NATIONAL SECURITY
DATA AND POLICY
INSTITUTE

PRODUCT NO. 00010

MICROELECTRONICS SUPPLY CHAIN ANALYSIS

APRIL 15, 2025

NATIONAL SECURITY DATA AND POLICY INSTITUTE

Product No. 00010

Microelectronics Supply Chain Analysis

April 15, 2025

Executive Summary

The United States leads in the advanced microelectronics ecosystem via its dominance over design and intellectual property; however, the vast scale and complexity of the global network supporting manufacturing introduces vulnerability. Although certain dependencies, such as the flow of rare earth materials, are widely understood, others are more difficult to identify and model.

This study combines data extraction and materials flows to provide high-level summaries of the global dependency structure for 18 essential component materials within the advanced microelectronics space. We developed a methodological pipeline to rapidly scale up the extraction, processing, and presentation of origin and materials flow analysis from ground truth data. This early-stage research is the first step toward a broader understanding of points of vulnerability and leverage in the system.

Implications and Main Takeaways

- The economic and security importance of microelectronics means that commercial vendors gather data for facets of the system. However, the resulting fragmented data landscape means that there is no single quantitative resource that provides a comprehensive view of the system. Harmonizing data and generating uniform coverage remains an analytical challenge.
- Comtrade economic data flows frequently indicate a less concentrated supply chain than the geographic resource data would indicate. This suggests that materials pass through multiple export points, underscoring the complexity of the supply chains. Figure 1 draws from the past ten years of Comtrade data to highlight 13 commodities for which more than half of global trade passed through a single country for any year in the decade.
- Many critical materials for advanced electronics originate as byproducts of other economically valuable materials, notably bauxite, lead, refined oxygen, and zinc. Production of microelectronics components is thus vulnerable to the economic logic of the otherwise unrelated paired materials and the component material.
- Reprocessing and reworking existing materials and improving industrial facilities can expand domestic and international supplies of key materials.

Commodity Dominance Summary (Countries Controlling ≥50% of Global Value)

Commodity	Countries	Years of Dominance	Avg Share	Max Share
Boron and Tellurium	CHN	[2016]	0.5%	0.5%
Cobalt Ores	ZAR	[2019, 2020, 2021]	0.8%	0.8%
Cobalt Oxides	GBR, ZAR	[2022, 2024]	0.6%	0.7%
Gallium Group Articles	BRA	[2024]	0.6%	0.6%
Gallium Group Powders	DEU	[2024]	0.6%	0.6%
Hydrides and Nitrides	USA	[2024]	0.6%	0.6%
Oxides of Boron	USA	[2024]	0.8%	0.8%
Phosphorus	KAZ, VNM	[2021, 2022, 2023]	0.6%	0.7%
Photographic Goods	JPN	[2024]	0.6%	0.6%
Rare Earths	CHN, THA, VNM	[2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024]	0.6%	0.8%
Rare Gases	USA	[2024]	0.6%	0.6%
Tantalum Articles	USA	[2024]	0.8%	0.8%
Unwrought Iridium	ZAF	[2024]	0.6%	0.6%

Figure 1: Commodities with more than half of yearly trade value flowing through a single country, 2015-2015. "Years of Dominance" records the years for which Comtrade ascribed more than half of the value flow associated with a commodity to a single exporter. Countries records which country was associated with the flow. Average and maximum (max) share present the average and maximum concentration for the commodity's value flows for the decade spanning 2015-2025.

Introduction

Obtaining visibility into global supply chains for industries supporting national security is important in a world of densely interconnected manufacturing systems. Nations specialize in different segments of the production pipeline, causing supplier networks to grow complex and potentially dependent on one or a few relationships. Advanced electronics represent one such domain. Maintaining consistent access is essential to the defense and intelligence technologies of the United States, but several multilevel network dependencies characterize the sector. The complexity leads observers to focus on horizontal elements of the chain, such as end-point companies that produce devices, or on prominent vertical components like particularly vulnerable materials. This dynamic obscures the complicated relationships and network dependencies that may arise out of the system as a whole.

Characterizing the entire advanced electronics supply chain is challenging on multiple fronts. At the most basic level, there is a shortage of accessible, validated data with insight into the extraction and manufacture of constituent materials. Ideally, an analyst would be able to create pipelines that can scale to arbitrary inputs and which synthesizes data on extraction locations, entities involved in component production, intermediate manufacture and processing, transportation, and end-product use.

However, compiling this data requires overcoming significant hurdles. The fundamental challenge is data availability. Information on materials origins ranges from widely accessible, such as for domestic deposits of primary materials commodities, to strategically obscured, such as levels of production by sanctioned entities or informal artisanal mines. Where there have been investments in building commercial datasets, the impetus has been to focus on commercially important materials rather than on those that are important for national security. Additionally, extraction and manufacturing depend not only on geography but also on the frequently interconnected public and private sector actors whose operations can be kept private. Unlike geography, actors are frequently in flux as firms and governments enter lucrative or strategic markets while other markets contract.

The second major hurdle is data fragmentation. Extraction, processing and operations, and manufacturing are all essential components that determine the resiliency and vulnerability of supply chains. Yet data on each of these facets are developed and maintained for different analytical infrastructures and rarely put together. Even within the same data unit, the necessary data is not always compiled. For example, the United States Geological Survey (USGS) maintains yearly summaries of the production and import of critical minerals, with estimated production released as quantitative data tables, while import dependencies are reported in a qualitative written report. Together, the two data sources are a valuable source of information, but using them would require the development of a processing and synthesis infrastructure.

This report is the first installation in a larger project that seeks to overcome these challenges. Using artificial intelligence tools, we will connect disparate data sources to expand visibility into supply chains for materials critical to national security. Here, we begin by focusing on developing data sources to identify the origins of selected critical materials, allowing for initial quantification of the concentration of national points of origin. We design the data to quantify extraction and reserves as well as processing and manufacturing. We base the former on reserves information published by the United States Geological Survey (USGS) and public data on the mining industry.

We take the first steps towards building visibility into processing and manufacturing streams by integrating data on major exporter countries with industry-specific reporting on firm activity and consolidation. Combining this data allows us to analyze important transit points in critical supply chains. We developed a statistical workflow that incorporates the ground truth data, builds yearly network models of trade, and extracts and presents original visualizations of statistics that characterize trends in extraction and resource flows. In this report, we present these plots for our 18 focus materials; however, our workflow is extensible and can be adapted for additional materials or interactive dashboard presentations.

As we continue to develop this project, we intend to refine and extend our data pipeline and the analytic tools and frameworks to conceptualize resource-based leverage in transnational supply chains. The next stage of the project will build on our work identifying points of origin by quantifying leverage points and bottlenecks.

Our report proceeds as follows: we introduce the data and methods used for our analysis before summarizing the origin and material flows for key critical materials. Where possible, we accompany our analysis with visualizations displaying country-level concentration of global production and trade. We visually summarize trends in the structure of the global flows for specific materials by plotting the Herfindahl - Hirschman Index (HHI) over time.

Data and Methods

For our analysis, we aggregated data on materials overviews, origins, and trading flows. For each material of interest, identified in Table 1, we present a brief summary of the importance of the material for the advanced microelectronics industry and the challenges associated with its global supply chains. We source these summaries from geographic data collected by the USGS, peer-reviewed scholarship, market reports from trade publications, and policy analysis produced by materials and supply chain experts. We complement these summaries with geospatial visualizations of important countries of origin for each material. To build this dataset, we identified open-source datasets and commercial data vendors for origin points for raw materials, comparing their holdings and production methodology.

For naturally occurring materials, such as minerals used in semiconductor manufacturing and chip fabrication, we extracted data on known reserves from the USGS 2024 data release (National Minerals Information Center 2024). This gave us 151 known reserves for the materials of interest and closely related or precursor substances.[1] We improved precision by identifying locations of active mines and projects in development from an open-source mining dataset run by the Digbee technology company (Digbee 2024). At the time of access, the database comprised 1,833 locations of development and production extractive mining projects, sourced from company filing documents. We obtained coverage for boron, cerium, cobalt, dysprosium, gallium, iridium, neodymium, phosphate, tantalum, and yttrium.

We deepen our analysis by assessing the concentration of global trade in the identified materials. We characterized trade flows by identifying major global exporters and presenting yearly summaries of export concentrations for each material. To produce information on concentration, we mapped the materials of interest to Harmonized System (HS) codes at the 6-digit level, the highest resolution available. The Harmonized Codes associated with the materials of interest are described in Table 1.

[1] As an example of precursor substances, gallium is often a byproduct of bauxite (aluminum) and zinc mining processes. Likewise, germanium is a byproduct of lead, zinc, and coal mining.

This produced a dataset of 79,780 records detailing annual country-level exports for the materials covered under each HS code and spanning 1988-2024. Using the associated Harmonized System Codes, we source trade data from the United Nation's Comtrade database, accessed via the World Bank's World Integrated Trade Solution platform (United Nations 2024). The Comtrade database provides a comprehensive report of annual imports and exports for more than 200 countries and thousands of individual commodities. Although known to be subject to reporting asymmetries, the Comtrade data is nevertheless the most complete and granular dataset that we were able to identify (Chen et al. 2022).

Using the Comtrade data, we estimate the annual export trade activity for each material by summing the value of all reported exports, and estimate the value of each country's annual exports of a particular commodity by summing the reported value of all product exports in a given year. Using these variables, we estimate an annual proportion of a given material's export activity originating with a given country by dividing the country's reported exports by the total exports for the product and year. We then plot the ten top exporters for each commodity in each year of our data, labeling the top annual exporter for each commodity of interest as well as countries that control 75% or more of the value of exports for a given commodity.

To estimate concentration, we derived the Herfindahl - Hirschman Index (HHI) for each of the Comtrade commodities that we mapped to the materials of interest. HHI is a widely used measure of market concentration. It is generated by squaring the market share of each entity of the market shares of all entities in the market. Here, we estimate the yearly HHI for each commodity by summarizing the proportion of export values associated with a given country. The index approaches zero when the market is occupied by a large number of entities and has a maximum value of $10,000$ when the market is controlled by a single firm. In general, markets with an HHI of between $1,000 - 1,800$ are considered to be moderately concentrated while those with an HHI greater than 1,800 are highly concentrated (United States Department of Justice 2024).

We extend our analysis by producing annual commodity-level export networks, modeling trade flows as a directed graph from an exporting country to a partner importer. We extract structural statistics for each annual product network, producing estimates of country structural importance via PageRank scores, degree centrality, closeness centrality, and eigenvector centrality. We additionally take global network measures of annual clustering coefficients. Our followup products will present this research in more depth.

Table 1: Included HS Codes

Target Material	**Associated HS Code**	**Description**
Boron (B)	280450, 284011, 284019, 284020, 281000	Boron, tellurium; Refined borax; Disodium tetraborate; Other borates; Oxides of boron, boric acids
Dysprosium (Dy), Neodymium (Nd) & Yttrium (Y)	280530	Rare-earth metals, scandium and yttrium
Cerium (Ce)	284610	Cerium compounds
Gallium (Ga)	811291, 811299	Gallium, hafnium, indium, niobium, rhenium, or thall

Target Material	Associated HS Code	HS Category
Germanium (Ge)	282560	Germanium oxides and zirconium dioxide[2]
Iridium (Ir)	711041, 711049	Iridium, osmium and ruthenium unwrought; Iridium, osmium and ruthenium in other semi-man
Phosphorus (P)	280470	Phosphorus
Ultrapure silicon	280461	Silicon containing by weight $\geq$ 99.99% silicon
Gallium Nitride (GaN) & Indium Phosphide (InP)	285000, 811291, 811299	Hydrides, nitrides, azides, silicides and borides; Gallium, hafnium, indium, niobium, rhenium or thall; Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium
Cobalt (Co)	260500, 810510, 810590, 282200, 282734, 291523	Cobalt ores, Unwrought Cobalt, Cobalt articles, Cobalt oxides, Cobalt chloride, Cobalt acetates
Tantalum (Ta)	810390, 810310	Tantalum articles, Tantalum unwrought
Neon (Ne), Krypton (Kr) & Xenon (Xe)	280429	Rare gases
Photoresist Polymers	370790	Photographic goods; chemical preparations other than sensitised emulsions[3]

Results

In the following section, we summarize points of origin and global market structure for raw materials and globally traded commodities for the 18 materials of interest. We structure these summaries into six overarching groups: critical minerals used in semiconductor manufacturing, quartz used in semiconductor manufacturing, semiconductor materials, materials for chip fabrication in high-performance processors, gases for etching and cleaning, and photoresist compounds.

Critical Minerals Used in Semiconductor Manufacturing: Boron

Boron and associated derivatives are used for a wide array of applications, ranging from detergents to agriculture to aerospace and defense. Within advanced microelectronics, boron compounds are

[2] We omitted HS code 811230, comprising "Germanium and articles thereof, including waste," for having no recorded trade activity after 2018.

[3] HS Code refined from (Murashige 2023)

used to manufacture semiconductors and electronic components (Starzecki 2024). Economically viable deposits of boron are associated with volcanic activity and climates, with deposits appearing in the Andes, southern Eurasia, and the Mojave Desert (Brioche 2025). We treat boron separately from the remaining critical minerals for semiconductors as global boron flows exhibit unique traits.

While some estimates believe that global boron reserves are adequate to meet current and future demand (Brioche 2025), other sources identify supply chain concentration and uncertainty over the true sizes of reserves as points of vulnerability (Mermer & Şengül 2020). Boron is also "almost non-recyclable" and has few cost-effective substitutes, making the supply all the more critical (Elevli et al. 2022).

Turkey dominates the extractive market for boron, holding the most significant known deposits. Additionally, Turkish boron deposits are of a form that is particularly adaptable to heat-resistant glass, thus increasing their importance for advanced electronics uses (Brioche 2025, Elevli et al. 2022). Turkey's dominance over known reserves can be seen in Figure 2, which uses data from the USGS to estimate boron production in 2024. Materials flows for processed boron derivatives tracked by Comtrade are also concentrated there, though to a lesser extent than raw material extraction. Of the four categories associated with boron products, refined borax and disodium tetraborate have a market that is dominated by the United States. Conversely, oxides of boron and other forms of borates have lower market concentration, with the most dominant exporter of oxides of boron and boric acids —-also the United States—historically responsible for 50% of global market export value. The boron and tellurium market has been moderately concentrated, with no single country controlling more than half of the global annual value.

Critical Minerals used in Semiconductor Manufacturing: Rare Earths

Rare earths and rare earth compounds (REEs) are well-known as a set of minerals that are crucial for advanced technologies and for which supplies are heavily concentrated by Chinese producers (Ilankoon et al. 2022). We are specifically interested in dysprosium (dy), cerium (Ce), neodymium (Nd), phosphorus (P), and yttrium (Y); however, as most information and analysis treats the category as a whole, we follow convention and refer to "REEs" rather than specific materials.

In addition to maintaining nearly 60% of global mine production (see Figure 3), Chinese firms dominate physical production infrastructure as well as the patents required for processing. Moreover, REE concentrates produced outside of China by nations like the United States and Myanmar are often still exported to China for processing (Ilankoon et al. 2022).

Cerium is the most abundant of the rare earth materials. It is expected to remain with excess supply in the market (Daigle & DeCarlo 2021), and efforts to recover cerium from waste streams will further help reduce the risk of global bottlenecks and shortages (Bleiwas 2013). Indeed, the relative abundance of cerium in rare earth ores is a source of stress on the rare earth extraction supply chain, as separating it from more desirable rare earth elements is an industrial challenge. This has led cerium to be sold at rates that do not cover the costs of extraction and processing (Golev et al. 2014). Efforts are underway to reduce this stress by increasing the industrial uses of cerium (Sims et al. 2022).

Progress toward establishing rare earths processing infrastructure outside of China is limited by a

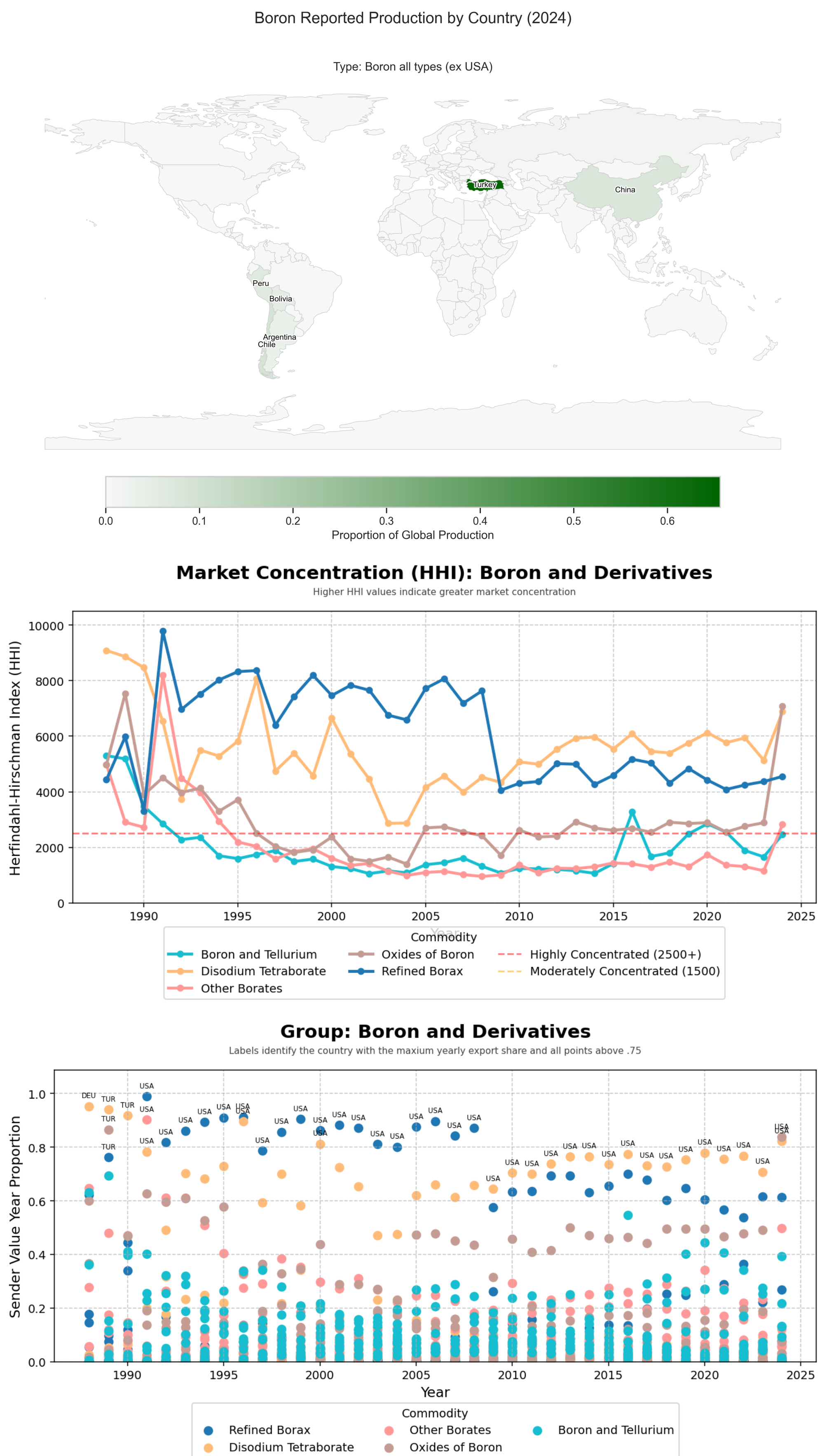


Figure 2: International Boron Producers (2024)

shortage of research and development investment and by the challenge of managing waste generated by the rare earth purification and separation processes (Ilankoon et al. 2022). These trends are exacerbated by price volatility for rare earth commodities, which creates uncertainty that deters investors (Golev et al. 2014).

Efforts to increase the resilience of the rare earth supply chain have generated research into alternative and domestic sources. One analysis suggests that even at low yields, waste streams and industrial byproducts could meet current global demand (Golev et al. 2014).

China's central role in the rare earth market can be seen in Figure 3, which presents USGS estimates of the proportion of rare earths China produced in 2024. The concentration and dominance of China in rare earth materials flows is likewise evident in the historical HHI index for the Rare Earths category: China reported approximately three-quarters of the value of annual REE exports for most years covered by the Comtrade data.

Critical Minerals Used in Semiconductor Manufacturing: Germanium, Iridium, and Black Phosphorus

The remaining group of target materials that are critical for semiconductors range from trace minerals that are among the rarest on earth, such as iridium, to new materials derived from phosphorus, which is distributed but in high demand. These summaries cover germanium, iridium, and black phosphorus. Germanium and iridium are produced as byproducts of existing mining processes; germanium is a zinc byproduct, while iridium is produced as a byproduct of platinum mining. Black phosphorus is a form of the phosphorus element that has recently been discovered to have semiconductor properties.

Germanium extraction is technically complex. Production of the element is most closely associated with zinc residues, but it can also be extracted as a byproduct of coal burning and recovered from recycled materials (Shanks III et al. 2017). Germanium's status as a byproduct of zinc extraction makes it difficult to estimate worldwide production and reserves. The element has recently been associated with zinc concentrates originating in Canada, China, the Democratic Republic of the Congo, and Finland, and is a coal byproduct in China and Russia (Shanks III et al. 2017).

Potential substitutes for germanium depend on the intended application and range from silicon and gallium arsenide to niobium and tantalum (Tolcin 2025, Moskalyk 2004). The United States, China, Congo (Kinshasa), and Russia had extraction sites that were either active or in development in 2024 (Tolcin 2025). Similarly, countries that produce or commercially recycle the material include the United States, Belgium, Canada, China, Germany, and Russia.[4] A leading producer of germanium, China banned all exports to the United States in December 2024. At the same time, additional processing facilities were established in Congo (Kinshasa) and the United States (Tolcin 2025).

Iridium is a member of the platinum group of metals, which are among the least abundant elements on earth. Most reserves are located in South Africa and Russia, with a small percentage mined in the United States (Smith et al. 2022). Figure 4 displays global platinum production as an indicator of iridium production because iridium is a byproduct of platinum mining. Iridium supplies are

[4] We do not include a production map for Germanium, as 2023 and 2024 production estimates were not released by USGS.

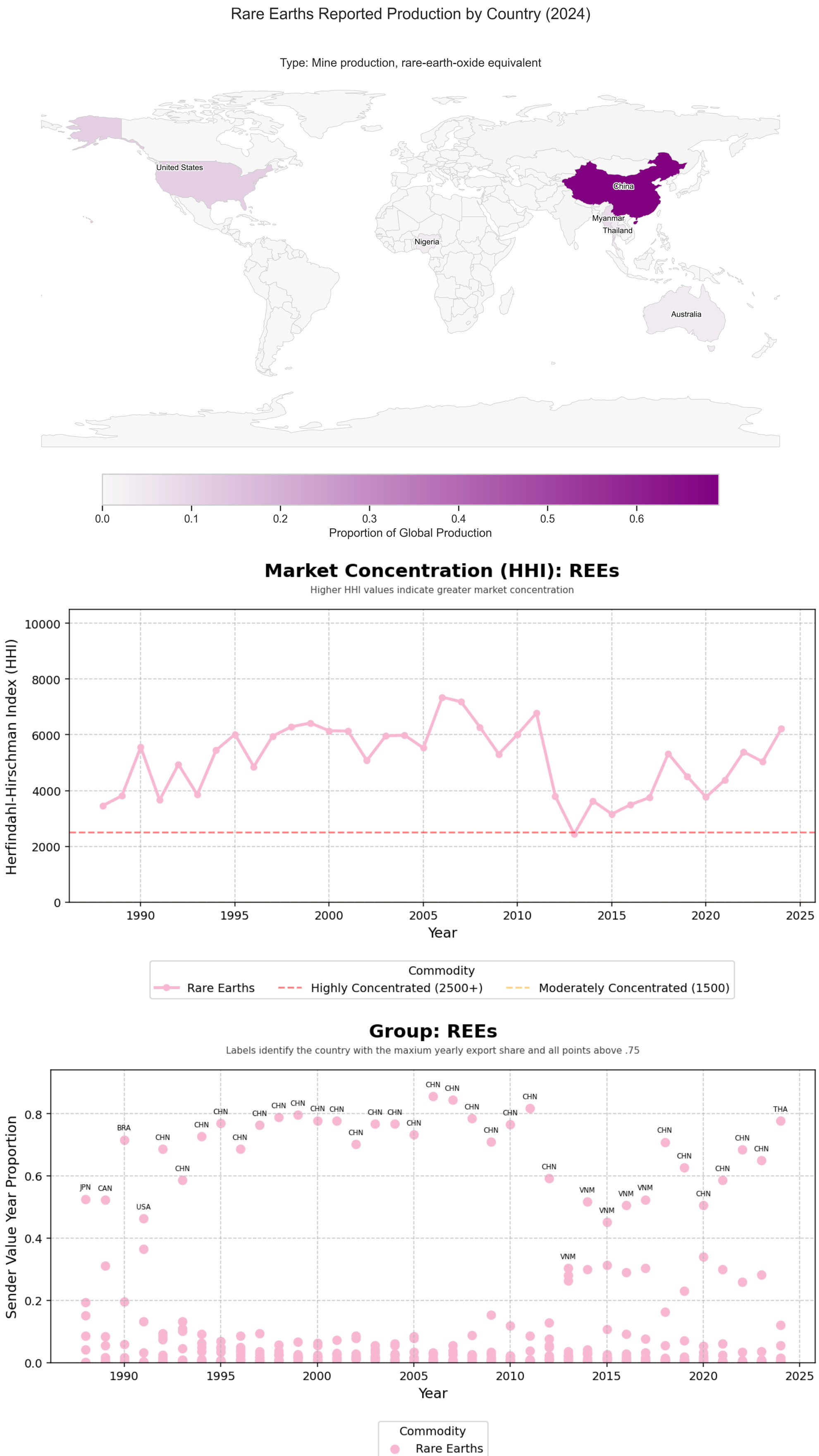


Figure 3: Production (2024) and Material Flows for Rare Earth Elements

vulnerable, driven by scarcity and incentives to process other metals in the platinum group instead. Additionally, the United States lacks significant domestic supplies of the metal: There are two platinum group mines operating in the United States, but they produce less than 7% of the world supply, and both are owned by a South African company (Smith et al. 2022). The development of iridium substitutes is an active area of scientific research (Hirohata et al. 2017).

Black phosphorus, one of the four main types of phosphorus, is an emerging nanomaterial and semiconductor material (Xia et al. 2019, Zhang et al. 2021). Ongoing research is focused on environmental stability and polymerization methods intended to improve the utility of black phosphorus (Zhang et al. 2021). Phosphorus, the base material for black phosphorus, is globally abundant, yet the supply chain is under pressure because it is fundamental across industries ranging from agricultural to defense (Nedelciu et al. 2020). The data we present below is drawn from USGS reports on phosphate rock, which is primarily mined for the manufacture of elemental phosphorus (Jasinski 2025), with distribution summarized by Figure 4. The United States mines phosphate rock from ten mines located in Florida, Idaho, North Carolina, and Utah. Globally, the leading producers of phosphate rock are China, Morocco, the United States, and Russia (Jasinski 2025).

Figure 5 summarizes the market flows for iridium (via platinum), phosphorus, and germanium. In general, the number of exporters has diversified in recent years, as demonstrated by the reduction in HHI. Kazakhstan and Vietnam have been leading exporters for phosphorus, the most concentrated of these markets.

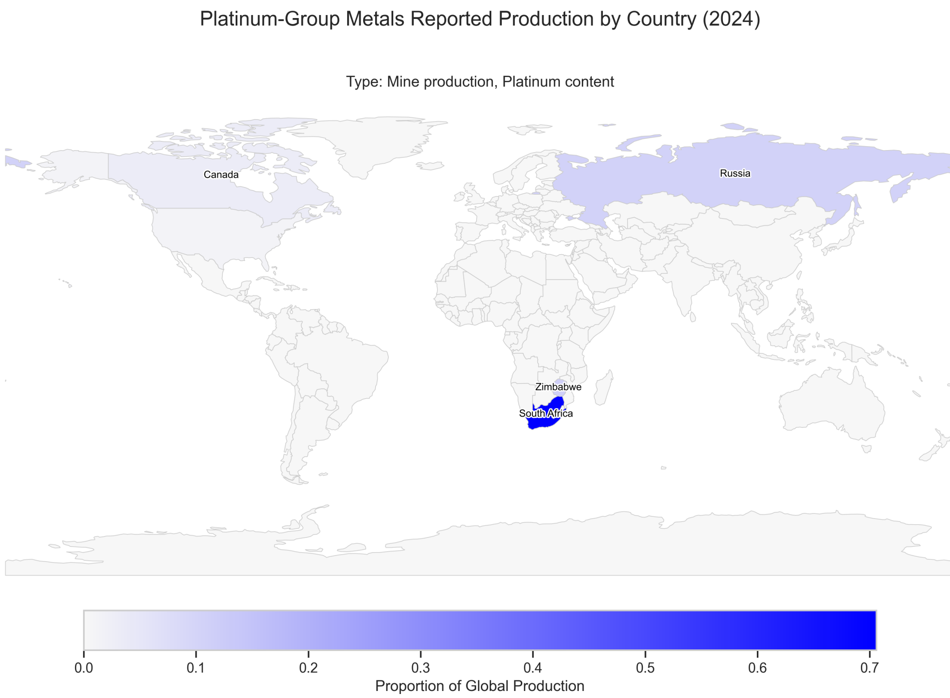
Quartz Used in Semiconductor Manufacturing: Ultra High Purity Quartz

Ultra-high purity quartz (HPQ) is the principal raw material for producing silicon, which is classified as a critical mineral by countries worldwide, including the United States, Australia, the European Union, India, South Korea, and the United Kingdom (Jennings et al. 2024, 1). HPQ differs from cultured quartz, which is increasingly produced through industrial processes (Goodin 2025). Figure 6 summarizes significant exporting countries for the ultrapure silicon market; similar data for HPQ flows are difficult to estimate, partly because trade data combines HPQ with other industrial quartz products (Goodin 2025).

A point of vulnerability for HPQ and ultra-pure silicon is that, for most applications, there are no economically viable substitutes or alternatives. Cultured quartz can be used as a substitute for HPQ; however, the practical use of manufactured quartz is of limited economic viability. Economically viable industrial processes to manufacture HPQ are actively being researched, with Jiangsu Pacific Quartz Co. Ltd leading efforts in this field (Zhang et al. 2023, 2)

A limited number of the world's HPQ resources are suitable for direct electronics or optical use. Table 2 presents a summary of exploitation and exploration sites.[5] HPQ is scarce due to its geographic concentration and rarity, and few companies extract the material. The Spruce Pine mine in the United States supplies approximately 70% of the global supply of HPQ and is processed by two companies, Sibelco and The Quartz Corp. Production was temporarily diminished after Hurricane Helene damaged operations on September 26, 2024. Both resumed full operation in October 2024 (Goodin 2025). In Australia, Simcoa Operations Pty Ltd was the only company

[5] This data is presented as a table rather than the usual map as estimates of quartz reserves often do not differentiate between HPQ and quartz for other industrial uses.



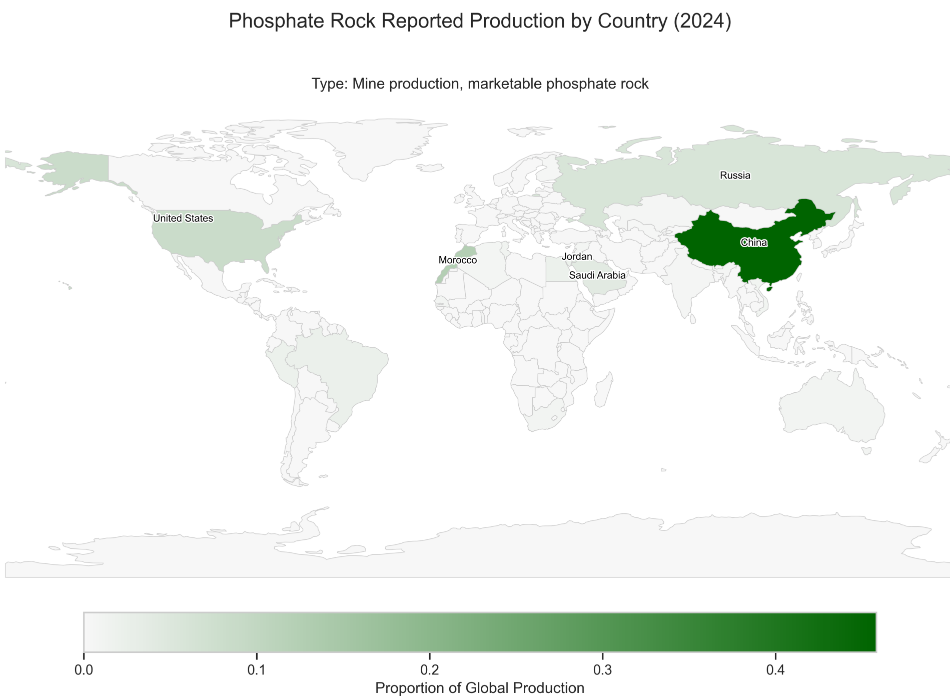


Figure 4: Resource Distributions for Platinum and Phosphorus

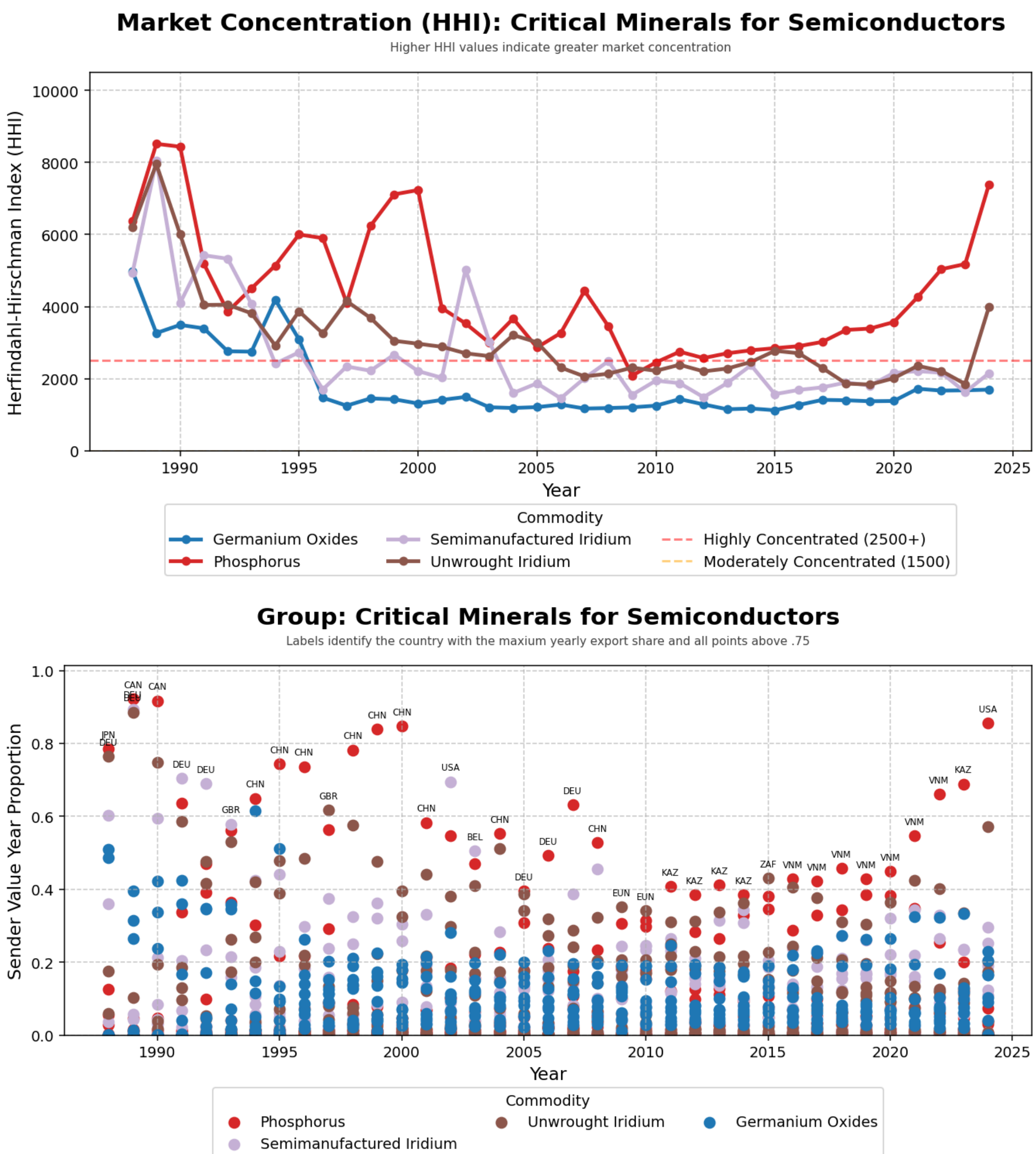


Figure 5: Market Concentration for Germanium, Iridium, and Phosphorus

mining HPQ in 2024; however, the country discovered potentially significant reserves (Goodin 2025, 2).

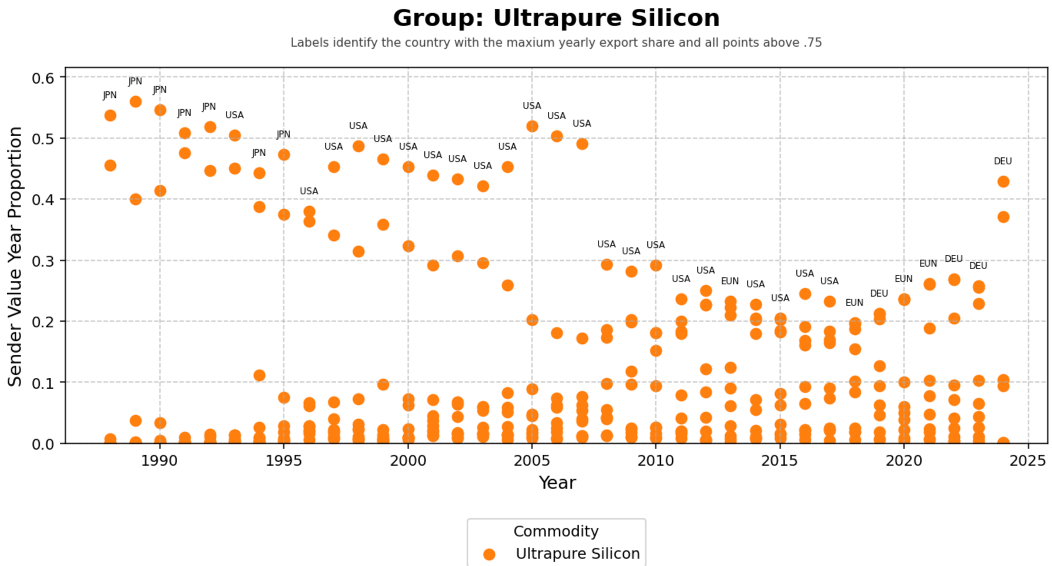
Notable Global HPQ Deposits	
Location	**Country**
Bahia, Minas Gerais, Para, Santa Catarina	Brazil
Baie Johan-Beetz Hydrothermal Deposit; Horse Creek Quartz Mine (Mount Wilson Quartzite); Moberly Mine (Mount Wilson Quartzite)	Canada
Ivigtût Project	Greenland
Nordland County; Svanvik, Nesodden (Hydrothermal veins); Tana, Mårnes (Quartzite); Drag, Setesdal (Pegmatites)	Norway
Southern Urals (Kyshtym)	Russia
Spruce Pine Pegmatite Complex	USA
HPQ Exploration Sites	
Location	**Country**
Arabian Shield Qinling, Anhui, Hubei Provinces	Saudi Arabia China
Potential Reserves with Limited Processing Infrastructure	
Continent	**Country**
Asia	Mongolia
Africa	Angola, Madagascar, Cameroon, Mauritania, and Nambia)

Table 2: Notable global HPQ deposits and exploration locations, data sourced from (Jennings et al. 2024, Zhang et al. 2023)

Semiconductor Materials: Gallium and Indium

Gallium Nitride (GaN) and Indium Phosphide (InP) are components of semiconductor chips that possess valuable electronic properties for cutting-edge applications. GaN can withstand higher voltages and electricity than silicon, while InP has exceptional radiation hardiness. InP is also a target material for both China's domestic semiconductor industry and the consumer electronics industry (Jaffal 2022). The former seeks to use InP to expand their semiconductor manufacturing capacity without relying on GaN imports, while the latter uses InP to expand features that leverage position and proximity sending.

GaN is vulnerable to Chinese control over the production and processing of raw gallium, which is extracted as a byproduct of bauxite mining (Funaiole et al. 2023). China accounts for 99% of worldwide low-purity gallium production, and Chinese firms dominate worldwide bauxite processing facilities. High-purity refined gallium is known to be produced by Canada, China, Japan, Slovakia, and the United States (Dair 2025). The United States dominates research into GaN technologies, but Chinese firms operate a majority of GaN fabrication facilities (Shivakumar et al. 2024).



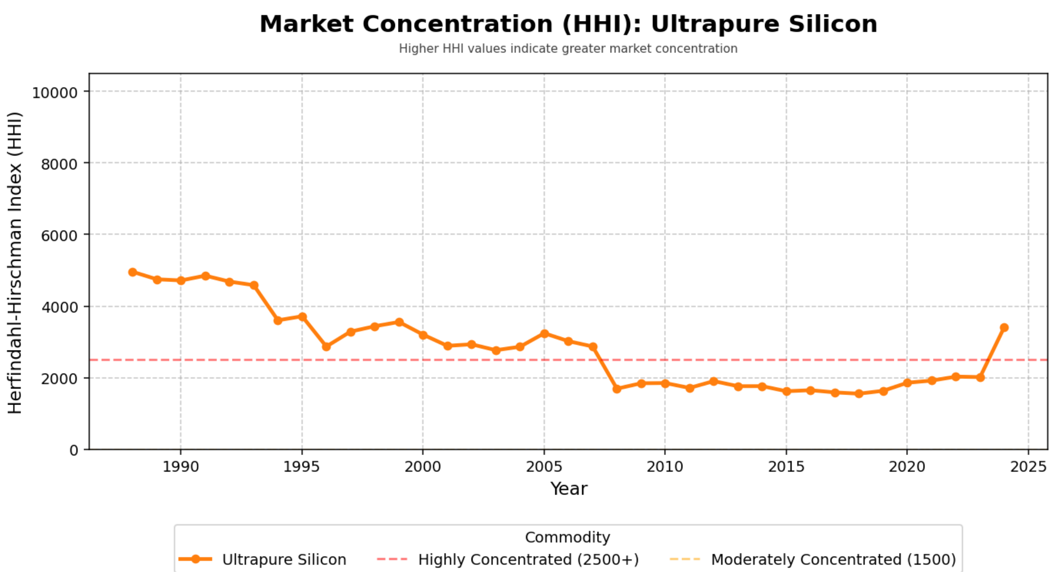


Figure 6: Exporter Concentrations for Ultrapure Silicon

No unrefined gallium has been recovered domestically since 1987 (Dair 2025). This may change in the future: Since China imposed export restrictions on gallium in 2023, the United States has attempted to restart domestic production, with at least one company exploring the feasibility of launching a domestic gallium industry. Additional efforts to diversify the supply chain for gallium include recovering the material from scrap in Canada, China, Japan, Slovakia, and the United States (Dair 2025).

Materials flows for gallium and related products reflect the dynamics of the GaN system: Constituent materials, such as raw gallium and GaN fabrication facilities, are extremely concentrated in China, as shown in Figure 7. At the same time, the United States and other countries refined gallium for commercial and military applications, reducing the HHI index for gallium articles, powders, hydrides, and nitrides tracked by Comtrade.

China is likewise the leading producer and exporter of indium, which is extracted as a byproduct of zinc smelting (Tolcin 2023). Refining of the material is sensitive to external conditions, with sources in both France and China periodically ceasing refining when faced with fluctuation in the price and availability of power (Tolcin 2023). Indium phosphide production is associated with the Beijing Tongmei Xtal Technology Co (China), Freiberger Compound Materials GmbH (Germany), JX Nippon (Japan), Sumitomo Electric Industries, Ltd (Japan), and Umicore (Belgium) (Beijing Tongmei Xtal Technology Co., Ltd. 2023).

Materials for Chip Fabrication in High-Performance Processors: Cobalt and Tantalum

Cobalt (Co) and tantalum (Ta) are elements widely used in industrial applications. In processors, they help to protect internal wiring (Bourzac 2018). The Democratic Republic of Congo is the leading producer of both.

Cobalt is known primarily for its uses in defense and energy infrastructure, such as in heat-resistant alloys and lithium-ion batteries. Within advanced microelectronics, the material is used to control electrical resistance in integrated circuits. The distribution and market concentration of cobalt is presented in 8. Cobalt mining and production increased to record levels in 2023, with the US importing the mineral across an array of formats. The United States has limited domestic production of cobalt from sites in Idaho, Michigan, and Missouri, although low commodity prices caused one domestic mine to suspend production (Ewing 2024). The Democratic Republic of the Congo is the world's leading source of mined cobalt, while China is both the largest producer and consumer of refined cobalt (Ewing 2024).

Viable substitutes for cobalt exist for many applications, though often at a considerable loss of efficiency. Neodymium-iron-boron alloys or nickel-iron alloys are targets to replace cobalt in magnets (Ewing 2024). In addition, efforts are being made to recover cobalt from waste and scrap, with scrap products representing an estimated 25% of cobalt consumption (Ewing 2024). Materials flows for cobalt became more concentrated after approximately 2015, with the Democratic Republic of the Congo emerging as the major exporter of cobalt ores and oxides. China and the United Kingdom are both important exporters of cobalt oxides.

Tantalum is critical to enabling miniaturization of electronics and components (Habecker 2022). Figure 9 shows the distribution and market concentration for Tantalum. Historically, tanatalum

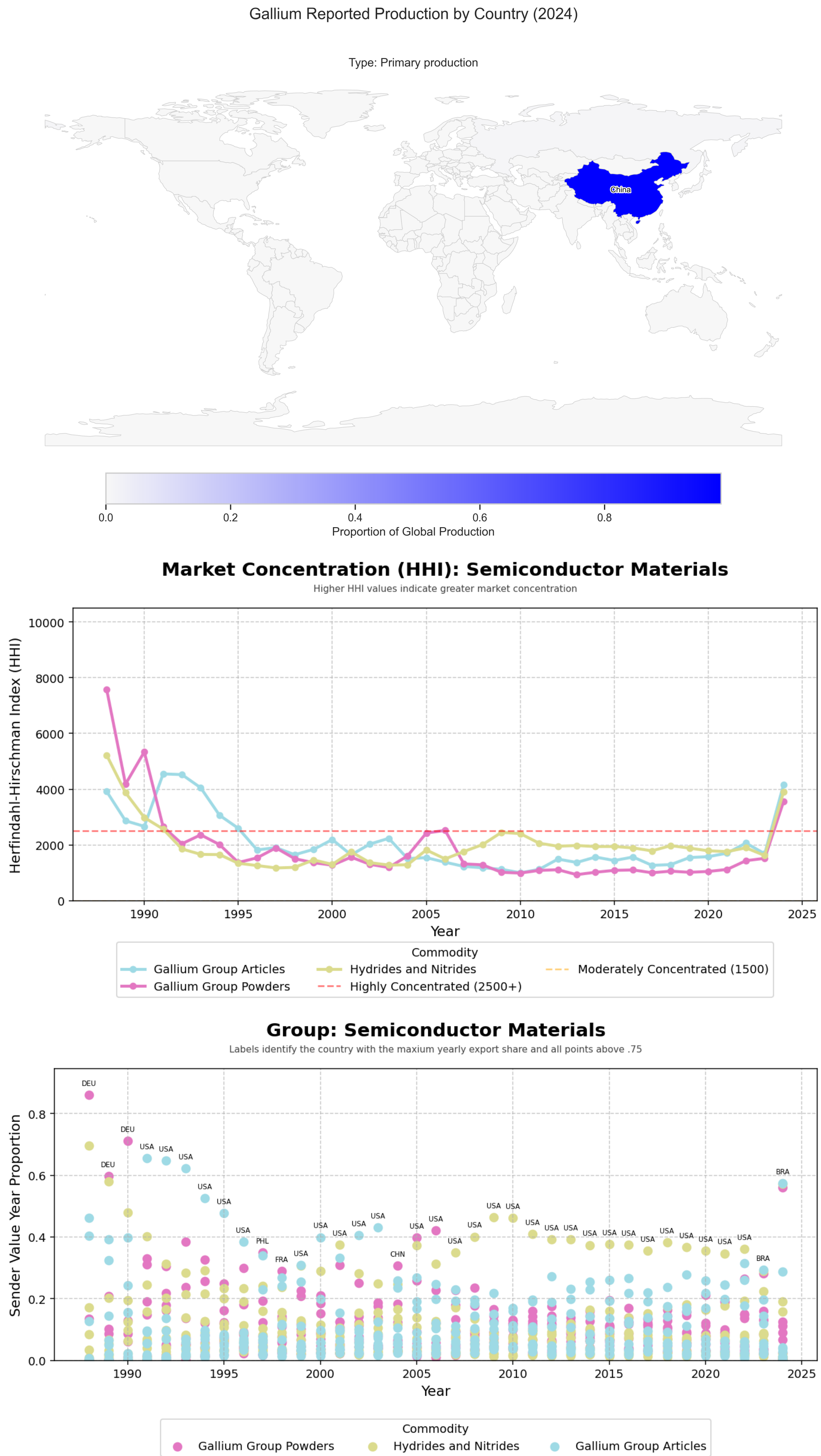


Figure 7: Exporter Concentrations for Gallium and Associated Commodities

is one of the semiconductor materials not produced by the United States, as domestic sources of the material are not commercially recoverable (Friedline 2025, Khan et al. 2021). Unlike cobalt, whose production is very concentrated, with the Democratic Republic of the Congo, tantalum production has a broader dispersion, with Rwanda, Nigeria, and Brazil also serving as extraction points. Globally, China is the leading exporter of tantalum products by value, although the Chinese share in material flows has stabilized at approximately 40% of global value.

Gases for Etching and Cleaning: Krypton, Neon, and Xenon

Krypton (Kr), neon (Ne), and xenon (Xe) are used to manufacture gas lasers and to operate semiconductor manufacturing equipment. Beyond their manufacturing use, xenon shows promise as a material that aids the miniaturization and densification of computer storage and memory systems (Linköping University 2025).

These gases are produced in an industrial process where they are mechanically separated from the air. They are isolated by air separation units (ASUs), of which about one hundred had the capacity for krypton and xenon isolation in the early 2020s (EFC Gases & Advanced Materials 2022). This typically occurs as part of the process of purifying oxygen, although purifying krypton and xenon requires additional equipment beyond that required to produce oxygen. This creates a long-term supply dependency based on market prices: Whether ASUs are built with the capacity to extract the two depends on whether it was economically desirable to do so at the time that the ASU was designed and built (EFC Gases & Advanced Materials 2022).

ASU facilities are often built to support steel and petrochemical manufacturing and located near the end-use for isolated oxygen. As a result, the supply chains are susceptible to disruption; examples include interruptions caused by natural phenomenon, such as the shutdowns during the Covid-19 pandemic; geopolitical instability, such as the war in Ukraine; and export controls, such as Russia's 2022 limitations on neon supplies (Burgess 2023, EFC Gases & Advanced Materials 2022). To offset these sources of vulnerability, semiconductor manufacturers are attempting to reduce gas consumption in their industrial processes and to establish manufacturing capacity near semiconductor manufacturing sites.

The noble gas supply chain is difficult to predict as the production of noble gases is deeply embedded with other supply chains and the market is characterized by long-term confidential contracts (Burgess 2023, EFC Gases & Advanced Materials 2022). Overall the supply of high-purity gases is dominated by four manufacturers: Air Liquide (France), Dayo Nippon Acid (Japan), Linde (USA), and American Air Chemical (USA) (Burgess 2023). However, within the category, neon gas has been highly reliant on factories in Mariupol, Ukraine which accounted for the majority of global neon gas production (Burgess 2023). Ukraine likewise produced nearly half of the global supply of krypton and xenon. The United States is the top exporter of noble gases as recorded by Comtrade flows, which reflects both domestic manufacturing and the length and density of the chains.

Photoresist Compounds

Photoresist polymers are used for creating semiconductor chips. The market is heavily dominated by Japan, with Japanese countries controlling 73% of the market for photoresists in 2022 (Murashige

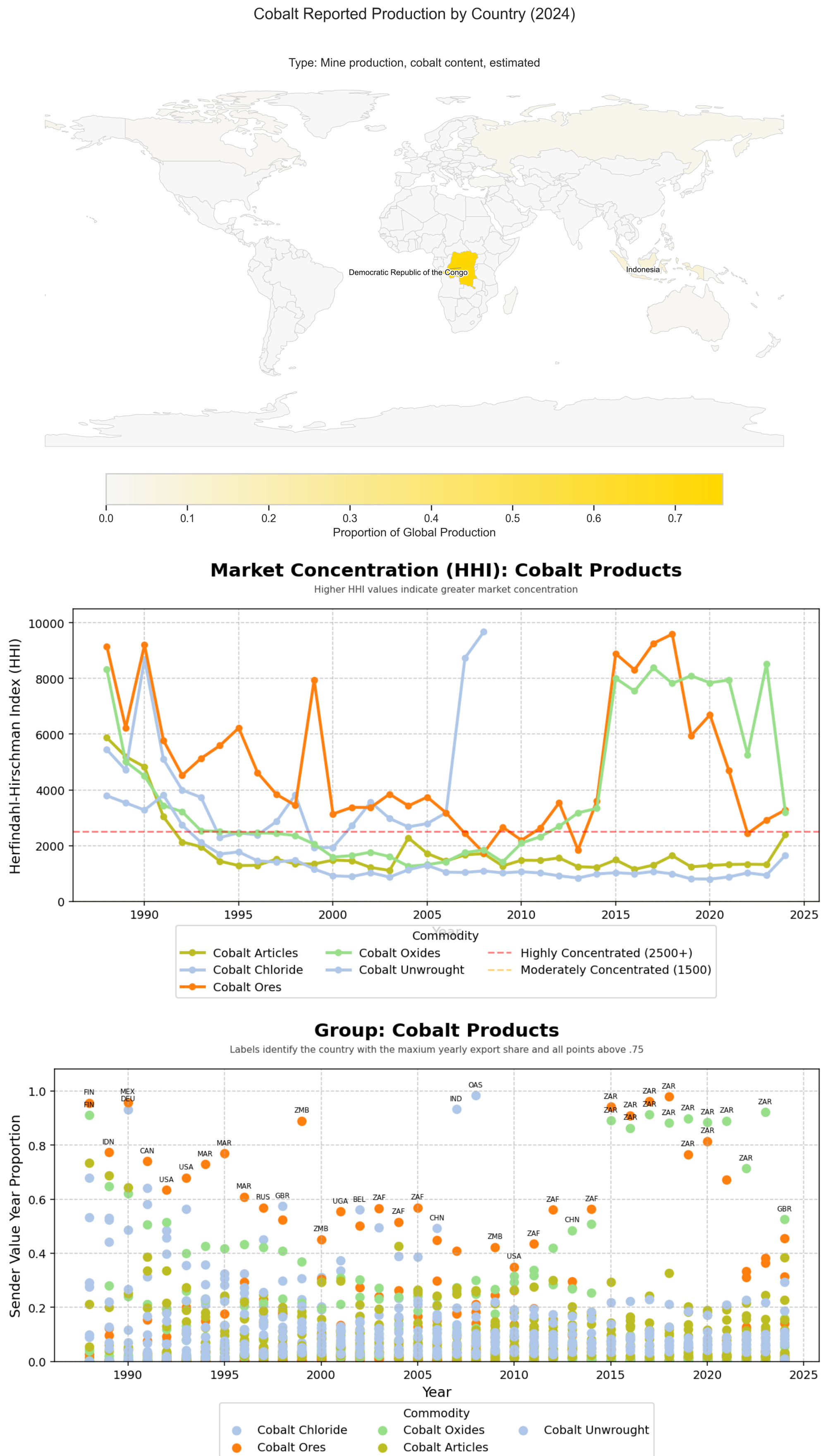


Figure 8: Cobalt Distributions

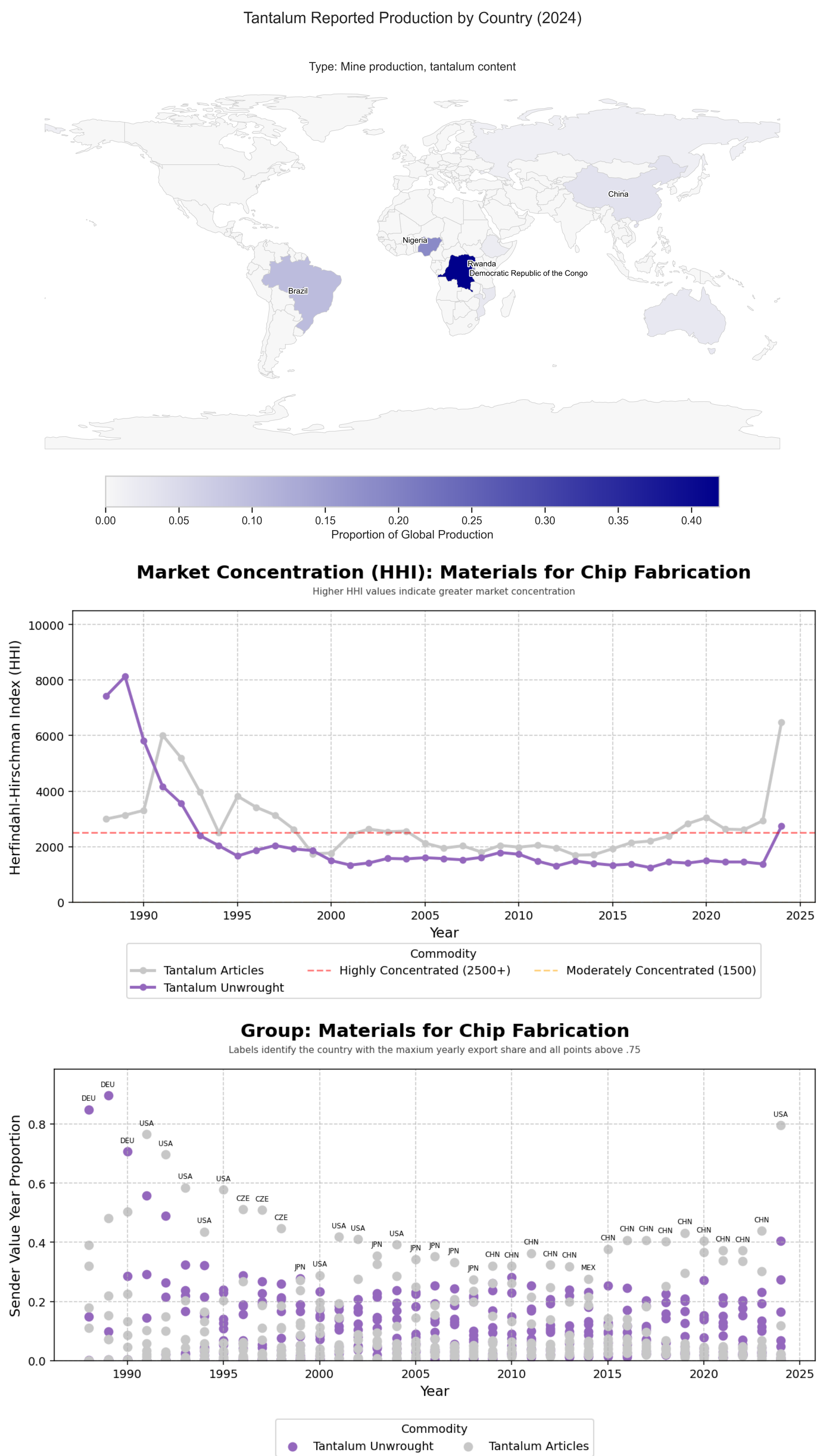


Figure 9: Tantalum Distributions

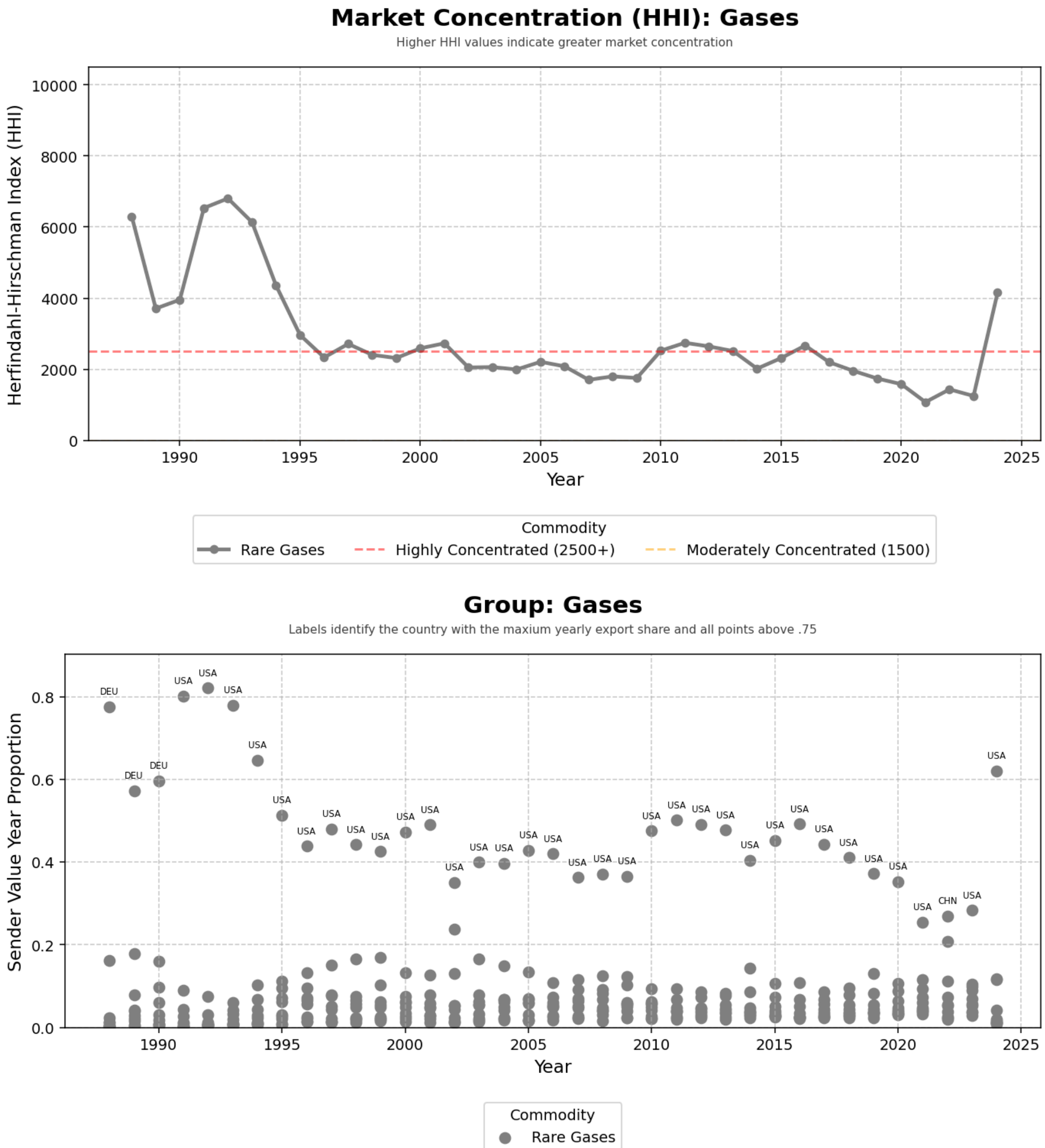


Figure 10: Exporter Concentrations for Selected Gases for Etching and Cleaning

2023). Additionally, two Japanese companies, JSR Corporation and Shin-etsu Chemical, account for 90% of the lithography machine market. Historically, photoresist polymers used for semiconductor materials were exclusively produced in Japan; however, starting in 2020, Shin-etsu Chemical announced their intent to build plants in Taiwan (Pte. 2024). JSR Corporation followed with plans to produce photoresists in South Korea (Jo 2024). Nevertheless, Japan maintains considerable leverage over the semiconductor manufacturing industry, which they have used as an economic and political tool. One such example is Japanese restrictions on photoresist exports to South Korea from 2019 - 2023 (Yoon 2023).

Figure 11 shows Japan's dominant role in the market flows for the Harmonized System tracking of chemical preparations for photographic use, of which photresist polymers are a constituent (Murashige 2023). Note that both plots under-report Japan's dominance as a supplier of photoresist polymers, as the HS category includes other chemicals used for photography and photographic uses.

References

Beijing Tongmei Xtal Technology Co., Ltd. (2023), 'Prospectus: Initial public offering and star market listing of shares', Company Filing. Filing document subject to procedures with the Shanghai Stock Exchange and the China Securities Regulatory Commission.

Bleiwas, D. I. (2013), Potential for recovery of cerium contained in automotive catalytic converters, Technical report, US Geological Survey.

Bourzac, K. (2018), 'Cobalt could untangle chips' wiring problems', *IEEE Spectrum* .
URL: *https://spectrum.ieee.org/cobalt-could-untangle-chips-wiring-problems*

Brioche, A. S. (2025), Boron, Technical report, United States Geological Survey.

Burgess, W. (2023), 'Noble gases and the shock of war: Laser and semiconductor manufacturers adjust to price increases while securing supply chains', *SPIE* .
URL: *https://spie.org/news/photonics-focus/mayjune-2023/supplying-noble-gases-for-photonics-in-war-time*

Chen, C., Jiang, Z., Li, N., Wang, H., Wang, P., Zhang, Z., Zhang, C., Ma, F., Huang, Y., Lu, X. et al. (2022), 'Advancing UN Comtrade for physical trade flow analysis: review of data quality issues and solutions', *Resources, Conservation and Recycling* **186**, 106526.

Daigle, B. & DeCarlo, S. (2021), *Rare earths and the US electronics sector: supply chain developments and trends*, Office of Industries, US International Trade Commission Washington, DC, USA.

Dair, L. (2025), Galium, Technical report, US Geological Survey.

Digbee (2024), 'Digbee mining database', Available online. Accessed: 2024-03-28.
URL: *https://digbee.com/data*

EFC Gases & Advanced Materials (2022), Krypton and xenon in semiconductors, Technical report.
URL: *https://www.efcgases.com/blog/krypton-and-xenon-in-semiconductors/*

Elevli, B., Yaman, İ. & Laratte, B. (2022), 'Estimation of the Turkish boron exportation to europe', *Mining* **2**(2), 155–169.

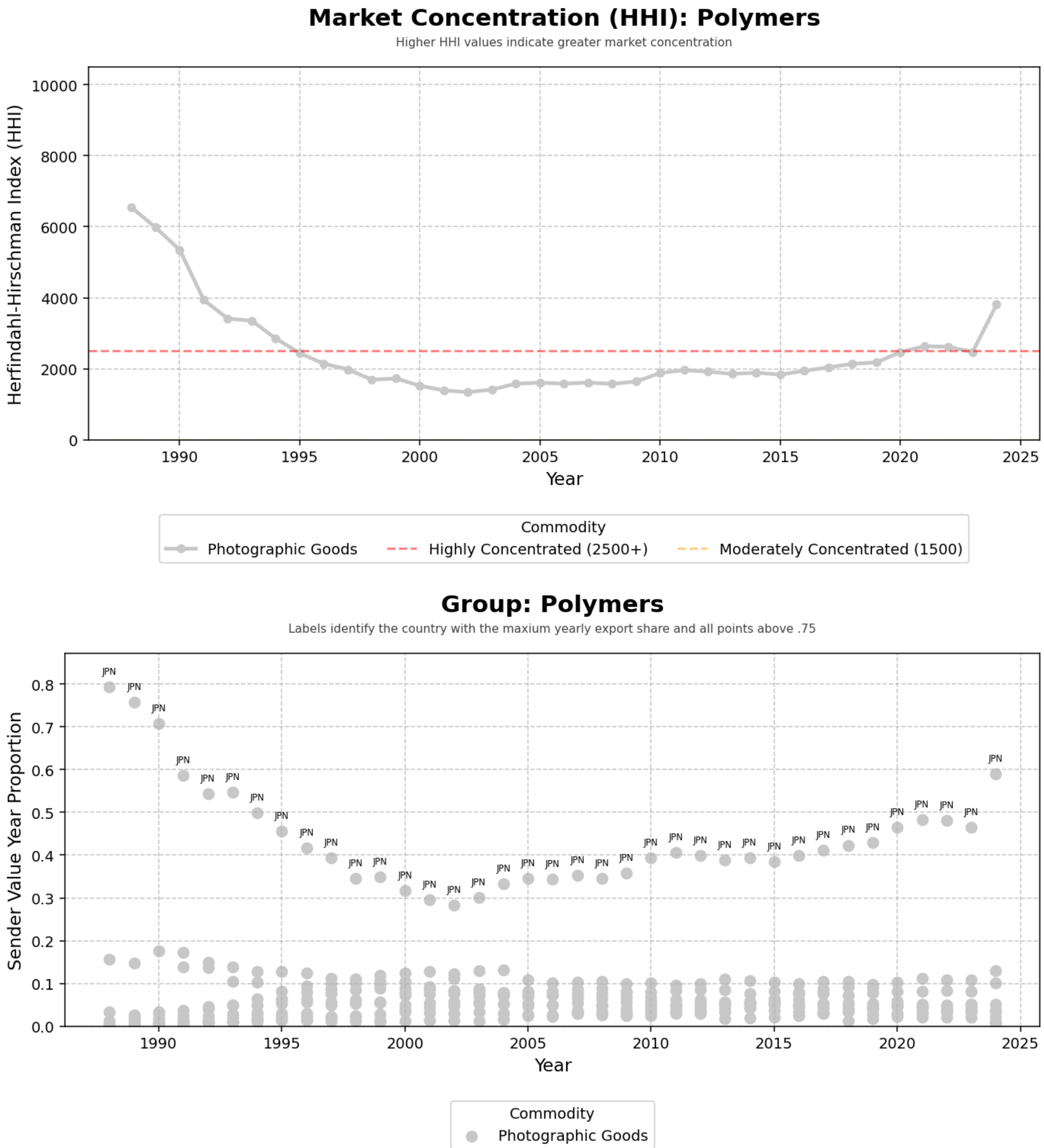


Figure 11: Exporter Concentrations, Chemical Preparations for Photographic Use

Ewing, S. M. (2024), Cobalt, Technical report, United States Geological Survey.

Friedline, C. A. (2025), Tantalum, Technical report, United States Geological Survey.

Funaiole, M. P., Hart, B. & Powers-Riggs, A. (2023), 'Mineral monopoly: China's control over gallium is a national security threat'. Published July 18, 2023.

Golev, A., Scott, M., Erskine, P. D., Ali, S. H. & Ballantyne, G. R. (2014), 'Rare earths supply chains: Current status, constraints and opportunities', *Resources Policy* **41**, 52–59.

Goodin, R. C. (2025), Quartz (high-purity and industrial cultured crystal), Technical report, United States Geological Survey.

Habecker, K. (2022), 'Tantalum and next-generation electronics', *Global Advanced Metals* .
URL: *https://globaladvancedmetals.com/tantalum-and-next-generation-electronics/*

Hirohata, A., Huminiuc, T., Sinclair, J., Wu, H., Samiepour, M., Vallejo-Fernandez, G., O'Grady, K., Balluf, J., Meinert, M., Reiss, G. et al. (2017), 'Development of antiferromagnetic heusler alloys for the replacement of iridium as a critically raw material', *Journal of Physics D: Applied Physics* **50**(44), 443001.

Ilankoon, I., Dushyantha, N., Mancheri, N., Edirisinghe, P., Neethling, S., Ratnayake, N., Rohitha, L., Dissanayake, D., Premasiri, H., Abeysinghe, A. et al. (2022), 'Constraints to rare earth elements supply diversification: Evidence from an industry survey', *Journal of Cleaner Production* **331**, 129932.

Jaffal, A. (2022), 'Indium phosphide industry moving into consumer applications', *Semiconductor Today: Compounds & Advanced Silicon* **17**(8).
URL: {*https://www.semiconductor-today.com/features/PDF/semiconductor-today-october-november-2022-Indium-phosphide.pdf*

Jasinski, S. M. (2025), Phosphate rock, Technical report, United States Geological Survey.

Jennings, A., Senior, A., Guerin, K., Main, P. & Walsh, J. (2024), 'A review of high-purity quartz for silicon production in Australia', *Australian Journal of Earth Sciences* **71**(8), 1085–1097.

Jo, H.-r. (2024), 'Japan's JSR to produce advanced chip materials in Korea', *The Korea Herald* .
URL: *https://www.koreaherald.com/article/3852712*

Khan, S. M., Mann, A. & Peterson, D. (2021), 'The semiconductor supply chain: Assessing national competitiveness', *Center for Security and Emerging Technology* **8**(8), 1–98.

Linköping University (2025), Better digital memories with the help of noble gases, Technical report. Accessed: 2025-04-11.
URL: *https://www.sciencedaily.com/releases/2025/01/250130140818.htm*

Mermer, C. & Şengül, H. (2020), 'Addressing potential resource scarcity for boron mineral: A system dynamics perspective', *Journal of Cleaner Production* **270**, 122192.

Moskalyk, R. R. (2004), 'Review of germanium processing worldwide', *Minerals engineering* **17**(3), 393–402.

Murashige, A. (2023), Trends in high-end photoresists: Strategic direction for Japan to remain

strong, Technical Report No. 215 (2023016), Mizuho Bank, Industry Research Department.
URL: *https://www.mizuhogroup.com/asia-pacific/china/insights/2023-11*

National Minerals Information Center (2024), U.S. Geological Survey mineral commodity summaries 2024 data release (ver. 2.0, march 2024), Technical report, United States Geological Survey.
URL: *https://doi.org/10.5066/P144BA54*

Nedelciu, C. E., Ragnarsdottir, K. V., Schlyter, P. & Stjernquist, I. (2020), 'Global phosphorus supply chain dynamics: assessing regional impact to 2050', *Global Food Security* **26**, 100426.

Pte., F. T. (2024), Japanese companies monopolize the EUV photoresist supply market, Technical report. Published May 13, 2024.
URL: *https://www.fountyltech.com/news/japanese-companies-monopolize-the-euv-photoresist-supply-market/*

Shanks III, W. P., Kimball, B. E., Tolcin, A. C. & Guberman, D. E. (2017), Germanium and indium, Technical report, US Geological Survey.

Shivakumar, S., Yoon, J. & Sirkar, T. (2024), Gallium nitride: A strategic opportunity for the semiconductor industry, Technical report, Center for Strategic and International Studies (CSIS). Published May 20, 2024.
URL: *https://www.csis.org/analysis/gallium-nitride-strategic-opportunity-semiconductor-in*

Sims, Z. C., Kesler, M. S., Henderson, H. B., Castillo, E., Fishman, T., Weiss, D., Singleton, P., Eggert, R., McCall, S. K. & Rios, O. (2022), 'How cerium and lanthanum as coproducts promote stable rare earth production and new alloys', *Journal of Sustainable Metallurgy* **8**(3), 1225–1234.

Smith, B. J., Graziano, D. J., Riddle, M. E., Liu, D.-J., Sun, P., Iloeje, C., Kao, E. & Diamond, D. (2022), Platinum group metal catalysts: Supply chain deep dive assessment, Technical report, USDOE Office of Policy (PO), Washington DC (United States).

Starzecki, J. (2024), 'The critical importance of boron supply in North America', *Innovation News Network* .

Tolcin, A. C. (2023), Indium, Technical report, United States Geological Survey.

Tolcin, A. C. (2025), Germanium, Technical report, United States Geological Survey.

United Nations (2024), 'UN Comtrade data', World Integrated Trade Solution (WITS). Accessed: 2024-03-28.
URL: *https://wits.worldbank.org*

United States Department of Justice (2024), 'Herfindahl-Hirschman Index', *Antitrust Division* .
URL: *https://www.justice.gov/atr/herfindahl-hirschman-index*

Xia, F., Wang, H., Hwang, J. C., Neto, A. C. & Yang, L. (2019), 'Black phosphorus and its isoelectronic materials', *Nature Reviews Physics* **1**(5), 306–317.

Yoon, J. K. (2023), 'How Japan's reversion of trade limit impact Korea's material tech development', *THE ELEC* .
URL: *https://www.thelec.net/news/articleView.html?idxno=4432*

Zhang, R., Tang, C., Ni, W., Yuan, J., Zhou, Y. & Liu, X. (2023), 'Research status and challenges of high-purity quartz processing technology from a mineralogical perspective in china', *Minerals* **13**(12), 1505.

Zhang, Y., Ma, C., Xie, J., Ågren, H. & Zhang, H. (2021), 'Black phosphorus/polymers: status and challenges', *Advanced Materials* **33**(37), 2100113.