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Journal

Technology and Culture, 59(2)

ISSN

0040-165X

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Publication Date

2018

DOI

10.1353/tech.2018.0029

Peer reviewed

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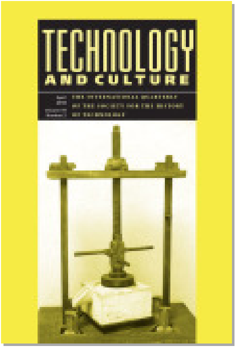

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Technology and Culture, Volume 59, Number 2, April 2018, pp. 251-288 (Article)

Published by Johns Hopkins University Press
DOI: *https://doi.org/10.1353/tech.2018.0029*

The FinFET Breakthrough and Networks of Innovation in the Semiconductor Industry, 1980–2005

Applying Digital Tools to the History of Technology*

DOUGLAS O'REAGAN and LEE FLEMING

ABSTRACT: The "FinFET" design for transistors, developed at the University of California, Berkeley, in the 1990s, represented a major leap forward in the semiconductor industry. Understanding its origins and importance requires deep knowledge of local factors, such as the relationships among the lab's principal investigators, students, staff, and the institution. It also requires understanding this lab within the broader network of relationships that comprise the semiconductor industry—a much more difficult task using traditional historical methods, due to the paucity of sources on industrial research. This article is simultaneously 1) a history of an impactful technology and its social context, 2) an experiment in using data tools and visualizations as a complement to archival and oral history sources, to clarify and explore these "big picture" dimensions, and 3) an introduction to specific data visualization tools that we hope will be useful to historians of technology more generally.

Douglas O'Reagan is a postdoctoral fellow in digital humanities at the Massachusetts Institute of Technology, having earned a Ph.D. in history from the University of California, Berkeley. Lee Fleming is director of the Coleman Fung Institute for Engineering Leadership at the University of California, Berkeley. He earned his Ph.D. in management science from the Stanford School of Engineering and was previously the Albert J. Weatherhead III Professor of Business Administration at the Harvard Business School. The authors would like to thank the interview subjects who provided invaluable insights; Guan-Cheng Li, whose technical expertise was fundamental to the project; the editor and anonymous referees for the paper, whose feedback has been tremendously useful; and the National Science Foundation, whose funding through grant 1360228, "Beyond Patent Citations as Measures of Innovative Search and Success," contributed to this project.

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*With all images in this article, please see the digital version for links to full-size, colored images for easier interpretation.

Introduction

The “FinFET” transistor emerged from a lab at the University of California, Berkeley, in the early 2000s and represented a dramatic improvement in semiconductor design. In essence, the technology added a third dimension to the standard two dimensions of the MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) and enabled an order-of-magnitude shrinkage in transistor size. This provided a major advance for a field predicated on packing ever-smaller transistors onto semiconductors, in turn allowing more computing power in a smaller physical space. The resulting patent, filed in October 2000 and granted in July 2003, has since been cited as prior art by 1,026 patents, placing it within the top 0.01 percent of most-cited patents from that year.[1] If earlier advances in semiconductor technology are any indication, FinFET technology will enable for some time the acceleration of electronics into everyday life, with unpredictable but dramatic implications for technology and society.

This sort of breakthrough technology is (by definition) rare, though hardly unprecedented in the semiconductor industry. Adherence to Moore’s Law—the proposition that the semiconductor industry will double the number of transistors in an integrated circuit every year (later revised to every two years)—is, in the words of one leading researcher, “an act of will.”[2] In its original formulation, Moore’s Law was simply an observation about the pace of technological change and economic growth in semiconductor manufacturing, but in order to meet the pace of change necessary to match its predictions, the U.S. semiconductor industry reshaped itself in the late 1980s through 2000s to fundamentally change its overall research structure, relationship with the government and military, strategy for exploiting university research, and ultimately its cutthroat, competitive, independent industrial culture.

Much has rightly been made of the importance of public-private research consortia for “pre-competitive research” that reshaped the U.S. semiconductor industry.[3] As leaders in U.S. industry saw themselves losing ground to Japan through the 1990s, they organized into trade groups and identified a few key challenges. Among these challenges were the great and

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[1] See https://www.google.com/patents/US6413802 for a list of these referencing patents. This many future citations makes it the forty-third most-cited patent in the 2002–03 year in any technology, out of about 330,000. The vast majority of patents are never cited by another. This figure of 1,026 future citations is as of May 2016.

[2] Chris Mack, “Using Learning Curve Theory to Redefine Moore’s Law,” 58. For more on Moore’s Law, see David Brock, ed., *Understanding Moore’s Law*; Arnold Thackray, David Brock, and Rachel Jones, *Moore’s Law*.

[3] See, for example, Larry D. Browning and Judy C. Shetler, *Sematech*; David P. Angel, *Restructuring for Innovation*; Robert R. Schaller, “Technological Innovation in the Semiconductor Industry.” Christophe Lécuyer tells a similar story of California’s public-private semiconductor research program, MICRO, in Lécuyer, “Semiconductor Innovation and Entrepreneurship at Three University of California Campuses.”

rising cost of research and development, the splintering of industry expertise through spin-offs and start-ups, and trade policy that allowed Japanese firms to dump products below cost on U.S. markets to gain market share.[4] These were issues the federal government was in a position to address, and this public-private collaboration helped break down the industry's distrust of government.

SEMATECH was one representative of a broader effort to develop networks of support for long-term research among academics, military funders, government trade policymakers, and industrial scientists and engineers. As illustrated below, private firms such as Intel, headed by Gordon Moore, led the advances in chip capacity and in meeting the predictions of Moore's Law, but they did so increasingly in collaboration with others. SEMATECH was one tool that these firms and the U.S. defense establishment hoped to use to manage the rising cost of research and development, by creating a common well of research. Industry and government planners also worked in the late 1980s and early 1990s to capitalize on the relative freedom of academic researchers from the short-term demands of industrial science. Individual universities lacked the capital for cutting-edge research equipment, but networks of academic centers, supplied with federal funds and direction from industry, were intended to circumvent these limitations.

The FinFET emerged from the center of one of these networks, and much of its success derived from the ability of its academic inventors to draw on federal support, physical and intellectual resources of nearby academic institutions, and close collaboration with industry. Networks are well known to influence the invention and diffusion of technology, and theoretical models like Actor-Network Theory can be useful in conceptualizing these influences. However, illustrating such networks can be challenging in practice. A historian interested in studying a breakthrough like FinFET might interview inventors, developers, and users; read trade publications, grant proposals, and press clippings; calculate economic importance; study the science associated with the technology; and compare technologies that unsuccessfully attempted to fill similar roles. The networks of power, prestige, money, institutional affiliations, and other social connec-

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[4] Finding data on employee mobility in this industry is difficult. Certainly employee entrepreneurship was common in the early semiconductor industry—see Ross Knox Bassett, *To the Digital Age*; Christophe Lécuyer and David C. Brock, *Makers of the Microchip*; Michael Riordan and Lillian Hoddeson, *Crystal Fire*. See also Paul Almeida and Bruce Kogut, "Localization of Knowledge and the Mobility of Engineers in Regional Networks"; Neus Palomeras, "Markets for Inventors." The best relevant data for the 1990s and 2000s seem to be in Bruce Fallick, Charles A. Fleischman, and James B. Rebitzer, "Job-Hopping in Silicon Valley." Palomeras, "Markets for Inventors," indicates that for IBM, the largest firm in the industry from 1970 to 1999, about 12 percent of inventors who filed a patent at IBM filed a patent with another company. Of those, the large majority went to start-ups. Thus, even with "high" rates of employee mobility, movement between established firms is not overwhelmingly common.

tions involved in its development would likely play a major role in understanding the origins and impact of the technology. Mapping out such networks using snowballing oral histories and archival research is possible, but extremely time consuming and laborious.

This article has two objectives: first, to better understand the origin of a fundamental breakthrough in transistor technology; and second, to illustrate how digital tools can aid research into the history of technology. It maps the changing structure of invention in the semiconductor industry—and the sources of the FinFET technology more specifically—by combining traditional methods with newer tools such as big data analysis and visualization.[5] In particular, we use and provide a tool that automatically maps inventor networks: http://fung-storage.coe.berkeley.edu/inventors. The tool generates social network diagrams of patent co-inventorship in real-time, enabling immediate and productive exploration and comparison of change over fields, organizations, and time—starting from any chosen inventor(s) or field of technology, for any period since 1976.[6] We also used or created digital tools to visualize other elements of patents (such as lexical similarity and patent citations) that allow new means of tracing intellectual heritage.[7] Such tools have their limits, and must be used at least

[5] The traditional structures for sharing academic knowledge (i.e., printed journals, even if now digitized) are a difficult fit for large-scale images and data sharing, and the history of technology has not had as much reason as some scientific fields to tackle challenges of presentation, archiving, and citation associated with large-scale data and visualization. We would like to thank the editors of *Technology and Culture* and the Johns Hopkins University Press for working with us to find innovative solutions, and thanks to reviewers for feedback on the greater or lesser success of initial efforts at presenting this material.

[6] The limit of 1976 is an unfortunate effect of that being the first year the United States Patent and Trademark Office (USPTO) began tabulating patent data in a form that has since been digitized. We use a publicly available database developed by the Fung Institute, which has improved on the USPTO's raw data considerably. Details are available at the "Tools and Data" page lined above.

[7] While not especially common in the history of science/technology or STS literature, patent citation analysis is a standard tool in econometric analysis of science, innovation, and business—largely because patents and citations have the great merit of being relatively easily quantifiable. Examples include Lee Fleming and Olav Sorenson, "Science as a Map in Technological Search"; Jeffrey L. Furman and Scott Stern, "Climbing atop the Shoulders of Giants"; Manuel Trajtenberg, "A Penny for Your Quotes." There has been more recent skepticism about what, exactly, is captured by patent citations, however. Often, patent examiners (who work for the USPTO) add citations, and inventors have disincentives to cite more than required, as it limits the patent's breadth. For more discussion of the merits of citation-based analysis, see Juan Alcácer and Michelle Gittelman, "Patent Citations as a Measure of Knowledge Flows"; Christopher Anthony Cotropia, Mark A. Lemley, and Bhaven N. Sampat, "Do Applicant Patent Citations Matter?"; Bronwyn H. Hall, Adam B. Jaffe, and Manuel Trajtenberg, "Market Value and Patent Citations." Differences in motivations between scientific peer-review writing and patent writing are discussed in Greg Myers, "From Discovery to Invention"; Kathryn Packer and Andrew Webster, "Inventing Boundaries"; Mark Peter Jones, "Entrepreneurial Science."

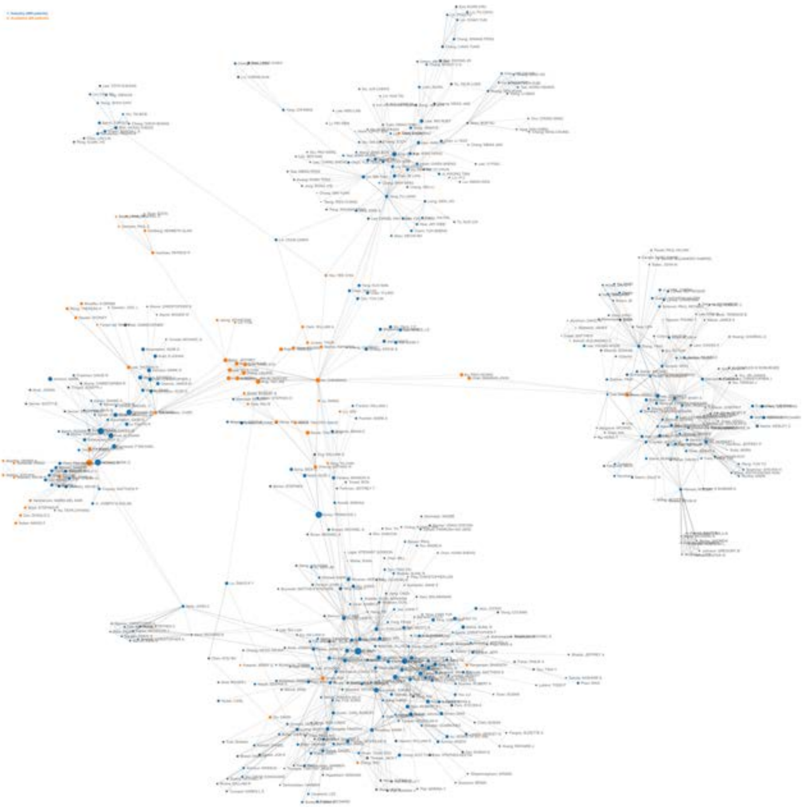

FIG. 1 Co-Inventor network of one of the FinFET inventors, Chenming Hu. As with all images in this article, please see the digital version for links to full-size, colored images for easier interpretation. Hu, at the center of this network, serves as a rare, university-based nexus point among primarily industrial clusters. In the digital version, orange dots are university-affiliated investors, blue are industry-affiliated, illustrating university inventors’ overall importance in bridging networks of otherwise-insular private firms. This was generated with the following parameters: inventor: Chenming Hu; patents applied for 1998–2002; to three generations of co-inventorship. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_1_Hu_1998_2002_3_gen_applied_univ.tif.)

as carefully and skeptically as any other historical evidence. Still, images like the following—which shows the FinFET inventors as rare nexus points among dense networks of private industry inventors—illustrate the potential for mapping scientists and inventors as knowledge brokers (fig. 1).

Digital tools are far from a panacea, and there is a real danger that the current hype for digital humanities will lead to a backlash that discourages their use among historians. We hope to model one possible middle path: creating digital tools that are simple enough to use so that they lower the investment cost for historians of technology to enter into this sort of research; but then using these as just one more set of tools in the historian's toolbox, combined with many others. Patent data has real limits, which we will discuss, but enables images of an industry on a scale otherwise largely impossible. Combined, qualitative research and "big data" analysis offer more than either can offer alone—more than the sum of their parts.

This is especially important in the study of industrial science and technology, where the vast majority of scientific research takes place, and yet which is far less thoroughly studied than academic science simply because industry researchers tend to leave behind fewer archival sources. Especially for technologies still in use, access to both oral histories and archives can be limited, as firms worry about revealing trade secrets.

The FinFET breakthrough emerged from the system imagined by early 1990s planners in the semiconductor industry: funded by the Defense Advanced Research Projects Agency (DARPA); using networks of universities with industrial support to allow long-term research too expensive for individual universities to afford; and dispersed into industry through close collaboration, movement of researchers with hands-on experience into and out of industry, and informal presentations. Although SEMATECH withdrew from federal funding in 1994, the FinFET story highlights the ongoing importance of these military-industrial-academic structures in the semiconductor industry through the 2000s. These connections were multidirectional, as the FinFET team (and UC Berkeley) benefited substantially from industrial guidance and direct aid, even as it developed a technology with great value for industry. The origins and impact of this technology lie in the intermediary position the academic inventors played between military funding and long-term industrial interests, and this social—and intellectual—position was one consciously constructed by industry leaders in response to perceived threats from Japanese industry. The technology itself was no "disrupter," breaking from existing models, but rather a continuation and recombination of earlier technologies. We will explore, for each of these aspects of the technology's history, the extent to which these digital tools and visualizations can contribute to historical understanding.

Invention in the Semiconductor Industry, 1980–2005

By the 1980s, Japanese semiconductor manufacturers increasingly threatened American market share. Japanese industry dumped devices on U.S. markets at below-market price, an issue partly addressed in a 1986 trade agreement between the two countries. Further, American electronics manufacturers found Japanese semiconductors more reliable and supported by better customer service.[8] By 1989, the trade surplus in semicon-

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[8] Angel, *Restructuring for Innovation*; Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin, "The 'Non-Globalization' of Innovation in the Semiconductor In-

ductor devices between the two nations favored Japan by $1.5 billion.[9] In response, the American semiconductor industry overcame a fiercely competitive industry culture and suspicion of government involvement to form SEMATECH, a public-private partnership sponsored in part by DARPA, in 1987.[10]

From the government's perspective, semiconductors were an important section of the U.S. economy, but an even more important resource in ensuring the U.S. military's technological superiority. If war broke out, reliance on foreign semiconductors would be as bad as reliance on foreign oil. For semiconductor manufacturers, government involvement reduced the very real threat of an antitrust-minded Justice Department taking apart this collaborative "pre-competitive research" unit. A trade agreement between the United States and Japan in 1986 intended to curb Japanese dumping had little immediate impact, but symbolized the possibilities of industry representatives lobbying as a group for government action.

If SEMATECH was the keystone of a move toward industry cooperation, it was neither the first nor only effort made. In 1982, an industry lobbying group called the Semiconductor Industry Association formed the Semiconductor Research Corporation (SRC), which sought to enlist universities as a site of long-term research, as well as a training ground for new researchers.[11] The same year, a group of executives formed the Microelec-tronics and Computer Technology Corporation (MCC), a research consortium aimed at improving American industry's competitiveness.[12] In 1994, the National Defense Authorization Act formed a Semiconductor Technology Council to advise the secretary of defense on semiconductor-related matters; it included representatives from both federal agencies and industry.[13] In its first report, this council cast both SEMATECH and the SRC as short-term thinkers, and argued that the government should be "moving the emphasis of its major

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dustry"; Schaller, "Technological Innovation in the Semiconductor Industry"; Board on Science, Technology, and Economic Policy, *Securing the Future*.

[9] Angel, *Restructuring for Innovation*, 1.

[10] This account of the early history of SEMATECH mostly follows Browning and Shetler, *Sematech*.

[11] In addition to the histories listed above, there are useful details in the book-length history of the industry written by SRC vice president and chief scientist Robert Burger, *Cooperative Research*.

[12] David Gibson and Everett Rogers, *R&D Collaboration on Trial*.

[13] Organizations represented from government: Department of Defense, Office of Science and Technology Policy, Department of Energy, Assistant to the President for Economic Policy, Department of Commerce, and National Science Foundation. From industry: Intel, KLA Instruments Corporation, Micron Semiconductor, AT&T Bell Labs, IBM, JS Kilby Co., Applied Materials, Inc., California Institute of Technology, Compaq, and Centigram Communications. The executive director came from the Defense Advanced Research Projects Agency (DARPA), and shifted to be a vice president at KLA Instruments in 1996. Semiconductor Technology Council, "First Annual Report," September 1996. Available at the Freedom of Information Act archive for DARPA, http://www.dod.mil/pubs/foi/Science_and_Technology/DARPA/.

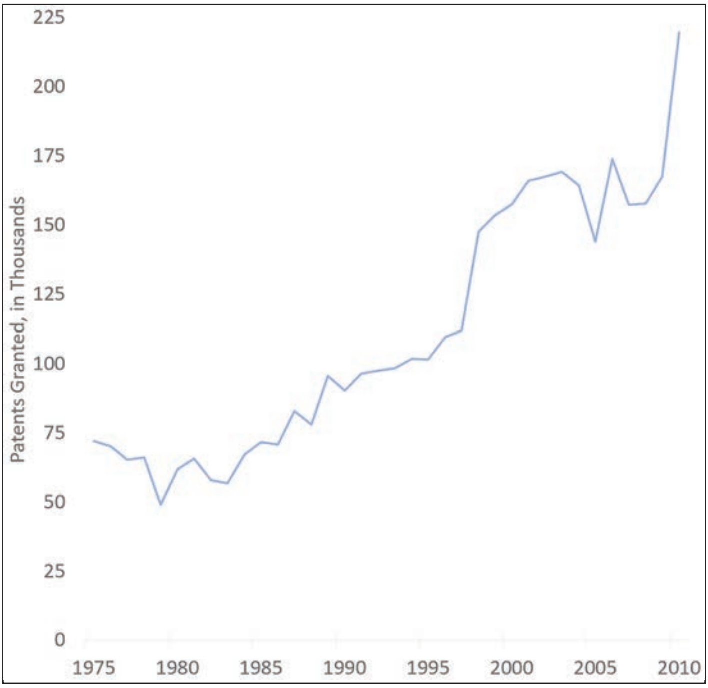

FIG. 2 Patents granted each year by the U.S. Patent and Trademark Office, 1975–2010. (Source: Data drawn from USPTO statistics, available at http://www.uspto.gov/web/offices/ac/ido/oeip/taf/us_stat.htm.)

semiconductor fabrication R&D investments away from infrastructure toward longer range research."[14] In April 1991, the White House Office of Science and Technology Policy sponsored a conference for semiconductor firms to think through a longer-term roadmap for the industry, which led to a National Technology Roadmap for Semiconductors. Every few years, similar roadmaps projected the following fifteen years, both projecting and promising technological advances through coordinated effort.[15]

These efforts, combined with a resurgent U.S. industry, stronger enforcement of patents in U.S. courts generally, and ongoing growth in importance of computing in society, led to an explosion in patenting in semiconductor technology in the 1990s. Patenting in America as a whole increased exponentially in this period, reflecting the shift in American law toward stricter protection of intellectual property[16] (fig. 2). Semiconductor

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[14] Semiconductor Technology Council, "First Annual Report," September 1996, available at the Freedom of Information Act archive for DARPA, http://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/DARPA/10-F-0709_Semiconductor_Technology_Council_First_Annual_Report_September1996.pdf.

[15] On the history of these roadmaps, see Schaller, "Technological Innovation in the Semiconductor Industry."

[16] The history and transnational shaping of intellectual property law remain areas

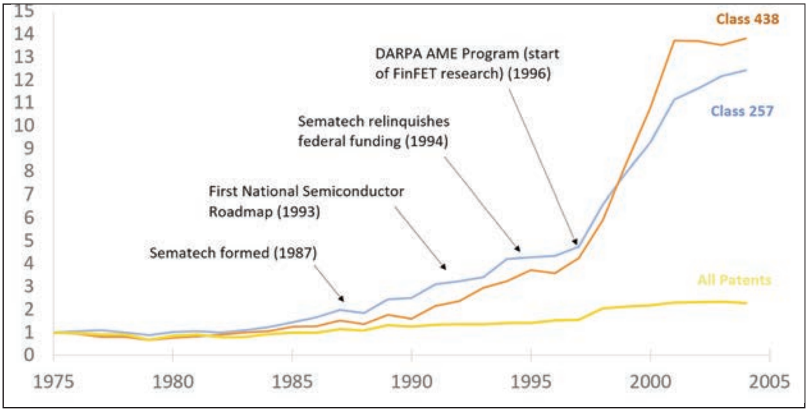

FIG. 3 Patenting in semiconductor classes vs. all technologies, 1975–2005. These technology classes are defined as follows: 438 ("semiconductor device manufacturing: process"), defined at http://www.uspto.gov/web/patents/classification/uspc438/defs438.htm; and 257 ("active solid-state devices [for example, transistors, solid-state diodes]"), http://www.uspto.gov/web/patents/classification/uspc257/defs257.htm.

patenting increased even faster than this exponential overall growth. In two patent technology classes that together represent most of the industry (patents for semiconductor devices, and patents for methods of manufacturing these devices), the number of patents granted in 2005 was about fifteen times as many as in 1975, compared to about twice as many overall patents being granted (fig. 3).

As semiconductor patenting increased in the 1990s, so too did the percentage of these patents that were both generated by universities and within the top 1 percent of most-cited electronics patents in their year[17] (fig. 4). However important other research institutions (such as Bell Labs or IBM) were for the industry, university-generated patents were increasingly influential in the 1990s to early 2000s period. This is consistent with the national reports and efforts in the 1990s to fund collaborative research between academia and industry. Unfortunately, the full causation for this

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where legal and STS scholars and historians of technology would benefit from much more active engagement and collaboration. Notable exceptions include: Mario Biagioli, Peter Jaszi, and Martha Woodmansee, eds., *Making and Unmaking Intellectual Property*; Sally Smith Hughes, "Making Dollars out of DNA"; Christine MacLeod, "Reluctant Entrepreneurs"; Alex Wellerstein, "Patenting the Bomb." On the history of U.S. patent law in the twentieth century, see Alain Pottage and Brad Sherman, *Figures of Invention*; Christopher May and Susan K. Sell, *Intellectual Property Rights*; Susan K. Sell, *Private Power, Public Law*; Wyatt Wells, *Antitrust and the Formation of the Postwar World.*

[17] For a discussion of the NBER U.S. Patent Citations data and the categories it has been broken down into (such as electronics, which includes semiconductors), see http://www.nber.org/patents/; and especially Hall, Jaffe, and Trajtenberg, "The NBER Patent Citations Data File."

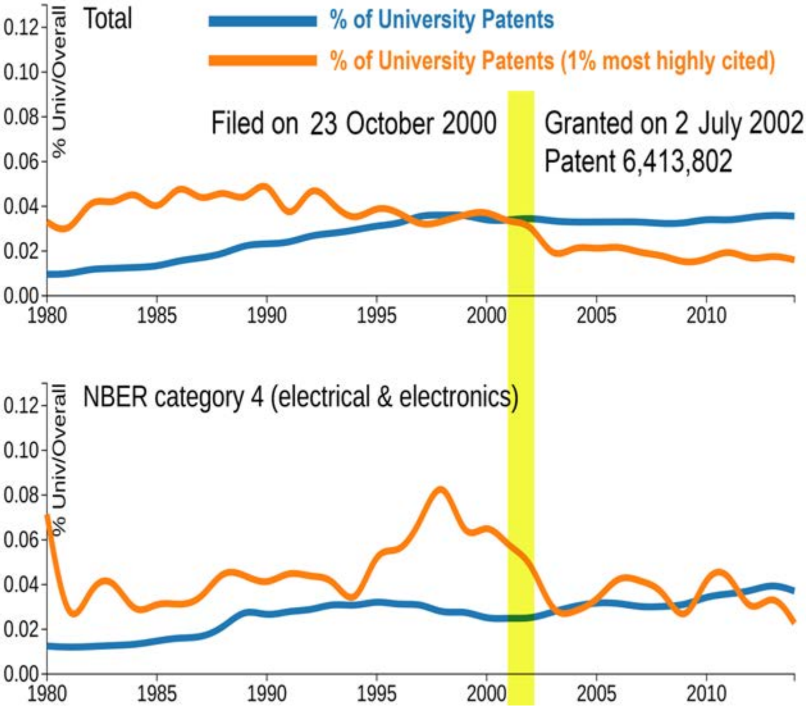

FIG. 4 Percentages of patents and highly cited patents generated by universities, as proportion of all patents in that year. Uses NBER categories. The yellow shading shows the years between which the FinFET patent was filed and then granted.

sharp uptick in semiconductor patenting—and university patents and breakthroughs in semiconductors rising so sharply in relative citation—remains beyond the scope of this article. However, increasing investment in research and development (correlated with the increase in patenting) pushed American firms—and eventually international firms—to band together into research consortia from the late 1980s on.[18]

Much of the investment went into finding successive improvements on a decades-old technology: the metal-oxide-semiconductor (MOS) transistor. MOS technology took an improbable path to being the dominant industry technology, widely dismissed in the 1960s as inferior in all relevant respects to alternatives like the bipolar gallium-arsenide transistor.[19]

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[18] On the development of collaboration with international industry, including an International Technology Roadmap for Semiconductors to replace National Semiconductor Roadmaps, see Schaller, “Technological Innovation in the Semiconductor Industry.” On motivations behind SEMATECH, see Browning and Shetler, *Sematech*.

[19] This summary draws on Bassett, *To the Digital Age,* as well as Angel, *Restructuring for Innovation*; Richard W. Ahrons, “Industrial Research in Microcircuitry at RCA”; David A. Laws and Michael Riordan, “Making Micrologic.”

By 1975, it became more than a niche technology useful in supercomputing, led by shifts in the electronics industry toward high-speed, low-power integrated circuits. MOS transistors could scale well, unlike gallium-arsenide transistors, and so they were a better fit for handheld calculators, electronic watches, and other consumer and military uses. Incremental advances in MOS technology through the 1980s and early 1990s (both theoretical advances and manufacturing technologies) allowed more and more transistors to fit on a silicon chip, fulfilling the near-term goals of the industry roadmaps.

The standard MOS design could not be extended indefinitely however, and this led to growing concern among industry leaders who were coming to depend on the advances Moore had observed in 1965. Predictions such as "Beyond 2004, we will have no new [silicon-based] devices," attributed to a researcher at Fujitsu in a front-page *Wall Street Journal* article in 1996, existed in trade journals as well as newspapers.[20] However much might be spent on industry R&D, MOS designs could not just shrink forever, as shorter and shorter "gate lengths" (the relevant metric for measuring the overall size) made it progressively harder for the gate to "pinch off" the flow of electricity. Eventually, they would reach an endpoint when it would be physically impossible. Even before then, the problem's difficulty would escalate quickly.

As useful as these national and international R&D consortia like SEMATECH and MCC were at coordinating and supporting research and development, they were part of an ongoing investment in infrastructure to support improvement of MOS technology. Any move away from MOS would come at tremendous cost, as it would require completely restructuring the industry's manufacturing methods, equipment, and training. Randall Isaac, vice president of IBM's research division, commented in January 1997 that for these reasons, "It is unlikely that the present worldwide semiconductor infrastructure will be regenerated to support a technology successor."[21] In much the same way historians of economics and technology have discussed "path dependence" constraining other large technological systems, the same networks that had come to support the semiconductor industry's continued innovation equally limited the paths of that innovation.[22]

All of this matters for the history of the FinFET transistor because its success can only be understood in the context of this industry's recent history. At the time of its development, American firms had come to recognize the value of networks of support for pre-competitive research, yet

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[20] David P. Hamilton and Dean Takahashi, "Silicon Slowdown."

[21] Randall Isaac, "Beyond Silicon . . . and Back Again."

[22] The literature on path dependence and technological system is extensive, but a good starting point is the essays in Wiebe E. Bijker et al., *The Social Construction of Technological Systems.*

such institutions were still tentative, both emerging and restructuring in the 1990s. The FinFET inventors sat at a crucial nexus point in this industry, a rare connection among various firms, academic institutions, and government support structures. These networks of innovation are difficult to describe purely in prose, so we combine data visualization tools with oral histories and archival sources.

History of the FinFET (Multi-Gate) Transistor

Given the George H. W. Bush administration's curtailment of DARPA funding for semiconductor research in the early 1990s, SEMATECH's voluntary withdrawal from public funding in 1994, and the resurgence of American industry in world markets in the late 1980s and first half of the 1990s, one might expect the next major semiconductor breakthrough to emerge from American industrial research, rather than directly from a defense program. The FinFET breakthrough of the late 1990s, however, was very much a product of the industrial planning and military-industrial-academic institutions of the late 1980s. Part of its inspiration (and one of the lab's researchers) came from Japanese industrial research; it emerged from a DARPA program that primarily targeted universities; and as government-industry commissions like the National Advisory Committee on Semiconductors had planned years earlier, it came from collaborative university-based research.

The 1998 International Technology Roadmap for Semiconductors, created by the World Semiconductor Council, projected technologies for the years 1999 to 2014.[23] At the time of that report, the most far-reaching ongoing research targeted transistor with a gate length of 130 nanometers (nm) by 2002, as opposed to the 1998 state-of-the-art of about 250 nanometers. Beyond 2002, there were no known solutions being pursued—even in lab settings—for the ever-more-ambitious targets, including the far-off target of a 35 nm gate fifteen years in the future (2014).

In this context, the DARPA Advanced Microelectronics (AME) program's 1997 call for proposals for research on sub-25 nm devices was tremendously ambitious, and intentionally so. The program chief for the AME program, Fabian Pease, had been a researcher in semiconductor physics at Stanford University, and was well aware of projections that the field would eventually need to abandon MOS designs altogether. Pease had two goals in requesting research plans targeting what industry planners envisioned only being feasible more than twenty years in the future: first, to make progress beyond the limits of industry's near-future innovation,

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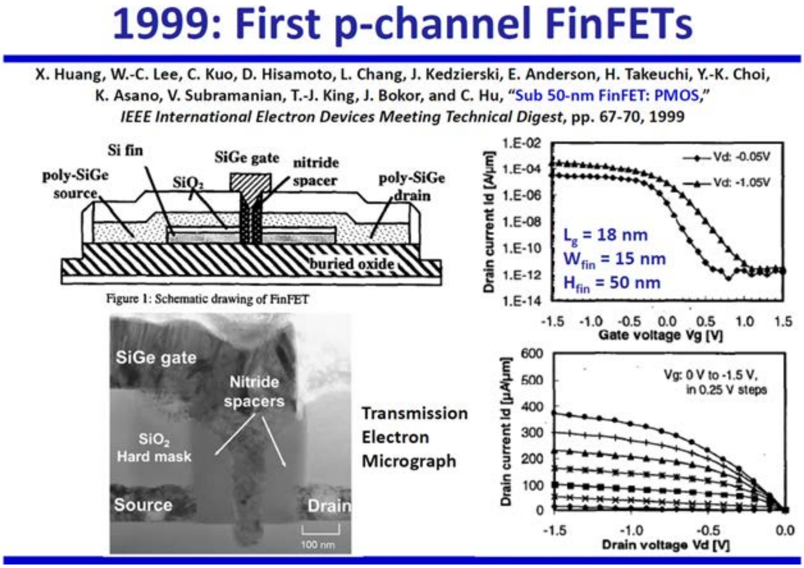
[23] The World Semiconductor Council was a successor to the U.S.-based Semiconductor Industry Association's roadmaps, revised to include Japanese, South Korean, and European manufacturers in discussions and projections, now that the U.S. government funding no longer required exclusively American participation and benefit.



1999: First p-channel FinFETs

X. Huang, W.-C. Lee, C. Kuo, D. Hisamoto, L. Chang, J. Kedzierski, E. Anderson, H. Takeuchi, Y.-K. Choi, K. Asano, V. Subramanian, T.-J. King, J. Bokor, and C. Hu, "Sub 50-nm FinFET: PMOS," *IEEE International Electron Devices Meeting Technical Digest*, pp. 67-70, 1999

Figure 1: Schematic drawing of FinFET

Transmission Electron Micrograph

FIG. 5 Presentation slide by Tsu-Jae King-Liu, one of three chief inventors of the FinFET. (Source: "FinFET: History, Fundamentals and Future," Power-Point presentation given on 11 June 2012.)

per DARPA's mandate for long-term defense (and industrial) technology; and second, more generally, to see from the proposals whether "whiz-bang physics" devices were the next phase, as no one could imagine paths that would extend the life of MOSFET.[24] The response to the latter consideration was definitive: of the ten to twelve proposals submitted, all were scaled MOS transistor designs. Applicants included IBM, AT&T, Stanford, MIT's Lincoln Labs, and Notre Dame.

The most thorough of the proposals DARPA received, in Pease's recollection, came from researchers at the University of California, Berkeley. "Novel Fabrication, Device Structures, and the Physics of 25 nm FETs for Terabit-Scale Electronics" proposed two solutions, one of which was to build essentially a three-dimensional version of the standard planar MOSFET design (fig. 5). There are multiple viewpoints on the intellectual origins of the FinFET design. The concept of expanding the two-dimensional MOSFET design into the third dimension, wrapping a gate around the path, existed as early as 1990 in a paper published by Digh Hisamoto, a researcher at Hitachi.[25] It built on an even earlier proposal for a "trench transistor" studied by Texas Instruments in the mid-1980s.[26] The paper received substantial attention within the community of MOSFET research-

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[24] Interview with R. Fabian Pease.

[25] Digh Hisamoto et al., "A Fully Depleted Lean-Channel Transistor (DELTA)."

[26] Digh Hisamoto, email message to authors.

ers, and several of the FinFET research team members attributed the basic idea for this innovation to Hisamoto.[27]

There is, of course, a large difference between having an idea and developing a functional technology, and in any event, the head of Berkeley's research team, Chenming Hu, recalls an invention process that did not rely on Japanese corporate research. Once he had been approached about the DARPA program by Jeffrey Bokor (a colleague in the Department of Electrical Engineering, who had heard of the DARPA program while windsurfing with its director, Fabian Pease), Hu sketched out possible sub-25 nm transistor ideas on a legal pad during a long flight. One of these ideas was a fin-shaped field-effect transistor (hence the nickname "FinFET").[28] Joining with fellow Berkeley faculty Tsu Jae King (later Tsu Jae King Liu) and Jeffrey Bokor, Hu typed up his proposal and sent it off to Pease at DARPA.

Another way to establish the technology's intellectual origins—and its indebtedness to defense investment at various levels—is to chart the FinFET patent's backward citations (that is, patents it cited as prior art; the ones they cited; and so on)[29] (fig. 6). The different colors in this image represent different organizations responsible for the cited patents, and so the variety of colors points to the FinFET team drawing on a wide variety of embedded networks. As university researchers, the FinFET team members were not limited by a corporation's interest in citing only their own patents (in order to strengthen the company's intellectual property), nor by the limitations of working solely with one company's researchers. They were, however, deeply indebted to government (and especially military) sponsorship, even beyond the funding they themselves received. Using an automated program we have developed that identifies patents that explicitly cite government support, 6 percent of these patents on which FinFET builds explicitly acknowledge funding from government (mostly military) grants, compared with only 2.19 percent of all patents since 2001 that similarly acknowledge government aid.[30]

FinFET was not just the product of Hu, Bokor, and King (a point they

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[27] Interview with Tsu-Jae King Liu and Jeffrey Bokor; interview with Jeffery Bokor.

[28] Interview with Chenming Hu.

[29] We intend to make available to the public a tool to generate patent citation diagrams similar to this one, though more work will be necessary to make the resulting visualizations as clean and uncluttered as possible without manual tweaking.

[30] These statistics draw from forthcoming research that analyzes the language of all patents in the database (hence, since 1975) to find acknowledgements of government support. It then extracts from the acknowledgement the specific government agency (and when possible, grant numbers). The 2.19 percent figure represents 70,512 patents citing government aid between 2001 and 2014, out of a total of 3,225,075 patents filed in that window. 1.9 percent of patents in semiconductor patent classes cite government support in this window. This smaller number, of course, does not negate the importance of government aid in "pre-competitive" research that might not be acknowledged in the later stages of research on patentable technologies, but it does indicate that government aid in this sector primarily focused on this early research.

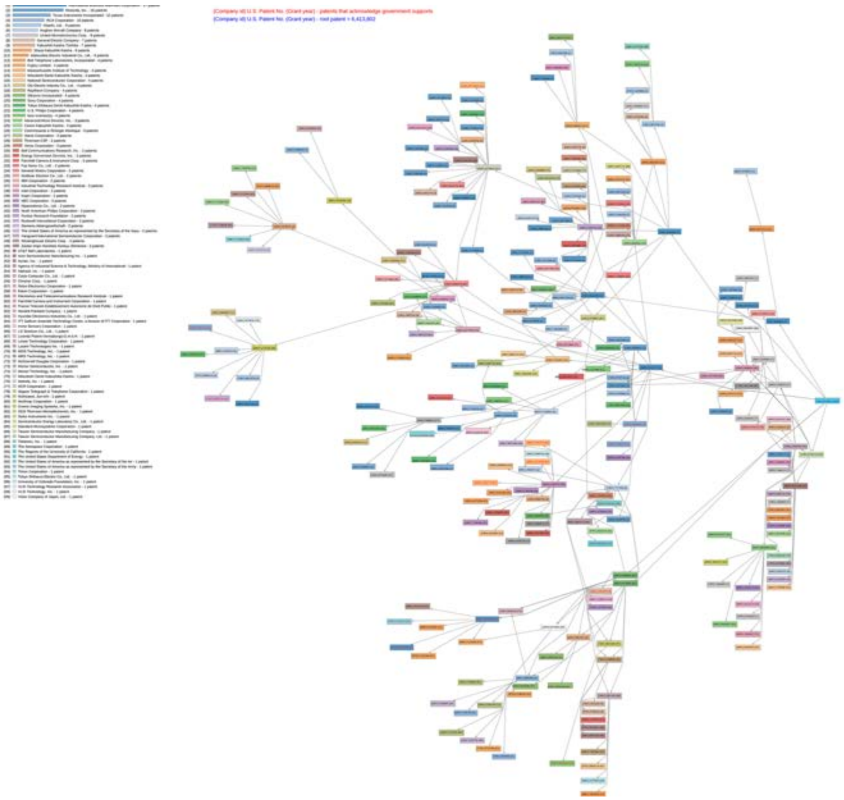

FIG. 6 Prior art citation map for patent 6413802, “Finfet transistor structures having a double gate channel extending vertically from a substrate and methods of manufacture,” up to three generations back, serving as a sort of family tree for the patent. As different shading (or coloring in digital version) illustrates, the FinFET patent drew from a diverse array of both university- and industry-assigned patents. The FinFET patent is on the far right, in light blue. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_6_FinFET_citation_map.tif.)

themselves made repeatedly in interviews). The research to design and manufacture a working FinFET transistor spanned 1996 to 1998, during which at least eighteen graduate students, postdocs, and visitors from industry made significant contributions, from more theoretical work to specific hands-on expertise, such as the lithography crucial to the fabrication process. Ideas and people flowed in across borders as well as between industry and academia. While there is not space to detail the contributions of each graduate student and postdoc, as well as the lab staff, grant officers, and other workers involved directly or indirectly with the project, a few examples might illustrate these contributions. Digh Hisamoto joined the research team shortly after the initial proposal to DARPA, on leave from Hitachi. He and the Fin-

FET team members all describe this timing as a fortunate coincidence, and he contributed both to conception and fabrication of the test devices.[31] Several of the lab's graduate students and postdocs ended up in the semiconductor industry both in Silicon Valley and outside the United States. For example, Vivek Subramanian, a postdoc on the team, moved between industry and academia, spending part of his time at Berkeley and part at Matrix, a memory company eventually acquired by SanDisk.[32] Access to equipment and technical expertise at Stanford and Lawrence Berkeley National Laboratory also played key roles.

Interviews we conducted with the FinFET teams, the DARPA administrators associated with the program, and other researchers in the industry at that time indicate that other factors contributed to FinFET's subsequent success, including an unusual combination of academic freedom to pursue long-term research (as opposed to short-term needs of industry); the ability to draw on research equipment and funding of nearby research facilities (Stanford and Lawrence Berkeley National Lab among them); and substantial connections to industry that would facilitate the flow of information, including tacit knowledge.

To explore at least one of these networks and paths for knowledge diffusion, we developed the Patent Co-Inventor Social Network Tool, available at http://fung-storage.coe.berkeley.edu/inventors/. This tool starts from a given set of inventors who have filed patents in the United States Patent and Trademark Office (USPTO), then finds anyone with whom they have co-invented (that is, both are listed as inventors on the same patent) in any chosen time frame since 1975. It then repeats this process, finding the co-inventors' co-inventors, and again out to any desired degree of co-inventorship. It maps out these co-inventor relationships as social network diagrams, illustrating the connections among inventors. Since the diagrams render nearly instantly, users can generate multiple images to explore change in networks across time, differences between industries, and other aspects of technology and society.

As a "normal" case, we might see images such as the following, starting from two prolific inventors at IBM working in the semiconductor industry, who at the time were leading IBM's contribution to the DARPA AME program (figs. 7 and 8). In fact these inventors are far from normal, as they both filed many influential patents over the course of very successful careers.[33] Still, we can see that out to three degrees of co-inventorship, the vast majority of those with whom they were connected were affiliated with one institution: IBM. In contrast, the FinFET team served as the nexus

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[31] Interviews with Hisamoto and Hu, noted above.

[32] Interview with Vivek Subramanian.

[33] The large majority of patenting inventors receive only one patent, and the vast majority of patents are never cited by another patent. J. Singh and L. Fleming, "Lone Inventors as Sources of Technological Breakthroughs."

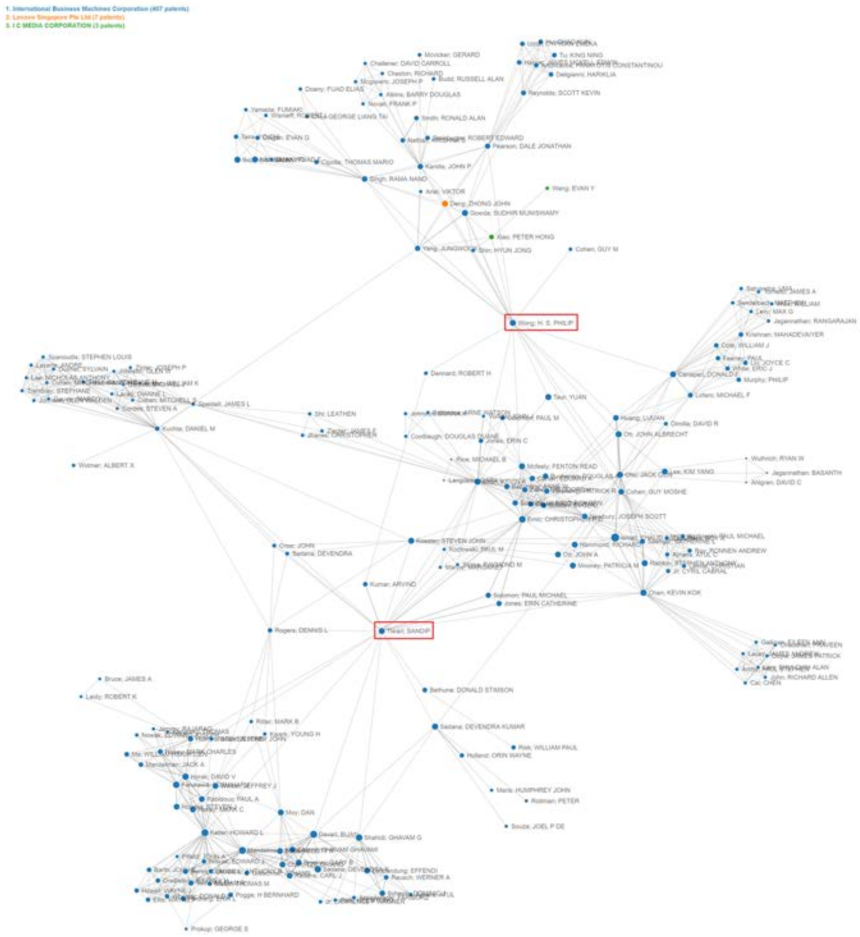

FIG. 7 Co-invention network diagram for the project leads for IBM’s contribution to the DARPA AME program, for patents granted 1998–2001. Above, networks to two generations of co-inventorship. The inventors, Sandip Tiwari and HS Philip Wong, are highlighted in boxes. Despite being prolific, influential inventors, their networks remain largely within IBM (colored blue in full-size, digital version). (Click images for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_7_IBM_1998-2001_2gen_applied.tif.)

point among many sub-networks, connected in part by the lab’s students and principal investigators (PIs) moving into and out of industry, facilitating the flow of tacit knowledge[34] (figs. 9 and 10). As these images illustrate,

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[34] This “industry-academy” view is an option for all visualizations made using the Patent Co-Inventor Network Visualization Tool. It defines “academia-affiliated” as anyone who has invented a patent that was assigned to a university, college, or board of rectors, as stipulated under the Bayh-Dole Act of 1980.

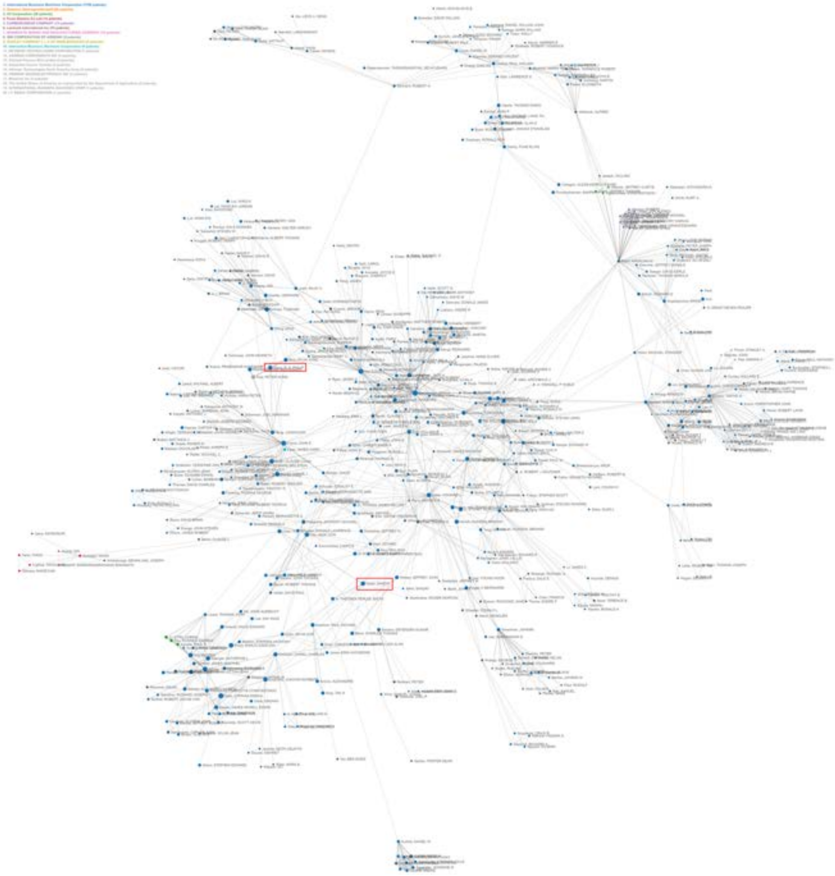

FIG. 8 Co-invention network diagrams for the project leads for IBM's contribution to the DARPA AME program, for patents granted 1998–2001. Above, three generations of co-inventorship. The inventors, Sandip Tiwari and HS Philip Wong, are highlighted in boxes. Despite being prolific, influential inventors, their networks remain largely within IBM (colored blue in full-size, digital version). (Click images for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_8_IBM_1998-2001_3gen_granted.tif.)

this team served as one of the few connections among major firms, including IBM, AMD, Micron, and Intel. Intel aggressively pursued this technology, inviting the FinFET team to present at their campuses multiple times in the early 2000s.

Figure 10 represents a variation on the tool's diagrams, coloring the inventors not by their company or university affiliations, but rather by whether they had filed patents on behalf of universities—thus, illustrating academic-industrial linkages. Here, the FinFET team is at the center of the industry networks, but notably not the only university-affiliated inventors at nexus

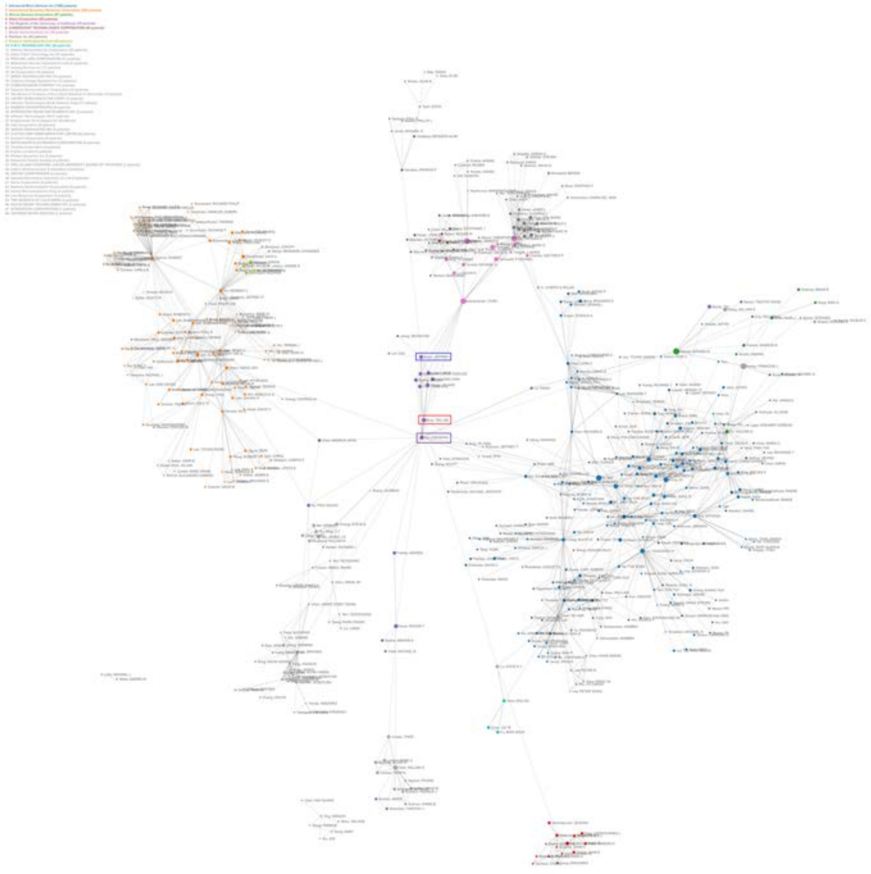

FIG. 9 Co-Inventor network of FinFET PIs, patents applied for 1996–2001, to three generations of co-inventorship. These inventors are in boxes in the center, and are rare bridges among a wide array of different private firms and universities (each colored differently in full-size, digital version). (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_9_UCB_1996-2001_applied_3gen.tif.)

points within these diverse industrial sub-networks. Academia was, as devised by the Semiconductor Industry Association and other 1980s planners, building bridges among otherwise disconnected industrial research teams.

The central, brokerage position of the FinFET team between these other networks in this period serves as a broad-scale demonstration of the research team’s varied networks: their prior experience in industry, visits from industry researchers like Hisamoto, and later movement of grad students, postdocs, and even the PIs themselves into industry positions. These interconnections, in turn, emphasize a point made by Christophe Lécuyer about the University of California’s connections to the semiconductor in-

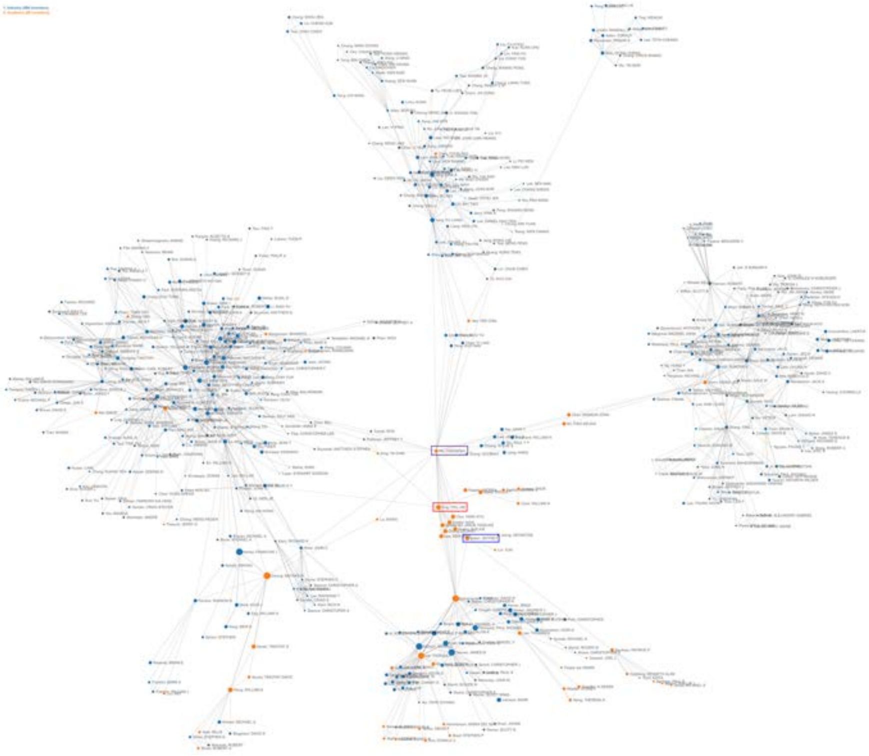

FIG. 10 Co-Inventor network of one of the FinFET inventors, Chenming Hu. Hu, at the center of this network in a box (as are the other FinFET inventors), serves as a rare, university-based nexus point among primarily industrial clusters. In the digital version, orange dots are university-affiliated investors, blue are industry-affiliated. This was generated with the following parameters: inventor: Chenming Hu; patents applied for 1998–2002; to three generations of co-inventorship. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_10_hu_1998-2002_3gen_applied.tif.)

dustry in prior decades: that industry knowledge flowed into academia as much as the opposite.[35] It also fits with quantitative research on the importance of these “knowledge brokers” in promoting creativity and innovation in social networks of inventors.[36]

One of the key advantages of FinFET was that for all the manufacturing challenges it represented—moving to three-dimensional design on a mass scale was no small feat—it remained fundamentally a MOS transistor technology. It was successful at drawing interest from industry and sup-

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[35] Lécuyer, “Semiconductor Innovation and Entrepreneurship at Three University of California Campuses.”

[36] Lee Fleming, Charles King III, and Adam I. Juda, “Small Worlds and Regional Innovation.”

port from DARPA because it was not too disruptive of existing industry, and that industry's accumulated physical and intellectual capital. Here, too, the deep interconnection with industry illustrated in figures 9 and 10 likely played a role, keeping focus on what industry wanted and helping create the coalition of support for a technology that was necessary to move from idea to industrial reality. Even this much innovation was a challenge to digest, and it was 2011 before Intel announced that it was sufficiently comfortable with the FinFET (and had exhausted existing technologies sufficiently) that it was moving toward 3-D transistors as an active technology. That same year, the industry's risk-averse nature informed a *New York Times* article that described FinFET as a "controversial technology within the chip industry," with "a number of the company's competitors say[ing] they believe Intel is taking what could be a disastrous multibillion-dollar gamble on an unproved technology."[37] A technology further from the mainstream, or less capable of close, sustained work at integrating it into industry planning, would surely have been seen as even more of an unacceptable risk.

Of course, this brokerage role was itself something that evolved over time. As figure 11 illustrates, in the years leading up to the FinFET project, its principal investigators brokered connections to various networks on which they could draw. In the years following the breakthrough, the network grew in around them (figs. 11 and 12). Partly this reflects the movement of the team's postdocs, grad students, visiting industry researchers, and even principal investigators into new industry positions following the breakthrough, and thereby forging new connections. Chenming Hu took a leave from UC Berkeley to serve as chief technology officer of Taiwan Semiconductor Manufacturing Company (TSMC) from 2001–04, and he maintains that the TSMC board likely did not even know about FinFET when making that hiring decision.[38] These TSMC connections represent the light blue cluster that dominates the center of the "after" image. Still, even without TSMC, the principal investigators' increased centrality in the field, and extensive connections to the industry relative to "before" are obvious.

Visualizing the Semiconductor Industry: Limits and Experiments

There are real limits to what historical patent data can tell us. In very practical terms, even with cutting-edge equipment supporting a highly developed patent database, drawing network diagrams including the thou-

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[37] John Markoff, "Intel Increases Transistor Speed by Building Upwards."

[38] Interview with Hu. However, TSMC is one of the few firms internationally that has patented in FinFET technology subsequently, whatever Hu's involvement. That list includes (in order from most to fewer patents with "FinFET" in the patents' abstracts) IBM, TSMC, AMD, Samsung, Global Foundries, Micron, Infineon, Freescale Semiconductor, and Toshiba.

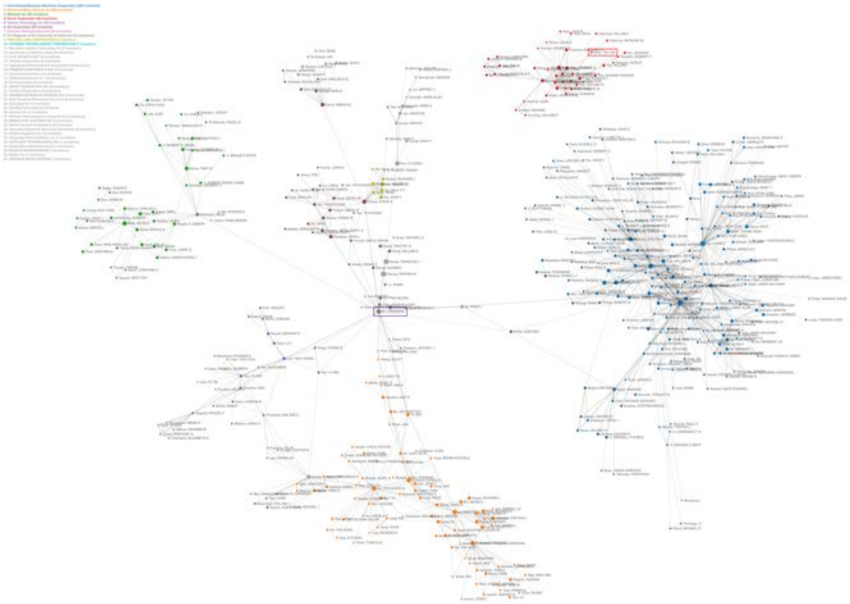

FIG. 11 Before: all FinFET PIs out to three generations of co-inventorship, 1996–2001 (the five years preceding the FinFET patent). Chenming Hu is highlighted in the left-most box (purple in the digital version). Tsu-Jae King is in an unconnected, smaller network to the top-right (red box in the digital version). Jeffrey Bokor did not have patents granted prior to 2001. Compare to figure 12 to see the greatly expanded, integrated networks built since the breakthrough FinFET patent. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_11_UCB_1996-2001_granted_3gen.tif.)

sands of inventors active in some fields and time frames would be overwhelming. The resulting diagrams can quickly become a hairball—difficult to see on computer screens, impossible to print, and impossible to interpret meaningfully. Cutting down on the data, on the other hand, undermines the chief strength of using this sort of systematic data in the first place; it gives an otherwise inaccessible "big picture" to complement the human-level detail only attainable through other sources.

We have argued that the FinFET principal investigators' brokerage roles, bridging otherwise rarely interconnected sub-networks (usually representing individual firms), were important in building the alliances necessary to move from concept to industrial production. As such, it would be desirable to show a full picture of the industry, to illustrate the relative rarity of such links between sub-networks. There were too many inventors involved in the semiconductor industry for us to include them all in any one image, even in a given year (at least after the exponential growth took off in the 1990s). One option is to limit to one technology sub-class, as illus-

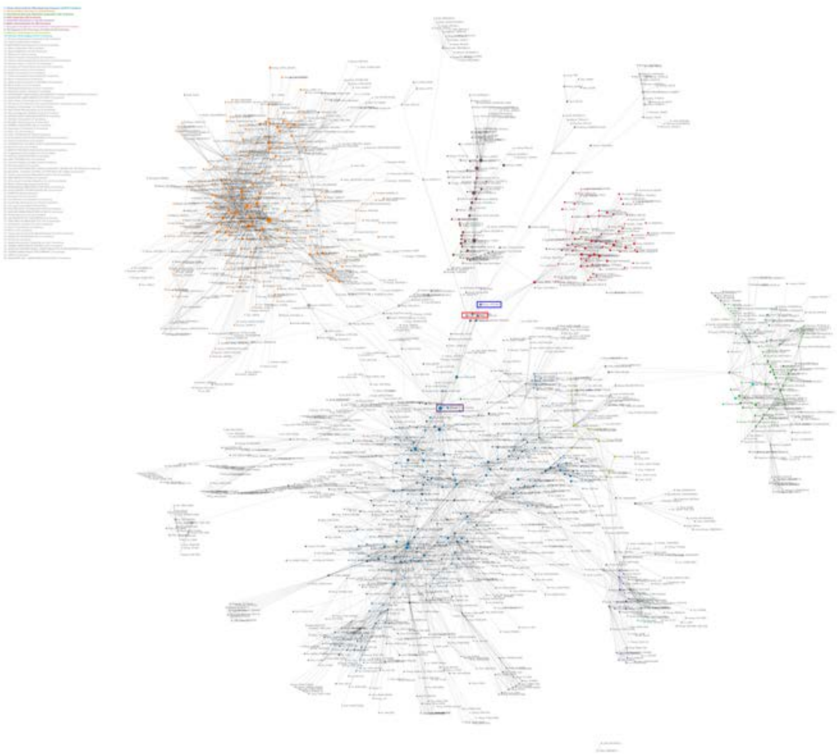

FIG. 12 After: same settings as figure 11, but 2001 to 2006 (five years since FinFET published). The FinFET inventors are highlighted in boxes (in the digital version, Chenming Hu is in purple, Tsu-Jae King in red, and Jeffrey Bokor in blue). Compared to figure 11, note the vastly expanded networks in which the inventors operated. As the full-size, digital version’s coloring and legend best show, these networks also represented far more firms. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_12_UCB_2001_2006_3_gen.tif.)

trated in this linked image.[39] However, sub-classes can change over time for reasons internal to USPTO bureaucracy. Another option is to choose a smaller sample of patents to represent the whole. To test this, we built an option into the Patent Co-Inventor Network Visualization Tool to start from 120 random patents granted by the USPTO in a given year for which a patent examiner assigned a particular technology class. It finds the inventors on these patents, their co-inventors, and co-inventors’ co-inventors.

[39] This image shows all inventors who filed a patent that was later classified into class 438 (Semiconductor Device Manufacturing: Process), sub-class 283 (Including Passive Device, e.g. Resistor, Capacitor, etc.), between 1998 and 2000. Image URL: http://fung-storage.coe.berkeley.edu/inventors/images/finfet/uspto_class_438_283_1998_to_2000_2_gen.tif.

The hope is that expanding outward far enough from random starting points (and repeating several times to check that each iteration seems roughly similar) will characterize the industry. The following, based on Class 438—"Semiconductor Device Manufacturing: Process," represents an attempt to visualize the evolution of the semiconductor industry as a whole over time.[40]

The images representing 1980 through about 1995 are fairly undramatic, as the scale of patenting in the system grew steadily and American firms slowly became better represented in the list of most-patenting organizations. Japanese firms (e.g., Hitachi, Canon, and Toshiba), which dominate the top of this list through the 1990s, begin to give way to American firms (IBM, AMD, and Micron). Intra-firm patenting (which represents either joint patenting by inventors from different firms/universities, or more likely, the movement of personnel among firms, bringing with them tacit knowledge and trade secrets) is very rare, and when present, seems far more common for Japanese inventors/firms than their American counterparts.

The later images show much larger sub-networks (i.e., total number of inventors patenting within each firm), and relatively more frequent connection among firms. To some degree, this increased connectivity is a normal feature for any social network with more members.[41] Still, even in these sprawling post-2000 networks, connections among sub-networks remain relatively rare, indicating limited movement of researchers among major firms (as opposed to splitting into smaller start-ups more likely missed by random sampling), and thus a limited flow of technology through the extremely important mechanism of movement of tacit knowledge and trade skills.[42] This remains true even if we increase the period

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[40] The compromise used here—sampling 10 patents per month (120 per year) as starting points—certainly adds some randomness to the visualizations. We mapped each year multiple times and over various amounts of patents sampled, until we found a sample size that would consistently produce results reflecting the top patenting firms in this class and year. We have included a link to an alternate version of the 2000 visualization so readers can compare. The tool also supports mapping entire patent sub-classes, such as the linked image of all patents in sub-class 438.283 from 1998 to 2000, for a different way to combine thoroughness with manageable data size for visualization.

[41] Fleming, King III, and Juda, "Small Worlds and Regional Innovation"; Brian Uzzi, Luis A. N. Amaral, and Felix Reed-Tsochas, "Small-World Networks and Management Science Research."

[42] On the issue of technology transfer, it is of course possible for technology to flow without inventors switching jobs. Yet a substantial literature in both the history of technology and in business studies has demonstrated that patent licensing, journals, and other formal mechanisms for communicating knowledge are severely limited without the movement of people. See, for example, H. M. Collins and R. G. Harrison on scientific research equipment, "Building a TEA Laser"; David Kaiser on theoretical physics tools, *Drawing Theories Apart*; or Kathryn Steen on business's emphasis on "working knowledge" in the nineteenth-century chemical industry, *The American Synthetic Organic Chemicals Industry*. Using a random sample of inventors to map a patent class over a year has flaws, but it is a necessary compromise with strains on rendering and

examined to three- or five-year increments (to capture longer periods in which inventors might move), or expand the network to find co-inventors of the co-co-inventors (what we call three "generations," as opposed to the two-generation settings used above). The industry's own perceived need for more cooperative research among firms, even at substantial monetary cost, was a driving force behind the founding of research consortia and increased government coordination of industry research in such forms as SEMATECH.[43]

Of course, patents are only one limited aspect of technology. Ajay Agrawal and Rebecca Henderson, in studying transmission of technology between MIT and affiliated industry, found that patents capture only a relatively minor amount (they estimate 10 percent) of technology transfer, with much of the remaining information moving in the form of tacit knowledge or "know-how" carried with researchers/inventors as they change jobs, or in the form of informal communications like conferences.[44] Andrew J. Nelson makes a similar point in regard to Stanford, and Martin Kenney, David C. Mowery, and Donald Patton in the context of the University of California system.[45] That is precisely the strength of these patent co-authorship network diagrams, however—the linkages are more reasonably interpreted as job migration (with accompanying movement of tacit knowledge) rather than firms jointly patenting technologies. These are maps of inventors' relationships, not just of patents, and so they provide more insight into flows of technology than maps of patent citations or other patent data alone might allow. They are an imperfect and incomplete tool, but a valuable complement to other tools and methods.

Finally, while historians of technology have demonstrated time and again that networks of support and alliance-building are extremely important in defining which technologies are "better" at a given point in time, an objection could be made that the FinFET was successful simply because it was obviously superior to competing technologies of the day. To address this, we adapted one final visualization tool—which we hope to make pub-

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comprehension. Mapping the entire semiconductor patent classes (or even more broadly, a set of all patents using the term "semiconductor") is technically possible, but would be far too dense and the scale too large to interpret by eye. Research on social network analysis has developed terminology and statistical descriptors for studying such networks, but they tend to be quite abstract. See Stephen P. Borgatti, Martin G. Everett, and Jeffrey C. Johnson, *Analyzing Social Networks*.

[43] Browning and Shetler, *Sematech*; Angel, *Restructuring for Innovation*. As mentioned above, these were far from the other increased government research consortia. In California, a state-level semiconductor public-private venture, dubbed MICRO, played a similar role to SEMATECH's national efforts. See Lécuyer, "Semiconductor Innovation and Entrepreneurship at Three University of California Campuses."

[44] Ajay Agrawal and Rebecca Henderson, "Putting Patents in Context."

[45] Andrew J. Nelson, "Putting University Research in Context"; Kenney, Mowery, and Patton, "Electrical Engineering and Computer Science at UC Berkeley and in the Silicon Valley."

licly available in the near future to study the history of any patent—that we call "TechFlow." Since a patent's citations are often influenced by political and social factors as well as actual similarity to other technologies, citations can be a poor resource for mapping a technology's unique contributions.[46] This visualization attempts to "see around" a given technology by mapping out patents that are linguistically similar to our central patent (in this case, the FinFET patent), regardless of explicit citations (fig. 16).

This visualization is very complex, but much of that complexity can be ignored for these purposes.[47] The dots represent patents that are most linguistically similar to the FinFET patent. The gray bars cover tight clusters of patents that are most similar to one another, which we have then spread out chronologically from left to right, 1975 to 2010. The large yellow dot (whose size indicates that it received many more future citations) is the FinFET patent. We can see that this patent is part of a tight cluster of extremely similar patents (in terms of words used), neither the origin nor the end of its line of study. It is probably not wise to rest too much analytical weight on this image without lengthier analysis and more technical detail than is possible (or helpful) here; but it is, at least, one indication of the continuity of semiconductor research before and after this "breakthrough."

FinFET did not emerge from nowhere, nor did it succeed just through obvious and apparent greatness—otherwise, the other patents around it in this image, describing very similar technologies, would have had much more impact. It was the network of academic-industrial connections that allowed the FinFET inventors to address specific industrial concerns in an achievable way, and to both draw on and contribute to industrial technology.

Conclusion

The various sources for the FinFET innovation we identify and emphasize here—the use of academia as a long-term, ambitious research wing of industry, ongoing defense funding even after the Cold War's end, scientific

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[46] A similar issue of the politics of scientific paper citations is well-studied in the field (and journal) of "scientometrics," such as in Loet Leydesdorff, *The Challenge of Scientometrics*; Bruno Latour, *Science in Action*.

[47] TechFlow uses the LASSO (Least Absolute Shrinkage and Selection Operator) method to generate a set of words characterizing each patent, which devalues common words like "the" and "and" in favor of differentiating terms like "doping" or "dielectric." Starting from the top tags for a chosen, central patent, it finds the 100 patents with the most similar tags, on the premise that similar tags will describe similar technologies. It arrays these patents on the image into clusters of especially similar word usage, which are represented on the image by grey bars. It then stretches the clusters out chronologically from left to right, 1975 to 2010. Overall similarity and difference among the clusters determines vertical spacing. The most popular tags are the words along the edge, with lines for each illustrating this word's usage throughout the patents. The size of a patent's circle represents how frequently cited it is by later patents (serving as a proxy for the patent's future significance).

research and publication, and networks of personal, often informal communication—preceded the 1980s. Academic research has been vital from the start, such as Purdue University physicists playing a key role in the invention of transistors.[48] The importance of defense spending for computing has a long and active scholarship.[49] Personal contacts and informal communication were fundamental to the growth of the semiconductor industry. In its first decades, this especially meant the movement of personnel from a few major research institutions like Bell Labs. William Shockley, one of the inventors of the transistor at Bell Labs, left to form Shockley Semiconductor, the first major firm in the industry. His connections to former colleagues remained extremely valuable in keeping abreast of major innovations.[50] Texas Instruments likewise leveraged the expertise and connections of Gordon Teal, hired from Bell Labs, in its move into transistors.[51]

Where these analogies break down—and thus where FinFET stands out—is in the immense amount the international semiconductor industry had invested in MOSFET technology by the 1990s. The industry had earlier experienced major technological shifts (usually seen in retrospect as advances) such as from germanium to silicon transistors, or from individual transistors to integrated circuits. Each of these required the technology's proponents to convince major players (often the military) that the ways in which they excelled—cost, speed, energy use, potential for miniaturization—were in fact the most important, and that trade-offs were minimal. Changing the shape of the industry required both social and financial capital. Still, individual firms (such as Gordon Moore's famous start-ups, Fairchild and Intel) were able to drive such shifts. By the 1990s, collaborative research institutions had not only sewn together the prospects of the major American semiconductor firms, their success had convinced the international industry to work together, even at the expense of U.S. federal funding. Yet this came at a cost: everyone being on the same page of the same roadmap meant detours were dangerous, even unthinkable.

This is the central paradox of FinFET: it was a tremendously innovative, breakthrough technology, in large part because it was not too radical and fit within existing industrial planning and expectations. The semiconductor industry cannot continue to meet the predictions of Moore's Law forever. As Moore himself noted, "All good exponentials come to an end," and transistors approach fundamental limits of a "gap" an atom's width apart.[52] Even before that, increasing manufacturing costs and technical challenges

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[48] Bassett, *To the Digital Age.*

[49] To cite just a few works where this is a key theme, see Martin Campbell-Kelly et al., *Computer*; Alex Roland and Philip Shiman, *Strategic Computing*; Thackray, Brock, and Jones, *Moore's Law*.

[50] Thanks to an anonymous reviewer for raising this comparison.

[51] On both Shockley and Texas Instruments's debts to Bell Labs, see Thackray, Brock, and Jones, *Moore's Law*, 140.

[52] Quoted in ibid., xxi.

have created speculation that fundamentally new technologies might have to take over—a devastating prospect given the capital sunk into MOSFET. The DARPA Advanced Microelectronics program was conceived in part as a test of whether that time had already come. Its answer—the FinFET—was valuable precisely because it was not especially disruptive.

The basic proposition that networks of support are intrinsic to technology has a long and venerated tradition in history of technology and STS circles, yet there is value in being able both to quantify and visualize aspects of these networks. Teaching and public outreach are obvious beneficiaries, as such images can capture attention that even eloquent writing simply will not. They also have value in research, especially if their findings are supported, contrasted, and contextualized by careful archival research, oral history, and other historical methods.

More broadly, historians face a tremendous challenge when studying modern history: a crushing overload of sources. This has led to recent calls for more use of quantitative methods in the history of science and technology:

> For some time, historians of science have recognized a mismatch between many of our most prized methodological approaches and whole classes of phenomena that demand scrutiny. . . . There is a problem of scale. . . . Close-focus case studies, deep archival excavations, microhistories, and comparable investigations . . . seem to be no match for the brute fact of exponential growth—the extraordinary expansion of people, places, and papers that has marked the scientific life at least since World War II.[53]

Databases and analyses of them have their own biases and quirks, of course, and the challenge of using unfamiliar tools to convince scholars remains acute. Together, though, these different sources provide a fuller context than any of them alone. Hopefully, the increasing public availability of easier-to-use digital tools will allow researchers to use these kinds of data visualizations like any other in the historian's toolbox—with care and balance, but available when needed without requiring extensive special training.

In the case of the FinFET breakthrough, oral histories are indispensable in tracing the human-level, closer-down story of its invention: the lab dynamics, the motivations and history of DARPA's Advanced Microelectronics program, and various lab members' roles. Contemporary press and insider accounts highlight broader perceptions of crisis in the industry about the future of MOS technology, and thus the motivations for DARPA undertaking such a long-shot program in the first place. The data visualization provides the widest lens of all: the overall context and evolution of the industry, as seen in figures 13 through 15 (and accompanying links), and then insight into the ways that the inventors and their university labs

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[53] David Kaiser, "Booms, Busts, and the World of Ideas," 276.

FIG. 13 Inventors in semiconductor manufacturing (sampled from class 438), 1980. Compare with figure 14 (representing 1990) and figure 15 (2005) to see how inventors' job mobility and the overall growth of the industry knit distinct firm-based networks into a far larger, industry-spanning network. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_13_class_438_1980_1981.tif.)

fit into the ecosystem of semiconductor research and development in the 1990s and 2000s.

One specific area where the data tools changed our understanding might seem simple: combined with oral histories (which otherwise might have seemed anecdotal on this point), they convinced us of the relative rarity and importance of inter-firm linkages such as those provided by the UC Berkeley lab, with its reach (via graduate students, visitors from industry, and personal connections of the PIs) into many parts of industry and government. Much of the mythos around Silicon Valley emphasizes the mobility of skilled employees, how talent gets poached, how shortages of skilled workers create a seller's labor market.[54] We expected connections between Berkeley and these diverse clusters to be plentiful, but even we were surprised at the dramatic brokerage position of the FinFET inventors. How

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[54] See footnote 4 for the literature on employee mobility in the semiconductor industry, much of which conflates "spin-offs" and employee mobility via switching existing, established firms.

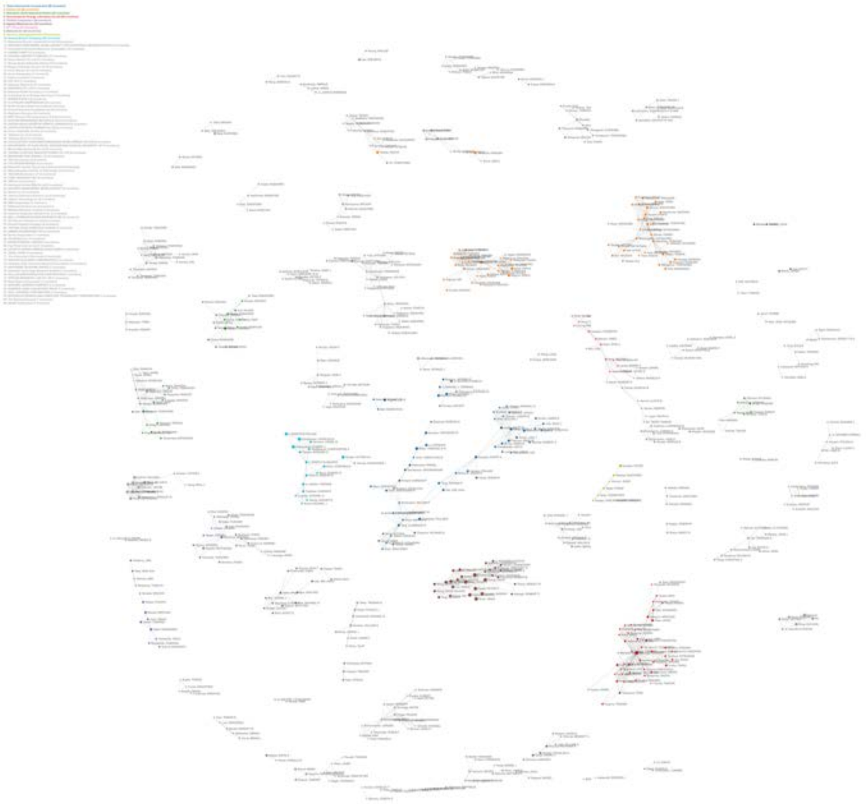

FIG. 14 Inventors in semiconductor manufacturing (sampled from class 438), 1990. Compare with figure 13 (representing 1980) and figure 15 (2005) to see how inventors' job mobility and the overall growth of the industry knit distinct firm-based networks into a far larger, industry-spanning network. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_14_class_438_1990_1991.tif.)

many interviews would it have taken to shake the specter that our sources had only the limited (if invaluable) perspectives of their local worlds? How many more until "we conducted X interviews" would become a mighty enough rhetorical bludgeon to demand assent? At the least, these tools saved us tremendous time and expense in shaping which and how many interviews we needed in order to be convinced that we understood our story. Given the realities of economic and time constraints on research, it is difficult to imagine these figures having been generated via interviews.

Of course, there are real limits on what these specific tools (and likely any digital tool) can tell us, especially in isolation. The most obvious limitation here is that co-invention is just one way of creating a network, and thus these tools miss important connections of different kinds, for example,

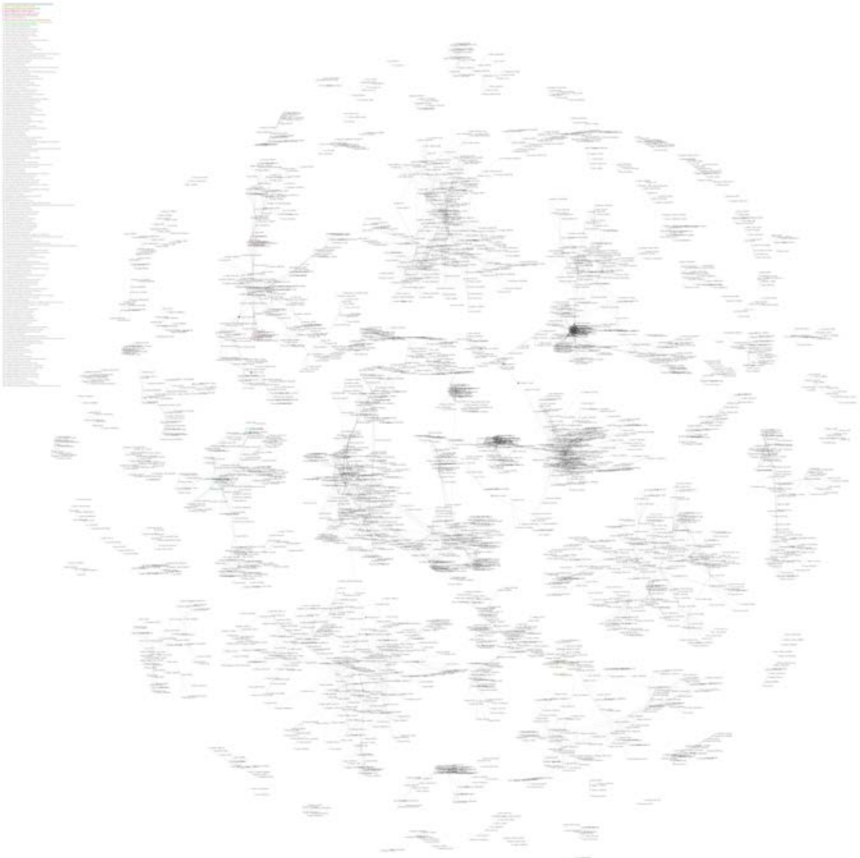

FIG. 15 Inventors in semiconductor manufacturing (sampled from class 438), 2005. Compare with figure 13 (representing 1980) and figure 14 (1990) to see how inventors’ job mobility and the overall growth of the industry knit distinct firm-based networks into a far larger, industry-spanning network. (Click image for full-size version; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_15_class_438_2005_2006.tif.)

those who develop friendships in graduate training, meet at conferences, publish in scientific journals together, etc., but never patent together. Further, in an ideal world, data would exist going back to the pre-Intel years of early Silicon Valley. Possibly future iterations of these or other tools can create, clean, and link patent data, scientific journals, graduate school, and conference attendee information, or other sources, going back to the 1950s or earlier, to map out more of these dimensions. Through these and other methods, much exciting work remains to be done on the history of the FinFET, the international semiconductor industry, and changing patterns in networks of inventorship among industry and academia. Historians might (and probably should) be skeptical about embracing digital tools as the key

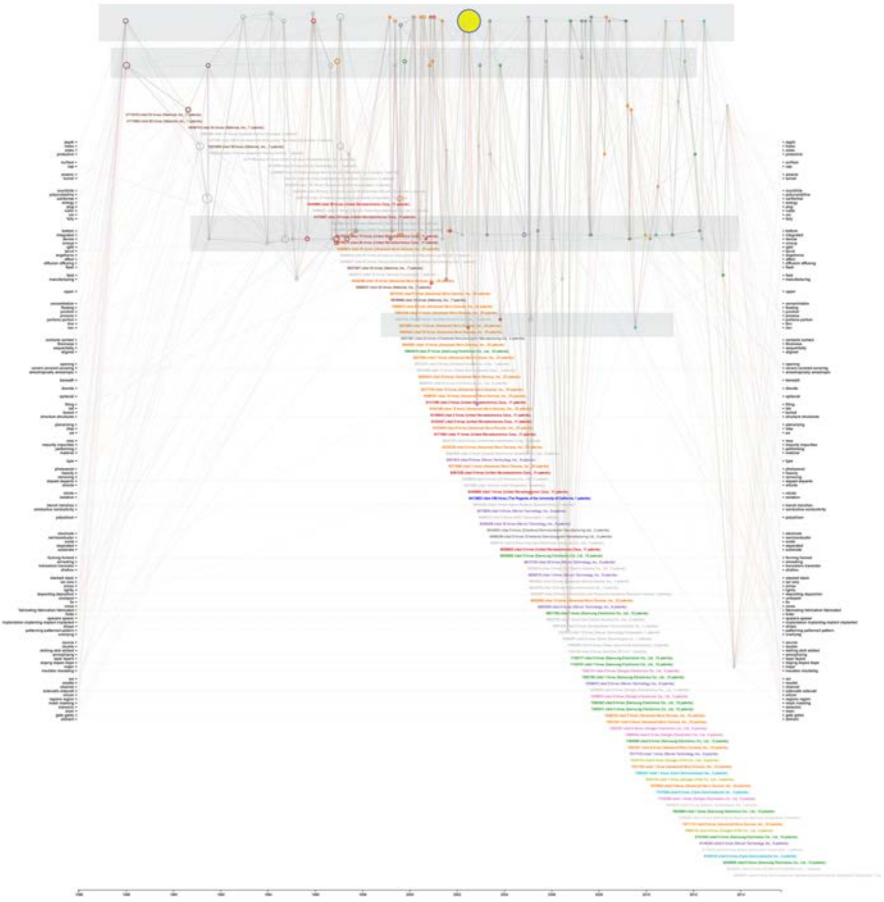

FIG. 16 The tech-flow visualization for the FinFET patent. Patents, represented as dots, are scaled according to future citations. The gray bars represent tight clumps of linguistically similar patents from 1975 to 2010. The lines show the movement of particular words through these clusters, which can perhaps be interpreted as "technological trajectories." Additional research remains to define them more rigorously and theoretically, but the coherent groupings across time illustrate the potential for finding new patterns through this linguistic analysis. (Click the image to see it full-size; http://fung-storage.coe.berkeley.edu/inventors/images/finfet/Figure_16_Techflow.tif.)

to accessing this modern history, especially after the grandiose claims of yesteryear's "Cliometric Revolution" gave way to a modest reality.[55] Still, digital tools hold tremendous potential as *one* set of tools, allowing a particular kind of objectivity and thoroughness otherwise unavailable, particularly in the face of overwhelming amounts of information.

[55] On cliometrics, see J. W. Drukker, *The Revolution That Bit Its Own Tail.*

The fiftieth anniversary of Moore's Law in 2015 brought a new wave of predictions of its imminent demise, just as FinFET finally came into full production.[56] The full scope of its historical significance will only play out in time, but its importance since patenting speaks to the lasting significance of early-1990s efforts to structure university research as the long-term research arm of the semiconductor industry, and as a destination for defense funding that would benefit the industry without limiting international cooperation. From a fiercely competitive national industry to one willing to work together with each other, with the government, and eventually with international industry, the U.S. semiconductor industry has evolved substantially since the 1980s. In doing so, it has built research and development networks that both enable long-term research (such as the DARPA AME program enabling FinFET) and constrain its future ("It is unlikely that the present worldwide semiconductor infrastructure will be regenerated to support a technology successor").[57] Understanding the industry's history, and the history of technologies and technologists within that industry, will require mapping out those networks with all the tools we can bring to bear.

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[56] Examples in recent years include Charles C. Mann, "The End of Moore's Law?"; Brooke Crothers, "End of Moore's Law"; "The End of Moore's Law."

[57] Isaac, "Beyond Silicon . . .and Back Again," 58.

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Appendix

We encourage readers to try different uses of the Patent Co-Inventor Network Visualization Tool. For example, you might try all patents in a specific sub-class over time, or re-create our own efforts. It is impossible to isolate every variable and satisfy every possible objection in a journal format, but one value of such tools is their relatively quick and easy reproducibility.

TechFlow uses the LASSO (Least Absolute Shrinkage and Selection Operator) method to generate a set of words characterizing each patent, which devalues common words like “the” and “and” in favor of differentiating terms like “doping” or “dielectric.” Starting from the top tags for a chosen, central patent, it finds the 100 patents with the most similar tags, on the premise that similar tags will describe similar technologies. It arrays these patents on the image into clusters of especially similar word usage, which are represented on the image by gray bars. It then stretches the clusters out chronologically from left to right, 1975 to 2010. Overall similarity and difference among the clusters determines vertical spacing. The most popular tags are the words along the edge, with lines for each illustrating this word’s usage.