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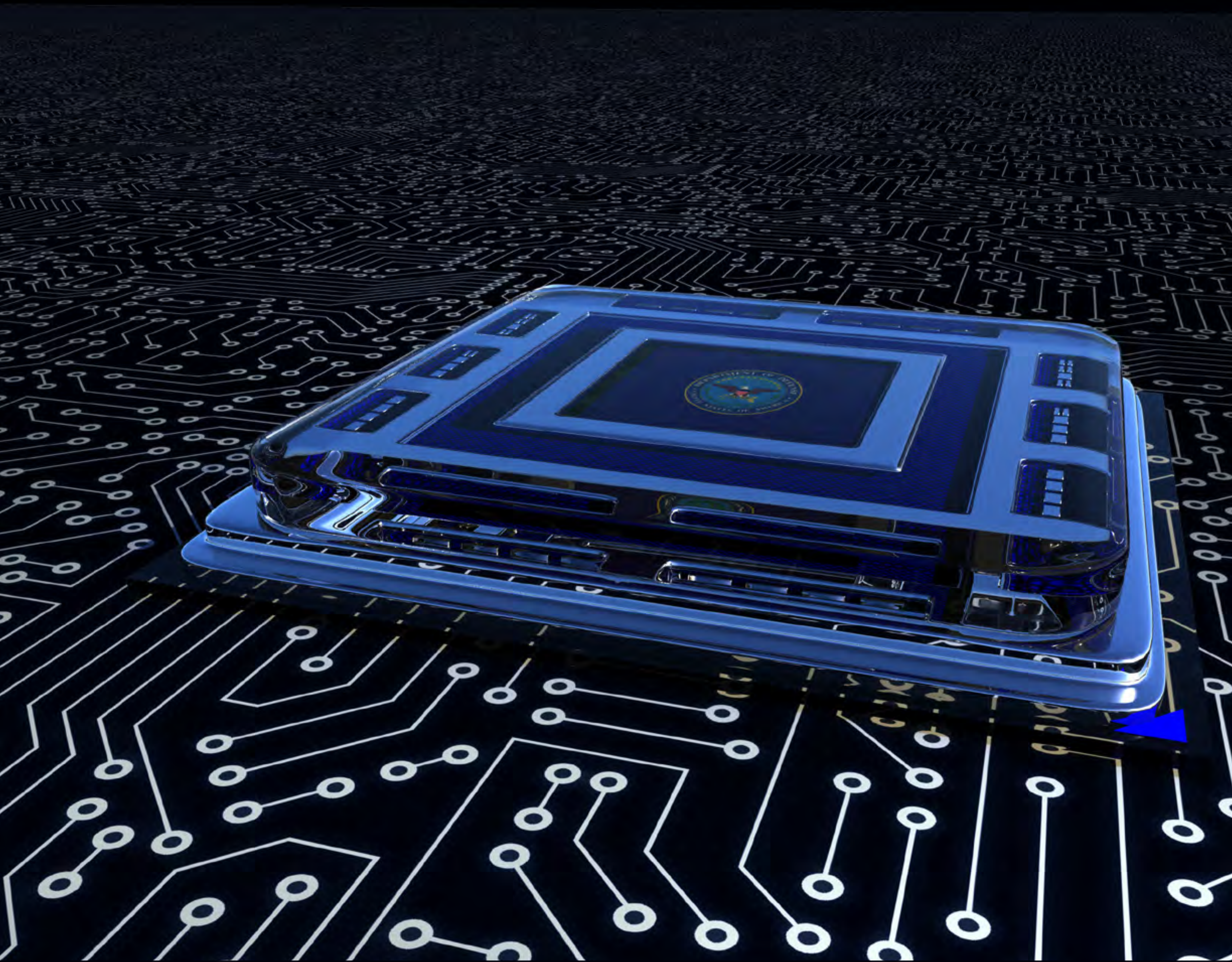
Consortia Analysis and Recommendations Trade Study



A POTOMAC INSTITUTE FOR POLICY STUDIES REPORT

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Potomac Institute for Policy Studies
901 N. Stuart St, Suite 1200
Arlington, VA 22203
www.potomacinstitute.org
Telephone: 703.525.0770; Fax: 703.525.0299

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EXECUTIVE SUMMARY

The Potomac Institute for Policy Studies conducted a six-month study to identify and understand key lessons learned from public-private research and development (R&D) collaborations in the semiconductor industry. The goal of the study was to provide recommendations to the United States government (USG) on how these lessons learned can be applied to new R&D initiatives. These recommendations were focused on the semiconductor industry, which has ambitious goals to explore areas that could lead to leaps ahead in computing, in part based on the foundational scientific concepts originally outlined by Gordon Moore.

Methodology

The objectives of the study were to identify lessons learned from the history of semiconductor R&D consortia and government R&D efforts involving technology transition, and to apply these to the current needs of the semiconductor industry. During the course of the study, the team conducted a thorough literature review and analysis of relevant case studies. Over 75 organizations were researched, over 20 existing reports on various aspects of the subject were studied, and multiple experts were interviewed. During the analysis of the information collected, the study team focused specifically on lessons learned and keys to success that would be relevant to the R&D efforts in the semiconductor industry.

Findings

Broadly speaking, this study supports the need for a strategic investment by the U.S. government to reinvigorate the semiconductor industry. Moore's Law – the model that has driven the massive economic and performance gains in the semiconductor industry over the past five decades – is plateauing. This inflection point in industry provides an opportunity for U.S. government investment in R&D to influence the future direction of industry.

The government's role in similar historical cases has been to buy down the innovation risk in areas that industry may not be willing to provide up-front investment, but that can have huge overall benefits for the industry and the U.S. economy.

Five major findings emerged from the research and analysis conducted for this study:

1. Consortia budgets need to be large enough, and stable over time (>5 years), to match the size and scope of that organization's goals.

2. A major cause of failure or delay in technology transition is due to a lack of willingness to fund later technology readiness level (TRL) stage development of promising technologies for DOD applications.

3. It is critical for public-private R&D efforts to follow industry's lead, while maintaining independence.

4. A successful near-term research direction for industry that would directly benefit the DOD is the development of low-volume manufacturing models for advanced technologies.

5. Other Transaction Agreements (OTAs) are specifically designed to be used as funding mechanisms for U.S. government R&D and prototype programs. They are currently very underutilized.

Recommendations

These findings led to five clear recommendations for the USG to implement:

1. Ensure that the funding level of any major public-private R&D initiative is at a magnitude that mirrors previous successful initiatives: $200-$300 million per year, 10-year timeline, total budget of $2-$3 billion.

2. Include costs for technology transition and insertion in the budget of all major R&D programs.

3. Follow industry's lead; make sure the USG still benefits.

4. Focus public-private R&D efforts on low-volume, customizable manufacting solutions to technical challenges.

5. Use OTA acquisition mechanisms in all R&D programs.

This report substantiates these findings and explains the recommendations. For further data supporting the findings described in this study, a section containing illustrative case studies of organizations and programs is also included. These case studies provide basic histories of the organizations and programs and focus on the specific key lessons learned relevant to public-private R&D initiatives that these organizations highlight. Additional supporting data collected for the study, including subject matter experts interviewed, organizations evaluated, and sources cited are included in the Appendices.

INTRODUCTION

Microelectronics are an essential enabler for Department of Defense (DOD) missions. Our defense platforms rely on the semiconductor industry to maintain critical mission capabilities. After having spawned the microelectronics industry, the DOD saw itself become a relatively minor player due to its low-volume needs. This small market, combined with the government's highly complex procurement rules, has made the relationship with industry even more difficult. With commercial demand dwarfing that of the United States Government (USG), it is no longer in a position to influence the microelectronics industry.

Many decades of steady progress have been made, based on regular feature-size scaling of complementary metal oxide semiconductor (CMOS) technology known as "Moore's Law." This period saw the emergence of large manufacturing facilities (fabs) making a relatively small number of "generic" parts (CPUs, memory technologies, GPUs, and FPGAs) in very high volumes.

The microelectronics industry is currently undergoing a major paradigm shift. Moore's Law scaling is coming to an inevitable end as transistor dimensions approach atomic proportions.[1] Diminishing performance returns are already being seen at the latest state- of-the-art transistor sizes and the cost per transistor has begun to rise for the first time in 50 years.[2] The paradigm of scaling-based progress is ending and a new paradigm will be taking its place involving non-scaling-based performance enhancers, such as 3D integration, novel architectures, and novel materials. This new paradigm will be characterized by a major shift to specialization: customized integrated circuits (ICs) made in lower volumes per part.[3] This shift is a major opportunity for the USG as this emerging trend is more aligned with its needs for custom low-volume parts. The USG must be aware of the current paradigm change and take advantage of the opportunity to once again influence the direction that the microelectronics industry is taking in the "post-Moore" world.

STUDY OVERVIEW

Study Approach

The study team began by performing a comprehensive data gathering effort and literature review, looking at a large number of current and past public-private research and development (R&D) consortia emphasizing those with relevance to the microelectronics industry. Publicly available information was used, including information on organization websites, organization annual reports, data from the NSF awards database, and external reports on related subjects (e.g. R&D consortia, technology transition, public-private partnerships).

The external reports gathered were also studied to identify broadly applicable best practices and keys to success in collaborative R&D and technology transition. The reports ranged from focused assessments on specific R&D consortia and public-private partnership organizations, to assessments on successes and failures on the topics of technology transition, building and supporting a healthy domestic manufacturing industry, and effective innovation within industry. The reports included in the literature review, as well as other sources cited, are included in Appendix A.

The team performed preliminary assessments of both domestic and overseas R&D consortia. A total of 79 organizations were studied, 55 domestic and 24 foreign. A standard "data template" was created for data collection to ensure that a comparable set of information was collected for each organization. This basic data included mission, technology readiness level range, funding, members, organizational structure, and level of government involvement. This initial list of organizations assessed is listed in Appendix C. A full set of the preliminary data collection sheets for these organizations is provided as a separate attachment.

Over the course of collecting information on organizations and their operations, the study team collected a range of metrics the organizations used to measure and assess their success and/or progress towards their stated goals. A short list of the most relevant and useful metrics for success, as identified by the study team, is listed on page 21.

Members of the study team traveled to attend a workshop hosted by DARPA's Microsystems Technology Office (MTO) in San Jose (July 18-19, 2017) and visited the new Bridging the Innovation Development Gap (BRIDG) center in Kissimmee, FL (Aug 9, 2017). Potomac Institute representatives also attended Semicon West in San Francisco (July 11-13) and spoke with many of the key consortium members there. Some organizations of interest, including IMEC and LETI, also held their own events at this conference, which PIPS representatives attended. Finally, members of the study team visited IMEC in Leuven, Belgium (Nov 9-10).

Over the course of the study, numerous interviews with subject matter experts with years of experience in technology transition and public-private collaboration were conducted. These interviews allowed the study group to cross-examine preliminary findings with experts as they were developed, and the interviewees were able to provide a series of lessons learned from past government efforts and potential avenues of success around persistent roadblocks to successful public-private partnerships in R&D. The full list of experts interviewed is listed in Appendix B.

The information obtained through data gathering, onsite interviews, expert consultations, and industry information interchange was compiled and analyzed by the study team. The compiled research findings were analyzed and used to form recommendations for the USG.

Case Studies

After the initial data search was finished, the study group filtered the list of organizations to narrow the study focus. To this end, a number of "downselect" criteria were used, which included degree of microelectronics focus, technology type (mostly standard microelectronics), organizational, degree of government support, and type of organizational structure. The team also made sure to consider a number of examples of historical significance to complement the large number of current organizations studied.

For the purposes of examining successful technology transition, the organizations working in the "mid-range" of TRL levels (4-7) were determined to be the most relevant. A short list was created of relevant organizations and programs to evaluate in added depth. The study team used criteria such as relevance to the semiconductor industry, a focus on components R&D, research activities that span a wide range of TRLs, and past or planned engagement with a majority of the semiconductor industry. The shortlisted organizations or programs studied in depth included:

1. VHSIC
2. SEMATECH
3. IMEC
4. ITRI
5. Faraday Centres
6. Fraunhofer Society
7. SUNY Poly
8. BRIDG
9. Manufacturing USA

Information was compiled for each down-selected organization regarding their business model and operational structure, and to the extent possible data was gathered regarding the organizations' own evaluations of best practices and lessons learned from experience in the research and development enterprise. The study team performed an analysis of the organizations by various attributes including size, budget/funding, TRL range focus, and degree of government involvement.

Case studies summarizing information gathered on most of the shortlisted organizations are included in this report. Two of the organizations, BRIDG and Manufacturing USA, were determined to be too recently formed to have demonstrated a record of success. Also, SUNY Poly has recently undergone significant organizational restructuring, and therefore was not included as a case study.[5,6]

LESSONS LEARNED FOR SUCCESSFUL PUBLIC-PRIVATE CONSORTIA

Over the course of the study, over 75 organizations and multiple reports were studied, particularly those supporting R&D technology transition as well as consortia-based management approaches. Numerous interviews with industry Chief Executive Officers (CEOs), Chief Technology Officers (CTO)s, research consortia subject matter experts (SMEs), and government R&D program managers were conducted. From analysis of the literature and discussions with experts, a few recurring themes emerged and are discussed below.

Finding 1: Operational budgets need to be large enough, and stable over time, to match the size and scope of that organization's goals.

The organizations studied ranged widely in both size and scope of goals. Many organizations smaller in size have narrowly focused goals, such as prototyping and systems development for a specific range of technologies, or R&D support for local small and medium size businesses. These smaller focused goals are not an accurate comparison to the ambitious objective of affecting an industry as large and global as the semiconductor industry.

In successful programs and organizations with such ambitious goals, nearly all maintained yearly operating budgets of over $200 million (in current buying power equivalence) and were able to sustain such levels of funding for at least a decade or more. The top R&D consortia in both Europe (IMEC) and Asia (ITRI) both have annual budgets over $500 million today and have received significant government funding steadily since their inception decades ago, funding which is unlikely to end any time soon.[7] Both SEMATECH and IMEC obtained government funding in 5-year grant blocks, a timeframe which provides a minimal amount of needed stability. The VHSIC program was planned as a 10-year, multi-hundred-million-dollar effort from the beginning, signaling to industry that the program intended to see through its promise of significant R&D results transitioned to the U.S. Industrial Base.[8]

There is a strong correlation between budget size and scope of consortia goals. For ambitious goals of influencing a hi-tech, global industry (or in some cases multiple industries), an organization needs sufficient resources to have a significant impact on the R&D directions as a whole. Today's commercial industry leaders have substantial R&D operations of their own. Intel alone spent nearly $13 billion in R&D in 2016, and the top ten companies in the semiconductor industry all spent over $1.5 billion each that year.[9] These companies are not likely to take notice of opportunities for collaboration unless they see significant advantages to be gained. R&D programs with yearly budgets that are less than a percent of commercial industry leaders go largely unnoticed. The converse effect is, however, also true: when an R&D center brings on a major industry leader as a member, it causes a large amount follow-on interest from the rest of the industry.

Research programs truly capable of influencing the direction of a major industry nearly always involve multidisciplinary efforts that focus not only on material and technical challenges, but also creating the necessary infrastructure support for integrating the new technologies into existing systems. This often involves addressing a range of constantly evolving issues, such as design engineering, equipment sourcing and adaptation, achieving yield and reliability requirements, and even workforce training, to name a few.

An ambitious research program requires significant investment in equipment and expertise to conduct. The R&D consortia most successful in influencing industry for the longer term maintain(ed) their own independently run facilities and staff, with an infrastructure and effective business model to support them. To build and maintain all of these resources, both physical and informational, requires significant funds. Annual budgets not large enough to support such efforts either result in the organization shrinking the scope of its goals or failing to achieve any significant impact on the desired industry.

To impact a major industry, a collaborative R&D organization needs to build strong relationships with a majority of that industry's players. The organizations and programs with relevant goals and scope each has/had their own mechanisms for building and maintaining such relationships. A common element across all organizations is the fact that sufficient resources are necessary to both incentivize a majority of the industry to work with the organization/program as well as to maintain long-term relationships with them.

In addition to having operational budgets large enough to impact a majority of the desired industry, collaborative R&D organizations need to show members of that industry that they have stable funding to continue their R&D until the technologies being developed become of practical commercial interest. R&D programs, especially those focusing on technology readiness level (TRL) challenges that are at early and mid- stages, typically need at least five years to make significant progress and more often a decade or longer to produce significant commercially-relevant results. Major USG programs, for example, have often taken five years or more to achieve technical success and continued engineering work in the private sector to make those solutions market ready took additional years. DARPA's radiation-hardened-by-design (RHBD) Program officially operated from 2004 to 2009, with multiple years of industry qualification work required afterwards.[10] Widespread adoption by the aerospace industry only began in 2012 and onwards.[11,12] Similarly, the IARPA Trusted Integrated Chips (TIC) program, which sought to develop a viable way to split the front-end-of-line (FEOL) fabrication processes from the back-end-of-line (BEOL) processes, began in 2011 and lasted over five years, with final efforts to transition the technology to commercial industry still underway.[13] While the TIC program has demonstrated technical feasibility,[14] it is still working on overcoming challenges of adapting industry's infrastructure to implement it, as well as developing other design techniques to fully leverage the split-fabrication technique for security.[15] Similarly, R&D on extreme ultraviolet (EUV) lithography technology begun by the USG at National Labs has continued in the private sector for several decades now. Photolithography expert Chris Mack stated 2015 that EUV developers have "promised a 100W source 'by the end of the year' (or early next year) every year since 2006."[16] EUV tools have only recently (2017) been inserted into Industry Roadmaps for SOTA feature patterning.[17] The sustained work required on EUV was only possible by consistent long-term R&D support begun by the USG and continued by private industry for example ASML, through their partnerships with IMEC and SUNY Poly's Albany Nanotech campus. Organizations that provide large amounts of funding for only a short number of years (< 5) with no continued support for the longer term are far less likely to attract serious industry partners willing or able to bring a major technology advancement all the way to a marketable product or set of products.

A key requirement for a public-private R&D program with an ambitious objective of substantive industrial impact is to have a sufficient budget which includes longer term sustainment support. The sizes and timeframes of successful R&D organizations that have had major impacts on commercial industries leads us to our first and strongest recommendation.[18]

Recommendation 1: Ensure that the funding level of any major public-private R&D initiative is at a magnitude that mirrors previous successful initiatives: $200-$300 million per year, 10-year timeline, total budget of $2-$3 billion.

A budget size similar to comparable programs in the history of the semiconductor industry is necessary for success if the USG aims to accelerate and guide the shift to a post-Moore landscape for the global semiconductor industry and effective technology transition to U.S. industry. The large scope of programs aimed at significantly advancing integration of new materials, developing entirely new architectures, and revolutionizing circuit design tools requires investment on the level of $200-$300 million per year, preferably with a stable program strategy extending roughly 10 years.

Finding 2: A major cause of failure or delay in technology transition is due to a lack of willingness to fund later TRL stage development of promising technologies for DOD applications.

This study examined the entire TRL-focus range for the various organizations studied. Upon closer inspection, most organizations ended up being pulled towards evolutionary innovation and short-term commercialization (later TRLs) or towards basic and early applied research (early TRLs). The engineering and development work necessary to push a promising technology through the late middle TRLs, in the range of 6-8, often receives insufficient support.

A likely cause of this problem is that there remains a strong mismatch between the typical end of government support (usually around technical proof of concept) and when serious commercial support begins (usually around pilot-manufacturing runs). This mismatch is exacerbated by disagreements that often arise on both sides as to when a new TRL level has been successfully reached[19] and when R&D results change from pre-competitive to industry proprietary Intellectual Property (IP).

R&D programs aimed at progressing through early TRLs focus almost entirely on achieving technical milestones, with little-to-no effort put towards the later prototyping, and qualifying work necessary for integrating the new technology into the target system.[20] The costs and risks of such integration efforts are significant and commercial companies are not always willing to pay them. This is especially true for technologies that have little-to-no commercial market outside of the defense industry. Commercial companies must not only consider the promise of success of developing a new technology but they must also factor in the expected market size and full lifecycle costs of bringing that technology to maturity. Those other concerns are at the root of the gap commonly referred to as the "valley of death." Therefore, if the USG wants to see more of its promising technologies evolve from proof of concept to manufactured products, it needs to be willing to pay the costs to cover this gap.

A few notable examples exist of when the government or public-private organization was willing to cost-share or pay the necessary technology insertion costs. The VHSIC program reserved at least 20% of its total funds to pay for technology insertion, in some instances paying the full cost of technology insertion and demonstration. In the early 1990s, the DARPA Optoelectronics program, taken over by program manager Andrew Yang, funded late-stage R&D aimed specifically at inserting new technologies in that field into commercial systems.[21,22] DARPA felt that the technologies developed in the program so far were still facing barriers achieving more widespread adoption. To accomplish this, DARPA funded two public-private consortia aimed at creating commercial high-speed fiber optic networks, which were highly successful in driving widespread adoption of fiber-optics technologies. The DARPA Rad-hard-by-design (RHBD) Program was effectively transitioned to other interested agencies (DTRA and NRO) who paid for several years of costly qualification work required before this technology could be deployed in space.[23] Although DARPA does not traditionally fund technology transition, it is often judged by transition success.[24,25] The existence of such historical precedents for government programs leads to our next recommendation.

Recommendation 2: Include costs for technology transition and insertion in all major public-private R&D program budgets.

Following the best practices identified in successful programs and organizations studied, we recommend that 20-25% of R&D program budget be allocated for funding technology transition and insertion work. These funds would be reserved for use in the final years of programs, to support only the results of those that have successfully completed performance milestones in the normal R&D evaluation process. Technology transition plans should be included in proposals from late-stage performers. These funds could be used for later stage TRL work by existing performers, or to establish technology insertion programs with new commercial performers, as was done in the VHSIC program in the 1980s.

Finding 3: It is critical for public-private organizations to follow industry's lead, while maintaining independence.

Commercial entities are driven by market forces and profit requirements, which limits the R&D efforts they decide to pursue all the way to maturity. In order for public- private R&D organizations and programs to achieve their goals, they must provide an economically justifiable benefit for commercial companies that interact with them (e.g. as members, partners, or customers). A key to the success of notable collaborative R&D organizations is their recognition of this important fact. Different organizations have found different approaches that work for them: the Fraunhofer Society provides evolutionary innovation and resources that benefits small and medium size companies; ITRI provides opportunities for information and expertise sharing across the semiconductor R&D ecosystem and even across different industries; IMEC built on top of an initial expertise niche in lithography to have a major impact on many segments of the industry; SEMATECH served as a pioneer of pre-competitive research for U.S. semiconductor manufacturing equipment. All organizations, however, made listening to industry needs a high (if not top) priority.

Most successful collaborative R&D business models derive significant revenue from private contracts, which requires closely following the expressed needs and interests of the industry.[26] Figure 1 shows a schematic that reflects a particular business strategy that adopts this perspective. The strategy is to maintain a steady source of public, or core, funding while focusing all growth efforts on increasing private funding.

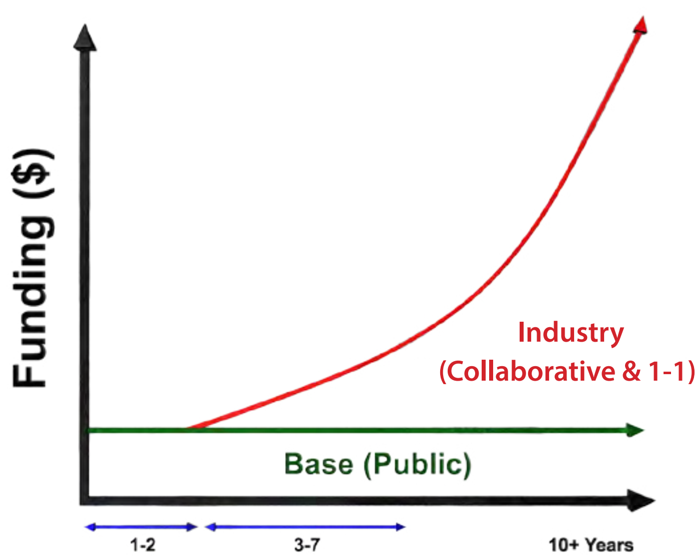


Figure 1.
An example revenue model for a sustainable Public Private Research Consortium.

This strategy therefore achieves growth without requiring increasing public funding. It also assumes that the first two years are needed to build the consortium, forming partnerships and acquiring the necessary resources, which will need public funding to cover the high risks at this early stage. In later years, the majority of the organization's revenue should come from private funds, which naturally motivates the organization to stay closely in tune with industry needs and trends. Even in later years, however, the organization's core funding is necessary for it to pursue riskier, longer term projects that help the organization remain independent and bring the next generation of promising technologies through later TRLs to the point where they are attractive to commercial companies.

Applying this strategy more broadly to public-private partnerships in general, it becomes apparent that another key to maximizing the success of technology transition efforts is for the organization to maintain a strategy of aligning its efforts to industry trends and needs. However, just as the independent (higher risk) R&D made possible by organizations' core public funding is critical to their long-term success, a public-private partnership needs a mechanism for ensuring that the public entities participating in the partnership also benefit through reducing their cost of new technology R&D – and thereby their risk of investment. This theme of focusing on following industry trends but balancing that influence with mechanisms for riskier independent efforts leads to our third recommendation.

Recommendation 3: Follow industry's lead; make sure the USG still benefits.

In deciding specific projects to fund, USG public-private R&D programs should maintain close interaction with industry representatives to maximize the ability to provide results that meet their needs and interests. 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.

Therefore, when choosing broader research directions to pursue, R&D programs should always make fulfilling USG-unique needs a top priority. If programs can successfully find avenues to meet both industry and government needs, both short and long-term benefits will be compounded. This was the case in the successful VHSIC program in the 1980s, which saw not only the insertion of the chips it developed into commercial systems, but also directly into a significant number of military systems.

Finding 4: A desirable near-term research direction for industry that would directly benefit the DOD is the development of low-volume manufacturing models.

In considering specific research areas that could follow the previous finding, this study recognizes a unique opportunity brought about by new "post-Moore" trends in the semiconductor industry. It is increasingly recognized that future performance gains in the semiconductor industry will come from innovation in computing structures, circuit designs, and hardware specialization – not feature-size scaling. Examining the broader effects of this paradigm shift, it is apparent that this will cause increased segmentation in the overall semiconductor market, providing an opportunity for more specialized, lower-volume manufacturing models.[27,28,29]

Low-volume, high-mix manufacturing models are ideal for serving DOD needs, which are inherently wide ranging in capabilities and lower in volumes (relative to commercial markets). Low-volume manufacturing models already provide successful business cases for a small number of commercial companies[30] and developing further low-volume manufacturing methods would increase their abilities and lower the barrier for start-ups and small businesses with unique technologies to compete in the commercial industry. Increasing the ability for a wider range of technologies to be commercially viable, especially at lower production volumes, would benefit the USG enormously in the long-term.

There is currently a historic convergence of industry interest with DOD need for low-volume manufacturing methods. This should be exploited by USG investments to help influence the direction of this technology trend.

Recommendation 4: Have government R&D efforts focus on low-volume, customizable manufacturing solutions to technical challenges.

The post-Moore future will be dominated by a new manufacturing paradigm featuring increased specialization and combinations of parts made in lower volumes than before. The USG R&D programs should pay particular attention to manufacturing approaches for the new technologies it develops with a special focus on low-volume customized approaches. Appropriate investments should be made to enable these new manufacturing methods.

Finding 5: Other Transaction Agreements (OTAs) are specifically designed to be funding mechanisms for USG R&D and prototype programs.

Other Transaction Agreement (OTA) authority is granted in U.S. Code 2371b[31] 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).[32,33] 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 intellectual property (IP) policies, allowing for much more flexible handling of IP rights and licensing of R&D results. OTAs are an acquisition tool with potentially revolutionary impact on DOD R&D but are very much underutilized today.[34]

Other transaction agreements (OTAs) come in a variety of forms and are typically distinguished according to whether the purpose is for research or a prototype. Many government efforts aimed at developing new technologies to serve government needs include research and prototype development. Section 845 of the FY1994 National Defense Authorization Act (NDAA) describes the authority allowed by Congress for the use of OTAs, and many agencies including NASA, DARPA, and others have used these mechanisms in the past. For the purposes of public-private R&D programs, an OTA consortium management approach would allow for the flexibility of this acquisition structure, allowing for the government technical managers to review and approve proposals but delegate administration and contracting responsibilities.[35]

A consortium management firm (CMF) focuses on managing the organizational and contractual infrastructure of the consortium, leaving the technical oversight to the program managers.[36] The traditional government roles, e.g., technical proposal reviews, remain the responsibility of the government organization. The consortium manages the relationships and communication between the strategic partners, stakeholders, and Industry members. In practice, the government sponsoring organization writes a blanket contract to the CMF, which then engages with the performer community using an OTA mechanism. Many government agencies responsible for the management of large-scale research and prototyping programs have benefitted from leveraging the contracting capabilities of consortium management firms.

The typical process for government agencies using a consortium-based OTA structure would be for the government to provide the research requirement to the CMF; the CMF develops the request for white papers or proposals based of the research topics in one of many forms – Broad Agency Announcement (BAA), Request for Proposals (RFP), Special Project Announcement, etc. This announcement need not be limited to consortium members. The CMF organizes all submitted white papers and proposals and provides them to the government for review and selection. Once desired projects are selected, the CMF generates the award contracts.

This model has been found to be highly effective in practice. For example, it has been shown to bring the award cycle down significantly. As an example, Advanced Technology International (ATI) was able to reduce contracting time from 270 days to 50.[37] All contracts are commercial contracts; thus, for a government organization working with a CMF, there is effectively no difference to using a traditional contracting agent. However, using a CMF versus traditional contracting agent can save time in awarding contracts, as well as can afford the program manager time to focus on the technical details of the research instead of the administrative and contracting details.

There are many examples where OTAs were effective at capturing non-traditional performers, and were much more compatible with industry business models in general. OTAs can also be executed in a much timelier manner than traditional FAR-based contracts. The OTA-based consortia models we have explored in this study, of which many are described in our initial findings report, have been very effective in providing DOD with needed technologies in a timely manner at reasonable cost.[38,39,40]

Recommendation 5: Use OTA acquisition mechanisms in all R&D programs.

USG agencies should use the OTA authority they have been granted to achieve better results for their R&D programs. OTAs are flexible enough that large R&D initiatives can be structured as a single OTA,[41] or individual programs can be given their own OTAs to be managed separately. Benefits include shorter contracting time, less government time spent on administrative aspects, a more diverse set of performers and more effective technology transitions.

OTAs are a less well-known acquisition vehicle by government acquisition experts, and some reluctance to using non-traditional measures should be expected. This is why it is important for leadership to give guidance to use OTAs, and for performers and potential commercial transition partners to learn about OTAs and the flexibility they can provide, so all parties involved can maximize the potential OTAs provide.

ANALYSIS OF SELECT CASE STUDIES

The study team performed an extensive assessment of R&D programs and consortia. Based on this analysis the study team assessed a general set of metrics for success in R&D consortia. The set of R&D programs and consortia was then down-selected and in-depth case studies were conducted to provide a more detailed assessment of successes and challenges.

General Metrics for Success

Over the course of this study, the research team noted a wide range of metrics that different organizations used to measure their progress towards and level of success in reaching their stated goals. From this larger list, we have analyzed those metrics most applicable for public-private R&D programs. Particular attention was paid to measuring the ability of new technologies resulting from these types of R&D efforts to successfully end up being utilized by USG agencies and the resulting growth of domestic representation in the global semiconductor industry. Below are the metrics of success that may be most relevant and useful for the USG.

1. Total number of transition partners.
2. Total number of technology insertion projects into DOD programs.
3. Percentage of transition partners that are domestic companies/organizations.
4. Self-rated satisfaction of transition partners.
5. Self-rated size of impact that participation in the program had on the performer's or transition partner's business.
6. Number of products, especially products acquired by the USG, that contain IP resulting from the collaborative work, as identified by performers and transition partners.
7. Likelihood the organization will bid for or act as a transition partner for a future public-private R&D program.
8. Likelihood the performer and/or transition partner would have made specific gains/advancements/ etc. without participating in the program.
9. Number of Patents and copyrights granted/acquired by transition partners within 10 years of the program's start.
10. Amount of IP being licensed by performers and transition partners over the first 10 years after the program's end.

11. Revenue per year from IP licensing from performers and transition partners over the first 10 years after the program's end.

Lessons Learned for public-private R&D efforts

The study team down-selected to organizations that have had a major impact on a global industry. For a program or organization to have a major impact on a global industry, research demonstrated that the budget needed to be large enough to accomplish the following goals:

- Attract the participation of most of the companies in that industry.
- Tackle large, industry-wide problems holistically.
- Develop not only new technologies, but support infrastructure (design, test, etc.) to ensure the industry can easily integrate new technologies into their existing systems.
- Pay the lion's share of technology insertion costs.

Case Study Selection Criteria

This study's research includes a set of case studies describing organizations and programs, which aimed to impact one or more industries on a national or global level within 10-15 years of their start. These organizations and programs were selected because they possess at least one of the following success criteria:

- A technology or process that becomes widely adopted and recognized as producing a significant advantage/advancement for the industry.
- Public recognition as being a critical contributor to the advancement of a basic metric of the industry. (semiconductor industry = transistor size; solar industry = cost per kWh).
- Name recognition/acknowledgement in the majority of the industry as a major influencer.

Based on the metrics summarized above, the following case studies present organizations and programs most relevant to major public-private R&D efforts in microelectronics, along with discussions of major keys to their success and/or lessons learned that both contributed to the findings listed in the previous section and are applicable to USG goals.

Very High Speed Integrated Circuits Program (VHSIC)

History: The Very High Speed Integrated Circuits Program (VHSIC) was a joint Army, Navy, Air Force program launched by the Department of Defense (DOD) in 1980. The stated goal of the program was to give "… systems developers and acquisition managers a military qualified microelectronics technology that was on par with or better than the technology available commercially."[42] Senior officials within the program have clarified that the actual goal was to both develop and demonstrate new integrated circuit (IC) technologies that would leapfrog past the leading-edge IC capabilities in signal and data processing for military applications, and also ensure the widespread adoption of the new technology in military systems.[43] VHSIC was the highest priority technology program in the DOD at the time, and was considered vital to maintaining the military superiority of the United States.

VHSIC received over $1 billion in funding over ten years, starting with a total budget of $339 million in 1980. It was managed under USD R&D and included offices in each Service for contracting and administration. The major program activities included four overlapping phases of technology R&D and a technology insertion effort. The primary industry participants contracted on the program were Honeywell, Hughes, IBM, Texas Instruments, TRW, and Westinghouse in Phase 1. The participants were down-selected in Phase 2 of the program to Western Electric, RCA, and Harris. In 1982, the program initiated an aggressive program to insert VHSIC technology into weapon systems by actively subsidizing the six Phase 1 contractors to insert VHSIC technology into defense systems. This expanded the costs by $442 million to a total of $781 million. By the end of the program, the total budget was increased again to over $1 billion and included co-funding from contractors and systems program offices.[44] Budgets of that size in the 1980s would be equivalent to a budget of $2 billion to $3 billion today.

The main goal of the program was a resounding success. Integrated circuit technology leapfrogged from >1μm to 0.5μm[45] and was successfully integrated into 30 military projects and over 60 other commercial insertion projects. Important achievements were also made in microelectronics infrastructure including the development of the hardware description language (VHDL),

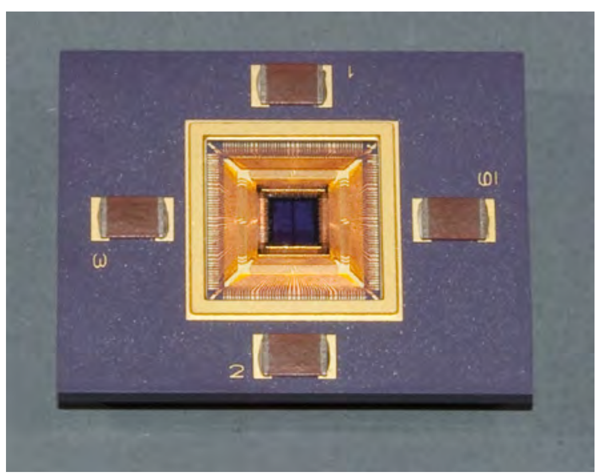


Image credit: Smithsonian Institute.

which became an industry standard and is still used in VLSI design today. Additionally, information on the technology development was disseminated through over 1,000 documents. VHSIC sponsored training courses, workshops, and conferences, numerous design tools were created, and VHSIC technology was widely adopted by a significant portion of the commercial U.S. semiconductor industry. The long-term effect of VHSIC was to shift the trajectory of the industry at large and ensure wide availability of its technologies in military systems.

Keys to Success and Lessons Learned: VHSIC was a program run through the DOD that leveraged commercial activities to supplement its funding levels.[46] The goals of the programs were ambitious – to leapfrog commercially available state-of-the-art technology and shape the future trajectory of industry. The broad success of VHSIC in achieving its goals provides key practices for success that should be emulated in the creation of a similar program today. The four keys to success best exemplified by VHSIC are 1) its sufficiently large size, 2) its multifaceted approach to solving major technology challenges, 3) its commitment to paying for technology insertion, and 4) its engagement with all levels of industry.

The first crucial key to VHSIC's success was the program's sufficiently large size. Because of the ambitious objectives of the program, a comparably large budget was required. It's ten-year, $1 billion level of funding allowed it to attract the participation and full commitment of top industry companies – without fear of erratic federal funding – and within a short time the rest of the industry followed suit.[47] The size of the budget was also sufficient to develop not only the core IC technology but also the supporting infrastructure (hardware description language, EDA tools, and testing protocols). Without these tools, the results of the VHSIC program would not have been as widely adopted by the commercial industry. The large size of the budget also allowed VHSIC to hand out a high number of small-medium dollar contracts to address specific design problems. Contracts were given to small and large industrial contractors, universities, research institutes, and government laboratories.

The second major key to success for the VHSIC program was how it approached developing a new generation of microelectronics technology in multiple ways, rather than focusing on problems in isolation. In addition to creating manufacturing processes for ICs with sub-micron transistor sizes, the VHSIC program invested the necessary time and resources into developing electronic design automation language, the VHSIC Hardware Description Language (VHDL) which later became an industry standard.

The third critical strategy utilized to great effectiveness by VHSIC is the commitment to paying for technology insertion. The program actively promoted the application of VHSIC technology in defense systems at the earliest possible date, which was a novel method of facilitating adoption in already existing systems. Not only did they encourage adoption, they also paid the Services to insert

VHSIC chips to increase near term demand for the program's technologies by system developers. Furthermore, the program provided subsidies to contractors to increase the quantity and reduce of the cost of chip production.[48] Overall, 20-25% of the budget was allocated for technology insertion. This proved critical to incentivizing commercial companies that had not participated in the program to agree to technology insertion projects and to build momentum for the viability of VHSIC chip production as an industry trend.

The final factor in the success of VHSIC was the early and sustained engagement with industry at all levels of the program. As mentioned earlier, VHSIC supported the production efforts of contractors by paying $192 million to increase quantity and reduce cost of chips from $5,000 to $500.[49] The overall goals of the program targeted military needs while complementing commercial goals. To stay competitive with VHSIC contractors, other major defense contractors and IC suppliers made significant investments to develop their own VHSIC-manufacturing capabilities independently from the DOD subsidies. The program had managed to convince commercial industry that VHSIC was the future, so they invested their own money into building the necessary infrastructure, with hopes of future military contracts, and effectively pushing the commercial development forward. Convincing industry that investing in VHSIC technology was the proper action was in part the result of coordinated public relations efforts to spread good news about the program and paint it in a positive light. This included giving away VHSIC design tools, which is in part how private companies were able to start building VHSIC tools themselves (at no additional cost to VHSIC program), openly sharing information, and handing out high numbers of small contracts to any performer – from companies to researchers to individuals – with an innovative solution to an ongoing design roadblock. This was funded by Phase 3 of the program, which was conducted concurrently with Phase 1 and 2. It was doubly useful, as it both recruited innovated solutions and talent, and created a network of advocates for the program in the field at minimal cost.

Conclusion: The VHSIC program is a prototypical example of a major DOD microelectronics program. It was motivated by direct military need and had the ambitious goal of impacting the entire U.S. microelectronics industrial base to ensure availability of the desired technology to the DOD. Sufficient resources were allocated to the program to achieve these goals which included the willingness to pay for technology transition. A major part of the U.S. industry was engaged in this effort and lasting impact was made including the development of a hardware description language (VHDL) which is still used today. Valuable lessons can be learned from this program. It is important to note that the microelectronics industry has become much more globalized since the VHSIC program executed which adds to the challenges of undertaking a comparable effort today.

SEMATECH Consortium

History: SEMATECH was a non-profit consortium of semiconductor companies that worked to increase the competitiveness of the U.S. semiconductor manufacturing equipment industry. A major motivation was the fear of growing Japanese competition in this area. SEMATECH was created in 1987 by DARPA at the direction of Congress. The consortium began with an annual budget of $200 million, half contributed by the government and half by private industry. The original goals aimed to return the U.S. semiconductor industry to a leading position in the global market, without specification of the means and/or methods to be used. In 1992, the government recommitted to another five years of supporting the consortia, but it stipulated that in 1997 SEMATECH would be weaned from public funding, becoming a fully private research and development consortium.

At its inception, SEMATECH had 14 members, all based and operating in the U.S. The consortium specifically excluded any international semiconductor companies, as well as the U.S. subsidiaries of foreign companies. SEMATECH also operated an independent research fab in Austin, TX. Upon transitioning to a fully private consortium, SEMATECH decided to allow international companies to join its membership, which boosted its revenue, at least in the short term. At peak membership, the consortium boasted 138 members. Over time, however, many smaller U.S. companies could no longer afford member dues and subsequently withdrew from the consortium. In 2003, SEMATECH began a major partnership with the Albany Nanotech campus of SUNY. Later in 2010, faced with the need to close its facility in Austin, SEMATECH agreed to relocate to SUNY Albany, using facilities provided by the university. In 2015, SEMATECH was absorbed into SUNY Polytechnic, changing its name to SUNY Poly SEMATECH and ceasing to be an independent entity.

Over the first 10 years, many in the semiconductor industry considered SEMATECH to be accomplishing its goal. While it no longer specifically supported U.S. companies alone after 1997, SEMATECH continued to be a major conductor of R&D in the industry for many years. Over time, with all of its revenue and board of directors coming from private industry, influence over SEMATECH's activities – and consequently benefit from its R&D – became consolidated in a smaller and smaller number of major industry players. Today SEMATECH has only 12 members and exists only as a part of the current operations at the College of Nanoscale Science and Engineering (CNSE) in New York.[50]

Keys to Success and Lessons Learned: SEMATECH is a relevant example today because it was the first major pre-competitive R&D consortium in the United States. In examining the keys to SEMATECH's success, the history of the organization can be divided into two phases: early SEMATECH and late SEMATECH. Early SEMATECH serves as an excellent positive example, with many keys to success to highlight. Late SEMATECH, in contrast, shows how the loss of many of the keys to success that the organization had practiced in earlier years led to the decline in size and influence of the organization on the global semiconductor industry.

Early SEMATECH exemplifies three keys to success for a major R&D consortium: 1) its sufficiently large size and stable operation for more than a decade, 2) its engagement with a majority of the industry, and 3) its independent control of research facilities, equipment, and staff.

The first key to success, SEMATECH's budget size, especially with the 50% contribution from industry, was critical. Being able to match funding with the initial members of the consortium to the level of $100 million per year, for at least five years was critical in attracting a majority of U.S. semiconductor companies to be a part of the consortium. The budget was also sufficiently large for SEMATECH to exist and operate independently from the consortium members, and not have to use facilities provided by any single member, which would have provided that member with significant control over the activities of the entire consortium.

The second key to early SEMATECH's success was that its membership included a majority of the U.S. industry, and when the consortium became international, it quickly expanded its membership list to represent a majority of the global industry as well. In its first decade of operation, with the goal of supporting U.S. companies, the results of SEMATECH's R&D work were shared with all members immediately, which meant that advances it produced quickly reached a majority of the U.S. industry. This contributed to major influence over the what technologies and processes were available in the United States.

The third critical factor in SEMATECH's early success was the fact that the consortium operated its own R&D facilities. With no single member having ownership over the research equipment and facilities, the work was truly collaborative and all members had a reasonable amount of access to SEMATECH's facilities. Furthermore, the research staff consisted of scientists and engineers loaned out from member companies. Even though the SEMATECH staff were employees of different companies, they worked at the SEMATECH site, and therefore gained a sense of loyalty to SEMATECH's mission during their time there. Bringing experts from different companies to work together under one roof also had an enormously positive effect on information sharing and innovation born out of combining creative minds from different backgrounds. This improved both the work done at SEMATECH and, when the employees returned to their companies, improved innovation at the member companies.

SEMATECH in its later years lost many of the keys to success it had when it began. It grew increasingly dominated by a few large member interests and focused on shorter term projects. Its management became risk averse and unwilling to take on longer term efforts as well. With its move to Albany, NY it also lost the benefit of having its own independently run fab. It slowly lost customers until it was finally absorbed into SUNY Poly in 2015.

Conclusions: SEMATECH was the first major pre-competitive R&D consortium in the United States. Originally focused on re-invigorating the U.S. semiconductor tool business, its legacy is more likely to be in the organizational structure experience of pre-competitive consortia. It set some valuable precedents including serious DOD–industry cost-sharing, letting industry run the organization, bringing most of the industry together, and real collaboration for pre-competitive challenges. The early SEMATECH was successful following these principles. The later SEMATECH (after the end of DOD funding) began to lose its way and eventually most of its keys to success, leading to its inevitable decline and final absorption into SUNY Poly.

Industrial Technology Research Institute (ITRI)

History: The Industrial Technology Research Institute (ITRI) in Taiwan is one of the world's most successful microelectronics R&D organizations. ITRI has been successful in its goal of making Taiwan a world leader in the semiconductor industry, revolutionizing the industry landscape by pioneering the pure-play foundry model, producing the Taiwan Semiconductor Manufacturing Company (TSMC), the world's largest and most successful pure-play semiconductor foundry. ITRI was formed in 1973, when Taiwan's Ministry of Economic Affairs (MOEA) combined three existing research organizations, funding the new institution with $213 million, which would be equivalent to a budget of $1.2 billion today.[51, 52]

Since its beginning in the early '70s, ITRI has grown from three research institutes with 400 employees to eight research centers – supported by six core labs – over 6,000 employees, and an annual budget of $700 million, half of which is provided by the Taiwanese government.[53] Today, 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. Its focus has grown beyond semiconductors into areas including biomedical, green energy, materials, IT, photonics, and Internet of Things technology. Semiconductor industry analysts have described Taiwan as "the best place in the world to turn ideas into physical form," in large part because of ITRI.[54]

Image creditL: YSH1005

Keys to Success and Lessons Learned: A key aspect of ITRI's success is the sustained critical mass of funding that characterizes this organization. It has an annual budget of $700 million about half from government and half from industry. The government level of support has been solid over the past several decades. This budget is consistent with ITRI's ambitious objectives of major technology development and commercial impact for the benefit of Taiwanese industry.

Another key to its success is the premium ITRI places on close interaction with industry. Solving industry problems and encouraging early and rapid technology transition extends ITRI's research efforts across nearly all TRL levels. It thus works hard to engage with most of the major players in Taiwan and other countries in the research programs it works on. This ensures more successful technology transition.

Like early SEMATECH, ITRI is a non-profit organization staffed by "assignees" from industry, government and academia. It does not believe in a permanent staff feeling that this would weaken the focus on successful technology transition of its R&D to Industry. This gives ITRI significant autonomy, allowing it to resist becoming captive to any single company. The strong ties to industry helps make ITRI unafraid to cancel efforts it believes are unsuccessful or no longer relevant for industry exploitation.

Another important key to ITRI's success is its willingness to not only develop specific technologies but also the supporting infrastructure required to ensure successful commercial exploitation. This is an aspect we have found to be common to successful R&D consortia.

Conclusions: ITRI is the premier R&D consortium in Asia today. It has a long track record of success playing a major part in turning Taiwan into a high-tech driven economy. A major achievement was the development of the pure-play foundry model and the birth of TSMC, the world's largest pure-play foundry, to which it still maintains close ties. ITRI has achieved this success by providing long-term sustained critical mass of funding that is cost-shared between government and industry. Strong engagement of industry is another key aspect of their success.

Interuniversity Microelectronics Center (IMEC)

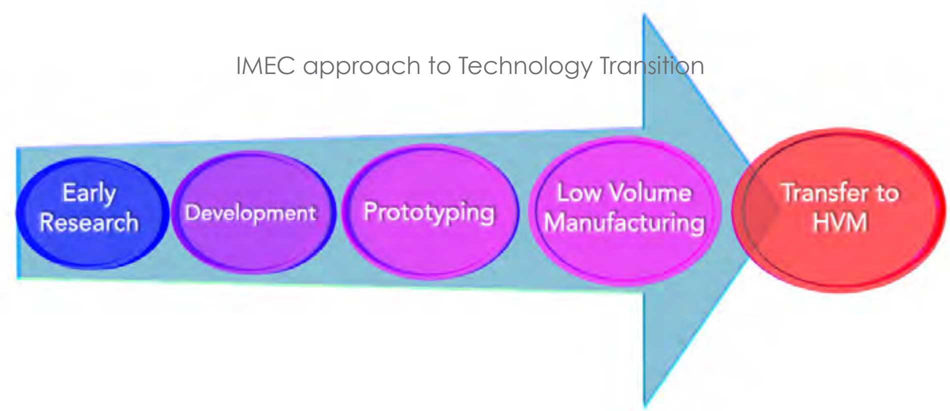
History: IMEC is a world class non-profit R&D consortium located in Leuven, Belgium. It was founded by the Flemish government in 1982 to strengthen the local microelectronics industry and economy. It has since grown into a major R&D consortium with 3,500 researchers and an annual budget of $600 million. Total infrastructure investments in its main facility are in excess of $1 billion. The IMEC campus contains state-of-the-art fabrication facilities including 200 mm and 300 mm wafer fabs. In recent years, IMEC has expanded beyond Moore's Law scaling research into new areas of semiconductor-related research, including heterogeneous integration, neuroscience, bio-integration, and alternative energy production and storage. They have complemented their strong capabilities in hardware R&D with a recent merger with the "iMinds" Institute in Ghent adding considerable software R&D capabilities.[55]

IMEC began as a partnership between the local Catholic University (KU) in Leuven and the lithography tool maker ASML. In its beginning, IMEC was able to leverage the high demand for ASML machines to add a majority of the semiconductor industry to its members list. IMEC continued gaining considerable success performing pre-competitive research in support of enabling the Moore's Law Scaling Roadmap for a large number of commercial organizations including major semiconductor firms and fabs. A major key to IMEC's success is its philosophy of "co-development": developing fabrication processes in parallel with measurement and testing protocols, design rules and toolkits, and other aspects necessary to aid transitioning the technology to industry production.

IMEC hopes to translate its successful R&D business model to "post-Moore" technologies including advanced packaging, biotechnology, medical, photonics, neuroelectronics, artificial intelligence, hardware security and green energy to name a few. Internet of Things R&D is a key element of their new focus. IMEC's vision of the future of the industry is increased hardware specialization and integration of a wider mix of components into more compact systems (e.g. system-in-package (SiP) and system-on-chip SoC).

Keys to Success and Lessons Learned: IMEC's budget comes from 74% outside contracts with industry and 26% government funds (from Belgium and the EU). The substantial amount of industry funding guarantees that their work remains relevant. Of the public funding, 16% is "core" funding from Flanders which comes in five-year blocks while 11% comes from competitive EU contracts. The long-term sustained government funds are very important for the success of the organization, as it allows them to explore new areas of research before they have clear industry customers. This avoids too much of a short-term focus in their research portfolio. Overall, about 15-20% of the IMEC revenue comes from "service" activities, including multi-project wafer runs and low-volume production. This also helps to diversify the funding sources and provide stability for the organization.

From the beginning, IMEC has addressed not just specific microelectronics R&D topics but also sought to help develop the infrastructure required by the industry. This meant working on design research in addition to fabrication challenges, for example. The Europractice multi-project wafer service, modeled on the U.S. MOSIS organization, is also located at IMEC. IMEC places high value on technology transition of their work and the strategy for this is shown in the figure below. In addition to prototyping, they also offer low-volume manufacturing as well as technology transfer services for high volume manufacturing.



IMEC's success has been based on their CMOS R&D in support of the ITRS Semiconductor Roadmap goals. In this area, they have been able to partner with a significant fraction of the major players in the semiconductor industry, most notably ASML. As an independent non-profit, they are an attractive entity for industry to work with as they do not compete with their customers. Industry protects its interests by appropriately compartmentalizing the R&D they perform at outside consortia like IMEC.

The keys to IMEC's success to date have rested on a number of basic elements. They are an independent non-profit organization which is attractive for industry. They have substantial in-house fabrication facilities with a critical mass of world class researchers. They support important infrastructure needs of the microelectronics industry in addition to working focused R&D projects. They offer prototyping and low-volume manufacturing services. Their focus on industry sponsored research ensures the relevance of their R&D portfolio. They have an "open innovation" model in which IP is readily shared with all team members in the early stages of a project. More proprietary relationships with commercial customers come in at later stages of a technology's development. There are different types of IP models depending on the stage of research and the needs of their customers. One size does not fit all. The IP management system IMEC has in place is very important in its sustained success with a wide variety of customers who are often commercial competitors. Finally, the long-term sustained government support they receive

(26% of budget) allows them to explore new technologies when they are still considered too risky for industry sponsorship.

Conclusions: IMEC is one of the world's premier R&D consortia. Starting from humble beginnings at KU Leuven, it has grown into a large organization with a major impact on the semiconductor industry. It has engaged with a large segment of the main industry players in microelectronics and played a major role in keeping the ITRS Roadmap on track. Keys to success have been their significant fraction (74%) of industry funding and engagement with a large segment of the main microelectronics players. The long-term sustained government support from Belgium and the EU have also been very important permitting more high risk work to be undertaken.

Faraday Centres/Partnerships

History: The Faraday Centres, also called Faraday Partnerships, were a network of R&D centers in the UK started in the late 1990s. Thoughts of creating a UK version of German Fraunhofer Society began as early as 1992, with proponents in both major political parties. It took a few years and changes in Parliament to an initiative to create a series of R&D centers to be started.[56]

The initiative aimed to encourage businesses to engage with the science base and partake in a two-way exchange of information with universities, collaborative R&D and development projects, and technological and dissemination events.[57] Intermediary organizations facilitated this flow of value added knowledge, and were required to demonstrate an existing and strong connection with both industry and academia.[58] The Department of Trade and Industry (DTI) offered up £1.2m (roughly $1.75m) in funding spread over three years to individual centers, with smaller government Research Council sponsors providing up to £1m (roughly $1.45m) over four years on a pump-priming basis. The goal was for the partnerships to bring in enough alternate funding streams, from both business and competitively awarded monies from existing government schemes, to become self-supporting.[59, 60]

Critics noted that a number of misconceptions about the structure of the Fraunhofer model led to related structural flaws in the Faraday Centres. Furthermore, Fraunhofer enjoys a large degree of public and political support in Germany, a feature notable lacking for the Faraday Centres in the UK. Critically, no sustained core public funding ever materialized for the initiative as a whole from DTI.[61] Instead the centers – which were originally designed to work in partnership with universities and research laboratories, receiving different funds to develop the research ideas they discovered or created – were forced to apply for the same research grants alongside those basic research institutions, essentially competing with them. This resulted in a shift in the Faraday Centre activities away from an industry focus towards basic and early applied research. As a result, the high competition for roughly the same amount of research funds caused most of the Faraday Centres to fail. By 2010, only one Faraday Centre remained.

The Faraday Centre program is widely regarded as a failure.[62,63] The acknowledgement of this is clearly evident in the creation of the Catapult centres, a series of technology and innovation centres started in 2011 and implemented by the Technology Strategy Board. The program attempted to directly address the failings of the Faraday Centres and avoid past mistakes.[64] UK Catapults were built off the previous Technology and Innovation Centres (TICs), and featured over $1.6 billion private and public investment. Each of the UK Catapults receives public grants ranging from $8-$16 million per year as core funding to pay for infrastructure, recruitment, skill development, etc.[65] Particular emphasis was placed on the need for "long-term, stable government funding.[66] The centres also follow the Fraunhofer funding model with more accuracy, utilizing both core and competitive public funding to account for half of the program budget, with commercial income increasing over time. [67] Furthermore, unlike the Faraday Partnerships, Catapult centres are established with physical infrastructure, with associated technical expertise and operate from TRL 4 to 7, often onsite.[68] There are currently 10 Catapult centres in operation and they have maintained public funding levels to this point.[69]

Lessons Learned: The Faraday Centres were established to rejuvenate a faltering UK manufacturing industry through targeted focus in key research areas. The failure of the Faraday Centres to create a sustained, positive impact on UK manufacturing and innovation in targeted fields offers several lessons for the purposes of this study. First, the program suffered from an insufficient amount of core public funding that severely limited their ability to undertake projects that pursued their original goals, which were broad and aimed at revitalizing entire industries in the UK. A remark in a 2010 report from the UK House of Commons summarizes how insufficient funding and unstable planning hindered the Faraday Centres from the start, "This initiative suffered from poor support from industry, a 'piecemeal approach' and a 'variety of governance models.'"[70] This speaks to the second failure of the Faraday Centres: a lack of industry participation. There was no incentive to keep industry partners engaged and involved. The lack of sustained funding drove the few commercial partners who originally joined away. The third lesson was the lack of funding for transition efforts. No funds were committed to help commercial partners bridge the valley of death from proof of concept to prototyping, and no effort was made by centers themselves. These three problems eventually led to the collapse of nearly all centers, and have been, for the most part, rectified in the newly attempted Catapult Centres.

Conclusions: Despite fairly widespread political support for a UK innovation initiative in the model of Germany's Fraunhofer Society, the wrong lessons were applied to the UK version. The program lacked the necessary financial support needed to engage with a majority of the industry from the outset. After a short span of existence with little tangible success, the Faraday Partnerships were closed or folded into other programs.

An ambitious goal accompanied by no public core funding, a lack of major industry involvement, and no funds available for paying for technology transition led to failure and closure within three years. The Catapult Centres in the UK are attempting to accomplish a similar mission while learning from these mistakes.

Manufacturing USA

History: The Manufacturing USA Consortia Effort (formerly known as the National Network for Manufacturing Innovation (NNMI)) is a group of research centers, called Manufacturing Innovation Institutes (MIIs) modeled in part after the Fraunhofer society. The NNMI was begun in 2012 with the setup of the "America Makes" Center in 2012.[71] This effort was motivated by a series of prior PCAST reports recommending a major funded initiative to promote U.S. manufacturing competitiveness. Since 2012, a total of 10 centers have been established around the U.S. focusing on areas including additive manufacturing methods, digital manufacturing, photonics, flexible electronics, and power electronics to name a few.[72]

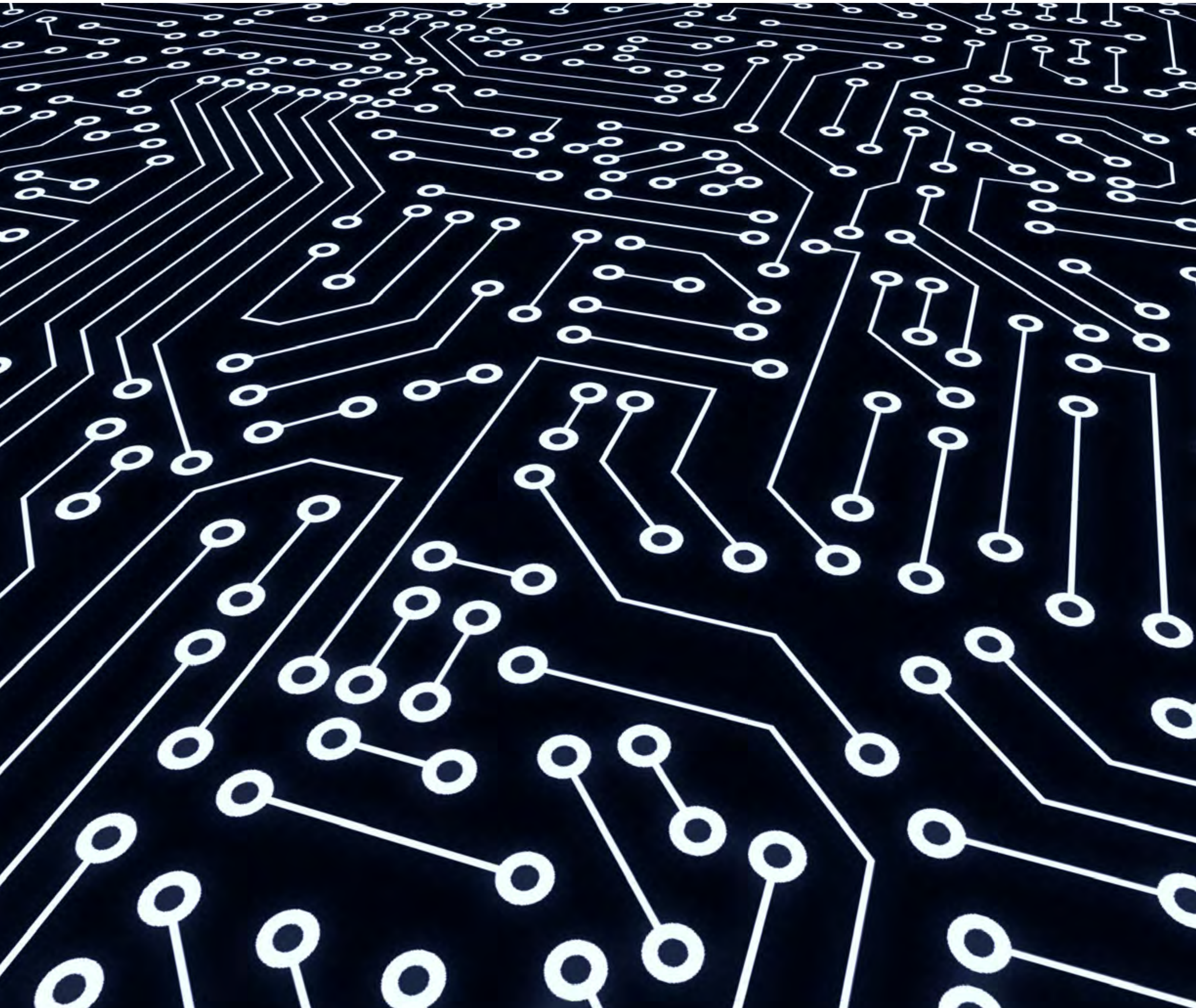
The NNMI centers work to address an important problem with U.S. manufacturing; overcoming the "valley of death" between R&D validation and commercial exploitation for new manufacturing technologies. Government-industry cost-sharing is an important aspect of these organizations. They are loosely based on similar overseas R&D consortia such as the Fraunhofer Institutes in Germany. They are run by non-profit organizations and comprised of industry, academic and government members. Each MII receives a total of $70 - $100 million in government funding spread over 4-5 years. This is expected to be matched at least 1:1 by consortia members. The MIIs are, however, intended to become fully "self-supporting" after the first five years at which time all government support will end.[73]

Lessons Learned: There are a number of positive aspects of the MIIs. The concept of 50:50 industry-government cost-share is one of them ensuring real industry engagement as well as the relevance of the projects pursued. The *type* (i.e. cash vs in- kind) of cost-sharing is of course very important with a higher value placed on the former. The mid-range TRL focus of Manufacturing USA is also appropriate for addressing the valley of death challenges in technology transition of R&D Programs. The regional focus of these MIIs can also be helpful in fostering a strong community of interest around specific center goals.

A major shortcoming in the Manufacturing USA organizational structure is the abrupt sunsetting of all government funding after the first five years. Our study of similar R&D consortia worldwide has shown that sustainability can only be achieved with a long-term funding commitment by government. This funding can be well under 50% once the center is established but should not dip much below 20% for the long-term sustainability of the consortium. This minimum level of government funding is critical to continue to make the centers attractive to industry and provides vital independent research and development (IRAD) funds, which can be used for high risk exploratory work that industry typically shies away from.

The above funding problem has been a factor in another major shortcoming, which is that many MIIs have not managed to achieve engagement with a majority of the industries they serve. This lack of strong connections to industry will significantly limit the impact the MIIs can have.

Conclusions: The MIIs were set up to address the problem of U.S. manufacturing competitiveness. The organizational aspects of significant industry cost-share and regional "center of excellence" focus are positive aspects of these centers. So is their focus on "valley of death" relevant R&D TRL levels. Their long-term sustainability is in doubt however due to the abrupt sunsetting of all government support after a relatively short period of five years. This will make them less attractive for industry as well as less able to execute longer term higher risk efforts not typically done by industry but vital for a healthy R&D enterprise.



CONCLUSIONS

In 2017, the global semiconductor industry is expected to spend around $56 billion in R&D.[74] There exist many organizations that focus on collaborative R&D in the semiconductor industry to identify and develop the next technologies that will propel the industry forward and increase the performance and range of applications for microelectronics in various aspects of daily life. These mid-stage R&D efforts are more important than ever, as the industry shows a shift away from the paradigm of scaling down transistor and circuit size that has driven it for the past 50 years and searches for a new set of research directions to guide it. Despite the number of existing early-stage and pre-competitive collaborative R&D organizations serving the semiconductor industry, the large number of studies and reports published in recent years on the subject of technology transition and the famous "valley of death" show that more improvements can still be made in identifying, developing, and transitioning promising technologies.

This presents a very important opportunity for the DOD, which in recent decades has slid into a difficult relationship with the commercial semiconductor industry, seeing its relative size as a customer fall to less than one percent of industry revenue. New research directions for the semiconductor industry are still in their infancy, and therefore R&D support and collaboration at this stage can greatly influence the types of technologies that become major market drivers in the future.

Many recent government agencies recognize this opportunity and intend to seize it. It is therefore important that such efforts be implemented correctly and learn from past successes and failures in the semiconductor industry. The findings of this study focus on helping the USG do just that. One major way to ensure success is for government public-private R&D efforts to expand their support and strategy to fit the size and ambition of their goals. Without sufficient resources, the initiative will be unable to achieve the necessary technical results or sufficient interaction with the industry to see those results commercially adopted. Also, for public-private R&D efforts to be successful in seeding change in the industry, their technology transition efforts will need to be extended past where government R&D programs traditionally operate. The new initiatives should plan not only to fund efforts in proving technical feasibility, but also development efforts beyond that to achieve success in insertion into systems and pilot production. It will be difficult for such programs to move with the speed or adaptability provided in traditional contracting and acquisition mechanisms. Luckily there exist acquisition vehicles that are much more suited to rapid R&D and prototyping, in OTAs. OTAs have been used very little in recent years and suffer from a lack of understanding in the acquisition community of how to use them. It would greatly benefit USG agencies to use OTAs.

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APPENDIX B: INTERVIEWS WITH SUBJECT MATTER EXPERTS

The Potomac Institute study team interviewed a number of experts in technology development and government R&D program management. Their names and biographical summaries are included below.

Mr. Michael Swetnam is the CEO and Chairman of the Potomac Institute for Policy Studies. Mr. Swetnam is currently a member of the Technical Advisory Group to the United States Senate Select Committee on Intelligence. In this capacity, he provides expert advice to the U.S. Senate on the R&D investment strategy of the U.S. Intelligence Community. He also served on the Defense Science Board (DSB) Task Force on Counterterrorism and the Task Force on Intelligence Support to the War on Terrorism. From 1990 to 1992, Mr. Swetnam served as a Special Consultant to President Bush's Foreign Intelligence Advisory Board (PFIAB). Prior to forming the Potomac Institute for Policy Studies, Mr. Swetnam worked in private industry as a Vice President of Engineering at the Pacific-Sierra Research Corporation, Director of Information Processing Systems at GTE, and Manager of Strategic Planning for GTE Government Systems. Prior to joining GTE, he worked for the Director of Central Intelligence as a Program Monitor on the Intelligence Community Staff (1986-1990). Mr. Swetnam served in the U.S. Navy for 24 years as an active duty and reserve officer, Special Duty Cryptology.

Honorable Lee Buchanan is a former Assistant Secretary of the Navy for Research, Development, and Acquisition, which is responsible for all research development and procurement of defense systems for the Navy and the Marine Corps. Hon. Buchanan also served as the Deputy Director of the Defense Advanced Research Agency in the role of the Chief Operating Officer for the central Research and Development Organization for the Department of Defense. There, he directed a multibillion-dollar program of basic and applied research conducted by industry, universities, and national and military laboratories. Hon. Buchanan served as a Director at CloudShield Technologies, Inc.

Nicholas Babiak is the President of SKYLET, Inc. He has over 20 years of experience as a senior executive, commercial business development, senior program manager, technologist, and senior science advisor for commercial industry, the Office of the Secretary of Defense, and the United States Air Force. He has extensive experience in virtually every phase of military science and technology including research, development and testing of a broad range of state-of-the-art weapon systems. He is a recipient of the Department of Defense's Top award for program management, the "Pioneer Award," has Top Secret, SCI clearances, and was promoted to the Rank of Air Force Colonel four years before contemporaries. Mr. Babiak served as Vice President, Business Development at Cambridge Research Associates. Within three years of joining the firm, he doubled its revenues. Prior to that, he was Deputy Director of the Systems Center, Defense Mapping Agency, Department of Defense. Before serving at the Defense Mapping Agency, he attended the Air War College, where he graduated with honors and highest academic achievement award and was the winner of the best technical research paper, "ADA, the New DOD Weapon Systems Computer Language – Panacea or Calamity?" Mr. Babiak has also served as Chief of Emerging Technologies for the United States Air Force; Office of the Secretary of Defense; Deputy Director, Very High Speed Integrated Circuits (VHSIC); and Principal Advisor on Embedded Computer Resources to the Deputy Chief of Staff/Logistics and Engineering, Headquarters, USAF.

Michael McGrath was a former Vice President at Analytic Services Inc. (ANSER), he led business operations in Systems and Operations Analysis. He previously served as the DASN (RDT&E), where he was a strong Navy proponent for improvements in technology transition, modeling and simulation, and test and evaluation. In prior positions, he served as: Vice President for Government Business at the Sarnoff Corporation (former RCA corporate lab); ADUSD for Dual Use and Commercial Programs in the Office of the Secretary of Defense, with responsibility for industrial base and commercial technology investment programs; Program Manager at the Defense Systems Research Projects Agency (DARPA), where he managed manufacturing technology programs; and Director of the DOD Computer-aided Acquisition and Logistics Support program, automating the interface between DOD and industry for technical data interchange and access. His early government career included positions in Logistics Management at Naval Air Systems Command and in Acquisition Management in OSD. He has served on Defense Science Board and National Academies studies, and is an active member of the National Defense Industrial Association, the National Materials and Manufacturing Board, the Board on Army Science and Technology, and several university and not-for-profit advisory boards.

Dan Holladay is currently the Executive Director of Operations and Technology Programs for Bridging the Innovation Development Gap (BRIDG). Dan is responsible for development of new programs in advanced materials and emerging technology fields – with an initial focus on advanced universal smart sensors and photonics devices. Before joining UCF, Holladay worked at SEMATECH for 20 years in management and director positions for the international consortium's industry-directed technology development programs. Holladay was the Director of Advanced Technologies for SEMATECH's national and international emerging technology initiatives (including energy), led the formation of the U.S. PV Manufacturing Consortium, and was the executive lead for Department of Energy programs and U.S. federal relationships. From 2000 to 2008 he served as the Associate Director and Director of Operations for SEMATECH's advanced R&D lab/fab. Holladay has spent more than 30 years in the semiconductor industry, equally split between manufacturing and R&D. With extensive experience managing process-engineering and operations groups, Dan also has overseen departments in maintenance, equipment engineering, facilities engineering, and failure/analytical/test labs.

Mr. Richard Dunn is an expert consultant working with the Institute for National Security Studies on the National Science & Technology Accelerator. Mr. Dunn was the first General Counsel of DARPA, where he served from 1987 to 2000. He is considered by many as the "father of DOD Other Transactions" (OT) authority. While serving at DARPA, he advocated for legislation authorizing OT agreements (OTA), and drafted the OT legislation used to create DARPA's OT authority. He has personally negotiated dozens of OTAs, provided advice on hundreds more, and taught courses on OT contracting. Currently, Mr. Dunn provides advice and engages in research and analysis related to the deployment and implementation of technology in the military and civil sectors through OT partnering and other innovative means; he conducts research in national security operations, technology and their interactions; and, analyzes laws, policies and practices that impact the effective implementation of technology. His pro bono work includes appointment to several study groups of the National Academy of Science and Defense Science Board. Other pioneering efforts involved obtaining authority to conduct prototype projects outside the normal contracting statutes, and special authority to recruit and pay scientists and engineers without regard to Civil Service laws. Additionally, he championed and obtained authority to award incentive prizes to spur technology developments. All these authorities are in use and have served as models for other agencies. His awards include the Presidential Rank of Meritorious Executive and the Secretary of Defense Medal for Meritorious Civilian Service. After leaving DARPA he was a senior fellow at the Smith School of Business, University of Maryland. Previously he served in the NASA Office of General Counsel, in private legal practice and was on active duty as a Judge Advocate in the USAF for nine years. He holds a B.A. cum laude (Distinguished Military Graduate) from University of New Hampshire; a J.D. from University of Maryland; and an LL.M. highest honor, from George Washington University.)

Prof. Patrick Bressler has been the Executive Vice President of Fraunhofer USA since October 1, 2014. He manages the operations of the seven Fraunhofer USA Centers. Tasks include developing technology transfer and innovation partnerships with U.S. universities and companies, and strengthening transatlantic collaboration in applied science and technology between the United States and Germany. Dr. Bressler serves on scientific review panels and international expert groups, in particular, in materials research and transatlantic cooperation and science and technology. Patrick is an adjunct professor of electrical and computer engineering at Michigan State University. From 2010 to 2014, he was the director of Fraunhofer Brussels and a member of several advisory committees to the European Commission (EC) on science and innovation, in particular, proposal review panels and as an independent expert on the EC's Key Enabling Technologies High Level Group and Electronics Leadership Group. He chaired the European Science Foundation's Materials Science and Engineering Committee from 2012 to 2015. Earlier career stages include academia and industrial research jobs and over a decade as a senior scientist at the Berlin synchrotron radiation facility in the field of synchrotron radiation instrumentation and condensed matter physics. He holds a PhD in semiconductor and surface physics from the Technical University Berlin, Germany.

Mr. Barun Dutta is a Partner and Chief Technology Officer at Alta Berkeley. He is based at the London office of the firm and has a core expertise in computer, communications, and software technology with a focus on wireless, internet infrastructure, and data communication. Mr. Dutta also advises the firm's portfolio companies in the wireless, internet infrastructure, data communications, and software sectors and is based in the London office. His professional career in computer, communications, and software technology goes back 14 years. In his role as the firm's Chief Technology Officer, Mr. Dutta is involved in collaborating with leading scientists, writing research papers and still gives plenary and academic talks at scientific conferences. He is a Senior Scientist at IMEC in Brussels, Belgium. Prior to joining IMEC, Mr. Dutta had been involved for nine years in both operational, strategic, research activities and senior research roles at various entities of AT&T Bell Labs and Bellcore on either side of the Atlantic in networking and telecommunications sectors and with corporate start-up entities. He was an Advisor to several pioneering networking and internet start-up efforts. Mr. Dutta serves as a Director at Oclaro (New Jersey), Inc., Castify Networks, SA, and UbeeAirWalk, Inc. He holds an M.B.A. from MIT Sloan School of Management, a B.A. with a major in Physics from Middlebury College and a degree from Rutgers University.

Mr. Chris Van Metre was named the third President of Advanced Technology International in May 2012. Mr. Van Metre's experience includes strategic planning, technology roadmapping and multi-organizational and multidisciplinary consortia formation. Prior to being named President and CEO of ATI, Mr. Van Metre was SCRA's Senior VP of Business Development Operations, working with the senior leaders in each of SCRA's Sectors and affiliated institutes, as well as SCRA's industry, academic and government partners, to identify areas of value synergy where collaborative solutions merit pursuit. He also completed a 20-year Navy career where he served in a variety of leadership and management positions in both staff and operational assignments, including submarine command. Mr. Van Metre holds a Bachelor of Science degree in Aerospace Engineering from the University of Notre Dame. He completed graduate coursework at Tulane University and numerous executive education courses in Business Development and Marketing Strategy (Kellogg – Northwestern University, MBDi, Karass Negotiation, Furman's Diversity Leadership Institute). Mr. Van Metre earned Navy designation as a specialist in Nuclear Engineering and Master Training Specialist (Curriculum Development). Mr. Van Metre serves on the Advisory Board for The Citadel's School of Engineering Leadership and Program Management. He is a member of the Navy League of the United States, the National Defense Industrial Association and past-President of the Charleston, SC chapter of the Notre Dame Alumni Association.

APPENDIX C: ORGANIZATIONS ASSESSED

The Potomac Institute study team gathered basic profile data using open source information on a wide range of existing organizations from various industries, whose goals related to improving technology transition and innovation. Those organizations and programs are listed below.

ORGANIZATION	LOCATION	TRI Level	FUNDING ($M/YR)
A*STAR	Singapore	4-6	540
AIM Photonics	Rochester, NY	4-7	122
AIST	Japan	4-6	890
Breakthrough Energy Coalition (Gates)	International	6-9	1000
BRIDG (forming)	Kissimmee, FL	3-6	.
Cambridge Pharmaceutical CRYO-EM Consortium	United Kingdom	2-5	.
Cardiac Safety Research Consortium (CSRC)	USA (Decentralized)	5-9	.
CEA-LETI	France	4-7	350
Chip Implementation Center (CIC)	Taiwan	4-7	.
CIES Consortium	Japan	4-6	.
CMP	France	4-9	.
Corporation for National Research Initiative (CNRI)	Reston, VA	N/A	>0.5
DIUx	Mountain View, CA	4-7	45
DOE Clean Energy Manufacturing Initiative	Washington, DC	N/A	.
Energy Materials Network	Washington, DC	N/A	40
Engineering Biology Research Consortium	Emeryville, CA	N/A	0.6
Federal Laboratory Consortium	Cherry Hill, NJ	N/A	>3.1
Florida Institute for Cybersecurity Research (FICS)	Gainesville, FL	1-7	.
Fraunhofer Society	Germany (Decentralized)	4-7	2330
Global Research Collaboration (GRC)	Durham, NC	4-6	>16
H2USA	Washington, DC	2-7	>1.6
IMEC	Belgium	4-7	600
Industry-University Cooperative Research Centers	USA (Decentralized)	2-4	109
Innoenergy	Netherlands	7-9	>344
ITRI	Taiwan	4-6	650
Joint Initiative for Metrology In Biology	Stanford, CA	6-9	.

ORGANIZATION	LOCATION	TRI Level	FUNDING ($M/YR)
Manufacturing Demonstration Facility (MDF)	Oak Ridge, TN	5-8	3.6
Manufacturing USA (NNMIs)	Gaithersburg, MD	4-7	900
Manufacturing Extension Partnership	Gaithersburg, MD	7-9	300
Massachusetts Technology Collaborative	Boston, MA	6-9	300
MEMs Exchange	Reston, VA	6-9	.
Metal Oxide Semiconductor Implementation Service (MOSIS)	Marina Del Rey, CA	2-9	3.5
MForesight	Ann Arbor, MI	6-9	2
Nanoelectronics Research Initiative (NRI) SRC	USA (Decentralized)	1-2	5
NASA Space Technology Mission Directorate	USA (Decentralized)	1-3	.
Netherlands Organization for Applied Scientific Research (TNO)	Netherlands	5-9	463.6
Nextflex	San Jose, CA	4-7	69.4
NSF Innovation-Corps (I-CORPS)	USA (Decentralized)	4-7	26
Power America	Raleigh, NC	4-7	28
Rapid Reaction Technology Office (RRTO)	.	6-8	23
Sandia Science & Technology Park (SS&TP)	Albuquerque, NM; Livermore, CA	3-9	.
Semiconductor Industry Association (SIA)	Washington, DC	N/A	.
Semiconductor Research Corporation (SRC)	Durham, NC	1-5	17
Strategic Pharma-Academic Research Consortium (SPARC)	Indianapolis, IN	6-7	.
Sunshot Initiative	Washington, DC	2-9	107
SUNY Poly	Utica, NY	1-6	500
Trusted Acces Program Office (TAPO)	.	2-9	30
TSMC Cyber & Univ MPWs	Taiwan	2-9	.
US Advanced Battery Consortium (USABC)	East Hartford, CT	3-7	.
United Technologies Research Center (UTRC)	East Hartford, CT	3-9	3900
Finnish Technical Research Center (VTT)	Finland	1-9	>200
World Intellectual Property Organization (WIPO)	Switzerland	N/A	400

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ACRONYMS LIST

ASIC	Application Specific Integrated Circuit
BRIDG	Bridging the Innovation Development Gap
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DTRA	Defense Threat Reduction Agency
FAR	Federal Acquisition Regulations
FPGA	Field Programmable Gate Arrays
IARPA	Intelligence Advanced Research Projects Agency
IC	Integrated circuit
IMEC	Interuniversity Microelectronics Center
IoT	Internet of Things
IP	Intellectual Property
ITRI	Industrial Technology Research Institute
ITRS	Industrial Technology Research Institute
LETI	Laboratoire d'électronique des technologies de l'information (Laboratory fo Electronics and Information Technology)
MTO	Microsystems Technology Office
NRO	National Reconnaissance Office
NSF	National Science Foundation
OSD	Office of the Secretary of Defense
OTA	Other Transaction Agreement/Authority
PCAST	President's Council of Advisors on Science & Technology
PR	public relations
R&D	research and development
RHBD	radiation-hardened-by-design
SCRA	Supply Chain Risk Assessment
SEMATECH	Semiconductor Manufacturing Technology
SoC	System on Chip
SOTA	State of the Art
SUNY	State University of New York
TIC	Trusted Integrated Circuits
TRL	technology readiness level
TSMC	Taiwan Semiconductor Manufacturing Company
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

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