Policy Brief

Betting the House: Leveraging the CHIPS and Science Act to Increase U.S. Microelectronics Supply Chain Resilience

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Executive Summary

In August 2022, the CHIPS and Science Act appropriated over $52 billion to protect and promote the domestic U.S. semiconductor industry. Coverage of the CHIPS Act has primarily focused on the $39 billion in incentives allocated to subsidize the construction of new semiconductor fabrication facilities in the United States.

However, the CHIPS Act also authorizes an investment tax credit as well as billions of dollars allocated to increase production and innovation in other associated parts of the microelectronics supply chain. This includes specific provisions related to manufacturing mature technologies, advanced packaging, a research and development network, information and communications technology security, workforce support, and wireless supply chain innovation.

This paper contends that, if appropriately allocated, the funds provided by these provisions present the United States with a once-in-a-generation opportunity to increase microelectronics supply chain resilience far beyond re-shoring semiconductor fabrication. In support of this argument, this paper focuses specifically on the two ends of the microelectronics supply chain: upstream raw materials inputs, and downstream assembly, test, and packaging (ATP) of finished microelectronics. This paper's key findings and recommendations include:

- U.S. production of materials consumed by the semiconductor industry is limited and U.S.-based ATP capacity is low, making up only 3 percent of global capacity.

- Efforts to re-shore semiconductor fabrication will not meaningfully increase supply chain resilience if there is no commensurate effort to re-shore materials production and ATP capacity.

- CHIPS Act provisions provide the executive branch with significant flexibility on implementation. Though not the primary focus of the CHIPS Act, targeted funding could increase U.S. production of materials consumed in semiconductor fabrication and ATP capacity, increasing overall microelectronics supply chain resilience.

- U.S. policymakers should identify specific technology supply chain chokepoints and opportunities to target investments accordingly. This paper identifies several opportunities related to chemical production and recycling as well as substrate and printed circuit board manufacturing.

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Introduction

With the signing of the CHIPS and Science Act in August 2022, the U.S. government appropriated $52 billion to protect and promote the domestic semiconductor industry. Coverage of the CHIPS Act has primarily focused on the $39 billion in incentives allocated to subsidize construction of new semiconductor fabrication facilities in the United States. However, the CHIPS Act also provides an investment tax credit as well as billions of dollars allocated to increase production and innovation in other associated parts of the microelectronics supply chain. These include specific provisions related to the manufacturing of mature technologies, advanced packaging, a research and development (R&D) network, information and communications technology security, workforce support, and wireless supply chain innovation.

"If the CHIPS Act funds the construction of leading-edge semiconductors at an Arizona facility but those very semiconductors still have to be made using materials sourced from competitor countries and, once fabricated, sent to Asia for assembly, test, and packaging (ATP) before they can be used, then the resiliency of the U.S. semiconductor supply chain is not meaningfully increased by this act."

While the vast majority of CHIPS Act funds are understandably focused on re-shoring semiconductor manufacturing capacity, more attention should be paid to the $15.2 billion made available for other microelectronics-related initiatives. Importantly, the CHIPS Act provides the relevant executive branch agencies with significant leeway to implement its many provisions. Agencies should use this flexibility in a manner that maximizes overall semiconductor supply chain resilience. Additionally, agencies can use this flexibility to focus CHIPS Act funds on parts of the semiconductor supply chain that were not necessarily explicitly called out in the legislation itself.

Spending $39 billion to re-shore leading-edge logic and memory manufacturing will do little to materially increase U.S. semiconductor supply chain resilience if accompanying efforts to re-shore and near-shore the broader ecosystem are not made. For example, if the CHIPS Act funds the construction of leading-edge semiconductors at an Arizona facility but those very semiconductors still have to be made using materials sourced from competitor countries and, once fabricated, sent to Asia for assembly, test, and packaging (ATP) before they can be used, then the resiliency of the U.S. semiconductor supply chain is not meaningfully increased by this act.

Previous CSET research has analyzed prospects for re-shoring semiconductor fabrication and advanced packaging, as well as semiconductor workforce needs in the United States.[1] This paper contends that, if properly used, the funds allocated by these provisions present the United States with a once-in-a-generation opportunity to increase microelectronics supply chain resilience far beyond re-shoring semiconductor fabrication. In support of this argument, this paper focuses specifically on the two ends of the microelectronics supply chain where U.S. capacity is lacking: upstream raw materials inputs, and downstream ATP of finished microelectronics.

Upstream materials used in semiconductor fabrication include highly purified elements (such as aluminum and copper), chemicals (such as tin-oxide photoresist), common gases (like nitrogen and helium), and specialty electronic-grade gases (such as tungsten hexafluoride). Downstream materials used in semiconductor ATP again include certain common and electronic-grade gases as well as bonding wire, ceramics, substrates, lead frames, and resins. There are few, and in some cases no, U.S.-headquartered suppliers of many of the aforementioned materials. In many instances, even where there is a U.S.-headquartered supplier for a material, they frequently are producing or sourcing the materials from facilities located overseas, typically in Asia.

The downstream semiconductor ATP ecosystem is also almost entirely located in, and dominated by, countries and firms in Asia. Because many of the same geographic concentration risks threaten both semiconductor fabrication and ATP, efforts aimed at re-shoring semiconductor fabrication will not increase supply chain resilience if there is no commensurate effort to re-shore semiconductor ATP. However, U.S. efforts to re-shore ATP must contend with challenging economics. ATP is a labor-intensive and low-margin sub-segment of the semiconductor industry. Construction costs and labor rates are significantly higher in the United States than Asia, and the current U.S. workforce lacks the skills to meet these industries' needs. U.S. policymakers will need to carefully consider how to re-shore or near-shore capacity in light of these realities.

This paper contends that the U.S. government should leverage this unique opportunity and carefully coordinate funding to ensure adequate support is given to upstream and downstream stages of the U.S. semiconductor supply chain. Specifically, funds should be directed to immediately resolve known chokepoints in material supply chains and ATP for which there is no U.S.-based capacity. Funds should also be directed to allies to promote near-shoring of these supply chains where an economic case for re-shoring does not exist. Finally, incentives and funds should be directed toward innovative efforts that will increase overall supply chain resilience.

The CHIPS Act

The CHIPS Act appropriated $39 billion to encourage the construction of new fabs, $11 billion for a variety of R&D programs, $2 billion for U.S. Department of Defense microelectronics requirements, and $2.2 billion for myriad efforts to protect and promote semiconductor supply chains.[2] Table 1 provides a more detailed overview of these appropriations.

Table 1. CHIPS Act Appropriations Related to Semiconductors, (Billions of USD)

<table>
<tr><th>CHIPS Act Provisions</th><th>FY22</th><th>FY23</th><th>FY24</th><th>FY25</th><th>FY26</th><th>FY27</th><th>Total</th></tr>
<tr><td>Financial Assistance Program (Incentives)</td><td>19</td><td>5</td><td>5</td><td>5</td><td>5</td><td>0</td><td>39</td></tr>
<tr><td>National Semiconductor Technology Center</td><td>2</td><td rowspan="4">2</td><td rowspan="4">1.3</td><td rowspan="4">1.1</td><td rowspan="4">1.6</td><td rowspan="4">0</td><td rowspan="4">11</td></tr>
<tr><td>National Advanced Packaging Manufacturing Program</td><td>2.5</td></tr>
<tr><td>National Institute of Standards and Technology Semiconductor Metrology R&D</td><td rowspan="2">0.5</td></tr>
<tr><td>Manufacturing USA Institute for Semiconductors</td></tr>
<tr><td>Department of Defense Semiconductor R&D Network</td><td>0</td><td>0.4</td><td>0.4</td><td>0.4</td><td>0.4</td><td>0.4</td><td>2</td></tr>
<tr><td>Department of State Technology Security and Innovation Fund</td><td>0</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.1</td></tr>
<tr><td>National Science Foundation CHIPS Education Fund</td><td>0</td><td>0.025</td><td>0.025</td><td>0.05</td><td>0.05</td><td>0.05</td><td>0.2</td></tr>
<tr><td>National Telecommunications and Information Administration Wireless Supply Chain Innovation Fund</td><td colspan="6">1.5</td><td>1.5</td></tr>
</table>

Source: Author's compilation from H.R.4346, 117th Congress.

In addition to these direct funds, the CHIPS Act also enacted an Advanced Manufacturing Investment Credit, which will provide a 25 percent credit to firms making investments in a U.S.-based facility "for which the primary purpose is the manufacturing of semiconductors or semiconductor manufacturing equipment."[3] This provision, which was added to the CHIPS Act relatively late in the multi-year deliberations, has the potential to eclipse the overall dollar value of the incentives and R&D programs depending on how many firms make use of the credit between January 1, 2023 and December 31, 2026.

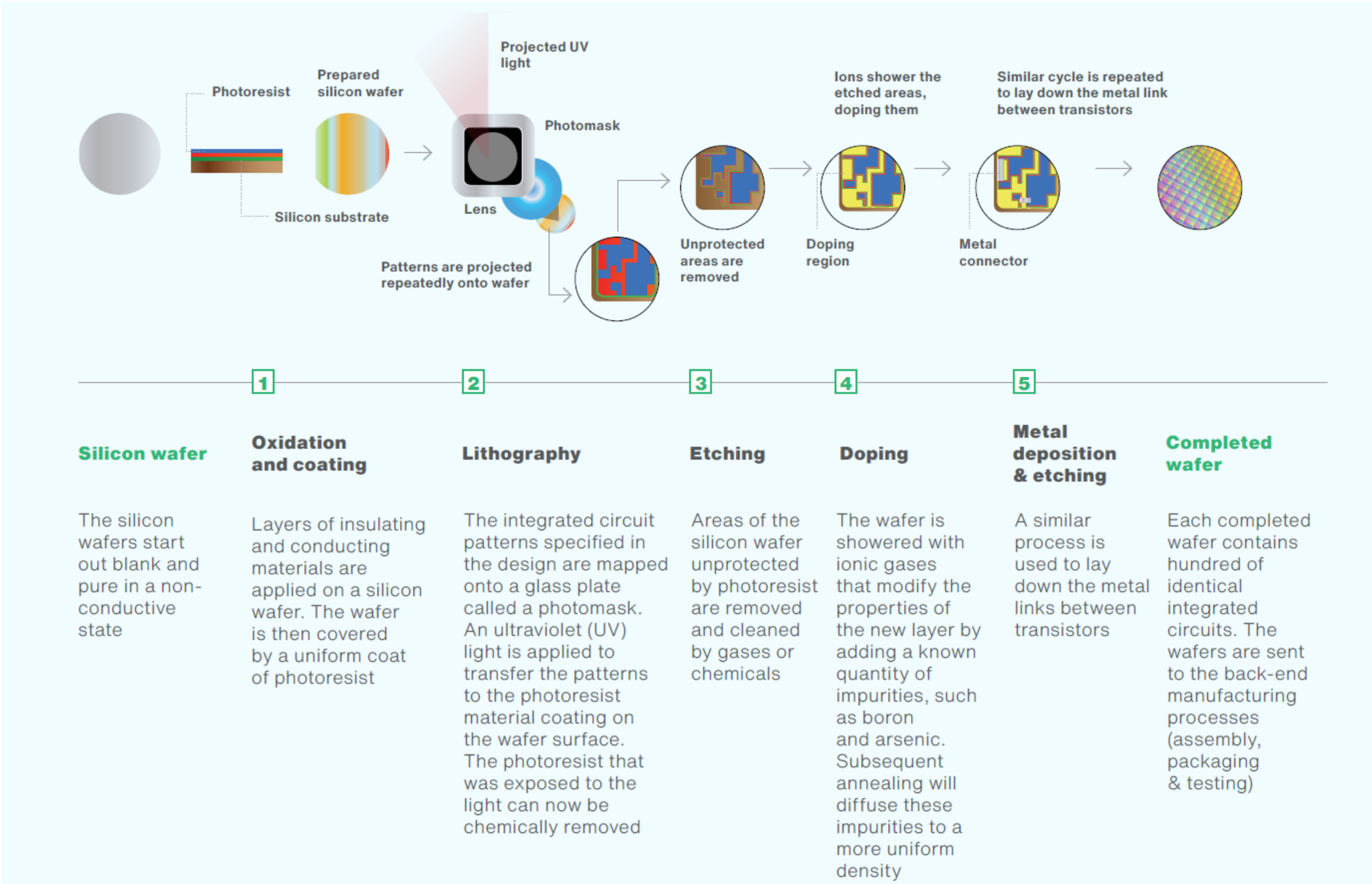
The CHIPS Act provides implementing executive branch agencies with significant latitude for regulatory interpretation. As will be discussed below, executive branch agencies should leverage this statutory flexibility to focus efforts on increasing the resilience of front- and back-end semiconductor supply chains.

Surrounded on All Sides: Upstream and Downstream Chokepoints in Semiconductor Supply Chains

The process of semiconductor production involves three general steps: design, fabrication, and ATP. After individual components have been designed, they are then fabricated on silicon wafers using semiconductor manufacturing equipment and specialty materials. After fabrication, completed wafers are sent for ATP. ATP involves the use of specialized equipment and materials to dice the wafers into individual chips (assembly), test the chips for operability (test), and finally package them onto a larger device to protect and enable their functionality (packaging).[4]

Previous CSET research has documented the complexity of the semiconductor supply chain in detail.[5] This research has focused on the importance of semiconductor manufacturing equipment, fabrication, and advanced packaging in particular.[6] This paper expands on previous research, focusing on the two extreme ends of the semiconductor manufacturing process: materials used in semiconductor fabrication (Figure 1) and the need to cultivate an economically viable and innovative ATP ecosystem. This section is divided in two parts.

Figure 1. Materials, Chemicals, and Gases used in the Wafer Fabrication Process



Source: Semiconductor Industry Association and the Boston Consulting Group, “Strengthening the Global Semiconductor Supply Chain in an Uncertain Era,” April 2021.

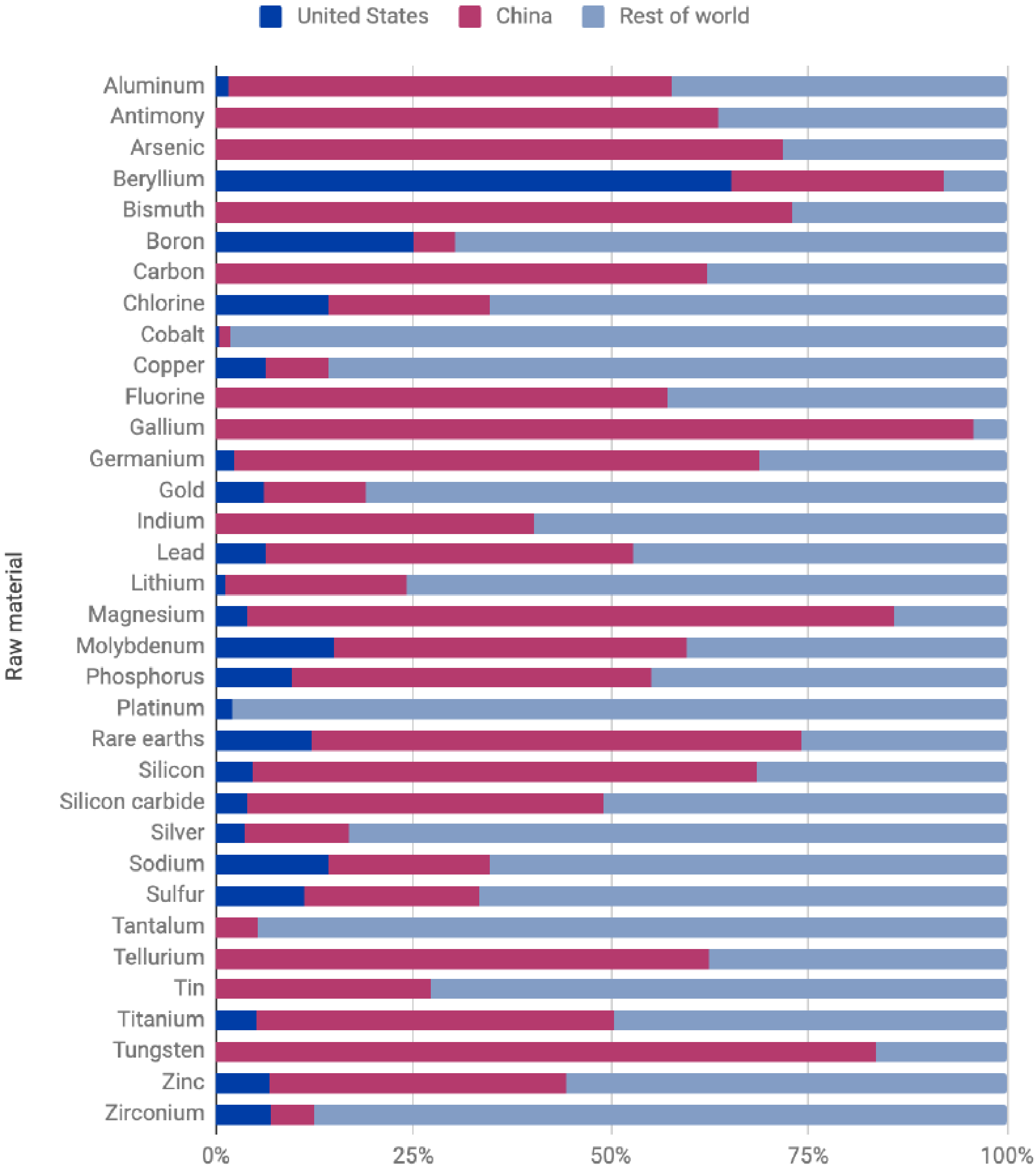
The first part of this section focuses on materials used in semiconductor fabrication, including raw materials, chemicals, and electronic-grade gases. In practice, these materials include everything from "photoresists used for photolithography [and] hydrogen fluoride used in wafer processing [to] polyimide used in substrates and molding materials."[7] U.S.-based production of these materials is insufficient to meet current domestic demand and will be inadequate to meet forecast domestic demand. More information is included in Appendix 1.

The second part of this section focuses on the lack of ATP capacity and its associated ecosystem in the United States. Previous CSET research has documented in detail the promise that advanced packaging holds for the semiconductor industry, and particularly for artificial intelligence (AI) and high-performance computing (HPC) applications.[8] This section expands on that research to focus on the associated ecosystem of suppliers needed to support re-shoring of ATP capacity. Specifically, there is a need for expanded printed circuit board capacity, substrate manufacturing, and high-volume ATP facilities. More information is included in Appendix 2. Appendix 3 presents a list of recent investments in semiconductor-related facilities that provides a rough order of magnitude for the scale of funds being directed to materials, substrate, and ATP facilities.

Upstream Chokepoints: The Materials Ecosystem

The term "semiconductor materials" refers to both materials that have semiconducting properties, such as silicon, as well as materials that are used in semiconductor manufacturing, such as tungsten. Previous CSET research has found that, while the United States generally lacks raw material production capacity, the country has a small domestic production capacity for semiconductor materials such as bare silicon wafers as well as the materials that are added to these wafers to fabricate semiconductors.[9] However, many chokepoints remain. One industry association representing semiconductor materials suppliers assessed that there was either one or no U.S.-based supplier for certain photoresists, electronic grade gases, deposition targets and precursors, and spin-on dielectrics.[10] Chinese firms also maintain a leading position in the production of raw minerals, meaning many U.S. semiconductor material firms are also highly dependent on China for the supply of raw materials (Figure 2).[11] Increasing U.S.-based semiconductor fabrication will not increase overall U.S. semiconductor supply chain resilience if these upstream material dependencies are not adequately reviewed and mitigated.

Figure 2. Primary Production of Raw Materials by Country/Region, 2019



Source: Saif M. Khan, Alexander Mann, and Dahlia Peterson, “The Semiconductor Supply Chain: Assessing National Competitiveness,” Center for Security and Emerging Technology, January 2021.

Materials, Chemicals, and Gases

There are a wide variety of materials used to make semiconductors. One semiconductor manufacturing equipment company estimates that 66 of the 118 elements in the periodic table are, or have been, used by the semiconductor industry to fabricate devices.[12] The U.S. Geological Survey's list of critical minerals includes 35 minerals, of which 30 are relevant to semiconductor manufacturing.[13] Many materials go through supplemental processing to meet the stringent purity and performance requirements associated with semiconductor manufacturing, and U.S. capacity for this synthesis and purification is generally lacking. For example, while there are current U.S. suppliers of sulfuric acid and isopropyl alcohol (IPA), there are no U.S. suppliers of ultra-high purity sulfuric acid and IPA suitable for advanced semiconductor manufacturing.[14]

The most prominent chemicals and gases used in semiconductor manufacturing include atmospheric gases, specialty gases, fluoropolymers, photoresists and photoresist ancillaries, chemical mechanical planarization slurries, and deposition materials.[15] One study found that over four hundred chemical products were used in a semiconductor factory.[16] In almost all cases, there are fewer than five suppliers of these specialty chemical products globally. Many products are produced by large multinational corporations like Linde (Ireland), Air Liquide (France), BASF and Merck (Germany), JSR and Shin-Etsu (Japan), Entegris and Dupont (United States) that make these chemicals and gases at facilities outside the United States.[17]

Though these firms are headquartered in the United States or allied countries, they maintain a considerable production footprint in Asia in general, and China in particular. For example, Linde estimates its property, plants, and equipment in China are second in value only to its U.S. assets, while Air Liquide invested $170 million to expand China-based production of ultra-pure gases for semiconductor manufacturers in 2021.[18] The reason for this presence in China is due to the increasing demand from semiconductor firms operating in China, but also the supply that China's other industrial assets offer. Frequently, these chemicals and gases are indirectly produced and captured as byproducts of other industrial operations. Notably, the production of rare gases such as krypton and xenon are dependent on air separation units co-located with steel manufacturing. One industry association reports the semiconductor industry gets 80 percent of its supply of krypton and xenon from China and Ukraine, which in turn source most of their supply from Russia.[19] Again, purity requirements dictate that even commercial off-the-shelf versions of these products must undergo supplemental processing, further constraining supply and the number of vendors.

In addition to the supply of these materials, gases, and chemicals already being complicated and constrained, the CHIPS Act also may introduce a demand shock. One industry analysis estimated that there needs to be a 37 to 49 percent increase in supply of all semiconductor grade wet chemicals over the next four years to meet the anticipated demand stemming from new fab construction in the United States.[20] Given that most of the global supply of these materials, chemicals, and gases already resides outside the United States, it is important that the U.S. policymakers attempt to leverage CHIPS Act funds to increase domestic or allied production capacity to meet anticipated demand.

There are already some initial signs that the CHIPS Act is indirectly increasing material availability in the United States. Several of TSMC's Taiwanese-based suppliers have announced their intention to establish facilities in Arizona near its new fab, which is scheduled to begin production in 2024 (see Appendix 3 for a list of recent investments semiconductor-related facilities).[21] Sunlit Chemical, a Taiwanese supplier of electronics grade chemicals, announced a $100 million facility to produce "hydrofluoric acid and other high purity grade industrial chemicals used in the manufacturing of semiconductors" in early 2022.[22] While TSMC's presence in Arizona appears to be incentivizing some materials suppliers to co-locate and increase domestic production, a recent application by TSMC to create a Foreign Trade Zone near its Phoenix fab lists roughly one hundred "foreign-status" materials and chemicals not produced in the United States.[23] While materials suppliers already have some market-based incentives to co-locate with their fab customers, U.S. policymakers should ensure that fab projects that take receipt of CHIPS Act funds include clear commitments from their suppliers to increase domestic production in areas where chokepoints remain. For example, policymakers could encourage SEMCO, a Samsung subsidiary and key supplier of substrates used in advanced packaging, to establish production in Texas near Samsung's existing foundry.[24] As will be described in the following section, the U.S. domestic production of substrates is insufficient to meet current and forecast demand, and firms in Asia dominate in this sub-market. This necessitates that policymakers craft incentives to attract leading firms back to the United States.

Downstream Chokepoints: The ATP Ecosystem

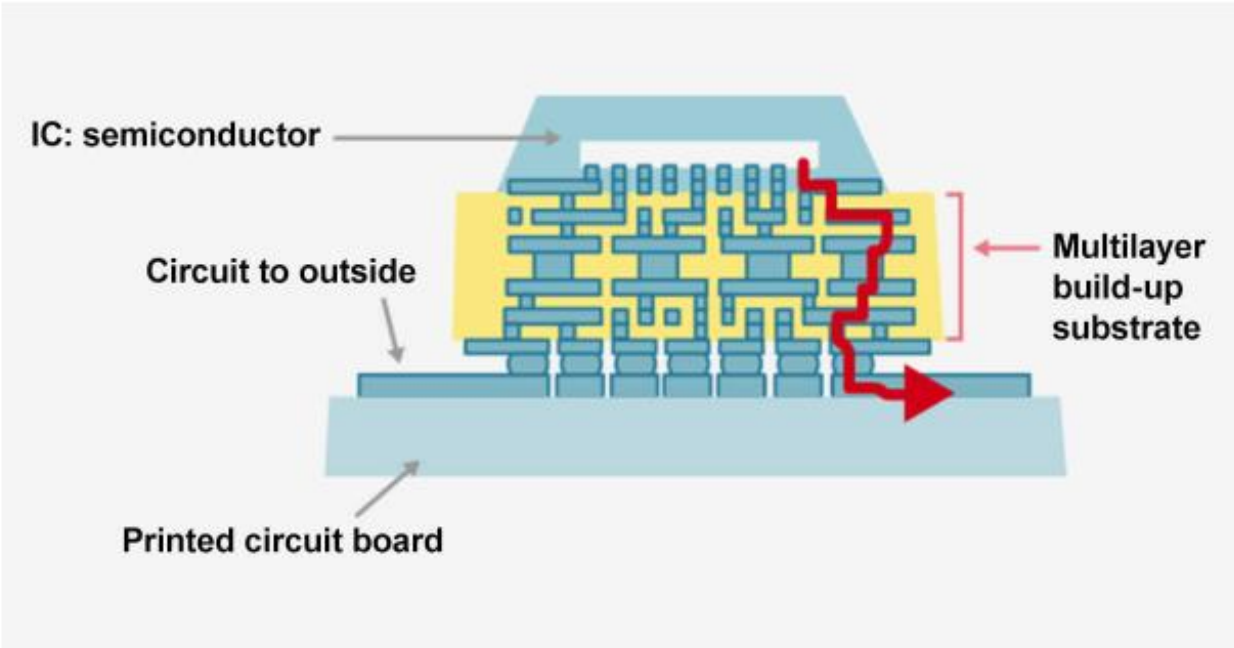
Previous CSET research has found that U.S. firms do not maintain leading market shares in the provision of ATP services or the materials used in ATP. U.S-based ATP capacity is roughly 3 percent of total global capacity, and no U.S. firms lead in the supply of packaging materials.[25] There is low to no capacity for production of leadframes, bond wires, ceramics, substrates, resins, and die attach materials outside of specific defense use cases. The lack of an ATP ecosystem in the United States is due to a multi-decade trend of semiconductor manufacturers choosing to locate these facilities in Asia due to favorable costs and proximity to electronics assembly firms. The result of this trend is that roughly 81 percent of global ATP capacity is concentrated in Asia, and firms in Japan, China, and Taiwan maintain dominant market shares for nearly all ATP materials, especially substrates and printed circuit boards.[26]

CSET research also asserted that U.S. re-shoring efforts should have a concurrent focus on semiconductor advanced packaging, while accepting that there exists little (or in some cases no) economic rationale for reshoring commoditized ATP materials like leadframes and bonding wires.[27] This section argues, however, that the focus on re-shoring advanced packaging must focus specifically on increasing substrate and printed circuit board (PCB) production capacity.

ATP Substrates and Printed Circuit Boards

U.S. government efforts to re-shore semiconductor fabrication capacity should be paired with a concurrent focus on re-shoring the ATP materials ecosystem. On top of the lack of overall ATP capacity in the United States, currently there are no commercially and technologically competitive U.S. suppliers of the printed circuit boards and substrates necessary to integrate a finished semiconductor in an electronic device. The lack of a U.S. source of these products and services means that the vast majority of U.S.-fabricated semiconductors still must be sent overseas to Asia for ATP.

Figure 3. The Hardware “Stack” for Microelectronics ATP

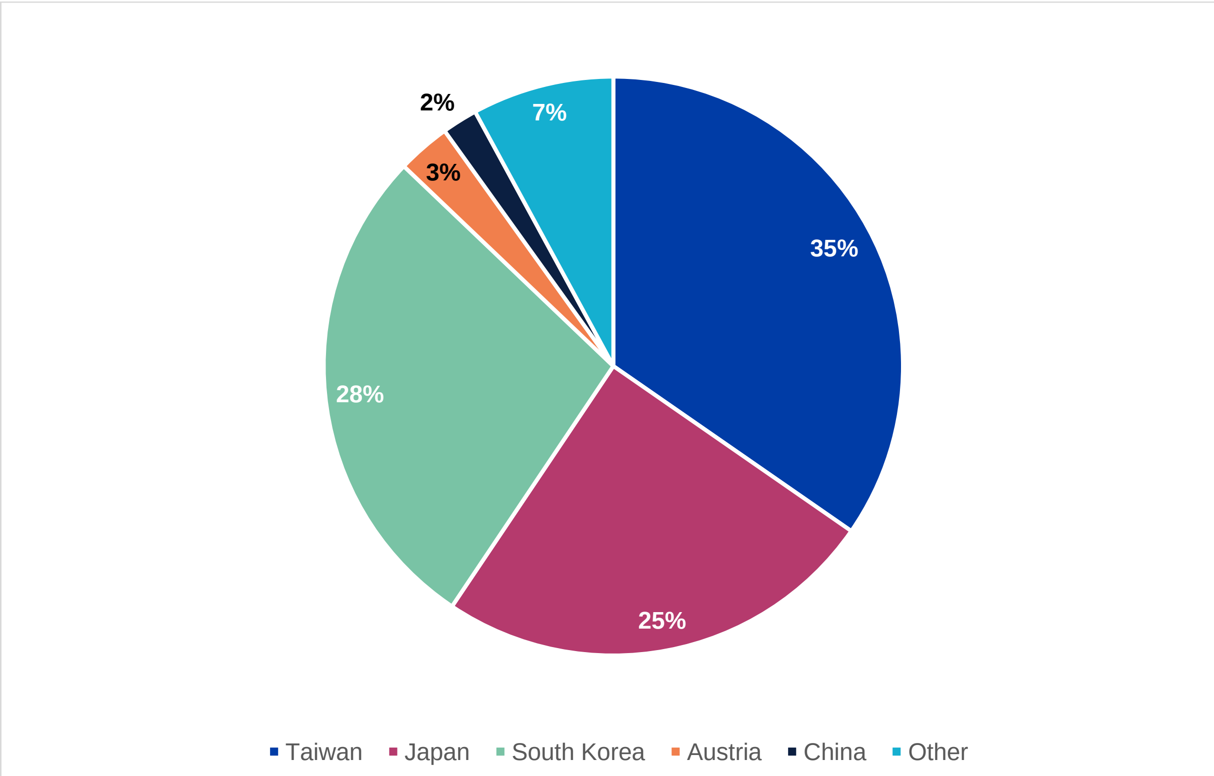


Source: Ajinomoto, “Ajinomoto Build-up Film: A Microfilm Insulation for Electronic Devices.”

If a complete electronic assembly is a house (Figure 3), PCBs form the foundation while substrates are the plumbing and framing. Once a chip has been fabricated, it is packaged on a printed circuit board using substrates to protect and connect the chip(s) to the electronic device. There are an extremely limited of number of substrate and printed circuit board suppliers in the United States, and their products cannot compete with Asian firms in terms of scale, quality, or cost. One industry analyst assessed that “the United States is 20 years behind Asia in PCB manufacturing technologies necessary for next-generation electronics applications and 30 years behind in the capability to manufacture the PCB-like substrates necessary for advanced microelectronics packaging.”[28] If this deficit is not remedied, the gap between U.S. capabilities and industry-leading capabilities will expand despite efforts to re-shore semiconductor fabrication.

Specific chokepoints in the back end of the semiconductor supply chain abound. No U.S. substrate suppliers rank in the top 20 by market share and 95 percent of leading suppliers are located in Asia (Figure 4). Importantly, Ajinomoto build-up film (ABF, made primarily by firms in Japan and Taiwan), a single-source substrate intensively consumed in packaging 5G, HPC, and AI semiconductors, is almost exclusively produced in Asia and has been in short supply for years. One estimate suggests the semiconductor industry will need 185 million square feet of advanced substrate manufacturing space by 2025, yet only 145 million square feet of capacity will have been constructed by that time.[29] This 40 million square foot gap is substantial. One Japanese firm anticipates spending $1.6 billion to build a ~2 million square foot substrate manufacturing facility over an 18-month period, implying that $32 billion in global investment in substrate capacity expansion needs to occur to meet forecast demand by 2025.[30]

Figure 4. Leading Suppliers of IC Substrate by Country, 2020



Source: Matt Kelly and Jan Vardaman, “An Analysis of the North American Semiconductor and Advanced Packaging Ecosystem,” IPC, November 2021.

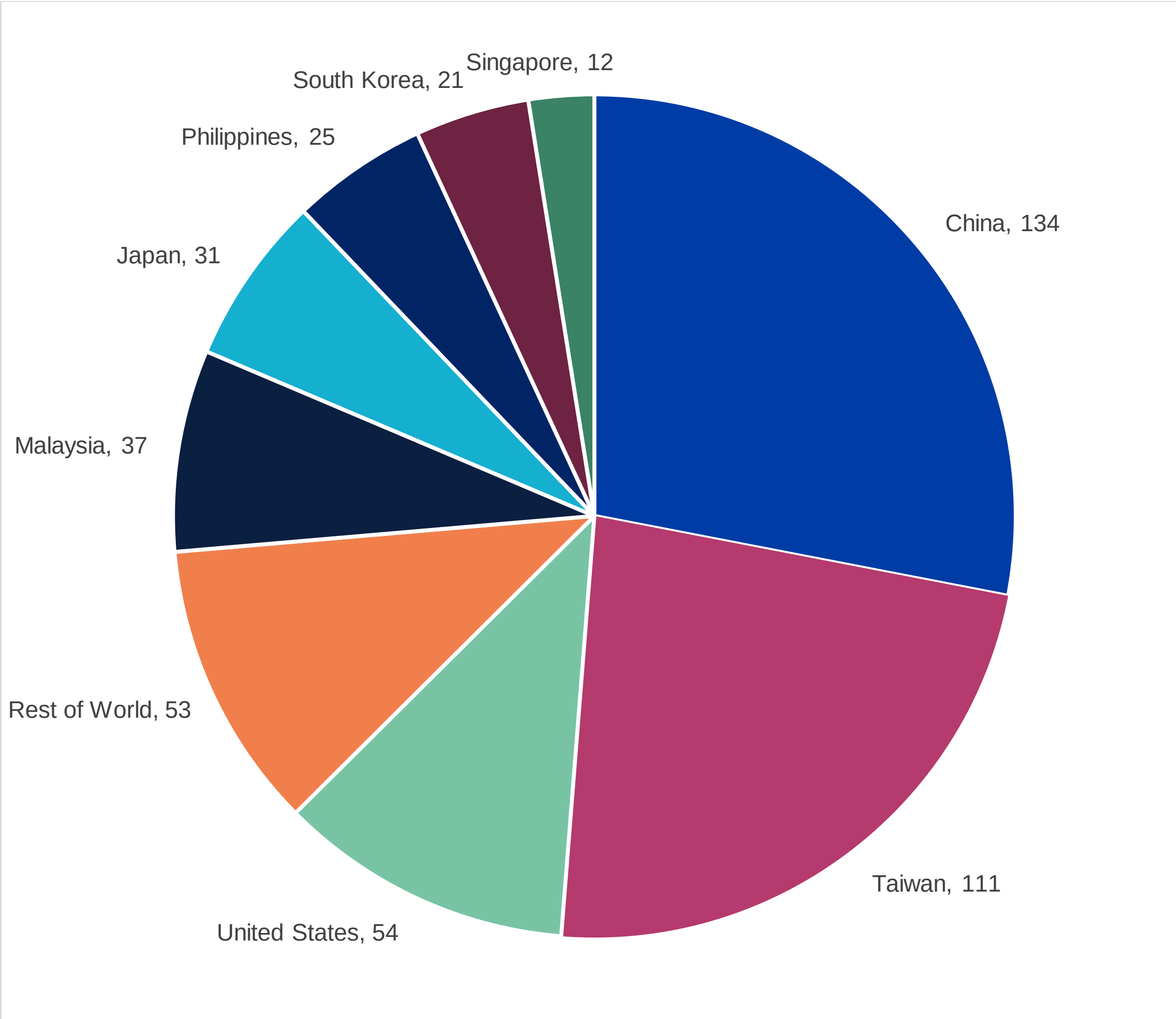
Note: Chart created by author using Kelly and Vardaman report data.

U.S. PCB production is also lacking in terms of capacity and technical competitiveness. There are less than 150 PCB suppliers in the country today, down from over two thousand in the late 1990s, and 80 percent of global production capacity is in China while only 4 percent resides in the United States.[31] Similar to ATP, PCB production moved overseas due to the cost competitiveness of firms in Asia and the proximity to electronics assemblers. In particular, there is “negligible capacity” in the United States to produce high-density interconnect PCBs necessary for advanced packaging.[32] Specifically, U.S. additive process capacity to produce high-density substrates of 6 to 50 microns (which would be competitive with firms in Asia) is insufficient to meet U.S. demand.[33] Current U.S. capacity is so low that the National Defense Authorization Act for Fiscal Year 2022 amended sourcing requirements on PCBs that would have stipulated that beginning in January 2023 “mission critical systems” only use PCBs from non-competitor countries. However, due to the lack of PCBs available from U.S. firms and allied countries, the implementation timeline of these requirements was pushed back to 2027.[34]

ATP Capacity

U.S. ATP capacity is limited in terms of number of facilities, capacity, and technological competitiveness. Only 3 percent of global ATP capacity resides in the United States, and this capacity is mainly due to the presence of Intel company-internal ATP facilities and boutique ATP facilities that serve the defense industry. There is a distinct lack of high-volume outsourced assembly and test (OSAT) services[35] in the United States (Figure 5). The result of this is that the vast majority of chips made in the United States by firms like GlobalFoundries (New York) and Texas Instruments (Texas) are sent to OSATs based in Southeast Asia and China or at company-internal facilities based in the same region. U.S. headquartered integrated device manufacturers (IDM) operate 48 of their 59 ATP facilities outside the United States, most of which are located in the Philippines (11), Malaysia (10), and China (9).[36] For example, though Intel maintains ATP facilities in the United States, it reports that its Vietnamese assembly and test factory is the company’s largest, employing 2,800 in a factory that has seen total investment of $1.5 billion. The company also recently announced plans to construct a $7 billion ATP facility in Malaysia (see Appendix 3 for a more complete list of recent investments in ATP and substrate-related facilities).[37]

Figure 5. Geographic Location and Number of ATP Facilities Globally, 2021



Source: SEMI assembly and test database.[38]

Cross-Cutting Opportunities

The previous section detailed several looming challenges that must be addressed concurrently with efforts to re-shore semiconductor fabrication:

- Geographic concentration of global ATP capacity and the associated materials ecosystem in Asia.
- A corresponding lack of ATP capacity and the associated ecosystem in the United States.
- Competitive firms in Asia that enjoy first-mover advantages and considerable advantage in terms of technology and market share.

This section recommends that U.S. policymakers use the statutory latitude afforded them in the CHIPS Act to partially focus efforts on re-shoring the broader ATP ecosystem, identifying incentives to encourage existing suppliers to expand capacity in the United States or allied countries, and funding innovation, especially in materials science, to create a commercially competitive ATP ecosystem. Specifically:

- **Fund innovation in upstream materials supply chains.** As examples, this section argues that funding innovation in hydrofluorocarbons, photoresist, and recycling of ultra-high purity process gases technologies all merit CHIPS Act funds.
- **Encourage re-shoring or near-shoring of ATP capacity and the associated ATP ecosystem.** As examples, this section argues that directing CHIPS Act funds toward establishing domestic substrate and PCB capacity targeting AI and HPC applications would improve supply chain resilience.

Upstream: Materials Supply Chain Innovation

CHIPS Act funds should focus on promoting innovation in semiconductor materials, beginning with hydrofluorocarbons. HFCs and other fluorinated greenhouse gases have been used in the semiconductor industry since the 1980s.[39] HFCs are used in semiconductor fabrication during the etch/wafer cleaning and chemical vapor deposition processes and are highly valued for their extreme purity.[40] Importantly, more advanced semiconductor fabrication techniques consume (and thus emit) HFCs more intensively.[41] This is because chips are being built on wafers vertically, increasing the density of the circuitry by "putting more layers down and etching more layers off using HFCs."[42] Efforts to identify replacement chemicals have not been successful, and HFC consumption/emissions are expected to increase substantially as the United States re-shores semiconductor fabrication in the coming years.[43] This trend presents an upcoming supply chain chokepoint for the U.S. semiconductor industry and potentially complicates U.S. commitments to international environmental agreements. The U.S. semiconductor industry "has no alternatives to HFCs yet," according to a leading industry association, but identifying such alternatives would present a win-win for supply chain resilience efforts and environmental protection goals.[44]

Another set of chemicals for which the semiconductor industry has not yet identified an alternative is photoresist. "Photoresist" refers to a family of customized chemicals that, when deposited on a bare wafer and exposed to patterned light (via a photomask), selectively dissolve and impart a circuit pattern.[45] The production of photoresist is dominated by the Japanese firm JSR Corporation, though other firms in Japan, South Korea, China, Germany, and the United States are also active in the market.[46] Notably, the two main U.S. suppliers are DuPont and an Oregon-based startup called Inpria (now owned by JSR Corporation). Production of extreme ultraviolet lithography (EUV) photoresist, which is used by firms like TSMC and Samsung to manufacture their most advanced chips, is almost entirely concentrated in Asia. While Inpria maintains a U.S. production presence for EUV photoresist, the scale of their production will be insufficient to meet anticipated demand and they are now owned by a Japanese firm. The U.S. firm Dupont is similarly focused on serving clients in Asia, having chosen to expand its EUV photoresist production capacity in South Korea rather than the United States in 2020.[47]

Like HFCs and photoresist, ultra-high purity process gases are intensively consumed during semiconductor fabrication, particularly during the deposition, etch, and lithography stages.[48] Production of these gases resides almost entirely outside the United States. Using CHIPS Act funds to encourage investment in recycling technologies at fabs would result in a win-win for supply chain resilience and environmental protection. The benefits of recycling process gases are well understood: done right, recycling can provide reliable supply at a predictable cost. The costs are equally well-understood: recycling requires investment in supplemental equipment as well as ongoing operating expenses, in addition to developing the know-how.[49] CHIPS Act funds should encourage industry to invest in recycling technologies at the fab level. This could be accomplished through two mechanisms: (1) preference receipt of CHIPS Act funds on applications from proposed fab projects that have a detailed recycling and environmental remediation plan for capturing atmospheric gases as well as ultra-high purity rare gases that exceed current industry best practices and/or (2) fund an industry consortium to develop and commercialize rare gas recycling technologies (separation, pressurization, and/or purification). This consortium could be housed under the National Institute of Standards and Technology's new metrology initiative funded by the CHIPS Act as NIST's Fluid Metrology Group already maintains a list of 49 semiconductor process gases.[50]

Downstream: ATP Capacity and Ecosystem

CHIPS Act funds should be directed to encourage creation of a commercially competitive advanced packaging ecosystem. Previous CSET research has encouraged re-shoring of high-volume advanced packaging capacity specifically as well as funding innovation in chiplets, fan out wafer level packaging, and equipment innovation.[51] This section provides more specific recommendations related to ATP capacity, substrate capacity, and PCB capacity as well as potential funding avenues and costs.

Because the U.S. ATP ecosystem is almost nonexistent, it is difficult to assess what it would cost to establish a high-volume advanced packaging facility, leading-edge substrate production, and commercially-viable printed circuit board production domestically. News reports and company filings help provide some context, however.

Publicly traded U.S. semiconductor companies' annual filings indicate their ATP facility locations and estimate the value of those assets in China, which is presumably one of the most cost-competitive locales for them to have established operations. Intel has previously estimated that it would cost anywhere from $650 million to $875 million to relocate its ATP facility from China to another country.[52] Its public financial filings also indicate that it estimates the current value of its China-based ATP facility at around $851 million.[53] Amkor Technology, a leading outsourced semiconductor assembly and test (OSAT) firm as well as Micron, onsemi, Qorvo, and Texas Instruments also own packaging facilities in China and assess these assets are worth anywhere between $200 million and $570 million (Table 2).[54]

Table 2. U.S. IDM and OSAT Facilities in China[55]

<table>
<tr><th>U.S. Firm</th><th>China ATP Facility Location</th><th>Total China PPE Value (2021)[56]</th></tr>
<tr><td>AMKOR</td><td>Shanghai</td><td>$432 million</td></tr>
<tr><td>Micron</td><td>Xi'an</td><td>$436 million</td></tr>
<tr><td>onsemi</td><td>Leshan</td><td rowspan="3">$217 million (total)</td></tr>
<tr><td>onsemi</td><td>Shenzhen</td></tr>
<tr><td>onsemi</td><td>Suzhou</td></tr>
<tr><td>Qorvo</td><td>Dezhou</td><td rowspan="2">$200 million (total)</td></tr>
<tr><td>Qorvo</td><td>Beijing</td></tr>
<tr><td>Texas Instruments</td><td>Chengdu</td><td>$570 million (shared w/ Shanghai R&D lab)</td></tr>
</table>

Source: Annual company filings.

Given China's low labor rates and favorable subsidies, these costs likely represent a lower-bound of overall facility cost (and, importantly, do not take into account operating expenses). Assuming costs in the United States are at least double, this suggests that if CHIPS Act funds are directed toward re-shoring high volume ATP capacity, U.S. policymakers should expect each new ATP facility would cost somewhere between $750 million and $1.5 billion.

The cost of establishing a substrate facility in Asia similarly represents a lower bound relative to the United States, but is helpful for assessing the overall rough order of magnitude. Samsung Electro-Mechanics (SEMCO), a subsidiary of the South Korean conglomerate, reportedly spent $910 million in 2021 to establish a substrate factory focused on advanced packaging in Vietnam. This is roughly the same cost estimate made by some industry analysts, who believe that a state-of-the-art substrate facility in the United States would cost over $1 billion and take two years to build.[57] In November 2022 a South Korean substrate supplier announced a $600 million substrate facility in Georgia, providing one example of U.S.-specific costs.[58] Alternately, U.S. policymakers could consider near-shoring ATP capacity, PCB and substrate production, and the broader materials ecosystem. Efforts are already underway by some border states in Mexico to increase their participation in the electronics supply chain, and Mexican government officials have announced their intent to offer incentives designed to attract semiconductor suppliers in 2023.[59]

Based on these observations, at least some CHIPS Act funds should be directed towards expanding the overall resilience of the ATP ecosystem in the United States. This could be accomplished via several different avenues:

- Preference receipt of CHIPS Act funds on applications that can demonstrate the proposed fab project will include a co-located advanced packaging facility.
- Preference receipt of CHIPS Act funds on applications that can demonstrate the proposed fab project will include investment in noble-/exotic-gas recycling commensurate with industry-leading best practices.
- Preference receipt of CHIPS Act funds on applications that can demonstrate the proposed fab project will outsource ATP to U.S.-based facilities or, barring that, facilities located exclusively in non-competitor countries.
- Leverage CHIPS Act funds via the Department of State's Technology and Innovation Fund to incentivize allied production of substrate and PCB capacity, ideally outside of Asia.

    - For example, the State Department could coordinate with the Department of Defense to expand substrate and PCB production in Mexico, particularly for substrates and PCBs used in national security systems.
- Leverage CHIPS Act funds via the Department of Defense's Semiconductor R&D Network to increase printed circuit board innovation domestically and in allied countries.
    - Consult with NSWC-Crane, the Department of Defense Executive Agent for Printed Circuit Boards, to review the past 10 years of DPA Title III funding, small business innovation research (SBIR) funding, and small business technology transfer (STTR) funding directed towards Department of Defense PCB production to assess what projects may merit further funding.[60]
    - Assess what the cost differential is between a high-volume PCB facility located in Asia and a similar facility in the United States or Mexico (both greenfield construction costs and reoccurring operational costs).
    - Determine current and forecast demand for semiconductors and printed circuit boards by service branch and program. Assess where this demand can be consolidated (either via prime contractor or across programs).
- Leverage CHIPS Act funds to encourage the construction of one high-volume U.S.-based substrate facility capable of providing ABF substrates for AI and HPC end uses.
    - Identify an existing firm engaged in substrate production and encourage formation of a joint venture or co-located facility with a current or proposed fab project domestically.
    - Create an industry consortium under the auspices of the National Advanced Packaging Manufacturing Program to pursue innovation in non-ABF substrates.

Conclusion

This paper finds that upstream and downstream chokepoints in the semiconductor supply chain present challenges to the U.S. government's goals of increasing semiconductor supply chain resilience using CHIPS Act funds. It recommends that, if appropriately allocated, CHIPS Act funds present an opportunity to increase microelectronics supply chain resilience far beyond re-shoring semiconductor fabrication. In support of this argument, this paper focuses specifically on the two ends of the microelectronics supply chain: upstream raw materials inputs and downstream ATP of finished microelectronics. It recommends that the government identify specific technology supply chain chokepoints and opportunities and target investments accordingly. This paper proposes several opportunities related to chemical production and recycling, as well as uses substrate and PCB manufacturing as examples.

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Appendix 1. Market for Select Materials, Chemicals, and Gases Used in Semiconductor Fabrication[61]

Material	U.S. Supplier	Market Leader	Other Suppliers
Silicon Wafer	N/A	Shin-Etsu	Zing Semi Siltronic Sumco SK Siltron Globalwafers
Photoresist	DuPont	JSR	Kempur Ruihong TOK Shin-Etsu Sumitomo Dongjin Merck
Photoresist Ancillaries	Brewer DuPont	Brewer	Kempur Ruihong Merck Nissan JSR Shin-Etsu Cheil
Photomask	Photronics	Toppan	Newway DNP
Electronic Grade Gases	Entegris	Merck	718 Huate Nata Air Liquide Linde Showa Denko Matheson Wonik SK Materials
Wet Chemical	CMC DuPont Entegris	BASF	Jianghuawei Jingrui Merck Kanto MGC Dongwoo Soulbrain
CMP Slurry and Pad	DuPont CMC	DuPont CMC	Anji Merck Fujifilm Hitachi Fujimi Fujibo JSR Cheil Dongjin
PVD Targets	Honeywell	JX Nippon	KFMI Linde Tosoh
ALD/CVD Precursors	Entegris	Merck	Nata/UpChem Air Liquide Adeka SKTC/TriChem Hansol
Electroplating Metals	Entegris DuPont	Entegris	Shinyang BASF
Spin on Dielectrics	N/A	Merck	Samsung SDI

Source: Bureau of Industry and Security, "Public Comment 52. SEMI. Kim Ekmark. 04/05/21," Regulations.gov, April 6, 2021.

Appendix 2. Market for ATP Products and Services[62]

Product or Service	Sub-Segment	Notable U.S. Supplier with Domestic Production Capacity	Market Leaders
Materials	Leadframes	None	SH Material (Japan), Mitsui High-Tec (Japan), ASM Pacific (China), Shinko (Japan), Kangqiang (China), Hualong (China), Trinity (China), Yongzhi (China)
	Bond wires	None	Heraeus (Japan), Tanaka Denshi (Japan), Nippon Micro (Japan), Doublink (China), Kangqiang (China), YesDo (China), KDDX (China)
	Ceramic packages	None	Amkor (U.S.), Quik-Pak (U.S.), NGK (Japan), Alent (U.K.), Hitachi (Japan), Kyocera (Japan), LG (South Korea), Sumitomo (Japan), BASF (Germany), Mitsui High-Tec (Japan), Henkel (Germany), Toray (Japan), Tanaka (Japan), Zhongwei (China), Yixing (China)
	Substrates	None	Ibiden (Japan), NanYa (Taiwan), Shinko (Japan), Samsung (South Korea), Shennan Circuits (China), Zhuhai Yueya (China), AKM (China)
	Encapsulation resins	None	Sumitomo (Japan), Henkel (Germany), Hitachi (Japan), Sinopaco (China), HHCK (China)
	Die attach materials	None	Henkel (Germany), Hitachi (Japan), Sumitomo (Japan), Darbond (China), Hysol Huawei (China), Y-Bond (China)
Equipment	Assembly inspection	KLA, Cohu	KLA (U.S.), ASM Pacific (China), ASTI (Singapore), Koh Young Tech (South Korea), Cohu (U.S.), MIRTEC (South Korea), Grand Tec (China), others

	Dicing	None	DISCO (Japan), Accretech (Japan), ASM Pacific (China), Longhill (China), SYNOVA (China), others
	Bonding - Die Attach	None	Besi (Netherlands), ASM Pacific (China), Fasford Tech (Japan), Canon (Japan), Hoson (China), PROTEC (South Korea), JIAFENG (China), DIAS Automation (China), others
	Bonding - Wire bonding	None	Kulicke & Soffa (Singapore), ASM Pacific (China), Hesse (Germany), Shinkawa (Japan), JIAFENG (China), DIAS Automation (China), others
	Bonding - Advanced interconnect	None	ASM Pacific (China), SSP (South Korea), KOSES (South Korea), DIAS Automation (China), others
	Packaging	None	TOWA (Japan), ASM Pacific (China), Besi (Netherlands), HANMI (South Korea), Trinity Tech (China), Grand Tec (China), DIAS Automation (China)
	Integrated assembly	None	ASM Pacific (China), Grohmann (Germany)
Assembly, Test, and Packaging	OSAT	None	ASE (Taiwan), Amkor (U.S.), JCET (China), Powertech (Taiwan), TongFu (China), Tianshui (China), UTAC (Singapore), others
	In-house (IDMs and Foundries)	Intel	Intel (U.S.), Samsung (South Korea), S.K. Hynix (South Korea), Micron (U.S.), TSMC (Taiwan), others
Printed Circuit Boards	N/A	TTM Technologies	TTM Technologies (U.S.), Unimicron (Taiwan), Ibiden (Japan), SEMCO (South Korea), Nan Ya PCB (Taiwan)

Appendix 3. Select Investments in Facilities Related to Semiconductor Materials and ATP, 2021 to Present[63]

Semiconductor Supply Chain Segment	Supplier	Product(s)	Announced Investment Total	Location
ATP	Intel	Advanced packaging	$3.5 billion	U.S.
ATP	SkyWater Technology	Advanced packaging	Unknown	U.S.
ATP	Northrop Grumman	Advanced packaging	Unknown	U.S.
ATP	Intel	Packaging and test	$7 billion	Malaysia
ATP	ASE Group	Packaging	$300 million	Malaysia
ATP	SEMCO	Packaging	$850 million	Vietnam
ATP	AMKOR	Packaging	$200 million	Vietnam
Materials	Linde	Ultra-high-purity nitrogen, oxygen and argon	$600 million	U.S.
Materials	Entegris	Electronic-grade chemicals and gases	$500 million	Taiwan
Materials	Merck	Electronic-grade chemicals and gases	$600 million	Taiwan
Materials	Merck	Electronic-grade chemicals and gases	$1 billion	U.S.
Materials	Air Liquide	Electronic-grade chemicals and gases	$500 million	Taiwan
Materials	Air Liquide	Ultra-high purity hydrogen, helium, and carbon dioxide	$60 million	U.S.
Materials	JSR	Photoresist	$514 million	U.S.

Materials	Shin-Etsu	Photoresist	$217 million	Taiwan, Japan
Materials	DuPont	Electronic-grade chemicals and gases	$50 million	U.S.
Materials	GlobalWafers	Silicon Wafers	$5 billion	U.S.
Materials	SK Siltron	Silicon Wafers	$302 million	U.S.
Materials	Edwards Vacuum	Vacuum and abatement products	$127 million	U.S.
Materials	Sunlit Chemical	Hydrofluoric acid	$100 million	U.S.
Materials	KPCT Advanced Chemicals	Electronic-grade sulfuric acid	$200 million	U.S.
Substrates	Nan Ya PCB	ABF substrates	$302 million	Taiwan
Substrates	AT&S	IC substrates	$2 billion	Southeast Asia
Substrates	SEMCO	IC substrates	$920 million	Vietnam
Substrates	STMicroelectronics	IC substrates	$754 million	Italy

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