The Vibrant Moore's Journey of Integrated Circuits

The Magical Power of Big Numbers

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This file is a revision of the slideshows of the speech at the annual Marie Curie Chemistry Camp on July 30th, 2021. The title of the speech is "The Vibrant 'Moore's' Journey of Integrated Circuits: The Magical Power of Big Numbers".

- Connecting the Dots
  - In preparing to speak to you about the 70 spectacular years of semiconductor integrated circuits (IC), I have been given the opportunity to revisit and connect all the events, stories, and insights that I have witnessed, experienced, and held close to my heart over my 40 years in the semiconductor industry. Having the luxury of hindsight, I am now able to appreciate the true profoundness of that journey and find myself praising and admiring the magic of nature's laws and the wonders of human craftmanship!

- Fabulous Epic
  - The history and development of semiconductors is just as epic as the development of quantum physics in the early 20th century (1895-1945). The development of semiconductors is not just basic science—it is science, engineering, and craftmanship. Furthermore, this story goes beyond the history of quantum physics in that it involves business factors like money and profit.

Lessons

Lesson 1: The origin and evolution of the semiconductor world: Abiding by Moore's Law

- The magical power of big numbers

Lesson 2: The magical lithography machine

- Playing Moore's games with wavelengths

Lesson 3: Major milestones in the spectacular semiconductor journey

Lesson 4: "To be Moore, or not to be Moore?"

- A career drifting in and out of Moore's Law twice

Lesson 5: Big number is beautiful: magic power and super intelligence emerge when the number approaches infinite

- Artificial Intelligence
- The ethics of engineering

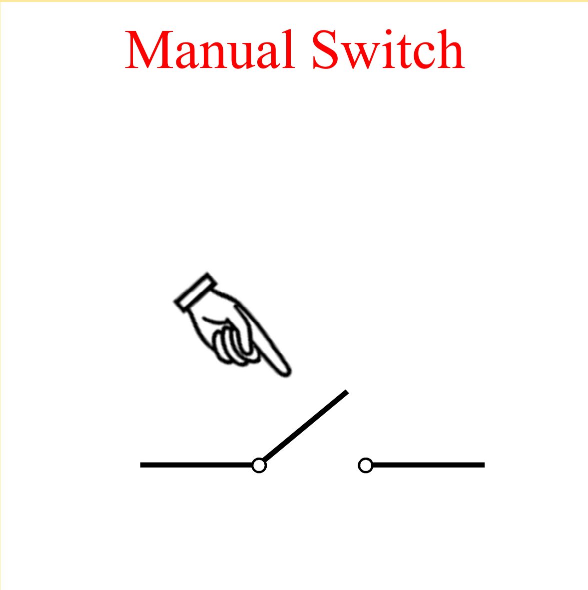
Conclusion: Curiosity, Imagination, Values

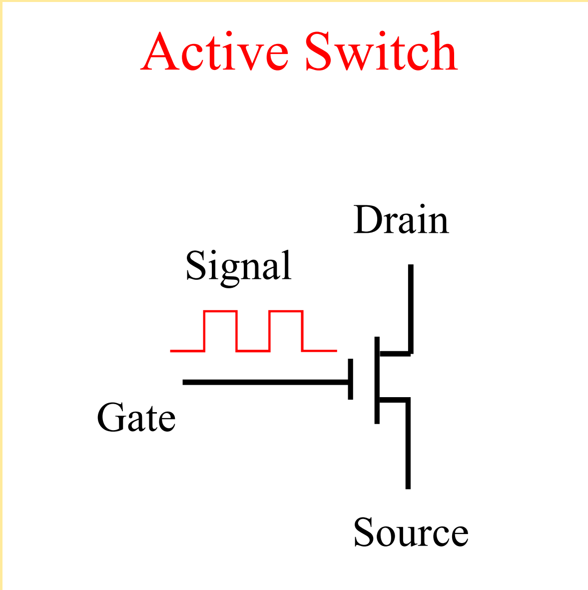
Lesson 1

The origin and evolution of the semiconductor world: Abiding by Moore's Law

Essential Basic Knowledge I – Transistor

- Transistor: A switch that can be actively controlled by electrical signals.
- The "active" switch function and characteristic of transistors foreshadow its destiny for artificial intelligence.





Essential Basic Knowledge II – Integrated Circuits (IC)

- Integrated Circuits: Multiple transistors linked by metal interconnections.

  - Memory – e.g., Static Random-Access Memory (SRAM)
  - Calculation circuit – e.g., Adder
  - Logic circuit – e.g., “AND”, “OR”
  - Heartbeat circuit – Clock

- An IC, using programming instructions given by a human and following its clock sequence, can perform memory storage and access, mathematical calculations, and logical judgements. Isn’t this essentially a human brain?

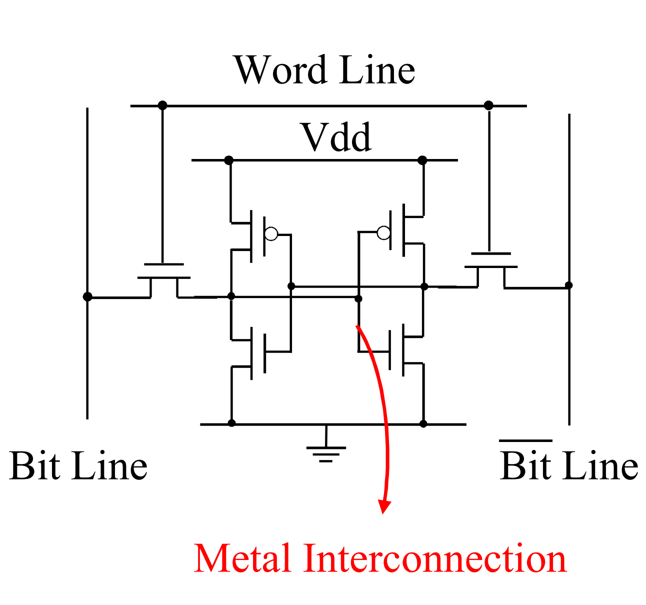
- In Chinese, the term for “computer” translates to “Electrical Brain”, a very apt and vivid description!

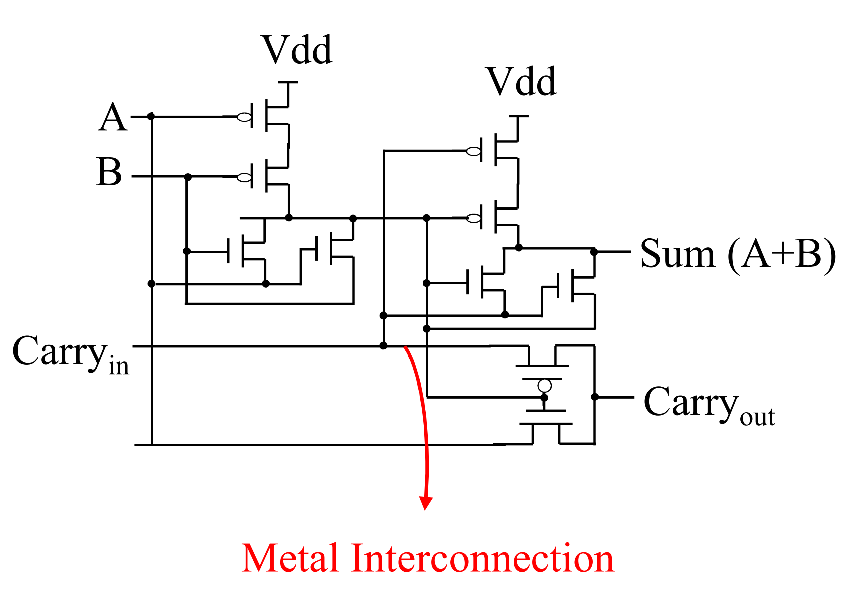
Essential Basic Knowledge III – Basic IC circuit elements

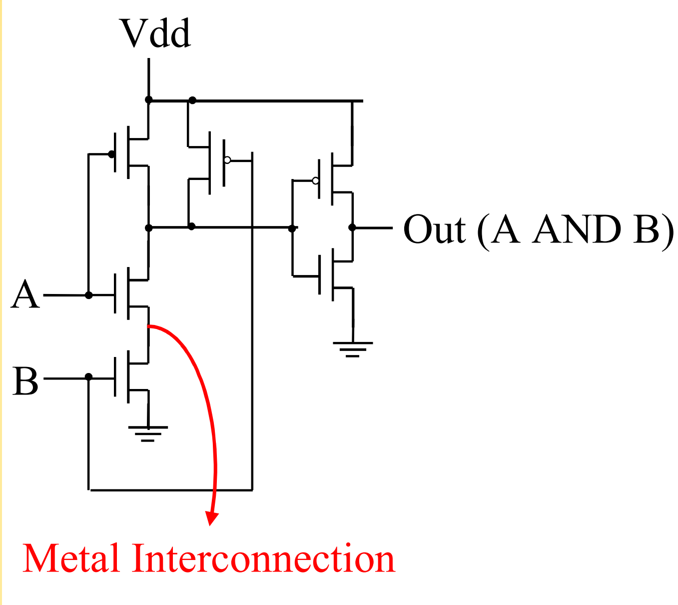
Memory
SRAM
6 Transistors

Computing circuit
Adder
10 transistors

Logic circuit
AND
6 transistors







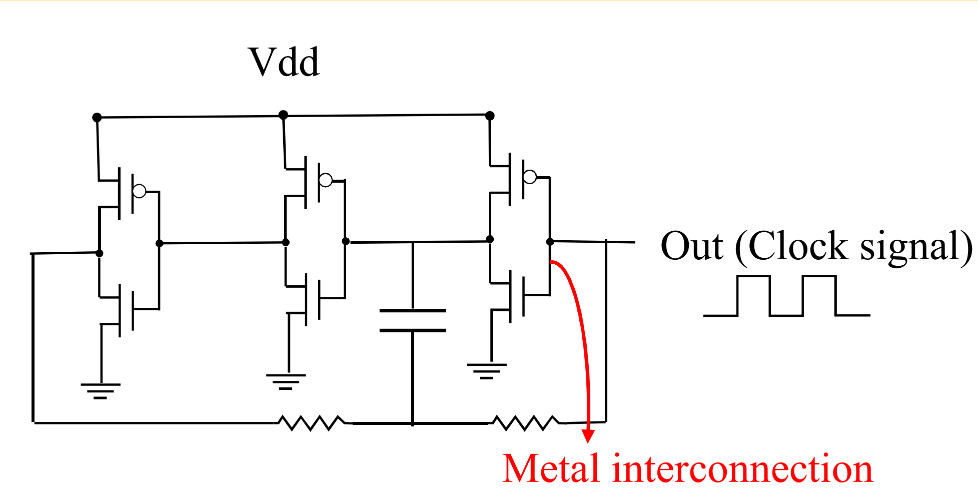
: P-type Transistor : N-type Transistor

Essential Basic Knowledge IV – Basic IC circuit elements (cont.)

Heartbeat circuit

Clock

6 transistors



- The frequency of clock in a computer CPU or a cellular phone APU has currently already exceeded 3GHz, approximately 3 billion clock cycles per second (the time scale is in nanoseconds).

- The human heart beats 1.2 times per second (the time scale is in seconds).

An IC, using programming instructions given by man and following its clock sequence, can perform memory storage and access, mathematical calculations, and logical judgements—isn't this essentially a human brain? In fact, the Chinese term for a computer translates to "electrical brain" — a very apt and vivid description!

The origin and evolution of the semiconductor world:

The magical power of numbers

The origin and evolution of the semiconductor world is similar to how our universe originated and formed. Both follow patterns laid out by the magical power of numbers and great magnitudes of scale and quantity!

Nature's law

13.8 billion years ago

Einstein's General Relativity (Law of Physics)

2022

The universe was just a small dot

Universe continued to expand

The universe contains 10^{22} stars
Diameter: 10^{27} m

Man-made law

1958

Moore's Law (Empirical Law)

2021

Two transistors per chip
Each 3×10^{-3} m in size

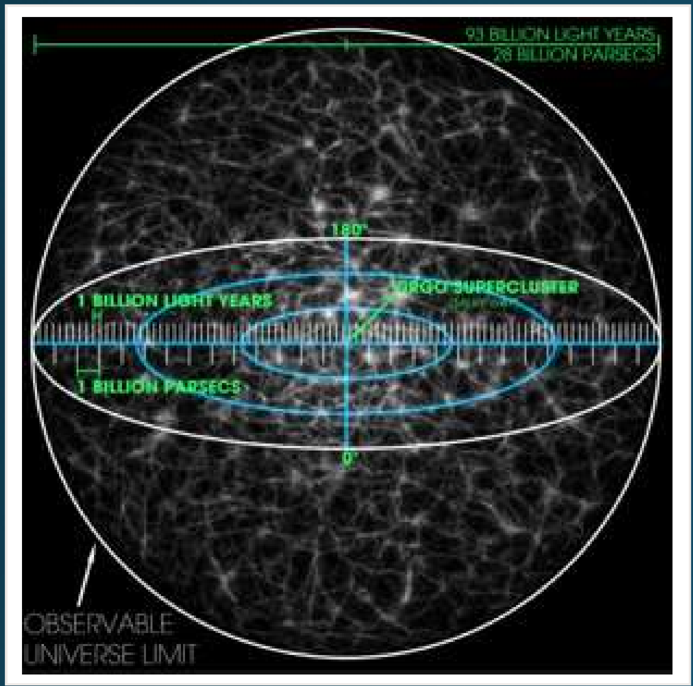
Transistors continued to decrease in size

5×10^{10} transistors per chip
Each 3×10^{-9} m in size

"Seven Brief Lessons on Physics" by Carlo Rovelli

Universe vs Transistor

Diameter 10^{27} m



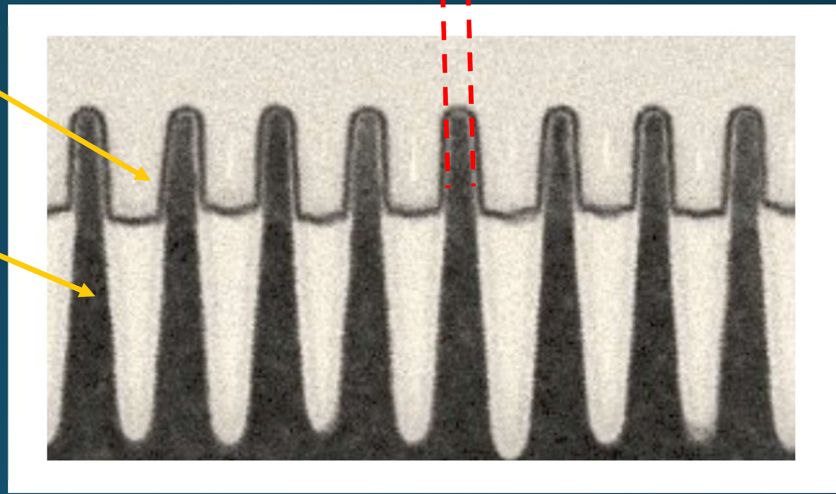
- Observed by the Hubble telescope.
- Each small white dots represents one galaxy. There are 1.25×10^{11} galaxies, each containing 10^{11} stars.

https://en.wikipedia.org/wiki/Observable_universe

Current channel width 5nm

Gate

Fin



- Observed by an electron microscope.
- The width of each 3D FINFET transistors' channel is 5nm. One chip contains 5×10^{10} transistors

https://wccftech.com/tsmcs-5nm-will-enter-mass-production-in-2021-claims-source/

The origin and evolution of the semiconductor world: Abiding by Moore's Law

- A semiconductor chip invented 60 years ago (1958) contained only 2 transistors (each 10^{-3} m in size), and now (2021) a chip has evolved to containing 5×10^{10} transistors (each 3×10^{-9} m in size).

Every 20 months (1.67 year), the number of transistors doubled:

$$2^{(2020-1958)/1.67} = 2^{37} = 6\times10^{10}$$, amazingly close to 5×10^{10}

The fact that human technology development follows an empirical law in precisely the same manner as nature follows the universal Law of Physics is truly amazing!

- Moore's Law can be explained using geometric series; but General Relativity requires the more advanced Riemann Curvature Tensor to be fully explained.

What if Moore's Law applied to automobiles?

In 1885, Karl Benz, a German engineer built a gas engine in Mannheim and placed it on a horse carriage with three wheels. At the time (136 years ago), the size of a three-wheel carriage was about 3m long × 2m wide.

Based on Moore's law, if the area of an automobile reduced by 50% every 20 months (1.67 years):

$$2^{(2020-1885)/1.67} = 2^{81} = 5\times10^{22}$$

The area of an automobile should be:

$$6m^2 / 5\times10^{22} = 1\times10^{-22}\,m^2$$

The size of an automobile now should be 10^{-11} meter (10^{-2} nm), entering the sub-atomic regime. Moore's Law does not apply to automobiles because humans do not have the need to continue to reduce the size of a car.

There is no other object in the history of human civilization that follows a rule like Moore's Law.

What if Moore's Law applied to airplanes?

When the Wright Brothers invented the airplane in 1903, people had hoped that airplanes would keep increasing in size and be made as large as possible. Yet, after 70 development cycles, the biggest airplane (Airbus Beluga) has a size of 56 meters—it has not scaled by a factor of 2^{37} as Moore's Law would have otherwise suggested.

Moore's Law does not apply to airplanes due to the limitations of physics and mankind not having a strong enough demand for these developments.

There is no other object in the history of human civilization that follows a rule like Moore's Law.

Number! Number! And Number!

In my experience, if I cannot describe an event with mathematics or explain it with numbers, I probably have not thought about the event clearly enough. Plato, the great ancient Greek philosopher said, "Let no one ignorant of geometry enter here".

Nature and human affairs generally do not exhibit geometric progression. This is because the competition between activators and inhibitors will lead to an equilibrium state.

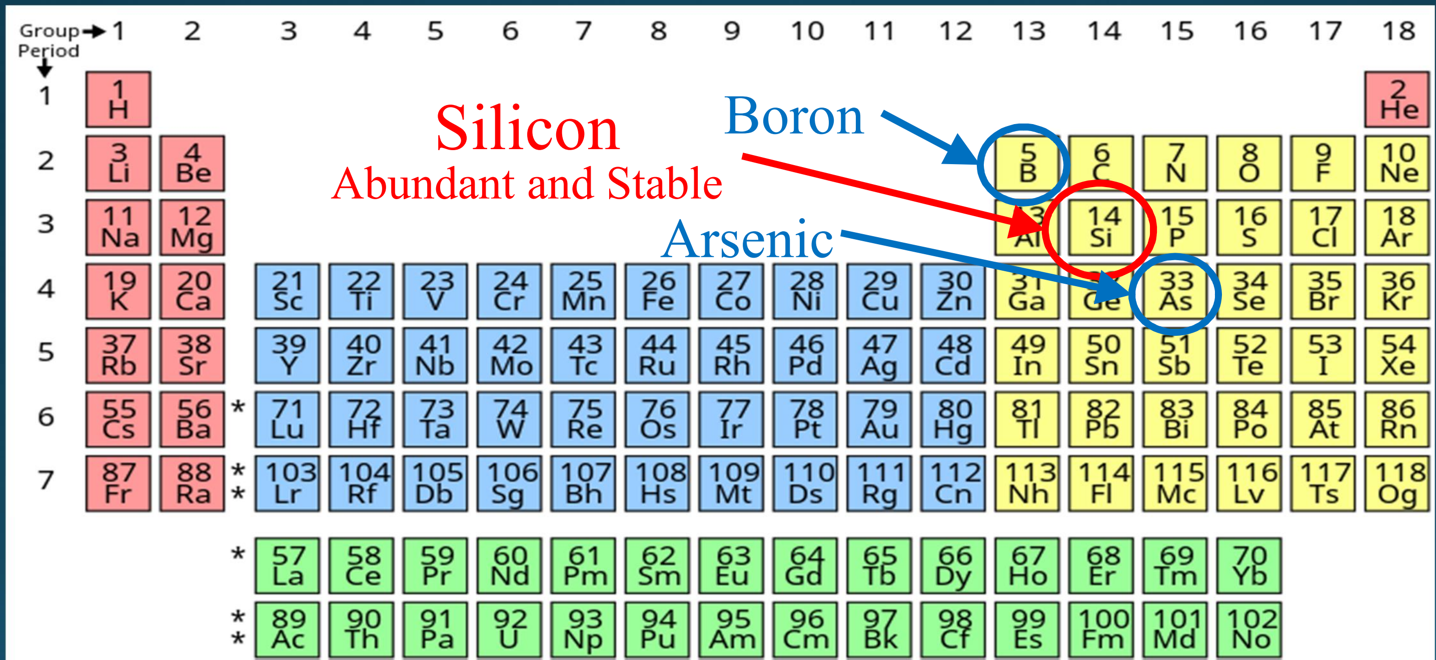
- Covid-19 –using mask wearing, hand washing, social distancing, vaccines, drug treatments and therapies as inhibitors to suppress or eliminate the virus spread.
- Human cell division – having activator CDK (cyclin dependent kinase) to activate cell division, and inhibitor CDKI (CDK Inhibitor) to inhibit cell division. Furthermore, the length of telomere at a terminal of the chromosome in a cell is shortened as cell divides; when the length is shorten to a degree to support the stability of the chromosome, the cells dies. Through the CDKI controlling of progress of cell division and the telomere controlling of cell death, the number of cell is kept from explosive growth.

Earth shattering geometric mechanism

IC chips, due to the burning-desired demand of human, have managed to increase activators and challenge the limitations of physics. After 37 cycles (2^{37}), the development of IC chips is still in progress. It will without doubt generate earth shattering results.

The Periodic Table – Magical Silicon Atom

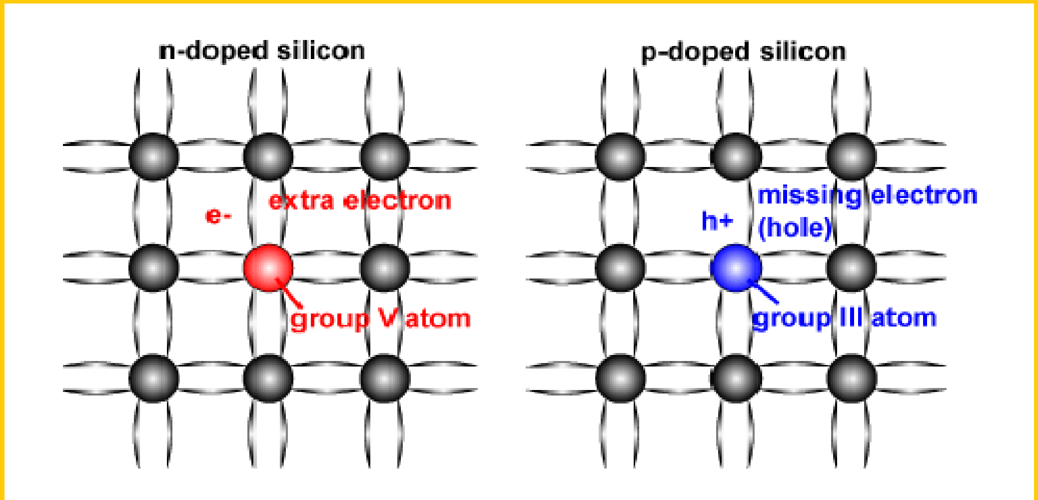
- Nature has prepared for humans with the silicon atom to manufacture and operate IC.
- Silicon ($3s^2 3p^2$) and carbon ($2s^2 2p^2$) are both Group IVA tetravalent elements that can form a diamond cubic lattice crystal structure.
- Diamond merchants may say, “A diamond is forever”; I say, “Silicon is for the Soul.”



https://en.wikipedia.org/wiki/Periodic_table

Essential Basic Knowledge V: Electrons and Holes

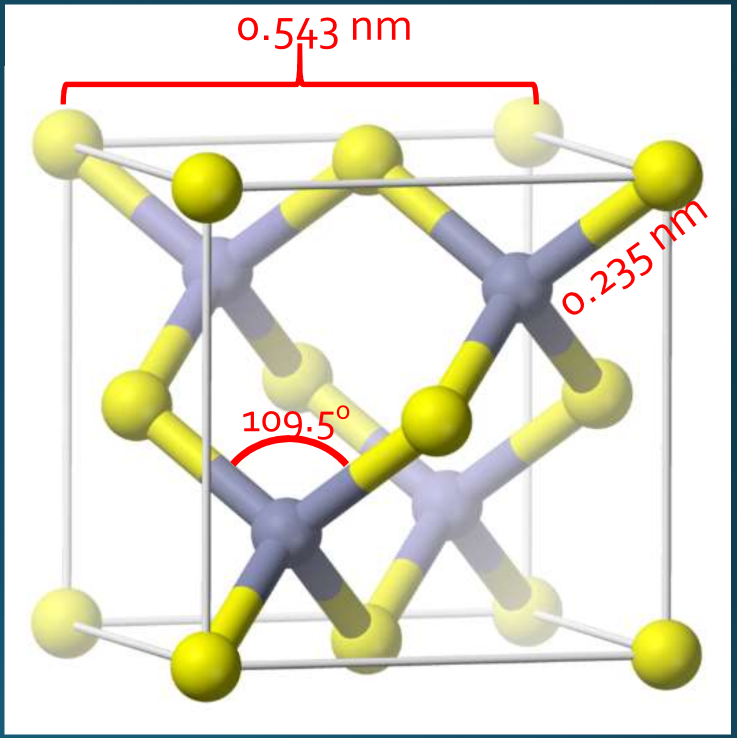
- Tetravalent silicon:
  - Doping with a pentavalent phosphorus or arsenic: providing an extra electron, becoming n-type semiconductor.
  - Doping with a trivalent boron: missing one electron and forming a hole, becoming p-type semiconductor.



https://www.pveducation.org/pvcdrom/pn-junctions/doping

The strongest crystal structure: Diamond Cubic

- The magical tetravalent element that formed the strong diamond cubic crystal structure.
  - Silicon crystal
    size: 0.543 nm
    Si-Si: 0.235 nm
  - Carbon crystal (Diamond)
    size: 0.357 nm
    C-C: 0.154 nm
- Unlike silicon wafers, artificial diamonds cannot be mass-produced at low cost.

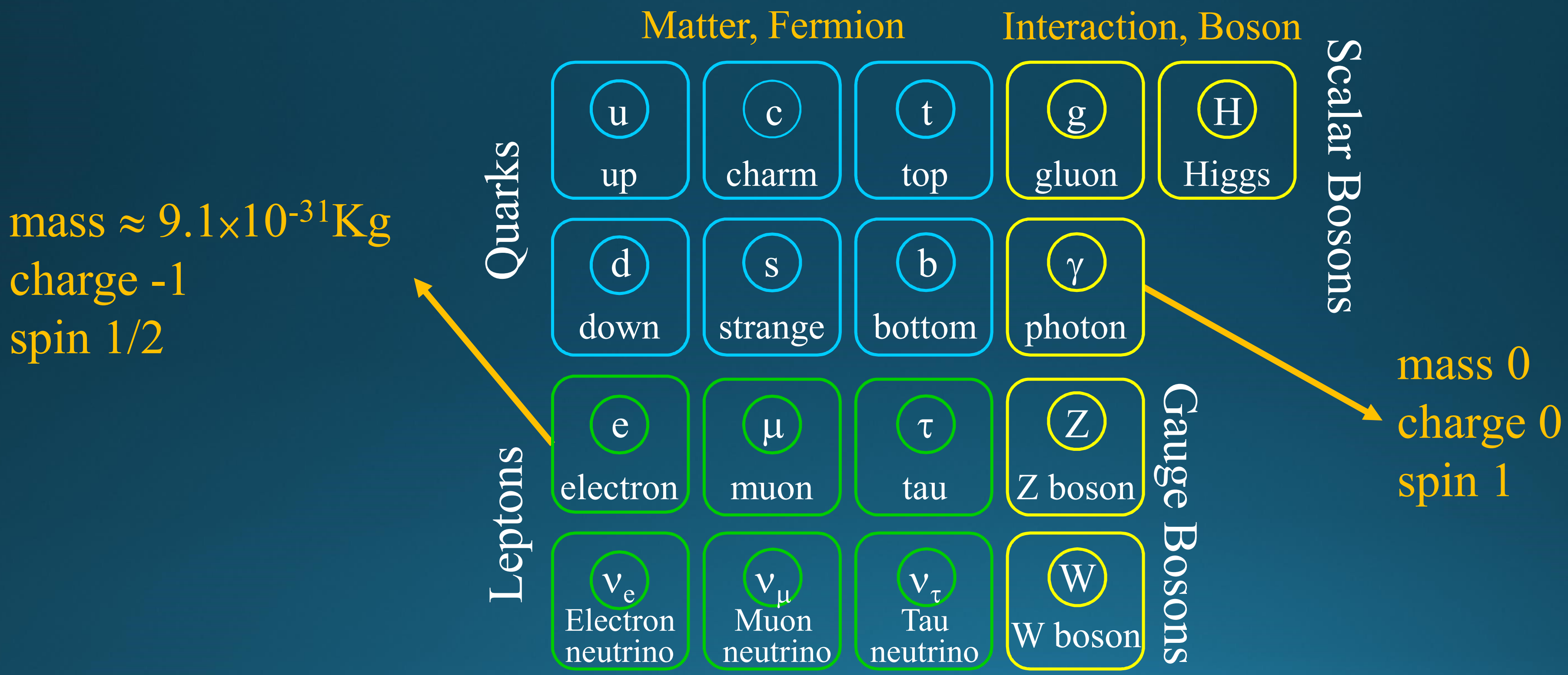


https://en.wikipedia.org/wiki/Cubic_crystal_system

A Diamond is Forever, Silicon is for Soul.

Standard Model of Elementary Particles – Magical Electron and Photon Particles

- Nature has further prepared for humans with two elementary particles, photons and electrons, to manufacture and operate IC.
- Humans have been ingenious to use photons as a copy machine / sculpting knife to pattern designed circuits onto wafers, produced by growing silicon crystals, and then manipulate electrons along those patterned circuits.



https://en.wikipedia.org/wiki/Elementary_particle

~~The origin of the semiconductor~~

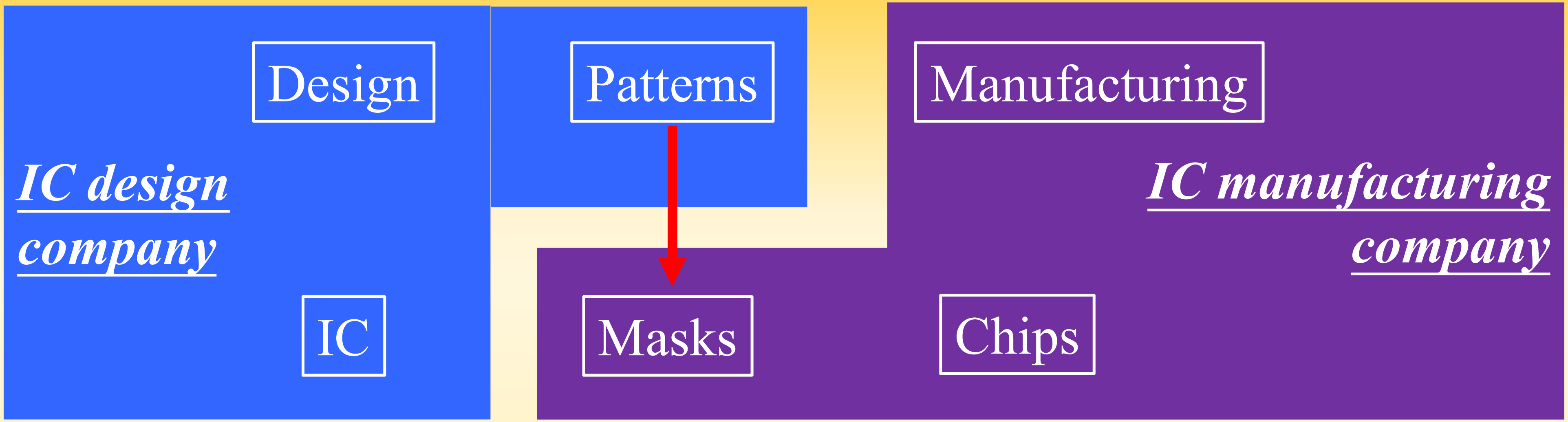
1. Nature
   Nature has prepared mankind with the silicon Atom and two Elementary Particles photons and electrons.

2. Man-made
   The semiconductor industry is a game in which humans use light (Elementary Particles photons) as photocopier/sculpting knife to carve circuit patterns on the silicon-Atom-based wafers and manipulate the Elementary Particles electrons on their circuit patterns.

Lesson 2

The magical lithography machine:
Playing Moore's games with wavelengths

Essential Basic Knowledge VI: The process of IC chip formation

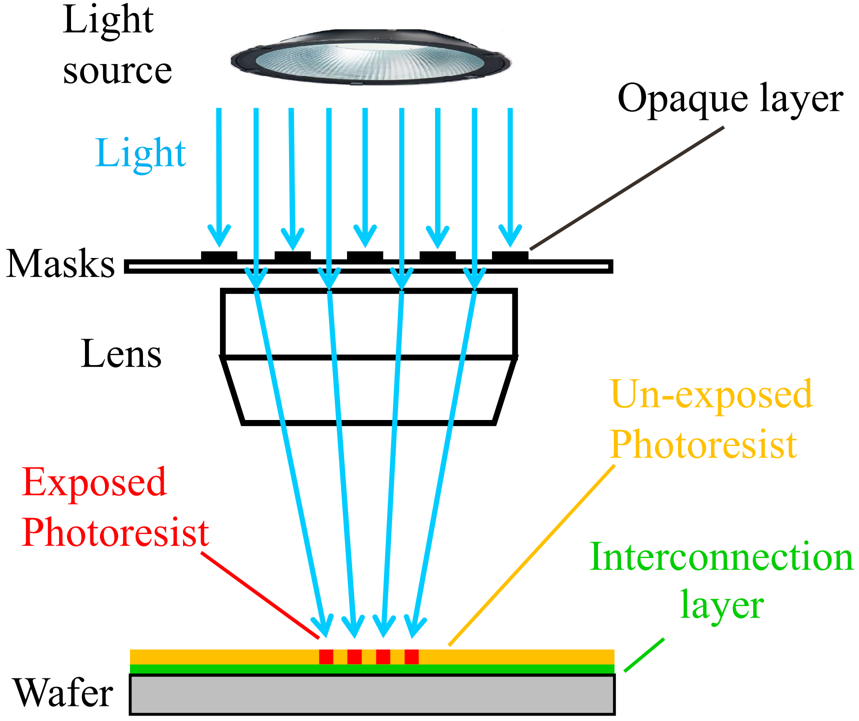


Steps:

1. Transform the designed IC into multilayer design patterns, creating multiple masks, each based on the design pattern of its layer.
2. Use a lithography machine to sequentially imprint the design patterns of each mask layer into patterned circuits of a corresponding layer on the wafer.
3. Stack the layers of patterned circuits on the wafers to form IC, and diced to become the IC chips.

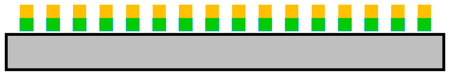
Essential Basic Knowledge VII: The lithography Machine

Lithography Process

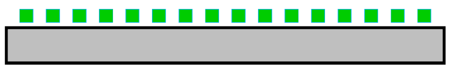


Step 1:
Exposure

Step 2:
Development



Step 3:
Etching



Step 4:
Removal of photoresist

Essential Basic Knowledge VIII: The fundamentals of the lithography machine

Light wavelength and resolution

$R = \lambda / (2NA)$

$NA = n \sin \boldsymbol{\theta} < 0.4$

$R \sim \lambda / n \sim \lambda$

R= Resolution

λ = Wavelength of the light used for image formation

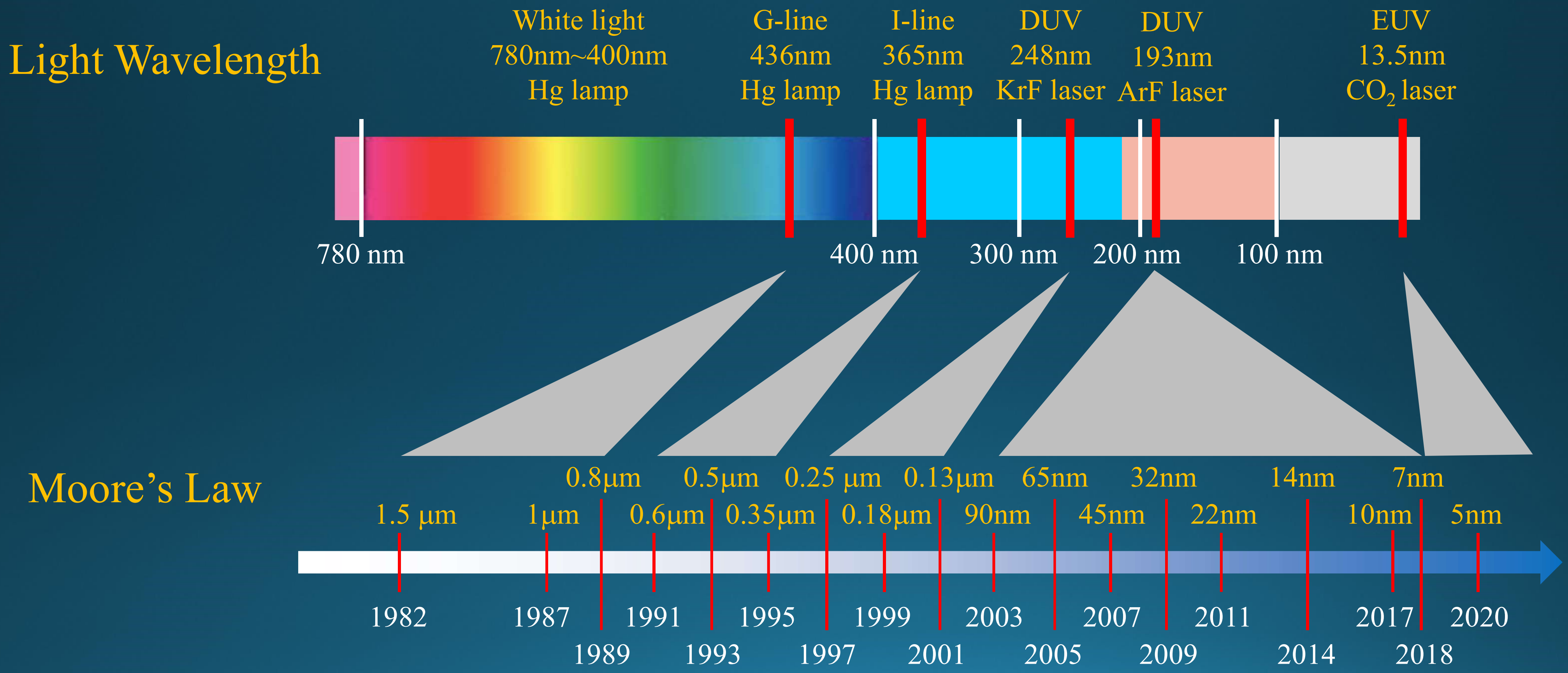
NA = Numerical aperture of the lens, < 0.4 for most optical systems. Used for determining the ability of an optical system to collect light.

$\boldsymbol{\theta}$ = Angle of the lens collecting light

n = Refractive index of medium

Moore's Law: Playing games with wavelengths

The light sources of lithography machines used by the semiconductor industry have progressed from white light to G-line/I-line, DUV, and now currently EUV.



Moore's Law

- Approximately every 20 months (1.67 year), the number of transistors in an IC chip doubled (each transistor reduced in area by 50% , that is the linear dimension is miniaturized with 70% ratio.).

- Each generation of the technology node is named according to the transistor size reduced to 70% of its previous generation.

40 nm →(70%) 28 nm →(70%) 20 nm →(70%) 14 nm →(70%) 10 nm

→(70%) 7 nm →(70%) 5 nm →(70%) 3 nm →(70%) 2 nm

How did TSMC come to surpass Intel in the technology?

1. TSMC challenged the physical limitations of light waves, successfully extending the application of 193nm deep UV (DUV) light all the way down to 7nm node technology.

2. Afterwards, TSMC successfully applied extreme UV (EUV) light in the mass production of 7nm and 5nm technologies.

TSMC successfully beat the physical limit of light wavelength – a Miracle
Diligence compensates Nature's Clumsy (not TSMC's Clumsy)

- TSMC pioneered 24 hours / 3 work shifts R&D operation to reduce the cycle time of Moore's law.

- Motorcycle culture in Taiwan: squeezing and flexible
  - The process modules and materials used for each technology node were used continuously for the next few generations of technology nodes. The process modules and materials were not replaced until truly unusable.

- The tortoise and hare: Continuous & Incremental Improvement culture.
  - For example: From 1990 to 1995, TSMC did not completely follow Moore's Law but gradually and incrementally developed eight generations or sub-generations (0.8, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, and 0.35 μm) of process technology.

The TSMC miracle:

How was the 193nm DUV extended for use to the 7nm technology node?

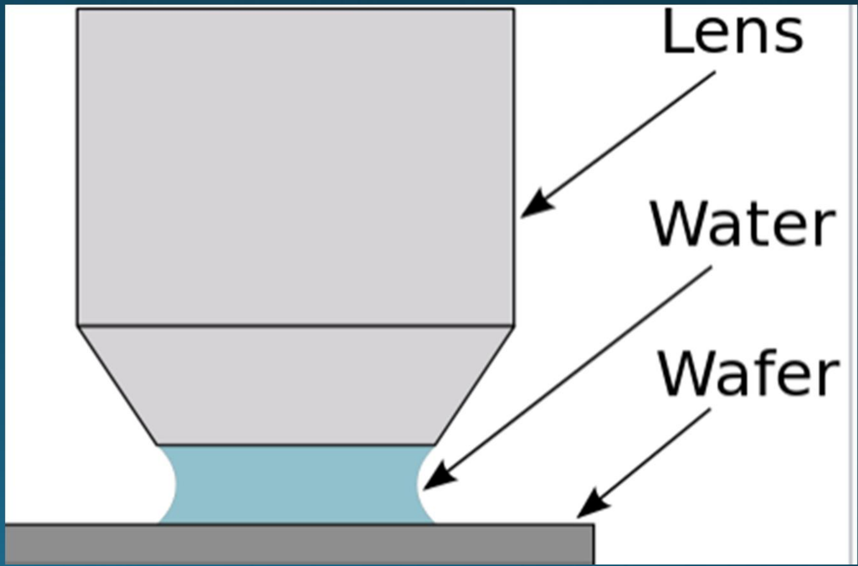
1. Immersion exposure:
   Having a layer of water between lens and wafer to reduce light wavelength

$$\lambda_w = \lambda_a / n = 193nm / 1.33 = 145nm$$

$\boldsymbol{\lambda}_w$ = light wavelength in water

$\boldsymbol{\lambda}_a$ = light wavelength in air

n = refractive index in water, 1.33

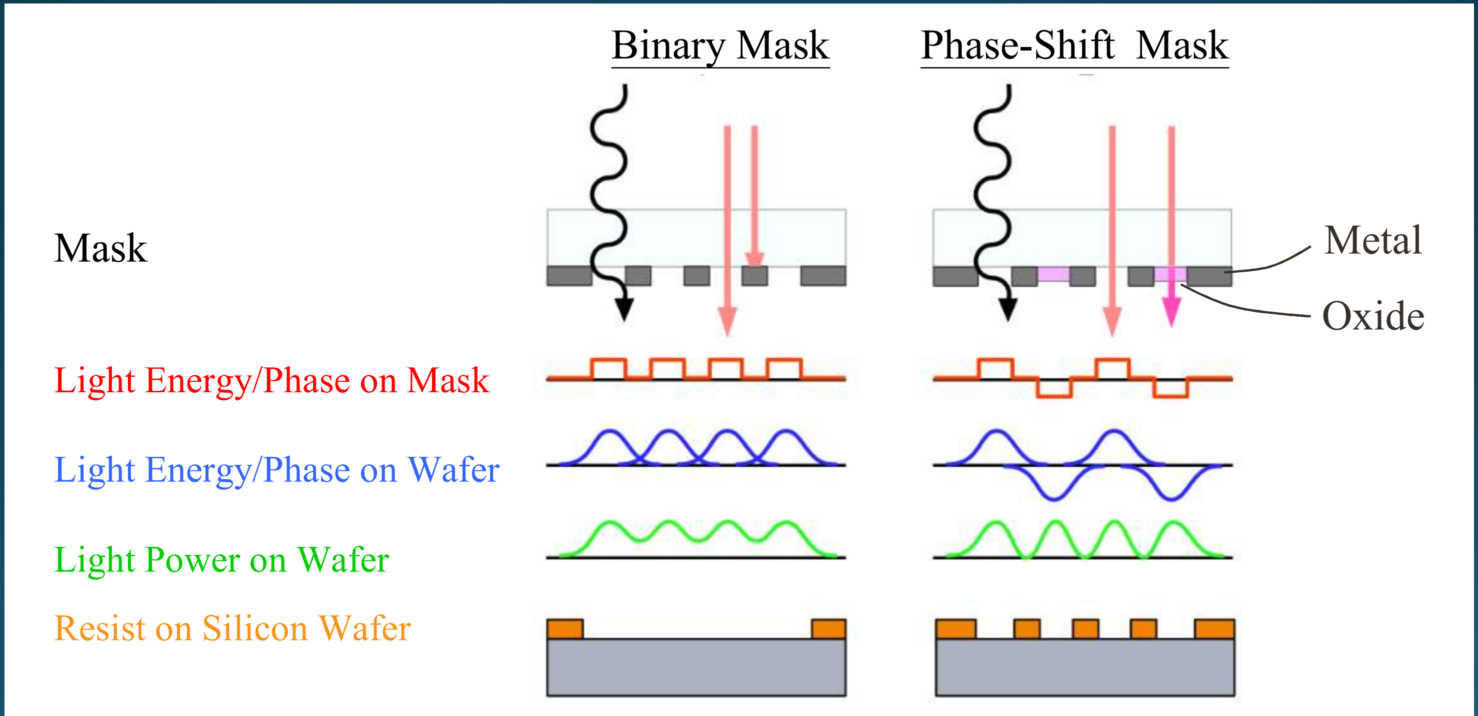


https://en.wikipedia.org/wiki/Immersion_lithography

The TSMC Miracle:

How was the 193nm DUV extended for use to the 7nm technology node? (Cont'd)

2. Phase-Shift Mask:
   Adding a phase-shift layer on the mask to induce interference patterns on wafer for enhancing resolution

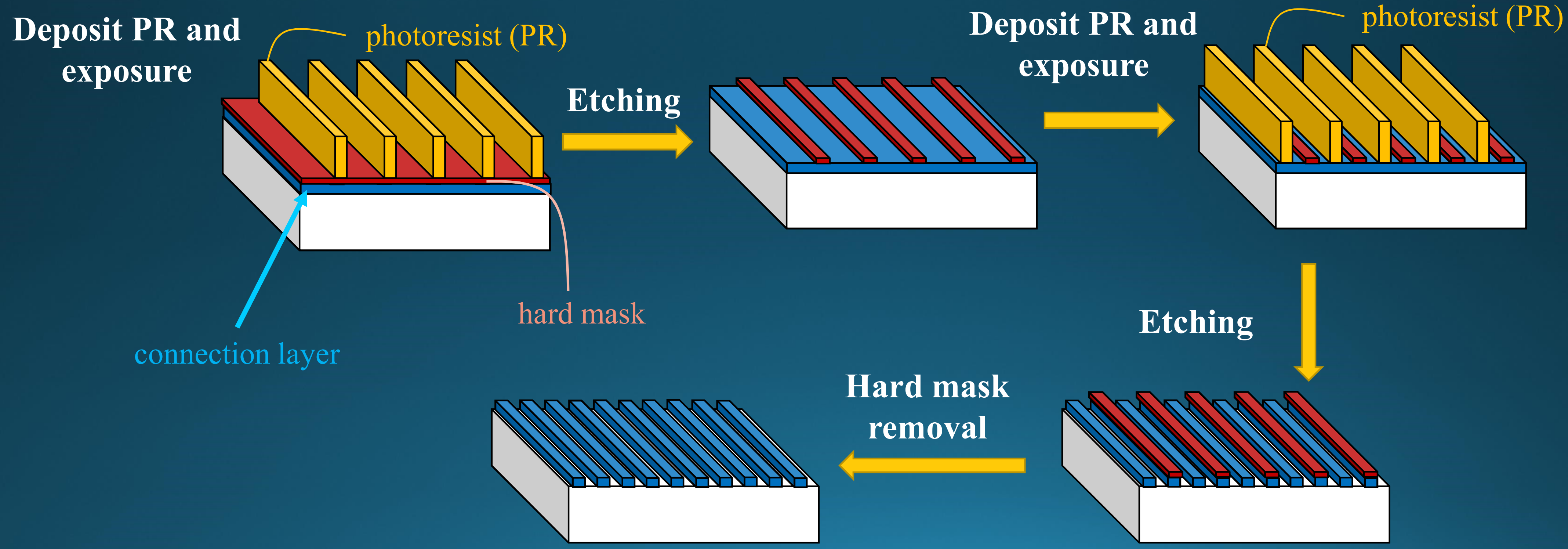


https://en.wikipedia.org/wiki/Phase-shift_mask

The TSMC Miracle:

How was the 193nm DUV extended for use to the 7nm technology node? (Cont'd)

3. Multiple exposures:
   depositing and patterning a hard mask layer on wafer, and then using the patterned hard mask to pattern the underlying circuit layer. The process steps may be repeated several times to enhance resolution.



TSMC finally surpassed Intel in 2017 with the 10nm technology node

- Through diligent work, TSMC eventually succeeded in using 193nm DUV to mass-produce 10nm and 7nm technology node products. As a result, TSMC was able to continue its development of advanced technology nodes using EUV to mass-produce 7nm and 5nm technology node products.

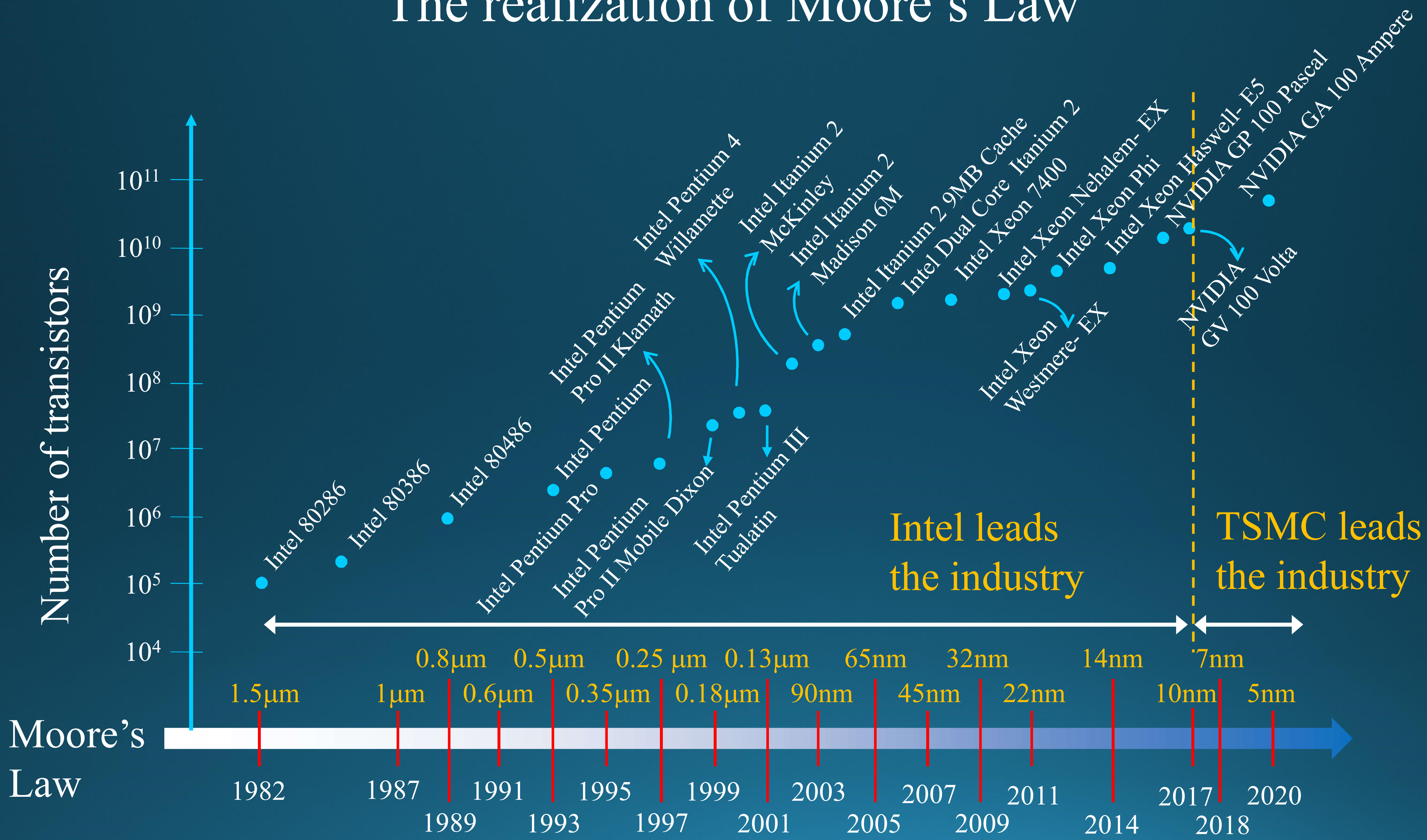
- Intel was unsuccessful in using 193nm DUV to mass produce 10nm technology node products, finally losing its dominance and industry leadership in semiconductor IC manufacturing.

Intel CEO Pat Gelsinger (presentation in "Intel Unleashed: Engineering the Future" webcast on 2021/3/23):

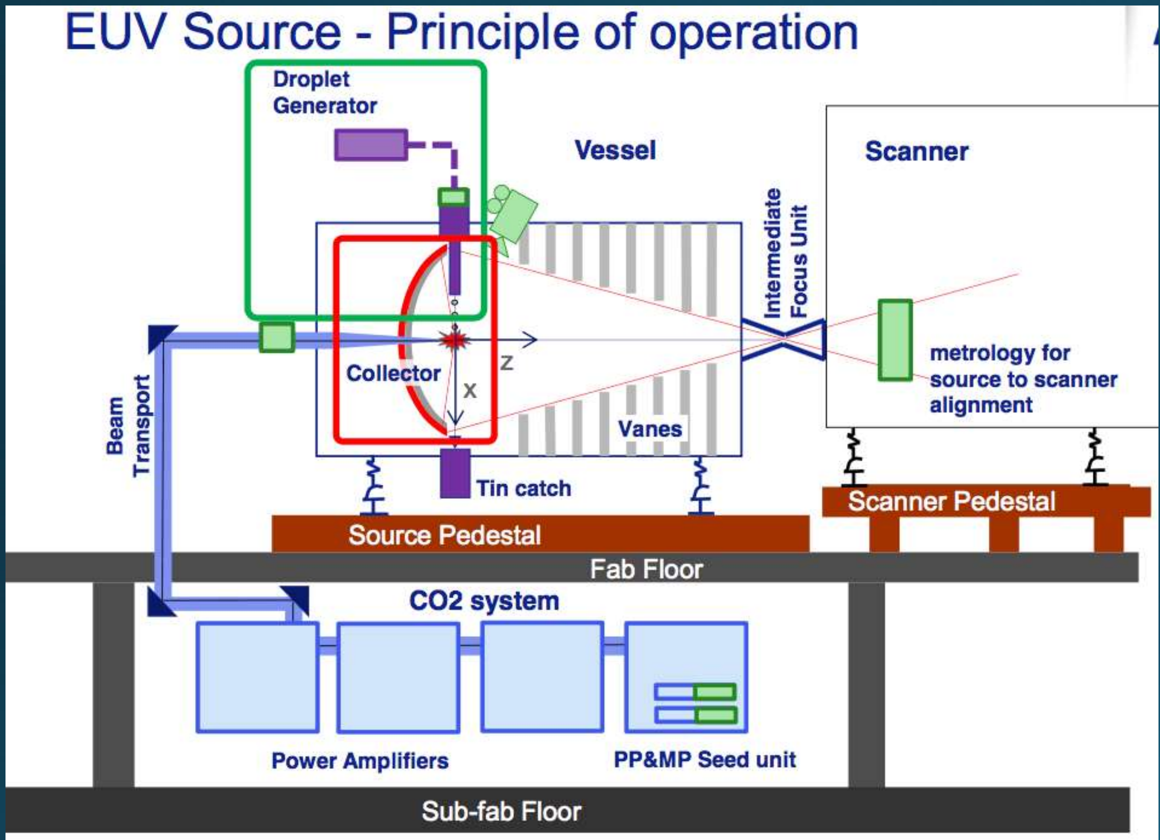
> "When Intel initially designed 7 nanometers, EUV was still a nascent technology so we developed our process to limit the use of EUV. But this also increased the process complexity. As EUV then matured and became more reliable, we experienced the domino effects of our 10-nanometer delay which pushed out 7-nanometers and ultimately put us on the wrong side of the EUV maturity curve."

https://www.nextplatform.com/2021/03/24/the-once-the-future-and-the-fabulous-intel/

The realization of Moore's Law



The beautiful EUV lithography masterpiece: a Manmade Star

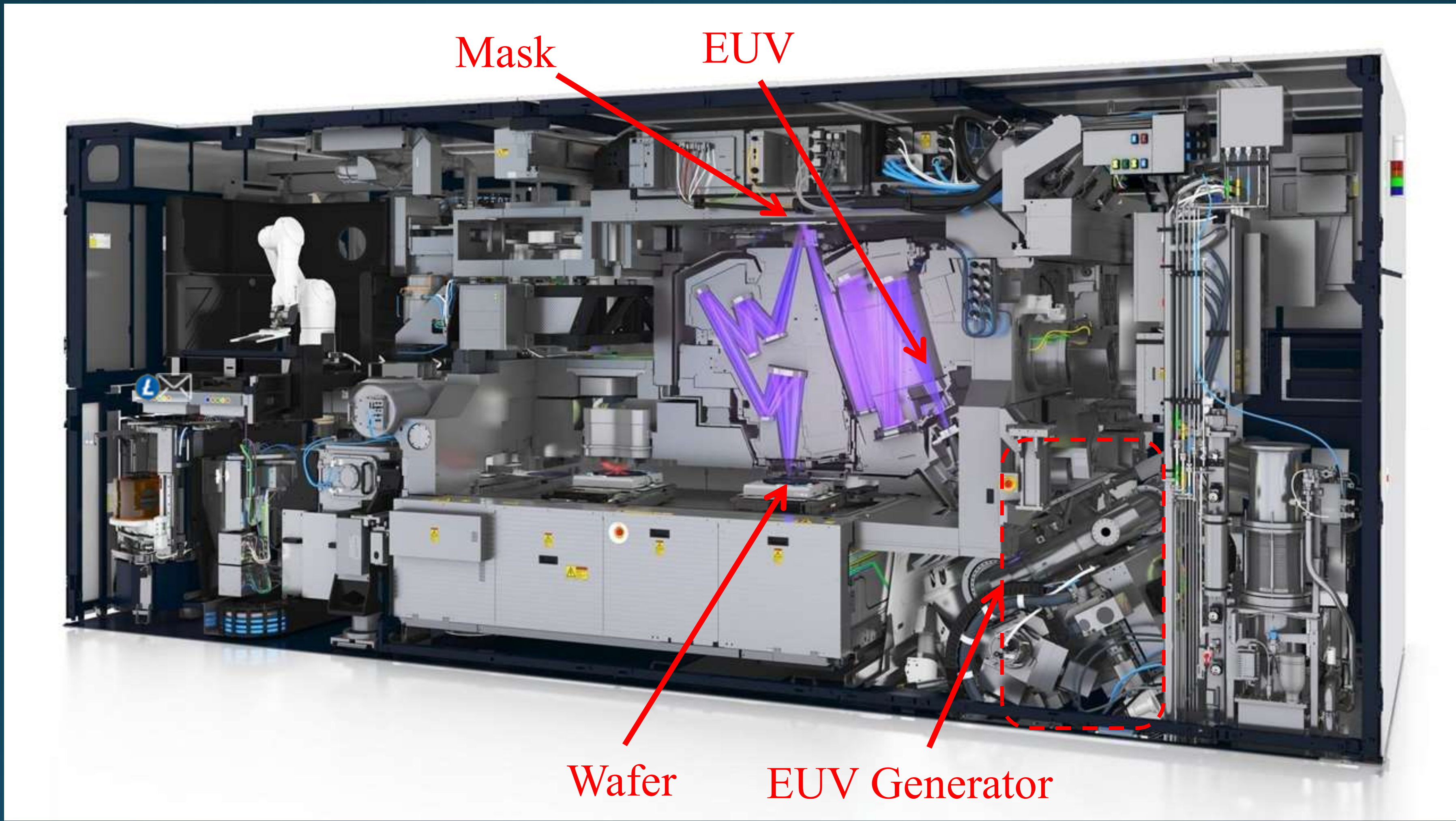


1. CO_2 laser wavelength (λ=10.6um)
2. The CO_2 laser strikes tin droplets (50 thousand drops/sec), causing them to evaporate into gas and be converted to plasma (Laser Produced Plasma, LPP).
3. When the temperature of the plasma reaches 4×10^5 degrees (30eV), its energy will excite the tin atoms into extremely excited states: high energy multicharged ions (Sn^{+8} –Sn^{+19}).
4. At this high energy state, when a multicharged ion interacts with electrons and returns to a lower energy state ion or atom, it generates EUV.

https://iopscience.iop.org/article/10.1088/1361-6595/ab3302/pdf
https://semiengineering.com/why-euv-is-so-difficult

- An EUV machine is like a star shining light, using high temperatures and giant energy to violently generate light.
- An EUV lithography machine with an output power of 250 Watts requires an input of 1.25MW power (conversion rate 0.02%). Each workday consumes 30MWHs of electricity—equivalent to three thousand times the electricity an average household consumes in a day.

EUV Lithography Machine



https://technews.tw/2021/02/15/euv-mass-production-of-lithography-technology/

Three trucks carrying EUV lithography machines to TSMC's wafer manufacturing site in Taiwan, August 2020

https://www.ctwant.com/article/67825

Another new man-made sun is rising – MIT Commonwealth Fusion Systems (CFS)

1. The EUV machine uses a CO2 laser to excite tin drops in a localized region around the laser beam focus in a chamber and to produce extremely hot (4×10^5 ^oC) plasma of tin ions for generating EUV light, so that the extremely hot plasma of tin ions are kept isolated and far from the chamber walls.

2. In similar fashion, CFS uses very high magnetic fields to confine and localize extremely hot (1×10^8 ^oC) plasma of protons and electrons for igniting nuclear fusion reactions while keeping them isolated and far from the chamber walls.

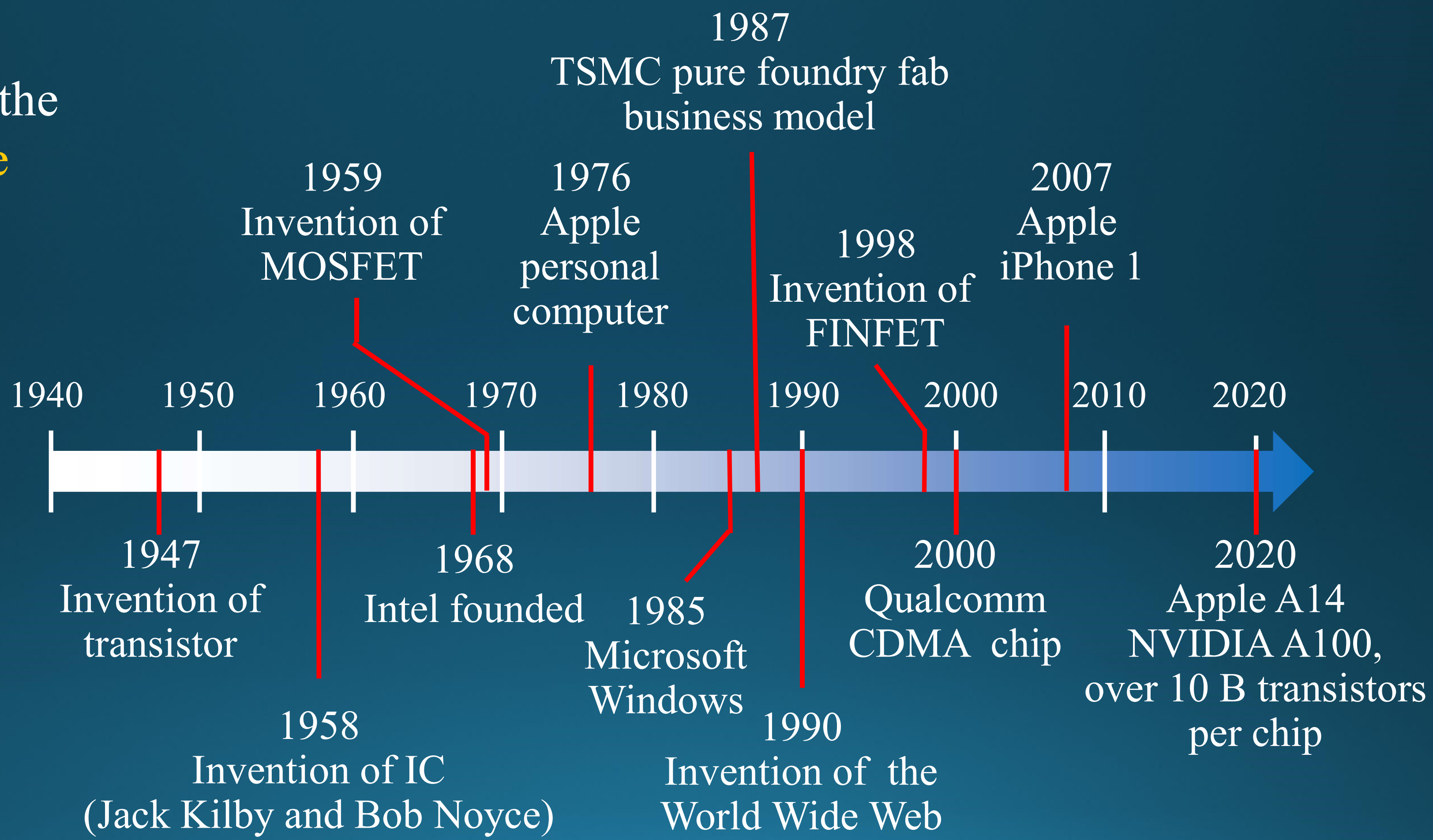
If MIT's CFS could be inspired and encouraged by the success of the EUV machine to successfully produce huge amounts of nuclear fusion energy, human civilization will be thoroughly revolutionized by these two man-made suns.

Lesson 3

Major milestones of the spectacular semiconductor journey

Major milestones in semiconductor history: An epic poem

There are many beautiful moments along the spectacular journey of the semiconductor—I have personally selected 12 such moments



Two milestones that affected me the most

1. Apple released the iPhone 1 (2007)
   – Megica, the company I founded, was acquired by the largest smartphone chip design company (2009)

2. TSMC's pure semiconductor foundry business model (1987)
   – I was fortunate and honour to participate from 1990-1997

Two milestones that affected me the most – Episode 1

The release of the iPhone 1 (2007)

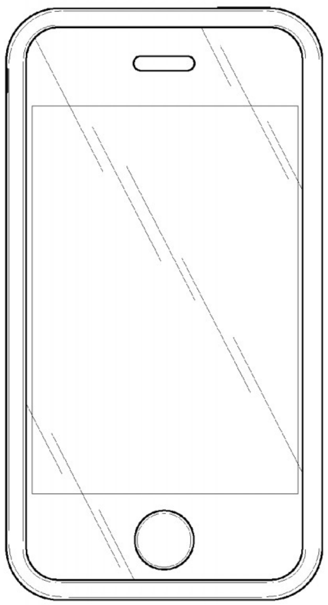
iPhone 1

https://en.wikipedia.org/wiki/IPhone_(1st_generation)

- The year that the most people began to realize the significance of semiconductors to mankind is 2007: Apple released its first smartphone: the iPhone 1 (Apple began development in 2004 under the codename Project Purple).
- The invention of personal computers in 1976 had only changed our working style; while the invention of the iPhone 1 in 2007 had thoroughly changed our entire lifestyle and civilization.

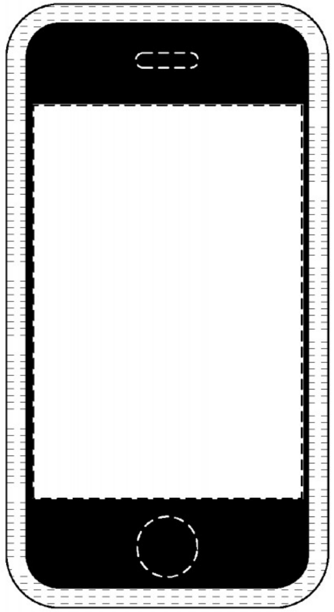
iPhone 1 Design Patents

Filing Date:
1/5/2007



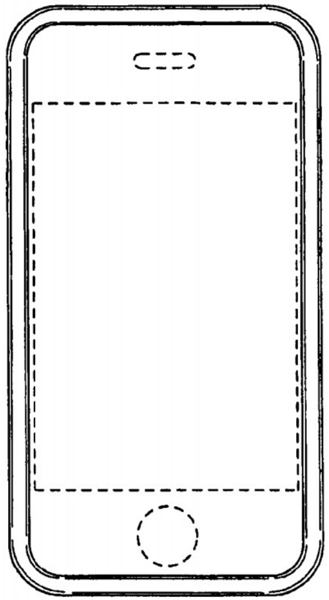
D580,387

Filing Date:
1/5/2007



D558,758

Filing Date:
1/5/2007



D558,756

No physical keyboard: Invention of the touch virtual keyboard

I often wonder what the smart TV and smart car would look like if Steve Jobs were still alive?

2007 iPhone 1
S5L8900 processor

Design: PA Semi
Manufacturer: Samsung (South Korea)
Specifications:
- 90nm technology node
- approximately 1.375×10^8 transistors
- Chip surface area 72mm^2 (8.8 mm × 8.5 mm)

https://second.wiki/wiki/samsung_s5l
https://www.quora.com/How-many-transistors-were-on-the-first-iPhones-processor
"The one Device: The Secret History of the iPhone" by Brian Merchant

2020 iPhone 12
A14 Bionic chip

Design: Apple
Manufacturer: TSMC (Taiwan)
Specifications:
- 5nm technology node
- 1.18×10^{10} transistors
- Chip surface area 88mm^2 (10.3 mm × 8.6 mm)

Computing capability: neural engine can perform 11×10^{18} tasks per second

http://news.moore.ren/industry/261391.htm

Two milestones that affected me the most – Episode 1 (Cont’d)

The release of the iPhone 1 (2007)

- Megica, the company I founded, was acquired by the largest smartphone chip design company (2009)
  - The revolutionary iPhone 1 combined the previously unrelated phones and computer industries into a single industry: smart phone.
  - The release of iPhone 1 resulted in many infringement lawsuits of related patents and a wave to purchase phone-related patents.
    - In 2011, Apple, Microsoft, Sony, and RIMM joined together to purchase Canada’s Northern Telecom’s phone patents for $4.5 billion.
    - In 2012, Google acquired Motorola Mobility for 12.5 billion US dollars aiming for its phone patents.
  - In the presence of the iPhone 1, the largest smartphone chip company inevitably stepped into the field of computer chips. By the same reason yet in a reverse direction, in order to prevent other major computer chip companies from filing patent infringement lawsuits, it acquired Megica in 2009.

- Harvard University established its School of Engineering in 2007
  - For years, Harvard had been debating internally whether to upgrade its engineering program from being the Division of Engineering and Applied Sciences to the School of Engineering and Applied Sciences.
  - Harvard believed that with the existence of MIT, a neighbor strong in engineering, there had been no need to expand its engineering program.
  - It was not until 2007 that Harvard clearly realized that technology has begun to affect the humanity and social sciences departments they are most proud of. That same year, Harvard established its School of Engineering.

Two milestones that affected me the most - Episode 2
TSMC's pure foundry fab business model

- TSMC pioneered the pure foundry fab business model:
  Investing massive amount of money (from billions of US dollars during the early stages to tens of billions of US dollars nowadays) to build up fabs for producing customer's chips only. TSMC provides manufacturing services to its customers, does not have its own products, and does not compete with its customers. TSMC treats its customers' products like its own products, and its customers treat TSMC's fab like their own fabs.

- TSMC: Taiwan Semiconductor Manufacturing Company
  The success of TSMC is written in its name: Taiwan Semiconductor Manufacturing Company. The name emphasizes two major characteristics and strength: Taiwan and manufacturing; that means "Made In Taiwan" (MIT). "Made In Taiwan" becomes a proud statement on the global stage, and it forms a foundational pillar to Taiwan's economy and global standing.

https://www.cw.com.tw/article/5034316

Two milestones that affected me the most – Episode 2 (Cont'd)
TSMC's pure foundry fab business model

- Concept of "Shared Capacity" in the semiconductor manufacturing
  - Interestingly, some of the most successful startup companies in recent years, such as Airbnb (shared lodging), Uber (shared ride), and WeWork (shared office), would come to adapt and build up this "Shared Capacity" business model as non-conventional and breakthrough methods of operations in their own respective industries.
- Unique advantage due to the concept of "shared process technology"
  - The development and manufacturing of each process technology was tested and validated against numerous customer products.
  - Not only is every customer's application different, their design styles also vary widely. The wide range of customers also function to refine each generation of TSMC's process technology by providing cases for comprehensive debugging and uncovering all potential weaknesses of the process technology.
  - With each uncovered weakness, TSMC would perform failure-mode analysis to find failure causes, and improve their process technology or create new design rules based on the found causes, eventually allowing their technology to accommodate all different customers with a common process technology having wide process window, and resulting in high yield and low cost manufacturing.

https://www.cw.com.tw/article/5034316

Two milestones that affected me the most – Episode 2 (Cont'd)
TSMC's pure foundry fab business model

- TSMC established a model for cost-effective "Volume Production" technology
  - TSMC deems a technology to have been successfully developed only when production volume surpasses 10,000 wafers per month with high yield and low cost; these volume production technologies differ from technologies producing small volume of 1, 10, or 1,000 wafers per month.
- TSMC pioneered in-line production monitoring at critical process steps by expensive wafer defect inspection equipment
  - TSMC pioneered the concept of applying very expensive wafer defect inspection equipment for in-line production monitoring at critical process steps since its early days. The very expensive wafer defect inspection equipment include KLA defect inspection machine, Scanning Electron Microscope (SEM) and etc. Most other IC manufacturing fabs then used these very expensive equipment only for failure-mode analysis on the finished defective IC wafers or chips. By doing so, TSMC's wafer production is, analogously, not walking blindly in the dark, instead, they lighted up lamps, opened eyes along the way, and therefore, the wafers could safely arrive the finished point. The in-line production monitoring concept ends up with high-yield cost-effective wafer manufacturing.

From an Everybody's Public Innovation Platform to a "Billionaires Club" Innovation Platform at TSMC

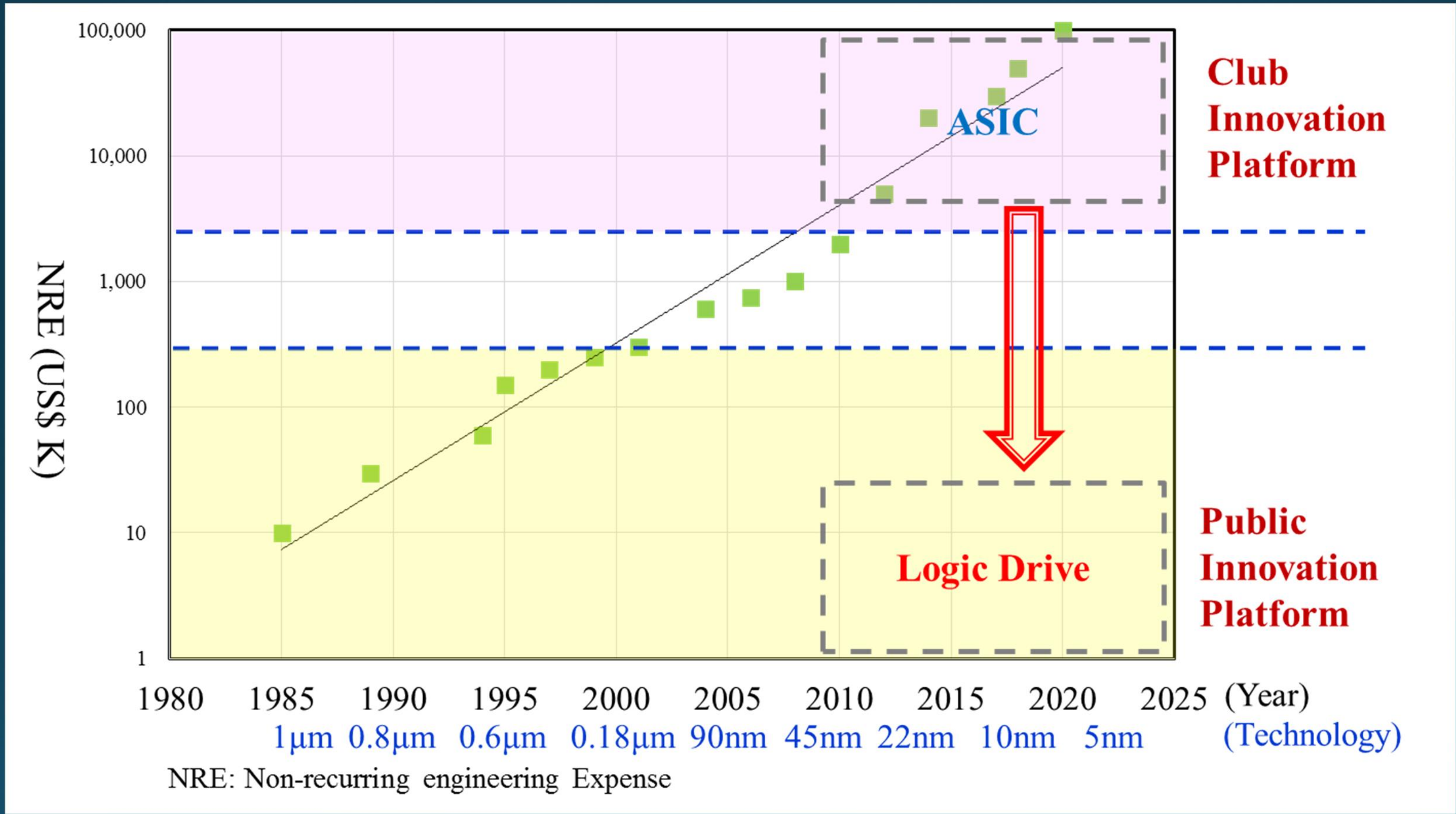
- Public Innovation Platform
  - Between 1990 and 1997 when I was at TSMC, a creative and talented IC designer could found an IC design company, design IC chips, and use the advanced processing technology between 1um to 0.35nm then at TSMC to realize his dream by raising funding from several hundred thousands to two million US dollars.
  - Many current successful companies such as Nvidia, Qualcomm, Broadcom, Marvell, Realtek, and many other IC design companies all started based on the public innovation platform.
  - Many companies joined in the competition on this public innovation platform. Many have been successful till now, some were dominating at one time then fell, and some failed and exiting from the competition. The severe competition among the IC design talents subsequently led to the birth of the life-changing iPhone 1 in 2007. (The 2007 iPhone 1 used many chips designed by innovative IC design companies and manufactured by TSMC).

- Club Innovation Platform
  - To establish a complete 7nm processing line, the cost of the manufacturing equipment would cost approximately 15 billion US dollars.
  - Developing a 10nm IC chip would cost approximately tens (or even hundreds) of millions of US dollars. Just a set of 10nm mask costs 3 million US dollars and roughly 9 million US dollars for 7nm mask.
  - Only a system company like Apple and major IC design companies like Qualcomm, MediaTek, NVIDIA, and AMD have resources to "buy into" the game using processing technology more advanced than 10nm.

Logic Drive - a device bringing back the public innovation platform

- In 2016, iCometure proposed the concept of the Logic Drive. The goal are:
  - Provide a new path for creative and talented chip designers to realize their innovation using TSMC technology more advanced than 10 nm technology node at an affordable cost in a range of several hundred thousands to a couple million US dollars.
  - Provide a device storing for computing logic. The hardware circuits of the FPGA IC chip in the Logic Drive can be re-configured by software for a new computing logic, and the re-configuration data is stored in the non-volatile flash memory chip packaged in the same Logic Drive. The Logic Drive is now like the Solid-State Drive or Solid-State Disk (SSD); the only difference is that SSD is for storing data memory, while logic drive is for storing computing logic.

Logic Drive brings back the "Public Innovation Platform"



The concept of the Logic Drive

- An IC chip uses software to configure and re-configure hardware circuits.

- The Logic Drive is based on standard commodity FPGA (Field Programmable Gate Array) IC chip:
  1. Using technology more advanced than 10 nm, the Logic Drive's standard commodity FPGA IC chip would contain a sufficient number of transistors and provide fast processing speed with low power consumption.
  2. Standardizing FPGA IC chips and designing and converting them into a commodity like DRAM.
  3. Packing a plurality of standard commodity FPGA IC chips in an advanced multi-chip package to further increase the number of transistors.
  4. New standard commodity FPGA IC chip structure and algorithm: The brain-like elasticity and integrality of the FPGA IC chip would likely inspire new ground-breaking architectures and algorithms, especially in artificial intelligence and machine learning, such as the CGRA (coarse grained reconfigurable array).

- As a result, the price of the FPGA IC chip will decrease significantly, power consumption will decrease, and the speed and function will increase significantly.

- Smart and creative IC designers can purchase the Logic Drive and use software to configure the hardware circuits of FPGA IC chips that use the most advanced process technology. This allows the realization of their ideas at a lower, attainable cost.

If using Logic Drive, TSMC could Provide both Public Innovation platform and Club Innovation Platform

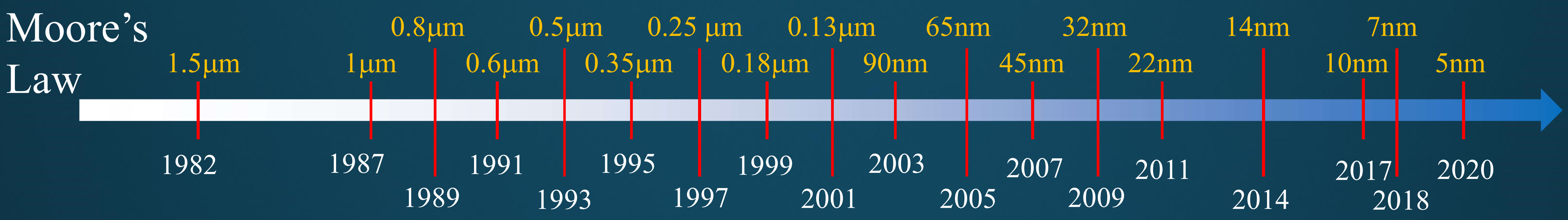
- If TSMC provides a portion of its fab capacity of technologies more advanced than 10 nm for producing Standard Commodity FPGA IC Chiplets, for use in the Logic Drive, TSMC could be both Public Innovation platform and Club Innovation Platform.
- This is a way for the 99% of common public to participate in the game of the wealthy 1% to realize their dreams. The pure foundry business model will become a paradigm and greatly contribute to the human civilization.

Lesson 4

"To be Moore, or not to be Moore?"

A career drifting in and out of Moore's Law

"To be Moore, or not to be Moore?": A career drifting in and out of Moore's Law



IBM	AT&T Bell Labs	TSMC	Megic Megica Qualcomm	iCometrue
Moore's Law	More than Moore	Moore's Law	More than Moore	Moore's Law and More than Moore

1982-1984: IBM. Followed Moore's law, participated in the development of the first and second generations of CMOS processes. CMOS 1(1.0 um) and CMOS 2 (0.8 um)

1985-1990: AT&T Bell Labs. With the prediction then that lithography at 0.1-0.2 um would reach the physical limitation of light wavelengths, I decided to leave the wave of Moore's Law to develop non-Moore's law technology.

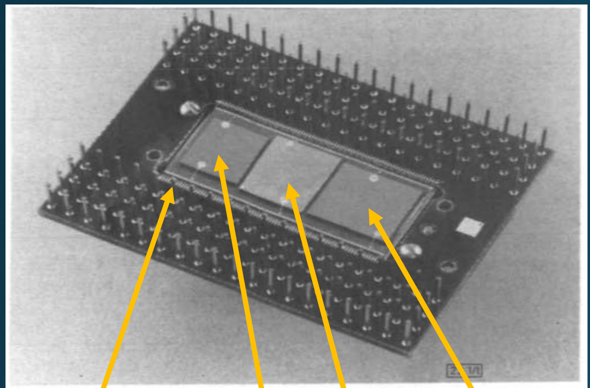
1990-1997: Led the TSMC R&D team. Followed Moore's Law and developed eight generations of process technology from 0.8, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45um to 35um.

1999-2011: Megic, Megica, Qualcomm. Departed from Moore's Law for the second time. Founded Megic and promoted the development of Megic/Megica technology. Fortunately surviving the waves of Moore's Law.

Departing from Moore's Law, a challenging but interesting journeys

AT & T Bell Lab

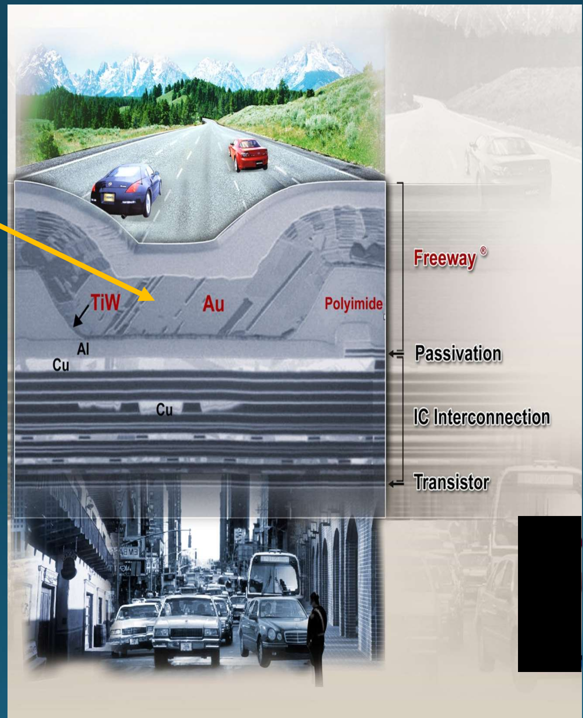
Multi-chip module based on silicon substrate



Cryogenic performance of a CMOS 32-bit microprocessor subsystem built on the silicon-substrate-based multichip packaging technology; M.S. Lin; A.S. Paterson; H.T. Ghaffari; Electronics Letters, Volume 26, Issue 14, 5 July 1990, p. 1025 – 1026

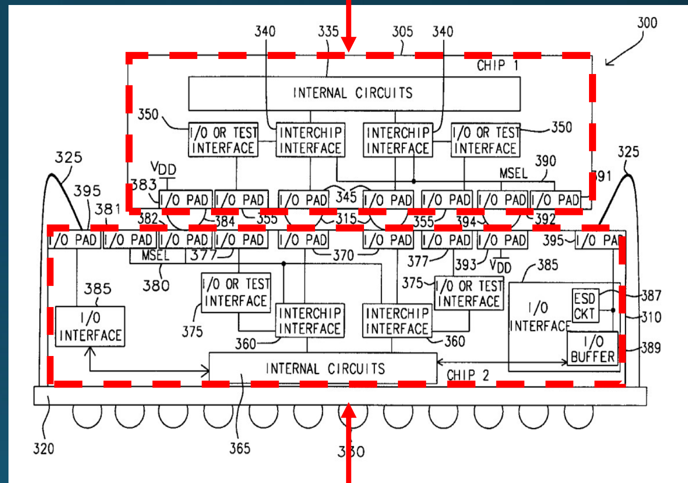
Megic/Megica

Freeway Technology



US Patent #6,383,916
Filing Date: 2/17/1999
Inventor: Mou-Shiung Lin

Megic Technology



US Patent #6,180,426
Filing Date: 3/1//1999
Inventor: Mou-Shiung Lin

To finally be Moore's or non-Moore's now?

- After decades of riding the ebbs and flows of life in the world of semiconductors, what would I finally be Moore's or non-Moore's? The truth of the matter is that the aforementioned Logic Drive that I first proposed in 2016 is actually a fusion of both Moore's law and non-Moore's law approaches:
  - The Logic Drive utilizes the power of Moore's Law by using standard commodity FPGA chips or chiplets fabricated in a technology more advanced than 10 nm that contain a sufficient number of transistors and provide fast processing speed with low power consumption.
  - However, the Logic Drive also leverages non-Moore's Law concepts by packaging a multitude of standard commodity FPGA chips into an advanced multi-chip package, in which the number of transistors would be greatly increased.

- Interestingly enough, the current development of multichip packaging technology (the non-Moore's Law technology) would appear to be starting its very own miniaturization journey following a scaling process much like the Moore's law in the IC chip: the number of transistors within an area or volume of the multi-chip package will be increased yearly.

Lesson 5

Big Number is Beautiful

Magic Power and Super Intelligence Emerge when the Number Approaches infinite

How magical power and super intelligence emerge when the number approaches infinity

In his essay "The West Lake Diary", Xu Zhimo, a Chinese romantic poet from the early 20^{th} century, remarks:

> Thousands of sheep in front of the turquoise hills, cuddling next to each other, forming a layer of velvety snow, it is beautiful; a skyful of stars, like thousands of sparkling eyes looking down on the land from the limitless blue sky, it is beautiful; a sea of clouds on the summit of Mount Tai, tens of thousands of cloudy peaks silently sitting in the morning light, it is beautiful; the millions of waves on the sea, wearing all manner of white caps, glimmering in the sunlight, rising and falling, it is beautiful; and tens of millions of birds resting on the "feather island" near Ireland, a blanket of feathers covering the setting sun in the west, the deafening chorus of so many birds singing simultaneously, it is beautiful; …… When the numbers are enormous, it is beautiful.
> There is beauty in the enormity of numbers. When the numbers are enormous, it seems to follow a certain law of nature, naturally forming a special arrangement, a special tempo, a unique style, exciting our aesthetic natures, stimulating our aesthetic souls.

The remarks are perhaps the best, most beautiful, and perfect expression articulating the foundation of this talk.

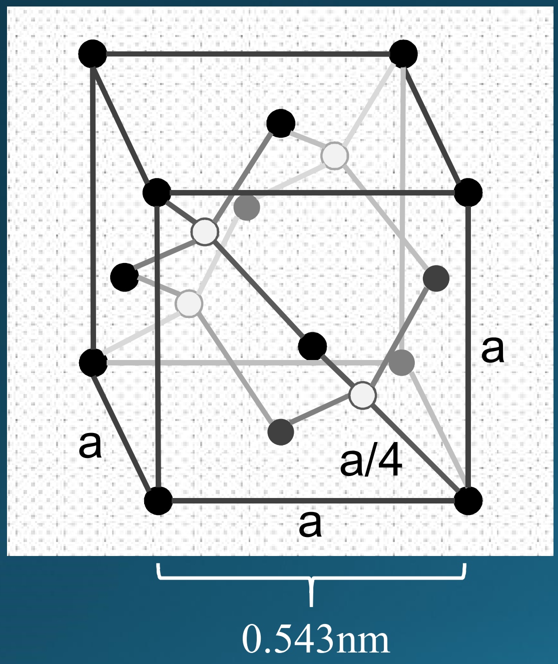
The limitless power and possibilities unlocked by infinite number

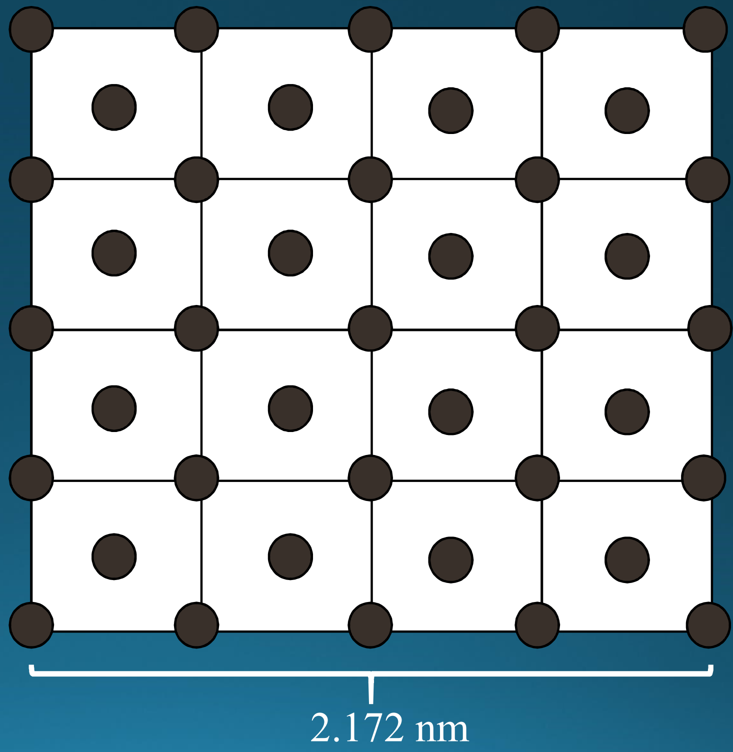
- The human brain contains 10^{11} neurons—for comparison, in following Moore's Law, a semiconductor chip now already contains 5×10^{10} transistors.
  - In 2015, the gravitational wave was detected and heard, confirming the theory of General Relativity proposed by Einstein over a hundred years ago.
  - In 2016, the artificial intelligence program AlphaGo beat master players in the game Go.
- Behind these astonishing events are signs of ever expanding numbers (tens of billions) of transistors on a semiconductor chip.

Astonishing craftmanship: 2nm transistors

- A 2nm x 2nm area contains 41 silicon atoms.
- Mankind can use 2nm technology node to design and mass-produce an area containing only 41 atoms!
- The distance between the two strands of DNA is 2nm.
- Are humans able to manipulate and play with atoms at the atomic level?

Silicon crystal lattice

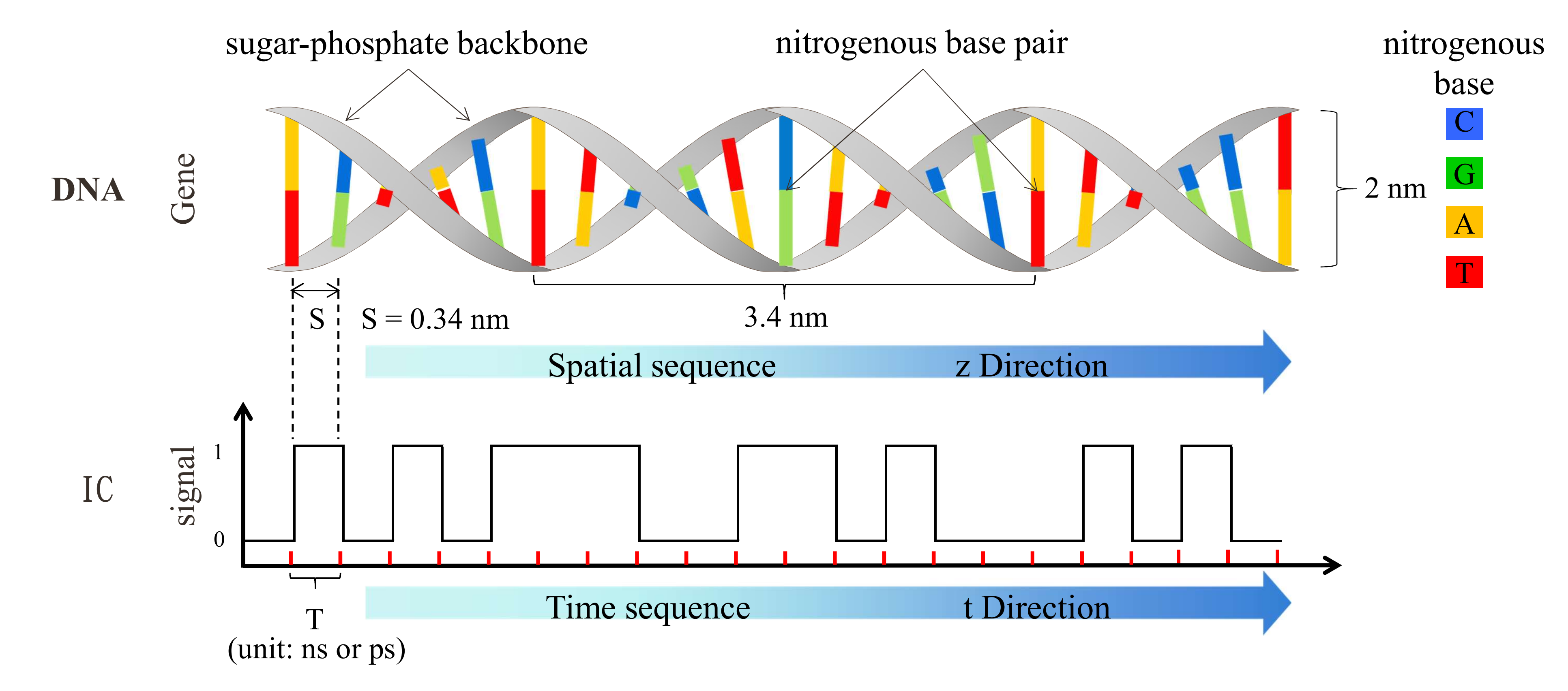




Curious analogy of Nature's DNA and man-made IC

	Man-made IC	Nature's DNA
message transfer algorithms	precisely and faithfully transfers electrical signal according to the time sequence of the two digits of 0's and 1's in the signal sequence. The time period (T) between two neighboring digits is in nano- or pico-seconds.	comprised of A(adenine), T(thymine), C(cytosine), G(guanine)—the four types of nitrogenous base arranged into A-T and C-G pairs. DNA precisely and faithfully transfers gene message according to the spatial sequence of A-T and C-G pairs within the gene sequence. The spatial distance cycle (S) is 0.34 nano-meters (the distance between two neighboring nitrogenous base pairs).
Moore's law	the function of IC abides by the algorithm of time sequencing, the size of IC follows space miniaturization.	the function of DNA abides by the algorithm of space sequence, and yet, the time it takes to perform gene sequencing of DNA follows time shortening.
Duplication method	utilizes photo-masks as molding plates to precisely duplicate/copy IC at volume.	utilizes two DNA backbones as scaffolding mold to precisely duplicate/copy genes at volume.

Time Sequence in man-made IC vs. Spatial Sequence in Nature's DNA



Space and time in the biological evolved DNA and human crafted IC?

- Space and time may play a hidden and mysterious role in both nature's DNA and man-made IC.
  - Could there possibly be an insight here related to complex space and time theory in physics?
  - Could this be a hint or clue at the future of DNA computing or Quantum computing?
- The fabric of space and the nature of time in physics challenge our knowledge and imagination, and we, as human beings, may be often caught in confusion and hardly understand the true reality and beauty of space and time.

Chips generating astonishing intelligence

- The human brain contains 10^{11} neurons, and one semiconductor chip now already contains 5×10^{10} transistors.
- One EUV lithography machine can print 150 wafers, each having 12-inch diameters and containing 2,000 chips. In a year, one EUV lithography machine can produce:

$$2{,}000 \text{ Chips} \times 150 \text{ wafers} \times 20 \text{ hours} \times 365 \text{ days} = 2.2\times10^{8} \text{ chips}$$

$$2.2\times10^{8} \text{ chips} \times 5\text{x}10^{10} \text{ transistors} / 10^{11} \text{ neurons} = 1.1\times10^{8} \text{ human brains}$$

- One EUV lithography machine can produce the number of transistors equivalent to the number of neurons in 1.1×10^{8} human brains, in which the number of human brains is close to 140 million of worldwide new-born babies in 2020.

Close your eyes, take a deep breath, and think about it…
Does this make you feel joyful or fearful?

Chips generating astonishing intelligence:
How the advancement of semiconductors will affect human civilization?

- Improve human civilization
  - Semiconductors will continue to provide astonishing contributions in the future, solving nature's great mysteries and improving human medical heath, life, and civilization.
  - Example: The spinning speed of the Muon particle in a magnetic field was recently discovered to contradict the known laws of physics by the Fermi Lab in Chicago. With the artificial intelligence capabilities of today's chips, we may solve the problem and may potentially discover the fifth fundamental force or other unknown basic particles.
- Destroy human civilization

  The fierce geographic and political conflict between the liberal democratic system and totalitarian autocratic system may ends up:
  - Elites of liberal democratic systems use algorithms to manipulate data to greedily and insatiably get what they want.
  - Dictators of totalitarian autocratic systems violate personal privacy, creating fraud to brain-wash and control the thoughts and actions of their citizens.

Chips generating astonishing intelligence: Instilling ethics in engineering

- The surging number of transistors has led us to the point where abuses of science and technology could result in great danger and the potential for mass destruction. Young scientists and engineers should establish and abide by the disciplines of Engineering Ethics as early as possible.
- Is it appropriate to follow Moore's Law and produce a new generation of iPhone every 1-2 years? Would this be eco-friendly?
  - Apple has been devoted to protecting the environment. Perhaps providing a new generation of iPhone every 5-6 years instead could reduce the consumption of electricity, water, and materials for the production of chips.
  - Consider switching to the Logic Drive, re-using IC chips by using software reconfiguration instead of manufacturing new chips each time.
- Harvard University School of Engineering and Law School established a joint professorship with the title of Professor of Engineering and Law in 2013.
- Harvard University School of Engineering pioneered the Embedded Ethics for Computer Science (EthiCS) initiative in 2018 and held its first worldwide "Conference on Ethics of Engineering" in Jan 2019. It is now planning to soon incorporate and add AI and Responsibility (AIR) research and courses.

*i*Cometrue :

*i*nspire × *i*magine × *i*nnovate × *i*nvention

$= i^4 = 1$

i^4 means:

i. be filled with curiosity, use your eyes to watch and read, use you your ears to listen, and use your brain to get **inspiration**;

i^2. then **think out of box to imagine**;

i^3. finally **distill and purify imagination to innovate**;

i^4. and **find an embodiment, the embodiment is the invention**.

$i^4 = 1$

From the smallest of smalls to the biggest of bigs…

Space: 10^{-9} m (Semiconductor) to 10^{27} m (Universe)

Time: 10^{-11} s (Semiconductor) to 4.3×10^{17} s, i.e, 13.8 billion years (Universe)

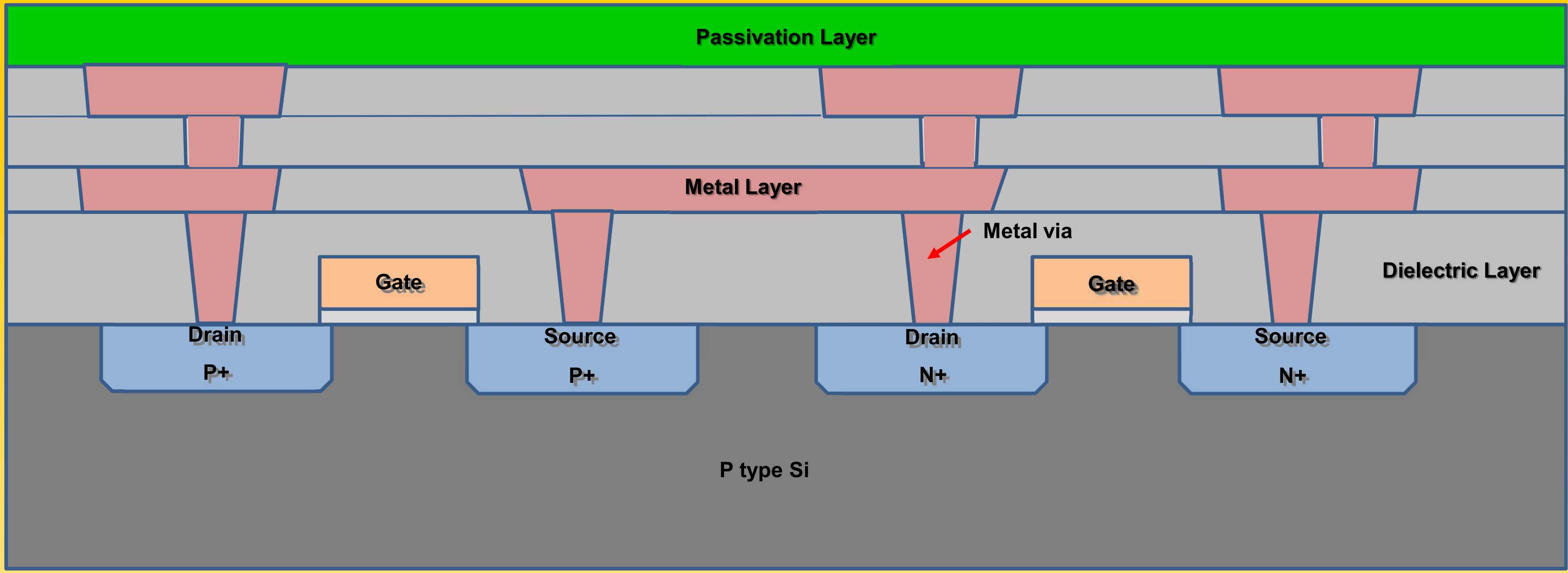
"one is all, and all is one"

Curiosity, Imagination, Values

Harvard College believes the purpose of education is to establish the ethical value for the students, not only to learn knowledge. Harvard thinks when a Harvard graduate makes critical decision in his/her life, he/she relies on his/her ethical value and religious belief, not the knowledge he/she learned from college, no matter he/she is a president, congressman, public officer, soldier, teacher, lawyer, doctor, engineer, or businessman.

Appendix

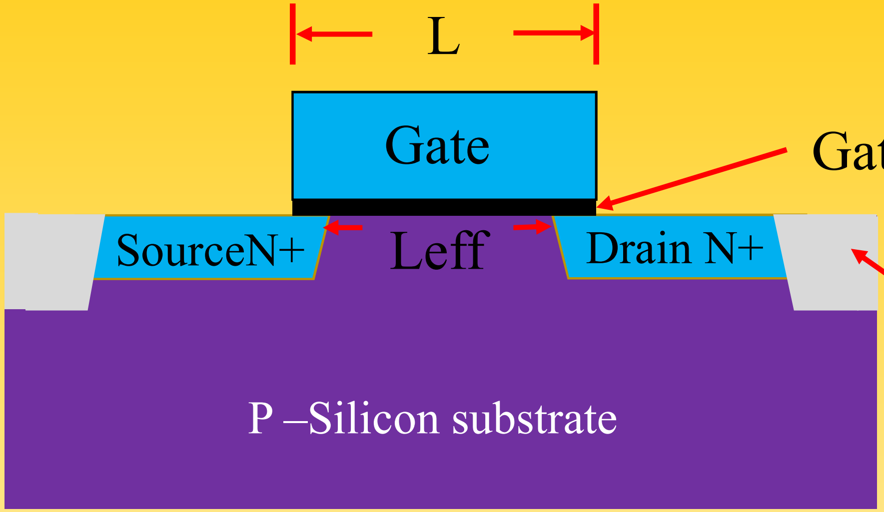
Essential Basic Knowledge: IC Structure Layers

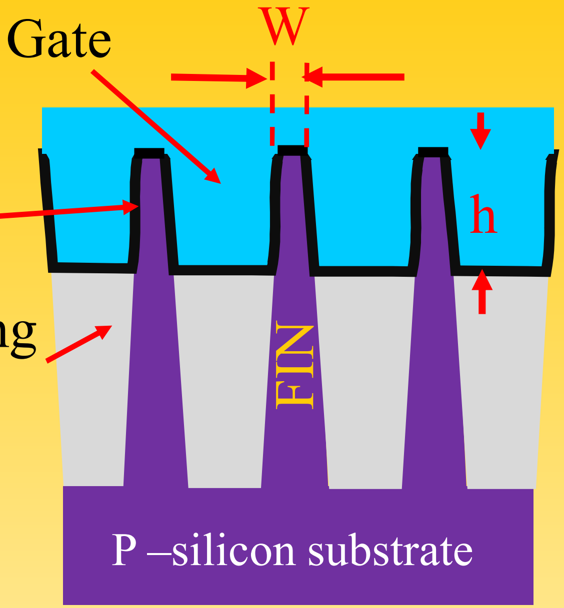


Essential Basic Knowledge: The significance of Technology Node

The size of L or Leff is the technology node
Current channel length, L
Effective Channel Length, Leff
Planar MOSFET prior to 20 nm (before 2014)

Definition of next technology node: the number of transistors doubled per unit area.
Channel Width, W
Effective Channel Width, Weff
FINFET, after 20 nm (after 2014)





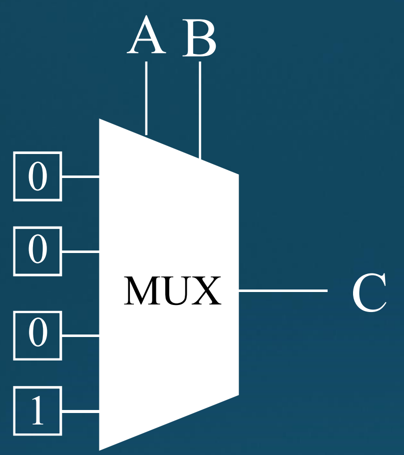
Weff = W+2h

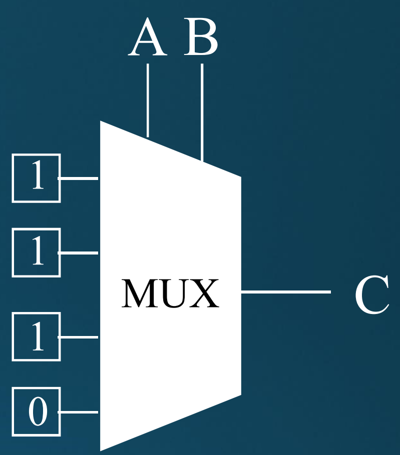
Current = k W_{eff}/L_{eff}

7 nm FINFET
W = 6 nm,
h = 52 nm,
Weff = 110 nm,
increase 18 times

Logic Drive
Software-Defined Hardware

FPGA Look Up Table





A	B	C = A AND B
0	0	0
0	1	0
1	0	0
1	1	1

A	B	C = A OR B
0	0	1
0	1	1
1	0	1
1	1	0

Example: A hardware circuit can be programmed to perform different logic functions such as AND or OR with different data stored in memory cells on the chip.