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Moore's Law: The potential, limits, and breakthroughs

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Abstract. Moore's Law is a concept that notes the doubling of the number of transistors on a microchip around every two years, resulting in exponential advancement in computing power and diminishing costs. However, as transistor sizes have approached the physical limits of silicon-based technology, maintaining this pace of growth has become increasingly challenging. As a result, researchers have been exploring alternative solutions, such as System-in-package(SiP), Chiplets, Non-volatile memory, Biocomputing, quantum computing, and photonics. While these technologies are still in the early stages of development, they offer promising solutions to the challenges facing the continued growth of computing power. As we continue to explore new avenues for technological advancement, we may find that Moore's Law continues to hold true in unexpected and exciting ways.

Keywords: Moore's Law, Sip, Chiplet, Non-volatile memory, Biocomputing, quantum computing, photon-based computing, organic field-effect transistors (OFETs).

1. Introduction

Moore's law is a prediction made in 1965 by Gordon Moore, the co-founder of Intel, which stated that the number of transistors on a microchip would double approximately every two years, resulting in a corresponding increase in computing power. This prediction has held true for several decades and has been the driving force behind the rapid advancements in computer technology that we have witnessed in recent years [1-3]. However, as the size of transistors approaches atomic levels, it is becoming increasingly difficult to continue this rate of growth, and many experts believe that we are reaching the limits of Moore's law [4].

While Moore’s Law held steady for decades, it has begun to erode throughout the past decade or so. As feature sizes approach the boundary between macrophysics and quantum physics, the difficulty of developing advanced processes is increasing, resulting in higher research and development costs [5]. As the process continues to exponentially reduce the feature size in accordance with Moore's Law, it will face two challenges: the first being the economic obstacle, and the second being the physical obstacle.

To address these limitations, researchers are exploring new technologies such as System-in-package(SiP), Chiplets, Non-volatile memory(NVM), Biocomputing, quantum computing, and photonics. SiP is a technology that integrates multiple electronic components, such as microprocessors,

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memory, and sensors, into a single package to improve performance and reduce size and power consumption [6]. Chiplet is a new technology that allows the integration of multiple small chip components, or chiplets, into a single system, enabling greater flexibility, scalability, and cost-effectiveness in semiconductor manufacturing [7]. Quantum computing uses quantum-mechanical phenomena to perform calculations, potentially leading to significant increases in computing power [8]. Biocomputing mimics the structure and function of the human brain, allowing for more efficient and adaptable processing. Photonics, which involves the use of light to transmit data, could enable faster and more energy-efficient communication between computer components [9].

In summary, Moore's law has been a driving force behind the rapid growth of computing power, but we are reaching the limits of its predictions. To continue advancing, we need to explore new technologies and approaches, as well as optimize existing ones, to ensure that computing power continues to increase at a rapid pace.

2. The limit of Moore's Law

Since Gordon Moore came up with Moore's Law, the semiconductor industry is booming, and human society is rapidly entering the information age. Recently, the semiconductor industry and society as a whole have grown concerned about whether Moore's Law has reached its limit as the feature size of semiconductor manufacturing processes becomes increasingly difficult to shrink [10]. For one, the exponential progress integral to Moore's Law had already begun to slow as early as the late 1989s, as discovered in assessments of chip-related heat dissipation [11], It has also been recognized that the strategy that has propelled progress thus far is approaching an undeniable limit, and the industry has begun a "More than Moore" approach which looks at other means of accomplishing what has since been accomplished through silicon-based ICs [3].

Chief among these efforts is the building of devices based on a single molecule which are manipulated and arranged as engineers or computer-aided designs dictate. It has almost universally been the declared and executed upon goal by computer scientists, electrical engineers, and chemists to follow along the path of making transistors smaller by any means, but this strategy of just scaling down transistors and packing them ever tighter is reaching a definite limit [2]. Multiple strategies have been theorized to overcome this, however, such as building ICs three-dimensionally, developing new computational models (e.g., machine learning), and formulating more efficient architectural designs [5]. Modern conceptions of the universe fundamentally constrain the idea that Moore's Law might be followed forever. Moore acknowledged this himself when saying that "no exponential is forever" [4]. There will almost certainly come a point where – assuming it was even possible to reach that point – laws of physics and facts of matter prevent humans from developing smaller and more complex electrical circuits. This imposes a very hard line on the degree to which Moore's Law can be extrapolated out into the future. There are starting to be signs that the progress integral to Moore's Law is approaching a limit of sorts irrespective of whether or not the circuits are based on semiconductor transistors. One of the causes of this limit is the difficulties posed at the subatomic level and the growing levels of sophistication required of the chemical processes used to overcome these difficulties. One such conflict comes when trying to increase the ability to control an electron flow through the use of microscopic gates, which can be interfered with by a process called "drain-induced barrier lowering" [2]. Two tweaks to the structure of IC address the drain-induced barrier lowering, but their combined effect introduces a quantum-mechanical phenomenon called "quantum tunneling," which decreases control - the very thing that this entire endeavor was meant to increase [3].

Physical realities are not the only constraints that can limit the exponential development of Moore's Law. The term "Moore's Second Law" refers to the economic limitations that could potentially impede progress at a faster rate than humanity's capacity to overcome the challenges posed by chemistry and physics [12]. The reason for this limitation is that the monetary cost of developing more complex electrical components increases at a similar rate to the exponential growth of the complexity itself. For example, lithography methods for producing ICs are approaching a level that some experts believe will make producing smaller devices "economically impractical" [13]. The rate of both technological

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improvement and return on investment has historically offset the increase in cost to produce more powerful devices, as customer demand and an increased ability or desire to base more and more of daily life on IC technology continually outpace the rate of increased research and development costs. And so it makes sense from a business perspective to continue innovating. But this need not necessarily continue to be the case. As the efficiency of micro-transistors and integrated circuits increase while the price the consumer pays per unit of computation power decreases, there is a real possibility that IC technology could become so cheap that further innovation is no longer justified by a commensurate increase in profit [14]. If a doubling of transistor density will bring the company a ten or even one percent increase in profit, then it makes sense to carry on, but if down the line a doubling of transistor density will bring something like a 0.000001% increase in profit, then there's almost no point to pursuing progress when it would be much easier to put out the already developed technology for practically the same profit levels.

3. The solution and future direction to Moore's Law

The technology that simply reduces the transistor size reached its limit in the early 2000s. This implies that reducing the size of a transistor no longer results in increased speed or decreased power consumption [15]. Therefore, it is necessary to develop new technologies to break through the limit of Moore's law. There are three different directions of how to exceed Moore's Law given by the industry and academia: More Moore, More than Moore, and Beyond CMOS. There are many exciting research and concepts in these areas, but due to space reasons, only some of them can be introduced.

3.1. 3D SiP integration

3D System-in-package (SiP) solutions are a form of improving chip density by stacking silicon dies in three-dimensional space while connecting these chips to each other. 3D integration refers to the ability to connect dies even when vertically stacked, through the use of Through Si Via (TSV) technology [16]. 3D SiP packaging involves optimizing the use of 3D integration by packaging these dies into chips through intelligent positioning, such as Package-on-Package designs that layer larger packages (such as logic dies) over smaller memory dies. This ensures that integration is happening along short lengths [17].

3D SiP Packaging and Integration thus improves on the effectiveness of circuits and transistor density in a way that goes beyond Moore's law. Instead of relying purely on transistor density, SiP technologies, and especially 3D SiP, go beyond Moore's law in a way that has been called "More than Moore" [16]. This is because the density of 3D SiP is not gained through any one circuit's density, but rather the density of the entire circuit through its 3D packaging and interconnection. While much has been said about the potential thermal or mechanical limits of transistor density in integrated circuits, the intent of Moore's Law may be understood to be the density of circuits, which 3D SiP does provide for. Interconnection is possible in the modern context because of the ability to use very short connecting wires with high densities [16].

3D integration through TSV interconnects is especially useful because TSVs have the highest possible densities out of 3D options [16]. Vertical stacking provides for a smaller form factor in two dimensions, while ensuring that vertical layers are concentrated in ideal spaces. Thus the advantages of 3D SiP integration and packaging can be understood as a series of benefits coming from vertical stacking. For example, creating smaller chip areas is associated with higher yields and lower cost [17], and the use of 3D packaging allows for shorter interconnects, which should provide for both better performance and a better form factor [17]. Finally, even outside of these direct improvements to chips themselves via 3D integration and packaging, 3D SiP also enables new strategies for design. One example of a new strategy is Heterogenous Integration, where layers can be released in such a way that different specialized layers can be integrated together in vertical stacking to save space [17]. Despite these advantages, however, there are also disadvantages to 3D SiP technology. For example, some problems observed in 3D heterogenous integration are the mismatch in Coefficient of Thermal Expansion (CTE) between copper and silicon, which can cause structural strength to silicon when thermal increases occur[18]. Because there are still increasing pressures for chip density and higher thermal loads, the interconnectivity of chips in 3D expansion means that there may be some tradeoffs between 3D SiP

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integration (which is most effective with silicon TSVs) and the TDP approved for a given package, especially given 3D cooling challenges [19]. Furthermore, 3D packaging increases the vulnerability of chips to environmental ingress such as moisture intrusion due to poor interlayer adhesion, or electromigration due to void effects in soldered contacts [20].

In the context of chiplets, heterogenous SiP packaging allows for distinct units such as processor cores and memory chips to be packaged together, which further enables the possibility to technologies such as Processor in Memory [21]. Thus, SiP is one of the technologies that extends the capacity of chiplet designs. While chips themselves can also be SiP integrated and packaged, these chips can also themselves be packaged in 3D for similar benefits that apply to specific contexts.

3.2. Chiplets

Chiplets are small, multichip modules [22]. According to Frazelle (2), they are the individual integrated circuits (ICs) that comprise multichip modules (MCM). In this sense, one can think of chiplets as the building blocks of CPUs. Individual chips are made of silicon wafers that are variable in quality [23]. Therefore, multiple tiny chiplets can reduce some of the imperfections arising from faulty wafers. Chiplets emerged as an attempt to transmit more information from smaller nodes [7]. This allows for larger ICs capable of greater information transfer. Chiplets are commonly found in devices such as desktop computers, laptops, and smartphones.

In the article, Le defined three broad categories of advantages associated with chiplets: technology, development cost, and business. In terms of technology, Li suggested that there is always room for improvement in terms of chiplet design [16]. They also note that chiplets improve signal transmission and bandwidth issues. In terms of development cost, Li suggested that well-developed research and development techniques allow developers to produce more powerful chiplets without substantially raising the cost of the products themselves [7,16]. By integrating multiple small chiplets into a large monolithic chip, processing power improves markedly but does not noticeably change in cost. Finally, the business sphere is related to the development cost aspect of chiplet advantages in that the reduced costs of chip and chiplet production opens up unique opportunities for developers, suppliers, and buyers [7]. Contrastingly, some disadvantages of chiplets include interconnect interfaces and protocols, packaging technology, and quality control [16]. While the ostensible use of chiplets enhances yields and decreases the need for large dies, it also increases a number of these fabrication issues. Furthermore, without the proper QC, the integration of multiple chips in a chiplet also increases the chances of failure. The importance of testing these chips is important, but having more units across chiplets makes testing more difficult.

Some of the challenges that chiplets face are similar to those that face other 3D System in Package solutions. Some of them are market-related, such as the importance of quality technologies. The ability to develop Known Good Dice (KGDs) is important in order to prevent package failure [7]. The cost of testing chips increases prices, and combined with the burdens of optimizing memory, suggests that further optimizing chiplets will need to be balanced with the price of testing that is necessary to further increase the number and complexity of chiplets.

3.3. Non-volatile memory (NVM)

Moore's Law has posed several challenges such as reduced power consumption, heat dissipation, and data storage as the number of transistors increases and their size decreases. However, Non-volatile memory (NVM) technology can be a solution to address these challenges [24].

Here are a few ways in which NVM technology can help to address these challenges:

Power Consumption: As the number of transistors on a microchip increases, so does the power required to operate them. NVM technology can help to reduce power consumption by providing a storage solution that does not require constant refreshing, as is the case with volatile memory such as Random Access Memory (RAM). In fact, Magnetoresistive RAM (MRAM) has demonstrated significant advantages as a fast, relatively low-power, high-endurance, radiation-resistant non-volatile memory that can be integrated into the CMOS as a back-end-of-line (BEOL) process [18]. This can help to reduce the overall power consumption of a computing system and improve energy efficiency.

Heat Dissipation: As the size of transistors decreases, the amount of heat generated by a microchip increases, leading to challenges in heat dissipation. NVM technology can help to address this issue by providing a storage solution that does not require constant refreshing, as is the case with volatile memory. For example, Emerging Non-Volatile Memories (NVMs), like Intel and Micron's 3D XPoint [24], are expected to hit the market soon. These memory technologies have high-density, ultra-low idle power (eliminating the need for cell refresh), low latency, and data persistence, unlike DRAM [25-27]. This can help to reduce the overall heat generated by a computing system and improve its reliability and lifespan.

Data Storage: As the number of transistors on a microchip increases, so does the amount of data that needs to be stored. NVM technology can help to address this issue by providing a high-density, non-volatile storage solution that can store large amounts of data in a small space. This can help to increase the storage capacity of a computing system without increasing its size or power consumption.

Integration: NVM technology can be integrated into existing computing systems, providing a way to enhance their performance and capabilities without requiring a complete redesign. This can help to extend the lifespan of existing computing systems and reduce the cost and complexity of upgrading to new technologies.

Overall, NVM technology provides a promising solution for addressing some of the challenges encountered in Moore's Law, including power consumption, heat dissipation, data storage, and integration. By providing a high-density, non-volatile storage solution, NVM technology can help to enhance the performance and capabilities of computing systems, while reducing their power consumption, heat generation, and overall complexity [26].

3.4. Photon-based computing

Another reason of restricted Moore's Law is due to the heat generated by the large number of transistors packed into a small space, which limits the performance of the chip.

One proposed solution to this bottleneck problem is to use photon-based computing. Photonic computers use photons as the carrier of information transmission. Optical interconnection replaces wire interconnection, optical hardware replaces electronic hardware, and optical operation replaces electrical operation. A laser is used to transmit signals, and optical fiber and various optical elements form an integrated optical path to carry out the data operation, transmission, and storage [9]. Photons, or particles of light, can carry large amounts of information without generating heat, which makes them ideal for high-speed computing. Photon-based computing transmits data using light instead of electricity, which significantly reduces the heat generated by the chip.

One approach to implementing photon-based computing is to use optical interconnects. Optical interconnects are devices that can transmit data using light instead of electricity. They consist of a source that produces light, a waveguide that guides the light, and a detector that receives the light. By using optical interconnects, data can be transmitted at much higher speeds and with lower power consumption than with traditional electrical interconnects.

Another approach is to use photonic processors. Photonic processors use light to perform calculations, which can be much faster and more efficient than traditional electronic processors. Photonic processors can be used to perform complex calculations such as Fourier transforms, which are used in signal processing and image recognition [9].

In conclusion, using photon-based computing can potentially solve the bottleneck problem of Moore's law by reducing the heat generated by the chip, enabling faster data transmission, and allowing for faster and more efficient computation. However, there are still many challenges to overcome, including the development of practical and cost-effective photonic components and the integration of photonics with traditional electronics.

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3.5. Biocomputing

Another solution to solve the limit of Moore's Law is to use biological molecules for calculation and information processing. Biological molecules, such as DNA, RNA, and proteins, have unique properties that make them well-suited for certain types of computing tasks. For example, DNA can store vast amounts of data in a very compact form, and enzymes can perform complex computations with high accuracy and speed.

One approach to using biological molecules for computation is called DNA computing. DNA computing is a technology that utilizes DNA molecules for both storage and processing of information [28]. For example, the research team at the University of Washington and Microsoft Research Institute cooperated to synthesize 35 files with a total size of about 200MB into DNA sequences and store them and designed specific primers to mark the address of each file on the DNA sequence (similar to the storage path on the hard disk) [29].

Another approach is to use proteins as computing elements. Theoretically, protein-based biological computers can be made by using protein molecules as components. Because protein molecules are not only much smaller than electronic components on silicon chips, but also have low impedance and low energy consumption, they have not only huge storage capacity and the ability to process information at high speed, but also better solve the heat dissipation problem [30]. Proteins are capable of performing complex computations with high accuracy and speed. For example, researchers have used protein-based circuits to perform logical operations and to control the movement of nanoparticles.

Overall, the use of biological molecules for computation and information processing holds great promise for overcoming the bottleneck problem of Moore's Law. Despite the potential of this technology, there are several obstacles that need to be addressed before it can be adopted on a larger scale. Some of these challenges include improving the accuracy and speed of biological computations, as well as developing effective methods for integrating biological systems with conventional electronic devices.

3.6. Quantum computer

Quantum computers have the potential to solve some of the challenges associated with Moore's Law. Quantum computers utilize the principles of quantum mechanics and employ quantum bits, or qubits, to execute computations. The ability of qubits to exist in multiple states simultaneously enables quantum computers to perform certain calculations much faster than classical computers [31].

One way quantum computers can help address the challenges of Moore's Law is by providing a more efficient way to simulate the behavior of atoms and molecules. This is important for a wide range of applications, from drug development to material science. Classical computers are limited in their ability to simulate complex systems because they require significant computational power and time. Quantum computers, on the other hand, can perform these simulations much faster and more accurately, making them an attractive option for researchers and scientists [8].

Quantum computers can aid in addressing the challenges of Moore's Law by offering a more efficient method for solving particular optimization problems, which often require selecting the best solution from an extensive pool of possibilities [8]. This is an important problem in many industries, including finance, logistics, and transportation. Classical computers are limited in their ability to solve these types of problems because they become increasingly difficult as the number of options increases. Quantum computers, however, can solve these problems much faster by using quantum algorithms such as the quantum annealing algorithm [32].

Overall, quantum computers have the potential to solve specific problems much faster and more efficiently than classical computers [33]. Even though they are still in the early stages of development and not yet widely accessible, quantum computers provide a thrilling opportunity for researchers and scientists to tackle the obstacles related to Moore's Law.

3.7. Polymers

Polymers can potentially help address some of the challenges associated with Moore's Law. Polymers are large molecules made up of repeating units called monomers, and they have a wide range of applications in various industries, including electronics [32].

One way polymers can help solve Moore's Law problems is by providing a more efficient and cost-effective way to manufacture electronic devices. Conventional manufacturing methods for electronic devices involve complex and expensive processes, such as photolithography, which can become increasingly difficult as device sizes continue to shrink. Polymers offer an attractive alternative because they can be easily molded into complex shapes, making them ideal for creating smaller and more intricate devices [34].

Polymers also have unique electronic properties that make them well-suited for use in electronic devices. For example, some polymers have high electron mobility, which means that they can conduct electricity efficiently. This property makes them ideal for use in organic field-effect transistors (OFETs), which are used to amplify or switch electronic signals in a variety of applications, including displays and sensors [34].

Additionally, polymers can be used to create flexible and stretchable electronic devices, which have a wide range of potential applications in healthcare, robotics, and wearables. These devices can be made by combining polymers with other materials, such as metals or conductive carbon nanotubes, to create flexible circuits that can be easily integrated into clothing or other flexible substrates [35].

Overall, polymers have the potential to provide a more efficient and cost-effective way to manufacture electronic devices while also offering unique electronic properties that can be tailored to specific applications. While there are still challenges to overcome, such as improving the reliability and stability of polymer-based devices, they represent an exciting opportunity to address some of the challenges associated with Moore's Law [36].

4. Conclusion

In conclusion, Moore's Law has been a driving force behind the exponential growth of computing power over the past several decades. While the limitations of this law have become increasingly apparent, there are several solutions that have emerged to address these challenges. So, is Moore's Law that is going to die? Obviously, the answer is no. In the article, we mentioned many methods to solve problems. New materials, chip architectures, and optimization techniques are all being developed to help extend the lifespan of Moore's Law and continue to drive progress in the field of computing.

We must admire the great creativity of the engineers who are able to find new ways out of Moore’s law when it seems to be completely stagnant. In fact, the blind pursuit of smaller transistor sizes won't last forever, but that doesn't mean the era of building more complex and powerful electronic systems is coming to an end. There are still many talented researchers who are constantly challenging and promoting the limit of Moore's law. While it is uncertain how long the predictions of Moore's Law will continue to hold true, it is clear that the pace of technological advancement will not slow down anytime soon.

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