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# KEY TO PROGRESS: THE SEMICONDUCTOR TECHNOLOGY

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**Abstract**

Future progress in our life is unthinkable without semiconductor technology. Below is a brief sur-vey of the development facilitated by the integration of silicon devices since the discovery of the transistor 75 years ago, hinting also at the limitless future opportunities. In all sectors of everyday life integrated circuits are fundamental components in our instruments, their role in the industrial food-chain and their accessibility is of global-political importance, as witnessed today.

**Keywords**: *semiconductors, IC, complexity, functionality.*

## 1. Introduction

The device that changed everything was the point contact bipolar GE tranzisztor 75 years ago patented at Bell Lab, earning John Bardeen, Walter Brittain and William Shockley the Nobel Prize in physics. The next revolutionary breakthrough in technology was the innovation by Jack Kilby, and independently by Robert Noyce in 1958. They proved that the individual active amplifying and switching semiconductor devices can be wired along with passive circuit elements on the very same substrate creating thereby a complete integrated circuit (IC). Noyce even prepared a real monolithically integrated circuit by using aluminum wiring on the semiconductor substrate itself. The Nobel-Prize for physics was granted for this achievements to Kilby alone in 2000, as the Intel founder Robert Noyce deceased years earlier. Around 1960 started the glorious advancement of silicon technology, facilitating the ever increasing digitalization of today [1].

## 2. Why just Silicon?

The forbidden energy-gap of silicon (Eg = 1.12 eV) and the intrinsic-conduction determining the thermal noise makes silicon just in the temperature range of the human activity (−40°…+140°C) suitable for the realization of reliable digital switching operation without additional thermal stabilization.

High temperature annealing of Si in an oxygen-containing environment forms a natural oxide layer on the surface, which is an excellent insulating layer and can act as masking layer against doping of the silicon substrate. In the IC technology this phenomenon is until now utilized as the basis of the so called planar technology in the two dimensional architecture.

Albeit silicon, due to its indirect band-structure, is not able to emit intensive light, its perfect crystal structure free of defects and its high charge carrier mobility combined with proper down-scaling to reaching the physical limits make it predestined for high-frequency operation.

Silicon is bio inert material, i.e. from the point of toxicity it can be implanted in living organisms in bio inert fashion [2].

## 3. Moore's low for digital ICs

In 1965, Gordon E. Moore, an Intel executive, established an empirical "law". [3].

The exponential capacity increase (the number of transistors integrated on a chip) (Fig. 1) in chip manufacturing according to the "Moore prediction" was only a medium-term observation at the dawn of technology, an economic forecast that had become a self-fulfilling prophecy, i.e. a self-followed roadmap for sixty years! It had the special merit, according to Intel, that it helped with coordination: software houses could develop in advance for chips that would be released in two years, which created a market for the new device. Digital technology soon became dominated by complementary metal-oxide-silicon (C-MOS) circuit architecture. (Fig. 2).

However, the development of integration has not always been smooth (Fig. 3). By 1980, power consumption per chip had reached an unmanageable level. Thus, the supply voltage was gradually reduced from 5V to 1V, allowing the industry to develop steadily for 30 years. Around 2010, dissipation performance became a problem again. According to simulation projections, the thermal conditions on the square centimeter of chip surface "would soon reach the temperature prevailing in the core of a nuclear power plant”!

The solution was brought about by a three-dimensional 3D thin substrate. FinFET (shark fin field control) (Fig. 4), and the application of multicore processor architecture, which ensures further complexity increase based on size reduction (Fig. 1). The thin substrate may be a 2D semiconductor or graphene in the future [4].

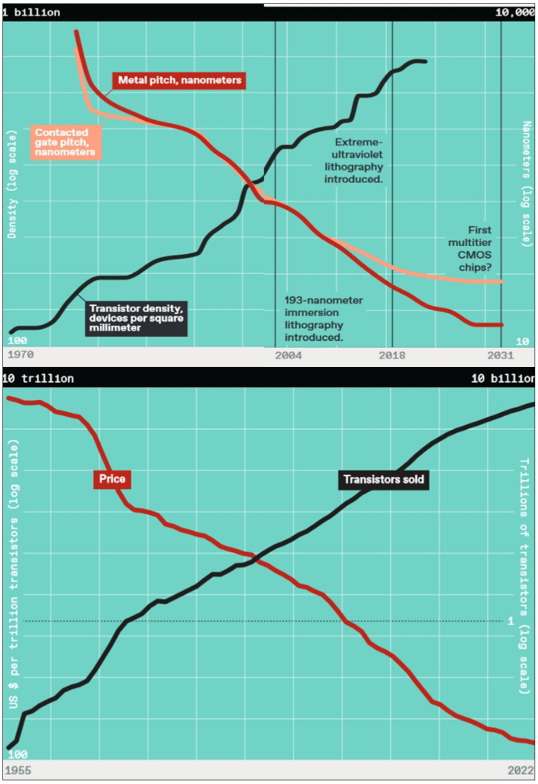


**Fig. 1.** *Moore's Law forecasts an exponential increase in transistor density (top, black curve on left ordinate), which can only be achieved by reducing characteristic dimensions (red curve on left ordinate). According to the bottom figure, this involves an exponential increase in the number of transistors sold per chip (black curve on the right ordinate) and an exponential decrease in its specific price (red on the left ordinate).*

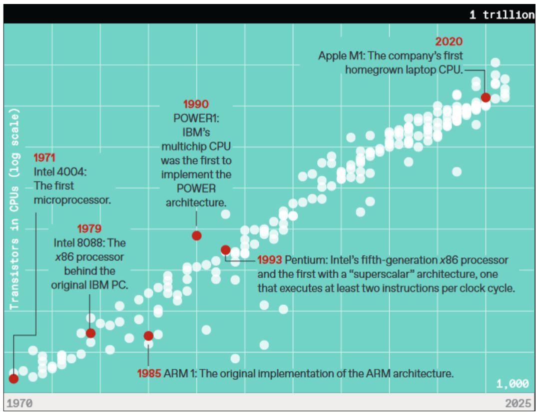


**Fig. 3.** *The advent of Intel microprocessors gave a great impetus to the increase in circuit complexity. By 1985, they had reached an element density of 1 million transistors/cm$^2$. Application-specific software needs have driven CPU architecture development, so today processor chips have element densities of over 100 million transistors/mm$^2$.* [3]

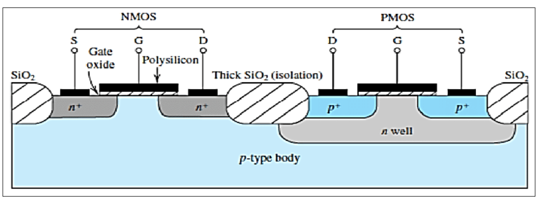


**Fig. 2.** *Cross-sectional image of the complementary MOS inverter basic circuit, which is still dominant in planar silicon technology.*

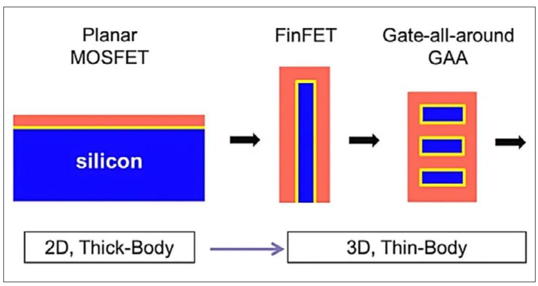


**Fig. 4.** *Transition from two-dimensional (2D) planar transistor design to 3D FinFET and all-around control electrode thin-substrate silicon technology.*

## 4. Rearrangement in the supply-chain

The continuous increase in productivity, i.e. the throughput of wafer processing, is a fundamental economic aspect. In fact, this is what drives to increase wafer diameter and reduce critical dimensions. To this day photolithography remains the dominant topological technology in the industry. However, optical imaging of ever smaller dimensions could only be achieved by reducing the wavelength of UV illumination from 435 nm to 13.5 nm and increasing numerical aperture NA (**Fig. 5**). **[5]**

The value of the clean-room filling vacuum equipment to achieve this is over US$200 million. It represents today the absolute top performance of precision mechanics, optics, robotics and control technology, comparable only to high-tech space technology (**Fig. 6**). **[6]**

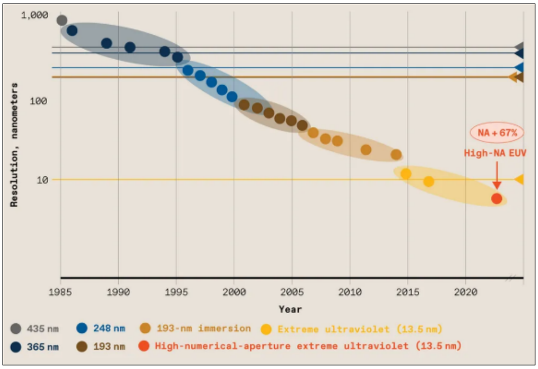


**Fig. 5.** *Decrease in wavelength of UV photolithography stepper illuminators over 35 years.*


**Fig. 6.** *ASML EXE:5000 large numerical aperture extreme UV lithography equipment of considerable size (Source: ASML) illustrating UV radiation beam-paths.* **[6]**

Today, the sole equipment supplier in contemporary lithography is the Dutch multinational company, ASMLithography. Thus, the development is European, but the well-capitalized users are mostly companies operating in Asia (**Fig. 7**).

The circuit design with the greatest intellectual added value is operated by large US and partly by European IC manufacturers, who use the chip production capacity of the Foundries to have mass production carried out in Asia (**Fig. 8**). Especially in conflictive economic situations, this fragmented supply chain is rather risky.

In 1986, in addition to 5 Japanese and 3 American manufacturers, 3 European companies (Philips, Siemens, SGS-Thomson) were also represented in the top ten.

## 5. What to expect in 25 years?

The principle of operation of transistors, the basic element of digital circuits, is expected to remain field controlled charge transmission down to < 1nm. On the other hand, special integrated constructions optimized for specific applications will appear.

Perpendicularly positioned channels (**Fig. 3)** can also increase the element density on silicon substrate - possibly using new materials, probably stacked 3D structures. **[4]**

The currently most frequently used 300mm diameter Si wafers will be replaced by 450 mm substrates (**Fig. 9**) which requires retooling of

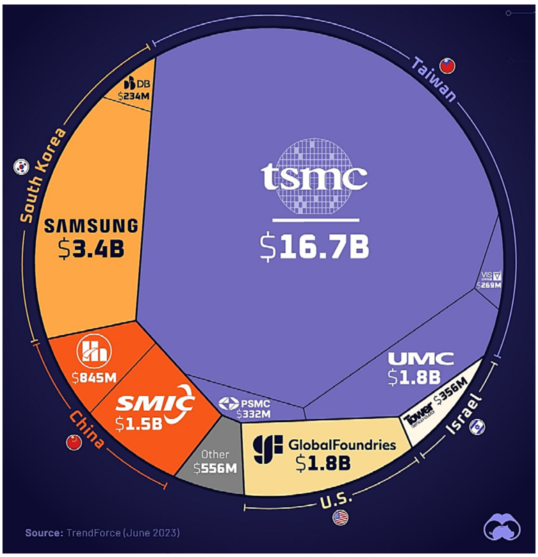


**Fig. 7.** *The distribution of the top ten most advanced IC Foundries, of the ASML customers, illustrating the dominance of Asia.* **[7]**

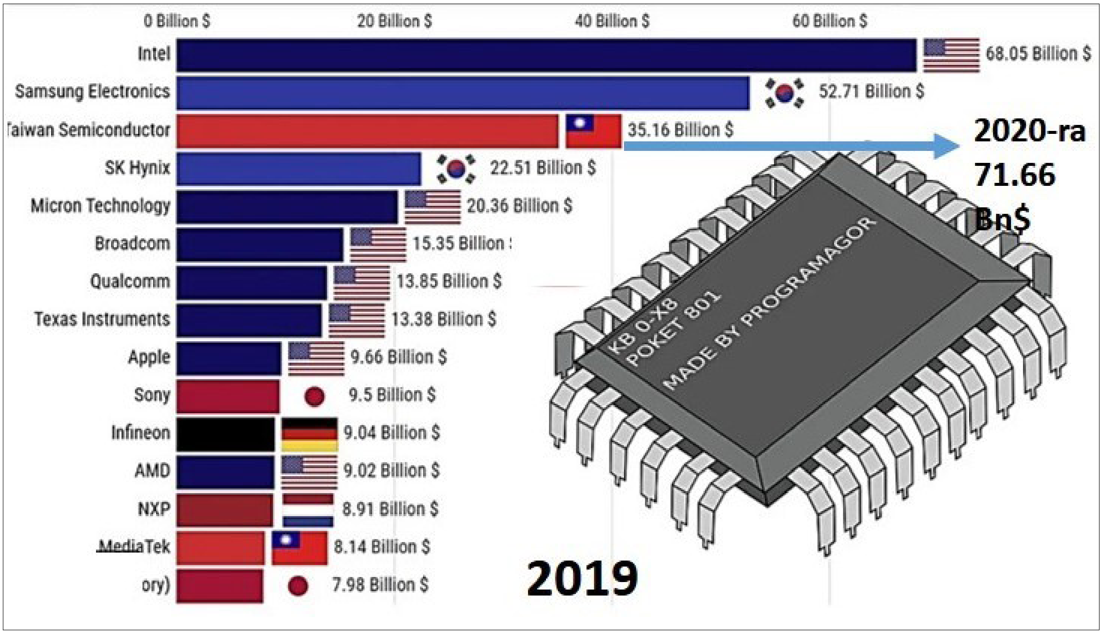


**Fig. 8.** *World's leading IC makers by annual turnover in 2019. By 2020, Taiwan's TSMC topped the list ahead of Samsung* [7]

the entire production line, especially lithography. The critical size reduction (Fig. 5) will only be achieved by increasing the numerical aperture NA. Exposure on such a large surface at the correct resolution requires beam angle manipulation (Fig. 8).

Such a FAB investment at today's prices costs hundreds of billions of US$, and only the most capitalized manufacturers can afford it. Due to enormous field strengths occurring on ultra-thin layers (1 V/1 nm = 1 GV/m!), operation at lower voltage levels is preferred in circuits. Controlling IC power consumption remains a dominant problem!

Based on experience, the introduction of a new operating principle can take 20-25 years. According to our current vision, quantum technology will not advance fast enough to threaten the dominance of transistor-based IC technology in everyday computing within a quarter of a century. What is the basis for such a statement?

## 6. Quantum computer technology

The basic problem of quantum state (qubit) computing is the elimination of thermal noise, which even near absolute 0K breaks down the difference between the two logical states within less than 20μs.

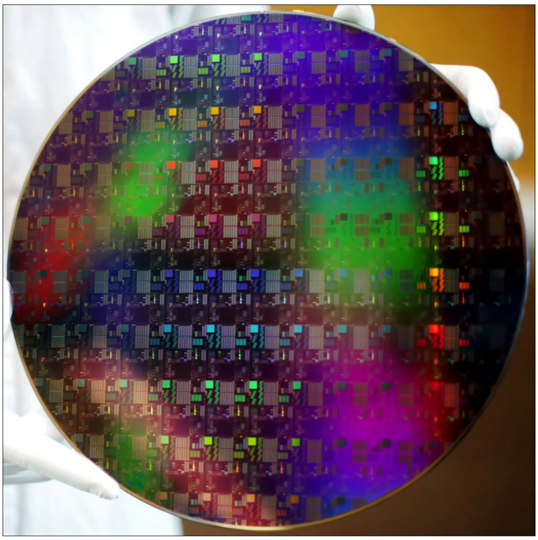

**Fig. 9.** *A 300 mm diameter Si wafer processed at GlobalFoundries Dresden.*

IBM's new cryo-CMOS controller chip (Fig. 10) uses 14nm fin-FET technology to operate at roughly 4K (-269.15 C°). They managed to reduce the previous power requirement of 100 W/qubit to 10 mW/qubit. This enabled to increase the number of qubits per chip. [8]


**Fig. 10.** *IBM's family of quantum chips has been developed from 5 qubit levels since 2016*

Quantum technology will provide the computing background for artificial intelligence (AI) primarily through cloud services (Fig. 11). ). It is estimated that if fully deployed, the continuous operation of an AI service accessible to all would require around 100 TWh, which is equivalent the annual energy demand of an advanced economy, like the Netherlands or Sweden. These data call for common sense and at the same time indicate the direction of future development, which is primarily to reduce energy consumption.

Advances in quantum computer technology are unlikely to be fast enough to threaten silicon IC technology's hegemony in computing and automation for another 25 years.

## 7. Conclusions

Transistors influence our daily lives in all areas, from industrial process control to communications, agriculture, transportation, health services, education and culture support.

It can already be forecasted that in the coming quarter of our century, integrated circuits combined with sensors will help to solve all upcoming problems of mankind, including climate adaptation!

However, global developments like the recent COVID crisis and the ongoing wars have highlighted the fragility of this perfectly established, global supply chain. Due to the profit maximizing efforts of the large manufacturing companies, processes requiring living labor have been outsourced in recent decades to countries with cheaper wages. With their far-sighted economic vision and policy, primarily Asian tigers, South Korea, Taiwan, Singapore, Hong Kong, and China have not only caught up with the previously leading Japan (Fig.7. and 8), but have also become irreplaceable as microelectronic suppliers to European and American industry. This is especially valid for the Taiwanese company TSMC, that owns the most advanced state-of-the-art technology. As a result of these measures, TSMC is now the manufacturer of over 70% of the highest integrated circuit chips globally!

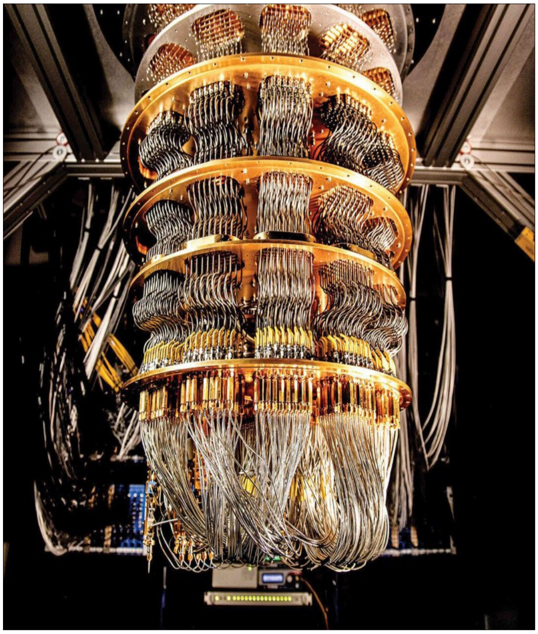

**Fig. 11.** *A cryo generator developed by Google to cool a quantum chip. Qubits can be ions, fotons, and atoms. The Google qubit is made up of superconducting metal elements with a low energy state of logical 0 and a higher power state of 1. They can be microwaved to either state or both. Thermal noise is critical for the safety of running larger algorithms.*

When supply routes were disrupted by the pandemic and wartime sanctions policy, European and U.S. carmakers and other key industries had to shut down for weeks due to parts shortages. This sharply highlighted the need to establish sovereignty in IC supply. Nowadays, both in the USA and the EU, the so-called Chips Act subsidies encourage domestic manufacturers and try to eliminate the current total vulnerability. [9]

Obviously, the US wants to maintain its economic development advantage in the longer term. It wants to prevent the People's Republic of China from annexing Taiwan as part of its country at all costs. On the other hand, a local war is not in the interest of either party. Paradoxically, this stalemate around Taiwan, is the key to "peace". Therefore, the USA has imposed sanctions against the European monopoly manufacturer ASML blocking the export of state-of-the-art lithography equipment (Fig. 6) to mainland China. With this, they hope to maintain the 6-7 year lag in the application of state-of-the-art chip technology.

## Refereces

[1] Cressler, J.D.: *Silicon Earth. A Historical Perspective on the Invention/Discovery of the Transistor*. IEEE Electron Devices Magazine, June 2023, 16–24.
[2] Bársony I.: *Szilíciumtechnológia – és amit neki köszönhetünk*. Székfoglaló előadások a Magyar Tudományos Akadémián, Magyar Tudományos Akadémia, Budapest, 2021, 7–11.
[3] Crass S.: *The Transistor's Amazing Evolution from Point Contacts to Quantum Tunnels*. Spectrum, IEEE.org, December 2022, 30–31.
[4] Radosavljevic M., Kavalieros J.: *Taking Moore's Law to New Heights, When Transistors Can't Get Any Smaller, the Only Direction Is up*. Spectrum, IEEE.org, December 2022, 32–37.
[5] Moore S.K..: *The Transistor of 2047*. Spectrum, IEEE.org, December 2022, 38–39.
[6] Schoot J. van: *This Machine Could Keep Moore's Law on Track*. IEE Spectrum, April 2024, https://spectrum.ieee.org/high-na-euv
[7] Révész B. Á.: *Íme, ők a legerősebb katonák a globális chipháborúban.* https://mandiner.hu/makronom/2023/11/legerosebb-katonak-globalis-chiphaboruban
[8] Adrian Cho: *Quantum computers take key step toward curbing errors.* https://www.science.org/content/article/quantum-computers-take-key-step-toward-curbing-errors?utm_source=sfmc&utm_medium=email&utm_campaign=DailyLatestNews&utm_content=alert&et_rid=581465878&et_cid=4612861
[9] https://www.european-chips-act.com/