*Technologies series*

# Semiconductor Chips

*A truly globalised product, manufacturing delays have hit many industries hard.*

## What it is

**Out of the pan and into the chip fryer**

Integrated circuits embedded in semiconductor material,[1] usually silicon, are commonly referred to as 'chips'.[2] These chips are used in an ever-increasing number of industries as 'smart-products' become popular, including everything from wearables to household appliances.[3]

## How it works

Photolithography is used to layer transistors and circuits sequentially on silicon wafers to create semiconductor chips.[4] This takes place in a highly specialised factory or 'foundry', under hermetically sealed, sterile, nitrogen-rich conditions.

The processes are highly complex, and cost billions to develop and deploy at scale.[5] Chips' nanoscale architectures can include billions of transistors. Although silicon remains the material of choice for the near future,[6] it is approaching limits of efficiency.[7] New materials such as gallium nitride and silicon carbide,[8] or carbon nanotubes and graphene, are expected to replace it,[9] but this will require increased innovation.[10]

## Applications

Semiconductor chips are found in almost every aspect of modern life, including:

- **Consumer electronics.** Smartphones and tablets all use large numbers of semiconductor chips; and even vehicles are beginning to fall into this category.
- **Solar panels** generally use silicon semiconductors to generate electricity from light.[11]
- **Internet of Things (IoT).** 5G-enabled devices, commonly regarded as being necessary for the IoT to become a reality, require 30-40% more chip content than equivalent 4G devices.[12]

## Implications and issues

Chips are used, often unseen, in a wide range of products. Dependence globally on highly localised areas of expertise has become more understood in the light of SARS-CoV2-related disruption to global supply chains and manufacturing. Production lead times are long, and disruptions reverberate for some time. Other issues include:

1. **Manufacturing.** About 75% of chip manufacturing takes place in Taiwan and the rest of Asia, which often supply companies outside the region that lack the requisite expertise and factories.[13] The US has announced plans to increase national production,[14] and several companies are making sizeable investments.[15] The EU has announced plans to produce 20% of the world's semiconductors by value by 2030.[16] And China, currently the world's largest importer, has also announced plans for more local production.[17]
2. **Market share.** Intel, Samsung,[18] and Taiwan Semiconductor Manufacturing Co., (TSMC) account for the vast majority of the market.[19] TSMC dominates the production of the smallest, most advanced chips,[20] and Intel dominates the intellectual property (IP) landscape.[21]
3. **Metrics.** Although 'process node' or transistor gate length, e.g. *5nm process node*, is still used as a metric of progress, notwithstanding that it no longer accurately reflects physical advancements, transistor density has been suggested to better reflect these.[22]
4. **Raw materials.** Originating from across the world but with highly specialised supply locations,[23] disruption to supply chains affects all.[24]
5. **Trade-wars.** The USA blacklisted the Chinese semiconductor manufacturer (SMIC), from acquiring manufacturing capabilities to produce <10nm chips.[25] In 2019, Japan placed restrictions on South Korea's obtaining chemicals critical for semiconductor manufacture.[26]
6. **Automotive Industry.** With chips nowadays accounting for up to 40% of a car's value, delays in chip deliveries have led to a ~$61bn sales hit, and many manufacturers halting production.[27]

A highly globalised product, semiconductor chips are vulnerable to precisely the sort of systemic shocks that SARS-CoV2 has delivered to the global economy. Efforts to re-shore and protectionist measures more generally are likely to be complex and expensive, but could drive innovation. ■

[1] A semi-conductor is any material that is able to conduct electricity better than an insulator, such as glass, but less well than a conductor, such as copper. This electrical conductivity can be altered by changing the temperature (lower is more efficient) and 'doping' semiconductors by introducing imperfections in their crystal lattices.

[2] A detailed report on the state of semiconductors is provided in the report described in Varas, A., et al., 2021. *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era*. Boston Consulting Group [online] Available at: <https://www.bcg.com/publications/2021/strengthening-the-global-semiconductor-supply-chain> [Accessed 13 May 2021].

[3] See, Cameron, J., & Llewellyn, P., 2020. *Wearables*. Llewellyn Consulting.

[4] A thin wafer of semiconducting material, which will form many individual chips (100s – 1,000s), is first oxidised at ~1,000ºC to create a non-conductive layer. Following this, a layer of photo-resist is applied, creating a light-sensitive layer on top of the non-conductive layer. Into this light-sensitive layer, the circuit pattern is developed using photomasks and light to reveal the non-conductive oxide layer beneath. This oxide layer is then etched away to reveal the circuit pattern underneath. Following this, another oxidation layer is created on top, followed by a conductive polysilicon layer, and a photo-resist layer. This is again exposed to light using photomasks to determine the pattern. At this point, the silicon is 'doped' by introducing atomic impurities (other elements) into its crystalline structure. Following the doping, the previous photo-resist layer is removed, leaving the conductive polysilicon layer exposed again. Here the chip undergoes another round of oxidation; application of photoresist; and then photomasking the desired pattern and exposing the chip to light. Contact holes are then etched in, allowing contacts and connections to be made with the conductive layers revealed beneath. A final layer of insulation is applied using photoresist material and photomasking. Excess material is then polished away using both chemical and mechanical processes. This process can be repeated many times until the desired chip architecture has been created, and then each chip on the wafer undergoes quality control. See, Horiba, 2021. *Photolithography*. Horiba [online] Available at: < https://www.horiba.com/deu/semiconductor/markets/semiconductor-processing/toolsequipment/photolithography> [Accessed 13 May 2021].

[5] See, King, I., Leung, A., & Pogkas, D., 2021. *The Chip Shortage Keeps Getting Worse. Why Can't We Just Make More?* Bloomberg [online] Available at: <https://www.bloomberg.com/graphics/2021-chip-production-why-hard-to-make-semiconductors> (paywall) [Accessed 13 May 2021].

[6] See, Knight, W., 2021. *To Make These Chips More Powerful, IBM Is Growing Them Taller*. Wired [online] Available at: <https://www.wired.com/story/chips-more-powerful-ibm-growing-taller> [Accessed 13 May 2021].

[7] Techradar, 2021. *Silicon Chips are Reaching their Limit – Here's the Future*. Techradar [online] Available at: <https://www.techradar.com/in/news/silicon-chips-are-reaching-their-limit-heres-the-future> [Accessed 13 May 2021].

[8] So-called 'third-generation semiconductors', silicon carbide and gallium nitride offer better performance at higher temperatures in high-frequency, high-power devices, and radiation resistance. However, they are not at the level of technological development of silicon semiconductor chips, and will require further effort before they can be manufactured efficiently at scale. See, Green, J., 2021. Detailed Introduction to the Third Generation of Semiconductor Materials. Stanford Advanced Materials [online] Available at: <https://www.sputtertargets.net/blog/introduction-to-the-generations-of-semiconductors.html> [Accessed 17 May 2021].

[9] See, Shulaker, M., Wong, H.-S. P., & Mitra, S., 2016. *How We'll Put a Carbon Nanotube Computer in Your Hand*. IEEE Spectrum [online] Available at: <https://spectrum.ieee.org/semiconductors/devices/how-well-put-a-carbon-nanotube-computer-in-your-hand> [Accessed 13 May 2021] & Batra, G., Santhanam, N., & Surana, K., 2018. *Graphene: The next S-curve for semiconductors?* McKinsey [online] Available at: <https://www.mckinsey.com/industries/semiconductors/our-insights/graphene-the-next-s-curve-for-semiconductors> [Accessed 13 May 2021].

[10] In 1965, Gordon Moore, co-founder of Intel, observed that the number of transistors on a one-inch computer chip approximately doubles every year, while the costs halve. Now that period is 18 months and increasing.

[11] See, Solar Energy Technologies Office, 2021. *Solar Photovoltaic Cell Basics*. Office of Energy Efficiency and Renewable Energy [online] Available at: <https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics> [Accessed 13 May 2021].

[12] See, Wu, D., 2020. *Apple Faces Shortages in Power Chips for iPhone 12*. Bloomberg [online] Available at: <https://www.bloomberg.com/news/articles/2020-11-05/apple-is-said-to-face-shortages-in-power-chips-for-iphone-12> (paywall) [Accessed 13 May 2021].

[13] Fitch, A., & Santiago, L., 2020. Why Fewer Chips Say 'Made in the U.S.A.'. Wall Street Journal [online] Available at: <https://www.wsj.com/articles/why-fewer-chips-say-made-in-the-u-s-a-11604411810> (paywall) [Accessed 13 May 2021].

[14] In addition to a call for investment, the US President has also requested a report on the risks in the semiconductor supply chain. See, Hunnicutt, T., & Bose, N., 2021. *Biden to press for $37 billion to boost chip manufacturing amid shortfall*. Reuters [online] Available at: <https://www.reuters.com/article/us-usa-biden-supply-chains-idUSKBN2AO13D> [Accessed 13 May 2021] & Industry and Security Bureau, 2021. *Risks in the Semiconductor Manufacturing and Advanced Packaging Supply Chain*. Federal Register [online] Available at: <https://www.federalregister.gov/documents/2021/03/15/2021-05353/risks-in-the-semiconductor-manufacturing-and-advanced-packaging-supply-chain> [Accessed 13 May 2021].

[15] These investments include $12bn from TSMC to build a (current generation) 5nm chip manufacturing plant in Arizona, due to begin production from 2023/24; a prospective $25bn investment again from TSMC to manufacture (next generation) 3nm chips in Arizona; $20bn from Intel to construct a further two plants, also in Arizona; and $17bn from Samsung to manufacture (potentially 3nm) chips in Texas. TSMC is also investing ~$180bn in manufacturing capacity for next generation 3nm chips, to be produced by 2022, in south Taiwan. See, TSMC, 2020. *TSMC Announces Intention to Build and Operate an Advanced Semiconductor Fab in the United States*. TSMC [online] Available at: <https://pr.tsmc.com/english/news/2033> [Accessed 13 May 2021], Nellis, S., 2021. TSMC looks to double down on U.S. chip factories as talks in Europe falter. Reuters [online] Available at: <https://www.reuters.com/technology/exclusive-tsmc-looks-double-down-us-chip-factories-talks-europe-falter-2021-05-14> [Accessed 16 May 2021], Nellis, S., 2021. *Intel to spend $20 billion on U.S. chip plants as CEO challenges Asia dominance*. Reuters [online] Available at: <https://www.reuters.com/article/us-intel-manufacturing-idUSKBN2BF2WU> [Accessed 13 May 2021], & Chen, S., 2017, Iqbal, A.S., 2021. *Samsung to build a $17 billion chip manufacturing plant in Texas*. SamMobile [online] Available at: <https://www.sammobile.com/news/samsung-foundry-usd-17-billion-chip-plant-texas-usa> [Accessed 16 May 2021], & *TSMC to Build 3nm Fab in Southern Taiwan*. CustomPC [online] Available at: <https://www.custompcreview.com/news/tsmc-build-3nm-fab-southern-taiwan> [Accessed 13 May 2021].

[16] See, Nardelli, A., & Drozdiak, N., 2021. *EU Sets 2030 Target to Produce Cutting-Edge Semiconductors*. Bloomberg [online] Available at: <https://www.bloomberg.com/news/articles/2021-03-04/eu-sets-2030-target-to-produce-cutting-edge-semiconductors> (paywall) [Accessed 13 May 2021].

[17] Beijing wants 70% of all chips used by Chinese industry to be produced domestically by 2025, up from 15% in 2018. However, in recognition of their reliance on imports and the likelihood of this continuing for the foreseeable future, they have made recent efforts to crack down on nationalist rhetoric against TSMC. For more on expertise in advanced packaging, see, Liu, C., Ting-Fang, C., & Li, L., 2019. *China chip designers say Beijing goals impossible without US tech*. Nikkei [online] Available at: <https://asia.nikkei.com/Business/China-tech/China-chip-designers-say-Beijing-goals-impossible-without-US-tech> [Accessed 13 May 2021], Ting-Fang, C., & Li, L., 2021. *US-China tech war: Beijing's secret chipmaking champions*. Nikkei [online] Available at: <https://asia.nikkei.com/Spotlight/The-Big-Story/US-China-tech-war-Beijing-s-secret-chipmaking-champions> [Accessed 14 May 2021], and Ye, J., 2021. *Chinese state media pushes back on chip nationalism after social media vilifies TSMC's Nanjing expansion*. South China Morning Post [online] Available at: <https://www.scmp.com/tech/tech-war/article/3133359/chinese-state-media-pushes-back-chip-nationalism-after-social-media> [Accessed 17 May 2021].

[18] See, Kim, S., 2020. *Samsung Intensifies Chip Wars With Bet It Can Catch TSMC by 2022*. Bloomberg [online] Available at: <https://www.bloomberg.com/news/articles/2020-11-17/samsung-intensifies-chip-wars-with-bet-it-can-catch-tsmc-by-2022> [Accessed 13 May 2021].

[19] Collectively these 3 companies account for just under half of the market (~188bn out of $378bn). See, King, I., Leung, A., & Pogkas, D., 2021. *The Chip Shortage Keeps Getting Worse. Why Can't We Just Make More?* Bloomberg [online] Available at: <https://www.bloomberg.com/graphics/2021-chip-production-why-hard-to-make-semiconductors> (paywall) [Accessed 13 May 2021].

[20] TSMC manufactures chips for tech companies such as Apple, and even for other chip designers and manufacturers like Qualcomm, AMD, and even Intel. It is particularly dominant at the smaller and more advanced end of the chip spectrum, taking ~92% of the revenue at '10-5nm process node' chips. Samsung accounts for the remaining 8%. See, Hille, K., 2021. *TSMC: How a Taiwanese chipmaker became a linchpin of the global economy*. ArsTechnica [online] Available at: <https://arstechnica.com/gadgets/2021/03/tsmc-how-a-taiwanese-chipmaker-became-a-linchpin-of-the-global-economy> [Accessed 13 May 2021].

[21] See, Varas, A., et al., 2021. *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era*. Boston Consulting Group [online] Available at: <https://www.bcg.com/publications/2021/strengthening-the-global-semiconductor-supply-chain> [Accessed 13 May 2021].

[22] Although '5nm process nodes' have been reported as having entered volume production, the number does not reflect the actual physical properties of the semiconductor chips, such as their gate length. Instead it is a shibboleth from the late 1990s. Other metrics such as transistor density have been purported to reflect performance better, but it is a complex calculation with many other factors affecting a chip's performance in a particular context. See, Wong, P. H.-S., et al., 2020. A Density Metric for Semiconductor Technology [point of view]. *Proceeding of the IEEE* [e-journal] https://doi.org/10.1109/JPROC.2020.2981715 & Morris, K., 2020. *No More Nanometers*. Electronic Engineering Journal [online] Available at: <https://www.eejournal.com/article/no-more-nanometers/> [Accessed 9 May].

[23] For example, a single mine in the US is responsible for almost all the very highest grade of silicon used in semiconductors. Another example is Japan's production of chemicals vital to the manufacturing of semiconductors, including hydrogen fluoride (Japan accounts for 70% of the global supply), fluorinated polyimide, and photoresists (in which Japan accounts for 90% of the global supply). See, The Japan Times, 2019. *Japan approves first export of hydrogen fluoride to South Korea since controls tightened*. The Japan Times [online] Available at: <https://www.japantimes.co.jp/news/2019/08/30/business/japan-exports-hydrogen-fluoride-south-korea> [Accessed 13 May 2021] & Beiser, V., 2018. The Ultra-Pure, Super-Secret Sand That Makes Your Phone Possible. Wired [online] Available at: <https://www.wired.com/story/book-excerpt-science-of-ultra-pure-silicon> [Accessed 14 May 2021].

[24] See, Varas, A., et al., 2021. *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era*. Boston Consulting Group [online] Available at: <https://www.bcg.com/publications/2021/strengthening-the-global-semiconductor-supply-chain> [Accessed 13 May 2021].

[25] See, Alper, A., 2020. *Trump administration pressed Dutch hard to cancel China chip-equipment sale: sources*. Reuters [online] Available at: <https://www.reuters.com/article/us-asml-holding-usa-china-insight/trump-administration-pressed-dutch-hard-to-cancel-china-chip-equipment-sale-sources-idUSKBN1Z50HN> [Accessed 13 May 2021] & Reuters, 2020. *U.S. blacklists dozens of Chinese firms including SMIC, DJI*. Reuters [online] Available at: <https://www.cnbc.com/2020/12/18/us-adds-chinese-drone-company-dji-to-economic-blacklist-.html> [Accessed 13 May 2021].

[26] In the summer of 2019, Japan placed restrictions on the export of key chemicals to the South Korean semiconductor manufacturing industry including hydrogen fluoride (Japan accounts for 70% of the global supply), fluorinated polyimide and photoresists (in which Japan accounts for 90% of the global supply). South Korea's $80bn industry exports of semiconductors depend on these. These restrictions were relatively short-lived, and Japan has since approved the export of these chemicals, but the situation remains sensitive. See, The Japan Times, 2019. *Japan approves first export of hydrogen fluoride to South Korea since controls tightened*. The Japan Times [online] Available at: <https://www.japantimes.co.jp/news/2019/08/30/business/japan-exports-hydrogen-fluoride-south-korea> [Accessed 13 May 2021].

[27] Electronics comprise an underappreciated proportion of a vehicles value these days, accounting for up to 40%. Car manufacturers were seemingly caught unaware, and due to the low margins of the industry, at least when compared with consumer electronics companies such as Apple, were unable to pay premiums to ensure timely fulfilment of their orders. See Nicholas, K., et al., 2021. *Carmakers Face $61 Billion Sales Hit From Pandemic Chip Shortage*. Bloomberg [online] Available at: <https://www.bloomberg.com/news/articles/2021-01-27/covid-pandemic-slows-down-chipmakers-causes-car-shortage> (paywall) [Accessed 13 May 2021] & Williams, M., 2021. *Semiconductor shortage will hit auto industry well into 2021*. Automotive Logistics [online] Available at: <https://www.automotivelogistics.media/news/semiconductor-shortage-will-hit-auto-industry-well-into-2021/41476.article> (paywall) [Accessed 13 May 2021].