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The Pillars Necessary for a Strong Domestic Semiconductor Industry

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All major U.S. defense systems and platforms rely on semiconductors for their performance, and the erosion of U.S. capabilities in microelectronics is a direct threat to the United States' ability to defend itself and its allies.

The **COMPETES** and **USICA** legislation, currently being reconciled in Congress, represents a national strategy to secure U.S. competitiveness and national security in the twenty-first century. Both the House and Senate legislation call for $52 billion to support U.S.-based semiconductor research and production. They also authorize several programs to both expand U.S. semiconductor fabrication capacity and support the continued research and development (R&D) of advanced chips. The key question is how these intentions can best be turned into reality.

There are several challenges that the domestic semiconductor industry confronts, such as international competition, capital investment requirements, workforce needs, gaps in the supply chain, and the shortfall in venture capital funding and technical support needed to enable commercialization of promising technologies. Addressing these issues requires a focus on the following:

- **Tax incentives**: How can a competitively awarded federal incentives program support investments by companies and consortia in the establishment, expansion, and modernization of semiconductor manufacturing facilities and infrastructure within the United States?
- **Workforce development**: How can federal government support for nationwide workforce development address gaps in the current U.S. semiconductor manufacturing and R&D workforce? How can the federal government help ensure that every segment of the industry chain has enough workers—with the right skills and supported by the right curricula and training programs—to enable the entire semiconductor industry to compete internationally from facilities located in the United States?

- **Packaging**: How can federal support help ensure that the United States has state-of-the-art capabilities in advanced semiconductor packaging, including leading-edge tools, facilities, expertise, post-fabrication infrastructure, a pipeline of skilled workers, and operational support for characterization, intellectual property protection, and productive international collaborations?
- **Research and development**: How can the creation of a public-private National Semiconductor Technology Center (NSTC) help integrate existing U.S. research, design, and manufacturing capabilities, address gaps in the existing U.S. microelectronics infrastructure, and help coordinate U.S. research and investment as the industry grapples with unprecedented technological challenges?

A Focus on the NSTC

While detailed parameters, structure, and operations of the NSTC will need to be further clarified by Congress and the Biden administration, the NSTC is clearly envisioned as an enterprise that will operate in the space between the U.S. research base and existing and envisioned domestic semiconductor design and manufacturing operations.

For the new organization to have maximum impact, it should not replicate existing U.S. capabilities in basic and applied research, workforce development, and technology development and transfer. Rather, it should serve as a mechanism that connects and enables cooperation across established institutions and programs to address recognized areas of opportunity in the U.S. semiconductor ecosystem.

This means that the NSTC should take strategic advantage of expertise and advanced facilities found in existing research and production facilities, enhance the potential of others, and selectively invest in new capabilities—all connected within a networked structure.

Leveraging Existing U.S. Research Assets

Standing up a new research organization to address gaps in the U.S. semiconductor industry chain, which have been decades in the making, is a daunting challenge. Fortunately, two factors significantly enhance the prospect of the NSTC's success: (1) the existence of U.S. institutions that are already addressing some elements of these challenges and can be reinforced and leveraged through new federal investments, and (2) the examples of successful past and current research organizations in the United States and other countries that can be drawn upon as a rich source of precedents and best practices. An important function of the NSTC will be to coordinate its efforts closely with those of existing workstreams to identify gaps where its efforts and resources can be concentrated to the best effect, leveraging rather than duplicating ongoing institutional efforts.

Key organizations in the existing research intermediary space include:

- **Semiconductor Research Corporation (SRC)**: Perhaps, the greatest single asset the United States enjoys in global competition in technology-intensive industries is its superb system of research universities, by far the best in the world. The SRC is a consortium founded by the U.S. semiconductor industry to support research by university-based research teams focusing on the space between "blue sky" basic research and early product development in all segments of the semiconductor production chain. By focusing large numbers of the most talented students on research themes of direct relevance to the industry, over time the SRC has enabled thousands of students to enter careers in the semiconductor industry.

- **National Institute of Standards and Technology (NIST)**: NIST is an arm of the Department of Commerce that has supported semiconductor research and the development of industry standards for decades. It currently has nearly 50 semiconductor-related programs under way, with a mix of basic and applied research efforts. NIST has a range of equipment available to industry for research, including two nanofabrication facilities and measuring tools and instruments used in making custom chips.

- **National Laboratories**: The Department of Energy oversees a system of 17 National Laboratories with deep scientific and engineering expertise and formidable research equipment and infrastructure. The National Labs have a mandate to transfer technology to industry and have developed a sizable number of institutional mechanisms to facilitate this process. Sandia National Laboratory has collaborated with the semiconductor industry on many projects for more than three decades.

- **The College of Nanoscale Science and Engineering (CNSE)**: CNSE is part of the State University of New York (SUNY). In addition to providing science and engineering education, CNSE operates the most advanced 200- to 300-millimeter wafer fabrication facilities in the academic world. It hosts an array of research consortia comprised of some of the leading semiconductor firms in the world, including IBM, Global Foundries, and Applied Materials. There is no other educational and research facility in the United States with comparable assets.

- **Federally Funded Research and Development Centers and University Affiliated Research Centers**: These are federally funded enterprises that address long-term research needs of the federal government that cannot be met through in-house research or research contracts. Some of these entities, such as the MIT Lincoln Laboratory, are engaged in advanced microelectronics research and development.

- **Manufacturing USA**: The Manufacturing USA initiative was founded by the federal government as a network of research institutes across the country to develop manufacturing technologies in many different sectors through public-private university collaboration. These institutes seek to address some of the same challenges facing the U.S. semiconductor industry, including the need to bridge the “valley of death” between the research and commercial spheres. A number of these institutes are pursuing specialized microelectronics themes such as photonic integrated circuits, wide bandgap semiconductors, and flexible electronics.

Learning from Sematech

The most salient institutional U.S. precedent for the NSTC is Sematech, an industry and government research consortium established in 1988. Like the NSTC, the Sematech initiative emerged at a time when the rapid erosion of U.S. capabilities in semiconductor manufacturing threatened U.S. competitiveness and national security. As with the NSTC, Sematech was conceived of as an element of a broader national effort to regain industry leadership. Significantly for present purposes, Sematech pursued its objectives in close collaboration with the SRC, the federal laboratories, and, in later years, CNSE.

In its formative stages, Sematech’s mission was not fully defined, maturing through a long series of industry and government brainstorming sessions, conferences, and workshops. These refinements were necessary to address the teething challenges that characterized its first years of operation. The NSTC effort is approaching such a definitional phase. Policymakers should pay heed to several methods introduced by Sematech in its early years as it responded to particular challenges:

- **Road mapping**: Sematech innovated the International Technology Roadmap for Semiconductors (ITRS)—"perhaps the best road mapping effort of all time in any industry"—helping to sustain the efficiency gains anticipated by Moore's Law. Most significantly, the road map forged within Sematech was the vehicle through which the annual federal investment of $100 million in Sematech leveraged $8–$9 billion in annual private investments. Today, much larger sums are in play.

- **Development of common standards**: Sematech became a vehicle for developing common standards that enabled the interoperability of tools and software that had previously been incompatible, a fact that had imposed enormous costs and operational burdens on device firms and tool and materials suppliers. In particular, Sematech enabled the development and deployment of Computer-Integrated Manufacturing (CIM) by U.S. firms. At present, the looming prospect that "beyond Moore's Law," technological pathways could diverge into a babel of new material4s and processes, is an indicator that institutional mechanisms for formulating and adopting common standards accepted by industry will be necessary.

- **Improving performance**: Sematech introduced a system of "blind benchmarking" where members could compare their performance metrics with those of other members on an anonymous basis. This process resulted in a "wake-up call," enabling lagging members to take radical steps to improve their operations. A similar program, "Iron Man," facilitated performance benchmarking by equipment makers against comparable Japanese tools. Sematech established equipment productivity teams to identify common problems with a particular tool and share information on how to make the tool perform at the highest level of efficiency. The result was a steady improvement in manufacturing yields and quality.

- **Shoring up the supply chain**: Sematech deepened the relationship between the device makers and their equipment and materials suppliers, establishing a vehicle for ongoing collaboration known as SEMI-Sematech. Sematech defined technological objectives for suppliers, enabling them to focus their developmental efforts on a few clearly understood targets, and provided an opportunity for suppliers to test, benchmark, assess, and ultimately improve their equipment in a factory environment. Sematech also provided funding to the suppliers through research contracts.

- **Reduced cost and risk**: Sematech enabled member companies to reduce their research costs through pooling of effort, and perhaps more importantly, the consortium reduced the risks associated with investments in manufacturing by enabling debugging of new equipment and processes in a precompetitive—but real—manufacturing environment. When the members invested in their own new facilities, they could do so with equipment and processes that had already been proven, a dynamic that accelerated the entire industry's development cycle and enabled it to leapfrog their Japanese rivals.

- **Leveraging federal laboratories**: The federal laboratories represent a vast concentration of extremely high-quality expertise and research infrastructure that should be part of any comprehensive effort to renew U.S. leadership in semiconductor manufacturing. At a time when relationships between the industry and the federal labs were underdeveloped, Sematech played a key role as "matchmaker," fostering industry and laboratory collaborations that were particularly valuable for industry-leading device makers and smaller equipment makers—the quality of Sandia's capabilities, for example, "often exceeded Sematech's needs."

Leading Technology Research Organizations

The NSTC can benefit from studying the institutional structures and operational practices found across leading U.S. and foreign civilian research institutions. In addition to Sematech and CNSE, already noted above, these organizations include:

- **Taiwan's Industrial Technology Research Institute (ITRI)**: ITRI deserves much of the credit for propelling Taiwan from a largely agrarian economy to one of the preeminent high-tech powers in the world within the space of a few decades. Through training, licensing, and funding, ITRI created the Taiwan Semiconductor Manufacturing Corporation (TSMC), which today is the world's most advanced manufacturer of chips.

- **Germany's Fraunhofer Gesellschaft (FhG)**: The Fraunhofer institutes are widely regarded as the world's best organization for applied research relevant to industry. The Fraunhofer is the public organization most responsible for Germany's export prowess in manufactured goods and the stellar reputation of German engineering.

- **Interuniversity Microelectronics Center (IMEC)**: IMEC is a world-leading research organization based in Leuven, Belgium. It is thoroughly international in character, employing 4,000 researchers from 90 countries and operating numerous R&D centers around the world, including in the United States. Given the reality that to carry out its mission, the NSTC necessarily must engage foreign partners, IMEC's institutional culture, financial model (no single firm or government accounts for a large share of its budget), and skill at convening competitors in productive collaborations are important points of reference.

- **Canada's Industrial Research Assistance Program (IRAP)**: IRAP operates under the auspices of the National Research Council of Canada and functions as a bridge between Canada's research base and the country's small and medium enterprises. IRAP enjoys a strong and growing reputation both inside and outside of Canada.

- **Advanced Research Products Agency – Energy (ARPA-E)**: A U.S. government research agency established with the intention that it become a "DARPA for energy," ARPA-E promotes research projects with revolutionary commercial potential in the energy sector. The agency was launched in 2009, and a 2017 performance review by the National Academies of Sciences, Engineering, and Medicine concluded that although not enough time had passed to determine whether its work would generate game-changing technologies, there were clear indicators that the agency was making progress toward its mission and goals.

- **Bell Laboratories**: Bell Labs was at one time the R&D arm of AT&T. Although it has since been broken up and absorbed by a succession of owners, Bell Labs in its heyday—which spanned most of the twentieth century—was recognized as the foremost research and innovation center in the world. Bell Labs is particularly noteworthy because it successfully engaged both in exploratory research (its scientists won numerous Nobel Prizes) and in innovation, where it pioneered transformational technologies such as the transistor (the basic building block of all digital products) as well as the first electrical-relay digital computer, the first system of satellite communications, the first silicon solar cell, the first electronic telephone switching system, and the first cellular telephone systems. According to one assessment, Bell Labs was "an ivory tower with a factory downstairs," and even researchers pursuing pure scientific discovery were well aware that their knowledge could and would be put to practical use.

Key Attributes of Semiconductor Research Organizations

Although these organizations differ substantially with respect to their role within national innovation systems, as well as in their structure and their operational practices, they share important attributes.

BUILDING NETWORKS

Semiconductor research organizations bridge the gap between research and application. All of the organizations cited above serve as "bridges" connecting the national research base with the needs of industry in the form of new products and industrial processes. This has three aspects:

- **They connect the research community**: This includes universities, public and private laboratories, and innovative small enterprises. This fosters an expert community that shares familiarity with relevant scientific themes being pursued across many scientific disciplines.
- **They establish close relations with the business community**: This creates a greater awareness of specific technological needs of industry as well as an eye toward potential commercial and industrial applications stemming from emerging scientific discoveries.
- **They are integrators**: Their infrastructure possesses physical and organizational characteristics that enables integration of knowledge drawn from multiple disciplines ("silo-breaking") with the practical needs of industry in the form of new products and industrial processes.

TECHNOLOGY INTEGRATION

In order to succeed in the bridging function, research enterprises must master the process of integration, convene multiple fields of science as well as companies with differing work cultures, and close the gap between the research world and industry to produce commercial products and manufacturing processes. The manner in which this is done varies from one organization to another, and all of the methods used should be considered in setting up the NSTC.

- **Expert staff and equipment**: The leading research organizations usually operate well-equipped physical sites staffed with highly competent engineers and scientists, where industry and academic partners pursue technology objectives in a common work environment (e.g., CNSE, IMEC, Bell Labs, ITRI, and Fraunhofer).
- **Forging connections across communities**: Several organizations have internal structures explicitly designed to bridge barriers between academic disciplines and between the research community and industry. In ITRI, these take the form of "technology integration laboratories"; at the Fraunhofer, the integration function is exercised by pairing internal "research units" with close ties to the science base with "business units" familiar with the needs of industry. IMEC is noteworthy for its success in convening an extraordinarily diverse community of researchers from many countries and academic disciplines in productive collaborations.
- **Knowledge sharing**: The best research enterprises have succeeded in creating vast and sophisticated knowledge-sharing and transfer networks linking various segments of the research and business communities. These are both formal (e.g., Fraunhofer) and informal, based on webs of personal connections and the fostering of communities of researchers (e.g., ITRI, IRAP, ARPA-E).
- **Network building**: IRAP and ARPA-E have no physical sites, but what makes them more than mere funding agencies is internal structures, methods, and specialized personnel focused on bridging the gap between research and commercialization. They do not simply issue grants and wait for results; they engage in hands-on supervision and mentoring of, and participation in, projects for their entire duration. If necessary, they draw in additional technological and business expertise, engage in strategic course corrections, and line up their performers with financial backers and industry partners. Both ARPA-E and IRAP are centered on a small elite cadre of empowered individuals who commonly

have backgrounds both in academic disciplines and the business world. IRAP Industrial Technology Advisers (ITAs) are viewed as “trusted advisers” to the projects they supervise. ARPA-E project teams include technology-to-market specialists whose only focus is to bring the technology in question to commercial fruition or industrial application.

CLEARLY DEFINED MISSION AND ROLE

At present, the NSTC’s mission and place within the existing semiconductor innovation system is not yet precisely defined—a threshold challenge that must be addressed soon. It envisions an institution that “tackles Moore’s Law transitions [and] post-CMOS [complementary metal-oxide semiconductor] research into new materials, architectures, processes, devices, and applications,” suggesting that the NSTC is expected to pursue technological breakthroughs requiring explorations of novel scientific themes, with at least some projects involving long time horizons. At the same time, it visualizes a center that “bridges the gap between R&D and commercialization,” suggesting a focus on the more prosaic task of applied research for industry that yields short-term results of immediate value. Experience suggests that a single research organization usually cannot successfully pursue both of these missions at the same time, with Bell Labs and IMEC representing important exceptions.

In seeking to clarify what the NSTC’s mission should be, policymakers should consider the roles of successful civilian research enterprises within their national systems of innovation:

- **Providing strategic focus**: Sematech’s mission was to conduct applied research with a very narrowly defined focus: to enable U.S. industry to regain world leadership in semiconductor manufacturing of silicon-based CMOS devices. It did not seek to develop revolutionary products or new process pathways but to improve, refine, standardize, and demonstrate manufacturing processes and tools in factory environments for the benefit of its members. The intended and actual result was not technological breakthroughs but a dramatic industry-wide improvement in U.S. semiconductor manufacturing competency and in the competitiveness of the materials and equipment industries needed to support that improvement.

- **Defining projects**: The Fraunhofer’s mission is very clearly understood to be applied research only. Its projects are of short duration (six months to two years) and are expected to produce useable results within that timeframe. As a result, the Fraunhofer’s projects yield incremental technological improvements with immediate practical and commercial applications, not breakthrough innovations. However, the cumulative effect of thousands of Fraunhofer-generated incremental technological achievements over many decades—frequently grouped together to develop broader competencies such as factory automation and green technologies—underlie the superb quality, performance, and reputation of postwar German manufacturing.

- **Building ecosystems**: ITRI sees itself as “the cradle of future industries,” an institution for creating new high-tech industries in Taiwan. Instead of engaging in basic research or pursuing technological breakthroughs, it scans the world for promising emerging technologies, acquires the intellectual property, and applies it in its own laboratories to develop and refine domestic manufacturing capability, often with astonishing efficiency and speed. ITRI’s breakthrough innovations have been organizational and institutional in character: the creation of new companies and industries by spinning off large pieces of itself; the pioneering of the foundry business model in semiconductors; and the methodical rationalization of domestic small businesses to form nearly complete industry chains.

- **Enabling scientific translation**: IMEC emphasizes exploration of fundamental science themes with potential relevance to industry. Because Europe is not a major base for large-scale semiconductor device manufacturing, IMEC seeks to ensure that Europe remains at the leading edge of semiconductor research and technology, maintaining a capability to scale up manufacturing at an appropriate moment. IMEC has proven particularly strong in enabling the development of world-leading semiconductor production and design equipment.

- **Conducting applied research**: CNSE's focus is on applied research in nanotechnology with applications in the semiconductor industry and, increasingly, in a wide range of other technology-intensive sectors.

- **Swinging for the fences**: ARPA-E was created solely to pursue transformational technological breakthroughs comparable to those of DARPA—achievements such as the internet, personal computing, GPS, smart weapons, and other technologies that collectively define key elements of the modern world. Like DARPA, ARPA-E has no research facilities of its own and executes its mission through a small, elite group of program managers who are accorded extraordinary decisionmaking authority and autonomy. ARPA-E does not engage in Fraunhofer-style "incremental" applied research—in baseball parlance, it "swings for the fences," seeking game-changing home runs rather than singles and doubles.

- **Connecting small business**: IRAP's mission is to support the technical improvement of small businesses across Canada's vast geographical space by connecting them with relevant segments of the country's research base. It does not perform basic or applied research itself but, like ARPA-E, relies on a small but highly skilled cadre of technology advisers to provide advice and dispense government funds to support promising private innovation efforts.

INDUSTRY ORIENTATION

Public-private partnerships combine public purpose with private flexibility. Features common to successful partnerships include "industry initiation and leadership of projects, cost-sharing, predictable limits to public commitments of resources, clear objectives, and learning through evaluation of measurable outcomes. Effective leadership and cost sharing can help motivate participants in a partnership to act in ways that advance their objectives."

In fact, the most successful "bridging" research organizations are all industry-led or structured to ensure their orientation toward industry needs. Although Sematech was 50 percent government funded, it was led by senior semiconductor industry executives and managers. ITRI and the Fraunhofer require most projects to be funded or cofunded by industrial partners, and the Fraunhofer is structured so that the more private money an institute attracts, the more public funding the institute receives from headquarters. Industry personnel commonly participate in the research itself. CNSE's research projects are cofunded by industry partners and pursue applied research themes of interest to those partners. Most ARPA-E projects originate from bid proposals by industry and academia for projects with commercial potential. The effect of such practices has been to channel government research funding toward research themes of relevance and importance to industry.

Industry leadership provides partnerships with technical expertise, experienced management, and proven flexibility while also enhancing the consortium's credibility with its members and the policy community. The experience of the Sematech consortium underscores the need for the commitment of senior management of the participating firms in a consortium.

INSTITUTIONAL AUTONOMY

Leading public research organizations enjoy significant autonomy from day-to-day government oversight. Sematech was loosely supervised by DARPA pursuant to a memorandum of understanding, with DARPA holding one nonvoting seat on the Sematech board and the consortium subject to annual assessments by the Government Accountability Office. Although ARPA-E is part of the Department of Energy, it exists outside the department's bureaucracy and operates on a separate budget, its director is appointed by the president, and the director reports only to the secretary of energy, not intermediate-level officials. The Fraunhofer is organized as a "public association" not normally subject to governmental direction. Although ITRI is subordinated to Taiwan's Ministry of Economic Affairs, in legal terms, it is a not-for-profit research organization and, in practice, enjoys wide latitude in planning and executing its technology and innovation policies. IMEC's management, not its public and private members, enjoys the final right to determine the key technologies the center will focus on. And CNSE operates within the SUNY system but is not subject to university-type rules on issues such as faculty tenure and human resources policies and sets its own research priorities in conjunction with its industry partners. Both Sematech and CNSE represented well-funded programs with strong bipartisan support, reflecting recognition of the strategic importance and long-term benefits of the semiconductor industry.

INSTITUTIONAL REPUTATION

The Fraunhofer enjoys one of the strongest brands in the research world, its name being virtually synonymous with the excellence of German manufacturing and engineering. The Fraunhofer itself was named for a German physicist and engineer who made groundbreaking scientific discoveries and also developed commercial technologies that enabled Germany to dominate the optical products industry for more than a century. The brand is a powerful recruiting tool and enables the formation of collaborations with the world's most technologically advanced multinationals and research organizations. IMEC is regarded as one of the foremost centers for microelectronics research in the world, and its main technology partners include nearly all leading semiconductor producers in the world. Largely due to ITRI, Taiwan is recognized as perhaps "the best place in the world to turn ideas into physical form."

The NSTC should aspire to build a brand with similar strength, recognizing that the process takes time. A good first step would be to find a different abbreviation—"NSTC" is already taken by the White House National Science and Technology Council. The NSTC designation could eventually be used as a seal of approval for the best U.S. semiconductor research centers and education and training programs.

STRONG LEADERSHIP

The quality and reputation of the leadership of a research organization is critically important to its success. ARPA-E's first director was Arun Majumdar, a mechanical engineer with a long record of achievement in academia, industry, and government, who by all accounts was responsible for the organization's rapid emergence as a driving force in energy research and innovation. Sematech recruits were drawn to the organization, in part, by the prospect of working alongside its CEO, the legendary Robert Noyce. Institutes are led by individuals renowned for achievements in science, engineering, and business who are usually faculty members at the institutes' affiliated universities. During a critical point in its history, ITRI was headed by Morris Chang, the eventual founder of TSMC and perhaps the most famous of Taiwan's high-tech pioneers. Bell Labs' extraordinary culture of creativity has been attributed primarily to a single individual, Mervin Kelly, who rose from employment as a researcher to become the organization's chairman.

QUALITY OF STAFFING

The world's leading applied research enterprises are elite organizations with extremely talented, technically competent, and creative personnel. Factors enabling the recruitment of talented employees include the brand and prestige of the organization, the nature of the work environment, and prospects for professional development.

- In the United States, ARPA-E program directors are recruited from diverse backgrounds in science, engineering, government, and industry, many of them having experience in two or more fields. Pay levels are exempt from civil service requirements, and directors enjoy considerable operational and decisionmaking authority. ARPA-E's flat horizontal structure, emphasis on informal teamwork, and absence of rigid hierarchies are important factors in recruiting creative talent.

- Elite research intermediaries are often closely linked with universities in which the curriculum is relevant to the organization's focus. The College of Nanoscale Engineering in Albany is both a university and an industrial research laboratory—students are attracted to CNSE by the prospect of doing cutting-edge research relevant to industry needs alongside experienced individuals drawn from industry backgrounds, who in some cases are also CNSE faculty members. Each Fraunhofer institute is tied with one or more adjacent universities, and the majority of the institutes' researchers are graduate or post-doctoral students that commit to half-time employment. ITRI is located next to two of Taiwan's best scientific research universities, Tsing Hua and Chiao Tung, which supply many of ITRI's scientists, engineers, and researchers.

- The best research centers attract young graduates in large part because employment in these organizations develops technical, leadership, and professional skills and relationships that translate into desirable jobs in private industry or in the science establishment. ITRI alumni go on to become leaders of Taiwanese industry. According to one estimate, a five-year commitment by students to training at a Fraunhofer institute enables alumni to double the income they could otherwise receive by entering industry jobs with only a PhD.

VENTURE INVESTMENTS

The NSTC should establish, structure, and manage a public-private investment fund that would contribute to the domestic semiconductor ecosystem. Both ITRI and the Fraunhofer manage investment funds that offer models for consideration:

- ITRI's Industrial Technology Investment Corporation (ITIC) is ITRI's wholly owned venture capital arm. Since it was established in 1979, it has invested over $4 billion and has played an important role in financing ITRI spinoffs, including the United Microelectronics Corporation. ITIC investments are backed by the deep technological expertise of ITRI itself and the global network of partnerships ITRI has developed with leading-edge manufacturers, universities, and technology-oriented investment entities.

- Fraunhofer Ventures assists spinoffs from the Fraunhofer institutes through seed and management support funding, business planning, technology transfer, technical training, and facilitating industry partnerships and external investors. The Fraunhofer frequently holds a minority equity stake in the new ventures.

- ARPA-E funds early-stage technology development and devotes a substantial proportion of its resources to enabling start-ups to commercialize technologies developed in its programs.

- CNSE incubates and spins off nanotechnology-based start-ups, usually created by its own faculty and graduates.

The ITRI and Fraunhofer investment funds normally invest in ventures that are also funded by private capital. The ventures themselves benefit from technology transfer, management training and business counseling, assistance in lining up external funding and relationships with established technology firms, and in some cases, incubation arrangements with the research institutes.

NETWORK STRUCTURE

Sematech began as a public-private partnership operating at one site, equipped with state-of-the-art tools and staffed by some of the U.S. semiconductor industry's foremost talent to address R&D themes of greatest urgency to the industry. Significantly, Mervin Kelly, who is attributed with forging the research culture that made Bell Labs one of the greatest innovation centers of all time, strongly believed that "physical proximity was everything; phone calls alone would not do. Quite intentionally Bell Labs housed thinkers and doers under one roof." In addition, as a central national hub, the NSTC can provide leadership, establish well-defined goals, and ensure that all major technological gaps are being addressed.

Importantly, however, although based in a single location, Sematech tapped into local expertise in every region of the United States by establishing centers of excellence in conjunction with SRC to pursue focused technological goals at the country's best research universities. (One of the very first Sematech/SRC centers of excellence, created in 1988, was in Albany, a forerunner of what evolved into CNSE.)

ITRI and IMEC offer similar organizational models featuring a single major center supported by a network of widely distributed regional and international research nodes. SRC has already created such a regional ecosystem in the United States, and the NSTC can draw upon it to address specific research needs, as Sematech did. IRAP and ARPA-E do not operate physical sites but offer good models with respect to their internal culture and techniques for bridging the space between research and application on a nationwide basis.

WORKFORCE DEVELOPMENT

Although semiconductor fabrication plants are highly automated, they do not run themselves. Any effort to expand U.S. capabilities in semiconductor manufacturing must ensure that a large enough workforce exists in the United State with the skill sets needed to staff new and expanded fabrication plants, supply chain firms, and design centers. SRC and U.S. research universities are partially addressing this challenge at the high end of the skills spectrum, turning out engineers and scientists with knowledge and skills relevant to the semiconductor industry. These efforts should be supported and, where necessary, should receive additional resources.

However, the largest proportion of workers in a semiconductor fabrication plant consists not of PhD engineers and scientists but technicians, operators, and support personnel with the myriad specialized skills needed to conduct some of the most complex and demanding manufacturing processes in human history. In addition, building a semiconductor facility requires construction workers with advanced skills, including installation of precision tools and construction of specialized systems for HVAC, water, power, safety, and exotic materials handling. There is a chronic shortage of workers with such skills in the United States, and any effort to expand U.S. semiconductor manufacturing capability will make this shortage more acute.

CNSE and manufacturers in the region around it, including IBM, GE, and GlobalFoundries, have supported the development of facilities and curricula at nearby community colleges to enable the training of such skilled technical "blue-collar workers of the future." Some of these efforts are exemplary models, but collectively they have not achieved sufficient scale to meet industry needs even in their own region, much less in the country as a whole. The NSTC would be in a position to address the skills challenge on a national scale while addressing the local contexts of the challenge. It can play a role in diagnosing and forecasting U.S. semiconductor workforce needs; identifying existing institutions and programs that are effective education and training vehicles; aligning incentives among state and local governments, community colleges and universities, and large and small firms; developing a set of best practices to facilitate scale-up where appropriate; and launching initiatives for addressing gaps both in thematic areas and in regions around the United States.

MISSION DEFINITION

The NSTC should be assigned or tasked with creating and defining a "moonshot vision"—a clear objective with widespread recognition toward which it can direct all of its resources and initiatives according to a timetable, with agreed performance milestones. The relationship between the NSTC and the existing elements of the U.S. semiconductor ecosystem in this effort must be clearly established and understood by all players. Absent that mission clarity, the NSTC will be vulnerable to the kinds of centrifugal forces that nearly destroyed organizations such as Fraunhofer and Sematech in their early years. Even if this is avoided, absent mission clarity, the NSTC will be at constant risk of frittering away its resources in scattershot activities.

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When the NSTC's mission is defined, the federal government should establish a process for periodically evaluating whether the NSTC is accomplishing its mission, together with recommendations for better performance. Sematech was evaluated at intervals by the Government Accountability Office, but the real measure of its success or failure was its progress toward its stated goal of restoring U.S. leadership in silicon-based CMOS semiconductor manufacturing by 1993—a target that was met.

PERFORMANCE ASSESSMENT

External review of a research agency's performance can play an important role in identifying institutional weaknesses and, in some cases, the need for course correction. Fraunhofer institutes are subject to regular performance audits by experts from the business and university communities. The government of France requires periodic performance assessments of all of its public research organizations by independent committees of experts with no connection with the organizations, who are often not French nationals.

Performance benchmarks for the NSTC will need to be established and refined, and the center itself must be subject to periodic external review. As a new organization that will take time to reveal its impact, the NSTC must show in the interim that it is following best practices with respect to organizational structure, metrics, and strategy.

The legislation creating ARPA-E set forth broad goals for the agency but left the task of developing and applying performance criteria and metrics to a congressionally mandated five-year review by the National

Academies of Sciences, Engineering, and Medicine (NASEM). Given that the NASEM review committee grappled with this task in considerable depth, its methods and conclusions should be considered in the current context. NASEM acknowledged that "all metrics are imperfect" but utilized several "external" metrics to benchmark the agency's performance:

- Publications in scientific journals, recognizing that the most novel achievements do not always get published in top journals;
- Patents, with the caveat that less than half of new-to-market technologies are patented and that process innovations are more likely to be held as trade secrets and not patented;
- The ability to attract follow-on funding from public and private sources; and
- Market engagement, in the form of new firms launched and adoption of innovations by industry.

The NASEM committee also conducted exhaustive case studies of individual projects and project portfolios to enable qualitative assessment of whether these advanced the agency's mission, addressing several questions:

- Whether the projects sought to achieve "transformational" objectives rather than incremental ones;
- Whether the projects contributed to transforming conservative, risk-averse attitudes toward innovation widespread in the energy and utilities sectors; and
- Whether ARPA-E's programs spurred the formation of new communities of researchers in specific fields.

Although external review is essential, the most important performance assessment for the NSTC should be its own internal, ongoing review of its progress toward its objectives. It should establish milestones for progress, collect performance data, and conduct regular intermediate evaluations. Among many suggestions, the NASEM committee that reviewed ARPA-E recommended that the agency implement an internal system of benchmarking its performance along the lines of the process the NASEM used to conduct its one-time assessment. Specifically, the NASEM suggested that the agency link data from its internal database of project-level metrics to program-level goals (including indicators of commercial and noncommercial outcomes), connect those goals to observable innovation metrics, and translate those metrics into a regular assessment of whether the agency is on track to achieve its mission and goals.

LEARNING FROM EXPERIENCE

Even ultimately successful public research organizations encounter major—and potentially existential—problems, frequently soon after launch.

The Fraunhofer struggled in its early years with corrosive internal disputes over whether its mission should be basic or applied research, as well as the hostility of established German research entities to a new organization that lacked a clearly defined role within the research system. Despite consensus on comparatively well-defined goals, Sematech's first years were characterized by disagreements over technology focus that were so serious that several founding members left the consortium.

A consortium centered on CNSE successfully developed technology for fabricating semiconductors on 450-millimeter wafers only to find that no device maker, including project participants, planned to use the technology in the foreseeable future. For some, this was a failure; for others, it was a research effort with shared costs that revealed a potential dead-end was valuable in itself.

ITRI faces chronic political pressure to distribute its research activities more broadly across Taiwan despite the major operational advantages associated with concentration of its activities at a single alpha site in Hsinchu. These problems, and the manner in which they were addressed, are as worthy of study by U.S. policymakers as the best practices of the same organizations.

In a similar vein, the NASEM committee that reviewed **ARPA-E** in 2016–17 recommended that the agency systematically accumulate data on initially promising technological pathways that failed and should not be further pursued. The committee suggested that the agency should explore publishing an annual, easily referenced lessons-learned document "focused on what performers learned does not work, for the benefit of the scientific community, to aid in the review of existing programs, and to serve as a reference for future programs." Such an initiative would undoubtedly provide ammunition for critics, but that concern is outweighed by its value to the U.S. semiconductor ecosystem.

The Need to Act Now

Winston Churchill is credited with first saying, "Never let a good crisis go to waste." Responding to today's exigencies, the United States can do well to learn from past experience.

Sematech succeeded in substantial part because the existential challenge posed by Japanese chipmakers fostered a sense of urgency and a concern that if action were not forthcoming soon, irreparable gaps would appear in the U.S. microelectronics ecosystem, with cascading adverse consequences for the U.S. defense posture and civilian economy. The result was the rapid launch of a major consortium with a well-defined mission. Here are some leading lessons learned from that effort:

- **Get an early start**: Brainstorming, road mapping, site selection, and recruiting efforts began well before Sematech was formally launched at the beginning of 1988.
- **Establish a clear objective**: An ambitious but achievable and precisely designed objective was established at the outset—world leadership in silicon-based CMOS manufacturing based on 0.35-micron design rules by 1993. Despite numerous hurdles, that goal was met. Buttressed by the trade agreement with Japan and Sematech's improvements in quality and productivity, the U.S. industry was able to achieve market share parity with Japan in 1992. By 1993, U.S. device makers were capable of manufacturing chips at the 0.35-micron node using entirely U.S.-made tools (a capability that was subsequently allowed to erode).
- **Maintain a research focus**: Research thrust areas were narrow, directly relevant to the task at hand and carefully defined, including lithography, multilevel metals, process technology, and furnaces/implants.
- **Stay the course**: Despite such advantages, Sematech encountered numerous obstacles during its early "shakedown" phase, and the same is likely to occur when the NSTC is launched. The sooner the effort is launched, the more likely such problems can be identified and addressed in real time. Then as now, the effort to ensure the continued existence of a leading-edge semiconductor industry chain in the United States was a matter of national security.

Accordingly, the NSTC should:

- **Develop a vision**: Establish technological milestones and provide the leadership needed to establish a resilient nationwide networked structure.

- **Identify common goals and platforms**: Successful research cooperation requires not only a shared vision but also agreeing on rules and conventions regarding who does what and where, identifying the common points of reference, figuring out how financial resources and equipment are shared, and creating mechanisms to resolve potential conflicts.
- **Figure out the appropriate funding model**: Public-private partnerships, which combine public purpose with private flexibility, are a diverse set. It is important to determine at the outset if the NSTC will be a funding institution (e.g., ARPA-E), operate like a Federally Funded Research and Development Center, or provide research services to members with matched funding from industry and an assured funding base from the government. Other supplementary approaches drawing on existing or hybrid models could be deployed as well.
- **Build on existing assets**: Build upon the very substantial microelectronics R&D infrastructure, leveraging what already exists in the United States. Use institutions that can identify and address gaps in conjunction with industry and seize opportunities to cooperatively build out that infrastructure.
- **Establish criteria for participation**: To enhance the brand and ensure the effectiveness of its network, the NSTC should establish the criteria for core and affiliated organizations to participate in the NSTC system.
- **Learn from others**: Draw upon and learn from the successes (and failures) of U.S. and foreign research organizations.
- **Engage with stakeholders**: Create a network that stakeholders and experts can share to develop a workable organizational model for the new entity, again in conjunction with existing models, such as the SRC.
- **Maintain long-term bipartisan support**: Long-term political support and the sustained funding it engenders is essential, as seen with the successful efforts of Sematech and CSNE at Albany. ■

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