Proliferation of DARPA Technology: Case Studies of MRAM and SiGe-based Phased Arrays

Strategic Planning Support to Electronics Resurgence Initiative

Potomac Institute for Policy Studies
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Executive Summary

The Defense Advanced Research Projects Agency (DARPA) must ensure that its federal research and development expenditures bolster U.S. defense capabilities and commercial sector and not those of potentially adversarial nations. To support DARPA's Microsystems Technology Office (MTO) in its technology transfer efforts for the Electronics Resurgence Initiative program, the Potomac Institute for Policy Studies investigated the global proliferation of select technologies that were strongly reliant on initial DARPA funding to catalyze their development. DARPA Spintronics, which launched commercial efforts related to magneto random access memory (MRAM), was used as a case study, as were the DARPA efforts towards silicon-based RF technologies [i.e SiGe bipolar complementary metal-oxide-semiconductor (BiCMOS)-based phased arrays].

The objective of this study was to collect and analyze data to create a report tracking the proliferation of these select technologies, starting from the initiation of U.S. federal investment via DARPA and carrying through the following period of commercial R&D efforts, industrial partnerships, and mergers and acquisitions. To execute this study, information was gathered from interviews with Program participants and individuals involved with subsequent commercialization efforts. Reputable internet sources throughout the microelectronic community were also utilized.

Our research found that investments by DARPA were critical to the development of highly capable MRAM memory and SiGe RF technologies. Industry partners were highly reluctant to conduct initial research and development activities- it was not clear that the technologies were viable nor did markets exist to motivate early internal funding. However, as a result of DARPA funding, these technologies have found profitable transitions in the commercial sector and the defense-industrial base. Additionally, the rapid development of both MRAM and 5G-enabling mmWave technologies were greatly assisted by the highly specialized workforce that was trained via DARPA funding. The graduate students who had worked on DARPA projects are now currently employed throughout the domestic and foreign technological ecosystems.

Our research also found that past investment in MRAM and SiGe BiCMOS-based phased array technologies has resulted in commercial sectors strongly reliant on foreign-owned manufacturing capabilities. Despite a significant amount of domestic research and development efforts, there are no MRAM or SiGe-capable mass production foundries owned and operated by U.S.-based firms and no U.S.-owned firm has plans to build one. Indeed, high-volume low-cost semiconductor manufacturing is largely located in the Asia/Pacific region. The limited availability of domestic fabrication options raises barriers that discourage domestic commercialization of USG-funded microelectronic technology.

The analytic output of this case study was used to develop recommendations that could enable DARPA to better ensure that DARPA-funded technology remains on American shores. The recommendations are as follows:

Recommendation #1. DARPA MTO programs, particularly ERI, should include low-volume high-mix (LVHM) manufacturers as Performers and fund the development of LVHM-enabling manufacturing technologies.

Recommendation #2. DARPA should facilitate the transition of ERI-funded technology into the U.S. defense-industrial base (DIB) by including defense contractors as Performers on the ERI Program and by providing them early access to multi-project fabrication runs with necessary Process Design Kits.

Recommendation #3: DARPA should consider policy changes that enable the domestic capture of students trained via ERI funding.

Recommendation #4. DARPA should seek to partner with R&D organizations of major US companies and identify internal champions of these new technologies that can evangelize them to the business units who are typically much more short term focused.

Introduction

The Defense Advanced Research Projects Agency (DARPA) has a singular mission: invest in cutting-edge research that produces breakthroughs at the interface of technology and national security.[1] DARPA is strongly committed to exploring high-risk high-reward non-requirements driven R&D in an effort to prevent technological surprise and maintain U.S. military supremacy.[2] Since its formation in 1958, DARPA has developed and transitioned a diverse array of products into the United States' space, defense, academic, and private sectors.[3] Indeed, countless DARPA programs have produced innovations that are invaluable to the modern warfighter and have revolutionized commercial industries.[4,5]

DARPA and its Microsystems Technology Office (MTO) have a rich history of successfully developing and transitioning microelectronic technologies into the domestic and worldwide marketplace, and its investments can be directly traced to the dominance of the U.S. semiconductor industry over the last 50 years.[6] The United States' semiconductor production market share, which had reached 82% by 1992, was in large part due to DARPA's support of the Semiconductor Manufacturing Technology (SEMATECH) consortium.[7,8] SEMATECH was created in 1987 by DARPA with an annual budget of $200 million, half contributed by government and half by private industry.[9] The goal of this R&D consortium was to return the U.S. semiconductor industry to a leading position in the global market. Initially composed of 14 domestically-based and -operating semiconductor companies, the program eventually allowed international companies to join after

[1] About DARPA. Retrievable from https://www.darpa.mil/about-us/about-darpa
[2] Cheng, J. (2014, March 10). With R&D Budgets, High Risk Has Its Rewards. Retrievable from https://defensesystems.com/articles/2014/03/10/darpa-research-budget-increase.aspx
[3] Richardson, J.J., Larriva, D.L., & Tennyson, S.L. (2001, May). The Potomac Institute for Policy Studies. *Transitioning DARPA Technology*.
[4] Ibid.
[5] (2017, March). Defense Advanced Research Projects Agency. *DARPA Technologies That Are Making a Difference Today*. Retrievable from https://www.darpa.mil/attachments/DARPA_ChangingHowWeWin.pdf
[6] Defense Advanced Research Projects Agency. *DARPA 1958-2018*. Retrievable from https://www.darpa.mil/attachments/DARAPA60_publication-no-ads.pdf
[7] Chappell, W. Defense Advanced Research Projects Agency. *Furthermoore: The Intertwined History of DARPA and Moore's Law*. Retrievable from https://www.darpa.mil/attachments/DARAPA60_publication-no-ads.pdf
[8] SEMATECH. Retrievable from https://www.darpa.mil/about-us/timeline/sematech
[9] (2017, December 31). Potomac Institute for Policy Studies. *DARPA Consortia Analysis and Recommendations Trade Study (CARTS)*.

transitioning to a fully private consortium in the late 1990s after the USG support ended. MTO continues to lead innovation of the U.S. semiconductor sector today via the Electronics Resurgence Initiative (ERI), which aims aims to develop novel "post-Moore's Law" microelectronics.[10]

The stated goal of the ERI is to stimulate the U.S. semiconductor ecosystem and lower barriers to novel semiconductor technology.[11] Through investments in R&D thrusts targeting innovations in design, architecture, and materials and integration, DARPA is aiming to reverse recent trends that have seen the size of the U.S. semiconductor manufacturing sector rapidly diminish, threatening the Department of Defense's access to state-of-the-art microelectronics.[12-14] Business pressures, notably high costs associated with R&D and manufacturing,[15] have led to extensive merger and acquisition activity in the industry.[16,17] A significant portion of these transactions have involved the sale of domestic manufacturers to firms based overseas, such as IBM's semiconductor division to UAE-based GlobalFoundries,[18] Netherlands-based NXP's purchase of Freescale Semiconductor,[19] and the merger of Jazz Semiconductor with Israel-based Tower Semiconductor.[20,21] China has also been aggressively pursuing U.S.-based microelectronics companies and their intellectual property.[22,23]

U.S.-based firms are leading innovators in microelectronics-related research and development activities and continue to represent a significant fraction of the overall global microelectronics market.[24,25] However, most state-of-the-art *manufacturing* activities occur at semiconductor foundries owned and operated by foreign companies. This severely limits the ability of U.S. microelectronic innovation efforts to positively impact the domestic economy and makes it challenging for the United

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[10] Synek, G. (2018, July 3). DARPA Aims to Take on Electronics in The Post-Moore's Law Era. Retrievable from https://www.techspot.com/news/75345-darpa-aims-take-electronics-post-moore-law-era.html
[11] Merritt, R. (2018, July 27). Moore's Law, China vs. Team USA. Retrievable from https://www.eetimes.com/document.asp?doc_id=1333519
[12] Ibid.
[13] Moore, S.K. DARPA Plans a Major Remake of U.S. Electronics. Retrievable from https://spectrum.ieee.org/tech-talk/computing/hardware/darpas-planning-a-major-remake-of-us-electronics-pay-attention
[14] Rapp, N., & Pressman, A. (2017, December 20). See Semiconductor Industry Consolidation in 1 Chart. Retrievable from http://fortune.com/2017/12/20/chip-mergers-broadcom-qualcomm-intel-nvidia/
[15] Qualls, W. IBM Microelectronics. Retrievable from https://business.illinois.edu/idm/IBM-BCS%20Case%20final.pdf
[16] Johnsa, E. (2017, November 23). 3 Trends Behind the Semiconductor M&A Wave, and 5 Companies That Could Be Next. Retrievable from https://www.thestreet.com/story/14400354/1/reasons-for-semiconductor-industry-consolidation.html
[17] Patterson, A. (2017, September 14). Chip Consolidation Nearly Over, Analyst Says. Retrievable from https://www.eetimes.com/document.asp?doc_id=1332297
[18] (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study.*
[19] (2015, December 7). NXP and Freescale Announce Completion of Merger. Retrievable from http://investors.nxp.com/phoenix.zhtml?c=209114&p=irol-newsArticle&ID=2120581
[20] TowerJazz History. Retrievable from http://www.jazzsemi.com/history.html
[21] (2008, September 19). Tower Semiconductor Completes Merger with Jazz Technologies. Retrievable from https://www.businesswire.com/news/home/20080919005342/en/Tower-Semiconductor-Completes-Merger-Jazz-Technologies
[22] (2015, July 13). China Chipmaker Plans Bold $23B Bid for Micron. Retrievable from https://www.cnbc.com/2015/07/13/chinas-tsinghua-unigroup-makes-23b-bid-for-micron-technology.html
[23] McLaughlin, D., & Strohm, C. (2018, November 1). China State-Owned Company Charged With Micron Secrets Theft. Retrievable from https://www.bloomberg.com/news/articles/2018-11-01/u-s-says-china-state-owned-co-stole-micron-trade-secrets
[24] Wolf, Stu. Subject Matter Expert [Interview].
[25] (2018). IC Insights. *The McClean Report*. Retrievable from http://www.icinsights.com/services/mcclean-report/

States Government to access a Trusted and Assured supply of microelectronic components for defense- and intelligence-related applications.[26]

Spin-based magnetic random access memory (MRAM) and SiGe bipolar complementary metal-oxide-semiconductor (BiCMOS)-based phased arrays are two representative technologies that were initially developed using DARPA R&D funds only to largely exit the domestic manufacturing sphere soon after commercialization. While GlobalFoundriesUS still offers trusted advanced SiGe BiCMOS to the DoD, it is a foreign-owned company with an uncertain financial future.[27,28] The causes of these transitions may be complex, but it is critical for program managers and office directors leading federal R&D efforts to understand and consider the potential commercialization pathways for the technologies being developed with U.S. taxpayer dollars. Technology developed via funding from DARPA and other federal R&D funding sources should be for the benefit of U.S. (or allied) industry and warfighters, not those of potentially adversarial nations.

The Potomac Institute for Policy Studies examined the proliferation of MRAM and SiGe BiCMOS-based phased arrays technologies in the United States and abroad starting from the initial DARPA Programs. These two representative technologies provided useful case studies for technology transition pathways. The lessons learned as a result of this study are readily applicable to other DARPA funded technologies and provide valuable input for current Programs to have more successful transition outcomes.

MRAM

Background

In the early 1990s, DARPA funded the GMR Consortium (Honeywell, Nonvolatile Electronics Inc., Federal Product, Naval Research Lab, and HRL) to develop a non-volatile, radiation-hardened, random-access memory that could replace the bulky and expensive memories that were common at the time.[29] The key outcome of this consortium was the discovery that a new universal nonvolatile memory with the density of DRAM, the speed of SRAM, unlimited write cycles, and significantly lower write-power requirements than flash memory could be developed. Two major DARPA efforts followed up on this work. In 1993, DARPA Spintronics was initiated to further develop magnetoresistive memories and complementary sensors, resulting in the commercial production of MRAM.[30] Two key performers were involved- IBM and Motorola.[31] In 2008, the DARPA program STT-MRAM was initiated and played a significant role in developing the fundamental processes and infrastructure required to launch spin-transfer torque-MRAM (STT-MRAM) commercialization, including the NIST testing standards.[32] At the onset of the program, internal industry R&D efforts

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[26] (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study.*
[27] Cooper, R.K. (2018, August 31). GlobalFoundries Cuts 455 Positions Amid Strategy Shift. Retrievable from https://www.bizjournals.com/albany/news/2018/08/31/globalfoundries-cuts-455-positions-amid-strategy.html
[28] Rulison, L. (2018, May 11). So Is GlobalFoundries Profitable? Yes and No…. Retrievable from https://www.timesunion.com/business/article/So-is-GlobalFoundries-profitable-Yes-and-no-12906650.php
[29] Wolf, S.A., Treger, D., & Chtchelkanova, A. (2006, May). *Spintronics: The Future of Data Storage?.* Retrievable from http://physics.ucsc.edu/~galers/class/Reference/Spintronics.pdf
[30] Ibid.
[31] Spintronics. Defense Advanced Research Projects Agency. Retrievable from https://www.darpa.mil/about-us/timeline/spintronics
[32] Shenoy, Dev. Subject Matter Expert [Interview].

were just beginning. By year 3 of STT-MRAM, Intel announced a $100 million investment into spintronics, Grandis was a commercial success, and Honeywell began utilizing STT-MRAM in radiation-hardened microelectronics.

Magnetic random access memory is a non-volatile memory that stores information in magnetic moments instead of electric charge.[33] A recent development in MRAM, spin-transfer torque-MRAM, is particularly exciting. STT-MRAM nearly matches the high performance of both DRAM and SRAM (speed, density), requires low power, is as inexpensive as flash memory, scales well below the 10 nm node, and leverages existing CMOS manufacturing techniques and tools. Emerging STT-MRAM technologies utilize a perpendicular magnetic tunnel junction (pMTJ), wherein the magnetic moments are perpendicular to the silicon substrate instead of parallel to the silicon substrate as in the in-plane magnetic tunnel junctions (iMTJs) incorporated into earlier iterations of STT-MRAM technologies.[34]

In 2016, the commercial MRAM market was valued at approximately $1.1 billion.[35] By 2025, the global MRAM market is expected to reach $4.80 billion.[36] Much of the growth is expected to be due to the rapid adoption of STT-MRAM, particularly pMTJ-STT-MRAM.[37] Despite the commercial MRAM market originating in the United States, the North American region accounts for just 36% of the total market revenue.[38] U.S.-based firms are leading innovators in MRAM-related research and development activities, but all major manufacturing activities occur at semiconductor foundries owned and operated by foreign companies (Figure 1).[39] This severely limits the ability of MRAM commercialization efforts to positively impact the U.S. economy and imposes obstacles that need to be overcome for the United States Government to access a Trusted and Assured supply of MRAM components for defense- and intelligence-related applications.[40]

As a first step to understanding this issue, the Potomac Institute for Policy Studies examined the proliferation of MRAM technologies in the United States and abroad starting from the two DARPA Spintronics performers, Motorola and IBM.

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[33] Ofstedahl, M. (2014, August 11). What is STT-MRAM? Retrievable from https://www.eetimes.com/author.asp?section_id=36&doc_id=1323466
[34] Ibid.
[35] Coughlin, T. (2016, September 15). MRAM is Becoming Mainstream Memory. Retrievable from https://www.forbes.com/sites/tomcoughlin/2016/09/15/mram-is-becoming-mainstream-memory/#4a8aa6a5766a
[36] (2017, April). Magneto Resistive RAM (MRAM) Market Worth $4.80 Billion by 2025. Retrievable from https://www.grandviewresearch.com/press-release/global-magneto-resistive-ram-random-access-memory-mram-market
[37] Coughlin, T. (2016, September 15). MRAM is Becoming Mainstream Memory. Retrievable from https://www.forbes.com/sites/tomcoughlin/2016/09/15/mram-is-becoming-mainstream-memory/#4a8aa6a5766a
[38] (2017, April). Magneto Resistive RAM (MRAM) Market Worth $4.80 Billion by 2025. Retrievable from https://www.grandviewresearch.com/press-release/global-magneto-resistive-ram-random-access-memory-mram-market
[39] Wolf, Stu. Subject Matter Expert [Interview].
[40] (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study*.

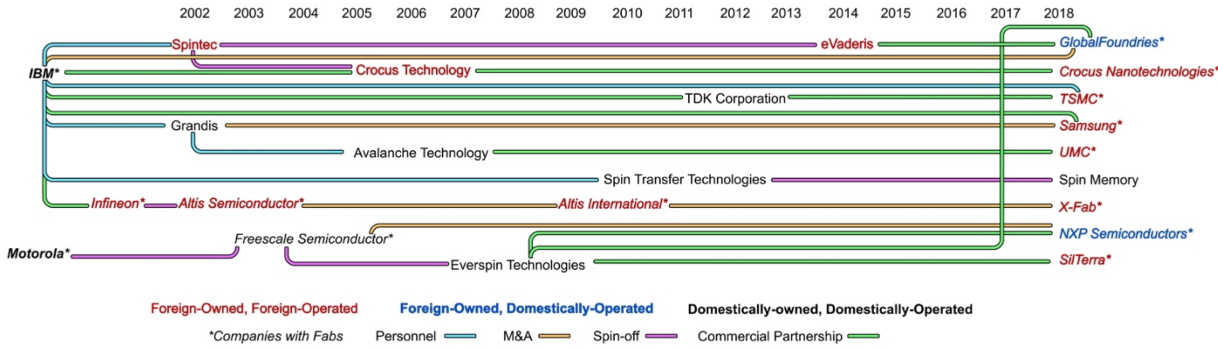

Figure 1. Technology produced by the DARPA Spintronics Performers IBM and Motorola were transitioned into firms that are pre-dominately owned by foreign companies.

DARPA Spintronics Performer: Motorola

DARPA Spintronics culminated with the commercial development of MRAM by Motorola, then subsequently by Freescale Semiconductor, which was spun out of Motorola as a subsidiary and then became an independent company.[41] In 2006, Freescale released the first commercial MRAM product (Toggle MRAM), which was manufactured at Freescale's fab in Chandler, AZ due to an earlier investment by Motorola to transition a back-end-of-line production line for MRAM fabrication.[42,43]

In 2008, Freescale Semiconductor transferred its MRAM technology, related intellectual property, and products to EverSpin Technologies, a joint venture between Freescale Semiconductor and the venture capital firms New Venture Partners, Sigma Partners, Lux Capital, Draper Fisher Jurvetson, and Epic Ventures.[44] All of these firms are based in the United States.[45-49] In 2014, EverSpin subcontracted its STT-MRAM manufacturing to GlobalFoundries,[50] but continued to utilize the back-end-of-the-line MTJ deposition facility for 200 mm Toggle production at the Chandler, Arizona fab.[51] In March 2015, NXP Semiconductors N.V., a Netherlands-based company, merged with Freescale Semiconductor and took ownership of the Chandler fab.[52,53] In November 2018, EverSpin announced a multi-year

[41] Wolf, S.A., Treger, D., & Chtchelkanova, A. (2006, May). *Spintronics: The Future of Data Storage?*. Retrievable from http://physics.ucsc.edu/~galers/class/Reference/Spintronics.pdf
[42] Dr. Jon Slaughter. DARPA60. Retrievable from https://d60.darpa.mil/speakers/DrJonSlaughter.html
[43] Wolf, Stuart. Subject Matter Expert [Interview].
[44] (2008, June 9). Freescale Launches Independent Company to Accelerate MRAM Business. Business Wire. Retrievable from https://www.businesswire.com/news/home/20080609005545/en/Freescale-Launches-Independent-Company-Accelerate-MRAM-Business
[45] New Venture Partners. Retrievable from https://www.crunchbase.com/organization/new-venture-partners#section-overview
[46] Sigma Partners. Retrievable from https://www.crunchbase.com/organization/sigma-partners
[47] Lux Capital. Retrievable from https://www.crunchbase.com/organization/lux-capital#section-overview
[48] DFJ. Retrievable from https://www.crunchbase.com/organization/draper-fisher-jurvetson#section-overview
[49] EPIC Ventures. Retrievable from https://www.crunchbase.com/organization/epic-ventures
[50] Manufacturing Locations. EverSpin Technologies. Retrievable from https://www.businesswire.com/news/home/20080609005545/en/Freescale-Launches-Independent-Company-Accelerate-MRAM-Business
[51] Governance Documents. EverSpin Technologies. Retrievable from http://investor.everspin.com/phoenix.zhtml?c=254442&p=irol-govhighlights
[52] NXP Semiconductor Reports Fourth Quarter and Full-Year 2015 Results. Retrievable from http://investors.nxp.com/phoenix.zhtml?c=209114&p=irol-newsArticle&ID=2135489
[53] (2015, December 7). NXP and Freescale Announce Completion of Merger. Retrievable from http://investors.nxp.com/phoenix.zhtml?c=209114&p=irol-newsArticle&ID=2120581

partnership with Malaysia-based SilTerra to create additional manufacturing capacity for Toggle MRAM.[54] Currently, EverSpin Technologies focuses on stand-alone MRAM chips.[55]

Motorola's and subsequent spin-offs' successful commercialization of MRAM was largely due to Motorola's willingness to invest in the technology and the required foundry recapitalizations.[56] However, US government agencies and members of the defense-industrial base were involved from the beginning of DARPA Spintronics and expressed interest, helping ensure that Motorola realized a tangible business case. The Defense Threat Reduction Agency (DTRA) is one such agency that signaled commitment early in the project. Additionally, EverSpin has relied on a long-term commitment from Honeywell, which manufactures radiation-hardened microelectronics with MRAM produced by EverSpin.[57] The commitment of the DARPA project manager, Stu Wolf, was crucial to the success of the program. Three years into the project, Motorola's MRAM effort was transferred from the R&D division to the Semiconductor Products Division, which sought to kill the program due to the perceived lack of a profitable business case.[58] Dr. Stu Wolf saved the program by convincing the DARPA director to contribute $4 million to fund the transfer of the MRAM work back to the R&D division of Motorola.

DARPA Spintronics Performer: IBM

The widespread global proliferation of MRAM-related intellectual property can largely be traced back to IBM. IBM's long-term strategy since DARPA Spintronics has aimed to develop embedded MRAM as a replacement to embedded DRAM, an extremely difficult and challenging target.[59] In the short-term, IBM's MRAM research groups have been highly active in developing spintronic-related intellectual property, which has been routinely licensed to various semiconductor manufacturers located around the world. Additionally, a number of IBM scientists were exposed to IBM's MRAM work and went on to found MRAM-related companies and laboratories. The following is a list of companies that obtained MRAM-related intellectual property from IBM through a series of personnel transfers and commercial partnerships, as detailed in the brief summaries provided.

Crocus Nanoelectronics. From 1989-1991, Dr. Bernard Dieny worked as a visiting scientist at IBM and was heavily involved in developing giant magneto resistance-based technologies for hard-disk drives.[60] In 2002, he founded Spintec as a research lab in Grenoble, France that performed basic research and development, built prototypes, and then commercialized the technology.[61,62] Spintec experienced rapid growth, growing from an initial cadre of 8 permanent staff to 40 permanent staff, 31 researchers, and 60 Ph.D. students and post-docs via Grenoble University in a span of just 8 years.[63]

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[54] (2018, November 6). Everspin and SilTerra Join Forces to Create New Manufacturing Center for MRAM. Retrievable from https://www.design-reuse.com/news/45098/everspin-silterra-mram-manufacturing-center.html?utm_content=257555&utm_campaign=45098&utm_medium=socnewsalert&utm_source=designreuse
[55] Worledge, Daniel. Subject Matter Expert [Interview].
[56] Wolf, Stuart. Subject Matter Expert [Interview].
[57] (2016, December 1). EverSpin Technology Lists Amidst Strong MRAM Growth. Retrievable from https://www.sramanamitra.com/2016/12/01/everspin-technology-lists-amidst-strong-mram-growth/
[58] Wolf, Stuart. Subject Matter Expert [Interview].
[59] Worledge, Daniel. Subject Matter Expert [Interview].
[60] Dieny, Bernard. Subject Matter Expert [Interview].
[61] Ibid.
[62] About Us. Spintec. Retrievable from http://www.spintec.fr/organization/
[63] Dieny, Bernard. Subject Matter Expert [Interview].

Spintec continues to file five to ten patents per year, typically on MRAM-related technologies.[64,65] This patent portfolio allows Spintec to launch start-up companies.[66] To date, four start-ups have been spun-off from Spintec.[67]

Crocus Technology was spun-out of Spintec in 2006 to develop MRAM technologies, then switched focus to magnetic sensors due to the stronger business case.[68-70] Crocus Technology sought a European-based funding source to build a foundry, but was unable to raise the necessary funds.[71] In 2011, Crocus Technology established a joint venture with Rusnano called Crocus Nanoelectronics.[72] All technologies for this firm, including Crocus Technology's magnetic sensors and STT-MRAM, are fabricated at a 300 mm fab in Moscow, Russia.

In 2011, IBM and Crocus signed a joint technology development agreement and a mutual patent license agreement.[73,74] Under the terms of these agreements, the two firms agreed to jointly develop semiconductor technology that combines Crocus' thermally assisted next-generation Magnetic-Logic-Unit (MLU) technology with IBM's MRAM technology and processing capabilities.[75] This enabled Crocus to access IBM's patents that allow for a high scalability of MRAM.[76]

GlobalFoundries. In 2014, eVaderis was spun-out of Spintec as a fab-less company that specializes in developing intellectual property related to advanced circuit designs for embedded memory.[77,78] In 2017, eVaderis entered into an agreement with GlobalFoundries to provide scalable, advanced memory IP.[79-81]

Additionally, on October 20, 2014, IBM announced the transfer of its semiconductor division to GlobalFoundries.[82] According to the terms of the contract, IBM paid GlobalFoundries $1.5 billion in exchange for the acquisition and operation of its microelectronics foundries, related technologies, and

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64 Full List of Patents Since the Creation of SPINTEC. Retrievable from http://www.spintec.fr/list-of-patents/
65 Dieny, Bernard. Subject Matter Expert [Interview].
66 Ibid.
67 Spin-off. Retrievable from http://www.spintec.fr/spin-off/
68 Crocus Technology. Retrievable from https://www.mram-info.com/crocus-technology
69 About Us. Spintec. Retrievable from http://www.spintec.fr/organization/
70 Dieny, Bernard. Subject Matter Expert [Interview].
71 Ibid.
72 Crocus Technology. Retrievable from https://www.mram-info.com/crocus-technology
73 Worledge, Daniel. Subject Matter Expert [Interview].
74 Martens, R. (2011, October 6). Crocus and IBM to Jointly-Develop MRAM Technology, Sign Patent License Agreements. Retrievable from https://www.mram-info.com/crocus-and-ibm-jointly-develop-mram-sign-patent-license-agreements
75 Ibid.
76 Ølholm, M. (2011, October 6). IBM and Crocus Join MRAM-Forces. Retrievable from https://semiaccurate.com/2011/10/06/ibm-and-crocus-join-mram-forces/
77 EVADERIS: A New Start-Up Recently Launched by SPINTEC. Retrievable from http://www.spintec.fr/the-startup-evaderis/
78 Spin-off. Retrievable from http://www.spintec.fr/spin-off/
79 Dieny, Bernard. Subject Matter Expert [Interview].
80 Hilson, G. (2018, March 30). MRAM on the Rise. Retrievable from https://www.eetasia.com/news/article/18033003-mram-on-the-rise
81 (2017, June 29). eVaderis Joins FDXCelerator™ Program to Deliver Memory IP to GlobalFoundries 22FDX Technology Platform. Retrievable from http://www.evaderis.com/2017/06/29/evaderis-joins-fdxcelerator-program-deliver-memory-ip-globalfoundries-22fdx-technology-platform/
82 (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study.*

personnel. Included in the sale was IBM's intellectual property related to embedded DRAM.[83] However, GlobalFoundries is no longer working on scaling embedded DRAM below the 14 nm node.[84]

Intel. Several subject matter experts have noted that Intel is actively engaged in research and development activities related to spintronics.[85-88] Indeed, conference abstracts and patents confirm that Intel researchers are developing MRAM technologies,[89,90] in addition to spintronic logic devices.[91] While the PIPS study team was unable to learn more about Intel's spintronics activities, we can confirm that Intel gained valuable knowledge by participating in DARPA Spintronics and STT-MRAM as silent observers.[92-94]

Micron. In 2012, Micron entered a partnership with IBM to develop STT-MRAM as a replacement for DRAM due to concerns regarding the end of Moore's Law scaling for DRAM below the 20 nm node.[95,96] This research thrust was terminated because stand-alone DRAM continued to scale and STT-MRAM technology was not at a development point to enable profitable commercialization.[97] Micron then lost interest in MRAM and exited the partnership.

Samsung. The key performer in DARPA STT-MRAM was Grandis,[98] a STT-MRAM firm founded by Paul Nguyen, a thin films expert from IBM.[99] Grandis received significant assistance from DARPA in the form of funding and connections to universities.[100] The company was able to leverage this in discussions with venture capitalists, raising a significant amount of capital that enabled their manufacturing processes to scale-up. However, Grandis did not have sufficient funds to build a semiconductor foundry and opted to look for a buyer.[101] Discussions with IBM and Intel faltered,[102] and in 2011, Grandis was purchased by Samsung.[103]

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83 Worledge, Daniel. Subject Matter Expert [Interview].
84 Dent, S. (2018, August 28). Major AMD Chip Supplier Will No Longer Make Next-Gen Chips. Retrievable from https://www.engadget.com/2018/08/28/global-foundries-stops-7-nanometer-chip-production/
85 Dieny, Bernard. Subject Matter Expert [Interview].
86 Shenoy, Dev. Subject Matter Expert [Interview].
87 Nikonov, Dmitri. Subject Matter Expert [Interview].
88 Gallagher, Bill. Subject Matter Expert [Interview].
89 Clarke, R. (2018, October 22). IEDM: Intel Embeds MRAM in FinFET Process. Retrievable from https://www.design-reuse.com/news/44990/intel-mram-finfet.html
90 Intel and VMRAM and MRAM Patents…Interesting Indeed. Retrievable from https://www.spintronics-info.com/spintronics_info/intel_and_vmram_and_mram_patents_interesting_indeed
91 Nikonov, Dmitri. Subject Matter Expert [Interview].
92 Shenoy, Dev. Subject Matter Expert [Interview].
93 Wolf, Stu. Subject Matter Expert [Interview].
94 Nikonov, Dmitri. Subject Matter Expert [Interview].
95 Worledge, Daniel. Subject Matter Expert [Interview].
96 Johnson, R.C. (2016, July 7). IBM, Samsung Put New Spin on MRAM. Retrievable from https://www.eetimes.com/document.asp?doc_id=1330058
97 Worledge, Daniel. Subject Matter Expert [Interview].
98 Shenoy, Dev. Subject Matter Expert [Interview].
99 Grandis. Retrievable from https://www.crunchbase.com/organization/grandis#section-overview
100 Shenoy, Dev. Subject Matter Expert [Interview].
101 Wolf, Stuart. Subject Matter Expert [Interview].
102 Ibid.
103 McGrath, D. (2011, August 2). Samsung Buys MRAM Developer Grandis. Retrievable from https://www.eetimes.com/document.asp?doc_id=1259991

In 2013, Samsung entered a partnership with IBM to pursue a commercialization pathway for STT-MRAM as a potential replacement for DRAM due to concerns regarding the end of Moore's Law scaling for DRAM below the 20 nm node.[104,105] This research thrust was shut down because stand-alone DRAM continued to scale and STT-MRAM technology was not at a development point to enable efficient commercialization.[106] However, IBM and Samsung continued to work together and developed an embedded flash replacement at the 28 nm node that is being sold to NXP.

Spin Memory Technologies. Spin Transfer Technologies was founded in 2011 and is headquartered in Fremont, CA.[107] The firm was founded with intellectual property developed in the lab of New York University Professor Andrew Kent,[108] who was a post-doc at IBM from 1992-1994.[109] In 2016, STT announced that it had achieved the fabrication of perpendicular MRAM magnetic tunnel junctions, delivering samples of STT-MRAM to customer in North America and Asia in 2017.[110] In late 2018, this firm was renamed Spin Memory and announced a commercial partnership with Applied Materials to develop embedded MRAM.[111,112]

TSMC. In 2007, IBM worked with TDK Corporation to commercialize intellectual property related to perpendicular magnetic tunneling junctions (pMTJs) and circuit designs.[113,114] In 2012, TDK engaged in a partnership with TSMC to further develop this technology for use as a simple flash replacement.[115,116] Additionally, in 2015, Dr. Bill Gallagher left IBM for TSMC and currently leads their MRAM efforts.[117,118] Dr. Gallagher was the IBM project manager responsible for their DARPA Spintronics efforts in 2000.[119] TSMC is currently working towards commercializing MRAM as an embedded flash replacement and as a replacement for 10 nm SRAM for low-power applications.[120,121]

UMC. In 2006, a VC-backed firm called Avalanche Technology was founded in Fremont, CA with the goal of producing and commercializing STT-MRAM.[122] Avalanche leadership does not intend on raising the required funds to build a dedicated foundry and is instead a fabless company that focuses

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104 Worledge, Daniel. Subject Matter Expert [Interview].
105 Johnson, R.C. (2016, July 7). IBM, Samsung Put New Spin on MRAM. Retrievable from https://www.eetimes.com/document.asp?doc_id=1330058
106 Worledge, Daniel. Subject Matter Expert [Interview].
107 Spin Transfer Technologies. Retrievable from http://www.spintransfer.com/background/
108 Ibid.
109 Andrew Kent. Retrievable from http://www.physics.nyu.edu/kentlab/
110 Hilson, G. (2017, June 13). MRAM Momentum Poised to Disrupt Memory Workhorses. Retrievable from https://www.eetimes.com/document.asp?doc_id=1331860
111 (2018, November 12). Spin Memory Teams with Applied Materials to Produce a Comprehensive Embedded MRAM Solution. Retrievable from https://www.design-reuse.com/news/45138/spin-memory-applied-materials-embedded-mram.html?utm_content=257555&utm_campaign=45138&utm_medium=socnewsalert&utm_source=designreuse
112 Ibid.
113 Worledge, Daniel. Subject Matter Expert [Interview].
114 (2007, August 19). IBM and TDK Launch Joint Research & Development Project for Advanced MRAM. Retrievable from https://www-03.ibm.com/press/us/en/pressrelease/22180.wss
115 Ranjan, Rajiv. Subject Matter Expert [Interview].
116 Worledge, Daniel. Subject Matter Expert [Interview].
117 Ibid.
118 20th Anniversary Spin-Torque MRAM Symposium. Retrievable from https://researcher.watson.ibm.com/researcher/view_group_subpage.php?id=7406
119 Ibid.
120 Worledge, Daniel. Subject Matter Expert [Interview].
121 eFlash. Retrievable from http://www.tsmc.com/english/dedicatedFoundry/technology/eflash.htm
122 Ranjan, Rajiv. Subject Matter Expert [Interview].

on circuit design and materials work. The firm initially worked at SEMATECH in Austin, TX to develop STT-MRAM at the 65-90 nm nodes. To pursue research and prototype development at smaller nodes, Avalanche sought to develop a BEOL capability at SUNY Poly with the end-goal of moving to the Trusted foundry owned by GlobalFoundriesUS. Despite initial partnerships with instrumentation companies, the arrangement fell through. In 2016, Avalanche contracted production of the first pMTJ-based STT-MRAM to Sony Semiconductor Manufacturing Corp.[123] In early August 2018, Avalanche and UMC announced a partnership for joint development and production of MRAM to replaced embedded flash.[124] The current VP of Technology at Avalanche, Dr. Yiming Huai, was a co-founder, board member, CTO, VP of Engineering at Grandis.[125] As noted above, Grandis was founded by a researcher from IBM.

X-Fab. In 2000, IBM worked with Infineon Technologies to develop stand-alone MRAM technology.[126,127] This partnership led to the creation of Altis Semiconductor, a joint venture of IBM and Infineon, that aimed to commercialize MRAM.[128] In 2010, IBM and Infineon fully divested Altis Semiconductor, selling 100% of their shares to French entrepreneur Yazid Sabeg, who renamed the firm Altis International.[129] Altis International, which operated a foundry in France, was purchased by Germany-based X-Fab Silicon Foundries AG in 2016.[130] Infineon had previously spun-off its memory division as Qimonda AG, which declared bankruptcy and closed in 2009.[131,132]

SiGe-Based RF Phased Arrays

Background

On October 1st, 2018, Verizon launched the first commercial 5G network in the world in Sacramento, Houston, Indianapolis, and Los Angeles.[133] 5G, the next generation of wireless technology, has several significant advantages over currently available technologies, including the ability to move more data at greater speeds, reduce latency and therefore provide greater responsiveness, and connect to multiple devices simultaneously.[134] These core characteristics will enable a wide range of revolutionary

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123 Clarke, P. (2016, October 31). Sony Revealed as MRAM Foundry for Avalanche. Retrievable from http://www.eenewsanalog.com/news/sony-revealed-mram-foundry-avalanche

124 UMC and Avalanche Technology Partner for MRAM Development and 28nm Production. Retrievable from http://www.avalanche-technology.com/2018/08/06/umc-and-avalanche-technology-partner-for-mram-development-and-28nm-production/

125 Avalanche Technology Leadership. Retrievable from http://www.avalanche-technology.com/company/leadership/

126 Worledge, Daniel. Subject Matter Expert [Interview].

127 (2003, June 10). IBM, Infineon Develop Most Advanced MRAM Technology to Date. Retrievable from https://www-03.ibm.com/press/us/en/pressrelease/5269.wss

128 Ibid.

129 (2010, August 12). IBM and Infineon Divest Joint Venture Altis Semiconductor. Retrievable from https://www.infineon.com/cms/en/about-infineon/press/press-releases/2010/INFXX201008-067.html

130 Clarke, P. (2016, October 4). X-Fab to Swallow Altis Semiconductor. Retrievable from https://www.eetimes.com/document.asp?doc_id=1330569

131 Smith, T. (2006, March 31). Infeon DRAM Biz to Spin Off as Qimonda. Retrievable from https://www.theregister.co.uk/2006/03/31/infineon_founds_qimonda/

132 Crothers, B. (2009, February 2). After Chipmaker's Collapse, Memory Prices Rise. Retrievable from http://news.cnet.com/8301-13924_3-10154742-64.html

133 Flato, H. (2018, October 1). Verizon Turns on World's First Commercial 5G Network in Sacramento. Retrievable from https://www.verizon.com/about/news/verizon-turns-worlds-first-commercial-5g-network-sacramento

134 Seagan, S. (2018, October 2). What is 5G? Retrievable from https://www.pcmag.com/article/345387/what-is-5g

technologies, such as autonomous vehicles, virtual reality/augmented reality, and remote surgery.[135] By 2021, an estimated $2.3 billion is expected to be spent on 5G mobile infrastructure, enabling over 20 million 5G connections.[136] The United States is well positioned to lead the industry due to significant investments in infrastructure, but the global industrial leaders are located primarily in Asia and Europe.[137-139]

The rapid commercial development of 5G communications systems was enabled by the covergence of independent research thrusts focused on developing low cost highly integrated silicon based RF technology. The development of SiGe BiCMOS fabrication processes and phased array applications is an important representative example of this.[140] SiGe BiCMOS processes enable the integration of RF, analog, and digital components onto a single chip, reducing the total number of required microelectronic devices and optimizing power consumption.[141] Phased arrays, meanwhile, electronically steer electromagnetic beams in specific directions via constructive/destructive interference controlled by modulating the phase of the electromagnetic waves emitted from the radiating elements.[142] SiGe BiCMOS-based phased arrays enable 5G base stations to overcome limitations associated with atmospheric absorption by transmitting a high gain signal to a series of coordinated antennas that work together to increase signal strength in a specific direction.[143,144]

DARPA-funded efforts have directly and indirectly enabled the rapid development and subsequent commercialization of cost-effective SiGe-based phased arrays. Not only did these projects facilitate current efforts in 5G,[145] but they transformed the technology composing DoD radar and communication systems.[146] Domestic semiconductor firms are major suppliers of SiGe-based (and CMOS-based) phased arrays, but all of these companies subcontract out their semiconductor manufacturing to foundries that are not owned by U.S.-based firms.[147] Indeed, European and Asian

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135 Cheng, R. (2018, October 17). The 5G Revolution is Coming. Here's Everything You Need to Know. Retrievable from https://www.cnet.com/how-to/the-5g-revolution-is-coming-heres-everything-you-need-to-know/
136 5G – Statistics & Facts. Retrievable from https://www.statista.com/topics/3447/5g/
137 (2018). The Potomac Institute for Policy Studies. *Global Technology Trends*.
138 Rebeiz, Gabriel. Subject Matter Expert [Interview].
139 (2018, June 6). The Potomac Institute for Policy Studies and Venable LLP. *The Fast Approaching 5G Revolution: Disruptions and Opportunities*.
140 Fritze, Michael. Subject Matter Expert [Interview].
141 BiCMOS. Retrievable from https://www.st.com/content/st_com/en/about/innovation---technology/BiCMOS.html
142 Phased Array Antenna. Retrievable from http://www.radartutorial.eu/06.antennas/Phased%20Array%20Antenna.en.html
143 Millimeter Waves: How We Got Here, the Physical Challenges, and 5G Opportunities. Retrievable from https://www.nutaq.com/blog/millimeter-waves-how-we-got-here-physical-challenges-and-5g-opportunities
144 Kinney, S. (2017, July 14). Adapting Phased Array Antennas for 5G Millimeter Wave Systems. Retrievable from https://www.rcrwireless.com/20170714/5g/phased-array-antennas-5g-millimeter-wave-tag17-tag99
145 (2017, July 11). Phased Array Antennas & The Roadmap to 5G Wireless. Retrievable from https://www.macom.com/blog/phased-array-antennas--the-roadm
146 Lee, Michael & Adams, Charlie. Subject Matter Experts [Interview].
147 Rebeiz, Gabriel. Subject Matter Expert [Interview].

foundries dominate the market (Figure 2),[148-152] posing national security concerns and obstacles that the United States Government must address to maintain a trusted and assured supply of these components for defense- and intelligence-related applications.[153] As a first step to understanding this issue, the Potomac Institute for Policy Studies examined the development and proliferation of SiGe BiCMOS-based phased arrays technologies starting from original DARPA efforts in the United States and abroad.

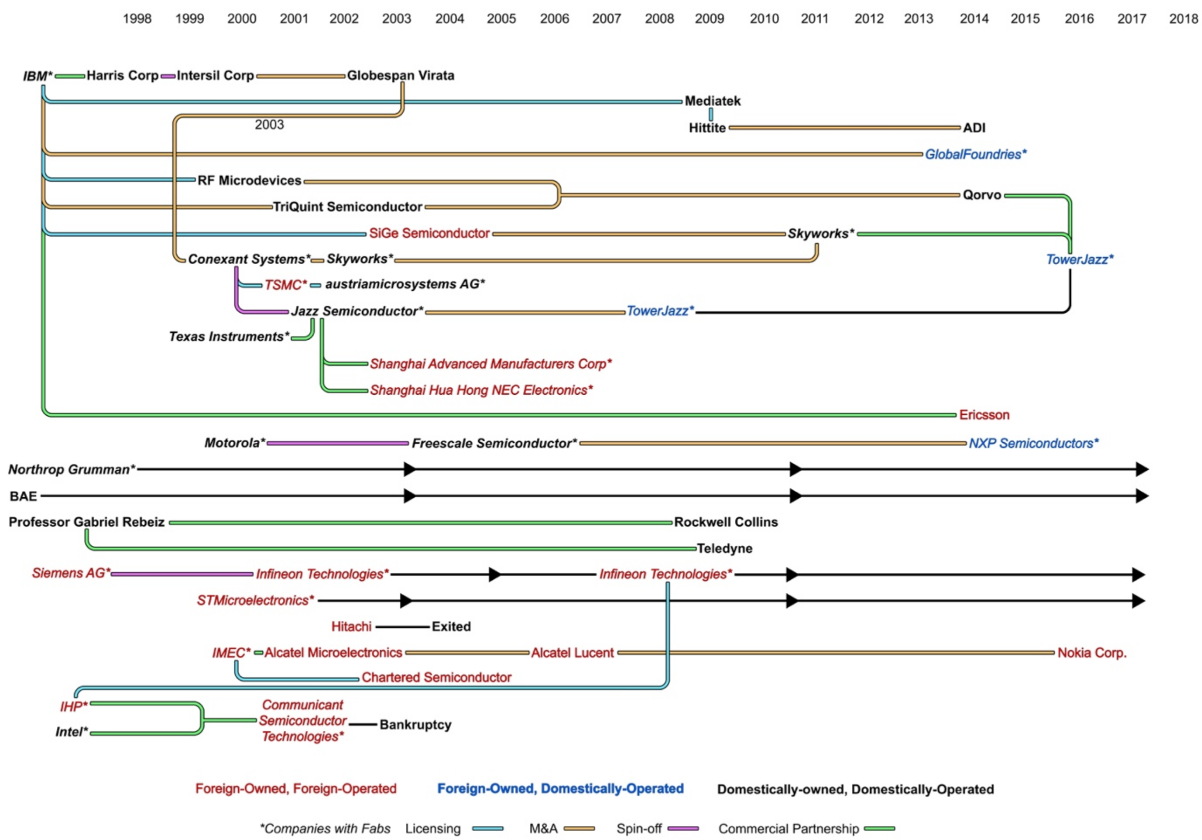

Figure 2. Despite a significant amount of domestic R&D efforts, European- and Asian-owned companies dominate the SiGe BiCMOS market. However, Northrop Grumman operates a SOTP SiGe BiCMOS foundry and additional multinational-owned foundries are operating on-shore.

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148 Neiger, C. (2017, September 18). How Skyworks Solutions Makes Most of its Money. Retrievable from https://www.fool.com/investing/2017/09/18/how-skyworks-solutions-makes-most-of-its-money.aspx

149 (2012, February 27). TowerJazz Receives Innovation Award from Skyworks Solutions. Retrievable from https://www.prnewswire.com/news-releases/towerjazz-receives-innovation-award-from-skyworks-solutions-140534743.html

150 (2016, November 16). TowerJazz. *TowerJazz (TSEM) Investor and Analyst Day*.

151 Cressler, John. Subject Matter Expert [Interview].

152 Rebeiz, Gabriel. Subject Matter Expert [Interview].

153 (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study*.

The United States

DARPA-Funded Development of Phased Arrays

Phased-array technologies, which bend, steer, and focus electromagnetic energy by controlling the constructive and destructive interference patterns of the emitted electromagnetic waves,[154] formed the backbone of U.S. missile defenses during the Cold War.[155] Numerous DARPA and ARPA projects have enabled their continuous evolution from 1958 to current day. Notable acheivements from these R&D efforts include the deployment of the AN/FPS-85 radar, an active phased array developed through the ARPA program Hard Point Demonstration Radar, at Eglin Air Force Base between 1965 and 1969. Similar radars, the PAVE PAWS radar and the COBRA DANE radar, were deployed to Beale Air Force Base and Shemya, Alaska, respectively.

Beginning in the late 1980s, DARPA funded several programs that rapidly improved the performance characteristics of phased array technologies via the incorporation of III-V and II-VI compound semiconductors, including GaN, GaAs, and InP.[156] These programs include Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC, 1988-1995), High Density Microwave Packaging (HDMP, 1993-1996), Microwave and Analog Front End Technology (MAFET, 1995-1999), Wide Band Gap Semiconductor for RF Applications (WBGS-RF, 2002-2008), Nitride Electronic Next Generation Technology (NEXT, 2010-2013), and Intra/Interchip Enhanced Cooling (ICECool, 2012-current). However, the reliance on costly difficult-to-integrate compound semiconductors significantly limited the adoption of phased array technologies to the defense-industrial base.[157,158] Indeed, to allow for mass commercial adoption of phased array technologies for radar and communications applications, capable silicon-based RF technologies first needed to be developed.[159]

Initial SiGe-Related R&D Efforts

In 1982, to develop high-performance low-cost RF integrated circuits (RFICs), IBM began investigating the epitaxial growth of SiGe via ultra-high vacuum chemical vapor deposition.[160] This standard manufacturing process involves introducing small amounts of germanium into the silicon wafer at the atomic scale.[161] By 1994, IBM researchers demonstrated the first RFICs composed of SiGe.[162] In 1995, IBM internally funded the first SiGe technology qualification, which mirrored that of a BiFET qualification with pFETs, LPNPs, resistors, capacitors, inductors, diodes, and HBTs.[163] Qualification in the 200-mm standard CMOS line was completed in 1996, enabling IBM's launch of commercial SiGe chips.[164,165] By 1997, it was well known in the microelectronics community that SiGe

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154 A Brief History of Phased Array Testing. Retrievable from https://www.olympus-ims.com/en/ndt-tutorials/intro/breif-history/
155 Herd, J.S., & Conway, M.D. (2016, March). Proceedings of the IEEE. *The Evolution to Modern Phased Array Architectures*.
156 Ibid.
157 Lambrechts, W., & Singa, S. (2017). *SiGe-based Re-Engineering of Electronic Warfare Subsystems*. Springer.
158 Szweda, R. (2003, November). Phased Array Radars-What Next for GaAs? Retrievable from https://www.sciencedirect.com/science/article/pii/S0961129003011876
159 Fritze, Michael. Subject Matter Expert [Interview].
160 Moniz, J.M. (1997). Is SiGe the Future of GaAs for RF Applications? Retrievable from https://ieeexplore.ieee.org/document/628275
161 Lambrechts, W., & Singa, S. (2017). *SiGe-based Re-Engineering of Electronic Warfare Subsystems*. Springer.
162 Moniz, J.M. (1997). Is SiGe the Future of GaAs for RF Applications? Retrievable from https://ieeexplore.ieee.org/document/628275
163 Harame, D.L., & Meyerson, B.S. (2001, November). The Early History of IBM's SiGe Mixed Signal Technology.
164 Ibid.
165 Moniz, J.M. (1997). Is SiGe the Future of GaAs for RF Applications? Retrievable from https://ieeexplore.ieee.org/document/628275

offered higher performance, novel radio architectures, and significantly lower cost than GaAs and InP.[166]

However, highly integrated single-chip transceivers need CMOS devices to enable functions like digital interfaces, AD-conversion, built-in self tests, or data storage.[167] As a result, IBM's qualification of a BiCMOS technology began, with funding support from DARPA to merge a heterojunction-based bipolar silicon RF technology with highly integrable Si-based CMOS.[168] DARPA funding enabled IBM to offer low-cost small batch manufacturing runs via the Metal Oxide Silicon Implementation Service (MOSIS), which drastically reduced the cost of the qualification process.[169-171] By the end of 1998, a 500 nm BiCMOS process was qualified in Essex Junction.[172] In 1999, IBM qualified a 250 nm SiGe BiCMOS technology. That same year, IBM partnered with Harris Corporation to supply a redesigned WLAN chip based on SiGe with improved performance characteristics and sharply reduced costs.[173] Later in 1999, Harris Semiconductor was spun off from Harris Corporation as Intersil Corp.,[174] which continued to rely on IBM's SiGe BiCMOS processes for several years.[175] This highly profitable partnership enabled IBM to overcome internal and external resistance to the reliance on SiGe BiCMOS processes for RF applications and is a key moment in the developmental history of SiGe BiCMOS.[176] Intersil was later purchased by GlobespanVirata,[177] which then merged with Conexent Systems, Inc.[178]

In January 2000, IBM licensed its 5HP SiGe process to RF MicroDevices, which incorporated the technology into a number of devices and then purchased IBM's GPS business in 2001.[179] In June of 2002, IBM sold its VCO, receiver, and W-CDMA SiGe wireless chip business to TriQuint Semiconductor for $22 million. In 2003, IBM licensed its power amplifier IP to Ottawa-based SiGe Semiconductor.[180] Also in 2003, IBM expanded its East Fishkill foundry to accommodate the

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166 Ibid.

167 Böck, J., Aufinger, K., Boguth, S., Dahl, C., Knapp, H., Liebl, W., Manger, D., Meister, T.F., Pribil, A., Wursthorn, J., & Lachner, R. (2015). IEEE. *SiGe HBT and BiCMOS Process Integration Optimization Within the DOTSEVEN Project.*

168 Harame, D.L., & Meyerson, B.S. (2001, November). The Early History of IBM's SiGe Mixed Signal Technology.

169 MOSIS Semiconductor Service. Retrievable from https://www.darpa.mil/about-us/timeline/mosis

170 Myerson, Bernard. Subject Matter Expert [Interview].

171 Fritze, Michael. Subject Matter Expert [Interview].

172 Harame, D.L., & Meyerson, B.S. (2001, November). The Early History of IBM's SiGe Mixed Signal Technology.

173 (1999, February 23). Harris Semiconductor Announces "Next-Gen" WLAN Solution: PRISM II Has Half the Chips, Half the Power, 4x the Range. Retrievable from https://www.harris.com/press-releases/1999/02/harris-semiconductor-announces-next-gen-wlan-solution-prism-ii-has-half-the

174 Dunn, D. (1999, July 19). Harris Semiconductor to Become Intersil Corp. Retrievable from https://www.eetimes.com/document.asp?doc_id=1122319

175 Mokhoff, N. (2004, March 19). Intersil Expands Analog to IBM Foundry. Retrievable from https://www.eetimes.com/document.asp?doc_id=1148888

176 Myerson, Bernard. Subject Matter Expert [Interview].

177 Smyser, S. (2003, July 17). Analysis: GlobespanVirata Falls Short in Intersil Buy. Retrievable from https://www.eetimes.com/document.asp?doc_id=1189905

178 (2003, November 3). Conexant and GlobespanVirate Announce Plan to Merge; Combination Will Create the Worldwide Leader in Semiconductor Solutions for the Broadband Digital Home. Retrievable from https://www.businesswire.com/news/home/20031103005467/en/Conexant-GlobespanVirata-Announce-Plan-Merge-Combination-Create

179 Telford, M. (2004, March). The Advanced Semiconductor Magazine. *SiGe Slips Into Main Fabs.* Retrievable from https://ac.els-cdn.com/S0961129004002819/1-s2.0-S0961129004002819-main.pdf?_tid=f4de767b-c078-420b-990c-f5b6e66ef010&acdnat=1540585623_5717a79df461624b117de50ead087a5e

180 Ibid.

manufacturing of BiCMOS at the 180 nm node.[181] SiGe BiCMOS at the 130 nm node was made available in 2005.[182]

Recognizing the commercial impact of SiGe-based technologies, other U.S.-based foundries rapidly stood up internal R&D efforts and developed in-house SiGe BiCMOS processes with few external partnerships.[183,184] In early 2000, Conexant Systems Inc. announced an enhanced SiGe process technology based on 350 nm BiCMOS.[185] In October of 2001, Conexant licensed this IP to TSMC, which became the first pure-play foundry to offer SiGe BiCMOS.[186] TSMC then licensed this process to austriamicrosystems AG in 2003.[187] In early 2003, TSMC introduced its own 180 nm SiGe BiCMOS process.[188]

In February 2002, Conexant Systems Inc. announced plans to spin-off a foundry dedicated to the manufacture of SiGe BiCMOS.[189] Conexant had a 45% stake in the new foundry, called Jazz Semiconductor,[190] and contributed specialty process technologies and manufacturing equipment.[191] A private equity firm called The Carlyle Group payed $20 million and contributed $30 million for a 55% stake in Jazz Semiconductor.

In 2003, Jazz Semiconductor entered into a second-source partnership with Shanghai Advanced Semiconductor Manufacturing Corp., which utilized Jazz's 350 nm SiGe BiCMOS process.[192] Also in 2003, Jazz signed Shanghai Hua Hong NEC Electronics as a second source for its 250 nm and 180 nm CMOS processes.

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181 (2003, October 30). IBM Expands Chip Foundry Services for Wireless Applications. Retrievable from https://www-03.ibm.com/press/us/en/pressrelease/6266.wss

182 (2005, August 5). IBM Announces Next Generation Silicon Germanium Technology. Retrievable from https://www-03.ibm.com/press/us/en/pressrelease/7819.wss

183 Myerson, Bernard. Subject Matter Expert [Interview].

184 Cheivalier, P., Avenier, G., Canderle, E., Montagné, A., Ribes, G., & Vu, V.T. (2015). IEEE. *Nanoscale SiGe BiCMOS Technologies: From 55 nm Reality to 14 nm Opportunities and Challenges*.

185 Lineback, J.R. (2003, January 31). Three Years Ago…Conexant Joined SiGe Club. Retrievable from https://www.eetimes.com/document.asp?doc_id=1173748

186 Telford, M. (2004, March). III-Vs Review. *SiGe Slips Into Main Fabs*. Retrievable from https://www.sciencedirect.com/science/article/pii/S0961129004002819

187 (2003, October 9). Austriamicrosystems Offers SiGe Performance for BiCMOS Prices. Retrievable from https://www.businesswire.com/news/home/20031009005349/en/austriamicrosystems-Offers-SiGe-Performance-BiCMOS-Prices

188 Telford, M. (2004, March). III-Vs Review. *SiGe Slips Into Main Fabs*. Retrievable from https://www.sciencedirect.com/science/article/pii/S0961129004002819

189 (2002, February 25). Conexant to Spin Off Fab as New Foundry Company for SiGe Processes. Retrievable from https://www.eetimes.com/document.asp?doc_id=1176092

190 (2002, May 6). Conexant's Foundry Spin-Off Becomes 'Jazz Semiconductor,' Serves 27 Customers. Retrievable from https://www.businesswire.com/news/home/20080919005342/en/Tower-Semiconductor-Completes-Merger-Jazz-Technologieshttps://www.eetimes.com/document.asp?doc_id=1177182&utm_source=eetimes&utm_medium=relatedcontent

191 (2002, February 25). Conexant to Spin Off Fab as New Foundry Company for SiGe Processes. Retrievable from https://www.eetimes.com/document.asp?doc_id=1176092

192 Telford, M. (2004, March). III-Vs Review. *SiGe Slips Into Main Fabs*. Retrievable from https://www.sciencedirect.com/science/article/pii/S0961129004002819

Several weeks prior to Conexant's 2000 announcement, Texas Instruments issued a press release announcing its 350 nm SiGe BiCMOS process.[193] By February 2004, SiGe BiCMOS was relegated to the status of a niche technology at Texas Instruments due to internal development of a 90 nm CMOS process, with an advanced architecture manager at Texas Instruments saying that "we are definitely and decidedly moving away from silicon germanium".[194] This move was part of a broader transition of wireless technologies from SiGe BiCMOS to CMOS due to CMOS availability at smaller nodes, lower costs, and improved integration.[195] Texas Instruments has since been outsourcing SiGe BiCMOS production to Jazz Semiconductor.[196]

In early 2000, Motorola was the first company to qualify the SiGe:C HBT BiCMOS process. This 350 nm process exhibited f_t= 45 GHz and f_{max}= 90 GHz.[197] In 2004, Motorola spun-off its semiconductor business as Freescale Semiconductor, Inc, which continued manufacturing activities at Motorola's Chandler, AZ fab.[198,199] In March 2015, NXP Semiconductors N.V., a Netherlands-based company, merged with Freescale Semiconductor and took ownership of the Chandler fab.[200,201]

DARPA TEAM

From 2002 to 2007, DARPA sponsored the Technology for Efficient Agiled Mixed Signal Microsystems (TEAM) program to (1) develop RF SoC phased array technologies based on commercially available SiGe BiCMOS processes and (2) develop the next generation of SiGe BiCMOS processes at IBM.[202,203] Dr. Dan Radack was the initial program manager, followed by Dr. Michael Fritze.[204-206] TEAM was the first large program focused on integrating silicon into microwave and mmWave technologies, funding researchers at UC-Berkeley, IBM, MIT, Lincoln Laboratories, University of Michigan, BAE Systems, Jazz Semiconductors, Northrop Grumman, and Boeing.[207] The program funded efforts into design, accurate modeling, and new packaging.[208,209] Performers from the

193 Lineback, J.R. (2003, January 31). Three Years Ago…Conexant Joined SiGe Club. Retrievable from https://www.eetimes.com/document.asp?doc_id=1173748
194 Lineback, J.R. Bye-Bye, SiGe BiCMOS in Cell Phones, Says TI. Retrievable from https://electroiq.com/2004/02/bye-bye-sige-bicmos-in-cell-phones-says-ti/
195 Lehbrink, Wolfgang. Subject Matter Expert [Interview].
196 Telford, M. (2004, March). III-Vs Review. *SiGe Slips Into Main Fabs*. Retrievable from https://www.sciencedirect.com/science/article/pii/S0961129004002819
197 SiGe:C Technology. Retrievable from http://cache.freescale.com/files/technology_manufacturing/doc/SIGE_FACT_SHEET.pdf?fromsite=zh-Hans
198 (2004, December 2). Motorola Completes Separation of Freescale Semiconductor. Retrievable from https://newsroom.motorolasolutions.com/news/motorola-completes-separation-freescale-semiconductor.htm
199 Governance Documents. EverSpin Technologies. Retrievable from http://investor.everspin.com/phoenix.zhtml?c=254442&p=irol-govhighlights
200 NXP Semiconductor Reports Fourth Quarter and Full-Year 2015 Results. Retrievable from http://investors.nxp.com/phoenix.zhtml?c=209114&p=irol-newsArticle&ID=2135489
201 (2015, December 7). NXP and Freescale Announce Completion of Merger. Retrievable from http://investors.nxp.com/phoenix.zhtml?c=209114&p=irol-newsArticle&ID=2120581
202 Fritze, Michael. Subject Matter Expert [Interview].
203 (2002, November 4). DARPA Contracts Worth Up to $20 Million to BAE Systems. Retrievable from https://www.theengineer.co.uk/issues/november-2002-online/darpa-contracts-worth-up-to-20-million-to-bae-systems/
204 Fritze, Michael. Subject Matter Expert [Interview].
205 Rebeiz, Gabriel. Subject Matter Expert [Interview].
206 Radack, Dan. Subject Matter Expert [Interview].
207 Rebeiz, Gabriel. Subject Matter Expert [Interview].
208 Fritze, Michael. Subject Matter Expert [Interview].
209 Rebeiz, Gabriel. Subject Matter Expert [Interview].

defense-industrial base targeted silicon-based devices operating between 20 and 26 GHz, while universities and IBM Yorktown Heights aimed for 60 GHz.[210]

All of the performers described below developed technologies that were fabricated using IBM's 130 nm SiGe 8HP process or Jazz Semiconductor's 180 nm HX SiGe processes.[211,212] Multi-project wafer runs at these foundries via MOSIS in combination with DARPA-funded process design kits enabled DIB companies to gain early, cost-effective access and allowed chip designers to gain familiarity with the technology.[213] This shortened DoD acquisition times by eliminating additional corporate investments that were required prior to the development of a clear profitable business case. Additionally, DARPA-funded MOSIS runs facilitated the formation of long-term business parterships between the DIB and commercial foundries.

During TEAM, Northrop Grumman developed an advanced SiGe radar chip that integrated RF and digital capabilities.[214] A single SiGe RFIC was able to replace 32 heritage ICs, including 16 GaAs multi-function RF MMICs and 16 Si power and logic control ASICS. Production costs of the SiGe devices were also significantly lower than for GaAs devices. As a result of IBM's work on TEAM, the company gained valuable connections with the other performers that transitioned into long-term commercial partnerships.[215] As a direct result of TEAM, IBM developed the world's first monolithic mmWave TX and RX chipset.[216] IBM also reported that the fabrication of the first monolithic phased array ICs at 24 and 77 GHz was supported by TEAM.[217]

Additionally, IBM developed a 2nd generation chipset post-TEAM that was connectable to FPGAs via an uncompressed 2 GB/s video link.[218] This design was licensed to Mediatek, and subsequently to Hittite, which then developed a catalog product. Hittite was purchased by ADI, which still currently supports the 60-GHz TX and RX ICs as products. The 60-GHz chipset became the basis of an E-band chipset developed by a Haifa-based IBM research team.

In a partnership with Mediatek, IBM co-developed packaged 60-GHz TX and RX phased arrays with re-used IP from the TEAM chipsets.[219] These were the first to use low-cost multi-layer organic packages. These phased arrays were licensed to Hittite, with current applications unknown. IBM has used this technology in numerous recent innovations, including a multi-spectral imaging platform for mmWave radar imaging that was linked to AI for gesture recognition.

BAE transitioned their work on TEAM to two programs.[220] BAE used the BAE Systems EW SoC design in the ALQ-239 Digital Electronic Warfare System (DEWS), which was selected by Boeing for incorporation into the F-15 in 2015. DEWS provides simultaneous jamming with minimal interference to the aircraft's radar and warning receiver. Additionally, TEAM was transitioned to the Long Range

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210 Ibid.
211 Valdes-Garcia, Alberto. Subject Matter Expert [Personal Correspondence].
212 Cressler, John. Subject Matter Expert [Interview].
213 Fritze, Michael. Subject Matter Expert [Interview].
214 Lee, Michael & Adams, Charlie. Subject Matter Experts [Interview].
215 Myerson, Bernard. Subject Matter Expert [Interview].
216 Valdes-Garcia, Alberto. Subject Matter Expert [Personal Correspondence].
217 Ibid.
218 Ibid.
219 Ibid.
220 Thompson, Rick. Subject Matter Expert [Personal Correspondence].

Anti-Ship Missile Sensor (LRASM). This was developed in 2010 by the Electronic Systems' research and development group and serves as a precision-guided anti-ship missile designed to give the US Navy the ability to strike high-value targets from long ranges while avoiding counter fire.

Immediately following the conclusion of TEAM in 2008, Tower Semiconductor (based in Migdal Haemek, Israel) merged with Jazz Semiconductor. As a result, Jazz Semiconductor became a subsidiary of Tower Semiconductor.[221] In 2009, the firm was re-branded as TowerJazz.[222] Jazz Semiconductor Trusted Foundry, a wholly owned U.S. subsidiary of TowerJazz, currently operates a SiGe BiCMOS production line at the 130 nm node and has been accredited as a Category 1A and 1B Trusted Supplier by the DoD Trusted Program.[223,224]

DARPA SMART

After TEAM, DARPA MTO sponsored the Scalable Millimeter-wave Architectures for Reconfigurable Tranceivers (SMART) program.[225] Led by program manager Dr. Mark Rosker, the goal of the program was to develop silicon-based mmWave phased arrays.[226,227] Performers on the project included Northrop Grumman, Raytheon, and Teledyne/UC-San Diego, which targeted phased arrays capable of operating at 94 GHz, wide-band, and 44 GHz, respectively.[228] This program successfully developed the first analog beam phased arrays, enabling the commercial transition of the technology. For example, during Phase III, Teledyne produced 44 GHz EHF satellite communications (SATCOMM) chips, which were available commercially for the defense-industrial base.[229,230]

Notably, the United States Navy became aware of the work and funded a portion of SMART to develop wide band 10-20 GHz 4-beam chips for SATCOMM.[231] The Office of Naval Research (ONR) then sponsored the $300 million Integrated Topside (InTop) program, which sought to commercialize silicon-based microelectronics for SATCOMM and electronic warfare (EW).[232] Performers on this project included Northrop Grumman, Raytheon, and Lockheed Martin.[233,234]

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221 (2008, September 19). Tower Semiconductor Completes Merger with Jazz Technologies. Retrievable from https://www.businesswire.com/news/home/20080919005342/en/Tower-Semiconductor-Completes-Merger-Jazz-Technologies

222 (2009, November 5). Tower and Jazz Semiconductor Announce Major Acheivements in First Year of Merger, Launch New Brand and Website. Retrievable from http://www.towerjazz.com/prs/2009/pdf/pr_110309.pdf

223 (2015, March 23). Jazz Semiconductor Trusted Foundry (JSTF) Announces Accrediation by United States Department of Defense DMEA as a Category 1A and 1B Trusted Supplier. Retrievable from http://towerjazz.com/prs/2015/0323.html

224 Cressler, John. Subject Matter Expert [Interview].

225 Rebeiz, Gabriel. Subject Matter Expert [Interview].

226 Ibid.

227 Wallace, H.B. (2014, October 30). DARPA MMW System Programs and How They Drive Technology Needs. Retrievable from https://www.ece.ucdavis.edu/dmrc/files/2014/09/Bruce_wallace_darpa_web.pdf

228 Rebeiz, Gabriel. Subject Matter Expert [Interview].

229 Keller, J. (2012, November 14). DARPA Taps Teledyne to Continue Work on Fabricating Smart Radar Antenna Technology. Retrievable from https://www.militaryaerospace.com/articles/2012/11/teledyne-smart-antenna.html

230 Rebeiz, Gabriel. Subject Matter Expert [Interview].

231 Ibid.

232 Integrated Topside. Retrievable from https://www.onr.navy.mil/en/About-ONR/History/tales-of-discovery/integrated-topside

233 Rebeiz, Gabriel. Subject Matter Expert [Interview].

234 Lee, Michael & Adams, Charlie. Subject Matter Experts [Interview].

As a result of InTop, Lockheed Martin built several silicon-based phased arrays for radar, EW, and SATCOMM applications.[235] Northrop Grumman produced a Low Band Receive SiGe device that was able to replace 32 legacy devices and another device based on High Band Receive SiGe replaced 8 legacy devices.[236] Northrop Grumman also participated in other DoD-sponsored programs using knowledge gained from TEAM and SMART. During the AN/SLQ-32(V)Y Surface Electronic Warfare Improvement program, Low Band and High Band Transmit SiGe integrated 8 legacy equivalent parts onto a single device. In the U.S. Marine Corp AN/TPS-80 Ground/Air Task Oriented Radar (G/ATOR) program, a single device based on SiGe RFIC replaced 4 GaAs ICs and 4 Si ICs.

ONR continued to fund DIB performers to work on silicon-based phased arrays. From 2008-2009, Ball Aersopace worked on a USN contract to develop a 4-beam phased array for communications data link (CDL) applications.[237] This work produced the first design of a 4-beam CDL. In 2016, the USN contracted with BAE to deliver 12 4-beam phased arrays with 4 facets for aircraft carriers, which relied on integrated phased arrays from Ball Aerospace and ViaSat.[238]

In 2009, Rockwell Collins began working with researchers at UC-San Diego to produce commercial SiGe-based SATCOMM devices for the aerospace industry.[239,240] With only internal funding, Rockwell Collins developed low-cost high-performance SiGe-based weather radars and SATCOMM phased arrays that are expected to be on all commercial aircraft by 2022.[241-243] Boeing was the initial market leader in the SATCOMM phased-array sector, having transitioned all chips from GaAs to Si by 2012.[244] Ths program was eliminated by 2015 due to the high costs imposed by Boeing's defense customers.[245] Rockwell Collins, which was not burdened by defense customers, specialized in the commercial sector.[246,247] In 2017, United Technologies announced plans to acquire Rockwell Collins for $30 billion, but the deal has not yet been finalized.[248,249] Additionally, Viasat produced 20-30 GHz phased arrays for SATCOMM for the internet service provider sector.[250,251]

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235 Rebeiz, Gabriel. Subject Matter Expert [Interview].
236 Lee, Michael & Adams, Charlie. Subject Matter Experts [Interview].
237 Rebeiz, Gabriel. Subject Matter Expert [Interview].
238 Howard, C. (2016, September 28). BAE Systems and Ball Aerospace Collaborate to Bolster U.S. Navy's Ability to Share Critical Data. Retrievable from https://www.intelligent-aerospace.com/articles/2016/09/bae-systems-and-ball-aerospace-collaborate-to-bolster-u-s-navy-s-ability-to-share-critical-data.html
239 Rebeiz, Gabriel. Subject Matter Expert [Interview].
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241 (2015, March 16). Rockwell Collins Team with OneWeb to Provide Unprecedented Connectivity to Aviation. Retrievable from https://www.rockwellcollins.com/Data/News/2015-Cal-Yr/CS/FY15CSNR15-OneWeb.aspx
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243 Oster, Sasha. Subject Matter Expert [Interview].
244 Rebeiz, Gabriel. Subject Matter Expert [Interview].
245 Torrieri, M. Phased Array Antennas: Can They Deliver? Retrievable from http://interactive.satellitetoday.com/via/may-june-2017/phased-array-antennas-can-they-deliver/
246 Rebeiz, Gabriel. Subject Matter Expert [Interview].
247 (2015, March 16). Rockwell Collins Team with OneWeb to Provide Unprecedented Connectivity to Aviation. Retrievable from https://www.rockwellcollins.com/Data/News/2015-Cal-Yr/CS/FY15CSNR15-OneWeb.aspx
248 (2017, October 4). Mega-Merger: What UTC-Rockwell Collins Means for Aerospace. Retrievable from https://www.co-production.net/manufacturing-latest-news/422-aerospace-industry-reaching-an-agreement.html
249 Oster, Sasha. Subject Matter Expert [Interview].
250 Rebeiz, Gabriel. Subject Matter Expert [Interview].
251 Viasat Phased Array Flat Panel Antenna Selected by SES Networks for the 03b mPower System. Retrievable from https://www.viasat.com/news/viasat-phased-array-flat-panel-antenna-selected-ses-networks-o3b-mpower-system

Other Relevant DARPA Programs

Numerous additional DARPA programs have contributed to the development of SiGe-based phased arrays. The Adaptive RF Technology (ART) program, led by Dr. Bill Chappel, Dr. Troy Olsson, and Dr. Tom Rondeau, aimed to develop SiGe-based reconfigurable RF integrated circuits.[252,253] The Efficient Linearized All-Silicon Transmitter ICs (ELASTx) program, led by Timothy Hancock, Dev Palmer, and Sanjay Raman, has aimed to develop monolithic, high power, high linearity, mmWave silicon-based transmitter integrated circuits, including power amplifiers and phased-arrays.[254-256] The Arrays at Commercial Timescales (ACT) program, led by Bill Chappel and Roy Olsson, was the first concentrated phased array program after SMART and seeks to shorten development timescales for phased arrays.[257,258] Northrop Grumman and Rockwell Collins were highly successful performers in ACT,[259,260] delivering highly integrated beamforming modules capable of operating at ~12 GHz.[261] The technology developed by Rockwell Collins during ACT has been the subject of multiple proposals to AFRL, ARL, and DARPA, and is currently being applied to a range of commercial application markets, including phased arrays for AESAs, SATCOMM, and EW.[262]

The Diverse Accessible Heterogeneous Integration (DAHI) program led by Sanjay Raman, Dan Green, and Tim Hancock aims to produce next-generation phased arrays dubbed wafer-scale phased arrays by combining emerging materials and devices with CMOS technology.[263,264] Lastly, the Multifunction RF (MFRF) program led by Bruce Wallace and John Gorman has aimed to develop a common RF system that will use agile freuqnecies, waveforms, and apertures.[265,266] IBM's success with their 60-GHz phased array enabled the firm to serve as a performer in this program, during which IBM developed the first Si-based scaled mmWave phased array module consisting of 4 ICs and a package with 64 dual polarized antennas operating at 94 GHz.[267] The associated IC, dual polarized 94-GHz phased array TRX, still holds the record for the highest level of monolithic integration at W-band. This design was licensed by Ericsson, which IBM worked with to jointly develop a dual polarized

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252 Rebeiz, Gabriel. Subject Matter Expert [Interview].
253 Adaptive RF Technology (ART). Retrievable from https://www.darpa.mil/program/adaptive-rf-technologies
254 Rebeiz, Gabriel. Subject Matter Expert [Interview].
255 Efficient Linearized All-Silicon Transmitter ICs (ELASTx). Retrievable from https://www.darpa.mil/program/efficient-linearized-all-silicon-transmitter-ics
256 (2014, September 15). The Path to Efficient-yet-Linear Watt-Class mmWave CMOS PAs. Retrievable from http://pasymposium.ucsd.edu/docs/RAB_PAsymp2014_v1.pdf
257 Rebeiz, Gabriel. Subject Matter Expert [Interview].
258 Arrays at Commercial Timescales (ACT). Retrievable from https://www.darpa.mil/program/arrays-at-commercial-timescales
259 Keller, J. (2018, April 4). Military Researchers Seek to Make RF Phased Array Common Modules Available to the Defense Industry. Retrievable from https://www.militaryaerospace.com/articles/2018/04/rf-phased-arrays-electronic-warfare-ew.html
260 (2017, September 14). Rockwell Collins Demonstrates New Directional Communication Link With Longer Range and Anti-Jamming Capability. Retrievable from https://www.rockwellcollins.com/Data/News/2017-Cal-Yr/GS/20170914-ATC-Directional-Comms.aspx
261 Rebeiz, Gabriel. Subject Matter Expert [Interview].
262 Oster, Sasha. Subject Matter Expert [Interview].
263 Diverse Accessible Heterogeneous Integration (DAHI). Retrievable from https://www.darpa.mil/program/diverse-accessible-heterogeneous-integration
264 Rebeiz, Gabriel. Subject Matter Expert [Interview].
265 Multifunction RF (MFRF). Retrievable from https://www.darpa.mil/program/multifunction-rf
266 Rebeiz, Gabriel. Subject Matter Expert [Interview].
267 Valdes-Garcia, Alberto. Subject Matter Expert [Personal Correspondence].

64-element array TRX at 28-GHz. This device is now a key component of an Ericsson 5G base station product. Northrop Grumman produced an advanced multifunction RF sensor with a SiGe device that integrated all array electronics on a single device for W-band AESA.[268]

The European Union

Early Efforts

After IBM's invention of SiGe in the 1980s, the technology was readily adopted by bipolar transistor technology companies.[269] In 1995, Siemens AG published a report detailing a SiGe-based IC capable of operating at f_{max}= 75 GHz. In 1999, Siemens spun-off its semiconductor business into Infineon Technologies, which continued to develop SiGe BiCMOS processes.[270] In 2000, STMicroelectornics qualified its 350 nm SiGe BiCMOS process.[271,272] STMicroelectronics went on to develop SiGe BiCMOS processes at the 350 nm, 250 nm, 130 nm, and 55 nm nodes.[273] In early 2002, Hitachi developed a prototype SiGe:C HBT.[274,275] This device was incorporated into commercial devices by the end of that calandar year.[276]

In 2001, Belgium-based Alcatel Microelectronics announced the release of a SiGe BiCMOS process at the 350 nm node that was co-developed with IMEC, a Belgium R&D organization.[277] This technology enabled the development of wireless components with frequencies up to 10 GHz. In 2006, Alcatel merged with Lucent Technologies (a spin-off from AT&T) to form a French-American company called Alcatel-Lucent.[278] This company then merged with Nokia to form Nokia Corporation in 2016.[279] Nokia Bell Labs has continued to develop SiGe BiCMOS-based mmWave phased array RFIC antenna systems and is currently testing these technologies for incorporation into 5G in partnership with Japan-based NTT DOCOMO.[280,281] In 2003, under a non-exclusive agreement

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268 Lee, Michael & Adams, Charlie. Subject Matter Experts [Interview].
269 Lehbrink, Wolfgang. Subject Matter Expert [Interview].
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275 Lehbrink, Wolfgang. Subject Matter Expert [Interview].
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280 (2018, February 11). A Fully Integrated Scalable W-Band Phased-Array Module With Integrated Antennas, Self-Alignment and Self-Test. Retrievable from https://www.bell-labs.com/our-research/publications/298214/
281 (2018, April 24). Nokia Bell Labs and NTT DOCOMO Collaborate on 5G Innovations for Massive Capacity, Low-Latency Support of Future Wireless Applications. Retrievable from https://www.nokia.com/en_int/news/releases/2018/04/24/nokia-bell-labs-and-ntt-docomo-collaborate-on-5g-innovations-for-massive-capacity-low-latency-support-of-future-wireless-applications

through IMEC's Industrial Affiliation Program, Singapore-based Chartered Semiconductor licensed IMEC's 180 nm SiGe-based bipolar module, plus test chip structures and bipolar model.[282]

In 2001, IHP and Intel engaged in a partnership to found Communicant Semiconductor Technologies, a $1.5 billion foundry that was anticipated to provide SiGe:C, BiCMOS, and CMOS technologies.[283] IHP provided the SiGe:C process technology, while Intel provided 180 nm CMOS technology in exchange for 20% of the manufacturing capacity. Additional investment was provided by the Dubai Airport Free Zone Authority, the Brandenburg regional government and the German federal government. In November, 2003, Communicant declared bankruptcy after the withdrawal of the Dubai Airport Free Zone Authority investors, who were planning fab investments at Dubai Silicon Oasis. Also in 2003, IHP began developing prototypes using its f_T=80-30 GHz 250 nm SiGe:C BiCMOS process.[284]

EU-funding

In 2008, an European Union-funded effort called DOTFIVE launched with the goal of developing a 0.5 THz SiGe heterojunction bipolar transistor and establishing a leadership position for the European semiconductor industry in SiGe technologies for millimeter wave applications.[285,286] This three-year program was worth €14.75 million with €9.7 million in European Commission funding, making it the largest nanoelectronics project under EU Framework Programme 7.[287] Foundries involved included Infineon Technologies and STMicroelectronics, as well as IMEC and IHP. By the end of the project, the 500 GHz goal was achieved by IHP.[288] Infineon is anticipating this product to be released by the end of 2018.[289]

In late 2012, the EU kicked off a follow-on project called DOTSEVEN with the goal of pushing SiGe HBT to 700 GHz and demonstrating working systems at 240 GHz.[290,291] The main objective was to reinforce and further strengthen Europe's leading edge position in SiGe HBT technology and modeling as well as SiGe-enabled mmWave applications so as to stay significantly ahead of non-

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[288] Dotfive Results. Retrievable from http://www.dotfive.eu/index.php?id=185
[289] Lehbrink, Wolfgang. Subject Matter Expert [Interview].
[290] Schroter, M., Boeck, J., d'Alessandro, V., Fregonese, S., Heinemann, B., Jungemann, C., Liang, W., Kamrani, H., Mukherjee, A., Pawlak, A., Pfeiffer, U., Rinaldi, N., Sarmah, N., Zimmer, T., & Wedel, G. (2016). IEEE. *The EU DOTSEVEN Project: Overview and Results*.
[291] Towards 0.7 THz Silicon-Germanium Heterojunction Bipolar Technology. Retrievable from https://www.scribd.com/document/145852234/Dotseven-Brochure-Vf

European competition.[292] This program was sponsored by the European Commission at €12.3 million over 3.5 years.[293] In this program, the only foundries involved were Infineon and IHP.[294]

As part of this effort, the performers sought to develop fully integrated mm-wave circuits.[295] Approximately halfway through the project, Infineon had developed a 130 nm SiGe BiCMOS technology with f_t of 250 GHz and f_{max} of 370 GHz.[296] Infineon also investigated the suitability of IHP's advanced HBT concepts for future industrial mass production for upcoming BiCMOS generations. Constraints considered included yield, cost, and compatibility with standard production techniques in a 130 nm CMOS line.

The involvement of the European Union was critical to these developments.[297] Initially, industry partners were highly reluctant to conduct research and development activities into 500 GHz- and 700 GHz-capable devices because (1) it was not clear those levels could be achieved, and (2) no markets for those technologies existed. Additionally, EU funding encouraged cooperation between industrial companies (Infineon and STMicroelectronics) and public-private partnerships (IMEC and IHP), allowing novel processes developed through research activities to be manufactured at scale.

SiGe BiCMOS-based Phased Arrays and 5G

The communications industry, led by Ericsson, Nokia, and others, observed the potential of applying emerging phased array technologies toward communications and convinced their suppliers (Intel, NXP, IDI, Infineon, etc.) to produce modules and base stations.[298] Qualcomm, Intel, Samsung, and Fujitsu internally developed CMOS-based analog beam phased arrays for high volume consumer products (i.e. cell phones, wireless routers, etc) at 28 GHz and 39 GHz. SiGe BiCMOS-based analog beamforming chips, optimal for high power applications, were utilized by base-station companies NXP, ADI, Samsung, and Ericsson. ZTE and Huawei have led the sub-6 GHz base station market, incorporating GaN-based amplifiers and CMOS-based digital components. While no base station company is hosted within the United States, domestic semiconductor firms (i.e. ADI, Texas Instruments, Qualcomm, Xylinx, Alterra, NXP Freescale, Qorvo, Skyworks, etc) supply the overwhelming majority of ICs.

However, all of these domestic firms subcontract out their semiconductor manufacturing to foundries that are not owned by U.S.-based firms.[299] Taiwan-based TSMC produces chips for Qualcomm, Intel, and MTK, while other foundries operate in Korea (Samsung) and Europe (NXP, Infineon, and

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292 Towards 0.7 THz Silicon-Germanium Heterojunction Bipolar Technology. Retrievable from https://www.scribd.com/document/145852234/Dotseven-Brochure-Vf
293 Schroter, M., Boeck, J., d'Alessandro, V., Fregonese, S., Heinemann, B., Jungemann, C., Liang, W., Kamrani, H., Mukherjee, A., Pawlak, A., Pfeiffer, U., Rinaldi, N., Sarmah, N., Zimmer, T., & Wedel, G. (2016). IEEE. *The EU DOTSEVEN Project: Overview and Results.*
294 Towards 0.7 THz Silicon-Germanium Heterojunction Bipolar Technology. Retrievable from https://www.scribd.com/document/145852234/Dotseven-Brochure-Vf
295 Schroter, M., Boeck, J., d'Alessandro, V., Fregonese, S., Heinemann, B., Jungemann, C., Liang, W., Kamrani, H., Mukherjee, A., Pawlak, A., Pfeiffer, U., Rinaldi, N., Sarmah, N., Zimmer, T., & Wedel, G. (2016). IEEE. *The EU DOTSEVEN Project: Overview and Results.*
296 Böck, J., Aufinger, K., Boguth, S., Dahl, C., Knapp, H., Liebl, W., Manger, D., Meister, T.F., Pribil, A., Wursthorn, J., & Lachner, R. (2015). IEEE. *SiGe HBT and BiCMOS Process Integration Optimization Within the DOTSEVEN Project.*
297 Lehbrink, Wolfgang. Subject Matter Expert [Interview].
298 Rebeiz, Gabriel. Subject Matter Expert [Interview].
299 Ibid.

STMicroelectronics). Israel-based TowerJazz and UAE-based GlobalFoundries, which acquired IBM's semiconductor manufacturing business in 2014,[300,301] are also major suppliers.[302-306]

The commercialization of automotive radar is dominated by European companies that had previously benefited from the EU-funded DOTFIVE and DOTSEVEN initiatives.[307] Notably, Infineon is the clear market leader.[308] However, other firms have produced microelectronic components for this market sector, including NXP Freescale, ADI, and Texas Instruments.[309] As with the ICs for base station components and consumer products, all of these chips are produced by foundries that are not owned by U.S.-based companies.

In addition to the IP that was generated, the rapid development of the 5G mmWave market was directly enabled by the highly specialized workforce that was trained via DARPA funding.[310] The graduate students who had worked on DARPA projects are now currently employed throughout the domestic and foreign 5G mmWave technological ecosystem. Firms such as NXP Freescale and ADI were not funded by DARPA, but are staffed by students who were trained under DARPA contracts. As a further example, the IBM personnel that led IBM's TEAM effort are the same individuals developing IBM's 5G components.

Recommendations

The study team developed a series of recommendations to DARPA MTO to enable DARPA to better ensure that DARPA-funded intellectual property contributes to an ecosystem of innovation that flourishes in the United States. The recommendations are described in detail below.

Recommendation #1. DARPA MTO programs, particularly ERI, should include low-volume high-mix (LVHM) manufacturers as Performers and fund the development of LVHM-enabling manufacturing technologies.

An important characteristic of state-of-the-art MRAM and SiGe BiCMOS technologies is their reliance on manufacturing facilities that cost upwards of $15 billion.[311] This recommendation suggests DARPA invest in innovative research that will produce technologies and markets with a higher probability of maintaining a domestic manufacturing base.

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300 (2015, July). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Microelectronics Strategy Study*.
301 According to the terms of the contract, IBM paid GlobalFoundries $1.5 billion in exchange for the acquisition and operation of its microelectronics foundries, related technologies, and personnel.
302 Neiger, C. (2017, September 18). How Skyworks Solutions Makes Most of its Money. Retrievable from https://www.fool.com/investing/2017/09/18/how-skyworks-solutions-makes-most-of-its-money.aspx
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304 (2016, November 16). TowerJazz. *TowerJazz (TSEM) Investor and Analyst Day*.
305 Cressler, John. Subject Matter Expert [Interview].
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308 Lehbrink, Wolfgang. Subject Matter Expert [Interview].
309 Rebeiz, Gabriel. Subject Matter Expert [Interview].
310 Ibid.
311 (2018, August). Potomac Institute for Policy Studies. *Trusted State-of-the-Art Foundry Access Impact Analysis, Assessment, and Strategy Report*.

Regardless of the size of the potential market, any state-of-the-art MRAM and SiGe BiCMOS technology requiring high-volume low-mix production in a modern foundry will very likely not be produced by a domestically-owned fab. The majority of the commercial fabrication infrastructure for this exists in the Asia-Pacific region. One way out of this conundrum is to revolutionize the type of semiconductors under development and how they are manufactured.

DARPA should fund innovative research into groundbreaking technologies that, upon commercialization, would be amenable to LVHM manufacturing methods. The development of such fabrication capabilities should be an integral part of the the DARPA ERI Program. This is consistent with the post-Moore trend of increasing specialization of hardware to function.

Specifically, program managers should seek to fund the development of LVHM-enabling manufacturing technologies such as multiple electron beam direct write (MEBDW) tools. MEBDW-based processes typically utilize a complementary electron beam lithography (CEBL) approach in which metal-interconnect grating patterns are formed optically and MEBDW is used to complete the interconnect and write via hole patterns, creating customized IC patterns.[312] Full pattern writing is also being explored. EBL approaches drastically reduces mask costs and equipment costs.[313,314] However, commercially available MEBDW tools are not yet available and remain under development.[315] These efforts currently include an AFRL-sponsored $35 million contract with Multibeam Corporation to manufacture an EBL system for IC production by 2020.[316] Additionally, ERI should also seek to include low-volume high-mix foundries as Performers in funded projects. Numerous high-mix low-volume facilities are currently operating in the United States.[317] As demonstrated in this report, DARPA programs build connections between semiconductor foundries and potential customers when both are included as Performers, facilitating commercial partnerships beyond the lifetime of the DARPA contract.

Recommendation #2. DARPA should facilitate the transition of ERI-funded technology into the U.S. defense-industrial base (DIB) by including defense contractors as Performers on the ERI Program and by providing access to multi-project fabrication runs with necessary Process Design Kits.

When a DARPA-funded technology achieves success in the commercial market or in the DIB, the United States benefits via economic growth and the creation of new markets. However, only technology transitions into the defense-industrial base provide DoD with an asymmetric advantage over potentially adversarial counterparts. This recommendation ensures that ERI-funded technologies are accessible by companies in the DIB.

ERI program managers should ensure that DIB companies are included as Performers early on and have early access to multi-project wafer runs at commercial foundries via MOSIS and/or TAPO. As shown in this report, DARPA programs facilitate the development of relationships between the DIB

312 (2017, October). Potomac Institute for Policy Studies. *Low-Volume, High-Mix Manufacturing Models in the Semiconductor Industry.*
313 Ibid.
314 (2015, April). Potomac Institute for Policy Studies. *E-Beam Direct Write Workshop.*
315 Ibid.
316 (2017, May 25). Multibeam Secures $35M Defense Contract to Build E-Beam System. Retrievable from http://www.multibeamcorp.com/PR_MB20170525.htm
317 (2015, June). Potomac Institute for Policy Studies. *DoD Needs for Specialized Low Volume Fabrication.*

and the commercial sector that are likely to continue after the conclusion of the Program. Additionally, the availability of DARPA-funded multi-project manufacturing runs via MOSIS and/or TAPO is critical for the internal technology development similar to what occurred at Northrop Grumman during DARPA TEAM. Cloud-based infrastructure that enables secure IC design and access to intellectual property by disparate design teams should also be funded. For example, AFRL's microelectronics challenge provides access to the Trusted Silicon Stratus. This would likely shorten DoD acquisition timelines, as DIB companies are typically reluctant to invest in high-cost process design kits unlss there's a clear near-term business case

Recommendation #3: DARPA should consider policy changes that enable the domestic capture of students trained via ERI funding.

The rapid development of the 5G communications market was directly enabled by the availability of a highly skilled workforce that was trained via DARPA funding. The availability and willingness to move overseas is a key factor that is enabling European and Asian companies to lead the 5G communications market. This recommendation ensures that DARPA develops and implements policy changes that ensures that ERI-funded students and post-doctoral fellows achieve employement in the domestic microelectronics ecosystem.

There are numerous opportunities for DARPA to impact the career trajectories of the students working on ERI-funded projects. For example, DARPA could sponsor workshops and networking events that bridge connections between students and domestic companies, facilitating post-graduation employment. Additionally, the availability of clearable students in an academic research laboratory could serve as a criteria in the Performer review process. The impacts of these policies, both intended and unintended, need to be carefully considered and weighed prior to their implementation. However, this is beyond the scope of this study.

Recommendation #4. DARPA should seek to partner with R&D organizations of major US companies and identify internal champions of these new technologies that can evangelize them to the business units who are typically much more short term focused.

Individuals that championed the potential of emerging technologies developed by DARPA were critical to the commercial success of both MRAM and SiGe BiCMOS technologies. Additionally, the availability of a corporate R&D unit that was separate from the related business unit enabled (1) operation within USG FAR and DFARS requirements, and (2) the gradual development of a profitable business case. This is an important "lesson learned" from our study.

During DARPA Spintronics, Motorola's MRAM effort was transferred from the R&D division to the Semiconductor Products Division, which sought to kill the Program due to the perceived lack of a short-term profitable business case. The Program was saved after DARPA contributed additional funding to Motorola to transfer the MRAM work back to the R&D division of Motorola. At IBM's R&D unit, Bernie Myerson, an IBM executive, was able to promote internal investment efforts towards developing innovative SiGe BiCMOS processes for RF applications. His work enabled IBM to win DARPA funding that was critical to the commercial partnership between IBM and Harris Corporation. This highly profitable relationship enabled IBM to overcome internal and external resistance to the potential of SiGe BiCMOS processes for RF applications and was a key moment in the developmental history of SiGe BiCMOS.

Conclusion

To support DARPA's Microsystems Technology Office in its technology transfer efforts for the Electronics Resurgence Initiative program, the Potomac Institute for Policy Studies investigated the global proliferation of MRAM and silicon-based RF technologies [i.e SiGe BiCMOS-based phased arrays]. Our research found that investments by DARPA were critical to the development of MRAM memory and SiGe RF technologies. As a result of DARPA funding, these technologies have found profitable transitions in both the commercial sector and the defense-industrial base. Notably, a simple set of Performers lead to globalization via interconnected pathways including personnel transfers, mergers and acquisitions, spin-offs and commercial partnerships. A detailed mapping of these complex transition pathways is provided in this report. Furthermore, individuals that championed the potential of these emerging technologies played a pivotal role in the commercial success of both MRAM and SiGe BiCMOS technologies. DARPA enabled DIB companies to have early, cost-effective access to commercial foundries via MOSIS, forming the foundation for future long-term partnerships and rapidly shortening the technology development timeline. Additionally, the availability of a corporate R&D unit that was separate from the related business unit enabled (1) operation within USG FAR and DFARS requirements, and (2) the gradual development of a profitable business case.

DARPA Program Managers have the ability to structure their programs such that they fund only commercial companies, both commercial and defense-industrial base companies, or only defense-industrial base companies. In this study, only the first two funding structures were studied. In the development of both MRAM and SiGe-based RF technologies, commercial firms were responsible for developing the early designs and process protocols, then maturing the technologies to achieve commercial entry. This was successfully accomplished in both of the case studies examined in this report. In both of these case-studies, the commercial firms used DARPA funding to build on initial in-house capabilities that had been developed earlier. However, commercial firms follow the most profitable business case, resulting in technology transition pathways that eventually led to foreign-owned companies. Fortunately, several foreign-owned multinational firms operate domestically-located fabrication facilities, including Samsung, NXP Semiconductors, and GlobalFoundries. However, long-term DoD access to technologies manufactured by multinationals isn't assured, motivating the development of contingency plans to minimize supply disruptions. For example, GlobalFoundriesUS still offers trusted advanced SiGe BiCMOS to the DoD, but the UAE-based company is struggling with an uncertain financial future.[318]

Long-term access to advanced microelectronic technologies is best assured via the defense-industrial base, which provides the most robust means of minimizing long-term supply chain variability and risk. Notably, our data suggest that DIB firms should be included as early Performers in DARPA Programs to maximize their ability to uptake and advance DARPA-funded technologies. The two MRAM Programs, STT-MRAM and Spintronics, did not include DIB Performers. Meanwhile, every SiGe RF-based DARPA Program included DIB Performers. It is therefore not surpising that there are no MRAM suppliers in the DIB, while Northrop Grumman is now a major supplier of SiGe-based components for military radars, electronic warfare, and satellite communication technologies. Recapitalization efforts and technology development at these fabs, which typically operate at SOTP or legacy nodes, could be facilitated via DoD investments.

[318] (2018, October). Potomac Institute for Policy Studies. *Trusted State-Of-The-Art Foundry Access*

The data collected in this study indicates that two technology transition paths exists for USG-funded technologies. One leads into the commercial (non-defense) sector, while the second results in uptake by the defense-industrial base (defense-specific). When a DARPA-funded technology achieves success in the commercial market or in the DIB, the United States benefits via economic growth and the creation of new markets. However, only technology transitions into the defense-industrial base provides DoD with an asymmetric advantage over potentially adversarial counterparts. Indeed, recent high-profile cases in the commercial software and artificial intelligence sectors illustrate this point.[319,320] Even worse, competitor nations could obtain the DARPA-funded IP via legal or illegal actions, as the Chinese have done in recent years. There is a clear need to be aware of the optimal outcome of DARPA or USG-funded research and then develop policy to achieve the desired outcome beneficial to the DoD or USG.

[319] Khan, I. (2018, November 1). Engadget. US Charges Chinese, Taiwan Firms for Stealing Secrets From Micron. Retrievable from https://www.engadget.com/2018/11/01/us-charges-chinese-taiwan-firms-for-stealing-from-micron/
[320] Brown, M., & Singh, P. (2018, January). Defense Innovation Unit Experimental. *China's Technology Transfer Strategy: How Chinese Investments in Emerging Technology Enable a Strategic Competitor to Access the Crown Jewels of U.S. Innovation*. Retrievable from https://admin.govexec.com/media/diux_chinatechnologytransferstudy_jan_2018_(1).pdf

Appendix 1: MRAM Subject Matter Experts

Bernard Dieny. Dr. Dieny graduated from Ecole Normale Supérieure de Cachan and earned a Ph.D. in Physics from the University of Grenoble, France. Throughout his career, he has contributed to major breakthroughs in spintronics, including the discovery of spin valves. Dr. Dieny has spent most of his career in CEA/Grenoble. He co-founded SPINTEC in 2001 and has been the lab's chief scientist since then, where he has led efforts that have resulted in 4 MRAM-related start-up companies. He also spent two long-term assignments at IBM Research and University California, San Diego.

Bill Gallagher. Dr. Gallagher worked as a Research Staff Member at IBM, where he performed experiments on magnetic tunnel junctions and invented cells that formed the basis of magnetic random access memory (MRAM). He then led a significant effort that demonstrated increasingly sophisticated MRAM circuitry, while attracting government funding and a number of development partner companies. Through the ensuing eighteen years Dr. Gallagher led IBM's MRAM R&D program, eventually serving as senior manager overseeing combinations of MRAM, phase change memory, and quantum computing research. In 2010 he began work on integrated power electronics with magnetic components. In June of 2015, he joined TSMC in Hsinchu, Taiwan as a Technical Director.

Rajiv Ranjan. Dr. Ranjan is the Founder and CTO of Avalanche Technology, a leader in spin transfer torque MRAM. He has served in this role since 2006. Previously, Dr. Ranjan was the Executive Director of R&D at Seagate, where he led technology development that fueled a doubling of revenue to more than $10 billion. His technology pioneering efforts have led to the productization of low-noise media perpendicular media and laser texturing. These technologies are now widely used in the storage devices that revolutionized the data storage industry.

Dev Shenoy. Dr. Shenoy was a Program Manager at DARPA, where he led the STT-MRAM program. He is currently the Director of Microelectronics Innovation and Ventures at Information Sciences Institute, USC. Prior to this role, he was a systems engineering advisor to the Office of the Secretary of Defense and is an executive-in-residence at Columbia Technology Ventures. He has previously served as the Chief Engineer at the Department of Energy.

Stu Wolf. From 1993-2005, Dr. Wolf served as a Program Manager at DARPA, where he coined the name Spintronics for the program to develop MRAM. He also managed the Spins IN Semiconductors (SPINS) project, the Quantum Information Science and Technology (QuIST) project, and the Frequency Agile Materials for Electronics (FAME) project, among several others. Dr. Wolf has also worked as a Branch Head at the U. S. Naval Research Laboratory, where he both managed and performed research on superconductivity and magnetism. He is currently an Adjunct Research Staff Member at the Institute for Defense Analysis (IDA) where he supports programs at both DARPA and OSD. He is also a Professor Emeritus at the University of Virginia in both Physics and Materials Science and Engineering and the Emeritus Director of the Institute for Nanoscale and Quantum Science and Technological Advanced Research (Nanostar).

Daniel Worledge. Dr. Worledge is currently a Distinguished Research Staff Member and Senior Manager in the MRAM group at IBM Research. He completed his Ph.D. in Applied Physics at Stanford University in 2000, then joined IBM Research as a post-doc. He has been at IBM for 18 years.

Appendix 2: 5G Subject Matter Experts

Charlie Adams. Dr. Adams works at Northrop Grumman as the Director, Programs of the ATL Foundry & DMEA Programs. His lab led Northrop Grumman's efforts to design and test RF microelectronic components throughout the TEAM program. They also fabricate custom RF components for military systems, particularly radar.

John D. Cressler. From 1984 to 1992, Dr. Cressler was on the research staff at IBM Thomas J. Watson Research Center, and from 1992 to 2002 he served on the faculty at Auburn University. In 2002, he joined the faculty at Georgia Tech and is currently the Schlumberger Chair Professor of Electronics, in the School of Electrical and Computer Engineering. His research focuses on the advancement of SiGe electronics, with particular application to extreme environments.

Michael Fritze. Dr. Fritze is currently a Vice President at the Potomac Institute for Policy Studies responsible for the Microelectronics Policy Portfolio. Prior to this position, he was the Director of the Disruptive Electronics Division at the USC Information Science Institute. From 2006-2010, Dr. Fritz served as a Program Manager at DARPA MTO. He was responsible for several programs, including TEAM. From 1995-2006, Dr. Fritze was a staff member at MIT Lincoln Laboratory, where he worked on fully-depleted silicon on insulator technology.

Brian Gaucher. Brian is currently a Senior Manager/Principal RSM of IBM's Cognitive Environments Lab, where he is focused on creating human-machine partnerships to enhance cognition. Prior to this role, he was a Senior Manager in IBM's Smarter Energy Department. From 1993-2009, Brian worked as a research staff member at the IBM T.J. Watson Research Center, where he managed a communication system design and characterization group with research interests that included cellular, Bluetooth, WiFi, UWB and 60 GHz multi-Gbps wireless communication design, 77 and 94 GHz radar and biomedical applications of wireless technology, in addition to advanced CMOS and SiGe. Brian served as a co-PI for the TEAM efforts at IBM.

Dave Harame. Dr. Harame is currently the Chief Technical Officer, RF Technology & Enablement, a Senior Fellow at GlobalFoundries. Prior to this position, he worked at IBM as the Chief Technical Officer, 200 mm Specialty Foundry. In this role, Dr. Harame led the development of the world's first successful SiGe technology generally available for analog and communications circuits used in wireless communications equipment, optical network interfaces, GPS and cellular telephones.

Alvin Joseph. Dr. Joseph is currently the Chief RF Technologist and a fellow at GlobalFoundries. Before his current role, he worked at IBM as a Senior Technical Staff Member and a Distinguished Engineer. There, he was the chief technologist and the lead client facing engineer for development of the two noteworthy RF front-end-module technologies- silicon germanium power amplifiers and silicon-on-Insulator RF switches.

Mike Lee. Mike is currently at Northrop Grumman, where he works as a Program Manager supervisor. Prior to this position, he served as the program manager of Northrop Grumman's efforts in several DARPA programs that followed TEAM, including HEALICS, ACT, CHIPS, and RF-FPGA.

Wolfgang Lehbrink. Wolfgang has worked at Infineon Technologies for the last 16 years. He served as a marketing manager for four years, then transitioned into his current role in product marketing for automotive radar.

Bernie Myerson. Bernie is an IBM Fellow and currently serves as IBM's Chief Innovation Officer. He also drives technical strategy and corporate initiatives within IBM's Corporate Strategy Organization. In 1980, Dr. Meyerson joined IBM Research, leading the development of high performance silicon:germanium communications technology. He founded and led IBM's highly successful Analog and Mixed Signal business until 2003, moving on to lead IBM's global semiconductor development alliances. Broadening his scope, in 2006 he assumed leadership of strategic alliances for the Systems and Technology Group. In 2010 he assumed the role of Chief Innovation Officer, his team focusing on the early identification of major technical and/or business discontinuities impacting business and society, their driving innovation across the breadth of IBM as required to proactively address the opportunities such discontinuities create. In 2013, his team was integrated into IBM's Corporate Strategy function, responsible for the definition and execution of corporate-wide technical and business initiatives.

Sasha Oster. Dr. Oster is the Senior Engineering Manager of the Directional Electromagnetic Systems team within the Advanced Technology Center at Rockwell Collins, located in Cedar Rapids, IA. Her team specializes in research and development of electronically steered arrays (ESAs) system up through millimeter-wave frequencies. Sasha's expertise is in millimeter-wave, RF, and photonic systems research and development. Previously, Sasha worked at Intel Corporation in advanced microelectronic packaging research, working on millimeter-wave, sensors, wearable, and silicon photonics. Sasha received her Ph.D. in Electrical Engineering from Iowa State University.

Dan Radack. Dr. Radack was a program manager in DARPA's Microelectronics Technology Office from 1997-2006, where he led a number of projects focused on microelectronic component innovation. One of his projects, TEAM, funded the development of SiGe BiCMOS processes that enabled the creation of systems-on-a-chip for silicon-based phased arrays. He is currently at the Institute for Defense Analyses.

Gabriel Rebeiz. Dr. Rebeiz is the *Wireless Communications Industry Chair* Professor of electrical and computer engineering at the University of California San Diego. Prior to this appointment, he was at the University of Michigan from 1988 to 2004. He received his Ph.D. from the California Institute of Technology. He has contributed to planar mmWave and THz antennas and imaging arrays from 1988-1996, and his group has optimized the dielectric-lens antennas, which is the most widely used antenna at mm-wave and THz frequencies. Prof. Rebeiz' group also developed 6-18 GHz and 40-50 GHz 8- and 16-element phased arrays on a single silicon chip, the first mm-wave silicon passive imager chip at 85-105 GHz, and the first silicon 100 GHz wafer-scale phased array. He is also an expert on millimeter-wave planar antennas, phased arrays, and satellite communication systems. He has worked on automotive radars at 24 GHz and 77 GHz since 1998 as a consultant and as a subcontractor to several leading phased-array and automotive radar companies. He was a performer on several relevant DARPA projects.

Dave Sobczak. Dave is currently the Director, A&D Program Management and Trusted Foundry at GlobalFoundries. Prior to this role, he worked at IBM for 18 years as a Project Manager and Manager, Aerospace & Defense Business and Trusted Foundry.

Rick Thompson. Rick has experience in developing advanced hardware and software products for the Department of Defense, medical, and commercial industries. He has specific expertise in advanced sensing technologies, including RF photonics and other advanced RF devices. From 2002 to 2013, Rick worked at BAE Systems as the Director of Spectral and Image Exploitation Technologies, where developed sensor exploitation sensors using RADAR, EO/IR, Hyperspectral, LADAR, and bio-electronics. BAE was a key Performer for the DARPA TEAM Program. He is currently the Director of Strategic Programs at Nuvotronics.

Alberto Valdes-Garcia. Dr. Valdes-Garcia is currently a Research Staff Member and Manager of the RF Circuits and Systems group at the IBM T.J. Watson Research Center. From 2006 to 2009, Dr. Valdes-Garcia served in the IEEE 802.15.3c 60GHz standardization committee. Since 2009 he has served as a Technical Advisory Board member with Semiconductor Research Corporation (SRC), where he was Chair of the Integrated Circuits and Systems Sciences Coordinating Committee in 2011 and 2012. IBM was a key performer in the DARPA TEAM Program.