From Mine to Microchip

Addressing Critical Mineral Supply Chain Risks in Semiconductor Production

By Gracelin Baskaran and Meredith Schwartz

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THE ISSUE

Semiconductors are a vital and mineral-intensive component in the electronic devices that power the modern economy. Four minerals central to semiconductor production—gallium, germanium, palladium, and silicon—face heightened supply chain risks due to dependence on China and Russia. Building resilient supply chains for these minerals is essential for the next generation of chipmaking. To date, enacted legislation has focused on downstream manufacturing, leaving American technologies highly vulnerable to minerals supply chain disruptions. A new policy playbook for semiconductor minerals is necessary to incentivize private sector investment and foster cooperation with allies and strategic partners.

INTRODUCTION

Semiconductors are a critical technology for economic security, and they are also incredibly mineral intensive. Semiconductors are present in all types of electronics, including smartphones, computers, automotives, energy storage, medical devices, lighting, and military and aerospace applications. Four indispensable minerals—gallium, germanium, palladium, and silicon—face significant supply chain risks. While current government funding and tax incentives, such as the Inflation Reduction Act (IRA), focus on addressing supply chain vulnerabilities and stimulating private investment, they are limited to metals used to manufacture electric vehicle (EV) batteries. Moreover, though the CHIPS and Science Act of 2022 was designed to boost semiconductor manufacturing, it does not include any support for the related mineral inputs.

The CHIPS Act provided over $280 billion for advanced chip manufacturing, packaging, and workforce development. The bill focused almost entirely on onshoring downstream capabilities, and as a result significant funding has **gone to companies** such as Intel and Micron to enable them to build and expand fabrication facilities for chipmaking. Yet the CHIPS Act did not include any provisions to incentivize the diversification of critical mineral supply chains for semiconductors. This is a major national security oversight. Without alternative sourcing, the semiconductor supply chain remains highly dependent on China and other U.S. adversaries. This has already backfired. In August 2023, China imposed export restrictions on gallium and germanium, alarming the U.S. semiconductor industry. China accounts for **98 percent** of the world's refined gallium and **68 percent** of the world's germanium production. The United States, meanwhile, produces no gallium **and less than 2 percent** of the world's refined germanium. The U.S. Geological Survey (USGS) **estimated** that just a 30 percent supply disruption of gallium could cause a $602 billion decline in U.S. economic output, equivalent to 2.1 percent of gross domestic product (GDP), posing a significant economic threat.

The United States needs policies that incentivize investment in mineral supply chains that are independent of Chinese control. Just as the IRA has spurred private sector investment in lithium, copper, nickel, and graphite for EVs, the right set of tax incentives and grant programs could bolster the mineral supply chains on which semiconductor technologies rely.

MINERAL INPUTS FOR SEMICONDUCTORS

Semiconductors control the flow of electric currents within electronic devices. In order to perform this function, semiconductors use a **variety of minerals** for their different conductive and insulative properties. The manufacturing process is extensive and complex, requiring industry-specific equipment (e.g., **lithography** machines) and precise processes (e.g., etching, packaging, and cleaning for impurities). The type of semiconductor and the stage of manufacturing determine the minerals needed. For example, **fluorine** is used in etching and purifying, while **titanium** comes into play during advanced packaging.

Because it can be conductive, semiconductive, or even insulative, silicon is the most common material for chip wafers. After initial manufacturing, silicon wafers undergo a process called **doping**, where additional metals such as gallium, arsenic, iridium, and phosphorous are introduced to slightly alter the wafers' conductivity. **Copper and cobalt** make up the wires connecting these billions of transistors together into one integrated circuit. By the end of the manufacturing process, a dozen different minerals may have been used in the creation of a single chip.

This paper focuses on gallium, germanium, palladium, and silicon for several reasons. First, the primary application for gallium, germanium, and silicon is the semiconductor industry, with U.S. demand for these minerals consequently being driven by the industry. In contrast, demand for copper, titanium, and cobalt is driven by the energy, construction, automotive, and aerospace industries. Second, these same three minerals—gallium, germanium, and silicon—are the **most used** semiconductor materials and lack good substitutes; other materials such as arsenic are only needed in trace amounts for gallium arsenide (GaAs) chips, which are increasingly being **substituted** with higher-performance gallium nitride (GaN) compounds. Finally, the United States is reliant on foreign adversaries for the import of these four essential minerals, whereas it was a top exporter of **iridium**, **fluorine**, and **phosphorous** in 2022 and already has a plethora of allied sourcing options in India, Israel, Japan, and South Korea.

Table 1: Semiconductor Minerals Risk Comparison

Mineral	Chips Industry Driving Need?	No Good Substitute?	Reliant on Foreign Adversary?
Gallium	Yes	Yes	Yes
Palladium	Somewhat	Yes	Yes
Germanium	Yes	Yes	Yes
Silicon	Yes	Yes	Yes
Cobalt	No	No	Yes
Copper	No	No	Somewhat
Arsenic	Somehwat	No	Yes
Titanium	No	Yes	Yes
Fluorine	No	Yes	No
Phosphorous	No	No	No
Iridium	Somewhat	No	No

Source: Author's research.

Considering the industry specificity of these four minerals, U.S. reliance on imports from foreign adversaries, and the export restrictions and supply disruptions that gallium, germanium, palladium, and silicon already face, or are likely to face, prioritizing new sourcing is key for U.S. economic security.

CRITICAL MINERALS FOR SEMICONDUCTORS: WHICH MINERALS POSE THE GREATEST RISKS?

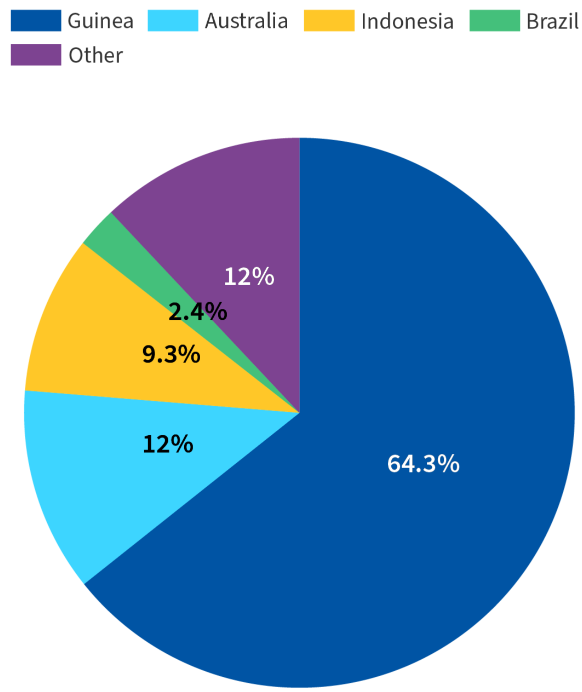
GALLIUM

Gallium is key to unlocking higher-power and higher-frequency electronics. Yet, the mineral is also the semiconductor mineral with the **highest supply chain vulnerability** due to the concentration of its global production in China and the high dependence of U.S. semiconductor manufacturing on Chinese imports. Used to produce **GaN** and GaAs high-performance chips, gallium offers higher speed, lower resistance, and lower production costs when compared to alternatives. Gallium is an indispensable, non-substitutable material for the United States' defense industry's next generation of electronic devices. These kinds of chips can be found in mobile phones, automotives, satellites, and LiDAR sensors. Today, China produces **98 percent** of the world's gallium, meaning that even as the United States reshores semiconductor fabrication facilities with CHIPS Act money, the semiconductor industry remains reliant on materials sourced from China.

The difficulty in diversifying gallium sources centers on the mineral's availability. It is exceedingly rare in the Earth's crust—**less than 19 parts per million** (ppm)—and is sourced only as a byproduct of bauxite mining. The United States has small bauxite reserves (just **20 million metric tons)** and minimal mining activity. Guinea, however, has the world's largest bauxite reserves, at 7.4 billion metric tons, followed by Australia (5.1 billion) and Brazil (2.7 billion). **In 2022**, 64.3 percent of global bauxite exports came from Guinea, 12.0 percent from Australia, 9.3 percent from Indonesia, and 2.4 percent from Brazil. Most of these exports went to China for refining. For example, 81.5 percent of Guinea's bauxite exports went to China, as did 97 percent of Australia's and 100 percent of Indonesia's.

If the United States seeks to increase its bauxite imports from non-Chinese sources, the private sector will need to invest in mineral-refining infrastructure in bauxite-rich allied nations and secure offtake agreements with Western mining companies. As an established ally, Australia would be an excellent partner for the United States to develop a bauxite-to-gallium refining pipeline. Guinea and Brazil are also potential partners for sourcing bauxite, and investing in the development of refineries can boost economic development in these states while decreasing dependence on China and minimizing the related supply chain vulnerabilities.

Figure 1: Top Bauxite Exporters in 2022



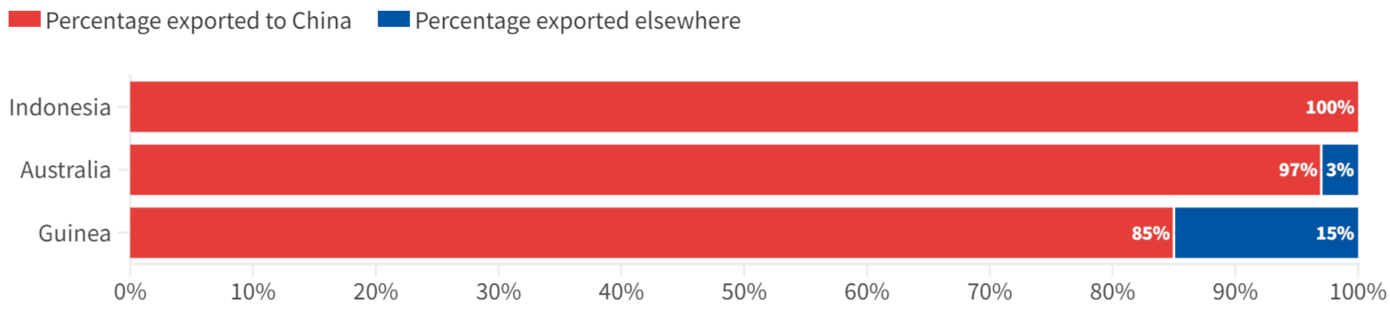
Source: "Aluminum ore," Observatory of Economic Complexity, https://oec.world/en/profile/hs/aluminium-ore.

GERMANIUM

Due to its high electron mobility, germanium is a key material for high-speed transistors. Fiber-optic cable manufacturing accounts for **one-third** of germanium demand. Germanium wafers are high performing and can be found in computer processors, infrared detectors, communication systems, and radar systems. No alternatives to germanium exist without significant performance losses.

Germanium is sourced as a byproduct of the processing of zinc ores; it does not occur as a natural metal. The Earth's crust is **only 1.5 ppm germanium**, making the mineral one of the rarest metals on the periodic table. Countries

Figure 2: Share of Bauxite Exports Headed to China



Source: "Aluminum ore," Observatory of Economic Complexity, https://oec.world/en/profile/hs/aluminium-ore.

with the greatest zinc reserves, aside from China, include Australia, Peru, and Mexico.

As the world's leading producer of refined germanium, China accounts for about **60 percent** of global supply. Since imposing export restrictions last year, germanium **prices have climbed** over **70 percent**, to $2,280 per kilogram. The United States produces some germanium from zinc mines in Tennessee and Alaska, but **over half** of its domestic consumption is **imported**, largely from China (53 percent), Belgium (22 percent), Germany (11 percent), and Russia (9 percent).

Germanium needs significant refining to become suitable material for semiconductors, and germanium refining infrastructure is currently dominated by China. Companies in the United States face **significant hurdles in justifying investment** in new refining capacity for germanium. Germanium refining is particularly expensive, as the metal needs to reach purity levels of over **99.999 percent**. The process is not only costly, but technically challenging and energy intensive. While China manages to keep production costs low **through reduced environmental and social safeguards**, manufacturers outside of China have not been able to compete. Without the kind of government subsidies Chinese competitors have, U.S. companies will not be competitive in the face of higher labor and power costs, necessitating financial incentives to reduce the cost of doing business.

PALLADIUM

Palladium is one of six platinum group metals (PGMs). Metals in this group are characterized by high melting points, heat and corrosion resistance, and catalytic properties. Palladium is used in the metal connections attaching chips to circuit boards, and **palladium plating** is used on semiconductors to ensure longevity and reliability. As semiconductors advance and chips become increasingly compact, the **risk of oxidation** and deterioration rises. Palladium's durability and corrosion and oxidation resistance make it a crucial protective shield on chips to ensure their sustained performance.

The United States produces just 5 percent of the world's palladium from its two operations in Montana, both owned by Sibanye Stillwater, a South African company. Domestic production represents just 16 percent of the nation's consumption, leaving domestic industry reliant on imports from other palladium-rich nations.

Russia holds the world's **largest palladium reserves** and produces over **40 percent** of the world's palladium from just two top-performing projects. In 2021, the United States imported **35 percent** of its palladium from Russia. Following Russia's 2022 invasion of Ukraine, the Biden administration warned the semiconductor industry to diversify its palladium supply chains. Compounding matters, the World Platinum Investment Council predicts a **1.28 million ounce** palladium deficit in 2024, equivalent to over one-third of Russia's total production in 2022. These deficits are largely the result of supply issues as mine producers restructure in response to a period of suppressed prices.

South Africa holds the world's **second-largest reserves** of palladium, contributing **34 percent** of the world's production. The country's largest venture, Mogalakwena, produces 6 percent of the world's palladium and is owned by Anglo American, a UK company. The industry faces several challenges in South Africa, including rising production costs, energy and transport infrastructure failures, lack of permitting, labor disputes, and declining ore grades. South Africa ranked **62nd** out of 84 jurisdictions in the 2021 Fraser Investment Attractiveness Index, one place below the Democratic Republic of the Congo and just above Ecuador. The index indicates that South Africa is not an attractive option for Western private sector investment because of the aforementioned risks without government-led incentives.

The total **cash cost** for mining one ounce of palladium in Mogalakwena is $590, compared to just $402 at Norilsk in Russia. With palladium prices down to just **$923 per ounce**, Russian palladium mining operations have a 56 percent greater profit margin than Anglo American's project in South Africa. However, the South Africa mining operations are more economical than those in the United States. The Sibanye Stillwater palladium mine in Montana faces 2024 operating costs of **$1,032 per ounce**, greater than the current selling price of palladium. As current palladium prices make domestic mining operations untenable, the United States needs to be incentivizing investment in countries such as South Africa where operation costs will be more competitive with Russia and, therefore, projects will be more likely to succeed.

SILICON

Silicon is the **most important** mineral for semiconductor manufacturing and is used to make silicon wafers, the largest portion of the semiconductor materials market. Integrated circuits with billions of transistors are squeezed onto less than a square inch of silicon. Although Japan and South Korea perform the majority of global silicon wafer manufacturing, China **accounts** for 79 percent of global raw silicon production and 75 percent of the ultra-high-purity polysilicon needed for semiconductors, demonstrating the need for polysilicon manufacturing in allied countries in order to diversify silicon sourcing and reduce potential supply disruptions.

Silicon is the second-most common element in the Earth's crust and is mined in open pits as silica sand. However, silicon is bound to oxygen, alumina, and magnesium, so it has to undergo extensive refining to extract silicon metal and produce high-purity polysilicon. In the early 2000s, an oligopoly of seven companies, known as the Seven Sisters and all located in the United States, Japan, and Germany, dominated the polysilicon market. Today, six companies dominate the global polysilicon supply—**five out of those six companies** are Chinese owned.

Analyses of gallium, germanium, palladium, and silicon supply chains highlight both the dominance of foreign adversaries in the production of these critical raw materials and the importance of commercially viable, Western mineral-refining projects. Building a resilient domestic semiconductor industry will require not only incentives and subsidies in downstream manufacturing, but also support to develop mining and refining capabilities in allied countries.

LESSONS FROM THE IRA: WHAT WORKED TO INCENTIVIZE INVESTMENTS IN EV MINERAL SUPPLY CHAINS

The IRA was the Biden administration's flagship legislation meant to incentivize the transition to clean energy and EVs. Several provisions created financial mechanisms to expand and strengthen critical mineral projects, including the Section 30D Clean Vehicle Tax Credit, the 48C Investment Tax Credit, the 45X Production Tax Credit, additional grant funding for the Defense Production Act (DPA) Title III program, and Department of Energy loan programs.

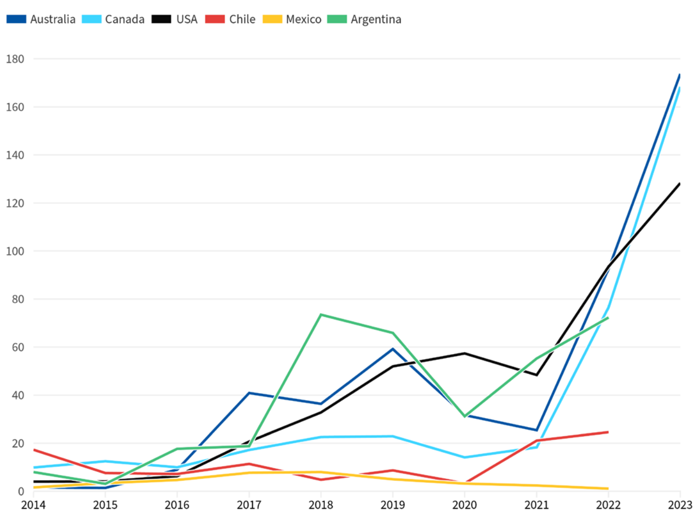
The **Section 30D New Clean Vehicle Tax Credit** provides up to $7,500 in tax credits for qualifying EV purchases. To be eligible, vehicle manufacturers must meet several criteria, including sourcing requirements for critical minerals and components. As part of 30D, vehicles eligible for a $3,750 tax credit at purchase must: (1) ensure that **50 percent** of critical minerals contained in EV batteries produced in 2024 (increasing to 80 percent by 2027) are extracted and processed in the United States, or a country with which the United States has a free trade agreement (FTA) or critical minerals agreement (CMA); and (2) do not contain any critical minerals extracted or processed by a Foreign Entity of Concern, such as China or Russia. To take advantage of the 30D program, EV manufacturers are looking to quickly diversify critical mineral supply chains away from China, but there is little evidence that Section 30D is actually driving mining companies to expand operations in FTA countries. Although lithium- and nickel-mining explorations in countries such as Australia and Canada have moderately increased in 2023, exploration in lithium-rich FTA countries, such as Chile, has stalled. At the same time, exploration in non-FTA countries, such as **Argentina**, has increased because it has a more favorable domestic investment policy climate. Without extending IRA benefits to Argentina, there is little incentive to export minerals to the United States instead of China.

Some critical mineral projects may qualify for the IRA's

Qualifying Advanced Energy Project Investment Tax Credit (48C) or its **Advanced Manufacturing Production Tax Credit** (45X). The 48C credit was renewed and expanded under the IRA with an additional $10 billion in funding. So far, the Department of Energy has announced $6 billion for projects investing in clean energy manufacturing as well as the refining, processing, and recycling of critical materials. **Albemarle, Novonix, and MP Materials** have all received the 48C Investment Tax Credit for their critical minerals projects. The 45X credit aims to spur domestic production capacity by offering a 10 percent tax credit to companies producing critical materials for EV battery manufacturing in the United States. These two credits are especially desired by the private sector, as they can be sold in exchange for cash. However, the credits are restricted to projects within the United States, limiting their reach; companies investing abroad—even in allied nations—largely do not qualify.

Finally, the IRA included grant funding in the form of an additional $500 million toward DPA Title III grants,

Figure 3: Exploration Budget for Lithium by Country, 2014-2022 (USD, millions)

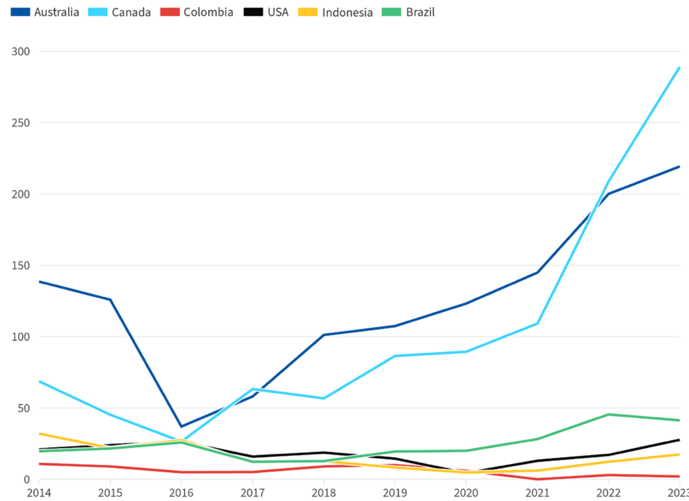


Source: S&P Capital IQ Pro.

which provide financial support to critical mineral projects that protect, expand, or restore industrial base capabilities critical to national security. DPA Title III grants have so far been awarded for **nickel** production, **lithium** mining, **graphite** processing, **rare earth** element separating, and **cobalt** extraction feasibility studies in the United States and Canada.

While the rollout of these programs has not been

Figure 4: Exploration Budget for Nickel by Country, 2014-2022 (USD, millions)



Source: S&P Capital IQ Pro.

without criticism, the IRA has catalyzed investment in EV mineral supply chains. For example, Syrah Resources began production earlier this year of its natural graphite anode material facility in Vidalia, Louisiana, funded by the Department of Energy. The Vidalia processing facility will **source graphite** from Syrah Balama's mining operations in Mozambique, originally funded through a loan from the U.S. Development Finance Corporation, creating the first fully vertically integrated supply chain for natural graphite anode materials outside of China.

CHIPS 2.0: POLICY RECOMMENDATIONS TO INCENTIVIZE INVESTMENT IN SEMICONDUCTOR MINERALS SUPPLY CHAINS

The United States needs a comprehensive legislative package that incentivizes private investments in projects at home and abroad aimed at securing, and ensuring, supplies of critical minerals for the semiconductor industry. As discussed, current supply chains for gallium, germanium, palladium, and silicon are highly dependent on foreign adversaries, leaving vital semiconductor supply chains vulnerable to supply disruptions that can bring significant economic consequences. Recommendations to create more resilient semiconductor supply chains include the following:

1. **Initiate an Investment Tax Credit (ITC) for mineral processing and refining projects at sites**

with Western-allied mining operations. Australia has significant bauxite and zinc reserves mined by Western mining companies such as Rio Tinto and Glencore. In 2022, Western companies mined **98 million metric tons** of bauxite ore in Australia, accounting for nearly all of the country's bauxite production and 24.5 percent of global production. However, a midstream vulnerability in this supply chain remains—this ore is being sent to China to be refined into gallium and germanium. Since Western companies are already controlling upstream bauxite mining, the United States needs to focus on securing the midstream processing and refining of bauxite into gallium. Therefore, the United States should offer incentives (including tax credits) to the private sector to encourage onsite, Western-controlled refining capabilities to close supply chains.

The IRA's 48C Investment Tax Credit could be a good guidepost for this type of new tax credit, but the current program needs to be expanded to allow projects abroad to qualify. Western mining companies already own some of the largest mining projects in Peru, Guinea, South Africa, and Australia: **Glencore** controls the largest zinc mine in Peru, **Rio Tinto** owns bauxite mines in Guinea, and **Anglo American** possesses the largest palladium mine in South Africa. To ensure that bauxite and zinc are refined into gallium and germanium by a Western partner onsite—and not sent to China for refining—the United States should offer an investment tax credit for companies setting up refining projects that will work jointly with already established Western mining operations. These refining investments are critical to securing the entire mineral supply chain upstream and downstream.

2. **Fund a research and development laboratory to build the technological know-how for semiconductor-specific critical mineral refining.** Refining gallium, germanium, and silicon to needed purity levels of over 99 percent for the semiconductor industry requires specific technology, infrastructure, and know-how, all of which are currently lacking. The United States has only **one company** that refines high-purity gallium, **one operation** for refining germanium, and **three companies** producing high-purity polysilicon. In order to be competitive globally, the United States needs to innovate and ramp up production quickly to generate minerals in a more cost-effective way.

   The Department of Energy already funds laboratories focused on critical minerals for EVs and clean energy. For example, the **Critical Minerals Innovation Hub** at the Ames Laboratory and the **Minerals and Materials Supply Chain Facility** (METALLIC) bring together the expertise of several leading national laboratories to find solutions to critical minerals supply challenges for the EV industry. The Department of Commerce should fund similar initiatives focused on minerals for the semiconductor industry. If the United States wishes to build and expand critical mineral refining operations at home and abroad, it needs to invest in national laboratories that will develop the capabilities, technologies, and skills needed to produce refined semiconductor minerals at scale.

3. **Subsidize price premiums to ensure Western companies can compete for offtake agreements.** Western-owned mining and refining operations face higher production costs than their Chinese and Russian competitors due to higher labor, energy, and environmental standards. For example, Anglo American's cash costs to produce palladium in South Africa are 41 percent higher than Russia's costs to do so domestically. Furthermore, China is **investing in bauxite smelting facilities in Indonesia** which run on coal, making them energy intensive and environmentally dirty, but inexpensive. Western companies looking to invest in bauxite refining in an environmentally responsible way do not have this option. As a result, these companies need to place a premium on their prices, making it difficult to compete for offtake agreements.

   The U.S. government should offer a direct subsidy to U.S. semiconductor manufacturers to offset the price premium for Western-produced semiconductor minerals. This will incentivize chip producers to diversify from China and enter offtake agreements with Western mining and refining operations. Just as the $7,500 30D tax credit was designed to incentivize EV manufacturers to source critical minerals outside of China, chip manufacturers need to be incentivized through a subsidy to source gallium, germanium, palladium, and silicon from Western-allied sources despite the higher price.

4. **Dedicate more DPA Title III funding toward projects focused on securing semiconductor mineral supply chains.** DPA Title III provides an upfront source of capital needed for the private sector to make investments in projects crucial to national security that they may be unable to finance otherwise. The Department of Defense has awarded funding to projects for EV minerals and for downstream semiconductor manufacturing, but no funding has been put toward the production of upstream gallium, germanium, palladium, or silicon. In 2023, a DPA Title III grant was awarded to **Raytheon** for military-grade GaN produced at its semiconductor foundry in Andover, Massachusetts. The project is a worthwhile investment, but in order to fully secure the supply chain, DPA funds need to be targeting projects that produce the refined and purified gallium needed for GaN, as this refining is currently dominated by China.

   The DPA Title III program should also be expanded to include project development in more allied countries such as Australia, Japan, and member states of the European Union aimed at expanding potential reserves and refining capacity. Tables 2 and 3 illustrate how grant funding of projects in Australia, Canada, and Norway would be invaluable to securing critical supplies of gallium, germanium, palladium, and silicon. Considering how central semiconductors are to defense technologies, the use of DPA funds for critical minerals projects related to semiconductors should be prioritized.

TARGET COUNTRIES FOR CRITICAL MINERALS INVESTMENTS TO SECURE SEMICONDUCTOR SUPPLY CHAINS

As the United States builds alternative supply chains for gallium, germanium, palladium, and silicon outside of China, it also needs to target countries for investment that are mineral rich and allied with U.S. interests and that offer economically viable and cost-effective opportunities. Because China and Russia hold significant reserves of vital commodities and are top producers of bauxite, zinc, palladium, and silicon, it is vital for the United States to partner with mineral-rich allies that can compete with foreign adversaries.

To secure the bauxite needed for gallium production, the United States should be encouraging Western investment in Australia and Guinea. Australia is currently the top global producer of bauxite, but China is close behind, despite having just 14 percent of Australia's bauxite reserves. This indicates that there is significant opportunity to increase Australia's total production. Furthermore, Australia is currently sending 97 percent of its bauxite to China, allowing the latter to dominate the refining of bauxite into high-purity gallium. Similarly, although Guinea holds the world's largest bauxite reserves and is responsible for nearly 65 percent of the globe's exports, the country sends over 80 percent of its bauxite to China. DPA Title III funds should be leveraged for Australian refining projects, and projects in both Australia and Guinea should be eligible for the investment tax credit. This will give the private sector an influx of cash to boost gallium production from Australian and Guinean bauxite ores under Western control.

Australia and Peru will be key allies for securing zinc deposits for germanium production. Australia holds the world's largest zinc reserves, estimated to be double the size of China's, but currently has less than one-third of China's output. Peru has more modest reserves—about one-quarter the size of Australia's—but currently produces more zinc than Australia. DPA Title III and the ITC can free up capital for investments in Australian and Peruvian zinc and germanium projects while national laboratories build the expertise and innovative technologies needed to drive successful germanium refineries outside of China.

South Africa's palladium reserves will be key to countering Russia's lead in the commodity, with Canada as a strong secondary resource. South Africa and Russia both produce about 40 percent of world's palladium (see Table 3), despite South Africa holding less than half the reserves of Russia. South Africa also has the distinct advantage of an open trade regime and a strong U.S. business presence; as the largest U.S. trade partner in Africa, approximately **600 U.S. businesses** operate there. The U.S.-South African trade relationship is united under the African Growth and Opportunity Act, the U.S. Generalized System of Preferences (GSP), the Trade and Investment Framework Agreement (TIFA), and a bilateral tax treaty. Still, the mining sector in South Africa faces a number of challenges in attracting

Table 2: Global Reserve Landscape for Semiconductor Mineral Ores

Commodity	Largest Reserve Source	#2 Reserves	#3 Reserves	#4 Reserves	#5 Reserves
Bauxite (gallium)	Guinea (7.5 billion metric tons, 24% of global reserves)	Australia (5.1 billion metric tons, 16.5% of global reserves)	Brazil (2.7 billion metric tons, 8.7% of global reserves)	Indonesia (1,0 billion metric tons, 3.2% of global reserves)	China (700 million metric tons, 2.3% of global reserves)
Zinc (germanium)	Australia (66 million metric tons, 31.4% of global reserves)	China (31 million metric tons, 14.8% of global reserves)	Russia (22 million metric tons, 10.5% of global reserves)	Peru (17 million metric tons, 8.1% of global reserves)	Mexico (12 million metric tons, 5.7% of global reserves)
Palladium*	Russia (320 million oz)	South Africa (150 million oz)	United States (42.4 million oz)	Canada (40.5 million oz)	Zimbabwe (40 million oz)

Note: No USGS data is available for total palladium reserves as calculations are for Platinum Group Metals (PGMs), which is composed of six metals. Silicon is excluded due to its wide availability according to USGS.

Source: Author's elaborations based on USGS and S&P.

Table 3: Global Production Landscape for Semiconductor Mineral Mining

Commodity	Largest Producer (2022)	#2 Producer	#3 Producer	#4 Producer	#5 Producer
Bauxite (gallium)	Australia (102 million metric tons, 25.5% of global production)	China (90 million metric tons, 22.5% of global production)	Guinea (86 million metric tons, 21.5% of global production)	Brazil (33 million metric tons, 8.3% of global production)	Indonesia (21 metric million tons, 5.3% of global production)
Zinc (germanium)	China (4.0 million metric tons, 32.0% of global production)	Peru (1.4 million metric tons, 11.2% of global production)	Australia (1.2 million metric tons, 9.6% of global production)	United States (760,000 metric tons, 6.1% of global production)	Mexico (740,000 metric tons, 5.9% of global production)
Palladium	Russia (3.1 million oz, 43% of global production)	South Africa (2.6 million oz, 36% of global production)	Canada (570,000 oz, 8% of global production)	Zimbabwe (504,000 oz, 7% of global production)	United States (356,000 oz, 5% of global production)
Silicon	China (6.0 million metric tons, 68.2% of global production)	Russia (640,000 metric tons 7.3% of global production)	Brazil (400,000 metric tons 4.5% of global production)	Norway (360,000 metric tons, 4.1% of global production)	United States (310,000 metric tons, 3.5% of global production)

Source: USGS data.

needed investment. High production costs and the risks of doing business in South Africa discourage potential Western investors. Implementing the ITC and direct price subsidies could offset some of these risks and encourage more Western palladium mining projects in the country.

Finally, silicon production should be further supported in Brazil and Norway, which currently account for 5 percent and 4 percent of global silicon production, respectively (see Table 3). China has a formidable lead in silicon production, necessitating further investment in Brazilian and Norwegian silicon projects. To establish alternative silicon supply chains for the semiconductor industry, policymakers should leverage: (1) DPA Title III funds for silicon refining in Norway; (2) the ITC for production in Brazil; (3) direct subsidies to put prices on a more competitive footing with less-expensive Chinese materials; and (4) a national laboratory to further research and development in purified polysilicon.

CONCLUSION

Supply chains for semiconductor critical minerals are fraught with vulnerabilities, as China and other U.S. adversaries continue to dominate the mining and refining of gallium, germanium, palladium, and silicon. Meanwhile, U.S. policymakers have so far done little to incentivize diversification of these supply chains by the private sector. The semiconductor industry needs a set of tax incentives and funding programs to spur the private sector, just as the IRA spurred investments in EV mineral supply chains. To address supply chain vulnerabilities, policymakers should prioritize: (1) creating an investment tax credit for processing and refining projects; (2) opening national laboratories focused on semiconductor mineral research and development; (3) expanding eligibility for DPA Title III grants; and (4) offering direct subsidies to encourage offtake agreements with Western companies. ■

***Gracelin Baskaran** is director of the Critical Minerals Security Program at the Center for Strategic and International Studies (CSIS) in Washington, D.C. **Meredith Schwartz** is a research associate with the Critical Minerals Security Program at CSIS.*

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