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Leading Edge;
Pushing the Boundaries and the Future of Compute

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Leading Edge;
Pushing the Boundaries and the Future of Compute

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Key Takeaways

- Moore's Law has been one of the most important drivers of productivity and economic growth over the last 50 years.
- Continuation of the regular doubling of computing performance is becoming increasingly difficult and is highly dependent on a few companies we deem to be some of the most important companies in the world today.
- The eventual end of Moore's Law will not mean the end of computational progress. The future of computing is a convergence of traditional silicon-based computing and new types based on neuromorphic and quantum principles.

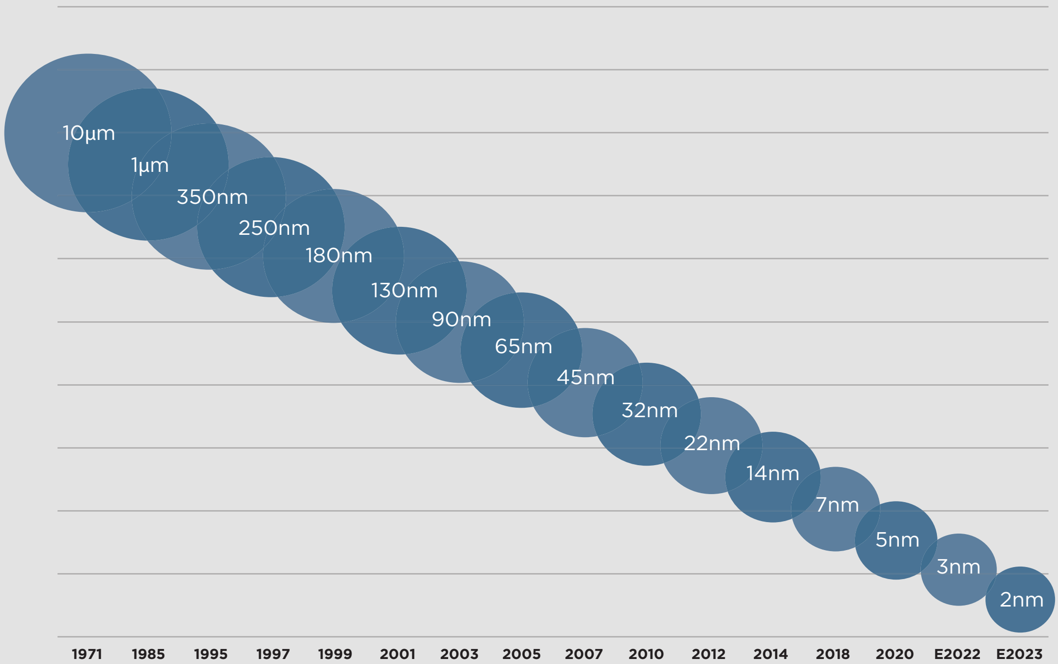
For more than 50 years the semiconductor industry has managed to develop technologies that have ensured the continuation of what has been termed Moore's Law, the periodic doubling of the number of components on an integrated circuit leading to an exponential growth in computing power. As a consequence, Moore's Law has been instrumental in driving productivity and business model development and therefore economic growth over the last half century. See also The Butterfly Effect and Taiwan as the Future IT Hotspot.

A common way to denote progress in the semiconductor ecosystem is the concept of "node" size. Nodes have become successively smaller over the past decades, as manufacturing technology has progressed, please see figure 1 on the next page. Whereas in the early 1970s, state-of-the-art process technology operated at the 10 micrometer (µm) node, the smallest features created today are in the range of 5 nanometers (nm), 2000 times smaller.

Through history, Moore's Law has been declared and predicted to be dead many times, as the industry approached sub-micron sizes. Starting from 1 µm (1.000 nm) distance between individual transistors, many people became skeptical in the law's viability and how well it would hold up. However, the industry has now reached 5 nm as Apple's newest iPad Air tablets will come equipped with the company's new A14 Bionic 5 nm processor produced by Taiwan Semiconductor Manufacturing Company (TSMC).

The ever continuation of Moore's Law is the result of many companies' work on pushing the boundaries of physics. The value chain within semiconductors covers semiconductor production equipment (SPE), with companies like ASML, LAM and Applied Materials, the photo mask producers like Hoya and AGC as well as semiconductor IP and design service companies like

Figure 1: Technology Nodes through Time



Source: Wikipedia as of Oct. 2020

ARM, Synopsys and Cadence. These companies have been the drivers of Moore's Law and as such are vital for the producers and designers of semiconductors, whether it be the independent foundries like TSMC who produce chips for fabless semiconductor design companies or integrated device manufacturers (IDM's) like Intel or Samsung, who are chip designers but also manufacture their own chips. This also includes the fabless semiconductor design companies like Apple, HiSilicon, Nvidia and Mediatek who outsource production to foundries like TSMC.

The industry has over the years developed along with Moore's Law, and as Moore's Law has been increasingly difficult to keep up with, many companies have either been acquired or simply fallen by the wayside. This has resulted in highly consolidated end-markets for the remaining players. This working paper considers how much further we can expect Moore's Law to evolve while highlighting a few of the most concentrated markets in the semiconductor value chain as well as focusing on some of the most important companies within the industry.

The Importance of Lithography

While continuous progress on all levels of the value chain has been instrumental in the continuation of Moore's Law, it is our view that a particular development within the equipment side, namely lithography, has been essential for the industry's ability to advance.

Making transistors is done by "printing" them on a silicon wafer. This is achieved by shining light through a photo mask, which penetrates the silicon and etches the pattern onto a wafer. As you decrease the size of the transistor, you must make the light source smaller and more precise. This is due to fundamental limitations, dictated by physics, that link the wavelength of light with the dimension of the features that can be etched with the light source.

Lithography equipment is defined by the type of light source, and therefore the wavelength of the light used as the source for the exposure of the silicon wafer. In the 1990s, deep ultraviolet lithography ("DUV") was introduced, first operating at a 248 nm wavelength using krypton fluoride ("KrF") lasers and then shifted over time to argon fluoride ("ArF") lasers, operating at a wavelength of 193 nm. As semiconductor nodes have continued to shrink, ever smaller wavelengths have been required to fabricate the critical layers of an IC. That is how extreme ultraviolet or EUV lithography was born. It was the result of a large scale industry effort spanning a period of over 20 years, with Dutch company ASML playing a leading role.

ASML is critical to Moore's Law

ASML is one of the world's leading manufacturers of semiconductor production equipment. It is the technology leader in lithography systems with a market share of over 80%. In the period up to the advent of EUV three companies supplied DUV equipment, Japanese companies Nikon and Canon as well as ASML. ASML today plays an even more critical role in the continuation of Moore's Law, as ASML's two Japanese competitors, have both abandoned efforts to develop their own technology. ASML is currently the sole supplier of EUV lithography technology.

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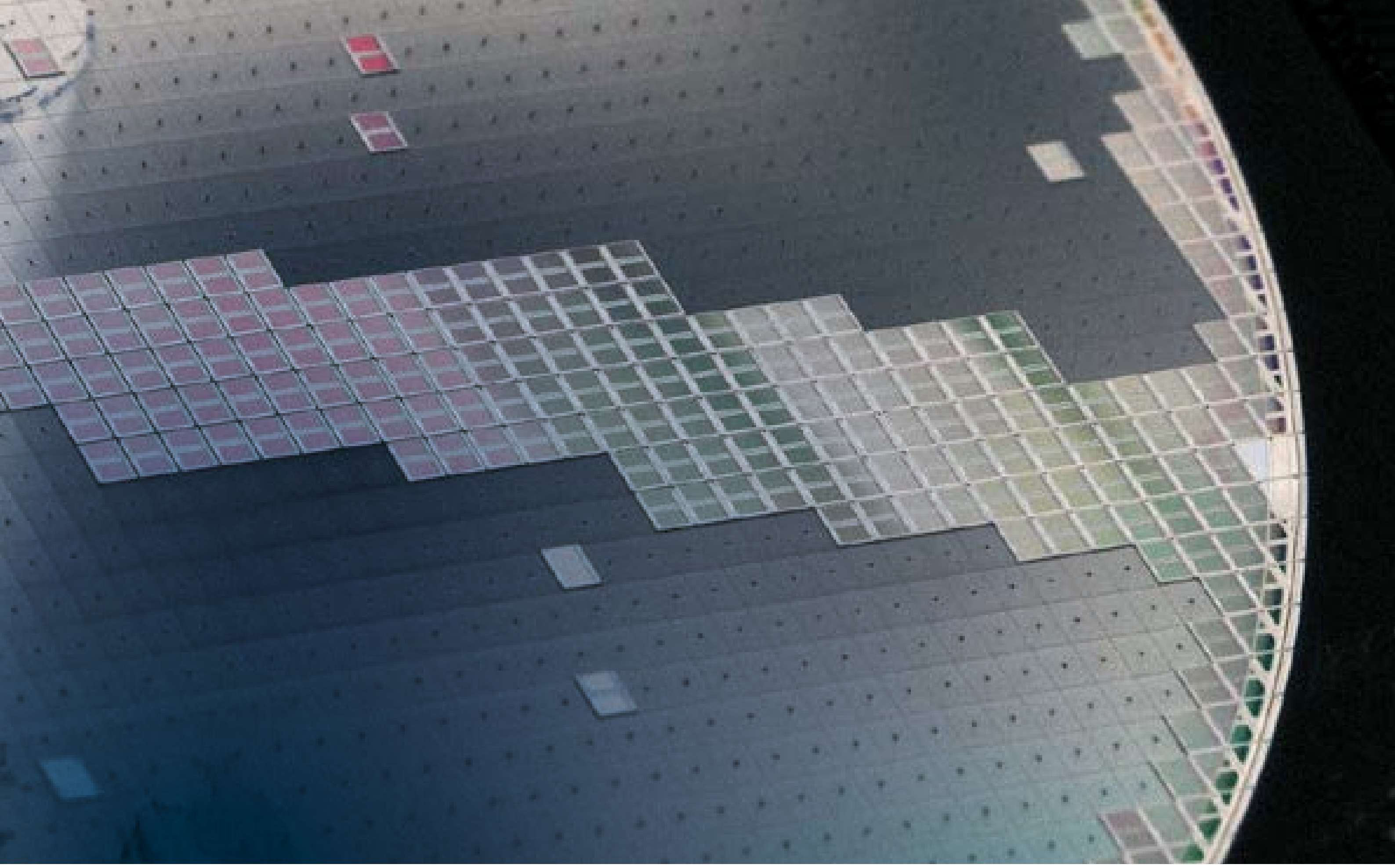
It is worth highlighting how extremely complex EUV technology is: a laser generates plasma in a vacuum chamber at a temperature of 220,000°C, which is 30-40 times hotter than temperatures on the surface of the sun. The laser is aimed at a stream of tin droplets inside the lithography system, where it strikes and flattens 50,000 of these tiny droplets every second. The laser takes two shots at each of these tin droplets, with the second hit transforming the flattened droplet into plasma that emits the EUV light. This EUV light is then directed onto the wafers after passing through numerous mirrors.

With several 100,000 components, a EUV lithography system is one of the most complex machines ever built. In total, it weighs 180 tons and consumes more than 1 MW of electrical power. First generation versions of EUV machines cost USD120 million and future versions will see price rises as their productivity increases, something which ASML is being compensated for. The importance of this huge industrial effort cannot be underestimated. If the development had failed, Moore's Law would have stopped, the chip industry would have gone ex-growth and we probably would be looking at significantly lower overall productivity growth of the world economy.

Hoya is sole supplier

Hoya is a leading Japanese technology company that operate in four main businesses with the shared commonality stemming from a deep research effort over many years into glass technology. The divisions are electro optics (semiconductor and LCD photomask/blanks, optical lenses and glass substrates for HDDs); imaging (cameras and lens modules); health care (eyeglasses and contact lenses); and life care (endoscopes). For us, the Photomasks business it the most exciting. Hoya is a dominant player and the growth outlook is favorable as the mass adoption of EUV lithography will drive robust demand. AGC and Hoya are the two sole suppliers of EUV mask blanks which is a vital component in a lithography machine.

Although we have no precise estimates of the price of a EUV mask blank, Hoya has indicated that the price is similar to a "medium-sized car", let's say USD30,000, and roughly 10-20 times more expensive than an optical blank for DUV – the technology prior to EUV. The lithography process requires an average of five EUV mask blanks for 7 nm applications, 14 for 5 nm, and 22 for 3 nm. As EUV ramps up over the coming years there will be a significant positive mix-effect for Hoya, which today is the sole supplier of mask blanks to Samsung and TSMC. AGC is the supplier to Intel, but Intel so far has not introduced commercial EUV. Hoya can therefore be considered the current sole supplier of mask blanks for EUV.



Consolidation in Semiconductor manufacturing

In the early days of the semiconductor industry, chips were designed and produced by the same company. However, only a handful of manufacturers, like Intel, have stuck to this business model until today. In the 1980s, chip manufacturers began separating design from production. Specialization made it possible for manufacturers to focus on developing new ways to push the physical limits and thereby keep Moore's Law alive. At the same time, a much larger number of tech companies were able to concentrate on designing chips for a staggering number of new products, including PCs, consoles, smartphones and networks.

The semiconductor industry has seen significant consolidation over the years. In 2001, nearly 30 semiconductor manufacturers produced leading-edge chips. Going forward, there will likely only be two manufacturers: TSMC and Samsung now that Intel has announced the company is considering going the foundry-route and outsourcing leading-edge manufacturing. Besides the technical complexities of producing at the atomic level, costs are also becoming prohibitively expensive for everyone except for the volume leaders. The cost of a fab is rising at around 13% a year, and is expected to reach USD16 billion or more by 2022, while the R&D going into starting a new fab can reach USD4 billion.

TSMC dominates leading edge

One can debate who belongs in the tech 'Hall of Fame' but one person for sure would be Morris Chang, founder of TSMC. Working for Texas Instrument in the 1980s, Chang identified what problems independent semiconductor companies – without their own production facilities – had getting off the ground. In those days it typically cost USD50-100 million to start a new chip company, primarily because of the cost of manufacturing. You could contract production from Intel or Texas Instruments or Motorola, but it was not reliable — and they were also your competitor!

In the mid-1980s, Chang was asked by the Taiwanese government to identify where Taiwan could invest in order to build global capabilities in technology. In an interview in 2007 Chang observed:

"When I was at TI and General Instrument, I saw a lot of Integrated Circuit designers wanting to leave and set up their own business, but the only thing, … that stopped them from leaving those companies was that they couldn't raise enough money to form their own company. Because … it was thought that every company needed manufacturing, … and that was the most capital-intensive part of a semiconductor company. And I saw all those people wanting to leave but being stopped by the lack of ability to raise a lot of money to build a wafer fab. So, I thought that maybe TSMC, a pure-play foundry, could remedy that. And as a result of us being able to remedy that then those designers would successfully form their own companies, and they will become our customers, and they will constitute a stable and growing market for us."

The rest is history. By being able to build scale through offering to produce for a very large number of fabless companies, TSMC eventually outgrew industry leader Intel. Indeed today, Intel is no longer the technology leader and will find it very hard to return to its former manufacturing glory.

> **In brief, we don't know when Moore's Law will stop working, but most likely we still have a few 'doublings' ahead of us.**

In contrast, companies like Apple, Amazon, Nvidia and AMD and others have been able to leverage the competencies of TSMC's ecosystem in manufacturing and challenge the position of Intel in overall chip performance. It is probably fair to say that TSMC is partly responsible for the growth of most of the large semiconductor companies in the world today.

The USD 65 billion foundry market is highly concentrated and TSMC holds a market share north of 50%. Samsung Electronics' foundry business holds second place with a market share of approx. 18%. Other foundries are Global Foundries, Taiwanese company UMC and Chinese foundry SMIC. TSMC and Samsung are the only companies producing at the leading edge, all other foundries have thrown in the towel years ago.

> **As a result, the future of computing will not (and cannot) be based on ever-increasing processing power (i.e. Moore's Law), but rather on understanding and drawing inferences from massive collections of data**

It should be noted that smaller leading node chips are growing strongly which is a segment dominated by TSMC. Its sales are 3x its nearest direct competitor which produces scale advantages in the form of lower unit costs and market share gains. In the second quarter of 2020, some 36% of TSMCs sales were in the most advanced 7 nm node. This equates to approx. USD3.3 billion, equal to the total foundry sales of Samsung, SMIC and UMC, in all their nodes combined.

How long can EUV extend Moore's Law?

The next generation high-NA EUV machines promises to reduce shrink down to 2 – perhaps 1 nm before the end of this decade. Furthermore, there are several options to choose from in order to keep Moore's Law going like using innovative materials (so called doping), creating new kinds of transistors such as migrating from planar CMOS FET to FinFET and eventually to so-called Gate All around FET.

When we step below 1 nm and start measuring node size in picometers, many forces prevent transistors from becoming smaller. You can aim smaller, but you can't break the rules of physics. However, when we do hit the limits, there is still one place where transistors can be put and that is the vertical axis. If transistors are stacked on top of each other, we can automatically double, triple or even quadruple the number of transistors per square millimeter, making the potential of this approach significant, assuming issues with excessive heat can be resolved.

In brief, we don't know when Moore's Law will stop working, but most likely we still have a few 'doublings' ahead of us. Today's most advanced chips have more than 50bn transistors, and going from 7 to potentially 1 nm will mean that we can multiply this by 8 by perhaps 2030 to 400bn transistors without moving to the 3rd dimension. Added to this, there is the potential for better optimized software and faster code.

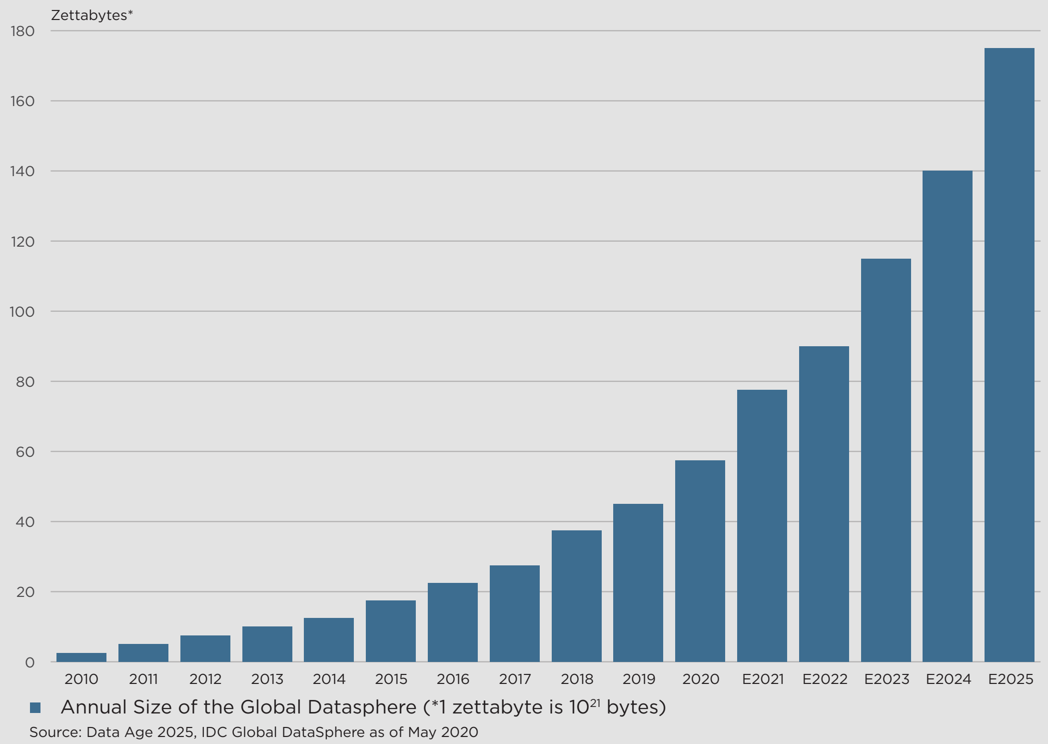
Even if chipmakers are able to squeeze out a few more generations of even more advanced microchips, the days when you could reliably count on faster, cheaper chips every couple of years are clearly over. That doesn't, however, mean the end of computational progress. In fact, we need a new regime for computing in order to reap the potential from the age of edge computing.

Edge Computing and the Data Era

The future of computing is centered on making sense of 'dark' data – see figure 2. Around 90% of the world's data is 'dark', meaning humans and computers do not have the ability to use it in any meaningful way, and by 2025 more than 460 exabytes of data (equivalent to 213 million DVDs) will be created every day. However, that data has the potential to be extremely valuable, and new data-centric computing methods such as machine learning are increasingly being used to harness such data.

To manage data requires a lot of power and extracting insights to drive the Data Era requires a significant amount of computational power – but current CPU architectures are not optimal. Therefore, specialized chips that are designed to accelerate specific types of computation in datacenters with a focus on data analysis and machine learning have

Figure 2: Data Explosion



Source: Data Age 2025, IDC Global DataSphere as of May 2020 taken market share over recent years. These are graphics processors that perform many similar calculations in parallel. Parallel processing in multi-core processors can still increase performance, but these gains come at a cost when all cores on the processor communicate with one another, as this consumes a lot of energy – so much so that the communication between chips is now responsible for more than half of the total power consumption of the computer.

The Future of Compute

As a result, the future of computing will not (and cannot) be based on ever-increasing processing power (i.e. Moore's Law), but rather on understanding and drawing inferences from massive collections of data. There are multiple ways to continue the exponential growth of computing performance – not by using the traditional architecture but by redefining computing itself. Breakthroughs in physics and the biological sciences are the new tools that will drive artificial intelligence, the Internet of Things, robotics, and autonomy . When Moore's Law eventually comes to a stop, neuromorphic and quantum computing will together with traditional silicon-based computing be the harbingers of a whole new era in computing, something we will explore in future White Papers.

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