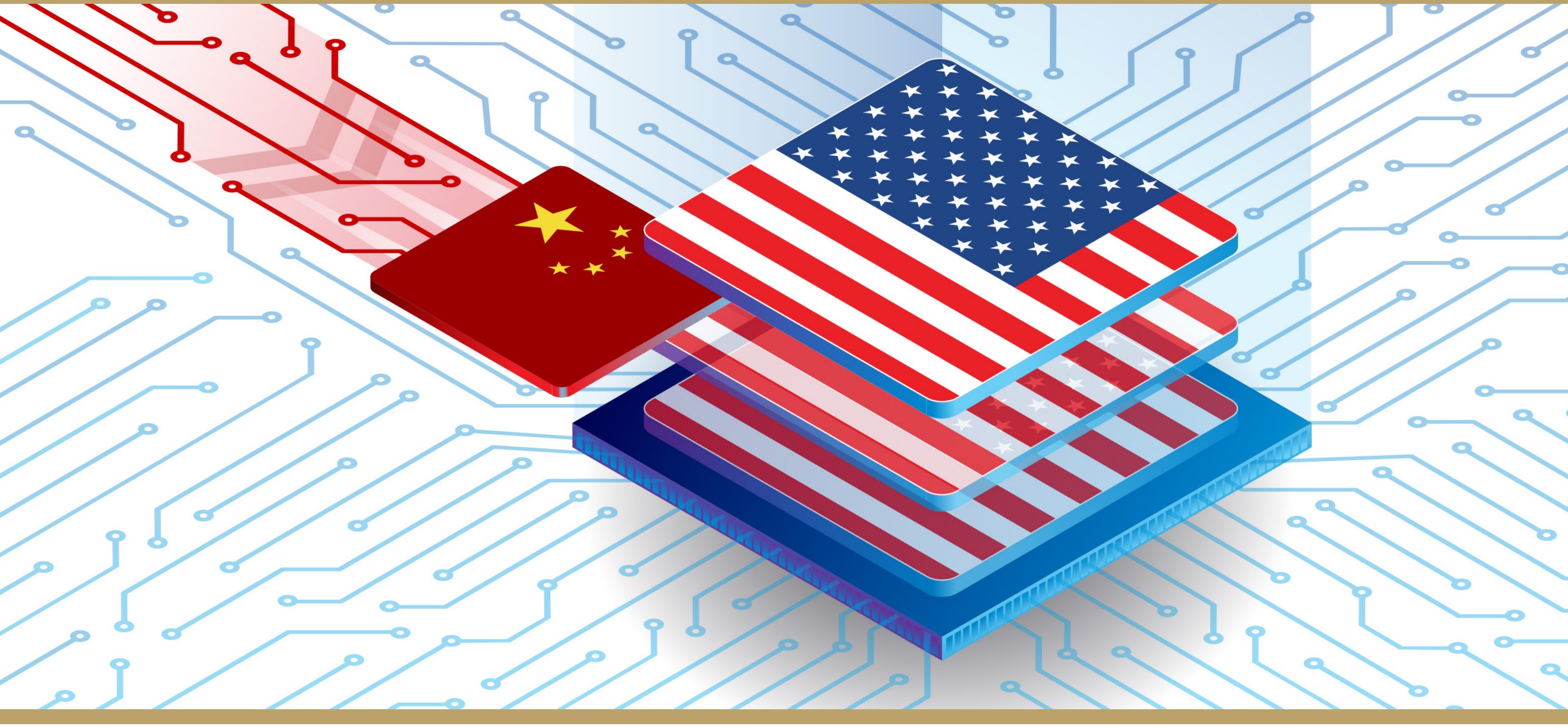
CUTTING OFF OUR NOSE TO SPITE OUR FACE

US Policy toward Huawei and China in Key Semiconductor Industry Inputs, Capital Equipment, and Electronic Design Automation Tools

National Security Report



Douglas B. Fuller

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

CUTTING OFF OUR NOSE TO SPITE OUR FACE

US Policy toward Huawei and China in Key Semiconductor Industry Inputs, Capital Equipment, and Electronic Design Automation Tools

Douglas B. Fuller

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

NSAD-R-20-059

Contents

Figures

Figure credits:

Figure 1. IC Value Chain. Copyright 2013 from Fuller, Douglas B., Akintunde I. Akinwande, and Charles G. Sodini. "Global Reorganization of the IT Industry and the Rise of China." In *Technology Transfer between the US, China and Taiwan: Moving Knowledge*, edited by Douglas B. Fuller and Murray A. Rubinstein, 71–98. New York: Routledge, 2013. Reproduced by permission of Taylor and Francis Group, LLC, a division of Informa plc.

Figure 2. Cadence and Synopsys Market Share of "Core" EDA, 2013–2019. Reproduced from Ader, Jackson E., Sterling Auty, Matthew Parron, and Sahil Sharma. "Assuming Coverage of EDA." Research report. J.P. Morgan, September 11, 2019. Courtesy J.P. Morgan Chase & Co., Copyright 2020.

Figure 3. EDA R&D's Growing Share of Overall Semiconductor R&D Expenditure, 2014–2018. Reproduced from Ader, Jackson E., Sterling Auty, Matthew Parron, and Sahil Sharma. "Assuming Coverage of EDA." Research report. J.P. Morgan, September 11, 2019. Courtesy J.P. Morgan Chase & Co., Copyright 2020.

Figure 4. Top Global Wafer Fab Equipment Providers, 2018. Reproduced from Ramel, Jerome, and David O'Connor. "Entering the EUV Era: Winners and Losers." Research report. BNP Paribas, April 8, 2020. Used with permission from Exane BNP Paribas.

Figure 5. Semiconductor Market Demand Shares. Reproduced from Teng, Donnie, Aaron Jeng, Bruno Cheng, and Tetsuya Wadaki. "China SPE Sector." Anchor Report. Nomura, January 13, 2020. Used with permission.

Tables

Table credits:

Table 1. 2018 Percentage American Share in Wafer Fab Equipment. Reproduced from Ramel, Jerome, and David O'Connor. "Entering the EUV Era: Winners and Losers." Research report. BNP Paribas, April 8, 2020. Used with permission from Exane BNP Paribas.

Table 2. Chinese Semiconductor Capital Equipment Producers. Reproduced from Teng, Donnie, Aaron Jeng, Bruno Cheng, and Tetsuya Wadaki. "China SPE Sector." Anchor Report. Nomura, January 13, 2020. Used with permission.

Foreword

This paper is part of the "Measure Twice, Cut Once: Assessing Some China–US Technology Connections" research series sponsored by the Johns Hopkins University Applied Physics Laboratory.

As competition has intensified between the United States and China, actions to disengage their technology establishments from one another have also intensified. The two countries' systems for research and development, production, and sale of cutting-edge technologies have been substantially, though by no means uniformly, commingled. More recently, there have been concerted efforts by both nations' governments to reverse some or all of that commingling. Policymakers' priorities include perceived risks to national security, worry about economic disadvantage from proliferation, and concern about uses of technologies that intentionally or indifferently may harm civil liberties or the environment.

To explore the advisability and potential consequences of decoupling, the Johns Hopkins University Applied Physics Laboratory commissioned papers from experts in specific technology areas. In each of these areas, the authors have explored the feasibility and desirability of increased technological separation and offered their thoughts on a possible path forward. Other papers in this series include:

- *Two Worlds, Two Bioeconomies: The Impacts of Decoupling US–China Trade and Technology Transfer* by Rob Carlson and Rik Wehbring
- *The History and Future of US–China Competition and Cooperation in Space* by Matthew Daniels
- *Symbiosis and Strife: Where Is the Sino–American Relationship Bound? An Introduction to the APL Series "Measure Twice, Cut Once: Assessing Some China–US Technology Connections"* by Richard Danzig and Lorand Laskai
- *An Entwined AI Future: Resistance Is Futile* by Christine Fox
- *The Telecommunications Industry in US–China Context: Evolving toward Near-Complete Bifurcation* by Paul Triolo
- *Addressing the China Challenge for American Universities* by Rory Truex
- *US–China STEM Talent "Decoupling": Background, Policy, and Impact* by Remco Zwetsloot

Summary

Semiconductors are core components in telecommunications, artificial intelligence computing, and many other high-tech goods. It is not surprising, accordingly, that the United States has placed semiconductors front and center in its policies designed to crush Huawei. By placing Huawei and its affiliates on the Entity List in May 2019, the American government has tried to cut Huawei off from the American semiconductor technology. On May 15, 2020, the US government doubled down on this gambit by restricting Huawei's access to two areas of particular American strength in the semiconductor value chain: capital equipment for chip production and electronic design automation (EDA) for chip design. The US government further tightened those restrictions on August 17, 2020.

This paper has four major findings. First, over the next five years, even substantial Chinese efforts to replace American capital equipment and EDA tools with homegrown alternatives are very unlikely to succeed. Second, the severity of constraints on Huawei will depend more on the availability of international alternatives to American technology than on the availability of Chinese products. The lack of suitable legal alternatives to American EDA tools globally will severely challenge Huawei's ability to design chips. In contrast, for chip manufacturing, alternatives to American capital equipment might be obtained within a comparatively short time, so manufacturing firms might still be able to produce Huawei's chips relatively quickly if they choose to eschew American technology to do so. Third, these constraints will most likely knock Huawei down but will not knock it out of the telecommunications industry. Finally, the longer-term costs for American capital equipment and EDA tool vendors could loom large if foreign customers perceive American-made or -designed products as carrying significant political risk and strive to develop alternative sources.

To illuminate these points, this paper first presents a brief introduction of the evolution of the semiconductor industry's value chain since the 1980s with an emphasis on how the reorganization of the global semiconductor industry helped to revive the American industry in the face of Japanese competition. This point provides important context for considering current calls for decoupling and deglobalization. The paper's next section examines the EDA industry in the United States and China and Huawei's EDA options if the export controls are fully implemented. This is followed by an examination of the fabrication capital equipment industries in the United States and China. This illuminates Huawei's integrated circuit manufacturing options if US export controls are fully implemented. The concluding section of this paper considers whether even the most stringent implementation of the current controls actually will impact Huawei as envisioned. The conclusion recommends an alternative American approach to technological competition with China that is focused on reinforcing our semiconductor capabilities instead of trying to tear down China's.

Calls for decoupling from China are all the rage in Washington, but the history of the semiconductor industry suggests smart globalization yields better outcomes than blunt techno-nationalism. In the 1990s, the United States pursued the former backed by critical investments at home while Japan pursued the latter.

The Evolution of the Semiconductor Industry's Structure

The spectacular revival of the American semiconductor industry from near death in the mid to late 1980s was at least partially due to the willingness of American industry to reinvent the semiconductor value chain, often in conjunction with Taiwanese firms.[1] In approximately a decade, integrated device manufacturers (IDMs) that combined most of the segments of semiconductor production in-house largely gave way to a plethora of organizations focused on smaller portions of the semiconductor value chain. Principal among these were "pure-play" foundries focused on fabrication and fabless design houses focused on chip design.[2] This reorganization of the industry into a classic global value chain cemented America's near monopoly on electronic design automation (EDA) tools, induced the rise of American dominance in fabless design, and boosted the competitive position of American semiconductor capital equipment manufacturers.

While the last two decades have witnessed worrisome trends in the offshoring of fabrication and design in the American semiconductor industry, one must acknowledge the prominence of proverbial win–wins (mutually beneficial interactions) in this globalized industry. Although the rise of Taiwan's foundries arguably lowered the American share of global fabrication capacity (and today, even cutting-edge fabrication capacity), this rise benefited both American fabless design firms and capital equipment makers by creating reliable suppliers and consumers, respectively. Similarly, the rise of fabless design firms abroad has enhanced rather than displaced the market for America's EDA vendors. These win–wins stand in sharp contrast to the rise of Japan's industry in the 1970s and 1980s, when rising Japanese fabrication also meant lost market opportunities for American capital equipment makers because Japanese firms often favored Japanese equipment vendors and sometimes withheld their cutting-edge production equipment from American firms.[3]

The semiconductor value chain can usefully be viewed as consisting of three large blocks of activities (excluding marketing and distribution) (Figure 1).

- **Design:** Execution of a design idea into code (typically a GDSII file) that serves as the blueprint for the integrated circuit (IC) in the fabrication stage.
- **Fabrication:** Guided by the design code, inscribes circuitry onto physical materials (typically with a type of silicon as the main material) using lithography and treats the physical materials with chemicals. The three main processes repeated in fifty or more iterations are deposition (of materials onto the wafer), lithography, and etching (removal of unwanted materials from the treated wafer). The result of this fabrication process is the bare, unpackaged and thus unprotected IC die.
- **Assembly and Testing (A&T):** The IC die undergoes (1) assembly of its packaging, which protects it and allows it to connect to other electronic components and devices, and (2) testing to see if it works properly, resulting in the final IC chip.

[1] Fuller, Akinwande, and Sodini, "Leading, Following or Cooked Goose?"

[2] Fuller, Akinwande, and Sodini, "Global Reorganization of the IT Industry."

[3] Browning and Shetler, *Sematech*. For example, American firms were concerned that Nikon was not providing them with cutting-edge lithography equipment, so if an American alternative was not maintained, American firms would be at a critical disadvantage in advanced semiconductor fabrication.

Turning to IC design, it is helpful to differentiate innovative from detailed design.[4] The innovative design function captures higher-value design skills. This function can often provide a high barrier to entry because designers capable of performing this function usually have at least a master's degree in electrical engineering and require significant training, mentoring, and experience. In the past, it has been difficult to find these engineers in emerging economies. However, with the upgrading of engineering skills in the developing world made possible via modularized production, this situation is changing. Detailed design consists of less-complex tasks such as translating the component definition or the innovative IC design into mask data (this data is called "mask data" because it consists of detailed digitized drawings that will appear as layers in the silicon fabrication process) that is ready to be sent to wafer fabrication. Globalization of these detailed design skills preceded that of innovative design skills. Intellectual property (IP) vendors, such as ARM and CEVA, and EDA tool providers, such as Cadence and Synopsys, provide much of the technology for both innovative and detailed IC design.[5]

There is significant know-how at the interface of the design and fabrication functions. The IC fabrication process and resulting device specifications are captured in a sophisticated set of models that are provided by wafer foundries. These models encapsulate the detailed physics of the transistors so that the designers can simulate the operation of the circuit before fabrication. Successful wafer foundries have considerable expertise in making this interface user-friendly, particularly by employing web-based tools for easy information transfer. Critically, despite the fragmented, modular nature of the supply chain and the ability to digitize/codify most of the requisite information, intensive knowledge exchange between EDA tool vendors and foundries is still key to both sides maintaining their respective competitive edges because the pace of technological change in the IC industry is still rapid. Similar to the key role of EDA tool vendors for design-for-manufacturing, the capital equipment vendors provide to fabrication firms (foundries and IDMs) a large and critical knowledge input embedded in their capital equipment.

Traditionally, the vertically integrated IDMs performed all three functions. However, in the last decades of the twentieth century, they outsourced assembly and testing operations, and then, over the last twenty-five years, many IDMs have transitioned to a fab-light strategy that utilizes less internal chipmaking capacity.[6] Concomitantly, the industry has witnessed the rise of dedicated design firms and dedicated fabrication firms (pure-play foundries). There are two types of dedicated design firms: fabless design houses that design and market their own chips and design service firms that undertake part of or the whole design process for other firms.

Foundries typically have large research and development (R&D) departments for process technology and also capture value by being more efficient in fabrication as a result of not only their focus but also their flexibility: multiple processes and multiple products share the same fabrication facilities and even the same wafer in the case of multiproduct wafer production. Foundries also compete by providing their customers ever-more-detailed information about the timing and quality of production. Through the internet, customers of leading foundries can receive real-time data on their wafers as they are being fabricated. Data flows in both directions: a design firm must reveal IP to a foundry for the foundry to be able to fabricate

[4] The following four paragraphs are drawn from Fuller, *Paper Tigers, Hidden Dragons*; and Fuller, Akinwande, and Sodini, "Global Reorganization of the IT Industry."

[5] Cadence and Synopsys also sell significant IP for semiconductor design, but their global share of that market is 5 and 20 percent, respectively, compared to ARM's 45 percent (Steves, *Electronic Design Automation [EDA] Report*).

[6] Hurtarte, Wolsheimer, and Tafoya, *Understanding Fabless IC Technology*.

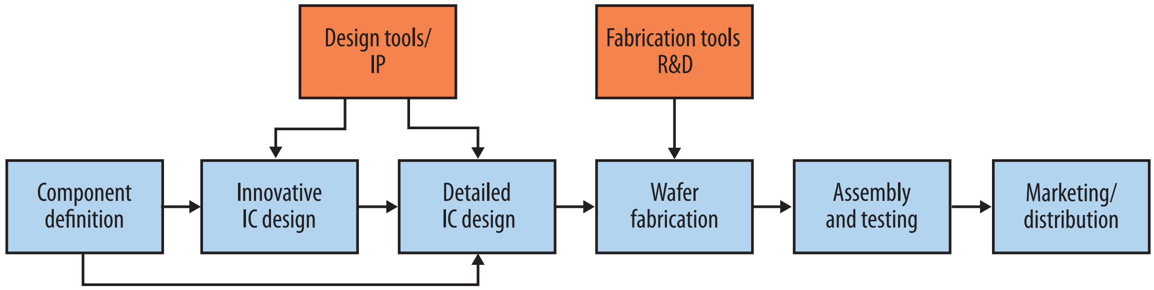


Figure 1. IC Value Chain

the chips. As a result, foundries strive to protect customer IP to keep clients and attract new ones.

As Figure 1 shows, the export controls the present US administration is pursuing are targeted at the key technology inputs, EDA tools and capital equipment, into the IC industry's two most technology-intensive segments, design and fabrication.

EDA Tools

The Development of the EDA Tool Industry

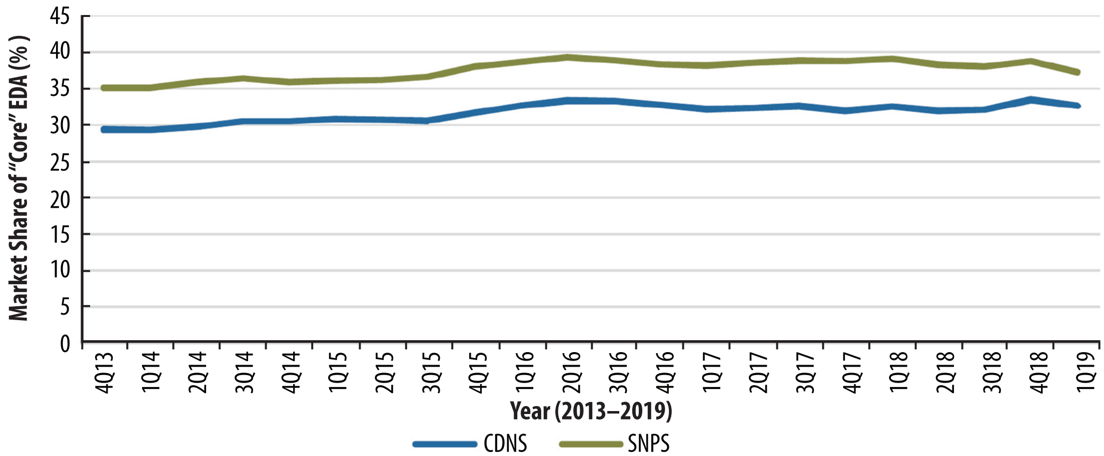
The software-based EDA industry is a recent phenomenon. Today's dominant EDA vendors—Mentor Graphics (1981), Cadence (1987/1988), and Synopsys (1987)—were all founded in the 1980s. Before the 1980s, computer-aided design (CAD) functions were typically sold with their requisite hardware, workstations. Much of the earlier CAD work was done inside systems companies. For example, IBM was a systems company par excellence as it made both chips and the end products the chips went into, such as mainframe computers. Today there are EDA tools to cover the whole design process, usually referred to as the design flow.[7]

Three things happened in the 1980s to create the software-based EDA industry we know. First, technological advances to develop software tools across all the important design functions proceeded apace so one could have a suite of EDA tools to cover the entire design flow. Second, the rise of general-task, powerful workstations allowed software-only EDA firms to gain a competitive edge. Third, standardization of EDA tools allowed them to gain wider acceptance in the commercial marketplace.[8]

In the 1990s, a fourth development that spurred the EDA industry was the maturation of pure-play foundries making chips for fabless design firms. Neither the foundries nor the fabless design firms were going to spend the money required to develop in-house EDA tools, as larger firms such as IBM had done in the past. Consequently, fabless design firms relied on EDA vendors for their design tools, and the EDA firms began to work closely with the

[7] The design flow for digital design generally takes the following path. The path goes from a conception of how the chip will operate within a larger electronics system (architecture stage) through to the use of various design languages to define the circuitry moving from greater to lesser levels of abstraction (behavioral to register transfer level [RTL] to gate level design) in the process. These processes along with the architectural level are commonly referred to as front-end design. The back end of design consists of the processes of implementation of these abstract designs into a design for real physical components and connectors embedded in silicon (Fuller, Akinwande, and Sodini, "Globalization").

[8] This brief introduction of the EDA industry is based on Sangiovanni-Vencentelli, "Tides of EDA"; and Krolikoski, "Evolution of EDA Standards."



Reproduced from Ader et al., "Assuming Coverage of EDA." Courtesy J.P. Morgan Chase & Co., Copyright 2020.

Figure 2. Cadence (CDNS) and Synopsys (SNPS) Market Share of "Core" EDA, 2013–2019

foundries to ensure that the EDA software could create fabrication-ready designs.

The pace of innovation in IC design is so rapid and occurs across such an array of chip products that two features of the industry have emerged. Just to attempt to keep pace, the two largest vendors, Cadence and Synopsys, routinely spend 30 percent or more of their revenues on R&D each year.[9] Consequently, the EDA industry has not yet developed one dominant platform for design and instead has an oligopoly of three large players. Indeed, it is not uncommon for different design teams within the same firm to use EDA tools from different vendors (interviews conducted in April and May 2020[10]). Some go so far as to argue that each of the "Big Three" EDA vendors offers a superior tool in one specific segment of the design flow. Consequently, best practice is to use tools from all three vendors.[11] Nevertheless, switching costs for entirely replacing one firm's EDA tools with another's appear high, so market shares have been fairly stable (see Figure 2).[12]

The other feature is that acquiring new technology from start-ups is very common despite the Big Three remaining the dominant firms for three decades. The increasing amount of overall semiconductor R&D spending taken up by EDA firms (see Figure 3) and the ability of venture-backed start-ups to take on higher-risk projects means these new firms make attractive targets for acquisition; at the same time, they find it difficult to compete with the established triumvirate. In other words, the start-ups can offer a particular advanced tool for a certain design task, but because these start-ups typically do not produce wider sets of tools, they have a very narrow competitive position. As a result, their best strategy more often than not is simply to sell themselves to one of the dominant firms.[13] The Big Three have consistently

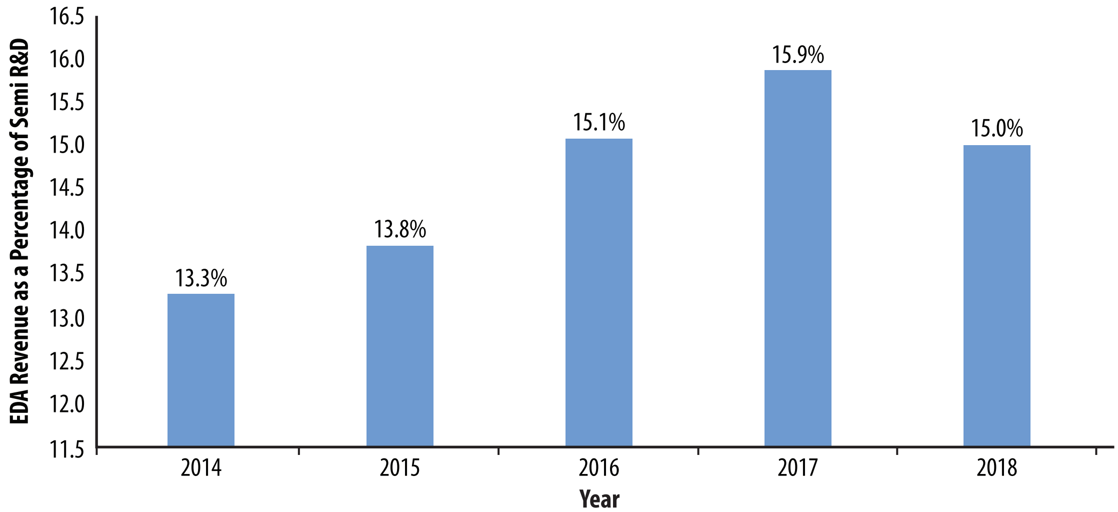
9 Ader et al., "Assuming Coverage of EDA."

10 To encourage interview subjects to share their knowledge, I promised to keep the interviews anonymous.

11 An interview subject who is an IC design expert claimed that Synopsys had the best compiler, Cadence the best layout tools, and Mentor the best verification tools (interview, May 2019). Another design expert agreed with this assessment (April 2020). Both experts argued simultaneously using tools from all three vendors was best.

12 Ader et al., "Assuming Coverage of EDA." One reason switching costs may be high is simply the fact that designers can grow comfortable with tools from one provider and getting down the learning curve with another company's tools may appear formidably inefficient at the team if not individual level (interview, April 2020).

13 Henkel, Ronde, and Wagner, "Entrepreneurship as a Contest."



Reproduced from Ader et al., "Assuming Coverage of EDA." Courtesy J.P. Morgan Chase & Co., Copyright 2020.

Figure 3. EDA R&D's Growing Share of Overall Semiconductor R&D Expenditure, 2014–2018

captured two-thirds of the EDA market broadly defined over time.[14] Since all three firms are based in America (Germany's Siemens acquired Mentor in 2017) and their EDA technology is overwhelmingly of American origin, these firms' EDA tools fall firmly under the Entity List export controls.

In the specific case of concern to us, Huawei will be cut off from legal use of the EDA tools of the three major EDA tool vendors once its current contracts with each vendor expire.[15] Without access to the EDA tools of the Big Three, Huawei will not be able to design chips effectively for the immediate future.

In the next subsection, this paper will demonstrate that China's homegrown EDA efforts are very unlikely to fill the gap left by export controls on the Big Three even over the medium term of five years.

EDA in China

The Chinese government has been very active in promoting the IC industry going back to the 7th Five-Year Plan (FYP) (1986–1990). China's early leading firm in design, state-owned Huada, was founded in 1986. The IC-related industrial policies during the 8th and 9th FYPs included trying to strengthen China's IC design and EDA tool technologies. As part of the 908 Project during the 8th FYP, Huada received older, foreign CAD technology (the forerunner of EDA technology) with the help of ex-Berkeley professor Ed Lien (Lian Yongnian). During the 9th FYP's 909 Project, 100 million RMB was distributed among seven design firms/centers, including Huada, and some of these firms eventually came under Huada's control.

[14] Ader et al., "Assuming Coverage of EDA." American EDA firms plus America-based Mentor Graphics accounted for approximately 73 percent of market revenue in 2018. This calculation is based on Boston Consulting Group's report of US EDA vendors being 60 percent of total revenue (Varas and Varadarajan, "Restricting Trade with China") added to Ader et al.'s calculation of Mentor representing 13 percent of total revenue (Ader et al., "Assuming Coverage of EDA").

[15] Although EDA contracts are often for three years, I was told by an industry source that Huawei's contracts are one-year contracts and that EDA companies' applications to the Department of Commerce for export licenses had all been rejected (interview, December 2019). Zhang, Tan, and Qu ("How Does Huawei?") also reported that the contracts are annual. However, two other design contacts said the length of contracts varies in China depending on the vendor (interviews, April 2020).

Further policies to support IC design and fabrication were pushed from 2000 to 2013, including a number of tax breaks for industry activities[16] and a number of state procurement projects for chips, such as a "Golden Card Project" to purchase IC cards. Huada was a major beneficiary of these procurement projects. It nonetheless proved unable to expand into commercial markets.

Industry interview subjects are skeptical of the ability of China's EDA firms, including Huada Empyrean, to compete with the established giants.

The IC Mega-Project started in 2014 and directed some funds toward EDA development but has not spurred much progress thus far.[17] State-dependent Guowei, in Shenzhen, has received 400 million RMB in national and local government funding to develop EDA tools. More promising, Huada's main subsidiary, Empyrean, has received hundreds of millions of RMB in state-backed venture funding,[18] some of which came from the IC Mega-Project's Big Fund.[19] Huada Empyrean has indeed enjoyed some success: it offers sets of tools covering the complete design flow for analog chips as well as EDA tools for LCD driver chips.[20] No other Chinese EDA companies can offer tools covering complete design flows.[21] Industry interview subjects are skeptical of the ability of China's EDA firms, including Huada Empyrean, to compete with the established giants, sentiments echoed by Professor Liu Leibo of Tsinghua at a recent industry forum.[22] The total market for local EDA tools in 2019 was only 77 million USD, representing 10 percent of total EDA sales in China.[23]

China's EDA development is not limited by just the difficulty of matching the product scope the Big Three EDA providers have created over the past few decades. The Big Three's close links with leading foundries provide them an inside track on keeping up with changes on the manufacturing side and thus allow them to keep their software up to date with the latest process technology ahead of would-be rivals. New Chinese competitors have access only once the new process is developed, and their access will not be as wide as it is for the Big Three.

To make matters worse for would-be Chinese challengers, the Chinese marketplace is shifting away from their strengths. China's fabless design industry is consolidating into large firms, resulting in more of the EDA tool market being in the hands of firms that can afford the relatively expensive offerings of the Big Three. Furthermore, the design revenues are shifting to digital design areas and away from the relative strength Chinese EDA firms have in analog design.[24]

Piracy is still an issue for these smaller vendors that are reliant on their home market. Part of this is due to the incomplete protections for IP in China, but the larger issue is that some of these smaller vendors allow their products to be downloaded

[16] Under the State Council Circular No. 18 and No. 4 in 2000 and 2011, respectively.

[17] Some argue that the IC Mega-Project neglected the EDA industry until ZTE was placed on the Entity List in 2016. ZTE was removed from the Entity List in 2018.

[18] Stewart, "Why Chinese EDA Tools Lag Behind."

[19] "Domestic EDA Industry's Development [in Chinese]," IC Smart. Only approximately 25 million RMB was received by Huada from the Big Fund in its first tranche (2014–2018), which is often referred to as Big Fund I (Ramani and Arcuri, "China EDA Deep Dive").

[20] These are the chips used in flat-panel/liquid-crystal displays. Stewart, "Why Chinese EDA Tools Lag Behind."

[21] For example, the other firms often mentioned as promising EDA tool vendors have quite narrow foci: Avatar (physical implementation tools), Xpeedic (signal integrity, packaging, and RF solutions), and Pro-Plus (simulation and yield enhancement).

[22] Ye, "How to Solve."

[23] Ramani and Arcuri, "China EDA Deep Dive."

[24] Ramani and Arcuri, "China EDA Deep Dive."

rather than accessed by license keys. This type of access provides easy opportunities for the software to be copied illegally. Presumably, because these smaller firms are desperate for sales, they are more willing to provide more convenient access to their software than the Big Three, which employ the more-protective license key model.

From the EDA companies' perspective, Huawei's continued use of their tools without paying is preferable to Huawei trying to develop alternative EDA tool vendors on the off chance that these alternative EDA vendors emerge as peer competitors.

Additionally, the best software application engineers in China do not want to work in obscure EDA when they can make much more money working for Tencent, Alibaba, and other internet firms. Consequently, only three hundred or so EDA tool development engineers are employed by local Chinese EDA vendors compared with more than five thousand such engineers worldwide at Synopsys.[25] A potential advantage for China's EDA industry is the fact that foreign EDA tool vendors employ at least fifteen hundred engineers in China.[26] Offsetting that potential advantage is the fact that the global EDA engineering workforce is approximately forty-five thousand, so China's total EDA workforce still represents a relatively small portion of the global total.[27] In the short term, being cut off from American-origin EDA tools would be a highly problematic for Huawei. Even in the medium term of years rather than months, it is unlikely that local firms could fill the gap.

Huawei and the EDA Vendors' Response

If the controls are fully implemented and no licenses are granted for selling EDA tools to Huawei, Huawei will not have legal access to the Big Three's EDA tools. There are no Chinese or other foreign vendors that can fill the gap sufficiently to allow Huawei's HiSilicon to continue to design chips legally. Because the vast majority of the Big Three's EDA tools today are accessed via license keys that provide online access to the EDA software, the preferred method for gaining illegal access to the Big Three's EDA tools is to hack the license keys.[28] With the right technical support, hacking these licenses is feasible as attested to by interview subjects and past cases, such as InnoGrit's hacking of Synopsys's license keys.[29] If forced into a corner with no choice, Huawei could choose to hack license keys for Big Three's tools.

Would the EDA vendors try to seek legal remedies? It would be difficult to do so in China given the ill will that full implementation of the export controls would generate there. From the EDA companies' perspective, Huawei's continued use of their tools without paying is preferable to Huawei trying to develop alternative EDA tool vendors on the off chance that these alternative EDA vendors emerge as peer competitors (as unlikely as that would be). Turning a blind eye to the hacking in hopes of a loosening of the controls in the future might very well be the smartest move for the Big Three vendors.

I believe, however, that Huawei probably will not have to choose the blunt instrument of hacking

[25] Stewart, "Why Chinese EDA Tools Lag Behind."

[26] Stewart, "Why Chinese EDA Tools Lag Behind."

[27] Ramani and Arcuri, "China EDA Deep Dive."

[28] EDA tool vendors are often plagued by illegal overuse of EDA tools, e.g., a contract that specifies access for one user for one server, but the tool vendor discovers that the server is utilizing the tool 24-7. However, in the context of being completely cut off from legal access to the EDA tools, this form of IP theft is irrelevant.

[29] See details of Synopsys's case against InnoGrit at https://www.docketbird.com/court-documents/Synopsys-Inc-v-InnoGrit-Corp/Order-by-Judge-Lucy-H-Koh-Denying-52-Motion-to-Dismiss-lhklc3S-COURT-STAFF/cand-5:2019-cv-02082-00066.

license keys. The interim final rules announced on May 15 require knowledge that one is working with a designated Entity List firm. The final rule issued on August 17 offers an either–or clause, where either knowledge on the part of the provider of the good or service (e.g., EDA software) to Huawei is required, or Huawei and its affiliates "touching" the product (e.g., EDA software) somewhere along the supply chain[30] is sufficient to make the product controlled. However, to be legally liable, a firm still has to have knowledge that it supplied Huawei or dealt with a Huawei-touched supply chain.[31] These requirements have already encouraged creative circumvention. On July 13, 2020, a well-placed representative for small foreign EDA tool vendor had already told me that at least one Entity List company had set up a shell company with no apparent links to the Entity List–designated firm to serve as a legal front for EDA licenses.

Other tactics may emerge if the major EDA vendors do not passively accept these onerous regulations. Some have speculated that Synopsys's new joint venture with AMEDAC (全芯智造), formed in September 2019, is designed as a vehicle to add plausible deniability to any charges of dealing with Huawei and its Entity List–designated affiliates. Speculating as to how this exchange might work, AMEDAC could provide tools to a Huawei front company. By adding two intermediaries between Synopsys and Huawei, Synopsys could claim to not know what AMEDAC was doing, and AMEDAC could deny any knowledge of supplying Huawei. There are rumors that another of the Big Three has set up a partnership that looks suspiciously like a vehicle for circumvention. With the broader controls incorporated into the August 17 final rule, these joint venture gambits might not provide enough legal cover to be worth the risk, however.

Capital Equipment for Fabrication

The capital equipment necessary to fabricate chips is one of the most technology-intensive segments of the IC value chain and a focus of US government efforts to constrain Chinese capabilities.[32] Our discussion parallels US government focus by ignoring the upstream equipment for making the raw silicon wafers and the downstream equipment for the assembly and testing processes.

America's predominance in this industry, even outside lithography, has been neither continuous nor dependent on America's own share of fabrication capacity.

Fabrication production requires a number of processes. In approximate order, the production process requires cleaning a wafer, depositing thin film on the wafer (deposition), treating the wafer with other processes (e.g., ion implantation), applying photoresist liquid to the wafer (coating), employing lithography (this involves baking photoresist and shining light through patterned glass called mask/photomask to create circuit patterns), etching (removing unwanted nonhardened materials), deposition (applying films of various materials on wafer via chemical vapor deposition [CVD] and physical vapor deposition [PVD]), chemical mechanical polishing (CMP), oxidation, implantation (introducing dopant impurities into the semiconductor), diffusion, and cleaning between each of these processes. Repeated rounds

[30] Huawei just has to be a purchaser, end user, intermediate consignee, or ultimate consignee. In other words, Huawei just has to somehow be involved in the relevant product's supply chain.

[31] This point was confirmed by a legal expert on the Entity List via email on September 14, 2020.

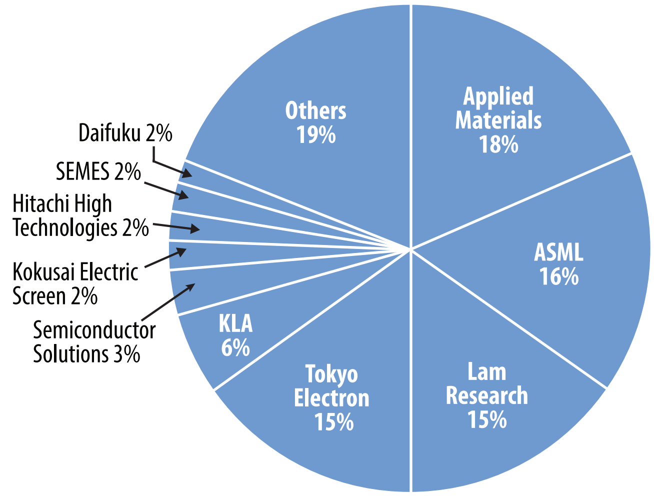
[32] The US regulations include testing equipment (see https://www.govinfo.gov/content/pkg/FR-2020-05-19/pdf/2020-10856.pdf), but this equipment is not as critical to American capital equipment industry nor the effort to block Huawei, so I focus on front-end fabrication equipment in this paper.

of photolithography and other processes are needed to complete the layers of circuitry on the IC. Inspection and process control equipment play important roles in fabrication as well. Different types of equipment are needed for each production process. Today, typically one supplier is dominant (more than 50 percent of the market share) for each type of equipment.

American Firms in the Semiconductor Capital Equipment Industry

Today, American firms represent 52 percent of global revenue in IC capital equipment compared to Japan's 27 percent and Europe's 17 percent. In the narrower relevant category of wafer fab equipment, three of the five largest firms, comprising 71 percent of 2018 revenue, are American: Applied Materials, Lam Research, and KLA (see Figure 4). Applied Materials is the largest firm with 18 percent of revenue. Nevertheless, going forward, ASML of the Netherlands is likely to be the largest firm because it monopolizes high-end lithography, extreme ultraviolet (EUV lithography), and dominates lithography generally.[33] America withdrew from the lithography market in 2001 when ASML acquired SVG, the last American lithography equipment producer.

America's predominance in this industry, even outside lithography, has been neither continuous nor dependent on America's own share of fabrication capacity. In the 1980s, Japanese firms looked poised to wipe out the American capital equipment makers along with much of the rest of the American industry. Between 1983 and 1990, America's share of global IC capital equipment revenue declined from 66 percent to 44 as Japanese suppliers pulled ahead. Sematech was in no small part what rescued the American industry, including American lithography production, from oblivion by organizing vertical and horizontal cooperation



Reproduced from Ramel and O'Connor, "Entering the EUV Era" and used with permission from Exane BNP Paribas.

Figure 4. Top Global Wafer Fab Equipment Providers, 2018

among the American industrial participants and conducting a number of successful projects to improve product and process technologies.[34] In the wake of this successful public–private partnership to revive American industry, the one major error was, arguably, the approval of the sale of the last American photolithography maker, Silicon Valley Group Lithography (SVGL), to ASML in 2000. At the time, SVGL was ahead of ASML in EUV lithography research.[35]

Today, the most prominent American firms have large market shares across a number of categories of IC capital equipment (see Table 1). American firms as of 2018 monopolized production of four product areas: optical mask-making lithography (not IC lithography), bevel edge removal (dry), gate stack tools, and ultra-high-dose doping equipment. In other areas, such as etch, metrology, and inspection, American firms maintain a monopolistic position in certain high-end products. This sounds like a very dominant position, but interviewees believe that these monopolies are not secure ones. Japanese firms and others can make

33 Ramel and O'Connor, "Entering the EUV Era."

34 Browning and Shetler, *Sematech*.

35 Robertson, "ASML's SVG Purchase."

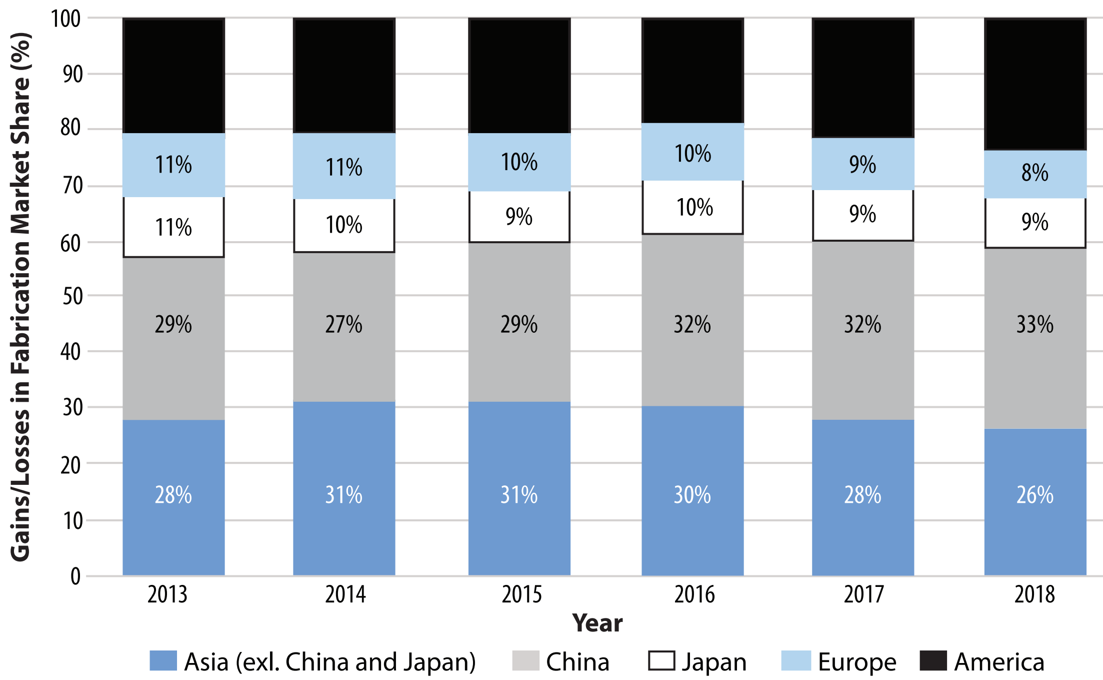
Table 1. 2018 Percentage American Share in Wafer Fab Equipment

Product lines where US has >70% market share	Company								
	Applied Materials	Axcelis	KLA	Lam Research	Mattson	Nano-metrics	Rudolph	Veeco	Total
Optical Mask-Making Lithography	100.0								100
Epitaxy	74.2								74
Plasma CVD	52.1			35.5					88
Sputtering	74.4								74
Electrochemical Deposition	16.1			76.5					93
Other Disposition								70.2	70
Molecular Beam Epitaxy								70.2	70
Bevel Edge Removal (Dry)				100.0					100
Conductor Etch	32.7			53.2					86
CMP and Post-CMP Clean	70.3								70
Rapid Thermal Processing	76.1				11.2			7.9	95
Gate Stack Tools	100.0								100
Doping Equipment	68.2	17.8							86
Medium-Current Implanter	67.9	2.8							71
High-Current Implanter	86.2	9.8							96
High-Energy Implanter	10.4	66.9							77
Ultra-High-Dose Doping Equipment	100.0								100
Process Control	11.5		51.1			4.2	3.3	0.3	70
Thin-Film Metrology			40.6			24.3	4.9	1.5	71
Optical Metrology			46.4			29.2	1.1		77
Wafer Inspection and Defect Review	15.2		63.3				4.2		83
Macro Defect Inspection			68.5				16.5		85
Unpatterned Wafer Inspection			96.3						96
Patterned Wafer Inspection	15.8		68.2						84
Optical Patterned Wafer Inspection	6.0		87.5						94
Scanning Electron Microscope Defect Review and Classification	59.9		11.0						71
Process Control Software			58.5				16.0		75

Reproduced from Ramel and O'Connor, "Entering the EUV Era," and used with permission from Exane BNP Paribas.

every one of these pieces of equipment if given some time, and one type of equipment, bevel edge removal tools, is an optional tool in fabrication rather than a necessary one (interviews, April and May 2020).

To give an example of how latent or trailing competitors can come back, we can look at the experience of American companies. In 2010, Applied Materials lagged far behind in conductor etch products. By devoting R&D resources and



Reproduced from Teng et al., "China SPE Sector," and used with permission.

Figure 5. Semiconductor Market Demand Shares

working closely with key customers, Applied Materials was, within five years, again able to become an industry leader in selling equipment for advanced process nodes. Huawei does not have five years to wait if cut off from American equipment-laden fabs, but industry insiders think the Japanese firms only need two years to fill the gaps left by eschewing American equipment. And this assumes market-based competition. If concerned countries are willing to throw money at inducing this transition, the catch-up of foreign capital equipment could be even faster.

What Tokyo Electron did in the wake of the United States placing Fujian Jinhua on the Entity List illustrates the capabilities of competitors of American firms. As American capital equipment makers pulled out of Fujian Jinhua, Tokyo Electron made a big show of staying put in Fujian Jinhua's fab, meaningless though this show of support was given that there were few other tools available to see fabrication through to the end. Building on this publicity stunt, Tokyo Electron went around to other fabs in China saying that American equipment could not be trusted because it carried political risk. For Tokyo Electron's American competitors, the problem with this sales pitch is that it is the best kind—the truth. Consequently, American equipment vendors have claimed that they lost sales to Japanese vendors in the wake of Fujian Jinhua (interview, July 2019). To be clear, these sales were in products where Tokyo Electron already had competing products, but it is a large and capable firm with many such products.

These policy-driven headwinds working against American competitiveness should be of great concern because China already was and will continue to be a large market for IC capital equipment. Even appropriately conservative estimates of China's market size, which sensibly do not count reexported imports of foreign assemblers, place China's market as being approximately the same size as the United States'.[36] It is estimated that

[36] Varas and Varadarajan ("Restricting Trade with China") calculate the Chinese market demand as 23 percent of global

China's share of global fab capacity will increase by 13.4 percent of total global fab capacity from 2007 to 2021, while the American share will shrink by over 5.6 percent of total global fab capacity (see Figure 5 in Khan and Flynn[37]). By the end of 2018, China's installed capacity was just behind America's at 12 and 13 percent of the global total, respectively.[38] America's share of global installed fab capacity had already shrunk from 20 percent in 2000 to 12.8 percent in 2013.[39]

Taiwan and Korea represent almost half of global capacity (22 and 21 percent of total global capacity, respectively). American capital equipment firms have been lucky because these nations, which have invested the most in fabrication capacity over the past several decades, do not have their own large domestic capital equipment producers. Taiwanese producers in particular have been known to favor American equipment because the original generation of fab managers at firms such as TSMC (Taiwan Semiconductor Manufacturing Company) all returned from working in fabs in the United States. Unfortunately, changing the Department of Commerce's Foreign Direct Product Rule in order to block TSMC and others from using American equipment to fabricate for Huawei could go a long way to harm, perhaps irreparably, this accumulated advantage.

In addition to interviews that form the basis of the above analysis, there has been a private industry study, which must remain anonymous, that has emphasized a somewhat slower replacement rate. By this estimate, a de-Americanized fab would take four to six years to build. The major hurdles for replacing American equipment are high-end inspection, process control, and etching equipment, so this study suggested that rather than replacing American firms, the faster approach would be to replace American content. All the major American vendors have some production overseas, principally in Southeast Asia, and the idea would be to reorganize production of these American multinational corporations to remove American content. Such a move would result in the capital equipment vendors remaining compliant with the Entity List while still being able to provide equipment legally to foundries serving Entity List–designated firms. Executives from KLA, the leading supplier of metrology, inspection, and process control tools, admitted to considering using the firm's manufacturing sites outside of the United States to maintain business as usual.[40]

The August 17 rule makes clear that the Trump administration will interpret American content broadly, so de-Americanizing overseas production would perhaps be even more difficult than envisioned under the May 15 interim rules.

Having been briefed on this private group's report but not privy to the detailed contents of the report, I would like to add a note of caution before accepting the report's pessimistic conclusions for non-American capital equipment vendors. The report seems to approach de-Americanization with the historically reasonable assumption that firms are still generally on a commercial footing even with government subsidies playing a role as they always do in fabrication. With Sino–American technological rivalry heating up, this assumption may not hold any longer. When pressed into a corner, China might provide such large subsidies that less inefficient and thus more costly alternative equipment might become a viable alternative. The

demand in 2018, which is close to the share for US demand according to Nomura (Figure 5).

37 Khan and Flynn, *Maintaining China's Dependence*.

38 VerWey, "Chinese Semiconductor Industrial Policy."

39 Houseman, Bartik, and Sturgeon, "Measuring Manufacturing."

40 "KLA Corporation (KLAC) CEO Rick Wallace on Q1 2020 Results - Earnings Call Transcript."

countries providing such equipment might also try to seize the opportunity by providing their own subsidies as well.

How long would it take TSMC or another fab, such as Samsung's foundry services, to create a fab line that designed out American equipment in order to serve Huawei? Assuming the foundry would not build a whole new fab building on a greenfield site,[41] the amount of time needed to move in new equipment and get the new fab line up and running is one year to fifteen months.[42] Of course, for any equipment for which an immediate off-the-shelf replacement from a non-American company is not yet available, the time to develop the equipment would have to be added to the fifteen months needed to move in and ramp up production. Thus, the minimum amount of time would be more than three years. This delay would be a stumbling block for Huawei because Huawei is very unlikely to have existing chip inventories that can last so long.[43] The same policy leaves American capital equipment firms with either the stain of political risk in the eyes of their most loyal customers for many years to come and/or incentives to accelerate offshoring production of what is the final bastion of American-made machine tool excellence. As with EDA tools, the trade-off appears to be a poor one.

[41] There are a lot of fab shells (fab facilities without any equipment) sitting empty in East Asia, so it is a fair assumption that the foundry undertaking this project would not have to build a greenfield fab.

[42] This estimate assumes six months for equipment move-in and six to nine months for testing and pilot production (or approximately twelve months to go from equipment installation to ten thousand wafers per month), which is moving at the rapid foundry-in-Asia speed. Former and current fab managers and/or top executives at the following foundries provided these estimates: Huahong (China), SilTerra (Malaysia), SMIC (China), and TSMC (Taiwan). TSMC's Nanjing fab was able to move in equipment in under six months.

[43] For some chips, Huawei may have built chip inventories that can last eighteen months or more.

The August 17 rule makes clear that the Trump administration will interpret American content broadly,[44] so de-Americanizing overseas production would perhaps be even more difficult than envisioned under the May 15 interim rules. Moreover, the new regulations explicitly prohibit interaction with Huawei supply chains without a license (see footnote 30), so TSMC and Samsung, the most advanced foundries, are much less likely to go to the trouble of de-Americanizing their supply chains if these regulations effectively prohibiting interaction with Huawei look likely to remain in force. Mainland Chinese foundries backed by the state, in contrast, would still be eager to pursue Huawei's business and de-Americanization of the supply chain. Thus, the trade-off for the United States looks even worse when one considers the signals this move would send to Chinese policymakers and fabrication firms, the latter of which have used plenty of American equipment in their fabs. I will now turn to this issue.

IC Capital Equipment Makers in China

For the last three decades, China has very actively encouraged fabrication production through a variety of industrial policies, from the 908 Project in 1991 through the second installment of the Big Fund[45] in 2019.[46] For the last two decades, these policies have succeeded in increasing China's share of global fabrication capacity from less than 1 percent of total fabrication in 2000 to 12 percent[47] in 2018, even if much of that capacity remains foreign-owned. In 2019, China's semiconductor capital equipment spending reached 18 billion

[44] Covington, "Commerce Department Further Restricts Huawei Access."

[45] The Big Fund was the large national investment fund started as part of the 2014 National IC Mega-Project.

[46] See Fuller, "Growth, Upgrading and Limited Catch-up," for an overview.

[47] Houseman, Bartik, and Sturgeon, "Measuring Manufacturing"; and VerWey, "Chinese Semiconductor Industrial Policy."

USD, 20 percent of total global capital equipment expenditure.[48]

While these industrial policies have often paid lip service to building a capital equipment sector, the concentration of resources has been primarily on fabrication and, secondarily, design, with the capital equipment sector given relatively little policy support. This policy sequencing actually makes eminent sense because a new industry often tries to serve its domestic market first before selling overseas. Even established multinational firms often suffer from what international business scholars call the liability of foreignness. Thus, China has chosen to foster first domestic fabrication capacity, which in turn can serve as the initial market for China's emerging domestic capital equipment vendors.

There are early signs that the relative neglect of the capital equipment industry by industrial policy-makers is changing. Under the first installment of the Big Fund, semiconductor material and capital equipment firms received only 4.2 percent of the total installment. Furthermore, these funds were spread among fourteen firms: seven materials firms and seven equipment makers. However, under the second tranche of the Big Fund, the government aims to channel more funds to materials and capital equipment firms and target the development of what was deemed the most "core" equipment, CMP and lithography.[49] The government also intends to push harder for firms to verify and purchase more local equipment.[50]

Currently, Chinese producers are producing "noncritical" equipment for fabs. In other words, they are not competing with the likes of Applied Materials in CMP and deposition equipment, nor with LAM in etching (interviews, July 2019). They have been able to sell more equipment outside of IC fabrication for solar panel, IC A&T, and flat-panel display manufacturing. Estimates place domestic producers as accounting for only 5 to 10 percent of the total semiconductor equipment expenditure in China in 2018.[51]

Most of the domestic producers only produce one or two types of semiconductor equipment (see Table 2). Only NAURA and AMEC make a substantial range of equipment. The three firms that American competitors and equity analysts alike have identified as most promising are not surprisingly NAURA, AMEC, and the Chinese–American hybrid firm (its headquarters is still in the United States) ACM.

NAURA emerged via the mergers of a number of state-owned semiconductor capital equipment firms as well as the acquisition of an American wafer cleaning equipment firm, Akrion. Its controlling shareholder is the Beijing municipal government. In 2018, the firm reported less than 300 million USD from sales of semiconductor equipment. In comparison, Applied Materials had over 17 billion USD in revenue in 2018. China's largest capital equipment maker is still a minnow in this sector.

AMEC was founded by returnees who left Applied Materials and other firms. Now this firm's dominant shareholder is the Shanghai municipal government. The firm's main business is selling deposition equipment for the production of LEDs, not IC fabrication. In LED equipment, it is the third largest supplier given its price-competitive products in China, which is the largest producer of LEDs. However, the market is only 500 million

48 Teng et al., "China SPE Sector."

49 The Chinese government has a secretive EUV lithography project, but Chinese lithography wannabes, such as SMEE, are even further behind leading international firms in lithography than Chinese capital equipment vendors are in other areas. However, many foreign suppliers of EUV lithography subsystems have been under intense cyberattacks in recent years, with China being the suspected culprit.

50 Li and He, "The Big Fund Second Tranche." Before the second tranche of the Big Fund, there were already reports of the Chinese government using these funds to push fabs to buy local capital equipment (interview, July 2019).

51 Teng et al., "China SPE Sector."

Table 2. Chinese Semiconductor Capital Equipment Producers

	NAURA	SMEE	Kingsemi	AMEC	CETC	Kingstone	Piotech	SKY	HWATSING	ACM	PNC	Changchuan Tech.	AccoTest	RSIC	Jingce Electronic
Oxidation/Diffusion Furnace	✓														
Lithography		✓													
Coater			✓												
Etcher															
Si Etcher	✓			✓											
Metal Etcher	✓			✓											
Plasma Etcher	✓			✓											
Ion Implanter					✓	✓									
Film Disposition															
PVD	✓							✓							
CVD	✓						✓	✓							
Metal Organic Chemical Vapor Deposition				✓											
Atomic Layer Deposition	✓						✓								
CMP									✓						
Cleaning Equipment	✓		✓							✓	✓				
Test Equipment												✓	✓	✓	✓
Listing Status	A-share	Unlisted	A-share	A-share	Unlisted	A-share	Unlisted	NEEQ	Unlisted	NASDAQ	A-share	A-share	Unlisted	Unlisted	A-share

Reproduced from Teng et al., "China SPE Sector," and used with permission.

USD in sales.[52] In the etching market, AMEC has 1 percent market share or 80 million USD in revenue as of 2018.

ACM was founded in the United States by David Wang in 1998. In 2006, he returned to China to set up a subsidiary, ACM Research. The firm focuses on cleaning tools and wafer-level packaging for A&T. Wang was the largest shareholder until new investments reduced his holdings from 25 percent to a little over 2 percent. The dominant shareholders are investment vehicles of the Shanghai government. Ostensibly, this move was done in preparation for listing the firm on Shanghai's answer to NASDAQ, the STAR board, but it is a sign of the state encroaching on all the promising private firms in this strategic industry. ACM has 2 percent of the global cleaning market to NAURA's 1 percent, but this firm generates the smallest sales revenues of these three promising Chinese firms at just under 100 million USD in 2018.

While these firms may one day be competitive in the critical equipment in IC fabrication, that day is clearly a long way off. If TSMC or other foundries

52 The two largest producers, Germany's Aixtron and America's Veeco, have respectively left and been hammered in the LED equipment business. The margins in this China-centered business are simply too low. Even AMEC, the homegrown champion, had to allow its margins to suffer to take market share (Teng et al., "China SPE Sector").

are cut off from US capital equipment, turning to the Chinese producers to fill the gap will not be an option.

Huawei and Other Actors' Responses to the Capital Equipment Controls

If the controls continue with maximum stringency (i.e., with no licenses to export granted) and Huawei manages to maintain access to EDA tools, the firm still faces the problem of locating a fab to manufacture the chips legally. In the short term, no fab can offer advanced process nodes without using American equipment. If an existing fab chose to continue using its American equipment illegally to fabricate chips for Huawei, it would most likely find that its American capital equipment could no longer be serviced by the capital equipment vendors. This problem would bring the whole production process to a halt or, at the very least, make it much less efficient. A Chinese fab might, at the behest of the government, try to do this, but these fabs do not have the most advanced nodes (below fourteen nanometers in mass production). Huawei's most advanced chips could not utilize these fabs.

Stringent implementation of the Entity List export controls would provide incentives for American firms to move some production offshore to avoid the export controls.

Given Huawei's over 10 billion USD in orders from TSMC in 2019 alone, it is not difficult to imagine that foundries would be eager to fulfill Huawei's chip orders despite the difficulties presented by American export controls. The two most likely candidates given their proven foundry businesses in advanced process nodes are TSMC and Samsung, which also happen to be industrial and political heavyweights in their respective countries. Unlike Chinese foundries, such as SMIC, there is no doubt that these two firms will continue to have access to advanced EUV lithography from ASML in the Netherlands.

If offering chip manufacturing services to Huawei were simply a commercial transaction, it probably would not be worth the expense of engaging a wide range of equipment vendors to de-Americanize fab lines in the eyes of the foundries or perhaps the non-American equipment vendors themselves. The advent of these export controls has threatened to usher in a new era where the US war against Huawei elicits a commensurate response in increased financial support for Huawei from the Chinese government. With a gush of Chinese subsidies to keep Huawei's chip capabilities alive, Huawei would be in position to offer prices for manufacturing services that could make de-Americanizing some production lines worthwhile for TSMC and Samsung. Similarly, because these two companies are national champions in their respective countries, some government support to retain (in the case of TSMC) or attract (in the case of Samsung) Huawei as a customer would most likely be forthcoming. Finally, the largest semiconductor capital equipment-producing country after the United States, Japan, might well be induced to provide some policy support for this opportunity to regain competitive advantage in this sector. For these reasons, de-Americanization of advanced fab equipment might occur relatively quickly (closer to two years than to six years). Counterbalancing these proactive state-backed measures to de-Americanize fabrication, the reinforced rules of August 17 heighten the legal liability of interacting with Huawei in any capacity without a license and thereby add serious additional risks to any such de-Americanization endeavors.

Equally or perhaps even more disastrous would be the potential response of American equipment manufacturers to offshore production.

Semiconductor manufacturing equipment is the last bastion of American-made machine tools. Unfortunately, stringent implementation of the Entity List export controls would provide incentives for American firms to move some production offshore to avoid the export controls. The risks associated with the legal liability of potentially interacting with Huawei might or might not offset these pressures to offshore.

Strategies Going Forward

American EDA and capital equipment firms play critical roles in providing technology-intensive inputs to the global semiconductor industry. Given the overwhelming dominance of American EDA technology and segments of market dominance in the IC fabrication equipment sector, one can understand the temptation on the part of some US government officials to try to weaponize this value chain in pursuit of national security. Unfortunately, these attempts to weaponize the value chain will probably blow up in our face.

If the aim is to deter Huawei from stealing American technology, cutting off Huawei from American suppliers will most likely have the opposite effect. The true aim for those pushing the expanding Entity List agenda is the misplaced goal of enhancing national security through destroying Huawei's telecommunications infrastructure business. The gains in doing so appear minimal.

The efforts against Huawei provide an illuminating test case. One may question whether Huawei is even a worthy target. If the aim is to deter Huawei from stealing American technology, cutting off Huawei from American suppliers will most likely have the opposite effect. The true aim for those pushing the expanding Entity List agenda is the misplaced goal of enhancing national security through destroying Huawei's telecommunications infrastructure business. The gains in doing so appear minimal. Without these measures, the United States is already effectively keeping Huawei out of the US market, so government policy has already effectively addressed any concerns about Huawei compromising the security of our domestic telecommunications network. If the concern is that American forces overseas will have to operate using "dirty" networks or that our allies' networks will be compromised, keeping Huawei equipment out of such networks buys little security. Telecommunication security experts have told me there are six to ten countries that can hack any network, and a number of those countries capable of doing so are far from being US allies (e.g., China, Russia, and North Korea; interviews, April 2020).[53]

Even if a stringent version of the controls is implemented and a coalition of firms to de-Americanize the fabrication supply chain does not emerge, the national security hawks will fail in their aim to destroy Huawei's telecommunications infrastructure business. Huawei's HiSilicon chip division would die in this scenario, but Huawei would simply revert to its business model of ten years ago. At that time, Huawei's in-house chip design capabilities were inchoate, but it already was the third largest infrastructure firm after Ericsson and Nokia.[54] Even the chips and, more importantly, optical components Huawei needs from American suppliers are readily available because these firms are manufacturing them offshore. In some cases, they are even manufacturing them in China.

53 See also the following report that suggests a wide range of network vulnerabilities that a wide range of actors can potentially exploit via undersea cables: NATO Cooperative Cyber Defense Centre of Excellence, "Undersea Cables."

54 Fuller, *Paper Tigers, Hidden Dragons*.

While the rules now prohibit chip suppliers from designing for or selling directly to Huawei, there is as yet no clear explanation of how the US government is going to effectively regulate offshore supply chains using intermediaries. In this light, the US government would be well advised to remove Huawei from the Entity List. Failing that, it would be advisable to issue licenses to the EDA and capital equipment vendors and the customers of those products, for example, TSMC.

Strategic and Selective Decoupling?

Some argue that the leverage that EDA tools and capital equipment provide the United States over China should be used to maintain a technology gap between the two countries. They argue that the United States should even decouple China from access to technology that lags more than several generations behind the most advanced process nodes and the critical EDA tools that interface with the foundries. This could possibly work in the short term but would be a strategic error for several reasons. First, the commercial costs would be squarely on American shoulders, especially given America's near monopoly on EDA. Second, the diplomatic costs would be very high and not just with China's government. What would be the justification for cutting off Alibaba, Baidu, Montage, and many other Chinese firms that design or aspire to design cutting-edge chips, often for perfectly innocent commercial reasons? Third, the United States would undermine the very infrastructural power it has in this industry over the medium term or even sooner. We do not know how quickly one of the big EDA vendors could be displaced by new entrants because the United States has not put other countries with economic clout in the position of being forced to seek alternatives. This policy would encourage others, not just China, to consider alternatives. Furthermore, this policy would force foundries to question priority of positioning (i.e., which EDA vendors have priority when working on new process nodes). EDA vendors derive a lot of their expertise at the design–foundry interface from their favored position as the firms working with the foundries early on for each new node. If the foundries face enough uncertainty, they may include a new close partner or two to hedge their bets, leading over time to eroding positional power on the part of the EDA tool vendors.

If the United States is determined to try to keep the latest process nodes out of fabs in China, the smarter approach would be a multilateral one focusing solely on capital equipment. A multilateral approach would diffuse the commercial and diplomatic costs. The history of post-CoCoM export controls, which ceased in 1994, shows that America's allies generally have been much less strict in their implementation of the controls. To bring the Dutch fully on board with not selling the most advanced EUV lithography equipment to China-based fabs, the United States must demonstrate that there are equally enticing markets elsewhere. US policy should be to make one of those enticing markets the United States by encouraging investment in advanced fabs at home. However, the United States can also rely on the interests of the Taiwanese and Korean government in encouraging large investments in advanced fabs in their respective countries. Together, the weight of these markets might gain Dutch compliance. This strategy has the additional benefit of being less likely to alienate a large swath of the Chinese business class by cutting them off from world-class fabrication. Under this policy, they are able to avail themselves of TSMC or Samsung as much as any other firm.

Rebuilding American Competitiveness

Rather than expanding the Entity List's controls, the United States would be better advised to look to reinvigorate its domestic IC industry. Efforts could usefully include:

- Partial government subsidization of corporate training costs of design and fabrication engineers to improve prospects for retaining and growing the American workforce in the IC industry. This would go some ways toward upgrading America's labor force while increasing federal spending on chip R&D.

- Expanded federal R&D investments. Although these investments have resulted in sixteen-fold returns in terms of GDP growth,[55] the semiconductor industry spends twenty-five times the amount the federal government does on chip R&D.
- Reform the American visa system so the many thousands of talented engineers who wish to remain and work in the American IC industry are able to do so without unreasonable bureaucratic hurdles.[56]
- Most ambitiously, the US government should subsidize generous investment in advanced fabrication by American IDMs and foundries. Without such subsidization, it will be very hard to compete with Korea, Taiwan, and perhaps soon China. Encouragingly, Congress has developed two recent bills, the CHIPS for America Act and the American Foundries Act,[57] to address R&D, training, and fabrication investment. Despite the billions in proposed spending, the United States needs to invest even more beyond what these bills propose to remain competitive across critical semiconductor industry areas.

Beyond industry-level measures to boost competitiveness, it is critical to address the exorbitant burden of the dollar as the dominant international reserve currency. The US dollar is overvalued by approximately 35 percent[58] because America's deep and open capital markets encourage two-thirds of the world's excess savings to flow into the United States. This overvaluation in effect taxes exports, undermining American competitiveness.[59] Tellingly, GlobalFoundries' estimated cost disadvantage for manufacturing in the United States is 20 to 30 percent,[60] so ending dollar overvaluation alone could address this foundry competitive gap.

The bipartisan Baldwin–Hawley bill proposed in 2019 would address the excess capital inflows by levying a variable tax on capital inflows that could be adjusted to America's investment needs.[61] The bill also proposed authorizing the Federal Reserve to counter other countries' central banks from excessive dollar buying to devalue their currencies.

Resolving dollar overvaluation is critical for industrial policies because no matter how effective American policies to boost domestic capabilities become, the international competitiveness of those capabilities can be undermined by currency manipulation. In addition to continued concerns about China's currency interventions, the two non-US providers of advanced fabrication capacity, Taiwan and Korea, have been extremely aggressive in depreciating their currencies vis-à-vis the dollar over the last several decades.[62] Without addressing this root issue of competitiveness, the best laid plans for industrial resurgence in America will be for naught.

55 Jackson, "Semiconductors Are the Engine."

56 Hunt and Zwetsloot, "Chipmakers."

57 At the time of writing, provisions from these two bills were included in amendments to the National Defense Authorization Act and the HEALS Act.

58 Roach, "American Exceptionalism."

59 Pettis, "Washington Should Tax Capital Inflows"; and Tilford and Kundnani, "Dollar Hegemony."

60 Waters, "US Chip Industry Plots Route."

61 Pettis, "Washington Should Tax Capital Inflows"; and Tilford and Kundnani, "Dollar Hegemony."

62 Cline, "Fundamental Equilibrium Exchange Rates."

Bibliography

"国产EDA产业发展提速，华大九天获'大基金'投资" ["Domestic EDA Industry's Development Accelerates, Huada Empyrean Receives Investment from the 'Big Fund'"]. IC Smart, September 12, 2018. http://www.icsmart.cn/21664/.

Ader, Jackson E., Sterling Auty, Matthew Parron, and Sahil Sharma. "Assuming Coverage of EDA." Research report. J.P. Morgan, September 11, 2019.

Browning, Larry D., and Judy C. Shetler. *Sematech: Saving the US Semiconductor Industry*. College Station, TX: Texas A&M University Press, 2000.

Cline, William R. "Estimates of Fundamental Equilibrium Exchange Rates." Policy brief. Peterson Institute of International Economics, November 2017. https://www.piie.com/publications/policy-briefs/estimates-fundamental-equilibrium-exchange-rates-november-2017.

Covington. "Commerce Department Further Restricts Huawei Access to U.S. Technology Abroad and Expands Reach of Entity List." Covington alert, August 20, 2020. https://www.cov.com/en/news-and-insights/insights/2020/08/commerce-department-further-restricts-huawei-access-to-us-technology-abroad-and-expands-reach-of-entity-list.

Fuller, Douglas B. "Growth, Upgrading and Limited Catch-up in China's Semiconductor Industry." In *Policy, Regulation, and Innovation in China's Electricity and Telecom Industries*, edited by Loren Brandt and Thomas G. Rawski, 262–303. Cambridge: Cambridge University Press (2019).

———. *Paper Tigers, Hidden Dragons: Firms and the Political Economy of China's Technological Development*. Oxford: Oxford University Press (2016).

Fuller, Douglas B., Akintunde I. Akinwande, and Charles G. Sodini. "Global Reorganization of the IT Industry and the Rise of China." In *Technology Transfer between the US, China and Taiwan: Moving Knowledge*, edited by Douglas B. Fuller and Murray A. Rubinstein, 71–98. New York: Routledge, 2013.

———. "The Globalization of R&D's Implications for Technological Capabilities in MNC Home Countries: Semiconductor Design Offshoring to China and India." *Technological Forecasting and Social Change* 120 (2017): 14–23. https://www.sciencedirect.com/science/article/pii/S0040162517304080.

———. "Leading, Following or Cooked Goose? Innovation Successes and Failures in Taiwan's Electronics Industry." *Industry and Innovation* 10, no. 2 (2003): 179–196. https://www.tandfonline.com/doi/abs/10.1080/1366271032000096635.

Henkel, Joachim, Thomas Ronde, and Marcus Wagner. "And the Winner Is—Acquired! Entrepreneurship as a Contest Yielding Radical Innovations." *Research Policy* 44, no. 2 (2015): 295–310. https://www.sciencedirect.com/science/article/pii/S0048733314001607.

Houseman, Susan N., Timothy J. Bartik, and Timothy Sturgeon. "Measuring Manufacturing: How the Computer and Semiconductor Industries Affect the Numbers and Perceptions." In *Measuring Globalization: Better Trade Statistics for Better Policy - Volume 1. Biases to Price, Output, and Productivity Statistics from Trade*, edited by Susan N. Houseman and Michael Mandel, 151–194. Kalamazoo, MI: W.E. Upjohn Institute for Employment Research (2015). https://doi.org/10.17848/9780880994903.vol1ch5.

Hunt, Will, and Remco Zwetsloot. "The Chipmakers: U.S. Strengths and Priorities for the High-End Semiconductor Workforce." Center for Security and Emerging Technology, Georgetown University, 2020. https://cset.georgetown.edu/research/the-chipmakers-u-s-strengths-and-priorities-for-the-high-end-semiconductor-workforce/.

Hurtarte, Jorge S., Evert A. Wolsheimer, and Lisa M. Tafoya. *Understanding Fabless IC Technology*. Oxford: Newnes, 2007.

Jackson, Keith. "Semiconductors Are the Engine of the Global Economy—and America Isn't Making Enough of Them." *Fortune*, June 30, 2020. https://fortune.com/2020/06/30/america-tech-semiconductor-manufacturing-investment/.

Khan, Saif, and Carrick Flynn. *Maintaining China's Dependence on Democracies for Advanced Computer Chips*. Brookings Institution, April 2020. https://www.brookings.edu/wp-content/uploads/2020/04/FP_20200427_computer_chips_khan_flynn.pdf.

"KLA Corporation (KLAC) CEO Rick Wallace on Q1 2020 Results - Earnings Call Transcript." Seeking Alpha, May 5, 2020. https://seekingalpha.com/article/4343405-kla-corporation-klac-ceo-rick-wallace-on-q1-2020-results-earnings-call-transcript?part=single.

Krolikoski, Stan. "Evolution of EDA Standards Worldwide." *IEEE Design & Test of Computers* 28, no. 1 (2011): 72–75. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5708261.

Li, Na, and Leshu He. "大基金二期有望带动万亿元资金进场" ["The Big Fund Second Tranche Holds Promise to Spur One Trillion Yuan into the Industry"]. 第一财经日报 [*First Financial Daily*], March 23, 2020.

NATO Cooperative Cyber Defense Centre of Excellence. "Strategic Importance of, and Dependence on, Undersea Cables." NATO Cooperative Cyber Defense Centre of Excellence, November 2019. https://ccdcoe.org/uploads/2019/11/Undersea-cables-Final-NOV-2019.pdf.

Pettis, Michael. "Washington Should Tax Capital Inflows." Carnegie Endowment for International Peace, August 6, 2019. https://carnegieendowment.org/chinafinancialmarkets/79641.

Ramani, Pradeep, and Timothy Arcuri. "China EDA Deep Dive." UBS, July 15, 2020.

Ramel, Jerome, and David O'Connor. "Entering the EUV Era: Winners and Losers." Research report. BNP Paribas, April 8, 2020.

Roach, Stephen S. "From American Exceptionalism to European Exceptionalism." *Project Syndicate*, July 22, 2020. https://www.project-syndicate.org/commentary/european-rescue-fund-weakens-dollar-hegemony-by-stephen-s-roach-2020-07?barrier=accesspaylog.

Robertson, Jack. "ASML's SVG Purchase Will Boost Technology, Market Lead, Say Analysts." *EE Times*, October 3, 2000. https://www.eetimes.com/asmls-svg-purchase-will-boost-technology-market-lead-say-analysts/#.

Sangiovanni-Vencentelli, Alberto. "The Tides of EDA." *IEEE Design & Test of Computers* 20, no. 6 (2003): 59–75. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1246165.

Steves, Mitch. *2019 Electronic Design Automation (EDA) Report*. RBC Capital Markets, May 7, 2019.

Stewart, Randall. "Why Chinese EDA Tools Lag Behind." Technode, November 13, 2019. https://technode.com/2019/11/13/silicon-why-chinese-eda-tools-lag-behind/.

Teng, Donnie, Aaron Jeng, Bruno Cheng, and Tetsuya Wadaki. "China SPE Sector." Anchor Report. Nomura, January 13, 2020.

Tilford, Simon, and Hans Kundnani. "It's Time to Abandon Dollar Hegemony." *Foreign Affairs*, July 28, 2020. https://www.foreignaffairs.com/articles/americas/2020-07-28/it-time-abandon-dollar-hegemony.

Varas, Antonio, and Raj Varadarajan. "How Restricting Trade with China Could End US Semiconductor Leadership." Boston Consulting Group, March 9, 2020. https://www.bcg.com/en-us/publications/2020/restricting-trade-with-china-could-end-united-states-semiconductor-leadership.

VerWey, John. "Chinese Semiconductor Industrial Policy: Prospects for Success." *Journal of International Commerce and Economics* (August 2019). https://www.usitc.gov/publications/332/journals/chinese_semiconductor_industrial_policy_prospects_for_success_jice_aug_2019.pdf.

Waters, Richard. "US Chip Industry Plots Route Back to Homegrown Production." *Financial Times*, August 3, 2020. https://www.ft.com/content/ff7996bb-1309-4921-89c1-11aa8e6507de.

Ye, Zhanqi. "如何解开大国"芯"事" ["How to Solve a Large Country's Chip Problem"]. 财新 [*Caixin*] no. 1 (January 1, 2020).

Zhang, Erchi, Mei Tan, and Hui Qu. "华为怎么突围" ["How Does Huawei Break out of Its Encirclement?"]. 财新 [*Caixin*] no. 21 (June 3, 2019).

About the Author

Douglas B. Fuller is an associate professor at City University of Hong Kong. He has researched and published extensively on technology policy in China. His publications include *Paper Tigers, Hidden Dragons: Firms and the Political Economy of China's Technological Development* (Oxford University Press, 2016/2019), *Technology Transfer between the US, China and Taiwan: Moving Knowledge* (Routledge, 2013/2018), *Innovation Policy and the Limits of Laissez-faire: Hong Kong's Policy in Comparative Perspective* (Palgrave, 2011), and numerous articles.

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY