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Moore's Law & the Race for the Rest of the Chessboard

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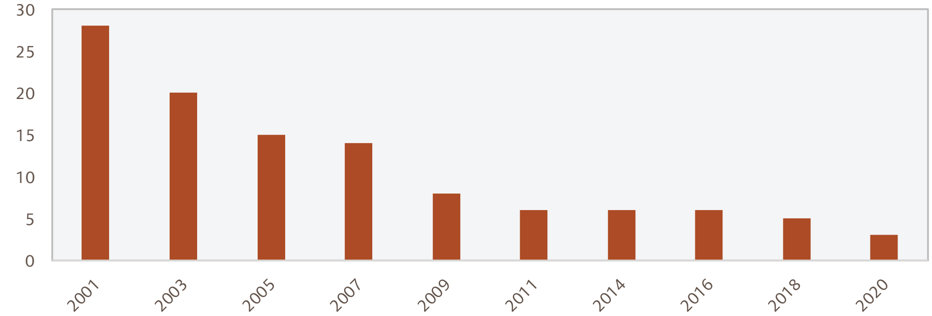
- Many of the computational challenges we as a society are trying to solve today are "Second half of the chessboard" problems that require the most advanced processors and memory chips.
- The Cambrian explosion of exciting breakthroughs in AI, autonomous driving, 5G, and cloud computing will generate double-digit growth in semiconductor revenues for the foreseeable future.
- Superstar firms have come to dominate all subsectors of the increasingly concentrated semiconductor industry, reflecting the winner-takes-all trend experienced throughout the economy over the last two decades.
- Market concentration, plus formidable barriers to entry, implies pricing power. This explains why the semiconductor industry is not only attractive from a growth perspective but is also delivering operating margins and return on capital that are twice the SPX average.
- Relative to the overall equity market, the semiconductor industry appears to be fairly valued, especially when today's historically low interest rates are taken into account.
- Bottom-line: We have a constructive view on the semiconductor sector and believe it possesses considerable upside.

Gordon Moore, the famous founder of Intel, set forth his prediction in 1965 that the number of transistors per silicon chip should double every two years. Thanks to human ingenuity and R&D focus, the semiconductor industry has largely kept pace with "Moore's Law." However, it has become increasingly difficult to keep up with the frenetic pace of innovation and investment, forcing many players (e.g., IBM, UMC, and Global Foundries) to bow out as the laws of physics and yield challenges complicate matters at such microscopic geometries **(Figure 1)**. By 2020, even Intel had fallen behind. Today, the cadence of process migration at the leading edge is purely a battle between Taiwan Semiconductor (TSM) and Samsung Electronics, each armed with the latest photolithography tools from ASML.

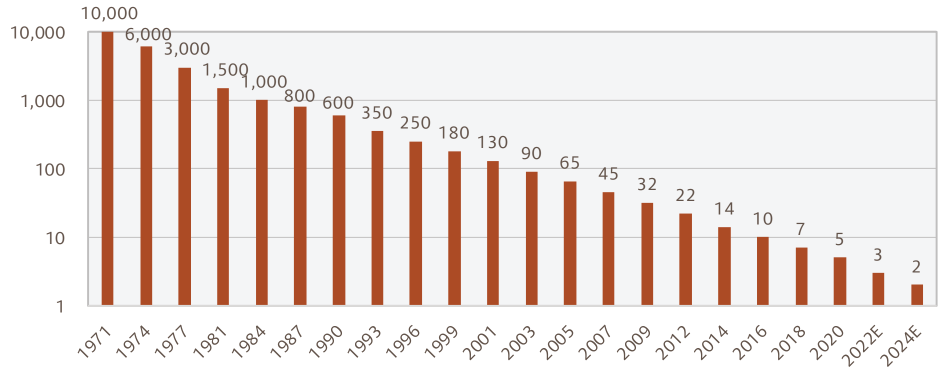
The next challenge is to initiate volume production of 3 nm devices, at which point the focus will move on to 2 nm. This ceaseless reinvention, illustrated

Figure 1: And then there were three – Number of leading-edge process-manufacturing firms



Source: The Economist, Bloomberg, Epoch Investment Partners in **Figure 2**, is driven by computing demands that keep getting ratcheted higher, reflecting profound advances in AI, autonomous driving, cloud computing, advanced networking, and the communications revolution enabled by 5G. Transistor shrink is the critical innovation that enables faster computing speeds, lower power consumption, and reduced manufacturing costs. Considering that the latest iPhone apps processor, the A14, has 12 billion transistors on a die that is the size of a snowflake and running on a small lithium-ion battery, the chip needed to be manufactured at N5 (the industry-leading 5 nm node ascribed by the width of the transist-or gate).

Figure 2: The incredible shrinking universe (device size in nm, log scale)



Source: PC Magazine, Epoch Investment Partners
Note: For reference, most atoms are 0.1 to 0.5 nm in diameter

Addressing Second Half of the Chessboard Problems

Indeed, many of the computational challenges we are striving to solve today are "second half of the chessboard" problems that require the most advanced processors and memory chips available. This reference comes from an old story that illustrates the power of exponential growth. As the story goes, an Indian King was once offered a chess set and was so pleased with it, he granted the merchant anything he wanted in return. The merchant coyly suggested he only wanted rice--one grain of rice for the first square, two rice grains for the second square, four grains for the third square, and doubling so forth. By the time the granary staff got to the back half of the chessboard 2^{32} (4,294,967,296 grains of rice), they were already in deficit. We believe the chess board story illustrates Moore's Law, and we are certainly on the second half of the chess board today.

In a similar vein, today's ADAS (advanced driver assistance systems) engineers are tasking their vehicles' core processors to make split-second critical decisions in differentiating pedestrians, cyclists, animals, potholes, signage, and other drivers' intentions, as the autonomous vehicle (AV) navigates through a busy intersection. As another example, the Bitcoin network must crunch through $7.2e^{22}$ hashes (a type of mathematical function) alone to solve one puzzle in the chain, consuming 72 terawatts of power in the process.[1]

And coming back to chess, in 2016, Google's neural network engine, AlphaZero, using its custom-built tensor processing units (TPUs), emphatically defeated the reigning chess program at the time, Stockfish 8, after only nine-hours of self-taught training. A year later, AlphaZero defeated the reigning world-champion Go (围棋, which means "surrounding game") player, a feat once thought impossible since the game has 10^{250} possible moves.

At the forefront, enabling the development of these next-generation chips which are tackling exponentially more difficult problems, are TSM and Samsung. In 2020, industry vanguard TSM began producing in volume at 5 nm for Apple. In 2021, both TSM and Samsung will embark on risk production at 3 nm.[2] Both will also begin greenfield, next-gen facilities in the U.S.

Moving Nimbly Through the Next Inflection Point

> "Today about a trillion chips are made a year, or 128 for every person on the planet. Ever more devices and machines contain ever more semiconductors: an electric car can have over 3,000 of them."
>
> *—Economist, Jan 2021*

According to the Semiconductor Industry Association (SIA), global semiconductor revenues likely reached $440 bn in 2020, up 6% yoy, with the largest categories being "Memory" ($118 bn in revenues) and "Application-Specific Logic Chips" (also $118 bn). They are also the industry's fastest expanding segments and we expect both to continue double-digit growth in the near term to address the astonishing opportunities in AI, autonomous driving, 5G, cloud computing, and so on **(Figure 3)**. In turn, we believe semiconductor revenues overall will accelerate to double-digit yoy increases for the foreseeable future.

Indeed, many of these new opportunities create a multiple-fold expansion in semiconductor content. For example, while an average car may have $400 of semiconductor content, a luxury vehicle may have upwards

1. *https://www.thebalance.com/how-much-power-does-the-bitcoin-network-use-391280*
2. *Risk production refers to an early stage of mass production when there is still a risk of miscalibration or misalignment in the manufacturing process.*

Figure 3: Near-term growth drivers of semiconductor demand

Rise of AI/ML	Drives demand for high speed compute and storage Used in drug discovery, AVs, IoT, ….
Shift to cloud data centers	Data infrastructure spending rising 10%+ annually Cloud IT infrastructure spend to surpass $100 bn in 2024
5G wireless technology	Faster speeds, increased capacity, reduced latency Mobile data for connected cars, IoT, AR/VR, …
Proliferation of IoT	Smart home assistants & applicances, AVs, … IoT device chip sales to grow 25%+ annually
AVs and EVs	Such vehicles have much higher semiconductor content Growing by 25%+ annually
PC gaming	Cinematic realism drives graphics processor demand Strong growth for high performance graphics cards

Source: Bloomberg, Epoch Investment Partners, BAML, media reports

of $2,000 worth. Further, changing the powertrain from ICE (internal combustion engine) to an EV (electric vehicle) will require an additional $500 of semiconductors, while upgrading to ADAS level 3 or 4 will necessitate another $1,000 of silicon.

As a second example, although the smartphone market is ex-growth in unit terms, the ongoing 5G revolution entails a substantive increase in semiconductor content. The apps/baseband processor for a 5G phone is easily double that of its 4G counterpart, while memory intensity (both DRAM and NAND) is also at least 50% higher. At the same time, mobile operators expect 5G units to more than double from 250 million units in 2020 to 500 million+ in 2021.

The industry also expects hyperscalar investments to accelerate in 2021. Hyperscalars (data centers with more than 100K servers) typically refer to Google, Amazon, Facebook, Microsoft, IBM, Alibaba, and Tencent. According to UBS, after 3% growth in 2019 and 11% growth in 2020E, hyperscalars are due to increase capex by 26% yoy in 2021. COVID has undoubtedly accelerated cloud migration, some would say compressing three years of transitions into one year, and hyperscalars are finding it imperative to keep investing aggressively.

Meanwhile, to address AI/ML opportunities, many of the world's most innovative companies are investing in new silicon architectures. Google's "Tensor Processing Unit" (TPU), which we referenced earlier, is the world's leading AI-specific ASIC (application specific integrated circuit). Amazon has also designed its own supercomputing "Graviton" chip based on ARM cores to power its cloud division. Similarly, Alibaba has developed its own AI chip XuanTie (玄铁) to extract intelligence from the troves of data the company has gathered. Meanwhile, Apple's in-house M1 chip enables it to deliver computing features to end-users on the company's own terms and cadence.

The commonality is that Google, Amazon, Apple, NVIDIA, and Qualcomm all rely on TSM and Samsung to tape-out[3] and manufacture these leading chips on their behalf. As the difficulties of nanometer production increase and the laws of physics create more electrical leakage at such atomic-level geometries, no player other than TSM and Samsung is capable of such advanced manufacturing.

We expect the confluence of the above secular trends and innovations to drive strong demand for leading-edge semiconductors for the foreseeable future. In fact, during 2020 year-end earnings, TSM raised its five-year CAGR from 5%-10% to 10%-15%. Further, Samsung's management spoke of the enormous opportunities in advanced foundry as well as the structural demand for memory with global data continuing to grow at a 40%+ yoy clip. NAND (or flash memory) is used to store this veritable mountain of data while DRAM (or working memory) is used to manipulate and compute this data. **Figures 4 and 5** illustrate where the demand for memory is coming from. In turn, semiconductor manufacturers are ratcheting up capex dramatically,

Figure 4: DRAM bit demand per application (% share)

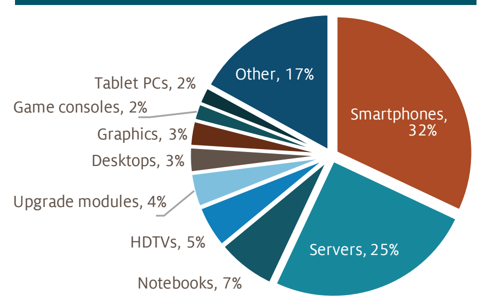
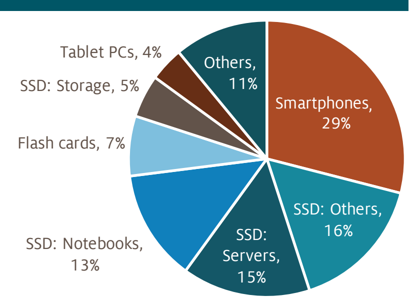


Figure 5: NAND bit demand per application (% share)



Source: US Semiconductors 2021 Outlook; The "Momentum" Trade Is Waning, But Fundamentals Should Remain Strong © UBS 2021. All rights reserved. Reproduced with permission.
DRAM: Dynamic random access memory (main system memory used by most computers)
NAND: Short for "Not And" logic gate (most common type of flash memory)
SSD: Solid-state drive (storage device replacing hard disks)

3. *Tape-out refers to the final result of an integrated circuit's design cycle*

which is especially beneficial for semiconductor equipment companies such as ASML and Applied Materials.

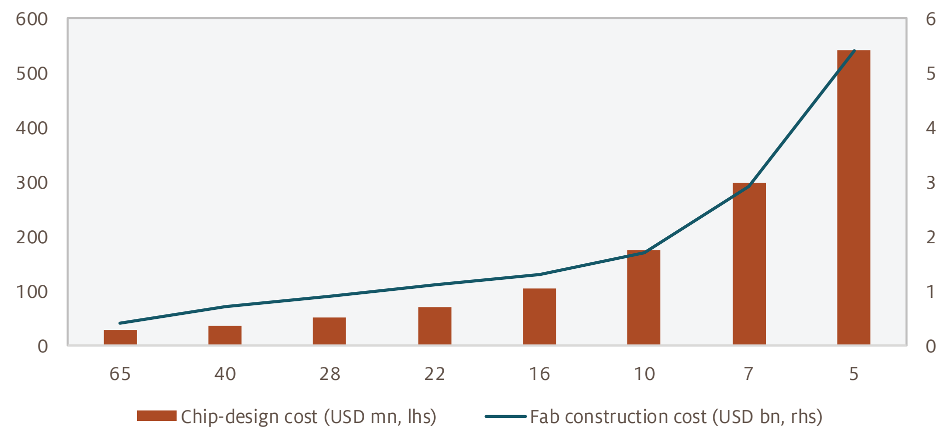
Winner-Takes-All

As a recent McKinsey study[4] emphasized, the top five semiconductor companies together make more money than the other 249 firms in the industry combined. Similarly, according to IC Insights, the top 5 companies share of total capex spending has risen from 25% in 1994 to 68% in 2019. Since fanatical effort is required to achieve and retain R&D and manufacturing leadership, the top companies have all chosen to focus on one product segment or a single step in the value chain. McKinsey cites several examples: TSM is the top manufacturer for chips at ten nm or below; ASML produces most advanced lithography equipment; Samsung leads the memory market; NVIDIA dominates in the production of graphics cards; Intel rules the roost in the market for desktop and laptop CPUs; and Qualcomm is the leader in the smartphone system-on-a-chip segment.

The Red Queen Effect

In 2019, global semiconductor production equipment (SPE, aka wafer fabrication equipment or WFE) revenues amounted to $49 bn and likely grew to an impressive $59 bn in 2020. With TSM having recently nearly doubled its capex target for 2021 to $25-$28 bn we believe global WFE revenue of $70 bn is within reach. ASML is the prime beneficiary of this record spend as the monopoly player in leading-edge photolithography equipment, which is the most critical tool in driving transistor gate widths down to the atomic level. Applied Materials and Lam Research will also benefit as they are the leading deposition and etch equipment companies in an oligopolistic segment. KLA Tencor, the near-monopoly leader in metrology, is another key beneficiary of the industry's unprecedented capex momentum.

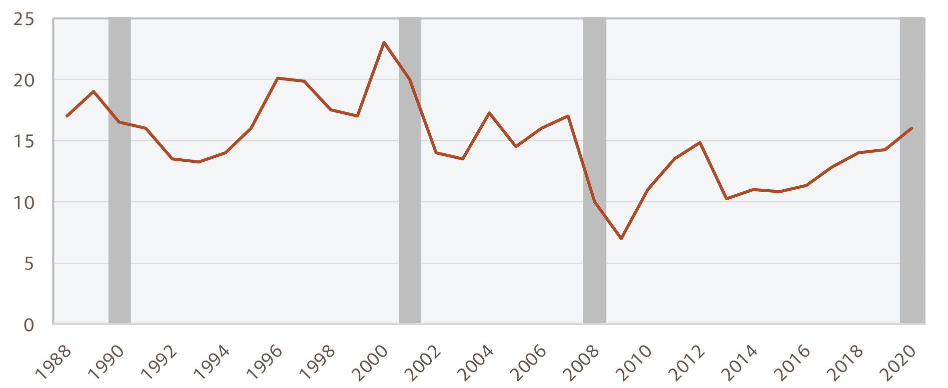
Figure 6: Chip design and fab construction costs soar as device size shrinks to 5 nm and then even smaller



Source: McKinsey

Massive capex requirements: Six times the average (% of sales) for U.S. companies

Figure 7: Semiconductor firms – Capex (% of sales)



Source: The Economist, Aswath Damodaran (http://www.stern.nyu.edu/~adamodar/pc/datasets/capex.xls)

"It takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

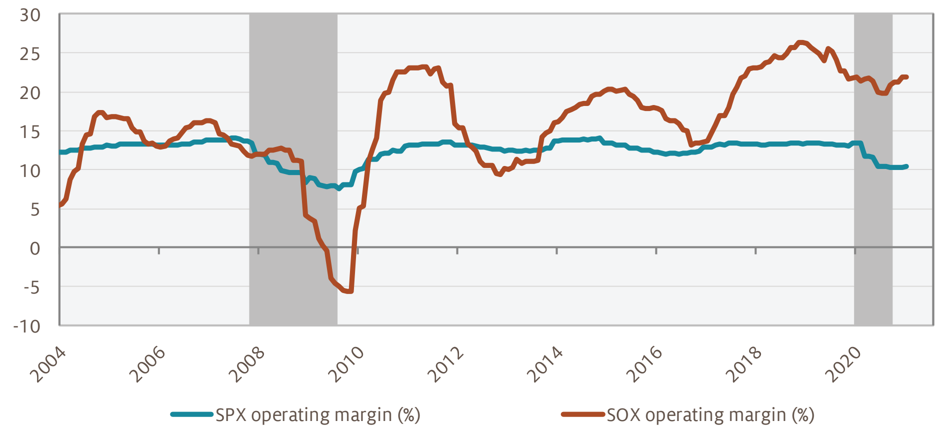
—The Red Queen

Market Concentration Plus Formidable Barriers to Entry Implies Substantial Pricing Power

The semiconductor industry not only features attractive revenue growth but also delivers high operating margins (OPM) and return on capital employed (ROCE), as illustrated in **Figures 8 and 9**. It hasn't always been this way, but decades of harsh competition, multiple bankruptcies, forced consolidation, and rising barriers to entry have forged the

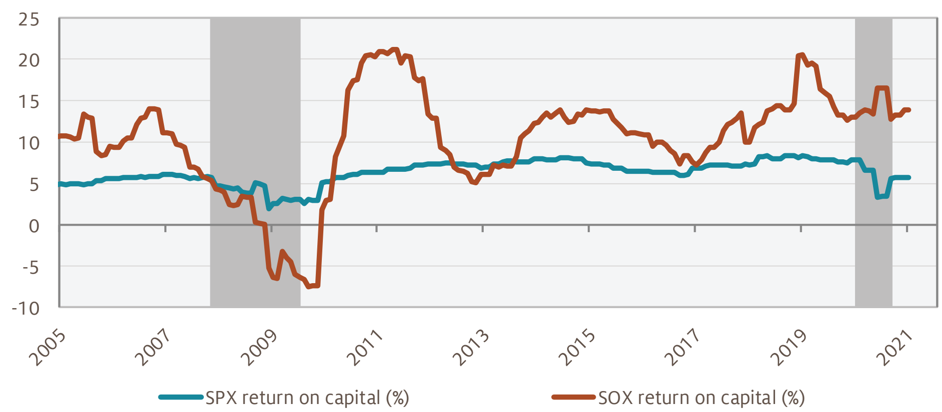
4. "Semiconductor design and manufacturing: Achieving leading-edge capabilities," 2020

Figure 8: Semiconductor operating margins are now roughly twice the market average



Source: Bloomberg, Epoch Investment Partners
SOX: Philadelphia Semiconductor Index of the 30 largest companies in the sector

Figure 9: The semiconductor industry's return on capital is also well above that for the SPX



Source: Bloomberg, Epoch Investment Partners

survivors into today's global champions. Most of these superstar firms are oligopolies or monopolies in their respective SAMs (serviceable available markets). Earlier, we discussed the emergence of TSM and Samsung as the only two companies capable of leading-edge outsourced manufacturing, but market concentration is the rule rather than the exception in all segments of the industry.

The DRAM market is also dominated by a small number of companies today—Samsung (with 45% market share), Hynix (29%), and Micron (22%). DRAM is the working memory or buffer memory needed to host the Excel, Bloomberg, Outlook, and other applications on our desktops, or the myriads of apps on our smartphones. In the 1980s, there were dozens of DRAM companies, but by 2000 the field had slimmed down to six, and since the bankruptcy of Elpida in 2012, three giants have ruled the roost in this high growth segment. Over the last decade, the triopoly has moved on from an aggressive fight over market share that decimated everyone's margins and this transformation has had an immensely positive effect on the segment's profitability. Samsung's DRAM operating profit margins today are expected to be between 35%-65% through the cycle. What safeguards this mouth-watering margin is that barriers to entry in DRAM manufacturing are sky-high. One industry veteran likens the challenge to trying to catch a high-speed train on foot! Indeed, the latest DRAM specs for DDR chips[5] for data centers supporting 6 billion transfers per second with zero errors, was unthinkable only a few years ago.

Analog semiconductors (estimated revenues of $56 bn in 2020) is another attractive subsector. After two decades of consolidation, the industry has stabilized with two resolute bellwethers, Texas Instruments and Analog Devices. Both are based in the U.S. and feature impressive 50% EBITDA margins through the cycle. Analog companies benefit from relatively low capex intensity due to longer product life cycles and most of the chips are produced on legacy 30 nm and older nodes. Additionally, once an analog chip such as a sensor, data converter, power manager, or amplifier is designed into a device, it is usually employed for the life of the product series.

Similarly, only the fittest semiconductor equipment makers have survived the harsh tests of fierce competition and protracted business cycles. ASML now enjoys a monopoly in photolithography (the critical semiconductor step where the circuit design is imprinted on the substrate) after competitors Nikon and Canon failed to keep pace and gave up about a decade ago. Further, KLA Tencor holds a near-monopoly in metrology and yield management, while Tokyo Electron is a near-monopoly in photoresist coating and development. Finally, Applied Materials, Lam Research, and Tokyo Electron have formed a triopoly in etch and deposition, instrumental steps where metal and dielectric composite

5. Double Data Rate 5 chips, which reduce power consumption and double bandwidth relative to DDR4 materials are deposited and etched away as the "silicon city" is built one layer at a time.

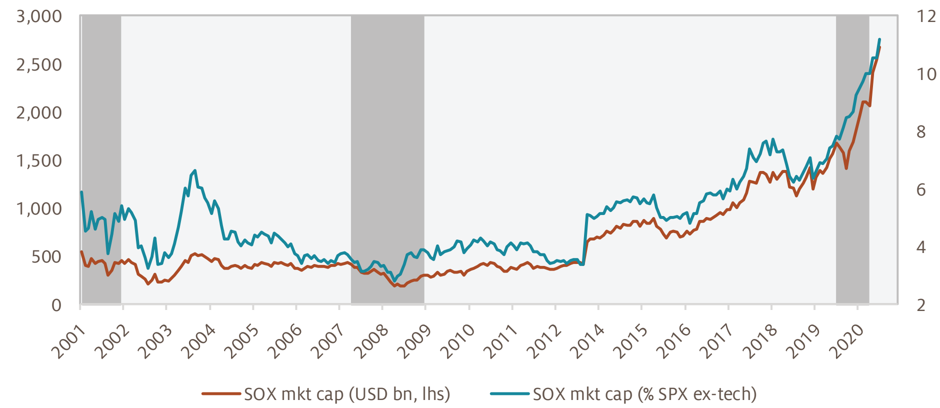
Implications for Investors: Superior Growth Prospects and Fair Valuations Suggest Considerable Upside

Semiconductor stocks have done well recently, with the SOX outperforming the SPX in four of the last five years **(Figure 10)**. Still, we believe semiconductor names offer significantly higher quality, with operating profit margins, RoE and ROIC all roughly double that of the SPX. Moreover, the SOX index possesses superior growth prospects (double digits near term), while trading just slightly above market multiples.

The SOX currently trades at 23x forward P/E and 16x forward EV/EBITDA, just slightly higher than the SPX's multiples (22x and 14x, respectively). Moreover, unlike market darling SaaS (software–as–a-service) businesses, semiconductor companies are already highly profitable and generate meaningful free cash flow (FCF), as shown in **Figure 11**.

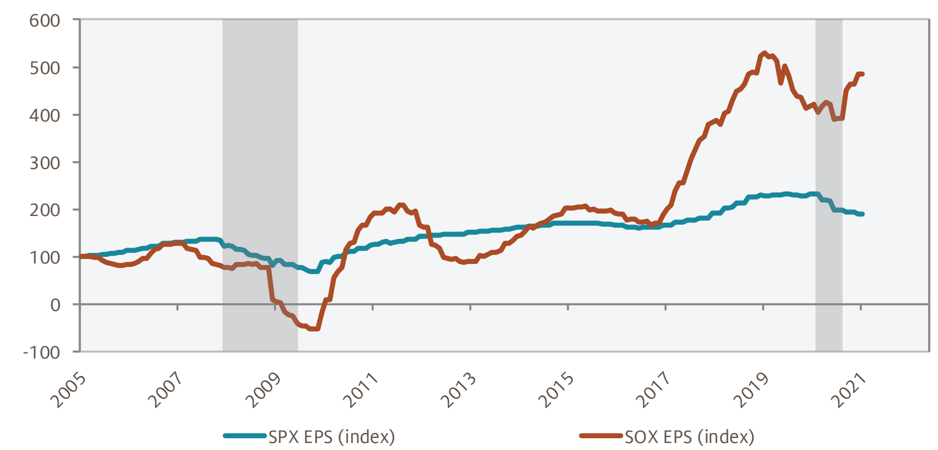
Relative to the overall equity market, the semiconductor industry appears to be fairly valued **(Figure 12)**, especially when today's historically low interest rates are taken into account. The sector has dramatically outperformed, but that has been entirely due to strong FCF generation, rather than multiple expansion. The bottom-line is that we have a constructive view on the sector and believe it possesses considerable upside.

Figure 10: Semiconductor index has significantly outperformed



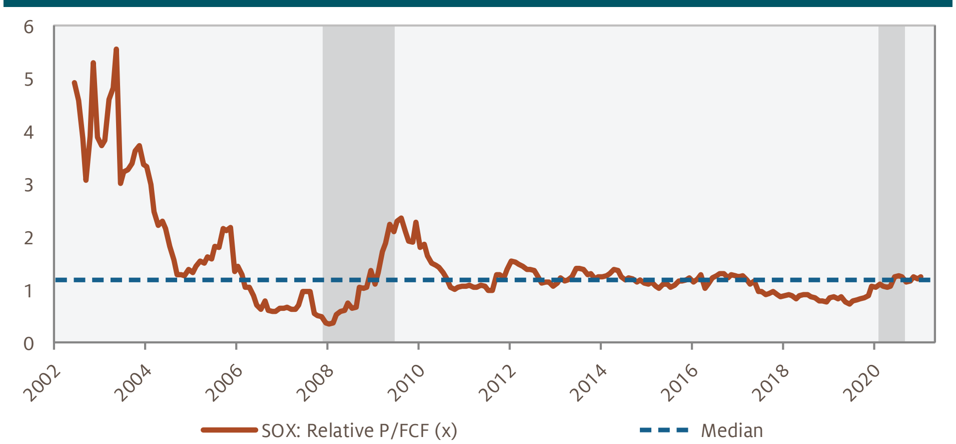
Source: Bloomberg, Epoch Investment Partners

Figure 11: Semiconductor's FCF generation has surged during the last five years



Source: Bloomberg, Epoch Investment Partners

Figure 12: The SOX index appears fairly valued



Source: Bloomberg, Epoch Investment Partners