The SEMATECH - Sandia National Laboratories Partnership: A Case Study

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Introduction

Background

SEMATECH was established in 1987 for defense and economic reasons to help the U.S. regain a competitive posture in semiconductor manufacturing. For 10 years SEMATECH was jointly funded by the federal government and semiconductor manufacturing companies representing 85 percent of the U.S. semiconductor industry. SEMATECH has spent about 80 percent of these funds on activities intended to produce useful results between 1 and 3 years. Very early in the establishment of SEMATECH, its members determined that their first priority would be to strengthen their U.S. based suppliers of semiconductor manufacturing equipment. This has been the primary thrust of SEMATECH.

SEMATECH first held some 30 workshops on a broad set of technical topics to assess the needs and opportunities to help the industry recover.[2] These workshops scoped manufacturing process development, lithography, front end processes (doping and thermal processes), back end processes (etch and film deposition), packaging, etc., to determine those manufacturing areas where SEMATECH should focus. These early meetings were an early form of what later came to be termed roadmapping. The scope of R&D needs identified in these workshops well exceeded what SEMATECH could hope to accomplish with its $200 million annual budget. Wayne Johnson of Sandia participated in five of these workshops and used the knowledge he gained as the basis for proposals he later submitted to SEMATECH on behalf of Sandia.

In the fall of 1989 the SETEC program was established at Sandia to support SEMATECH. This was initially a funds-in, work-for-others project that was fully funded by SEMATECH. Thus, the early work was entirely focused on SEMATECH's needs. Later in the program when SEMATECH funds were supplemented by Department of Energy (DOE) Cooperative Research and Development (CRADA) funds, attention was given to how this project would benefit Sandia's defense microelectronics program.

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[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

[2] W.J. Spencer and T.E. Seidel, "National Technology Roadmaps: The U.S. Semiconductor Experience," Proceedings ICSICT '95, October 24-28, 1995, Beijing, China.

DISCLAIMER

Characteristics of Semiconductor Competition

Of all the industry sectors, competition for semiconductors is probably the most intense. Companies in the U.S., Europe, Japan, South Korea, Taiwan, Singapore, and China all want a piece of this market. The dynamics of competition are partially explained by the commercialization flow chart shown in Figure 1.

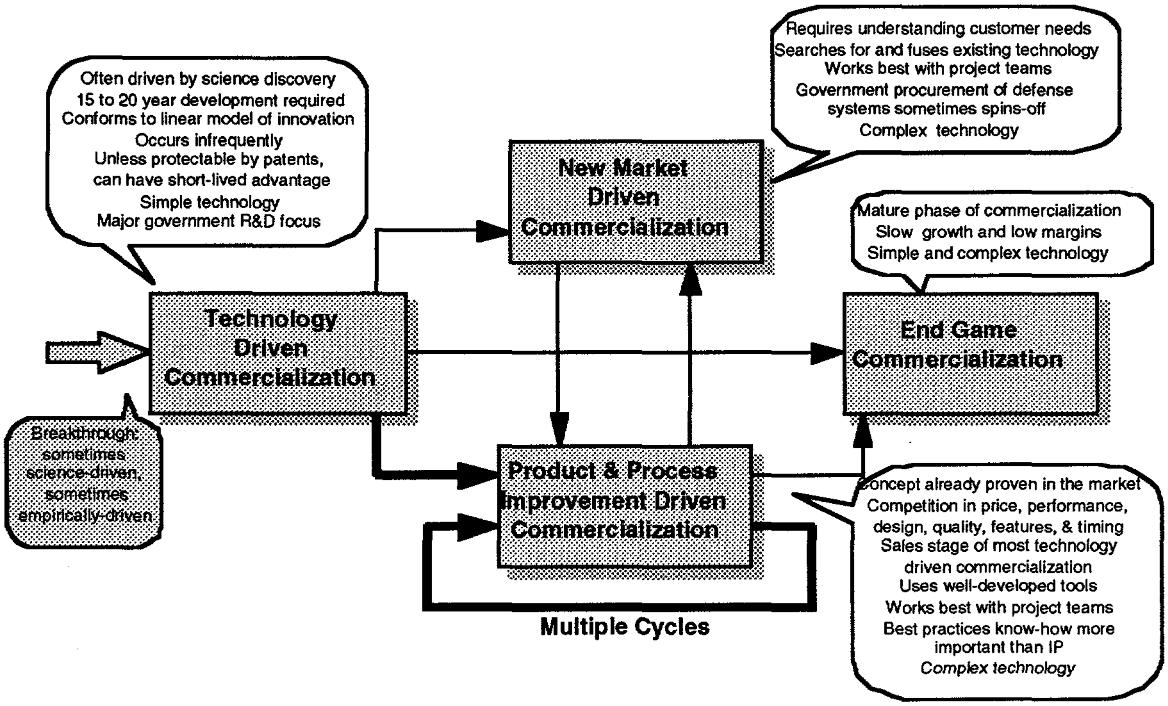

Figure 1: Summary of the ways in which technology is commercialized[3]. The semiconductor industry generally follows the dynamics of product and process improvement; however, the extent of cycle-to-cycle improvement (doubling of transistor density) is too large to term incremental.

Only six years after invention of the integrated circuit, Dr. Gordon Moore, co-founder of Intel, predicted that the number of transistors on a chip would double every year. This prediction was termed Moore's Law. It wasn't until the late 1970s that the doubling period was stretched out to 18 months. Thus the cycle illustrated by the multiple cycle feedback loop in Figure 1 has a period of only 18 months and doubling of transistor density occurs in each cycle. This increase in transistor density stems from reduction in the smallest feature size that can be manufactured and expansion in the dimension of a chip that can be reliably fabricated. It is innovation in integrated circuit design and manufacturing equipment - lithography steppers, material deposition, etchers, diffusion furnaces, ion implanters, etc. - that permits this doubling.

Because of the time sensitivity of competition in semiconductor manufacturing, manufacturers have increasingly abandoned central research laboratories. In fact, because of problems Gordon Moore and Bob Noyce experienced in transferring technology from Fairchild's central research laboratory to their manufacturing lines, they established Intel without a separate R&D laboratory. They did this because competition is driven by time-to-market and technology transfer from a central laboratory is too slow to synchronize with the product cycle. In addition, the exactness of understanding that researchers wish to pursue is rarely met in semiconductor development where process designers make empirical choices and try them to see if they work.

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3 James Gover, "Corporate Management of R&D: Lessons for the U.S. Government", Research-Technology Management, March-April, 1995, pp.27-36.

Gordon Moore reports that Intel, the world's largest and most profitable semiconductor manufacturer, continues to operate on the Noyce principle of minimum information,

> *One guesses what the answer to a problem is and goes as far as one can in an heuristic way. If this does not solve the problem, one goes back and learns enough to try something else. Thus, rather than mount research efforts aimed at truly understanding problems and producing publishable technological solutions, Intel tries to get by with as little information as possible. ... Locating development and manufacturing together allows Intel to explore variations on its existing technologies very efficiently. It does not, however, accommodate dramatic change.[4]"*

Although semiconductor evolution has seemingly followed a reasonably predictable, well-behaved path, because change is so rapid and is almost entirely driven by the availability of new generations of manufacturing equipment and increasingly complex computer-aided circuit design tools, it is a technology that no single expert can master. Kline[5], Kash, and Rycroft[6] term these complex systems.

Successful semiconductor development organizations must master non-linear, adaptive networks and evolve order out of chaos while operating at the edge of system disintegration. In this environment, as Stacy points out, long-term outcomes cannot be planned or predicted.[7] Consequently, semiconductor companies that made great investments in long-term research at the expense of focus on the next product cycle have lost market share to Intel, a company that has kept the next product cycle in clear focus while annually investing $2 billion in R&D. Note that focus on the next product cycle has not inhibited Intel's creativity. For example, Intel personnel invented the DRAM; Ted Hoff of Intel co-invented the microprocessor as a miniature version of Digital Equipment Corporation's PDP-8 minicomputer, and Woods and May of Intel identified radioactive trace elements in packaging material as the source of soft errors in DRAMs. Only recently has Intel created a central research group to pioneer new microprocessor architectures for future applications of computers.[8]

Now if central corporate laboratories in semiconductor companies have trouble synchronizing their research with the semiconductor product cycle so that they can deliver results that impact the next design cycle, it is reasonable to expect a government-owned national laboratory to have even more difficulty. If a national laboratory is able to overcome these difficulties and become a valued contributor to short-term semiconductor R&D, it can probably support any industry sector. It is for this reason that SEMATECH is such an important benchmark for a national laboratory.

SEMATECH's Program of Work at Sandia

Projects' Scope

Sandia has completed over 100 projects for SEMATECH - focusing on benchmarking equipment (both foreign and domestic manufacturing equipment); conducting reliability and ergonomics analysis of manufacturing equipment; developing computer-based models of the physical processes resident in manufacturing equipment; conducting research that leads to reduced contamination in manufacturing equipment; organizing multidisciplinary, rapid-response SWAT teams to address particular problems that arose at SEMATECH member company facilities; validating semiconductor

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4 Gordon E. Moore, "Some Personal Perspectives on Research in the Semiconductor Industry", in Engines of Innovation, edited by Richard S. Rosenbloom and William J. Spencer, Harvard Business School Press, 1996, p. 168.

5 Stephen J. Kline, "Models of Innovation and Their Policy Consequences", in Japanese/America Technological Innovation, edited by W. David Kingery, Elsevier Science Publishing Company, 1991.

6 Don E. Kash and Robert W. Rycroft, "Synthetic Technology-Analytic Governance: The 21St Century Challenge", forthcoming in Technological Forecasting and Social Change.

7 Ralph Stacey, "Management and the Science of Complexity: If Organizational Life Is Nonlinear, Can Business Strategies Prevail?", Research Technology Management, May-June 1996, pp. 8-10.

8 Dean Takahashi, "Intel Shifts Its Focus to Long-Term, Original Research", Wallstreet Journal, August 26, 1996.

manufacturing equipment control software; and developing advanced packaging and assembly technology for semiconductor chips.

Potential for Failure

There are several reasons why this experiment of a federal laboratory supporting the semiconductor industry could have failed:

- As previously noted, the demands on R&D organizations that support semiconductor development are so strong that few semiconductor companies have found value in central research laboratories and instead integrate their R&D with manufacturing. As a central research and development laboratory, Sandia had this hurdle to overcome.
- Immense cultural differences arise between institutions whose purpose is to make money and institutions whose purpose is to serve the public. While there has been much discussion, most of it off-the-record, about the insensitivity of federal labs to industrial time scales, companies are equally inexperienced in concerning themselves with public return from R&D.
- When Sandia's SEMATECH work began to receive public funds, Sandia became responsible to two masters: SEMATECH and the public. Thus, while Sandia had to meet SEMATECH's needs, it had to also make sure that the public was getting its money's worth.
- Companies perception of federal laboratories, particularly in fast-moving sectors like semiconductors, is negative and inhibits the development of strong relationships.

Despite these and other reasons why the SEMATECH-Sandia alliance could have failed, we believe that the evidence suggests that this experiment was a success and that it can serve as a benchmark for future government-industry partnerships.

Anecdotal Metrics

Anecdotal evidence of Sandia's success in supporting SEMATECH is strong. Several of SEMATECH's members, particularly, leading-edge companies, have provided written statements strongly endorsing Sandia's work and other members have either donated or loaned state-of-the-art manufacturing equipment to Sandia. Had it not been for Sandia's relationship with SEMATECH, little of this equipment would have found its way to Sandia. Anecdotal data from SEMATECH members' suppliers are even stronger and include endorsements ranging from major suppliers of equipment to small companies. However, many of these statements and interviews of SEMATECH employees make it clear that SEMATECH members and their suppliers entered into this alliance with Sandia with deep reservations stemming from the perception that a National laboratory is an extension of a university research laboratory without the pressures of tenure and that its researchers are more sensitive to pushing the frontiers of science than meeting the demands of making timely analysis and recommendations for the engineering of manufacturing equipment. Sandia's success has slowly changed that mindset.

SEMATECH members and SEMI/SEMATECH hiring of Sandia managers also suggests that this industry highly valued Sandia's work. Intel has hired Charles Gwyn, the manager of Sandia's SEMATECH work, to help manage their highly newsworthy XUV lithography program that is being conducted by a partnership of Sandia National Laboratories, Lawrence Livermore National Laboratory, and Lawrence Berkeley Laboratory; SEMI/SEMATECH has employed Glen Cheney, a former Sandia vice-president, as president of SEMI/SEMATECH; and when Mr. Cheney retired from SEMI/SEMATECH, he was replaced by Paul Peercy, Sandia's director of microelectronics programs. Recently, Gilbert V. Herrera, Sandia's deputy director of microelectronics programs was hired as SEMI/SEMATECH Chief Operating Officer.

Project Milestones: Output Metrics

According to Charles Gwyn, 95% of the projects that Sandia conducted for SEMATECH met project milestones and provided the output that SEMATECH was seeking. Thus, <u>project</u> and/or <u>output metrics</u> scores for Sandia's work are exceptionally high. Of course, project success does not necessarily guarantee that SEMATECH members achieved the <u>outcome</u> they were seeking.

Satisfaction and Support: Output and Projected Outcome Metrics

SEMATECH uses two methods to measure the return to their members from their projects. One method is termed support (how important is the project to each SEMATECH member?) and satisfaction (how well is the project working?). The former measure is a projected outcome metric while the latter measure is an output or process metric. SEMATECH members quarterly assign support and satisfaction scores to each project. Perfect scores for a project would be support - 1.0, satisfaction - 1.0. SEMATECH's goal is that each project have a 0.75 support score and a 0.60 satisfaction score. In the first quarter of 1996 the overall average of all SEMATECH projects was 0.76 support and 0.70 satisfaction. Sandia projects scored 0.73 support and 0.70 satisfaction. Between 1995 and 1996 Sandia's support and satisfaction scores increased 0.1. These data again suggest that Sandia's work produced the outputs that SEMATECH's members were seeking.

Return on Investment: Outcome Metrics

The second evaluation method used by all SEMATECH members except Intel is termed return on investment (ROI). The ROI algorithm is individual member company benefit divided by individual member company cost. Each member's technology transfer manager has primary responsibility for making this assessment. This measure is an outcome metric - members assess the outcome of a project by determining its impact on their business. Sandia's 1995 ROI score was 1.7 for evaluations performed by all SEMATECH members except Intel with leading edge members assigning Sandia's work a 2.1 score. (Intel has consistently rated Sandia's work higher than other SEMATECH members. We are unable to determine if that is due to the proximity of Sandia in Albuquerque to Intel in Rio Rancho, or it is due to the fact that Intel is the worlds' leader in semiconductor manufacturing.) For comparison purposes, the average 1995 ROI for all SEMATECH projects was 4.4, the 1993 average for all SEMATECH projects was 2.1, and the 1995 average ROI for SEMATECH's university projects was 1.0.

In 1996, Sandia's ROI score doubled to 3.7. These data suggest that both Sandia and SEMATECH has made great progress in managing these projects because it is unlikely the technical challenge of the work underwent very much change.

Sandia's SEMATECH program manager, Dr. Charles Gwyn, argues that caution should be exercised in interpreting the ROI evaluation. For example, the ROI does not include evaluation of Sandia's work by the equipment manufacturers which are direct beneficiaries of Sandia's work and are, therefore, much closer to Sandia's contributions. While SEMATECH should be lauded for applying ROI measurement technology to their projects (private sector evaluation of R&D leads the public sector by one or two decades), Dr. Gwyn, as well as members of SEMATECH's Executive Technical Advisory Board, believe that the methodology used by SEMATECH undervalued Sandia's work. Because Sandia did not develop complementary outcome metrics, to assess either public or private return, how much SEMATECH's ROI measurement undervalued the private outcome from Sandia's work, if it did at all, and a true measure of the public return from Sandia's work, are more speculative than we prefer.

Public Return

Because public funds were used to support much of the work that Sandia did for SEMATECH, this working relationship was intended to help Sandia as well as SEMATECH. The SEMATECH experience has provided Sandia with four assets needed to fulfill its nuclear weapons responsibilities to the American public:

- access to state-of-the-art semiconductor manufacturing equipment valued at $53 million,
- experience in operating this equipment in a manufacturing environment,
- strong relationships with semiconductor manufacturers and especially strong working relationships with semiconductor manufacturing equipment makers, and
- access to state-of-the-art emerging semiconductor technology valued at $25 million.[9]

Adjustments that Sandia had to make to be compatible with SEMATECH's culture were not always easy and often resulted in significant loss of independence. Nevertheless, this working relationship has brought many benefits to Sandia and the public. Of importance to Sandia is the opportunity it provided to prove to the semiconductor industry that it could treat them as a customer and that it was capable of doing real-world, market-pull, practical engineering work of immediate value to U.S. industry. It further linked Sandia to a wide array of semiconductor manufacturers and paved the

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[9] Estimate provided by Harry Weaver, Sandia National Laboratories.

way for the development of cooperative working arrangements with these manufacturers. It has also exposed Sandia to numerous of the semiconductor equipment suppliers and it may lead to a long-term cooperative working relationship under an umbrella CRADA with SEMI/SEMATECH, a consortium of U.S. companies that make semiconductor manufacturing equipment. Perhaps of most importance from Sandia's defense perspective, it aided Sandia in the development of radiation-hardened oxides for defense applications.

Conclusions

In reviewing SEMATECH's assessment of Sandia's work, several points emerge.

- First, the data suggest that some SEMATECH members have highly valued Sandia's work while other have not. Generally, the leading edge companies have found Sandia's work to have the highest value.
- Second, anecdotal evidence and ROI data indicate that SEMATECH's equipment suppliers found more value in Sandia's work than SEMATECH's members. This observation may result from the fact that Sandia engineers and scientists worked one-on-one with equipment suppliers and had a more distant working relationship with SEMATECH members.
- Third, Sandia seems to have excelled at ultra-long range projects and ultra-short range projects that required the rapid assembly of a SWAT team, and performed less well for intermediate range projects. We are unable to determine if this is a Sandia characteristic or a characteristic of SEMATECH's management style.
- Fourth, national laboratories are handicapped in supporting projects in the private sector by (1) the onerous CRADA[10] paperwork bureaucracy imposed by the federal agency governance system; (2) internal issues that include budget uncertainty, constantly varying overhead rates, and unsteady support for semiconductor R&D make it extremely difficult to plan long-term projects with companies and consortia, and (3) inconsistent support for national laboratory work in support of SEMATECH by DOE that sometimes eroded confidence in Sandia's ability to uphold its end of the SEMATECH contract.[11]
- Fifth, the experience with SEMATECH suggests that national laboratories should increase their investment in quantitatively measuring and publicizing the public and private outcome from their R&D projects. The clock is running on anecdotal evidence that only addresses R&D outputs. Much work remains to be done in this area.
- Sixth, we hope that our analysis of this project has been sufficiently objective and useful to demonstrate that useful learning accrues when national laboratories critically examine their R&D. With the exception of the research of Bozeman, Crow, Roessner, and Papadakis, all academics, little has been invested in studying the effectiveness of national laboratory R&D. This area needs much more attention if it is to move from the current state of only producing anecdotal evidence of success.
- Seventh, we believe that the SEMATECH program fully illustrates that national laboratories have the technical capabilities required to support companies, even companies that commercialize technology by making rapid product and process improvements. Expediting these partnerships is far more a management issue than a technical issue.

While this activity began as a case study of technology transfer between Sandia and SEMATECH, as it progressed, it became increasingly apparent that the issue was less technology transfer than technology management. In practically every instance where either Sandia or SEMATECH experienced displeasure during the evolution of a project, the source of their displeasure was exclusively a management issue (strategy, investment, timing, vision, etc.) rather than a technical issue. Without exception, Sandia's technical capabilities easily met and often exceeded SEMATECH's needs. As a generalization, we have come to believe that the technical resources of DOE's multiprogram national laboratories are capable of bringing to companies a wide variety of technical skills that could make companies much more competitive in international markets. The challenges are: (1) how to manage the resources of these laboratories and their interface with

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[10] While CRADA difficulties existed early in the SEMATECH program, according to Linda Cecchi, SNL, the CRADA process is now quite reasonable with most of the current delays being self-inflicted due to technical people or externally-inflicted by company lawyers nit-picking the model CRADA language.

[11] Personal communication, Charles Gwyn to James Gover.

companies in order to maximize their effectiveness, (2) how the laboratories can avoid favoring one company over another, (3) how to simultaneously serve public needs while supporting companies, and (4) how to determine an appropriate public - private funding algorithm that properly weighs public and private benefits. Much work is needed in each of these areas.

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