Shock-Proofing the Semiconductor Supply Chain: The Role of Industrial and Other Policies

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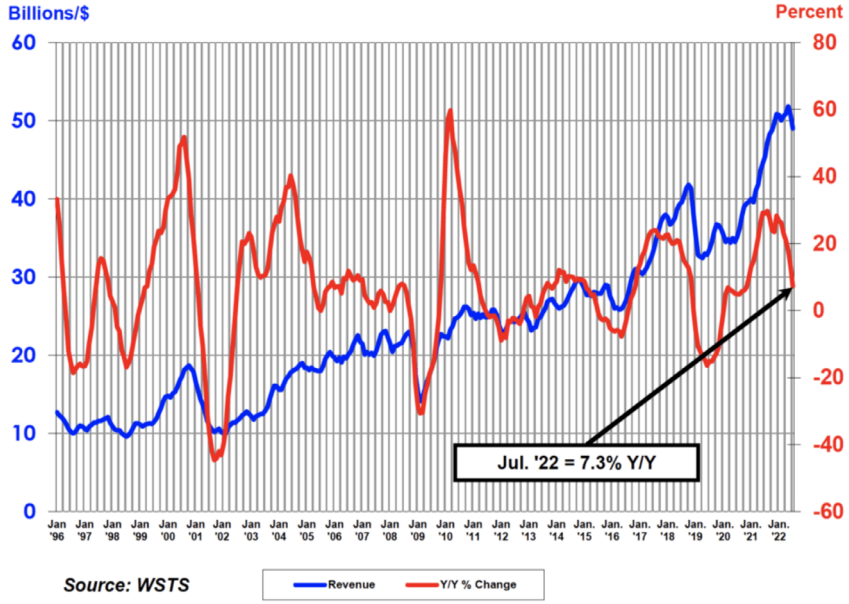
Some years back, the mathematician Clive Humby[1] asserted that data was the "new oil" however, it would be more accurate to claim that semiconductors—a scarce resource unlike data—deserve to be compared with oil. In 2021, global revenues from semiconductors, which are on a rising trend, amounted to almost $560 billion, and these devices are critical to the operation of some 200 downstream industries (Figure1). The importance of semiconductors to the functioning of so many activities was brought home when the Covid pandemic disrupted production and trade.

Figure 1. Revenues from global semiconductor sales



Source: Semiconductor Industry Association (2022). https://www.semiconductors.org/global-semiconductor-sales-increase-7-3-year-to-year-in-july-but-growth-slows/

1 C. Humby made this claim in 2006. https://medium.com/geekculture/stop-saying-data-is-the-new-oil-a2422727218c

The shortage of semiconductors forced a cutback in the output of vehicles, consumer durables, and electronic equipment of all kinds inflicting heavy losses (of up to $500 billion worldwide)[2] for example, on the auto industry.[3] The semiconductor drought also contributed to inflation in 2021 as manufacturers struggled to satisfy rising demand for a wide range of products.

The vulnerability of the globally dispersed semiconductor supply chain

The severity of the shock inflicted by the Covid pandemic was a wake-up call because it demonstrated the diminished resilience of a critical supply chain. To pare costs, lead firms had cut down on the number of suppliers and opted for lean inventories.[4] One consequence of this was that supplies of some inputs and equipment, and certain operations such as back-end manufacturing (assembly, testing and packaging, ATP) were concentrated in a few East Asian and European countries. The pandemic and geopolitical tensions that had been building for some time, also underscored China's role as a supplier of key materials and a provider of ATP services.

The electronics industry had endured shocks before when floods or earthquakes affected production in particular locations (e.g., the Fukushima tsunami crippled the operations of Renesas a key supplier of microcontrollers for automobiles[5]).[6] But this time was different. The impact of the shock was felt worldwide. Almost all segments of the semiconductor supply chain were affected, and recovery has been slow.

The US, Korea, Japan, and some of the European countries have responded by mobilizing a range of industrial and other policies to minimize the risks from supply chain choke points.[7] China meanwhile has been working to internalize much of the supply chain as perceived security concerns have mounted but to date only 15 percent of the equipment China needs can be sourced from domestic

2 Deloitte (2022). 'Semiconductor industry outlook.' https://www2.deloitte.com/us/en/pages/technology-media-and-telecommunications/articles/semiconductor-industry-outlook.html

3 The average modern ICE vehicle uses as many as a 100 ecus (electronic control units) made up of specialized chips that must endure extremes of temperature, humidity (e.g., in the engine compartment), vibration and last through thousands of cycles for up to 20 years. The embedded software in a high-end vehicle can contain 100 million lines of code more than in a F35 jetfighter. The chip supply constraining auto and consumer durable production was of mature chips of larger node sizes not the high end 5 nm or 7 nm ones.

4 Lean manufacturing and taut supply chains are among the issues discussed by D. Fuller (2021) 'Douglas Fuller on the global chip shortage'. Asiaexpertsforum. http://asiaexpertsforum.org/douglas-fuller-global-chip-shortage/

5 It took a global effort and the participation of some 80,000 workers to bring the damaged factory back into production two and a half months after the earthquake struck on March 11th, 2011. https://asia.nikkei.com/Business/Tech/Semiconductors/Fukushima-quake-shows-chipmaker-Renesas-value-of-resilience

6 Subsequent research has demonstrated that the direct costs of the earthquake were magnified by indirect costs that rippled through the supply chain. Where companies purchased highly customized products from individual suppliers, any interruption of supplies from these specialized firms could cause serious problems for firms further up the supply chain. D.R. Baqee and E. Farhi (2019) 'The macroeconomic impact of microeconomic shocks: Beyond Hulten's theorem.' Econometrica. 87(4). https://onlinelibrary.wiley.com/doi/abs/10.3982/ECTA15202 D. Acemoglu et al (2012). 'The network origins of aggregate fluctuations.' Econometrica 80(5). https://economics.mit.edu/files/8135; J. Sauvagnat and J-N Barrot (2016). 'Input specificity and the propagation of idiosyncratic shocks in production networks.' *Quarterly Journal of Economics*. 131(3). https://dspace.mit.edu/handle/1721.1/111134; Research has also shown that when supplies of certain products are interrupted, firms do find substitutes and alternative sources of supply, as Japanese manufacturers did when China halted the sale of rare earths in 2010.

7 https://www.g20-insights.org/policy_briefs/resilience-under-crisis-proposals-and-considerations-for-regional-and-other-trade-agreements/

suppliers.[8] Any lingering reservations regarding the efficacy of industrial policies in the western economies have been largely swept aside.

This note focuses mainly on the US response however, Korea, Japan and other countries are also taking steps to minimize supply chain vulnerabilities. Because American companies aggressively pursued cost minimization and outsourced the manufacture of semiconductors, the US share of global production has fallen from 37 percent in 1990 to 12 percent in 2022.[9] The US remains the dominant force in research, chip design and EDA (electronic design automation) software led by firms such as Cadence and Synopsis, vapor deposition and etching instruments (Applied Material, LAM Research), and yield management and diagnostic instrumentation (KLA-Tencor) however, many other critical pieces of semiconductor manufacturing equipment are produced in Europe,[10] Japan, and some in Taiwan and Korea (lithography-EUV, DUV, vapor deposition, testing etc.).[11] ATP is localized in a few SE. Asian countries and in China (22 percent). Japan, Korea, and Taiwan are suppliers of photomasks (e.g. Toppan), photoresists (controlled by Japanese manufacturers such as JSR, Tokyo Onika, Shin-Etsu and Fujifilm[12]), wafers, chemicals, and some lithography equipment (Tokyo Electron, Lasertek, Nikon, Canon). All manufacturers of chips obtain a large part of their raw materials from China including ultra-high purity polycrystalline silicon,[13] refined rare earths, gallium, cobalt, and some of the gases. The production process involves many steps spanning up to

8 China imported $378 billion worth of semiconductors in 2020, and self-sufficiency in this area as well as in other strategic products (petroleum products, grain, cooking oils) has become an overriding objective. *Financial Times* September 16th, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/08/fact-sheet-biden-harris-administration-announces-supply-chain-disruptions-task-force-to-address-short-term-supply-chain-discontinuities/; *Financial Times* (2022, November 15th) 'US curbs hit China's chip equipment makers.' China's Yangtze Memory Technologies a spinoff from SMIC (and majority owned by the Tsinghua Unigroup) based in Wuhan began producing 3D 128-layer NAND flash memory chips in 2020. Once it can achieve the desirable yields and scale at its two 100,000 wafers per day throughput fabs, Yangtze could compete on equal terms with the likes of SK Hynix, Samsung, and Micron that currently dominate the market. But ChangXin Memory Technologies YMTC's rival is already feeling the pinch of US sanctions. In mid 2022, China's SMIC began shipping semiconductors with a 7 nm node size (using multiple patterning with deep ultraviolet argon fluoride immersion lithography rather than EUV), only a generation behind the current state of the art 5 nm chip. It is rapidly closing in on the frontrunners, but yield might be an issue and low yields can cripple profits. Both Global Foundries and UMC have found it hard to keep up with the likes of TSMC and Samsung. *Financial Times* (August 17th, 2022) 'China's chip breakthrough presents a strategic dilemma.' https://www.ft.com/content/f0ddae61-a8a3-456d-8768-971c71ccb6dd; https://www.photonics.com/Articles/ArF_Immersion_Lithography_Supports_High-Volume/a57548; Advanced Micro-fabrication Equipment Inc or AMEC (and ACM Research) are Chinese firms that make etching equipment (including dry etch machines) and are challenging the leading players in this space, Applied Materials and LAM Research. China continues to seek technology from abroad by taking over foreign firms e.g., the acquisition in 2022 of the UK based Newport Wafer Fab by China's Nexperia, which is controlled by WingTech Technology. *Financial Times* (August 10th, 2022). 'The UK fight for the chip industry.'

9 More than 80% of the US semiconductor industry's profits come from overseas customers. China absorbed almost 30 percent of US semiconductor exports in 2021. And 70 percent of the semiconductor market is now in Asia while the US accounts for 21.7 percent. https://www.wilsoncenter.org/article/technology-and-supply-chain-resilience-opportunities-us-korea-cooperation; https://www.ft.com/content/98f22615-ee7e-4431-ab98-fb6e3f9de032; Close to 90 percent of the most advanced 5 nm node chips were produced by TSMC (in 2021) with Samsung and Intel slowly catching up. Taiwan's $147 billion semiconductor industry accounts for 15 percent of GDP and 40 percent of its exports. Economist (2022, May 28th) 'Bargaining chip'. https://www.economist.com/asia/2022/05/26/taiwan-is-worried-about-the-security-of-its-chip-industry

10 ASML of the Netherlands (and its lens supplier Carl Zeiss) is the sole producer of extreme ultraviolet (EUV) lithography equipment needed to manufacture chips with 5 nm nodes. The demand for energy efficient chips with such densities indicates that advances in product design can fully exploit their capabilities. 3 nm and 2 nm chips should become available during 2023-2024 using more advanced EUV technology plus new deposition and etch and inspection/metrology technologies. 3 nm transistors will use gate-all-around FETs instead of finFet as will 2nm transistors. https://www.anandtech.com/show/17385/applied-materials-new-tools-needed-for-3-nm-and-gaa-transistors

11 Applied Materials is a producer of equipment for wafer fabrication including vapor deposition, thermal processing, polishing and ion implantation. Some of this is produced in the US (e.g. Austin, TX)."

12 Rohm and Haas a subsidiary of Dow Chemical, is another supplier. https://www.utmel.com/blog/categories/technology/top-chinese-photoresist-manufacturers-guide

13 https://www.powerwaywafer.com/polycrystalline-silicon-wafers.html; China is the dominant producer with the US, Japan and Europeans accounting for about 18 percent of the total. https://www.universitywafer.com/polycrystalline-silicon.html

100 days and prior to delivery to the final customer, components can cross borders numerous times. The supply chain as it exists today is complex, geographically dispersed, and exposed to geo-political, economic, technological, and security related developments (Figure 2). The Ukraine conflict has resulted in shortages of neon gas. Drought caused by climate change throttled the supply of water to Taiwanese fabs and will be an additional source of disruption going forward.[14]

Figure 2. Semiconductor value added and shares by segment and firm headquarters

	Segment Value add	Market shares						
		U.S.	S. Korea	Japan	Taiwan	Europe	China	Other
EDA	1.5%	96%	<1%	3%	0%	0%	<1%	0%
Core IP	0.9%	52%	0%	0%	1%	43%	2%	2%
Wafers	2.5%	0%	10%	56%	16%	14%	4%	0%
Fab tools	14.9%	44%	2%	29%	<1%	23%	1%	1%
ATP tools	2.4%	23%	9%	44%	3%	6%	9%	7%
Design	29.8%	47%	19%	10%	6%	10%	5%	3%
Fab	38.4%	33%	22%	10%	19%	8%	7%	1%
ATP	9.6%	28%	13%	7%	29%	5%	14%	4%
Total value add		39%	16%	14%	12%	11%	6%	2%

Source: S. Khan et al (2021). https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf

No country can fully internalize the semiconductor supply chain.[15] The manufacture of chips is a complicated process involving as many as 1,000 steps (Figure 3 and references[16]). However, by working together, the US and its European and East Asian partners can partially insulate the supply chain from shocks to come. To achieve this requires the coordinated application of industrial, manpower, trade, technological and demand management policies by governments backed by generous subsidies in close collaboration with private firms that own or control all the elements of the supply chain.[17] It is the private sector that can augment production capacity, reorient FDI to disperse certain operations, and secure sources of materials.[18] Governments can speed up

14 They are among the principal suppliers of semiconductors. https://www.cnbc.com/2021/03/16/2-charts-show-how-much-the-world-depends-on-taiwan-for-semiconductors.html

15 Fuller (2021) maintains that it would be costly for both China and the US and for China it could take decades. 'Douglas Fuller on the global chip shortage'. Asia Experts Forum. http://asiaexpertsforum.org/douglas-fuller-global-chip-shortage/

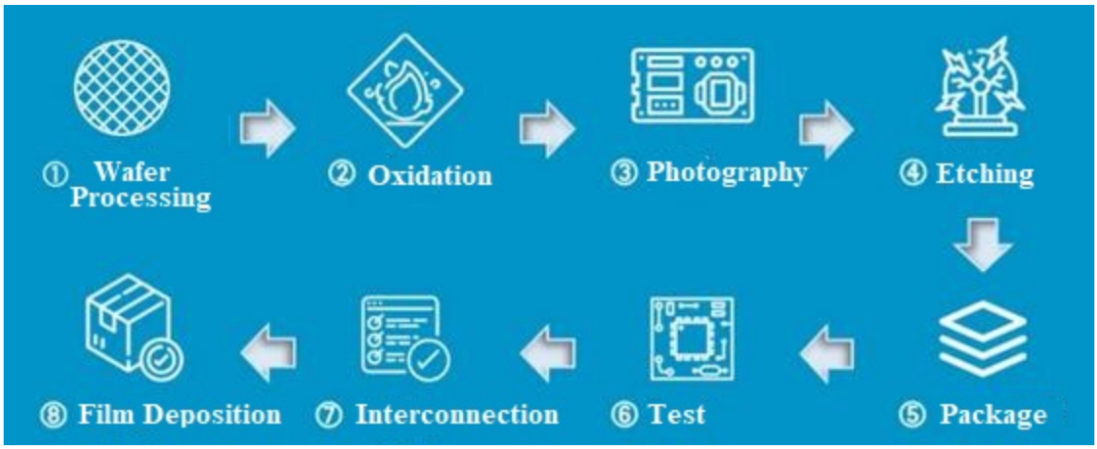
16 S.M. Khan, A. Mann, and D. Peterson (2021). 'The Semiconductor Supply Chain: Assessing National Competitiveness.' CSET Issue Brief. https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf

17 "You can't be a viable player in this game if you don't subsidize production. When the U.S., Japan, and Europe were not proactive in subsidizing, their capacity shrank vis-a-vis these other players." D. Fuller (2021) ibid.

18 ATP accounts for 10 percent of the chip's value but they constitute a critical final step. A single Taiwanese firms (ASE) with operations in Taiwan and SE Asia has 26 percent of the global back-end market (OSAT—outsourced semiconductor assembly and testing). An American firm, Amkor has 13 percent of the ATP market. https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf

adjustment and change. Resilience will come at a price. A reconfiguring of supply chains to factor in risk mitigation will raise unit costs because firms may need to contract with more than a single supplier, accumulate larger inventories, and shoulder the expense of distributing goods over newly designed chains.

Figure 3. Making chips



Source: Apogeeweb (2021). 'Semiconductor manufacturing steps with flowcharts.' https://www.apogeeweb.net/electron/semiconductor-manufacturing-steps-with-flow-charts.html

By exposing the vulnerability of a critical supply chain, the Covid pandemic has induced governments to double down on their efforts to enhance "semiconductor security." Much like energy or food security, ensuring an adequate supply of chips now has equal priority. So-called soft industrial policies have long been an integral part of the policy toolkit in advanced countries.[19] Some countries went further using industrial policy (a combination of fiscal, trade, exchange rate, wage, and technology policies) to nurture national champions and or "pick winners" in the hope that these would help drive growth once they mature and achieve scale. Now, in response to the shock administered by the Covid pandemic and the heightened awareness of the vulnerability of a vital product, industrial policy towards semiconductors has taken a more muscular turn reminiscent of what was closer to the norm in the 1970s and earlier.

19 A. Harrison and A. Rodriguez-Clare (2010) have this to say on soft industrial policies, echoing similar views by D. Rodrik and R. Hausmann. "[The goal of] "soft" industrial policy … is to develop a process whereby government, industry, and cluster-level private organizations can collaborate on interventions that can directly increase productivity….to shift the attention from interventions that distort prices to interventions that deal directly with the coordination problems that keep productivity low in existing or raising sectors. Thus, instead of tariffs, export subsidies, and tax breaks for foreign corporations, [soft IP] relies upon programs and grants to help particular clusters by increasing the supply of skilled workers, encouraging technology adoption, and improving regulation and infrastructure." 'From hard to soft industrial polices in developing countries.' VoxEu. https://cepr.org/voxeu/columns/hard-soft-industrial-policies-developing-countries; This and other aspects of the "new" 21st century industrial policy as conducted by European countries, Korea and Turkey are elaborated by K. Aiginger and D. Rodrik (2020) and contributors to the special issue of the *Journal of Industry Competition and Trade*. 20. https://link.springer.com/article/10.1007/s10842-019-00322-3; Aiginger and Rodrik observe, "Successful industrial policy maximizes synergies with other partial policies. It has on the one hand to contain sectoral elements, defining important sectors for a country today or ones that expected to be important in the future but on the seconds hand support horizontal activities shaping business conditions. Sectoral policy should use the drivers of a high road strategy, like innovation, education, and sustainability, and horizontal policy should give a higher priority to key sectors. This combination could be labeled matrix-oriented industrial policy, since rows sketch sectors to be prioritized and columns policy instruments especially relevant in these sectors." More detail on the status of IP and some lessons, can be found in A. Terzi, A. Singh, and M. Sherwood (2022). 'Industrial policy for the 21st century: Lessons from the past.' European Commission Discussion Paper 157. https://ec.europa.eu/info/sites/default/files/economy-finance/dp157_en_industrial_policy.pdf

The US, European countries, Japan, and Korea have unveiled polices aimed at building or in some cases rebuilding manufacturing capabilities that had been eroded as firms transferred production to countries offering attractive incentives, and cheaper land, labor, and utilities. These policies are backed by recent legislation e.g., the US CHIPS and Science Act, the EU Chips Act[20] and similar measures introduced by Korean and Japanese governments.

The "new" IP agenda includes the following seven objectives. Some such as the focus on greening and on R&D will reinforce ongoing initiatives. Others such as reshoring, training and creating a system for collecting and analyzing information to provide an early warning of impending problems, will entail considerable give and take in negotiations with the private sector, plus a testing and finetuning of policy instruments to arrive at the desired outcomes that probably lie several years in the future.

1. Bringing production of some key components, equipment, and final products back home

2. Minimizing the risks associated with over dependence on Chinese suppliers by friendshoring or allyshoring other elements of the supply chain because not all can be reshored by any one country

3. Working with the private sector to create an effective system for information gathering and monitoring the supply chain to anticipate and to preemptively deal with problems

4. Investing in the technical skills that will be required to reshore production and to accommodate future growth of output

5. Support for RD&I to push the technological frontier and enhance productivity and to minimize the industry's consumption of energy and water

6. Coordinating industrial with trade and other policies

7. Demonstrating a commitment to greening and electrification strategies that will minimize cyclical fluctuations in demand for semiconductors and lessen the risks for companies that are investing in expensive production facilities.

20 P. Timmers (2022). 'How Europe aims to achieve strategic autonomy for semiconductors.' Brookings. https://www.brookings.edu/techstream/how-europe-aims-to-achieve-strategic-autonomy-for-semiconductors/; https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733596/EPRS_BRI(2022)733596_EN.pdf; the Japanese government's support for the building of semiconductor fabs announced in October 2022. https://accesspartnership.com/strategy-for-revival-of-the-japanese-semiconductor-industry/; https://www.iiss.org/blogs/analysis/2022/03/japan-prioritises-semiconductor-industry-in-bid-to-enhance-economic-security; Korea introduced its System Semiconductor Vision and Strategy in April 2019 and followed it up with K-Semiconductor Strategy in May 2021, to build a K-Semiconductor Belt that will augment capacity and competitiveness in the manufacture of materials, components and equipment used to manufacture chips and in the area of fabless chip design. https://www.koreatimes.co.kr/www/tech/2021/05/133_308778.html https://koreajoongangdaily.joins.com/2022/07/21/business/economy/semiconductor-Korea-Smasung-Electronics/20220721153507163.html

Seven Industrial policy steps needed to shockproof semiconductor supply

Selective reshoring of semiconductor manufacturing and some of the component supply chain is the first.[21] Reshoring needs to include the production of cutting edge 5&3 nm node chips as well as legacy chips (logic, analog, optoelectronic, power management) that remain in widespread use with node sizes ranging from 40 nm to 800 nm.[22] This is being pursued through the provision of financial and other incentives such as grants, loans at preferential rates, tax benefits, highly reliable and low-priced power supplies,[23] and land allocations like those provided by East and SE Asian countries.[24] These incentives would narrow the cost disadvantage that weighs on production in the US. The CHIPS Act[25] is an attempt to level the playing field.[26] This legislation incentivizes semiconductor production to the tune of $39 billion with firms constructing new fabs receiving $3 billion per fab. $11 billion are allocated for R&D and seed funding is provided for a Multilateral Semiconductor Security Fund to secure the supply chain.[27] Government policy and geopolitical tensions have spurred investment in new fabs by Intel, TSMC, Samsung, Micron, Texas Instruments, and others.

A second objective is the "friendshoring or near shoring" of critical operations and supplies and possibly, the creation of new regional research and production hubs. This calls for both a dispersion of some operations away from China and SE Asia as well as an increase in the number of suppliers to build necessary redundancy into the supply chain. The onus is on private firms to treat resilience as a priority, to broaden their supplier processing networks and where possible secure multiple sources of raw material. Undoubtedly this will lead to an increase in costs. To make supply chains resilient firms

21 US firms are on track to reshore as many as 350,000 jobs across all sectors in 2022. Semiconductors are one of the sectors standing to benefit. WSJ (2022, August 20th. https://www.wsj.com/articles/u-s-companies-on-pace-to-bring-home-record-number-of-overseas-jobs-11660968061

22 Many industries depend on these legacy chips some of a customized nature. They include automobiles, medical devices, defense, broadband etc. Node sizes of logic chips for microcontrollers range from 40 nm to 250 nm nodes; analog chips have node dimensions of between 40 nm and 800 nm; while optoelectronic chips are in the 65 nm and 180 nm range. https://www.commerce.gov/news/blog/2022/01/results-semiconductor-supply-chain-request-information

23 A large state of the art fab can consume 100 megawatts of power in an hour and any outage or voltage sag can be damaging. https://blog.se.com/power-management-metering-monitoring-power-quality/2021/11/15/how-to-improve-power-reliability-for-semiconductor-fabs/; Electricity accounts for between 5 percent and 30 percent of the operating costs—depending on power tariffs. And scale of operation McKinsey (2013). Semiconductors. https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/operations/pdfs/bringing_fabenergyefficiency.ashx

24 Clyde Prestowitz (2022) maintains that it was industrial policy (larded with incentives), protectionism and mercantilism that was responsible for the successes of the Japanese and Taiwanese semiconductor industries. 'CHIPS as usual: A defense of US industrial policy.' Hinrich Foundation. https://www.hinrichfoundation.com/research/article/us-china/chips-us-industrial-policy/

25 Creating Helpful Incentives to Produce Semiconductors for America Act

26 For example, China has committed $150 billion to develop its semiconductor capabilities. Thus far (2022) the National Integrated Circuits Fund has invested $39 billion in new projects and another $50 billion will be forthcoming in the form of grants, equity investments and low-interest loans. In addition to the commitments by the central government, provincial governments are also intending to invest $25 billion in the industry. *Financial Times* September 16th, 2022. P.15. On China's semiconductor industry, its funding and objectives see. https://www.semiconductors.org/taking-stock-of-chinas-semiconductor-industry/

27 The CHIPS Act also authorizes the establishment of both a National Semiconductor Technology Center to conduct research and prototyping of advanced semiconductor technology and a National Advanced Packaging Manufacturing Program.

must embrace "just in case" operating procedures and in collaboration with the government, enlarge the inventories of key inputs[28] and products.[29]

A third objective is the instituting of a system of monitoring of supply chains by private firms, making firm contractual commitments to their suppliers, and the sharing of this information with public agencies.[30] Timely data sharing can help to identify bottlenecks in advance and avoid shortages.[31] Greater transparency can enable firms to track and trace their orders, better gauge the status of second and third tier suppliers and take remedial action where necessary.[32] Sometimes the unavailability of a minor part or chemical[33] from a single source can bring production to a halt.

The research, design and manufacturing of semiconductors is highly skill intensive. **Therefore, ensuring an adequate supply of skills is a fourth objective**. This cannot be done overnight and while the US has been able to overcome shortages by importing engineering talent,[34] reshoring on any scale must go hand in hand with measures to build technical and STEM skills, and channel them into the semiconductor industry. This is partly the responsibility of the state, but company training programs can make a vital contribution (Intel partnering with universities and community colleges and investing $100 million). Strengthening the workforce whether in the US, Europe, or in Korea must be a cooperative effort with public and private entities doing their share.[35]

Promoting technological advances to improve semiconductor performance, conserve materials, and minimize pollution[36] **depends on the volume and quality of research. Supporting this research much of which is conducted by the private sector is a fifth objective.** In both the US and Korea, government, and university institutes[37] are actively engaged in research on semiconductors that is shared with the private sector. In the US, they are backed by the DoD, the DoE, NSF and NIST. More important are the measures introduced to incentivize research by the corporate sector and start-

28 Including gases such as neon and helium, elements such as germanium and tantalum and high purity solvents. https://www.nist.gov/pml/sensor-science/fluid-metrology/database-thermophysical-properties-gases-used-semiconductor-0

29 Stockpiling semiconductors has its drawbacks because, many are application specific and cannot be substituted between different products.

30 C. Schuh et al (2022). 'The semiconductor crisis should change your long-term supply change strategy'. Harvard Business Review. https://hbr.org/2022/05/the-semiconductor-crisis-should-change-your-long-term-supply-chain-strategy

31 https://www.nytimes.com/2021/01/13/business/auto-factories-semiconductor-chips.html

32 TSMC has as many as 2,500 tier one suppliers and 10,000 tier two suppliers alone. https://www.techtarget.com/searcherp/news/252523892/CHIPS-Act-should-simplify-semiconductor-supply-chains; An element of distrust runs through relations between the US and Korea. The former has complained about state subsidies received by Korean firms, while the latter fears that the CHIPS Act and the IRA will only favor US firms. The request by the US Dept. Of Commerce to chipmakers to supply information on their supply chains has also met with resistance. https://www.cfr.org/blog/anticipating-us-south-korea-semiconductor-alliance

33 Chemicals include trichloroethylene, acetone, isopropanol etc.

34 Three fourths of PhDs in the semiconductor industry are foreign born.

35 China has an abundance of engineering talent however, it too would need up to 400,000 more workers to meet its 2030 production targets.

36 Demand especially for ultra-pure water (upw) is substantial to rinse and condition wafers. Making raw water ultra-pure is energy intensive. A 200mm wafer fab with a monthly throughput of 20,000 wafers, can use 3,000 cubic meters of upw in a day. https://www.mks.com/n/semiconductor-ultrapure-water; https://en.wikipedia.org/wiki/Ultrapure_water

37 https://www.ny.gov/americas-microchip-resurgence/roadmap-national-semiconductor-technology-center-new-york. "NY state is home to the most advanced publicly owned 300mm semiconductor R&D facility in the United States, the Albany NanoTech Complex. The facility is led by the State University of New York's NY CREATES, which serves as a resource for public-private and academic partnerships around the globe. The multibillion-dollar complex offers a fully integrated research, development, prototyping, and educational facility that provides technology acceleration, business incubation, pilot prototyping, and test-based integration support for onsite corporate partners including global industry leaders like IBM, GlobalFoundries, Samsung, Applied Materials, Tokyo Electron, ASML, and Lam Research."

ups often a source of breakthrough technologies. Tax credits, and grants for example via programs such as DARPA's Electronics Resurgence Initiative finance research on materials, architectures, processes, and supply chain security. The creation of public-private consortia also helps pool resources, disseminate findings, and narrow the "lab to fab" gap. The CHIPS Act will finance jointly with the private sector, including academia, a Semiconductor Technology Center, and an Advanced Packaging Manufacturing Program.[38] Together they will strengthen the ecosystem and the base of skills.[39]

Because no one country can create an entirely self-sufficient semiconductor production system (although China is attempting this feat), industrial policy must be meshed with trade policy,[40] **a sixth objective.** This calls for collaboration with partners in Europe and East Asia (e.g. with the Taiwan Semiconductor Research Institute and similar institutes in Korea) to align incentives and avoid competing subsidies. National security interests can be adequately served without the use of overbroad controls. Therefore, the US and its partners can improve the functioning of supply chains by removing or lowering tariffs on products and targeting export controls more narrowly. In this context, an updating of trade agreements could enhance supply chains flexibility (by minimizing arbitrary imposition of restrictive trade measures as during Covid) without compromising the protection of IP.[41]

Finally, an objective of public policies is to signal a credible commitment to long term policies that would sustain the demand for semiconductors—both leading edge and legacy ones—and minimize the cyclical fluctuations. For example, a commitment to greening energy, building smart grids, promoting electrification of transport, and harnessing digital technology to improve urban services would complement and smoothen demand for semiconductor using EVs, 5G telecommunications, mobile devices, AR/VR and the IoT.

38 https://www.semi.org/en/blogs/semi-news/house-passes-chips-funding-conference-with-senate-last-remaining-legislative-hurdle

39 The government has played a lead role in the creation of Taiwan's chipmaking ecosystem. It has provided leadership, helped develop the talent pool, supported R&D and been generous with financial incentives. https://www.brookings.edu/blog/order-from-chaos/2022/04/12/ensuring-a-stronger-us-taiwan-tech-supply-chain-partnership/

40 There is the Export Control Reform Act allows the President to control exports of emerging and foundational technologies. The FDPR is the extraterritorial application of US law to curb foreign produced exports containing US technology.

41 Changes include the internationalization of subsidized SOEs, the digitalization of trade, and increased trade in services. Proliferation of bilateral and FTAs. https://www.oecd.org/trade/understanding-the-global-trading-system/trade-challenges-and-opportunities/; "New commitments in international agreements could be considered to reinforce the capacity of supply chains to operate during a crisis and to prevent the introduction of harmful measures. Such commitments could, inter alia: (i) limit trade and investment policy discretion on essential goods; (ii) enhance trade facilitation practices and regulatory cooperation; (iii) improve transparency; and (iv) create consultation mechanisms and cooperation in crisis situations. Such commitments would be in the interest of both exporters and importers to preserve trust in their access to essential goods, and to avoid non-cooperative outcomes that lead to less resilient supply conditions." https://www.oecd.org/trade/resilient-supply-chains/international-agreements/; "USTR is working closely with trading partners and stakeholders through many bilateral and multilateral venues, including the U.S.-Mexico-Canada Agreement (USMCA), U.S.-European Union Trade and Technology Council, U.S.-Korea Free Trade Agreement (KORUS), Japan Comprehensive Partnership, U.S.-United Kingdom Trade Dialogue, as well as multilateral organizations such as the World Trade Organization (WTO), Asia-Pacific Economic Forum (APEC), and Organization for Economic and Commercial Development (OECD)." https://ustr.gov/about-us/policy-offices/press-office/blogs-and-op-eds/2022/april/building-resilient-and-secure-supply-chains-through-trade

Concluding observations on the complicating China factor

The efforts to strengthen the resilience of the supply chain—by the US, Korea, Taiwan, Japan European countries such as Germany[42] and the Netherlands - are complicated by the need to balance relations with China the biggest and fastest growing market.[43] The proposed US' Chip 4 alliance,[44] investment by Samsung, SK and TSMC in US based semiconductor facilities[45] (augmenting planned investment by Intel, Texas Instruments, and Micron) and Korea's participation in the Indo Pacific Economic Framework, will improve coordination among members and reduce the vulnerability of the supply chain.[46] However, it is in the interests of firms from the US and its partners to maintain access to suppliers in China and to continue meeting China's expanding demand for semiconductors, components, equipment, and final products through exports (China accounts for 40 percent of global IT production, Figure 4).[47] China is an important market for American companies such as Apple, AMD, Nvidia, Intel, and Applied Materials. Achieving a workable cooperative equilibrium will depend on a mix of communication and trust building among partners in the Chip 4 alliance whose interests are not necessarily in sync,[48] with European allies, and careful handling of relations with China.[49] Radical decoupling as envisaged by some would be immensely

42 Many German companies are reluctant to minimize their exposure to the Chinese market, which absorbs 9.5 percent of German exports, and 46 percent of German companies depend on the import of intermediate products from China. Likewise, the Dutch company ASML stands to lose hundreds of millions of dollars in sales if it cannot export its latest EUV equipment to China. *Financial Times* (November 2nd 2022).'Germany's dilemma over China.'

43 Deloitte (2020) The Rise of the Asia Pacific Big 4. https://www2.deloitte.com/cn/en/pages/technology-media-and-telecommunications/articles/rise-of-the-big-4.html

44 https://www.cfr.org/blog/anticipating-us-south-korea-semiconductor-alliance

45 *Financial Times* (2022, August 4th) Samsung and SK grow wary on China. https://www.ft.com/content/0b997942-93bd-4a67-9784-928af2641738

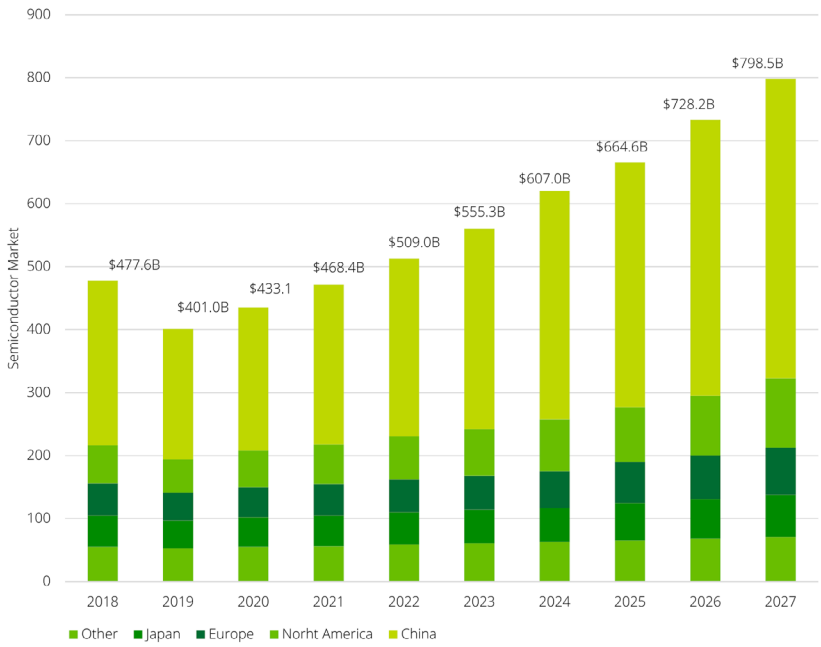
46 https://thediplomat.com/2022/08/china-tensions-are-deepening-south-korea-us-economic-coordination/

47 Deloitte (2022). '2022 Semiconductor Industry Outlook.' https://www2.deloitte.com/us/en/pages/technology-media-and-telecommunications/articles/semiconductor-industry-outlook.html; "For example, Korea imports 31.2% ($17.8 billion) of its semiconductors from China. In the case of memory semiconductors, the dependency is even greater. South Korea imports 76.7% ($13.9 billion) of all memory semiconductors from China. This rises to 78.3% ($14.1 billion) when including imports from Hong Kong. South Korea is also highly dependent on China as a market for its semiconductor exports. China accounts for 43.2% ($41.2 billion) of South Korea's total semiconductor exports, while Hong Kong accounts for 18.3% ($17.4 billion), meaning that 61.5% of semiconductors are exported to China and Hong Kong. The high volume of imports and exports of Korean semiconductors to and from China is due to the large amount of intra-company trade between Samsung Electronics and SK Hynix's Korean and Chinese subsidiaries. Most semiconductors produced by Korean companies in China are supplied to multinational companies such as Apple in China. And some are supplied to Chinese companies while the rest are exported to Korea or overseas." US companies also earn a disproportionate share of their profits from exports to China. https://www.wilsoncenter.org/article/technology-and-supply-chain-resilience-opportunities-us-korea-cooperation; https://www.ft.com/content/98f22615-ee7e-4431-ab98-fb6e3f9de032; However, TSMC is less exposed to China. Only 10 percent of its capacity—and not the latest fabs—are in China. https://www.cnbc.com/2022/08/17/china-needs-taiwans-biggest-chipmaker-more-than-the-other-way-around.html; The worry regarding a seizure of Taiwan's facilities elicited the following response from the company's chairman. "Nobody can control TSMC by force. If you take a military force or invasion, you will render TSMC factory not operable. Because this is such a sophisticated manufacturing facility, it depends on real-time connection with the outside world, with Europe, with Japan, with U.S., from materials to chemicals to spare parts to engineering software and diagnosis." https://www.cnbc.com/2022/08/02/apple-chipmaker-tsmc-warns-taiwan-china-war-would-make-everybody-losers.html; And then there is always this. https://www.theregister.com/2022/06/13/column/

48 *Financial Times* (Sept. 12. 2022). 'US Struggles to mobilize its East Asian Chip 4 alliance.' https://www.ft.com/content/98f22615-ee7e-4431-ab98-fb6e3f9de032

49 A. Gargeyas (2022). 'The Chip 4 alliance might work on paper, but problems will persist.' Diplomat. https://thediplomat.com/2022/08/the-chip4-alliance-might-work-on-paper-but-problems-will-persist/; C. Miller (2022). *Chip War: The fight for the world's most critical technology*. Scribner.

Figure 4. Semiconductor consumption by geographic region



Source: Deloitte. Rise of the Big 4: The semiconductor industry in Asia Pacific. https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/technology-media-telecommunications/cn-tmt-rise-of-the-big-4-en-082820.pdf

costly for all parties and is arguably infeasible.[50] Partial decoupling now seems to be baked in posing a considerable challenge to China as well.[51]

I thank David Evans for his comments that improved content and presentation.

50 D. Fuller (2022) warns against an aggressive application of curbs imposed by the US. "A short-term policy victory for the China hawks might prove pyrrhic. China currently has few allies and little hope in its fight for silicon supremacy. Even its own consumers and chip designers are reasonably content with reliance on international suppliers. Pushing broader controls will ultimately push Chinese and foreign businesses to develop an alternative semiconductor supply chain, to the benefit of China's quest to escape technological dependency on the United States." 'Biden's united front targets China's fight for silicon supremacy.' Hinrich Foundation. https://www.hinrichfoundation.com/research/article/us-china/biden-s-united-front-targets-china-s-fight-for-silicon-supremacy-eafq-v14/

51 The sanctions imposed on the export of semiconductor equipment to China will greatly hamper China in the medium term. https://research.gavekal.com/teaser/us-chip-sanctions-and-chinas-options/; *Financial Times* (2022, November 15th) 'US curbs hit China's chip equipment makers.'

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