End of Moore's Law and its Effect on Computing Development

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

In 1962, one of the founders of Intel, Gordon Moore, gave an observation that the density of semiconductors on a computing component would double every two years (Tardi, 2024). For an incredibly long time, this statement remained true. The industry developed so far that the modern iphone in 2024 is around 1464x faster and 98% smaller than the guidance computer that put a man on the moon in 1969 (*Mobile Phone vs. Apollo 11's Guidance Computer, 2024)*. But as semiconductors got smaller and smaller to fit on the same surface area, physics started to get in the way.

While nomenclature of semiconductor sizes keeps getting smaller in modern times, the actual size of the semiconductor does not. While companies to advertise that semiconductor sizes are "3 nanometers," in reality that would mean these semiconductors are 15 silicon atoms wide which is impossible due to the required doping to make a semiconductor useful for computing purposes (Traverso, 2024). In reality when a company says they are using a smaller semiconductor, the company is using a new line of production methods that increase the performance of a semiconductor. These production methods make the semiconductor more robust. This allows computer components to run faster while still being in the same size, which gives better performance metrics.

Using the theory of technological momentum, as established in Thomas Hughes' *The Evolution of Large Technological Systems,* this research paper will assess whether the computing industry can sustain current growth or be forced onto a new path. By examining different processes used in advanced semiconductor manufacturing, this paper will explore if the industry's focus must shift from merely improving individual semiconductors to optimizing their large-scale integration and application.

Background

A semiconductor is a type of material that can either conduct or block electricity from flowing depending on external factors in the environment. The most common of these materials used in electronics are silicon (S), germanium (Ge) and gallium arsenide (GaAs) (*Semiconductor Materials - IEEE IRDS^{TM}*, n.d.). These materials are used to create transistors, which are critical components to modern electronics. The most common transistor is the metal oxide semiconductor field effect transistor, or mosfet.

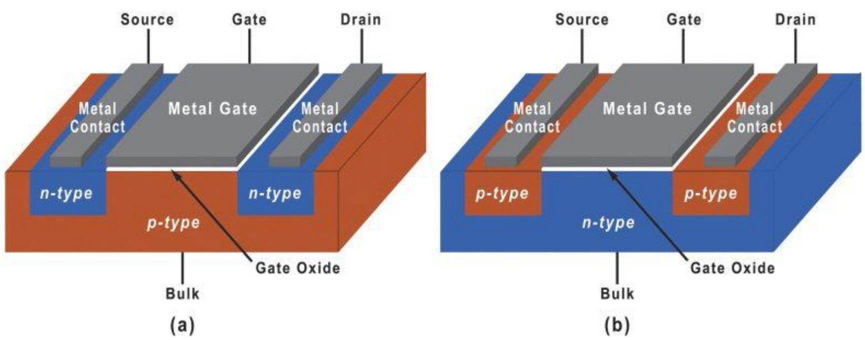

Figure 1. Picture of NMOS (a) and PMOS (b) MOSFET. Taken from MOSFET Physics (MOSFET Physics, n.d.)

As shown above in figure 1, a MOSFET has 4 pins. The gate pin controls whether the MOSFET is conducting or blocking electricity that flows through the source and drain pins. The body (shown above as bulk) pin is normally directly connected to the source pin to stabilize the voltage required to make electricity flow across the device. In this way, the MOSFET is a switch that can be turned on or off. These switches are the basics of modern computing. The size of these switches can be incredibly small but not on the scale of modern company advertising. For example, 3 nanometers, the most modern semiconductor architecture on the market as of writing this paper, does not indicate the size of the mosfet. This is because 3 nanometers would only allow for 15 silicon atoms to be used within the device. This amount of atoms would be impossible to use as doping, or adding impurities to the semiconductor, is required to make a mosfet work (Traverso, 2024). This is contrast to the past where shrinking the size of the mosfet was the main way to increase performance.

Technological Momentum

In *The Evolution of Large Technological Systems*, Hughes explains how technology embeds itself into society. Hughes believes that society starts at embedding the technology but is then further embedded through technological innovations and development (Hughes & Bijker, 1987). As an example, Hughes uses Thomas Edison and his power generation and electric light. Edison originally wanted to expand electric light, using his incandenscent lightbulb, into American cities. The incadencsent light bulb was the original invention but to implement it Edison had to generate and distribute energy around the citie. This is the invention and development phase within technological momentum (Hughes, 1987). During this time, society can either reject or accept the invention.

The next phase of technological momentum is innovation and expansion. In expanding his light electrical system into American cities, Edison created new companies to build generators, law underground wiring and created direct current (DC) distribution system. The DC distribution system was not perfect and had what Hughes called a reverse salient. Reverse salient hinders the development of emerging technological systems (1987). In this case, the reverse salient of poor long distance electrical transmission of DC electrical lines lead to another phase of Hughes' technological momentum.

Competition and differentiation arise from opposing companies that seek to innovate alongside. The example Hughes uses is with Nikola Tesla and George Westinghouse. Tesla and Westinghouse pioneered the alternating current (AC) power distribution system (1987). The AC system solved Edison's DC system problem of low range and is used today to transfer power across the US.

The final stage Hughes writes about is stabilization and momentum. This happens when technology is firmly embedded within society. Government organizations start to build around the technology and it starts to become integrated in everyday life (Hughes, 1987). For example, electrical light is used in almost every structure within the US and power is always available within most places in the US.

The computer component industry has had reverse salient in the past. While computer processing speed increased rapidly, memory sizes did not. Large physical sizes but low memory amounts limited how complex programs could be. This reverse salient was overcome by the invention of solid-state drives. In the semiconductor industry, a prevalent reverse salient is the size of the mosfet itself. Smaller mosfets bring up multitudes of problems but large mosfets cannot be used as modern computer processing units have billions of mosfets in there design. The decrease in mosfet size has led to problems in a variety of such, such as high pontiental electric fields, high leakage current, high variation in device dopant concentrations and heat dissipation (Chopra & Subramaniam, 2015). The industry has found ways around these reverse salients, such as finfets, gaafets and ribbonfets.

Mosfet Variations

The three major mosfet variations used for small scale transistors are fin fets (finfet), gate-all-around fets (GaaFET) and nano-sheet. Taiwanese Semiconductors (TSMC) uses the finfet and gaafet architecture. The nanosheet architecture is used by Intel and Samsung (Sundqvist, 2023). Finfets take the source and drain pins and raise them. This gives more the transistor more area within the source and drain to be able control electrical currents.

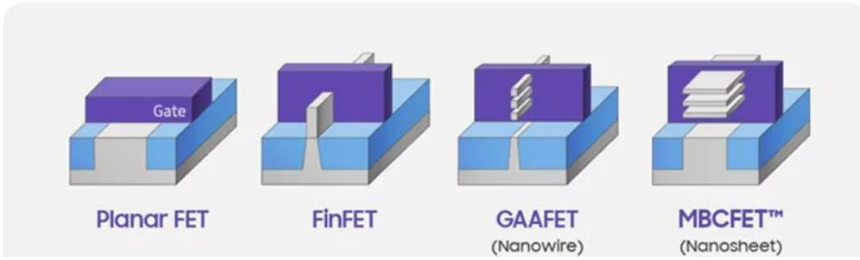

Figure 2. Types of MOSFET transistors. Taken from Samsung Semiconductors (GAA Structure Transistors, 2019)

Its downsides is that the finfet has higher parasytic capacitances (Bae et al., 2018). High parasytic capacitances lead to high current leakage which lowers the power to performance ratios. Gaafets take the raised pins on the finfet and cut away some extra material. This lowers parasytic capacitances at the cost of a more complex creation process (*Gate-All-Around FET (GAA FET)*, 2017). The final mosfet variation is the nanosheet fet. This uses the same essential structure of the gaafet but widens the individual pins for more current control.

Is this enough to overcome the reverse salient of mosfet size? For some time maybe. Graphical processing units (gpu) use billions of transistors and are essential for matrix heavy processing, such as large language models and video game graphics. While graphic cards performance is still increasing, it is coming at both a slower rate and longer time between releases (Walton, 2025). While this seems to indicate that the industry is still innovating through other ways to increase computer performance, it shows that the reverse salient of mosfet size is starting to affect the industry more and more.

Conclusion

Although transistor size is becoming more and more of a reverse salient to the momentum of the semiconductor industry, as of right now the industry has found ways around it. Different gate structures, such as the finfets, gaafets and nanosheet fets, have allowed the semiconductor producers to create more powerful transistors without needing to decrease transistor size. Although the rate of performance growth is not at the same rate of performance as before, as able to be seen within the graphical processing unit field, the industry has been able to keep producing new products every few years. While Moore's Law traditional interpretation has been broken, performance increases within his field continue to push on through adversity.

Bibliography

Bae, G., Bae, D.-I., Kang, M., Hwang, S. M., Kim, S. S., Seo, B., Kwon, T. Y., Lee, T. J., Moon, C., Choi, Y. M., Oikawa, K., Masuoka, S., Chun, K. Y., Park, S. H., Shin, H. J., Kim, J. C., Bhuwalka, K. K., Kim, D. H., Kim, W. J., … Kang, H. K. (2018). 3nm GAA Technology featuring Multi-Bridge-Channel FET for Low Power and High Performance Applications. *2018 IEEE International Electron Devices Meeting (IEDM)*, 28.7.1-28.7.4. https://doi.org/10.1109/IEDM.2018.8614629

Chopra, S., & Subramaniam, S. (2015). A Review on Challenges for MOSFET Scaling. *International Journal of Innovative Science*, *2*(4).

GAA Structure Transistors. (2019, November 20). Samsung Semiconductors. https://semiconductor.samsung.com/us/support/tools-resources/dictionary/gaa-transistors-a-next-generation-process-for-next-generation-semiconductors/

Gate-All-Around FET (GAA FET). (2017). Semiconductor Engineering. https://semiengineering.com/knowledge_centers/integrated-circuit/transistors/3d/gate-all-around-fet/

Hughes, T., & Bijker, W. E. (Eds.). (1987). The Evolution of Large Technological Systems. In *The social construction of technological systems: New directions in the sociology and history of technology* (1. pbk. ed., [Nachdr.]). MIT Press.

Mobile Phone vs. Apollo 11's Guidance Computer. (2024). Apollo11Space. https://apollo11space.com/mobile-phone-vs-apollo-11s-guidance-computer/

MOSFET Physics. (n.d.). Mks. Retrieved March 20, 2025, from https://www.mks.com/n/mosfet-physics

Semiconductor Materials—IEEE IRDS™. (n.d.). Retrieved March 24, 2025, from https://irds.ieee.org/topics/semiconductor-materials

Sundqvist, J. (2023, October 20). *The Semiconductor Showdown: TSMC's GAA FETs vs. Intel's RibbonFET*. https://www.blog.baldengineering.com/2023/10/the-semiconductor-showdown-tsmcs-gaa.html

Tardi, C. (2024, April 2). *What Is Moore's Law and Is It Still True?* Investopedia. https://www.investopedia.com/terms/m/mooreslaw.asp

Traverso, M. (2024, February 4). *A Node by Any Other Name: Transistor Size & Moore's Law*. Medium. https://medium.com/predict/a-node-by-any-other-name-transistor-size-moores-law-b770a16242e5

Walton, J. (2025, February 25). *The GPU benchmarks hierarchy 2025: Ten years of graphics card hardware tested and ranked*. Tom's Hardware. https://www.tomshardware.com/reviews/gpu-hierarchy,4388.html