No. 56
September 2024

The Mitchell Forum

Microelectronics: Macro Impacts from Competition to Crisis

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"[T]he erosion of U.S. capabilities in microelectronics is a direct threat to the United States' ability to defend itself and its allies."

-Sujai Shivakumar and Charles Wessner
"Semiconductors and National Defense: What Are the Stakes?"

Introduction

The United States military fields a wide range of incredibly sophisticated and capable weapon systems to foster peace and global security. However the operating effectiveness of most of these systems relies on a host of small components called microelectronics, which are manufactured and supplied through a supply chain centered on the Pacific and increasingly in China. Disruption of this fragile microelectronics ecosystem would devastate our weapon systems and prove daunting to our military forces and their readiness before or during a crisis.

Microelectronics are the small electronic devices that bring many of our modern conveniences to life. Most people first think of the semiconductors and integrated circuits in their personal computer or cellular phone, but there is a remarkable diversity in the types of microelectronics and how they are used. The basic building block starts with transistors, essentially on-off switches, that can change the characteristics and performance of a device to create processors, RF

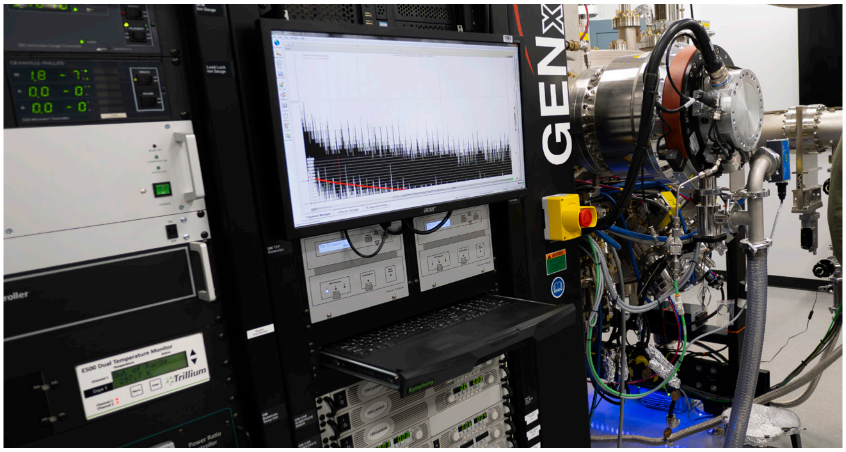

Figure 1: The Air Force Research Laboratory (AFRL) explores the the growth of oxide semiconductor materials such as Gallium Oxide to address the need for smaller and higher power electronics using a method called molecular beam epitaxy
Credit: AFRL, DVIDS

sensors, memory devices, and more. Few of us likely appreciate that a modern automobile or advanced aircraft requires thousands of individual microelectronics to function.

As prevalent as these components are in modern society, their supply lines prove surprisingly fragile. For example, the cascading impacts of the global COVID-19 pandemic reached far beyond the immediate public health, medical, social, and even political spheres, offering the Department of Defense key insights on the state of the microelectronics supply chain. The pandemic also inflicted a persistent disruption of the semiconductor industry that caused automakers to remove more than 11 million vehicles from production in 2021 and lose billions of dollars due to the shortage of the necessary chips, sowing chaos in both the new and used automotive markets.[1] Consumers were shocked at the sight of hundreds of new vehicles parked in lots, but these vehicles were unable to perform basic functions like raising and lowering windows or operating windshield wipers due to a lack of chips.

As the immediate crisis faded, consumer products once again lined the shelves and dealer lots filled up. Many naturally assumed that the problems had been fixed. Today's reality, however, is stark: though semiconductor supply is up and the industry is beginning to overcome the disruption, underlying structural risks have not changed. In fact, we may be more vulnerable now that potential adversaries recognize the fragility of the microelectronics supply chain.

The U.S. government, to its credit, has begun to respond. Congress passed the CHIPS and Science Act in 2022 with an aim to boost domestic research, development, and production of semiconductors. However, initial progress has been slow, and it is not clear if changes spurred on by the legislation will yield the specific improvements needed to ensure a resilient defense microelectronics supply chain.

The Modern Microelectronics Ecosystem

The invention of the Integrated Circuit (IC) sprang from contributions of many people; however, two American engineers, Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor, made the final breakthroughs in the late 1950's. The resulting monolithic IC remains the basis for modern chips.[2]

The United States dominated this new industry, initially with large-scale government funding and a voracious consumer in the Department of Defense. Though much more costly, the size, weight, and power consumption advantages of ICs over existing discrete transistor designs led to their adoption for use in aerospace vehicles and other military applications.[3] Some other early examples of military systems using ICs include the Minuteman II missile guidance set and the MIT-Lincoln Laboratories' Semi-Automated Ground Environment (SAGE) system that provided NORAD with an integrated air defense picture and command and control capability.

In these early years, government regulations and favorable industrial policies, coupled with purchasing agreements and the dollars behind them, ensured that the Department of Defense remained the customer of first choice.[4] These same factors and a strong anti-trust preference facilitated the rise of large government funded research labs that sustained the Defense Department's leading role.[5]

Commercial IC designs followed in the mid-1960s with applications in amplifiers, data converters, and power management devices, as well as specialty circuits for automotive, consumer, and communications applications.[6] For the next 10-15 years, the defense market and the commercial market coexisted without significant friction.

However, by the 1980s, rising commercial demand rapidly outstripped defense dollars. Microchips had become general purpose products and widely used in the commercial sector—the DoD no longer sat in the driver's seat. Along with changes to industrial policy and adjustments in the industry as microchips became commoditized, competition from Japanese firms and later the Asian tigers Taiwan, South Korea, and Singapore (and increasingly China) dramatically shifted the center of the microchip universe to the east.[7]

By late 1987, Japanese production of semiconductors surpassed U.S. production for the first time.[8] While the United States continues to lead in semiconductor design, the fabrication capabilities and advanced manufacturing processes needed to produce real chips in relevant quantities wholly relies upon a supply chain centered on the Pacific region.[9] Since then, vulnerabilities have not been addressed and only grown; a 2022 Center for Strategic and International Studies assessment of the semiconductor industry found the following:

- U.S.-based chip manufacturing has declined to around 10 percent of the world total and lacks the onshore capability to make the most advanced devices at the seven- and five-nanometer (nm) nodes [state of the art]. U.S. firms depend on sources in Taiwan and South Korea for production of their most sophisticated designs.

- The United States has very little onshore capability for the outsourced assembly, testing, and packaging (OSAT) of semiconductor devices, holding less than a 5 percent share of these essential functions, with most OSAT operations conducted in Taiwan, China, and Singapore.

- The disaggregation and offshoring of significant elements of the U.S. semiconductor production chain heightens risks relevant to national security, including the potential for intellectual property theft, the introduction of counterfeit devices, and the disruption of the far-flung and delicate chip supply chain by natural disasters or geopolitical conflicts.[10]

In other words, the United States can no longer produce highly sophisticated, state-of-the-art chips and semiconductor devices, nor does it have the capacity to scale up production within its own borders, leaving it highly vulnerable to various forms of industrial espionage.

Another Supply Chain Consideration: Rare Earth Minerals

China dominates the global rare earth economy, accounting for more than 60 percent of the world's rare earth mining, 85 percent of rare earth processing, and 92 percent of rare earth magnet production. With unique chemical and physical properties, rare earth elements prove crucial in the manufacturing of modern screens and displays, lighting, lenses, cameras, high powered magnets, batteries, and much more. Like microelectronics, rare earths enable critical defense technologies in computing, seekers, weapons, and other advanced applications. Perhaps recognizing the strength of their position, China has begun to restrict access to some of these critical materials. For example, China began restricting exports of gallium and germanium in August 2023 and followed with new controls on high-grade graphite exports in December. China dominates the global mining and production of these materials, which have significant commercial and national security uses. These restrictions further highlight the fragility of international supply chains for many critical materials.

Sources:
Lara Seligman, "China Dominates the Rare Earths Market. This U.S. Mine Is Trying to Change That," *Politico*, December 14, 2022; Mia Nulimaimaiti, "China's gallium and germanium exports tumble as controls on shipments to the West take toll," *South China Morning Post*, January 21, 2024; and "China's Export Controls on Critical Minerals – Gallium, Germanium and Graphite," FTI Consulting, December 19, 2023.

Defense Microelectronics and Potential Disruption

While a lot of public attention gets paid to the cutting edge of microelectronics development, DoD is most vulnerable in the area of older chips. The bulk of the defense community's need, when it comes to sustaining the readiness of its fielded forces and weapon systems, is commodity chips and microelectronics produced in the last decade. For example, a typical guidance computer or military radio design uses commodity chips as it does not require the state-of-the-art chips that populate the newest generation smart phone or tablet. This stems from the lower computational demands and the component's more narrowly defined function. Long acquisition lead times for older chips exacerbates this problem, as the defense technology cycle does not align well with the modern commercial approach that quickly moves on to newer generations and simply throws the old gear out. Most weapon systems remain in service for decades.

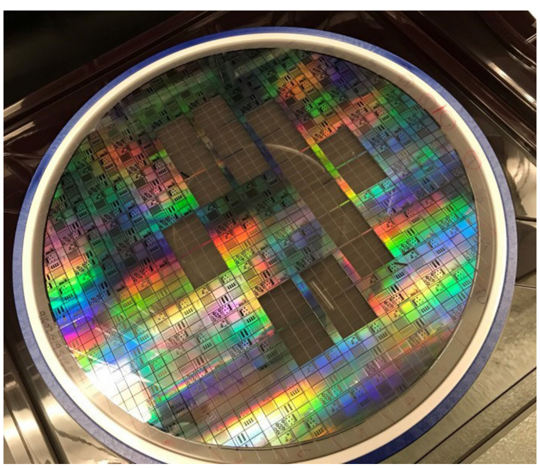

Figure 2: A 300 mm photonic integrated circuit (PIC) semiconductor wafer fabricated by AIM Photonics with components developed by the U.S. Naval Research Laboratory. Such semiconductors have useful potential applications in quantum navigation and timing.

Credit: Naval Research Laboratory, DVIDS

For DoD, the ability to quickly package commodity components to repair, upgrade, or sustain weapon systems can be the difference between success and failure on the battlefield. Take a relatively simple weapon like the Joint Direct Attack Munition or JDAM. This satellite-guided tail kit comprises a vast portion of the U.S. Air Force, Navy, and Marine Corps air-to-air and air-to ground precision munitions inventory. A single JDAM contains various microelectronics subcomponents—actuators, sensors, guidance and control computers, for example. These are not cutting-edge chips, but rather standard commodity chips and subcomponents—and much of the JDAM's microelectronic supply chain would be affected by a disruption in the Pacific. If the supply chain was disrupted during a crisis, the nation's ability to replenish munitions stockpiles would prove extremely limited. Similarly, hundreds and thousands of subcomponents of the weapon delivery systems would be unrepairable, grounding the high dollar platforms designed to deter our enemies and assure our allies. This could mean U.S. forces could run out of munitions to take out adversary sensors and shooters relatively early in a conflict with no fast or viable solution to backfill inventory. As we have seen in Ukraine, maintaining a sufficient level of munitions stock can mean the difference between victory and mere survival, as well as survival and definitive defeat.

Considering this example, an extreme reliance on a supply chain deeply rooted in a few companies in the Pacific region carries significant national security risk. The recent pandemic-driven disruption of industry served as a very clear example of how a range of incidents like political posturing, trade sanctions, natural disaster, blockade, or direct conflict could affect critical supply chains. As another more prescient example, when a 7.4 magnitude earthquake struck Taiwan on April 3, 2024, it caused significant damage and temporarily shut down chip fabrication. Though some processes and output resumed in the immediate aftermath, the industry is not yet back to operating at full capacity, and we should expect to see an impact in terms of costs and quantities. Because the island nation sits above the junction of two tectonic plates in a seismically active region of the world, the frequency and severity of seismic activity should not be surprising, but there are currently no alternatives or redundant manufacturing capabilities outside the region.[11] Any of these potential scenarios would challenge DoD's ability to sustain the readiness of its critical weapon systems. In the case of blockade or direct military conflict, this disruption would be aggravated by the increased wear and tear on weapon systems, attrition, and expenditure of weapons.

Though senior civilian and military leaders know that supply chain risks exist, the department has not fully explored the impact of a potential disruption—they do not understand the impacts in detail down to individual weapon systems and specific components. Without that detailed understanding, the department cannot act to prioritize actions and mitigate the risk. Embarking on the needed analysis to understand this challenge is needed now, followed by prioritizing weapon systems and attendant risk, then taking deliberate steps to mitigate that risk where possible. This kind of approach will require broad government support beyond just DoD as well as industrial policy and investment.

The Government Response

While DOD must better quantify the risks to communicate them effectively to the government and the American people, Congress and the administration recognize there are significant national security and competitive economic implications of the current state of the microelectronics ecosystem. This is why they enacted a federal statute in 2022 to revitalize domestic manufacturing of semiconductors, the CHIPS and Science Act. The act provides incentives and strengthens partnerships with the aim of bringing critical microelectronics manufacturing activities back to U.S. shores, but it's far too soon to realize its full effect. Evaluating the success of any legislation takes time—and it would not be fair to give the CHIPS Act a final grade today. Watching how U.S. industrial capacity and the commercial sector respond in the next decade will prove critical.

The CHIPS Act was primarily intended to revitalize U.S. commercial leadership in semiconductors; it was not designed to reduce or eliminate vulnerabilities in the weapon systems the U.S. military relies upon. For example, the Chinese dominance in worldwide supply of Printed Circuit Boards (PCB) introduces susceptibility to everything from weapon systems to the nation's power grid. Former Deputy Undersecretary of Defense Al Shaffer describes this strategic liability:

> *You're talking about something with over a hundred layers of substrate. Each of those layers has the potential for having something embedded. I have almost no doubt that we have pretty extensive vulnerabilities to systems being modified or shut down. The other thing that can happen: if you modify the data stream, which you can do by injecting code in a weapons platform, and the data that you're seeing is false? You lose.*[12]

Similarly, 90 percent of semiconductor assembly and test activities is conducted outside the United States, underscoring the need for an end-to-end examination of the entire microelectronics supply chain from raw materials to fabrication to assembly into finished products.

Figure 3: United Semiconductors won a NASA space manufacturing contract with AFRL sponsorship. Production facility in Los Alamitos, CA.
Credit: AFRL, DVIDS

What Must be Done Now?

The crucial first step toward a more resilient microelectronics ecosystem for DoD is identifying potential vulnerabilities that compromise its microelectronics supply chain. This includes analyzing everything from the sourcing of required rare-earth elements and other material required for fabrication to the impact of a potential disruption on critical warfighting capabilities. These efforts should prioritize weapon systems for analysis, catalog microelectronics components and subsystems, and determine the providence of those components. Relevant wargames and table-top analytic exercises to add operational context to the underlying analysis could further help decision makers more fully appreciate the warfighting impact.

With an accurate understanding of the vulnerabilities inherent in the microelectronics supply chain in hand, DoD would be well-positioned to raise awareness of the national security implications of the analysis across DoD, the Congress, and the administration. While these efforts are key to future success, it is also important to identify potential mitigation strategies today. DOD and the defense industrial base must take steps to help shape the implementation of CHIPS, follow on investments, and industrial policy to strengthen defense supply chains and build resilience.

Conclusion

Once the world leader in microelectronics and semiconductor manufacturing, the United States is now dangerously reliant upon a vulnerable global supply chain centered in the Pacific region. The disruption of that supply chain, similar to what was witnessed during the global COVID-19 pandemic, presents significant national security challenges at a time when the Chinese ability to affect the supply of chips has dramatically increased.

This effort must begin with a robust analytic effort that is shaped by real operational considerations and aimed at finding practical solutions. Understanding key supply chain nodes, potential risks, and the full implications of disruption to warfighters is a massive but necessary undertaking. Seeking the right economic and policy incentives, as well as practical manufacturing solutions and alternatives, to promote supply chain resilience is absolutely critical to the security of the United States and its allies. ✪

Endnotes

1 "Navigating Complexities: The Semiconductor Shortage's Effect on the Auto Industry," Applied Energy Systems, November 30, 2023.

2 "1959: Practical Monolithic Integrated Circuit Concept Patented," Computer History Museum. Kilby and Noyce both received the National Medal of Science and are widely recognized as co-inventors of the integrated circuit. Kilby would receive the Nobel Prize in 2000 for this pioneering work, though Noyce died a decade earlier and did not share in the award.

3 "1959: Practical Monolithic Integrated Circuit Concept Patented."

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5 Williams and Khan, "A Brief History of Semiconductors."

6 "IC at Fifty," Computer History Museum.

7 Williams and Khan, "A Brief History of Semiconductors."

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9 Sujai Shivakumar and Charles Wessner, "Semiconductors and National Defense: What Are the Stakes?" Center for Strategic and International Studies, June 8, 2022.

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11 Gemma Conroy, "Taiwan hit by biggest earthquake in 25 years: why scientists weren't surprised," *Nature*, April 3, 2024.

12 Alan Patterson, "Ex-DoD Official Says Chinese-Made PCBs Plague U.S. Systems," *EE Times*, March 22, 2024.

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