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Effective Availability in Global Semiconductor Trade: Assessing U.S. Supply Chain Risks and Policy Response

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Abstract

This paper examines the concept of effective availability in global semiconductor trade, with a focus on the United States' dependence on imported semiconductor inputs. Semiconductors—critical to advanced manufacturing, artificial intelligence, and defense industries—present both economic opportunities and strategic vulnerabilities due to the geographic concentration of supply. The study develops an effective availability framework that incorporates supplier diversification, tariff-equivalent restrictions, and geopolitical risk. Drawing on trade data, tariff measures, and industry reports, the analysis shows that although U.S. reliance on East Asia remains significant, recent policy interventions such as the CHIPS and Science Act (U.S. Congress, 2022) and targeted trade measures have begun reshaping sourcing patterns. Effective availability rose through 2023 before moderating in 2024, remaining above pre-2022 levels as imports diversified toward Japan, South Korea, Singapore, and Malaysia. The paper concludes that semiconductor resilience is not achieved through self-sufficiency but through diversified, trade-embedded supply chains supported by balanced and coordinated policy actions.

Keywords

Semiconductor Trade, Supply Chain Resilience, Effective Availability, Tariffs and Trade Policy, U.S. Import Dependence

1. Introduction

The global semiconductor trade plays a pivotal role in shaping twenty-first-century economic and technological progress. Semiconductors underpin innovation in artificial intelligence, communications, automotive, and defense industries, making their availability a central concern of macroeconomic stability. In 2023, global semiconductor sales reached USD 526 billion, with wafer fabrication capacity concentrated in East Asia—Taiwan Region and South Korea alone accounting for over 70 percent of leading-edge production, while Chinese mainland and Taiwan region together held nearly 60 percent of global assembly, test, and packaging (ATP) capacity (Singh et al., 2024).

Globalization has intensified cross-border integration of semiconductor supply chains, linking U.S. design and equipment firms with Asian fabrication hubs and European materials suppliers. Gereffi (1994, 1999) described such systems as global commodity chains (GCCs) governed by networks of transnational firms and buyers whose coordination determines production and trade outcomes. This structure delivers scale efficiencies but creates exposure to geopolitical and logistical shocks, as demonstrated by pandemic-era shortages and export control tensions.

The United States once dominated chip production, but since the 1990s, manufacturing has shifted overseas even as it retained leadership in design and research. Recent policy responses—including the CHIPS and Science Act (2022) and parallel initiatives in the European Union, Japan, and South Korea—seek to rebalance production through targeted investment incentives. Singh et al. (2024) estimates over USD 2.3 trillion in global wafer-fabrication investment planned for 2024-2032, with the U.S. expected to capture 28%, up from 9% before the CHIPS Act.

Semiconductor trade remains shaped by tariffs and export restrictions that define "effective availability"—the degree to which imported inputs remain accessible once policy and risk are accounted for. For example, Section 301 tariffs imposed by the USTR (2019) on Chinese semiconductors (10% - 25%) and the 2024 tariff expansion on chips (50%) and electric vehicles (100%) have significant implications for supply-chain costs and import substitution. The WTO (2023) reports that while the average applied tariff on semiconductor products in advanced economies is below 5%, targeted duties on strategic goods can exceed 50%, altering sourcing decisions and trade elasticity.

This paper investigates the effective availability of imported semiconductor inputs to the United States within global trade networks. It examines supplier diversification, tariff restrictions, and geopolitical risks that influence input flows and proposes an analytical index combining these elements. The study contributes to the literature on global trade and macroeconomic resilience by linking quantitative trade models with policy developments such as the CHIPS Act and recent tariff measures. The objectives are:

1) to quantify U.S. semiconductor import dependence and concentration across supplier regions;

2) to estimate the impact of tariffs and restrictions on effective availability;

3) to analyze diversification trends and policy implications for global supply-chain stability; and

4) to recommend balanced trade strategies that strengthen resilience without sacrificing openness.

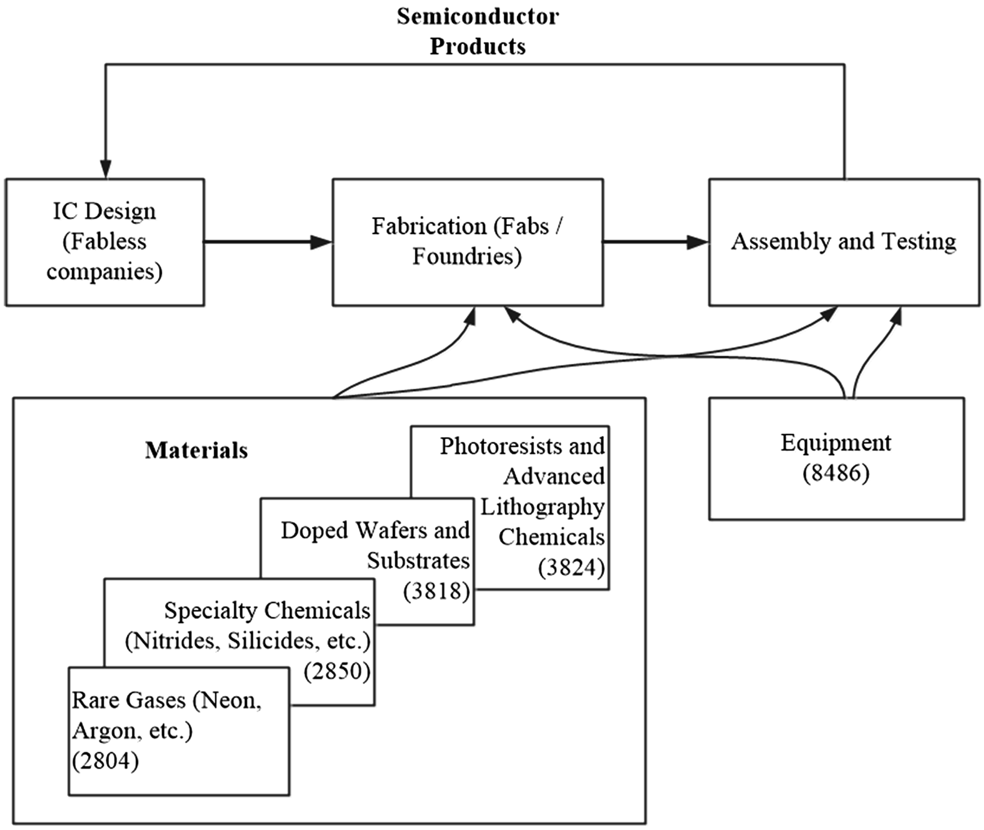


Figure 1. Diagram of the semiconductor industrial manufacturing chain.

2. Methodology

2.1. Structure of the Semiconductor Supply Chain and Data Scope

This study examines the global trade structure of the semiconductor industry through an integrated methodological framework combining descriptive analysis and network-based modeling. As illustrated in Figure 1, the semiconductor industrial chain can be broadly divided into a core manufacturing chain—comprising IC design (fabless companies), fabrication (fabs and foundries), and assembly and testing—and a supporting chain that includes materials and equipment. The materials segment encompasses rare gases (HS 2804), specialty chemicals (HS 2850), doped wafers and substrates (HS 3818), and photoresists and advanced lithography chemicals (HS 3824), while equipment for semiconductor manufacturing is classified under HS 8486. Table 1 summarizes these HS codes and their respective roles within the global semiconductor supply chain, highlighting each category's technological function, strategic importance, and degree of concentration risk in international trade. Together, these interlinked stages form the foundation of semiconductor production and global supply integration.

Table 1. HS codes and their importance in the global semiconductor supply chain.

HS Code	Category	Explanation and Relevance to Effective Availability
2804	Rare Gases (Neon, Argon, Krypton, Xenon)	These gases are essential for photolithography and etching processes in semiconductor fabrication. Disruptions in neon supply, for example, have historically caused bottlenecks in chip production, as 70% - 80% of global neon refining capacity has been concentrated in a few suppliers (notably Ukraine and Russia). Their inclusion captures upstream raw material vulnerabilities affecting wafer and chip production (Bernstein, 2023; OECD, 2024).
2850	Specialty Chemicals (Hydrides, Nitrides, Silicides, Borides)	These specialty chemicals are vital for doping and epitaxial layer formation, which determine transistor quality and circuit performance. Production is concentrated in Japan, South Korea, and Singapore, making supply vulnerable to disruption (Bernstein, 2023).
3818	Doped Wafers and Semiconductor Substrates	Doped wafers form the core substrate for semiconductor devices, defining chip structure and performance. Supply is highly concentrated in East Asia, particularly Taiwan region and South Korea, making this category a key indicator of fabrication-stage dependency and trade concentration (Bernstein, 2023; OECD, 2024).
3824	Photoresists and Chemical Preparations	Photoresists and other advanced lithography chemicals enable precise patterning in chip fabrication. Japan, supplying over 80% of global photoresists, dominates this segment—making it central to assessing concentration risk and export control exposure in high-end manufacturing (Bernstein, 2023).
8486	Semiconductor Manufacturing Equipment	Front-end process tools—including lithography, etch, deposition, and metrology systems—determine node capability and yield. Supply is heavily concentrated among firms such as ASML, Tokyo Electron, Applied Materials, and Lam Research, and remains subject to coordinated U.S.-Japan-Netherlands export controls. Even modest policy changes can restrict downstream capacity, making HS 8486 a critical category in evaluating effective availability (BIS, 2023; White House, 2024; Bernstein, 2023).

To analyze shifts in effective availability within the semiconductor supply chain, this study employs panel data from 2020 to 2024, primarily sourced from the United Nations Commodity Trade Statistics Database (UN Comtrade), which provides highly granular HS-level trade records. This period is chosen for its analytical significance. It encompasses the most policy-intensive phase of semiconductor realignment, defined by the implementation of the U.S. CHIPS and Science Act (U.S. Congress, 2022), the introduction of export controls on advanced nodes (2022-2023), and ongoing tariff adjustments under U.S.-China trade tensions. There post-COVID-19 years were further characterized by severe supply disruptions and widespread reshoring initiatives, offering a unique lens through which to examine how logistical shocks and diversification efforts have influenced availability. This period also captures the early outcomes of industrial policy and geopolitical segmentation, enabling quantitative assessment of how supplier concentration, regional dependency, and tariff-equivalent restrictions jointly shape effective availability. Focusing on 2020-2024 therefore allows the study to trace the transition from pre-pandemic interdependence to post-pandemic restructuring, providing an empirically grounded view of how market and policy dynamics are reshaping U.S. semiconductor supply resilience.

Trade data for 2024 are drawn from the UN Comtrade database's *provisional* *release* (accessed September 2025) and represent preliminary submissions by national statistical agencies pending final reconciliation. These official early data may differ slightly from finalized figures, but their inclusion enables timely analysis of post–CHIPS Act trade patterns while acknowledging that minor revisions may occur once the UN publishes the complete annual dataset.

The analysis centers on the U.S. import network, emphasizing four representative categories—base materials, packaging materials, production equipment, and integrated circuits—which together delineate the strategic layers of semiconductor manufacturing. By integrating trade data with policy and geopolitical indicators, the study examines how U.S. reliance on East Asian suppliers has evolved and evaluates the extent to which diversification and targeted policy interventions enhance or constrain overall system availability.

2.2. Construction of the Import Aggregator and Effective Availability Framework

In international trade models—particularly those based on constant elasticity of substitution (CES) or Armington-type preferences—countries import differentiated goods from multiple origins. For the United States, semiconductor inputs are sourced primarily from Japan, the European Union, China, South Korea, and Other Asian economies such as Singapore, Malaysia, and Taiwan Region. Rather than treating each bilateral import flow as a separate production input, we aggregate them into a single composite "import good" that enters the production function. This composite, known as the import aggregator, summarizes the effective availability of imported semiconductor inputs from all foreign suppliers.

To quantify this concept, we construct a CES-type import aggregator that combines semiconductor imports across partner countries using baseline trade shares as weights and an elasticity of substitution parameter, σ_M. This approach captures the degree to which imports from different suppliers can substitute for one another in response to policy shocks or supply disruptions.

Formally, let $I_j^M(t)$ denote country j's semiconductor imports (in real terms) aggregator. Here, j corresponds to the United States. We write the import aggregator as:

$$I_j^M(t)=\left[\sum_i \omega_{ij}\cdot\left(\left(1-\chi_{ij}(t)\right)\cdot M_{ij}(t)\right)^{\rho}\right]^{\frac{1}{\rho}},\rho=1-\frac{1}{\sigma_M},\sigma_M>1 \quad (1)$$

where $M_{ij}(t)$ is the physical flow of semiconductor imports from *i* to *j*, ω_{ij} are CES weights, and σ_M is the elasticity of substitution across foreign sources (micro Armington elasticity). This formulation adapts the framework of Funke and Wende (2023), who model export restrictions as reductions in tradable semiconductor varieties $N_{s,ij}(t)=\left(1-\chi_{ij}(t)\right)$. Here, the effective investment input arriving at j from i is scaled by a bilateral access share $1-\chi_{\{ij\}}(t)$ ∈ [0,1], where $\chi_{\{ij\}}(t)$ is the restriction factor (share of varieties blocked).

This model produces an empirically grounded index of effective availability for semiconductor imports, combining both policy restrictions and cross-supplier substitution dynamics. Beyond conventional resilience metrics such as supply-risk scores and the Hirschman-Herfindahl Index (HHI), the effective availability index captures both structural and policy-driven constraints—including tariffs, export controls, and geopolitical risks—while weighting them by trade elasticity to reflect how accessible inputs remain under varying policy environments. This dynamic approach enables the index to trace temporal shifts in accessibility and resilience that static concentration measures overlook, offering a more comprehensive representation of policy-adjusted trade vulnerability within the semiconductor sector.

2.3. Data and Parameterization

Trade flows $M_{ij}(t)$ are obtained from the UN Comtrade, USITC DataWeb, and OECD TiVA databases for HS codes 8541 (semiconductor devices), 3818 (chemical elements for electronics), and 8542 (integrated circuits). Weights ω_{ij} are calibrated from baseline trade shares in a reference year (e.g., 2020) to capture each supplier's relative importance:

$$\omega_{ij} = \frac{M_{ij}(t_0)}{\sum_k M_{kj}(t_0)} \tag{2}$$

Here, $M_{ij}(t_0)$ denotes the import value of semiconductor category M from supplier country i to j in the reference year t_0, where the summation index k covers all exporting partners. The normalized weights therefore sum to one, $\sum_i \omega_{ij} = 1$.

The elasticity of substitution (σ_M) determines the degree of flexibility in sourcing semiconductor inputs from multiple suppliers. A higher elasticity implies strong substitutability—allowing rapid redirection of imports during shocks—while a lower elasticity indicates concentration risk and limited resilience.

The Schreiber (2023) employs CES-based demand models to assess dependence on semiconductor production, assuming elasticities around 5 for intermediate goods. Broader manufacturing analyses, such as Ahmad and Riker (2020), estimate elasticities between 2 and 6 across sectors, while Simonovska and Waugh (2014) report a median elasticity of 4.1 at the macro level. Complementary studies by Devarajan et al. (2023) and Marquez (2005) find lower substitution elasticities (0.5 - 2) for technologically rigid intermediate inputs.

Balancing these findings, this study calibrates the elasticity of substitution σ_M over a range of 2 to 6. This range captures the spectrum of empirical estimates reported in the literature and allows for robustness testing across varying assumptions of cross-supplier flexibility. The calibration aligns the semiconductor trade model with established empirical research while reflecting both the technological specificity of advanced inputs and the diversification potential within global supply chains.

The restriction factor $\chi_{ij}(t)$ captures the share of semiconductor varieties or input flows from supplier country *i* that are rendered inaccessible to importer *j* at time *t* due to tariffs, export controls, sanctions, or other trade frictions. It thus transforms nominal import flows into effective access-adjusted quantities, linking trade policy and supply chain resilience directly to the import aggregator. A value of $\chi_{ij}(t)=0$ indicates unrestricted trade (full market access), whereas $\chi_{ij}(t)=1$ represents complete blockage (no import access). Intermediate values reflect partial restrictions—such as tariff costs, technology bans, or delays in export licensing.

Restriction factors are constructed from three observable components:

- **Tariff-equivalent barriers**, derived from the ad valorem rate on semiconductor products (HS 8541, 3818, 8542).
- **Export control coverage**, measured by the share of affected product lines (e.g., advanced-node chips, lithography systems).
- **Non-tariff measures and logistics delays**, proxied through the World Bank's *Logistics Performance Index (LPI)* or OECD Trade Facilitation indicators.

Formally, $\chi_{\{ij\}}(t)$ can be expressed as:

$$\chi_{ij}(t)=\min\left[1,\alpha\cdot\frac{\tau_{ij}(t)}{\tau_{\max}}+\beta\cdot\frac{E_{ij}(t)}{E_{\max}}+\gamma\cdot P_{ij}(t)\right] \tag{3}$$

where τ_{ij} is the average applied tariff rate (WTO, 2023 and USTR, 2019); $E_{ij}(t)$ is an export control intensity index based on licensing and technology-transfer restrictions (BIS, 2023; White House, 2024). The policy risk variable $P_{ij}(t)$ captures broader geopolitical or sanctions-related risks (OECD, 2024; Schreiber, 2023), normalized on a 0 - 1 scale. Each component is normalized using benchmark maxima $\tau_{\max}$ and $E_{\max}$, with weights α,β,γ (typically 0.4, 0.4, and 0.2, respectively) to reflect their relative influence on trade accessibility. Tariffs and export controls receive equal weights because both exert comparable direct effects on transaction costs and cross-border supply reliability, whereas policy risk—though less immediate—exerts a sustained influence on expectations and long-term contractual stability. This proportional structure aligns with empirical evidence on trade-cost elasticities reported by the OECD (2023) and BIS (2023), ensuring that the composite restriction index realistically mirrors observed policy intensities and translates these measures into a unified 0 - 1 scale quantifying the effective limitation on bilateral semiconductor trade.

Empirical calibration across major regions identifies approximate bounds for semiconductor-related restriction factors by policy context: 0.00 - 0.05 for allied economies, 0.10 - 0.50 for restricted or tariff-affected sources (notably China), and 0.70 - 1.00 for sanctioned states within U.S. trade. **Table 2** summarizes these estimated restriction factors by partner and policy period, highlighting how trade barriers intensified for specific regions following the introduction of tariffs and export controls.

Evolution over Time

- **Pre-2018:** Global semiconductor trade was largely tariff-free under WTO's Information Technology Agreement (ITA I & II), so $\chi_{ij} \approx 0$ for all major partners.
- **2018-2020:** The U.S.-China trade war introduced Section 301 tariffs of 10% - 25% on semiconductor devices, pushing $\chi_{\text{China, US}}$ toward 0.2.
- **2022-2024:** Export controls on advanced-node chips, AI processors, and lithography equipment further raised effective restrictions; Singh et al. (2024) and BIS (2023) estimate these policies affect roughly 40% - 60% of Chinese semiconductor export categories.
- **Future trend:** Allied reshoring and CHIPS Act cooperation with the EU, Japan, and Korea are expected to keep χ_{ij} below 0.05 for trusted partners, while emerging economies in ASEAN remain in the 0.03 - 0.08 range depending on regulatory harmonization.

Higher χ_{ij} values indicate greater exposure to policy risk and reduced effective availability in the import aggregator. As tariffs and export restrictions tighten, aggregate effective availability $I_j^M(t)$ declines unless offset by new suppliers or domestic production. Tracking $\chi_{ij}(t)$ over time quantitatively links trade policy intensity to supply-chain resilience of U.S. semiconductor imports.

Table 2. Estimated restriction factors for semiconductor trade by partner and period.

Country/Region	Period/Event	Restriction Factor (χ_{ij})	Notes and Sources
Taiwan Region, South Korea, Japan	2015-2024	0.00 - 0.05	Open trade partners; MFN tariffs < 2%
European Union	2015-2024	0.03 - 0.08	Minor regulatory barriers; tech cooperation
China	2018-2019	0.10 - 0.25	Section 301 tariffs of 10% - 25%
China	2020-2024	0.30 - 0.50	Export controls, advanced-node bans
Russia, Iran	2022-2024	0.70 - 1.00	Full export/sanctions block
Vietnam, Malaysia, Singapore	2020-2024	0.02 - 0.06	Minimal barriers, growing packaging roles

Source: Author's calculations based on tariff, export-control, and policy data compiled from USTR (2019), BIS (2023), White House (2024), Singh et al. (2024), WTO (2023), Schreiber (2023), and OECD (2024).

3. Results and Discussion

3.1. Global Supplier Weights and Concentration

Table 3 summarizes the dynamic import values (in billions of U.S. Dollars) of major suppliers across semiconductor categories, revealing a highly concentrated sourcing structure. Japan and the Netherlands supply over 80% of semiconductor equipment imports, reflecting technological dominance and limited substitutability—conditions that heighten upstream vulnerability. In contrast, Singapore and South Korea maintain notable shares in specialty chemicals and wafer substrates, supporting moderate diversification in midstream materials. China's role in semiconductor-critical HS categories remains limited, reflecting the ongoing impact of export controls and technology restrictions on its high-end trade capacity. The results reveal dual dependence structure: heavy reliance on a few advanced suppliers for equipment, offset by more diverse sourcing in materials. This asymmetry underscores that effective availability depends on both supplier substitutability and geopolitical alignment. From 2020 to 2024, import patterns rose sharply through 2022 amid post-pandemic recovery and booming demand, but diverged in 2023-2024 as inventories normalized and policy restrictions tightened—trends shaped by both market stabilization and U.S. industrial policy, notably the CHIPS and Science Act (U.S. Congress, 2022).

Table 3. Import for semiconductor manufacturing trade by partner and period.

HS_Category	Country	Import Value (B$)				
		2020	2021	2022	2023	2024
2804—Rare gases (neon, argon, etc.)	Japan	0.0146	0.0158	0.0139	0.0118	0.0123
	Netherlands	0.0008	0.0006	0.0020	0.0002	0.0002
	Singapore	0.0001	0.0002	0.0001	0.0011	0.0001
	China	0.0147	0.0150	0.0443	0.0354	0.0196
	Rep. of Korea	0.0009	0.0008	0.0058	0.0054	0.0094
	Malaysia	0.0171	0.0025	0.0463	0.0024	0.0216
	Other Asia, nes	0.0306	0.0497	0.0891	0.0364	0.0257
2850—Specialty chemicals (nitrides, silicides, etc.)	Japan	0.0056	0.0073	0.0075	0.0079	0.0070
	Netherlands	0.0002	0.0000	0.0000	0.0000	0.0001
	China	0.0119	0.0146	0.0138	0.0096	0.0093
	Rep. of Korea	0.0004	0.0004	0.0005	0.0004	0.0007
	Other Asia, nes	0.0000	0.0001	0.0001	0.0002	0.0008
3818—Doped wafers and substrates	Japan	0.7291	0.7521	0.8712	0.5919	0.6387
	Netherlands	0.0006	0.0018	0.0052	0.0044	0.0042
	Singapore	0.0246	0.0249	0.0336	0.0259	0.0461
	China	0.0478	0.1165	0.1981	0.1936	0.1436
	Rep. of Korea	0.1576	0.1701	0.1977	0.2051	0.1897
	Malaysia	0.0468	0.0445	0.0577	0.0458	0.0366
	Other Asia, nes	0.1944	0.2136	0.2643	0.1567	0.2078
3824—Photoresists and chemical preparations	Japan	0.6924	1.4231	2.0756	2.4571	2.0148
	Netherlands	0.0910	0.1300	0.1433	0.1198	0.1189
	Singapore	0.0523	0.0603	0.0769	0.0610	0.0662
	China	1.3496	0.8720	0.5269	0.3281	0.2831
	Rep. of Korea	0.1989	0.0931	1.2833	2.9307	1.6914
	Malaysia	0.0362	0.0383	0.0597	0.0339	0.0231
	Other Asia, nes	0.0216	0.0252	0.0265	0.0222	0.0366

Continued

8486—Semiconductor manufacturing equipment	Japan	3.0494	3.3540	4.6308	3.6486	3.8957
	Netherlands	1.6284	1.2517	1.1676	0.9179	1.4387
	Singapore	0.7746	1.0306	1.6354	1.6751	2.0968
	China	0.5794	0.6953	0.7575	0.6878	0.9242
	Rep. of Korea	0.3729	0.5435	0.7115	0.6456	1.0548
	Malaysia	0.3123	0.4713	0.7799	0.7696	1.0962
	Other Asia, nes	0.1779	0.2782	0.3165	0.5596	0.5600

Source: UN Comtrade.

To contextualize the United States within the global semiconductor production structure, domestic fabrication capacity remains comparatively limited despite recent policy incentives. As of 2024, the United States accounts for roughly 12 - 13 percent of global wafer fabrication capacity (Flamm & Bonvillian, 2025; OECD, 2024), with only a small share supporting leading-edge nodes below 10 nm. The majority of domestic output is concentrated in mature and specialty technologies used for analog, power management, and automotive applications. Although major investments—such as TSMC Arizona, Intel's Ohio and Arizona expansions, and Samsung's Texas facility—are underway under the *CHIPS and Science Act* (U.S. Congress, 2022), most of these projects are still under construction or early ramp-up. This limited domestic base underscores the findings in subsequent sections, where import dependence remains a defining feature of U.S. semiconductor supply resilience despite ongoing reshoring efforts.

3.2. U.S. Semiconductor Import Patterns and Visualization

3.2.1. Rationale for Using Chord Plots

Following the methodological precedent set by Ou et al. (2024) in *Acta Geographica Sinica*, the chord plot (**Figure 2**) is an effective visualization for illustrating trade dependencies and flow asymmetry within global semiconductor networks. Unlike bar or line graphs that only depict aggregate values, chord plots reveal the intensity, and temporal evolution of trade connections between the United States and its semiconductor suppliers across multiple years (2020-2024).

In **Figure 2**, each arc denotes a country–year pair, and the connecting ribbons represent import shares. This visualization captures dynamic interdependencies, showing both the scale and composition of U.S. semiconductor imports and the changing intensity of supplier concentration over time. It complements quantitative indices such as the CES-based import aggregators by visually expressing the organizational topology of supply relationships, distinguishing between monopolistic (few-source) and regionalized (diversified) trade patterns.

3.2.2. Interpretation of U.S. Semiconductor Import Chord Plots (HS 2804-8486)

1) HS 2804—Rare Gases (Neon, Argon, etc.)

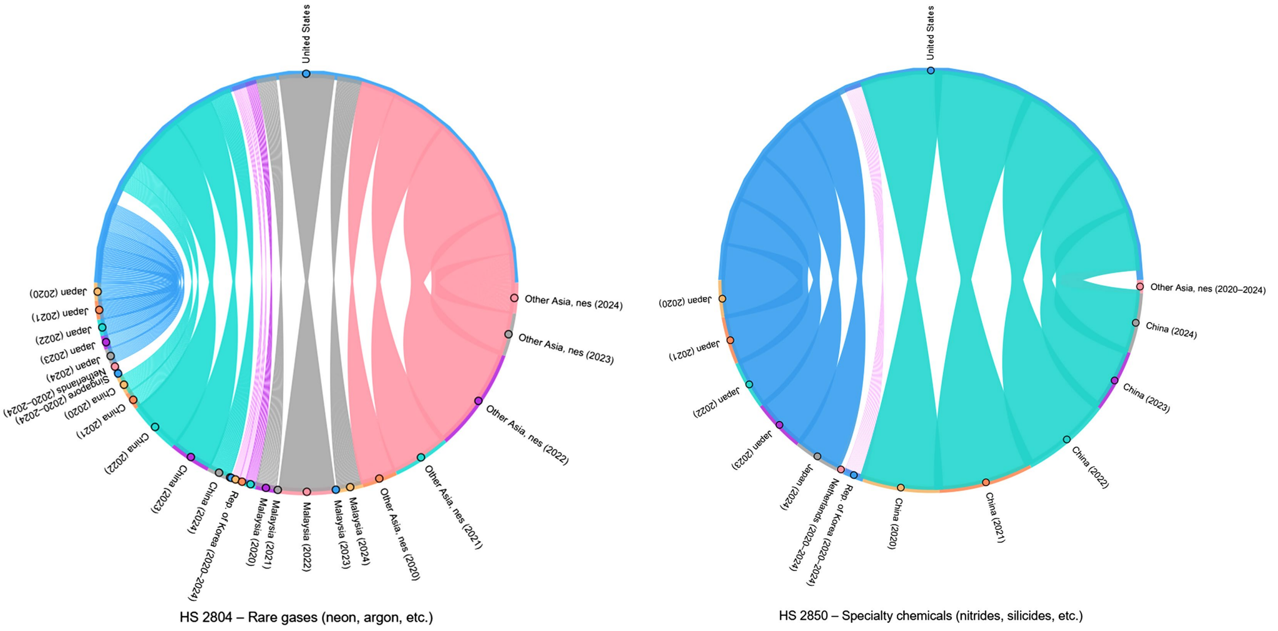
Figure 2(a) illustrates that, between 2020 and 2024, the United States maintained strong and persistent import linkages for rare gases with Japan, China, and Malaysia, highlighting their continued centrality in upstream semiconductor materials. Japan remained the leading supplier during 2020-2021, while diversification became more evident after 2022. The trade in upstream semiconductor materials maintains high spatial concentration yet shows gradual regional redundancy in the post-2020 period. Following geopolitical disruptions—particularly the Russia-Ukraine conflict, which curtailed global neon supply—U.S. import linkages expanded across East and Southeast Asia, reflecting a targeted strategy to enhance supply-chain resilience through redundant regional sourcing.

2) HS 2850—Specialty Chemicals (Nitrides, Silicides, etc.)

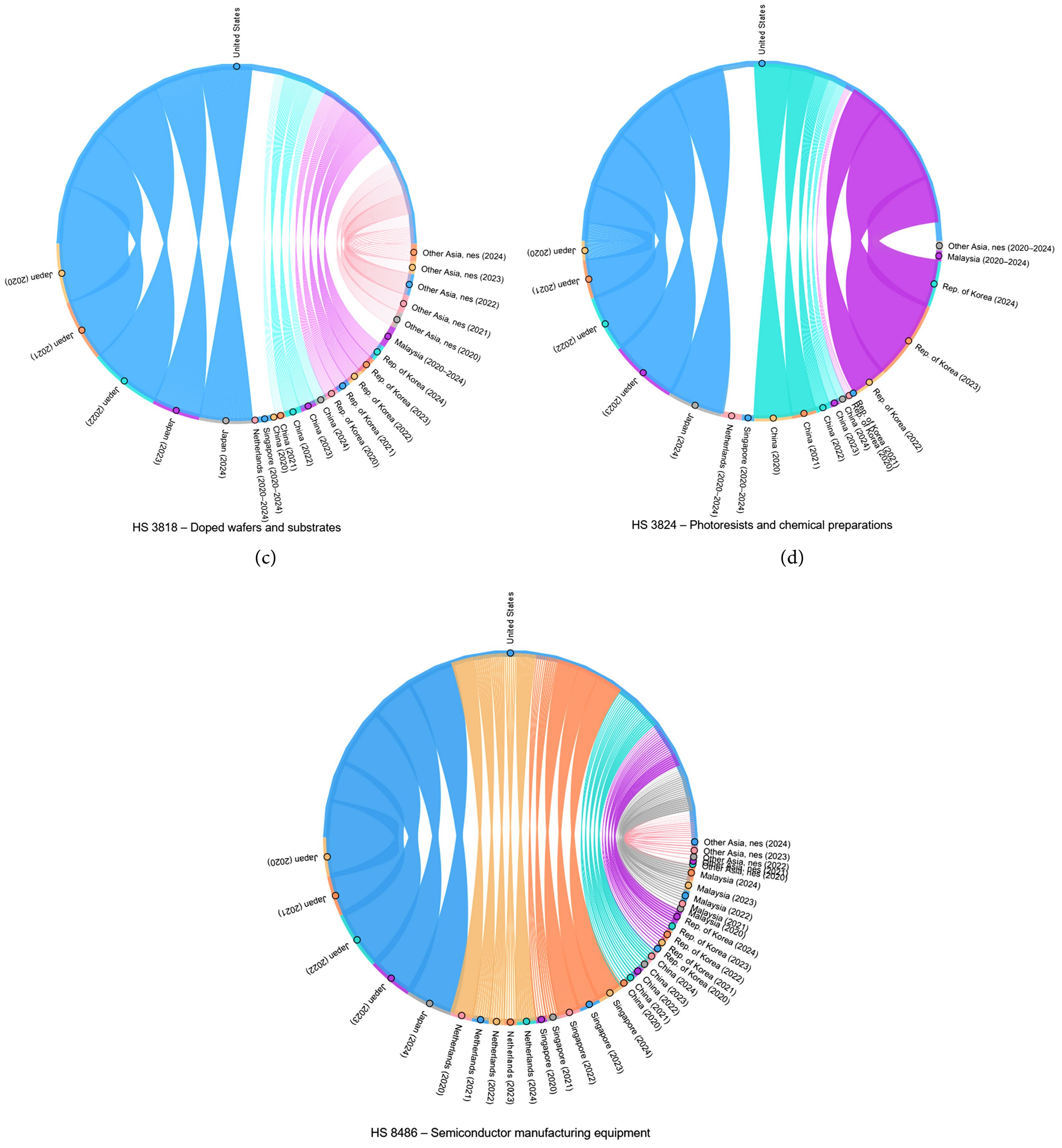
The chemical precursors network remains dominated by Japan and China, with minor contributions from the Republic of Korea and Other Asia (nes), as shown in Figure 2(b). From 2020 to 2024, Japan's share increased slightly before stabilizing around 0.7%, while China maintained a consistent lead with modest fluctuations. The overall chord structure shows limited structural change rather than a pronounced shift, indicating persistent bilateral concentration rather than substantial diversification. This stability suggests that while the United States has broadened marginal linkages within Asia, the core dependency pattern remains largely intact. The moderate variation aligns with CES-normalized results implying mid-range substitutability ($\sigma \approx 3 - 4$), where incremental diversification enhances resilience without fundamentally altering regional dependence.

3) HS 3818—Doped Wafers and Substrates

As shown in Figure 2(c), the wafer input network remains highly centralized, with Japan and South Korea consistently dominating U.S. imports, complemented by moderate contributions from China, Singapore, and Malaysia. From 2020 to



(a) (b)



(c) (d)

(e)

Figure 2. Import flow of U.S. semiconductor manufacturing materials and equipment.

2024, Japan's share fluctuated between 73% - 87%, while South Korea maintained a stable range of 16% - 21%, underscoring persistent concentration within two technologically advanced suppliers. Although China's participation expanded sharply after 2021—from 4.8% to a peak near 19.8% in 2022—this increase did not meaningfully alter the overall hierarchy, as Japan and South Korea continued to account for the majority of wafer-grade substrate imports.

Despite marginal diversification toward additional Asian economies, production remains effectively monopolized by a limited set of countries possessing advanced purification and epitaxial growth capabilities. This entrenched spatial concentration reinforces that wafer substrates constitute one of the most rigid and strategic bottlenecks within the global semiconductor value chain.

4) HS 3824—Photoresists and Advanced Lithography Chemicals

The chord plots for HS 3824 (**Figure 2(d)**) reveal a pronounced concentration of import flows from Japan, which consistently dominates the network across 2020-2024. Japan's share rose steadily from 0.69 in 2020 to a peak of 2.46 in 2023, maintaining clear supremacy in photoresist and advanced lithography chemical exports to the United States. Japan controls more than 80% of global photoresist supply, reflecting its long-standing technological monopoly in high-purity chemical synthesis and polymer formulation.

While China and South Korea exhibit notable but secondary participation—China's share declined sharply from 1.35 in 2020 to 0.28 in 2024, whereas Korea's increased from 0.20 to 1.69—these shifts represent reallocation within East Asia rather than genuine diversification. The chord structure remains vertically concentrated, with minimal expansion toward alternative suppliers such as the Netherlands or Singapore. The narrow branching and limited chord density underscore extremely low substitution elasticity, implying that U.S. supply security in photoresists and related chemicals continues to rely overwhelmingly on Japanese export stability and policy alignment.

5) HS 8486—Semiconductor Manufacturing Equipment

As shown in **Figure 2(e)**, the equipment trade network displays an increasingly diversified structure linking the United States with Japan, the Netherlands, Singapore, South Korea, and Malaysia. Japan and the Netherlands remain the core suppliers throughout 2020-2024—Japan's import share rising from 3.05 to 3.90, and the Netherlands fluctuating between 1.25 and 1.44—while Singapore, South Korea, and Malaysia show notable growth, particularly after 2022. Singapore's share more than doubled from 0.77 in 2020 to 2.10 in 2024, and both Korea and Malaysia surpassed 1.0 by 2024, indicating the rise of new assembly and distribution hubs within Asia.

This pattern identified semiconductor equipment trade as driven primarily by production dependency rather than market dependency. The chord plots show early dominance by Japan (Tokyo Electron) and the Netherlands (ASML), consistent with Ren et al. (2023), but increasingly visible ribbons toward Singapore and Korea after 2022 suggest a gradual transition toward multi-polar regional production and re-export nodes. While the upstream technology base remains highly oligopolistic, the expansion of intermediate assembly and testing capacities across Asia reflects deliberate U.S. efforts to geographically diversify import sources—an essential mitigation strategy against single-country export restrictions and geopolitical risk concentration.

3.2.3. Structural and Policy Insights

The chord plots collectively illustrate three key insights: 1) Structural asymmetry in U.S. import dependence—Semiconductor imports remain heavily concentrated in East Asia, though gradual diversification is evident through emerging secondary hubs such as Singapore and Malaysia. 2) Regionalization of material and chemical supply chains—Categories HS 2804, 2850, 3818, and 3824 exhibit increasing intra-Asian linkages. 3) Persistent oligopoly in equipment trade—Imports of semiconductor manufacturing equipment (HS 8486) continue to be dominated by a limited group of technologically advanced producers, particularly in Japan and the Netherlands.

From a policy perspective, these chord plots underscore the analytical value of structural visualization in identifying trade vulnerabilities. They reveal how import patterns adjust under major policy interventions—such as the U.S. CHIPS Act and Japan's export licensing reforms—while also indicating where diversification remains limited.

When combined with normalized CES elasticity indicators, the chord plots provide a multidimensional framework for evaluating semiconductor supply resilience, bridging quantitative substitution analysis with network-based dependency assessment.

3.3. Country-Level Trade Dynamics and Temporal Insights

Table 4 highlights evolving trade dynamics among the United States' key semiconductor suppliers from 2020 to 2024. The results reveal distinct regional shifts within East Asia's supply network, reflecting post-pandemic recovery, export-control adjustments, and strategic diversification under the CHIPS and Science Act (U.S. Congress, 2022). Their sustained leadership reflects deep technological specialization and strong policy alignment with the United States, resulting in low restriction factors ($\chi \approx 0.03$ - 0.05). Japan's consistent growth through 2024 and the Netherlands' post-2021 surge in lithography tool exports, driven by ASML's EUV systems, underscore their status as indispensable, low-risk partners.

East Asian suppliers—notably South Korea, Singapore, and Malaysia—have expanded their roles in specialty chemicals (HS 2850) and doped wafers and substrates (HS 3818). Their steady export growth and established roles in assembly, testing, and packaging (ATP) strengthen the resilience and substitutability of midstream inputs within the global value chain. By contrast, China's semiconductor exports contracted sharply after 2022 across all HS categories, particularly in equipment and wafer materials, following the imposition of U.S. export controls on advanced-node chips. The corresponding rise in restriction factors ($\chi \approx 0.3$ - 0.5) marks a clear phase of strategic decoupling in high-end trade.

Commodity-specific trends highlight these structural shifts. Imports of semiconductor equipment (HS 8486) peaked in 2022-2023 amid strong demand for lithography and etching tools, then eased in 2024 as export controls took effect. Photoresist and chemical imports (HS 3824) rose steadily, with Japan maintaining over 80 percent of supply, underscoring its dominance in advanced-node lithography. Doped wafer imports (HS 3818) shifted from China toward Korea and Malaysia after 2021, reflecting moderate substitutability ($\sigma_M \approx 3 - 4$). Compound materials (HS 2850) surged with electric-vehicle and power-semiconductor growth, while specialty gases (HS 2804) spiked in 2022 due to disrupted Ukrainian neon supply, prompting diversification toward Japan, Korea, and Malaysia.

Table 4. Country-level import dynamic.

Country/Region	Key Observations (2020-2024)	Interpretation
Japan	Maintained a leading share in advanced materials (HS 3824) and equipment (HS 8486); steady growth through 2024.	Japan's dominance in photoresists, wafers, and precision tools underscores its role as a low-restriction, high-availability partner ($\chi \approx 0.03$).
Netherlands	Imports surged post-2021 due to lithography tool exports (HS 8486), driven by ASML's EUV shipments.	A strategic supplier in front-end fabrication tools; exposure to export control coordination with U.S. slightly constrains availability ($\chi \approx 0.05$).
Singapore	Consistent mid-level supplier in HS 3818 and HS 3824; a key hub for ATP and distribution.	Functions as a regional logistics and test-packaging node; low restriction factor and strong diversification potential.
China	Sharp contraction post-2022 across all HS categories, especially 8486 and 3818, coinciding with U.S. export controls.	Reflects rising restriction factor ($\chi_{\text{China,US}} \approx 0.3 - 0.5$) and strategic decoupling in advanced-node semiconductor trade.
Republic of Korea	Growth across 3818 and 8486 categories through 2023; slight plateau in 2024 amid domestic capacity expansion.	South Korea's supply resilience supports moderate substitutability; key diversification source ($\chi \approx 0.02 - 0.05$).
Malaysia	Stable import levels, mainly in HS 3818 and 3824 categories.	Serves as a flexible ATP and component assembly partner; high substitutability and resilience in the CES framework.
Other Asia, nes	Gradual increase through 2024, reflecting the rise of Vietnam and Thailand in secondary assembly.	Indicates diversification into emerging Asian supply chains, offsetting risk from high-restriction partners.

The temporal pattern divides into three clear phases:

1) 2020-2021: Post-pandemic normalization and low restriction factors ($\chi < 0.1$) across partners.

2) 2022: Peak global demand and capacity expansion across all HS categories.

3) 2023-2024: Coordinated export controls among the United States, Japan, and the Netherlands, along with Chinese counter-measures, elevated restriction factors ($\chi \approx 0.4 - 0.5$) but were followed by partial stabilization and reallocation of imports toward allied suppliers.

Overall, the results indicate a transition from pre-2022 interdependence to post-2022 policy-aligned regional diversification. Effective availability declined temporarily under export-control alignment but rebounded by 2024 as alternative sourcing from Japan, Korea, and Malaysia offset constrained flows from China. This restructuring underscores how U.S. semiconductor supply resilience increasingly depends on strategic diversification within allied networks, rather than full reshoring or autarky.

3.4. Modeling Resilience and Effective Availability

To quantify how supplier concentration, policy restrictions, and diversification jointly influence U.S. semiconductor supply resilience, this section applies the CES-based import aggregator model introduced in Section 2.2. The model evaluates the effective availability index $I_j^M(t)$ under varying policy and market conditions, combining three parameters:

1) restriction factors $\chi_{ij}(t)$ representing policy-induced access limitations;

2) supplier weights ω_{ij} reflecting each partner's trade importance; and

3) the elasticity of substitution σ_M, which governs the ease of supplier replacement.

Together, these parameters capture how shocks—such as export controls, tariffs, or logistical disruptions—propagate through the import network and alter aggregate access to semiconductor inputs.

Table 5 shows the CES-based import aggregators for the five major HS categories—2804 (rare gases), 2850 (specialty chemicals), 3818 (doped wafers), 3824 (photoresists), and 8486 (semiconductor manufacturing equipment)—from 2021 to 2024, with all values normalized to 2020 (=1). The table captures both cross-year dynamics and cross-elasticity adjustments ($\sigma_M = 2-6$) to assess how effective availability evolved across categories and substitution scenarios.

The results reveal a clear post-pandemic rebound in effective availability, most pronounced in equipment (HS 8486) and inert gases (HS 2804). Across years, 2021-2022 mark the strongest expansion, as import volumes surged amid global semiconductor shortages and capacity buildup, while 2023-2024 reflect mild contraction and stabilization following new export-control measures and supply-chain reconfiguration.

Table 5. Estimated restriction-adjusted trade weights by HS category and partner economy, 2020-2024.

HS_Category	Country	Weight	Share (%)	Weight	Share (%)	Weight	Share (%)	Weight	Share (%)	Weight	Share (%)
2804—Rare gases (neon, argon, etc.)	Japan	0.18	18.48	0.19	18.67	0.07	6.91	0.13	12.70	0.14	13.85
	Netherlands	0.01	1.05	0.01	0.67	0.01	0.97	0.00	0.26	0.00	0.23
	Singapore	0.00	0.15	0.00	0.23	0.00	0.05	0.01	1.17	0.00	0.13
	China	0.19	18.61	0.18	17.73	0.22	21.98	0.38	38.20	0.22	22.03
	Rep. of Korea	0.01	1.11	0.01	0.99	0.03	2.86	0.06	5.78	0.11	10.62
	Malaysia	0.22	21.68	0.03	2.98	0.23	23.00	0.03	2.59	0.24	24.23
	*Other Asia, nes	0.39	38.91	0.59	58.73	0.44	44.24	0.39	39.29	0.29	28.91

Continued

2850—Specialty chemicals (nitrides, silicides, etc.)	Japan	0.31	30.99	0.33	32.53	0.34	34.49	0.44	43.57	0.39	38.93
	Netherlands	0.01	1.04	0.00	0.04	0.00	0.00	0.00	0.26	0.52	52.00
	China	0.66	65.68	0.65	65.04	0.63	63.07	0.53	52.86	0.04	3.99
	Rep. of Korea	0.02	2.06	0.02	1.92	0.02	2.11	0.02	1.99	0.00	0.45
	Other Asia, nes	0.00	0.23	0.00	0.46	0.00	0.32	0.01	1.32	0.05	4.63
3818—Doped wafers and substrates	Japan	0.61	60.70	0.57	56.83	0.54	53.52	0.48	48.38	0.50	50.42
	Netherlands	0.00	0.05	0.00	0.14	0.00	0.32	0.00	0.36	0.00	0.33
	Singapore	0.02	2.05	0.02	1.88	0.02	2.06	0.02	2.12	0.04	3.64
	China	0.04	3.98	0.09	8.81	0.12	12.17	0.16	15.82	0.11	11.33
	Rep. of Korea	0.13	13.12	0.13	12.85	0.12	12.15	0.17	16.77	0.15	14.97
	Malaysia	0.04	3.90	0.03	3.36	0.04	3.55	0.04	3.74	0.03	2.89
	Other Asia, nes	0.16	16.19	0.16	16.14	0.16	16.24	0.13	12.81	0.16	16.41
3824—Photoresists and chemical preparations	Japan	0.28	28.35	0.54	53.87	0.50	49.51	0.41	41.28	0.48	47.58
	Netherlands	0.04	3.72	0.05	4.92	0.03	3.42	0.02	2.01	0.03	2.81
	Singapore	0.02	2.14	0.02	2.28	0.02	1.83	0.01	1.02	0.02	1.56
	China	0.55	55.27	0.33	33.01	0.13	12.57	0.06	5.51	0.07	6.69
	Rep. of Korea	0.08	8.14	0.04	3.52	0.31	30.61	0.49	49.23	0.40	39.95
	Malaysia	0.01	1.48	0.01	1.45	0.01	1.42	0.01	0.57	0.01	0.55
	Other Asia, nes	0.01	0.89	0.01	0.95	0.01	0.63	0.00	0.37	0.01	0.86
8486—Semiconductor manufacturing equipment	Japan	0.44	44.23	0.44	43.99	0.46	46.31	0.41	40.98	0.35	35.20
	Netherlands	0.24	23.62	0.16	16.42	0.12	11.68	0.10	10.31	0.13	13.00
	Singapore	0.11	11.23	0.14	13.52	0.16	16.36	0.19	18.81	0.19	18.95
	China	0.08	8.40	0.09	9.12	0.08	7.58	0.08	7.72	0.08	8.35
	Rep. of Korea	0.05	5.41	0.07	7.13	0.07	7.12	0.07	7.25	0.10	9.53
	Malaysia	0.05	4.53	0.06	6.18	0.08	7.80	0.09	8.64	0.10	9.91
	Other Asia, nes	0.03	2.58	0.04	3.65	0.03	3.17	0.06	6.28	0.05	5.06

Source: Author's calculations based on UN Comtrade, USITC (2023), BIS (2023), WTO (2023), and SEMI (2023).

Equipment imports (HS 8486) maintained the highest overall index values, rising through 2022 before moderating in 2024, and displayed the greatest sensitivity to the substitution elasticity σ_M —about 1.5 - 2 percent variation between $\sigma = 2$ and $\sigma = 6$—reflecting high supplier concentration in Japan and the Netherlands. In contrast, specialty chemicals (HS 2850) and doped wafers (HS 3818) show more stable CES values across elasticities and years, suggesting moderate diversification potential and limited policy sensitivity. For instance, the HS 3818 index peaked at 1.13 in 2022 but fell to 0.82 in 2024, with under 0.5 percent variation across elasticities, indicating a relatively balanced supplier base in Korea, Japan, and Malaysia.

Table 6. U.S. Semiconductor Import Aggregator (Normalized to 2020).

Year	HS_Category	Total Imports	CES (σ = 2)	CES (σ = 3)	CES (σ = 4)	CES (σ = 5)	CES (σ = 6)
2021	2804—Rare gases (neon, argon, etc.)	1.074	1.574	1.605	1.619	1.627	1.632
	2850—Specialty chemicals (nitrides, silicides, etc.)	1.238	1.253	1.248	1.246	1.245	1.244
	3818—Doped wafers and substrates	1.102	0.995	0.994	0.994	0.993	0.993
	3824—Photoresists and chemical preparations	1.082	1.121	1.116	1.114	1.112	1.111
	8486—Semiconductor manufacturing equipment	1.106	1.017	1.020	1.021	1.023	1.024
2022	2804—Rare gases (neon, argon, etc.)	2.557	2.825	2.851	2.863	2.869	2.874
	2850—Specialty chemicals (nitrides, silicides, etc.)	1.205	1.197	1.190	1.187	1.186	1.185
	3818—Doped wafers and substrates	1.355	1.129	1.125	1.124	1.123	1.123
	3824—Photoresists and chemical preparations	1.717	1.578	1.567	1.562	1.559	1.558
	8486—Semiconductor manufacturing equipment	1.450	1.399	1.409	1.414	1.417	1.419
2023	2804—Rare gases (neon, argon, etc.)	1.176	1.377	1.391	1.397	1.400	1.402
	2850—Specialty chemicals (nitrides, silicides, etc.)	1.001	0.911	0.904	0.901	0.899	0.897
	3818—Doped wafers and substrates	1.019	0.768	0.759	0.756	0.754	0.753
	3824—Photoresists and chemical preparations	2.438	2.689	2.646	2.626	2.615	2.607
	8486—Semiconductor manufacturing equipment	1.291	1.101	1.100	1.100	1.101	1.101
2024	2804—Rare gases (neon, argon, etc.)	1.130	0.953	0.946	0.943	0.941	0.940
	2850—Specialty chemicals (nitrides, silicides, etc.)	0.987	0.795	0.796	0.796	0.796	0.796
	3818—Doped wafers and substrates	1.055	0.820	0.814	0.812	0.811	0.811
	3824—Photoresists and chemical preparations	1.734	1.780	1.758	1.748	1.743	1.739
	8486—Semiconductor manufacturing equipment	1.605	1.224	1.209	1.203	1.200	1.198
2021	Combined—All semiconductor-related imports	1.100	1.037	1.037	1.037	1.038	1.038
2022	Combined—All semiconductor-related imports	1.508	1.397	1.403	1.406	1.409	1.410
2023	Combined—All semiconductor-related imports	1.522	1.434	1.417	1.409	1.404	1.401
2024	Combined—All semiconductor-related imports	1.568	1.351	1.329	1.319	1.313	1.309

Source: Author's calculations based on the CES-based import aggregator model described in Section 2.2, using trade data from the UN Comtrade Database (2020-2024) and policy variables from the WTO (2023), BIS (2023), White House (2024), and USITC (2023).

Photoresists (HS 3824) remain highly concentrated, with normalized indices around 1.6 - 1.7, confirming persistent dependence on Japan's > 80 percent market share despite steady import growth. Rare gases (HS 2804) exhibit the largest year-to-year swings, peaking in 2022 (2.85 under $\sigma = 3$) following the neon supply shock linked to Ukraine, and normalizing as alternative suppliers emerged.

Normalized values (2020 = 1) illustrate how effective availability changed over 2020-2024: ratios > 1 indicate improved access via volume growth or new sourcing, while ratios < 1 signal tighter supply. Across all elasticities, the import network stabilized after 2022, supported by capacity expansion, near-shoring, and implementation of the CHIPS and Science Act (U.S. Congress, 2022). Overall, **Table 6** demonstrates that U.S. semiconductor supply-chain resilience has been strengthened not by self-sufficiency but by flexible, diversified, and policy-aligned trade networks that reduce concentration risks while preserving global collaboration.

3.5. Policy and Economic Implications

The CES-based analysis indicates that U.S. semiconductor effective availability improved moderately between 2020 and 2024, driven by diversification in midstream inputs and higher capital-equipment imports. Yet, persistent concentration in photoresists, high-purity chemicals, and advanced wafers continues to pose systemic risk. Higher import-aggregator values reflect stronger access and substitutability, while lower values reveal bottlenecks from supplier monopolies and coordinated export controls. Policies such as allied cooperation, reshoring incentives, and diversification tax credits can raise the effective elasticity $\boldsymbol{\sigma}_M$, expanding substitutable sourcing options. Overall, the results show that resilience depends not on self-sufficiency but on diversified, policy-aligned trade networks supported by strategic partnerships with Japan, South Korea, and Malaysia.

3.6. Summary of Key Findings

The results collectively show that U.S. semiconductor imports remain concentrated in East Asia, particularly in upstream materials and advanced equipment categories. Restriction-adjusted availability declined sharply after 2022 but partially recovered through diversification toward allied suppliers. The elasticity analysis confirms that higher substitutability significantly enhances supply resilience, underscoring that effective availability depends on balanced diversification rather than complete reshoring.

3.7. Limitations

While this study provides a comprehensive framework for quantifying effective availability in semiconductor trade, several limitations should be noted. First, the analysis assumes a constant elasticity of substitution (σ) across supplier categories, which simplifies comparison but may not fully capture variations in technological substitutability among inputs. Second, minor discrepancies may arise from HS-code aggregation and cross-classification, particularly where intermediate goods straddle adjacent product codes. Third, the analysis excludes service-based components of the semiconductor value chain—such as electronic design automation (EDA), intellectual property (IP) cores, and software-intensive design services—which increasingly contribute to overall supply resilience but are not reflected in merchandise trade data. Acknowledging these limitations helps clarify the scope of the model and identifies areas for future research, including the integration of service trade and dynamic elasticity estimation into the effective availability framework.

4. Conclusion

By developing and applying an effective availability framework to semiconductor trade data from 2020-2024, this study provides empirical evidence on how policy interventions, trade restrictions, and diversification efforts have reshaped the structure and resilience of the U.S. semiconductor supply chain. Through the integration of trade-network visualization, CES-based import aggregation, and elasticity sensitivity analysis, the research identifies evolving patterns of dependence, substitution, and adaptation across key input categories—base materials, packaging materials, production equipment.

1) Persistent concentration amid partial diversification. Despite policy-driven reshoring initiatives and investment incentives under the CHIPS and Science Act (U.S. Congress, 2022), the United States remains heavily dependent on East Asian suppliers, particularly for advanced fabrication equipment and lithography materials. While imports from allied economies such as Japan and the Netherlands increased modestly, substitution remains constrained by technological specialization and production capacity limits.

2) Tariff and restriction effects on effective availability. Incorporating restriction factors $\chi_{ij}(t)$ into the CES aggregator reveals reveals that tariffs and export controls have a measurable short-term impact on effective availability, reducing accessible import volumes by increasing trade costs and narrowing supplier options. However, these same measures have accelerated diversification toward alternative and allied sources, supporting the long-term stabilization of availability.

3) Elasticity and resilience dynamics. The substitution elasticity (σ_M) plays a central role in determining resilience under supply disruptions. Scenarios with higher elasticities (4 - 6) exhibit greater adaptive capacity and quicker recovery of effective availability following policy shocks. Conversely, lower elasticities (2 - 3) represent concentrated, high-risk structures where even small disruptions can substantially reduce import capacity. This underscores that enhancing substitutability—through technology standardization, capacity expansion, and multi-sourcing strategies—is essential for sustainable resilience.

4) Structural evolution and strategic implications. Between 2020 and 2024, the semiconductor trade network underwent a transition from pre-pandemic interdependence to policy-driven segmentation, forming clearer regional clusters around the United States, East Asia, and Europe. The data suggest that complete self-sufficiency remains infeasible; instead, resilience emerges through diversified, rule-based, and geopolitically aligned trade partnerships. Maintaining open yet secure supply networks will therefore be critical to sustaining innovation, competitiveness, and strategic stability in the semiconductor sector.

In conclusion, this study demonstrates that resilience does not require isolation. The path toward secure semiconductor supply chains lies in balancing efficiency with redundancy, policy with market mechanisms, and national interests with global interdependence. The effective availability framework developed here provides a quantitative foundation for evaluating these trade-offs and can be extended to future research on critical technology supply chains, strategic trade policy, and industrial decoupling scenarios.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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