The One-Transistor, One-Capacitor (1T1C) Dynamic Random Access Memory (DRAM), and its Impact on Society

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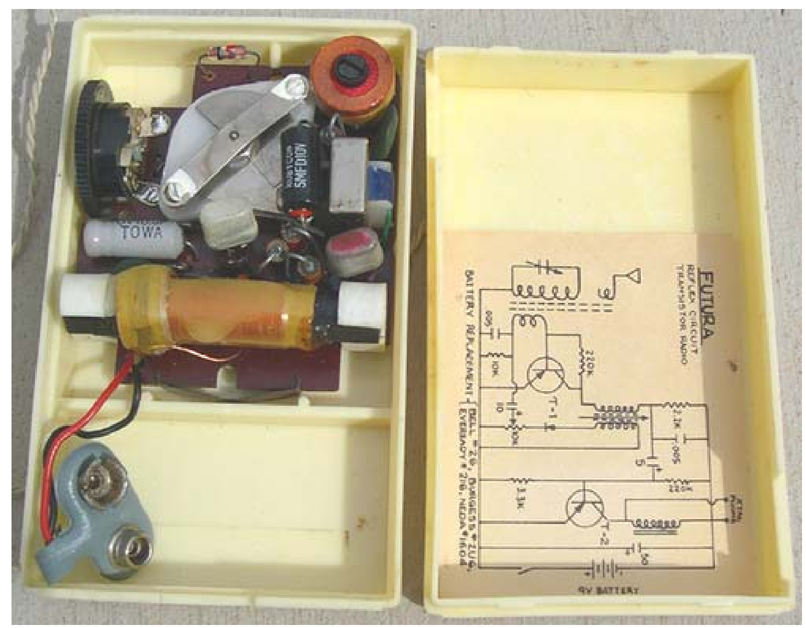
Abstract – Memory technology development, in particular dynamic random access memory (DRAM), has been the greatest driving force in the advancement of solid-state technology for integrated circuit development over the last 40 years. The origin of DRAM circuits and technology can be traced to Dr. Dennard's Patent (Number 3,387,286) granted on June 4, 1968. This truly visionary work, using a single transistor and capacitor (the 1T1C), is one of the most manufactured devices in the history of mankind. This talk will review the impact of his invention and discuss the brilliance of Dr. Dennard for conceiving the invention of the 1T1C cell prior to the maturity of metal oxide semiconductor (MOS) technology and in the face of critics that may have likely asked "why in the world would we want a memory, DRAM, that forgets its' contents!?"

Let’s Step Back in Time

- What are the following (hint: they were found in your local supermarket in the 50s, 60s, and early 70s)

Photos taken from ebay.com

- Does anyone remember the birth of the transistor radio?
- Below is seen the 2-transistor Furtura transistor radio (ca. 1955)
  - ✓ Note the output is via an earphone
  - ✓ Also note the schematic (not many, if any, consumer electronics products today come with a schematic)



Photos taken from ebay.com

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Evolution of the Transistor Radio

- These were a big deal both because they were portable (something not practically possible with vacuum tube radios) and because they used a new technology (solid-state devices that didn't wear out)

Photos taken from ebay.com

Growing Complexity

- Note the use of bipolar junction technology to replace vacuum tubes

Photo taken from ebay.com

What was going on with memory storage during this time?

- Dominated by the magnetic core memory seen below
- During the 1960s solid-state memory was developed based on the BJT
  - ✓ Ultimately wasn't successful (compared to MOS-based memory)

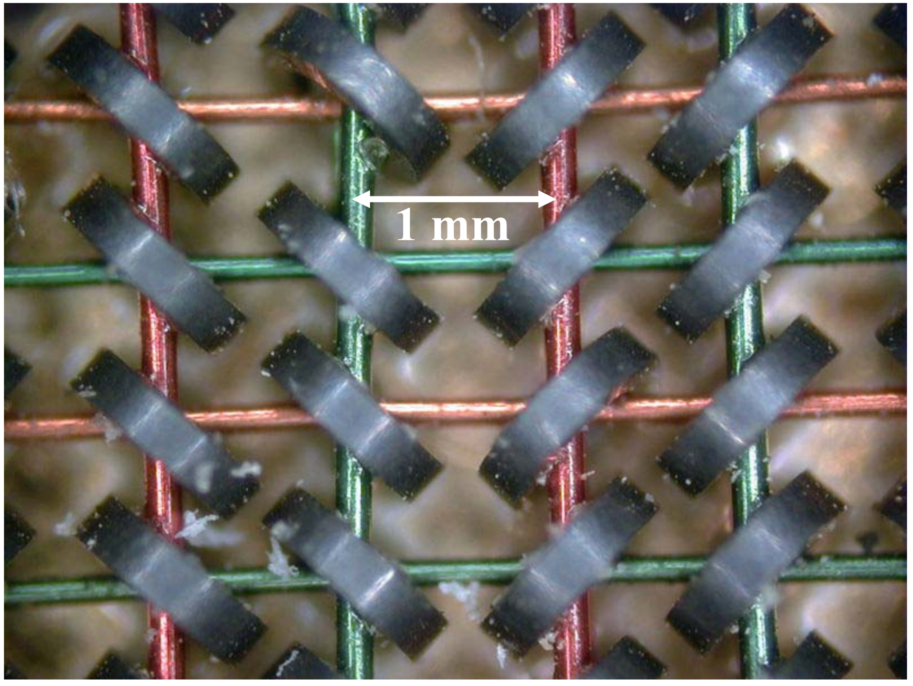


Image from wikipedia.org

So why is Dr. Dennard's invention such a big deal?

- During the excitement of bipolar technology replacing vacuum tubes in most electronic devices he filed an invention disclosure on July 14, 1967 that
  - ✓ Used metal-oxide-semiconductor (MOS) technology
  - ✓ Proposed a memory, the one-transistor, one-capacitor (1T1C cell), that forgets its contents!
- Why is using MOS technology such a big deal over bipolar?
  - ✓ MOS technology is scalable!
  - ✓ Another significant contribution from Dr. Dennard's is scaling theory.
- Why is a memory that forgets its contents such a big deal?
  - ✓ It's small!
  - ✓ It's fast!

Dennard's Scaling Theory*

- Predicted that MOS devices would continue to shrink in size (scale) over time
  - ✓ Higher density
  - ✓ Faster
  - ✓ Low power
- Also discussed how interconnect would scale
  - ✓ RC times of the lines don't scale but as distances shrink delays drop

* Dennard, R.H.; Gaensslen, F.H.; Rideout, V.L.; Bassous, E., and LeBlanc, A.R., "Design of ion-implanted MOSFET's with very small physical dimensions," *IEEE Journal of Solid-State Circuits*, Volume 9, Issue 5, Oct 1974, pp. 256 - 268

Scaling Theory

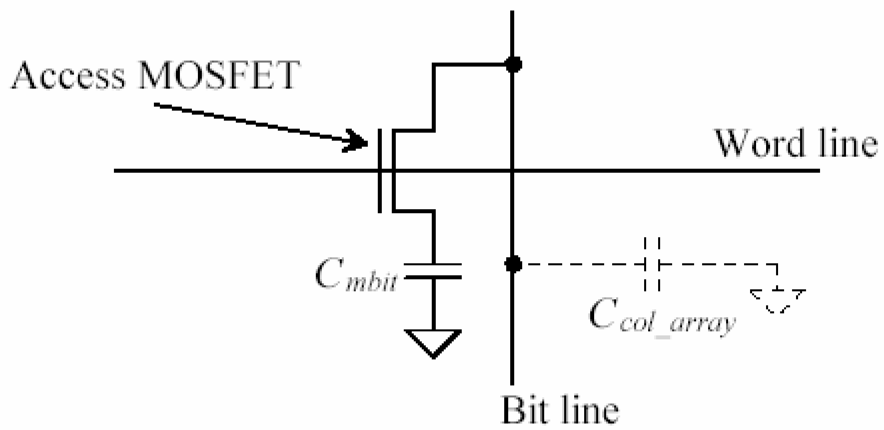
- ❑ Scaling from Dennard's paper
  - ✓ Device and Circuit Scaling
  - ✓ Interconnect Scaling
  - ✓ Scale parameter is about 1.4 ($1/\kappa = 0.7$)

Device or Circuit Parameter	Scaling Factor
Device dimension tox, L, W	$1/\kappa$
Doping concentration Na	κ
Voltage V	$1/\kappa$
Current I	$1/\kappa$
Capacitance $\varepsilon A/t$	$1/\kappa$
Delay time/circuit VC/I	$1/\kappa$
Power dissipation/circuit VI	$1/\kappa^2$
Power density VI/A	1

Parameter	Scaling Factor
Line resistance, $R_L = \rho L/Wt$	κ
Normalized voltage drop IR_L/V	κ
Line response time $R_L C$	1
Line current density I/A	κ

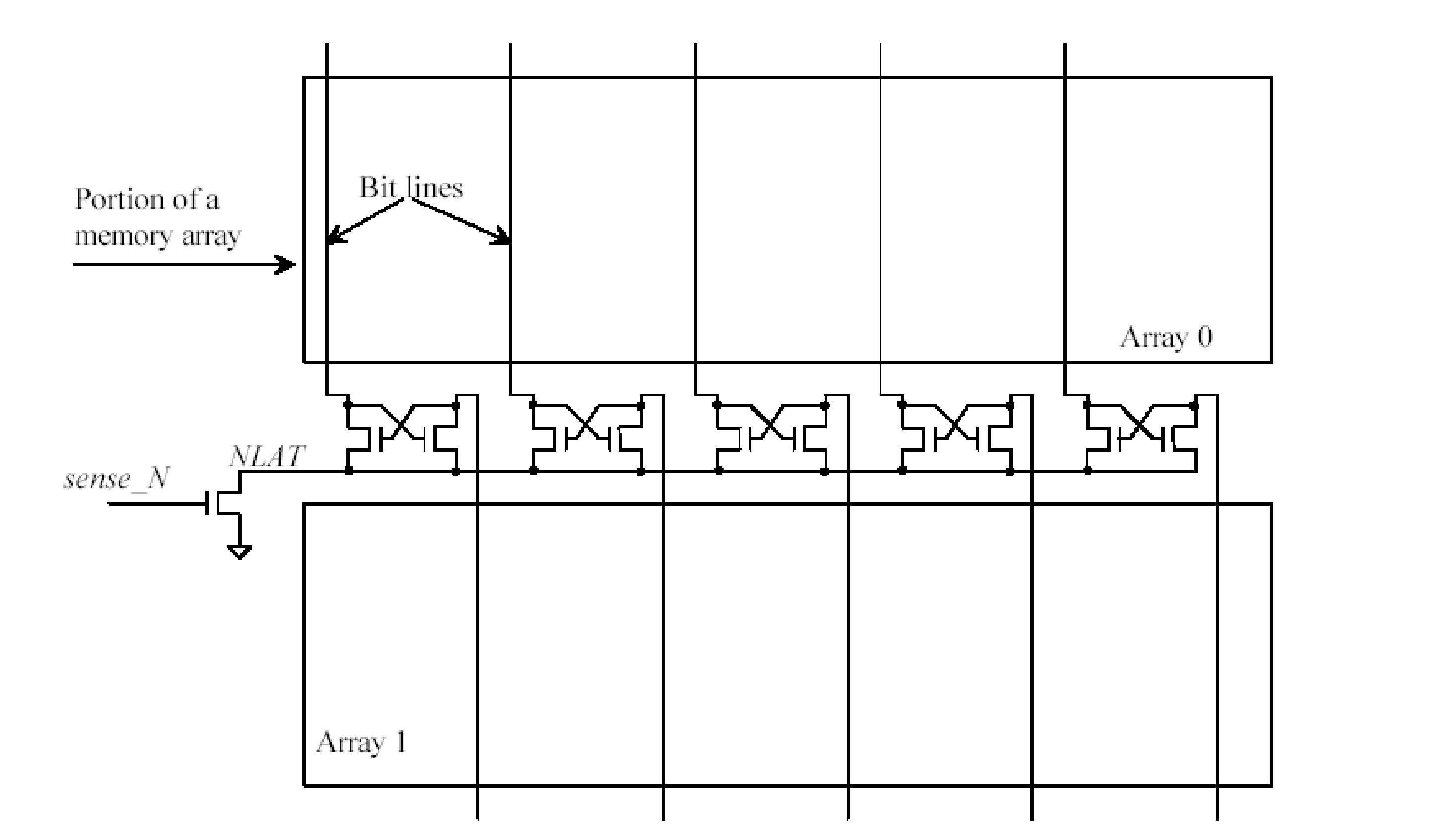
The One-Transistor, One-Capacitor (1T1C) Dynamic Random Access Memory (DRAM) cell

- The array is formed with word (row) and column (bit) lines



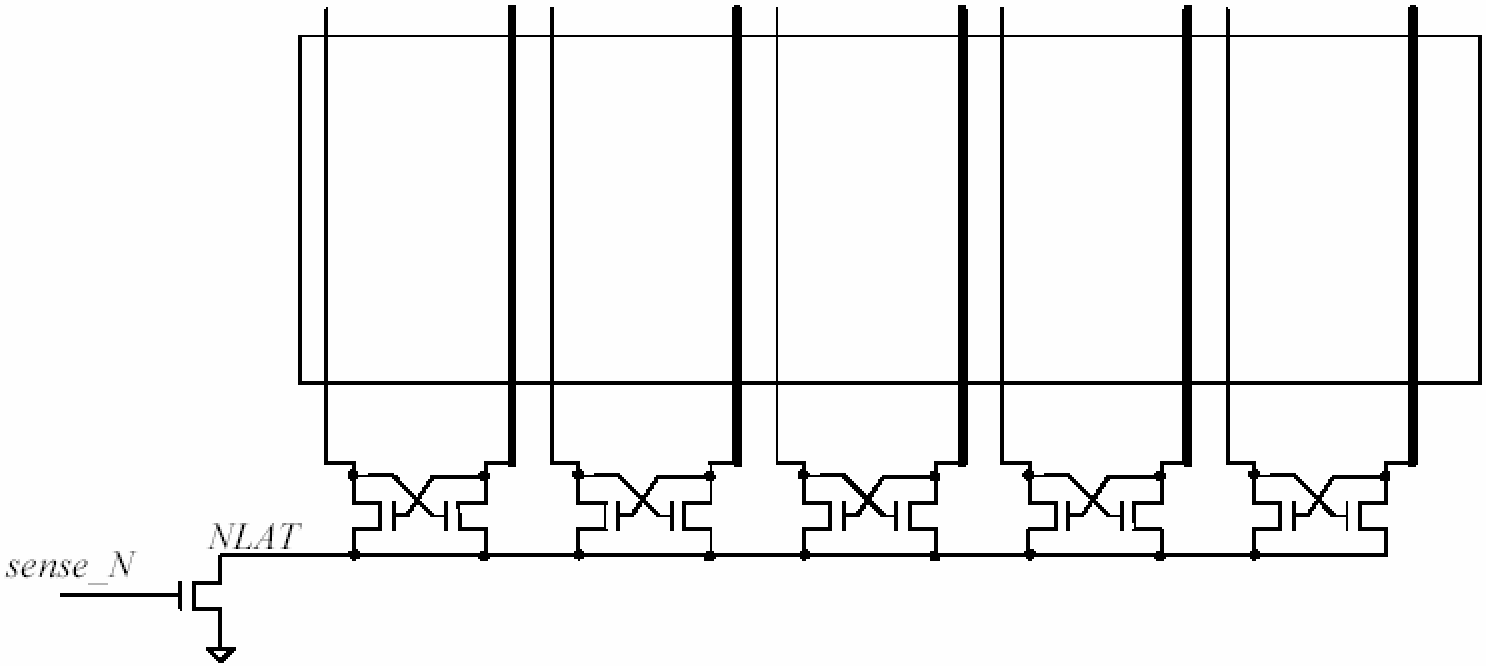
Folded and Open Arrays

- The open array

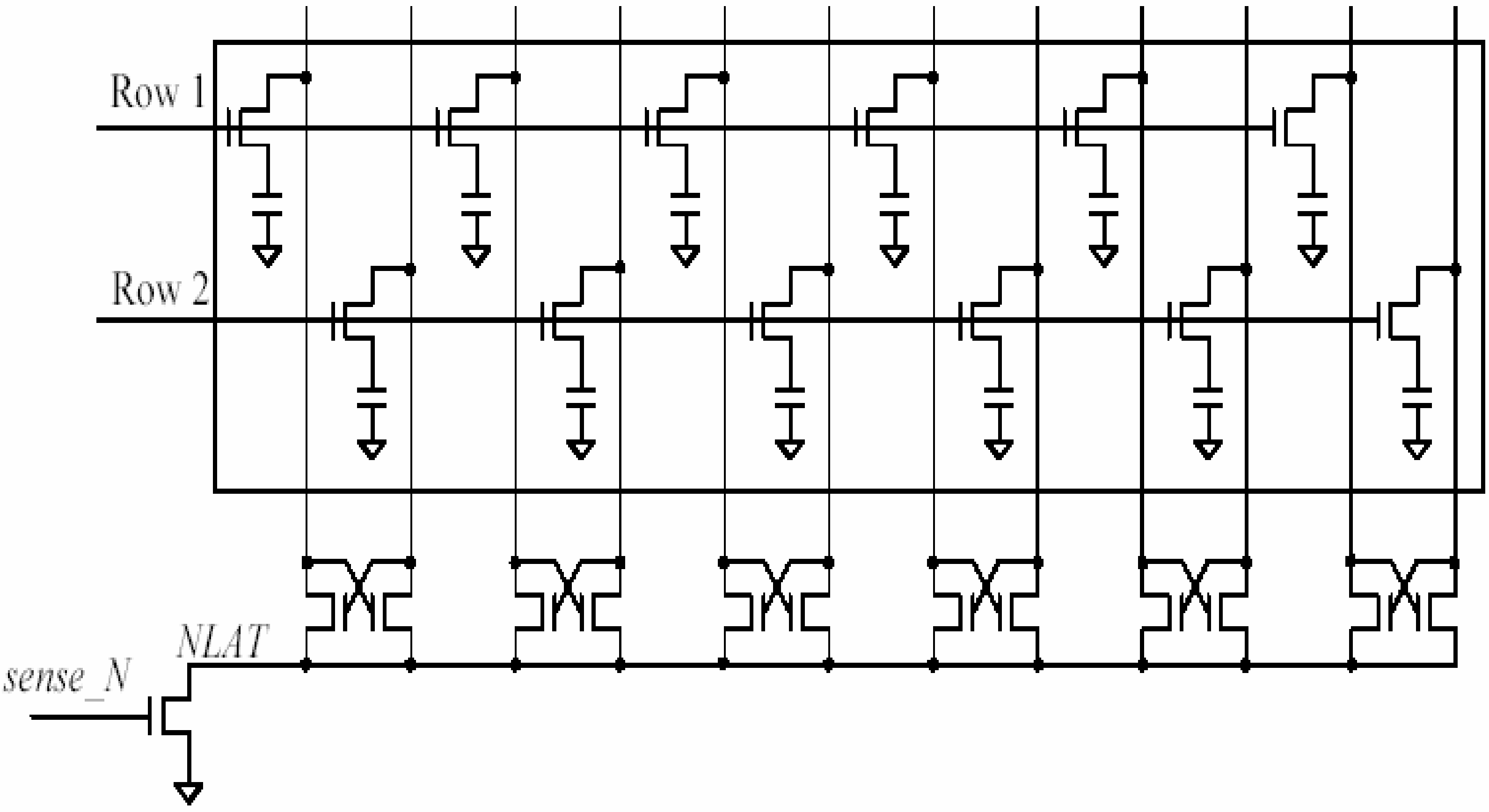


Folded and Open Arrays

- The folded array

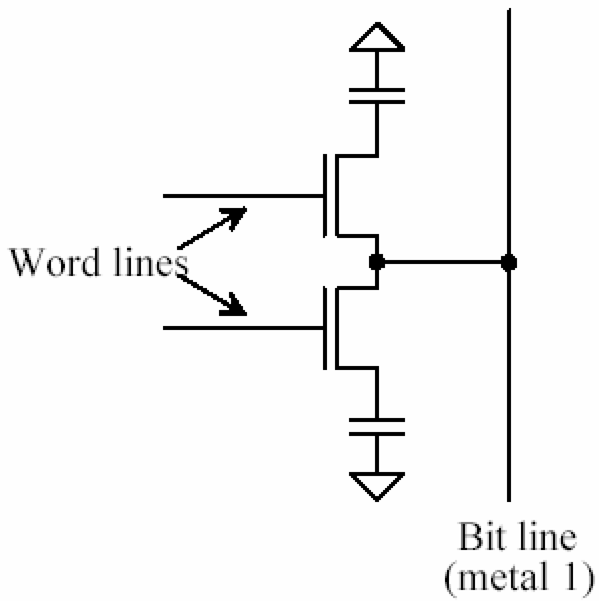


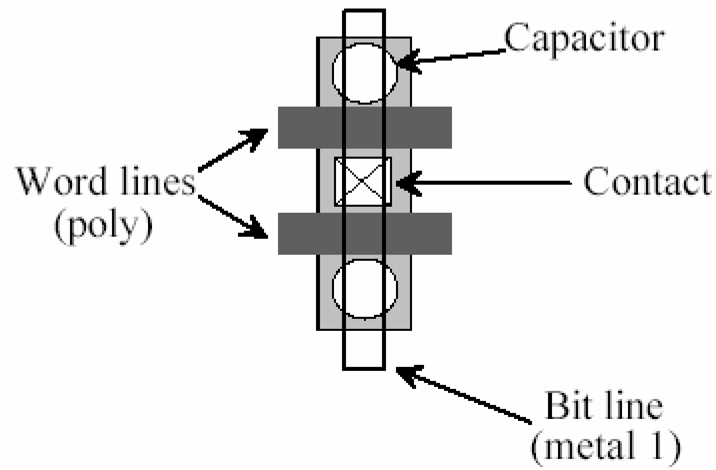
The Folded Array



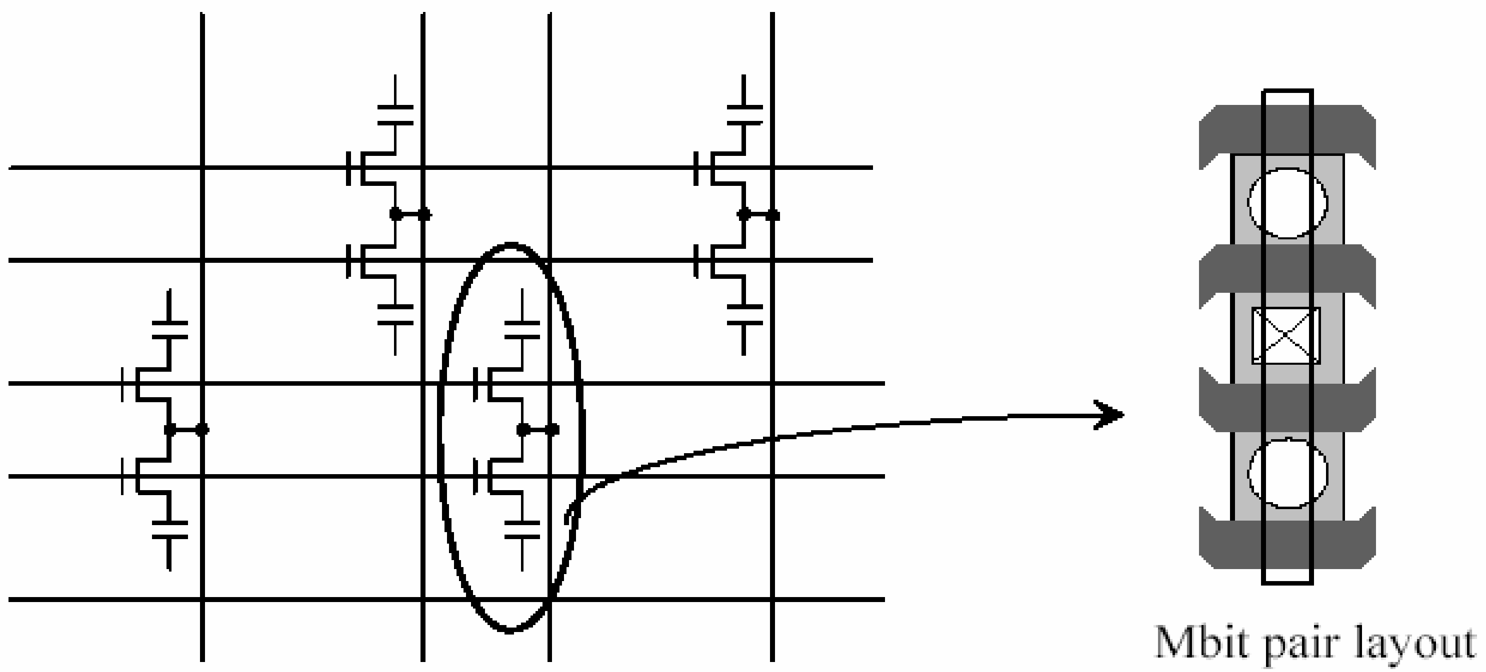
Further Reduction in Cell Size

- Sharing the bitline contact

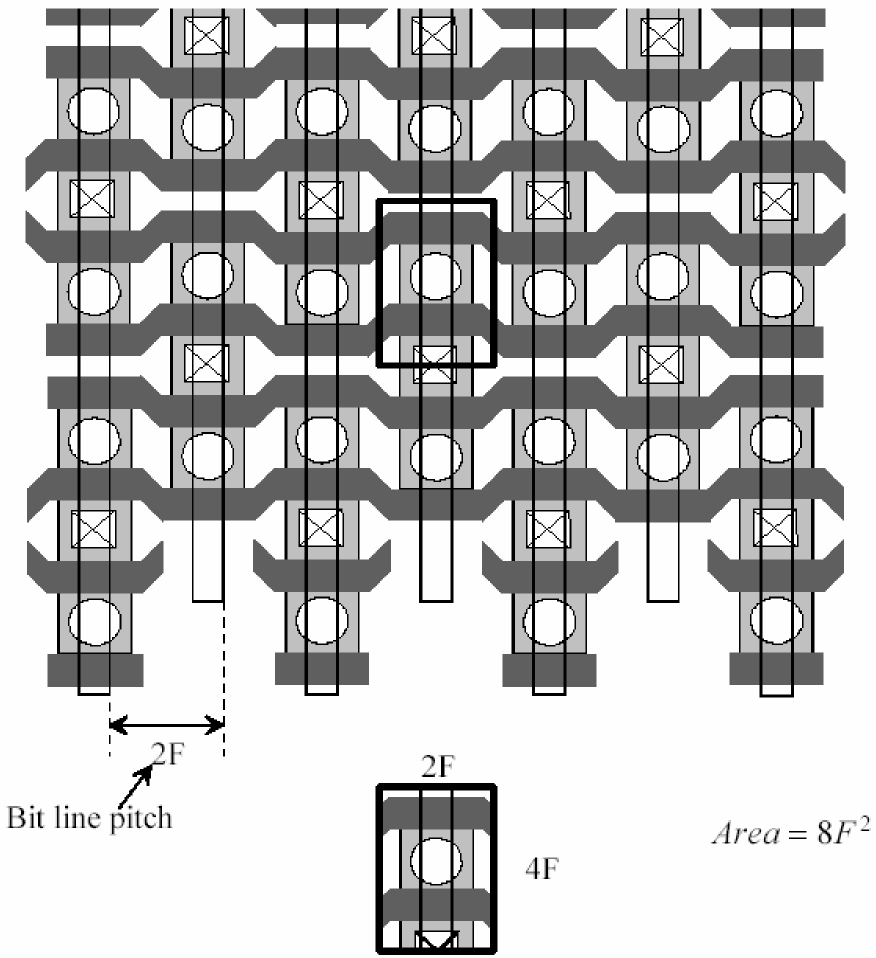




Mbit Pair: Folded Array

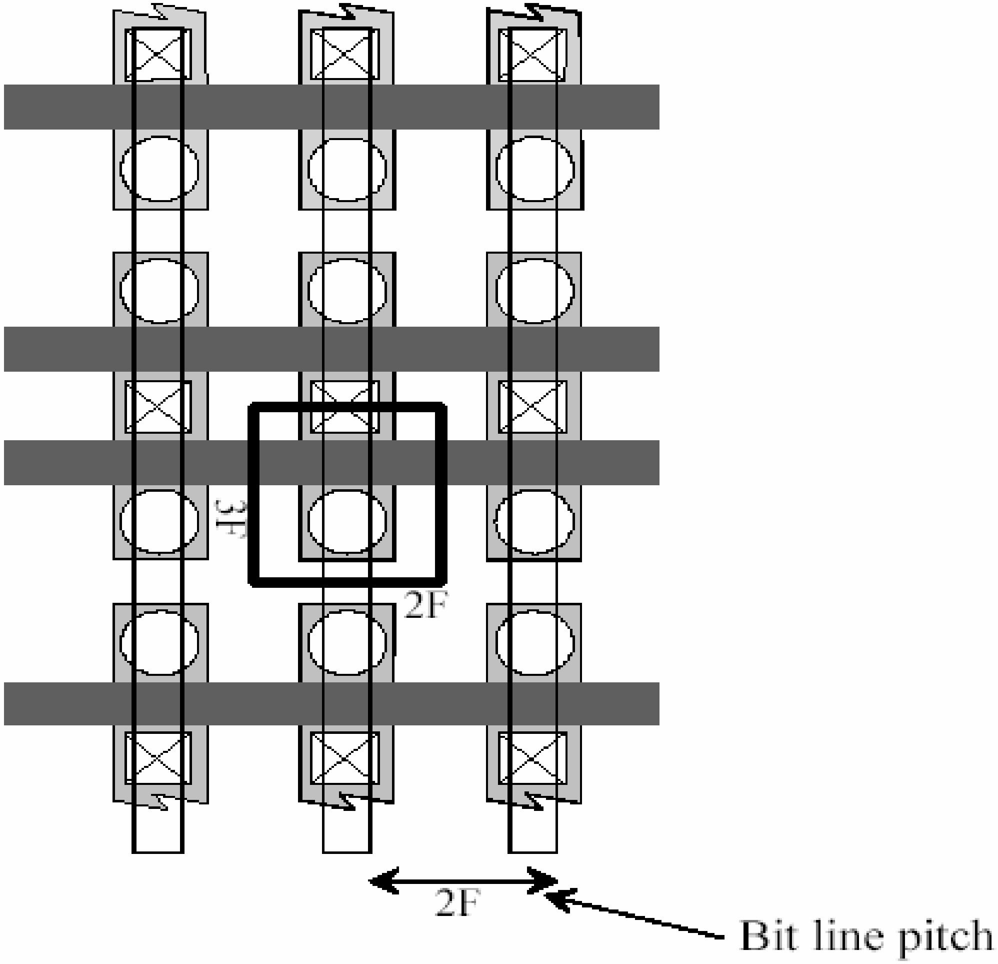


Folded Array Cell Size

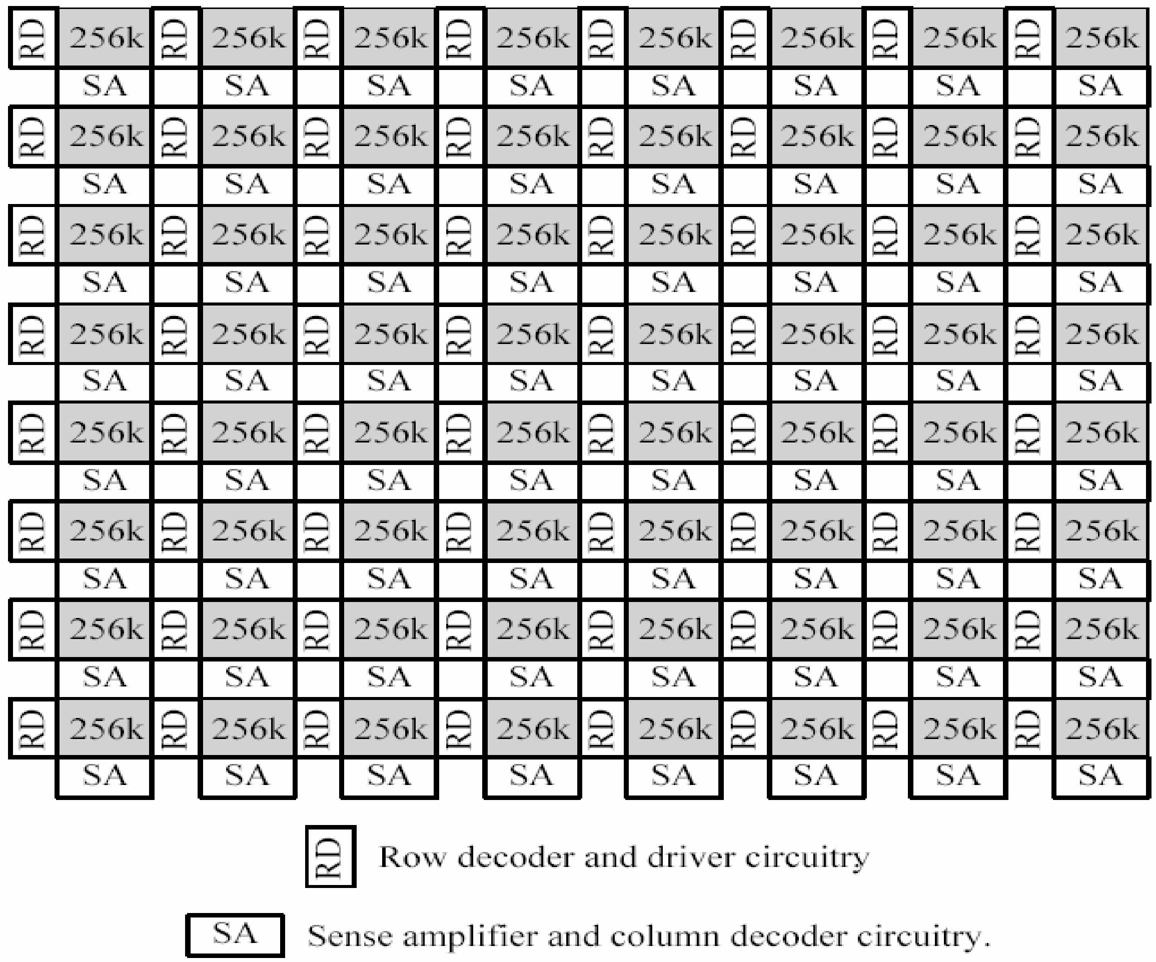


Open Array: $6F^2$

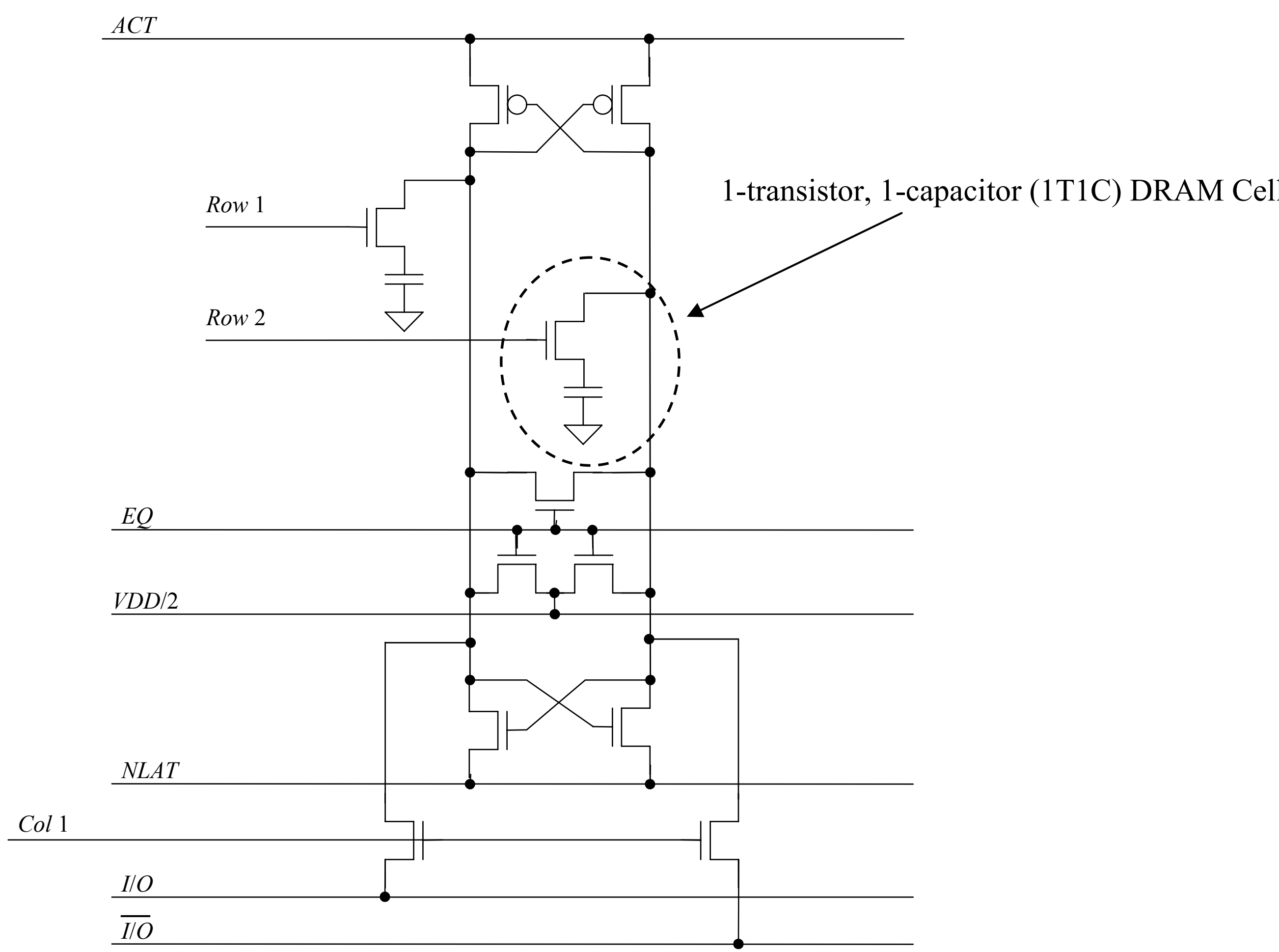
F is feature size, which is half the bit line pitch; that is, F = pitch/2.



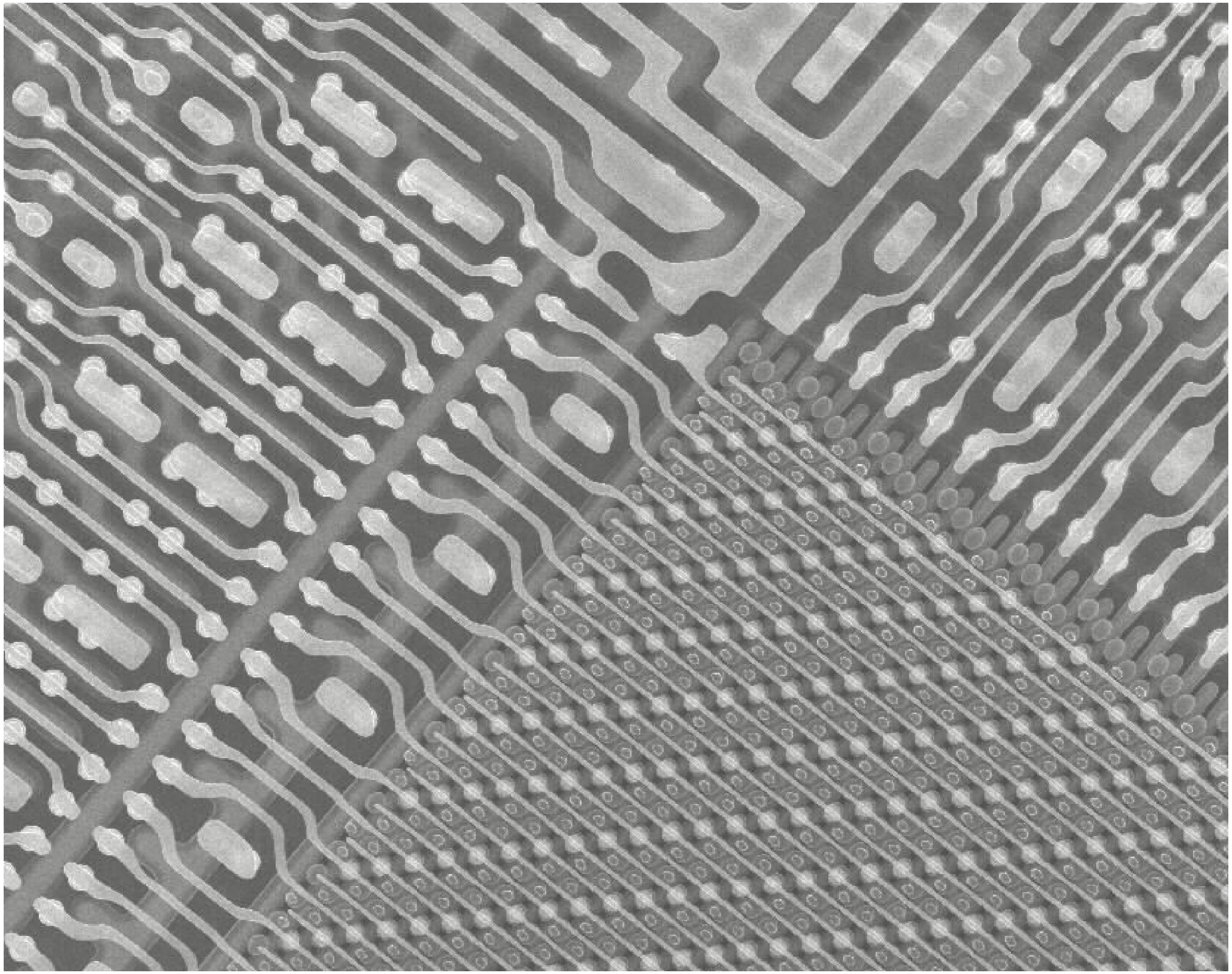
Array Block


RD
256k
SA
RD Row decoder and driver circuitry
SA Sense amplifier and column decoder circuitry.

The 1T1C DRAM Cell



SEM Photo of a Modern DRAM Array



How is DRAM used today?

Workstations

Units – 1.69M
DRAM – 5,741MB/unit average
DRAM Revenue – $1,164M
Source: iSuppli

Personal Digital Assistants

Units – 8.9M
DRAM – 65MB average
DRAM Revenue – $698M
Source: iSuppli

PC Servers, Enterprise

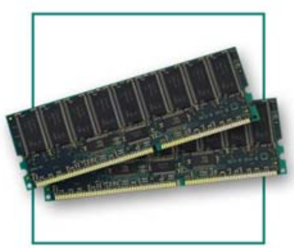
Units – 0.91M
DRAM – 24,581MB
DRAM Revenue – $2,684M
Source: iSuppli

Notebook Computers

Units – 51M
DRAM – 510MB
DRAM Revenue – $3,105M
Source: iSuppli

Desktop Computers

Units – 150M
DRAM – 560MB
DRAM Revenue – $10,048M
Source: iSuppli



Memory Upgrades

Units – 87M
DRAM – 295MB
DRAM Revenue – $3,060M
Source: iSuppli

Printers

Units – 112M
DRAM – 35MB
DRAM Revenue – $156M
Source: iSuppli

Communications and Networking Market

Cellular Phones

Units – 740M
DRAM – 5MB
Flash – 87MB

Set-Top Boxes

Units – 62M
DRAM – 56MB

Cable Modems

Units – 15.7M
DRAM – 8MB
Flash – 2MB

DSL Modems

Units – 55M
DRAM – 8MB
Flash –2MB

Cellular Base Stations

Units – 0.35M
DRAM – 256MB
Flash – 5112MB

LAN Switches

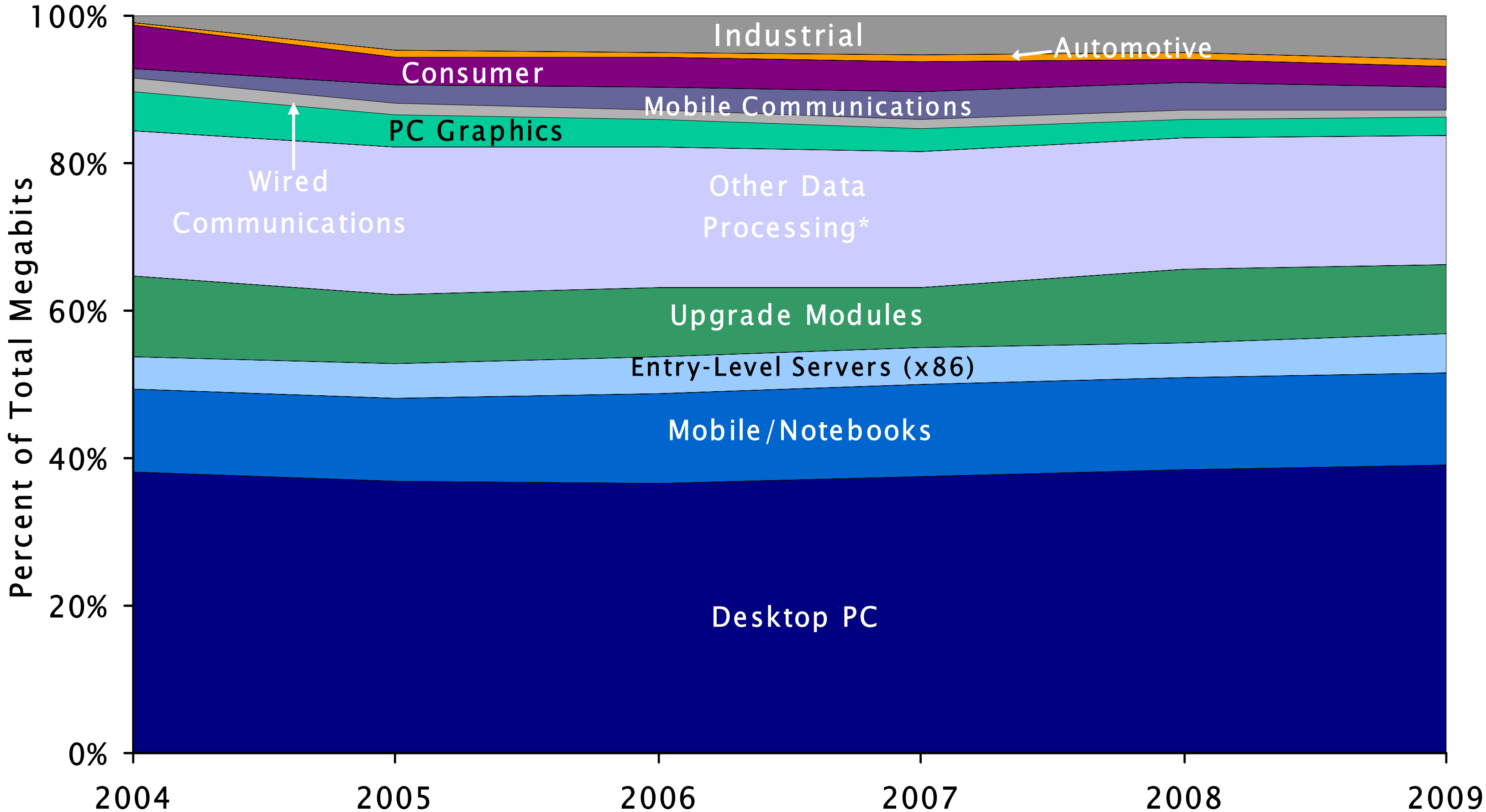
Units – 113.5M
DRAM – 15MB

Low-End to Mid-Range Routers

Units – 1.5M
DRAM – 406MB

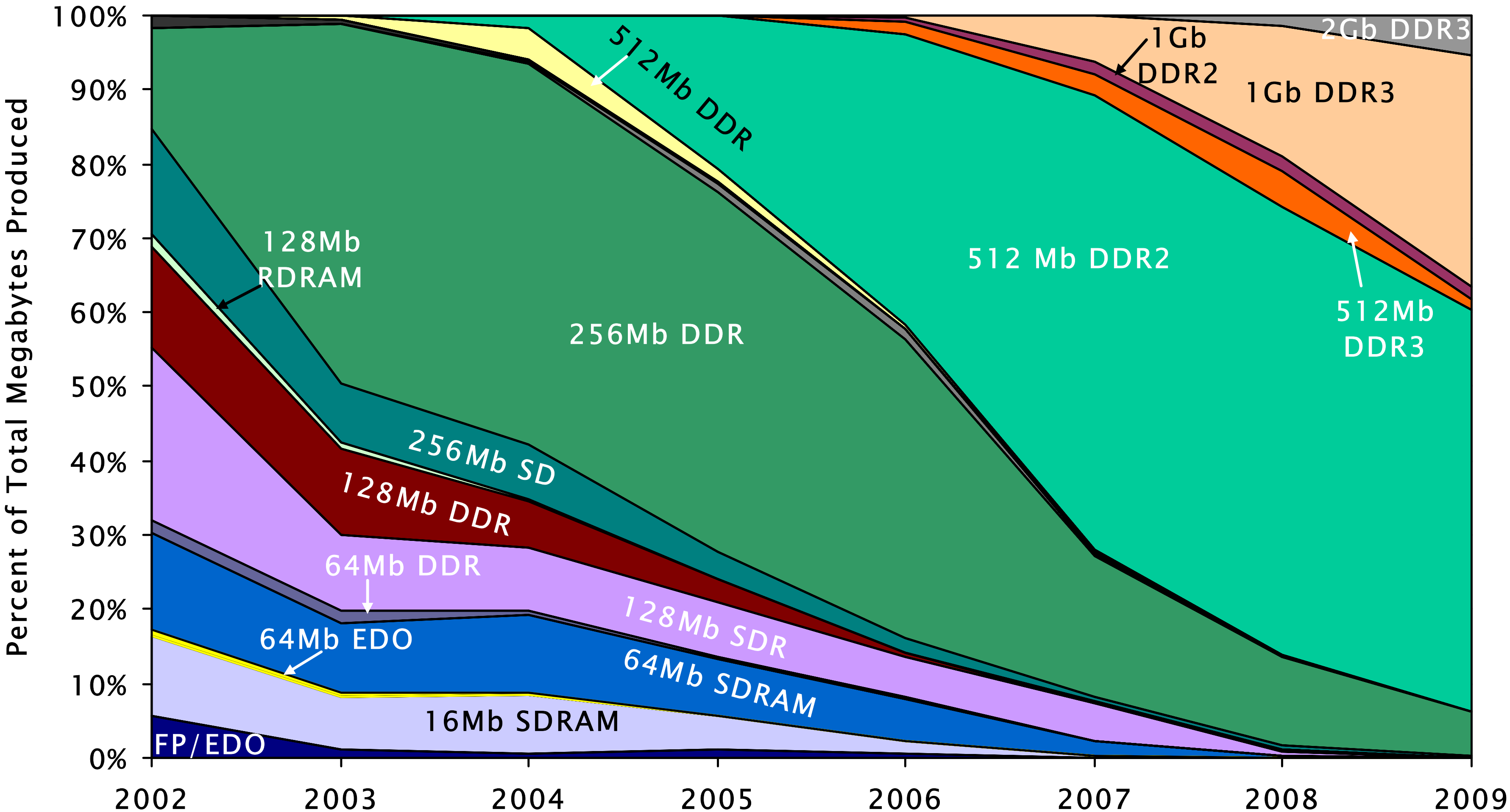
Sources: iSuppli, Gartner, Portelligent, Instat

DRAM Demand by End-Use Application



*Other Data Processing includes mainframe servers, enterprise servers, workstations, handheld PCs, storage cards, printers, and internet appliances

Worldwide DRAM Shipments by Type

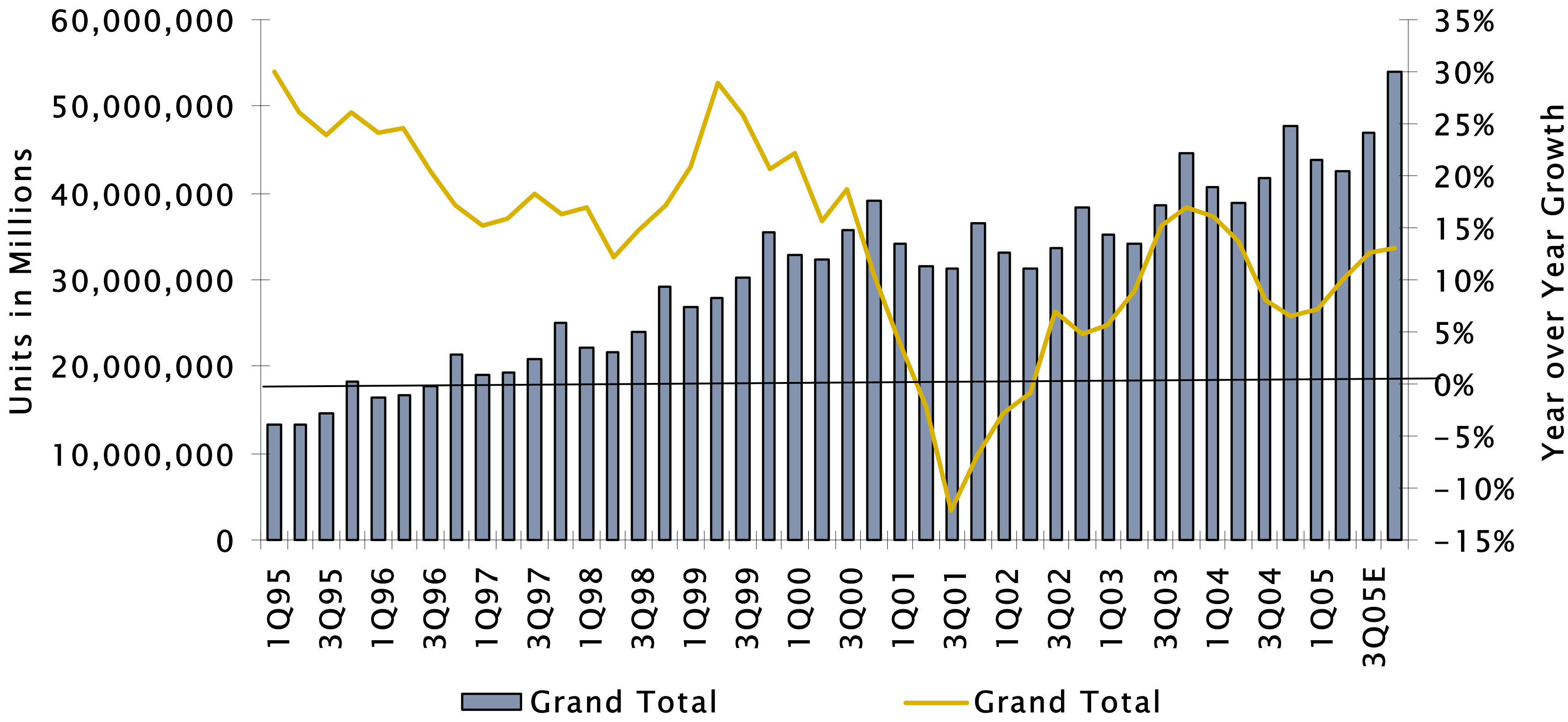


DRAM Technology Trends

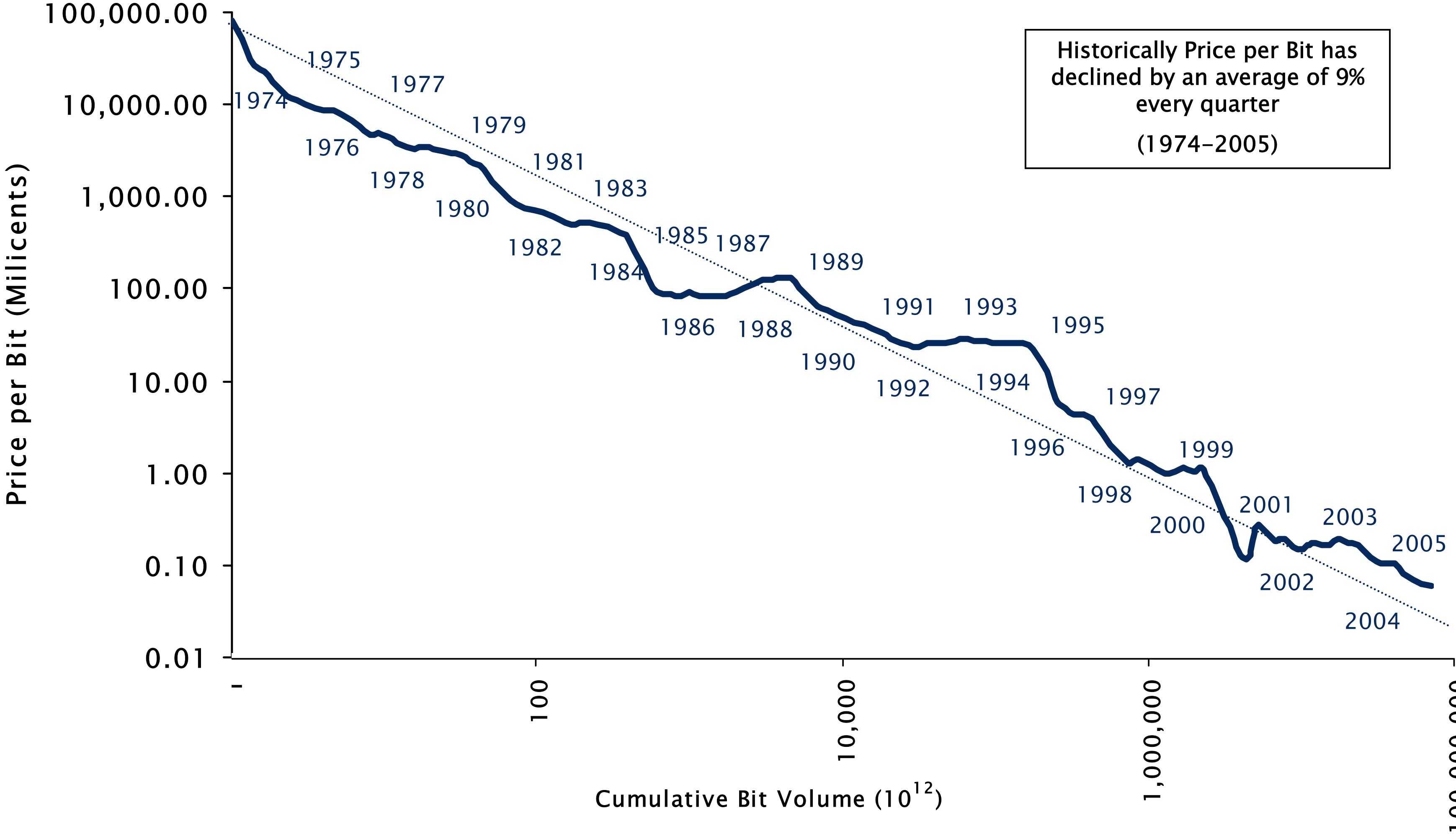
DRAM Density Trends

Source: IDC, Isuppli, Gartner, IC Insights Q106

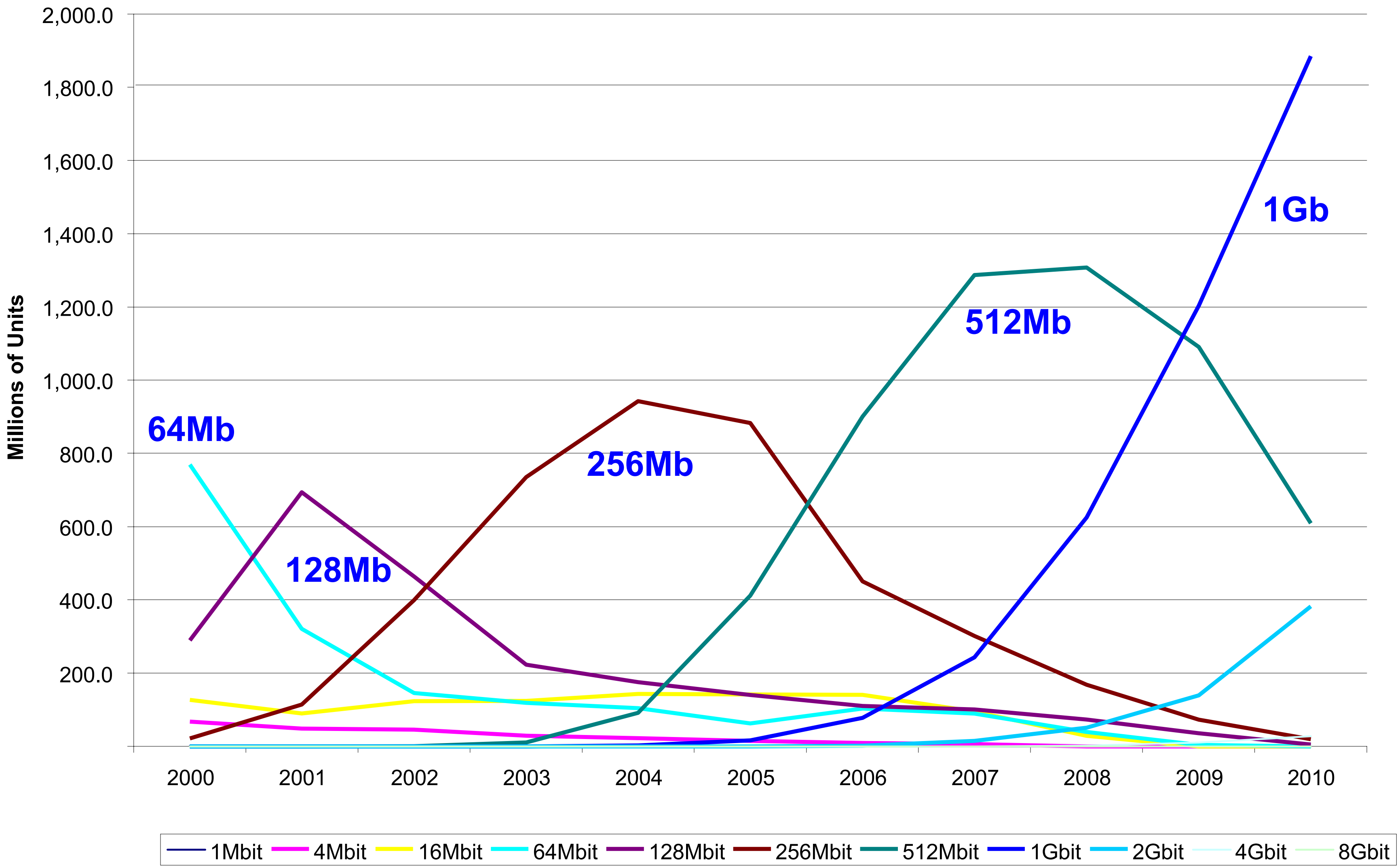
Historical PC Market Growth



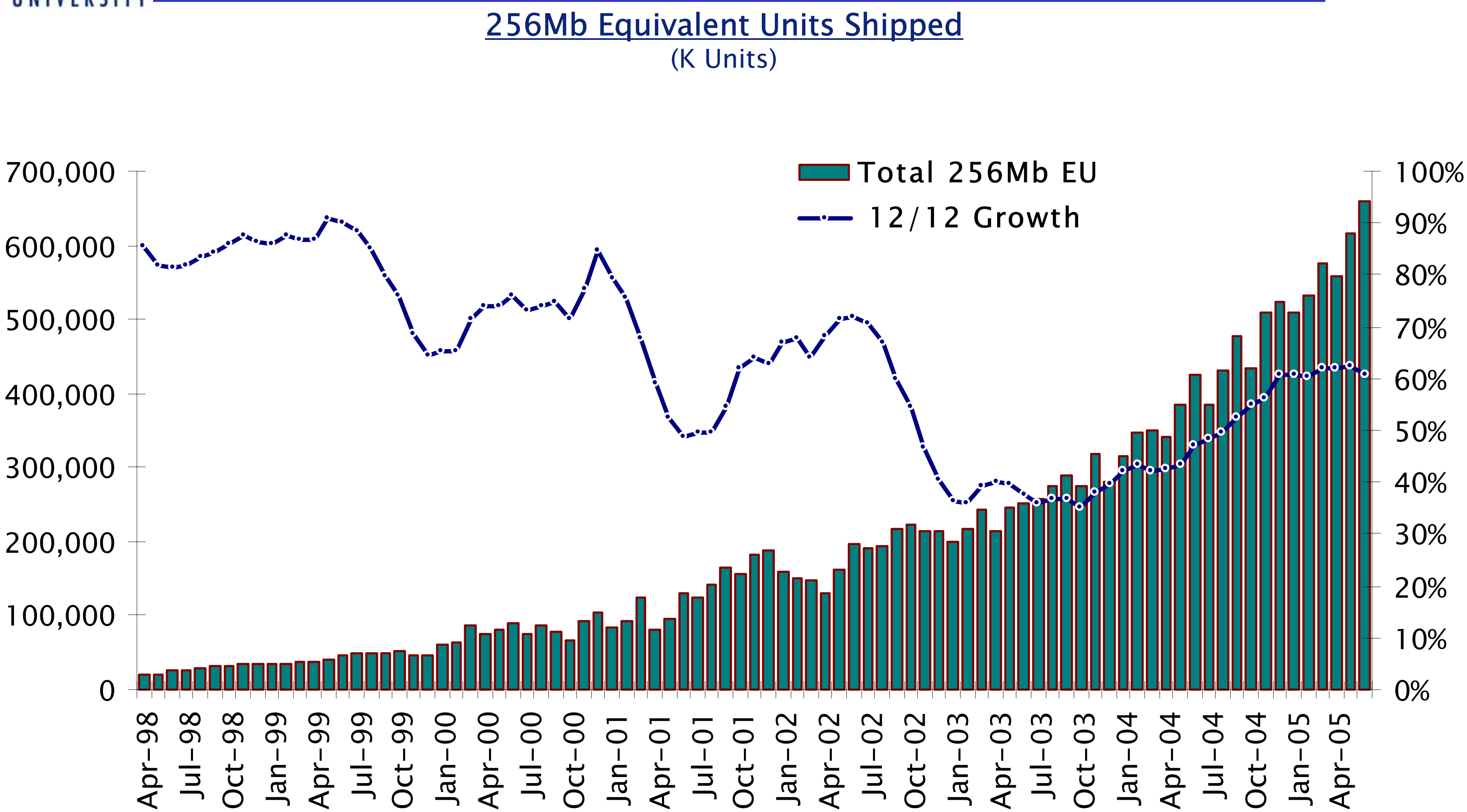
Price per Bit Cycles



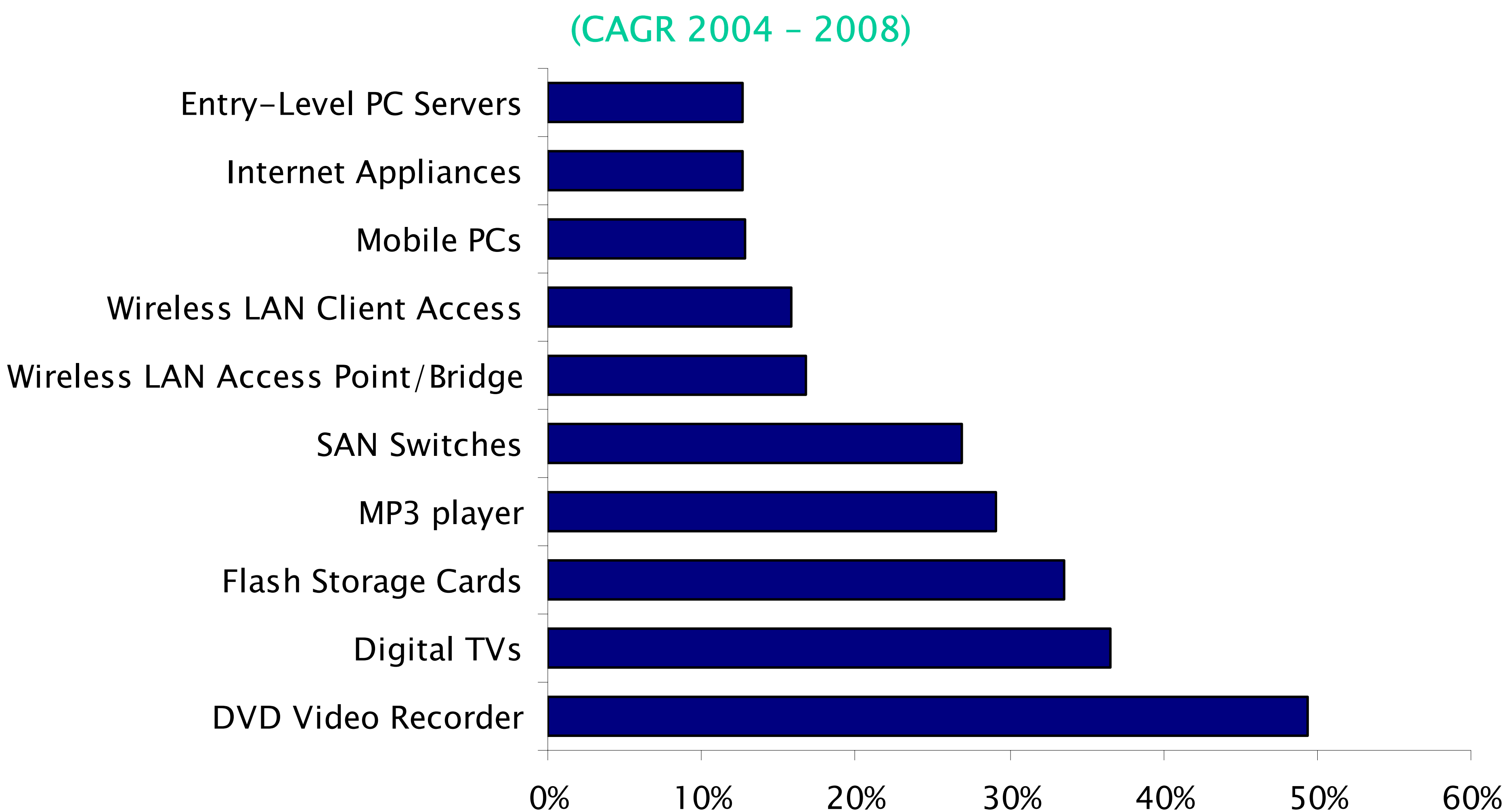
Americas DRAM Unit Shipments by Density



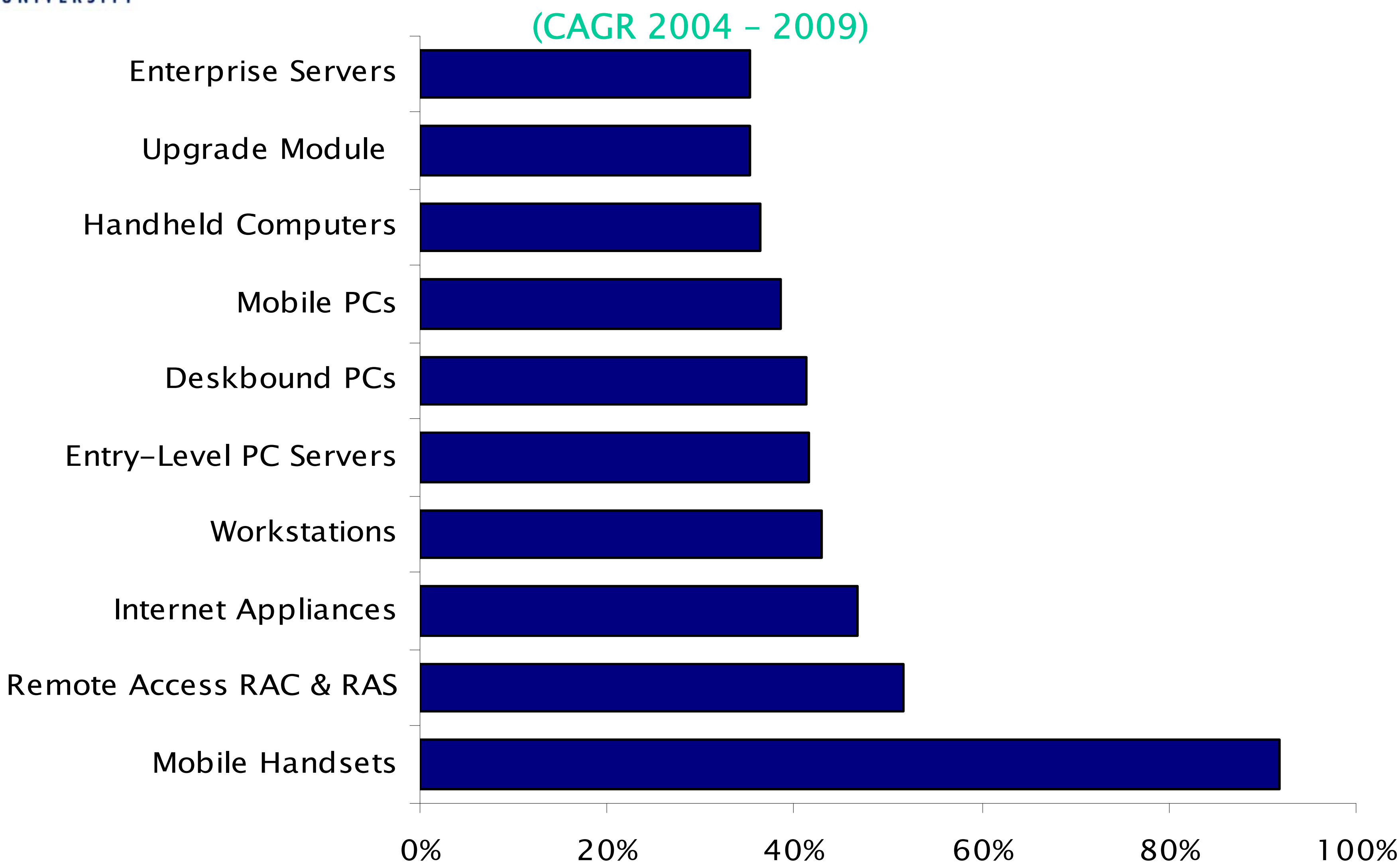
256Mb Equivalent Unit DRAM Shipments



DRAM Applications with the Highest Unit Growth Rates



Fastest Growing DRAM Consumption



Summary Overview

- DRAM chips are found in virtually every computer in use today. Looking at the simplicity of the 1T1C cell one might wonder about the significance of this invention by modern day standards. However, if it is remembered that this idea was conceived back in the 1960s before MOS technology had matured enough for production or the idea that circuits could be "dynamic" (only operating correctly for a short period of time) the significance of the invention becomes clear. What is usually not mentioned when talking about Dr. Dennard's contributions to the 1T1C memory cell is his contributions of seeing this idea to product (the true test for any practical electrical engineer). The MOS process development (and the concerns for defects and reliability which have a drastic effect on the dynamic operation of MOS circuits) and supporting circuitry are also extremely important contributions that Dr. Dennard made while at IBM. In summary, Dr. Dennard cut the path for modern DRAM memory chip developments.