Electronics for IoT

Semiconductors

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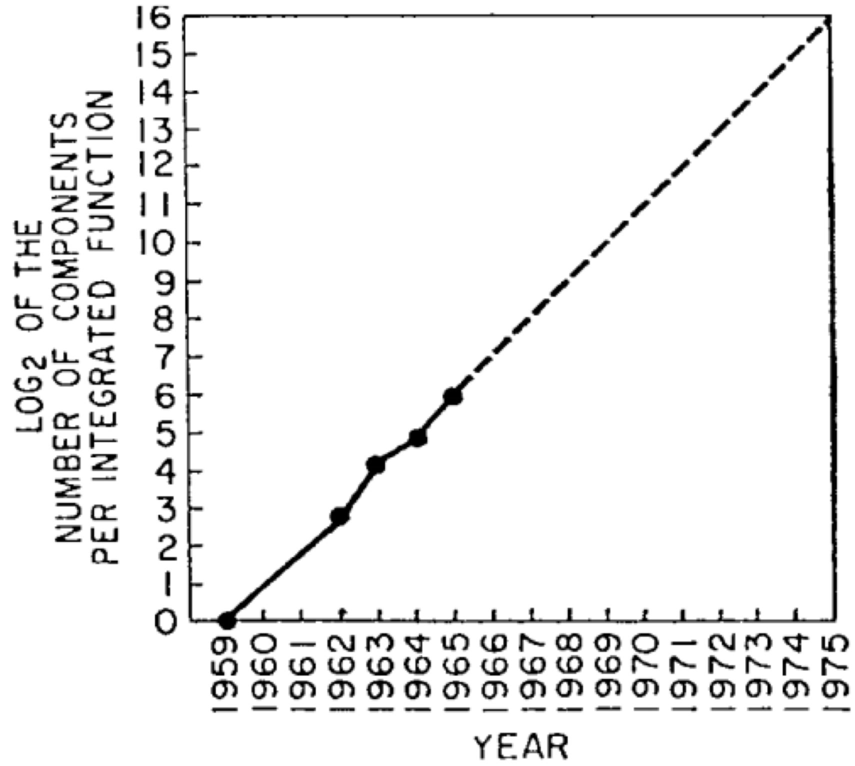
Moore’s Law

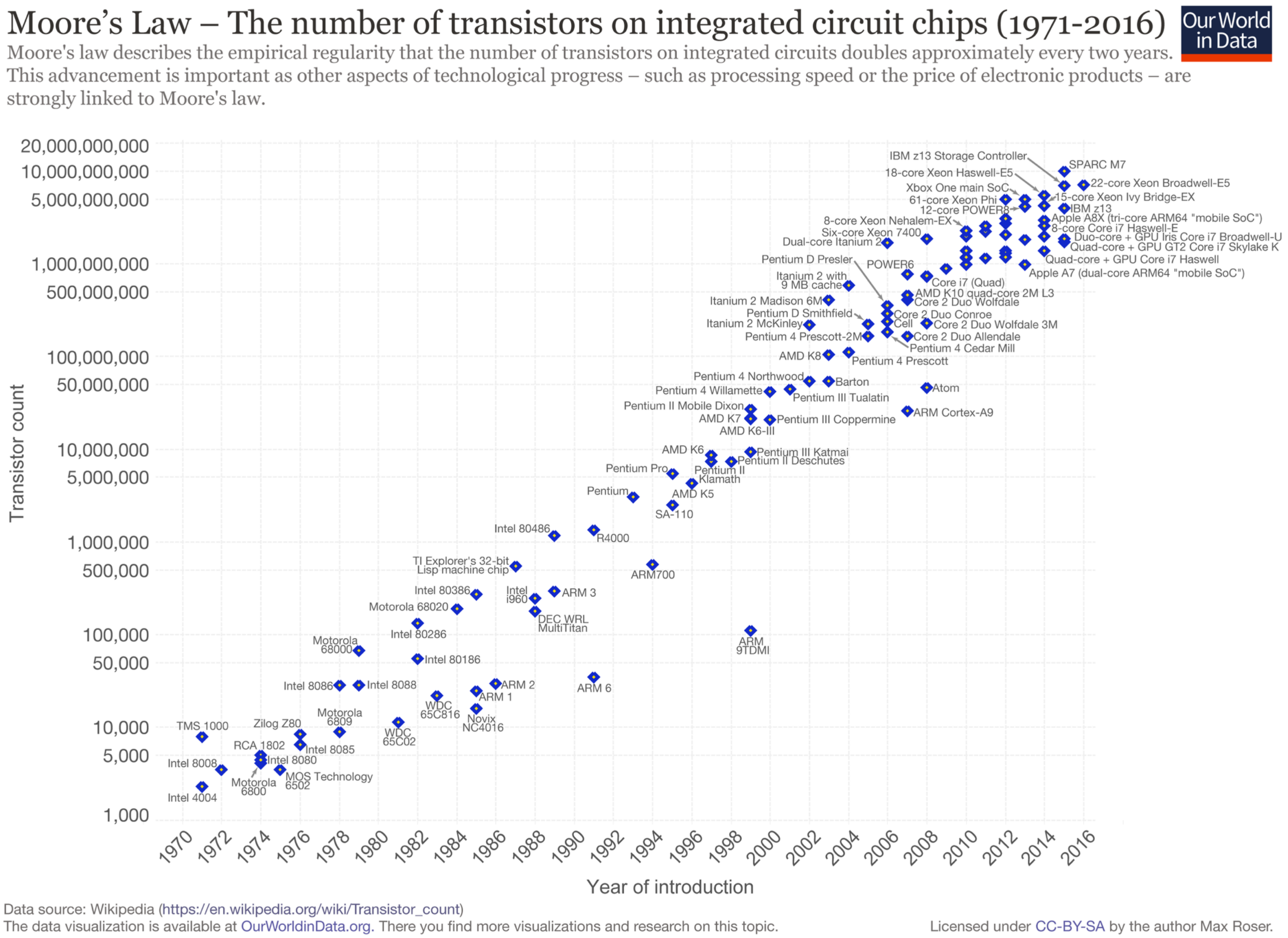
Cramming More Components onto Integrated Circuits

GORDON E. MOORE, LIFE FELLOW, IEEE

Electronics, April 19, 1965



Number of Transistors



Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.

Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

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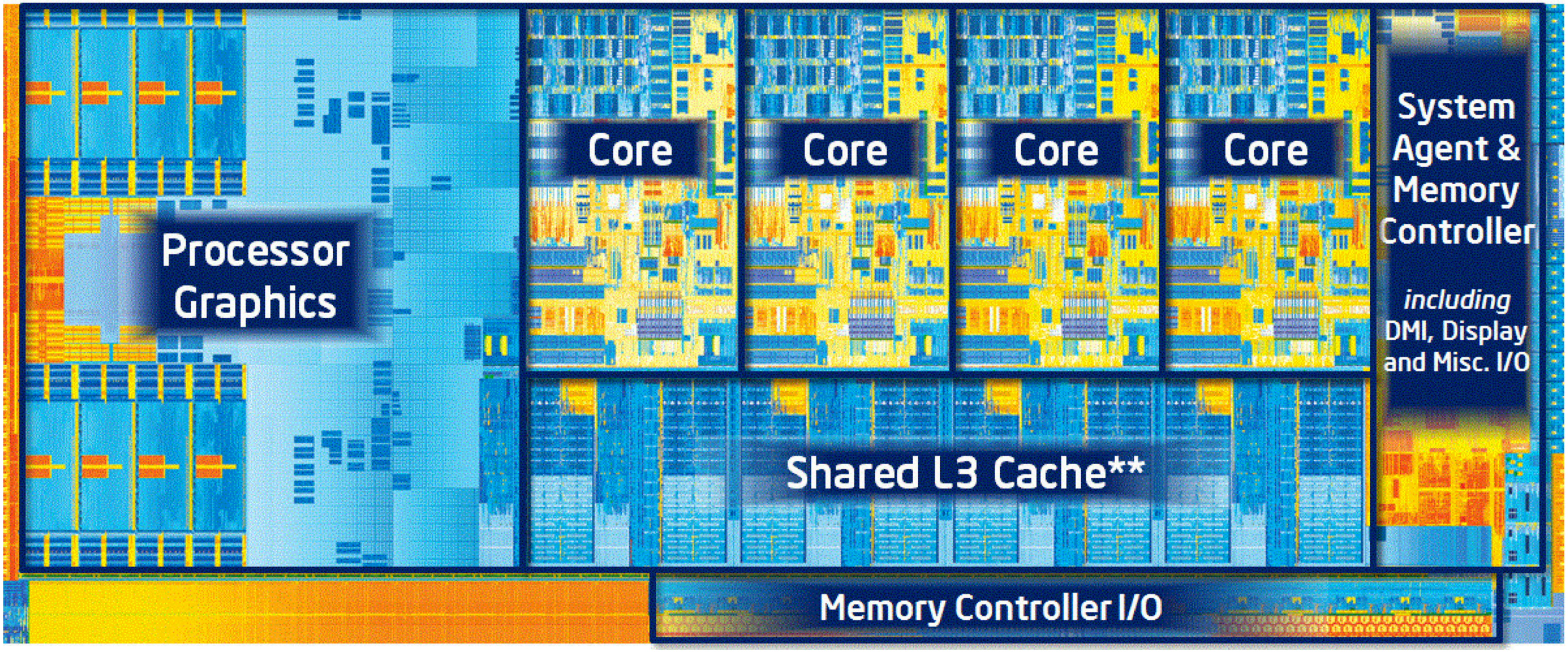
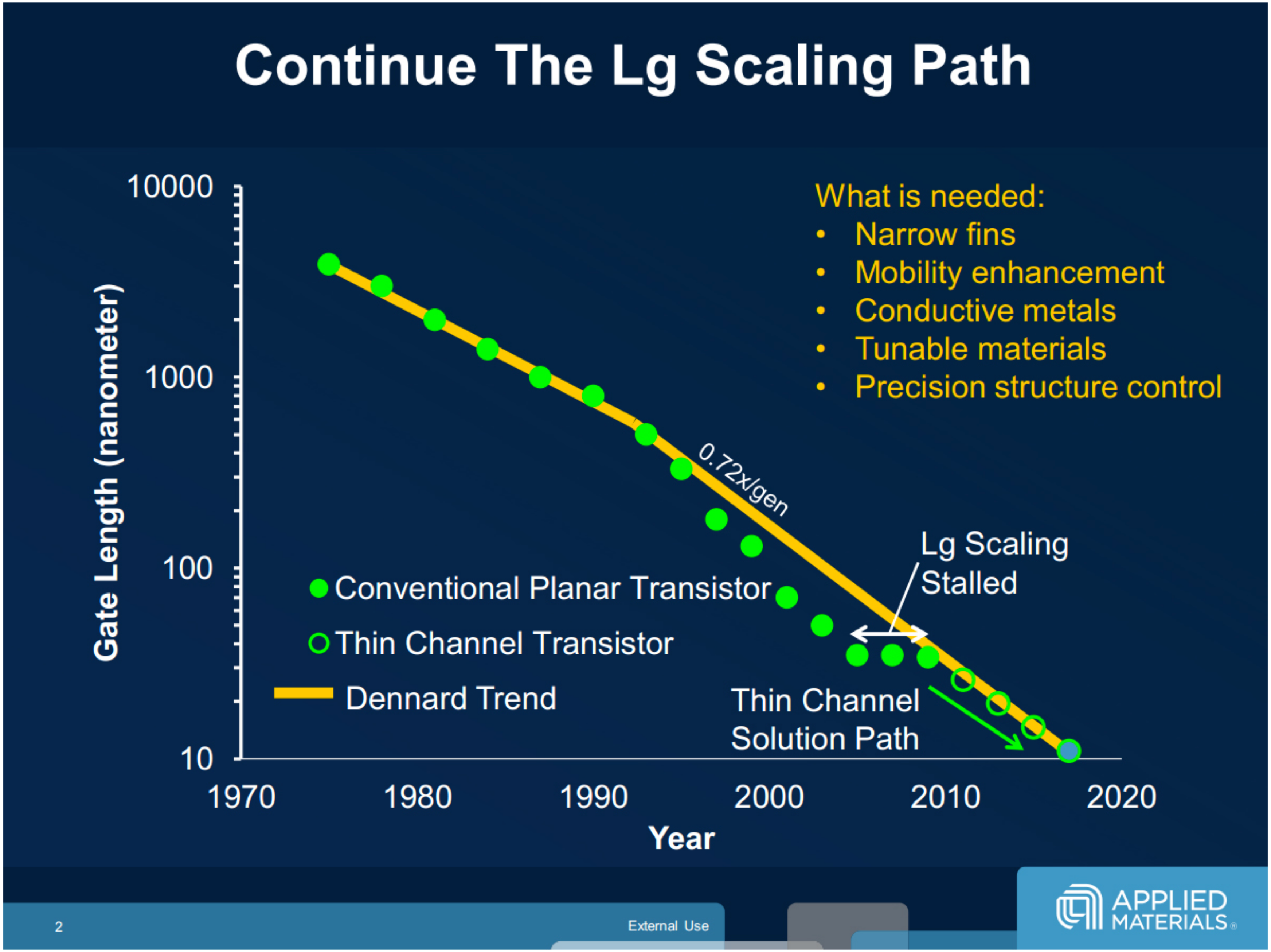
Processor


Processor Graphics
Core
Core
Core
Core
System Agent & Memory Controller
including DMI, Display and Misc. I/O
Shared L3 Cache**
Memory Controller I/O

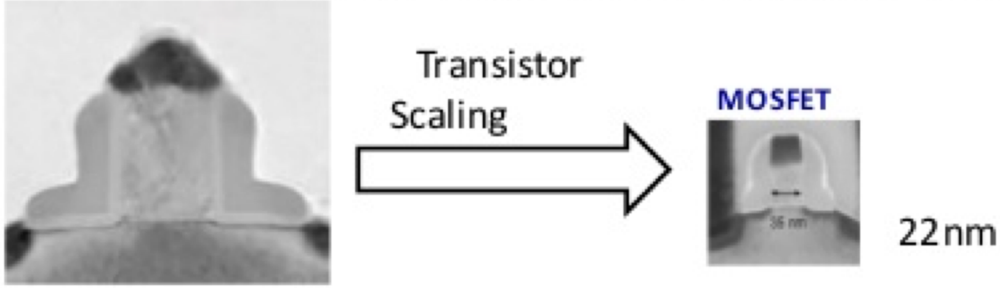


Continue The Lg Scaling Path

What is needed:

- Narrow fins
- Mobility enhancement
- Conductive metals
- Tunable materials
- Precision structure control

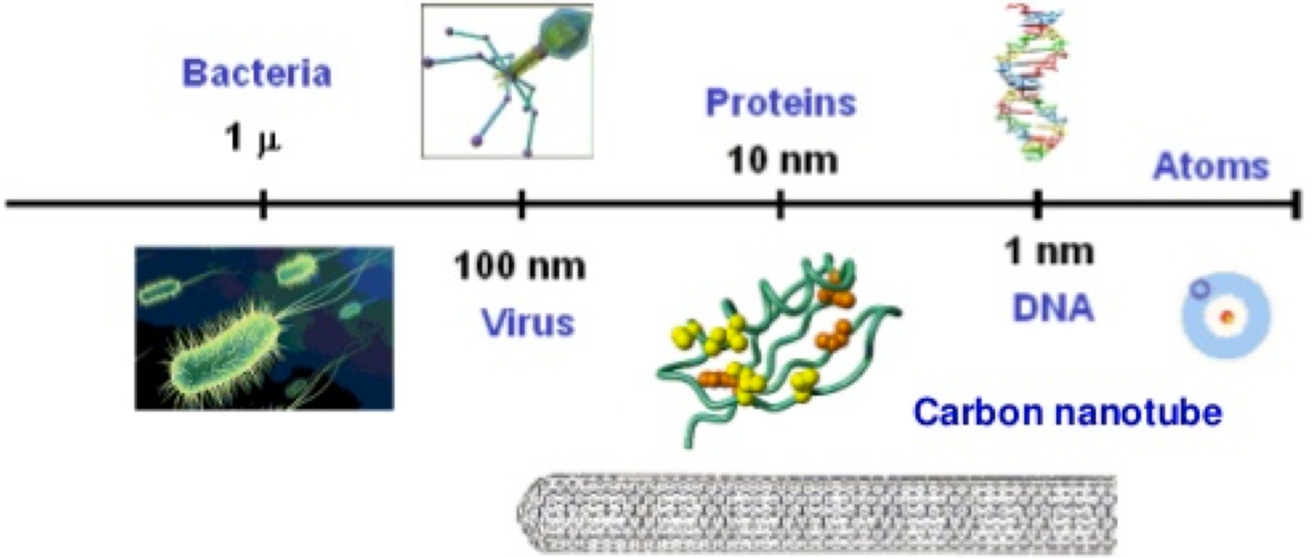
The Nanometer Size Scale



Transistor Scaling

MOSFET

22nm



Bacteria

1 μ

100 nm

Virus

Proteins

10 nm

1 nm

DNA

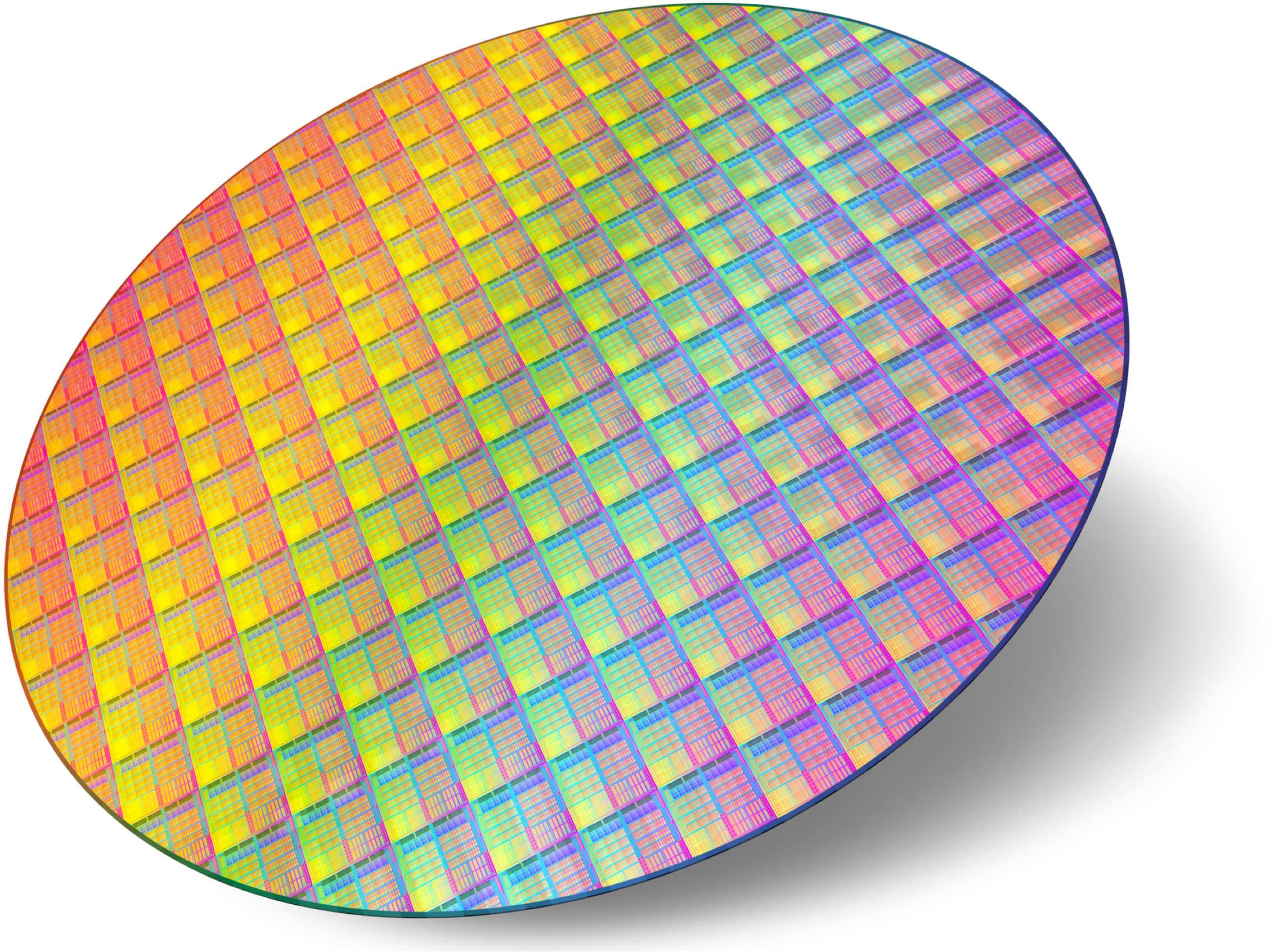
Atoms

Carbon nanotube

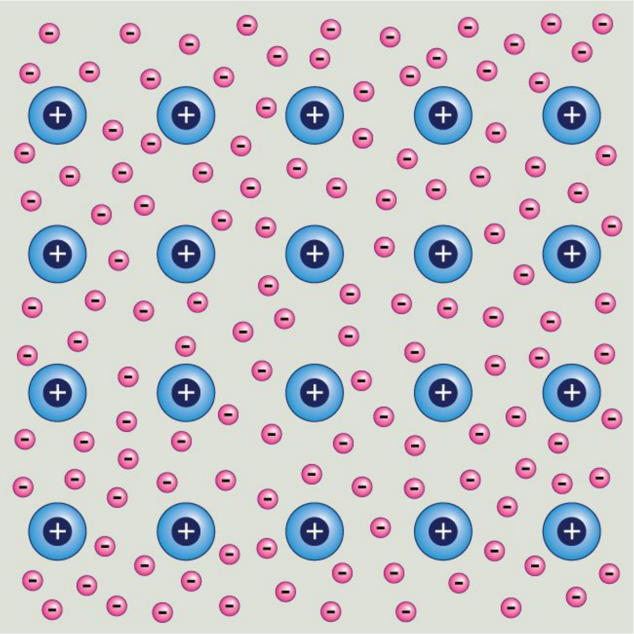
Scaling cannot go on forever because transistors cannot be smaller than atoms

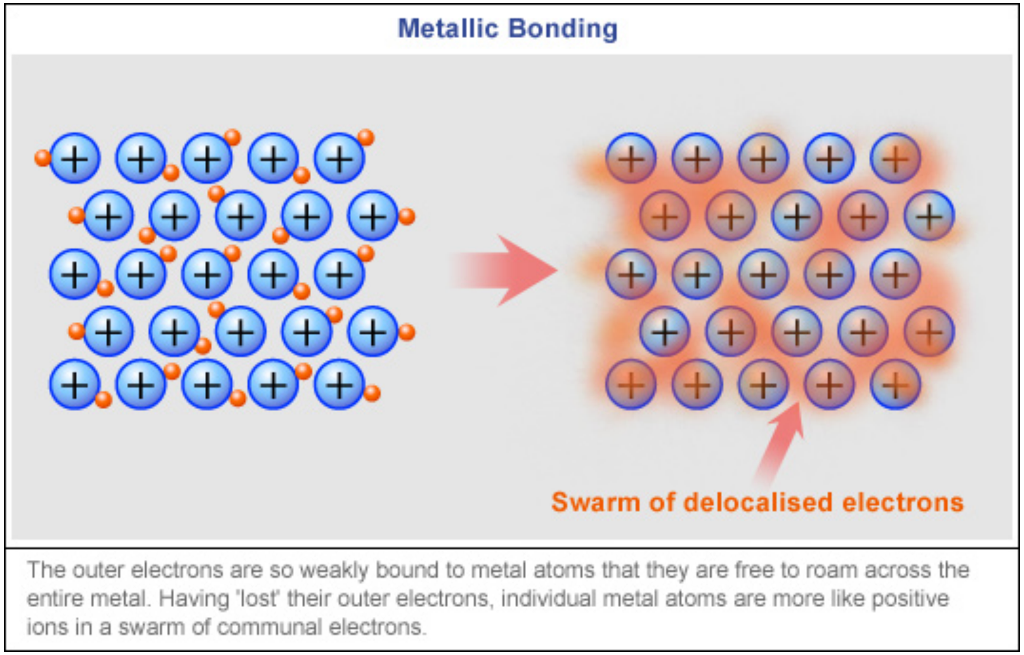
Yield

Silicon Wafer



Metals



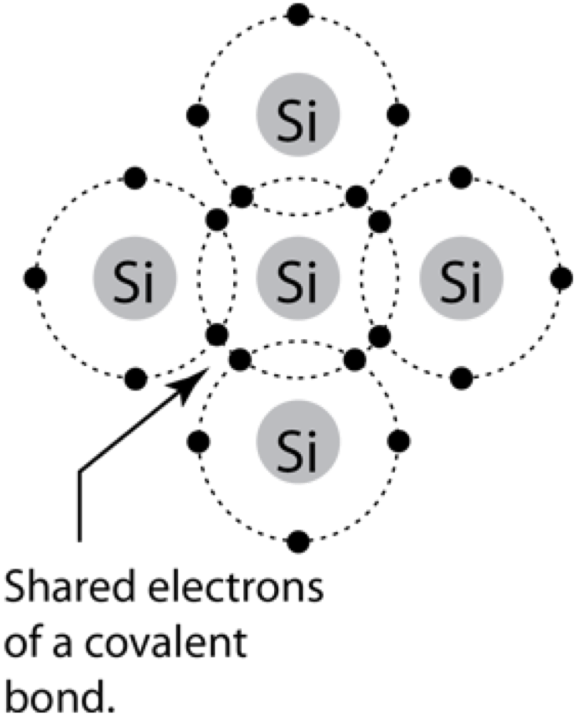


Metallic Bonding

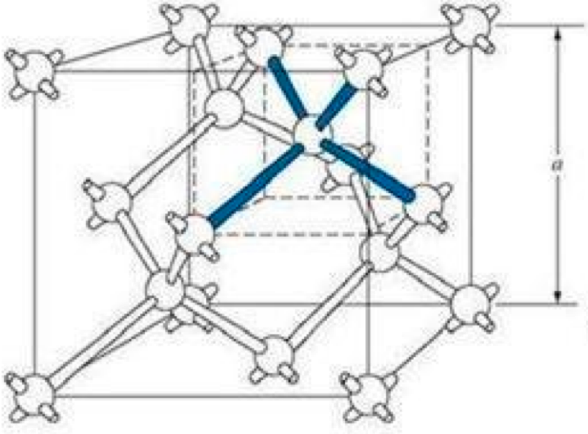
The outer electrons are so weakly bound to metal atoms that they are free to roam across the entire metal. Having 'lost' their outer electrons, individual metal atoms are more like positive ions in a swarm of communal electrons.

Insulators

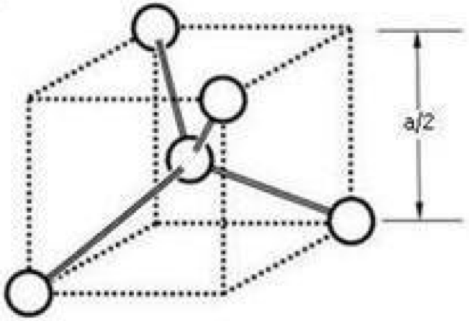
Semiconductors



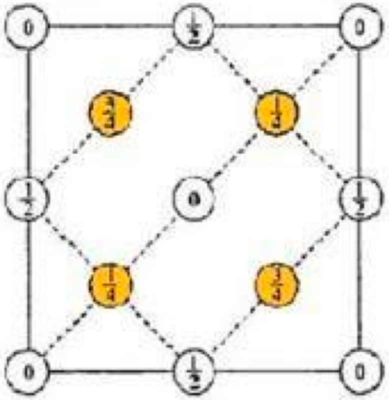
Lattice Constant



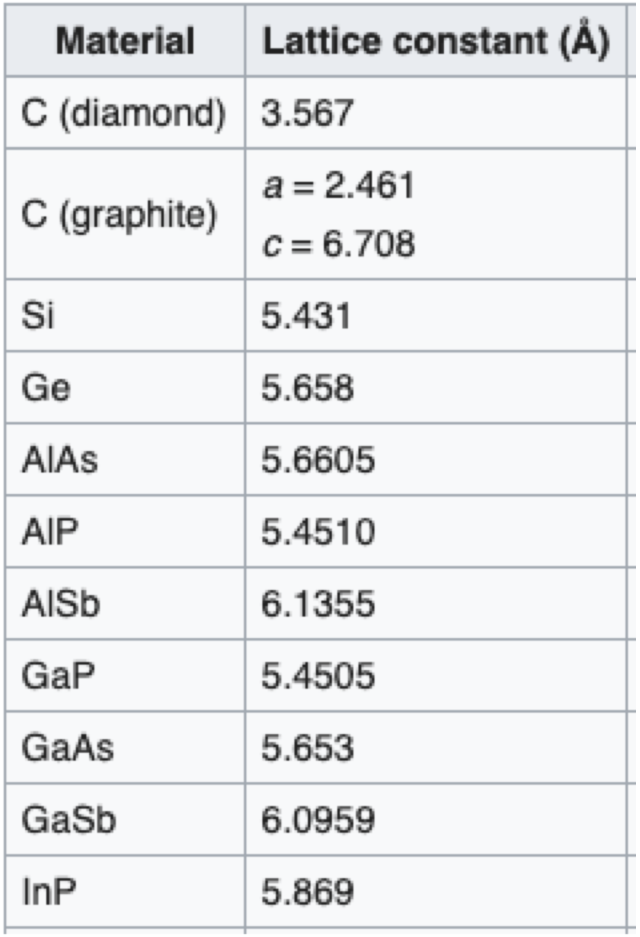
(a)



(b)

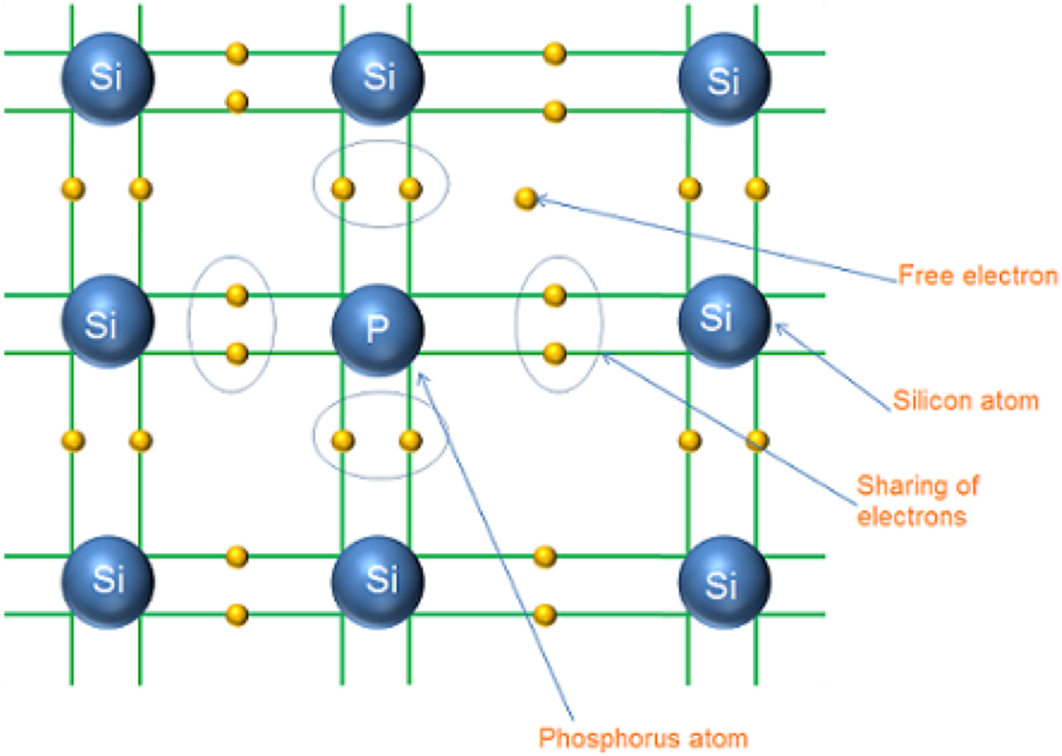


(c)

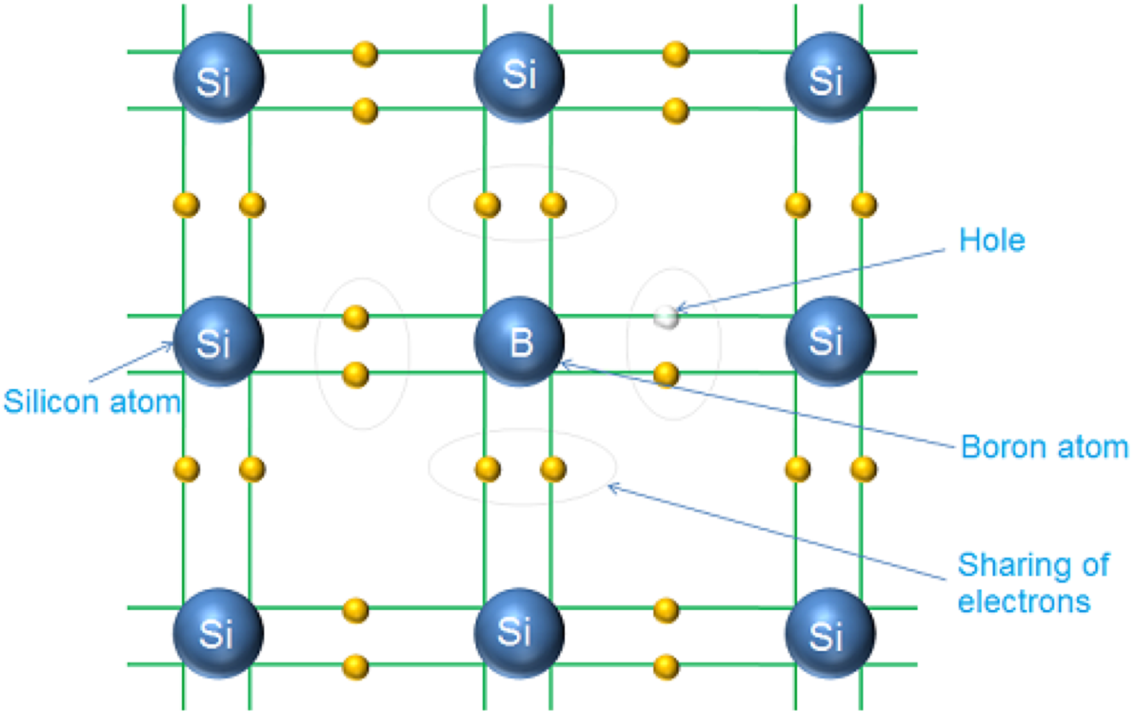


Material	Lattice constant (Å)
C (diamond)	3.567
C (graphite)	$a = 2.461$ $c = 6.708$
Si	5.431
Ge	5.658
AlAs	5.6605
AlP	5.4510
AlSb	6.1355
GaP	5.4505
GaAs	5.653
GaSb	6.0959
InP	5.869

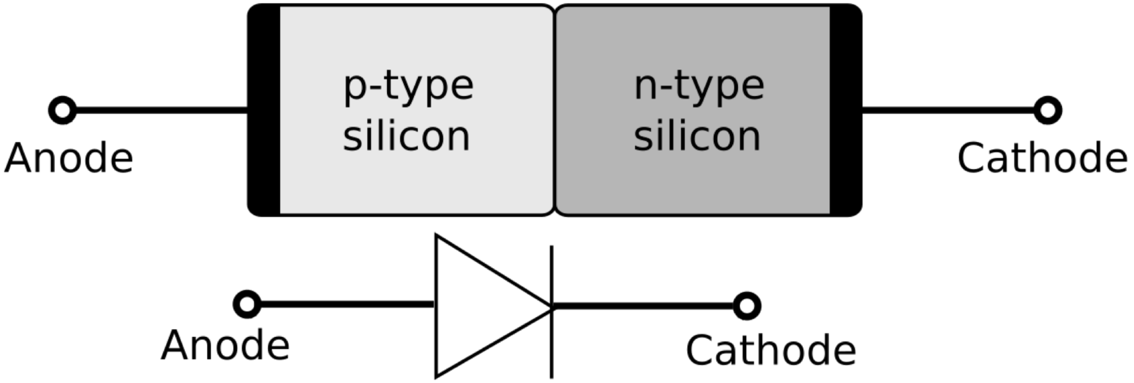
N-type Semiconductors



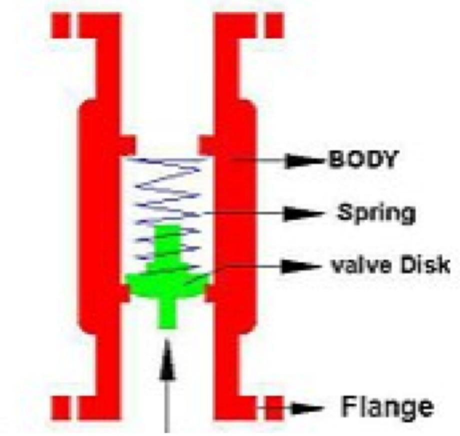
P-type Semiconductors

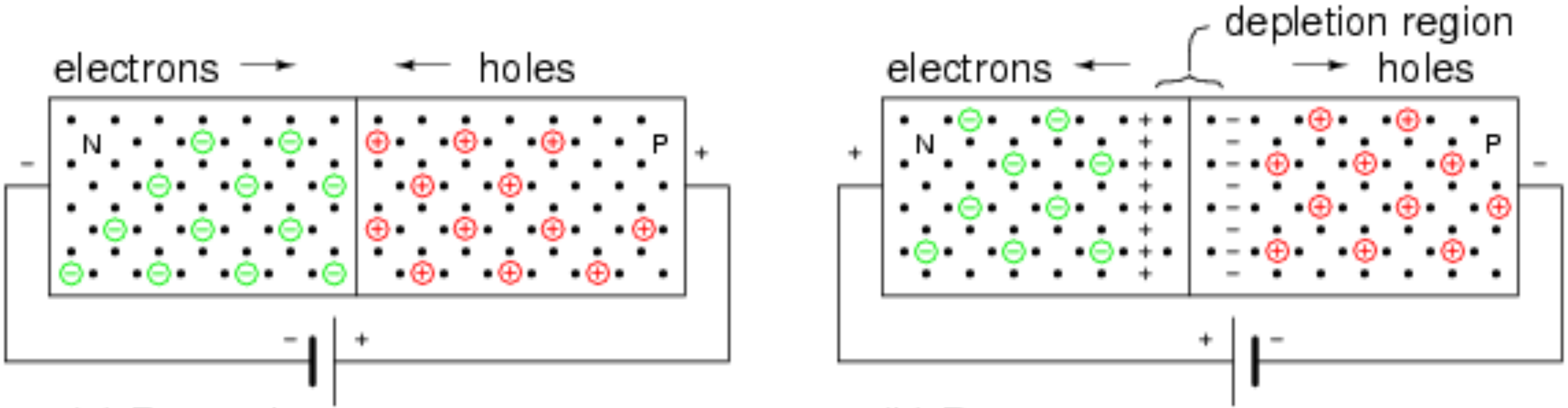


Diodes



Vertical check valve



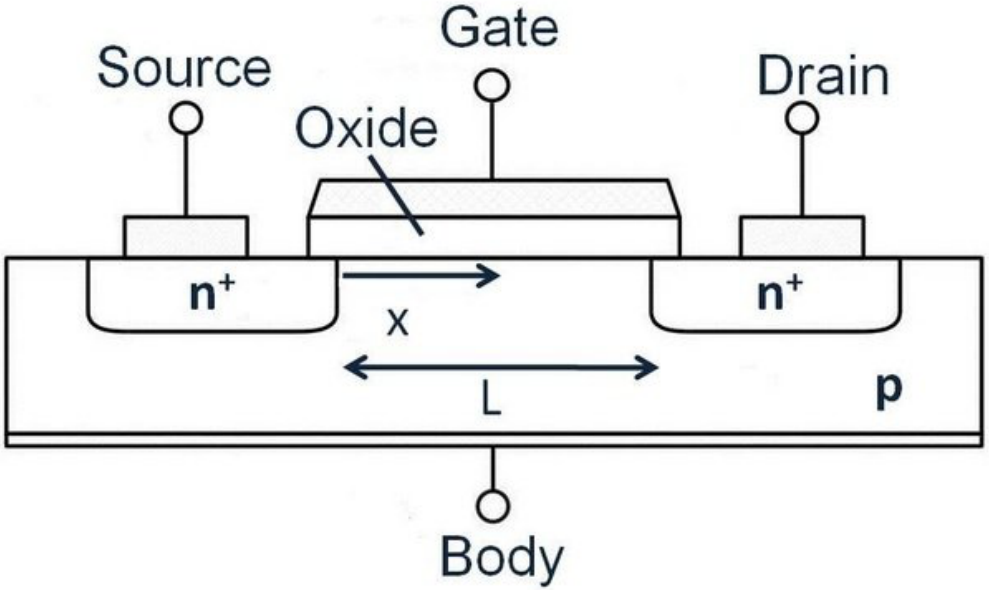


(a) Forward

(b) Reverse

Field Effect Transistor (FET)

MOSFET
Metal Oxide Semiconductor FET



Switch Logic – Example: Adder

Switch Logic

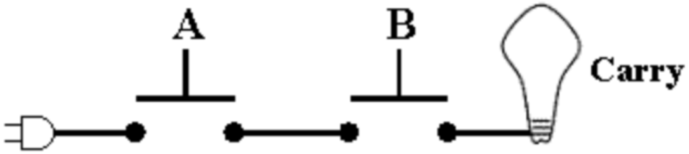
Building an Adder with Switches

Now that you are comfortable adding binary numbers together, let's see how we could make an adding machine using transistors. We will use simple light switches here to make things clearer—but this is not an oversimplification: the transistor logic works very similarly. For this example, we will build part of an adding machine that can add two binary digits (bits) together.

Here are the possible answers obtained from adding two bits:

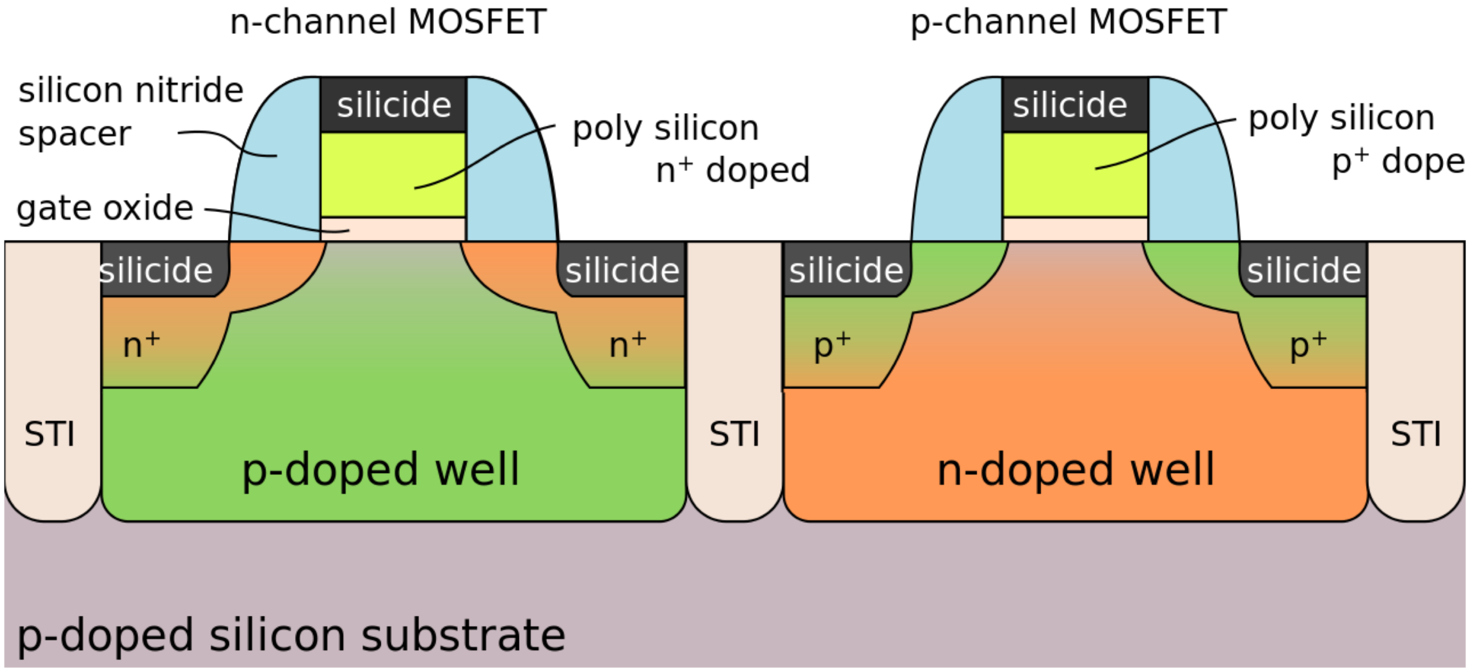
A	B	Carry	Sum
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

We'll just design the "Carry" output of the adder here (the Sum is a bit harder, but also can be done using only transistor switches). The Carry is 1 only if both of our inputs are 1. That is, the Carry is 1 when input A **AND** input B are 1. Thus we can use two switches in a row just as shown above to build the Carry output of our adding machine.



Using combinations of transistor switches, we can build circuits to add, subtract, multiply, and divide. We can also use them to make very simple decisions, by using the logical **AND** or the logical **OR** functions.

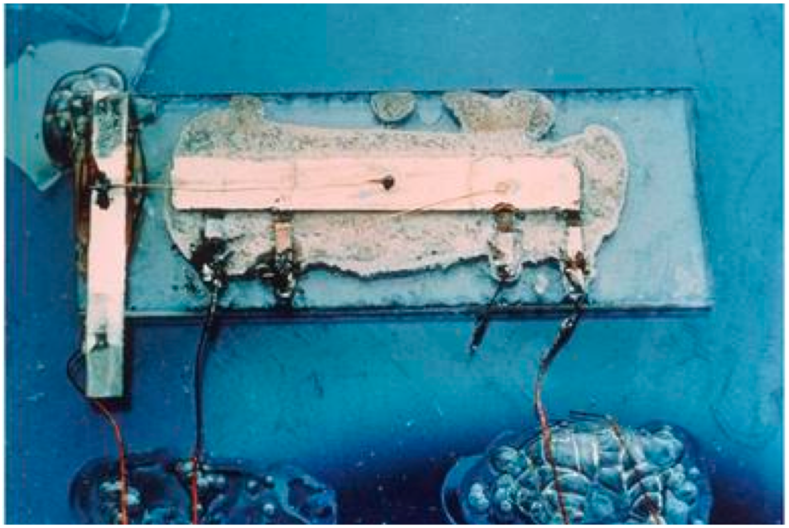
CMOS

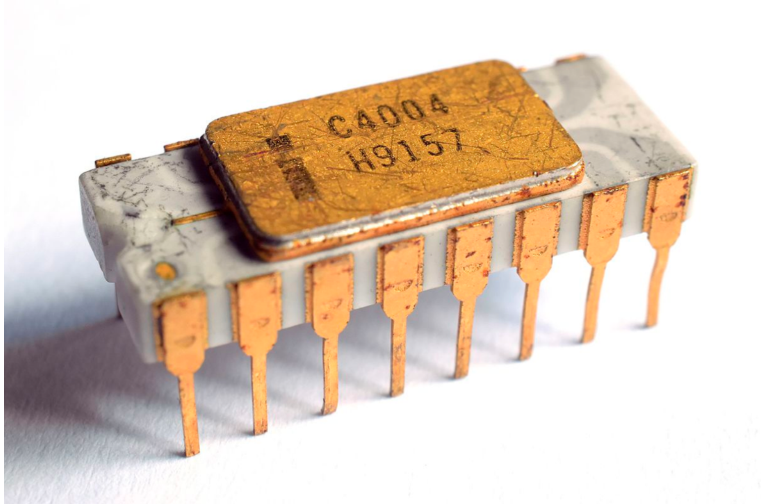

n-channel MOSFET
p-channel MOSFET
silicon nitride spacer
gate oxide
silicide
poly silicon n+ doped
poly silicon p+ dope
silicide
silicide
silicide
silicide
silicide
n+
n+
p+
p+
STI
STI
STI
p-doped well
n-doped well
p-doped silicon substrate

Acronyms

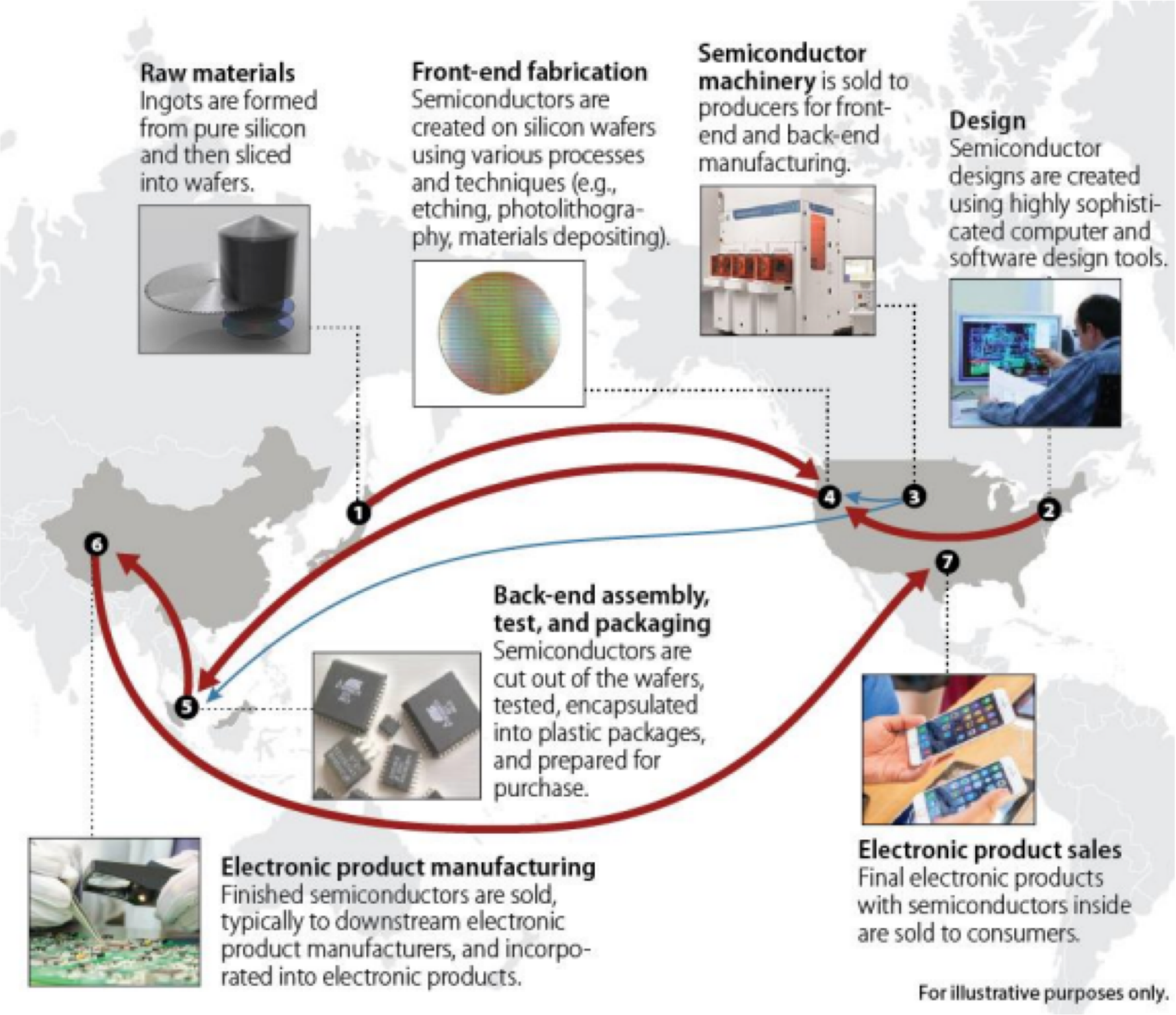
- Transistor
  - Semiconductor device
- Field Effect Transistor (FET)
  - Specific physical implementation
  - Alternative: Bipolar Junction Transistor (BJT)
- Metal Oxide FET (MOSFET)
  - Particular realization of FET
- NMOS, PMOS
  - Types of MOSFET transistors
- CMOS
  - Process capable of fabricating NMOS and PMOS FETs

Batch Fabrication





Semiconductor Production



Raw materials
Ingots are formed from pure silicon and then sliced into wafers.

Front-end fabrication
Semiconductors are created on silicon wafers using various processes and techniques (e.g., etching, photolithography, materials depositing).

Semiconductor machinery is sold to producers for front-end and back-end manufacturing.

Design
Semiconductor designs are created using highly sophisticated computer and software design tools.

Back-end assembly, test, and packaging
Semiconductors are cut out of the wafers, tested, encapsulated into plastic packages, and prepared for purchase.

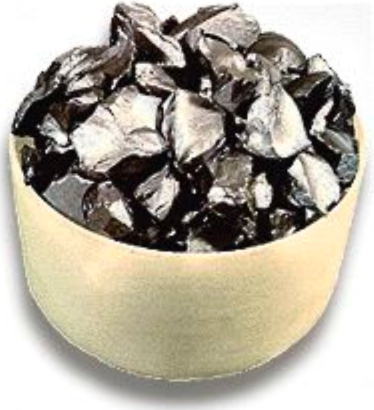
Electronic product manufacturing
Finished semiconductors are sold, typically to downstream electronic product manufacturers, and incorporated into electronic products.

Electronic product sales
Final electronic products with semiconductors inside are sold to consumers.

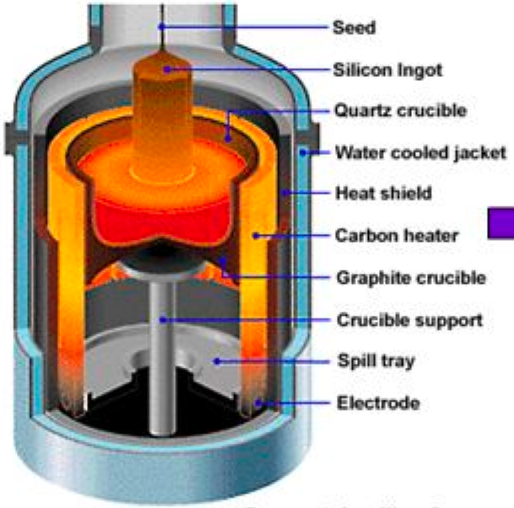
For illustrative purposes only.

IC Fabrication Overview

Procedure of Silicon Wafer Production



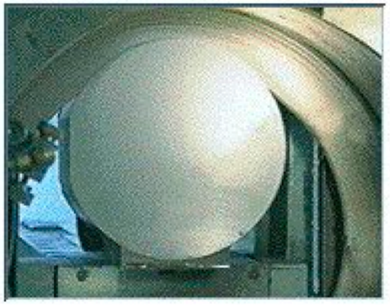
Raw material — Polysilicon nuggets purified from sand



Cz crystal pulling furnace

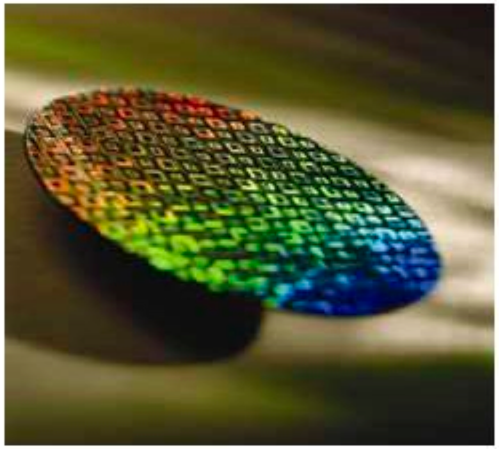
Crystal pulling

Si crystal ingot



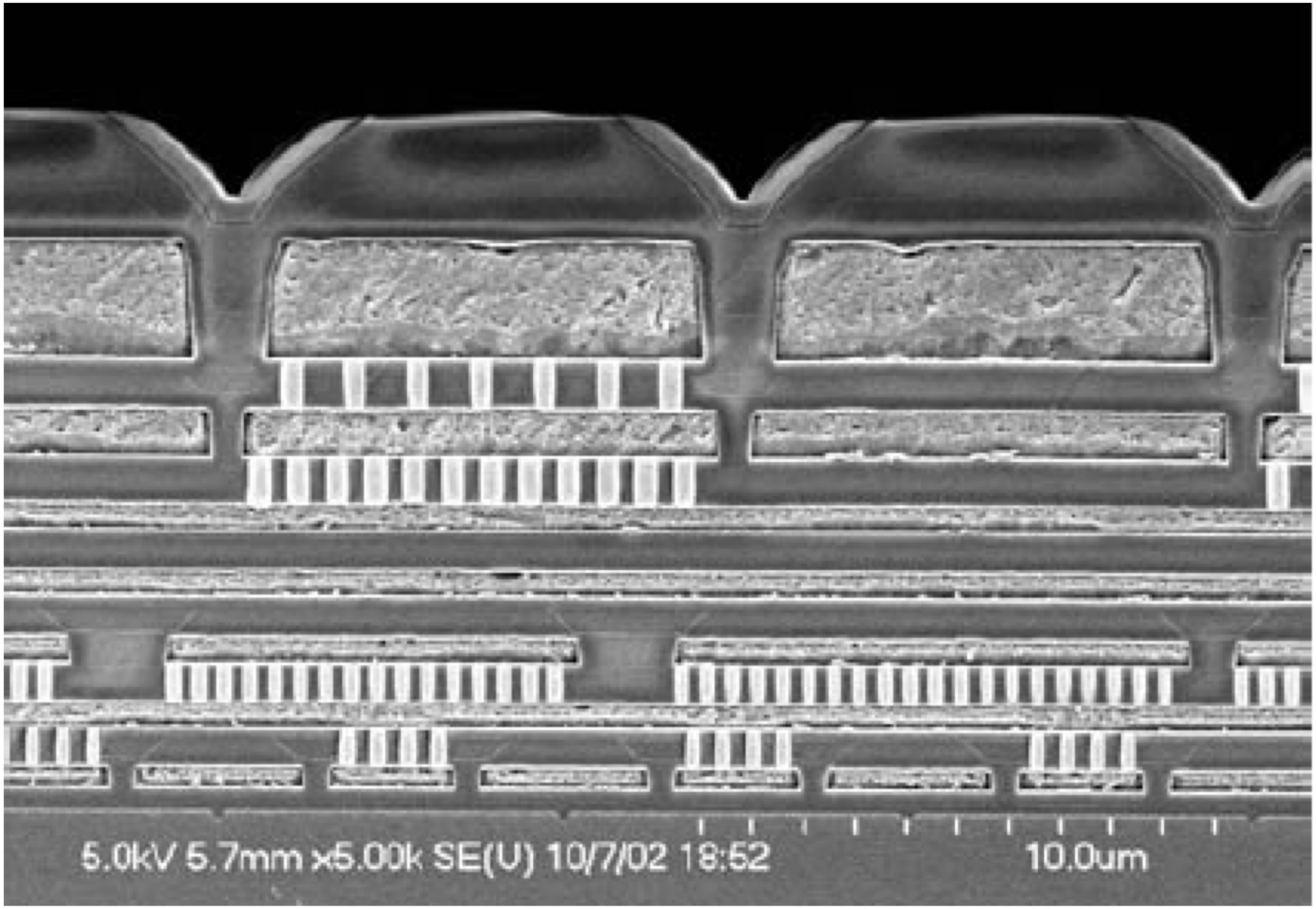
Slicing into Si wafers using a diamond saw

Final wafer product after polishing, cleaning and inspection

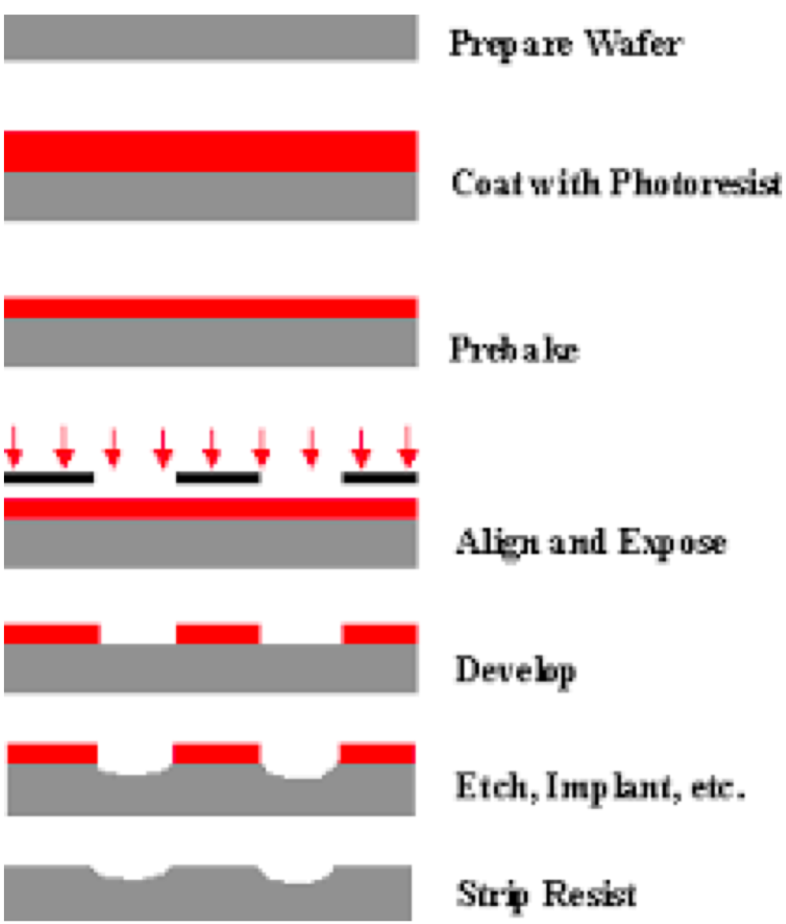


A silicon wafer fabricated with microelectronic circuits

Processed Silicon Wafer Cross-Section



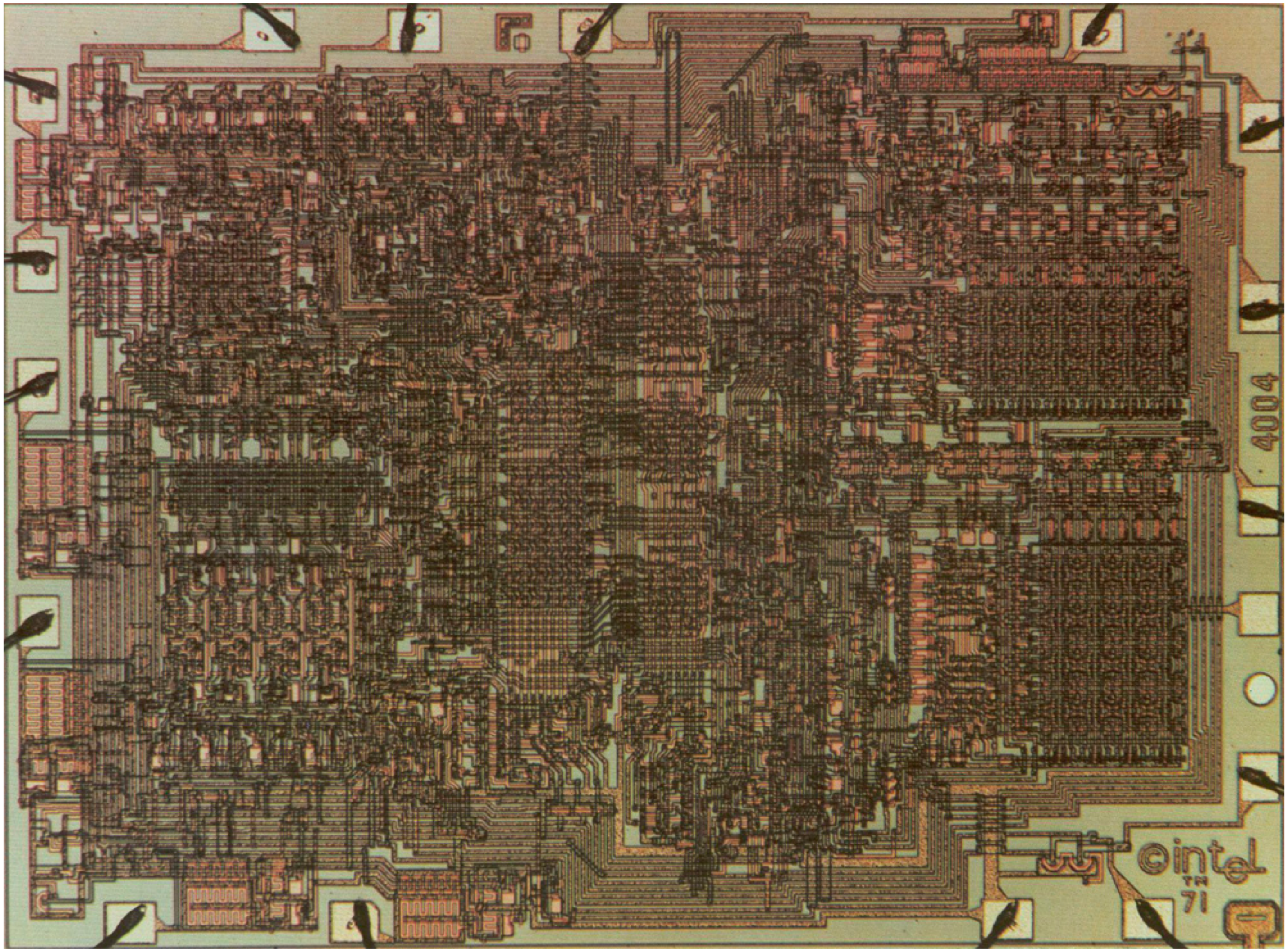
Lithography



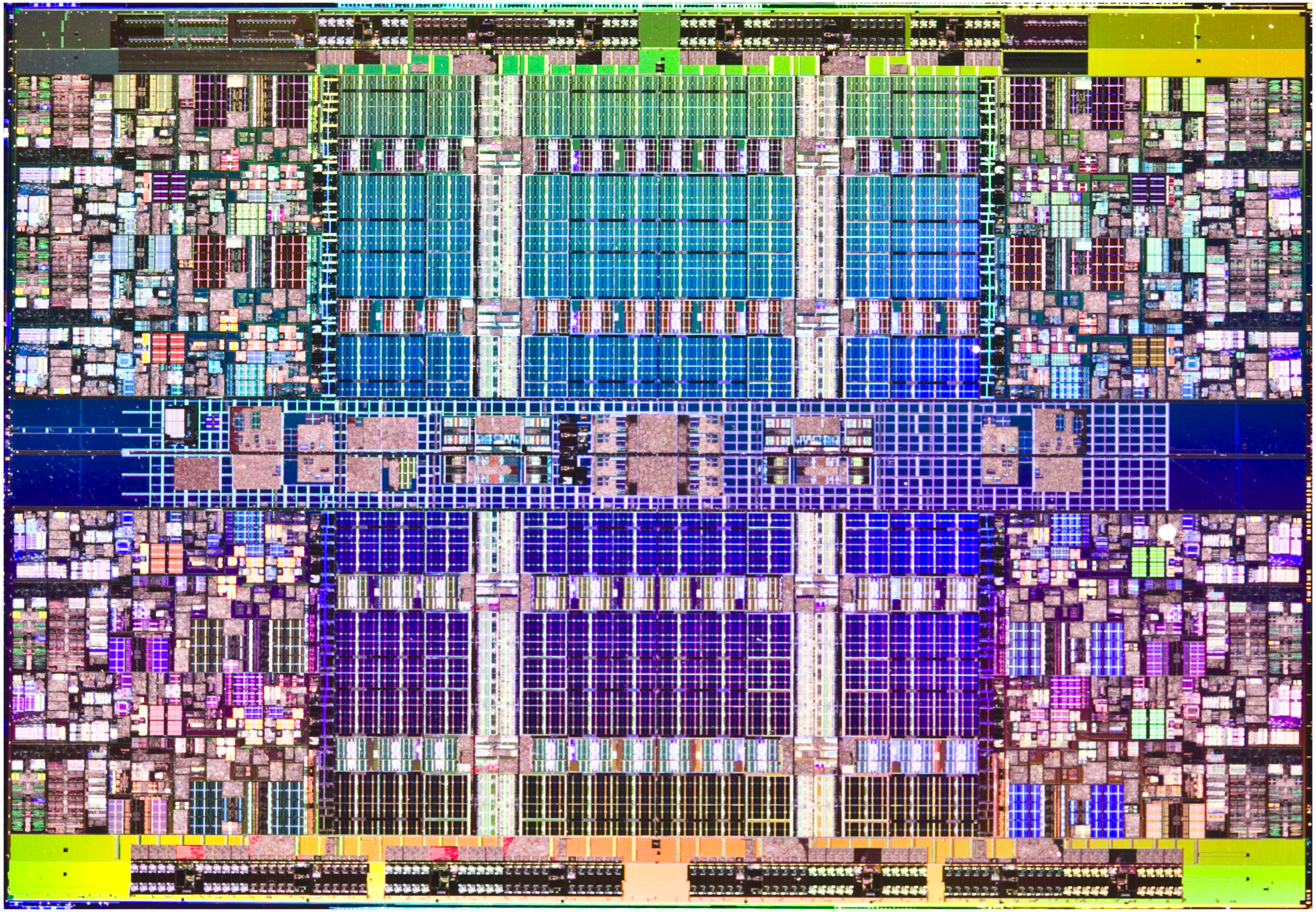
Example 1: XTR Junctions

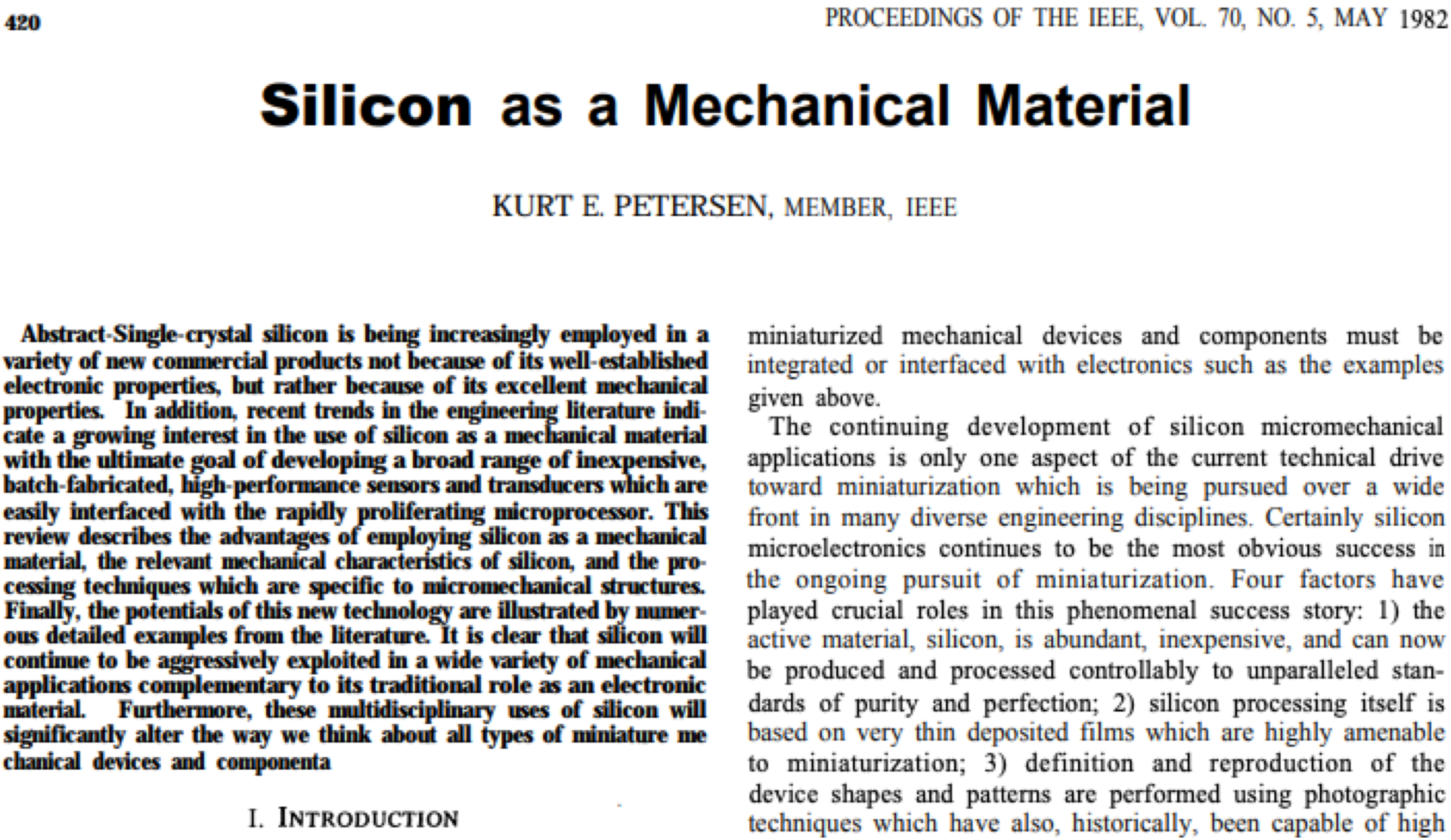
Example 2: Interconnect

Result



More of same …





420 PROCEEDINGS OF THE IEEE, VOL. 70, NO. 5, MAY 1982

Silicon as a Mechanical Material

KURT E. PETERSEN, MEMBER, IEEE

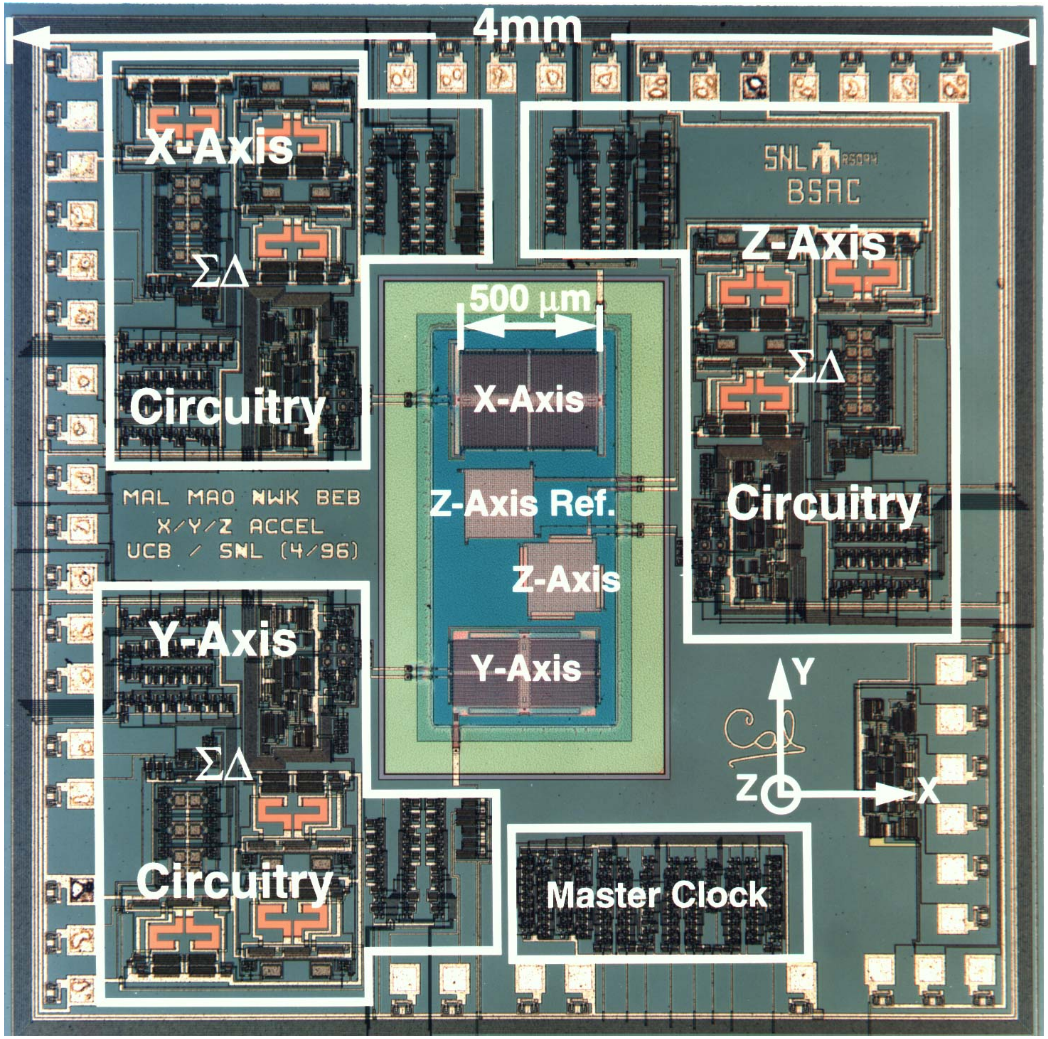
Abstract-Single-crystal silicon is being increasingly employed in a variety of new commercial products not because of its well-established electronic properties, but rather because of its excellent mechanical properties. In addition, recent trends in the engineering literature indicate a growing interest in the use of silicon as a mechanical material with the ultimate goal of developing a broad range of inexpensive, batch-fabricated, high-performance sensors and transducers which are easily interfaced with the rapidly proliferating microprocessor. This review describes the advantages of employing silicon as a mechanical material, the relevant mechanical characteristics of silicon, and the processing techniques which are specific to micromechanical structures. Finally, the potentials of this new technology are illustrated by numerous detailed examples from the literature. It is clear that silicon will continue to be aggressively exploited in a wide variety of mechanical applications complementary to its traditional role as an electronic material. Furthermore, these multidisciplinary uses of silicon will significantly alter the way we think about all types of miniature mechanical devices and components

I. INTRODUCTION

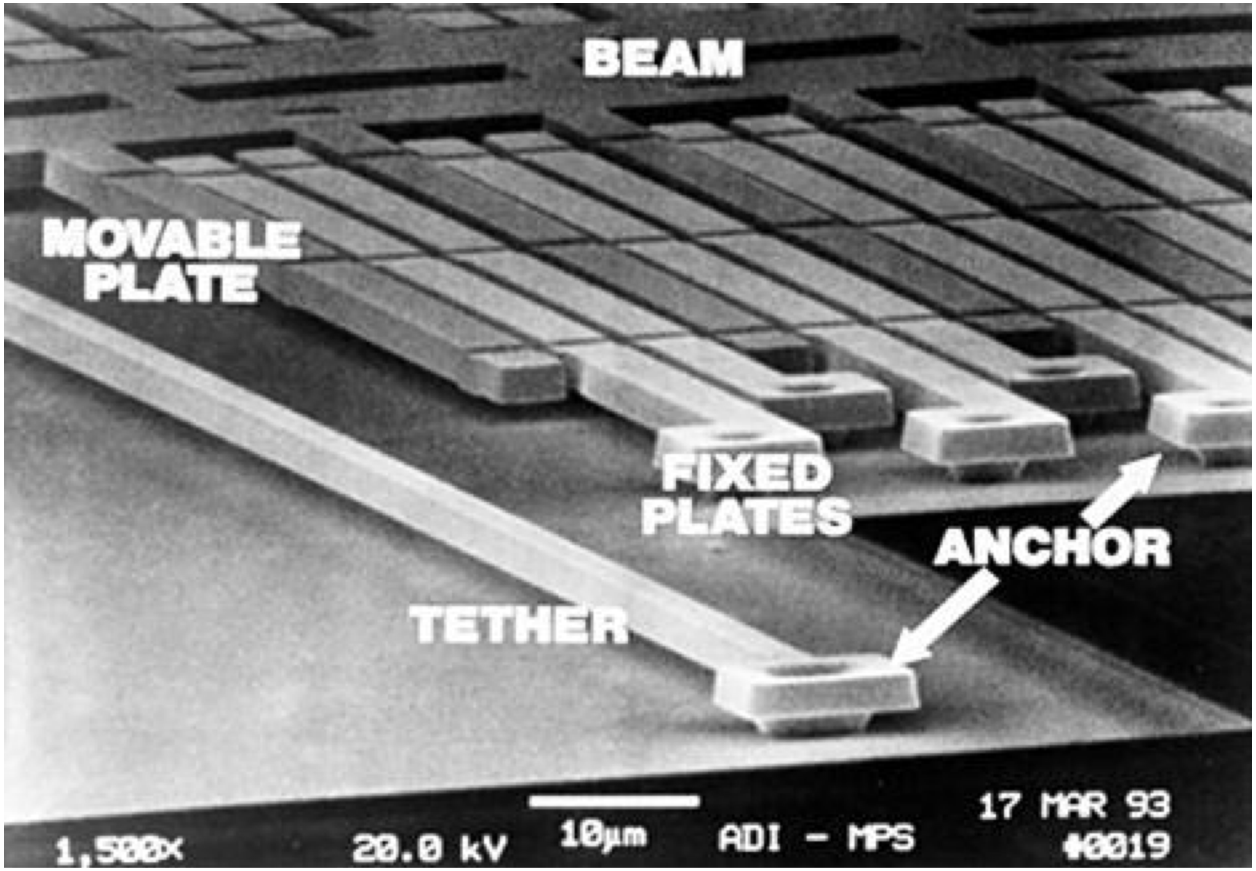
miniaturized mechanical devices and components must be integrated or interfaced with electronics such as the examples given above.

The continuing development of silicon micromechanical applications is only one aspect of the current technical drive toward miniaturization which is being pursued over a wide front in many diverse engineering disciplines. Certainly silicon microelectronics continues to be the most obvious success in the ongoing pursuit of miniaturization. Four factors have played crucial roles in this phenomenal success story: 1) the active material, silicon, is abundant, inexpensive, and can now be produced and processed controllably to unparalleled standards of purity and perfection; 2) silicon processing itself is based on very thin deposited films which are highly amenable to miniaturization; 3) definition and reproduction of the device shapes and patterns are performed using photographic techniques which have also, historically, been capable of high

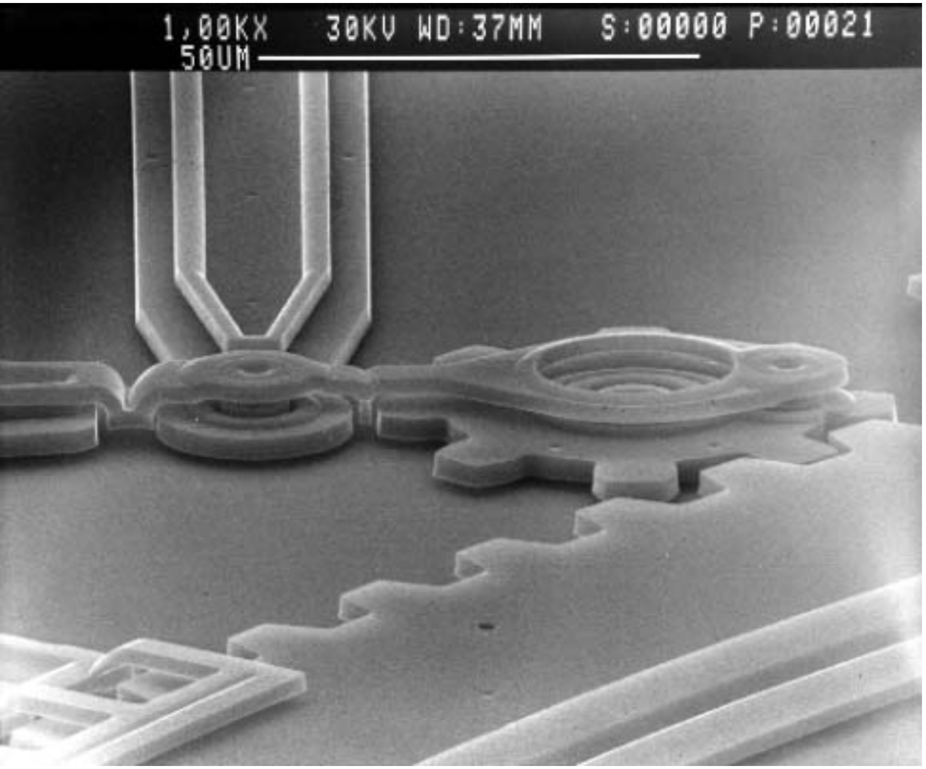
MEMS

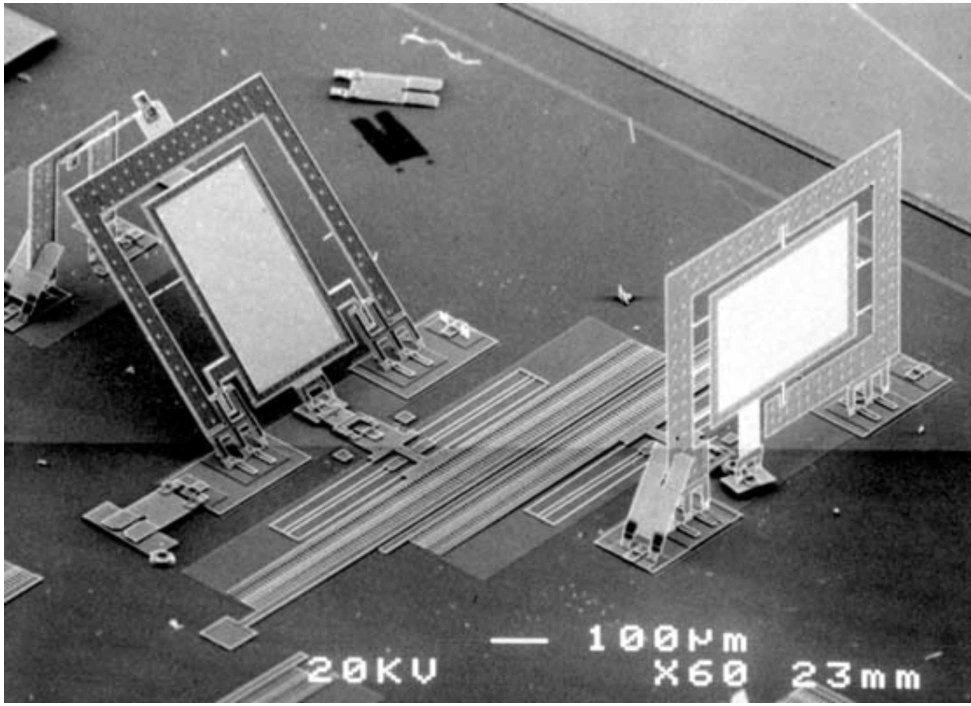

4mm
X-Axis
ΣΔ
Circuitry
MAL MAO NWK BEB
X/Y/Z ACCEL
UCB / SNL (4/96)
Y-Axis
ΣΔ
Circuitry
500 µm
X-Axis
Z-Axis Ref.
Z-Axis
Y-Axis
SNL
BSAC
Z-Axis
ΣΔ
Circuitry
Y
Cal
Z
X
Master Clock

MEMS Acceleration Sensor



Gears? 3D?





MEMS Process (Example)