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The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry

John VerWey

Abstract

In 1991 the United States International Trade Commission initiated an Industry and Trade Summary series of informational reports on products imported to, and exported from, the United States. As part of this series, analysts from the Office of Industries published a summary of the state of the Semiconductor Manufacturing Equipment (SME) industry in June 2006. This report provides updated information on the health and competitiveness of the U.S. semiconductor manufacturing equipment industry. After discussing the structure of, and relationship between, the semiconductor and semiconductor manufacturing equipment industries, this paper provides an overview of the SME industry's key characteristics, including supply and demand. The U.S. SME industry and market are then described along with trends in exports, imports and the balance of trade between 2014–18. The paper concludes with analysis of five challenges and opportunities that will affect the health and competitiveness of the U.S. SME industry: China's rise as a producer and consumer of semiconductors, artificial intelligence, the end of Moore's Law, the introduction of extreme ultraviolet lithography equipment, and foreign investment restrictions and export control reform.

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The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry

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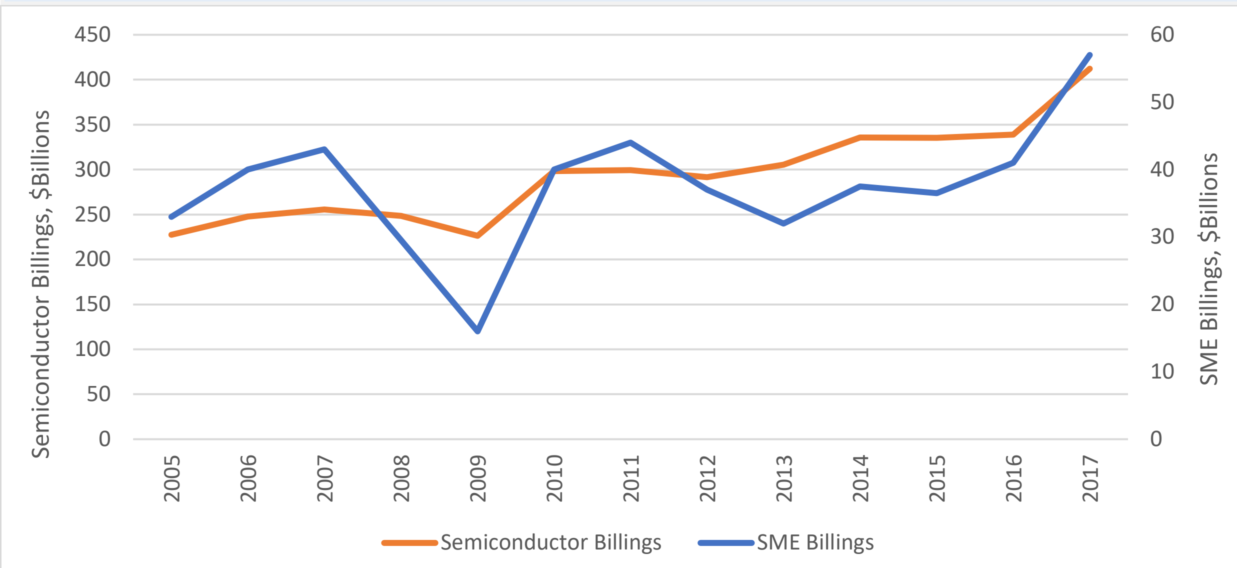
Introduction

Semiconductor manufacturing equipment (SME) refers to all machinery used in the production of semiconductors. Semiconductors, also known as integrated circuits, chips or microchips, are the building block for all information technology. The SME industry is primarily engaged in designing, manufacturing, marketing, refurbishing and servicing machinery used in the fabrication process of integrated circuits on silicon wafers. The SME industry is mature and geographically concentrated, with a small number of large firms located in a small number of countries supplying the vast majority of equipment. SME firms are frequently located in the same countries that produce semiconductors. U.S. production of SME is concentrated in California, Texas and Oregon. The competitiveness and fortunes of the U.S. semiconductor industry and the U.S. SME industry are closely correlated, with cycles of increased or reduced supply and demand affecting each commensurately (Figure 1).

Figure 1 Comparison between the global SME and semiconductor markets



Source: WSTS (Semiconductor) and SEAJ (SME).

Background: The Semiconductor Industry

The semiconductor industry grew out of Silicon Valley in the 1950s, eventually becoming the fourth largest U.S. exporter by value, behind only airplanes, oil, and automobiles.[1] The semiconductor industry is mature, with a small number of large companies engaged in fabrication activities in the United States, Japan, Europe, China, South Korea, Southeast Asia, and Taiwan (table 1). As will be discussed in detail below, the SME trade flows reflect this global value chain and the concentration in fabrication activities.

[1] SIA, *Factbook 2018*, June 5, 2018, 10.

Table 1 Worldwide rankings of Top-15 semiconductor suppliers

Company	HQ Location	Operating Model	2018 Forecasted Sales ($B)
Samsung	South Korea	IDM	$65.90
Intel	United States	IDM	$61.70
TSMC	Taiwan	Foundry	$32.20
SK Hynix	South Korea	IDM	$26.70
Micron	United States	IDM	$23.90
Broadcom	United States	Fabless	$17.80
Qualcomm	United States	Fabless	$17.00
Texas Instruments	United States	IDM	$13.90
Toshiba/Toshiba Memory	Japan	IDM	$13.30
Nvidia	United States	Fabless	$9.40
NXP	Europe	IDM	$9.30
STMicroelectronics	Europe	IDM	$8.30
Infineon	Europe	IDM	$8.10
Sony	Japan	IDM	$7.90
Western Digital /Sandisk	United States	IDM	$7.80

Source: IC Insights. "Nine Top-15 2018 Semi Suppliers Forecast to Post Double-Digit Gains," November 2018.

The semiconductor production process can be divided into three general steps: design, manufacturing, and assembly, test and packaging (ATP). The manufacturing and ATP stages of semiconductor production are referred to as front-end and back-end manufacturing respectively. The SME industry provides the equipment used in both front-end and back-end manufacturing.

The traditional operating model in the semiconductor industry featured large vertically integrated device manufacturers (IDMs) like Samsung (South Korea) or Intel (United States) performing chip design, manufacturing and ATP in-house. In response to rising costs associated with increasingly advanced research and development and semiconductor fabrication, some firms began to specialize in one or more of these production steps. Foundries, which operate chip factories (known as "fabs" in the industry jargon), exclusively engage in contract manufacturing. "Fabless" firms, in contrast, engage solely in chip design and partner with foundries to manufacture these designs in to physical chips. ATP firms test chips to verify that they are functioning as intended before assembling and packaging them for incorporation in to a finished product (smartphones, for example).

The SME industry supplies the machinery used by IDMs, foundries and ATP firms during front end and back end manufacturing. Some estimates indicate that 85 percent of SME spending focuses on front-end wafer manufacturing.[2] The Semiconductor Industry Association estimates that 45 percent of the value of a chip occurs at the design and manufacturing stages respectively, with the remaining 10 percent realized during the ATP stage.[3]

[2] Hall, "Overview of Semiconductor Equipment Industry," Seeking Alpha, January 15, 2019.
[3] SIA and Nathan's Associates, *Beyond Borders*, 2016, 3.

Background: The SME Industry

The SME industry began in the United States in the 1960s. Nascent semiconductor companies, which had previously developed both semiconductor manufacturing equipment and semiconductors in house, sought consistent and reliable manufacturing equipment suppliers that would allow them to create increasingly advanced chips at high volumes for consistent prices. As production techniques changed and technologies evolved over time, Japan and Europe emerged as leading suppliers of SME. The SME industry currently sells equipment to IDMs, foundries, and ATP firms engaged in front-end and back-end manufacturing (box 1).

Box 1 Front end and back end semiconductor manufacturing equipment[a]

- Front-end equipment
    - Silicon wafer manufacturing equipment
        - This equipment is used to produce pure silicon by growing cylindrical crystals and cutting these crystals in to wafers. This equipment includes saws, lasers and grinding and polishing equipment.
    - Wafer processing equipment
        - This equipment is used to make the electronic circuit pathways of a chip by placing conductive and nonconductive (thus the "semi-conducting" terminology) materials on the silicon wafer. This placement is achieved by depositing mixtures of elements (both chemicals and gases) to add, and remove, layers of material in patterns that are imparted via masks. This equipment includes chemical vapor deposition machines, photolithography tools, etching machines, metrology tools and quality/process control equipment.
- Back-end equipment
    - Testing equipment
        - Testing equipment is used primarily, though not exclusively, at the end of the semiconductor production process. SME at this stage of production includes microscopes, machine vision systems, voltage meters, probe machines, and scales.
    - Assembly and packaging equipment
        - This equipment is used to place finished semiconductors into packages for shipping or placement in electronic equipment. The backside of a wafer is prepared, and the individual chips on the wafer are separated before the die is attached to a package. The chips are attached to the package via wiring, which is then set up and trimmed using assembly equipment. Finally, the chip is encapsulated in plastic.

[a] USITC Publication 3868, June 2006.

Front-end manufacturing refers to the process that makes silicon wafers and then creates the chips on these wafers. This is accomplished by depositing film layers that act as conductors, semiconductors, or insulators to create circuit patterns on wafers, removing select portions, repeating these steps, and then performing heat treatment, measurement, and inspection. The entire fabrication process can require over 300 steps utilizing over 50 different types of semiconductor manufacturing equipment.[4] Back-end manufacturing refers to the process of assembling, testing and packaging chips once all the layers on a

[4] Axcelis, "Form 10-K," 2018, 3.

wafer have been fabricated. At this stage each chip on a wafer is tested to verify that it functions before being cut (diced) in to individual chips and packaged.

SME Industry Overview: Supply and Demand

Advances in all information technology (from processing power and speed to price), cloud computing and artificial intelligence are contingent on advances in semiconductor technology, which proceed directly from the ability of SME to fabricate these devices reliably and affordably. There are hardly any information technology goods produced today that do not incorporate, or rely on, semiconductor technology. As a result, the SME industry is considered a bellwether for the economy in general, with earnings reported by the leading companies closely followed by analysts looking for signs of growth or contraction in the semiconductor industry and the economy more generally.[5]

Demand for semiconductor manufacturing equipment is driven by semiconductor industry spending. Semiconductor industry spending in turn is driven by perceived demand for integrated circuits and, more generally, the electronic products in to which chips are incorporated. As a result, increased demand for consumer electronics (smartphones, personal computers), automotive devices, servers, and storage services will result in increased demand for chips, and thus SME. In periods of declining consumer demand, the SME industry will experience a corresponding drop in revenue.[6] The current drivers of demand for SME identified by one firm include artificial intelligence, mobile devices, extreme ultraviolet lithography, the Internet of Things, the increasing consumption of chips in automobiles, memory chips, and China's growing role as a producer and consumer of chips.[7] Several of these trends are discussed at length below.

Supply of SME is concentrated both geographically and at the firm level. The worldwide SME industry is mature, with a small number of large companies accounting for the great majority of revenue, profit and growth. In 2018 the top ten global SME producers were responsible for 69 percent of the overall sales (table 2).[8] This is an increase of 11 percent from the previous USITC report, which showed that the top ten SME producers in 2004 were responsible for 58 percent of sales.[9] Six of the same firms on this list in 2005 also appear on this list in 2018.

[5] Sozzi, "Trade War Sends Bellwether Tech Index Below Key Level," June 25, 2018.
[6] Oversupply of chips for use in select sub-markets can also play a large role in price adjustments. Historically this has been especially true in the market for memory chips.
[7] KLA-Tencor, "Form 10-K," 2018, 2.
[8] Statista, Global Market Share Held by Semiconductor Equipment Manufacturers in 1Q'17 and 1Q'18," 2019.
[9] USITC, "Industry and Trade Summary: Semiconductor Manufacturing Equipment," 2006, 9.

Table 2 Global market share held by SME firms in 2018 (percent of total)

Top Firms	Headquarters	2018
Applied Materials	USA	17.7
Tokyo Electron	Japan	15.0
Lam Research	USA	14.0
ASML	Netherlands	12.1
KLA-Tencor	USA	4.4
Screen Semiconductor	Japan	2.2
Hitachi High Tech	Japan	1.8
ASM International	Netherlands	0.9
Rudolph Technology	USA	0.4
Nova Measuring	Israel	0.3
Nanometrics	USA	0.3
Top 10 Total		69.1
Others		31.1

Source: Statista, "Global Market Share Held by Semiconductor Equipment Manufacturers in 1Q'17 and 1Q'18," 2018.

SME Industry Overview: Key Characteristics

Firm Specialization

Firm specialization is driven by the high research and development investments and capital expenditures required to compete in the SME industry. The semiconductor industry is second only to the pharmaceuticals and biotechnology industry in research and development investments as a percent of sales, averaging 18.7 percent of sales in 2017.[10] The SME industry also reflects this intensive research and development investment, though a review of financial filings from three of the leading U.S. firms indicates that R&D expenditures average between 10–15 percent.[11] Most SME companies compete in several sub-markets, but do not offer a suite of products to meet the needs of the entire semiconductor fabrication process.

Consolidation

The costs associated with developing semiconductor manufacturing equipment, which can reach $120 million per piece,[12] have led to ongoing industry consolidation. The geographic and firm-level concentration of the SME industry is not a new development. In fact, the previous iteration of this USITC report observed a similar level of concentration in photolithography, with ASML, Canon and Nikon responsible for 40, 30 and 30 percent of market share respectively in 2004.[13] Referring to the front-end manufacturing stages described in Box 1 of this report, the SME market's current concentration is apparent:[14]

[10] SIA, *Factbook 2018*, June 5, 2018, 22.
[11] Applied Materials, "Form 10-K," 2018; KLA-Tencor, "Form 10-K," 2018; Lam Research, "Form 10-K," 2018.
[12] Ting-Fang, "Chinese Chipmaker Takes Edge," May 15, 2018.
[13] USITC, "Industry and Trade Summary: Semiconductor Manufacturing Equipment," 2006, 9.
[14] Hall, "Overview of Semiconductor Equipment Industry," Seeking Alpha, January 15, 2019.

- Chemical Vapor Deposition equipment: Applied Materials (USA) has slightly more than 50 percent of global market share, followed by Lam Research (USA) and Tokyo Electron (Japan).
- Photolithography: ASML (Netherlands) maintains roughly 75 percent market share, followed by Canon (Japan) and Nikon (Japan).
- Etch equipment: Lam Research (USA) has roughly 60 percent market share, followed by Tokyo Electron (Japan) and Applied Materials (USA).
- Quality/Process Control equipment: KLA-Tencor (USA) has roughly 55 percent market share

Non U.S. Sales

The three largest semiconductor manufacturing equipment suppliers headquartered in the United States reported that over 90 percent of their fiscal years 2016, 2017 and 2018 total revenue derived from their SME business came from overseas sales.[15] As a result, U.S. SME firms must contend with potential changes in regulatory requirements, foreign currency fluctuations, tariffs, export controls, and political and economic instability, among other risks. China in particular is considered an important non-US growth region for the SME industry due to its increasing production of logic and memory chips and its role as the largest consumer of chips.[16]

Concentrated Customer Base

The three largest semiconductor manufacturing equipment suppliers headquartered in the United States all reported at least one customer that accounted for over 10 percent of their total revenue for FY 2018.[17] KLA-Tencor reported this to be the case with Samsung (South Korea), Applied Materials reported this to be the case with Samsung (South Korea), TSMC (Taiwan) and Intel (USA), and Lam Research reported that Intel (USA), Micron (USA) Samsung (South Korea), SK Hynix (South Korea) and Toshiba (Japan) all accounted for more than 10 percent of sales in 2018.[18] In addition to being concentrated at the firm level, the customer base for SME firms is highly geographically concentrated. As will be discussed in greater detail below, the top five importing countries for SME in 2018 accounted for 89 percent of all imports.

The Industry and Market[19]

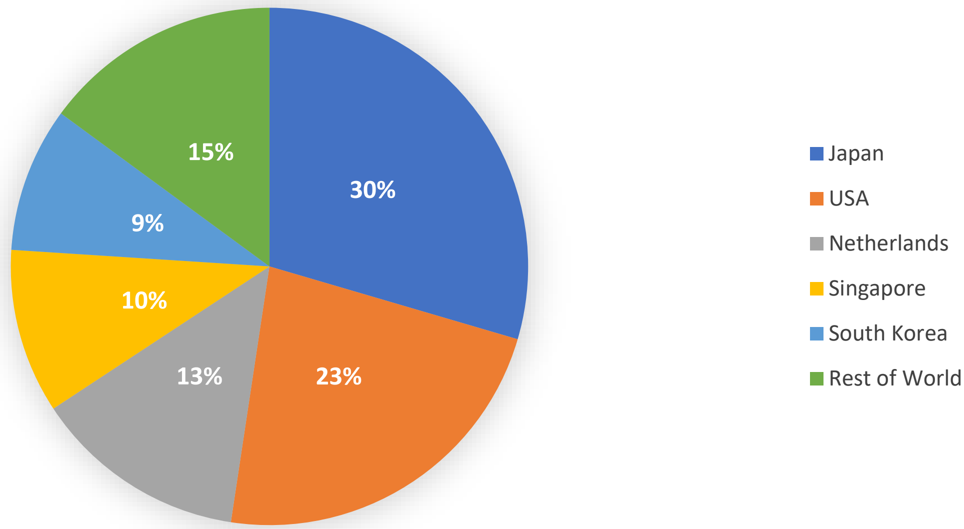
Top 5 Exporters of SME

Japan, the United States, the Netherlands, Singapore and South Korea were the largest exporters of SME from 2014–18 (figure 2). Worldwide exports of SME increased from $46.8 billion in 2014 to $83 billion in 2018 and for that five year period total worldwide exports were approximately $310 billion. The country

[15] Applied Materials, "Form 10-K," 2018; KLA-Tencor, "Form 10-K," 2018; Lam Research, "Form 10-K," 2018.
[16] KLA-Tencor, "Form 10-K," 2018.
[17] Applied Materials, "Form 10-K," 2018; KLA-Tencor, "Form 10-K," 2018; Lam Research, "Form 10-K," 2018.
[18] Note that these sales were likely made to a joint venture between Toshiba Memory (Japan) and Western Digital (USA)
[19] All trade statistics presented below are derived from digest data compiled by the USITC. A list of applicable HTS subheadings can be found in Appendix A.

that experienced the largest increase in exports by value was Japan, with an increase in exports from 2014–18 of $11.7 billion.

Figure 2 Top five exporters of semiconductor manufacturing equipment, 2014–18



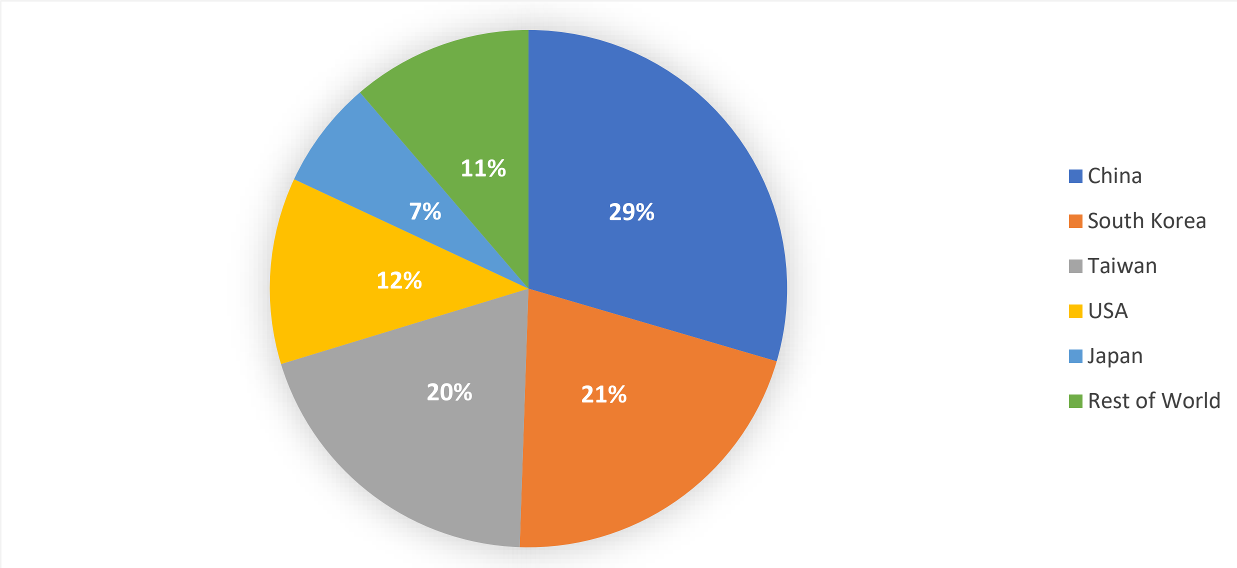
Source: IHS Markit, GTA, HS 8486 (accessed April 24, 2019).

The concentrated supply of SME from these five countries reflects the overall consolidation and competitiveness of firms engaged in the industry. As the next section shows, the industry is increasingly mature, with a small number of large firms controlling nearly two-thirds of global market share.

Top 5 Importers of SME

From 2014–18 the largest importers of SME were China, South Korea, Taiwan, the United States, and Japan (Figure 3). From 2014 to 2018, worldwide imports of SME increased from $51.4 billion to $92.8 billion and for that five year period total worldwide imports were approximately $298 billion. The country that experienced the largest increase in imports by value was China, growing from $11.1 billion in 2014 to $30.6 billion in 2018 (an increase of $19.4 billion). South Korea also experienced a notable increase in imports of SME during this time, growing from $7.7 billion in 2014 to $16.9 billion in 2018.

Figure 3 Top five importers of semiconductor manufacturing equipment, 2014–18



Source: IHS Markit, GTA, HS 8486 (accessed April 24, 2019).

The demand for SME in Asia reflects a broader trend in the industry; as semiconductors have become more intensively produced and consumed in Asia, the SME industry's supply chain has changed accordingly to meet this increase in demand. As will be discussed later in detail, China's ambitious plans for the development of its domestic semiconductor industry has fundamentally shifted demand for SME.

U.S. Market and Characteristics

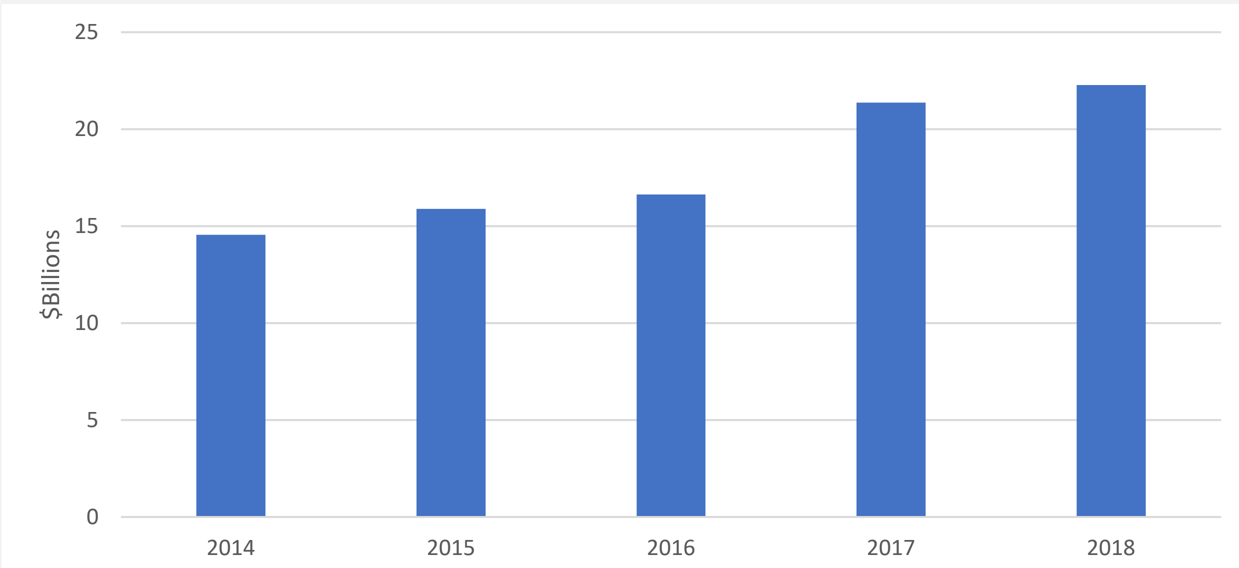
Like the global semiconductor industry, the U.S. SME industry is concentrated in terms of both supply and demand. According to some industry analysts, in 2018 the 170 companies engaged in the U.S. SME industry saw profits of $1.1 billion, exports of $13.3 billion and revenues of $19.7 billion.[20] Between 2013–18 the U.S. SME industry had an annual growth rate of 14.7 percent, a rate which is expected to slow dramatically from 2018–23 to just 1.7 percent.[21] According to some estimates, the semiconductor machinery manufacturing industry employed roughly 15,500 people in the United States in 2016 (the last year for which data is available).[22] A review of financial filings from five of the largest U.S.-headquartered SME firms however indicates that their total employment (which includes non-U.S. employees and employees engaged in non-SME work) was roughly 58,600 in 2018.[23]

[20] IBIS, "Semiconductor Machinery Manufacturing in the US," December 2018. 4. Note that USITC HTS digest data presents different export and import statistics than IBIS, which uses NAICS data.
[21] IBIS, "Semiconductor Machinery Manufacturing in the US," December 2018, 4.
[22] U.S. Census Bureau, "2016 County Business Patterns," 2016 (accessed April 25, 2019).
[23] Applied Materials, "Form 10-K," 2018; KLA-Tencor, "Form 10-K," 2018; Lam Research, "Form 10-K," 2018. "National Instruments, "Form 10-K," 2018; Keysight Technologies, "Form 10-K," 2018.

U.S. Exports of Semiconductor Manufacturing Equipment

The U.S. SME industry experienced rapid growth in domestic exports between 2014 and 2018 (Figure 4). In 2014, the SME industry exported roughly $14.5 billion in equipment and by 2018 that number had grown to approximately $22.3 billion. The largest value increases were exports of SME under HTS subheading 8486.20,[24] up $4.8 billion during this time period, and exports under HTS subheading 8486.90,[25] up $2.1 billion. Together, the two subsectors accounted for approximately 89 percent of the total absolute increase in U.S. exports during this time period.

Figure 4 U.S. domestic exports of SME, 2014–18

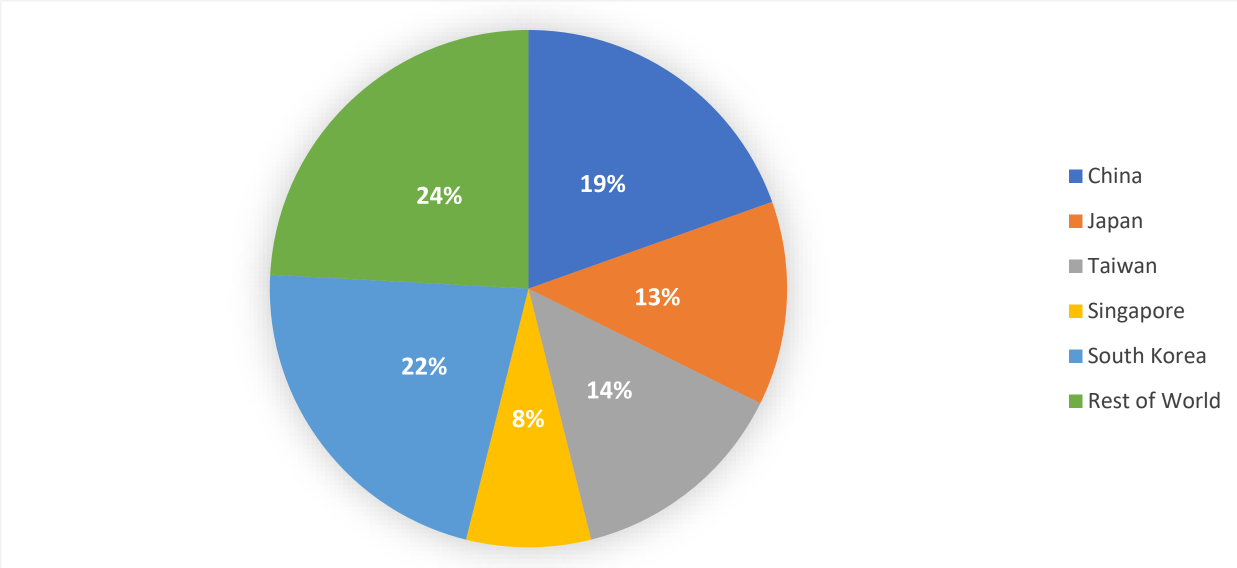


Source: Compiled by USITC staff from official U.S. Department of Commerce statistics.

This 35 percent growth between 2014–18 in exports reflects the global nature of the semiconductor industry. 84 percent of U.S. semiconductor manufacturing equipment sales take place outside of the United States.[26] In 2018, the $22.3 billion in exports went primarily to Asia, with the leading recipient countries being South Korea, China, Japan, Taiwan and Singapore (Figure 5). Together, these five countries accounted for 76 percent of total U.S. SME exports in 2018. U.S. domestic exports of SME increased the most to China growing from $1.9 billion in 2014 to $4.4 billion in 2018.

[24] HTS 8486.20 covers machines and apparatus for the manufacture of semiconductor devices or of electronic integrated circuits.
[25] HTS 8486.90 covers parts and accessories for machines and apparatus for the manufacture or repair of masks and reticules; assembling semiconductor devices or electronic integrated circuits; and lifting, handling, loading or unloading of boules, wafers, semiconductor devices, electronic integrated circuits and flat panels.
[26] Reuters, "Semiconductor Equipment Market Share 2018 Statistics," 2018.

Figure 5 Leading export destinations for U.S. SME, 2018

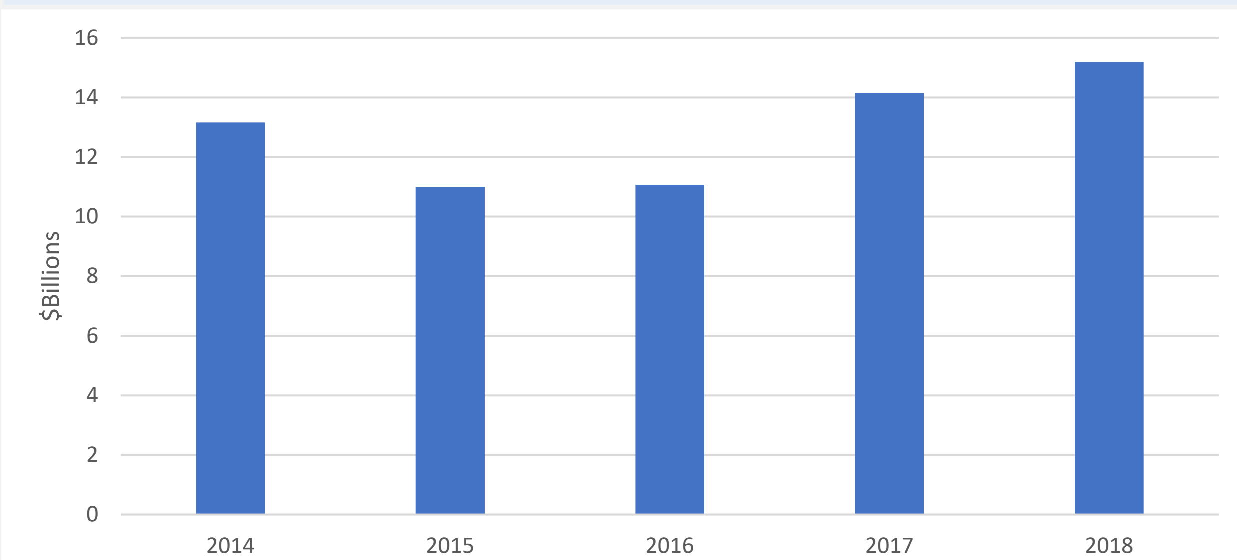


Source: Compiled by USITC staff from official U.S. Department of Commerce statistics.

U.S. Imports of Semiconductor Manufacturing Equipment

During the same time period imports of SME increased $2 billion dollars, from $13.2 billion to $15.2 billion (Figure 6). The addition of HTS subheading 8479.89.94 in 2016 was responsible for much of

Figure 6 U.S. general imports of semiconductor manufacturing equipment, 2014–18

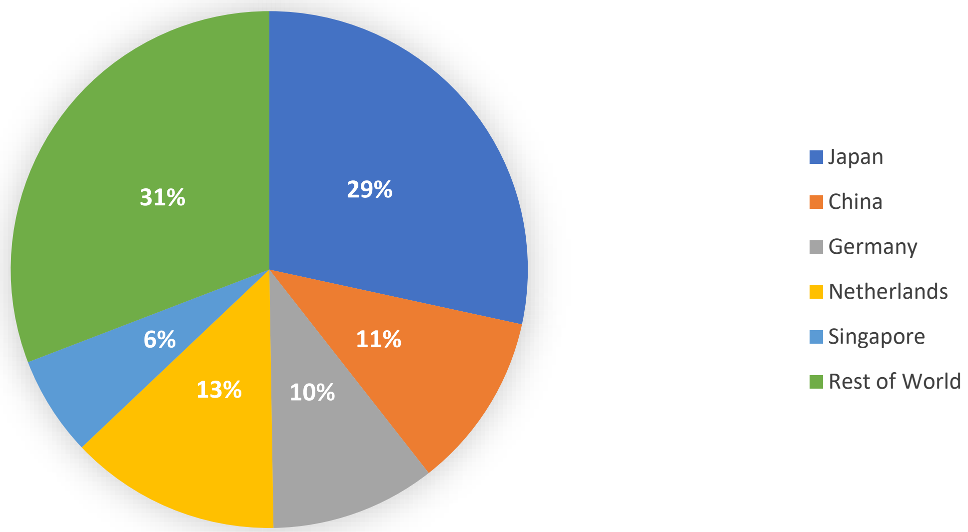


Source: Compiled by USITC staff from official U.S. Department of Commerce statistics.

this growth statistically.[27] Imports of this subheading increased from $1.38 billion in 2016 to $3.5 billion in 2018.

In 2018, the majority of U.S. imports of SME came from Asia and Europe, with the leading supplier countries being Japan, the Netherlands, China, Germany and Singapore (Figure 7). Together, these five countries accounted for 69 percent of total U.S. SME imports. U.S. imports for consumption of SME increased the most from China, growing from $898 million in 2014 to $1.67 billion in 2018.

Figure 7 Leading importers to U.S. of SME, 2018



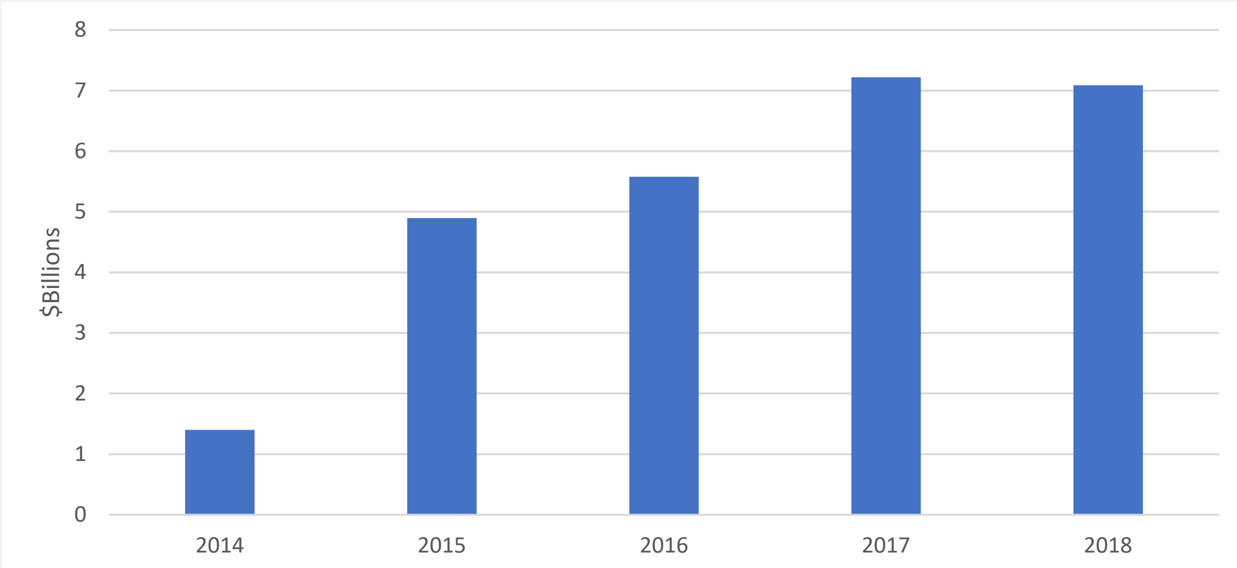
Source: Compiled by USITC staff from official U.S. Department of Commerce statistics.

U.S. Balance of Trade in Semiconductor Manufacturing Equipment

Because of the competitiveness of U.S. SME industry exports, the United States maintained a trade surplus each year from 2014–18, during which it grew from $1.4 billion to $7.1 billion (Figure 8). Several factors which present challenges and opportunities to the competitiveness of the U.S. SME industry are discussed in the following section, all of which will have a bearing on this considerable trade surplus.

[27] HTS subheading 8479.89.94 covers other machines and mechanical appliances having individual functions, not specified or included elsewhere in chapter 84, nesoi.

Figure 8 U.S. balance of trade in semiconductor manufacturing equipment, 2014–18



Source: Compiled by USITC staff from official U.S. Department of Commerce statistics.

Major Trends Affecting the Semiconductor Manufacturing Equipment Industry

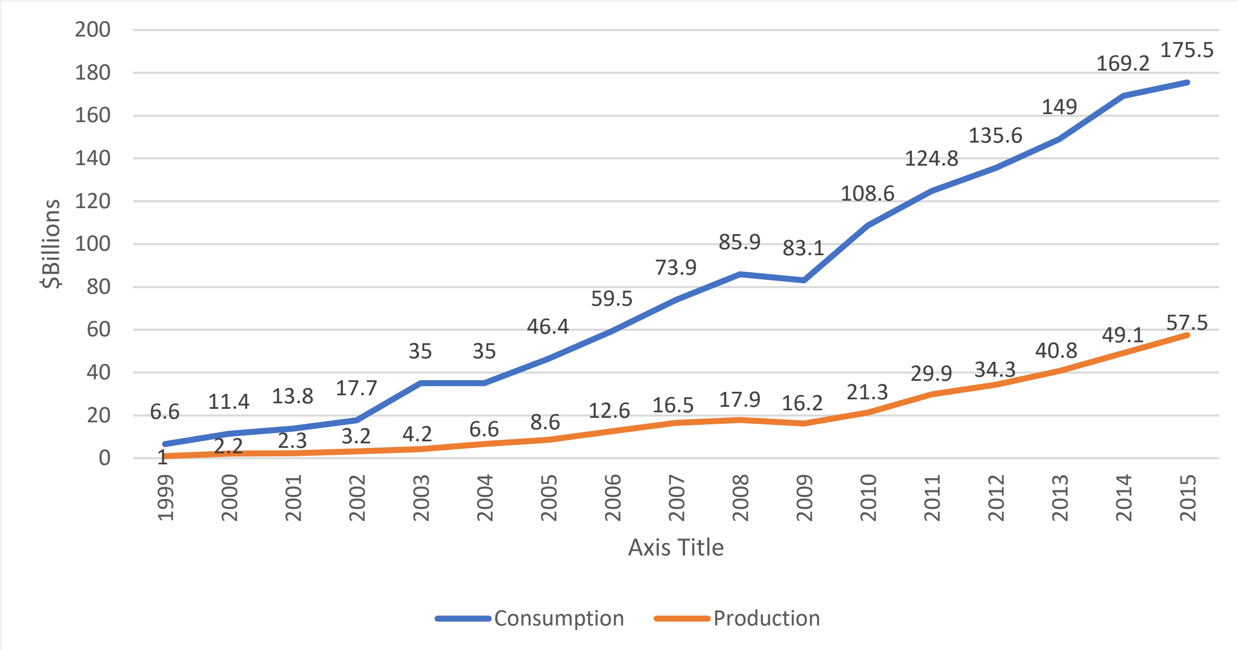
There are five current trends that present both challenges and opportunities to U.S. SME firms: (1) The rise of China as both a producer and consumer of semiconductors (2) opportunities created by greater use of artificial intelligence (3) the economic and physical limits of Moore's Law being reached (4) advances possible through the introduction of extreme ultraviolet lithography (EUV) tools and (5) foreign investment restrictions and export control reform.

(1) The Rise of China as Both a Producer and Consumer of Semiconductors

China's increasing production and consumption of semiconductors presents both challenges and opportunities for the semiconductor manufacturing equipment industry. China is the largest consumer of semiconductors in the world. As home to a large number of international firms that specialize in the manufacture and assembly of electronic products for the global market (notably Foxconn, the maker of Apple's flagship consumer electronics) and a growing domestic market, China's consumption of semiconductors has expanded much faster than its production in recent years (Figure 9).[28] Some estimates indicate China makes 90 percent of the world's smartphones, 65 percent of personal computers, and 67 percent of smart televisions, goods that all rely heavily on chips.[29]

[28] PWC, "China's Semiconductor Market," 2017.
[29] Tao, "How China's 'Big Fund' Helps," May 10, 2018.

Figure 9. China's integrated circuit consumption and production by value, 1999–2015[30]



Source: PWC, "China's Semiconductor Market," 2017.

China's consumption of semiconductors is not matched by domestic production. This has led to an imbalance in its imports and exports of semiconductors given that it must rely on substantial imports of chips in order to meet domestic demand. Between 2014 and 2018 China's trade deficit in integrated circuits expanded from $157 billion to $228 billion.[31] In an effort to reduce its reliance on imports of chips, China announced a National Integrated Circuit Plan ("National IC Plan") and Made in China 2025 ("MIC 2025"),[32] both of which articulated strategies designed to create "a closed-loop semiconductor manufacturing ecosystem with self-sufficiency at every stage of the manufacturing process – from IC design and manufacturing to packaging and testing, and the production of related materials and equipment."[33]

While there are many facets of China's national strategy to cultivate a commercially viable semiconductor industry, the aspect that has the greatest impact on the worldwide SME industry is China's intention to develop world class memory chip fabrication facilities and contract manufacturing foundries. China currently has at least 30 new semiconductor manufacturing facilities or manufacturing lines (new capacity in existing facilities) scheduled, 13 of which are focused on provided foundry services.[34] Much of the new remaining capacity is focused on memory chip fabrication facilities. Under the auspices of the National Memory Base Storage Plan, China announced a series of semiconductor factories focused on manufacturing memory chips valued at $54 to $84 billion with a goal of bringing the capacity of China's domestic memory chip suppliers from essentially zero today to less than 10 percent

[30] PWC, "China's Semiconductor Market," 2017.
[31] GTA IHS Markit (HS 8542) accessed March 21, 2019.
[32] For an extended discussion of both, see US Chamber of Commerce, Made in China 2025, March 16, 2017.
[33] USTR, *Section 301 Report*, 2017, 113.
[34] Lapedus, "China's Foundry Biz Takes Big Leap Forward," 2019.

of worldwide capacity by 2021.[35] While some of this new capacity in both memory chips and foundry services consists of facilities that are majority foreign owned (for example an Intel-owned fab in Dalian), much of it consists of Chinese-headquartered firms who intend to expand domestic production for domestic consumption.

Regardless of ownership however, all of these new facilities require vast amounts of semiconductor manufacturing equipment, a fact that is reflected in the trade statistics. SEMI estimates that wafer fab equipment sales in China doubled between 2013 and 2017, growing from $3.38 billion to slightly over $7 billion.[36] Chinese imports of SME grew from $11.2 billion in 2014 to $30.6 billion in 2018.[37] This increased demand has resulted in some of the best years the worldwide SME industry has ever seen, with all major sectors and subsectors of the industry reporting growth.

(2) Growth Opportunities Associated With the Rise of Artificial Intelligence

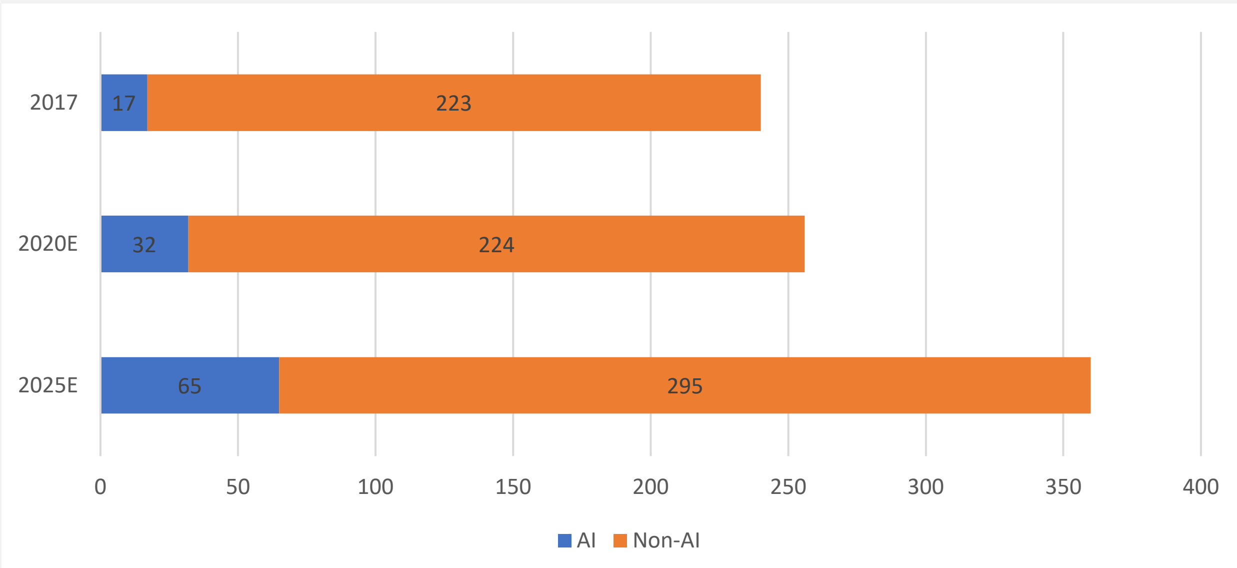
The current enthusiasm for artificial intelligence[38] systems is contingent on a reliable and affordable supply of the semiconductors on which these systems operate. The SME industry has been instrumental in developing semiconductors that are optimized for artificial intelligence functions. In fact, much of the work being done today in the field of artificial intelligence involves machine learning and deep neural networks, concepts which were widely published in academic literature in the 1980s but whose practical implementation had to wait until the SME and semiconductor industry's developed technologies which could implement these computing concepts on chip hardware. A U.S. government report on the future of artificial intelligence identified three factors driving the current wave of AI progress: availability of big data, improved machine learning approaches and algorithms, and more powerful computers.[39]

Artificial Intelligence systems are expected to be a large and growing driver of semiconductor consumption and thus consumption of SME. To take just one example, the automotive market, which historically has accounted for roughly 10 percent of semiconductor end use, is expected to see a 12.5 percent compound annual growth rate from 2017–21.[40] The primary reason for this expected increase in consumption of chips is the introduction of autonomous, connected and electric vehicles which make use of machine learning, a subset of artificial intelligence. While a conventional automobile contains roughly $330 value of semiconductor content, a hybrid electric vehicle with a full sensor platform can contain up to $1000 and 3,500 semiconductors.[41] As semiconductors are more widely and intensively consumed across industries, this trend will drive demand for SME. A recent market analysis forecast that the global deep learning chip market, which is a subset of the overall market for artificial

[35] Lapedus, "China Unveils Memory Plans," 2017; Lapedus, "Will China Succeed in Memory?," 2018.
[36] Lapedus, "China Unveils Memory Plans," 2017
[37] IHS Markit, HS 8486, (accessed April 23, 2019).
[38] For the purposes of this paper AI will be defined loosely as "a computerized system that exhibits behavior that is commonly thought of as requiring intelligence." Executive Office of the President, "Preparing for the Future of AI," October 2016, 6.
[39] Executive Office of the President, "Preparing for the Future of AI," October 2016, 6.
[40] Coffin and Kim, "U.S. Firms Are Becoming Leaders in the Automotive Semiconductor Market," USITC, 2017.
[41] Burghardt, et al, "What's Ahead for Automotive Semiconductors," April 2017; Cappel, "Automotive IC Industry Trends," 2018.

intelligence systems, will reach $29.4 billion by 2025, with a CAGR of 39.9 percent from 2018–25.[42] Another forecast of the AI semiconductor market more generally projected that AI semiconductors will be $65 billion of the overall $362 billion semiconductor market (19 percent) by 2025 (Figure 10).[43]

Figure 10 AI semiconductor total available market, billions



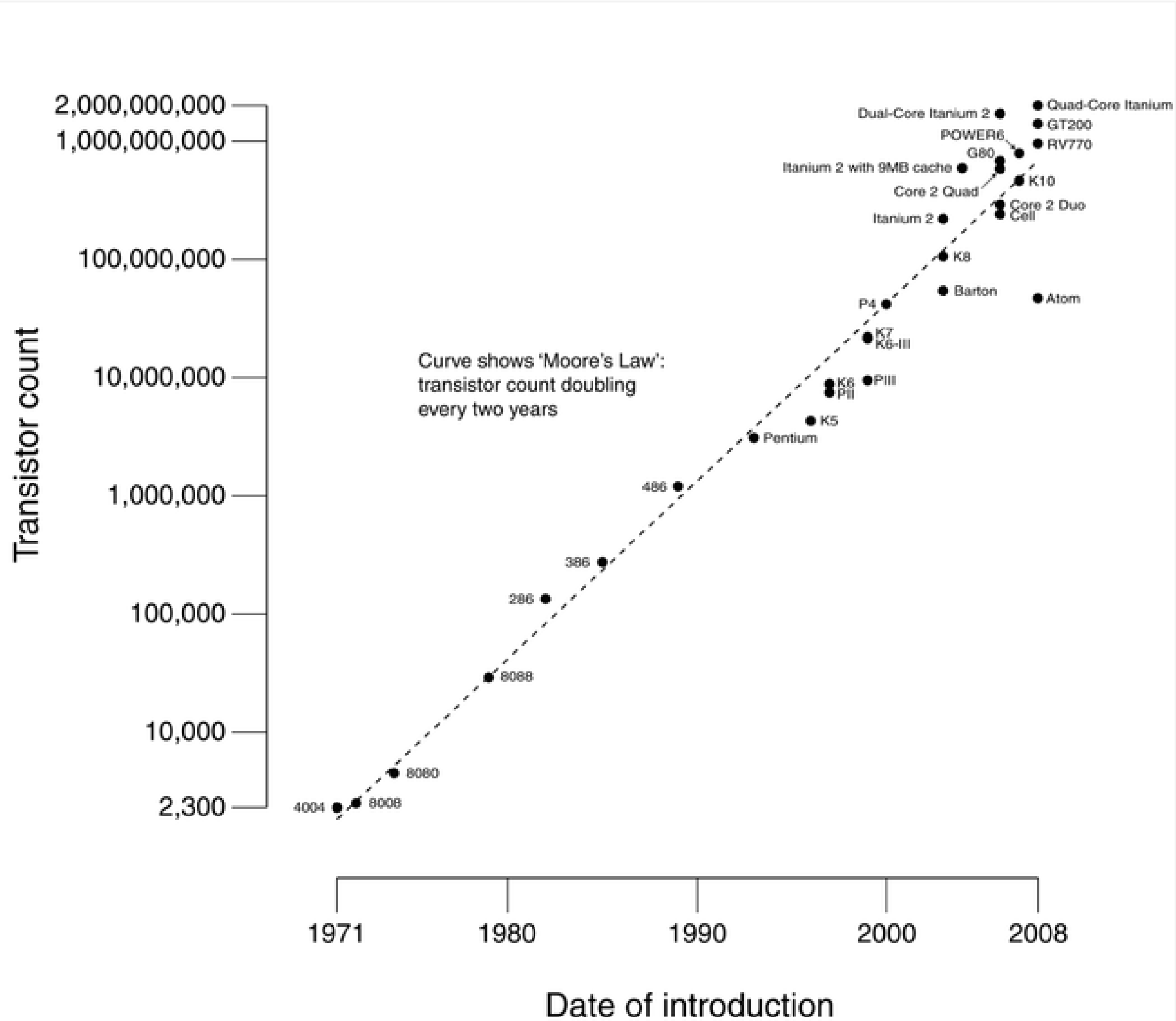
Source: Batra et al, "Artificial-Intelligence Hardware: New Opportunities for Semiconductor Companies," January 2019.

(3) The Limits of Moore's Law Being Reached

First articulated by co-founder of Intel Gordon Moore in a 1965 paper, Moore's Law theorized that the number of transistors embedded in an integrated circuit would double every 18 months to two years at the same or decreasing prices. The semiconductor industry effectively adhered to this pace of innovation for the past fifty years, offering faster processing speeds at the same or lower price to consumers through the use of SME tools which shrink the circuit design on semiconductor chips. The SME industry has been key to this "law" remaining on schedule, carefully collaborating with customers in the semiconductor industry to develop equipment that achieves greater yields (more functional chips per wafer), with fewer defects, at a steady cost. The potential end of Moore's Law represents a challenge and an inflection point for the semiconductor industry and the SME industry, both of which invested large amounts of their profit on research and development budgets designed to increase the number of transistors per chip.[44]

[42] Bailey, "AI Market Ramps Everywhere," 2018.
[43] Batra et al, "AI Hardware," 2019.
[44] Bailey, "Moore's Law Ending," 2018.

Figure 11 Central processing unit transistor counts 1971–2008



Source: Cardinal, "Moore's Law at 50," 2015.

As semiconductors have become more advanced and feature sizes have shrunk below 45 nanometers, the semiconductor and SME industries have had to contend with the fact that improvements in lithography will no longer result in better devices and smaller feature sizes to justify increased costs.[45] Given that a silicon atom is approximately half a nanometer in diameter, the most advanced 7nm chips in production today are approaching atomic limits. As scaling based progress slows, the economies of scale that previously provided incentive for semiconductor and SME firms to invest the R&D to continue scaling feature sizes down no longer exists. This new paradigm has led companies to specialize in new chip architectures on novel materials, 3D integration, and the introduction of specialized manufacturing equipment.

[45] Shalf and Leland, "Computing Beyond the End of Moore's Law," 2015, 4.

(4) The Introduction of Extreme Ultraviolet Lithography (EUV) Equipment

As circuit designs become smaller and their features more complex, expanded use of extreme ultraviolet (EUV) lithography tools will provide opportunities for the most advanced firms in the semiconductor industry to develop the next generation of chips. Photolithography is the process of using light to transfer patterns on to silicon wafers via a photomask. In much the same way that a slide projector uses light to display an image, the lithography process uses light, filtered through photomasks, to establish a pattern that forms the basic architecture of integrated circuits.

During photolithography, wafers covered with light sensitive chemicals (known as a photoresist) are exposed to light that has been filtered through a mask pattern. Photoresist is similar to the coating of regular photographic film except that, when exposed to light, rather than an image appearing, the physical structure and properties of the wafer change according to the mask image. Excimer lasers, which use a blend of chemicals mixed with a majority balance of neon, are used to provide high-resolution deep ultraviolet (DUV) light, allowing for transistor sizes below 45 nanometers (a human hair is 90,000nm). This process is repeated sequentially using several photomasks until the final circuit pattern is created. Close collaboration between the SME and semiconductor industries has resulted in the development of manufacturing equipment that adheres to this pace of innovation, maintaining Moore's Law for over fifty years.

The costs required to fabricate chips have increased in a predictable manner, operating under what is referred to Moore's Second Law or "Rock's Law," which says the cost of semiconductor tools doubles every four years.[46] Among the most expensive tools used in the semiconductor fabrication process are lithography tools. The industry currently uses Deep Ultraviolet Lithography tools for processing devices with feature sizes down to 30 nm. This is accomplished through multiple patterning processes, which require more deposition, etch and metrology equipment, allowing for more features on a device. However, the most advanced devices being manufactured today offer 7nm features, which require the use of Extreme Ultraviolet (EUV) lithography tools. The introduction of EUV lithography in recent years has been instrumental in maintaining the pace of innovation forecast by Moore's Law, but this has come at a cost. This technology has been pioneered by the Dutch firm ASML, which currently is by far theleading commercial supplier of EUV lithography tools and produces several dozen units per year at a cost of up to $120 million per unit.[47] As the semiconductor industry transitions from the DUV process to the EUV process, deposition, etch and metrology equipment will be used less intensively.[48]

The importance of EUV technology to maintaining Moore's Law and the fact that ASML is a sole source supplier has elevated the prominence of The Netherlands in SME-related trade data. Furthermore, given the advanced nature of the technology, there are only a few companies in the world that have the know-how to take advantage of this type of manufacturing equipment: TSMC (Taiwan), Samsung (South Korea), SMIC (China), Intel (U.S.) and GlobalFoundries (U.S.).[49] Because of the concentration of both

[46] Ross, "Five Commandments," 2003.
[47] Ting-Fang, "Chinese Chipmaker Takes Edge," May 15, 2018.
[48] Castellano, "Changes Coming at the Top in Semiconductor Equipment Ranking," 2018.
[49] Note that GlobalFoundries, after purchasing several pieces of ASML EUV equipment, announced it will not make use of them.

supply and demand and the value of EUV equipment, the growth in exports from the Netherlands to Taiwan, the U.S., and South Korea between 2014–18 is partially explained by sales of this technology alone. In addition, as EUV adoption increases, there will likely be a corresponding increase in exports of SME from the Netherlands.

(5) Foreign Investment Restrictions and Export Control Reform

The National Defense Authorization Act of 2019 contained two pieces of legislation with significant implications for the U.S. semiconductor and semiconductor manufacturing equipment (SME) industries. The Foreign Investment Risk Review Modernization Act ("FIRRMA") instituted the first major reforms to the Committee on Foreign Investment in the United States (CFIUS), which screens FDI in the U.S. for national security concerns, since 2007. The Export Control Reform Act ("ECRA") mandated that the U.S. Department of Commerce establish new controls on the export of "emerging and foundational technologies" pending a public comment process aimed at defining those terms and determining which industries/products meet those definitions.[50]

The United States has maintained export controls on SME for decades. The reason for these controls is the ability of SME to produce chips which are "dual use," i.e. those which could have commercial and/or military applications. U.S. firms are generally prohibited from exporting equipment to certain countries through the export control regime administered by the U.S. Department of Commerce's Bureau of Industry and Security and the U.S. Department of State's Directorate for Defense Trade Controls. FIRRMA stipulates that the U.S. Department of Commerce (which administers part of the U.S. export control regime) review its licensing processes of goods which may be "emerging" or "foundational" and specifically identified semiconductor manufacturing equipment as well as the semiconductors themselves as subjects of interest for future controls.[51] This move would conceivably have an impact on the ability of SME firms to sell in all global markets, though of particular interest is the possibility that these controls may target China, which, as previously mentioned, is the largest and fastest growing market for SME.

The passage of FIRRMA effectively ends the possibility of U.S. semiconductor companies being acquired by Chinese-controlled entities for the foreseeable future. This is because FIRMMA expands CFIUS's mandate to cover a broader range of transactions (including capital investments by limited partners as low as 5%) across a broader range of "critical" industries. Because China's National IC Plan and MIC2025 emphasized acquiring foreign technology/know-how as part of the strategy for catching up with semiconductor industry leaders, FIRRMA's new controls on FDI may slow progress in some areas. Even before FIRMMA was instituted CFIUS had acted to block the sale of a New England based semiconductor test equipment maker to a Chinese-controlled entity.[52]

[50] Jackson and Cimino-Isaacs, "CFIUS Reform," 2018.
[51] Federal Register. "Review of Controls for Certain Emerging Technologies," November 19, 2018, https://www.federalregister.gov/documents/2018/11/19/2018-25221/review-of-controls-for-certain-emerging-technologies.
[52] Roumeliotis, "U.S. Blocks Chip Equipment Maker Sale to Chinese State Fund," 2018.

As of June 2019, the U.S. Department of Commerce Bureau of Industry and Security (BIS) is soliciting comments from interested parties under the auspices of an Advance Notice of Proposed Rule Making (ANPRM) in response to a list of proposed "emerging" technologies that may be subject to new export controls. Several U.S. government studies have called in to question the utility of U.S. export controls on SME directed at China, citing foreign availability of similar equipment from third-country sources and an inability to certify that U.S. SME exported to China is being used for its declared end-use.[53] The SME industry has submitted extensive comments in response to this ANPRM solicitation, articulating a series of concerns about foreign availability and innovation.

Several firms have noted the possibility that export controls which exclusively control SME produced by U.S. firms will lead to trade diversion, with non-U.S. competitor firms benefitting from access to markets from which U.S. firms could be barred.. As previously discussed in this report, the SME industry is global and, while U.S. firms are competitive, their worldwide market share cumulatively hovers around 50 percent. One U.S. manufacturer of deposition, etch, and cleaning SME noted that "unilaterally imposed export controls would have no impact on the ability of non-U.S. companies to develop technologies or products comparable to ours because there is current foreign availability for all of our technologies."[54] This was the situation with anisotropic plasma dry etching equipment, which was controlled by BIS until 2016, at which point it was determined that widespread foreign availability of such equipment (particularly in China) indicated controls were no longer effective.[55]

Export controls can also inadvertently prevent U.S. semiconductor firms from entering growth markets, potentially costing them exponentially more revenue down the road. For example, in 2016 Intel was barred from shipping certain processors to China for use in a supercomputer under existing U.S. export controls. China then turned to a domestic supplier for those chips and, "less than a year and half later, the [computer] was the fastest…in the world…The effect of the U.S. export control was a substantial loss for Intel, costing hundreds of millions of dollars…"[56] This loss of market access and revenue can also affect future innovation.

A final concern with regard to these potential controls on emerging and foundational technologies is that they may inadvertently handicap innovation in downstream industries that rely on an abundant supply of affordable and reliable semiconductors. One U.S. firm reported that "controls would diminish our competitiveness relative to non-U.S. competitors because they could restrict our ability to generate profits to fund further development from a global sales base."[57] Several companies have noted that export controls on the U.S. commercial satellite industry offer a cautionary tale; a 2011 report by the Departments of Defense and State found that these controls led to a considerable loss of the U.S. industry's worldwide market share as non-U.S. firms created or expanded production of products for sale to U.S.-embargoed destinations.[58] Controls that restrict the sale of SME to particular countries may affect the ability of U.S. SME firms to engage in research and development partnerships and

[53] GAO, *Rapid Advances in China's Semiconductor Industry,* 2002, 2-3. GAO, *Validated End-User Program*, 2008, 1.
[54] Lam Research, "Comment on ANPRM," January 2019, 3.
[55] Applied Materials, "Comment on ANPRM," January 2019, 5.
[56] CSET/Georgetown University, "Comment on ANPRM," January 2019, 3.
[57] Lam Research, "Comment on ANPRM," January 2019, 5.
[58] Teredyne "Comment on ANPRM," January 2019, 26; IBM, "Comment on ANPRM," January 2019, 3.

collaborations with chipmakers and researchers in growth industries related to 5G, IoT and artificial intelligence that are based outside the United States.

Conclusion

This working paper provided updated information on the health and competitiveness of the U.S. semiconductor manufacturing equipment industry. In doing so, trends in production, consumption, imports, exports and the balance of trade were described. Information on product uses, U.S. and foreign producers, and leading firms were also discussed. The paper concluded with a discussion of five major trends that will have a bearing on the health and competitiveness of the U.S. SME industry. Future research in to this industry could make use of the Office of Industries Framework for Analyzing the Competitiveness of Advanced Technology Manufacturing Firms to describe the determinants of U.S. SME firm competitiveness in greater detail.[59]

[59] David et al. “Framework for Analyzing the Competitiveness of Advanced Technology Manufacturing Firms,” 2018.

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Appendix A Semiconductor Manufacturing Equipment Harmonized Tariff Schedule Subheadings and Descriptions

HTS8	HTS8 Description
8477.10.90	Injection-Molding Machines Of A Type Used For Working Or Manufacturing Products From Rubber Or Plastics, Nesoi
8477.90.25	Base, Bed, Platen And Specified Parts Of Machinery For Working Rubber Or Plastics Or For Manufacture Of Products From These Material, Nesoi
8477.90.45	Barrel Screws Of Machinery For Working Rubber Or Plastics Or For The Manufacture Of Products From These Materials, Nesoi
8477.90.65	Hydraulic Assemblies Of Machinery For Working Rubber Or Plastics Or For The Manufacture Of Products From These Materials, Nesoi
8477.90.85	Parts Of Machinery For Working Rubber Or Plastics Or For The Manufacture Of Products From These Materials, Nesoi
8479.89.83	Machines For The Manufacture Of Optical Media
8479.89.92	Automated Electronic Component Placement Machines For Making Printed Circuit Assemblies
8479.89.94	Other Machines And Mechanical Appliances Having Individual Functions, Not Specified Or Included Elsewhere In Chapter 84, Nesoi
8479.89.98	Machines And Mechanical Appliances Having Individual Functions, Not Specified Or Included Elsewhere In Chapter 84, Nesoi
8480.71.40	Injection Or Compression Type Molds For Rubber Or Plastics For The Manufacture Of Semiconductor Devices
8486.10.00	Machines And Apparatus For The Manufacture Of Boules Or Wafers
8486.20.00	Machines And Apparatus For The Manufacture Of Semiconductor Devices Or Electronic Integrated Circuits
8486.30.00	Machines And Apparatus For The Manufacture Of Flat Panel Displays
8486.40.00	Machines And Apparatus For The Manufacture Of Masks And Reticles; For The Assembly Of Electronic Integrated Circuits; Or For The Lifting, Ha
8486.90.00	Parts And Accessories Of The Machines And Apparatus For The Manufacture Of Semiconductor Devices, Electronic Integrated Circuits And Flat Pa
8515.90.20	Parts Of Electric Welding Machines And Apparatus
8543.90.11	Parts Of Physical Vapor Deposition Apparatus
8543.90.12	Parts Of Physical Vapor Deposition Apparatus Of Subheading 8543.70
9030.82.00	Instruments And Apparatus For Measuring Or Checking Electrical Quantities, Nesoi: For Measuring Or Checking Semiconductor Wafers Or Devices
9030.90.66	Printed Circuit Assemblies For Subheadings And Apparatus Of 9030.40 & 9030.82
9030.90.84	Parts And Accessories For Instruments And Apparatus For Measuring Or Checking Semiconductor Wafers Or Devices, Nesoi
9031.41.00	Optical Measuring/Checking Instruments/Appliances For Inspecting Semiconductor Wafers/Devices Or Photomasks/Reticle Used To Mfg Such Devices
9031.49.70	Optical Instrument & Appliance: To Inspect Masks (Not Photomask) Used To Mfg Semiconductor Devices; To Measure Contamination On Such Devices
9031.80.40	Electron Beam Microscopes Fitted With Equipment Specifically Designed For The Handling And Transport Of Semiconductor Devices Or Reticles

HTS8	HTS8 Description
9031.90.54	Parts & Accessories Of Measuring & Checking Optical Instruments & Appliances Of Subheading 9031.41 Or 9031.49.70
9031.90.70	Parts And Accessories Of Articles Of Subheading 9031.80.40