ASML

Need we say Moore?

Jos Vreeker

December 12, 2015

ASML | Who we are and what we do

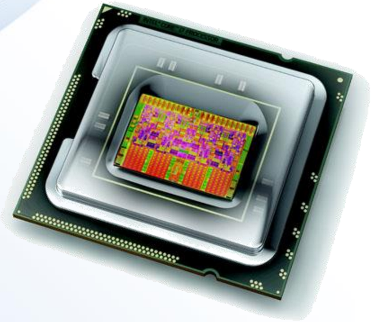
ASML | What did Gordon Moore publish in 1965

ASML | What did Moore’s Law bring

ASML | How did lithography enable Moore’s Law

ASML | What might the future bring

ASML is the world's leading supplier of lithography machines, used to make the most advanced computer chips.



ASML in 31 years

1984

Total market: € 463 million
Employees: < 60
Locations: 2 (NL, US)
Revenue: € 1.2 million
R&D: € <5 million

31

2015

Total market: € 6 - 7 billion
Employees: > 14.000
Locations: 70 in 16 countries
Revenue: € 5.6 billion (2014)
R&D: € 1.1 billion (2014; 80% NL)

ASML in 31 years

3,000 employees **8,600 employees** **2,400 employees**

More than 70 sales and service locations worldwide

Source: ASML Q4 2014

Before Moore's Law

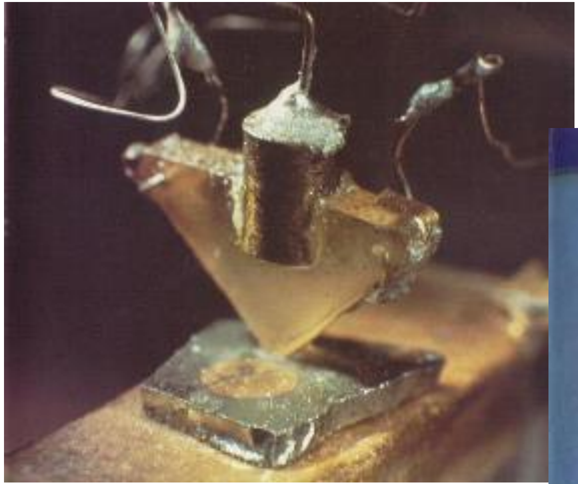
1951 Ford Country Squire

1958 Grundig tape recorder

1958 Pegasus 2 computer using vacuum tubes. Clock speed 8Hz,
Memory is a magnetic drum which holds 5120 words of 40 bits (in today's terms 25kB)

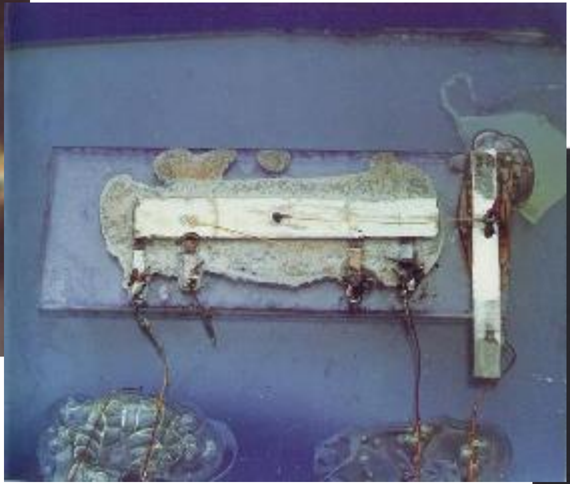
How it all started...

1947
The Point contact transistor
Bell Labs



1947 John Bardeen, William Shockley and Walter Brattain. (received Nobel price in 1956). Possibly the most important invention of the 20th century because it made all modern electronics possible.

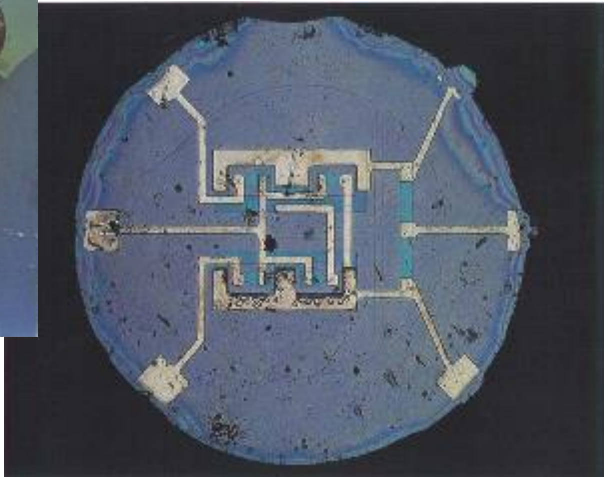
1958
The First IC
Texas Instruments



1958 First IC by Jack Kilby of Texas Instruments.
(received Nobel price in 2000)

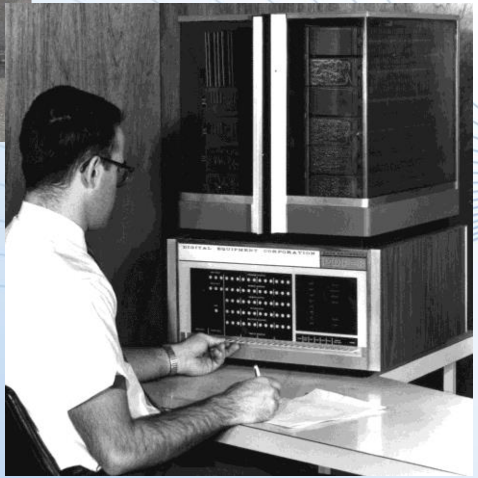
1961
The First Planar IC
Fairchild

1961 First planar IC by Robert Noyce of Fairchild. (died in 1990, otherwise would have shared the Nobel price in 2000). Kilby and Noyce recognized each other as co-inventors of the chip.



What did Gordon Moore publish in 1965?

1965 Aston Martin DB6



1965 Digital Equipment Corporation PDP8 minicomputer. Cost $18.000 and more than 50.000 sold.

1965 First telephone with keys instead of a rotating dial

Moore’s Law:

The amount of transistors per given area doubles every 2 years at similar cost

The most common version of Moore’s Law, namely a doubling of the amount of transistors per mm^2. ASML systems are between €50M and €100M and modern chip factories are between $6B and $13B. However, customers calculate with production cost per transistor and when they become smaller, more can be made at the same time which reduces the production cost/transistor. So miniaturization and mass production makes chips cheaper.

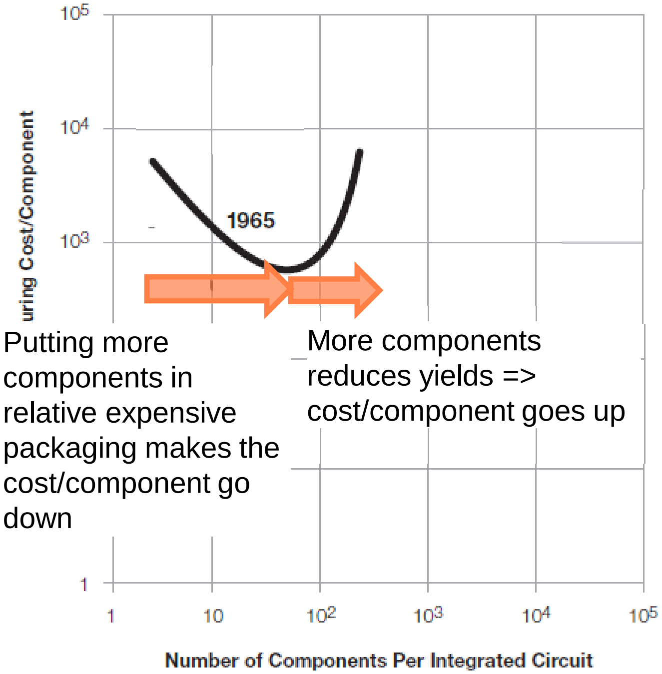
Factories and tools are more expensive, but:

Transistors can be made faster and therefore cheaper, so:

Electronics becomes cheaper, or has more functionality for the same price

What did Moore state?

minimum component costs

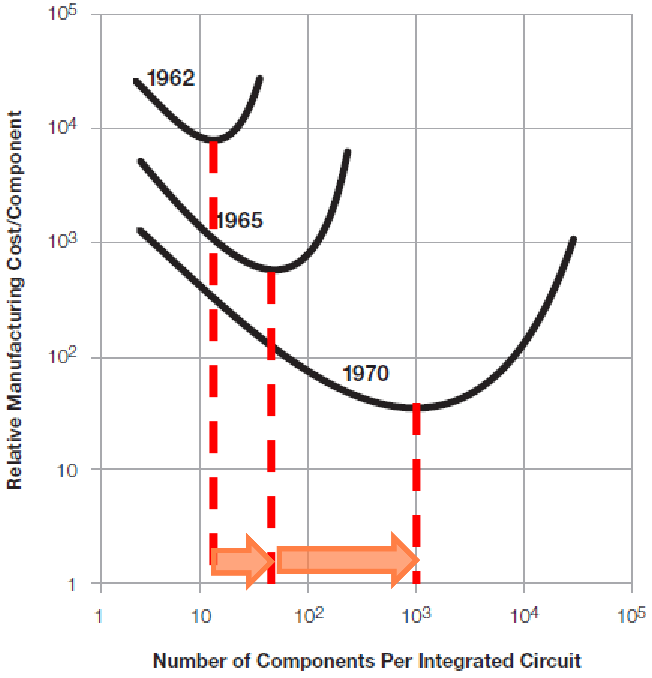


By putting more transistors into a relative expensive package the cost/transistor goes down.
However, if you put too many transistors in the package the chance of failure (yield=opbrengst) increases and the cost goes up again.
So there is an optimum number of transistors per package. This is what Moore stated.

G. Moore, ”Cramming more components onto integrated circuits”, Electronics, Vol. 38, Nb. 8 (**1965**)

What did Moore state?

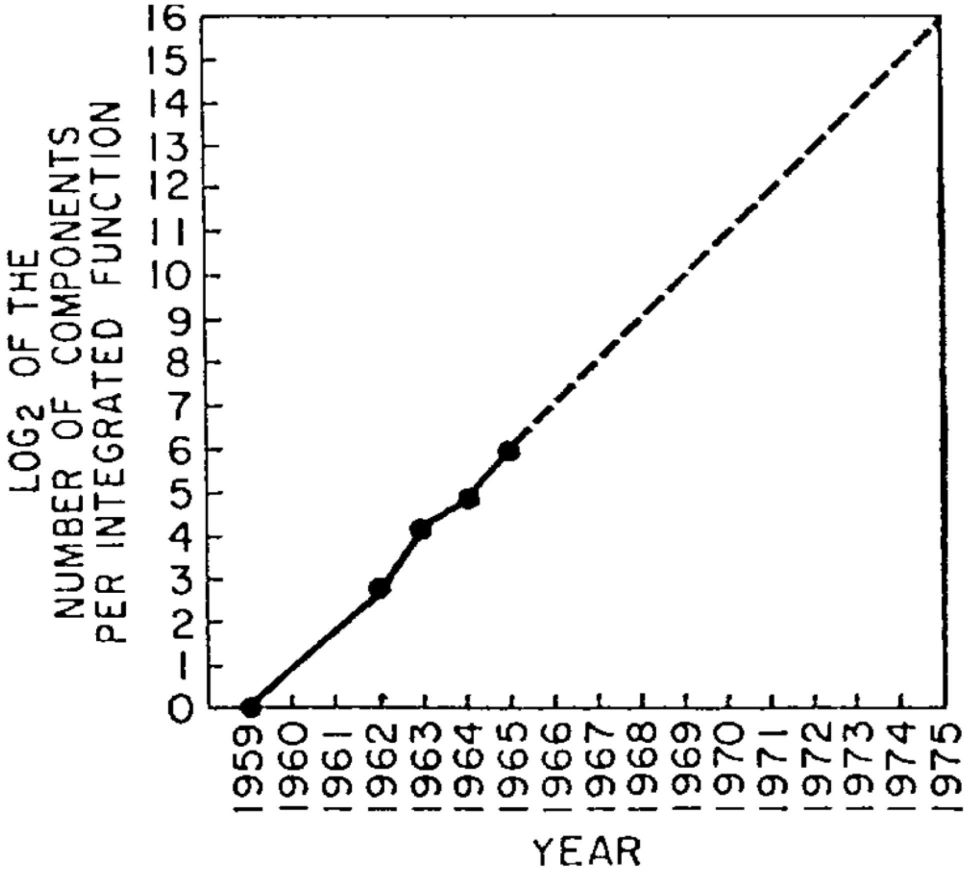
The **complexity for minimum component costs** has increased at a rate of roughly a **factor of two per year.**



The optimum number of transistors per package increased roughly by a factor of two per year, leading to an exponential growth of the number of transistors per surface area.

G. Moore, "Cramming more components onto integrated circuits", Electronics, Vol. 38, Nb. 8 (**1965**)

What did Moore state?



Moore then plotted the growth in this famous graph and extrapolated this to the mid 70's. However, the industry picked this up and continued the growth. Eventually Moore's Law became the guiding principle for the semiconductor industry.

The reason that Moore's Law is still pursued is that if it would stop, the development of electronics will slow down and as a consequence the sale of electronic gadgets and other equipment. This would have a serious impact on the world economy.

G. Moore, "Cramming more components onto integrated circuits", Electronics, Vol. 38, Nb. 8 (**1965**)

The challenge of Moore's law chessboard in numbers

The Best known example of exponential growth is the rice on the chessboard story.

When the creator of chess (ancient Indian Brahmin mathematician named Sessa or Sissa) showed his invention to the king, he was so pleased that he gave the inventor the right to name his prize. The man asked the king that for the first square of the chess board, he would receive one grain of rice, two for the second one, four on the third one, and so forth, doubling the amount each time. The king, arithmetically unaware, accepted the inventor's offer and ordered the treasurer to count and hand over the rice to the inventor. However, when the treasurer took more than a week to calculate the amount of rice, the ruler asked him for the reason. The treasurer then gave him the result of the calculation and explained that it would take more than all the assets of the kingdom. The story ends with the inventor becoming the new king.

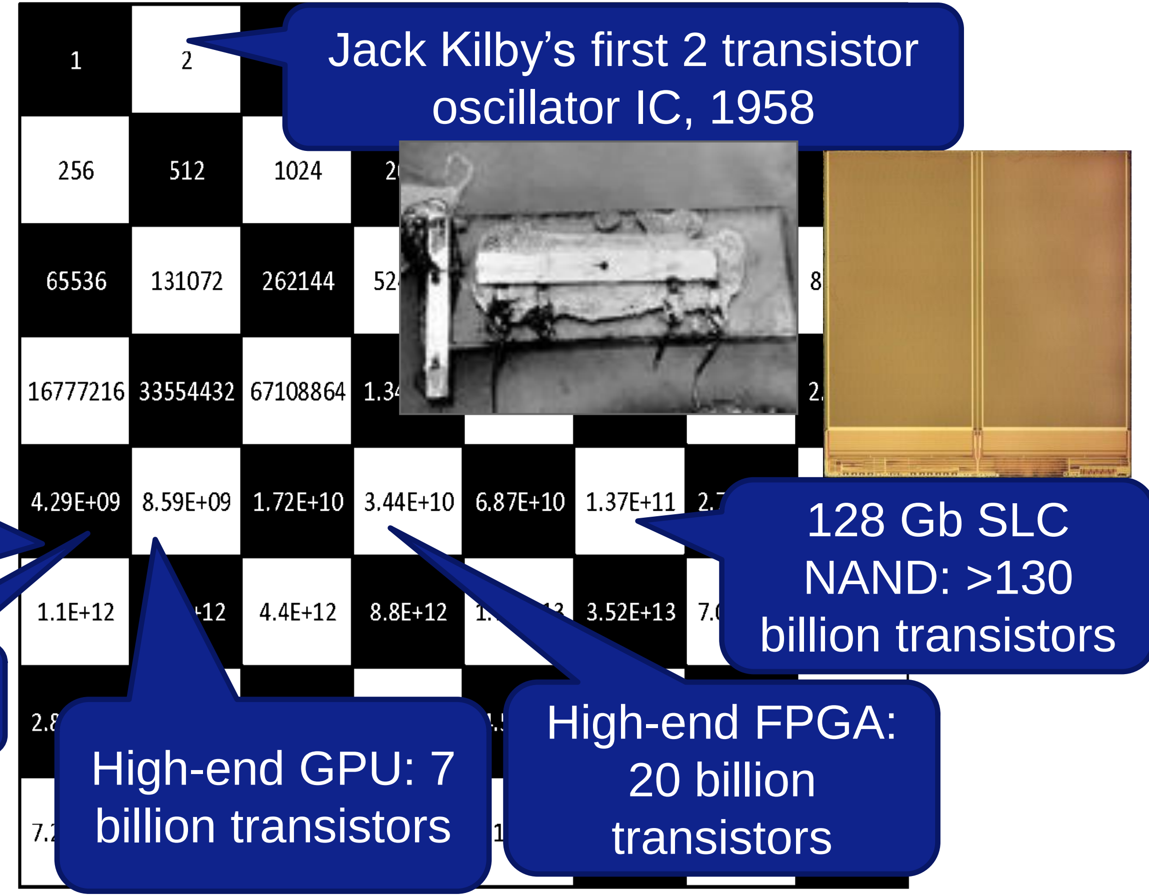
The first half of the board contains 100.000 kg of rice and the 2nd half 461,168,602,000 metric tons, or 1000x the global rice production in 2010.

1	2	4	8	16	32	64	128
256	512	1024	2048	4096	8192	16384	32768
65536	131072	262144	524288	1048576	2097152	4194304	8388608
16777216	33554432	67108864	1.34E+08	2.68E+08	5.37E+08	1.07E+09	2.15E+09
4.29E+09	8.59E+09	1.72E+10	3.44E+10	6.87E+10	1.37E+11	2.75E+11	5.5E+11
1.1E+12	2.2E+12	4.4E+12	8.8E+12	1.76E+13	3.52E+13	7.04E+13	1.41E+14
2.81E+14	5.63E+14	1.13E+15	2.25E+15	4.5E+15	9.01E+15	1.8E+16	3.6E+16
7.21E+16	1.44E+17	2.88E+17	5.76E+17	1.15E+18	2.31E+18	4.61E+18	9.22E+18

We moved to the second half of the board

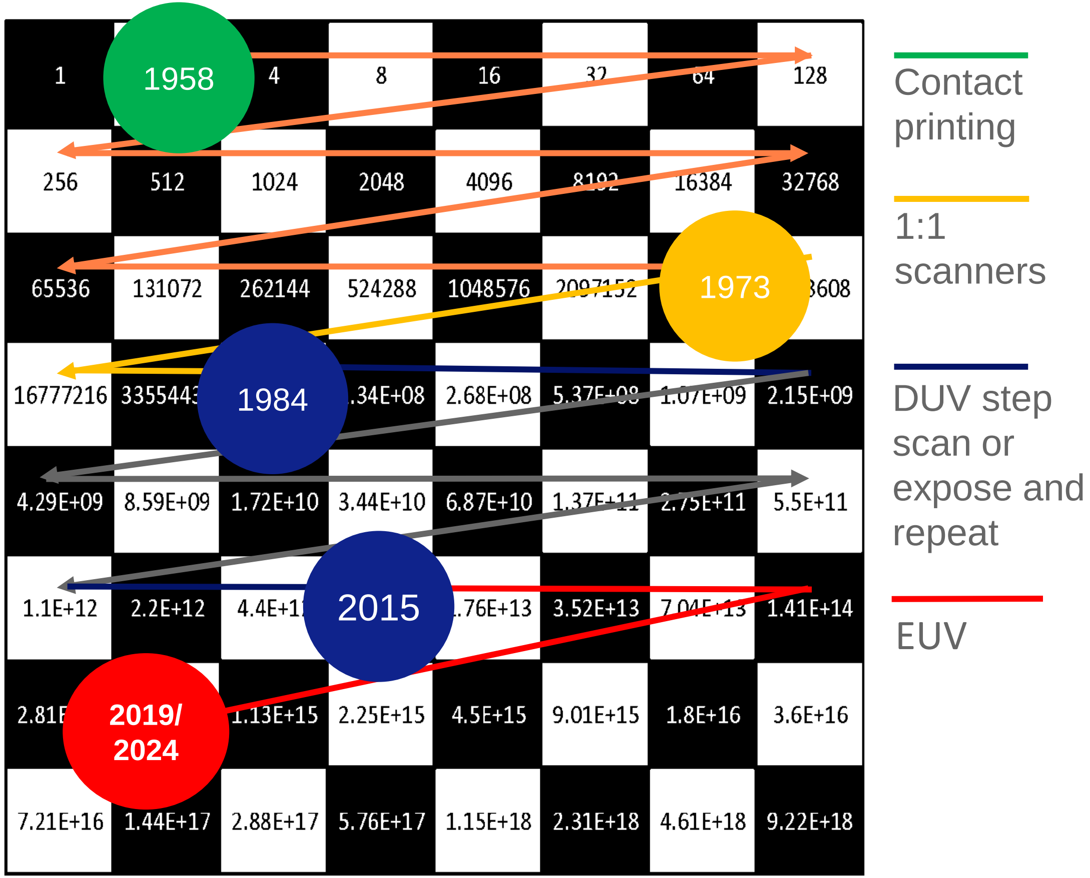
During the past 50 years 1.4 shrink/year.

Calculation transistors per memory chip: A 16GByte chip is 128Gbit (8 bits in a Byte). In a SLC chip you need 1 transistor per bit, so a 16GB chip contains more than 128 billion transistors, plus a few billion for contol circuitry.
MLC (multi level cell) chips have 2 bits per transistor, so 64billion for a 16GB chip.



MPU = Micro Processor Unit
DRAM = Dynamic Random Access Memory
GPU = Graphics processing Unit
SLC = Single Level Cell
NAND = NOT-AND gate
FPGA = Field-Programmable Gate Array

We are preparing to make an other 6 moves in 10 years



1973: 1:1 Scanners, 436 nm light
3 µm, 75 mm wafers, 40 Wafers/hour

1984: 436 nm and 365 nm light
1,2 µm, 100 mm Wafers, 40 Wafers/hour,

2015: 193 nm light, Immersion technology
19 nm, 300 mm Wafers, 275 Wafers/hour,

2019-2024: 13,5 nm EUV light
5 – 10 nm, 300 mm Wafers,
>100 wafers/hour

What else did Gordon Moore say

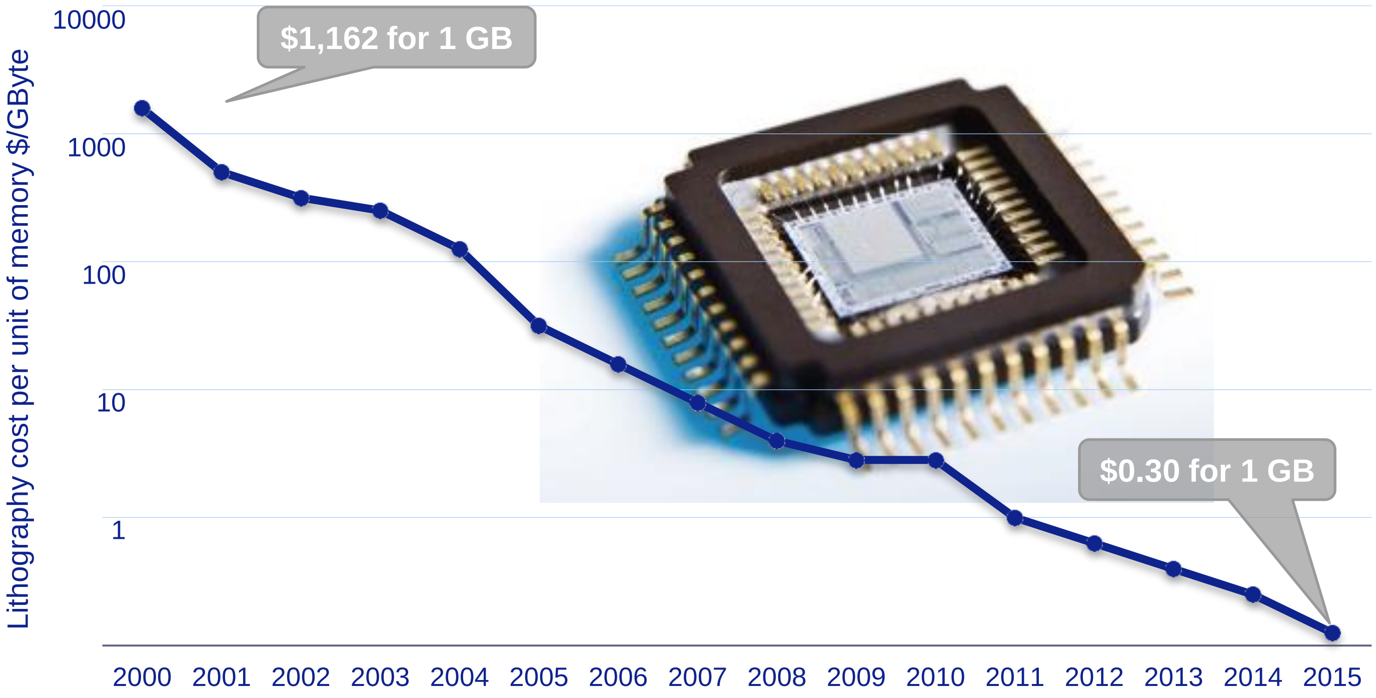
“Integrated circuits will lead to such wonders as home computers or at least terminals connected to a central computer, automatic controls for automobiles, and personal portable communications equipment.”

Gordon Moore is one of the few scientists who has put a cartoon in a scientific paper.
However, his prediction was spot-on, as an add from 2005 shows.
There computers are offered next to cosmetic products.

40 years
later

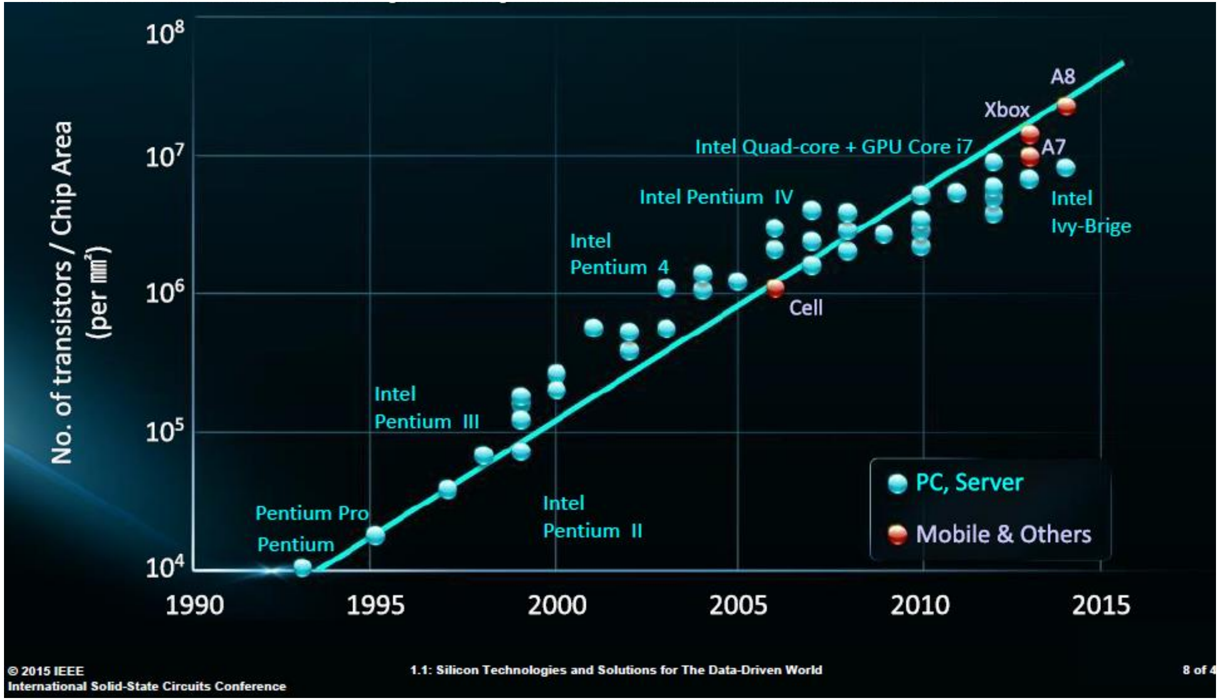
What did Moore’s Law bring?

Moore's law makes chips cheaper



Source: Gartner. High quality Flash

Moore’s law makes chips more powerful



Samsung: ISSCC 2015

Relentless innovation in your pocket

IBM 5150		Apple iPhone 6
1984	year manufactured	2015
$1500-$3000 roughly $5000 today	price	$649-$849
16-bit Intel 8088 4.77 MHz	processor	64-bit Apple A8 dual-core 1.4 GHz
16-265 kB	Working memory	1 GB
5” floppy disk 160 kB	internal storage	up to 128 GB
640x200 pixels	monitor	1920x1080 pixels

How did lithography enable Moore’s Law?

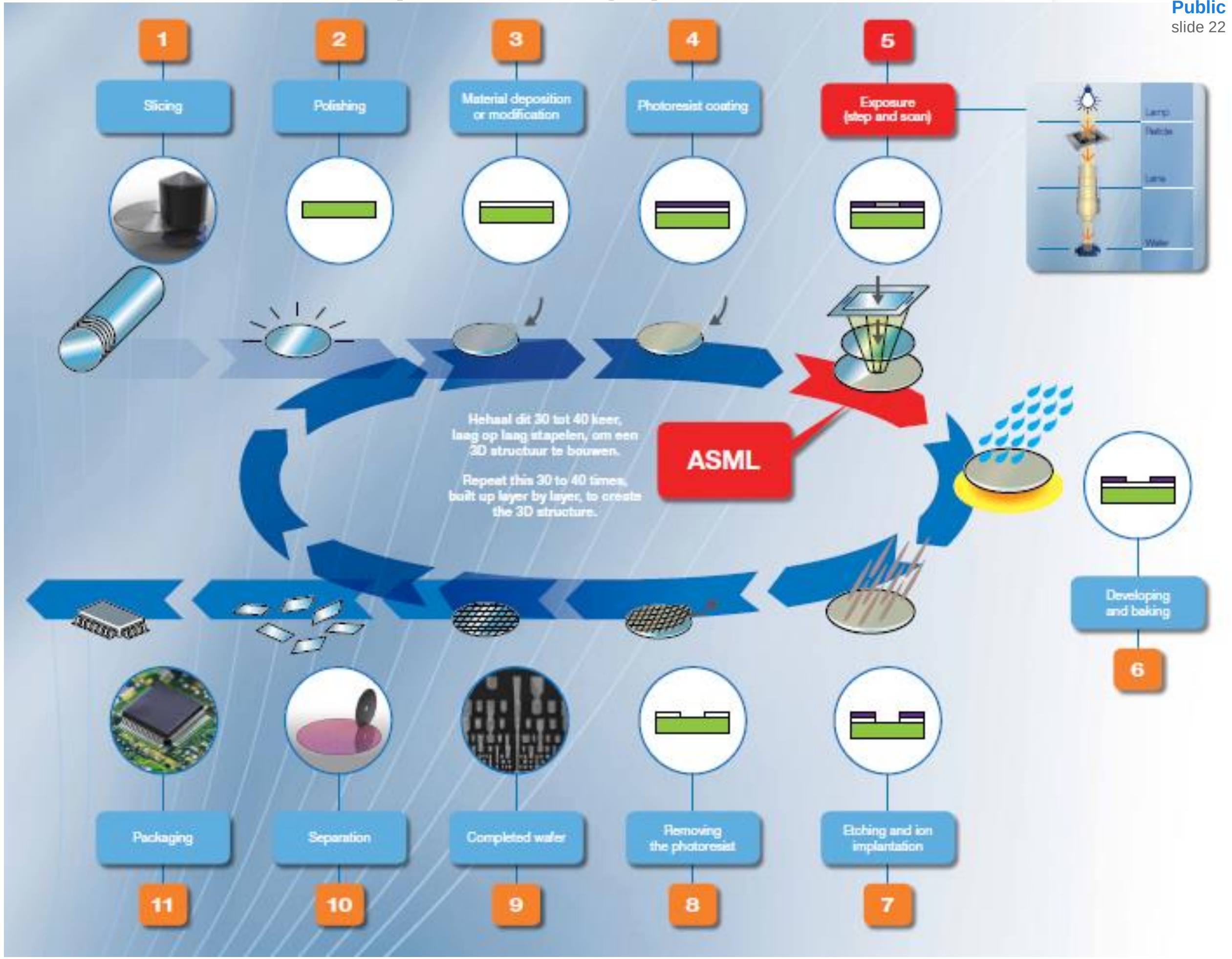
Litho is (still) the heart of the chipmaking process

How to make a computer chip

1. It starts with silicon, which is sand. The silicon is melted and shaped into a bar, which is then cut into discs.
2. The discs, called wafers, are polished.
3. The next step is depositing a layer of silicon dioxide on the wafer. This is done in machines from ASM International, one of the founders of ASML.
4. A layer sensitive to Ultra Violet light is deposited on the wafer. This is called photoresist.
5. Then the wafer enters an ASML system, a kind of copying machine. Light goes through a mask (that we call a reticle) that contains the structures of one layer of the chip. The light then goes through a lens that reduces the image size by 4 times and falls on the wafer with the photo sensitive layer. On areas where the light falls on the wafer, the photo sensitive layer slightly changes. When the wafer is fully exposed, it leaves the machine. The ASML system is only one step in the whole production process, but it is the most critical and also the most expensive step.
6. In the next step, the wafer is developed. Photoresist touched by the light is washed away until the structure of the chips remains.
7. Using acid, part of the silicon dioxide is etched away, but only in areas that are not protected. After that, the wafer is bombarded with charged particles (ions) that make the actual components of the chip.
8. The last step of the first layer of the chip is to remove the remaining photoresist.

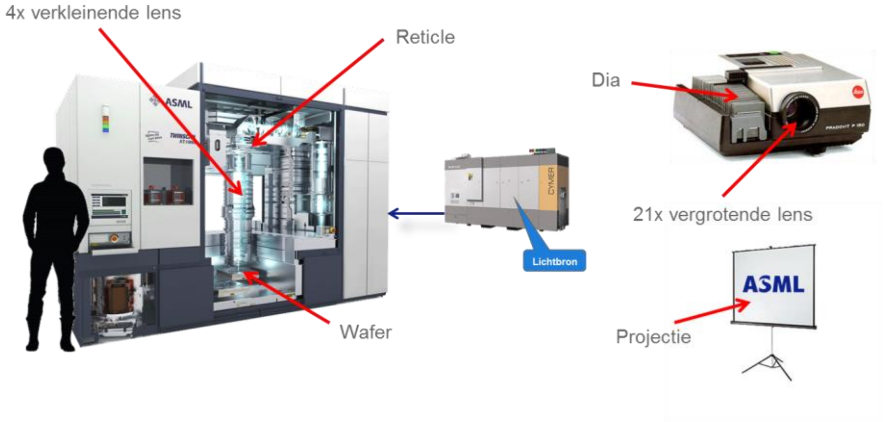
After this step, the whole process starts again from no.3 to make the next layer. A mask with a different pattern has already been loaded into the ASML machine. Depending on the complexity of the chip, this is repeated 30 to 40 times until the chip is ready. So a chip is built up layer by layer.

9. When the wafer is finished, all chips are tested.
10. After that, the chips are cut with a miniature circular saw.
11. The last step is to package the chips and connect them to the pins on the outer edges. They then can be placed in an iPad, computer or smartphone.

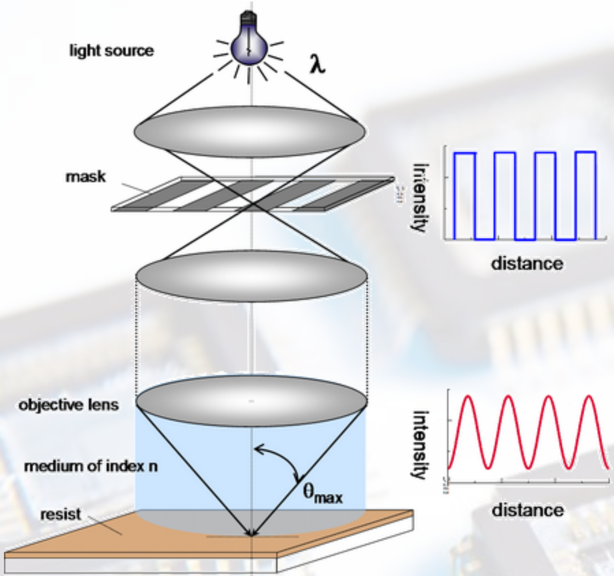


How does an ASML lithography machine work

Simplified:



The basic rule of lithography



© IBM Research

$NA = n \times \sin(\theta_{max})$

Schematic diagram of the optics of a projection exposure lithography system

John William Strutt, lord Rayleigh

Resolution:

$$R = k_1 \frac{\lambda}{NA}$$

Numerical aperture:

$$NA = n \sin(\Theta)$$

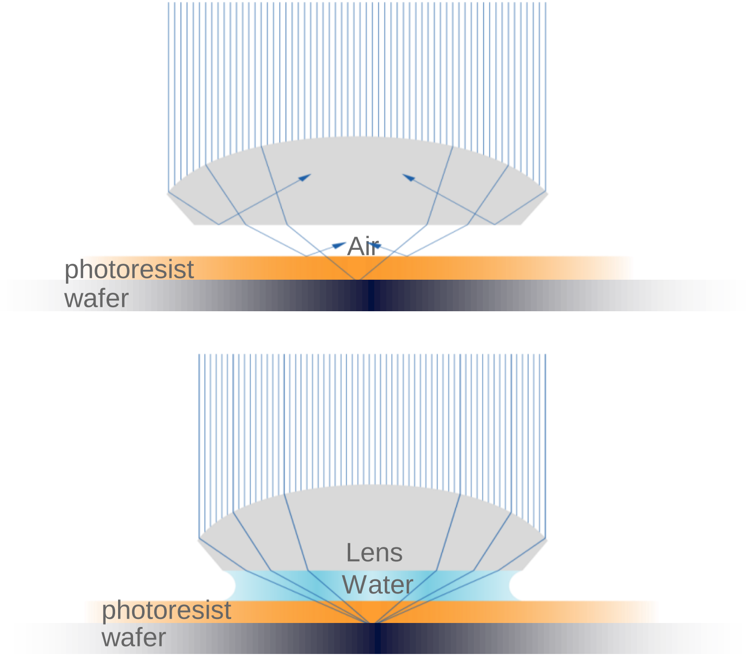
NA is calculated by the sine of the angle of the light bundle coming out of the lens. The maximum is 1, but then no light is coming out of the lens anymore. In practice the maximum NA is 0.95. Replacing the air by water increases the breaking index to 1.38 making an NA of 1.35 possible and thus reducing the resolution.

To print smaller lines:
- Reduce wavelength
- Increase NA
- Reduce k1

R = resolution (linewidth)
λ = wavelength of light
NA = Numerical Aperture
K1 = Litho process improvements, reticle, resist. (minimum 0.25)
n = breaking index. Air = 1; water is 1.38

Fluid thinking: the liquid lens scanner

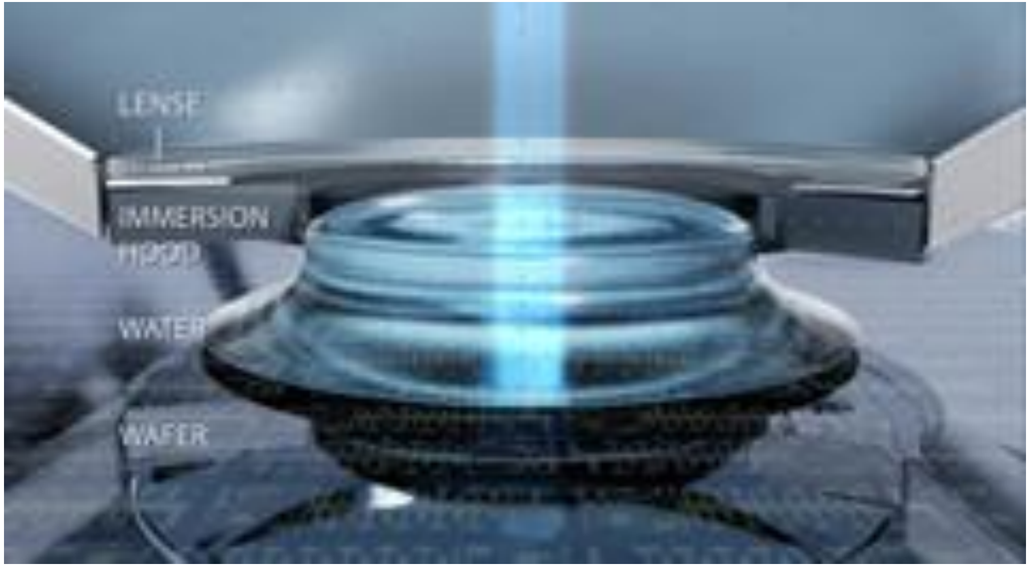
Water improves resolution and process latitude



Immersion lithography is currently the most used method in lithographic equipment.
The method comes from the field of microscopy and was invented by Robert Hooke in the 18th century.
The water needs to be very pure, the scanspeed is important because of microbubbles, and the temperature is tighly controlled.
The water puddle is very small and kept in place with air pressure and vacuum. It is constantly renewed.

Fluid thinking: the liquid lens scanner

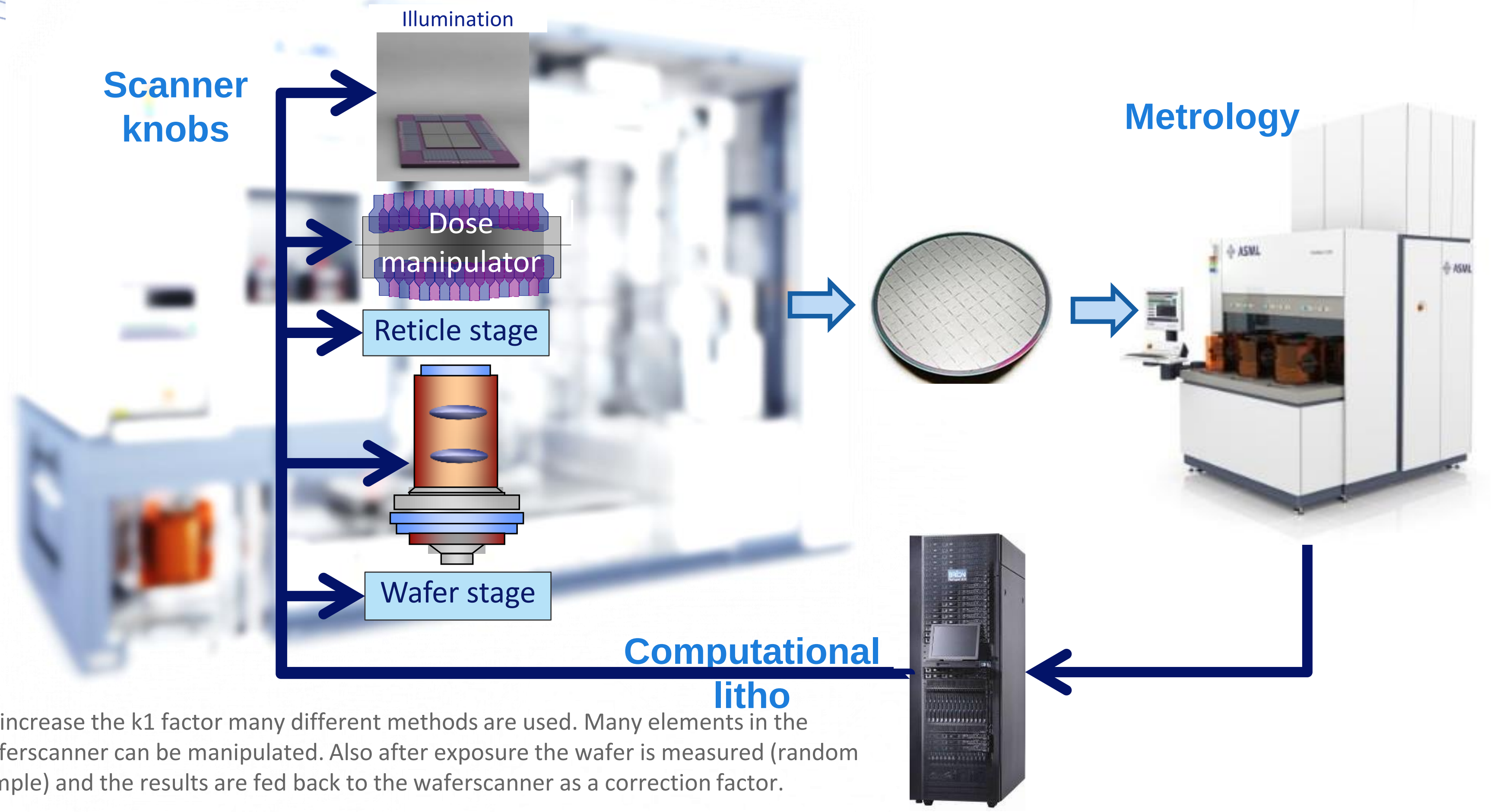
Water improves resolution and process latitude



The ASML scanner has two wafer tables of which one is used for exposing the wafer and the other one simultaneously measures the next wafer to be exposed.

When the exposure is finished and the second wafer must be exposed, the wafer tables change position so fast that the water puddle stays in position and has no time to move.

Low k1: use feedback to push performance to physical edge



To increase the k1 factor many different methods are used. Many elements in the waferscanner can be manipulated. Also after exposure the wafer is measured (random sample) and the results are fed back to the waferscanner as a correction factor.

Characteristics and challenges of an EUV system

Exposure wavelength of 13.5nm is absorbed by all known materials. So:

- System must operate in a vacuum
- Use mirrors instead of lenses
- The light is reflected by the reticle instead of going through
- Use MagLev waferstage instead of waferstage with airbearing

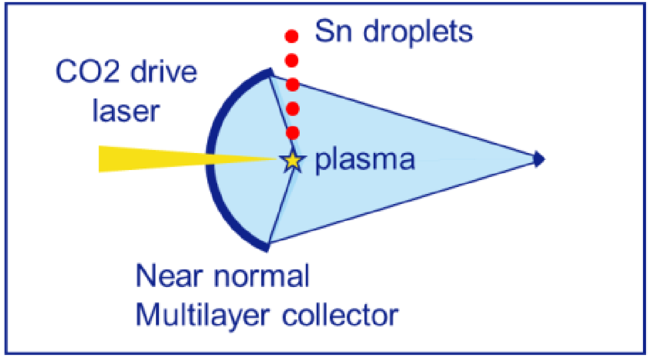
Remaining challenges:

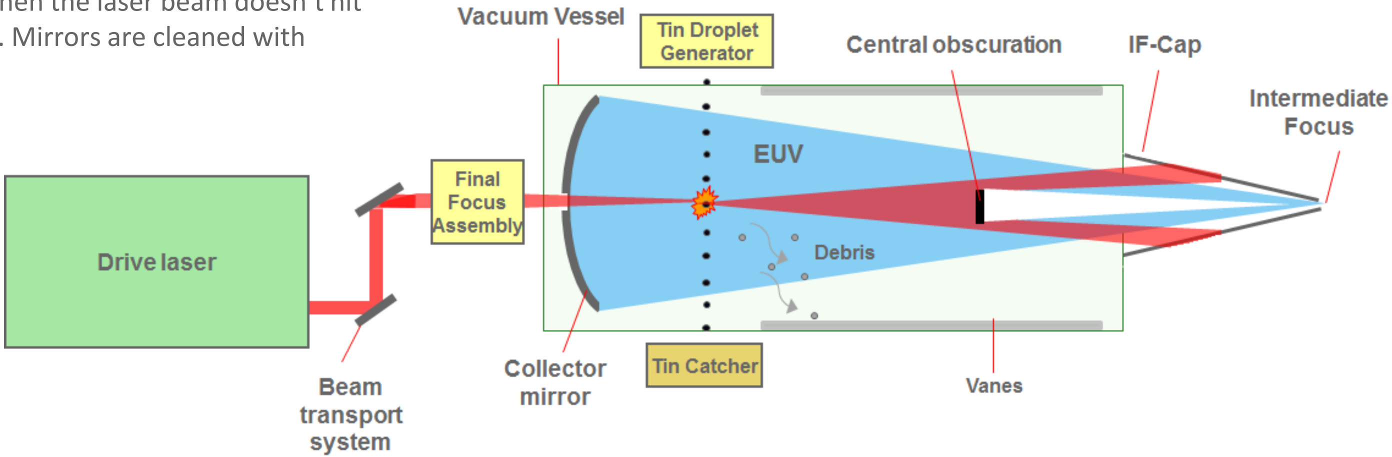
- Source power (LPP).
- Reticles (flatness, defects, shadowing effects caused by reflection)
- Resist (line-edge roughness, sensitivity)
- Inspection tools (availability of tools)

EUV = Extreme Ultra Violet

LPP Source - principle of operation

The principle of an LPP source (Laser Produced Plasma) is that a powerful laserbeam from a CO_2 laser hits a drop of liquid tin. The tin instantly heats to more than 300.000 degrees and forms a plasma. When the electrons fall back to the core, a photon of light is produced with a very specific wavelength of 13.5 nm.
The light is collected by a multilayer mirror and reflected into the wafer scanner. The tin droplets fall with a speed of 50.000 per second.
The real system has a central obscuration to avoid the CO_2 laser beam entering the waferscanner.
Debris on the mirror is a problem when the laser beam doesn't hit the tin droplet exactly at the center. Mirrors are cleaned with deuterium.





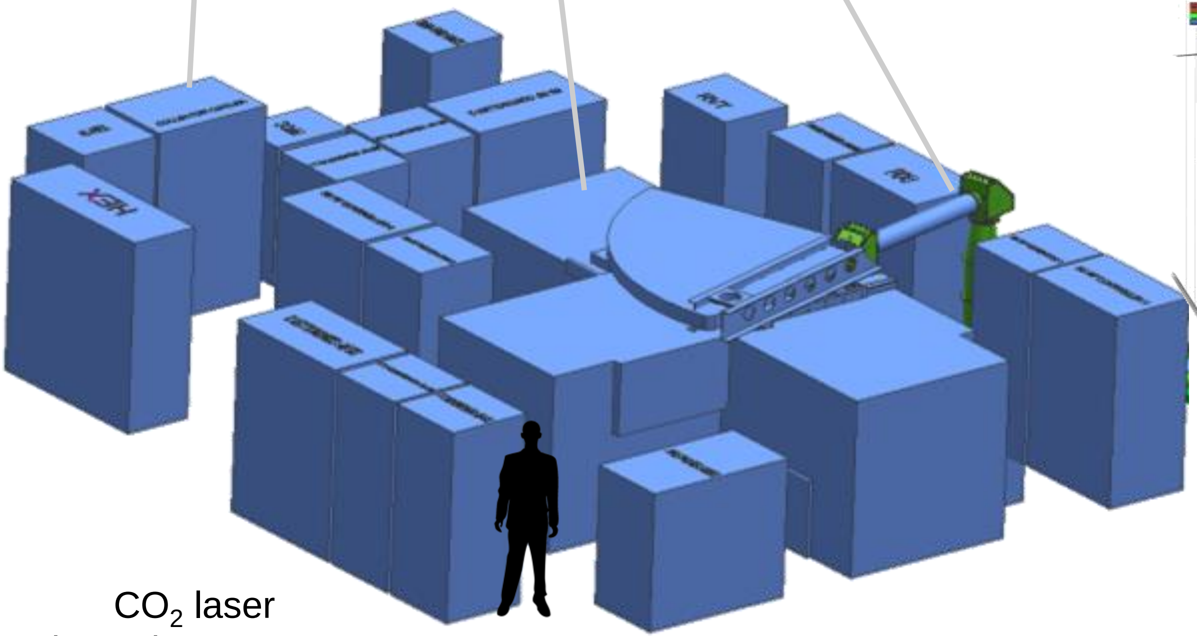
CO_2 System Overview

Scanner
Dimension: 9.5m x 3.5m

Beam Transport System

Heat exchangers and electronics cabinets

CO_2 Drive Laser

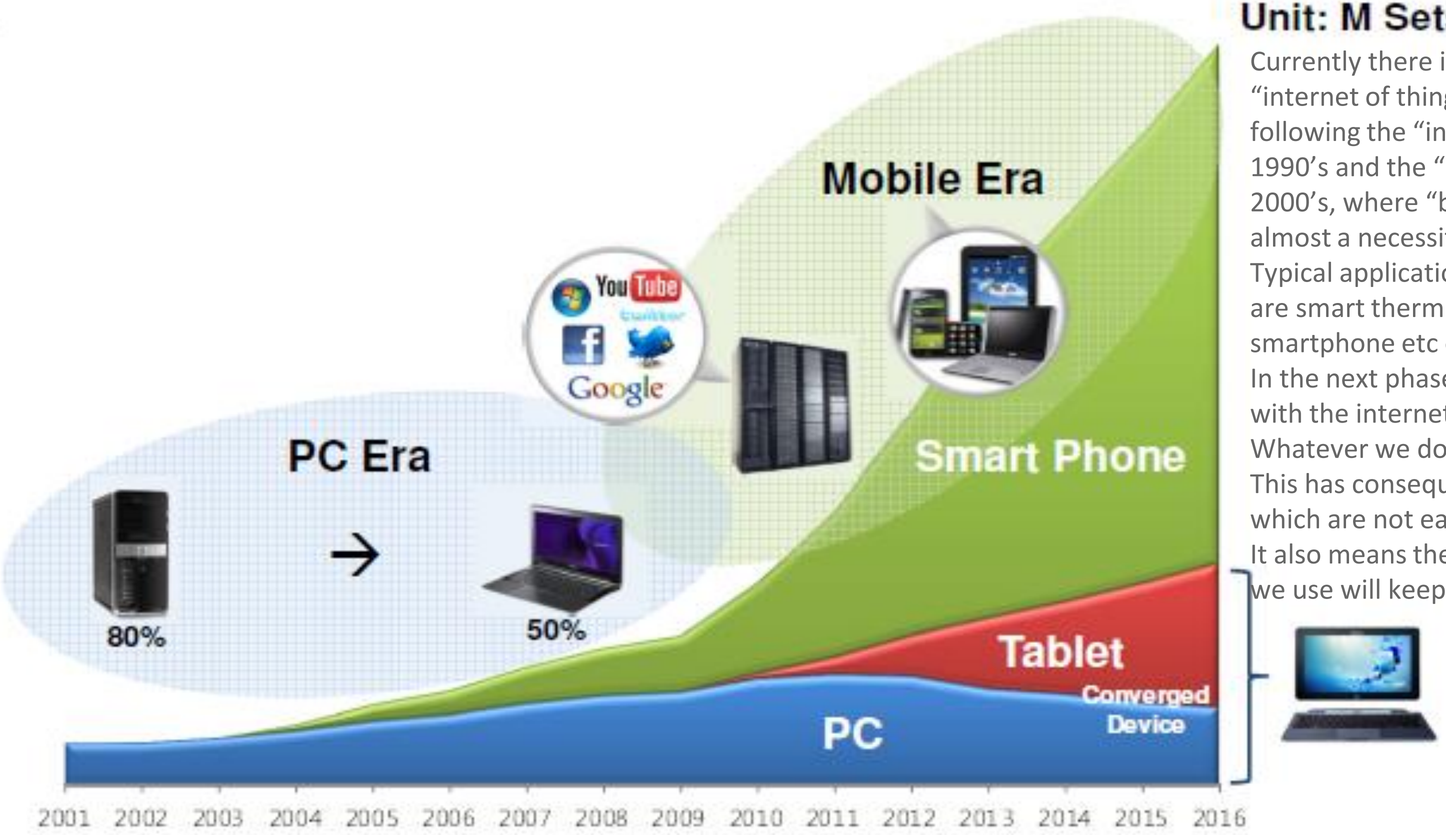


CO_2 laser
Dimension: 9m x 7m

EUV source, collector mirror and droplet generator

What might the future bring

The rise of smart phones and tablets



Currently there is much discussion about the "internet of things". This is a logical step following the "internet of companies"in the 1990's and the "internet of people" in the 2000's, where "being online" became almost a necessity.
Typical applications with the "internet of things" are smart thermostats, control lighting via the smartphone etc etc.
In the next phase we will always be connected with the internet, wherever we go and Whatever we do.
This has consequences for issues like privacy which are not easily solved.
It also means the the amount of electronics we use will keep on growing.

Internet of companies | Internet of people | Internet of things | Internet of everything

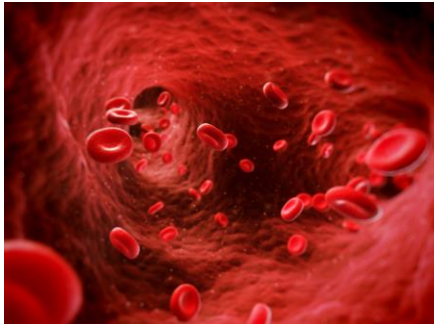
Source: Pablo Temprano, Samsung, ISS, Jan 2014

Moore’s Law will continue for foreseeable future

The semiconductor industry issues a “roadmap” every few years.
The graph gives the status in the 2013 report.
This roadmap is already outdated, as circuits of 10nm or smaller are exprected to go into mass production in 2017.
The latest is that structures of 5 nm are taken into development. They could be ready for production early next decade.
With structures of this size, a simple computer can have the dimensions of a red blood cell, which opens endless possibilities in medical systems.

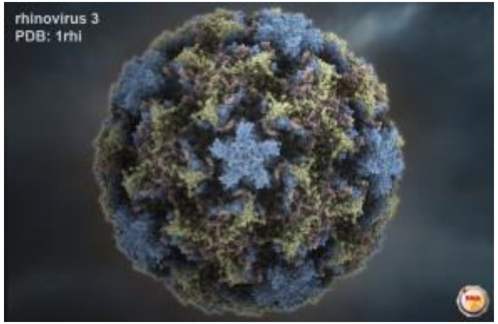
	Year of Production				
	2013	2015	2017	2021	2025
Logic	40	32	25	16	10
Flash	18	15	13	9	8
DRAM	28	24	20	14	10

© INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS **2013 EDITION. Values in nanometers**



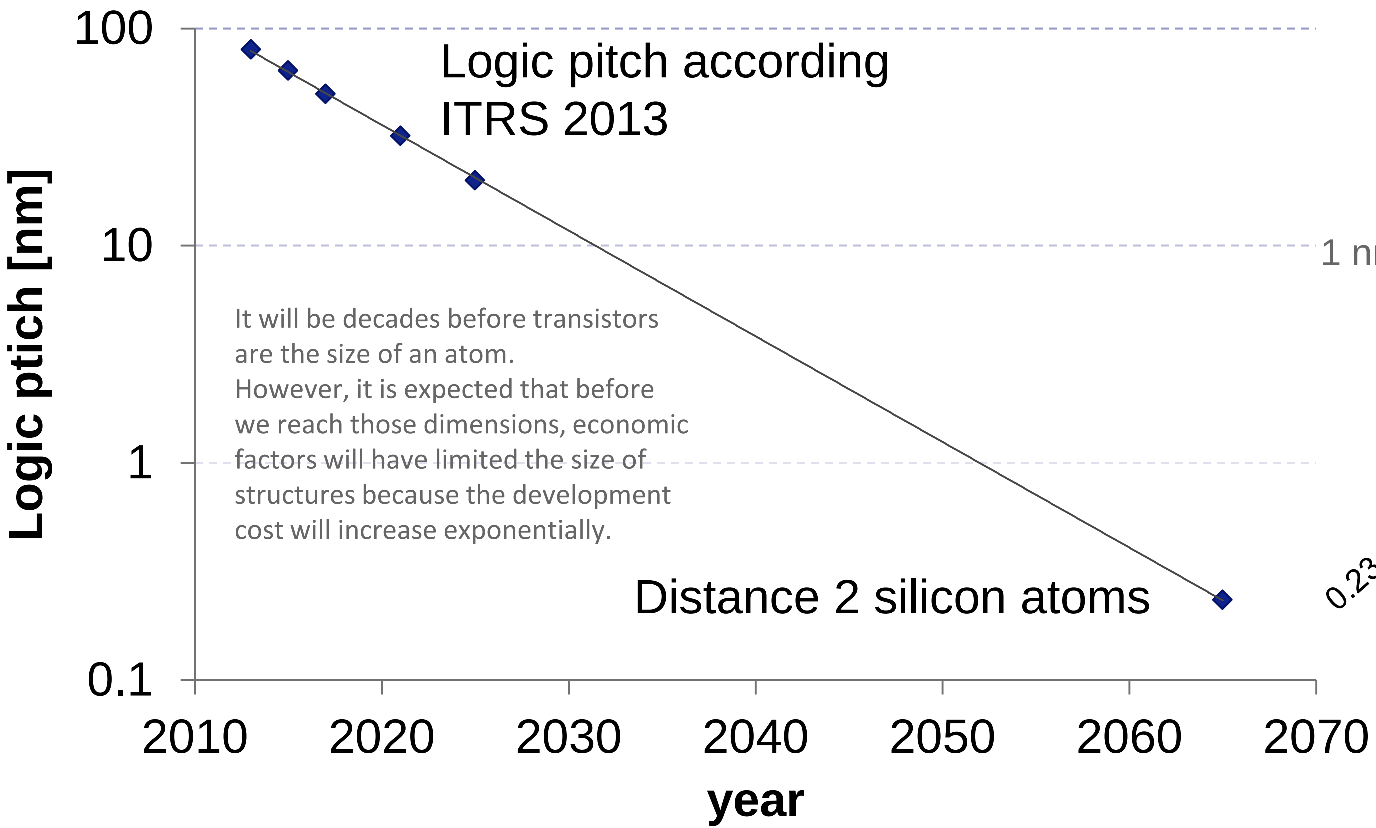
Red blood cell: 7 to 8 μm

Influenza virus: 100nm

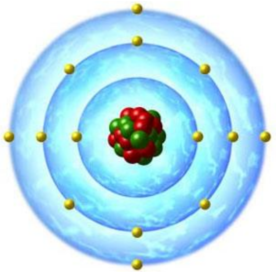


Rhino virus: 30nm

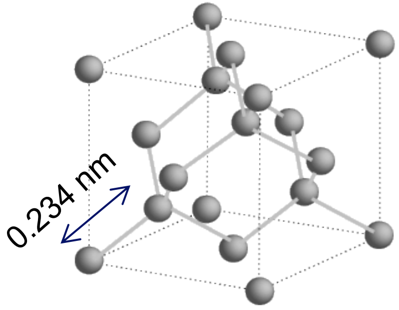
When is a transistor the size of an atom?



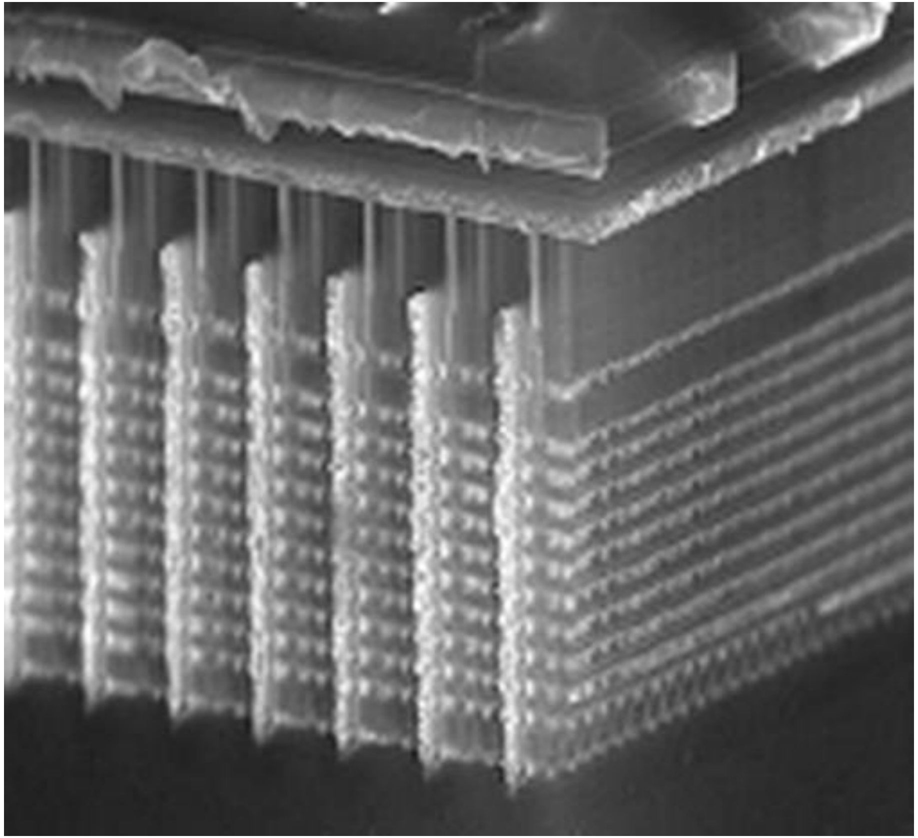
It will be decades before transistors are the size of an atom.
However, it is expected that before we reach those dimensions, economic factors will have limited the size of structures because the development cost will increase exponentially.



1 nm = 4 silicon atoms

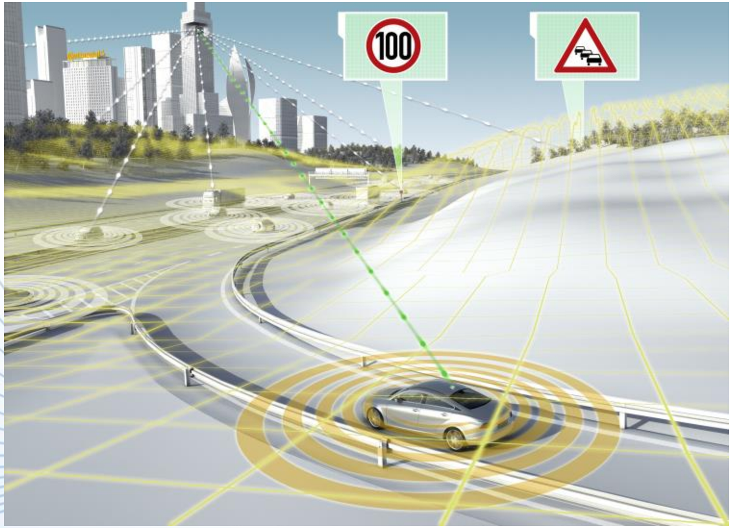


Going into 3rd dimension – another way to maintain Moore’s Law



One method of continueing Moore’s Law is building chips in the third dimension. This is not as simple as it sounds and the technical difficulties which must be overcome are numerious. Developments in this are are already going on for decades, but recently there are some important breakthroughs which make this a real, possible solution.

What might the future bring?



It is impossible to predict the future.
However, it is expected that within 5 to 10 years self-driving trucks will be a reality on the road. The main reason is that the cost of the system is small relative to the cost of a truck, and it has economic advantages for trucking companies.
It is expected that a system will emerge where trucks will drive between distribution centers outside large cities and that the distribution of goods will be done by smaller, electric trucks. Currently more and more cities are already limiting the access of gasoline trucks in the inner cities.
Within a few years our cars will also be continuously on-line.

What might the future bring?

Self-driving cars are (according to the car industry) not expected before 2030. The rest is pure speculation. However, it is expected that most breakthroughs will be made in the fields of medical care and alternative energy/energy conservation.

Summary

- Society would be very different without “Moore’s Law”
- It is not a physical law but an empirical observation based on economics.
- The law was re-written several times, including by Gordon Moore himself.
- Lithography has played a key role in enabling Moore’s Law
- Other critical elements include material science, transistor design, circuit architecture......
- There is no end in sight.

ASML