Progress in Scaling of Microelectronics and Future Trends

Robert H. Dennard, IBM Fellow

Thomas J. Watson Research Center
Yorktown Heights, New York

Chronology of the Microelectronics Era

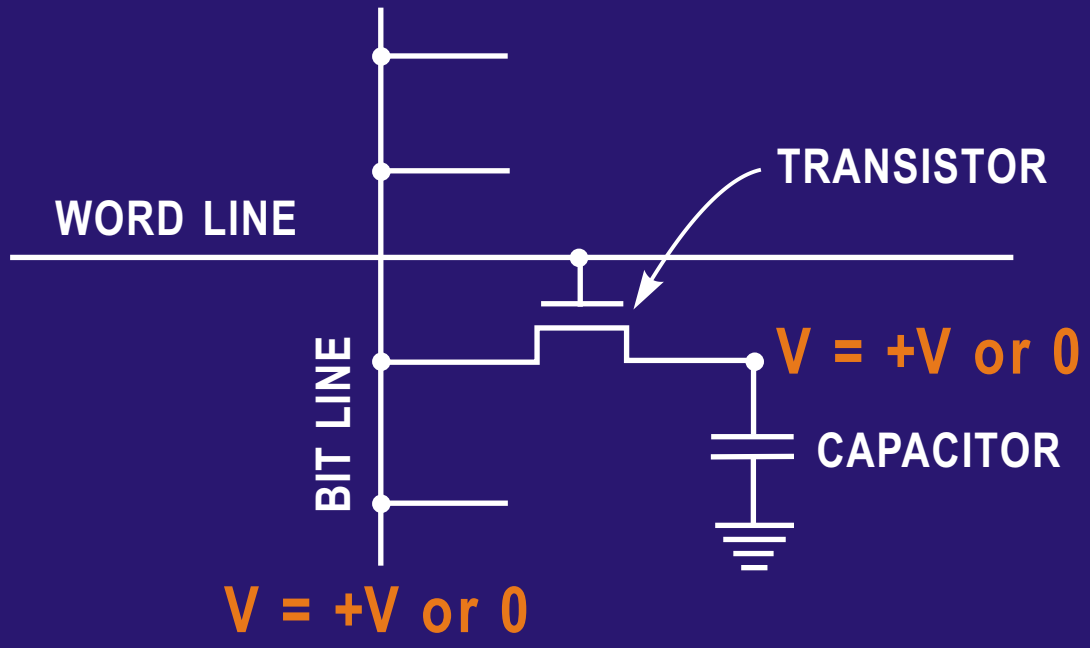
- **Phase I, 1926-1957, Discovery**
  - Rudimentary Semiconductor Device Concepts

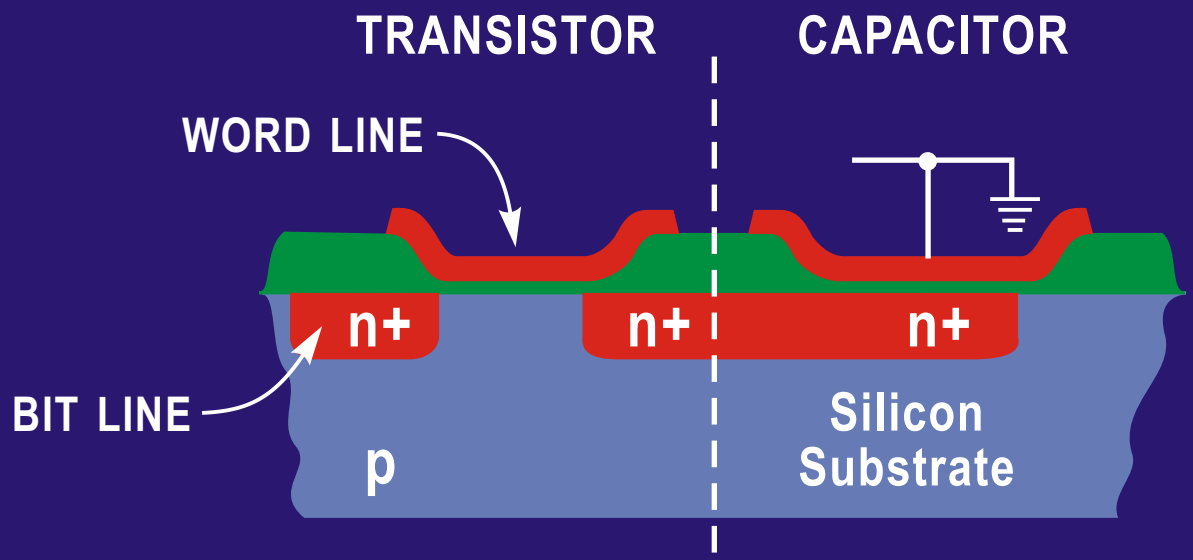
- **Phase II, 1958-1968, Basic Technology and Transistor Innovation**
  - Early Integrated Circuits
  - Control of Silicon Surface and Insulators

- **Phase III, 1969- , Integrated Circuit Production**
  - Commercial Applications
  - Continuous Evolution of Capability

(After Prof. C.T. Sah)

ONE - TRANSISTOR DRAM MEMORY CELL





STORED-CHARGE CELL

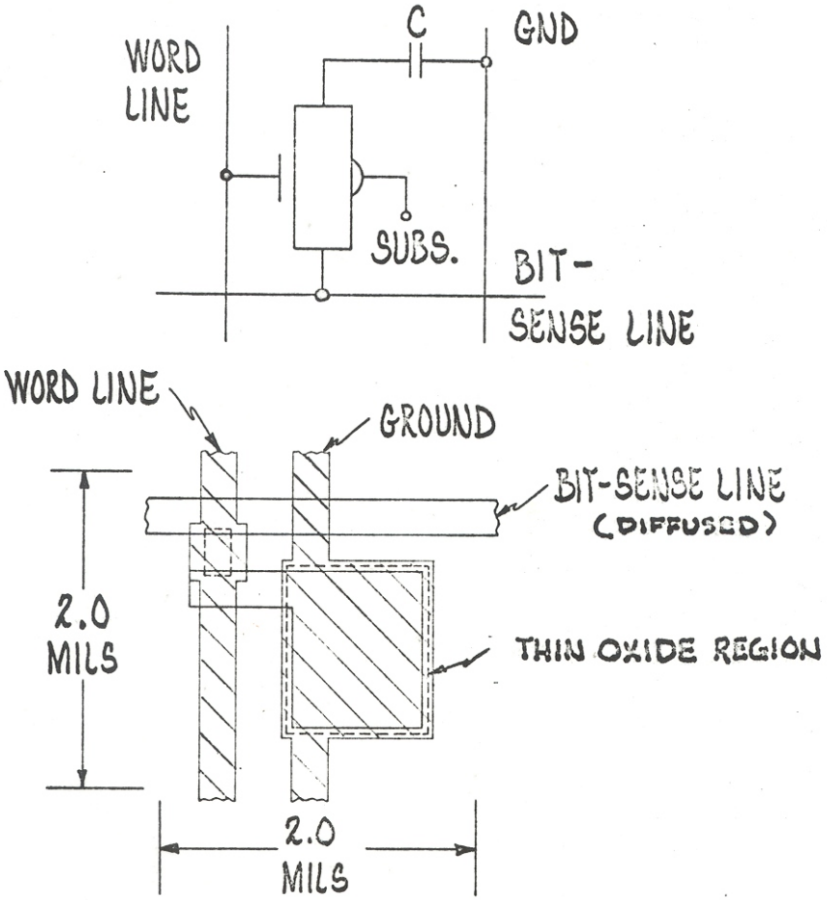


FIG. 2

June 4, 1968 R. H. DENNARD 3,387,286

FIELD-EFFECT TRANSISTOR MEMORY

Filed July 14, 1967 3 Sheets-Sheet 1

FIG. 1

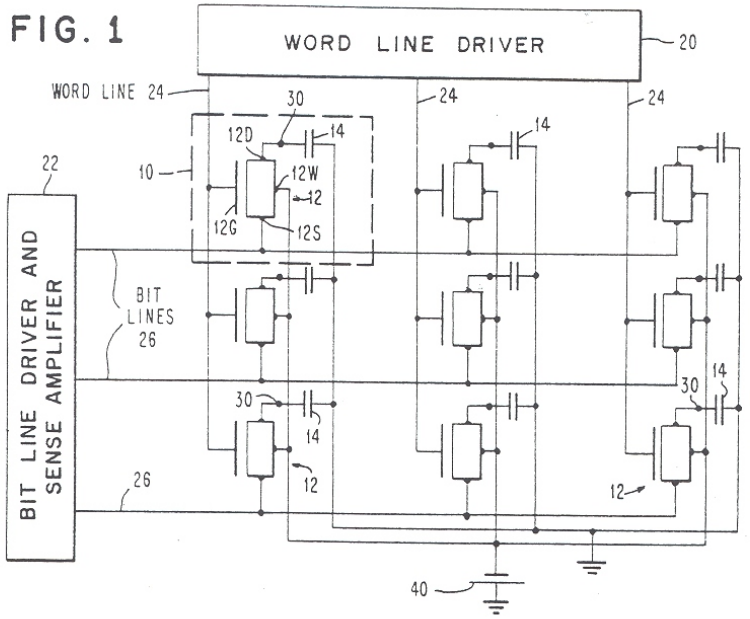
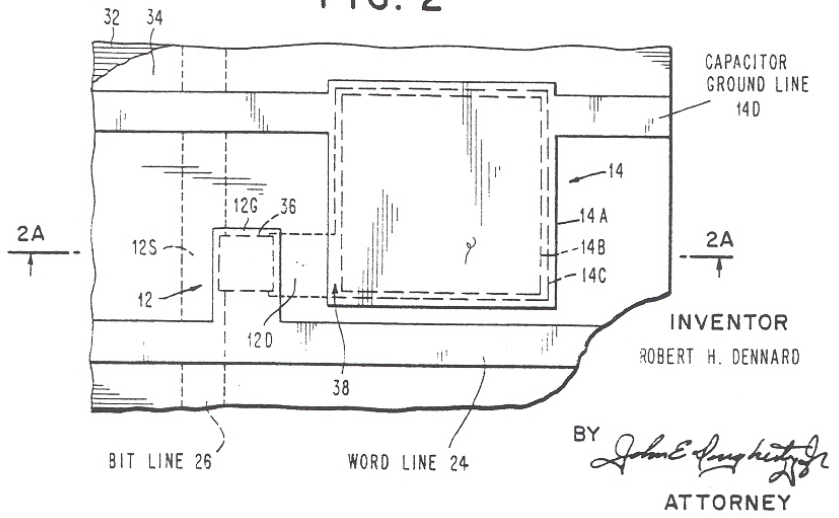


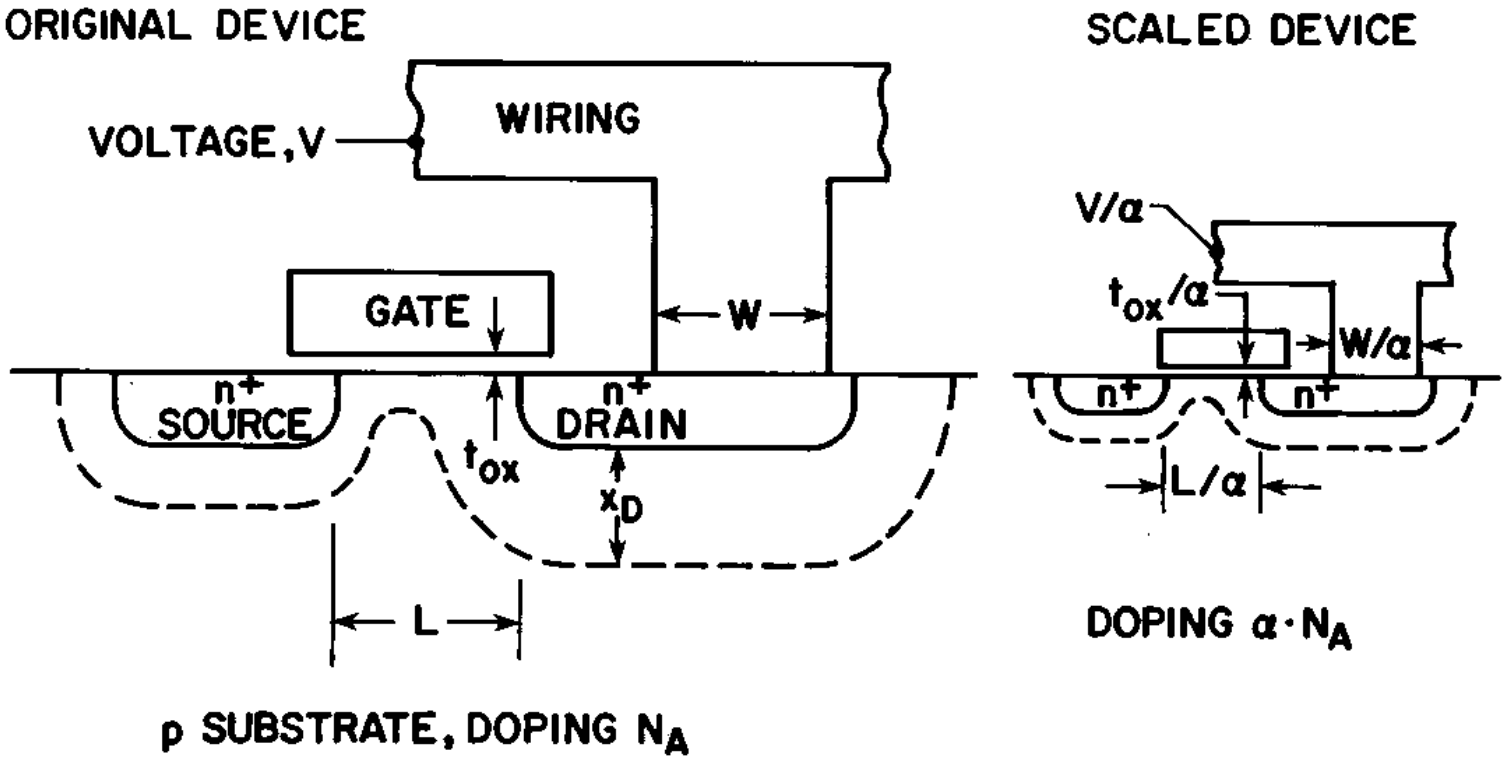
FIG. 2



INVENTOR
ROBERT H. DENNARD

BY John E. Laughlin Jr.
ATTORNEY

Scaling Principles for MOS Technology



RESULTS:

Density increases by ^{2} (wire)

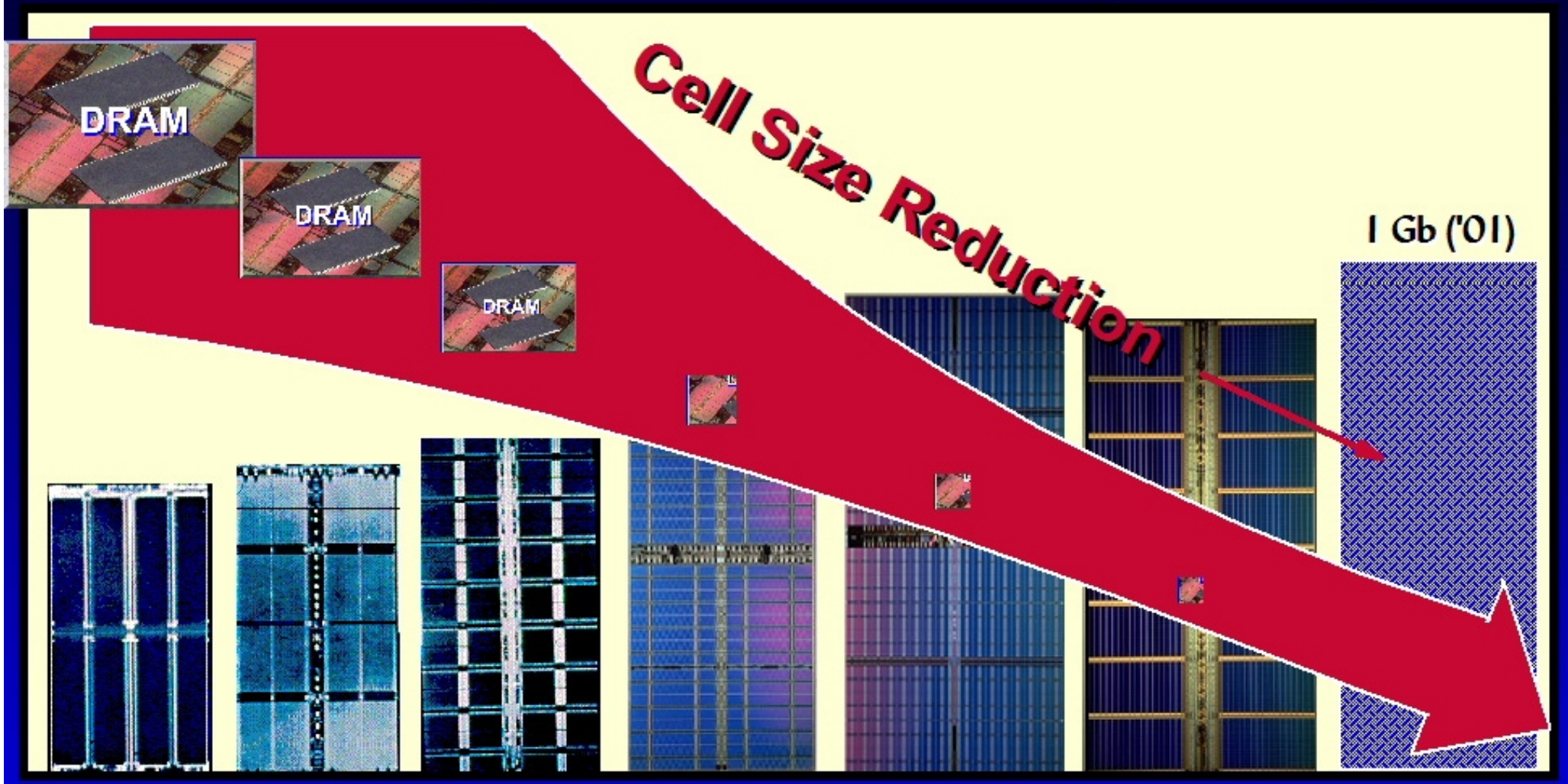
Speed increases by (device)

Power/circuit decreases by ^{2} (wire & voltage)

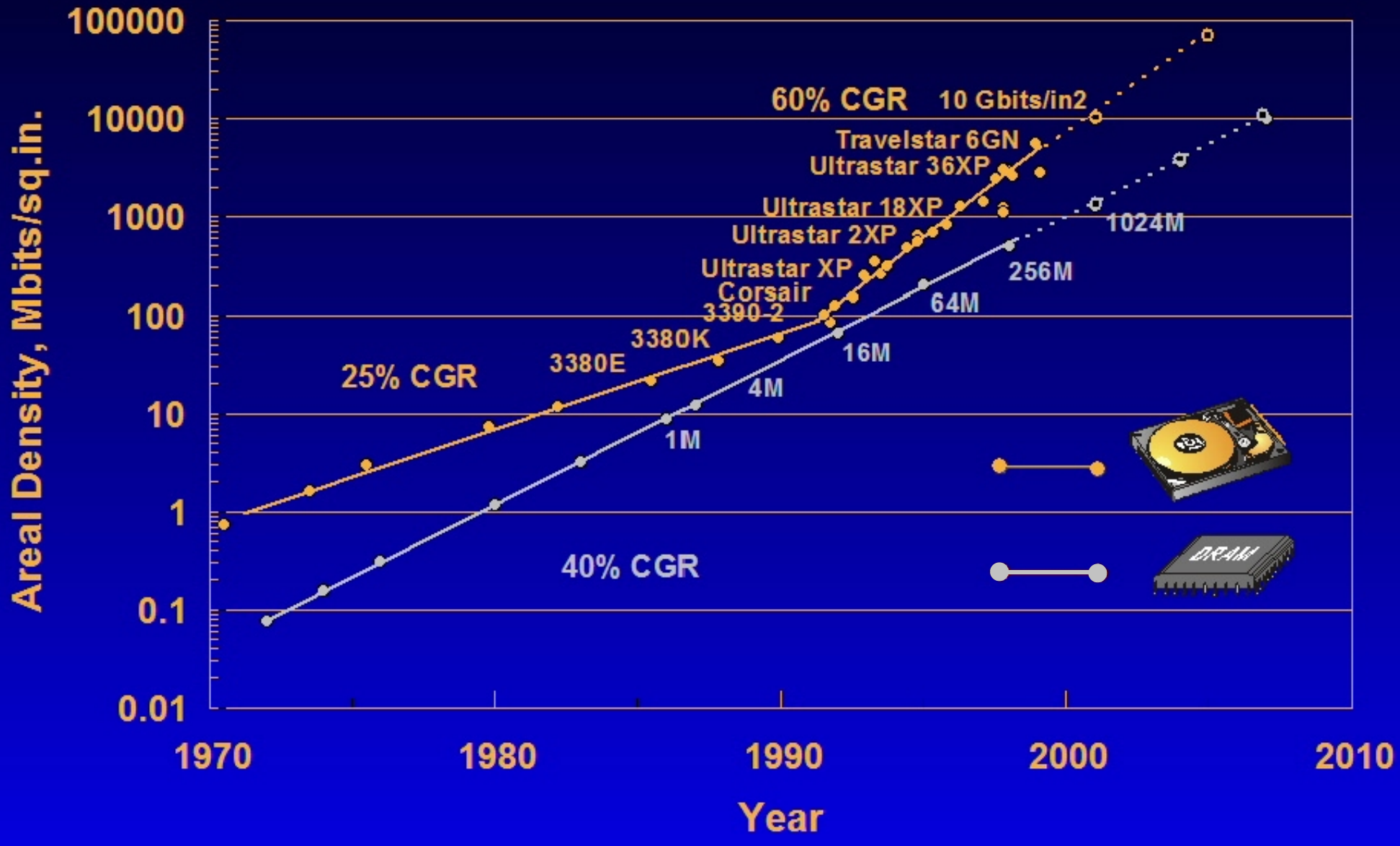
Wire RC unchanged by scaling

DRAM Evolution

- Bits/Chip Increase --- 4X/Gen. (~3 Years)



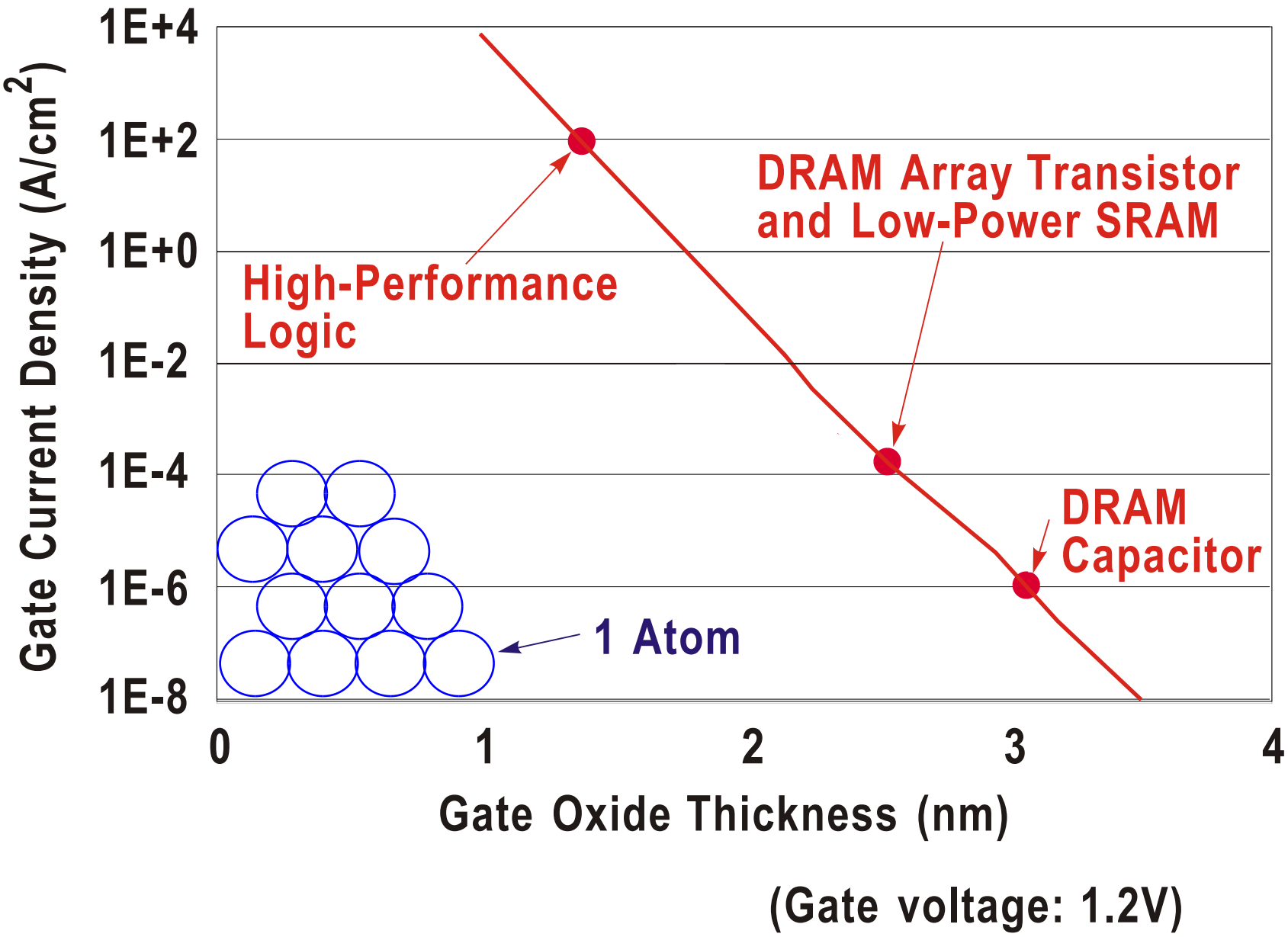
Areal Density of Magnetic HDD and DRAM



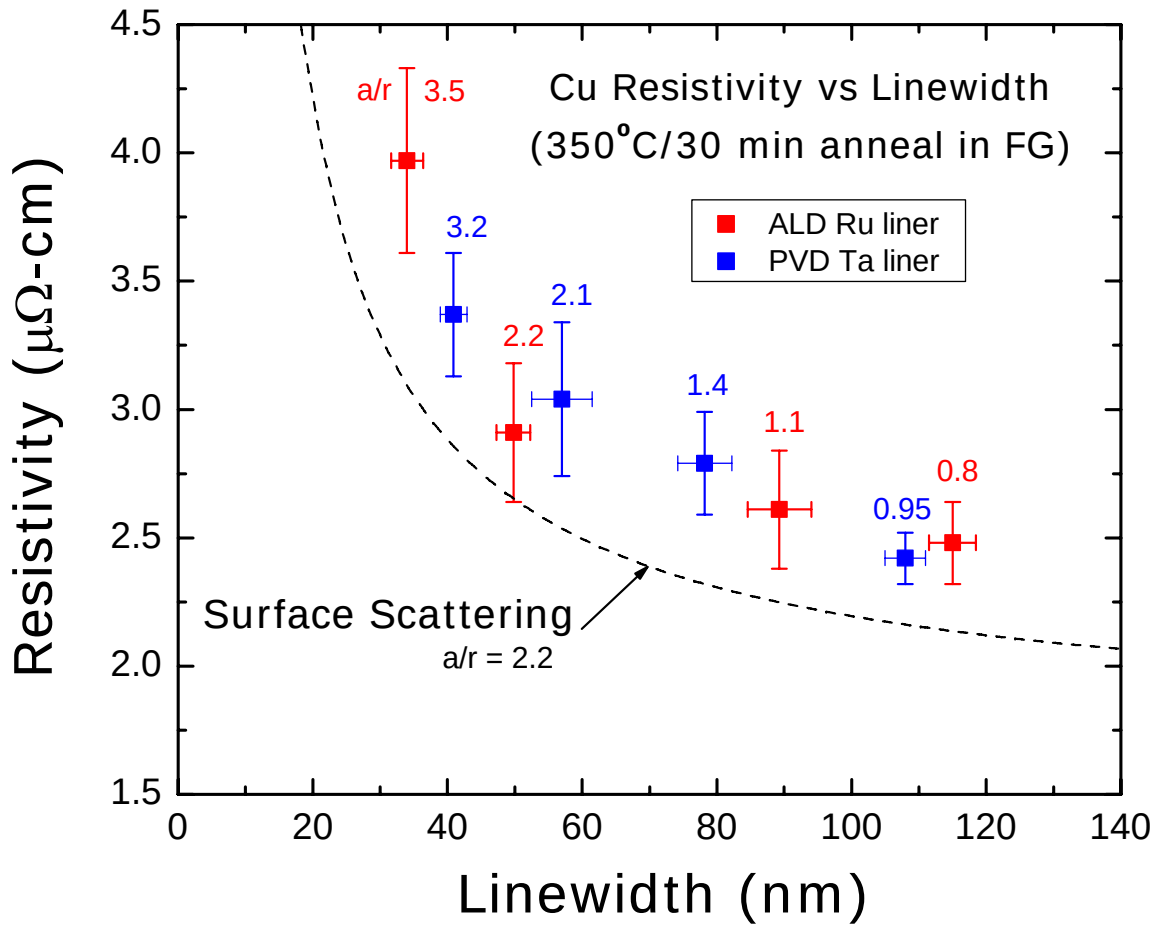
Future CMOS Technology Outlook – 45 nm and Beyond?

- **Transistor off-current limits voltage scaling**
  - lower voltage can be more energy efficient with lower performance
- **Gate-oxide tunneling limits conventional insulator scaling**
- **Increasing variability problems**
  - line edge control and roughness
  - doping fluctuations
  - soft errors (SER)
- **Strain engineering and surface orientation (HOT) for higher performance in near-term**
- **Several alternative structures for future**
  - challenging to build, incremental benefit in performance
  - needed to address variability problems

Limits of Oxide Scaling



Wire Resistivity vs. Linewidth



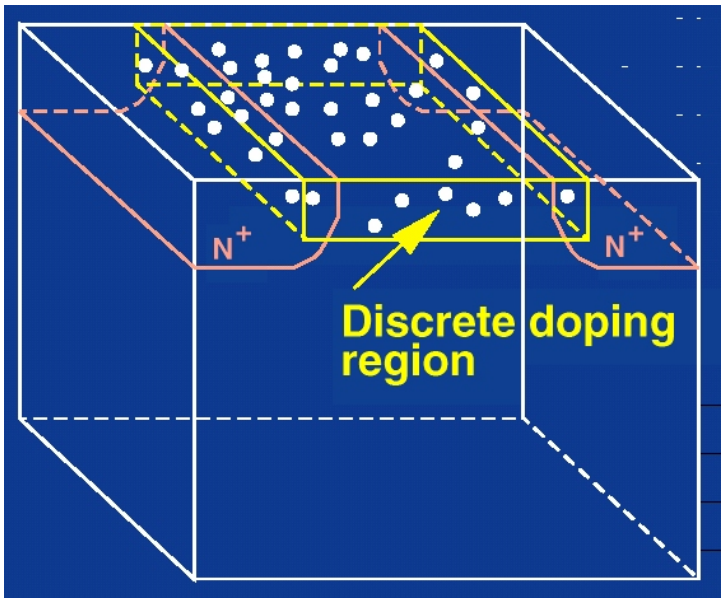
S. M. Rossnagel, et al., 2005 IEDM

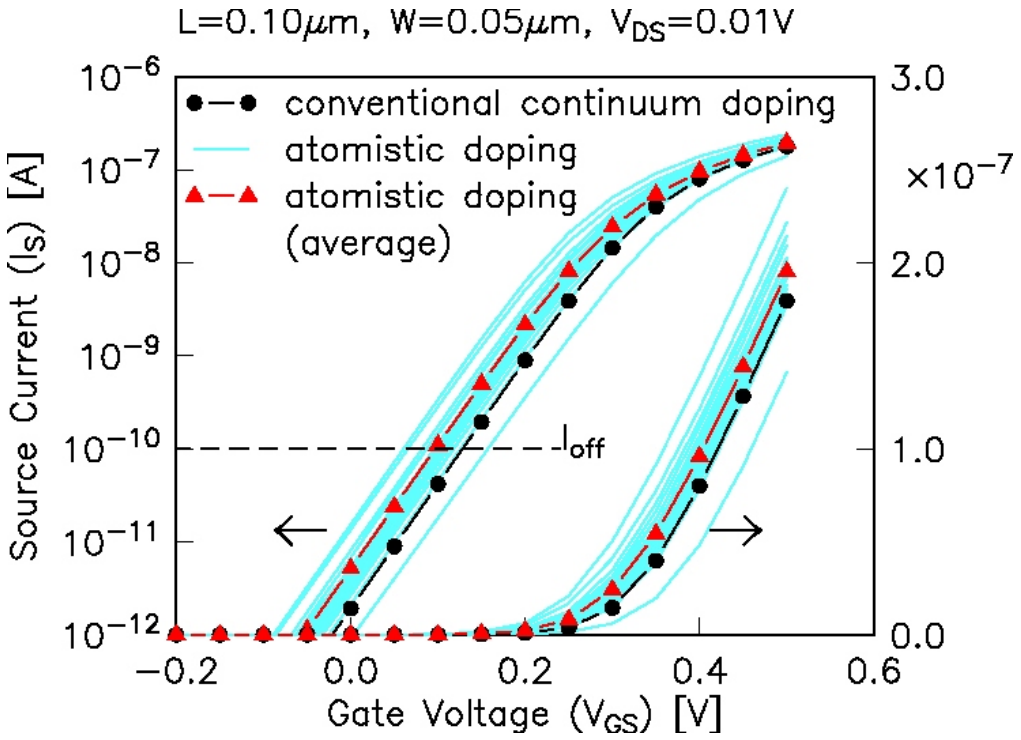
Discrete Random Dopant

Number and location of individual dopant atoms:

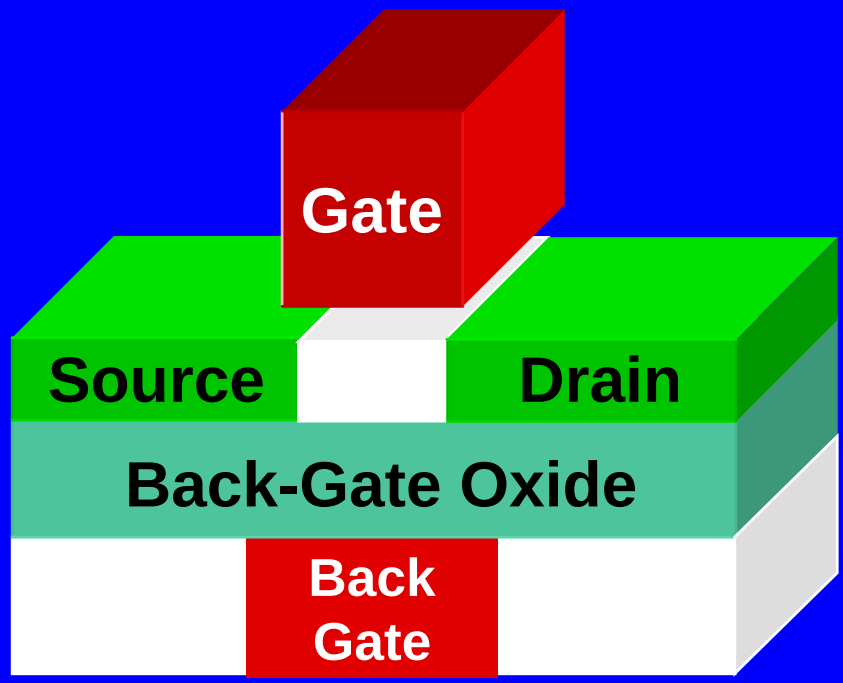
- statistical fluctuations of *I-V* characteristics
- ~ $10W^{-1/2}$ mV- $m^{1/2}$ (W in m's)

Solution: leave dopants out of channel





Back-Gate FET



- Undoped channel DG structure with thick back-gate oxide
- Back-gate tied to fixed DC potential
  - Creates vertical electric field, which confines inversion layer to top SOI surface and set V_T
  - Short-channel effects can be controlled with thicker T_{body} than UTB/DG
  - Back-gate potential supplements gate work function engineering

The Next Phase of Microelectronics-Technology Maturity

- **Device Performance Levels Off**
- **Circuit Density Fixed or Improving Slowly**
- **Costs Continue to Decrease for Some Time**
  - Stable process
  - Longer product life cycles
  - Focus on cost reduction in manufacturing, e.g. automation
- **Emphasis on System Level Performance**
  - Parallel to massively-parallel systems
  - Power dissipation becomes a major issue
  - Highly integrated functions on a chip

Changing Integration Strategy

Old

Processors:

Speed
Moderate Power

Short L
Lower Voltage
Multiple Wiring Layers

DRAM:

Low Cost
Low Power

Cell Density
Sparse Support Circuits
- More bits/sense line

Cell Capacitance and Voltage

New

Merged Processor and DRAM:

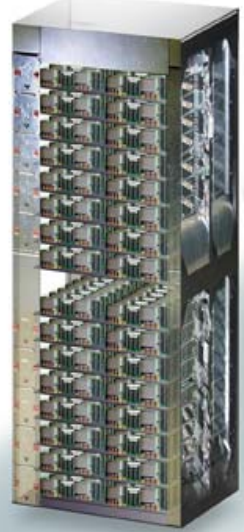
- Processor based
  - lower-voltage, fast devices
  - less DRAM density
  - higher DRAM speed

BlueGene/L System Buildup

System
64 Racks, 64x32x32 Chips

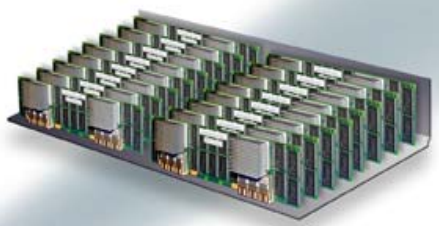
180/360 TF/s
32 TB

Rack
32 Node Cards



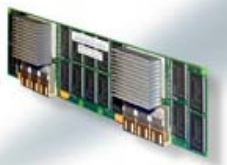
2.8/5.6 TF/s
512 GB

Node Card
16 Compute Cards



90/180 GF/s
16 GB

Compute Card
2 Chips



5.6/11.2 GF/s
1.0 GB

Chip
2 Processors

2.8/5.6 GF/s
4 MB

Conclusions

- **Scaling of Microelectronics Has Made Tremendous Progress in the Last Thirty-Five Years**
  - Many challenges have been met
- **Traditional Scaling May Slow Dramatically in This Decade**
  - Technology will evolve in other ways
- **Silicon Technology Will Reach a Very High Plateau**
  - Not easily challenged or replaced
- **Computing Power will Continue to Grow**
  - New applications will drive growth
  - Emphasis on design and energy efficiency