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Quantum's Industrial Moment

Strengthening U.S. Quantum Supply Chains for Scalable Advantage

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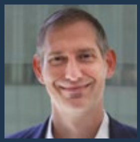

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Executive Summary

Quantum technologies are approaching a critical inflection point.[1] Over the next three to five years, quantum sensors and computers that have long remained confined to laboratory settings will begin transitioning into deployable systems with real-world utility, with significant economic and national security implications. Whether the United States captures quantum's benefits will depend not only on sustained scientific leadership but also on its ability to produce and deploy quantum systems reliably, competitively, and at industrial scale.

Persistent gaps in domestic supply chains—including manufacturing capacity—and reliance on foreign suppliers such as China and Russia risk constraining U.S. progress and shifting value creation abroad. Converting America's innovation lead into durable advantage will therefore require elevating the quantum industrial base to a central pillar of the national quantum strategy.

This report provides a framework for assessing and addressing the vulnerabilities of U.S. quantum supply chains across multiple dimensions, including:

- the overarching domestic and international challenges constraining U.S. quantum industrial strength;
- the diversity of quantum hardware modalities and their distinct enabling-technology dependencies across photonics and optics, cryogenics, and specialized materials and microfabrication; and
- the different categories of vulnerability—foreign dependence, insufficient domestic capacity, and performance and scalability gaps—affecting specific supply chain inputs.

The final chapter applies this framework to identify the most consequential vulnerabilities and a portfolio of actions to strengthen the industrial foundations of U.S. quantum leadership.

Key Takeaways

Quantum supply chains are heterogeneous and evolving. Multiple viable hardware approaches exist for building quantum systems, each with distinct supply chain dependencies. Enabling technologies such as photonics and optics, cryogenics, and specialized materials and microfabrication may be central to the operation of one hardware modality, supporting for another, and largely unnecessary for a third. As quantum systems advance in performance and scale, the enabling technologies underpinning them are evolving in parallel toward greater reliability and manufacturability. Consequently, the supply chains supporting early, low-volume quantum systems in the near term may differ considerably from those required to sustain next-generation systems over the next five or ten years. Advancing U.S. quantum industrial strength requires addressing the full spectrum of vulnerabilities: both modality-specific and generalized, and both near-term gaps and longer-term resilience and scale.

Commercialization is constrained by a self-reinforcing industrial gap. Demand for quantum systems remains too small and fragmented to justify sustained private investment in the specialized, quantum-grade components they require—devices built to tighter tolerances, lower noise floors, and more stringent stability requirements than standard equipment. In the absence of such capacity, domestic supply chains remain thin, costs stay high, and lead times lengthen, further suppressing the demand needed to attract investment. Ongoing consolidation among suppliers toward higher-volume markets compounds this dynamic, periodically eliminating quantum product lines and pushing developers toward foreign sources or costly vertical integration that diverts resources from core quantum innovation.

Federal support is misaligned with the binding constraints on scale and return on investment. Since the launch of the National Quantum Initiative in 2018, U.S. funding has increased substantially, but has prioritized fundamental research and quantum systems like computers and sensors, with less than 12 percent directed toward enabling technologies and manufacturing infrastructure.[2] While this emphasis was appropriate early on, reliance on trickle-down demand from system developers has proven insufficient to build the specialized, capital-intensive supplier base quantum technologies require. Without a stronger enabling-technology foundation, scientific progress will fail to translate into the economic and security advantages that make quantum a strategic priority in the first place. Targeted federal investment can catalyze private capital and accelerate the formation of the supplier base needed for industrial-scale quantum deployment.

International dynamics are tightening the window for U.S. action. China's state-driven push to industrialize quantum technologies is increasingly visible in enabling technologies and manufacturing, creating price pressure and scale advantages that threaten domestic and allied suppliers. At the same time, fragmentation among U.S. allies—especially with Europe—risks weakening collective access to critical inputs and markets while fueling China's rise. Given the geopolitical stakes of quantum leadership, poorly calibrated international policies—such as Europe's push for technological sovereignty and broad U.S. tariffs—can further restrict access to inputs and revenue at a moment when speed and capital efficiency are critical.

Three enabling-technology areas pose substantial vulnerabilities that risk stalling the development and scale-up of U.S. quantum technologies:

- **Photonics and optics:** Neutral-atom, trapped-ion, and photonic hardware modalities depend on stable, tightly specified laser and optical systems, yet supply is thin, internationally concentrated, and optimized for laboratory use rather than continuous, fielded operation. This mismatch creates a shared vulnerability across quantum technologies and defense applications that rely on similar precision photonics, such as remote sensing and directed energy.

- **Cryogenics:** Superconducting and semiconducting-spin modalities depend on extremely low temperatures enabled by dilution refrigerators, with few global providers and reliance on helium-3 gas, an isotope that is scarce, expensive, and tightly regulated. Scalability constraints extend beyond isotope supply. Today's cryogenic platforms are bulky and energy intensive, and system-level bottlenecks—wiring, interconnects, vibration control, and thermal management—increasingly bound achievable size and reliability. Photonic modalities avoid helium-3 but still require substantial cryogenic infrastructure at scale, reinforcing cryogenics as a gating enabler for large deployments.

- **Specialized materials and microfabrication:** Quantum hardware relies on ultrahigh-quality materials and tightly controlled fabrication, yet U.S. access to commercial (rather than research-grade) wafer supply and foundries remains limited. Critical dependencies—ranging from thin-film photonic wafers and heterogeneous integration to high-purity superconducting materials and isotopically enriched silicon wafers—often flow through foreign suppliers in China and other countries. Near-term action to anchor quantum-ready manufacturing within U.S. commercial foundries can prevent foreign reliance from becoming entrenched as expertise and capacity consolidate abroad.

Key Recommendations

Reflecting the diversity of U.S. quantum supply chain vulnerabilities, this report recommends a portfolio of actions to boost industrial resilience. We highlight a few of these recommendations below. While federal policy tools are critical, strengthening the U.S. quantum industrial base will also require major contributions from regional ecosystems, private capital, industry, and research institutions, as well as coordination with key international partners.

> **Reliance on trickle-down demand from system developers has proven insufficient to build the specialized, capital-intensive supplier base quantum technologies require.**

General Recommendations

Elevate enabling technologies—not just quantum systems—to first-order strategic priorities. Dedicated multiyear research and development (R&D), strategic procurement, and infrastructure programs can seed and scale domestic industrial capacity in laser systems, cryogenics, and new materials and manufacturing processes. Joint programs between enabling-technology providers and quantum system developers—rather than arm's-length subcontracting—can enable effective codesign and enhance deployable system performance.

Boost demand signal and capture early advantage through strategic procurement and pilot programs. Government demand can attract private investment in quantum systems and their enabling technologies while markets remain small. By prioritizing mission-aligned deployment—such as quantum computing for scientific research and quantum sensing for resilient navigation and timing—agencies can generate near-term value, build operational expertise, and accelerate supplier innovation in areas such as laser systems and cryogenics.

Build shared test and evaluation infrastructure. Facilities at the National Institute of Standards and Technology (NIST) and the national labs can reduce the need for enabling-technology start-ups to invest in costly specialized equipment and provide trusted, independent validation of component performance and reliability. By establishing common specifications and benchmarks, these facilities can accelerate component qualification and integration into deployed systems.

Expand access to commercial-grade material and device manufacturing. National laboratory and university fabrication facilities are essential for early prototyping but lack the capacity, process control, and intellectual property flexibility needed for sustained process refinement and productization. Meanwhile, high-volume commercial foundries are optimized for mature processes, not rapid iteration. Federal policy can incentivize commercial facilities to maintain agile quantum manufacturing R&D lines. Targeted tax credits, low-interest loans, and CHIPS and Science Act–style incentives—conditioned on state and private capital participation—can help bridge the gap between laboratory prototyping and commercial-scale production.

Secure trusted access to critical inputs for near-term progress while building long-term domestic resilience. Strategic engagement with allies and partners—via bilateral or existing multilateral frameworks—can mitigate immediate vulnerabilities where domestic capacity is insufficient, promote American exports, and help align policies to curb anticompetitive practices and dependence on untrusted suppliers. In parallel, sustained domestic investment can position the United States to lead the next generation of quantum supply chains—more efficient, reliable, and manufacturable—capable of supporting durable scale-up and delivering meaningful commercial and national security value.

Specific Recommendations

Advance domestic production of precision laser and optical systems. Launch multiyear advanced R&D programs to develop reliable, scalable, and manufacturable laser and optical systems critical to quantum technologies and defense applications. Agencies such as the Defense Advanced Research Projects Agency (DARPA), NIST, and the national laboratories can leverage expertise from suppliers, integrators, and end users to speed the transition from prototypes to production-ready platforms. Targeted low-rate initial production commitments—modeled on some defense technology programs—would strengthen demand signals that accelerate supplier maturation and reduce foreign dependence.[3]

Build next-generation cryogenic systems for scalable quantum platforms. Launch focused R&D programs to advance novel subkelvin architectures that can support large-scale quantum systems while reducing helium-3 use, energy consumption, and operational complexity. Programs should also tackle complementary scaling challenges in wiring density, vibration, and thermal management to enable a transition from laboratory infrastructure to deployable, data center–compatible platforms. Agencies including DARPA, NIST, and the national laboratories can mobilize cross-disciplinary engineering expertise to accelerate development and technology transition.

Anchor quantum-grade wafer-scale fabrication—including integrated photonics and solid-state qubit platforms—at commercial foundries. The Departments of Commerce and Defense should help establish domestic sources of thin-film photonic materials such as lithium niobate—currently sourced largely from China—and commercial integrated photonics R&D lines, including silicon photonics, relevant to quantum computing, sensing, and defense applications. Additionally, quantum-ready process modules should be established within cutting-edge complementary metal-oxide semiconductor fabrication lines to support superconducting and semiconducting-spin platforms, enabling the wafer-scale quality and uniformity required for utility-scale quantum systems.

Secure and steward critical quantum isotopes and materials. The federal government, through the Department of Energy Isotope Program or similar entities, should stabilize access to quantum inputs that are highly regulated (helium-3) and/or relatively low-volume (e.g., silicon-28 and alkali metals such as rubidium-87 and cesium-133) by providing strategic recovery and recycling, refining and enrichment processes, and dedicated reserves. These measures can mitigate supply shocks and ensure reliable access as quantum deployment scales.

The report elaborates on these priorities and outlines additional complementary recommendations, offering a credible path to convert American quantum innovation into enduring industrial and strategic advantage.

Introduction

In its 2025 National Security Strategy (NSS), the Trump administration calls on U.S. quantum technologies to "drive the world forward," underscoring their potential to transform security, scientific progress, and economic competitiveness.[4] The call is timely: After decades of research and development (R&D), quantum technologies are beginning to reach operational use, marking the start of a long-awaited quantum era. U.S. quantum sensors are advancing into field trials and early military deployments, enabling high-precision navigation and timing in GPS-denied environments.[5] Quantum computing firms are achieving rapid hardware and algorithmic progress toward error-corrected systems, with expectations of early applications in materials science and pharmaceuticals in the next few years.[6] Together, quantum computing and sensing are projected to comprise a roughly

$3 billion global market in 2027, while longer-term forecasts place the combined annual market at $35 billion or more by 2035.[7]

As quantum technologies mature, the next three to five years will be decisive. Whether the United States converts its quantum lead into durable strategic advantage will hinge not only on scientific breakthroughs but on the nation's capacity to manufacture and deploy quantum systems at scale. That, in turn, requires robust supply chains and an industrial base capable of reliably sourcing and manufacturing specialized materials, components, and subsystems.[8] As the NSS emphasizes, "Cultivating American industrial strength must become the highest priority of national economic policy."[9] For quantum, that means technology leadership can no longer be treated as an R&D activity, but as a major industrialization challenge.

The U.S. quantum industrial base is poorly positioned to sustain leadership. Despite a formidable innovation ecosystem—with the densest concentration of quantum start-ups and established firms of any country, building on world-class university and national laboratory research—thin and globally dispersed supply chains constrain U.S. progress.[10] Many critical inputs, including specialized materials, precision lasers, cryogenic systems, and quantum chips, are sourced from abroad, in some cases from geopolitical adversaries such as the People's Republic of China (PRC) and Russia. Even where domestic suppliers exist, reliance on a small number of firms—sometimes a single source—creates significant fragility. These gaps expose the U.S. quantum ecosystem to supply bottlenecks that slow development and complicate the transition from laboratory advances to large-scale deployment.

Meanwhile, competitors are moving quickly to secure quantum advantage. The PRC's centralized strategy and sustained public investment have preserved its global lead in quantum communications and brought it to near parity with the United States in quantum computing and sensing. Unlike the United States, the PRC pairs research investment with strong manufacturing capacity, positioning it to scale and deploy quantum systems rapidly. That emphasis is set to intensify under its upcoming 15th Five-Year Plan for 2026–2030, which elevates quantum technology as the top "future industry" within a broader overarching goal to build a "modernized industrial system."[11] In parallel, the European Union is preparing a Quantum Act that prioritizes "Made in Europe" supply chains and industrial capacity as the region seeks to enhance its technological sovereignty and reduce dependence on both China and the United States.[12]

The stakes are high. Countries that successfully combine frontier innovation with manufacturing scale will capture early economic and security advantages, shape global markets, and attract top talent and capital. As the United States has learned from the erosion of its semiconductor manufacturing base, once these reinforcing cycles of investment, capability, and market share take hold, they become extraordinarily difficult and costly to reverse. As the global quantum race accelerates, the United States faces a narrow but pivotal window to strengthen its quantum supply chains before it cedes the economic and security advantages of quantum technologies to foreign competitors.

Quantum science and technology became a national priority during the first trump administration. In 2018, a Republican-led Congress passed the National Quantum Initiative Act (NQIA) with broad bipartisan support, and a bipartisan group of lawmakers is leading its reauthorization in 2026. Here President Donald Trump signs the original NQIA into law in December of 2018. By his side is Michael Kratsios, then deputy assistant to the president for technology policy and current director of the Office of Science and Technology Policy, who in 2025 identified supply chains and enabling technology as one of five priorities for the current administration's quantum strategy. (White House Office of Science and Technology Policy)

Defining the Quantum Supply Chain Challenge

The United States enters this period with growing political momentum. Bipartisan and cross-sectoral support for quantum technologies has been building since 2018, when the Trump administration elevated quantum as a national priority and worked with Congress to enact the National Quantum Initiative Act (NQIA). Since then, annual federal quantum R&D investments have increased roughly fivefold to about $1 billion per year. The second Trump administration has reiterated its commitment to advancing America's quantum edge, identifying supply chain and enabling technologies as one of five priority areas and developing dedicated quantum offices or programs across multiple agencies, including the Departments of Commerce, Energy, and Defense.[13] Moreover, lawmakers from both parties are preparing to reauthorize the NQIA with a greater focus on applications, commercialization, and supply chains, and regional quantum ecosystems are also expanding across more than 12 states.[14]

The United States has the talent, institutions, and momentum to lead in quantum technologies; what it lacks is a coherent strategy to strengthen its quantum supply chains and broader industrial base over the coming years as these technologies mature.

A growing body of analysis has begun to examine vulnerabilities in quantum technology supply chains. Prior work has usefully identified specific chokepoints, developed manufacturing roadmaps to guide scale-up, and proposed data frameworks to track suppliers, components, and materials or to benchmark national quantum industrial strength.[15] However, much of this literature either assumes familiarity with the structural complexity of quantum supply chains across hardware modalities and enabling technologies, focuses on a narrow subset of technologies or inputs, or collapses distinct vulnerabilities into a single category. This ambiguity obscures the breadth and implications of the vulnerabilities affecting the U.S. quantum ecosystem and hinders the development of effective responses.

This report addresses that gap by offering a high-level framework for assessing and addressing quantum supply chain vulnerabilities. Rather than attempting an exhaustive mapping of every input and supplier, the analysis focuses on laying out the core structural dimensions shaping supply chain fragility across quantum technologies. Specifically, the report examines:

- **Ecosystem-level challenges to U.S. quantum industrial strength:** including the industry's nascency and fragmentation, insufficient domestic support for enabling technologies, and intensifying international competition
- **The layered structure of the quantum technology stack:** spanning atomic media and quantum materials and chips, operational environments such as cryogenic and vacuum systems, interface components and control hardware such as laser systems, and higher-level software, error correction, and quantum networks
- **Major quantum hardware modalities:** including atomic, photonic, and solid-state platforms—which realize and control quantum states in fundamentally different ways and therefore rely on distinct combinations of materials, components, and fabrication processes, exposing them to different supply chain vulnerabilities
- **Distinct categories of supply chain vulnerability:** including dependence on foreign suppliers, insufficient or fragile domestic capacity, and performance and scalability gaps in enabling technologies, each of which constrains quantum development and scale-up in different ways and calls for different policy responses

By examining these dimensions together, the report provides policy stakeholders with a structured diagnostic lens to probe where risks sit within the quantum ecosystem, which technologies and modalities they affect, and what the nature of the underlying vulnerability is. This high-level framing helps orient and interpret more granular analyses and tracking efforts, enabling clearer identification of priority gaps and the development of more effective, tailored responses.

The final chapter applies this framework to highlight key supply chain vulnerabilities and outlines a portfolio of actions to strengthen the industrial foundations of U.S. quantum leadership. These include targeted R&D investments and shared testing and manufacturing infrastructure, strategic procurement mechanisms to boost demand signals, and selective trade and coordination tools. While the report centers around federal policy tools, effectively addressing U.S. quantum supply chain vulnerabilities will also require major engagement from regional ecosystems, private capital, industry, and research organizations.

This report moves from context to structure to strategy, clarifying the nature of quantum supply chain vulnerabilities and how the United States can build a more resilient quantum industrial base. Over the next few years, building the capacity to supply the materials, components, and infrastructure required for deployment will be essential to securing America's quantum edge—and the substantial economic and security advantages it confers.

Ecosystem-Level Challenges to U.S. Quantum Industrial Strength

Quantum supply chains are embedded in a broader technological and strategic ecosystem that shapes investment, coordination, and scale across the entire industry.

Three ecosystem-level dynamics are particularly consequential today: the nascent and fragile state of quantum markets, underinvestment in enabling technologies and manufacturing infrastructure, and intensifying international competition. Together, these forces constrain the ability of U.S. firms to translate technical advances into stable supplier networks and deployable systems. Strengthening supply chain resilience therefore requires not only targeted interventions at critical nodes, but also policies that reinforce the broader industrial foundations needed for quantum scale-up.

A Nascent, Fragmented, and Commercially Fragile Industry

Quantum remains a young industry: technically diverse, rapidly evolving, and optimized for niche laboratory research rather than scalable manufacturing. Although a few quantum computing systems and sensors have entered early commercialization, most technologies remain at low levels of maturity. Today's quantum systems are built largely from research-grade components produced in small volumes, far from the scale and market stability needed to attract sustained private investment in manufacturing capacity and enabling supply chains.[16] This dynamic creates a self-reinforcing problem: Limited demand discourages investment in specialized, quantum-grade suppliers, while the absence of such investments slows technical progress, raises costs, and further suppresses demand and investments. As a result, many component makers produce only small batches of bespoke parts that are costly and slow to deliver and that prove unreliable at industrial scale.

Compounding these challenges is the heterogeneity of quantum hardware itself. As the authors discuss in the next chapter, quantum systems span multiple hardware modalities—the physical approaches to create, control, and measure quantum states—ranging from naturally occurring atoms or light particles to quantum states engineered within specialized materials. Although some components overlap, each modality relies on a distinct mix of materials, lasers and optics, vacuum and cryogenic environments, and control infrastructure. This diversity fragments demand across highly specialized supply chains, limiting standardization and preventing any single supplier or foundry from serving the full range of quantum hardware needs.[17]

Market consolidation in enabling-technology sectors further exacerbates quantum supply chain fragility. Because quantum remains a niche market compared to mass applications such as consumer electronics, suppliers of "quantum-grade" components—built to tighter tolerances, lower noise floors, and more exacting stability requirements than standard commercial or even scientific equipment—are often acquired and redirected toward higher-volume uses. For example, Minnesota-based Vixar was once the sole domestic commercial supplier of specialized chip-scale lasers used in compact quantum clocks and sensors, serving a global market of roughly 50,000 units per year.[18] After its acquisition by ams OSRAM in 2018, the company discontinued its quantum laser line to focus on far larger consumer markets, such as smartphone facial-recognition systems, where annual volumes reach the hundreds of millions.[19] Similar consolidation has affected numerous photonics and optics companies that were once critical suppliers to U.S. quantum firms. The sudden loss of specialized quantum suppliers can collapse entire supply chains and stall innovation, forcing U.S. developers to turn abroad or redesign products at significant cost.

> **Today's quantum systems are built largely from research-grade components produced in small volumes, far from the scale and market stability needed to attract sustained private investment in manufacturing capacity and enabling supply chains.**

As suppliers exit or consolidate, quantum technology companies are increasingly designing and manufacturing their own subsystems to reduce supply chain uncertainty. While this vertical integration can provide short-term resilience, it diverts resources from core innovation and fragments the ecosystem. Multiple firms end up duplicating R&D, competing for the same scarce talent, and perpetuating the absence of established third-party suppliers that a scalable quantum industry ultimately requires.

Takeaways and Recommendation

Quantum technologies are advancing rapidly, but the sector remains nascent, with thin demand, fragmented hardware approaches, and consolidation in adjacent supplier markets. At this early stage, private markets alone are unlikely to build the specialized, capital-intensive industrial base required for utility-scale quantum deployment. Barring intervention, this weakness risks preventing America's scientific lead from translating into meaningful economic and national security gains.

- **Government agencies should leverage their role as market catalysts to attract investment in the domestic quantum supply chains while markets remain small.** Targeted R&D support, strategic procurement, and infrastructure programs can all strengthen domestic suppliers of enabling technologies and generate credible early demand. Applied selectively, these measures can crowd in follow-on investment from states, industry, and private capital, stabilizing critical suppliers and creating the conditions to translate cutting-edge research into durable industrial, economic, and security returns.

- Private capital will be indispensable to building a robust domestic quantum industrial base, as the scale and diversity of enabling-technology gaps far exceed what government programs alone can sustain. One model is federal coinvestment with states and private partners in regional initiatives that proactively form supplier companies around validated supply chain bottlenecks, as demonstrated by New Mexico's recent launch of a quantum venture studio in partnership with national labs, universities, start-ups, and venture investors.[20]

Insufficient Domestic Support for Enabling Technologies

Despite federal recognition of quantum technologies as a strategic priority, U.S. government support for the field's domestic supply chains remains piecemeal and underresourced. Since the launch of the National Quantum Initiative in 2018, federal efforts have significantly expanded research funding and coordination, but these investments have focused overwhelmingly on early-stage science and system-level development rather than on the enabling technologies and manufacturing foundations required for commercialization and scale, despite the national strategy document's explicit recognition of the government's role in developing and fielding these capabilities.[21]

This imbalance is reflected in federal spending patterns. Of the roughly $5.1 billion invested in quantum information science (QIS) R&D between fiscal year (FY) 2019 and FY 2024, less than 12 percent was directed toward enabling technologies, such as quantum-grade lasers, cryogenic systems, and advanced manufacturing (Table 1).[22] The vast majority of funding flowed instead to fundamental research and to the development of complete quantum computers and sensors. While scientific and system-level advances are essential and were reasonable focus areas given the state of the technology several years ago, persistent underinvestment in enabling technologies has left critical supply chain bottlenecks unaddressed and slowed progress toward scalable, reliable deployment.

Table 1. U.S. Government Quantum Information Science R&D Investments by Budget Category, FY 2019–2024[23]

QIS R&D Budget Component	FY 2019–2024 Expenditures*
QIS for Fundamental Science	$1.42B (28%)
Quantum Computing	$1.36B (27%)
Quantum Sensing	$1.20B (23%)
Quantum Technology	**$0.61B (12%)**
Quantum Networking	$0.51B (10%)
Total	$5.08B (100%)

The "quantum technology" category includes "basic R&D on supporting technologies for QIS engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics" as well as largely unrelated activities, such as quantum technology use case development and assessments of cybersecurity risks. The share of federal funding that directly supports enabling technologies is therefore likely to be well below 12 percent.

*U.S. dollars in billions (% of total QIS [R&D] investments)

Note: FY 2019–2023 figures are actual expenditures, and FY 2024 figures are estimated expenditures, as reported by the Subcommittee on QIS under the Committee on Science of the National Science & Technology Council.

Federal quantum programs have implicitly assumed that investment at the system level would cascade down the supply chain through subcontracts. In practice, this indirect approach has proven insufficient to build the specialized, capital-intensive industrial base that quantum technologies require. The Defense Advanced Research Projects Agency's (DARPA's) Quantum Benchmarking Initiative (QBI)—the largest United States government quantum program, receiving hundreds of millions of dollars in congressional funding—illustrates both the promise and the limitations of this model.[24] By supporting 18 quantum computing companies in benchmarking and executing their plans toward utility-scale systems, QBI is helping reduce technical uncertainty and improve investor confidence.[25]

Yet for several quantum modalities, achieving utility scale hinges on their ability to solve persistent supply chain challenges, such as reliably sourcing scarce critical inputs, building high-power precision laser systems capable of continuous operation, and developing ultrahigh-quality material wafers and manufacturing processes. Addressing these challenges will require dedicated, sustained investment in enabling technologies in close coordination with system integrators. Bottlenecks in lasers, cryogenics, vacuum systems, fabrication, and packaging frequently emerge in parallel and interact in ways that make supplier integration and systems engineering central to scaling.

Sustained collaboration between quantum-enabling technology suppliers and system integrators is essential—but remains undersupported. Solving the tightly coupled technical and manufacturing challenges of scalable quantum systems requires sustained, direct collaboration between enabling technology suppliers and quantum system developers. Industry consortia such as the Quantum Economic Development Consortium (QED-C) play an important role by facilitating engagement through events and voluntary working groups, as pictured here, but they cannot substitute for federal R&D programs that embed supplier–integrator collaboration directly into funded technology development. To date, federal quantum programs have largely relied on indirect subcontracting rather than systematic codesign, leaving a critical gap as quantum technologies move toward utility-scale deployment. (QED-C®)

While industry-wide consortia such as the Quantum Economic Development Consortium (QED-C; with origins in the 2018 NQIA) play a major role in ecosystem-wide coordination and precompetitive collaboration, they cannot substitute for federal R&D programs that systematically embed supply chain integration into program design. Federal quantum programs have not institutionalized this integration, leaving enabling-technology suppliers with uncertain demand signals and shifting avoidable integration risks onto system developers.

Infrastructure gaps further compound these challenges. The United States has limited R&D facilities and test beds for developing, testing, and validating quantum-enabling technologies. In photonics, for instance, start-ups developing quantum-grade lasers often lack the costly equipment, which can reach into the hundreds of thousands of dollars, needed to rigorously characterize and validate device performance, reliability, and lifetime.[26] At the same time, downstream customers—quantum computing and sensing firms—would benefit from independent testing and third-party validation to verify specifications, compare suppliers, and reduce integration risk. In the absence of domestic testing and certification infrastructure, firms seek these capabilities overseas, shelve innovations, or forgo rigorous validation, slowing innovation and increasing uncertainty across the supply chain.[27]

A similar shortfall exists in access to fabrication facilities capable of producing quantum-grade components at scale. Most U.S. foundries are optimized for conventional silicon microelectronics and offer limited support for advanced photonic integration or the specialized superconducting and semiconducting materials required for large-scale quantum systems. University and national laboratory fabrication facilities can support proof-of-concept research but typically operate at small scale, rely on outdated tools, and lack the manufacturing controls essential to reproducibility. Commercial foundries, by contrast, offer high performance and reliability but are optimized for mature processes. As a result, U.S. companies face delays or turn to foreign facilities that have moved more quickly to incorporate quantum processes.[28]

Takeaways and Recommendations

While federal funding for quantum research and system development has rightly increased, persistent under-investment in enabling technologies, manufacturing capacity, and integration infrastructure has left critical gaps in photonic systems, cryogenics, and specialized materials and fabrication. These gaps continue to slow commercialization and reinforce fragile or foreign supply chains.

- **Federal quantum programs should elevate enabling technologies and manufacturing infrastructure to first-order priorities within the national quantum strategy.** Sustained R&D investments in enabling technologies, shared test and validation infrastructure, and accessible quantum-capable fabrication can attract private investment, lowering barriers for emerging suppliers while accelerating system-level integration and scale-up. This will require leadership from a variety of agencies, including the Departments of Commerce (and the National Institute of Standards and Technology), Energy, and Defense, as well as the National Science Foundation.

- **To align incentives and maximize practical impact, programs should promote sustained partnerships between enabling-technology providers and system integrators**, rather than relying on indirect subcontracting models that have proven insufficient to catalyze scalable breakthroughs or a resilient supplier base. For example, federal initiatives could fund supplier–integrator teams through multiyear programs tied to shared milestones and integration demonstrations, ensuring that component development is directly aligned with system-level scaling requirements. These efforts should also leverage industry-led coordination mechanisms—such as the QED-C—to support precompetitive collaboration for shared problem definition and cross-pollination among diverse stakeholders across the quantum ecosystem.

Intensifying International Competition and Fragmentation

The United States is not alone in its quantum ambitions. Every major technological power now views quantum technologies as a pillar of national and economic security. As geopolitical adversaries and allies alike race to build sovereign quantum ecosystems, intensifying competition and protectionist trade policies are complicating U.S. firms' access to critical inputs and markets, as well as the United States' broader efforts to strengthen its supply chains.

China's Relentless Quantum Industrial Drive

Adversarial competition from the PRC poses a growing challenge to U.S. and allied quantum supply chains. The country's sustained, centralized approach to quantum industrialization—combined with market-distorting practices and a documented record of intellectual property and trade secret theft in other advanced technology sectors—enables PRC organizations to iterate and scale quickly while undercutting Western suppliers.[29]

China's forthcoming 15th Five-Year Plan (2026–2030) is set to deepen this trajectory. Party guidance elevates the construction of a "modernized industrial system" to the top strategic priority, while quantum technology is now listed first among China's designated "future industries."[30] Analysts note that this emphasis on domestic quantum industrialization is already translating into concrete policy tools, including state guidance funds, technology parks, grand challenge competitions, and the use of state-owned enterprises as early customers and integrators.[31] In 2025, for example, the PRC's Ministry of Industry and Information Technology launched a "bounty-style" set of 17 "future industry innovation tasks" for quantum by 2026, including control systems for quantum computers exceeding 1,000 qubits (quantum bits) and a high-performance dilution refrigerator comparable to leading Western systems.[32] Paired with sustained state-led procurement, these efforts are increasingly positioning China to secure end-to-end domestic capability across the quantum supply chain, potentially outcompeting the West.

Early commercial impacts are already visible. Shanghai-based PreciLasers, founded in 2017, has rapidly become a leading supplier of quantum-grade fiber lasers, offering products nearly identical to those of established Western firms at lower cost.[33] U.S. quantum executives attribute this rise to state subsidies, preferential procurement, and accelerated iteration, possibly through reverse engineering.[34] PreciLasers' website confirms that the company originated from a team at the PRC-funded Chinese Academy of Sciences and is designated as a "National High-Tech Enterprise," "Specialized and Innovative (专精特新)

Enterprise," and "Little Giant (小巨人)"—designations that can unlock substantial state support.[35] Chinese firms are also gaining footholds in other enabling technologies. In 2024, state-affiliated media reported "mass production" of the EZ-Q dilution refrigerator by company QuantumCTek, with additional domestic firms announcing similar systems.[36] Chinese suppliers are also marketing quantum-grade diamond for sensing and research applications, signaling the emergence of early commercial capacity in these segments.[37]

These trends threaten to increase price pressure on U.S. suppliers and shift global demand toward Chinese firms. Although the United States has imposed tariffs on Chinese imports, exemptions for R&D mean that Chinese components can still be imported for quantum research by U.S. universities, research organizations, and companies with little or no added cost. Chinese efforts to replicate U.S. and allied technologies or access markets may also prove difficult to track, particularly if Chinese companies route products through third countries or opaque ownership structures, mirroring documented efforts to circumvent export controls in leading-edge artificial intelligence chips.[38]

Europe's Push for Technological Sovereignty

In parallel, growing friction with U.S. allies is weakening the transatlantic quantum ecosystem. The European Union's (EU's) drive for technological sovereignty seeks to reduce dependence on both China and the United States by restricting public investments in quantum to EU-based system integrators, subcontractors, and suppliers.[39] These policies deprive U.S. companies and component makers of critical early demand signals, slowing the scaling of enabling technologies that underpin supply chain resilience. This stands in contrast to U.S. practice, which has remained relatively open to allied participation. DARPA's Quantum Benchmarking Initiative is funding eight international quantum computing companies out of 18 performers, European institutions participate directly in the Department of Energy's National QIS Research Centers, and in 2025 Oak Ridge National Lab purchased a quantum computing system from Finland's IQM.[40]

However, the United States' own trade policy is also introducing frictions.[41] Many U.S. quantum and enabling-technology companies depend on European suppliers for specialized components and access to advanced foundries capable of fabricating quantum-grade components, often with no domestic alternatives. Tariffs intended to bolster domestic industry are instead raising costs and slowing development at a moment of intensifying global competition. Because some quantum components cost millions of dollars per unit, even modest tariffs can divert resources equivalent to an engineer's annual salary away from innovation. Without parallel investments to expand domestic capacity, these measures risk weakening U.S. competitiveness just as China charges ahead.

Unlike the United States, the People's Republic of China has coupled sustained public investment in quantum research with the expansion of advanced manufacturing capacity, positioning itself to scale and deploy quantum technologies more rapidly. This emphasis is set to intensify under China's 15th Five-Year Plan (2026–2030), which elevates quantum as the top "industry of the future" within a broader effort to build a modernized industrial system. Here, a superconducting quantum computer by Chinese company Origin Quantum is on display during the 2025 World Manufacturing Convention in Hefei, China. (Han Suyuan/China News Service/VCG via Getty images)

Takeaways and Recommendations

The push from the People's Republic of China to industrialize quantum technologies is rapidly building scale advantages in enabling technologies and manufacturing while protectionist policies across both sides of the Atlantic risk weakening collective access to critical inputs and markets. Absent a more coherent international approach, these dynamics threaten to disadvantage U.S. firms at a moment when speed, capital efficiency, and market access are central to quantum leadership.

- **U.S. policy should pair trusted access to indispensable foreign inputs in the near term with sustained investment in domestic supply chains for long-term resilience.** Strategic engagement with allies and partners—led by the Departments of State, Commerce, and Defense and coordinated through bilateral arrangements or existing multilateral frameworks such as the Quantum Development Group or Pax Silica—can mitigate immediate vulnerabilities where domestic capacity is insufficient and better align trade and coordination policies to reduce shared dependence on untrusted suppliers.

- **These same channels can also serve to deepen commercial partnerships with allies and partners to promote U.S. quantum systems and enabling technologies abroad.** Expanding market access—requiring mutual concessions such as lower U.S. tariffs and greater European reciprocity in access to R&D and procurement programs—can strengthen demand signals for U.S. suppliers, attract private investment into domestic manufacturing, and help establish U.S. technologies as global defaults before untrusted competitors lock in advantage. Agencies such as the U.S. Commercial Service, working in concert with industry organizations like the Quantum Economic Development Consortium, have a central role to play in translating diplomatic alignment into durable commercial outcomes.

The overarching challenges reviewed in this chapter—the industry's nascency, insufficient government support, and growing international pressures—are shaping the pace of U.S. quantum innovation as well as the resilience of its supply chains. The next chapter turns from these macro-level conditions to the quantum supply chains themselves, mapping their multiple layers, the diversity of hardware modalities, and the different categories of vulnerability affecting individual inputs.

Mapping the Structure of Quantum Supply Chains

This chapter introduces a framework that maps quantum supply chains across three dimensions: the technology stack, major quantum hardware modalities and their enabling-technology dependencies, and the different categories of vulnerability affecting individual supply chain inputs.

This framework provides a diagnostic structure for identifying where vulnerabilities arise within the U.S. quantum ecosystem and what types of risks they present. The following chapter applies this framework to highlight key vulnerabilities and outline targeted responses.

Layers of the Quantum Technology Stack

Quantum technologies span computing, sensing, and networking applications. Although their hardware implementations vary, all quantum systems rely on the creation, control, and measurement of extremely delicate quantum states, such as *superposition*, in which a quantum information unit can exist in multiple states at once, and *entanglement*, in which the states of two or more units become tightly linked, allowing coordinated operations and capabilities beyond what classical systems can achieve. These quantum states are highly sensitive to disturbance: Small amounts of noise, heat, vibration, or electromagnetic interference from the surrounding environment can disrupt or destroy them.

Harnessing quantum states requires not only quantum media—the substrates and atomic systems that host quantum effects—but also a tightly integrated stack of "classical" (nonquantum) supporting technologies that can maintain and control the quantum states long enough to be useful. These include cryogenic and vacuum environments that suppress environmental noise, precision lasers and optics that manipulate quantum states, and specialized control electronics and interfaces that coordinate system operation.

Quantum technology development and scale-up depend on distinct inputs at each layer, any one of which can become a binding constraint on system performance or deployment. Table 2 illustrates this multilayered model, which the authors adapted, with modifications, from the "quantum stack" framework developed by the QED-C and the MonArk Quantum Foundry.[42] This framework includes a quantum layer—atomic media and quantum-grade materials that directly host quantum states—and nonquantum hardware and software layers that control, stabilize, and connect quantum states and information units.

Although the quantum technology stack in Table 2 does not mention them explicitly, testing and manufacturing infrastructure are indispensable extensions of the quantum supply chains.[43] Building a resilient U.S. quantum industrial base requires not only access to critical inputs, but also domestic facilities to fabricate, integrate, and validate them domestically and at scale. This includes prototyping and metrology laboratories, advanced packaging and assembly lines, system-level test beds, and wafer-scale quantum foundries. These facilities form the practical backbone of the quantum ecosystem, enabling the development and integration of supply chain inputs into full quantum systems.

Table 2. Layers of the Quantum Technology Stack

Quantum technologies rely on a multilayered stack that spans quantum media, operating environments, interfaces, control systems, software, and networks. While different quantum hardware modalities—such as superconducting, photonic, or neutral-atom systems—draw on these layers in distinct ways, all depend on every layer of the stack to create, maintain, control, and connect fragile quantum states. Vulnerabilities at any layer can constrain system performance, scaling, and deployment.

Layer	Key Elements
Atomic Media and Quantum-Grade Materials Host or enable quantum states and require extreme purity, controlled composition, and specialized fabrication	▪ Quantum atomic species and isotopes (e.g., rubidium-87, cesium-133, strontium-87/88, potassium-40, barium and calcium ions) ▪ Rare-earth dopants (e.g., erbium, neodymium, ytterbium) ▪ Photonic materials: low-loss routing (e.g., silicon, silicon nitride); active and nonlinear (e.g., indium phosphide, gallium arsenide, lithium niobate, barium titanate), metamaterials ▪ Qubit hosting materials: Superconducting thin films (e.g., niobium, aluminum, tantalum); isotopically enriched semiconductors (e.g., silicon-28, germanium-70); high-purity diamond with engineered defects
Operational Environments Cryogenic and vacuum systems that suppress thermal, mechanical, and environmental noise to preserve quantum coherence	▪ Dilution refrigerators (using helium-3/helium-4 isotopic mixtures); pulse-tube cryocoolers ▪ Subkelvin cooling stages: sorption refrigerators; adiabatic demagnetization refrigerators (using materials such as holmium copper, gadolinium oxysulfide, or gadolinium aluminum perovskite) ▪ Cryogenic compressors and gas-handling systems ▪ Ultrahigh-vacuum chambers and pumping systems ▪ Thermometry, vibration isolation, and magnetic shielding
Interface Components Hardware that transmits, converts, and conditions optical, electrical, and microwave signals between classical control systems and quantum devices	▪ Optical interfaces: single-photon detectors, fibers, waveguides, high-numerical aperture lenses, large field-of-view microscope objectives ▪ Electronic, radio frequency (RF), and microwave interfaces: quantum-limited and cryogenic amplifiers, RF, and microwave cabling, filters, attenuators, high-density wiring ▪ Device-specific and hybrid interfaces: microfabricated ion-trap electrode structures; microwave-to-optical transducers (emerging)
Control Systems Electronics and photonics that generate, synchronize, and process signals to manipulate and measure quantum states	▪ Optical control systems: Stabilized/reference laser systems with electro-optic and acousto-optic modulators; high-performance spatial light modulators ▪ Electrical and microwave electronics: arbitrary waveform generators; microwave signal sources and synthesizers; digital-to-analog / analog-to-digital converters; integrated RF control and timing modules ▪ Cryogenic control logic: Cryogenic complementary metal-oxide semiconductor (CMOS) electronics; single-flux-quantum logic
Software and Error Correction Software, firmware, and algorithms that interface with hardware to control operations, perform calibration, and implement quantum error correction and feedback	▪ Core software stack: low-level control firmware; compiler, mapping, and scheduling software ▪ Calibration and performance maintenance: calibration and tuning algorithms; device characterization and benchmarking software ▪ Error management and correction: error-correction codes and decoding software; real-time feedback and control loops ▪ Advanced and artificial intelligence–enabled control-plane electronics
Networks Quantum and classical networking elements that distribute entanglement, transmit quantum information, and connect systems across distances	▪ Quantum communication protocols ▪ Photonic interconnect and hybrid quantum-classical transport ▪ Specialized optical fiber and cladding; free-space optical links ▪ Quantum networking hardware: quantum memories and quantum repeaters (emerging)

Quantum Hardware Modalities and Their Enabling-Technology Dependencies

Quantum technologies do not rely on a single mix of inputs from the quantum stack mentioned in the previous section. Instead, they rely on a set of partially overlapping and evolving supply chains tied to different quantum hardware modalities. As summarized in Table 3, leading modalities include neutral atoms, trapped ions, photons, superconducting circuits, semiconducting spins, and color centers—each reflecting different tradeoffs among performance, scalability, manufacturability, and deployment timelines.

These architectural choices create distinct dependencies on enabling technologies and associated supply chains.[44] Table 3 compares modalities across three enabling-technology categories that shape system operation and scalability, and that pose elevated supply chain risk: photonics and optics, cryogenics, and specialized materials and microfabrication.[45] The discussion below elaborates on these dependencies. Note that other inputs in the quantum technology stack—such as control electronics, software, and networking components—may also present meaningful gaps and require additional analysis.[46]

Table 3. Quantum Hardware Modalities Differ in Their Enabling-Technology Dependencies

Atomic, photonic, and solid-state systems differ in how they realize and control quantum states and therefore in how they depend on enabling technologies. The table compares major modalities across three enabling-technology domains—photonics and optics, cryogenics, and specialized materials and microfabrication—highlighting that each enabler may play a core, supporting, or limited role depending on the modality. This variation produces distinct, modality-specific supply chain vulnerabilities. For simplicity, this table focuses on the most mature quantum modalities and on quantum computing–oriented implementations and firms.

	Hardware Modality Qubit Approach	**Enabling-Technology Dependencies**			**Representative Firms Pursuing this Modality**
		Photonics and Optics	**Cryogenics**	**Specialized Materials and Microfabrication**	
Atomic	**Neutral Atom** Atoms confined in high-vacuum systems	**Core** Finely tuned laser systems cool and manipulate atoms and measure outcomes	**Limited or Unnecessary** Operate near room temperature; cryogenics not required but can be used for vacuum hygiene or networking	**Supporting** Integrated components important for scaling, but optical loss requirements less stringent than photonic systems; UHV-compatible materials and microfabricated trapping structures important for scaling	▪ QuEra (U.S.) ▪ Infleqtion (U.S.) ▪ Atom Computing (U.S.) ▪ Pasqal (France)
	Trapped Ion Charged atoms (ions) confined by electromagnetic fields in ultrahigh-vacuum (UHV)				▪ IonQ (U.S.) ▪ Quantinuum (U.S.) ▪ AQT (Austria)
Photonic	**Photonic** Light particles carried through optical circuits on photonic chips	**Core** Lasers drive single-photon sources; phase-stable, low-loss optics essential to performance	**Core** Cryogenic cooling (subkelvin to few kelvin) for photon detectors and some photon sources	**Core** High-quality photonic materials and heterogeneous integration central to performance and scaling	▪ PsiQuantum (U.S.) ▪ Xanadu (Canada) ▪ Quandela (France) ▪ ORCA Computing (UK) ▪ QC82 (U.S.)
Solid State	**Superconducting** Superconducting electrical circuits at extremely low temperatures	**Supporting** Control relies on electrical and microwave signals, but photonics emerging for optical links and microwave-to-optical interfaces for modular scaling	**Core** Operate at millikelvin temperatures via dilution refrigerators	**Core** Ultraclean, thin films or isotopically pure semiconductors central to performance	▪ IBM (U.S) ▪ Google (U.S.) ▪ Rigetti (U.S. & UK) ▪ IQM (Finland) ▪ QuantumCTek (China) ▪ Origin Quantum (China)
	Semiconducting Spin Spins of individual electrons or holes confined in tiny semiconductor structures at extremely low temperatures				▪ Intel (U.S.) ▪ Diraq (Australia) ▪ Quantum Motion (UK) ▪ Silicon Quantum ▪ Computing (Australia)
	Color Centers Engineered atomic-scale defects in crystals that show quantum properties	**Core** Lasers manipulate and measure qubits	**Limited or Unnecessary** Operate near room temperature; cryogenics not required	**Core** Ultrapure diamond growth, precise defect engineering, and nanophotonic structures central to performance	▪ Photonic (Canada) ▪ Quantum Brilliance (Australia) ▪ SaxonQ (Germany) ▪ XeedQ (Germany)

Photonics and Optics

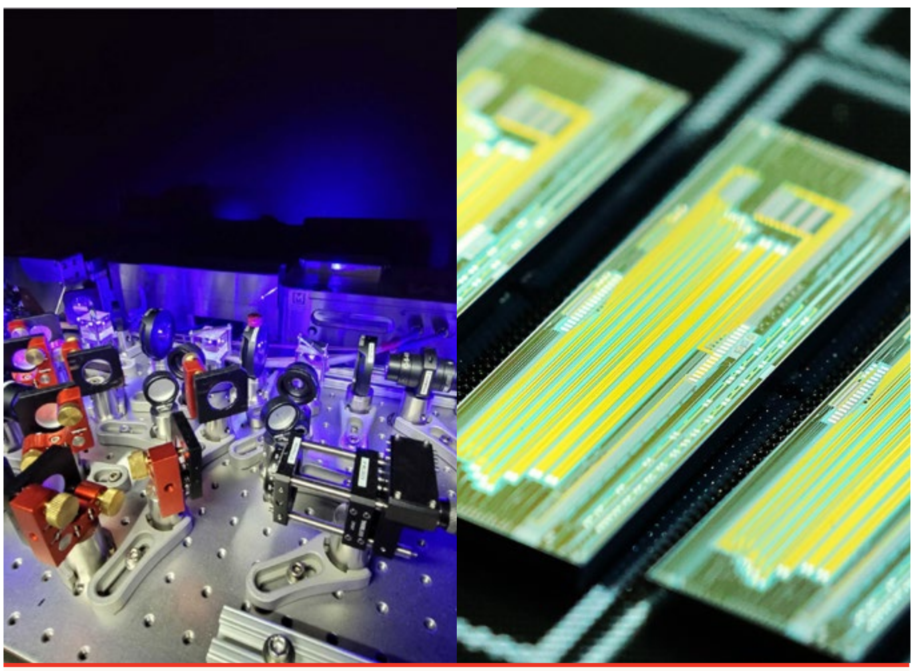
Photonic and optical technologies form the foundational hardware for generating, routing, manipulating, and detecting light in quantum systems. These technologies include electrically active devices—such as lasers, optical amplifiers, modulators, and detectors—as well as passive components including routing waveguides, beam and/or wavelength combiners and splitters, polarization controllers, lenses, resonators, and filters.

Historically, quantum platforms have relied on large assemblies of free-space optics and, more recently, modular, fiber-coupled components that still require extensive packaging and manual alignment, resulting in optical systems that are bulky, fragile, and costly. While not always strictly required for useful performance, the field is increasingly transitioning toward integrated photonics, consolidating many of these functions onto photonic-integrated circuits (PICs) to improve stability, scalability, and cost. Across individual devices and integrated quantum photonics, systems draw on a heterogeneous set of material platforms to exploit specific physical properties, including silicon and silicon nitride, established III–V semiconductors, electro-optic materials such as lithium niobate, and many other emerging platforms. The functions, fabrication, and heterogeneous integration of these materials into photonic chips—and their implications for scaling quantum hardware—are discussed in greater detail later in this chapter (see "Specialized Materials and Microfabrication").

The role of photonics and optics varies across quantum technologies and hardware modalities, depending on whether light is used primarily for state preparation, qubit control, interconnects, measurement, or long-distance quantum communication.

In neutral-atom and trapped-ion quantum systems, individual atoms serve as qubits, but light is the primary means of controlling them.[47] Neutral-atom platforms use lasers to trap and manipulate atoms, while trapped-ion systems rely on electromagnetic fields for confinement and lasers for quantum operations and readout. Because these interactions must match precise atomic energy transitions, both platforms depend on highly stable laser systems operating at multiple narrowly defined wavelengths. Each wavelength typically requires its own optical chain of tightly aligned seed lasers, amplifiers, frequency converters, modulators, and delivery optics. These components often cost tens of thousands of dollars each, and even a small multicolor laser system can exceed a million dollars, making photonics one of the dominant cost and scaling bottlenecks in atomic quantum hardware.

Efforts to scale atomic quantum platforms follow two parallel paths: improving the performance and manufacturability of individual free-space photonic and optical components—such as high-power lasers, metamaterial lenses, spatial light modulators, acousto-optic beam steering, and advanced detectors—and integrating photonic and optical functions on chip to reduce size, weight, power, and alignment complexity. Photonic integration can introduce tradeoffs in ultimate performance, especially in beam purity, requiring atomic systems to balance manufacturing cost against optical performance. Near-term implementations are therefore likely to rely on hybrid architectures that combine integrated photonics with selected free-space optics.



Photonics and optics play distinct but increasingly important roles across quantum hardware modalities. Atomic and ion-based quantum platforms rely on large assemblies of precision-stabilized laser systems and free-space optics to trap, control, and measure qubits (left; QuEra Computing), while photonic quantum computers perform computation directly in the optical domain using photonic integrated circuits (PICs). Across applications, quantum hardware is increasingly adopting PICs that integrate heterogeneous materials to consolidate multiple optical functions in compact, manufacturable formats (right; Beacon Photonics). Superconducting and semiconducting-spin platforms do not use light for qubit manipulation, but use photonics for calibration and characterization, and may leverage optical interconnects to link cryogenic systems at scale.

Where feasible, integrated and copackaged photonic subsystems are especially valuable for deployable atomic quantum sensors, for which robustness; manufacturability; and low size; weight; and power (SWaP) are critical.

In **photonic quantum computing,** light itself carries the quantum information. Systems generate single photons—often by using lasers to excite specialized photon sources—and direct them through PICs composed of waveguides, beam splitters, and interferometers. As photons propagate and interfere within these circuits, they enact quantum logic operations, with cryogenic single-photon detectors measuring the results at the output. Because computation occurs entirely in the optical domain, each lost photon directly reduces the probability of a correct result and forces the use of additional optical redundancy to maintain performance. This, in turn, increases system complexity and amplifies the system's cryogenic and associated energy demands. Reliable operation and sustainable scaling of photonic quantum computers therefore place especially stringent demands on ultralow-loss photonic materials and components, as well as on precise timing and phase control to keep light waves synchronized as they propagate through the system.

Diamond color-center systems similarly use light to control and measure qubits, but the quantum states reside in tiny, engineered defects inside a diamond crystal—such as nitrogen-vacancy (NV) or silicon-vacancy (SiV) centers—that act like solid-state artificial atoms.[48] Researchers and firms are pursuing these systems for quantum sensors, quantum networking components (like quantum memories), and for quantum processors. Lasers prepare and measure these defects. Because the light originates inside a solid material rather than free atoms, these defects must be embedded within microscopic optical features etched into or attached to the diamond that efficiently guide light into and out of the device.[49]

By contrast, **superconducting and semiconducting-spin qubit platforms** do not typically use light to store or directly manipulate quantum information; they operate primarily through electrical and microwave signals.[50] Nevertheless, photonics plays an important supporting role. Optical systems already support device characterization, calibration, and timing. Looking ahead, photonics is widely viewed as a potential solution to one of the most serious scaling challenges for these platforms: interconnecting multiple processing units housed in separate dilution refrigerators. Today, such refrigerator-to-refrigerator links must operate at cryogenic temperatures to ensure that single microwave photons can be distinguished from thermal noise. If microwave photons can instead be converted into optical photons, those signals could be transmitted and processed at room temperature, greatly simplifying system architecture and potentially enabling longer-distance interconnects.[51] Photonics is therefore emerging as a shared enabling dependency even for modalities where it is not central to qubit operation.

From a supply chain perspective, photonics and optics create both modality-specific and cross-cutting dependencies. Photonic, atomic, and diamond platforms rely heavily on laser systems, optical components, and, increasingly, integrated photonic systems, while superconducting and spin-based platforms depend on photonics primarily in supporting roles that are expected to grow as systems become more modular and networked. As a result, constraints in photonic manufacturing, packaging, or component availability can stall individual modalities today and evolve into shared bottlenecks across the ecosystem over time. Beyond securing current supply chain inputs, advances in photonics—such as more reliable and scalable laser sources, lower-loss and more manufacturable PICs, improved optical packaging, and robust microwave-to-optical interfaces—are a critical lever for strengthening quantum supply chains and enabling system-scale deployment.

Cryogenics

Cryogenics—the operation of systems at very low temperatures—plays an important but uneven role across quantum hardware modalities. While some platforms depend on extreme cooling for quantum behavior to emerge, others operate at or near room temperature and may use cryogenics only selectively to enhance performance. These differences translate into sharply divergent supply chain dependencies and scaling constraints.

For **superconducting and semiconducting-spin systems**, quantum behavior itself depends on ultralow temperatures. In superconducting platforms, electrical circuits must be cooled to millikelvin temperatures so that electrical current can flow without resistance. In spin-based platforms, extreme cooling reduces random thermal motion that would otherwise overwhelm the fragile quantum states stored in individual electrons. Achieving these conditions requires dilution refrigerators—the chandelier-like cryostats often broadly associated with quantum computing, even though many leading hardware modalities do not require them. Dilution refrigerators reach millikelvin temperatures by using helium-3, a scarce and tightly regulated isotope.

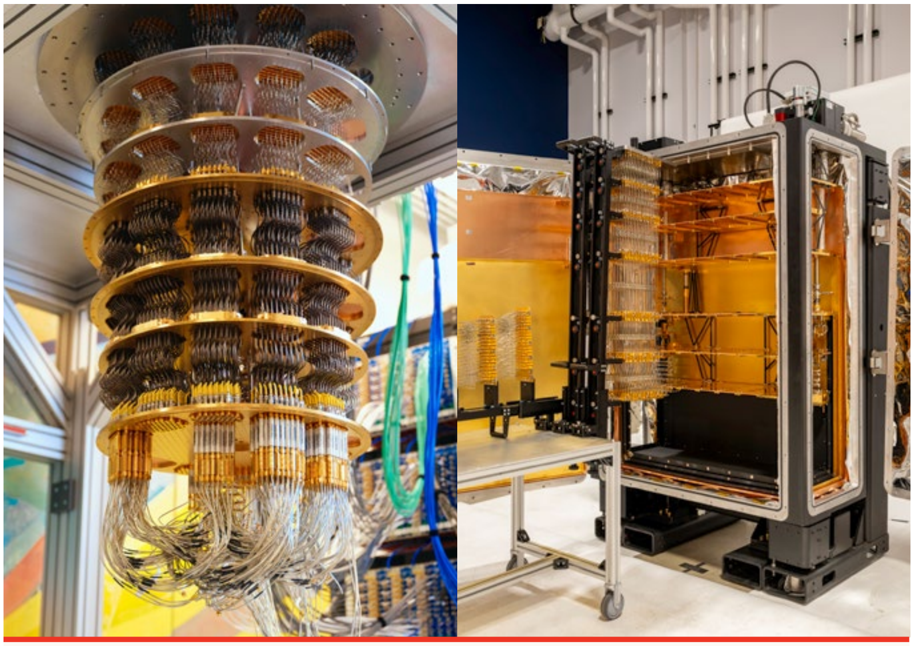
Cooling power directly constrains how much quantum hardware can operate within a single dilution refrigerator, making cryogenics a central architectural bottleneck for these quantum modalities.[52] Today's most advanced commercial systems, roughly the size of large industrial cabinets, deliver only tens of microwatts of cooling power and can support on the order of 1,000 physical qubits.[53] Limited cooling power also constrains system design: To minimize heat near the qubits, control electronics must remain outside the fridge but connected to them via highly specialized wiring that combines high data throughput with extreme thermal isolation. Scaling to fault-tolerant systems with millions of qubits will require data center–scale facilities housing dozens or even hundreds of interconnected dilution refrigerators, each linked through quantum-coherent connections that do not yet exist at scale.[54] The capital intensity, energy demands, and engineering complexity of such systems represent a qualitative leap beyond today's early quantum computing deployments.

Other quantum modalities operate at warmer cryogenic temperatures but can still impose substantial cooling requirements. **Photonic quantum computers** encode information in light rather than solid materials and therefore do not require millikelvin environments to generate quantum behavior. However, cryogenics remain essential for practical operation: Key subsystems such as single-photon detectors (notably superconducting nanowire single-photon detectors) must operate at subkelvin to few-kelvin temperatures to achieve the efficiency, timing resolution, and low noise required for computation. These systems are typically cooled using closed-cycle cryocoolers based on helium-4 (common helium) rather than helium-3.

Operating at higher temperatures does not eliminate cryogenic complexity. To operate a fault-tolerant quantum computer, photonic systems can impose substantial aggregate cooling and power demands, as tens of thousands of cryogenic-dependent components must operate continuously and in parallel. For instance, one leading photonic firm is developing a single quantum computer built around dozens of high-density cryogenic cabinets, housed in a football-stadium-scale facility and supplied by a dedicated cooling plant.[55]

By contrast, **atomic quantum platforms**, including trapped-ion and neutral-atom systems, operate largely near room temperature. In computing applications, qubits are encoded in individual atoms or ions confined in ultra-high-vacuum chambers and cooled using laser-based techniques that reduce atomic motion to microkelvin temperatures, a process distinct from cryogenic refrigeration and whose scaling has already been worked out. While some developers currently employ cryogenic subsystems to enhance vacuum quality, they are actively researching pathways to reduce their use of cryogenics.[56] As these platforms scale, selective use of cryogenic components may still prove advantageous, but they do not face the same fundamental dependence on low temperatures as solid-state architectures or photonic computing subsystems.[57]

From a supply chain perspective, cryogenics creates modality-specific dependencies. Dilution refrigerators, helium-3 availability, and cryogenic wiring and interconnects are core requirements for superconducting and spin-based platforms; moderate-temperature cryocoolers play a supporting role in photonic systems; and cryogenics are very limited and often optional in atomic modalities. As a result, constraints



Divergent cryogenic requirements create modality-specific supply chain constraints. Superconducting and semiconducting-spin systems require millikelvin temperatures for operation, achieved using dilution refrigerators like those shown here. These cryogenic systems are supplied by only a handful of manufacturers worldwide and rely on scarce, highly regulated helium-3, as well as dense cryogenic wiring to connect qubits to room temperature control electronics (left; Google Quantum AI). Industrially relevant, million-qubit systems would each require dozens of today's most advanced dilution refrigerators per system (right; Maybell Quantum). Meanwhile, photonic platforms can operate at warmer cryogenic temperatures but would still require large, centralized cooling infrastructure at scale, while atomic platforms operate largely near room temperature. Sustaining the scale-up of cryogenic-dependent quantum systems will require major breakthroughs in cooling efficiency.

in cryogenic manufacturing capacity, isotope supply, or system integration can directly limit deployment and scaling for some modalities while leaving others relatively insulated. Beyond securing access to current cryogenic systems, advances in cryogenic engineering—such as higher cooling power, improved efficiency, and tighter integration with control electronics—are a key lever for reducing long-term supply constraints and easing the path to large-scale quantum systems.

Specialized Materials and Microfabrication

Specialized materials and microfabrication often determine whether quantum technologies can progress from laboratory demonstrations to scalable, manufacturable systems.[58] Across modalities, useful performance depends on precise control of fragile quantum states, pushing requirements for material purity and process control well beyond those of conventional manufacturing. Quantum-grade materials, processes, and toolchains are often concentrated in a small number of global facilities and represent some of the thinnest and most consequential links in the quantum supply chain.[59]

> **Useful performance depends on precise control of fragile quantum states, pushing requirements for material purity and process control well beyond those of conventional manufacturing.**

For **solid-state quantum modalities**, engineered materials and interfaces directly host the qubits, making device performance highly sensitive to atomic-scale material quality. In **superconducting systems**, qubits are formed by patterning microscopic circuits from thin films of superconducting metals such as aluminum, niobium, or tantalum. These circuits incorporate nanometer-thick insulating barriers between metal layers that create the discrete energy states used to encode quantum information. Tiny defects at material surfaces and interfaces interact with a qubit's electrical fields, causing its quantum state to decay or drift and directly limiting performance.[60] In **semiconducting-spin platforms**, quantum information resides in the spin of single electrons or holes confined in nanoscale semiconductor structures that are easily disturbed by stray electric and magnetic fields from nearby atoms in the host material.[61] To reduce these disturbances, leading approaches emphasize ultraclean semiconductor stacks, nanometer-scale fabrication of control gates, and isotopically enriched silicon or germanium that reduces magnetic interference.[62]

For superconducting and semiconducting-spin platforms, access to advanced complementary metal-oxide semiconductor (CMOS)-compatible wafer fabrication tools—many developed for 300 mm semiconductor manufacturing—can offer qualitative performance benefits, including tighter control over thin-film deposition, interface cleanliness, and nanoscale patterning that reduce defects and variability, and therefore improving qubit coherence and yield. At the same time, smaller wafer formats currently allow for more cost-effective iteration during extended low-volume R&D cycles.

In **photonic and atomic quantum platforms,** the qubits are photons or atoms rather than embedded in engineered materials, but a wide range of photonic materials and specialized microfabrication and packaging techniques are required to build the high-performance optical subsystems on which these platforms depend (see text box for an overview of key photonic materials). These components—lasers, waveguides, modulators, splitters, and detectors—are implemented either as tightly aligned free-space assemblies or through integrated photonic approaches.[63]

Quantum Photonics Relies on a Wide Range of Materials

Modern quantum photonics—spanning both free-space optical systems and increasingly integrated photonic platforms—relies on a heterogeneous collection of materials that is shared with other photonics-intensive sectors, including telecommunications, data centers, and precision sensing. No single material provides all required optical functions, making multimaterial architectures increasingly common.

- **Silicon and silicon nitride** are foundational photonic materials. Silicon enables compact photonic waveguides compatible with mature semiconductor manufacturing, while silicon nitride provides ultralow-loss waveguides for high-coherence photonic circuits. Both commonly serve as base platforms for integrating additional photonic materials and for fabricating on-chip photonic structures and metasurfaces.
- **Established III–V semiconductors** such as gallium arsenide and indium phosphide provide optical gain, lasers, and telecom-band detectors and are indispensable for light generation and amplification in both bulk and integrated quantum systems.

- **Electro-optic and nonlinear materials** such as thin-film lithium niobate are increasingly adopted across quantum technologies for high-fidelity modulation and frequency conversion. Emerging integrated photonics platforms—including barium titanate, aluminum nitride, tantalum pentoxide, and alumina—are being explored to extend performance in speed, nonlinearity, and optical loss.

- **Metamaterials** are created by patterning subwavelength nanostructures into bulk substrates such as glass or plastic to engineer optical properties not present in the original material. They are of growing interest for advanced free-space components such as metalenses, which replace bulky multi-element optics with a single flat element and enable high-numerical-aperture focusing without thick curved glass.

Achieving full on-chip or copackaged functionality requires integrating multiple dissimilar materials within a single device or package, making heterogeneous photonic integration both increasingly important and technically challenging.[64]

An emerging pathway to improve the compactness, stability, and manufacturability of photonic and optical subsystems for quantum technologies is the use of PICs, which consolidate optical functions onto chips in much the same way that electronic integrated circuits route electrical signals.[65] PICs fabricated from different materials can then be combined through heterogeneous integration—sometimes called "light engines" or "laser systems on chip"—to leverage the distinct optical properties of each material within a single platform, as detailed in the text box.

Achieving full photonic functionality through heterogeneous integration relies on access to high-quality wafers, with performance shaped less by isotopic purity than by precise control of geometry and optical material properties, especially surface smoothness and wafer flatness, which directly determine optical loss. These requirements are often more stringent in optical dimensions than when the same materials are used for electronic components. Once wafers are sourced, each material must be patterned into PICs that perform specific optical functions—such as guiding, modulating, or converting light—using microfabrication processes tailored to that material's physical and optical properties. Individual PICs are then integrated using specialized techniques such as wafer bonding, advanced packaging, and nonstandard fabrication flows. The combined demands for high-quality wafers, dedicated PIC processing lines, and complex heterogeneous integration substantially narrows the pool of qualified foundries and constrains large-scale production.[66]

These distinctions also shape optimal manufacturing pathways. While 300 mm wafer formats offer advantages at high production volumes and enable access to the most advanced fabrication tools, they are significantly more expensive for prototyping and early-stage production. Many quantum platforms therefore continue to rely on 150–200 mm wafers, which currently better balance cost, iteration speed, and manufacturability during extended R&D phases.

A key difference between photonic and atomic modalities is how material quality and fabrication precision affect system performance and scaling. Photonic quantum computing is especially sensitive because photons themselves carry the quantum information; each lost photon directly reduces the chance of a correct result and forces added redundancy in optical components, making ultralow-loss materials and high-precision fabrication critical to scalability.[67]

By contrast, in neutral-atom and trapped-ion platforms, light is used to trap, manipulate, and measure qubits rather than to carry quantum information through the computation. Losses must remain below functional thresholds to enable reliable operation, but further reductions primarily reduce required laser power and heat load rather than directly improving computational fidelity. Because photonic integration can sometimes introduce tradeoffs—such as degraded beam quality or reduced flexibility—atomic platforms may accept less integrated optical solutions for certain optical functions, particularly where size, weight, and power constraints are less binding.

Even so, advanced microfabrication remains essential for the operation and scaling of atomic platforms in other ways, such as through chip-based ion traps and atom chambers that require high-precision fabrication and ultrahigh-vacuum compatibility, as well as the specialized optoelectronic subsystems needed to precisely control and measure individual atoms—such as spatial light modulators, acousto-optic beam steering electronics, and advanced optical detectors including scientific CMOS cameras and single-photon avalanche diodes—many of which remain performance limiting or immature for large-scale quantum systems.[68]

Categories of Vulnerability at the Input Level

Just as quantum supply chains vary by hardware modality and enabling technology dependencies, individual inputs—materials, components, and processes—exhibit distinct vulnerability profiles. As Table 4 summarizes, these input-level vulnerabilities fall into three categories: foreign dependence, insufficient domestic capacity, and performance and scalability gaps.

These categories map differently onto the evolution of quantum supply chains over time. Foreign dependence and insufficient domestic capacity primarily constrain the near-term, research-grade supply chain—the components and materials required to sustain prototyping, early deployments, and incremental performance gains. Addressing these vulnerabilities is essential to ensure continued experimentation, iteration, and commercialization within the United States.

By contrast, performance and scalability gaps shape the future supply chain. They encompass the next-generation components, subsystems, and fabrication and packaging processes required for utility-scale quantum systems. In many of these areas, no country has yet achieved industrial maturity. Strategic investment today therefore enables not only resilience but long-term leadership: The firms and nations that solve these scale-limiting challenges will shape the architecture and manufacturing base of deployed quantum systems.

Strengthening the U.S. quantum industrial base is therefore not a homogenous task; each vulnerability type calls for a distinct intervention approach: securing trusted sources and reducing strategic exposure, expanding reliable U.S. capacity, or maturing enabling technologies through dedicated investments.

In practice, these vulnerability categories often overlap: A given supply chain element may be primarily sourced abroad even as nascent U.S. capacity exists but remains fragile or technically immature. Nevertheless, these categories clarify the binding constraint—whether the core challenge is secure access, domestic production capacity, or technology readiness—and consequently which policy tools are most appropriate to tackle it.

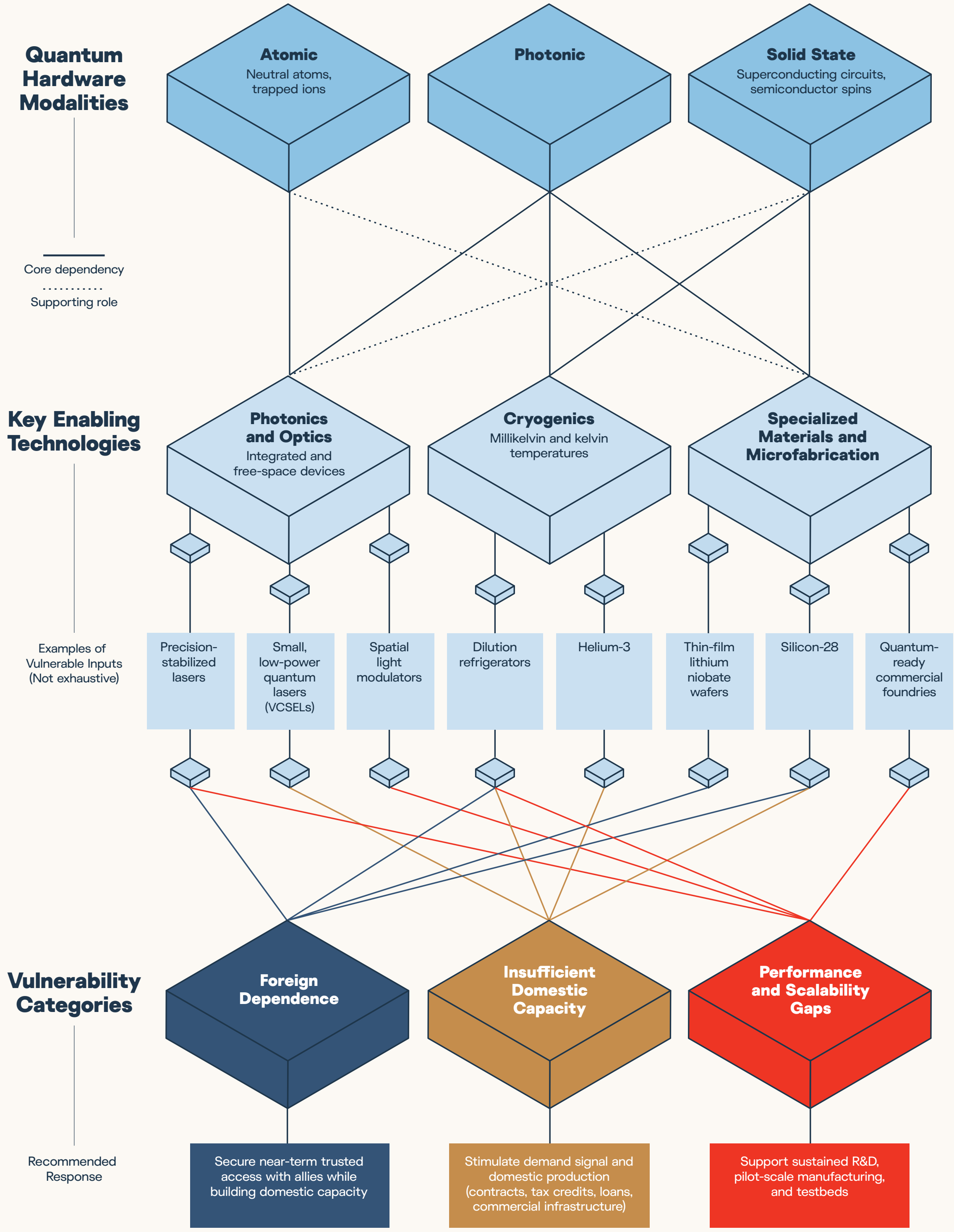
Table 4. Categories of Quantum Supply Chain Vulnerability at the Input Level

Vulnerabilities affecting individual materials, components, and processes fall into three categories: foreign dependence, insufficient or commercially fragile U.S. capacity, and performance and scalability gaps in enabling technologies. The table links each vulnerability type to illustrative (nonexhaustive) examples and corresponding recommendations. Additional examples of vulnerable inputs are provided in tables A1 and A2 in the appendix.

Vulnerability Category	Examples of Vulnerable Inputs *Not exhaustive*	Recommended Response
Foreign Dependence Inputs that are primarily or solely sourced from abroad, creating vulnerabilities to export restrictions, market distortions, or diplomatic tensions.	▪ Thin-film lithium niobate wafers for integrated photonics (primarily sourced from China) ▪ Magneto-optic crystals for optical isolators (China, Russia) ▪ Refined alkali metal isotopes, like rubidium-87 and cesium-133, and silicon-28 (Russia) ▪ Rare-earth dopants like erbium, ytterbium, and neodymium for laser systems (China) ▪ Holmium-based compounds for cryogenic systems (China) ▪ Commercial III–V semiconductor epitaxy (China, other Asian countries, UK) ▪ Precision-stabilized lasers (China, Germany, Japan)	Secure trusted sources with allies and partners for near-term progress continuity while building domestic sourcing capabilities for long-term resilience.
Insufficient Domestic Capacity U.S. sources exist but remain few, small volume, lower quality, or otherwise commercially uncertain to meet demand.	▪ Domestic cryogenic system suppliers have long lead times and limited throughput ▪ Domestic quantum-grade low-power lasers (vertical-cavity surface-emitting lasers or VCSELs) repeatedly discontinued in favor of higher-volume markets ▪ Photonic microfabrication at universities and national labs is insufficient to reach industrial scaling	Scale U.S. capacity by stimulating demand (e.g., via advanced R&D programs and early procurements) and production capabilities (e.g., via loans, tax credits, and investments in shared facilities).
Performance and Scalability Gaps Key materials, components, or processes that function in research or early prototype systems, or are newly emerging, and require significant advances in performance, efficiency, or manufacturability to support utility-scale quantum deployment.	▪ High-power, narrow-linewidth lasers with continuous operation for atomic computers ▪ Spatial light modulators for atomic computers ▪ Scalable millikelvin cryogenic systems for superconducting and semiconducting-spin qubit quantum computers ▪ Quantum-ready, high-purity fabrication processes for superconducting and semiconducting-spin qubit chips ▪ Microwave-to-optical interconnects for modular quantum computing and quantum repeaters for geographically distributed quantum networks	Advance enabling technologies through sustained translational R&D, test beds, and pilot-scale manufacturing to bridge the gap from laboratory innovation to commercial readiness.

Figure 1. U.S. Quantum Supply Chains Are Heterogeneous Across Hardware Modalities, Enabling Technology Dependencies, and Vulnerability Categories

The figure maps major modalities, key enabling technologies, illustrative vulnerable inputs, and corresponding categories of vulnerability with recommended policy responses. Key enabling technologies and their examples are illustrative rather than exhaustive, and not every example applies uniformly across modalities (for instance, photonic quantum systems require cryogenic systems but not dilution refrigerators specifically).



Source: CNAS analysis

Differences across the quantum technology stack, hardware modalities and enabling technologies, and vulnerability categories underscore that there is no single "quantum supply chain" or uniform gap to fill. Instead, quantum technologies depend on a network of interrelated and evolving supply chains, each with a distinct set of technical requirements and sources of fragility—both for sustaining near-term development and for achieving reliable operation and manufacturable scale (Figure 1). Effective policy responses must therefore be calibrated to these specific modalities, inputs, and constraints, rather than applied uniformly across the ecosystem.

The next chapter applies this framework to identify the most consequential vulnerabilities and to outline targeted interventions to strengthen the U.S. quantum industrial base.

Key Quantum Supply Chain Vulnerabilities and Recommendations

The preceding chapters established a high-leve framework for mapping the structure and diversity of quantum supply chains and their vulnerabilities. This final chapter applies that framework to identify concrete supply chain vulnerabilities confronting U.S. quantum technologies today and to outline practical pathways to address them. The analysis follows the same three enabling-technology categories introduced in the previous chapter—photonics and optics, cryogenics, and specialized materials and microfabrication—with a more comprehensive set of findings provided in Tables A1 and A2 in the appendix.

The recommendations in this chapter span the policy spectrum, including targeted R&D to mature critical enabling technologies, shared testing and manufacturing infrastructure to lower cost and improve quality, strategic procurements to boost demand signals, allied coordination to secure trusted inputs, and selective trade measures to reduce strategic exposure. While this report centers on federal policy levers, effective implementation will require active—and in some cases leading—participation across state governments, private capital, industry, and academia.

Vulnerabilities in Photonics and Optics

Photonic and optical systems underpin most quantum technologies and hardware modalities, as well as a wide range of nonquantum sectors, including telecommunications, precision sensing, semiconductor manufacturing, and next-generation defense systems like directed energy. Strengthening domestic capability in lasers and optics, integrated photonics, and related manufacturing would therefore boost not only quantum innovation but also sectors critical to U.S. national security and industrial competitiveness.

Yet the photonics and optics supply chains for quantum technologies remain thin, globally dispersed, and poorly aligned with quantum's emerging needs. Most commercial photonics supply chains are optimized for telecommunications and consumer markets, not for the high stability and reliability required by scalable quantum systems and certain defense applications. As quantum platforms move toward fielded systems, this mismatch is becoming a binding constraint.

Table A1 in the appendix summarizes a nonexhaustive set of vulnerabilities in the supply chains of quantum-relevant photonics and optics, with each entry indicating the affected quantum stack layer, hardware modality, and vulnerability type. For each vulnerability listed, the table also recommends actions to address them. Dependencies related to photonic materials—such as thin-film lithium niobate—and related manufacturing are addressed later in this report, under the section titled "Specialized Materials and Microfabrication."

Many critical inputs—ranging from precision laser systems and rare-earth materials to optical manufacturing equipment—are predominantly sourced from foreign suppliers, including China. This dependence introduces both geopolitical and commercial risk and reinforces the need to develop domestic alternatives through a combination of government-led efforts and incentives to commercial suppliers. Other elements remain technically immature and would benefit most from focused R&D.

The discussion below examines one of the most consequential vulnerabilities in greater depth: precision-stabilized laser systems.

Precision Laser Systems with Scalable Power and Manufacturing

Precision laser systems are foundational to quantum technologies across computing, sensing, and networking. They prepare quantum states, cool atoms or ions to suppress thermal motion, manipulate qubits during computation, and measure results at the end of an operation. These functions are central to leading hardware platforms, including trapped-ion, neutral-atom, and photonic systems.

Much like certain defense applications such as precision sensing and directed energy, quantum systems place exceptionally stringent demands on laser performance. A single quantum processor may require dozens of independent laser channels, each operating at a precisely defined wavelength that matches a specific atomic or optical transition.[69] These lasers must maintain an extremely narrow linewidth—meaning their color remains highly pure and stable over time—and scale to higher power levels, while remaining tightly synchronized for continuous operation. Achieving this performance typically requires a complex optical chain that integrates seed lasers with amplifiers, frequency-conversion stages, modulators, isolators, and active stabilization electronics.

The supply chain for quantum-grade lasers and photonic subsystems is thin, internationally concentrated, and structurally fragile. A small number of foreign suppliers—notably Germany's TOPTICA, Japan's Hamamatsu, and a handful of European specialty laser firms—dominate the market for free-space, narrow-linewidth, frequency-stable lasers used in atomic, ion-trap, and photonic quantum hardware. China's PreciLasers has also rapidly expanded capacity in specialty lasers and high-power fiber amplifiers and frequency-conversion subsystems. Supported by state backing, PreciLasers has built a reputation for delivering these amplification and conversion modules, at competitive cost and on short and predictable timelines—an execution advantage that has accelerated its adoption among quantum developers.

But while these vendors produce state-of-the-art equipment, their products are bulky and largely optimized for laboratory environments rather than high-power, sustained, ruggedized operation in commercial or defense-relevant quantum systems. Custom configurations and limited production volumes further constrain scalability.

Domestic production capacity exists across a few U.S. companies, but no single supplier currently delivers a full suite of quantum-grade laser subsystems at the performance, reliability, and volumes required for large-scale deployment.[70] Several critical elements are particularly constrained, including narrow-linewidth seed lasers, ultralow-noise optical amplifiers, high-power and efficient frequency converters, and wavelength-stabilized sources for atomic transitions. These components are essential for neutral-atom, trapped-ion, and precision-timing platforms, yet remain dependent on foreign manufacturing for both finished systems and key subassemblies.

In parallel, a small number of U.S. start-ups are attempting to transition from bulky free-space laser systems toward chip-scale systems and broader integrated photonic platforms that copackage light sources, modulators, and control optics to improve stability and manufacturability.[71] However, heterogeneous photonic integration remains a nascent and technically challenging domain in the United States. Achieving full functionality requires integrating dissimilar materials using bonding, advanced packaging, and nonstandard fabrication processes that lack robust domestic suppliers (see the section on "Vulnerabilities in Specialized Materials and Microfabrication").

Takeaways and Recommendations

U.S. quantum computing and sensing platforms—as well as defense-relevant applications such as precision sensing and directed energy—remain heavily reliant on foreign, research-grade laser systems that are poorly suited for scalable, reliable deployment. Focused domestic R&D, combined with shared testing and qualification infrastructure, can address these gaps while delivering spillover benefits across quantum and other dual-use markets.

- **Launch dedicated R&D programs for next-generation precision lasers.** Multiyear, advanced R&D programs can advance the development and production of high-power, narrow-linewidth laser systems by pooling requirements across quantum and related defense applications. The Defense Advanced Research Projects Agency is well positioned to lead this effort, building on prior programs on advanced laser systems.[72] The National Institute of Standards and Technology (NIST) and the national laboratories also offer substantial photonics and microfabrication expertise and could work with industry to accelerate development.[73] Priority areas include coherent beam combining, ultralow-noise optical and radio frequency stabilization, and scalable frequency conversion from tens of watts to kilowatt-class output. Programs should explore free-space, fiber-based, and chip-scale platforms, including emerging vertical-cavity surface-emitting lasers (VCSELs) and photonic-crystal surface-emitting lasers (PCSELs). Targeted early production commitments would create demand signals that support continued performance improvement.

- **Establish national test beds for laser qualification and reliability.** National laboratories or NIST should host shared facilities to test long-term stability, environmental robustness, tuning accuracy, and subsystem interoperability under realistic operating conditions. By reducing the need for firms—especially small and midsized suppliers—to each invest hundreds of thousands of dollars or more in specialized in-house testing, these test beds would lower entry barriers while providing trusted third-party performance validation. They would also support the development of common benchmarks essential for system integration and scale. Where possible, test beds should build on existing infrastructure, given the high fixed costs—often millions of dollars annually—required to operate and maintain such facilities.

Vulnerabilities in Cryogenics

Cryogenics underpin several quantum computing architectures and are among the most resource-intensive and constrained elements of quantum supply chains. They also support key components such as single-photon detectors and certain high-sensitivity quantum sensors, though scaling computers toward fault-tolerant, million-qubit systems will likely drive the steepest increases in cryogenic demand.

A single large-scale superconducting computing system could require dozens of today's dilution refrigerator models, each requiring tens of liters of scarce, tightly regulated helium-3 to reach millikelvin temperatures. Large photonic platforms may similarly need dozens of 1–4 K cryogenic racks. Although these systems avoid helium-3, they still rely on the same compressors, cryocooler subassemblies, and regenerator materials as dilution refrigerators. Each of these deployments will require warehouse-scale footprints and significant cooling infrastructure, making cryogenics both essential today and a gating factor for future scalability.[74]

Table A2 in the appendix summarizes a nonexhaustive set of vulnerabilities in the cryogenic supply chain, with each entry indicating the affected quantum stack layer, hardware modality, and vulnerability type. Many inputs, including dilution refrigerators, regenerator materials, and compressors, are sourced from foreign suppliers, including China, creating geopolitical and commercial exposure, and would benefit from targeted investments to grow domestic suppliers. Other inputs, like valves and controls, currently have strong domestic or allied supply and are not listed for simplicity, though emerging lower-cost Chinese alternatives could undercut trusted vendors and warrant ongoing monitoring.

To avoid disruptions and maintain steady development and scaleup, the United States must secure the supply chains for current cryogenic systems while also investing in next-generation platforms with more efficient cooling power and reduced reliance on helium-3. The sections below highlight two priority areas.

Near-Term Stabilization of Helium-3 Supply

Helium-3 enables millikelvin temperatures in dilution refrigerators but remains chronically scarce and expensive. Each refrigerator requires 10–100 liters, priced at $2,500–3,000 per liter and with lead times of 6–12 months.[75] Supply is dominated by the United States, Canada, and Russia, with production derived primarily from tritium decay associated with nuclear programs and select reactor-based recovery pathways.[76] Beyond quantum technologies, helium-3 supports neutron detectors for nuclear security and weapons detection, cryogenic research, and emerging medical imaging applications.[77] Helium-3 has also been proposed as a potential fuel for future fusion-energy reactors, though these applications remain speculative.[78]

In the United States, the Department of Energy (DOE) Isotope Program manages the national helium-3 reserve, processed at a tritium government facility and distributed through Linde Gas & Equipment, providing roughly 8,000–10,000 liters annually.[79] A new commercial supply line opened in 2022 through French multinational Air Liquide, sourcing from Canadian nuclear operator Laurentis Energy Partners, and adding an estimated 5,000–10,000 liters per year to global supply.[80] Russia's state nuclear corporation Rosatom also produces helium-3, but has offered inconsistent exports since 2008.[81]

The DOE has begun exploring future sources, including lunar helium-3 extraction, signing a purchase agreement for three liters to be delivered by 2029.[82] While the moon likely contains large quantities of helium-3 implanted by the solar wind, the economic, and technical feasibility of extracting it remains highly speculative.[83]

Takeaways and Recommendations

Helium-3 is a scarce and tightly regulated isotope. As superconducting, semiconducting spin, and other cryogenic quantum platforms move toward large, fault-tolerant systems, demand for helium-3-dependent dilution refrigeration will rise. Absent deliberate action to stabilize and expand supply, helium-3 availability risks becoming a gating factor for U.S. quantum deployment.

- **Recycle helium-3 from legacy neutron detectors for near-term buffer.** Many neutron detectors deployed in the early 2000s for security screening use helium-3, but modern alternatives do not. Retiring and replacing these legacy systems would free substantial recoverable quantities. The authors estimate that recycling helium-3 from decommissioned detectors could meet projected U.S. quantum demand for close to a decade.

- **Establish a dedicated helium-3 reserve for quantum applications within the Department of Energy (DOE) Isotope Program.** Today, the quantum ecosystem competes for helium-3 with federal and other commercial users. Creating a predictable allocation window or strategic reserve for quantum applications—while preserving national security prioritization—would reduce procurement uncertainty and support industrial planning. Expanding domestic recovery, purification, storage, and distribution capacity would further strengthen resilience.

- **Pursue diversified future supply pathways.** The DOE should continue expanding terrestrial recovery pathways, including enhanced tritium-derived recovery and evaluation of helium-3 extraction from natural gas–associated helium streams. At the same time, longer-term and higher-risk options—such as breeder reactors, advanced production methods, or lunar helium-3 extraction—may warrant exploratory research, though their economic and technical feasibility remains uncertain. A diversified approach would reduce long-term strategic exposure and improve surge capacity.

Next-Generation Cryogenics for Scalable Quantum Systems

Even if helium-3 supply stabilizes, today's cryogenic systems have limited availability and are not optimized for the performance and scale envisioned for fault-tolerant quantum computers with millions of qubits. For dilution refrigerators in particular, the United States has growing domestic suppliers such as Maybell Quantum, but the global market remains dominated by European firms.[84] Several Chinese suppliers have also emerged in recent years, reflecting substantial investment even if their reach remains limited for now.[85] Even among leading dilution refrigerator suppliers, average lead times of six to nine months suggest that a surge in demand could create significant scaling delays.[86]

Moreover, current dilution refrigerators were originally developed for physics laboratories rather than industrial computing environments. They provide limited cooling power at millikelvin stages relative to the growing heat loads introduced by dense wiring and control infrastructure and introduce mechanical vibration and acoustic noise that must be carefully mitigated to preserve qubit fidelity. These limitations may be manageable for small- to medium-scale processors, but they become severe bottlenecks for scaling quantum computing to large-scale, industrially useful computers.

A central challenge for dilution refrigeration is that cooling becomes prohibitively expensive, power intensive, and operationally complex as systems grow.[87] The efficiency of heat removal declines sharply as temperatures decrease, causing energy demand, helium-3 usage, system size, and maintenance burdens to grow at a faster rate than the quantum hardware they support. This dynamic suggests that scaling cryogenics will require rethinking system architecture and integration rather than simply enlarging existing cryogenic designs.[88]

Emerging approaches include more modular cryogenic designs that decouple dilution refrigerators' different temperature stages, as well as new ways of distributing cooling capacity across multiple interconnected units.[89] These approaches aim to improve reliability, reduce downtime, and make cryogenic infrastructure more compatible with data center–like deployment models.

While improved cryogenic architectures can enhance cooling efficiency, they cannot eliminate the fundamental constraints imposed by thermal transport and wiring as systems grow. As cryogenic installations expand, managing heat leaks and signal routing across larger and more complex cold environments becomes increasingly difficult, and growing wiring densities introduce additional heat loads that directly compete with limited cooling power. These effects can compound even in well-designed systems, making thermal management and interconnect design central determinants of performance, reliability, and achievable system scale.

At higher cryogenic temperatures, where cooling technologies are more mature, the challenge is less about basic feasibility and more about adaptation. Large-scale cryogenic plants have long existed for other industrial and scientific uses, but they were not designed to support dense arrays of quantum hardware, stringent vibration constraints, or the maintenance and uptime expectations of commercial computing systems. Adapting these platforms to quantum use cases will require continued advances in system integration and thermal management.

Without sustained progress in cooling efficiency and system architecture, cryogenics will remain a significant bottleneck to scaling quantum computers.

Takeaways and Recommendations

Existing cryogenic systems were not designed for dense, energy-efficient, industrial-scale quantum computing deployment and will require substantial innovation to support fault-tolerant systems.

- **Invest in next-generation cryogenic architectures that scale cooling capacity and throughput.** Federal R&D agencies—e.g., the Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), national laboratories, and the National Science Foundation—can sponsor advanced R&D programs on new cryogenic designs that break current scaling constraints, including modular and distributed dilution systems, alternative, and hybrid cooling cycles, and designs that deliver higher effective cooling power without proportional increases in helium-3 inventory requirements. The Department of Energy (DOE) could support the maturation and validation of promising approaches through sustained R&D and integration with national laboratory facilities, with a focus on reducing energy consumption and footprint.

- **Accelerate R&D on cryogenic interconnects, wiring, and thermal management for large-scale quantum systems.** Scaling quantum computers will require rethinking how control electronics, wiring, and thermal isolation are integrated with cryogenic environments, not simply improving refrigerators. DARPA and DOE efforts could advance high-density, low-thermal-conductance interconnects, cryogenic-compatible signal routing and multiplexing, and more efficient thermal management techniques.

- **Advance higher-temperature cryogenic platforms optimized for quantum hardware.** Efforts should prioritize improving vibration isolation, modularity, maintainability, and energy efficiency of cryogenic platforms above 1 kelvin. These advances are important for certain quantum computing modalities, hybrid architectures, and distributed quantum systems, where aggregate cooling demand and operational reliability drive scalability. NIST could support these efforts by developing benchmarks and qualification metrics for quantum-ready cryogenic performance.

Vulnerabilities in Specialized Materials and Microfabrication

Quantum hardware platforms require specialized materials and microfabrication processes with extreme purity and process control. Although the United States has a strong materials research base at universities and national labs, many critical advances depend on industrial optimization of materials and processes that cannot be achieved in laboratory settings. In the United States, these capabilities are concentrated in a small set of specialized equipment and materials process technology firms—such as Applied Materials, Lam Research, and KLA—with world-leading platforms for conventional semiconductor manufacturing, but only incipient efforts in quantum-ready production.[90] Semiconductor manufacturing foundries are also similarly only starting to pilot quantum lines.[91]

As a result, the United States lacks broadly accessible commercial capacity to reproducibly manufacture quantum-grade wafers at scale and the foundry capacity to process those wafers into devices across multiple quantum modalities.[92] Importantly, these gaps are not uniform: Different quantum platforms place distinct demands on materials, fabrication processes, and wafer sizes. Absent targeted action to anchor quantum manufacturing lines within established commercial foundries—rather than in standalone, quantum-only facilities—U.S. dependence on foreign suppliers and foundries is likely to deepen as processes mature and scale learning accumulates abroad.

These manufacturing challenges affect all quantum modalities, albeit in different ways. Below we highlight two pressing gaps: thin-film lithium niobate and other PIC materials used across several quantum hardware modalities and technologies and high-purity wafers and fabrication processes for superconducting and semiconducting-spin qubit chips.

Across these domains, targeted public investments can pull in private capital from the quantum community and well-established silicon and silicon photonics foundries—rather than costly and lengthy greenfield efforts—to develop cutting-edge quantum manufacturing lines in the United States. Allowing participation from trusted allies could help achieve the scale and throughput necessary for economically viable quantum-grade fabs and anchor the United States as a central hub in the global quantum manufacturing ecosystem.

CHIPS Act Funding Can Directly Support Domestic Quantum Manufacturing Efforts

The Microelectronics Commons program run by the Department of Defense—funded at $2 billion over five years under the CHIPS and Science Act—aims to accelerate on-shore prototyping and lab-to-fab transition for emerging microelectronics, including roughly $50 million annually for quantum-focused projects.[93] The program has funded if multiple regional hubs with $5–8 million project awards. These funding levels may be suitable for early-stage innovation but are insufficient to build industrial-scale quantum manufacturing capacity, including the transition of novel processes from universities and national labs into commercial foundries capable of sustaining scale-up.

The Department of Commerce's CHIPS R&D Office Broad Agency Announcement (BAA), released in September 2025 in effort to repurpose up to $7.4 billion in CHIPS Act funds, is seeking proposals that similarly strengthen U.S. manufacturing in quantum and other critical technologies.[94] The BAA explicitly calls for projects that expand domestic manufacturing fab capabilities for quantum hardware and optical lines.[95]

Applied strategically, these substantive CHIPS Act programs could support U.S. production of specialized photonic wafers, seed quantum-dedicated lines at commercial foundries, as well as expand R&D foundries at universities and AIM Photonics, to provide shared manufacturing capacity for the U.S. quantum ecosystem.

Designing Return-on-Investment Mechanisms Carefully

As the administration explores equity stakes, warrant structures, or other return-on-investment mechanisms for future federal awards, program design will matter greatly for quantum and photonics manufacturing. Leading commercial foundries and well-capitalized quantum firms already have alternative sources of private and, in some cases, foreign public capital and they may opt out of U.S. programs in favor of jurisdictions that offer comparable support with fewer conditions. This risks adverse selection, where federal funds flow primarily to the most capital-constrained firms, which may be least able to deliver strategically significant manufacturing capacity quickly.

A balanced approach—using equity or upside-sharing selectively and alongside nonequity tools such as loans, guarantees, or production incentives—might best align taxpayer returns with the core objective of these programs: attracting top-tier fabs and quantum hardware developers to build their most advanced capacity in the United States.

Thin-Film Lithium Niobate and Other Emerging Materials for Integrated Photonics

To improve performance, stability, and scalability, quantum hardware platforms that rely on laser systems are increasingly adopting PICs that consolidate multiple optical functions on chip by leveraging a variety of high-purity materials. This section focuses on thin-film lithium niobate because it is the most mature and widely adopted of the new electro-optic photonic platforms, but similar dynamics apply to emerging materials such as barium titanate, aluminum nitride, and tantalum pentoxide, which might enable more optimal transformation of light, higher speed, and reduced loss. Importantly, these same materials and photonic integration capabilities support large commercial and defense-relevant markets—including telecommunications, data centers, precision sensing, and directed energy—linking quantum photonics to broader photonics manufacturing and supply chain ecosystems.

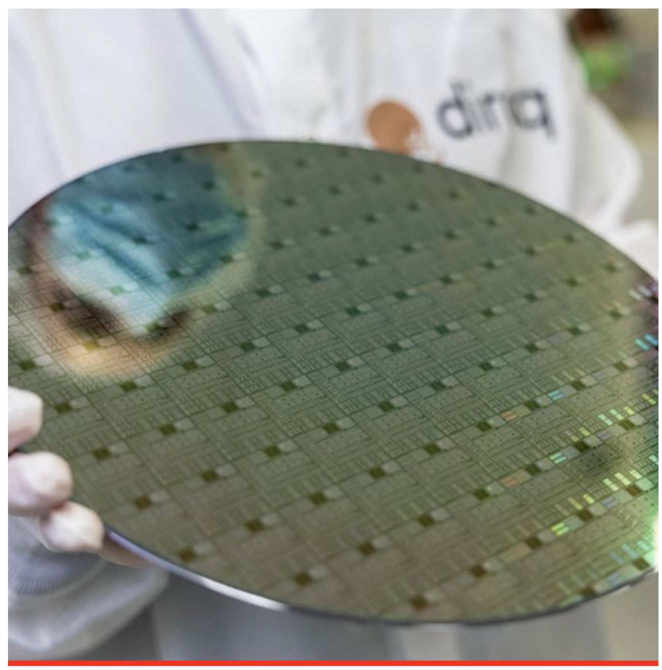
Three interrelated vulnerabilities now shape U.S. capabilities in these platforms: dependence on foreign suppliers for high-quality, thin-film photonic wafers suitable for device fabrication; limited domestic foundry capacity to process those wafers into devices at scale; and nascent know-how and infrastructure for heterogeneous integration of multiple photonic materials on a single chip or package.

In terms of material production, U.S.-based vendors (like Gootch & Housego in Ohio) produce bulk lithium niobate boules, but the United States does not have established commercial-scale production of the ultraflat, thin-film wafers required for advanced PICs. That market is dominated by China's CASTECH and NanoLN, as well as Japan's Sumitomo Metal Mining and NTT.[96] Recent restrictions on U.S. customers illustrate the risks of relying on Chinese suppliers.[97]

Even once wafers are procured, U.S. foundry capability to turn those wafers into devices remains limited. U.S. firms such as HyperLight (Massachusetts) and LightSynq (Massachusetts; recently acquired by IonQ) have pioneered the design of key etching and bonding processes for lithium niobate wafers, but rely on imported wafers and do not operate fabrication lines themselves.[98] Device manufacturing remains fragmented across university cleanrooms and federally funded facilities such as AIM Photonics (a Manufacturing USA Institute in New York) and Sandia National Laboratories (New Mexico).[99] These sites support early R&D and low-volume access but lack the throughput, tool diversity, and process standardization needed for commercial-scale production. Start-ups face wait times of several weeks or months and are deprioritized in favor of larger customers, slowing iteration and raising costs. In 2025, a new commercial foundry in Arizona began offering thin-film lithium niobate fabrication on 150 mm wafers, announcing a handful of research, commercial, and government customer orders.[100] While this represents an important step toward domestic capability, the facility remains early stage and low-volume, though it could gradually expand capacity and extend U.S. capabilities if demand grows.

Similar constraints apply to other emerging photonic materials. For example, barium titanate, despite its ultrafast light modulation properties, remains a niche platform supported by only a few emerging commercial actors and in-house programs.[101] Like lithium niobate, it illustrates how specialized wafer manufacturing and processing infrastructure often limits the deployment of advanced photonic materials.

These constraints interact with a broader systems challenge: Beyond the procurement of high-quality wafers and the processing of individual materials, advanced photonic systems increasingly require heterogeneous integration—the combination of multiple materials within a single chip or package. This approach allows different materials to



Quantum-grade materials and wafer-scale fabrication are emerging as bottlenecks for U.S. quantum scale-up. A silicon spin-qubit wafer fabricated on 300 mm tools at imec in Belgium illustrates the level of materials purity, process control, and foundry integration required to manufacture advanced quantum devices at scale. While such industrial capabilities are beginning to emerge in Europe, the United States lacks comparable capacity to produce quantum-grade wafers and to process them into devices at commercial scale. Similar gaps affect photonic wafers and heterogeneous integration for optical systems, underscoring how dependence on foreign materials suppliers and foundries risks becoming entrenched as quantum manufacturing capacity and process learning accumulate abroad. (imec) perform specialized optical functions on the same platform, but it also introduces substantial manufacturing complexity. A growing number of photonics start-ups are developing heterogeneous integration architectures for quantum technologies and other photonics-intensive applications, but most focus on design and depend on a limited set of external foundries, national laboratories, or research facilities to conduct the highly specialized microfabrication, bonding, and packaging steps.[102]

The manufacturing constraints of integrated photonics are compounded by the fact that multiple competing integration strategies remain under active development, and the field has yet to converge on standardized manufacturing pathways. A central challenge is identifying a minimally complex and cost-effective combination of materials and fabrication techniques that can deliver the greatest functional value across emerging applications, including quantum computing and artificial intelligence–focused data centers. Heterogeneous photonic integration therefore remains an immature but strategically important domain, requiring significant additional research, process refinement, and industrialization before it can reliably support large-scale, economically viable deployment.

A notable U.S. example of quantum photonic manufacturing is the collaboration between PsiQuantum and GlobalFoundries in New York. PsiQuantum has piloted its "Omega" quantum photonic chipset on 300 mm silicon photonics wafers at GlobalFoundries, integrating silicon-based photonic circuits with silicon nitride waveguides, barium titanate electro-optic switches, and superconducting single-photon detectors.[103]

This demonstrates that U.S.-based CMOS fabs can host quantum-grade photonic processes, but the line is effectively bespoke to the stringent performance requirements of a single firm—enabled by a substantial investment, likely in the tens of millions of dollars—rather than serving as a broadly accessible commercial platform for the wider quantum ecosystem. Similar concerns apply to IonQ's recent acquisition of the SkyWater semiconductor foundry for $1.8 billion.[104]

Absent additional commercial foundry capacity for the processing of high-quality photonic wafers and advances in heterogeneous integration R&D, U.S. production of quantum and enabling photonic technologies is likely to remain constrained and increasingly dependent on foreign suppliers. Competitors in China and Europe already offer more mature material platforms, and as they move to industrialize heterogeneous integrated photonics, the United States stands to fall behind on manufacturability, yield learning, and supply chain depth for quantum-relevant and commercial photonic subsystems.[105]

Takeaways and Recommendations

U.S. supply chains for advanced photonic materials and integrated photonics remain constrained by foreign dependence for high-quality wafers, limited domestic foundry capacity, and immature heterogeneous integration pathways.

- **Support domestic production of thin-film wafer materials.** Accelerating U.S. production of thin-film lithium niobate and other emerging photonic materials would reduce reliance on Chinese suppliers. This effort could leverage Defense Production Act authorities to address supply chain vulnerabilities in materials with clear national security relevance, while CHIPS Act funding can help derisk pilot-scale and early commercial production (see "CHIPS Act Funding Can Directly Support Domestic Quantum Manufacturing Efforts" text box). Parallel investments in materials such as barium titanate and tantalum pentoxide would position the United States to lead next-generation photonic platforms. Establishing crystal-growth and thin-film processing capacity—on the order of $100-300 million—could catalyze durable domestic supply.[106]

- **Establish a commercial-grade R&D PIC line.** The Department of Commerce could work with established silicon photonics foundries—such as GlobalFoundries, Tower Semiconductor, Honeywell, or others—to anchor commercial PIC manufacturing lines in the United States, leveraging CHIPS Act funding to attract private capital. The Defense Advanced Research Projects Agency's new Next-Generation Microelectronics Manufacturing center in Texas could also play a role in advancing heterogeneous photonic integration for a broad range of quantum and nonquantum developers.[107]

- **Expand and modernize research-grade photonics fabrication infrastructure.** The Departments of Defense and Energy and the National Science Foundation should strengthen fabrication lines at AIM Photonics, national labs, and universities to support early-stage R&D and workforce development. Targeted investments to upgrade tools, expand materials platforms, increase throughput, and shorten turnaround times—paired with clearer pathways for proprietary work and technology transfer—would reinforce the design-to-manufacturing pipeline for academic researchers and early-stage start-ups.

Superconducting and Semiconducting Quantum Manufacturing

Superconducting and semiconducting-spin qubit platforms depend on wafer-scale materials and fabrication processes that demand extreme purity and tight process control. In superconducting systems, qubit performance hinges on thin-film superconductors—primarily niobium, aluminum, and tantalum—deposited on high-purity silicon or sapphire substrates, where even small numbers of unintended atoms or microscopic defects at interfaces can interact with qubit electric fields and shorten coherence times.

Spin-qubit platforms face parallel requirements. Because quantum information is encoded in the spin of individual electrons or holes, device performance is highly sensitive to disturbances from nearby atoms in the host material. Fabrication therefore relies on isotopically enriched silicon-28 or germanium-70 to suppress nuclear-spin noise, yet industrial enrichment of these isotopes is limited to a small number of facilities globally—including in Russia and South Africa—creating cost and geopolitical vulnerabilities.[108] Achieving reproducible spin-qubit devices at scale requires not only isotopically enriched substrates, but also fabrication processes that produce defect-free crystal interfaces and electrically quiet insulating layers for nanometer-scale control gates.

Today, only a handful of foundries worldwide can meet these requirements. Europe is pulling ahead: In 2025, imec demonstrated 300 mm wafer-scale fabrication of both superconducting and spin qubits, showing that industrial complementary metal-oxide-semiconductor tools—operated within narrow thermal and contamination constraints—can produce high-coherence quantum devices.[109] Spin-qubit companies already partnered with imec and other European facilities for test fabrication at this level of sophistication.[110]

The United States still lacks an open commercial foundry that offers quantum-grade superconducting or spin-qubit processes at industrial scale. The Massachusetts Institute of Technology Lincoln Laboratory operates a 200 mm superconducting-qubit foundry for U.S. government–funded research organizations rather than as an open commercial service. NY CREATES' Albany NanoTech Complex—a publicly owned, R&D-focused 300 mm semiconductor facility—is fabricating superconducting processors for IBM's upcoming quantum computers, but the specific materials are unknown and the line is dedicated to IBM rather than open to other companies.[111] Other commercial foundries have demonstrated key building blocks: Intel has fabricated silicon spin-qubit devices for research programs and Applied Materials has relevant tooling and is exploring quantum processes.[112] However, establishing a dedicated commercial quantum line would require several hundred million dollars or more in investment, a sum that is difficult for any single firm to justify given the still-limited quantum market.

Takeaways and Recommendations

Superconducting and semiconducting-spin qubit platforms rely on quantum-grade wafers and fabrication processes with tight control over material defects, yet U.S. access to such materials and foundries remains limited.

- **Establish commercial R&D quantum process modules within existing U.S. semiconductor fabrication and advanced process development facilities.** With leadership from the CHIPS R&D Office, the United States should coinvest with established semiconductor manufacturers and foundries—such as GlobalFoundries, Intel, or others—alongside leading equipment providers like Applied Materials to stand up dedicated superconducting and semiconducting-spin manufacturing capabilities in 300 mm environments. Leveraging existing infrastructure and talent is far more efficient than building greenfield facilities, which would take years and require rare expertise. Public coinvestment on the order of a few hundred million dollars could help derisk early adoption and make these lines commercially viable.

- **Maintain mutual access to trusted allied fabrication capacity during domestic ramp-up.** Continued access to imec and other allied foundries would help sustain innovation as U.S. quantum lines scale, while reciprocal access for trusted international partners would expand the customer base for U.S. facilities and support financial viability.

- **Develop secure supplies of isotopically enriched materials.** Spin-qubit platforms rely on isotopically enriched silicon-28, which is produced at only a few facilities worldwide. Current U.S. research and early manufacturing demand likely falls in the kilogram-scale range annually (on the order of ~10 kg), though future industrial deployment could increase requirements. While large commercial foundries could incorporate this material into specialized process flows, the Department of Energy Isotope Program is well positioned to stabilize access for research and early manufacturing.

Additional Vulnerabilities for Quantum (and Adjacent) Manufacturing

The advanced material and manufacturing issues highlighted above regarding integrated photonics and superconducting and semiconducting qubits are major challenges for quantum hardware, but they are far from exhaustive.

An additional vulnerability for quantum and adjacent photonic technologies is limited U.S. access to high-quality, commercial-scale III–V epitaxial growth. This process enables the precise stacking of ultrathin compound semiconductor layers and underpins modern chip-scale laser and photonic devices. Global leadership in III–V epitaxy is concentrated in Taiwan, Japan, South Korea, and, increasingly China.[113] U.S. capacity is largely confined to internal lines at large firms—not readily accessible to start-ups nor necessarily tailored to quantum-grade requirements—and at national labs and universities, where long lead times and restrictions on proprietary work hinder rapid commercial iteration.[114] The access gap is acute for epitaxy-dependent chip-scale lasers such as vertical-cavity surface-emitting lasers (VCSELs), which are critical for quantum sensors and under exploration for quantum computing, as well as next-generation photonic-crystal surface-emitting lasers (PCSELs), which offer higher power and performance and where Japan holds early leadership.[115] U.S. tariffs have further increased costs and lead times from allied suppliers, and absent commercial access to advanced epitaxial growth, U.S. start-ups are constrained in developing advanced photonic components domestically.

Another vulnerability concerns the microfabrication of ion traps using semiconductor-style processes. Fabrication expertise is concentrated at a small set of organizations, including Oxford Ionics in the United Kingdom (UK)—recently acquired by American company IonQ—Alpine Quantum Technologies (AQT) in Austria, and Quantinuum, whose ion-trap chips are manufactured by Honeywell in the United States.[116] Sandia National Laboratories' Quantum Foundry Facility produces customized research-grade ion-trap chips, but U.S. commercial capacity remains limited.[117] Meanwhile, Europe is moving to industrialize ion-trap manufacturing via initiatives such as the CHAMP-ION project, funded by the Chips Joint Undertaking and coordinated by Silicon Austria Labs to establish a scalable pilot-line network for ion-trap chips across the European Union, underscoring growing international competition.[118]

Diamond color-center systems also face important bottlenecks. They require ultrapure, isotopically engineered chemical-vapor-deposited (CVD) diamond as a starting material for NV or SiV-based devices. Element Six (UK, owned by De Beers) is widely recognized as the leading supplier of quantum-grade CVD diamond for NV-based applications, marketing dedicated product lines for quantum networks and sensing.[119] In parallel, several Chinese firms now produce high-quality CVD diamond and explicitly advertise NV-center and quantum-research-grade substrates, indicating growing capacity outside traditional Western suppliers.[120] These firms have actively targeted customers in the United States and Europe, including academic laboratories, likely capturing demand not met by Element Six.[121] U.S. research laboratories can grow small-area CVD diamond suitable for experiments, and a small set of domestic firms (e.g., Great Lakes Crystal Technologies, WD Advanced Materials, and Coherent Inc.) markets quantum-relevant single-crystal diamond, including NV-engineered material.[122] However, there is little evidence of domestic wafer-scale commercial production comparable to leading foreign vendors.

These additional examples illustrate the wide range of highly specialized manufacturing challenges facing different quantum modalities. Strengthening U.S. quantum manufacturing will require a clear understanding of this diversity and a set of tailored policy actions calibrated to the needs of each quantum modality.

Conclusion

Quantum technologies are approaching a pivotal transition over the next three to five years: from laboratory breakthroughs to deployed systems with growing economic and national security impact. Whether the United States captures these benefits will depend not only on continued scientific leadership, but on its ability to develop, manufacture, and supply quantum systems reliably and at scale. Today, persistent gaps in domestic capacity and continued reliance on foreign suppliers, including from China and Russia, threaten to constrain deployment and shift value abroad.

This report clarifies what strengthening U.S. quantum supply chains entails by mapping their structure and vulnerabilities and outlining targeted steps to advance domestic capacity. The analysis shows that quantum supply chains are neither singular nor static but a set of partially overlapping and evolving networks. Key enabling technologies—such as photonics, cryogenics, and quantum-grade microfabrication—may be core to operating and scaling one hardware modality, supporting for another, and irrelevant for a third. Vulnerabilities also differ in kind: Some inputs are primarily sourced from foreign suppliers, creating geopolitical exposure, while others depend on fragile domestic capacity or immature technologies that cannot yet support utility scale. This heterogeneity underscores that no single policy lever can address all supply chain gaps.

Building on this diagnosis, the report presents tailored recommendations to address ecosystem-level challenges and input-level vulnerabilities, spanning both cross-cutting and modality-specific gaps and targeting near-term constraints as well as future scale-up barriers. The main text highlights the most consequential priorities, with a broader set of vulnerabilities and responses detailed in the appendix. Together, these actions constitute a portfolio approach—summarized in Table 5—aligned with the diversity and complexity of the challenge.

A central conclusion of this analysis is that markets alone cannot yet support the industrial-scale supply chains required to sustain U.S. quantum leadership. Quantum markets remain thin and fragmented, and early demand is insufficient to justify long-term manufacturing investment. Strategic government action can attract private capital and accelerate the development of a robust domestic supplier base. Domestically, this means supporting enabling-technology suppliers via sustained R&D programs and incentives, investing in shared testing and manufacturing infrastructure, and using federal procurement to create early demand for applications with high return on investment. Internationally, it requires countering anticompetitive practices, expanding market access for U.S. firms, and working with trusted partners to build secure and resilient supply chains.

This report does not attempt to cover every dimension of quantum supply chain vulnerability. It focused on hardware and input-level supply chains and highlighted some of the most consequential constraints affecting scale and resilience. These findings are therefore not comprehensive and will require ongoing monitoring as quantum technologies evolve. For example, the report did not provide in-depth analysis of gaps in control electronics, software layers, and networking components, and it did not examine the workforce and technical expertise required to develop a domestic supplier base, which warrant parallel policy attention.

As quantum technologies approach broader deployment and global competition intensifies, the United States has a narrow but meaningful window to convert its scientific lead into durable industrial advantage. Seizing it will require aligning innovation policy with industrial strategy and treating supply chains as a core pillar of the national quantum strategy. With deliberate action, the United States can ensure that its world-class quantum innovation ecosystem translates into enduring economic and security gains.

Table 5. A Portfolio Approach to Strengthening U.S. Quantum Supply Chains

The table gathers complementary domestic and international actions recommended throughout this report—spanning R&D investment, procurement, trade, and allied coordination—to address the diverse set of U.S. quantum supply chain vulnerabilities.

Domestic	
Accelerate domestic enabling-technology supply chains through R&D and strategic financing.	Targeted efforts can accelerate innovation and competitiveness of domestic suppliers of precision laser and optical systems, integrated photonics, cryogenics, and quantum-grade materials and microfabrication. Multiyear R&D programs—led by agencies such as the Defense Advanced Research Projects Agency, the National Institute of Standards and Technology (NIST), and the national labs—could pool requirements across quantum, defense, and other applications to create larger, more predictable markets. Complementary tools—including low-rate initial production commitments, targeted tax incentives, loans and loan guarantees, and export financing through agencies such as the Export–Import Bank, Small Business Administration, and International Trade Administration—can help firms scale production and compete internationally. Embedding close partnerships between enabling-technology suppliers and system integrators will be essential to support efficient codesign and deployable system performance.
Boost demand signals through high-ROI procurement.	Early government procurement and pilot programs can derisk private investment while markets remain small. By deploying quantum systems and enabling technologies in real agency use cases—such as quantum computing for scientific research and quantum sensing for positioning, navigation, and timing in GPS-denied environments—federal agencies can generate genuine near-term value, build hands-on technical expertise, and accelerate learning curves for suppliers in areas such as lasers, cryogenics, and photonic components.
Scale commercial-grade manufacturing for quantum-enabling technologies.	Research-scale fabrication alone cannot support reliable deployment or scale. Federal policy can use targeted tax credits, low-interest loans, and CHIPS-style incentives to catalyze commercial-grade manufacturing capacity for quantum-relevant materials, devices, and subsystems—including PICs, cryogenic components, and superconducting or semiconducting wafers. Public support should be structured to attract private capital and sustain production over time, reducing reliance on foreign suppliers as quantum markets mature.
Build shared test, qualification, and validation infrastructure.	Shared test beds hosted at NIST and the Department of Energy (DOE) national laboratories can lower entry barriers for emerging suppliers, standardize performance benchmarks, and accelerate system integration. Facilities for testing laser stability and reliability, cryogenic performance, and photonic or electronic component qualification can reduce the need for costly in-house testing while providing trusted third-party validation and supporting prestandardization efforts essential for scale.
Secure and steward critical isotopes and isotopically enriched materials.	The federal government can play a direct role in stabilizing supply quantum inputs that are low-volume, highly regulated, sourced from adversarial countries, or otherwise poorly served by commercial markets—such as helium-3, isotopically enriched silicon-28, rubidium-87, cesium-133, and various alkaline-earth metals. The DOE Isotope Program or similar entities can manage strategic recovery and recycling; specialized refining, purification, and enrichment; and dedicated reserves to cushion market disruptions and manage allocation across competing national priorities, especially as quantum demand grows.
Monitor quantum supply chain conditions.	To maintain situational awareness as technologies and markets evolve, an interagency process should monitor quantum supply chain vulnerabilities across hardware modalities and enabling technologies. Led by the International Trade Administration's Supply Chain Center in coordination with the Departments of Defense, State, and Energy, this effort could track emerging vulnerabilities in areas such as laser and optical systems, cryogenics, and materials, informing timely adjustments to R&D, procurement, manufacturing, and trade policies.
International	
Secure trusted allied access during domestic scale-up.	The United States can deepen bilateral and multilateral cooperation with trusted allies to ensure access to key supply chain inputs while developing domestic capacity. Targeted joint R&D programs could also pursue cutting-edge research in areas of allied strength such as cryogenics (e.g., Finland), photonics (e.g., Japan, Denmark), and quantum-grade materials and microfabrication (e.g., the Netherlands, Belgium, Japan, South Korea).
Expand trusted international demand for U.S. quantum technologies.	Scaling U.S. suppliers will require access to international markets while domestic demand remains limited. The U.S. Commercial Service, in coordination with the Quantum Economic Development Consortium and relevant agencies, can support partnerships and exports of U.S. quantum and enabling technologies to trusted allies and partners, reinforcing scale, learning, and supply chain depth.
Curb unfair trade practices and rightsize trade policies.	People's Republic of China–subsidized suppliers risk undercutting domestic and allied vendors in critical enabling technologies, while Europe's push for technological sovereignty is limiting U.S. access to quantum programs. The United States should strengthen enforcement against market-distorting practices, reassess R&D tariff exemptions that entrench reliance on suppliers from countries of concern, and press for greater reciprocity from European partners. At the same time, U.S. trade measures should be carefully calibrated: Targeted tariff exemptions among trusted allies can preserve access to essential components and markets while supporting domestic scale-up.
Protect innovation while enabling collaboration.	Safeguarding U.S. quantum leadership requires balancing research security with continued collaboration among trusted partners. The United States should strengthen intellectual property protection and data security practices while focusing controls on high-risk vectors and align these measures with like-minded countries to support trusted collaboration without enabling technology leakage.

Appendix

Methodology

Research for this report was conducted in 2025 and into February 2026. The methodology combined primary and secondary research approaches, including a private roundtable hosted at the Center for a New American Security in July 2025 with subject matter experts and relevant stakeholders in quantum and quantum-enabling technology and policy; over 30 semistructured interviews with experts from federal and state government, industry, and academia; and review of existing literature, government documents, and publicly available information of quantum and enabling-technology companies. Three subject matter experts reviewed a draft of the report and provided feedback.

Table A1. Key Vulnerabilities In Photonic And Optical Components And Related Recommendations

This table includes a nonexhaustive set of vulnerable inputs in the photonics and optics supply chains, with each entry indicating the affected quantum stack layer, hardware modality, and vulnerability category.

● Layer ● Modality ● Vulnerability Category	Vulnerable Input	Recommendations
● Control systems ● Atomic and photonic modalities ● Foreign dependence & performance and scalability gaps	**Precision Laser Systems with Scalable Power and Manufacturing** ▪ Ultrastable lasers are essential for controlling, cooling, and measuring qubits; each is tuned to a specific atomic or optical transition and supported by a full chain of seed lasers, amplifiers, frequency doublers, modulators, and isolators.[123] ▪ Key suppliers are headquartered in China (e.g., PreciLasers), Germany (e.g., TOPTICA), and Japan (e.g., Hamamatsu). ▪ Current products are adequate for research but face gaps in reliability, manufacturability, and cost required for system-level commercial quantum computers and sensors.	▪ Launch dedicated advanced R&D programs—e.g., through the Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), or others—to advance high-power, narrow-linewidth laser programs and drive breakthroughs in coherent beam combining, low-noise amplifiers, and high-power frequency conversion to meet quantum, directed energy, and other programs' requirements.
● Control systems ● Atomic modalities ● Insufficient domestic capacity	**Quantum-Grade VCSELs** ▪ These chip-scale lasers are critical for chip-scale atomic clocks and certain compact sensors like magnetometers and are under exploration for some quantum computing platforms. ▪ The market for quantum-grade vertical-cavity surface-emitting lasers (VCSELs) is currently small (50,000 units per year, amounting to about 10 wafers), and U.S. production has repeatedly disappeared in favor of high-volume consumer applications like for smartphones' face detection.[124] ▪ Emerging: Photonic-crystal surface-emitting lasers (PCSELs) offer higher power, narrow linewidths, and superior beam quality in a chip-scale form factor.[125] Early leadership is concentrated in Japan; if matured, PCSELs could enable scalable atomic quantum systems and other precision optical applications.	▪ Support the early growth of domestic VCSEL (and PCSEL) suppliers via dedicated R&D programs through the Department of Defense (DoD), NIST, Department of Energy (DOE), or other agencies. ▪ Alternatively, establish a federally anchored quantum VCSEL line (e.g., at Sandia National Labs, which has driven pioneering VCSEL work for atomic sensors) to ensure stable supply for quantum-grade applications while the market remains low volume.[126]
● Materials ● Photonic, atomic, diamond modalities ● Foreign dependence	**Rare-Earth Gain Media and Dopants (Erbium, Ytterbium, Neodymium)** ▪ These elements enable laser amplification and wavelength control across quantum computing, sensing, and networking platforms. ▪ Refining is dominated by China.[127] Emerging U.S. capacity (e.g., MP Materials, expected online by 2027) excludes heavy rare-earth elements like Erbium and Ytterbium, and may not meet quantum-grade purity needs, or generally favor larger defense and industrial customers.[128]	▪ Use DOE and DoD programs and authorities to establish domestic rare-earth refining and recycling, with reserved allocations for quantum companies.
● Materials ● Atomic modalities ● Foreign dependence	**Alkali Metals and Alkaline-Earth Metals** ▪ Essential for many atomic quantum sensors and computers.[129] ▪ Rubidium (Rb): Russia is a primary source of refined Rb-87, a key isotope. U.S. demand is small (<1 kg/year), but prices are high, and there is no domestic enrichment capability.[130] ▪ Cesium (Cs): Cs-133, used in beam atomic clocks underpinning financial networks, telecommunications, data centers, and some GPS ground systems, is produced in small global volumes, with Russia and China as key suppliers.[131] The United States has no active domestic cesium mining and limited processing capacity, with demand ~10 kg/year (order of magnitude).[132] ▪ Alkaline-earth metals (strontium, barium, calcium): Demand volumes are small, but performance depends on high isotopic purity, with limited domestic enrichment and processing capacity.	▪ Sustain small-scale domestic alkali-metal and alkaline-earth metals refining, purification, and isotope enrichment programs at the DOE's Isotope Program or similar entities.[133] ▪ Develop national buffer stocks to secure supply for research and commercial adoption.
● Materials ● Atomic modalities ● Foreign dependence	**Optical Isolators and Magneto-Optic Crystals** ▪ High-power optical isolators for lasers (both for quantum and defense applications) rely on crystals—such as terbium gallium garnet (TGG) or terbium scandium aluminum garnet (TSAG)—grown with exceptional optical purity. Their upstream supply chains depend on rare-earth inputs—particularly terbium oxide—whose mining, separation, and refining are heavily concentrated in China. In 2025, China expanded export controls to include terbium, highlighting geopolitical exposure.[134] Finished magneto-optic crystal growth is done by few specialized manufacturers globally, including firms in China and Russia.[135] ▪ Limited U.S. production of these and related materials exists (e.g., some TGG by Teledyne FLIR in Bozeman, Montana, and bismuth-doped iron garnet and potassium terbium fluoride by Coherent Inc.) and could be expanded to grow additional crystals.[136]	▪ Establish domestic growth of TGG/TSAG-class crystals and coating lines for high-power isolators (estimated cost <$5 million), similar to recent investments in optical crystals.[137] ▪ Maintain a strategic stock for national labs that can be distributed to quantum companies as well as defense contractors.
● Tooling ● Atomic and photonic modalities ● Foreign dependence	**Optical Manufacturing Equipment** ▪ Precision lasers and photonic components—spanning crystal growth, thin-film deposition, photonic-integrated circuits packaging, and metrology—rely heavily on European toolmakers.[138] ▪ Tariffs and licensing delays add substantial cost (which can reach the hundreds of thousands of dollars) and slow domestic production.[139]	▪ Provide targeted tariff carveouts or expedited licenses for essential photonics manufacturing equipment and metrology tools to avoid penalties that stall domestic production. ▪ Identify potential domestic suppliers of this equipment and support their development through dedicated R&D programs, targeted loans, and/or tax incentives.
● Networks ● Superconducting, semiconducting-spin, and atomic modalities ● Performance and scalability gaps	**Transducers** ▪ Immature microwave-to-optical transducers limit the ability to network cryogenic processors and integrate heterogeneous quantum hardware architectures, creating wiring and input/output bottlenecks that impede modular quantum scaling.	▪ Expand dedicated R&D programs for quantum transducers—such as DARPA's Heterogeneous Architectures for Quantum (HARQ)—with funding levels commensurate with the technical challenge, well beyond the current ~$1 million per performer.[140]

Table A2. Key Vulnerabilities in Cryogenic Systems and Related Recommendations

This table includes a nonexhaustive set of vulnerable inputs in the cryogenics supply chains, with each entry indicating the affected quantum stack layer, hardware modality, and vulnerability category.

● **Layer** ● **Modality** ● **Vulnerability Category**	**Vulnerable Input**	**Recommendations**
● Environments ● Superconducting, semiconducting-spin, prospective topological modalities ● Insufficient domestic capacity	**Helium-3** ▪ Essential for millikelvin cooling in dilution refrigerators (10–100 L per unit) but chronically scarce, with prices of $2,500–3,000/L and long lead times.[141] ▪ Global supply limited to the United States, Canada, and Russia, with production derived primarily from tritium decay associated with nuclear programs and select reactor-based recovery pathways.[142] ▪ Quantum competes with national security, medical, and research uses, heightening pressure on a narrow and rigid supply base.	▪ Recycle helium-3 from legacy neutron detectors. The authors estimate that recovered volumes could meet U.S. quantum demand for a decade. ▪ Establish a dedicated helium-3 reserve for quantum applications within the Department of Energy (DOE) Isotope Program to ensure access.[143] ▪ Consider pursuing additional helium-3 supply pathways, including terrestrial recovery from natural-gas deposits and longer-term options such as aneutronic generation, breeder reactors, and lunar helium-3 extraction, to diversify sources and reduce strategic exposure.
● Environments ● Superconducting, semiconducting-spin, prospective topological modalities ● Foreign dependence, insufficient domestic capacity, and performance and scalability gaps	**Dilution Refrigerators** ▪ Few firms dominate the global market, with lead times averaging six to nine months.[144] Scaling to million-qubit systems would require dozens of units per site, stressing production and infrastructure. ▪ Bluefors (Finland, with some U.S. manufacturing in NY) dominates >65% market share, followed by Oxford Instruments (UK), Leiden Cryogenics (Netherlands), and ZeroPoint (Canada).[145] Several emerging Chinese providers, led by Origin Quantum and QuantumCTek, have limited international reach but reflect substantial Chinese investment.[146] ▪ U.S. firms include Maybell Quantum and FormFactor (via acquisition of JanisULT), both in Colorado. **Pulse-Tube Cryocoolers** ▪ Pulse tubes provide the 4 K base stage for dilution refrigerators and are also used in stand-alone systems. ▪ They also have few suppliers: Cryomech (U.S., owned by Finland's Bluefors) leads, followed by Sumitomo (Japan), TransMIT (Germany), and Lihan (China). **Cryogenic Scaling Bottlenecks** ▪ Today's dilution refrigerators scale inefficiently: As qubit counts rise, cooling power, wiring density, and vibration limits drive disproportionate increases in energy use, helium-3 requirements, and system complexity.[147] ▪ At data center scale, these dynamics become economically and operationally prohibitive, requiring rethinking of cryogenic system architectures.	▪ Prioritize U.S. suppliers for critical quantum infrastructure and work with trusted international partners to secure supply resilience. ▪ Expand U.S. cryogenic production capacity by supporting both domestic firms and international companies willing to invest in U.S.-based manufacturing and intellectual property development. ▪ Fund dedicated R&D programs at the Defense Advanced Research Projects Agency, the DOE, the National Institute of Standards and Technology (NIST), and the National Science Foundation to accelerate next-generation cryogenic architectures—including modular and distributed dilution systems and alternative cooling cycles—that deliver higher effective cooling power, lower vibration, improved energy efficiency, and scalable throughput without proportional increases in helium-3 inventory. ▪ In parallel, fund R&D on cryogenic interconnects, wiring, and thermal management to reduce heat load and enable high-density signal routing at scale.
● Materials and subcomponents ● Superconducting, semiconducting-spin, prospective topological, photonic, and color-center modalities ● Foreign dependence	**The materials and components below are used in dilution refrigerators as well as in higher-temperature cryocoolers.[148] Even when components are sourced from allied countries, upstream subcomponents are often sourced from China.** **Regenerator Materials** ▪ Holmium copper ($HoCu_2$), gadolinium oxysulfide (GOS), and gadolinium aluminum perovskite (GAP) store and transfer heat within cryocoolers, with no U.S. manufacturers. ▪ Holmium is mined primarily in China and Russia and processed into $HoCu_2$ almost entirely by Toshiba (Japan), while GOS and GAP are produced solely by Konoshima Chemical (Japan).[149] **Helium Compressors and Compressor Capsules** ▪ Critical for circulating helium in cryocoolers. ▪ Cryomech (U.S., owned by Bluefors) is the main supplier but relies on subcomponents from Johnson Controls Hitachi (Japan).[150] ▪ Copeland (U.S.) produces smaller units for conventional refrigeration but not for cryogenic systems. **Cryogenic Microwave and RF Components** ▪ Essential for signal control, routing, attenuation, and noise reduction at millikelvin temperatures. ▪ Suppliers include Hermerc (China) and XMA (U.S.). **Cryogenic Tubing and Connectors** ▪ Cryogenic systems rely on thin-walled, nonstandard stainless steel tubing, with significant reliance on foreign suppliers like Mitsumi (Japan).[151] ▪ Vacuum Coupling Radiation fittings, which provide leak-tight seals in cryogenic high-vacuum environments, are commonly sourced from Swagelok (U.S.), with limited reliable alternatives.[152]	▪ Fund pilot-scale U.S. production of $HoCu_2$, GOS, GAP, and high-purity copper. Prioritize partnerships with industry to qualify new regenerator materials and reduce dependence on foreign suppliers. ▪ Leverage tax breaks, grants, or low-rate initial production contracts to incentivize U.S. manufacturers of compressors, valves, tubing, etc., to adapt their products for cryogenic use to reduce lead time and dependence on foreign producers. ▪ Establish regional or national test beds through NIST and/or the national labs to provide access to cryogenic environments spanning millikelvin to few-kelvin temperatures to accelerate device qualification, shorten development cycles, and ultimately relieve pressure on limited commercial units.

1. While many mature technologies—such as lasers, transistors, and magnetic resonance imaging—rely on quantum mechanics, this report follows the U.S. National Quantum Initiative in using "quantum technologies" more narrowly. Here, the term refers to emerging systems that engineer and control quantum phenomena (e.g., superposition, entanglement, and interference) to enable performance advances in computing, sensing, and networking that surpass the best-known classical approaches.

2. *National Quantum Initiative Supplement to the President's FY 2025 Budget* (National Science and Technology Council, December 2024), 7–8, https://www.quantum.gov/wp-content/uploads/2024/12/NQI-Annual-Report-FY2025.pdf. The "quantum technology" category includes "work with end-users to deploy quantum technologies in the field and develop use cases; basic R&D on supporting technologies for quantum information science and technology engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography."

3. "What is APFIT," Under Secretary of War for Research and Engineering, accessed February 12, 2026, https://ac.cto.mil/apfit/.

4. *National Security Strategy of the United States of America* (The White House, November 2025), https://www.whitehouse.gov/wp-content/uploads/2025/12/2025-National-Security-Strategy.pdf.

5. Constanza M. Vidal Bustamante, *Atomic Advantage: Accelerating U.S. Quantum Sensing for Next-Generation Positioning, Navigation, and Timing* (Center for a New American Security [CNAS], May 2025), https://www.cnas.org/publications/reports/atomic-advantage.

6. Matt Swayne, "Quantum Computing Roadmaps: A Look at The Maps And Predictions of Major Players," The Quantum Insider, December 18, 2025, https://thequantuminsider.com/2025/05/16/quantum-computing-roadmaps-a-look-at-the-maps-and-predictions-of-major-quantum-players/; Laura Clinton et al., "Towards Near-Term Quantum Simulation of Materials," *Nature Communications* 15, no. 211 (2024), https://www.nature.com/articles/s41467-023-43479-6; Nick S. Blunt et al., "Perspective on the Current State-of-the-Art of Quantum Computing for Drug Discovery Applications," *Journal of Chemical Theory and Computation* 18, no. 12 (2022), https://pubs.acs.org/doi/10.1021/acs.jctc.2c00574; C. Zhang et al., "Quantum Computation of Molecular Geometry via Many-Body Nuclear Spin Echoes," arXiv, October 22, 2025, https://arxiv.org/abs/2510.19550.

7. "State of the Global Quantum Industry: Forecasts," Quantum Economic Development Consortium (QED-C), 2025, https://quantumconsortium.org/publication/2025-state-of-the-global-quantum-industry-report/#-forecasts; Henning Soller, "The Year of Quantum: From Concept to Reality in 2025," McKinsey & Company, June 23, 2025, https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025.

8. Lucien Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum* (SRI, October 2023), https://www.sri.com/wp-content/uploads/2023/11/QTMR-Final-Report-of-Needs-Capabilities-and-Gaps-v5.pdf.

9. *National Security Strategy of the United States of America*.

10. *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science* (National Quantum Initiative Advisory Committee, June 2023), https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf; *Toward a Resilient Quantum Computing Supply Chain* (QED-C, June 1, 2022), https://quantumconsortium.org/publication/toward-a-resilient-quantum-computing-supply-chain/; Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology* (RAND, February 2, 2022), https://www.rand.org/pubs/research_reports/RRA869-1.html.

11. The State Council of the People's Republic of China, "Key Recommendations Document Outlines Priorities in China's Next Five-year Blueprint," press release, October 25, 2025, https://english.www.gov.cn/news/202510/25/content_WS68fc10abc6d00ca5f9a0703e.html; Elias X. Huber, "How China Plans to Turn Quantum into a Future Industry," Substack, November 22, 2025, https://www.chinaquantum.info/p/how-china-plans-to-turn-quantum-into.

12. *EU Quantum Act* (European Commission, 2025), https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/15512-EU-Quantum-Act_en.

13. Michael Kratsios, "White House Science Advisor, OSTP Director Michael Kratsios Welcomes Attendees to Quantum World Congress," September 2025, 5 min., 15 sec., https://www.quantumworldcongress.com/news-and-updates/white-house-science-advisor-ostp-director-michael-kratsios-welcomes-attendees-to-qwc; Matt Swayne, *White House Places Quantum And AI at The Summit of R&D Priorities* (Quantum Insider, October 2, 2025), https://thequantuminsider.com/2025/09/27/white-house-place-quantum-and-ai-at-the-summit-of-rd-priorities/; Dario Gil, *Powering the Future of Quantum* (Department of Energy, November 13, 2025), https://www.energy.gov/science/articles/powering-future-quantum; Department of Energy, "Energy Department Announces $625 Million to Advance the Next Phase of National Quantum Information Science Research Centers," press release, November 4, 2025, https://www.energy.gov/articles/energy-department-announces-625-million-advance-next-phase-national-quantum-information; C. Todd Lopez, "War Department Narrows Technology Development Focus to Half Dozen Areas," U.S. Department of War, November 19,

2025, https://www.war.gov/News/News-Stories/Article/Article/4337926/war-department-narrows-technology-development-focus-to-half-dozen-areas/; National Institute of Standards and Technology, "NIST Issues Broad Agency Announcement for Proposals to Advance Microelectronics Technologies," press release, September 24, 2025, https://www.nist.gov/news-events/news/2025/09/nist-issues-broad-agency-announcement-proposals-advance-microelectronics.

14. U.S. Senate Committee on Commerce, Science, and Transportation, "Cantwell, Young, Colleagues Introduce Bipartisan National Quantum Initiative Reauthorization Act," press release, January 8, 2026, https://www.commerce.senate.gov/2026/1/cantwell-young-colleagues-introduce-bipartisan-national-quantum-initiative-reauthorization-act. Quantum technology efforts at the state level include the Commerce Department–designated Quantum Tech Hubs in the Colorado–New Mexico–Wyoming and Illinois-Wisconsin-Indiana regions, as well as growing quantum innovation clusters in California, Maryland, Massachusetts, Montana, New York, and Texas.

15. Lukas Kingma, Freeke Heijman, and Carl Williams, *Official Summary: Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance* (NATO Transatlantic Quantum Community, May 12, 2025), https://www.fheijman.nl/QSC_report.pdf; Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum; Tracking the Global Supply Chain: A Framework for the Quantum Industry* (QED-C, September 22, 2023), https://quantumconsortium.org/publication/supply chain-framework-report/; Min-Ha Lee, *A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain* (Stanford Geopolitics, Technology, and Governance Center for International Security and Cooperation, October 2023), https://fsi9-prod.s3.us-west-1.amazonaws.com/s3fs-public/2023-11/2023-10-27_-_minha_lee_-_quantum_computing_mapping_supply_chain_vulns_final.pdf; *Toward a Resilient Quantum Computing Supply Chain*; Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology* (RAND, February 2, 2022), https://www.rand.org/pubs/research_reports/RRA869-1.html.

16. *Toward a Resilient Quantum Computing Supply Chain* (QED-C), 28–29, https://quantumconsortium.org/publication/toward-a-resilient-quantum-computing-supply chain/.

17. Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*.

18. Interviews with executives from two quantum technology companies in April and July 2025.

19. Vidal Bustamante, *Atomic Advantage: Accelerating U.S. Quantum Sensing for Next-Generation Positioning, Navigation, and Timing*, 33–34.

20. New Mexico Economic Development Department, "New Mexico Launches $25M Quantum Venture Studio," press release, August 25, 2025, https://edd.newmexico.gov/pr/new-mexico-launches-25m-quantum-venture-studio/.

21. *National Quantum Initiative Supplement to the President's FY 2025 Budget*; Subcommittee on Quantum Information Science under the Committee on Science of the National Science & Technology Council, *National Strategic Overview for Quantum Information Science* (September 2018), 9, https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf.

22. *National Quantum Initiative Supplement to the President's FY 2025 Budget*, 7–8. The "quantum technology" category includes "work with end-users to deploy quantum technologies in the field and develop use cases; basic R&D on supporting technologies for QIST engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography." The share of federal funding that directly supports enabling technologies is therefore likely to be well below 12 percent; Constanza M. Vidal Bustamante, "Quantum Computing's Industrial Challenge," in "Key Trends that Will Shape Tech Policy in 2026," Just Security, January 15, 2026, https://www.justsecurity.org/128568/expert-roundup-emerging-tech-trends-2026/.

23. Source: "Figure 2.2," in *National Quantum Initiative Supplement to the President's FY 2025 Budget* (Subcommittee on QIS under the Committee on Science of the National Science & Technology Council, December 2024), 8, https://www.quantum.gov/wp-content/uploads/2024/12/NQI-Annual-Report-FY2025.pdf. See also: Vidal Bustamante, *Atomic Advantage: Accelerating U.S. Quantum Sensing for Next-Generation Positioning, Navigation, and Timing*.

24. *Defense Advanced Research Projects Agency Defense-Wide Justification Book Volume 1 of 5 Research, Development, Test & Evaluation, Defense-Wide* (Defense Advanced Research Projects Agency [DARPA], June 2025), 117, https://comptroller.war.gov/Portals/45/Documents/defbudget/FY2026/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2026.pdf; Senate Committee on Appropriations, Department of Defense Appropriations Bill, 2026, S. Rep. No. 119–52, 119th Cong. (2025), 196, https://www.congress.gov/committee-report/119th-congress/senate-report/52/1.

25. DARPA, "DARPA Eyes Companies Targeting Industrially Useful Quantum Computers," press release, April 3, 2025, https://www.darpa.mil/news/2025/companies-targeting-quantum-computers.

26. Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*.

27. Interviews with quantum and enabling-technology company executives in July 2025.

28. LIGENTEC, "LIGENTEC," accessed January 5, 2026, https://www.ligentec.com/?srsltid=AfmBOoq25nzX-0Ruu46-IoNyhrj7tMa2yD19r5f00hYh1O1acjM6s0aoZ; imec, *Taking a Quantum Leap from Lab to Fab*, accessed January 5, 2025, https://www.imec-int.com/en/articles/taking-quantum-leap-lab-fab; IonQ, "IonQ to Increase Performance and Scale of Quantum Computers with Photonic Integrated Circuits in collaboration with imec," press release, November 7, 2024, https://www.ionq.com/news/ionq-to-increase-performance-and-scale-of-quantum-computers-with-photonic.

29. Camille Boullenois, Agatha Kratz, and Daniel H. Rosen, *Far From Normal: An Augmented Assessment of China's State Support* (Rhodium Group, March 17, 2025), https://rhg.com/research/far-from-normal-an-augmented-assessment-of-chinas-state-support/; U.S. Department of Justice, "Chinese Company Sinovel Wind Group Convicted of Theft of Trade Secrets," press release, January 24, 2018, https://www.justice.gov/archives/opa/pr/chinese-company-sinovel-wind-group-convicted-theft-trade-secrets; Federal Bureau of Investigation, "Chinese Telecom Conglomerate Charged with Multiple Crimes," press release, January 28, 2019, www.fbi.gov/news/stories/chinese-telecom-firm-huawei-indicted-012819.

30. The State Council of the People's Republic of China, "Key Recommendations Document Outlines Priorities in China's Next Five-year Blueprint"; Huber, "How China Plans to Turn Quantum into a Future Industry."

31. Huber, "How China Plans to Turn Quantum into a Future Industry."

32. "工业和信息化部办公厅关于组织开展2025年未来产业创新任务揭榜挂帅工作的通知 [Notice of the General Office of the Ministry of Industry and Information Technology on Organizing the 2025 'Unveiling the List and Appointing the Leader' Innovation Tasks for Future Industries]," Ministry of Industry and Information Technology, 2025, https://jxj.beijing.gov.cn/zwgk/2024zcwj/202507/W020250729375524188675.pdf; "KIDE Cryogenic Platform," BLUEFORS, accessed January 5, 2026, https://bluefors.com/products/kide-cryogenic-platform/.

33. "Acquisition Completion of NKT Photonics. Accelerating Growth in the Semiconductor, Quantum, and Medical Fields through Laser Business Enhancement," Hamamatsu Photonics K.K., May 31, 2024, https://www.hamamatsu.com/us/en/news/featured-products_and_technologies/2024/20240531000000.html.

34. Interviews with executives of quantum technology and enabling technology companies, 2025.

35. "上海又一'小巨人'冲刺A股IPO！[Another Shanghai 'Little Giant' Sprints Toward an A-Share IPO!]" Zhang Tong News Agency, March 12, 2025, https://www.sohu.com/a/870046620_546816; "关于进一步支持专精特新中小企业高质量发展的通知 [Notice on Further Supporting the High-Quality Development of Specialized, Refined, Distinctive, and Innovative Small and Medium-Sized Enterprises]," Ministry of Finance and Ministry of Industry and Information Technology, June 14, 2024, https://www.gov.cn/zhengce/zhengceku/202406/content_6958188.htm.

36. Zhang Weilan and Chen Zishuai, "China Makes Breakthrough on Dilution Refrigerator for Quantum Computing Chips," Global Times, February 28, 2024, https://www.globaltimes.cn/page/202402/1307818.shtml; "ez-Q Fridge-Platform500," QuantumCTek, accessed February 11, 2026, https://www.quantum-info.com/English/product/Quantum Computer Products/{cmspath/2024/1211/865.html; Prabhat Ranjan Mishra, "China's Quantum Computing Dilution Fridge Boasts 1,000 Microwatts of Cooling," Interesting Engineering, June 13, 2024, https://interestingengineering.com/innovation/china-dilution-refrigerator-origin-sl1000; Peng Hua You Ce, "稀释制冷机：量子计算的低温基石与国产化突围 [Dilution Refrigeration Machine: The Low-Temperature Cornerstone of Quantum Computing and Breakthrough in Domestic Production]," Zhi Hu, October 25, 2025, https://zhuanlan.zhihu.com/p/1965735150047458695.

37. NEOCRYSTECH, "Single NV Diamond 111," accessed January 5, 2026, https://www.neocrystech.com/product/Single-NV-Diamond-111.html; "High Concentration Quantum-Grade Single Crystal Diamond" 6CCVD, accessed January 5, 2026, https://6ccvd.com/product/high-concentration-quantum-grade-single-crystal-diamond/.

38. Karen Freifeld, "Two Chinese Nationals in California Accused of Illegally Shipping Nvidia AI Chips to China," Reuters, August 5, 2025, https://www.reuters.com/business/autos-transportation/two-chinese-nationals-california-accused-illegally-shipping-nvidia-ai-chips-2025-08-05/; U.S. Department of Justice, "Two Chinese Nationals Arrested on Complaint Alleging They Illegally Shipped to China Sensitive Microchips Used in AI Applications," press release, August 5, 2025, https://www.justice.gov/opa/pr/two-chinese-nationals-arrested-complaint-alleging-they-illegally-shipped-china-sensitive.

39. "What Are EuroHPC Quantum Computers?," The European High Performance Computing Joint Undertaking, accessed January 5, 2026, https://www.eurohpc-ju.europa.eu/eurohpc-quantum-computers_en; *Acquisition, Delivery, Installation, and Hardware and Software Maintenance of the EuroQCS-Italy Quantum Computer for the EuroHPC Joint Undertaking: Tender Specifications, Part 1: Administrative Specifications* (European Union, 2024), https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/tender-details/docs/bf9bdab0-9ee9-427a-b3e4-de28f4c88438-CN/Part1_Administrative_Tender-specification_%20EuroQCS-Italy_FINAL_V1.pdf.

40. "DARPA Eyes Companies Targeting Industrially Useful Quantum Computers," DARPA, April 3, 2025, https://www.darpa.mil/news/2025/companies-targeting-quantum-computers.

41. Constanza M. Vidal Bustamante, "Don't Let Tariffs Ruin America's Quantum Leadership," *Washington Examiner*, July 24, 2025, https://www.washingtonexaminer.com/op-eds/3478739/tariffs-america-quantum-technology-strategy-leadership/; *Tariff Costs and Uncertainty Are Threatening America's Quantum Competitiveness* (QED-C, August 19, 2025), https://quantumconsortium.org/publication/tariff-costs-and-uncertainty-are-threatening-americas-quantum-competitiveness/.

42. "Quantum Stack" framework, developed by Quantum Economic Development Consortium and MonArk Quantum Foundry. See: Emma J. Cantley et al., "Building Supply Chain Sustainability in the Quantum Industry: The Quantum Stack as Framework," unpublished manuscript; *Tracking the Global Supply Chain: A Framework for the Quantum Industry* (QED-C, September 22, 2023), https://quantumconsortium.org/publication/supply chain-framework-report/.

43. Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*; Lukas Kingma, Freeke Heijman, and Carl Williams, *Official Summary: Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance* (NATO Transatlantic Quantum Community, May 12, 2025), https://www.fheijman.nl/QSC_report.pdf.

44. Although this report does not examine these differences systematically, additional diversity in supply chain requirements exists even within individual modalities, as firms make specific design and implementation choices to balance competing objectives, such as performance, scalability, manufacturability, and deployment goals. For example, atomic quantum technologies may favor different atom species (e.g., rubidium versus strontium) because their atomic energy transitions offer different advantages for control, coherence, and scalability, which in turn require lasers operating at different wavelengths. They may also adopt distinct operating environments depending on the application: atomic computers typically rely on laser-cooled atoms in high-vacuum chambers, whereas many commercially deployed atomic sensors use warm atomic vapors in sealed glass cells that are easier to deploy on mobile platforms. These variations lead to some differences in specific supply chain requirements, but the variation is substantially greater across modalities than within them, making modality-level groupings analytically useful.

45. Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*.

46. Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*; *Control and Readout Electronics for Quantum Systems: An Enabling Technology Roadmap* (QED-C, March 25, 2022), https://quantumconsortium.org/publication/control-electronics-report/.

47. Loïc Henriet et al., "Quantum Computing with Neutral Atoms," *Quantum* 4, no. 4 (2020): 327, https://quantum-journal.org/papers/q-2020-09-21-327/; Colin D. Bruzewicz et al., "Trapped-Ion Quantum Computing: Progress and Challenges," *Applied Physics Reviews* 6, no. 2 (2019): 021314, https://pubs.aip.org/aip/apr/article-abstract/6/2/021314/570103/Trapped-ion-quantum-computing-Progress-and?redirectedFrom=fulltext.

48. Tim Schröder et al., "Quantum Nanophotonics in Diamond," *Journal of the Optical Society of America* B 33, no. 4 (2016): B65–B83, https://opg.optica.org/josab/fulltext.cfm?uri=josab-33-4-b65.

49. A. Sipahigil et al., "An Integrated Diamond Nanophotonics Platform for Quantum-Optical Networks," *Science* 354, no. 6,314 (October 13, 2016): 847–850, https://www.science.org/doi/10.1126/science.aah6875; Ryota Katsumi et al., "Recent Progress in Hybrid Diamond Photonics for Quantum Information Processing and Sensing," *Communications Engineering* 4, no. 85 (May 8, 2025), https://www.nature.com/articles/s44172-025-00398-2.

50. P. Krantz, et al., "A Quantum Engineer's Guide to Superconducting Qubits," *Applied Physics Reviews* 6, no. 2 (2019): 021318, https://pubs.aip.org/aip/apr/article/6/2/021318/570326/A-quantum-engineer-s-guide-to-superconducting.

51. Terence Blésin et al., "Bidirectional Microwave-Optical Transduction Based on Integration of High-Overtone Bulk Acoustic Resonators and Photonic Circuits," *Nature Communications* 15, no. 6,096 (July 2024),https://www.nature.com/articles/s41467-024-49467-8; Han Zhao, "Building Photonic Links for Microwave Quantum Processors," *Nanophotonics* 14, no. 11 (2025): 1895–1906, https://www.degruyterbrill.com/document/doi/10.1515/nanoph-2024-0599/html?srsltid=AfmBOoqQ07p1dSjMg8nyToE14Anms9MeaYEab1xNlLccghxJ6uKwtzQT.

52. *Cryogenics for Quantum Applications* (QED-C, February 23, 2026), https://quantumconsortium.org/publication/cryogenics-for-quantum-applications/.

53. "PT420," BLUEFORS, accessed January 5, 2026, https://bluefors.com/products/pulse-tube-cryocoolers/pt420-pulse-tube-cryocooler/.

54. "Hardware for Useful Quantum Computing," IBM, accessed January 5, 2026, https://www.ibm.com/quantum/technology; Pat Gumann and Jerry Chow, "IBM Scientists Cool Down the World's Largest Quantum-Ready Cryogenic Concept System," IBM, September 8, 2022, https://www.ibm.com/quantum/blog/goldeneye-cryogenic-concept-system.

55. "Building the Future of Computing," PsiQuantum, accessed January 5, 2026, https://www.psiquantum.com/australia; "PsiQuantum Taps Linde Engineering to Build Cryogenic Plant for Utility-Scale Quantum Computer," Quantum Computing Report, May 9, 2025, https://quantumcomputingreport.com/psiquantum-taps-linde-engineering-to-build-cryogenic-plant-for-utility-scale-quantum-computer/; Linde, "Linde Engineering to Deliver Large Cryogenic Plant to PsiQuantum in Australia," press release,

May 8, 2025, https://www.linde-engineering.com/news-and-events/press-releases/2025/linde-engineering-to-deliver-large-cryogenic-plant-to-psiquantum-in-australia.

56. J. M. Pino et al., *Demonstration of the QCCD Trapped-Ion Quantum Computer Architecture* (Honeywell Quantum Solutions, March 2, 2020), https://www.honeywell.com/content/dam/honeywellbt/en/documents/downloads/Beta_10_Quantum_3_3_2020.pdf; IonQ, "IonQ Announces Innovations in Compact, Room-Temperature Quantum Computing through Novel Extreme High Vacuum (XHV) Technology," press release, February 21, 2025, https://www.ionq.com/news/ionq-announces-innovations-in-compact-room-temperature-quantum-computing; IonQ Staff, "Extreme High Vacuum (XHV) Reduces Computational Energy Costs and Furthers Room Temperature Quantum Computing," IonQ, November 13, 2024, https://www.ionq.com/blog/extreme-high-vacuum-xhv-reduces-computational-energy-costs-and-furthers-room; Jwo-Sy Chen et al., "Benchmarking a Trapped-Ion Quantum Computer with 30 Qubits," *Quantum* 8, no. 1,516 (2024), https://quantum-journal.org/papers/q-2024-11-07-1516/.

57. Zhenpu Zhang et al., "High Optical Access Cryogenic System for Rydberg Atom Arrays with a 3000-Second Trap Lifetime," *PRX Quantum* 6, no. 2 (May 27, 2025): 020337, https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.6.020337; Corentin Monmeyran, "Pasqal Creates a Perfect 506-Atom Quantum Register," Pasqal, April 3, 2025, https://www.pasqal.com/blog/perfect-506-atom-quantum-register/.

58. *Toward a Resilient Quantum Computing Supply Chain.*

59. Kingma, Heijman, and Williams, *Official Summary: Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance*.

60. Morten Kjaergaard et al., "Superconducting Qubits: Current State of Play," *Annual Review of Condensed Matter Physics* 11, no. 1 (March 2020): 369–395, https://www.annualreviews.org/content/journals/10.1146/annurev-conmatphys-031119-050605; Irfan Siddiqi, "Engineering High-Coherence Superconducting Qubits," *Nature Reviews Materials* 6 (September 23, 2021): 875–891, https://www.nature.com/articles/s41578-021-00370-4; Conal E. Murray, "Material Matters in Superconducting Qubits," *Materials Science and Engineering*: *R: Reports* 146 (October 2021): 100646, https://www.sciencedirect.com/science/article/abs/pii/S0927796X21000413; John M. Martinis et al., "Decoherence in Josephson Qubits from Dielectric Loss," *Physical Review Letters* 95, no. 21 (November 16, 2005): 210503, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.95.210503.

61. Floris A. Zwanenburg et al., "Silicon Quantum Electronics," *Reviews of Modern Physics* no. 85 (July 2013): 961–1019, https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.85.961.

62. Guangchong Hu et al., "Single-Electron Spin Qubits in Silicon for Quantum Computing," *Intelligent Computing* 4 (May 2, 2025): 0115, https://spj.science.org/doi/10.34133/icomputing.0115; L. M. K. Vandersypen et al., "Interfacing Spin Qubits in Quantum Dots and Donors—Hot, Dense, and Coherent," *npj Quantum Information* 3, no. 34 (September 6, 2017) https://www.nature.com/articles/s41534-017-0038-y.

63. Jianwei Wang et al., "Integrated Photonic Quantum Technologies," *Nature Photonics* 14, (May 2020): 273–284, https://www.nature.com/articles/s41566-019-0532-1; Emanuele Pelucchi et al., "The Potential and Global Outlook of Integrated Photonics for Quantum Technologies," *Nature Reviews Physics* 4, no. 3 (March 2022): 194–208, https://tohoku.elsevierpure.com/en/publications/the-potential-and-global-outlook-of-integrated-photonics-for-quan/.

64. Luigi Ranno et al., "Integrated Photonics Packaging: Challenges and Opportunities," *ACS Photonics* 9, no. 11 (October 19, 2022): 3467–3485, https://pubs.acs.org/doi/abs/10.1021/acsphotonics.2c00891; Keuntae Baek et al., "Advanced Optical Integration Processes for Photonic-Integrated Circuit Packaging," *Advanced Materials Technologies* 10, no. 19 (June 25, 2025): e01848, https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/admt.202401848; Debapam Bose et al., "Anneal-Free Ultra-Low Loss Silicon Nitride Integrated Photonics," *Light: Science & Applications* 13, no. 156 (July 8, 2024), https://www.nature.com/articles/s41377-024-01503-4; Fabien Labbé et al., "Thin-Film Lithium Niobate Quantum Photonics: Review and Perspectives," *Advanced Photonics* 7, no. 4 (July 16, 2025): 044002, https://www.spiedigitallibrary.org/journals/advanced-photonics/volume-7/issue-04/044002/Thin-film-lithium-niobate-quantum-photonics-review-and-perspectives/10.1117/1.AP.7.4.044002.full; Mikhail Churaev et al., "A Heterogeneously Integrated Lithium Niobate-on-Silicon Nitride Photonic Platform," in *2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference*, Munich, (CLEO/Europe–EQEC, July 2023), https://research.ibm.com/publications/a-heterogeneously-integrated-lithium-niobate-on-silicon-nitride-photonic-platform--1; Di Zhu et al., "Integrated Photonics on Thin-Film Lithium Niobate," *Advances in Optics and Photonics* 13, no. 2 (June 2021): 242–352, https://opg.optica.org/aop/abstract.cfm?uri=aop-13-2-242.

65. "What is Integrated Photonics?," AIM Photonics, accessed January 6, 2026, https://www.aimphotonics.com/what-is-integrated-photonics; A. Katiyi and A. Karabchevsky, "Quantum Photonics on a Chip," *APL Quantum* 2, no. 2 (June 10, 2025): 020901, https://pubs.aip.org/aip/apq/article/2/2/020901/3349259/Quantum-photonics-on-a-chip; "What Is a Photonic Integrated Circuit?," Ansys, accessed January 6, 2026, https://www.ansys.com/simulation-topics/what-is-a-photonic-integrated-circuit.

66. A. W. Elshaari et al., "Hybrid Integrated Quantum Photonic Circuits," *Nature Photonics* 14, no. 5 (May 2020): 285–298, https://www.nature.com/articles/s41566-020-0609-x.

67. Jeremy L. O'Brien, Akira Furusawa, and Jelena Vučković, "Photonic Quantum Technologies," *Nature Photonics* 3, no. 12 (December 2009): 687–695, https://www.nature.com/articles/nphoton.2009.229; Terry Rudolph, "Why I Am Optimistic About the Silicon-Photonic Route to Quantum Computing," *APL Photonics* 2, no. 3 (March 6, 2017): 030901, https://pubs.aip.org/aip/app/article/2/3/030901/122954/Why-I-am-optimistic-about-the-silicon-photonic.

68. M. Brownnutt et al., "Ion-Trap Measurements of Electric-Field Noise near Surfaces," *Reviews of Modern Physics* 87, no. 4 (December, 2015): 1419–1482, https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.87.1419.

69. *Piercing the Fog of Quantum-Enabling Laser Technology (QELT),* (QED-C, September 9, 2020), https://quantumconsortium.org/piercing-the-fog-of-quantum-enabling-laser-technology-qelt/; Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*.

70. "IPG Photonics," IPG Photonics, accessed February 5, 2026, https://www.ipgphotonics.com/; "Coherent," Coherent, accessed February 5, 2026, https://www.coherent.com/lasers; "Vescent," Vescent, accessed February 5, 2026, https://vescent.com/.

71. "Beacon Photonics," Beacon Photonics, accessed February 5, 2026, https://www.beaconphotonics.com/; "PINC Technologies," PINC Technologies, accessed February 5, 2026, https://www.pinctech.com/; Monarch Quantum, accessed February 5, 2026, https://monarchquantum.com/.

72. "POWER: Persistent Optical Wireless Energy Relay," accessed February 5, 2026, https://www.darpa.mil/research/programs/power; "LUMOS: Lasers for Universal Microscale Optical Systems," accessed February 5, 2026, https://www.darpa.mil/research/programs/lasers-for-universal-microscale-optical-systems.

73. *Assessing U.S. Leadership in Quantum Science and Technology: Hearing Before the House of Representatives Committee on Science, Space, and Technology*, 119th Cong. (2026) (statement of James Kushmerick, director, Physical Measurement Laboratory, National Institute of Standards and Technology, United States Department of Commerce), https://republicans-science.house.gov/_cache/files/5/4/54f47ca1-e265-4010-a57c-5b61a96e30d3/6C72F82B08771F9CD1DB159C3D56BA071E1F48B-1BA05750DC388699B84D689D6.dr.-james-kushmerick-testimony.pdf; "Photonics for Quantum," Sandia National Laboratories, accessed February 10, https://www.sandia.gov/mesa/photonics-for-quantum/.

74. *Cryogenics for Quantum Applications*.

75. *Toward a Resilient Quantum Computing Supply Chain*, 89–90, 98"; Alan Boyle, "Interlune Announces Deals for Moon Mining Equipment—and for Selling Lunar Helium-3," GeekWire, May 7, 2025, https://www.geekwire.com/2025/interlune-moon-mining-vermeer-maybell-quantum-doe/.

76. *Cryogenics for Quantum Applications*.

77. National Isotope Development Center, "Supply and Demand of Helium-3 (He-3)," press release, accessed January 6, 2026, https://www.isotopes.gov/Supply-and-Demand-of-Helium-3; *The Helium-3 Shortage: Supply, Demand, and Options for Congress* (Congressional Research Service, October 6, 2011), https://www.congress.gov/crs-product/R41419.

78. The Edelgas Group, "Edelgas Publishes Comprehensive Market Report on Helium-3: Unveiling Key Insights into a Rare and Vital Isotope," press release, October 22, 2024, https://www.edelgasgroup.com/helium-3-market-report.

79. National Isotope Development Center, "Supply and Demand of Helium-3 (He-3)"; *The Helium-3 Shortage: Supply, Demand, and Options for Congress*; *Managing Critical Isotopes: Weaknesses in DOE's Management of Helium-3 Delayed the Federal Response to a Critical Supply Shortage* (United States Government Accountability Office, May, 2011), https://www.gao.gov/assets/gao-11-472.pdf.

80. Air Liquide, "Air Liquide Enters a Long-term Partnership to Secure its Supply of Helium-3," press release, December 7, 2021, https://www.airliquide.com/group/press-releases-news/2021-12-07/air-liquide-enters-long-term-partnership-secure-its-supply-helium-3; Laurentis Energy Partners, "Laurentis Is Helping Meet Global Demands by Increasing He-3 Production," press release, April 29, 2022, https://www.laurentisenergy.com/stories/laurentis-is-helping-meet-global-demands-by-increasing-he-3-production/; "Why Choose Airgas for Your Helium-3 Supply?," Airgas, accessed January 6, 2026, https://www.airgas.com/solutions/specialty-gases/pure-specialty-gases/helium3.

81. *The Helium-3 Shortage: Supply, Demand, and Options for Congress.*

82. Interlune, "U.S. Department of Energy Buys Helium-3 from U.S. Space Resources Company Interlune in Historic Agreement," press release, May 7, 2025, https://www.interlune.space/press-release/u-s-department-of-energy-buys-helium-3-from-u-s-space-resources-company-interlune-in-historic-agreement.

83. Aaron D. S. Olson, *Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies* (National Aeronautics and Space Administration, 2021), paper presented at the AIAA ASCEND 2021 conference, https://ntrs.nasa.gov/api/citations/20210022801/downloads/AIAA%20ASCEND%202021%20Paper_211018.pdf.

84. Bluefors, "Bluefors Announces Availability of New Ultra-Compact Dilution Refrigerator System," press release, February 12, 2025, https://bluefors.com/press-releases/

bluefors-announces-availability-of-new-ultra-compact-dilution-refrigerator-system/.

85. Zhang Weilan and Chen Zishuai, "China Makes Breakthrough on Dilution Refrigerator for Quantum Computing Chips," *Global Times*, February 28, 2024, https://www.globaltimes.cn/page/202402/1307818.shtml.

86. Narang and Levine, "The Supply Chain Chokepoints in Quantum."

87. *Cryogenics for Quantum Applications.*

88. "IBM Scientists Cool Down the World's Largest Quantum-Ready Cryogenic Concept System," IBM, September 8, 2022, https://www.ibm.com/quantum/blog/goldeneye-cryogenic-concept-system.

89. Corban Tillemann-Dick et al., Integrated Dilution Refrigerators, U.S. Patent US12449166B2, assigned to Maybell Quantum Industries, filed July 8, 2022, and granted October 21, 2025, https://patents.google.com/patent/US20230010758A1/en; "Connected Dilution Refrigerators for Scalable Quantum Computing," Quantum Design Oxford, June 13, 2025, https://qd-oxford.com/blog/2025_06_13_blog_item.html; *Cryogenics for Quantum Information Science and Technology* (QED-C, May 4, 2020), https://quantumconsortium.org/publication/cryogenics-for-quantum-information-science-and-technology/.

90. Jake Rochman, *Quantum Breakthroughs Begin with Material* (Applied Materials, June 25, 2025) https://www.appliedmaterials.com/us/en/newsroom/perspectives/quantum-breakthroughs-begin-with-materials.html.

91. Intel, "Intel Takes Next Step Toward Building Scalable Silicon-Based Quantum Processors," press release, May 1, 2024, https://www.intc.com/news-events/press-releases/detail/1693/intel-takes-next-step-toward-building-scalable; Global Foundries, "PsiQuantum and GlobalFoundries to Build the World's First Full-scale Quantum Computer," press release, May 5, 2021,https://gf.com/dresden-press-release/psiquantum-and-globalfoundries-build-worlds-first-full-scale-quantum-computer/; "Enabling the Quantum Revolution with SkyWater's Advanced Manufacturing," Skywater, March 3, 2025, https://www.skywatertechnology.com/enabling-the-quantum-revolution-with-skywaters-advanced-manufacturing/; "Tower Semiconductor Announces World's First Heterogeneous Integration of Quantum Dot Lasers on its Popular SiPho Foundry Platform PH18," Tower Semiconductor, March 2, 2023, https://towersemi.com/2023/03/02/03022023/; N. Solmeyer et al., "Enabling Quantum Sensors with Integrated Photonics," *Proceedings* 13376 (21 March 2025): 133760B, https://doi.org/10.1117/12.3042528.

92. Narang and Levine, "The Supply Chain Chokepoints in Quantum"; Kingma, Heijman, and Williams, *Official Summary: Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance.*

93. *Department of Defense Fiscal Year (FY) 2025 Budget Estimates, Office of the Secretary Of Defense Defense-Wide Justification Book Volume 3 of 5 Creating Helpful Incentives To Produce Semi-Conductors (CHIPS) for America,* (Department of Defense, March, 2024), https://comptroller.war.gov/Portals/45/Documents/defbudget/FY2025/budget_justification/pdfs/03_RDT_and_E/RDTE_CHIPS_PB_2025.pdf.

94. National Institute of Standards and Technology, "NIST Issues Broad Agency Announcement for Proposals to Advance Microelectronics Technologies," press release, September 24, 2025, https://www.nist.gov/news-events/news/2025/09/nist-issues-broad-agency-announcement-proposals-advance-microelectronics.

95. "View Grant Opportunity" Grants.gov, accessed January 6, 2026, https://www.grants.gov/search-results-detail/360651.

96. *Lithium Niobate Crystal Wafer: Competitive Landscape and Growth Trends 2025–2033,* (DiMarket, June 15, 2025), https://www.datainsightsmarket.com/reports/lithium-niobate-crystal-wafer-1832564#; "About Us," NanoLN, accessed January 6, 2026, https://m.nanoln.com/ABOUT_NANOLN.html; "Single-Crystal Products: LT (Lithium Tantalate) / LN (Lithium Niobate)," Sumitomo Metal Mining, accessed January 6, 2026, https://www.smm.co.jp/en/business/material/products/lithium/; Nippon Telegraph and Telephone,"World's First Long-haul Optical Inline-amplified Transmission over 100 Tbit/s Capacity Using Ultra Long-wavelength Band Conversion Toward IOWN/6G, Single-core Optical Fiber Capacity More Than Three Times Larger Than Current Technology," press release, September 3, 2024, https://group.ntt/en/newsrelease/2024/09/03/240903b.html.

97. Interview with a quantum enabling-technology company executive in January 2026.

98. Narang and Levine, "The Supply Chain Chokepoints in Quantum."

99. "Thin Film Lithium Niobate Foundry," QCI, accessed February 6, 2026, https://quantumcomputinginc.com/foundry.

100. QCI, "Thin Film Lithium Niobate Foundry"; QCI, "Quantum Computing Inc. Awarded TFLN Photonic Chip Contract by U.S. Department of Commerce's National Institute of Standards and Technology," press release, August 25, 2025, https://quantumcomputinginc.com/news/press-releases/2025/quantum-computing-inc.-awarded-tfln-photonic-chip-contract-by-u.s.-department-of-commerces-national-institute-of-standards-and-technology.

101. Peter Clarke, "IBM Spin-Off Brings Barium Titanate to Silicon Photonics," *Technology News,* July 11, 2021, https://www.eenewseurope.com/en/ibm-spin-off-brings-barium-titanate-to-silicon-photonics/; La Luce Cristallina, "La Luce Cristallina Launches

200-mm $BaTiO_3$ Wafer," press release, September 16, 2025, https://lalucecristallina.com/news/la-luce-cristallina-launches-200-mm-batio-e2-82-83-wafer/; PsiQuantum, "PsiQuantum Announces $10.8M Contract with Air Force Research Laboratory to Deliver Novel Quantum Chip Capabilities to the U.S. Air Force," press release, April 15, 2025, https://www.psiquantum.com/news-import/psi-quantum-afrl-omega.

102. "Beacon Photonics," Beacon Photonics, accessed February 5, 2026, https://www.beaconphotonics.com/; "PINC Technologies"; "Monarch Quantum," Monarch Quantum, accessed February 5, 2026, https://monarchquantum.com/.

103. PsiQuantum, "PsiQuantum Announces Omega, a Manufacturable Chipset for Photonic Quantum Computing," press release, February 26, 2025, https://www.psiquantum.com/news-import/omega.

104. SkyWater Technology, "IonQ to Acquire SkyWater Technology, Creating the Only Vertically Integrated Full-Stack Quantum Platform Company," press release, January 26, 2026, https://www.skywatertechnology.com/ionq-to-acquire-skywater/.

105. Matt Swayne, "China Ramps Up Photonic Chip Production With Eye on AI and Quantum Computing," Quantum Insider, June 13, 2025, https://thequantuminsider.com/2025/06/13/china-ramps-up-photonic-chip-production-with-eye-on-ai-and-quantum-computing/; Yongheng Jiang et al., "Monolithic Photonic Integrated Circuit Based on Silicon Nitride and Lithium Niobate on Insulator Hybrid Platform," *Advanced Photonics Research* 3, no. 2200121 (2022), https://einstein.nju.edu.cn/upload/uploadify/20221014/20220707-AdvancedPhotonicsResearch-Jiang-MonolithicPhotonicIntegratedCircuitBasedonSiliconNitrideandLithium_202210141730569235.pdf; Churaev et al., "A Heterogeneously Integrated Lithium Niobate-on-Silicon Nitride Photonic Platform," *Nature Communications* 14, no. 3499 (June 13, 2023), https://www.nature.com/articles/s41467-023-39047-7; "Integrated Photonics," imec, accessed February 7, 2026, https://www.imec-int.com/en/integrated-photonics.

106. Narang and Levine, "The Supply Chain Chokepoints in Quantum."

107. "Next-Generation Microelectronics Manufacturing," DARPA, https://www.darpa.mil/research/programs/next-generation-microelectronics.

108. P. G. Sennikov, R. A. Kornev, and N. V. Abrosimov, "Production of Stable Silicon and Germanium Isotopes via Their Enriched Volatile Compounds," *Journal of Radioanalytical and Nuclear Chemistry* 306 (October 2015): 21–30, https://link.springer.com/article/10.1007/s10967-015-4192-4; ASP Isotopes Inc., "ASP Isotopes Inc. Commences Commercial Production of Enriched Silicon-28 at its Second Aerodynamic Separation Process (ASP) Enrichment Facility," press release, March 27, 2025, https://ir.aspisotopes.com/news-events/press-releases/detail/56/asp-isotopes-inc-commences-commercial-production-of.

109. imec, "Imec Technology Lights the Path to Utility Scale for Diraq's Quantum Chips," press release, September 24, 2025, https://www.imec-int.com/en/press/imec-technology-lights-path-utility-scale-diraqs-quantum-chips.

110. "Imec Technology Lights the Path to Utility Scale for Diraq's Quantum Chips"; Samuel K. Bartee et al., "Spin-Qubit Control with a Milli-Kelvin CMOS Chip," *Nature* 643 (July 10, 2025): 382–387, https://www.nature.com/articles/s41586-025-09157-x.

111. Kylie Foy and Haley Wahl, "Superconducting Qubit Foundry Accelerates Progress in Quantum Research," Massachusetts Institute of Technology Lincoln Laboratory, June 15, 2023, https://www.ll.mit.edu/news/superconducting-qubit-foundry-accelerates-progress-quantum-research; Ryan Mandelbaum, "Building Quantum Computers with Leading-Edge Semiconductor Fab" IBM, November 12, 2025, https://www.ibm.com/quantum/blog/300mm-fab.

112. "Intel's New Chip to Advance Silicon Spin Qubit Research for Quantum Computing," Newsroom, June 15, 2023, https://newsroom.intel.com/new-technologies/quantum-computing-chip-to-advance-research; Qolab, "Qolab Secures Investment from Applied Ventures and Announces Collaboration to Advance Quantum Computing Manufacturing," accessed January 6, 2026, https://qolab.ai/qolab-secures-investment-from-applied-ventures/.

113. In China: "Breakthrough | Changguang Huaxin's High-Power Semiconductor Single-Chip Power Exceeds 100W!," Suzhou Everbright Photonics, accessed February 5, 2026, https://en.everbrightphotonics.com/news/59.html; "Epi Service," Ganwafer, accessed February 5, 2026, https://www.ganwafer.com/product-category/epi-service/; "GaAs RF Foundry: High-Performance in-House GaAs Epitaxy Mature Platform for Leading Edge Applications," Sanan IC, accessed February 5, 2026, https://www.sanan-ic.com/en/gaasfoundry. In Taiwan: "VPEC Expands Capacities with AIXTRON Technology," Visual Photonics Epitaxy, May 2, 2018, https://www.aixtron.com/en/investors/VPEC%20expands%20capacities%20with%20AIXTRON%20technology_n184; "About LandMark", LandMark Optoelectronics, accessed February 5, 2026, https://www.lmoc.com.tw/index.php?lang=en&temp=intro. In Japan: "Epitaxial Wafers," Sumitomo Electric Group, accessed February 5, 2026 https://global-sei.com/sc/products_e/epi/. In South Korea: "EPI Wafer: Product Information," Optowell Co., accessed February 5, 2026, https://www.opt-ron.com/wp-content/uploads/epi_wafer_brochure_optowell.pdf. In the UK: "IQE Products: The Foundation of Advanced Semiconductors," IQE, accessed February 5, 2026, https://www.iqep.com/products/; "About III-V Epi," III-V Epi, accessed February 5, 2026, https://www.iii-vepi.com/.

114. U.S. organizations with III–V semiconductor epitaxy capabilities include Coherent Inc., Sandia National Laboratories, MIT Lincoln Labs, Georgia Tech Research Institute, and University of California Santa Barbara.

115. Dr. Rüdiger Paschotta, "Photonic Crystal Surface-Emitting Lasers," RP Photonics, accessed January 6, 2026, https://www.rp-photonics.com/photonic_crystal_surface_emitting_lasers.html; Susumu Noda, Masahiro Yoshida, and Takuya Inoue, "The Tiny Ultrabright Laser that Can Melt Steel," IEEE Spectrum, April 14, 2024, https://spectrum.ieee.org/pcsel.

116. IonQ, "IonQ Completes Acquisition of Oxford Ionics, Rapidly Accelerating Its Quantum Computing Roadmap," press release, September 17, 2025, https://ionq.com/news/ionq-completes-acquisition-of-oxford-ionics-rapidly-accelerating-its-quantum; "The Home of Ion Trap Quantum Computing: Innsbruck. Austria," AQT, accessed January 6, 2026, https://www.aqt.eu/; Quantinuum, "Introducing Quantinuum: The World's Largest Integrated Quantum Computing Company," press release, November 30, 2021, https://www.quantinuum.com/press-releases/introducing-quantinuum.

117. "Quantum Foundry Facility (Q2F)," Sandia National Laboratories, accessed January 6, 2026, https://www.sandia.gov/quantum/quantum-foundry-facility-q2f/.

118. "Green Light for Europe's First Ion-Trap-Chip Pilot Line," Parityqc, May 18, 2025, https://parityqc.com/green-light-for-europes-first-ion-trap-chip-pilot-line.

119. Element Six, "Element Six Launches DNV-B1™—Its First Commercially Available, General-Purpose Quantum-Grade Diamond," press release, June 15, 2020, https://www.e6.com/en/about/news/dnv-b1-launch.

120. "Our Products," Crysdiam, accessed January 6, 2026, https://www.crysdiamonline.com/; "CVD/MCD," Made-in-China, accessed January 6, 2026, https://cnchenguang.en.made-in-china.com/; "Lab-Grown Nv Color Center Diamond for Quantum Research," Made-in-China, accessed January 6, 2026, https://8b99f21e3053561b.en.made-in-china.com/product/IadRDYhgHQkF/China-Lab-Grown-Nv-Color-Center-Diamond-for-Quantum-Research.html.

121. Narang and Levine, "The Supply Chain Chokepoints in Quantum."

122. "Enabling Room-Temperature Quantum Applications," Great Crystal Lakes Technologies, accessed February 5, 2026, https://glcrystal.com/product/; "Quantum SCD CVD Diamond," WD Advanced Materials, accessed February 5, 2026, https://www.wdadvancedmaterials.com/product-page/quantum-scd-cvd-diamond-wafer; "II-VI Advances Diamond Platform, Electronics Sector Presence," Photonics Spectra, February 2022, https://www.photonics.com/Articles/II-VI_Advances_Diamond_Platform_Electronics/a67752.

123. *Piercing the Fog of Quantum-Enabling Laser Technology (QELT)* (QED-C, September 9, 2020); Randazzese et al., *Quantum Technology Manufacturing Roadmap: Scaling Up Quantum*.

124. Interviews with executives from two quantum technology companies in April and July 2025; Vidal Bustamante, *Atomic Advantage: Accelerating U.S. Quantum Sensing for Next-Generation Positioning, Navigation, and Timing*, 33–34.

125. Dr. Rüdiger Paschotta, "Photonic Crystal Surface-Emitting Lasers," RP Photonics, accessed January 6, 2026, https://www.rp-photonics.com/photonic_crystal_surface_emitting_lasers.html; Susumu Noda, Masahiro Yoshida, and Takuya Inoue, "The Tiny Ultrabright Laser that Can Melt Steel," IEEE Spectrum, April 14, 2024, https://spectrum.ieee.org/pcsel;

126. Sandia National Laboratories, "World's Smallest Atomic Clock on Sale," press release, May 2, 2011, https://newsreleases.sandia.gov/atomic-clock/; "Photonics for Quantum," Sandia National Laboratories, accessed March 2, 2026, https://www.sandia.gov/mesa/photonics-for-quantum/.

127. Min-Ha Lee, *A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain* (Stanford Geopolitics, Technology, and Governance Center for International Security and Cooperation, October 2023) https://cisac.fsi.stanford.edu/publication/framework-assessing-vulnerabilities-quantum-computing-materials-supply-chain; Lee, *A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain*.

128. Interview with quantum-enabling technology company executive in July 2025.

129. Kingma, Heijman, and Williams, *Official Summary: Critical Vulnerabilities in the Quantum Sensing Supply Chain Within the NATO Alliance*.

130. Interviews with quantum technology company executives in April and July 2025.

131. "Cesium," U.S. Geological Survey, Mineral Commodity Summaries, January 2024, https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-cesium.pdf.

132. Interviews with quantum-enabling technology company executives in July 2025 and February 2026.

133. National Isotope Development Center, "DOE Awards $88.8M Contract to Build Stable Isotope Production and Research Facility at ORNL," press release, November 21, 2024, https://www.isotopes.gov/department-energy-awards-88m-contract-build-stable-isotope-production-and-research-facility.

134. *Global Critical Minerals Outlook 2025* (International Energy Agency, June 2025), 168, https://iea.blob.core.windows.net/assets/ef5e9b70-3374-4caa-ba9d-19c72253bfc4/GlobalCriticalMineralsOutlook2025.pdf.

135. "Products," CASTECH, accessed March 2, 2026, https://www.castech.com/product/TGG---Terbium-Gallium-Garnet-93.html; "TGG," Photonchina, accessed March 2, 2026, https://www.photonchinaa.com/product/tgg/.

136. "Laser Materials," Flir Defense, accessed February 5, 2026, https://defense.flir.com/defense-products/tgg/; "Magneto-Optic Faraday Rotator Garnet Crystals," Coherent, accessed February 5, 2026, https://www.coherent.com/resources/datasheet/optics/magneto-optic-lpe-garnet-faraday-rotator-crystals-ds.pdf; https://www.coherent.com/news/glossary/faraday-rotators-and-isolators.

137. Department of War, "Department of War Invests $18.5 Million to Expand Germanium and Silicon Optics Production," press release, December 22, 2025, https://www.war.gov/News/Releases/Release/Article/4366365/department-of-war-invests-185-million-to-expand-germanium-and-silicon-optics-pr/.

138. Interview with a quantum-enabling technology company in July 2025.

139. Constanza M. Vidal Bustamante, "Don't Let Tariffs Ruin America's Quantum Leadership," *Washington Examiner*, July 24, 2025, https://www.washingtonexaminer.com/op-eds/3478739/tariffs-america-quantum-technology-strategy-leadership/; *Tariff Costs and Uncertainty Are Threatening America's Quantum Competitiveness* (QED-C, August 19, 2025), https://quantumconsortium.org/publication/tariff-costs-and-uncertainty-are-threatening-americas-quantum-competitiveness/.

140. "HARQ: Heterogeneous Architectures for Quantum," DARPA, accessed January 6, 2026, https://www.darpa.mil/research/programs/heterogeneous-architectures-for-quantum.

141. *Toward a Resilient Quantum Computing Supply Chain*, 89–90, 98; Alan Boyle, "Interlune Announces Deals for Moon Mining Equipment—and for Selling Lunar Helium-3," GeekWire, May 7, 2025, https://www.geekwire.com/2025/interlune-moon-mining-vermeer-maybell-quantum-doe/.

142. *Cryogenics for Quantum Applications*.

143. National Isotope Development Center, "Department of Energy Awards $88M Contract to Build Stable Isotope Production and Research Facility," press release, November 12, 2024, https://www.isotopes.gov/department-energy-awards-88m-contract-build-stable-isotope-production-and-research-facility.

144. Narang and Levine, "The Supply Chain Chokepoints in Quantum."

145. Interview with quantum technology and quantum-enabling technology company executives in July 2025 and January 2026.

146. Zhang Weilan and Chen Zishuai, "China Makes Breakthrough on Dilution Refrigerator for Quantum Computing Chips," *Global Times*, February 28, 2024, https://www.globaltimes.cn/page/202402/1307818.shtml.

147. *Cryogenics for Quantum Applications*.

148. *Toward a Resilient Quantum Computing Supply Chain*, 88–89.

149. *Toward a Resilient Quantum Computing Supply Chain*, 89.

150. Interview with a quantum-enabling technology company executive, October 2024.

151. Interview with a quantum-enabling technology company executive, October 2024.

151. Interview with a quantum-enabling technology company executive, October 2024.

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