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The Potential Role of the Secondary Market for Semiconductor Manufacturing Equipment

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Abstract

This study explores the role of the secondary market for semiconductor manufacturing equipment (SMEs) during crises. We gathered data from various sources, including industry reports and business-to-business (B2B) platforms that specialize in second-hand equipment. Our analysis also includes interviews with seven high-level executives from leading firms in the sector and academics, offering insights into the operational, financial, and strategic dimensions of the used equipment market. Based on this data and stakeholder feedback, we developed a framework that categorizes equipment by type and semiconductor manufacturing process, indicating that standard back-end SMEs benefit most from the secondary market, whereas customized front-end SMEs may benefit less. The study not only addresses gaps in equipment supply and academic literature but also provides a comprehensive overview of the used semiconductor equipment market and supply chain.

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1. Introduction

Semiconductor chips have become integral to many sectors, underscoring their importance in everyday life. They are essential components in many products ranging from cars and personal computers to smartphones and televisions. The COVID-19 pandemic and subsequent supply chain crisis significantly affected the availability of these chips and thus disrupted production across diverse industries (Bloomberg, March 29, 2021), causing companies to hoard inventories (Reuters, December 17, 2020, July 12, 2022). According to Bloomberg, the lead time of Broadcom Inc. has increased to 22.2 weeks from the previous 12.2 weeks before the pandemic (Bloomberg, March 29, 2021).

The crisis of chip shortage was further exacerbated by the Russian-Ukraine conflict, which impacted the supply of neon, a vital ingredient for chip production. Approximately 54% of the world's neon supply, sourced from Ukrainian companies such as Ingas and Cryoin, was disrupted due to the conflict (Reuters, March 11, 2022). This disruption caused a significant threat to chip prices and availability. In an interview conducted in October 2021, Carl Mellander, the Chief Financial Officer at Ericsson, mentioned that the company faced challenges in delivering specific hardware to its clients (YahooFinanace, October 19, 2021). This issue was primarily due to a shortage of chips from suppliers and was exacerbated by logistical issues that caused a drop in the company's revenue (YahooFinanace, October 19, 2021).

The automotive sector, a significant consumer of semiconductor chips, experienced substantial setbacks due to this shortage. As highlighted during COVID-19, a missing 10-cent chip can still delay production on a $30,000 car (Zhou, 2022). In fact, the chip shortage, a consequence of the pandemic, caused car manufacturers to prioritize their limited chip supplies for their more profitable models (Voas, Kshetri, & DeFranco, 2021). The chip scarcity affected 964,000 vehicles in 2021 (Klayman, February 3, 2021). Furthermore, the automobile industry was anticipated to face a revenue loss of $61 billion in 2021 due to this shortage (Nicholas, January 27, 2021). For instance, Toyota Motor Company faced a decrease in its global output of cars and trucks by around 40% in October 2021 as a direct consequence of chip scarcity during COVID-19 (TheNewYorkTimes, September 10, 2021). In the months following the COVID-19 crisis,

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Volkswagen, Honda, Nissan, and Stellantis reported significant declines in sales due to chip shortage (Reuters, August 23, 2023; TheNewYorkTimes, Janaury 5, 2023). Similarly, Tesla's market position was adversely affected, with a roughly 5% drop in share value (Reuters, October 30, 2023). Furthermore, the Czech car sector projected a reduction of 250,000 vehicles in a year due to the chip shortage (Reuters, October 17, 2021). Thus, the semiconductor chip shortage has not only highlighted the fragility of global supply chains but also emphasized the critical interdependence of modern industries.

Notably, the impact of the chip shortage extended beyond the automotive industry, significantly affecting other sectors (Alamo et al., 2021), like the medical sector (FinancialTimes, February, 21 2023; TheWallStreetJournal, October 3, 2021). In other words, semiconductors are widely used across various sectors, including medical devices, computers, mobile phones, gaming systems, energy systems, and defense technologies (Ludwikowski & Sjoberg, 2021). In 2021, the US government launched a 100-day examination of essential supply chains, particularly targeting semiconductor chips, medical equipment, batteries, and rare earth minerals, to decrease reliance on international suppliers (Ramani, Ghosh, & Sodhi, 2022). While a small fraction of the world's chips is used in medical equipment compared to other sectors like automotive and consumer electronics, these chips are essential in devices like MRI machines, ventilators, pacemakers, and blood-sugar monitors. As emphasized by Mick Farrell, CEO of ResMed Inc., each chip can be life-saving, particularly in ventilators for patients struggling to breathe (TheWallStreetJournal, October 3, 2021). However, medical device makers have a lower priority for chip producers since they often place smaller orders, meaning medical device sectors will face additional challenges in addressing chip shortages in the medical sector (FinancialTimes, February, 21 2023). Therefore, the chip shortages have continued to impact the medical device sector, affecting the sales of surgical robotic technology and wound-protecting products, even as major chipmakers begin to recover their supply.

These events highlight the vital role of semiconductor chips in the modern technological landscape and underscore the vulnerabilities and interdependencies within global supply chains. Also, the ripple effects from this crisis created a necessity for increasing capacity in the semiconductor supply chains. However, increasing the capacity of the semiconductor supply chain

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is challenging. Firstly, it requires a huge investment. The supply chain is worth about half a trillion dollars (Khan, Mann, & Peterson, 2021). Building a semiconductor plant can cost more than $10 billion, and it requires specialized engineers (Lund, Manyika, Woetzel, Barriball, & Krishnan, 2020). This is why such expansion often needs government support. For instance, the U.S. government passed bills to provide over $50 billion to encourage building semiconductor facilities[1]. In contrast, the Chinese government allocates approximately $15 billion annually to support its semiconductor industry (Bloomberg, March 1, 2018). This level of subsidization represents a much higher percentage of the revenue of the recipient companies compared to government subsidies provided to firms in other countries (Khan et al., 2021).

Secondly, the manufacturing process is very complex. Producing a single computer chip can involve over 1,000 steps, and the chip might cross international borders around 70 times before it reaches the customer (Khan et al., 2021), causing a long lead time. A critical stage in semiconductor production is wafer fabrication, a process that is technologically complex and requires substantial financial resources (Ramani et al., 2022; Swaminathan, 2000). For instance, constructing a fabrication facility may require an investment of $4-20 billion, around two years for construction, and an additional two to three years of operational learning to achieve optimal production yields (Yang, Yang, & Fitch, 2021). Moreover, expenses related to acquiring advanced tools and equipment, research and development (R&D), and training for workers can increase costs by millions of dollars (Swaminathan, 2000; Yang et al., 2021). Beyond financial considerations, semiconductor manufacturing also demands a considerable amount of skilled labor and experiential learning, which makes the replication or imitation of this process challenging (Appleyard, 1996). Hence, the challenges associated with expanding capacity in the semiconductor industry, such as the substantial capital investment required for new facilities, the lengthy construction and ramp-up periods, and the complexity of the manufacturing process, can significantly constrain the supply of semiconductors.

[1] The two bills, United States Innovation and Competition Act of 2021, S.1260, 117th Cong. § 1002 (a)(2) (2021) and America COMPETES Act of 2022, H.R.4521, 117th Cong. § 1002(a)(2) (2022), would appropriate funding for the Creating Helpful Incentives to Produce Semiconductors for America Act (CHIPS Act), (included in the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (NDAA FY2021), Pub. L. No. 116-283, div. A, tit. XCIX, §§ 9901-9908, 134 Stat. 3388, 4843 (2021) (codified at 15 U.S.C. §§ 4651-4658).

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The secondary market for semiconductor manufacturing equipment might offer some opportunities for the challenges mentioned above. This includes trading used, surplus, or refurbished semiconductor components and equipment. It offers an alternative for manufacturers and consumers to obtain necessary semiconductor parts faster and often at lower costs than waiting for new production capacity to come online. This can be particularly valuable during periods of acute shortage like a pandemic, allowing for a more flexible and responsive supply chain that can adapt to sudden changes in demand or supply disruptions.

In response to these challenges and opportunities, we are investigating the following research question:

- Does the secondary market play a crucial role for semiconductor manufacturing equipment?

The secondary market of semiconductor equipment is growing. For example, in 2022, Moov's platform facilitated the procurement of second-hand equipment worth several million dollars for its Korean clients (YahooFinanace, March 1, 2023). With its headquarters in Tempe, Arizona, and Austin, Texas, Moov operates as a tech-centric marketplace and asset management platform, connecting buyers with sellers of second-hand semiconductor manufacturing equipment. Essentially, Moov offers a digital marketplace that provides real-time services and a comprehensive management, transaction, and fulfillment system. This allows manufacturers globally to trade used semiconductor equipment quickly and effortlessly. In fact, Moov experienced a sales surge of over 200% in 2021 compared to the previous year. The global value of the secondary market is estimated to be at least $10 billion annually, with expectations for it to near $50 billion annually in the coming years (Zhou, 2022). Also, given the limited competition in certain areas of the semiconductor equipment market, used equipment can be a strategic move to introduce competition, potentially leading to better prices and terms for new equipment purchases.

Although Moov Technologies witnessed a significant increase in sales within the secondary semiconductor market and demonstrated the potential to mitigate shortages during crises, the secondary market of the semiconductor industry has yet to fully adopt established e-business models designed to integrate the aftermarket into global supply chains (Hickey & Kozlovski,

Dr. Jafar Namdar and Dr. Maria Jesus Saenz*
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2020). Several barriers hinder the semiconductor industry's supply chain from effectively incorporating used equipment, with Moore's Law being a primary factor (Moore, 1965). Moore's Law posits that the density of transistors on a microchip doubles roughly every two years, simultaneously reducing the cost of computers by half. This principle has pushed the semiconductor industry towards computational power and efficiency. Consequently, major semiconductor manufacturers prioritize R&D and chip design over other considerations. This focus leads to allocating significant engineering resources to projects to improve yields, which can save millions of dollars. As a result, less attention is given to activities like the classification and valuation of components for resale in the aftermarket, which might only represent a few hundred dollars in value (Hickey & Kozlovski, 2020).

The other challenge related to incorporating aftermarket processes could be the high level of specialization and the lack of standardization. After a company picks a supplier, that supplier will be the only seller because its technology gets locked in with the company's manufacturing process (Pillai, 2013). This will lead to a high level of specialization. Additionally, a significant obstacle to developing reverse logistics (secondary market) within the semiconductor industry is the practice of Original Equipment Manufacturers (OEMs) assigning various product numbers to identical items. Essentially, the lack of standardized communication and information sharing across various components of the supply chain has previously been identified as a key obstacle to the implementation of used marketplaces (Loukis, Spinellis, & Katsigiannis, 2011). Table 1 summarizes the challenges and obstacles within the secondary semiconductor market.

Table 1: Obstacles and challenges within the secondary semiconductor equipment

Obstacle	Description
Technical knowledge complexity	There is limited information about the functionality and modifications of secondary equipment. When examining e-trading in the secondary market, limited information is shared by the seller or broker regarding the functional attributes, operational efficiency, and the historical maintenance and repair records of the equipment.
Market knowledge unavailability	In the semiconductor aftermarket, many traders prefer secrecy and self-serving tactics. This results in a lack of transparent pricing and visibility for the end users who buy and sell through third-party brokers.
Inconsistent Product Identification	The lack of standardized communication across the supply chain is a major barrier to setting up B2B marketplaces. Product descriptions frequently change as they move through the supply chain, leading to challenges like search issues, potential mismatches in equipment, and high transaction costs.

MIT Digital Supply Chain Transformation Lab
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IP Protection Considerations	Many innovations cannot be protected, yet they can still offer substantial advantages. Also, there is a general mistrust among participants in the secondary market for semiconductor equipment, and major players are concerned about the risk that components sensitive to IP might fall into the hands of competitors.
Lack of Systematic Reverse Logistics	The adoption of reverse logistics in the semiconductor secondary market is hindered by two factors. I. Cutting-edge OEMs must stay in line with Moore's Law, or risk being overtaken by competitors. Hence, they prioritize R&D above everything else. II. Large OEMs focus on securing contracts for next-generation technologies, which results in a supplier monopoly once chosen, restricting the resale of refurbished equipment to other manufacturers and reducing market flexibility.
Note: The information of this table is extracted from (Hickey & Kozlovski, 2020)	

2. Semiconductor Ecosystem

Before exploring the complexities of the secondary market for semiconductor equipment, it is essential to understand the semiconductor supply chain and its market dynamics clearly. By mapping out the journey of semiconductor production—from the procurement of raw materials to the complicated manufacturing and global distribution processes—we can identify the critical stages and interdependencies that define this sector's operational efficiency. Also, understanding the semiconductor market's dynamics, especially the supply-demand equilibrium and demand cyclicality, is vital. This foundational knowledge contextualizes the significance of equipment technology and highlights the market's responsiveness to innovation and scalability in the semiconductor domain.

2.1.Semiconductor Supply Chain

Figure 1 is a visual representation of the semiconductor ecosystem, which we learned after interviewing several executives. This illustration outlines the flow of processes within the semiconductor ecosystem, beginning with the design phase (Upstream), proceeding through manufacturing processes (Midstream), and ending with the delivery of final products to consumers (Downstream). The Upstream segment focuses on Integrated Circuit (IC) design and differentiates between two types of companies: Integrated Device Manufacturers (IDMs) and Fabless firms. IDMs, represented by Samsung and Intel, manage both design and manufacturing internally, whereas Fabless companies like Apple, AMD, Qualcomm, and Nvidia concentrate solely on design and outsource manufacturing operations. Generally, more than 80% of semiconductor design and innovation is concentrated in the US (GAO, 2022).

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Although IDMs are vertically integrated, some outsource certain production and assembly tasks. This process is known as the "fablite" approach (Varas, Varadarajan, Goodrich, & Yinug, 2021). Currently, the IDM model is more prevalent among firms specializing in memory and digital-analog-optimized (DAO) products, which are generally versatile (multipurpose) components with greater scalability. In 2019, IDMs accounted for approximately 70% of global semiconductor sales (Varas, Varadarajan, Goodrich, & Yinug, 2021).

Initially, the IDM model dominated the semiconductor industry. However, the growing investment requirements in research and development (R&D) and capital expenditure led to the growth of the fabless-foundry model. This means that the fabless model gained popularity starting in the 1990s due to the increasing complexity of semiconductor innovation, which made it challenging for many firms to manage both the capital-intensive manufacturing processes and the high R&D expenditure required for design (Varas, Varadarajan, Goodrich, & Yinug, 2021). Since fabless companies prioritize design and outsource fabrication, assembly, packaging, and testing tasks. They typically rely on foundries and Outsourced Semiconductor Assembly and Test (OSAT) companies for fabrication. While logic chips are predominantly produced by fabless companies, exceptions include Intel and, to a lesser extent, Samsung. This trend is driven by the rapid demand for high-performance capabilities, particularly for smartphones and emerging applications in Artificial Intelligence (AI). Noteworthy, as semiconductor technology is going towards smaller manufacturing nodes, the share of total semiconductor sales by fabless firms increased from less than 10% in 2000 to almost 30% by 2019, as reported by BCG (Varas, Varadarajan, Goodrich, & Yinug, 2021).

Moving the midstream section of Figure 1, which includes the Semiconductor Manufacturing process, involves Wafer Fabrication, Assembly, and Testing. Companies involved in wafer fabrication, such as TSMC, Global Foundry, UMC, SMC, and Powerchip, rely heavily on semiconductor equipment manufacturers and suppliers of semiconductor materials. Fabrication generally involves utilizing up to 300 distinct inputs, encompassing raw wafers, essential chemicals, specialized chemicals, and bulk gases (Varas, Varadarajan, Goodrich, & Yinug, 2021). Notable semiconductor equipment providers include Applied Materials, ASML Holding, Lam Research, and Tokyo Electron.

MIT Digital Supply Chain Transformation Lab
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Materials used in front-end manufacturing of semiconductors play a critical role, each serving specific functions essential for producing high-quality semiconductor devices. These materials include polysilicon, silicon wafers, photomasks, photoresists, wet processing chemicals, gases, and chemical mechanical planarization (CMP) slurries (Varas, Varadarajan, Goodrich, & Yinug, 2021). Polysilicon, renowned for its ultra-refined purity levels, acts as the foundation for semiconductor wafer production. Silicon wafers, derived from melted polysilicon, undergo meticulous processes such as slicing, cleaning, polishing, and oxidation to prepare them for circuit imprinting within fabrication facilities. Photomasks, featuring intricate patterns of opaque and clear areas, enable precise control of light exposure during the lithography process. Photoresist, applied as a crucial layer on silicon wafers, undergoes chemical reactions upon light exposure, facilitating pattern imprinting during lithography. Wet processing chemicals, including solvents, acids, etchants, and strippers, play pivotal roles in etching and cleaning steps during semiconductor manufacturing. Gases serve multifaceted purposes, shielding wafers from atmospheric exposure and serving as dopants, dry etchants, and components in chemical vapor deposition processes. Finally, Chemical Mechanical Planarization (CMP) slurries aid in polishing wafer surfaces post-film deposition, ensuring optimal flatness for subsequent manufacturing steps. Back-end materials include lead frames, organic substrates, ceramic packages, encapsulation resins, bonding wires, and die-attach materials. They typically have relatively lower technical barriers to produce compared to front-end materials (Varas, Varadarajan, Goodrich, & Yinug, 2021).

Additionally, sourcing materials is vital for the manufacturing process, with Dow Chemical being a significant player in this domain. In the Downstream domain, the path of manufactured semiconductors is outlined, leading to Original Equipment Manufacturers (OEMs) and Original Design Manufacturers (ODMs), ultimately reaching consumer markets through devices like smartphones, IoT gadgets, and computers.

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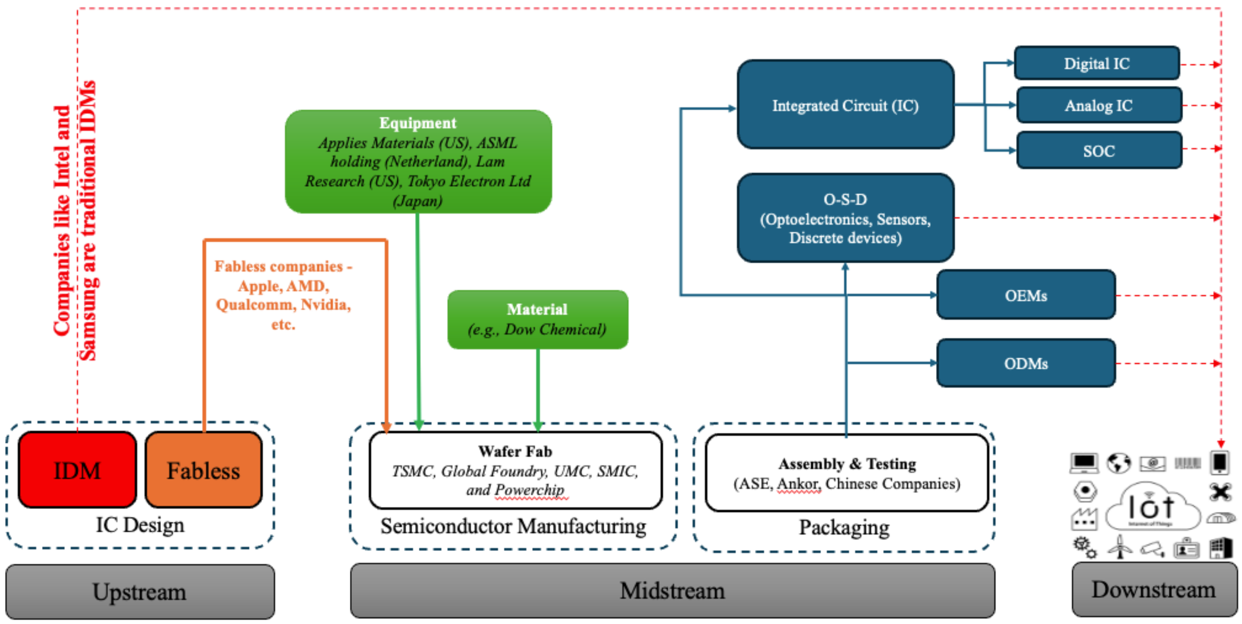

Figure 1: Overview of Semiconductor Ecosystem

Figure 1 further categorizes ICs into three branches: Digital, Analog, and System-on-a-Chip (SOC). Digital ICs encompass a variety of components such as CPUs, GPUs, FPGAs, ASICs, MCUs, and DSPs, as well as storage devices like DRAM, NAND flash, and NoR flash. Analog ICs include devices such as GBT, GaN, AD/DA, Power Discrete, and Modules. Lastly, SoCs combine the functionality of digital, analog, and often radio-frequency functions on a single chip. This integration allows for compact and energy-efficient solutions ideal for mobile devices, smart gadgets, and automotive control systems. An SoC can be found at the heart of every smartphone, where it controls everything from processing user inputs to managing cellular connections and running applications. Hence, Figure 1 offers a relatively comprehensive overview of the semiconductor industry's organizational framework, highlighting the interconnectedness and interdependencies within the ecosystem.

MIT Digital Supply Chain Transformation Lab
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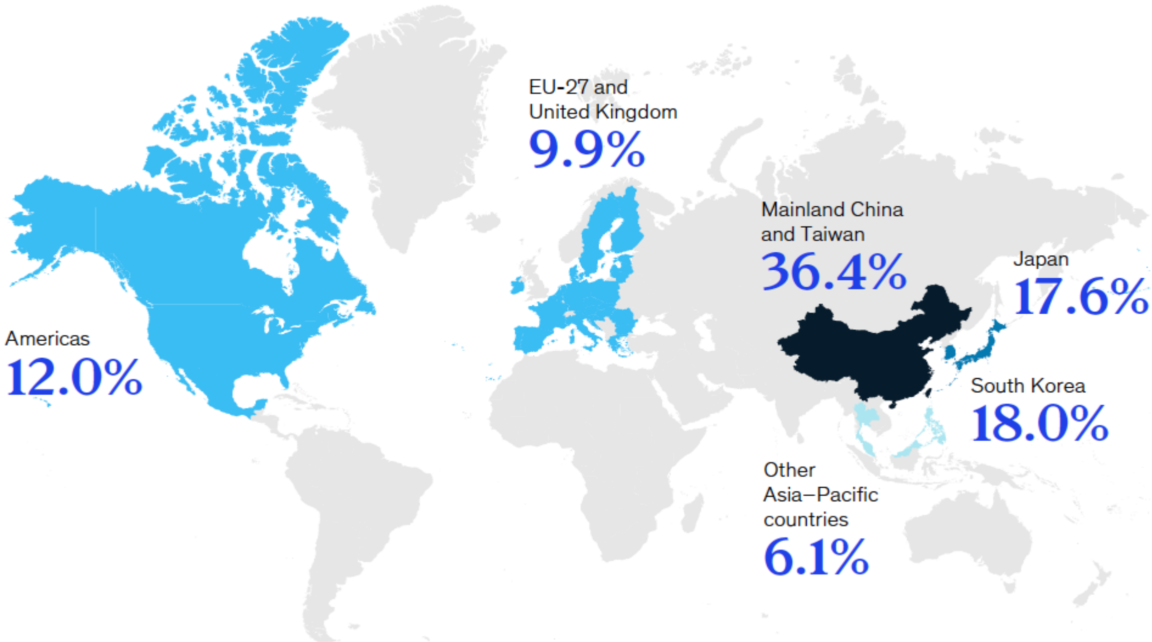

Figure 2: Semiconductor Concentration, adopted from McKinsey Global Institute (MGI) (Lund et al., 2020)

2.2. Dynamics of the Semiconductor and Semiconductor Equipment

In this section, we examine the market dynamics of the semiconductor industry through the lens of demand and supply. By breaking down our examination into these two subsections, we thoroughly understand the market's ever-changing nature.

2.2.1. Dynamics of Semiconductor Manufacturing Equipment (SME)

Cutting-edge SMEs are created by companies in the United States, Japan, and Europe, drawing on extensive international research and development endeavors (GAO, 2022). For instance, a Dutch company named ASML is the exclusive manufacturer of EUV scanners, which are considered the most advanced photolithography equipment available. Additionally, both ASML and the Japan-based company Nikon exclusively produce ArF immersion scanners, which are regarded as the next most advanced type of equipment in this field (GAO, 2022). The TRUMPF Group, a German company specializing in industrial machinery production, stands out as the sole provider of advanced Laser & power sources. This includes a CO2 laser backed by a 1MW power supply and a sophisticated cooling system (Varas, Varadarajan, Goodrich, & Yinug, 2021). Moreover, ASML

MIT Digital Supply Chain Transformation Lab
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holds a 17 percent share in the Semiconductor Manufacturing Equipment (SME) market, with 97 percent of its operations concentrated in the production of scanners and steppers. In contrast, prominent SME firms in the United States such as Applied Materials, Lam Research, and KLA, jointly command a 36 percent share in the SME market. These U.S. companies specialize in offering a diverse range of SME products, with a particular focus on deposition, etching, and process control tools (GAO, 2022). Since the goal of this study is the secondary market of SMEs, we provide a detailed analysis of SMEs in the following sections.

2.2.2. Semiconductor Manufacturing

The global distribution of semiconductor and consumer electronics exports is highly specialized, with Taiwan contributing 43% of the world's electronic integrated circuits and South Korea accounting for 50% of semiconductor memory products.[2] Moreover, the most sophisticated semiconductor fabrication facilities, capable of producing technology at or below 10 nanometers, are exclusively situated in South Korea (8%) and Taiwan (92%) (Lund et al., 2020). These locations represent critical vulnerabilities, as any disruptions from natural disasters, infrastructural failures, or geopolitical tensions could lead to significant interruptions in the global semiconductor chip supply (Lund et al., 2020).

While the semiconductor industry exhibits concentration, each region has distinct roles within the global supply chain. For instance, the Asia-Pacific region is in charge of nearly 80 percent of global wafer manufacturing capacity, whereas the United States and Europe excel in power semiconductor and CPU manufacturing (Varas, Varadarajan, Goodrich, & Yinug, 2021). In other words, the US takes the lead in R&D-intensive activities such as EDA and core IP, chip design, and manufacturing equipment. Conversely, Asia dominates in raw materials and manufacturing processes, encompassing wafer fabrication, assembly, packaging, and testing, which are notably capital-intensive.

Also, materials used in semiconductor manufacturing are regionally concentrated (Varas, Varadarajan, Goodrich, & Yinug, 2021). Silicon dioxide, primarily mined in the US, undergoes refinement to produce metallurgical-grade silicon. This silicon is then melted and re-crystallized

[2] 2018 exports for product codes HS854239 (electronic integrated circuits) and HS854232 (semiconductor memory products).

MIT Digital Supply Chain Transformation Lab
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into a single large crystal, known as an ingot, by a polysilicon manufacturer based in Japan. Subsequently, the ingot is sliced into multiple wafers in South Korea, where they undergo polishing before being transported to a fabrication plant.

2.2.3. Demand Dynamics of Semiconductors

The semiconductor sector is a fundamental factor in the economy, exhibiting consistent growth rates (Aubry & Renou-Maissant, 2013). For example, between 2001 and 2022, semiconductor demand increased from $139 billion to $573.5 billion, marking a significant 313 percent growth. Also, semiconductor prices have increased by 290 percent during the same timeframe, highlighting the increased demand for these components across various sectors of the economy (Robert Casanova, 2023). In fact, a study conducted in 2020 by the Semiconductor Industry Association (ISA) and the Boston Consulting Group (BCG) projected that global demand for semiconductor manufacturing capacity will increase by 56% by 2030 (Varas et al., 2021). With this expected upward trajectory and the increasing demand for chips, semiconductor firms have to increase their investments in research, design, and manufacturing capabilities.

However, the semiconductor industry is notorious for its cyclical nature (Aubry & Renou-Maissant, 2013), and the book-to-bill ratio is one of the most important metrics used to track these cycles (Tan & Mathews, 2010). This means the cyclical nature of the semiconductor demand is not confined to a time of crisis like COVID-19.

Several factors may lead to this cyclical nature of the semiconductor industry. The primary factor contributing to challenges in the semiconductor industry is known as the bullwhip effect, which is more pronounced compared to other industries (Forrester, 1997; Senge, 1990). Since semiconductors serve as intermediary goods with diverse applications, even minor fluctuations in demand within end consumer markets can lead to significant fluctuations in production, inventory levels, and investment within the upstream semiconductor sector. In fact, semiconductor demand is driven by end-users who purchase electronic devices, leading to global demand variation for semiconductors (Varas, Varadarajan, Goodrich, & Yinug, 2021).

Moreover, the establishment of semiconductor fabrication plants involves substantial investments and time commitments (Tan & Mathews, 2010; Wu, Erkoc, & Karabuk, 2005), resulting in notable delays and distortions in decision-making processes for firms due to feedback loops.

The semiconductor manufacturing process involves numerous steps, ranging from 400 to 1,400, depending on the specific product. This means the semiconductor supply chain is highly global. The cycle time to fabricate finished semiconductor wafers averages around 12 weeks, but for advanced processes, it can extend to 14-20 weeks. This extensive process requires a wide array of inputs, including raw wafers, various chemicals, and specialized equipment, across multiple stages and regions. Consequently, due to the complexity and duration of this manufacturing process, semiconductor lead times can be considerable and volatile (Varas, Varadarajan, Goodrich, & Yinug, 2021). Such volatility may contribute to demand quality.

Although holding inventory is a common strategy to mitigate the bullwhip effect and mitigate demand cyclicality, it is impractical in the semiconductor industry due to the high cost and rapid obsolescence of chips. Indeed, one industry expert highlighted in our interviews noted, "Semiconductor firms avoid holding inventories as it can significantly impact their stock prices." Additionally, the industry faces intense competition akin to strategic games (Tan & Mathews, 2010). According to Liu (2005), competition for market dominance between Taiwan's two largest semiconductor foundry companies, Taiwan Semiconductor Manufacturing Company (TSMC) and United Microelectronics Corporation (UMC), results in cyclicality in pricing, production, and capacity.

Lastly, changes in technology also play a big part in the ups and downs of the semiconductor industry. This industry is known for advancing quickly, following Moore's law, which means both products and processes get better (Dosi, 1982; Mathews & Cho, 2000). This fast progress leads to shorter product lifespans, lower prices, new uses for chips, and uncertainty in the market, all affecting how the industry cycles. For instance, when a new type of chip technology comes out, it often creates cyclical demand due to a big demand for computers, which then boosts processor sales (Tan & Mathews, 2010).

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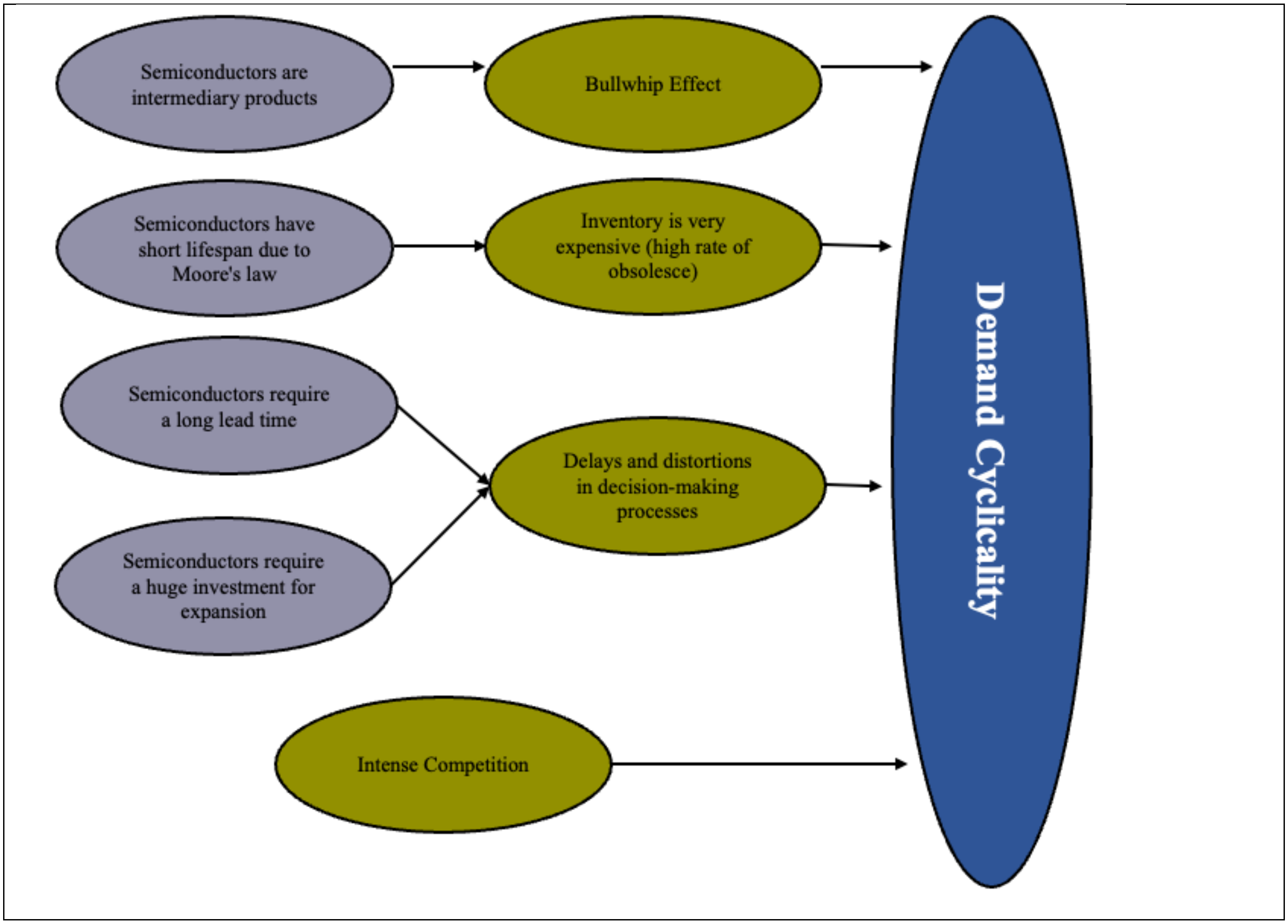

Figure 3: Factors Contributing to Cyclical Demand in Semiconductor Industry

3. Semiconductor Manufacturing Equipment (SME)

In this research, we focus on the secondary market for semiconductor manufacturing equipment (SME), covering both the back-end and front-end manufacturing processes, as detailed in Table 2. Front-end semiconductor manufacturing needs significant investment due to the extensive scale and complex equipment required. For instance, lithography, as one of the most important equipment of front-end manufacturing tools, stands out as one of the major investments for companies involved in semiconductor fabrication, determining the chip's level of sophistication that a facility can achieve (Varas, Varadarajan, Goodrich, & Yinug, 2021). Cutting-edge lithography equipment, particularly those utilizing Extreme Ultra-Violet (EUV) technology, are necessary for manufacturing chips at 7 nanometers and smaller. Each EUV machine carries a heavy price tag of $150 million. Generally, a modern semiconductor fabrication facility with standard capacity necessitates capital expenditure ranging from approximately $5 billion for advanced analog fabs to as much as $20 billion for advanced logic and memory fabs (Varas, Varadarajan, Goodrich, & Yinug, 2021). Typically, semiconductor manufacturing firms allocate 30 to 40% of their annual revenues to capital expenditure. Consequently, wafer fabrication alone constitutes around 65% of the total industry capital expenditure and contributes 25% to the value added. The majority of this manufacturing activity is concentrated in East Asia, particularly in Taiwan, South Korea, Japan, and mainland China (Lund et al., 2020).

The back end also requires considerable investments in specialized facilities. Companies focused on assembly, packaging, and testing typically allocate more than 15% of their annual revenues toward facilities and equipment. Although this stage requires less capital compared to front-end fabrication and relies more on labor, developments in advanced packaging are changing this landscape. Back-end activities represent 13% of the overall industry capital expenditure and contributed 6% to the industry's total value added in 2019 (Varas, Varadarajan, Goodrich, & Yinug, 2021). These operations are primarily concentrated in Taiwan and mainland China, with recent expansions observed in Southeast Asia, including Malaysia, Vietnam, and the Philippines (Lund et al., 2020).

Table 2: The semiconductor manufacturing equipment (SME) market considered in this study

Equipment	Description
Lithography	A process that involves transferring complex circuit patterns onto a silicon wafer. The process of lithography involves: • Drawing complex circuit patterns on a photomask, • Reducing the patterns using ultra-high-performance lenses, • Exposing the reduced patterns onto a silicon wafer, also known as a wafer.
Wafer Cleaning Equipment	Wafer cleaning equipment is used to remove contaminants from the surface of a wafer during the fabrication of microelectronic devices. The equipment is used to clean the semiconductor wafer prior to various processing steps, such as etching, deposition, and photolithography.
Deposition	Deposition is a process that deposits a blanket of materials on a surface. There are multiple ways to do this, including selective deposition, atomic-layer deposition, chemical vapor deposition and physical vapor deposition.

MIT Digital Supply Chain Transformation Lab
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Bonding	Semiconductor bonding equipment is used to bond two or more semiconductor wafers together to create a single structure. Semiconductor bonding equipment typically includes: • A microscope • A heated stage • A heated wedge or capillary to apply pressure to the wire at the interface of the bonding surface • A wire-feed mechanism
Dicing	Dicing equipment is an instrument used in the process of dicing, which is the final step in the semiconductor process flow. Dicing is the process of separating die from a semiconductor wafer after the wafer has been processed.
Metrology	Semiconductor metrology equipment is used to measure and characterize the physical and electrical properties of wafers after semiconductor processing. These instruments are designed to inspect thin films and wafers in-line after processing.

4. Data Collection

In this research, data was meticulously collected from various sources such as industry reports, in-depth interviews with executives, and prominent B2B platforms dedicated to the trade of second-hand semiconductor equipment.

To gain a deeper understanding of the market dynamics, we interviewed seven high-ranking executives from major corporations that play a significant role in this sector. These interviews provided valuable insights into the operational, financial, and strategic aspects of the used semiconductor equipment market.

Additionally, the study explores various B2B platforms that serve as critical hubs for buying and selling such equipment, analyzing their role in the ecosystem, market influence, and the breadth of information they offer about the equipment listed. The platforms are listed in Table 3. It is worth noting that some of these platforms provide detailed documentation and transparency regarding the specifications, condition, and pricing of the semiconductor machinery, which significantly aids in market analysis. This multi-faceted approach to data collection ensures a comprehensive view of the market landscape, offering stakeholders valuable insights into trends, opportunities, and challenges within the used semiconductor equipment sector.

In our data collection process, we employ different versions of each SME name. For example, when examining lithography, we search for terms like "photolithography" and "lithography" combined with "semiconductor" and "equipment." It's important to note that we restricted the time frame from 2010 to March 2024. This choice was deliberate because many equipment pieces become obsolete after a few years and might not be relevant to our study.

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Table 3: Platforms Utilized for Data Collection on Used Semiconductor Equipment

Platform	Website	Description
Catalyst Equipment	https://www.catalystequipment.com/	Catalyst Equipment specializes in trading all forms of used and refurbished semiconductor equipment, from wafer manufacturing to back-end processing, globally. The platform engages with buyers and sellers of both cutting-edge and mature tools and technologies, dealing with single items, complete production lines, and facilities, and are eager to collaborate with various organizations.
CSI SEMI	https://www.csisemi.com/	CSI Semiconductor Solutions Ltd offers a wide range of used and refurbished equipment to global clients in the semiconductor industry, including silicon wafer manufacturing, assembly, testing, and the solar and flat panel sectors.
EquipNet	https://www.equipnet.com/	EquipNet leads in global surplus asset management, boasting a cutting-edge equipment marketplace. Serving clients worldwide, from small enterprises to Fortune 500 companies, EquipNet ensures maximum financial returns, safety standards, and sustainability initiatives.
Fabsurplus	https://www.fabsurplus.com/	Fabsurplus was one of the first companies to re-market used semiconductor-related manufacturing equipment using the internet.
Infuneon	https://surplus.infineon.com/index.htm	Infineon's "Equipment Trade" department offers a platform for finding used semiconductor equipment, providing options for both selling surplus tools and sourcing refurbished or second-hand equipment globally.
LabX.com	https://www.labx.com/	Platform for new, used and refurbished lab equipment, supplies and services.
Machinio	https://www.machinio.com/	Machinio is the biggest global site for buying and selling machinery. They use technology to help buyers and sellers connect and make deals. Many dealers trust Machinio to help sell their equipment by introducing them to lots of new buyers.
Moov Technologies Inc.	https://moov.co/	Moov operates as an online marketplace, creating a worldwide network of purchasers, vendors, service professionals, logistics experts, and insurance providers, all committed to fostering a dependable and sustainable secondary market for semiconductor manufacturing machinery.
4Semi	https://www.4semi.com/	4Semi is an online directory that shows available or extra semiconductor equipment

The summary of collected data from platforms is presented in Table 3. The majority of the collected data is coming from vendor Fabsurplus (63%), followed by Machinio (12%) and Moov Technologies Inc. (7%). In terms of equipment types, Lithography (2%) and Wafer Surface Cleaning (1%) are the least frequently listed among the vendors. Conversely, Metrology (22%) equipment and Dicing (14%) are the most frequently listed equipment categories. Furthermore,

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different platforms exhibit varying frequencies of equipment. For instance, the predominant equipment listed on 4Semi is Dicing, whereas Infineon has not listed any Dicing equipment, and the majority of the equipment listed on Machinio is related to Assembling and Packaging.

Table 4: Summary of Collected Data from Vendors Listed in Table 3

Equipment	Vendor									
	4Semi	Catalyst Equipment	CSI SEMI	EquipNet	Fabsurplus	Infuneon	LabX.com	Machinio	Moov Technologies Inc.	**Total**
Lithography	3 (2%)	2 (1%)	135 (76%)	25 (14%)	2 (1%)	2 (1%)		6 (3%)	2 (1%)	177
Wafer Cleaning Equipment	163 (5%)	24 (1%)	37 (1%)	1 (<1%)	2776 (88%)	31 (1%)	2 (<1%)	87 (3%)	29 (1%)	3150
Deposition	20 (6%)	66 (19%)	34 (10%)	5 (1%)	61(18%)	9 (3%)		17 (5%)	132 (38%)	344
Bonding	63 (6%)	13 (1%)	161 (15%)		182 (17%)	22 (2%)		371 (34%)	276 (25%)	1088
Dicing	278 (22%)	276 (22%)	12 (1%)	4 (<1%)	575 (47%)		3 (<1%)	32 (3%)	56 (5%)	1236
Metrology		7 (1<%)	16 (1%)	6 (<1%)	1810 (94%)	8 (0%)		71 (4%)	14 (1%)	1932
Total	52 (1%)	388 (5%)	395 (5%)	41 (1%)	5433 (68%)	72 (1%)	5 (<1%)	584 (7%)	590 (7%)	7927 (100%)

Note: We limited the time frame from 2010 to March 2024. This decision was made because many pieces of equipment become outdated after a few years and may not be particularly relevant for this study. The collected raw data is available upon request.

- **Lithography**

Lithography is one of the most critical equipment in semiconductor manufacturing. Lithography involves creating circuit designs on a layer by first applying a photoresist over the material. This process uses a lithography tool that shines light through a photomask—a clear plate imprinted with the circuit design—to imprint this design onto the photoresist layer (The creation of photomasks also employs lithography tools) (Khan et al., 2021). The Netherlands and Japan are the sole suppliers of sophisticated lithography machinery, particularly extreme ultraviolet (EUV) scanners and, to a lesser extent, argon fluoride (ArF) immersion scanners, which are essential for manufacturing advanced semiconductor chips (GAO, 2022). More importantly, only one company based in the Netherlands is the sole global provider of advanced lithography equipment essential for producing cutting-edge semiconductors, as reported by the US Government of Accountability Office (GAO, 2022). ASML dominates the lithography market with an 82.9% market share, followed by Canon and Nikon. ASML's market share is more than 8x larger than second-place (KhaveenInvestments, 2023). The entire market cap of lithography is around $14 billion, which is summarized as EUV Scanners ($3.1 billion), ArFi scanners ($5.8 billion), ArF scanners ($0.78

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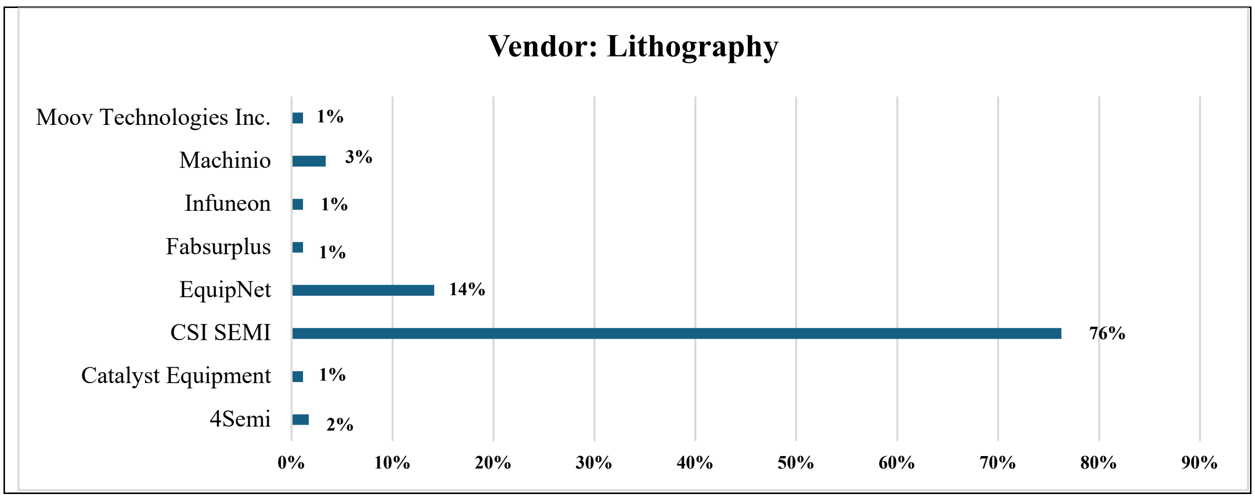
billion), KrF steppers (0.96 billion), i-line Steppers ($0.69 billion), Mask aligners ($0.12 billion), Chip making ($20 million), Mask making (0.50 million), Imprint lithography ($24 million), Resist processing ($2.1 billion).

As presented in Figure 4, the majority of second-hand or used lithography equipment in our sample is listed by CSI SEMI (76%), followed by EquipNet (14%). Geographically, the majority of lithography equipment is located in East Asia/Pacific (69%), followed by the US (8%). Notably, certain vendors lack detailed information about their equipment and its attributes. The literature identifies this issue as "Market knowledge unavailability," as discussed in Table 1. In the secondary market of semiconductors, many traders prioritize secrecy and self-serving strategies, resulting in a lack of transparent pricing and visibility for end users who engage in transactions through third-party brokers (Hickey & Kozlovski, 2020). We observed a similar trend in our data collection process, where out of 177 lithography equipment instances, only 36 specified their location.



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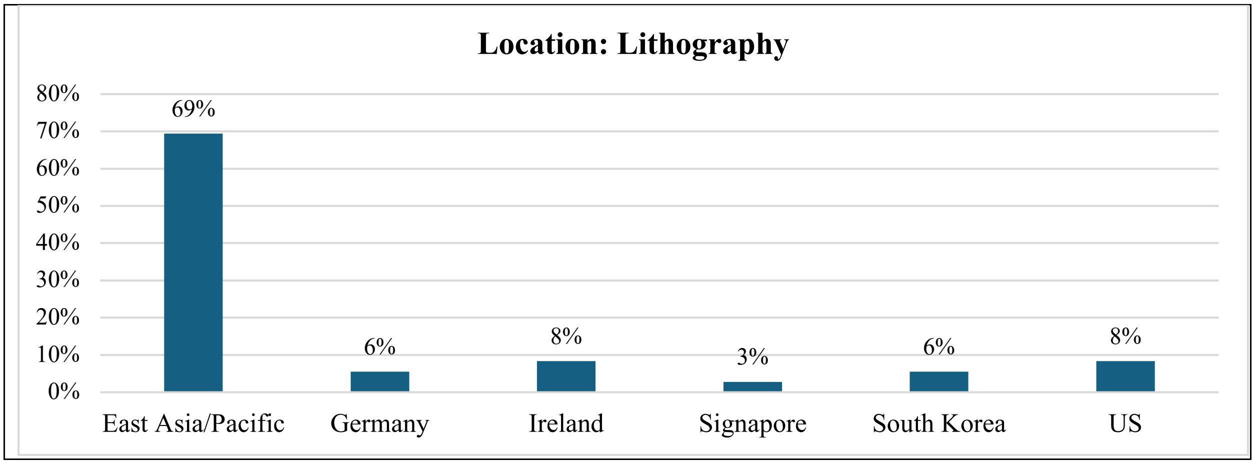

Figure 4: Summary of the Used Lithography Equipment by Vendor and Location

- **Wafer Cleaning**

The fabrication process of semiconductors, particularly ICs, requires precision at a very small scale and relies on specialized inputs and equipment (GAO, 2022). The ICs are constructed within cleanrooms, which are carefully controlled environments designed to prevent contamination by airborne particles that could affect the properties of the electronic materials. To provide context, the ambient air in a regular urban setting contains approximately 35,000,000 particles sized 0.5 microns or larger per cubic meter. In contrast, semiconductor manufacturing cleanrooms maintain strict standards, allowing for zero particles of that size (Varas, Varadarajan, Goodrich, & Yinug, 2021). Cleaning also involves removing residual materials from a wafer, such as those left behind after etching. Etching tools are crucial for creating permanent patterns in chips: after photolithography removes specific portions of a photoresist layer on a wafer, etching tools etch that pattern into the underlying substrate.[3] Following this process, cleaning tools are used to eliminate the etched materials (GAO, 2022). Etching and cleaning tools come in two main types: dry and wet. Dry etching tools, which utilize gases to etch the substrate, are the most prevalent and are particularly essential for intricate circuit features at advanced nodes. On the other hand, wet etching tools, which employ liquids, are less commonly utilized and are primarily used for wafer cleaning purposes. Japan and the United States lead in the production of wet etching and cleaning tools, while China and other countries also have a share in the market. Wet etching offers certain

[3] Etch, Applied Materials, accessed September 4, 2020, http://www.appliedmaterials.com/semiconductor/products/etch/info

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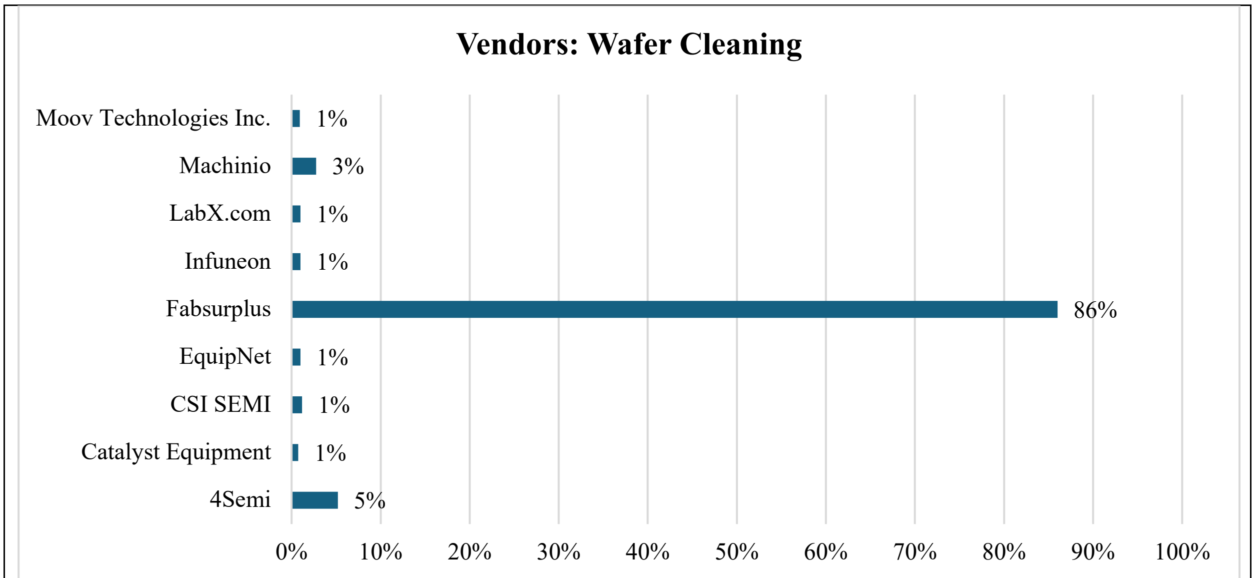
advantages over dry etching: it is cost-effective, poses less risk of damaging substrates, and allows for more selective etching, meaning it can target specific materials without affecting nearby ones unintentionally (GAO, 2022). However, it is slower and less capable of etching in different directions, which makes it challenging to create complex structures. Figure 5 presents a summary of the SMEs utilized for the cleaning process. According to our sample, Fabsurplus is the most active vendor in the cleaning process tools. Furthermore, the majority of these tools are located in the United States (75%) followed by Ireland (9%).



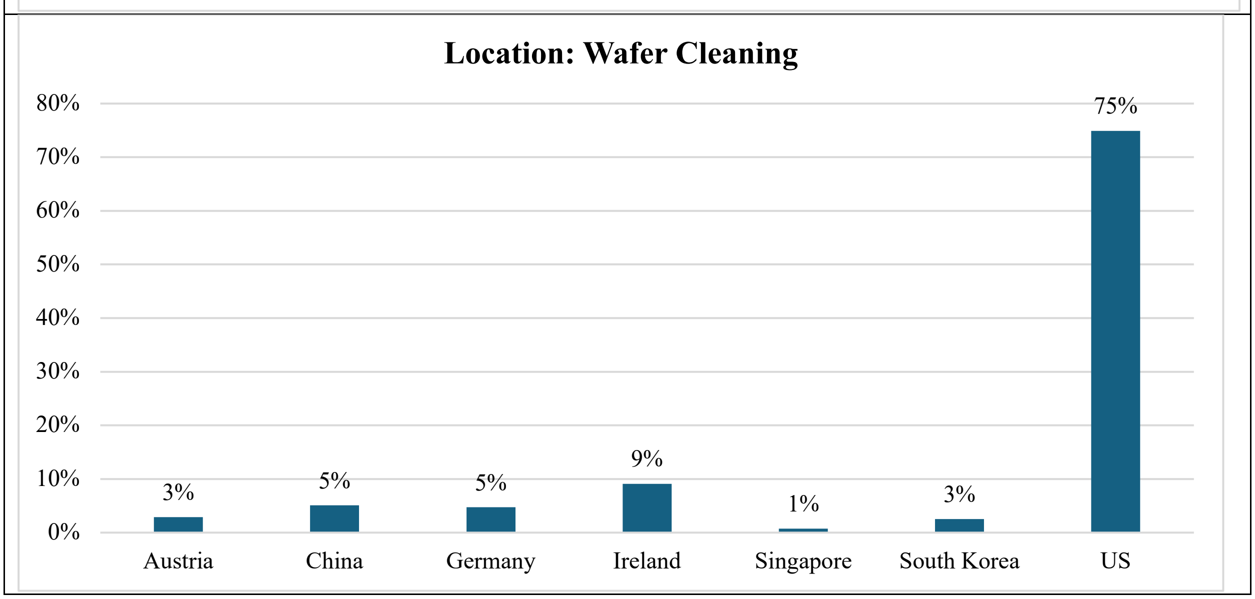


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Figure 5: Summary of the Used Wafer Cleaning Equipment by Vendor and Location

- **Deposition**

Deposition involves adding thin layers of materials onto a wafer to create components of chips. Various techniques are used, including chemical vapor deposition (CVD), physical vapor deposition (PVD), electrochemical coating, spin-coating, rapid thermal processing, and tube-based diffusion. Among these, advanced chemical vapor deposition (CVD) can be a major bottleneck. The United States, Japan, the Netherlands, and South Korea are key providers of deposition tools, with China also emerging in certain subsectors of the deposition market (GAO, 2022).

Plasma CVD has the largest market share, valued at $3.5 billion, with top firms including Applied Materials (U.S.), Lam Research (U.S.), ASML (Netherlands), Piotech (China), and SKY Technology Development (China). China's market share in CVD is currently only 0.7%. Similarly, low-pressure CVD and atomic layer deposition hold market shares of $1.4 billion and $1.6 billion, respectively, with concentrations in the U.S. and Europe, while China's share is less than 1% (GAO, 2022).

The United States, the Netherlands, Japan, and South Korea are the main producers of CVD tools, with China also increasing its capabilities in this area. CVD tools generate a chemical vapor that deposits films on the wafer atom-by-atom or molecule-by-molecule. Widely utilized in chip fabrication, CVD is employed to deposit most dielectrics (a type of insulator), silicon, and certain metals. ALD, capable of depositing layers as thin as a single atom, is particularly crucial for cutting-edge nodes.[4] However, in the Deposition (non-ICs) segment, China holds a significant market share of 13.2 percent, which is higher than its overall market share of 1.8 percent in the deposition market. AMEC and ASM Pacific are prominent Chinese manufacturers in this domain. Meanwhile, the United States and Japan dominate the production of deposition tools for various applications such as microelectromechanical systems (MEMS), disk drives, compound semiconductors, advanced packaging, and other products beyond chips (GAO, 2022). Figure 6 presents a summary of the second-hand SMEs utilized for deposition. Our sample indicates that

[4] For example, ALD is used to create fine structures in FinFETs, which are the predominant transistor structure used in leading-edge chips. Dennis Hausmann, "How Atomic Layer Deposition Works," Semiconductor Engineering, March 15, 2018, https://semiengineering.com/a-look-at-atomic-layer-deposition-2/.

MIT Digital Supply Chain Transformation Lab
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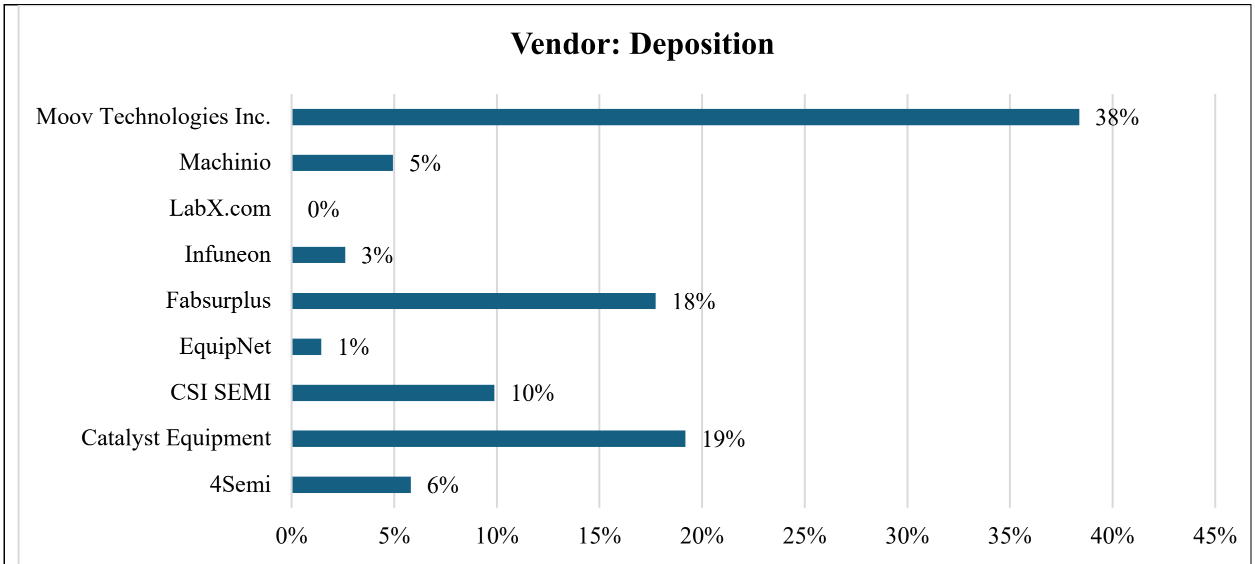
Moov Technologies Inc. provided the majority of the deposition tools. Furthermore, the majority of these tools are situated in the United States (68%), followed by Europe (29%) and Asia (4%).



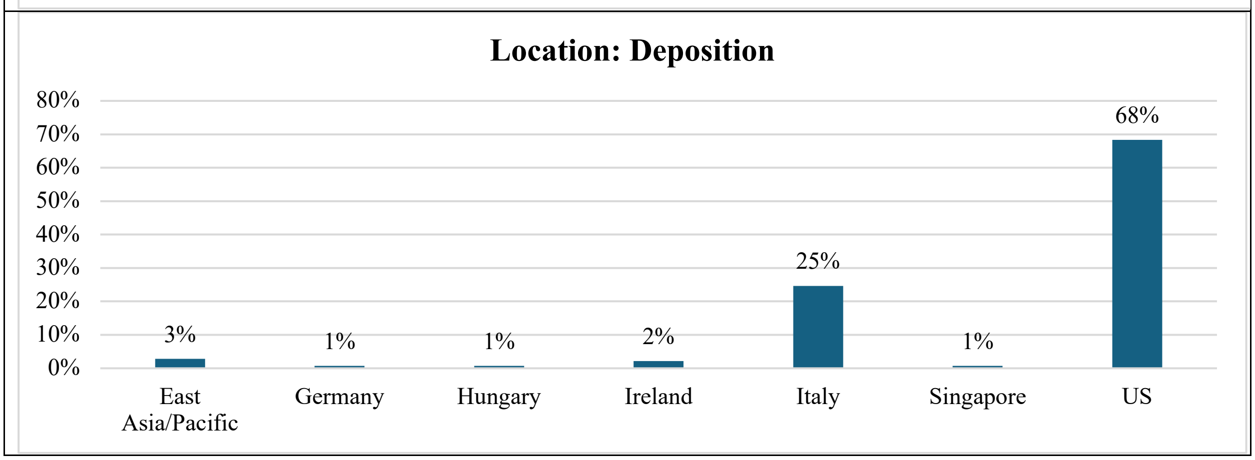


Figure 6: Summary of the Used Deposition Equipment by Vendor and Location

- **Dicing**

Dicing is part of the assembly and packaging process, which is considered the back-end of semiconductor manufacturing. Dicing tools are used to cut individual chips (dies) from the wafer and separate them. This process also involves thinning the wafer. Dicing tools include blade saws, laser saws, dicing accessories, and backside grinding equipment. The market for dicing tools is valued at approximately $0.69 billion. Figure 7 presents a summary of the second-hand SMEs utilized for dicing. The data indicates that Fabsurplus provided a majority of the dicing tools. Furthermore, the majority of these tools are situated in the United States (94%).

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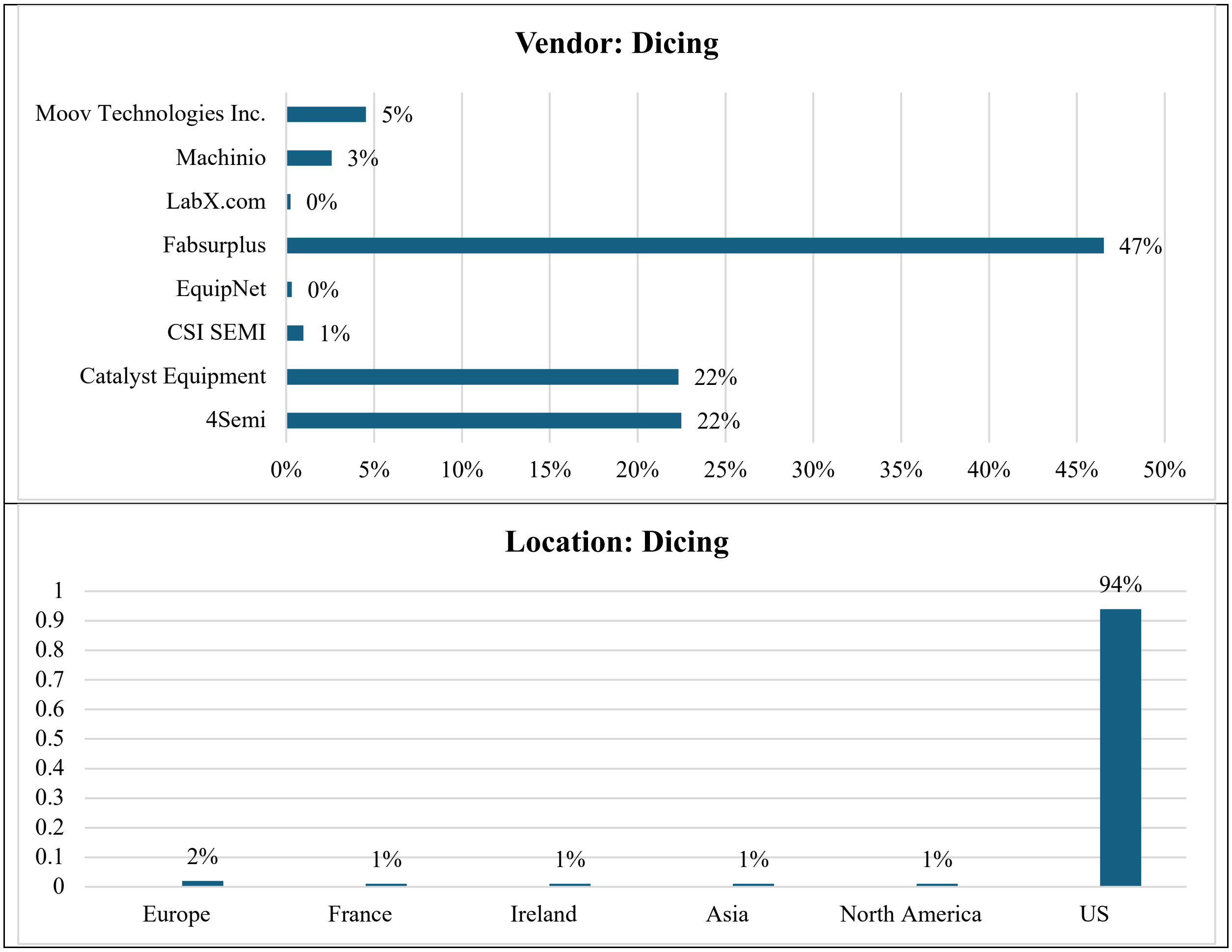

Figure 7: Summary of the Used Dicing Equipment by Vendor and Location

- **Bonding**

Bonding tools are part of the back-end manufacturing process, specifically within assembly and packaging. They encompass die attach tools, which connect dies to lead frames or substrates, wire bonders for making interconnects between lead frames and die pads, and advanced interconnect tools. The overall market for bonding equipment is valued at approximately $1.35 billion. China plays a significant role in this market, holding a dominant position in various segments (GAO, 2022). Specifically, China commands 35% of the market share in die attaching, 20.8% in wire bonding, and 33.0% in advanced interconnect technologies. Figure 8 presents a summary of the SMEs utilized for bonding. The data indicates that Machinio and Moov Technologies Inc. are the most active vendors in the bonding market. Furthermore, the majority of these tools are located in the United States (41%) and Ireland (40%).

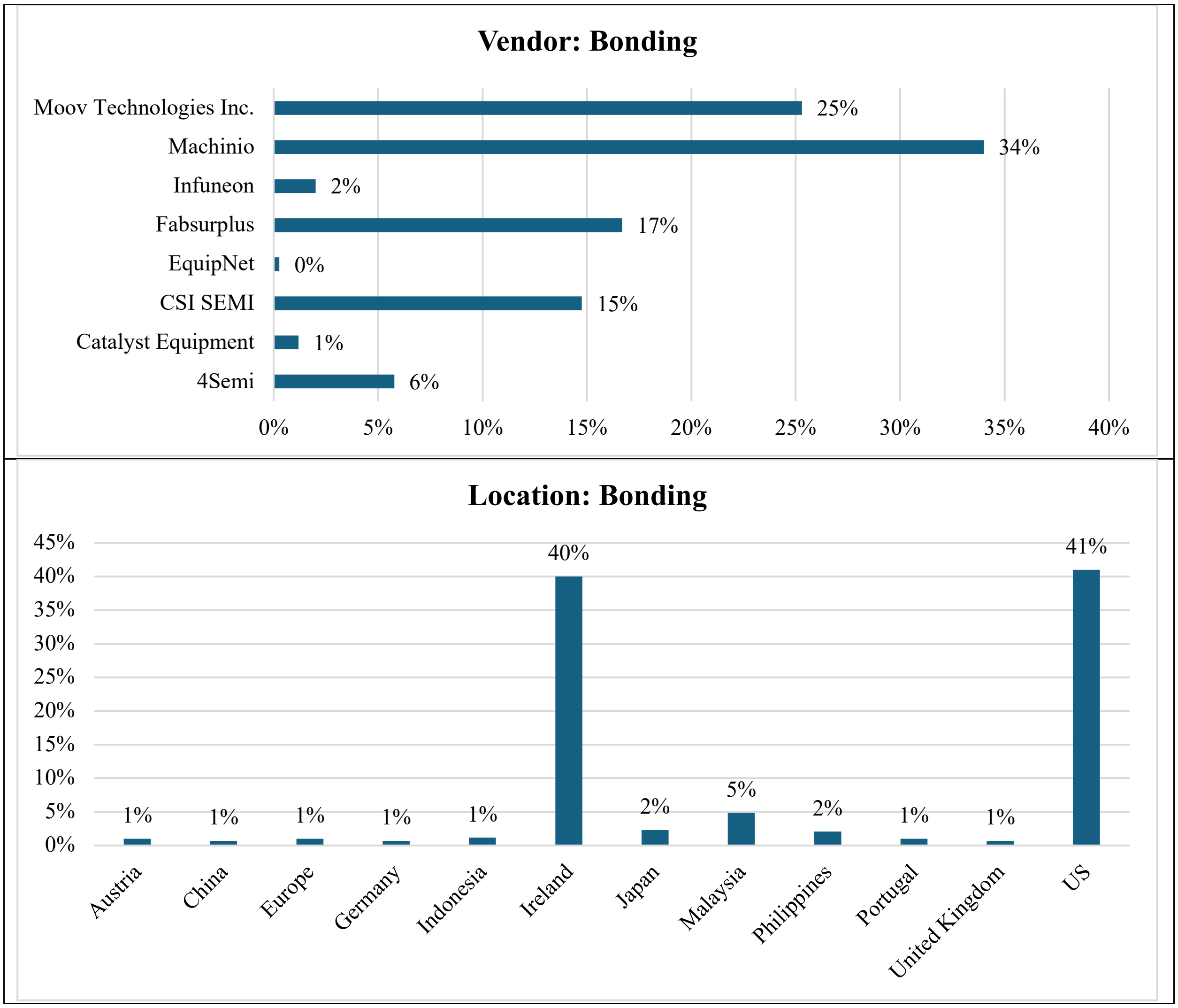

Figure 8: Summary of the Used Dicing Equipment by Vendor and Location

- **Metrology**

Metrology and inspection equipment play a crucial role in controlling the semiconductor manufacturing process. Given the complexity of the process, spanning several steps over one to two months, any defects detected early on could invalidate all subsequent work, leading to wasted time and resources. To mitigate this risk, stringent metrology and inspection procedures are implemented at key stages of the semiconductor manufacturing process, ensuring that a certain level of yield is achieved and maintained (GAO, 2022). Figure 9 presents a summary of the SMEs utilized for Metrology. The data indicates that Fabsurplus is the most active vendor in the

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metrology market. Furthermore, the majority of these tools are located in the United States (47%) and South Korea (40%).

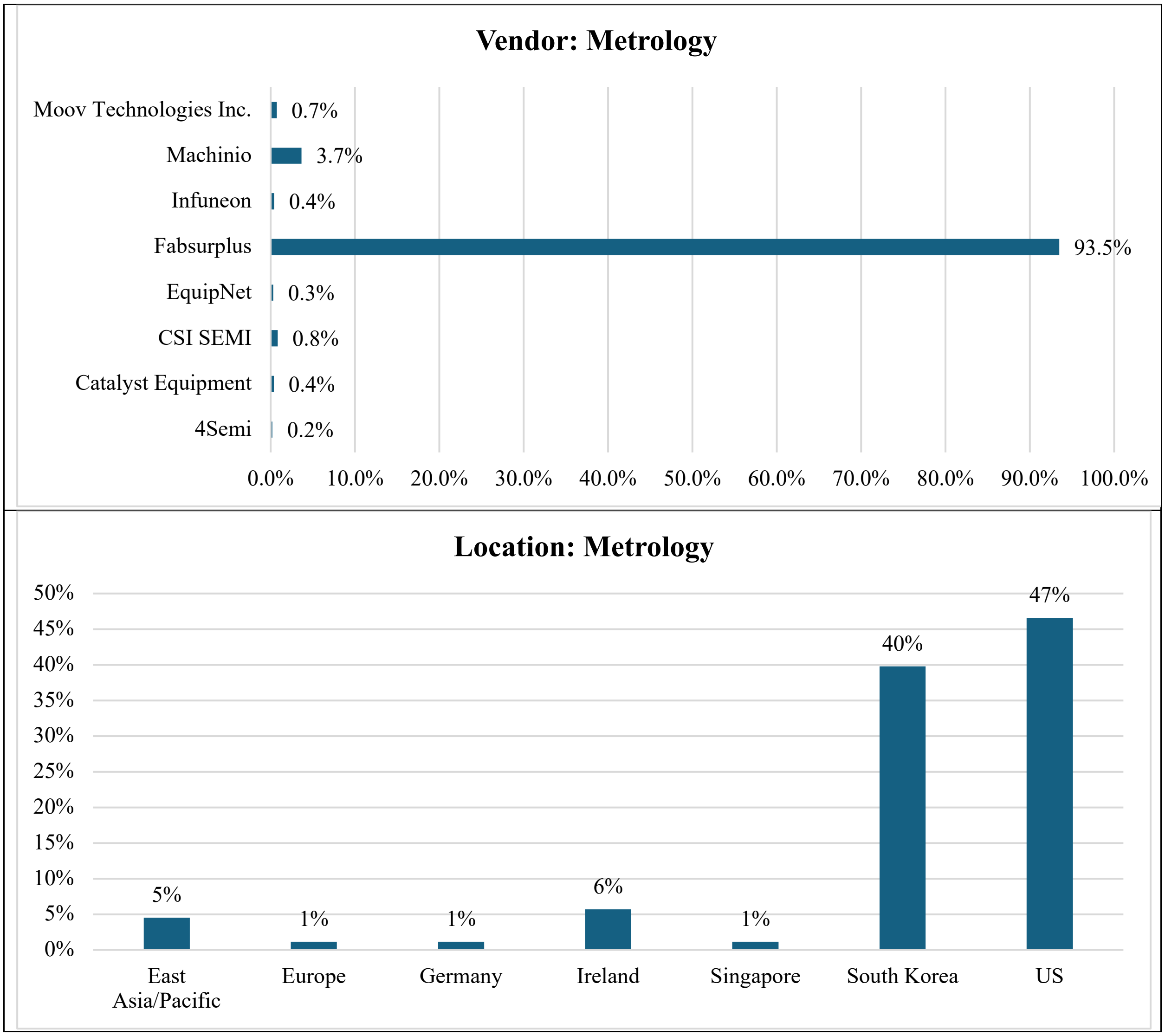

Figure 9: Summary of the Used Metrology Equipment by Vendor and Location

5. Framework of Secondary Market Potential for Semiconductors Equipment

After analyzing the different drivers of the semiconductor ecosystem, in Figure 10, we present a framework that helps understand the secondary market potential for semiconductors equipment. The 2x2 matrix looks at equipment type and semiconductor process. The X-axis categorizes equipment into customized and standard, and the Y-axis focuses on the semiconductor manufacturing process. In fact, the Y-axis refers to front-end and back-end processes. Front-end

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processes involve the initial stages of semiconductor manufacturing, such as creating integrated circuits on the silicon wafer through processes like photolithography, while back-end processes involve final assembly and packaging of semiconductor chips.

During our interviews, we learned that standard equipment is active in the semiconductor industry's secondary market. Standard equipment is not tailored to any specific manufacturing process or chip design, making it widely applicable across different manufacturing settings. This type of equipment is versatile and can be used to manufacture various types of semiconductor chips at different stages of the production process. These stages include the front end, where the chips are designed and their initial layers are constructed, and the back end, where chips are completed, packaged, and tested. For instance, a standard photolithography machine used in both front-end layering processes for different types of semiconductor chips, like memory and microprocessor chips, exemplifies standard equipment. It does not require unique or specialized adjustments to operate across different product lines. Another example would be metrology, one of the standard equipment active in the secondary market of SMEs.

In contrast, customized equipment can hardly be found in the secondary market of SMEs. Intellectual property (IP) rights are mentioned as another reason that may stop customized equipment from entering the secondary market. This type of equipment is designed specifically for producing a particular type of semiconductor chip and often comes with a "recipe," or set parameters and programming tailored to create a specific product. This customization is necessary for chips requiring unique production processes that standard equipment cannot accommodate. For example, a deposition machine customized to deposit a special material used only in high-performance processors is an example of customized equipment. This machine would be designed with specific settings, temperatures, and chemical deposition rates that are optimal for the specialized material used in these processors.

Moreover, we learned during our interviews that customized equipment like photolithography is typically used for innovative products with short-life products, such as iPhones and personal computers (PCs), which might require very advanced chips, which subsequently require advanced manufacturing technologies. For example, the production process of a single computer chip typically involves over 1,000 intricate steps, crossing international borders more than 70 times before reaching the end user. Each of these locations is highly specialized in one step of production, meaning they are using highly customized equipment with highly specialized skilled workers. For instance, cutting-edge products like PCs and AI tools rely on logic chips to process digital data (comprising zeroes and ones) and generate outputs. The production of such chips poses significant challenges, with only a handful of countries possessing the necessary technological capabilities. Primarily, the United States leads in designing most of the world's logic chips, while countries like South Korea, Europe, Japan, Taiwan, and China hold smaller shares. These chips encompass various types, such as microprocessors like CPUs, microcontrollers, digital signal processors, field programmable gate arrays (FPGAs), graphics processing units (GPUs), and others. Essentially, the manufacturing of such products is heavily influenced by Moore's Law. For instance, a "node" signifies a technology generation; a chip developed at a new node (e.g., "5 nm" introduced in 2020) contains roughly twice the transistor density of a previous node (e.g., "7 nm" introduced in 2018), making it more cost-effective as well.

According to the company representatives who participated in this study, standard SMEs are typically used for producing functional or durable items like kitchen appliances such as blenders, toasters, or refrigerators, which often utilize older, legacy chips in their production. This is because the primary innovation in these products is not reliant on advanced chip technology, and furthermore, their life cycles typically extend longer than those of innovative products. Therefore, we anticipate that functional products gain more benefits from SMEs' secondary equipment than innovative products. Firstly, because functional products are typically considered in the durable goods industry and have longer life cycles, manufacturers often offer extended guarantee periods and maintenance services. This makes older SMEs valuable for producing legacy chips and ensuring warranty coverage. Indeed, in one of our interviews, it was mentioned that certain chips must be manufactured using the exact same equipment to maintain compatibility with the entire system, citing the example of Boeing. In this context, where aircraft or tanks may require maintenance and service for up to 25 years, the chips used must be produced using the original equipment to be compatible with other parts of the system or product.

Another interviewee also noted that large companies such as Texas Instruments or TSMC typically do not purchase secondary semiconductor equipment for chip production. Instead,

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secondary market equipment is commonly acquired by entities like R&D departments, research startups, universities, and educational institutions for educational or research purposes.

Additionally, purchasing from the secondary market may not always be feasible because the equipment needs to be compatible with the entire production system, including preceding and subsequent steps. This compatibility becomes especially crucial when the machine is used to manufacture chips for aerospace or marine applications, as strict regulations must be adhered to.

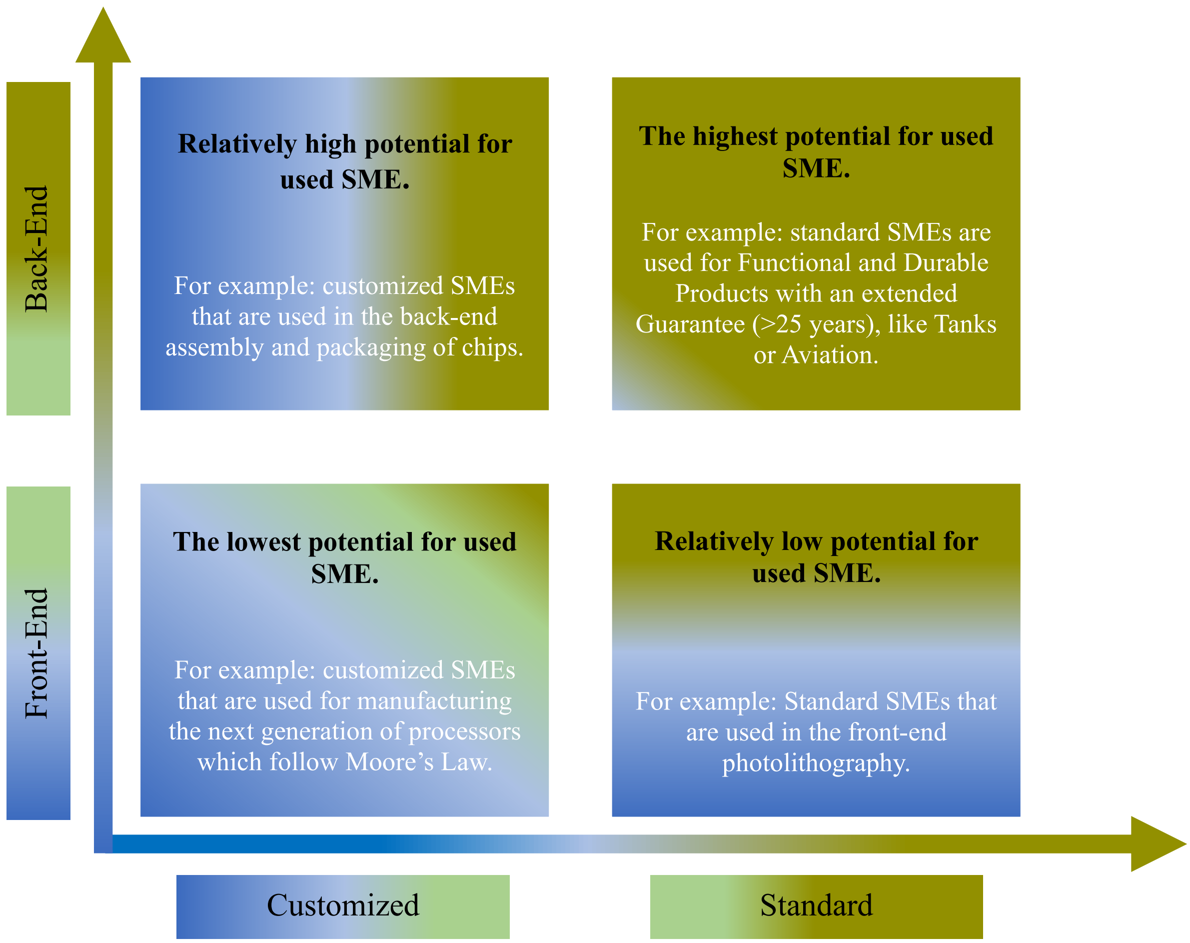

Figure 10: A 2x2 matrix focused on the equipment type and semiconductor process of the used semiconductor manufacturing equipment (SME)

6. Discussion and Conclusion

This study investigates the potential role of the secondary market of semiconductor manufacturing equipment (SMEs) in times of crisis. We collected data from diverse sources, including industry reports, detailed interviews with top executives and academics, and prominent B2B platforms

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specialized in the trade of second-hand semiconductor equipment. To analyze market dynamics, we conducted interviews with seven high-ranking executives from leading corporations in the sector and representatives from leading research laboratories in the field. These interviews provided valuable insights into operational, financial, and strategic aspects of the used semiconductor equipment market. Furthermore, we examine various B2B platforms serving as vital hubs for equipment trade, analyzing their significance in the ecosystem, market impact, and the extent of information they offer about listed equipment. Studying the market and supply chain of used semiconductor equipment is justified for several compelling reasons beyond addressing equipment shortages and filling gaps in academic research.

Firstly, according to a recent projection by SEMI (SEMI, December 13, 2021), sales of semiconductor equipment globally are expected to surpass $100 billion for the first time. Although data on the market for used semiconductor equipment is limited, historically, the secondary market has accounted for approximately 5 to 10% of the sales of new equipment. Given the rising demand for semiconductor equipment, the actual value of the secondary market is going to be considerably higher. However, there exists a gap in academic literature, specifically examining the role of the secondary semiconductor equipment market in navigating through disruptions. Studying this market can inform policymakers and regulators about the economic, environmental, and technological impacts of the secondary semiconductor equipment industry, leading to more informed decisions regarding trade policies, tariffs, and environmental regulations.

Secondly, existing anecdotal evidence indicates that second-hand semiconductor equipment could substantially mitigate recent equipment shortages. During periods of global supply chain interruptions, the secondary market may act as an alternative equipment source, thereby strengthening the resilience of semiconductor manufacturing supply chains. However, our interviews revealed that not all SMEs benefit from the secondary market; primarily, those using standardized back-end equipment gain the most. Furthermore, we identified challenges related to front-end and particularly customized equipment, which may hinder their entry into the secondary market.

Thirdly, our research indicates that the primary purchasers of second-hand semiconductor equipment are entities involved in education or research and development (R&D). Large

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enterprises rarely acquire used semiconductor manufacturing equipment for production purposes due to the need for extensive redesign of production processes.

Fourth, our study reveals that a specific relationship exists between the type of semiconductors and the secondary market for such manufacturing equipment. Certain types of chips, essential for system compatibility, must be manufactured using the same equipment that was originally used for their production. In scenarios where long-term maintenance and service are required, such as with aircraft or tanks that may need maintenance for up to 25 years, it is critical that the chips are produced using the original equipment to ensure compatibility with other system components. Additionally, products that rely on legacy or analog chips, known for their durability and functional longevity, tend to benefit more from the secondary market than products with rapidly evolving technologies and short life cycles, such as CPUs.

Overall, given the scarcity of research concerning the secondary market for semiconductor manufacturing equipment (SME), we posit that our study provides crucial insights. These findings are particularly beneficial to managers and policymakers, enriching their understanding of this market's dynamics and potential impact. Our analysis not only sheds light on the existing market conditions but also underscores the need for further investigation to harness the potential benefits better and navigate the challenges within this sector. By highlighting key aspects and implications, our research aims to facilitate informed decision-making and strategic planning in the context of semiconductor equipment recycling and redistribution.

Acknowledgment

The authors extend their sincere gratitude to the executives, who represent some key players in the semiconductor ecosystem and academics from the most prestigious research laboratories in semiconductor manufacturing, who generously contributed their time and expertise to the interviews and research conducted for this article. Their invaluable insights and perspectives have greatly enriched the understanding of the subject matter and have been instrumental in shaping the insights and the framework presented here.

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