

## **Moore's Law and Data Storage**

**Ben Kobler**

**NASA Goddard Space Flight Center**

**Greenbelt Road, MS 423, Greenbelt, MD 20771**

**Phone:+1-301-614-5539 FAX: +1-301-614-5267**

**E-mail: [kobler@gsfc.nasa.gov](mailto:kobler@gsfc.nasa.gov)**

**P C Hariharan**

**SES, Inc**

**7474 Greenway Center Drive, Greenbelt, MD 20770**

**Phone:+1-301-441-3694 FAX +1-301-441-3697**

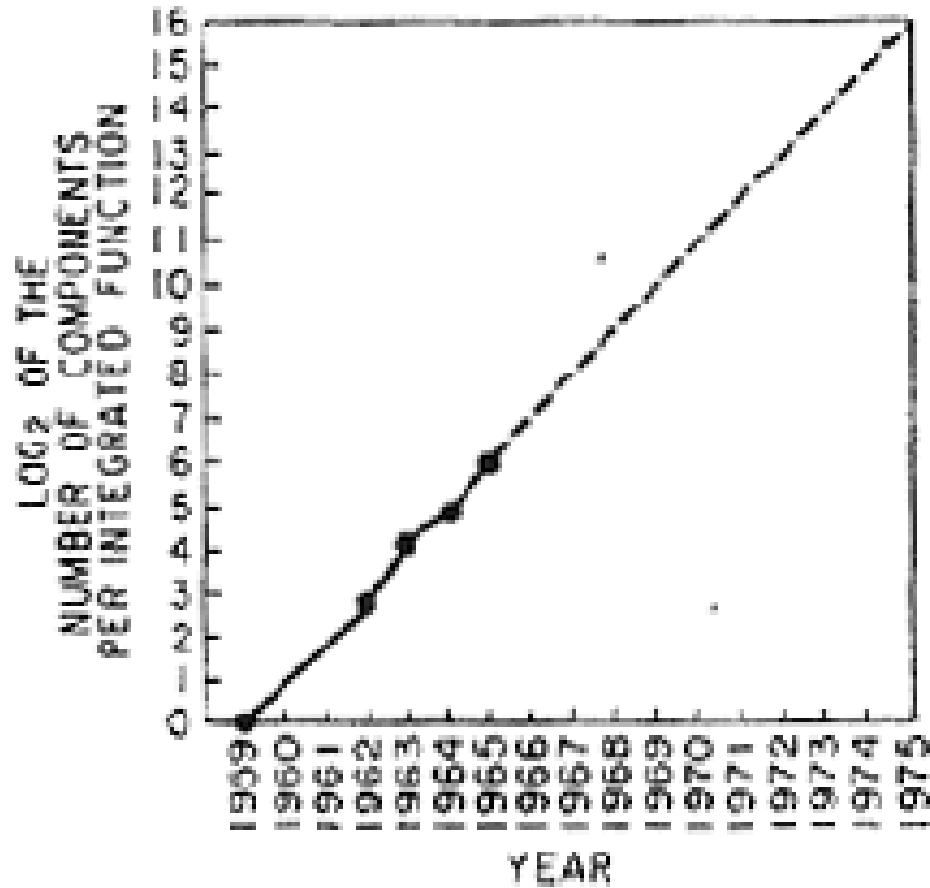
**E-mail: [hari@ses-inc.com](mailto:hari@ses-inc.com)**

**Presented at the THIC Meeting at the Raytheon ITS  
Auditorium, 1616 McCormick Dr**

**Upper Marlboro MD 20774-5301**

**November 5-6, 2002**

# 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

Transistor Count (K)

10,000,000

1,000,000

100,000

10,000

1,000

100

10

1

The Number of Transistors Per Chip  
Double Every 18 Months

Pentium® II Processor  
Pentium Pro Processor

Pentium Processor

i486™ Processor

i386™ Processor

80286

8086

8085

8080

8008

4004

'71

'76

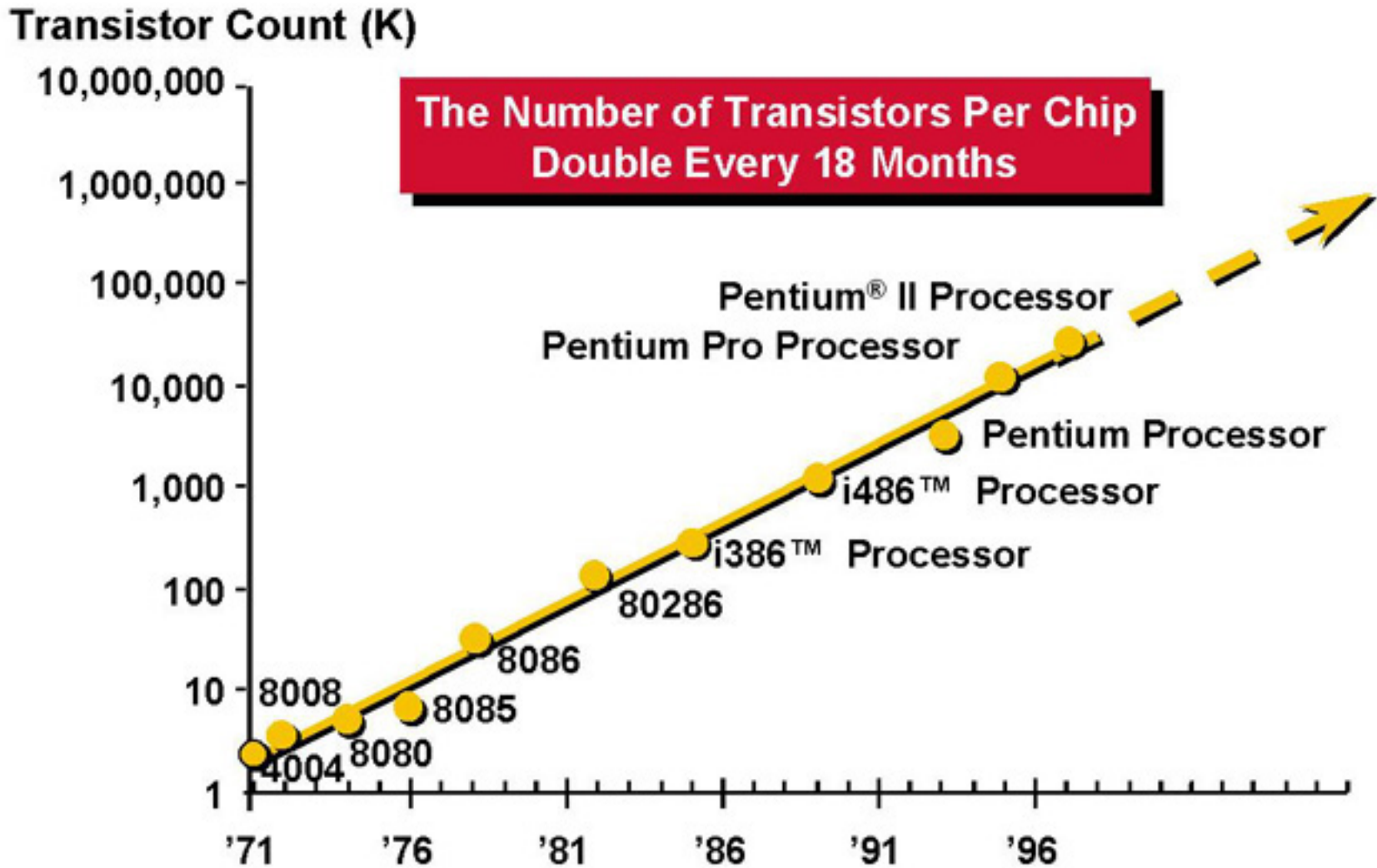
'81

'86

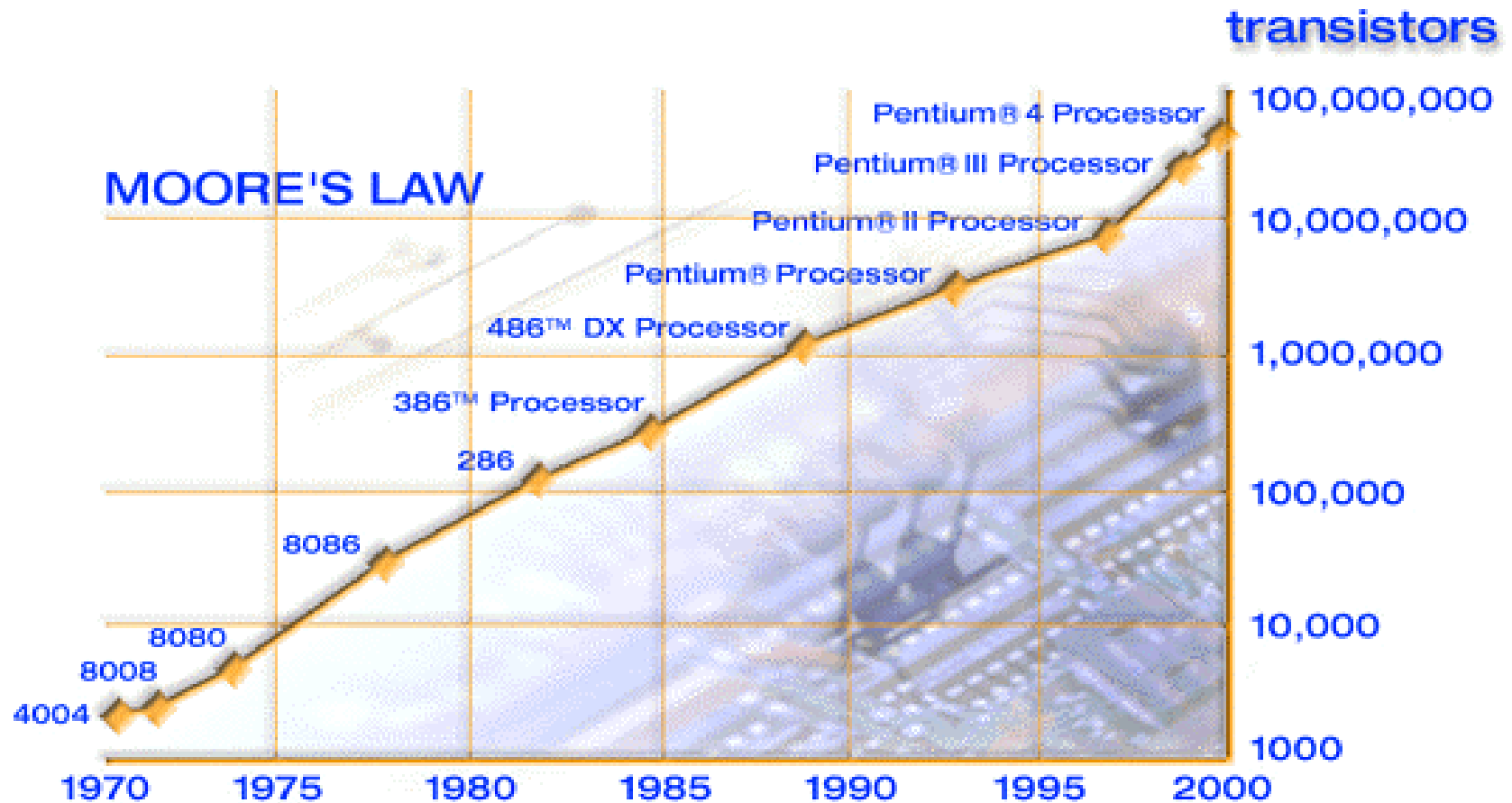
'91

'96

Source: Intel



# Moore's Law updated to Pentium 4



Source: Intel

## Moore's Law for Intel Processors

**Silicon Process  
Technology**

**1.5 $\mu$**

**1.0 $\mu$**

**0.8 $\mu$**

**0.6 $\mu$**

**0.35 $\mu$**

**0.25 $\mu$**

**Intel386™ DX  
Processor**



**Intel486™ DX  
Processor**



**Pentium® Processor**



**Pentium® Pro &  
Pentium® II Processors**



## 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, many of 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<sub>2</sub>**
- **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.**

## 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 <sup>2</sup>	1.36	33.3	41.4	201
μm <sup>2</sup> /bit	474	19.4	15.6	3.2

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

## DLT from Quantum

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

## Areal Density of Hard disk drives

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

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

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

## **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
<b>Recordable Specs</b>	100 Gb/in <sup>2</sup> 20 MB/s	200 Gb/in <sup>2</sup> 40 MB/s	400 Gb/in <sup>2</sup> 80 MB/s	800 Gb/in <sup>2</sup> 160 MB/s	1600 Gb/in <sup>2</sup> 250 MB/s
<b>Drive Configuration</b>	<ul style="list-style-type: none"> <li>• Angle Mux ~1000 pages</li> <li>• Blue Laser</li> </ul>	<ul style="list-style-type: none"> <li>• Custom SLM, Detector</li> <li>• Grayscale</li> </ul>	<ul style="list-style-type: none"> <li>• 2000 pages by using 2 wavelengths</li> </ul>	<ul style="list-style-type: none"> <li>• Custom laser</li> <li>• 4 <math>\lambda</math>'s</li> </ul>	<ul style="list-style-type: none"> <li>• 8 <math>\lambda</math>'s</li> <li>• Or more angles used</li> </ul>
<b>Re-Writable Specs</b>			200 Gb/in <sup>2</sup> 30 MB/s	400 Gb/in <sup>2</sup> 60 MB/s	800 Gb/in <sup>2</sup> 120 MB/s
<b>Drive Configuration</b>			<ul style="list-style-type: none"> <li>• Custom SLM, Detector</li> <li>• Grayscale</li> </ul>	<ul style="list-style-type: none"> <li>• 2000 pages by using 2 wavelengths</li> </ul>	<ul style="list-style-type: none"> <li>• Custom laser</li> <li>• 4 <math>\lambda</math>'s</li> </ul>

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<sup>2</sup>.**

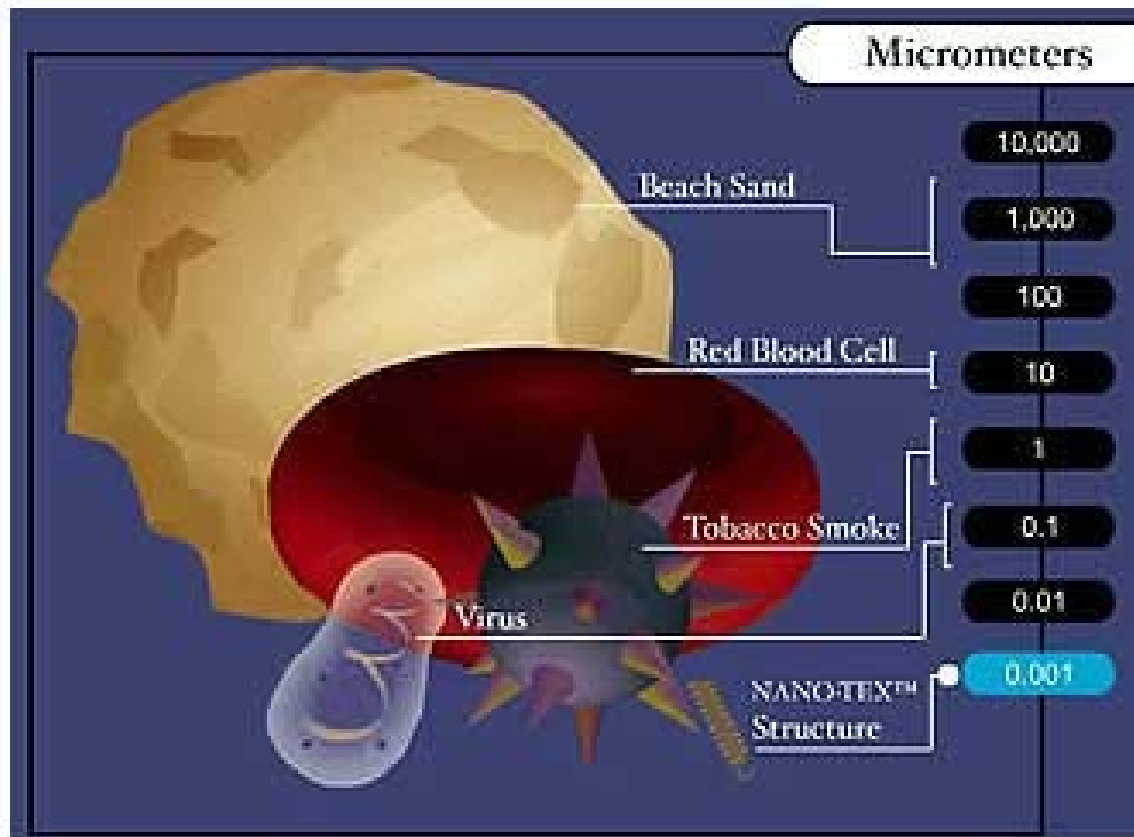
**<http://mems.sandia.gov/scripts/memscam.asp>**

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

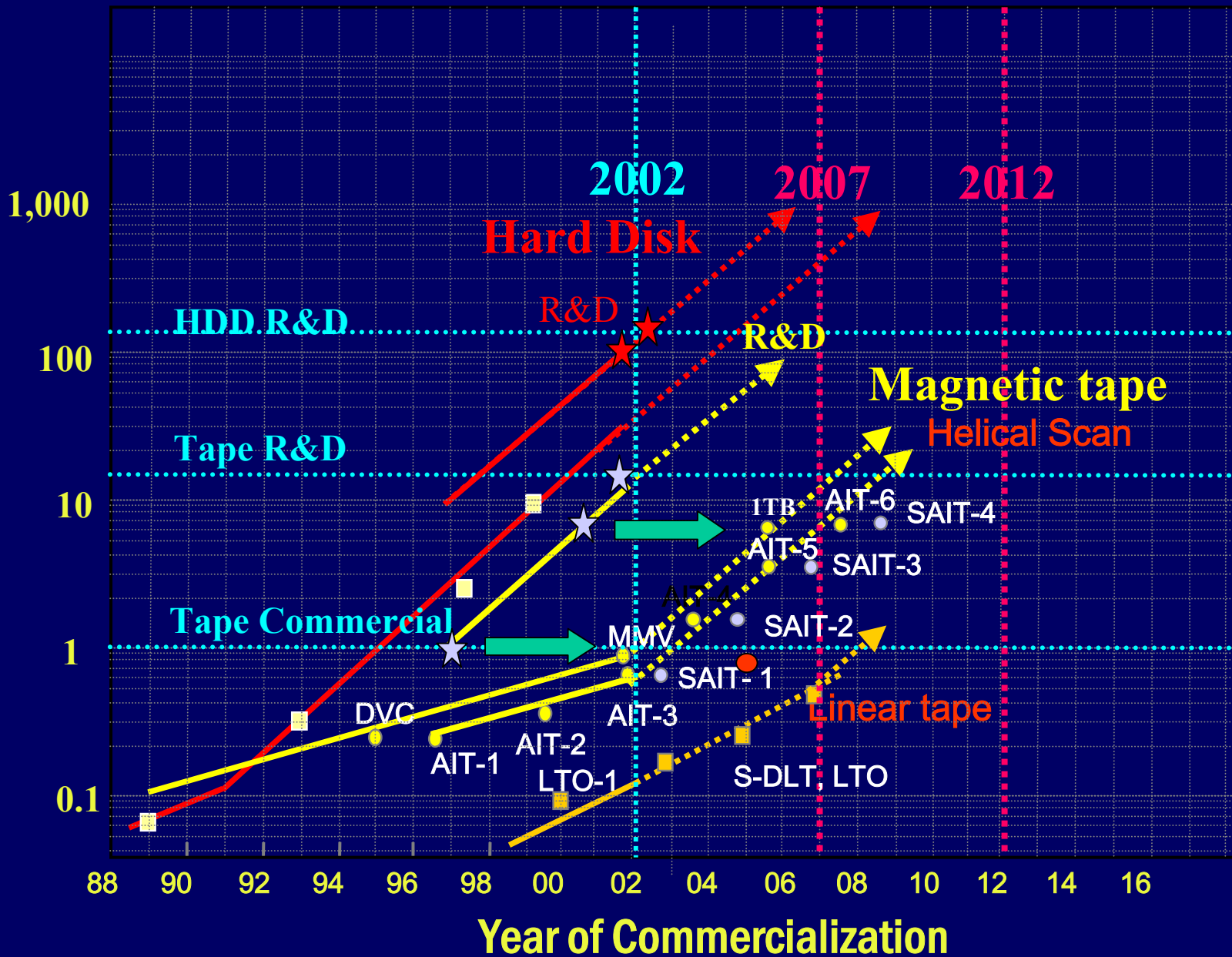
**High performance disk drives: 10,000 or 15,000 rpm**

## MEMS (continued)

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

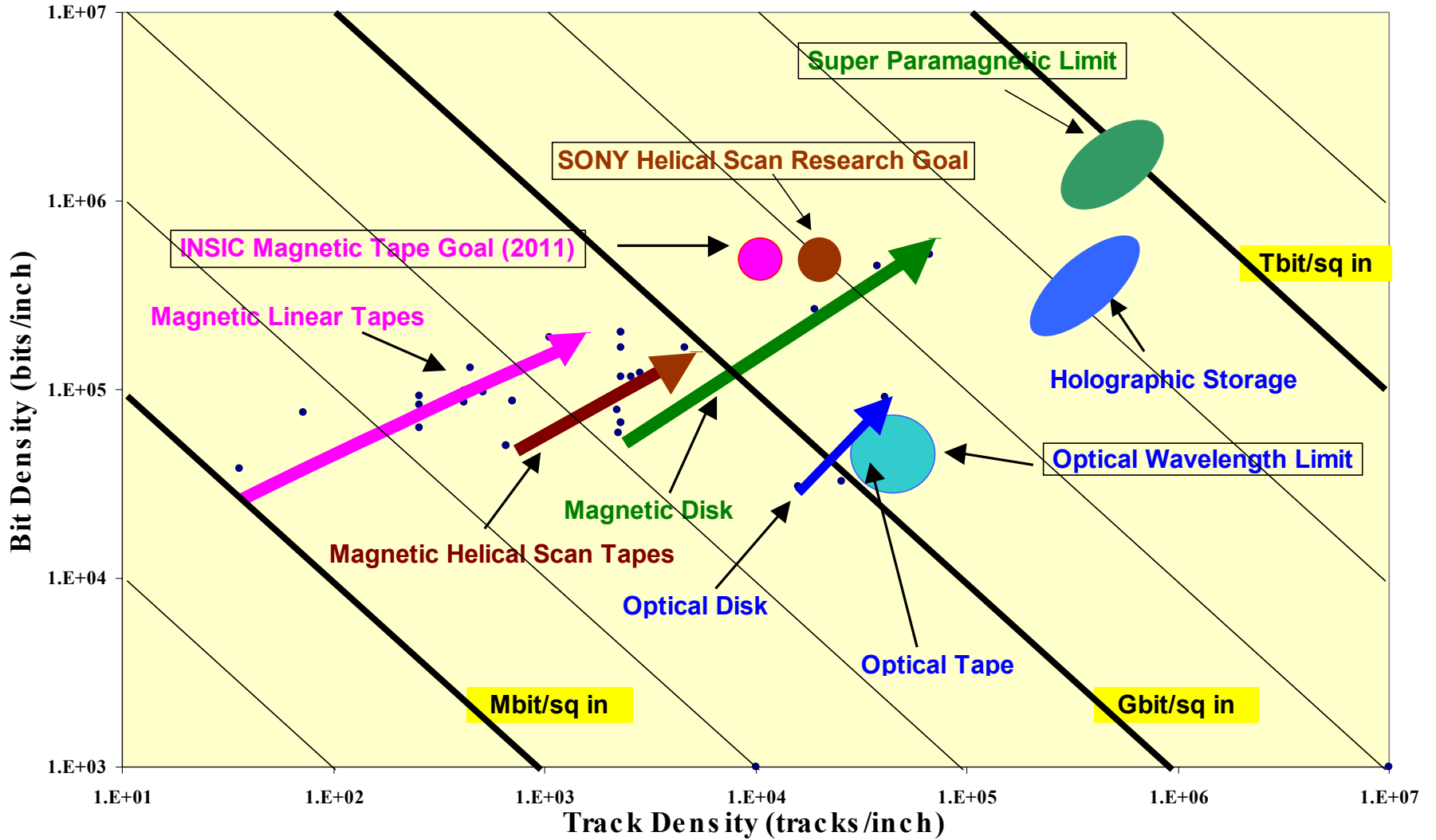


# Areal Density Growth (Gbit/sq in vs year)

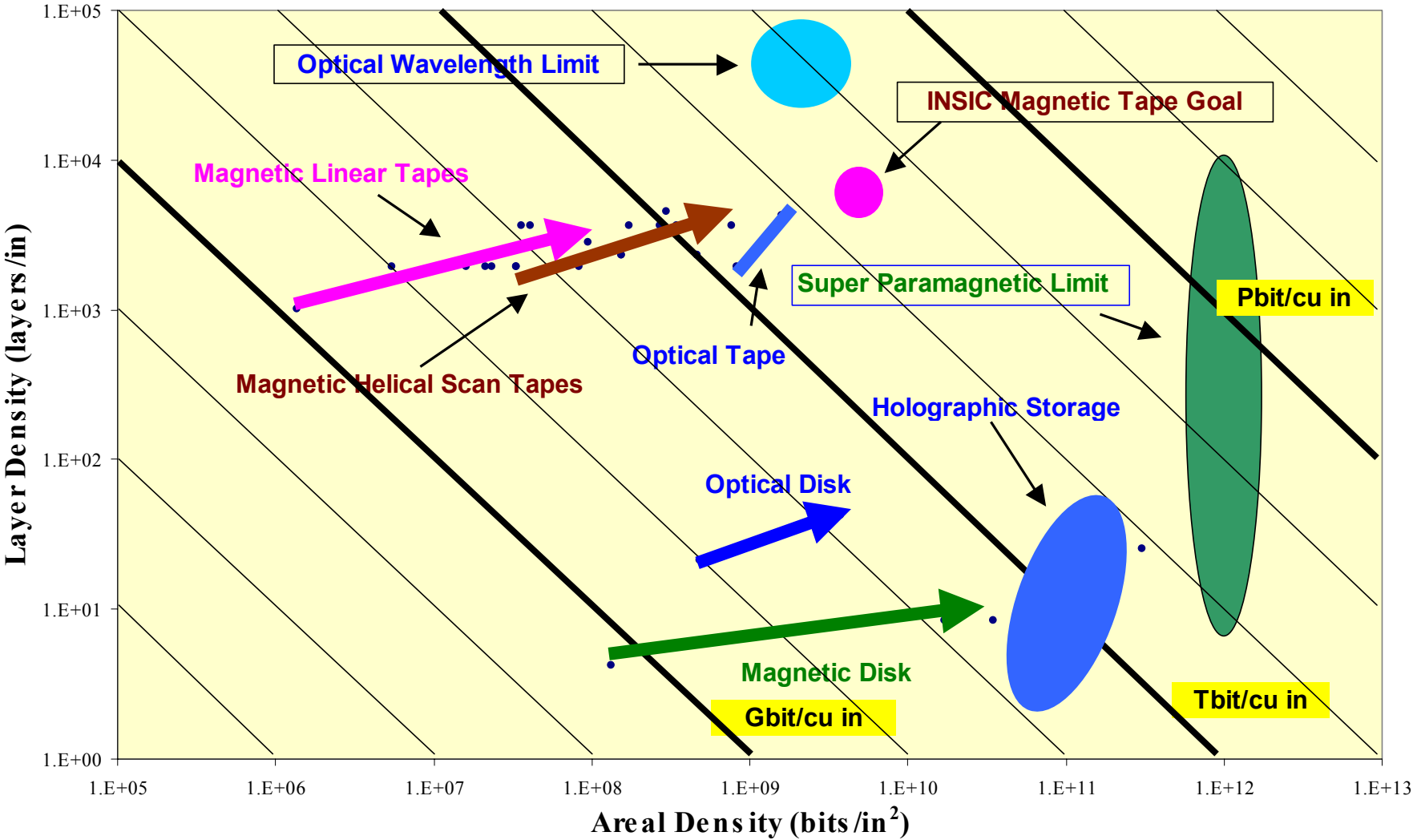


From THIC/Boulder June 2002. Dr. Seiichi Onodera

# Areal Density Trends (bits/in<sup>2</sup>)



# Volumetric Density Trends (bits/in<sup>3</sup>)



# 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  $5 \times 5 \times 5 = 125$  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<sup>2</sup>.

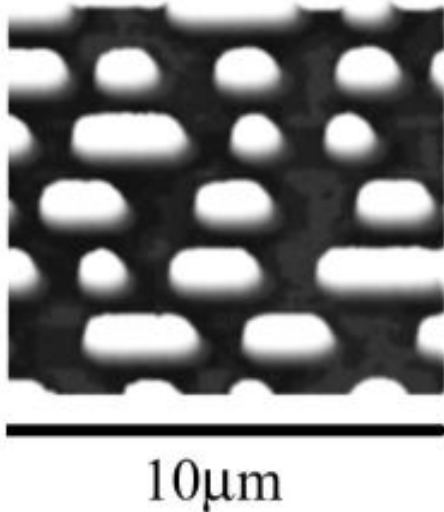
For comparison, DNA storage density is estimated to be 100 Tb/in<sup>2</sup>.

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

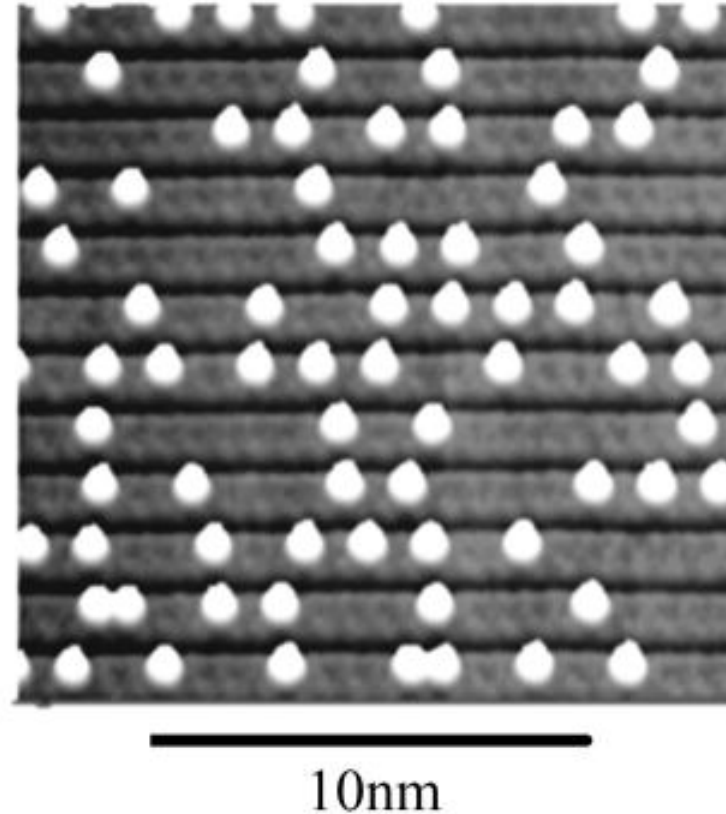
R. Bennewitz et al., [Nanotechnology 13, 499 \(2002\)](#).

# 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