# RADESA

RESEARCH AND DEVELOPMENT ECOSYSTEM ANALYSIS

POTOMAC INSTITUTE FOR POLICY STUDIES

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The Potomac Institute for Policy Studies is an independent, 501(c)(3), not-for-profit public policy research institute. The Institute identifies and aggressively shepherds discussion on key science and technology issues facing our society. From these discussions and forums, we develop meaningful science and technology policy options and ensure their implementation at the intersection of business and government.

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# EXECUTIVE SUMMARY

The United States Department of Defense (DOD) uses microelectronics in nearly all of its critical systems. Since the beginning of the industry, semiconductor technologies have not only provided strategic advantages for national security, but have also transformed daily life. The wide ranging transformative power of microelectronics has caused the microelectronics business to grow from a niche industry supporting the DOD into the massive global semiconductor industry we know today. As it has grown, the semiconductor industry has changed in ways that have made it difficult for the DOD to access state-of-the-art (SOTA) technologies needed for its systems.

There are fundamental differences today in the business models of commercial microelectronics manufacturers, who want high volumes and short lifetimes, and the DOD that needs low volumes for very long lifetimes. Where the DOD was once the main customer of the semiconductor industry, it now takes a backseat to the global commercial market that purchases the overwhelming majority of today's electronics. In the eyes of microelectronics manufacturers, the DOD is a minor customer with unusual needs and inconvenient methods for doing business. This leads to access challenges for the DOD in getting the parts they need. Moreover, given the global nature of the worldwide microelectronics supply chain, the DOD also faces security concerns with respect to counterfeit parts, malicious alterations, etc.

The DOD needs a comprehensive strategy for assured access to secure microelectronics to meet its needs now and in the long term. A key way to assure availability and access to needed microelectronics is for most segments of the semiconductor industry and R&D ecosystem to have strong domestic representation. A strong domestic supply chain eliminates the DOD's reliance on components that are produced in or pass through foreign nations. As the industry rapidly evolves, it is important to understand weaknesses and vulnerabilities in the domestic US semiconductor industry and R&D ecosystem, and to develop strategies to address them.

The Potomac Institute conducted a six-month study to examine the domestic semiconductor R&D ecosystem with the goals of identifying key vulnerabilities, or gaps, that prevent effective technology transition to domestic commercial production capabilities, and make recommendations to close those gaps. The Potomac Institute also examined what factors impede the DOD's ability to effectively transition technologies and promising innovations to commercial industry. These recommendations are aimed at helping the DOD ensure access to key microelectronics research capabilities.

## Key Findings

From the data gathered and analysis performed, the Potomac Institute developed the following findings:

**There is a serious lack of prototyping capabilities for emerging microelectronics technologies in the US.**

**The US is weak in key segments of the global semiconductor supply chain.**

**The US has strong commercial R&D efforts in low power, memory, and transistor scaling technologies.**

**Major roadblocks still exist to DOD technology transition for state-of-the-art innovation.**

- Public R&D funding ends too early to sufficiently lower commercial risk for investing in fully maturing technologies.
- Traditional US government (USG) contracting mechanisms are far too slow and restrictive for most companies.
- High-volume manufacturing business models are incompatible with DOD's wide ranging, custom low-volume needs.
- DOD volume is too small to impact major commercial technologies once they have reached market.

### *Conclusions Regarding the US R&D Ecosystem*

The analysis of the domestic semiconductor R&D ecosystem led to the conclusion that the semiconductor R&D areas most in need of direct DOD investment are:

1. Hardware Security
2. Advanced Packaging and Heterogeneous Integration
3. Non-von Neumann Computing Architectures

Increasing R&D efforts in these three areas will significantly improve the DOD's ability to build the capabilities necessary to ensure access to emerging technologies needed for future capabilities.

*Recommendations*

Based on the findings and conclusions of this study, the Potomac Institute developed the following five recommendations to help the DOD close critical gaps in the domestic semiconductor R&D ecosystem, improve its access to domestic R&D capabilities, and increase its ability to transition technologies to the commercial industry:

1

**The DOD should increase its investments in later-stage R&D and prototyping capabilities.**

Forming independent, public-private organizations to spur prototyping and technology transfer in each of the three key areas of hardware security, advanced packaging and heterogeneous integration, and non-von Neumann computing architectures may be warranted. These prototyping capabilities should also be used to serve the low-volume production needs of the DOD.

2

**The DOD should invest in collaborative R&D efforts with industry in the specific areas of Hardware Security, Advanced Packaging, and Non-von Neumann Computing Architectures.**

Investing in hardware security will 1) help meet the DOD's significant needs for protecting against hardware vulnerabilities and 2) increase adoption of more advanced capabilities available in the commercial industry. Investing in advanced packaging R&D will help the US close its gap in commercial representation in that section of the supply chain, which is becoming increasingly critical to enhancing performance of SOTA technologies. Investing in non-von Neumann computing architectures now, while many areas of the field are still young, can greatly accelerate disruptive advancements and give the DOD decisive advantage in a range of applications.

3

**The DOD should partner with US and allied semiconductor companies for pre-state-of-the-art technology development and early access to IP.**

Pursuing bilateral R&D agreements with companies in the areas of low power integrated circuits (ICs), advanced memories, and scaling technologies can increase DOD access to emerging technologies in these areas that will have a major impact on the industry.

4

**The DOD should no longer used Federal Acquisition Regulation (FAR)-based contracts for R&D programs.**

FAR-based contracts were meant for traditional product and service acquisition, not research and development. Other Transaction Agreements (OTAs) were specifically designed as funding mechanisms for research and are much more flexible and preferable to non-traditional commercial companies.

5

**The DOD should aim to align with industry in its R&D and prototyping efforts, while ensuring that unique DOD needs are met.**

Aligning technology development efforts with private industry needs maximizes the ability of the DOD to transition promising technologies to achieve wide commercial adoption, and increasing the ability to maintain trusted access to those technologies far into the future. Completely following or copying industry, however, will not fulfill all of DOD's needs.  Defense systems will always need unique capabilities as critical technology differentiators, and the DOD needs to ensure that the development and prototyping of technologies to meet these unique needs continues to occur.

# BACKGROUND

Microelectronics are critical assets of the Department of Defense (DOD). Virtually all United States national security systems have microelectronics as core components, from aircraft to satellites to computing and encryption systems. Looking to the future, the DOD seeks to dominate the battlefield with advanced capabilities in data analytics, artificial intelligence and autonomous systems, radar and wireless communications, space technologies, sensors and "Internet of Things" (IoT) systems, and biomedical technologies. The President's recently released National Security Strategy has placed an emphasis on more rapidly fielding new inventions and innovations to serve our national security, as well as protecting our data and the infrastructures that store and transmit it – for which microelectronics are a critical part.[1]

Unfortunately, the DOD is far from a typical customer for the semiconductor industry; simply guaranteeing basic *access* to needed microelectronics is a major concern. The DOD needs only low volumes of parts that are typically deployed for long lifetimes on the scale of decades, and must securely perform unique functions in environments much more extreme than typical commercial use. In contrast, the global commercial microelectronics market has billions of users who typically need parts for limited lifetimes and insist on few security measures. The DOD's priorities of security, uniqueness, and high performance are necessary, given its mission. Insufficiently secure microelectronics can contain vulnerabilities that compromise performance, leak sensitive information, steal intellectual property (IP), or render systems ineffective when needed. The DOD will always have a need for specialized and customized SOTA components to maintain dominance over adversaries that have access to the same commercial parts as we do.[2]

The US Government's (USG's) need for legacy parts in an industry where rapid obsolescence is the norm is problematic from the commercial perspective. The typical DOD program takes 10 years to develop a new system,[3] whereas the technology refresh cycle of the microelectronics industry is two years.[4] Even if a systems engineering program can access leading-edge, commercially available technology at its inception, by the time the first units of that complex system are produced, the microelectronics they use are already considered commercially obsolete. The problem of obtaining obsolete components is compounded by the long lifetimes of most DOD systems,[5] which all eventually need replacement parts to maintain performance throughout their lifetimes. Programs routinely find that critical parts for DOD systems are no longer sold by the original manufacturer or not manufactured by anyone at all.[6]

Another major factor in the rising difficulty of the DOD to access SOTA microelectronics is the growing cost of R&D investment necessary to develop SOTA manufacturing processes and fabrication facilities. The continuation of Moore's law has only been made possible through large increases in R&D investments, which has meant that fewer and fewer companies can commit the substantial resources required to compete at the industry's leading-edge. Companies known as integrated device manufacturers (IDMs) that both design and manufacture integrated circuits (ICs) are rare today, as most companies have narrowed their business models to either design (fabless) or manufacturing (pure-play foundries). This has had the effect of significantly reducing the number of entities with the ability to actually manufacture SOTA microelectronics. Those companies that still do compete at the leading edge operate with business models that require them to maximize product volume and minimize design and product development – so-called non-recurring engineering (NRE) costs. This greatly hinders the DOD's ability to find manufacturing partners willing to meet its low-volume, high-mix needs. Even opportunities the DOD might have to access leading-edge technologies at the development stage are hampered by restrictive and onerous acquisition regulations – the Defense Federal Acquisition Regulations Supplement (DFARS) and International Trade in Arms Regulations (ITAR). This often causes commercial companies to go outside the US to conduct R&D and prototype new technologies.

The best strategy to ensure access to critical microelectronics is not to copy or control the technologies developed by private industry, but to partner with private industry to make full use of its R&D and manufacturing capabilities, and its process (IP) necessary to keep producing those technologies once the commercial industry decides they are obsolete. The US government should also seek to eliminate single-point-of-failure risks in the future by enabling a fully domestic semiconductor supply chain, from design to distribution.

Given the wealth of relevant expertise within US borders, creating such a domestic supply chain is not an insurmountable challenge. Though the industry is becoming more globalized, US companies and universities still dominate at the cutting edge of chip and system design, for example. Key parts of this process will be identifying which segments of the global semiconductor supply chain have weak US representation or critical security vulnerabilities, and leveraging the right parts of the domestic R&D ecosystem to strengthen them. By working with industry and shoring up US domestic R&D capabilities, the DOD can pave the way to ensure future access to needed trusted parts, thereby maintaining the technological overmatch of the US military.

### *Purpose of Study*

The Research and Development Ecosystem Analysis (RaDESA) study provides the Office of the Deputy Assistant Secretary of Defense (ODASD(SE)) and the Defense Microelectronics Activity (DMEA) with an assessment of the strengths and weaknesses of the domestic semiconductor R&D ecosystem. The specific goals of the RaDESA Study are:

To assess the current state of the domestic microelectronics research and development ecosystem, focusing on activities most relevant for DOD needs.

To recommend ways to improve weaknesses identified in the domestic industrial R&D ecosystem.

To recommend strategies for overcoming major roadblocks to the DOD's ability to develop innovations and effectively transition R&D technologies into the domestic commercial industrial base.

# METHODOLOGY

For this study, the Potomac Institute surveyed market data covering the commercial semiconductor industry and conducted a rigorous analysis of the semiconductor R&D ecosystem. The Potomac Institute carried out comprehensive data collection – identifying market and industry reports, collecting additional data available from multiple publicly available sources, and obtaining insight and clarifying data from interviews with experts. Following these steps of data collection, an in-depth and structured analysis of the data was performed, wherein the study team evaluated the gathered data and drew on their expertise to identify and assess key trends and relationships. Analysis included the assessment of geographic, financial, technical, and market data, as well as the definition of evaluation criteria and the formulation of conclusions through structured discussion. Potomac Institute expert analysis identified connections between DOD applications, R&D areas, organizations conducting R&D, their commercial partners, and supply chain stages. The study team spoke with a diverse group of experts who have a wealth of knowledge about microelectronics, fabrication processes (including low-volume high-mix manufacturing and split-fabrication), R&D efforts, the commercial semiconductor market, and DOD acquisition policies. Finally, the strengths and weaknesses of domestic R&D capabilities were ranked based on our identified evaluation criteria, which were based on the level of domestic work being done in these R&D areas and their respective importance to the DOD. A more detailed outline of this three-step methodology follows in this section.

### *Data Collection*

To collect data for this study, a number of resources were employed. A mix of market research reports were collected, ranging from large-scale, semiconductor industry-specific market databases, to market forecasts and business models for semiconductor-related R&D consortia, as well as those of individual companies' R&D efforts. These resources provided data on trends in R&D, US market shares of different aspects of the global supply chain, geographic locations of R&D efforts, individual public-private organizations' research activities, and partnerships between public-private organizations and commercial companies in the semiconductor industry. In surveying R&D efforts relevant to the semiconductor ecosystem, the Potomac Institute identified two major types of R&D: public-private collaborative R&D, and "captive" commercial R&D. Public-private R&D (PPRD) efforts are pre-competitive and involve a mix of shared resources (funding, equipment, expertise, etc.) from public and commercial resources. Given the public aspect of these efforts, detailed information about PPRD activities is publicly available. Captive commercial R&D efforts are internal to individual commercial companies, which usually involve late-stage R&D[7] but can extend to earlier stage proof-of-concept work. Given the fully private and competitive nature of captive commercial R&D, detailed information is more difficult to obtain. The Potomac

Institute therefore chose to focus mainly on studying the PPRD aspect of the domestic R&D ecosystem.

Market research and forecasts used include *The McClean Report* from IC Insights and *The Global Semiconductor Market Forecast Report* from Inkwood Research. *The McClean Report* provided background on global economic trends in the IC industry, organized by supply chain stage and by IC product categories. It also provided a future outlook of growth in the IC industry. *The Global Semiconductor Market Forecast Report* from Inkwood Research also provided a high-level analysis of IC industry trends, especially in reference to the military and aerospace section of the market and trends. Market databases used include SEMI's *World Fab Forecast* and *Worldwide OSAT Database*. *The World Fab Forecast* provided comprehensive fab information, and was used to locate fabs dedicated to R&D and to provide data on what those fabs work on. *The Worldwide OSAT Database* provided information on all outsourced assembly and test centers (OSAT). The study also utilized the DMEA's list of accredited trusted suppliers. Information on domestic R&D organizations was analyzed from each organization's website and annual report, as well as public-private R&D consortia.

To investigate a diverse set of microelectronics related organizations, the Potomac Institute performed a comprehensive literature review, covering a wide range of public-private organizations located in the US focused on semiconductor R&D. Then it focused on analyzing relevant data including each R&D facility or consortia's focus, what type of R&D capabilities the research center had (e.g. design, modeling and simulation, testing, prototyping, and reverse engineering), and each entity's engagement with the semiconductor supply chain.

Funding information was also examined for each R&D organization to reflect the size of their efforts. For some organizations, only records of government funding were available, despite the centers also explicitly receiving revenue from private industry. These budgets therefore represent a lower bound. Overall, this only introduces minor uncertainties in the final analysis, as more complete data were generally available for the larger organizations. These cases are noted in Appendix C.

The Potomac Institute also worked to identify and evaluate challenges and best practices for effective R&D technology transition in general, studying over 20 reports and publications that focus on the subject. Reports came from a diverse and international set of sources – both government and private – and ranged from specific evaluations of the successes and challenges of individual R&D organizations to general research on public-private partnerships and technology transition. All reports were obtained through open source methods.

Subject matter experts also provided a wealth of knowledge on specific areas of R&D in the semiconductor industry. Discussion and interviews with them provided hand-on, case study-like detail to broaden conclusions drawn from data collected from other sources.

### *Data Analysis*

Following the collection of data, a rigorous analysis was performed, with the goal of assessing the strengths and weaknesses of domestic PPRD capabilities and the effectiveness of technology transition from domestic R&D to commercial and DOD applications. A distinction was noted between US-based R&D organizations and foreign-based organizations conducting R&D in the US. Companies operating in the US were noted as either domestic or foreign owned, and it was noted whether these companies were trusted, accredited suppliers. Data on commercial companies' partnerships with domestic PPRD organizations or consortia were analyzed, as well as any foreign commercial membership in domestic PPRD centers. R&D and pilot production facilities owned by each commercial company were also identified. Once the main categories of the R&D ecosystem were identified, relationships were made between the categories – specifically, relationships 1) between companies sponsoring R&D and the PPRD centers; 2) between PPRD Centers and the areas on which they focus R&D; and 3) between R&D and the DOD applications for which they are needed.

Finally, areas of domestic R&D were evaluated depending on a number of factors, including the number of organizations working in each area, the total number of unique commercial transition partners with all relevant organizations, the total funding (from available data) of all relevant organizations, and the number of relevant organizations with prototyping capabilities. This analysis provided the study team with the "gaps" in the R&D ecosystem. These results were used to develop recommendations of how to strengthen and promote a more fully domestic R&D ecosystem and semiconductor supply chain.

#### *Surveying the Commercial Supply Chain*

The Potomac Institute examined the level of representation of US companies in the collected market data in individual supply chain stages. Six specific supply chain stages were identified through standard industry classification.[8,9] The identification of these stages was important to determine which supply chain stages are well supported by domestic R&D, and which are vulnerable and need more support from domestic research efforts. The supply chain stage categories are as follows:

- Chip Design Tools
- Chip Design
- Equipment
- Mask
- Fab
  – Integrated Device Manufacturer
  – Foundry
- Packaging and Testing

Stages where the US has low representation – defined in this study as fewer than one third of total market share – were studied in greater detail to determine the major factors that contribute to low US representation. The Potomac Institute also examined all stages of the supply chain to identify any vulnerabilities specific to DOD security concerns, such as high risks of malicious insertion or loss of critical information.

### *Conceptualizing the Domestic R&D Ecosystem*

A comprehensive effort was made to construct an organized view of the R&D ecosystem for DOD-relevant applications. This involved mapping technology development and transition through four stages, from DOD applications to the commercial companies in the semiconductor supply chain. Three different figures were generated, a map showing the geographic spread of domestic R&D operations, a table showing the relative importance of individual R&D areas to critical DOD application needs, and a heat map showing the relative strength of each R&D area in the public-private sphere of the domestic R&D ecosystem.

The Potomac Institute study team identified six categories relevant to semiconductor R&D for DOD application needs based on an existing categorization used by the DOD. This existing categorization, listed below, was provided to the study team by the Deputy Assistant Secretary of Defense's office of Systems Engineering (DASD SE).[10]

- Data Analytics
- Autonomy and AI
- Radar and Wireless Communications
- Space
- Sensors and IoT
- Biomedical

Next, 13 areas of domestic R&D efforts were identified and defined by the Potomac Institute. These 13 areas were arrived at after surveying and harmonizing a variety of different categorizations of semiconductor R&D areas put forth in the aforementioned market reports.[11,12,13] The 13 R&D areas are defined as follows:

1. **Advanced Packaging and Heterogeneous Integration:** Research into new and improved ways to combine separately produced ICs into a single system. Research in this area is devoted to developing new and improved ways of packaging ICs into single systems for improved performance, wider functionality, and smaller size. 2.5D and 3D chip designs and packaging, as well as System on Chip (SOC) technologies are specific examples that fit into this R&D area.

2. **Bio-electrical Integration:** Research into technologies that would allow biological systems to interact seamlessly with semiconductor systems.[14]

3. **Hardware Security:** Research into new ways to protect the confidentiality and integrity of computing systems from hardware based attacks. Research in this area ranges from protecting and securing data stored and manipulated by microelectronics systems to the IP and hardware components of the semiconductor industry supply chain.

4. **Low Power:** Research into the improvement of energy efficiency of microelectronics systems. This includes the development of new systems that consume far less power to operate than traditional systems as well as the improvement of energy efficiencies of existing systems.

5. **Manufacturing Processes:** Research into improving existing manufacturing processes for ICs and developing processes for new technologies.

6. **Memories:** Research into improving data storage capabilities. Primary avenues of research include 3D memory structures and fast, non-volatile memories. Research in this area focuses on the application of new materials and/or devices to advance the speed, size, energy efficiency, and stability of memory storage technologies.

7. **MEMS:** Research into the invention and development of existing micro-electro-mechanical systems (MEMS) or systems that use electrical signals to cause non-electrical changes (mainly movement). Research in this area can include the invention and development of new MEMS, the adaptation of existing MEMS for new applications, and the improvement of manufacturing processes for MEMS.

8. **Non-von Neumann Computing Architectures:** Research into non-traditional computing architectures. The current standard computing paradigm is based on linear, step-by-step, instruction-based computing algorithms that pull a piece of data from memory, perform a manipulation (computation), and return data to memory. Research in this area encompasses creating and developing new computing architectures that do not follow the traditional computing architecture described, which includes (but is not limited to) quantum computing, neuromorphic computing, and other computing architectures associated with machine learning. Major applications for this R&D area include improving machine learning capabilities.

9. **Novel Materials and Devices:** Research into new devices, either incorporating new uses for traditional complementary metal oxide semiconductor (CMOS) materials or incorporating non-traditional CMOS materials into existing semiconductor systems. The most broadly defined of the R&D areas, this research focuses more on the discovery and integration of new materials and/or the creation and development of new devices and less on the specific uses of these new materials and devices.

10. **Photonics:** Research into components and systems that use light instead of electrons for data gathering, transmission, and storage. This research focuses on the application of photonics devices and their integration into larger semiconductor systems.

11. **RF/Wireless:** Research into improving capabilities for transmitting electromagnetic signals. Radio-frequency (RF) signal transmission, detection, and conversion are of significant use to a wide range of DOD capabilities, a more narrow set of applications in wireless communication is of high importance to many commercial industries.

12. **Scaling:** Research into continued shrinking of component (i.e. transistor) size that SOTA microelectronics fabrication processes can produce. The current leading-edge transistor size is 10nm, with technology roadmaps of industry leaders planning to move to 7nm, 5nm, and 3nm.[15] Historically these production methods have involved silicon, a small number of dopant materials, and photolithography. The latest advancements, however, have seen the need to incorporate a wider range of materials. Research in this area, however, is characterized chiefly by its goal of producing smaller transistors at similar manufacturing speeds and yields.

13. **Sensors:** Research into the use of traditional and non-traditional semiconductor components and systems for data gathering. This research includes using new materials and devices as sensors, as well as developing new uses for existing sensors.

Given the wide range of R&D conducted in the US – spanning all nine DOD-defined technology readiness levels (TRLs),[16] and ranging from fully public R&D conducted at universities and national labs to fully private commercial R&D – the Potomac Institute chose to focus on public-private collaborative organizations that chiefly conduct mid-range R&D spanning the commonly referred to valley of death.[17] To be considered, such organizations needed to meet the following criteria:

- A focus on R&D efforts reasonably characterized as being within the range of TRLs 4-7.
- Experimental facilities to provide prototyping, testing, design, modeling and simulation, or reverse engineering capabilities.
- Active engagement with industry members through a formal organizational process (i.e. membership, partnership, or established customer base).
- A mixture of public and private funds, and a collaborative operational model (fully private labs were excluded).

Using these criteria, the Potomac Institute generated a list of organizations conducting research and development in the US within this defined scope and collected further information on organizations on that list. The generation of this list was based on a comprehensive internal database the Potomac Institute compiled of R&D consortia and private industry research efforts, as well as existing internal expertise. This list of organizations was made up of both centers that are part of larger federal R&D networks, like Industry-University Cooperative Research Centers (IUCRCs) and Engineering Research Centers (ERCs), and independently operating centers, such as the Information Sciences Institute at the University of Southern California. Further information collected on each organization included funding levels, research focus, research capabilities, and industry partners. The list of industry partners was gathered from publicly available data regarding consortia membership and available market reports on R&D trends in the industry. This sequence of identification was critical to the later task of determining the success of technology transition from R&D to industry commercialization.

### *Clarifying Relationships in the R&D Ecosystem*

The next step in the rigorous analysis conducted by the Potomac Institute's study team was to determine interrelationships among different parts of the semiconductor R&D ecosystem. Three relationships were identified as critical for fostering a fully domestic R&D ecosystem: the relationships between DOD applications and R&D areas, R&D areas and R&D organizations, and R&D organization and industry partners. This analysis highlighted the flow of R&D efforts through increasing TRLs, and finally to industry applications.

In order to analyze which R&D areas were relevant to DOD application needs, the study team employed a variety of techniques and resources. Using both Potomac Institute expert technical analysis and knowledge of semiconductor capabilities, the team connected the thirteen R&D applications to the six DOD applications. These relationships were determined with a distinction made between areas of R&D *critical* to a given DOD need and R&D areas *relevant* to a DOD need. For example: for the DOD application radar and wireless communications, there are four *critical* R&D areas (MEMS, hardware security, advanced packaging and heterogeneous integration, and RF/wireless), and three *relevant* R&D areas (novel materials and devices, manufacturing processes, photonics). Each R&D area showed criticality or relevance with at least one DOD need. The resulting lists of relevant R&D areas for each DOD application are shown in Appendix B.

Beyond connecting domestic R&D efforts to DOD needs, the study team also conducted a detailed analysis tracing the relationships between research organizations and the categorized R&D areas. This analysis was necessary to understand where R&D is taking place, the extent to which it is funded, and who may be transitioning results of this research into commercial applications, both domestically and abroad. In order to determine which areas each R&D organization was working in, the Potomac Institute study team performed an analysis of publicly available information on each organization's R&D activities, studying program descriptions, research publications, and available progress reports from organizations being studied. The team determined two broad categories of R&D activities at each organization, the first being a list of *all R&D areas* each organization is active in, and the second being a list of up to two areas that were the *primary focus* of any given organization. For example, the AIM Photonics Manufacturing Innovation Institute (AIM Photonics MII) focuses mainly on photonics research, but also has R&D efforts in sensors and RF/wireless application, in aspects where advanced photonics capabilities are involved. The Potomac Institute also identified the types of R&D activities each organization performed – categorized as prototyping, design, modeling and simulation, and reverse engineering.

The final aspect of clarifying relationships in the R&D ecosystem consisted of linking commercial companies to the PPRD centers with which they partner. As mentioned in the previous section, identifying these connections was especially critical to assessing the effectiveness of the domestic R&D ecosystem in transitioning technologies from R&D to commercial applications. In order to determine how industry partners engaged with PPRD centers, the study team analyzed publicly available information from the PPRD centers detailing industry membership lists, making an effort to also note major semiconductor companies that did not participate with identified R&D organizations. This analysis was critical, given the fact that research being conducted domestically is of no use to the DOD from a trust and security standpoint if the resultant technology is transitioned to industry based in foreign, unallied nations.

### *Identifying Strengths & Weaknesses in the R&D Ecosystem*

In order to assess gaps in the R&D ecosystem that the DOD needs to strengthen, strong and weak areas of R&D were determined. Organizations were evaluated by using multiple figures of merit, which included amount of PPRD funding, number of domestic commercial transition partners, and the capability of conducting late-stage prototyping of new components. In addition to the evaluation of strengths and weaknesses (by R&D area) of the domestic R&D ecosystem, the Potomac Institute also considered the importance of R&D areas to the DOD's application needs. It was also noted which R&D areas receive especially strong or weak R&D interest from domestic commercial companies. The resulting combined analysis of the domestic PPRD ecosystem, the DOD's application needs, and captive domestic commercial efforts was used as a basis for generating findings and recommendations as to which R&D areas the DOD ought to invest in.

### *Addressing Roadblocks to Innovative Collaboration with Commercial Industry*

In addition to identifying specific gaps in the R&D ecosystem, the Potomac Institute worked to identify commonly occurring challenges to effective technology transition and possible solutions that have been shown to overcome them. To identify such challenges, the study team relied on a large body of literature it has gathered, consisting of over 20 reports published in recent years, as well as significant in-house expertise and discussions with experts on successfully creating and managing organizations and government programs devoted to technology transfer, late-stage R&D, and prototyping. In analyzing the reports and information gathered from experts, the study team identified the most commonly expressed problems, drawing them into a short list of findings. Possible solutions to these common problems were gathered from a combination of information in the reports examined and Potomac Institute expertise. The most promising solutions for the DOD were identified and used as the basis of forming recommendations.

To reiterate, the Potomac Institute team's assessment of the strengths and weaknesses of the domestic R&D ecosystem used the following methodology. For any given R&D area's domestic representation to be considered strong, it must: 1) have a high number of organizations pursuing research, 2) include organizations whose research budgets are collectively large enough to conduct meaningful R&D, 3) be critical to a high number of DOD application needs, 4) have affiliations with a high number of domestic companies for the purpose of technology transition. Areas with poor results in several of these areas were considered weaknesses in the domestic R&D ecosystem.

# FINDINGS: ASSESSMENT OF THE DOMESTIC SEMICONDUCTOR ECOSYSTEM

In order for the DOD to develop an effective microelectronics strategy, it must first have a detailed understanding of the current commercial semiconductor ecosystem. The following section begins with a detailed description the state of the global semiconductor industry supply chain, broken down by supply chain stage and depicted in terms of the foreign and domestic representation at each stage. Major findings regarding weaknesses in US representation and other major vulnerabilities for the DOD in the global semiconductor supply chain are discussed. Following that, the analysis results of the public-private domain of the R&D ecosystem are shown, detailing relative strengths and weaknesses in funding and capabilities for technology transition to commercial industry. Further analysis of the R&D ecosystem is discussed, evaluating each individual R&D area from the perspective of domestic R&D strength and importance to DOD applications.

***Domestic Presence in the Global Semiconductor Industry***

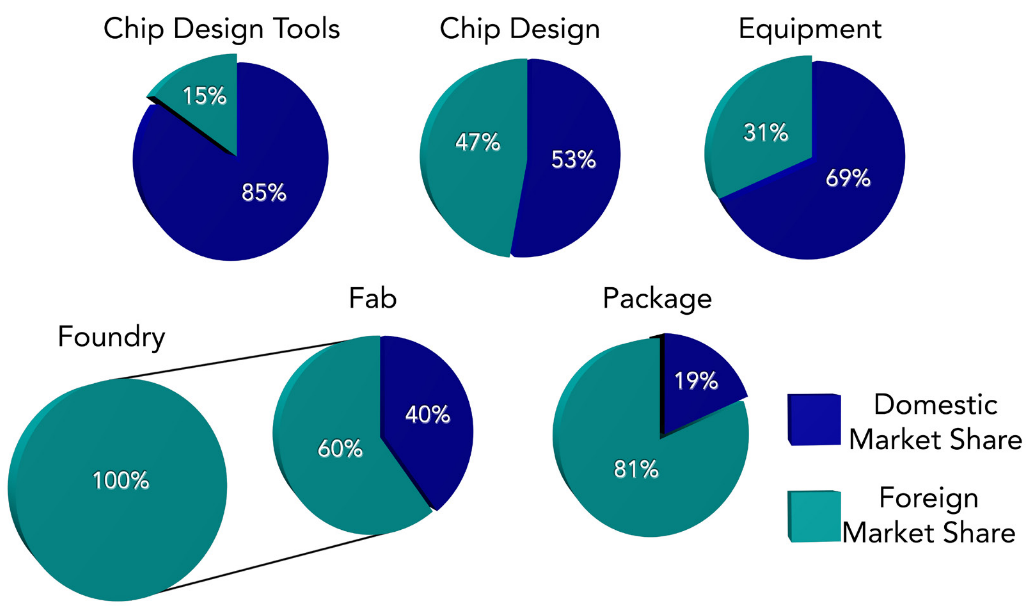



Figure 1.
US Domestic and Foreign Market Share by Stage in Semiconductor Production.

Overall, US companies represent nearly half of all global semiconductor industry sales, having re-gained the lead from Japanese companies in the mid-nineties (an overall market share level that the US has steadily maintained since then).[18] Though the US may be a dominant player in the industry as a whole, its relative strength at each stage in the supply chain varies significantly. Figure 1 shows the breakdown of global market share of US companies by major segments of the semiconductor supply chain. The percentages of domestic vs foreign market share were calculated using the total revenues (in dollars) of companies located within vs outside of the US, not by chip volume or wafer capacity. As the figure shows, the US is the clear leader with regard to manufacturing chip design tools, representing roughly 85% of global market share. The US is also relatively strong compared to the rest of the world in chip design (53% of global market share), manufacturing equipment[19] (at least 54.6% of global market share), and in fabrication (42% of global market share).[20]

*Finding: The US is weak in key segments of the global semiconductor supply chain.*

It is also immediately apparent that the US is weak in the packaging and testing segment of the semiconductor industry, with only 19% of global market share. This fits into the long running trend of IC suppliers sourcing support services oversees. Outsourced semiconductor assembly and test (OSAT) companies gained a market niche in Asia over past decades, as the packaging and test stage has historically been one of the least sophisticated and technical stages of the supply chain. Asian companies have come to dominate the sectors of package and test, representing 55% of the market and hailing predominantly from Taiwan, China, and Singapore.[21] This is a development the US should be uneasy about, because microelectronics packaging and testing is an increasingly important stage in the supply chain. Historically, packaging was a minor process consisting of enclosing chips in protective materials (usually plastic), connecting their I/O ports to external pins, and adding a label to identify the chip type and lot. Today, packaging has become so sophisticated as to determine a large part of the chip's performance. Recent trends in microelectronics have moved towards combining different components (processor, memory, sensors, converters, etc.) in a more compact form, stacking them vertically on a single package, or die. This new direction of engineering is known as advanced packaging and involves heterogeneous integration and 3D/2.5D technologies. Significant aspects of a module's functionality are now determined by the advanced packaging step. According to Yole Dévelopement, revenue for advanced packaging services was nearly $25 billion in 2017 and is forecast to reach $33 billion by 2022.[22] The US's weakness in this area will only become more critical in the future if nothing is done.

Two other critical weaknesses were identified. With the rise of the fabless business model in the semiconductor industry, the fabrication stage of the supply chain has split into companies that retained the ability to fabricate the chips they designed (known as integrated device manufacturers, or IDMs) and companies that specialized solely in the manufacturing process (known as pure-play foundries). The pure-pay foundries focused on selling their services to the increasing number of fabless microelectronics companies.[23] Looking at the IDM and pure-play foundries separately, it is noted that Intel, the world's second largest semiconductor company[24] makes up a majority of the US contribution to the global market share of the fab segment of the supply chain. This is, however, not necessarily a weakness for US industry, as Intel is a US company. When looking at the foundry part of the fab segment of the supply chain, shown in Figure 1, the US only makes up 10% of global market share.

The world's largest pure-play foundries, Taiwan Semiconductor Manufacturing Company (TSMC) and GlobalFoundries, are both foreign owned. Over the past decade, the pure-play/fabless business model for the industry has been growing and currently there is no sign of that trend reversing. The Trusted Foundry program that provides the DOD with access to secure SOTA microelectronics currently only contracts with the US subsidiary of GlobalFoundries (GFUS). The Trusted Foundry program previously involved IBM Microelectronics, but was re-negotiated with GFUS when IBM sold its fab facilities to this Emirati owned company in 2015. GFUS's agreement to provide trusted parts to the DOD ends in 2019, after which either party may renew or refuse future agreements on an annual basis. Refusal of future agreements is entirely conceivable, given that the high-volume business model of SOTA foundries is largely inconsistent with DOD needs. Without a major US company as a pure-play foundry, this segment of the semiconductor supply chain is a major weakness for US industry and DOD needs.

Despite the US lead in the chip design tools supply chain segment, this part of the industry has major security weaknesses. US dominance in chip design is made possible by two of the "Big Three" EDA/CAD companies – Mentor, Cadence, and Synopsys, who collectively represent the majority of global revenue.[25] Mentor, previously a US company, was purchased in early 2017 by the German technology conglomerate Siemens, reducing the US's near total dominance in this segment of the industry slightly.[26] Though Cadence and Synopsys (and until recently Mentor) are US companies, they have highly international operations and their growth in recent years has mainly been through mergers and acquisitions. Due to the nature of this growth, large amounts of their intellectual property for IC designs, as well as the software that makes up their design toolkits, are of diverse origins and are often not properly vetted for security. This creates a great risk of malware or defects making their way into IC designs, which are nearly impossible to catch at later stages since they are baked in to the design, so to speak.

Photomask production is not shown in Figure 1, mainly due to its shrinking role in the industry as of late. The steady shrinking of chip size over time has meant that mask production at SOTA nodes is now prohibitively expensive for all but the largest companies to carry out. As a result, the independent merchant photomask market is dwindling as major players increasingly produce masks in-house at SOTA nodes. This lack of competition in the domain of photomask manufacturing means the DOD has fewer options in terms of who it can go to for creating trusted photomasks, making it a weak point for the DOD. There is only one current US merchant photomask house (Photronics) and its capabilities are not compatible with all four major SOTA fabs.

At a very broad level, these are the major aspects of the domestic commercial industry that pose the greatest risks to the DOD's ability to access microelectronics from trusted and secure sources. Without US-based options for sourcing from every key stage of the semiconductor supply chain, the DOD's risk of mission failure may increase due to compromising critical systems information, using inadequate parts, or using parts that contain maliciously inserted hardware Trojans.

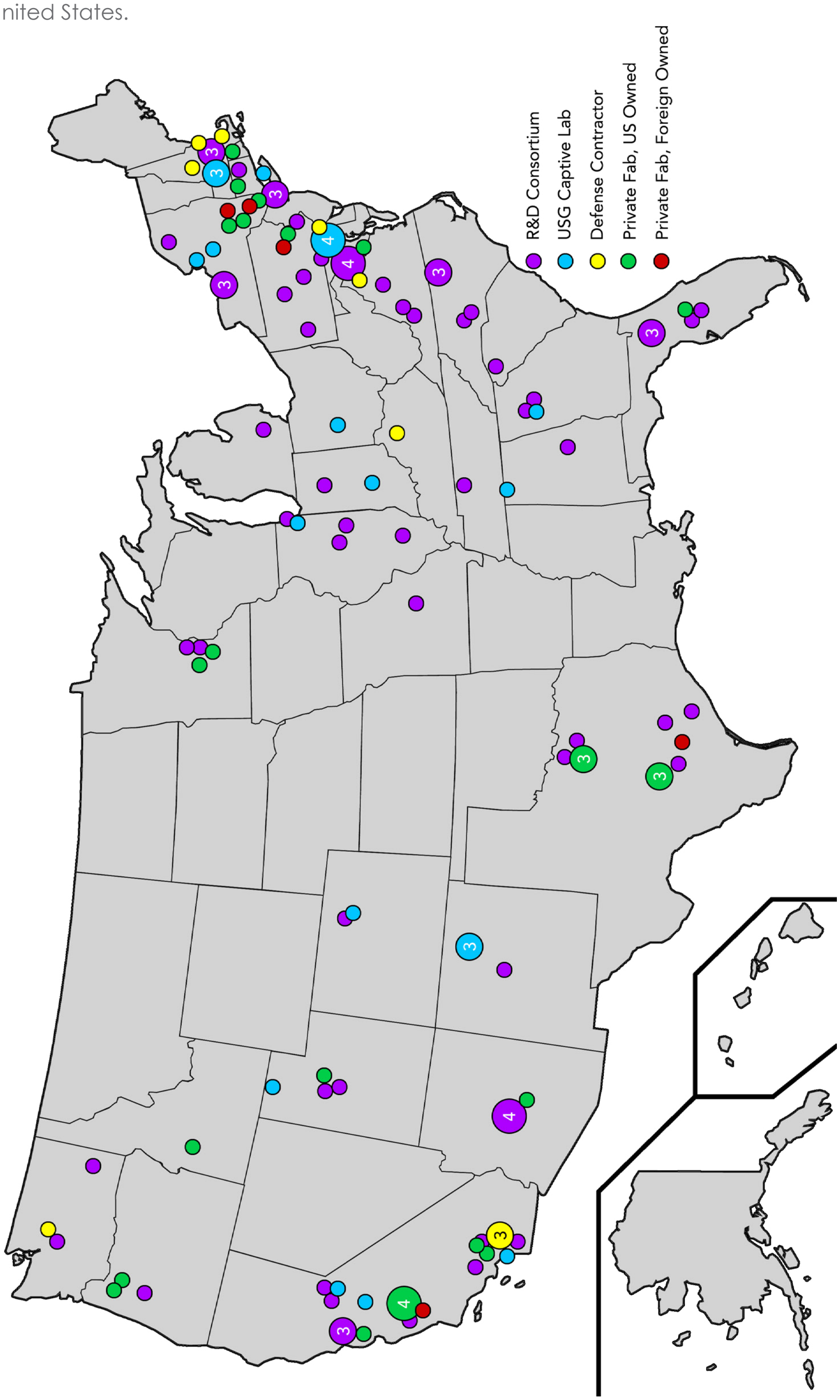
The best way for the DOD to strengthen these weaknesses in the domestic semiconductor supply chain is to strengthen the domestic R&D ecosystem that feeds new technologies into the domestic supply chain. Supporting the US in becoming a world leader in, for example, advanced packaging R&D, and providing robust avenues for US companies to capitalize on the fruits of this R&D is the most effective approach.

### *Assessment of the R&D Ecosystem*

The locations of all 45 identified PPRD centers are mapped out in Figure 2, showing their location in the United States. Figure 2 also shows the US locations of all commercial semiconductor companies' R&D facilities (both foreign and domestic owned), as well as the locations of semiconductor fabrication facilities of defense contractors and US government labs (including relevant Department of Energy labs[27]) A legend providing basic information on the individual research facilities shown in Figure 2 can be found in Appendix A.

Of the 45 centers investigated, a majority of them (31) are National Science Foundation (NSF)-funded Engineering Research Centers (ERCs) or Industry-University Collaborative Research Centers (IURCRCs).[28]There are also four relevant manufacturing innovation institutes (MIIs), managed by the Manufacturing USA network at the National Institute of Standards and Technology (NIST) that conduct mid-TRL level research that is intended to feed into the semiconductor industry. There are also some independently organized PPRD centers, such as the Florida Institute for Cybersecurity (FICS) in Gainesville, FL; the Center for Hardware Assurance, Security, and Engineering (CHASE) in Storrs, CT; and the newly formed research center in Kissimmee, FL – Bridging the Innovation Development Gap (BRIDG). It should be noted that the research campus at SUNY Polytechnic in Albany, NY, while investigated as part of this study, was excluded from the R&D ecosystem analysis, due to the many recent changes in the operational structure of the organiation.[29]

Figure 2: Semiconductor R&D facilities throughout the United States.



A majority of the PPRD centers identified in this study are funded at least in part through the NSF IUCRC and ERC programs, which do not focus solely on the semiconductor industry. The average annual budget of the 45 PPRD centers was $13.4 million. Only AIM Photonics had an annual operational budget of over $100 million, and only three other PPRD centers[30] had budgets of $50 million or more.[31] The total amount of funding found for all the PPRD centers investigated was just over $500 million, with more than half going to just six centers. The diversity of research efforts was also somewhat narrow, with PPRD centers conducting research in an average of three different R&D areas. Across all of the R&D organizations investigated, the average number of industry partners was fewer than 25. It is also unlikely that significant funding for most of the PPRD centers comes from industry, given that a recent analysis of funding of all ERCs (including ones not identified in this study) showed that only 7% of funding came from industry.[32] In examining types of R&D activities conducted (e.g. prototyping, modeling and simulation, testing, etc.) only 19 out of the 48 centers investigated had the capability for late-stage prototype production of the technology areas they researched, in most cases, even the centers that did have prototyping capabilities did not possess the ability to fabricate SOTA technologies.

### *Finding: There is a serious lack of prototyping capabilities for emerging microelectronics technologies in the US*

Our analysis of the 45 PPRD centers revealed that, even within the mid-TRL range that was the initial focus of this study, most research efforts were small, narrowly-focused, and mainly developing first proof of concept and discovering new combinations or uses for existing technologies. This is exemplified by the low number of organizations with prototyping capabilities, the low number of commercial transition partners, and low size and scope of most individual PPRD centers. This is in sharp contrast to the major research consortium SEMATECH, which once did serious later-stage R&D and enjoyed participation from a majority of the industry. SEMATECH began with an annual budget of $200 million in 1987 and grew beyond that in later years. Unfortunately, SEMATECH's capabilities and influence on the semiconductor industry began to decline in the mid-2000s, and it ceased to be an independent research entity in 2015.[33] Other major facilities in the US, which used to offer prototyping capabilities to government programs and the wider semiconductor, have also ceased being available. In 2017, the company Novati, which specialized in fabricating innovative technology prototypes, was sold to Skorpios, eliminating the ability of government researchers to use their services for prototyping new technologies.[34] In late 2017, effective control of the SUNY Poly nanotech campus in Albany, NY was transferred to IBM Research, effectively making it a captive resource for the company.

The low funding levels, narrow focus, and low connection to industry is likely due to the high prevalence of PPRD centers being located at universities, giving them stronger ties to the earlier stage research than the prototyping, manufacturing process engineering, and systems integration work more directly useful to commercial manufacturers. In looking at the IUCRC's, for example (which include the most centers examined in this study of any PPRD network), NSF evaluations of the IUCRC program as a whole focused largely on work done in the laboratory and students trained.[35] Most existing PPRD centers provide a valuable resource for workforce training, sharing scientific expertise, and conducting small-scale targeted technology development projects, but they are not suitable resources to meet the DOD's technology transition and prototyping needs.

Comparing the PPRD centers in the US to R&D capabilities elsewhere in the world, we see a significant difference in center size. Taiwan's Industrial Technology Research Institute (ITRI) for example operates six core labs, employs over 6,000 people, and has an annual budget of $700 million, half of which is provided by the Taiwanese government.[36] ITRI is more than simply a consortium of semiconductor companies and research universities; the institute fosters an entire innovation ecosystem that leverages the combined resources, knowledge, and experience of universities, R&D labs, and prominent Taiwanese semiconductor companies. Similar in size and scope, IMEC is a major R&D consortium located in Belgium that employs 3,500 researchers, has an annual budget of $600 million, and conducts not only leading-edge CMOS scaling research but also groundbreaking research in other areas including heterogeneous integration (Moore than Moore), biotechnology, medical, AI, HW security and green energy, to name a few.[37] Other major overseas R&D and prototyping organizations (LETI, ASTAR, Fraunhofer, etc.) each have annual budgets in excess of $500 million.[38] The US thus lacks a major, single PPRD organization with the same level of influence as these international entities.

Focusing on the R&D areas as a whole also yields important findings. Examining only the number of PPRD centers active in a particular R&D area can be misleading, because a single large R&D facility with connections to a majority of the industry can accomplish far more than five facilities, if those five receive minimal amounts of funding and have little industry interaction. Examining the total funding 13 distinct R&D areas and the ties those R&D areas have to the commercial industry reveals key strengths and weaknesses in the US R&D ecosystem.

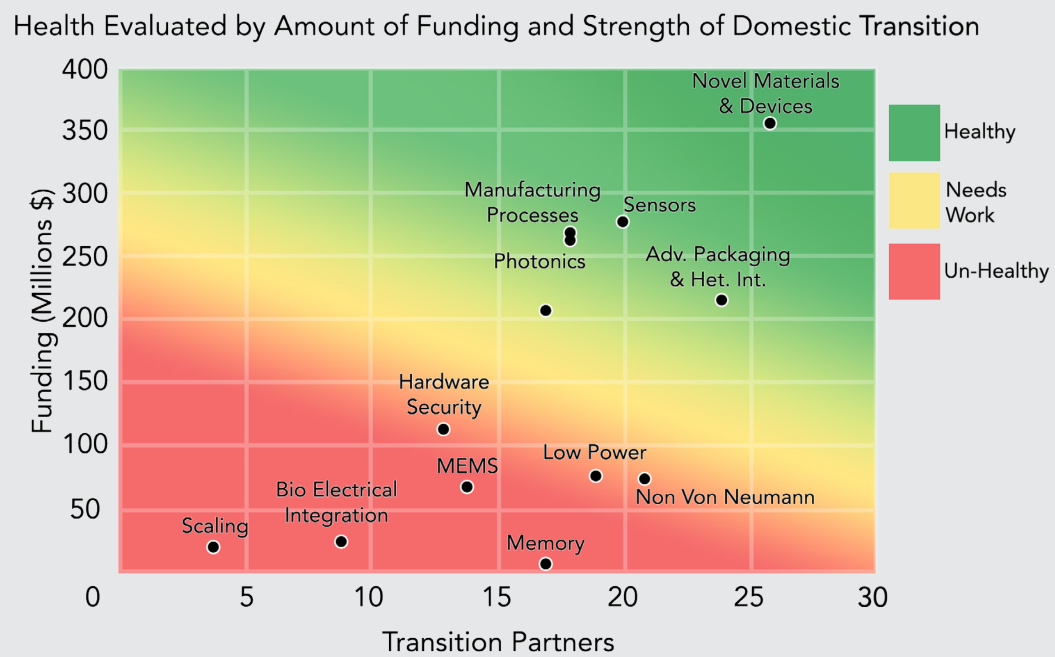



Figure 3: Health of Domestic Public-Private R&D Ecosystem, by R&D Area

Figure 3 plots these values: estimates of funding levels and total number of unique domestic commercial companies that operate with PPRD centers as transition partners. These were used as two major indicators of strength for individual areas of the R&D ecosystem. Innovative work to overcome research and engineering challenges of the commercial industry needs not only funding but also a healthy number of commercial companies as active transition partners in order to see widespread commercial adoption. In Figure 3, it becomes apparent that R&D areas such as novel materials and devices, manufacturing processes, advanced packaging, and sensors have relatively healthy numbers for both figures of merit. On the other end of the spectrum, it seems as if scaling, bio-electrical integration, and hardware security are the weakest. Memories also seems to receive a miniscule amount of funding, yet it has an average number of commercial transition partners.

*Finding: The US has strong commercial R&D efforts in low power, memory, and transistor scaling technologies.*

There exists a simple explanation for the seeming weakness of R&D activity in the areas of scaling and memories. The scope of the data gathered on these R&D areas, shown in Figure 3, was limited to PPRD centers, excluding proprietary R&D efforts conducted by commercial companies. Given the clear short-term importance of advancements in scaling research and memory technologies, private industry is directly investing heavily in those areas. The US is home to Intel and Micron, two of the largest players in leading-edge nodes and memory technologies. It is, therefore, not surprising to see funding of public-private R&D efforts in the US to be minimal in scaling and memories. These areas are too mature for public-private pre-competitive R&D.

A final step of our study of the domestic R&D ecosystem was to combine the analyses of the strengths and weaknesses of the PPRD ecosystem with the analyses of the importance of R&D areas to DOD application needs, and to include information to account for R&D areas that receive significant commercial R&D funding within the US. If a particular R&D area is of low importance to DOD needs, then it is much less of a vulnerability for the DOD if that area of the R&D ecosystem is weak. Additionally, if an area of the PPRD ecosystem is weak, but commercial R&D in the US in that area is strong, then the DOD does not necessarily need to devote more resources to conducting its own R&D, it simply needs to focus on partnering with the commercial entities strong in that R&D area to ensure needed access.

The resulting analysis – including considerations of PPRD strength, industry R&D strength, and importance to DOD application needs – was conducted in a quantitative manner, the details of which can be found in Appendix C. The results of the analysis are summarized in Figure 4, which is a heat map, illustrating the areas of low, medium, and high need, followed by a descriptive summary of the results of the analysis for each R&D area.

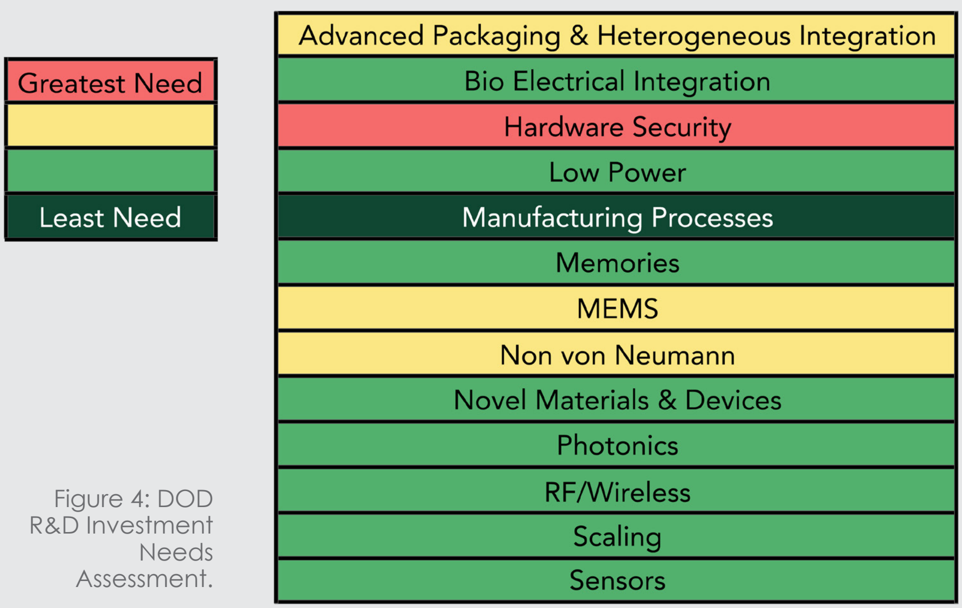



Figure 4: DOD R&D Investment Needs Assessment.

### Advanced Packaging and Heterogeneous Integration

This area has strong public-private R&D support, but the domestic share of the commercial industry is very weak, indicating insufficient domestic late-stage R&D and prototyping activities. When compared to high-level indicators of international efforts in this R&D area, US R&D strength is not high. Today, key microelectronics module functionality is often determined in the packaging stage. The very high importance to DOD application needs of this R&D area make it a key area. Thus, DOD requires access to secure domestic advanced packaging capabilities and the current situation is a major weakness.

### Bio-electrical Integration

This area is still mostly earlier stage R&D, with little funding outside university research and few domestic commercial transition partners. This makes it a weak point in the domestic R&D ecosystem but it is not critical to short-term DOD needs.

### Hardware Security

This area is the most important to DOD application needs; therefore, it needs to become a strong point in the domestic R&D ecosystem. Currently it has low levels of PPRD funding, a relatively low number of transition partners, and arguably only one or two centers with prototyping capabilities.

### Low Power

This area has a high number of commercial transition partners but a low level of PPRD funding, due to a high level of commercial proprietary R&D efforts. This area is also of high importance to DOD application needs, but given the large amount of commercial R&D activity, there is no need to build this from scratch.

### Manufacturing Processes

This area has healthy industry investment and PPRD support, making it a strong point in the R&D ecosystem. The results that research in this area provides are relevant, but not critical for DOD needs, with the notable exception that low-volume high-mix, manufacturing models are not being strongly pursued by industry. Supporting R&D centers that develop and employ low-volume, high-mix models would strengthen the DOD's ability to access a wider range of technologies.

### Memories

There is significant investment in industry funding, for example by one of the world's leading memory producers, Micron. There is little PPRD work as a result, making it a weak point in the PPRD ecosystem but a strong point in domestic commercial industry R&D.

### MEMS

This area has a low level of PPRD funding and an average number of publicly available prototyping facilities and domestic commercial transition partners, due to the commercial view of a small market cap and mostly custom processes not amenable to a foundry model. This area is of high importance to DOD applications, critical to half of the technology applications important to the DOD. MEMs manufacturing, however, does not lend itself well to a traditional foundry model as frequently each MEMS device developed for a certain application requires its own unique manufacturing process to be developed as well. This means each project is strongly dominated by high NRE costs.

### Non-von Neumann

This area has tremendous potential to provide revolutionary capability advancements, but research is still widely considered early stage. As a result, there is a high number of domestic commercial transition partners, but low PPRD funding. Even small amounts of funding in this area can have large impacts in the future. Some cutting-edge research is being done by commercial companies (e.g. Google, IBM, etc.) particularly in the machine learning space, but details are not widely shared and they seem to be focused on a narrow range of applications. It is not clear if many of the applications useful to the DOD are being researched significantly. This area is critical to only two DOD applications, but it is relevant to a majority of the six. Accelerated progress could provide major capability advancements in the long term.

### Novel Materials & Devices

This R&D area has the highest amount of PPRD funding and number of domestic commercial transition partners of all the areas studied, making it the strongest area of the PPRD ecosystem. This area is also of high importance to the DOD.

### Photonics

This research area has a strong amount of PPRD funding and high number of domestic commercial transition partners and is thus a strong point in the PPRD ecosystem. This area is of high importance to DOD applications.

### RF/Wireless

This area has an average amount of PPRD funding, a higher than average number of domestic transition partners, and a healthy number of centers with prototyping capability. This healthy interest is likely due to the rapidly emerging demand for more advanced wireless capabilities for mobile and IoT markets. Research in this area is critical for RF/wireless and IoT applications, but its importance to other DOD applications is limited.

### Scaling

R&D in this area has almost completely moved into the proprietary commercial space, with the end of gains from scaling in the near future. Like memories, it is a weak point in the PPRD ecosystem but a strong point in domestic commercial industry R&D. Similar to the area of RF/wireless research, scaling R&D is critical for a relatively narrow range of DOD applications.

### Sensors

This area has healthy industry investment and PPRD support, making it a strong point in the R&D ecosystem. It also has high important to DOD needs.

### *Major Roadblocks to Innovative Collaboration with Commercial Industry*

In addition to studying the domestic R&D ecosystem, the Potomac Institute also examined examples of successes and failures in government collaboration with commercial industry on R&D. How the government engages with commercial industry is as important as which specific R&D areas in which it chooses to engage. From analysis of the literature and discussions with experts, a few findings emerged and are discussed below.

*Finding: Major Roadblocks still exist to DOD technology transition for state-of-the-art innovation.*

**Public R&D funding ends too early to sufficiently lower commercial risk for investing in fully maturing new technologies.**

Over the course of the Potomac Institute's recent studies of collaborative R&D organizations, it became apparent that most PPRD centers have evolved to focus on more exploratory R&D, best characterized as taking place across TRLs 1-5.[39] This is not limited to the semiconductor industry, but can be seen in multiple high-tech industries. It has been noted by experts that this mainly stems from a difference in perspective in two key areas: when TRL milestones are achieved and IP rights.

First, there is a strong debate as to whose responsibility it is to fund the majority of the R&D efforts through mid-to-late TRLs. Researchers at public institutions (universities and national labs) are focused primarily on achieving technical milestones of discovery and proof of concept and view later development stages, when the potential for commercial success becomes more concrete, to be the sole responsibility of the commercial partners. Conversely, researchers in industry focus mainly on the remaining risk of failure in the technology or product being developed and finding a large enough commercial market to justify the NRE investment.[40] The engineering work required during the prototyping, system integration, and pilot production stage is significant, and commercial companies are not willing to risk the necessary time and resources on anything that is unlikely to provide a near-term return on investment. This is especially true for technologies that have little to no commercial market outside of the defense industry. The answer to this mismatch is that the truth lies somewhere between the estimates of both sides. Both sides would therefore benefit from extending their willingness to fund R&D efforts further into the valley of death, possibly through negotiating cost-sharing agreements for collaborative R&D.

The other major challenge involves intellectual property rights. Commercial entities are likely to see far more of the scientific and engineering knowledge gained from R&D as potentially necessary for commercial success and thus proprietary. Surprisingly, public institutions also see a major value in aggressively controlling as much of the IP that results from their R&D efforts as possible. Therefore, both sides are far less willing to enter into collaborative R&D agreements in the first place, due to the fear of losing any control over the results of that R&D. This second mismatch causes both sides to forfeit many opportunities for innovation that benefits all parties involved.

Recently, efforts have emerged to correct this lack of investment in mid-to-late stage technology development, for example through the Manufacturing Innovation Institutes (MIIs) that make up the National Network for Manufacturing Innovation (NNMI) initiative, now known as Manufacturing USA. For the Semiconductor industry specifically, the efforts of Manufacturing USA are more narrowly targeted (MIIs focused on photonics, flexible electronics, and energy storage, for example), smaller in funding size, and receive stable public funding for much shorter durations than major PPRD centers in other countries. For example, the Belgian organization IMEC has a yearly budget of over half a million dollars and ITRI in Taiwan has an annual budget of $700 million. Both research institutes conduct R&D and provide prototyping and pilot production capabilities in nearly every area relevant to the semiconductor industry. Both research institutes have also received stable (and even increasing) funding from their national governments over the entire decades long history of their existence. In contrast, AIM Photonics, the largest identified PPRD Center[41] in this study, has a budget just over $100 million per year, with federal funding, which makes up 18% of its overall budget, ending after the first five years.

### Traditional USG contracting mechanisms are far too slow and restrictive for most companies.

The Federal Acquisition Regulations – and the Defense Supplement (DFARS) – were constructed with traditional acquisition in mind: buying existing technologies and services such as tanks, planes, ammunition, etc. In these cases, the design and performance of the acquired product does not change significantly between when the contract begins and when the product is delivered. Research and Development projects, however, do not operate that way at all. The design, qualification and integration of many components into the overall system usually go through multiple iterations before the final product is delivered. Many details of the final system are not known at the outset of the program. Similarly, traditional acquisition is based on the paradigm of physical products when much of the most valuable assets involved in an R&D contract today are the critical design and operational information, also categorized more generally as IP. Furthermore, the FAR have existed and grown so much overtime, that it takes significant legal resources for any company to ensure that they do not violate any parts of the FAR before they can even enter into a traditional contract.[42] Similarly, the International Trade in Arms Regulations (ITAR) are based on the perspective of dealing with physical products, when their jurisdiction now covers software, intellectual property, and trade secrets, severely restricting how commercial companies can use IP involved in a DOD funded project anywhere else in their operations.[43] The combined effect of all of these regulations on R&D efforts is that many leading semiconductor companies are unable to enter into R&D contracts with the DOD. Even if the DOD paid many times more for R&D contracts, it would simply not be worth changes they would need to make to comply with the regulations in the FAR and ITAR. [44] Major defense contractors meet FAR and ITAR requirements because they have built their business model to serve DOD demands and have therefore adjusted their operations over years and built institutional expertise in relevant regulations to ensure that they easily comply, which is not the case for companies in other commercial industries.

Decades ago, however, the USG created a funding mechanism designed specifically for scientific research, technology development, and prototyping. As mentioned in another Potomac Institute Report focusing on collaborative R&D efforts:

> Other Transaction Agreement (OTA) DOD authority is granted in U.S. Code 2371b[45] to carry out prototyping projects. For this reason, OTAs are designed to be used for R&D and prototype contracts, which are often unconventional, involve performers that are not familiar with the traditional federal acquisition process and need to be adjusted over time. OTs are not standard procurement contracts, grants, or cooperative agreements, so they are generally not subject to the federal laws and regulations that apply to government procurement contracts (e.g., FAR/DFARS).[46,47] In this way, they are designed to be as flexible as possible, so that all parties involved can construct an agreement that enables what is important without being hampered by unnecessary and unrelated sections of the FAR. In particular, OTAs have no inherent IP policies, allowing for much more flexible handling of IP rights and licensing of R&D results.

While OTAs received somewhat wide use in the first years since their creation, they fell out of favor in the early 2000s. Today OTAs are still not widely used in the DOD.[48] OTAs provide an enormous opportunity to increase engagement with the PPRD ecosystem in the US as well as directly with the commercial semiconductor industry to accelerate critical R&D and prototyping that will serve DOD application needs.

### High-volume manufacturing business models are incompatible with DOD's diverse, custom low-volume needs.

The diverse range of microelectronics technologies that are critical to DOD is much wider than the range of technologies that have a wide commercial market demand. For example, most radiation-hardened circuits have no use outside of nuclear and space applications, and some technologies that employ unique materials or meet high performance and robustness demands only have military customers. Because many of these technologies have niche applications, demand for them is far lower in volume than for typical national or global markets. DOD demand for microelectronics, especially critical technologies, is best characterized as low-volume and high-mix.

Unfortunately, the current state of the semiconductor industry is not aligned to cater to low-volume, high-mix customers. This is especially true for microelectronics suppliers that fabricate SOTA technologies. Recent public disclosures by leading semiconductor manufacturers of costs for building facilities with leading-edge fabrication capabilities are in the tens of billions of dollars.[49] As a result, only those companies that can produce high volumes of products, sold at a significant profit, can economically justify the investment required to build the most advanced semiconductor fabs. Currently, Samsung and Intel are the only integrated device manufacturers (IDMs) manufacturing SOTA technologies, while the rest of the industry follows the fabless/pure-play model, the majority of which is serviced by just two foundries, TSMC and GlobalFoundries.

With high cost and access barriers to designing and manufacturing at SOTA nodes, it is nearly impossible for most innovative hardware ideas to leverage the capabilities of SOTA technologies, which ultimately impedes innovation in the industry.

### DOD volume is too small to impact major commercial technologies once they have reached market.

Leading semiconductor manufacturers produce chips in the billions. By necessity, their business models drive them to produce the lowest number of marketable products in the highest volumes possible. This is completely at odds with the DOD's perspective of needing customized components (typically only in the thousands) to provide unique performance capabilities to the US only. Once a company has developed a technology to the point where it is manufacturing it for the commercial market, it is nearly impossible for that company to alter its design or manufacturing process of that technology and remain profitable. Manufacturing production is streamlined for speed and efficiency, which any amount of customization destroys. NRE costs are too high for companies to customize a SOTA product after it has reached full commercial production.

Companies are, however, much more open to customization and creation of multiple variations of a technology while they are still in the initial development and prototyping stages. Before the die has been set on emerging technologies, so to speak, companies are still motivated to customize a product in ways that will ensure a guaranteed market. If the government engages with industry at this stage – pre-commercial production – then it is much more likely to achieve access, with the added benefit that it will reduce the risk of obsolescence down the road, since DOD systems will be integrating these technologies before they even reach the mainstream market. There are multiple examples of PPRD centers that successfully engage with a majority of the industry at this early R&D stage, and have tremendous influence the technologies that receive widespread adoption. For example, IMEC's pioneering work in extreme ultraviolet (EUV) lithography technologies over many years created the basis of technologies that now is enabling the continued advancement of scaling below 10nm. TSMC, the company widely credited with bringing the pure-play foundry business model to mainstream success, was created within ITRI. CEA Leti was instrumental in developing and refining fully depleted silicon on insulator (FDSOI) technology, which is now seeing rising demand in the industry due to its lower cost & superior power management at smaller dimensions. These organizations use a range of different approaches that work for them, indicating that there is no single approach that must be followed.[50,51]

# CONCLUSIONS

In addition to major R&D efforts in the American commercial industry, over 45 PPRD centers within the US were examined during the study. The Potomac Institute built an overall picture of the US R&D ecosystem, categorizing R&D areas, and the level of activity (both in funding and collaboration between PPRD centers and commercial companies for technology transition) to identify areas where R&D activity is insufficient to meet DOD needs. Major conclusions that follow from the findings of this analysis are discussed below.

Overall, three areas emerged as having significantly higher R&D needs for the DOD than others, as is shown in the heat map of Figure 4. Figure 4 shows hardware security as having the greatest need, the only area within the highest need classification, and three other areas with high need. Most other areas have moderately low need, with one R&D area – manufacturing processes – with very low need. The study team determined the MEMS R&D area to be of lower importance than first indicated in Figure 4. History has shown that the MEMs process does not lend itself well to a traditional foundry model as there is too much process diversity involved in MEMS manufacturing. This means each project is strongly dominated by high NRE costs.

The R&D area with the most need for investment by far is hardware security. Hardware security is the single most important technology area for DOD application needs. From the technical analysis performed during this study, hardware security is critical to four out of six DOD applications and relevant to two more applications. It is not surprising that DOD systems have a significant need for robust security, both in hardware and software. This high need of the DOD for advanced hardware security is compounded by its weak standing in the US R&D ecosystem. The PPRD ecosystem in the US currently puts very little funding into improving hardware security in technologies being developed. Not surprisingly, R&D efforts in this field are mainly conducted at government labs, although a few centers, like the Florida Institute for Cybersecurity (FICS) and the Center for Hardware Assurance, Security, and Engineering (CHASE), make hardware security a main focus. Unfortunately, technology transition ties to the commercial industry are also weak for hardware security R&D. Interactions with experts in the semiconductor industry indicate that the majority of end-users do not consider hardware security to be a high enough priority for them to pay a premium for it. This needs to change. The results of industry's disinterest in hardware security is every day more apparent with more and more public discoveries about major hardware vulnerabilities in a diverse set of mainstream commercial ICs.[52,53]

The second R&D area with high need for DOD investment is advanced packaging and heterogeneous integration. Despite the area being relatively strong in the domestic PPRD ecosystem, with over $200 million dollars a year going to R&D centers that work on it, a majority of those centers conduct research that is earlier stage or focused on heterogeneous integration of diverse IC types, not on prototyping actual advanced packaging technologies. Furthermore, advanced packaging and heterogeneous integration technologies are of high importance to the DOD: Potomac Institute technical analysis found them to be critical to four out of six DOD applications. Additionally, the small US representation in the independent packaging and testing segment of the supply chain means that there are far fewer domestic commercial transition partners that can take newly developed advancements and quickly put them through prototyping and pilot production. Finally, as previously mentioned, the importance of advanced packaging technologies in SOTA and emerging technologies in the semiconductor industry is rapidly growing, playing a crucial role in functionality of the entire microelectronics system. Advanced packaging technologies is already becoming a critical part of hardware security and therefore the DOD needs to have access to capabilities in this R&D area.

The third R&D area with significant need for DOD investment is non-von Neumann computing architectures. Novel kinds of computing architectures, including quantum computing and neuromorphic computing have tremendous potential to provide revolutionary capability advancements, but research is still widely considered early stage (with the possible exception of machine learning). Not only does the research in this area involve the creation of revolutionary new software, new kinds of hardware architectures are also integral to the advancement of the field. As a result, there is a high number of domestic commercial transition partners, but low funding in the public-private R&D space. Some cutting-edge research is being done by commercial companies (e.g. Google, IBM, etc.) particularly in the machine learning space, but details are not widely shared. Given that much of the research in this area is early stage, much of it is ready to be tested for a range of applications relevant for later-stage research efforts. To this end, even low funding levels can have large impacts in the future. These impacts will likely affect a significant number of DOD applications.

The goals of this study included not only gathering data on the domestic R&D ecosystem and analyzing it to identify gaps in R&D, but also to provide recommendations for closing those gaps most critical to the DOD and partnering more effectively with commercial industry to transition promising innovations and technologies. The recommendations presented below follow directly from the findings and conclusions.

### The DOD should increase its investments in later-stage R&D and prototyping capabilities.

In addressing the finding that the US is seriously lacking in compelling prototyping capabilities for emerging microelectronics technologies, our recommendation is that the DOD should commit to closing this gap. The USG should engage more seriously in "mid-TRL-range" R&D activities. The US is very strong in early range efforts but this progress is often lost by not investing at later TRL stages – when technologies have demonstrated promising performance but are still not ready for commercial exploitation. For areas of the R&D ecosystem that are the most important to DOD application needs, resources should be devoted to ensuring that they are strong, both in the PPRD ecosystem and in the domestic industry.

In cases where PPRD centers show the most activity in an R&D area, the DOD should engage with the strongest organizations, identifying the most useful products and encouraging their transition to domestic commercial entities accessible by DOD. In the case of weak domestic representation, both in the PPRD ecosystem and the fully commercial R&D ecosystem, the DOD should contribute the necessary resources to strengthen R&D efforts in those areas, possibly by forming new centers of innovation focused on that R&D area.

### The DOD should invest in collaborative public-private R&D efforts with academia and industry in the specific areas of Hardware Security, Advanced Packaging, and Non-von Neumann Computing Architectures.

The most useful strategy for forming new prototyping capabilities is to focus on the areas most critical to DOD needs. Forming independent, public-private organizations to spur prototyping and technology transfer in each of the three key areas of hardware security, advanced packaging and heterogeneous integration, and non-von Neumann computing architectures is recommended. Investing in hardware security will help meet the DOD's significant needs for protecting against hardware vulnerabilities and increase adoption of more advanced capabilities in the commercial industry, where it is needed. Investing in advanced packaging R&D will help the US close its gap in commercial representation in that section of the supply chain, which is becoming increasingly critical to enhancing performance of SOTA technologies. Investing in non-von Neumann computing architectures now, while many areas of the field are still young, can greatly accelerate disruptive advancements and give the DOD decisive advantage in a range of applications.

The public-private nature of these recommended organizations is critical to draw on the expertise and innovation that exists across the country in universities, government labs, and even private companies. Only with diverse participation can these facilities serve as the mid-to-late stage R&D bridge that connects public research efforts with domestic private industry. These prototyping capabilities should also be used to serve the low-volume production needs of the DOD. Therefore, it is imperative that the DOD be the creator of, and remain an active participant in, these public-private centers of innovation.

### The DOD should partner with US and allied semiconductor companies for pre-SOTA technology development and early access to IP.

Given that assured *access* to advanced technologies is of highest importance, the DOD need not duplicate R&D efforts in cases where the commercial industry is strong. Instead, the DOD should strive to maintain strong relationships with commercial entities to access leading-edge commercial off-the-shelf (COTS) technologies and access the necessary process IP to continue producing them when they are no longer available commercially. In technology areas where there is both high DOD need and a large amount of commercial R&D effort, the DOD should seek to partner with commercial industries in these R&D efforts. It makes sense to combine resources in areas where the government and private industry have mutual interests. This approach provides the added benefit of giving DOD programs access to emerging technologies at the stage where they are much more likely to achieve their performance and security requirements. Pursuing bilateral R&D agreements with companies in the areas of low power ICs, advanced memories, and scaling technologies can both increase DOD access to emerging technologies and have a major impact on the commercial industry.

### The DOD should no longer use FAR-based contracts for R&D programs.

FAR-based contracts were meant for traditional product and services acquisition, not R&D. While government acquisition experts are most comfortable with them, they contain requirements that are wholly incompatible with the way commercial R&D contracts and start-up investment contracts are constructed. FAR-based contracts provide no ability to negotiate terms on a case-by-case basis, have stringent and usually unacceptable requirements regarding IP ownership rights, and take far too long to put in place – typical FAR contracts take months, when many companies need funding within weeks, if not days, to justify pursuing a project.

The US government already has a funding mechanism specifically designed to fit the rapidly changing, highly unique nature of R&D work. OTAs are designed to be as flexible as possible, so that all parties involved can construct an agreement that enables what is important without being hampered by unnecessary and unrelated sections of the FAR. In particular, OTAs have no mandated IP policies, allowing for much more flexible negotiation of IP rights and licensing of R&D results. The DOD should implement a policy of using OTAs for R&D contracts. It should also take the steps necessary to ensure its acquisition workforce is adequately trained to handle a larger volume of OTAs.

### The DOD should aim to align with industry in its R&D and prototyping efforts.

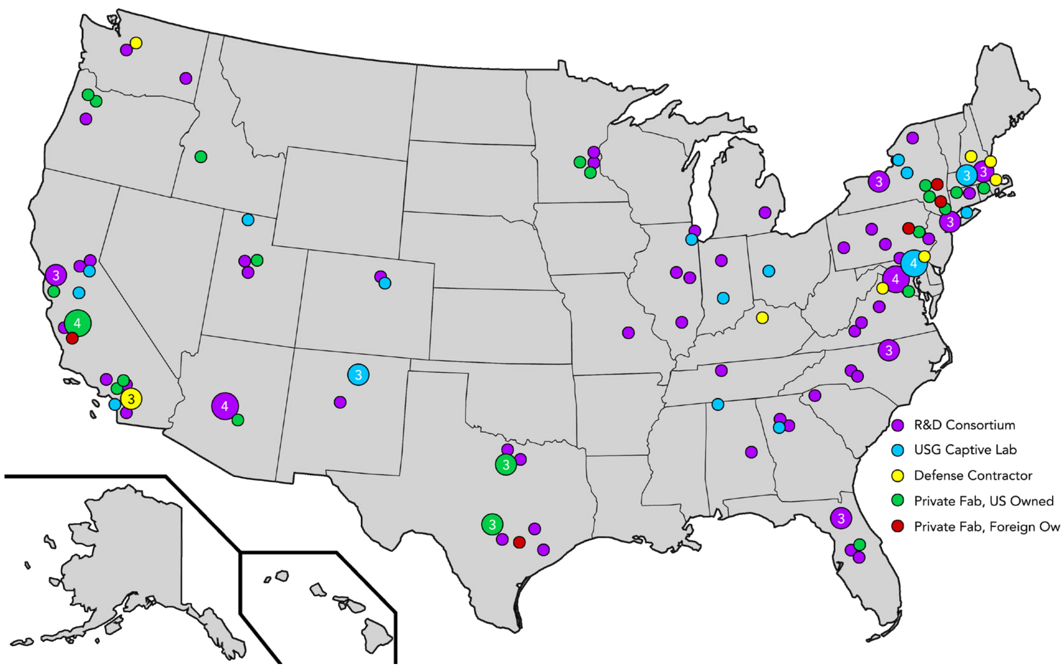
Aligning technology development efforts with private industry needs maximizes the ability for the DOD to transition promising technologies into wide commercial adoption, and to maintain trusted access to those technologies far into the future. A major characteristic of the world's most successful PPRD organizations is that they all make listening to industry needs a high (if not top) priority. The DOD should follow this best practice as well.

In conclusion, the strength of both the US representation in the global semiconductor industry and the domestic R&D ecosystem varies significantly in strength and relevance to DOD critical needs. There are many opportunities for the DOD to close critical gaps in both the public-private R&D sphere and the commercial industry. Major challenges still exist to closing these gaps and to working with the commercial semiconductor industry in general, but solutions also exist to overcome them. The findings, conclusions, and recommendations lay out major signposts for a pathway to creating a strong, robust domestic semiconductor industry that provides the DOD with many avenues for assuring access to critical microelectronics.

# APPENDIX A: R&D FACILITIES IN THE US

The Potomac Institute study team gathered open source and market analysis information on a wide range of existing R&D facilities and centers in the US[54-57] These facilities included government labs, private commercial R&D facilities (both US and foreign owned) and public-private R&D centers, whose goals related to increasing ties between academia, industry, and government, and improving technology transition and innovation. Those organizations and their locations within the United States are listed below.

This list serves as an augmented legend for Figure 2 in the main report. The list sorts facilities by the states in which they are located. The lists are also colored corresponding to the classification given in Figure 2, which is as follows:



| PUBLIC-PRIVATE R&D CENTERS | LOCATION (CITY/STATE) | |
|---|---|---|
| Center for Advanced Vehicle and Extreme Environment Electronics | Auburn | AL |
| Center for Embedded Systems | Tempe | AZ |
| Net-Centric & Cloud Software & Systems | Tempe | AZ |
| ERC for Quantum Energy and Sustainable Solar Technologies (QESST) | Tempe | AZ |
| Center for Integrated Access Networks(CIAN) | Tempe | AZ |
| Berkeley Sensor & Actuator Center | Berkeley | CA |
| Berkeley Sensor & Actuator Center | Davis | CA |
| Center for Hybrid Multicore Productivity Research (CHMPR) | San Diego | CA |
| Nanosystems ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) | Berkeley | CA |
| ERC for Extreme Ultraviolet Science and Technology | Berkeley | CA |
| NextFlex | San Jose | CA |
| Trusted Access Program Office (TAPO) | McClellan | CA |
| Metal Oxide Semiconductor Implementation Service (MOSIS) | Marina Del Rey | CA |
| Information Sciences Institute (ISI USC Viterbi) | Marina del Rey | CA |
| Nanotech - the UCSB Nanofabrication Facility | Santa Barbara | CA |
| ERC for Extreme Ultraviolet Science and Technology | Boulder | CO |
| Center for Hardware AssuranceSecurityand Engineering (CHASE) | Storrs | CT |
| Multi-functional Integrated System Technology (MIST) | Gainesville | FL |
| Multi-functional Integrated System Technology (MIST) | Orlando | FL |
| Center for High-Performance Reconfigurable Computing | Gainesville | FL |
| BRIDG | Kissimmee | FL |
| Florida Institute for Cybersecurity Research (FICS) | Gainesville | FL |
| Center for Fiber-Wireless Integration and Networking for Heterogeneous Mobile Communications | Atlanta | GA |
| 3D Systems Packaging Research Center | Atlanta | GA |
| Micro and Nanotechnology Lab | Urbana | IL |
| Center for Embedded Systems | Carbondale | IL |
| Advanced Electronics through Machine Learning | Champaign | IL |
| Digital Manufacturing and Design Innovation Institute | Chicago | IL |
| Cooling Technologies Research Center | Lafayette | IN |
| Center for Fiber-Wireless Integration and Networking for Heterogeneous Mobile Communications | College Park | MD |
| Center for Hybrid Multicore Productivity Research (CHMPR) | Baltimore | MD |
| Advanced Functional Fabrics of America | Cambridge | MA |
| FRAUNHOFER CMI | Boston | MA |
| Information Sciences Institute (ISI USC Viterbi) | Waltham | MA |
| Industrial Partnership for Research in Interfacial & Materials Engineering (iPRIME) | Minneapolis | MN |
| Center for Research in Intelligent Storage | Minneapolis | MN |

| PUBLIC-PRIVATE R&D CENTERS | LOCATION (CITY/STATE) | |
|---|---|---|
| Center for Electromagnetic Compatibility | Rolla | MO |
| CeramicComposite and Optical Materials Center | New Brunswick | NJ |
| Nanosystems ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) | Albuquerque | NM |
| Center for Freeform Optics | Rochester | NY |
| Center for Metamaterials | Potsdam | NY |
| Center for Metamaterials | New York | NY |
| Cornell NanoScale Facility (CNF) | Ithaca | NY |
| AIM Photonics | Rochester | NY |
| SUNY Polytechnic Institute | Albany and Utica | NY |
| Center for Freeform Optics | Charlotte | NC |
| Center for Dielectrics and Piezoelectrics | Raleigh (Centennial Campus) | NC |
| Center for Dielectrics and Piezoelectrics | Raleigh (Monteith Research Center) | NC |
| Center for Metamaterials | Charlotte | NC |
| Semiconductor Research Corporation (SRC) | Durham | NC |
| Center for Design of Analog Digital Integrated Circuits (Phase III) | Corvallis | OR |
| Center for Dielectrics and Piezoelectrics | University Park | PA |
| Data Storage Systems Center | Pittsburgh | PA |
| Center for Research in Intelligent Storage | Philadelphia | PA |
| CeramicComposite and Optical Materials Center | Clemson | SC |
| Institute for Space and Defense Electronics (ISDE Vanberbilt University) | Nashville | TN |
| Center for Electromagnetic Compatibility | Houston | TX |
| Center for Research in Intelligent Storage | College Station | TX |
| Net-Centric & Cloud Software & Systems | Denton | TX |
| Net-Centric & Cloud Software & Systems | Dallas | TX |
| Nanosystems ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) | Austin | TX |
| Center for Hybrid Multicore Productivity Research (CHMPR) | Salt Lake City | UT |
| Center for High-Performance Reconfigurable Computing | Provo | UT |
| Center for Energy Harvesting Materials and Systems | Blacksburg | VA |
| Multi-functional Integrated System Technology (MIST) | Charlottesville | VA |
| Center for Power Electronics Systems | Blacksburg | VA |
| Center for High-Performance Reconfigurable Computing | Blacksburg | VA |
| MEMS & Nanotechnology Exchange | Reston | VA |
| Information Sciences Institute (ISI USC Viterbi) | Arlington | VA |
| Center for Design of Analog Digital Integrated Circuits (Phase III) | Pullman | WA |
| Center for Design of Analog Digital Integrated Circuits (Phase III) | Seattle | WA |

| US GOVERNMENT CAPTIVE LABS (GOVERNMENT LABS, FFRDCS, & UARCS) | LOCATION (CITY/STATE) | |
|---|---|---|
| Georgia Tech Research Institute | Huntsville | AL |
| Lawrence Livermore National Lab (LLNL DOE) | Livermore | CA |
| DMEA | Sacramento | CA |
| Aerospace Corporation | Redondo Beach | CA |
| NREL (DOE) | Golden | CO |
| Naval Research Lab | Washington | DC |
| Georgia Tech Research Institute | Atlanta | GA |
| Argonne National Labs (ANL,DOE) | Lemont | IL |
| NSWC Crane (NAVSEA Crane) | Crane | IN |
| Army Research Lab | Adelphi | MD |
| NSA | Fort Meade | MD |
| Johns Hopkins Applied Physics Lab | Baltimore | MD |
| MIT Lincoln Labs | Lexington | MA |
| Institute for Soldier Nanotechnologies | Cambridge | MA |
| Sandia National Labs (SNL-DOE) | Albuquerque | NM |
| Los Alamos National Lab (LANL DOE) | Los Alamos | NM |
| Space Dynamics Laboratory | Albuquerque | NM |
| Brookhaven National Laboratory (DOE) | Shirley | NY |
| AFRL Rome Labs | Rome | NY |
| AFRL-Wright Patterson AFB | Dayton | OH |
| Space Dynamics Laboratory | Logan | UT |
| Aerospace Corporation | Chantilly | VA |

| DEFENSE CONTRACTOR R&D FACILITIES | LOCATION (CITY/STATE) | |
|---|---|---|
| McDonnell Douglas | Huntington Beach | CA |
| Northrup Grumman | Redondo Beach | CA |
| Raytheon Company | Redondo Beach | CA |
| Raytheon Company | Lexington | KY |
| Northrup Grumman | Linthicum Heights | MD |
| Draper Labs* | Cambridge | MA |
| Raytheon Company | Andover | MA |
| BAE Systems | Nashua | NH |
| BAE Systems | Manassas | VA |
| Boeing Defense Electronics | Seattle | WA |

| PRIVATE COMMERCIAL R&D FACILITIES (US-OWNED) | LOCATION (CITY/STATE) | |
|---|---|---|
| Qualcomm/NXP | Chandler | AZ |
| Apple | San Jose | CA |
| Endevco Corporation | Sunnyvale | CA |
| HRL Laboratories (Owned by Boeing and GM) | Malibu | CA |
| IBM Research | San Jose | CA |
| Microwave Monolithics | Simi Valley | CA |
| Noel Technologies. Inc. | Campbell | CA |
| United Technologies Research Center | Berkeley | CA |
| United Technologies Research Center | East Hartford | CT |
| Quorvo, Inc. | Apopka | FL |
| Micron | Boise | ID |
| Honeywell Incorporated | Plymouth | MN |
| Seagate | Bloomington | MN |
| GE Corporate R&D | Schenectady | NY |
| IBM Research | Albany | NY |
| IBM Research | Yorktown Heights | NY |
| Intel | Hillsboro | OR |
| Quorvo, Inc. | Hillsboro | OR |
| ON Semiconductors | Lower Gwynedd | PA |
| ON Semiconductors | East Greenwich | RI |
| Honeywell Incorporated | Richardson | TX |
| ON Semiconductors | Austin | TX |
| Qualcomm/NXP | Austin | TX |
| Quorvo Inc. | Richardson | TX |
| Skorpios (formerly Novati Technologies Inc.) | Austin | TX |
| Texas Instruments | Dallas | TX |
| ON Semiconductors | Lindon | UT |
| Micron | Manassas | VA |

| PRIVATE COMMERCIAL R&D FACILITIES (FOREIGN-OWNED) | LOCATION (CITY/STATE) | |
|---|---|---|
| Samsung | San Jose | CA |
| Globalfoundries | East Fishkill | NY |
| Globalfoundries | Malta | NY |
| Broadcom | Breiningsville | PA |
| Samsung | Austin | TX |

# APPENDIX B: EVALUATION OF IMPORTANCE OF R&D AREAS TO DOD APPLICATION NEEDS

As part of the Research and Development Ecosystem Analysis study, the Potomac Institute evaluated six major technology applications[58] and mapped the 13 identified technology development categories (referred to in the report as R&D areas) of the microelectronics industry to each application. R&D Areas mapped to each application were identified as either critical to the advancement in capabilities of that application, or relevant. For example, if R&D area X is *critical* for DOD application Y, then continued advancements in X are necessary to advance capabilities Y. If X is *relevant* to Y, then advancements in X will likely improve capabilities in Y, but Y can continue to improve significantly, even in the absence of breakthroughs in X.

**The technology applications identified by the DOD were as follows:**

1. Data Analytics
2. Autonomy & AI
3. Radar & Communications
4. Space
5. Sensors & IoT
6. Biomedical

**The 13 technology R&D areas used in this evaluation were as follows:**

1. Advanced Packaging and Heterogeneous Integration
2. Bio-electrical Integration
3. Hardware Security
4. Low Power
5. Manufacturing Processes
6. Memories
7. MEMS
8. Non-von Neumann Computing Architectures
9. Novel Materials & Devices
10. Photonics
11. RF/Wireless
12. Scaling
13. Sensors

The table below summarizes the results of the mapping of R&D areas to DOD applications. Each column in the table corresponds to a specific DOD application, under which is listed every R&D area critical or relevant to that application. Critical R&D areas (denoted by the blue boxes) are listed at the top, with relevant R&D areas (denoted by the green boxes) listed below.[59]

| DOD APPLICATIONS | DATA ANALYTICS | AUTONOMY & AI | RADAR & COMMS | SPACE | SENSORS & IOT | BIOMEDICAL |
|---|---|---|---|---|---|---|
| CRITICAL R&D AREAS | Memories | Adv. Packaging & Het. Int. | Adv. Packaging & Het. Int. | Adv. Packaging & Het. Int. | Adv. Packaging & Het. Int. | Bio-electrical integration |
| | Non-von Neumann | Low Power | MEMS | Low Power | MEMS | MEMS |
| | Scaling | Non-von Neumann | RF / Wireless | Novel Materials & Devices | Photonics | Novel Materials & Devices |
| | Hardware Security | Sensors | Hardware Security | | RF / Wireless | Photonics |
| | | | | | Hardware Security | Hardware Security |
| | | | | | Sensors | Sensors |
| RELEVANT R&D AREAS | Adv. Packaging & Het. Int. | Manufacturing Processes | Manufacturing Processes | RF / Wireless | Manufacturing Processes | Low Power |
| | Low Power | Memories | Novel Materials & Devices | Security & Cryptography | Memories | |
| | Manufacturing Processes | Novel Materials & Devices | Photonics | | Novel Materials & Devices | |
| | Novel Materials & Devices | Photonics | | | | |
| | Photonics | Security & Cryptography | | | | |

# APPENDIX C: SUMMARY TABLE OF PUBLIC-PRIVATE R&D ECOSYSTEM

This Appendix contains a summary table of the analyses the Potomac Institute performed on the data gathered on the public-private R&D ecosystem in the United States. The data was organized by R&D area, with each column in the table listing the figures of merit used to make an overall assessment of R&D areas most in need of DOD investment.

The full range of values for each figure of merit was broken into four major levels, the details of the divisions between levels and their corresponding color scheme listed at the bottom of the table. The data listed in the "PPRD Funding" column is a summation of the annual budgets from recent years of all PPRD centers that focus on the corresponding R&D area. This is used a broad figure of merit, intended to give an order of magnitude estimate of the total amount of resources contributed to US R&D in each area. For some of the funding inputs, only public funding amounts were available. Therefore, these values represent a lower bound on funding information, but only introduces minor uncertainties in the final analysis, as complete funding data was available for a majority of the organizations, including the largest PPRD centers. The data listed in the "# of Domestic Transition Partners" column is a summation of all unique (i.e. no company was counted twice in a single list, regardless of how many PPRDs to which a link was recorded) commercial companies with formal ties to the PPRD centers conducting research in that area. The figures listed in the "# of PPRD Centers with Prototyping Capabilities" column is a summation of all PPRD centers focusing in the corresponding R&D area that were identified as actively maintaining prototyping capabilities. The figures listed in the "Importance to DOD" column reflects a summation of the identified criticality and relevance of each R&D area to any DOD application. Criticality to each DOD application was considered twice as important as relevance to a DOD application. For example, the R&D area of low power was identified as critical to space applications and relevant to Biomedical applications, giving it an importance "score" of three. For specific R&D areas identified as having significantly strong or weak activity in commercial R&D, that was noted in the "Domestic Private R&D Interest" column and included in the final weighted average of all figures of merit.

A weighted average of all figures of merit listed was used to determine the overall need of each R&D area for DOD investment in public-private R&D efforts. The coloring of each R&D area in the leftmost column reflects the final result and is included as Figure 4 in the main report.

| R&D Area | PPR&D Funding ($ millions) | # of Domestic Transition Partners | # of PPRD Centers with Prototyping Capabilities | Importance to DoD | Domestic Private R&D Interest |
|---|---|---|---|---|---|
| Advanced Packaging & Het Int. | 213 | 24 | 7 | 9 | Weak |
| Bio Electrical Integration | 22 | 9 | 3 | 2 | |
| Hardware Security | 110 | 13 | 1 | 10 | |
| Low Power | 74 | 19 | 3 | 8 | Strong |
| Manufacturing Processes | 264 | 18 | 6 | 4 | |
| Memories | 4 | 17 | 0 | 4 | Strong |
| MEMS | 66 | 14 | 7 | 6 | |
| Non von Neumann | 71 | 21 | 1 | 4 | |
| Novel materials & Devices | 357 | 26 | 13 | 8 | |
| Photonics | 262 | 18 | 6 | 7 | |
| RF/Wireless | 203 | 17 | 7 | 5 | |
| Scaling | 16 | 4 | 1 | 2 | Strong |
| Sensors | 193 | 20 | 9 | 6 | |

| Color Scale | PPR&D Funding ($ millions) | # of Domestic Transition Partners | # of PPRD Centers with Prototyping Capabilities | Importance to DoD |
|---|---|---|---|---|
| Red | 0-87 | 0-5 | 0-2 | 9+ |
| Yellow | 88-175 | 6-11 | 3-5 | 6-8 |
| Green | 176-262 | 12-17 | 6-8 | 3-5 |
| Dark green | 263-350+ | 18+ | 9+ | 0-2 |

# ACRONYMS LIST

| | |
|---|---|
| AFB | Air Force Base |
| ASIC | Application Specific Integrated Circuit |
| BRIDG | Bridging the Innovation Development Gap |
| CMOS | Complementary Metal Oxide Semiconductor |
| COTS | Commercial off-the-shelf |
| CPU | Central Processing Unit |
| DARPA | Defense Advanced Research Projects Agency |
| DFARS | Defense Federal Acquisition Regulations Supplement |
| DMEA | Defense Microelectronics Activity |
| DOD | Department of Defense |
| DTRA | Defense Threat Reduction Agency |
| ERC | Engineering Research Centers |
| ERI | Electronics Resurgence Initiative |
| FAR | Federal Acquisition Regulations |
| FDSOI | fully depleted silicon on insulator |
| FPGA | Field Programmable Gate Arrays |
| IARPA | Intelligence Advanced Research Projects Agency |
| IC | integrated circuit |
| IoT | Internet of Things |
| IP | intellectual property |
| ITRI | Industrial Technology Research Institute |
| IURCRC | Industry-University Collaborative Research Center |
| LETI | Laboratoire d'électronique des technologies de l'information (Laboratory fo Electronics and Information Technology) |
| MEMS | Micro-electro-mechanical systems |
| MII | Manufacturing Innovation Institute |
| MTO | Microsystems Technology Office |
| NRE | Non-recurring engineering |
| NRO | National Reconnaissance Office |
| NSF | National Science Foundation |
| OSAT | Outsourced assembly and test |
| OSD | Office of the Secretary of Defense |
| DASD(SE) | Office of the Deputy Assistant Secretary of Defense |
| OTA | Other Transaction Agreement/Authority |
| PCAST | President's Council of Advisors on Science & Technology |
| PR | public relations |
| RaDESA | Research and Development Ecosystem Analysis |
| R&D | research and development |
| RF | Radio-frequency |
| RHBD | radiation-hardened-by-design |
| SCRA | Supply Chain Risk Assessment |
| SEMATECH | Semiconductor Manufacturing Technology |
| SoC | System on Chip |
| SOTA | State of the Art |
| TIC | Trusted Integrated Circuits |
| TRL | technology readiness level |
| UCF | University of Central Florida |
| USAF | United States Air Force |
| USG | United States Government |
| VHSIC | Very High Speed Integrated Circuits |
| VLSI | Very Large Scale Integration |

# ENDNOTES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2. Defense Science Board. (2017, March) *Final Report of the Defense Science Board Task Force on the Cyber Supply Chain*.

3. Potomac Institute for Policy Studies. (2016, May). *Ensuring Access to Trusted State of the Art Microelectronics*.

4. Friedman, T. (2015, May 15). Moore's Law Turns 50. *New York Times*, NY. Retrieved from: https://www.nytimes.com/2015/05/13/opinion/thomas-friedman-moores-law-turns-50.html.

5. Typical expected DOD lifetimes are 25 to 40 years. There are major systems today, like the B52 bomber, that are in their sixth decade of active use.

6. Air Force Studies Board, National Academy of Sciences. (2016) Optimizing the Air Force Acquisition Strategy of Secure and Reliable Electronic Components.

7. "late-stage" is typically characterized as focusing on advancing a technology through technology readiness levels (TRLs) 7 – 9. DOD definitions of TRLs can be found in the Defense Acquisition Guidebook, an excerpt of which was retrieved from: https://www.army.mil/e2/c/downloads/404585.pdf.

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19. Data for the equipment suppliers segment covered the top 11 global leaders, which represented nearly 80% of the global market. This study did not determine the breakdown of the remaining 21.4% of the equipment supplier market, and therefore that segment is left as "unknown."

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27. For example, the Pacific Northwest Lab and the Lawrence Berkeley do not conduct any research that falls within the scope of this study and are therefore not included.

28. These two programs designed to increase collaboration between government, academia, and industry, across a wide range of industries and scientific fields.

29. Within the past year, IBM research has taken over R&D operations of the facilities, making that campus much more of a private R&D facility than a collaborative, pre-competitive R&D center like the other PPRD centers considered in this analysis.

30. The three centers were Advanced Functional Fabrics of America, BRIDG, and the Informational Sciences Institute (ISI).

31. Detailed information on individual PPRD centers, such as budgetary information, R&D Focus, and R&D activities can be found in Appendix C.

32. "Total ERC New Cash Support, FY 2016 (19 ERCs)." Total ERC New Cash Support, FY 2016 (19 ERCs) | ERC Association, erc-assoc.org/about/erc_data/total-erc-cash-support-fy-2012-17-ercs.

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36. National Research Council. (2013). *21st Century Manufacturing: The Role of the Manufacturing Extension Partnership Program*. Washington, DC: The National Academies Press.

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44. Many companies would need to bring on legal experts in FAR and cease using lucrative IP internationally, leading to the re-engineering of many products.

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58. These application areas were specifically identified by the DOD as important for developing future capabilities.

59. There is no particular order to R&D areas listed within each category.

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