoscale devices

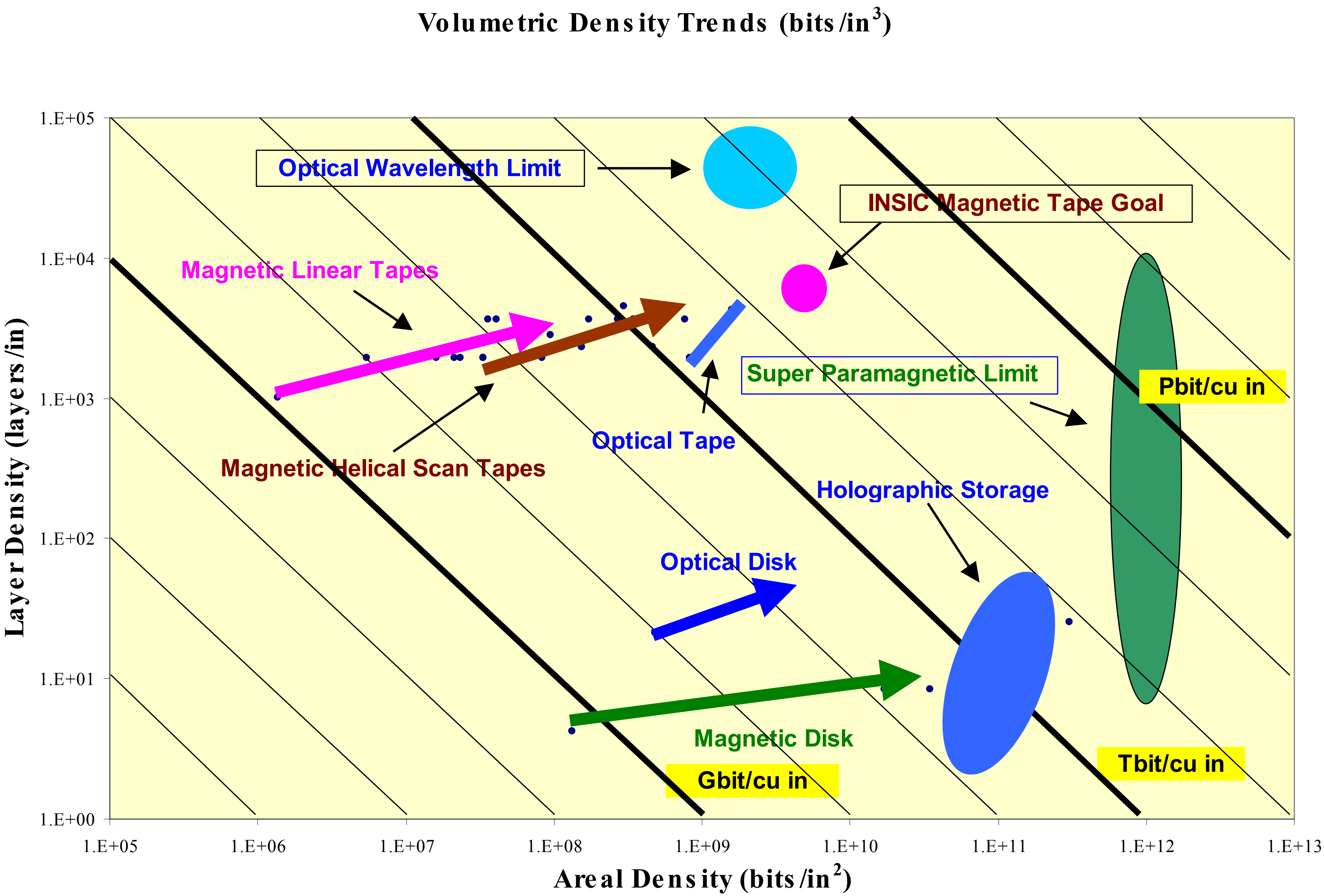


Areal Density Growth (Gbit/sq in vs year)



From THIC/Boulder June 2002, Dr. Seiichi Onodera


Areal Density Trends (bits/in²)
Super Paramagnetic Limit
SONY Helical Scan Research Goal
INSIC Magnetic Tape Goal (2011)
Magnetic Linear Tapes
Tbit/sq in
Holographic Storage
Optical Wavelength Limit
Magnetic Disk
Magnetic Helical Scan Tapes
Optical Disk
Optical Tape
Mbit/sq in
Gbit/sq in
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
Bit Density (bits/inch)
Track Density (tracks/inch)



Volumetric Density Trends (bits/in^3)
Optical Wavelength Limit
INSIC Magnetic Tape Goal
Magnetic Linear Tapes
Super Paramagnetic Limit
Pbit/cu in
Optical Tape
Magnetic Helical Scan Tapes
Holographic Storage
Optical Disk
Magnetic Disk
Tbit/cu in
Gbit/cu in
Layer Density (layers/in)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
1.E+10
1.E+11
1.E+12
1.E+13
Areal Density (bits/in^2)

How far can we go? Nanoscale storage

In 1959, Richard Feynman gave a visionary talk entitled “There’s Plenty of Room at the Bottom”. He asked the question whether it will be possible to shrink devices all the way down to the atomic level.

Allowing 5 x 5 x 5 = 125 atoms to store one bit, he estimated that all printed information accumulated over centuries since the Gutenberg Bible could be stored in a cube of material 1/200” = 0.1 mm wide.

The University of Wisconsin created a two-dimensional version of Feynman's atomic memory, formed on the **surface of silicon** by a small amount of gold. Extra silicon atoms (white) sit on top of **self-assembled tracks** that are formed by the gold. Each track is **exactly five atoms wide.**

Feynman's 1959 suggestion of spacing the bits 5 atoms apart was right on the mark.

Using Si atoms on a gold surface, density achievable is 250 Tb/in^2.

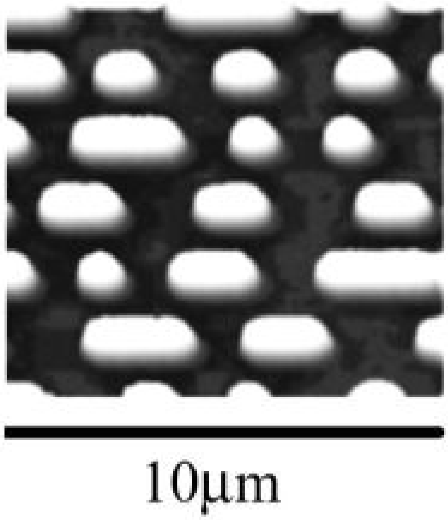
For comparison, DNA storage density is estimated to be 100 Tb/in^2.

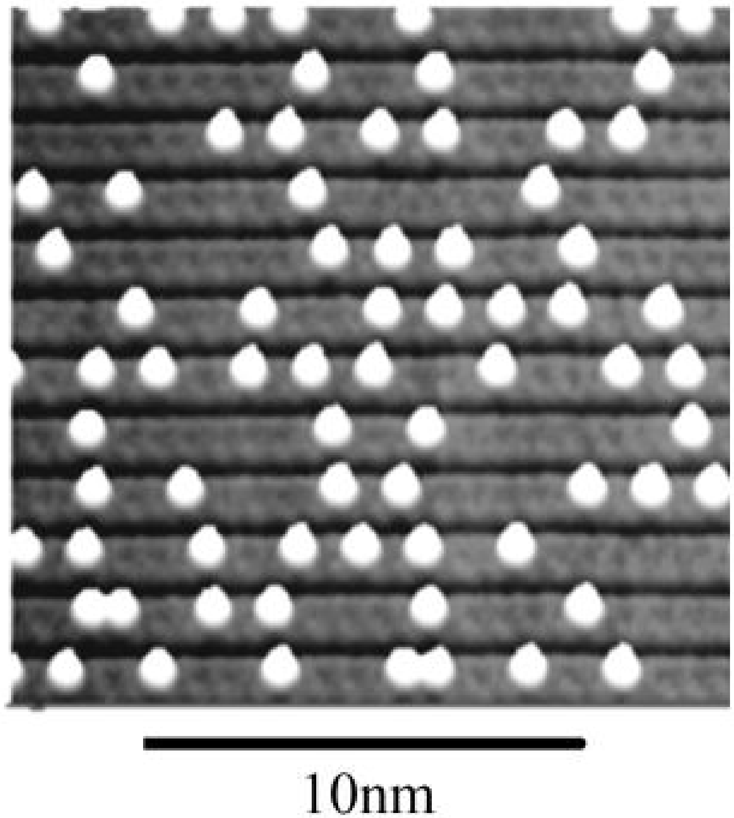
(32 atoms, on the average, to store a bit)

R. Bennewitz et al., Nanotechnology 13, 499 (2002).

University of Wisconsin Nanoscale Memory

X 10^6 areal density





CD-ROM

Au atoms on Si in tracks 5 atoms wide (Feynman, 1957)

Works at liquid He temperatures