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WHAT DO UNIVERSITIES REALLY OWE INDUSTRY? THE CASE OF SOLID STATE ELECTRONICS AT STANFORD

ABSTRACT. It is widely argued that, in the United States, the Department of Defense dictated the intellectual contours of academic science and engineering during the Cold War. However, in important ways, American science was also deeply influenced by industry. Between 1955 and 1985, Stanford University embraced three waves of industrial innovation in solid state technology (transistors, integrated circuits, and VLSI systems). As this essay shows, it was these transfers that enabled Stanford engineers to make significant contributions to the expanding fields of microelectronics and computing.

INTRODUCTION

Much of the literature on Cold War science and technology in the United States has examined the ways in which military patronage shaped the intellectual contours of research and teaching. In relation to MIT and Stanford, for example, Stuart Leslie and Rebecca Lowen have argued that the US Department of Defense redefined American science and the American system of higher education. Indeed, academic administrators and powerful staff did seek military contracts in areas of interest to the Department of Defense. In the process, they built new disciplines and enhanced the status of their institutions. Yet, according to Leslie and Lowen, MIT's and Stanford's achievements came at a high cost. By realigning research and teaching toward military priorities, the national security state became permanently imprinted upon American science.[1]

This article argues that, on the contrary, universities were exposed to a far wider array of forces. To build new programmes and develop new disciplines, universities cultivated close relations with industry. Corporations were a source of funds, ideas, and skilled personnel. More important, they also provided key technologies and processes. Universities actively sought to acquire new

[1] Stuart Leslie, *The Cold War and American Science* (New York: Columbia University Press, 1993); Rebecca Lowen, *Creating the Cold War University: The Transformation of Stanford* (Berkeley: University of California Press, 1997).

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technologies developed in industry. These technology transfers to academia were facilitated by personal friendships, but were fundamentally predicated upon the interests of industry. For many firms, transferring novel technologies and processes to academia expanded the skilled workforce that industry needed. In the late 1970s and early 1980s, American corporations also viewed a strong academia as a key weapon in competition against Japan.

Solid state electronics was one of the main engineering programmes at Stanford, which has become possibly the most prominent academic centre for solid state electronics in the United States. This enterprise was based upon massive technology transfers from industry, and was guided and supported by industrial firms such as Hewlett-Packard. Taking advantage of their proximity to Silicon Valley, Stanford administrators – including John Linvill, James Gibbons, and Frederick Terman – integrated three waves of innovation in solid state technology into the University's curriculum and research. In the mid-1950s, John Linvill, the programme's main architect, came from Bell Labs to Stanford, bringing expertise in transistor electronics. Linvill recruited other staff from Bell and sent Gibbons, a junior engineer, to Shockley Semiconductor Laboratory. At Shockley, Gibbons learned about the new technology of silicon processing. Gibbons later replicated Shockley's laboratory and made silicon devices on Stanford's campus. This formed the first wave of technology transfer.

During the mid-1960s, came a second wave. Under Linvill's leadership, Stanford's solid state electronics group incorporated integrated circuits, just developed at Fairchild Semiconductor, into their curriculum and research. The University also hired an experienced engineer from Shockley Semiconductor. Then, during the late 1970s, when researchers at Xerox PARC developed Very Large Scale Integration (VLSI) design techniques, the Stanford group incorporated this innovation into its activities, by establishing a Center for Integrated Systems (CIS). The CIS formalized Stanford's increasingly close relations with industry, and facilitated research at the intersection of solid state and computer science. As technology transfers from the Bell Labs, Fairchild, and Xerox PARC nourished their research programme, the solid state electronics group became productive. Stanford's innovations fed into the semiconductor and computer industries in Silicon Valley, and led to the establishment of new corporations such as Silicon Graphics and SUN Microsystems.

Building the Foundations

It was Frederick Terman, Dean of Stanford's engineering school, who initiated the University's research and teaching in solid state electronics. He was greatly aided in this enterprise by David Packard, president and co-founder of Hewlett-Packard (H-P). Packard was a former student of Terman. He was also a trustee of the University. Both had watched the field of semiconductor electronics since the invention of the transistor by William Shockley, John Bardeen, and Walter Brattain at the Bell Telephone Laboratories in 1947. They viewed solid state electronics as one of the most promising fields in electrical engineering, and wanted the University to build a programme in this new field. Packard had other reasons as well. With his business partner, William Hewlett, Packard was eager to transistorize their electronic measurement instrumentation business. They were also interested in producing semiconductor devices. The two men believed that if they supported solid state at Stanford, the University would become a local resource for their company and for other firms on the San Francisco Peninsula. Stanford would train engineers, whom Hewlett and Packard would hire.[2]

In 1955, with Packard's assistance, Terman hired John Linvill, who had made a name for himself at Bell by designing a new transistor-based amplifier that was widely used in local area networks. Terman liked Linvill's inventiveness, and expected that his appointment would give Stanford access to Bell Labs' technology and staff. Packard helped Terman recruit Linvill by offering him a salary-matching consulting arrangement with H-P, under which Linvill would give a series of lectures on transistors to H-P's engineering staff. Packard impressed upon Linvill the importance of building close relations with local electronics firms – especially those in the recently created Stanford Research Park.[3]

Linvill's appointment was critical. As Terman soon discovered, Linvill was his match as an academic entrepreneur. In the next fifteen years, the two men closely collaborated on building the solid state programme at Stanford. During 1955–1956, at Terman's urging, Linvill 'transistorized' the electrical engineering curriculum, with a two-quarter graduate course in 'transistor electronics'. The

[2] David Packard, *The H–P Way: How Bill Hewlett and I Built our Company* (New York: HarperBusiness, 1995). For Frederick Terman's institution building, see Leslie, *op. cit.* note 1, and Lowen, *op. cit.* note 1.

[3] John Linvill, oral history interview with author, 25 April and 30 May 2002.

course was an instant success, attracting seventy students in 1957 and 100 the following year. Many who took the course came from the Honors Cooperative Program, a continuing education programme that enabled working engineers to do graduate work at Stanford. Linvill also established the Solid State Laboratory, which worked on transistor circuits with support from the Office of Naval Research (ONR).[4]

At the Solid State Lab, Linvill and his doctoral students first developed transistor-based high frequency amplifiers, then expanded their scope to include device physics and silicon processing. To do this, the Solid State Lab needed a capability in the fabrication of semiconductor devices. This expertise was rare, and could be found in very few corporations. Fortunately, in late 1955, Shockley, the co-inventor of the transistor at Bell Labs, moved to the San Francisco Peninsula to start his own semiconductor venture, the Shockley Semiconductor Laboratory, which specialized in making silicon devices. The establishment of the new Laboratory provided a wonderful opportunity for technology transfer – from Shockley Semiconductor to the University. To get access to Shockley Semiconductor's technology, Linvill and Terman offered Shockley a junior faculty member to work as an apprentice. Shockley liked the idea. He needed PhDs with a solid knowledge of semiconductor physics, and expected that a strengthened programme at Stanford would supply the workforce he needed.[5]

[4] Leslie, *op. cit.* note 1, esp. 71–75; Christophe Lécuyer, 'Training Silicon Valley's Workforce: Continuing Education at Stanford', unpublished manuscript, September 2002; James Gibbons, 'John Linvill – The Model for Academic Entrepreneurship', *The CIS Newsletter*, Autumn 1996; Stanford University Archives and Special Collections (afterwards, SASC), Frederick Terman Papers, SC160, series II, box 15, folder 22, Frederick Terman to R. Holt, 11 March 1953; SASC, Linvill, oral history interview, 5 May 1987, Tape SV5; and Linvill, interview with author, 25 April and 30 May, 2002.

[5] Shockley located his new venture on the Peninsula because of his deep ties to the area. He was a native of Palo Alto. More important, his mother lived in the area and Shockley was interested in residing close to her. Terman also encouraged Shockley to locate his venture near Stanford. But according to James Gibbons, this encouragement was not the deciding factor. SASC, Frederick Terman Papers, SC160, series II, box 15, folder 21, Linvill, 'Description of Research Projects on Transistor Applications Undertaken in Summer 1955 under Task 7', 27 June 1955; SASC, Frederick Terman Papers, SC160, series III, box 48, folder 8, Terman to William Shockley, 20 September 1955 and Linvill to R. Wallace, 20 September 1955; Archives of the *Campus Report* (Stanford University), folder: John Linvill, 'Excerpts from Lecture for Stanford Alumni in Los Angeles: The New Electronics of Transistors', 15 February 1956; and Gibbons, interview with the author, 30 May 2002.

Linvill and Terman recruited James Gibbons, a former student of Linvill, whose task was also to reproduce Shockley's lab on campus. The enterprise was funded by the ONR.[6] Gibbons joined the Stanford faculty and the technical staff of Shockley Semiconductor in the autumn of 1957. Sending Gibbons to Shockley Semiconductor was a wise choice. The firm specialized in silicon, the material that became dominant in semiconductor technology. Shockley Semiconductor was teeming with talent. Shockley had hired an exceptional group of physicists and engineers – including Gordon Moore, Robert Noyce, Jean Hoerni, Jay Last, and Eugene Kleiner – who were to play a central role in Silicon Valley.[7]

At Shockley Semiconductor, Moore, Noyce, and Kleiner introduced Gibbons to key processes in semiconductor fabrication, such as crystal growing, lapping, solid state diffusion, and oxidation. Gibbons also got to know his contemporaries well. When eight staff members (Moore, Noyce, Hoerni, Last, Kleiner, Julius Blank, Victor Grinich, and Sheldon Roberts) rebelled against Shockley and left the firm to start their own venture, Fairchild Semiconductor, they asked Gibbons to join. Gibbons, who was interested in an academic career, declined the offer. Instead of starting a new semiconductor venture, Gibbons replicated Shockley's laboratory at Stanford. In March 1958, the laboratory fabricated its first silicon device, a four-layer Shockley diode. This was a substantial achievement. Stanford was probably the first university in the United States to fabricate silicon components.[8]

In addition to silicon processing, Linvill developed new sources of revenue for solid state electronics. In 1958, in collaboration with Terman and Packard, he established Stanford's solid state affiliates

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[6] Stanford received a $35,000 grant from the ONR to set up the laboratory.

[7] For the formation of the semiconductor industry in Silicon Valley, see Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W. W. Norton & Company, 1997) and Lécuyer, 'Fairchild Semiconductor and its Influence', in Chong-Moon Lee, William Miller, Marguerite Hancock, and Henry Rowen (eds.), *The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship* (Stanford: Stanford University Press, 2000), 158–183.

[8] Archives of the *Campus Report* (Stanford University), folder: John Linvill, Linvill, 'Application for Equipment Funds for Semiconductor Device Research', 25 February 1957 and 'Solid-State Devices Lab Tackles Silicon Transistors in Partnership with Industry', June 1958; SASC, Frederick Terman Papers, SC160, series V, box 7, folder 7, Terman to William Cooley, 6 March 1958; SASC, Frederick Terman Papers, SC160, series III, box 48, folder 8, Terman to Joseph McMicking, 25 June 1963; Gibbons, *op. cit.* note 4; Linvill, interview with author, 25 April and 30 May 2002; Gibbons, interview with author, 30 May 2002.

programme. This entitled electronics firms to attend a yearly meeting where doctoral students presented their latest results. In exchange for access to students and recent findings, corporations gave Stanford $5,000 a year over a five-year period. The solid state affiliates programme (joined by H-P, Fairchild, IBM, and Texas Instruments) generated substantial income. Proceeds grew from $5,000 in 1957–1958 to $70,000 in 1958–1959. By 1962, the affiliates programme had brought $330,000 into the solid state group. This income and the establishment of the device lab enabled Linvill to expand the solid state faculty. He recruited former Bell Labs colleagues, such as John Moll and Gerald Pearson, and in 1960, hired James Angell, the head of a transistor circuit research group at Philco. Angell strengthened the circuit side of the Stanford programme. Three years later, at Linvill's suggestion, the electrical engineering department appointed Shockley as a full professor. This was an appointment that Linvill later regretted, as Shockley lost interest in solid state physics and proceeded to develop racist theories of heredity instead.[9]

In keeping with Packard's advice and Terman's interest, Linvill strongly encouraged his faculty to cultivate close ties with local firms. In his view, these ties would enable the Stanford programme to identify problems and breakthroughs as they occurred. Academic staff consulted regularly for H-P, Shockley Semiconductor, Fairchild Semiconductor, and H-P. Associates, a semiconductor venture financed by H.P These relations with local firms were formative. Stanford developed a series of courses on semiconductor theory, semiconductor devices, and transistor circuits, based partly on what faculty members had learned through their consulting activities. Academic staff published these courses in a series of textbooks,

[9] Archives of the *Campus Report* (Stanford University), folder: John Linvill, 'A Plan for Industrial Liaison in Solid-State Electronics at Stanford University', no date; SASC, Frederick Terman Papers, SC160, series III, box 18, folder 11, Terman to E. Baldwin, 6 January 1958; Linvill, 'Proposed Budget for Funds from Industrial Associates of Stanford University in Solid State Electronics', 28 May 1958; Linvill, 'Companies to be Approached on Industrial Associates Plan for Solid State Electronics', 29 May 1958; Linvill, 'Plan of Industrial Liaison in Solid State Electronics', 24 July 1958; Terman to David Packard, 25 June 1958; Linvill to Mark Shepherd, 10 September 1958; Terman to Packard, 15 September 1958; and Linvill to Terman, 18 February 1959; SASC, Frederick Terman Papers, SC160, series V, box 7, folder 7, Terman to William Cooley, 6 March 1958; Adelaide Paine, 'Gerald Pearson', *The Solid State Journal*, June 1961, 42–44; Paine, 'Dr. John Lewis Moll', *Solid State Design*, November 1962, 16–19; Linvill, interview with author, 25 April and 30 May 2002; Gibbons, interview with author, 30 May 2002.

including two by Gibbons on *Physical Electronics and Models of Transistors* (1964) and *Semiconductor Electronics* (1966). Gibbons' second textbook became a classic and was adopted by many engineering schools in the USA.[10]

The group also built a vigorous research programme informed by knowledge of industrial practice. During the late 1950s and early 1960s, they worked on the fundamentals of semiconductor physics and device modelling techniques. These techniques became widely used by engineers to approximate the properties of transistors and diodes over a large range of conditions and applications. When, in the early 1960s, microelectronics attracted substantial industrial attention, Linvill reoriented the Stanford programme in that direction. He obtained contracts from the Department of Defense that combined work on solid state phenomena with the development of adaptive systems techniques.[11]

At first, the group did not make any major breakthroughs. Between 1955 and 1965, their main output was the twenty-five PhDs they produced. During this phase of 'capability building', Stanford's programme made modest contributions to the local semiconductor industry. Stanford students took jobs at IBM, the Bell Telephone Laboratories, and other large corporations on the East Coast, rather than in the small and entrepreneurial semiconductor ventures on the Peninsula. Large corporations looked like safer bets. One might speculate that, at this time, Stanford's programme had a larger impact on local electronics systems firms than on the semiconductor industry. The programme diffused knowledge about semiconductor devices and transistor circuits to instrumentation and telecommunication corporations, through consulting arrangements, lecture series, and the Honors Cooperative Program.[12]

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[10] SASC, Frederick Terman Papers, SC160, series III, box 37, folder 7, Linvill to Mervin Kelly, 31 July 1959; SASC, Frederick Terman Papers, SC160, series V, box 7, folder 8, Terman to William Cooley, 29 June 1961; Paine, 'Dr. John Lewis Moll', *op. cit.* note 9; Linvill, interview with author, 25 April and 30 May 2002; Gibbons, interview with author, 30 May 2002.

[11] SASC, Frederick Terman Papers, SC160, series III, box 18, folder 11, Linvill, 'Proposed Research in Solid-State Microelectronics', 5 February 1960; Archives of the *Campus Report* (Stanford University), folder: John Linvill, 'Microelectronic Research Occupies Solid State Laboratory', *Engineering News*, June 1961; Paine, 'Gerald Pearson', *op. cit.* note 9; Paine, 'Dr. John Lewis Moll', *op. cit.* note 9; Gibbons, interview with author, 30 May 2002.

[12] Linvill, interview with author, 25 April and 30 May 2002.

INTEGRATED CIRCUITS

Stanford's solid state programme grew substantially in size and influence during the second half of the 1960s and the 1970s. Terman, who had become Stanford's Provost, reoriented the electrical engineering department towards solid state electronics. In 1964, he nominated Linvill to the department's chairmanship, and gave him substantial resources to strengthen the solid state electronics programme. Industrial firms also contributed $1.5 million in gifts to the programme between 1967 and 1978. Linvill used these funds to employ new staff, including solid state specialists such as Robert Pritchard, William Spicer, and Robert White from RCA and General Electric. Under Linvill's leadership, the department also made a major thrust into integrated circuits. Planar integrated circuits were first developed in 1960 at Fairchild's R&D labs, just a few miles away from Stanford. Texas Instruments and Fairchild's spin-offs, such as Signetics, rapidly joined the game and further developed the new technology. By the mid-1960s, integrated circuits were faster than circuits made of discrete devices. Their density doubled every year. They were poised to have a major impact upon electronics.

Recognizing that microcircuits would revolutionize the curriculum just as had the transistor, solid state staff developed a series of graduate courses on integrated circuits. Angell organized a new course that introduced students to the special design rules that apply to integrated circuits. In 1964, Pritchard developed a laboratory course on microcircuits, and established the Integrated Circuits Laboratory as a component of the Solid State Lab. This lab was small and could fabricate simple circuits. Pritchard's course familiarized students with the complex processes – such as photolithography and thin film deposition techniques – used in the making of integrated circuits.[13]

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[13] Linvill also sought to recruit key Silicon Valley engineers and executives to the faculty. In the late 1960s, he attempted to hire Andy Grove. Grove had done innovative work on semiconductor surfaces at Fairchild Semiconductor and published a famous textbook on semiconductor physics. To Linvill's chagrin, Grove elected not to join the Stanford faculty. Linvill, James Angell, and Robert Pritchard, 'Integrated Electronics vs Electrical Engineering Education', *Proceedings of the IEEE*, 52 (1964), 1425–1429; Pritchard, 'Training New Engineers', in *Conference Proceedings on the Impact of Microelectronics II*, Chicago, 6 June and 7 June 1968, 159–167; personal communication, Jacques Beaudoin to author, 7 December 1995; Linvill, interview with author, 25 April and 30 May 2002; personal communications, Linvill to author, 21 August 2002 and 13 December 2003.

A few years later, Linvill spearheaded the development of a research programme on integrated circuits, closely coupled with systems research. Interestingly, much of the impetus for integrated circuits research at Stanford came from Linvill's interest in developing a reading aid for the blind. In 1962, Linvill became interested in building a device that would help his blind daughter, Candace, to read printed materials. Over the next few years, he designed a machine, the 'Optacon', in collaboration with a group at the Stanford Research Institute (SRI). The 'Optacon' scanned printed pages and presented a magnified vibratory facsimile of each letter on the tip of the reader's finger. With ONR funding, Linvill's students and the SRI group built and tested a prototype of this machine in 1966. The prototype proved the feasibility of the concept, but it was too bulky to be of practical use. A much smaller 'Optacon' required that the 'Optacon's' key components – especially high voltage circuits and photo-transistor arrays – be miniaturized. Pritchard's Integrated Circuits (IC) Laboratory could not fabricate circuits of such complexity. Making these circuits required a major upgrading of the IC laboratory.[14]

So, to develop a smaller 'Optacon' and upgrade the IC laboratory, Linvill and his allies at SRI applied for a large grant from the US Office of Education. It was an auspicious time for such proposals. As part of its Great Society programmes, Lyndon Johnson's administration was investing in new technologies for the handicapped. Between 1966 and 1971, the Office of Education lavishly funded Linvill's project with $1,800,000. This financed the transformation of the IC laboratory from a teaching lab into a research operation. To run it, Linvill recruited Jim Meindl from the Fort Monmouth laboratories of the US Army Signal Corps (Pritchard left the University shortly thereafter). Meindl had a knowledge of integrated circuits and excellent contacts in the Department of Defense. Meindl turned to Shockley Semiconductor for the expertise to process advanced integrated circuits. He hired Jacques Beaudoin, an experienced research engineer at Shockley, and made him the laboratory's chief engineer. Beaudoin helped Stanford master the complex technology of integrated circuit processing. The lab acquired new equipment and higher standards of cleanliness, and,

[14] SASC, Frederick Terman Papers, SC 160, series XIV, box 11, folder 1, Linvill, 'Notes for Conversation with FET', 25 September 1972; Linvill and Lester Hogan, 'Intellectual and Economic Fuel for the Electronics Revolution', *Science*, 195 (18 March 1977), 1107–1113; Linvill, interview with author, 25 April and 30 May 2002.

under his direction, the capability of making complex integrated circuits. Through his numerous Silicon Valley contacts, Beaudoin also kept the University apprised of the latest developments in industry. According to Linvill, Beaudoin made the difference between Stanford and its academic competitors in integrated circuits during the 1970s and 1980s.[15]

One of Beaudoin's first tasks was to help Meindl and his students design and fabricate the microcircuits for the 'Optacon'. In this endeavour, they received substantial help from Fairchild Semiconductor. In particular, the transducer research group at Fairchild R&D advised the IC Laboratory on how to design and process phototransistor arrays. The good relations that Gibbons and others had developed with Fairchild Semiconductor since the late 1950s began to pay off. In 1969, Beaudoin and Meindl succeeded in fabricating photo-arrays and high voltage circuits for the 'Optacon'. Soon, the IC Laboratory spun out of the Solid State Laboratory, and became an independent entity. With the chips it produced, Linvill and his students built a miniature version of the 'Optacon'. In 1971, Linvill and his group commercialized the device by forming a new firm, Telesensory Systems. This was the first spin-off from Stanford's solid state electronics programme.[16]

During the 1970s, in parallel with these commercial activities, Meindl and Linvill built a large integrated circuits research programme at Stanford. After completing the 'Optacon' project, they reoriented the IC Laboratory towards making custom integrated circuits for medical instruments. This was a shrewd move. Meindl and Linvill understood that a university could not compete successfully with industrial firms in the development of integrated circuit technology. Fairchild, Intel, and other Silicon Valley corporations were enormously innovative. They also mustered much larger resources than the Integrated Circuits Laboratory. Therefore, instead of competing with Silicon Valley, the IC Laboratory developed integrated circuits as a means to another end – namely, as a way to further electronic systems research.

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[15] SASC, Frederick Terman Papers, SC 160, series XIV, box 11, folder 1, Linvill, 'Notes for Conversation with FET', 25 September 1972; Linvill, interview with author, 25 April and 30 May 2002; personal communication, Beaudoin to author, 7 December 1995; personal communication, Linvill to author, 21 August 2002.

[16] Linvill, interview with author, 25 April and 30 May 2002; personal communication, Beaudoin to author, 7 December 1995; personal communication, Linvill to author, 21 August 2002.

Medical systems were good candidates for this task. The field of microelectronics-based medical instrumentation had received little attention from industry. Exploiting this opportunity, Meindl, Beaudoin, and the growing staff of the IC Laboratory developed a series of medical systems and related circuits in collaboration with the Stanford Medical School and with financial support from the National Institutes of Health. In the 1970s, they designed implantable flow meters for cardiac surgeons who performed heart transplants in animals. The group also developed very low power circuits used in ultrasonic cameras and, in collaboration with the departments of ophthalmology and radiology, designed an ultrasound imaging system for the inner eye that was later commercialized.[17]

In parallel with the IC Laboratory's medical research, the Solid State Laboratory set up a research programme on semiconductor materials and processes. Pearson and his students worked on gallium arsenide, while Spicer used photoemission techniques to study the electronic structure of semiconductors. But it was Gibbons' group that did the most influential work. They helped transform ion implantation, a technique used in nuclear physics, into a key manufacturing process. Gibbons' consulting work at Shockley Semiconductor piqued his interest in ion implantation. In the late 1950s, Shockley had directed his staff to develop ion implantation techniques for making high power silicon transistors. In 1966, Gibbons decided to launch a major effort on ion implantation as a transistor and integrated circuit manufacturing process. This was a risky decision. Ion implantation was viewed as a speculative field. Most semiconductor engineers and solid state physicists did not think that ion implantation would ever be used in semiconductor device manufacturing, because they believed that high energy ions

[17] Political considerations may also have led Linvill and Meindl to concentrate the IC Lab's efforts on medical instruments. In the late 1960s and the early 1970s, Stanford experienced considerable student unrest, much of it directed toward military-sponsored research. The medical programme deflected these criticisms. Pritchard, *op. cit.* (1968) note 13; Robert White and James Meindl, 'The Impact of Integrated Electronics in Medicine', *Science*, 195 (18 March 1977), 1119–1124; SASC, Frederick Terman Papers, SC 160, series XIV, box 11, folder 1, Linvill, 'Notes for Conversation with FET', 25 September 1972; Archives of the *Campus Report* (Stanford University), folder: James Meindl, Stanford University News Service press releases, 28 October 1970, 17 November 1971, 22 March 1973, 30 October 1973, 17 March 1976, 8 February 1978, and 10 December 1982; Gibbons, interview with author, 30 May 2002; Linvill, interview with author, 25 April and 30 May 2002; personal communication, Linvill to author, 21 August 2002; personal communication, Beaudoin to author, 7 December 1995.

would destroy the lattice structure of the silicon crystal. Therefore, only a few industrial laboratories, the Bell Labs, Sprague Electric, and Ion Physics Corporation, were investigating the process.[18]

While these industrial laboratories were working on ion sources and ion implanted devices, Gibbons and his students established the scientific basis of ion implantation technology. With funds from the NSF and ARPA, they constructed an ion implanter and started an experimental programme. They also calculated the penetration range statistics of implanted ions. In 1968, Gibbons and one of his students, William Johnson, published their research in a volume entitled *Projected Range Statistics*. Gibbons also published two long review articles on ion implantation in the *Proceedings of the IEEE*. These became classics in the field.[19]

Gibbons also promoted the use of this new process in industry. Starting in 1967, he alerted Gordon Moore of Fairchild Semiconductor to the potential of ion implantation. But according to Gibbons, Moore did not believe in the process, nor did any of the other semiconductor firms on the San Francisco Peninsula, which believed that ion implantation was too complex and capital intensive. Manufacturing engineers were also reluctant to introduce new technologies into their already very complex production processes. It was only in the early 1970s, when Mostek, a company in Texas, used ion implantation to produce semiconductor memories with desirable electrical characteristics (low threshold voltage) that firms in Silicon Valley converted to the new process. Once they did, they relied heavily upon the penetration range statistics that Gibbons and his group had calculated. By the late 1970s, ion implantation had become critical to the production of semiconductor memories and microprocessors. For the first time, a key technology partially developed at Stanford had found its way into Silicon Valley's wafer fabs.[20]

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[18] For a short history of ion implantation, see Richard Fair, 'History of Some Early Developments in Ion-Implanted Technology Leading to Silicon Transistor Manufacturing', *Proceedings of the IEEE*, 86 (1998), 111–137. Gibbons, interview with author, 30 May 2002.

[19] James Gibbons, John Moll, and Nils Meyer, 'The Doping of Semiconductors by Ion Bombardment', *Nuclear Instrumentation and Methods*, 38 (1965), 165–168; Gibbons, 'Ion Implantation in Semiconductors – Part I Range Distribution Theory and Experiments', *Proceedings of the IEEE*, 56 (1968), 295–319; and 'Ion Implantation in Semiconductors – Part II Damage Production and Annealing', *Proceedings of the IEEE*, 60 (1972), 1062–1097; Fair, *op. cit.* note 18; personal communication, Beaudoin to author, 7 December 1995; Gibbons, interview with author, 30 May 2002.

[20] Gibbons, interview with author, 30 May 2002.

Gibbons, in collaboration with Meindl, also started a new research area at Stanford, called 'process simulation'. As integrated circuits became increasingly dense and complex, the group thought that the best way to proceed lay through simulations rather than experiments. To Meindl and Gibbons, Stanford was uniquely positioned to develop a process simulation programme. The Solid State and IC Laboratories had accumulated a solid competence in solid state processes. They could also rely upon the rich process expertise of Silicon Valley. In 1971, Meindl and Gibbons obtained a contract from the Defense Advanced Research Projects Agency (DARPA) to develop a process simulation programme, which became known as the Stanford University Process Emulator (SUPREM). To carry out this project, they hired Robert Dutton, a recent Berkeley PhD. The goal was to develop a programme that would transform circuit designs into a series of device parameters, and then transfer these parameters into a process schedule.

To carry out the project, Dutton and his group relied extensively upon processing know-how in Silicon Valley – notably in relation to oxidation and epitaxy, two key processes that were well understood by industrial firms but much less so by Stanford engineers. With Gibbons' help, Dutton enlisted the collaboration of Bruce Deal, a senior scientist at Fairchild Semiconductor, and a world authority on oxidation. Deal joined the Stanford group on a part- time basis as a consulting professor. Dutton also secured the help of H-P scientists as well as researchers at Applied Materials, a manufacturer of semiconductor processing equipment. With their assistance, Dutton and his group developed a complex process simulation program. They released the first version of SUPREM in 1978.[21]

By the late 1970s, Stanford's electrical engineering department had a strong reputation in the semiconductor community. The Solid State Lab was recognized as one of the top academic centres in semiconductor physics. The Integrated Circuits Laboratory was a force to be reckoned with in microelectronics. The number of 'best paper' awards that the IC Laboratory received at IEEE International Solid State Conference, the main forum for the US integrated electronics community, is a good measure of its growing

[21] SASC, presidential papers, AA 4.4.9, folder: CIS 10/78–4/80, Meindl, 'The Existing Base for the CIS: Integrated Circuits Laboratory', 2 April 1979 and Linvill, 'The Electrical Engineering Department in the Center for Integrated Systems', 24 April 1979; SASC, Bruce Deal, interview with Henry Lowood, 12 July and 27 July 1988; Gibbons, oral history interview conducted by the author, 30 May 2002.

influence. From 1969 to 1978, the IC Laboratory received 25 per cent of the total number of 'outstanding paper' awards and 70 per cent of the 'outstanding paper' awards granted to universities. Moreover, the Solid State and IC laboratories had become large operations. By 1978, the Solid State Lab operated with a budget of $1.5 million. The IC Laboratory employed seventy people (including eight academic staff), with a budget in the $2.5 million range.[22]

The Center for Integrated Systems

The advent of Very Large Scale Integration (VLSI) opened up new opportunities for the solid state electronics group at Stanford. In the mid-1970s, Lynn Conway, a researcher at Xerox PARC, and Carver Mead, a professor at Caltech, developed a simplified approach to the design of integrated circuits, and standardized design methods developed in industry, notably in Silicon Valley. Their approach to integrated circuit design revolutionized solid state electronics. It enabled engineers to design chips without first having first to gain expertise in semiconductor physics and electronics. More important, their approach made possible the development of integrated circuits of unprecedented complexity – that is, VLSI circuits. In other words, Mead's and Conway's techniques enabled engineers to develop integrated systems. In particular, these techniques made possible the design of computer systems on a chip. Not surprisingly, their research attracted considerable attention, both in industry and academia. Their book, *Introduction to VLSI Systems* (circulated in draft form in 1977 and published three years later), became the bible of the semiconductor and computer engineering communities.

Linvill quickly realized that, like integrated circuits fifteen years earlier, VLSI techniques would radically transform the curriculum. In his usual way, when prompted by a major innovation originating in industry, he hired new staff and sought to incorporate the new technology into his department's research and teaching. One of Linvill's first steps was to hire Conway as an adjunct staff member to teach graduate courses on VLSI technology. Dutton and other staff, who were trained in VLSI at Xerox PARC, later integrated these techniques into their own courses. Also, beginning in 1977,

[22] SASC, presidential papers, AA 4.4.9, folder: CIS 10/78–4/80, Meindl, 'The Existing Base for the CIS: Integrated Circuits Laboratory', 2 April 1979.

Linvill made appointments in areas where the new VLSI techniques would have the greatest impact – namely, in computer and information systems. In a single year, Linvill recruited three new staff into the Information Systems Laboratory. He also hired Jim Clark and John Hennessy, two promising researchers in the areas of computer architecture and computer graphics. Clark and Hennessy joined the Computer Systems Laboratory, a joint facility of the electrical engineering and computer science departments.[23]

These new appointments enabled Linvill, Gibbons, and Meindl to build a major programme in VLSI research. These men centred the VLSI programme around a novel organization, the Center for Integrated Systems (CIS), which Linvill established in 1980. The Center emerged at the convergence of two factors: Linvill's determination that Stanford would master and contribute to the technologies of VLSI, and the fear of the Department of Defense and large US electronics firms (notably H-P) that American manufacturers were losing out to Japanese industry. Bill Hewlett, co-founder of H-P, actively supported Linvill's plans for the Center. He was deeply concerned by the growing strength of Japanese electronics firms, and thought that the proposed Center would bolster the competitiveness of US industry.[24]

The Center for Integrated Systems operated at the intersection of electrical engineering and computer science, and federated the activities of four laboratories (Solid State, Integrated Circuits, Computer Systems, and Information Systems) in the field of VLSI. The CIS consisted of two components: a new fabrication facility and an industrial consortium. The Center was funded by a group of seventeen firms, which, in addition to H-P, included Intel, Fairchild, Xerox, General Electric, Motorola, and Texas Instruments. These member firms paid a large entry fee ($750,000) and yearly dues. In return, electronics corporations gained access to Stanford research through biannual meetings, the distribution of pre-prints, and long-term on-campus visits by industrial scientists.

[23] Gibbons, *op. cit.* note 4; Linvill, interview with author, 25 April and 30 May 2002.

[24] SASC, presidential papers, AA 4.4.9, folder: CIS 10/78–4/80, The School of Engineering Advisory Council, 'Report to the President', 8–9 February 1979; Archives of the *Campus Report* (Stanford University), folder: Center for Integrated Systems, Hewlett, 'Remarks', 19 May 1982; Gibbons, 'Bill Hewlett: A Stanford Engineer's Engineer', *The CIS Newsletter* (Summer 2001), 1, 10–11; Linvill, interview with author, 25 April and 30 May 2002; personal communication, Linvill to author, 21 August 2002.

The participating companies also advised the Center on its research orientation. Their funds ($12 million), along with an $8 million contract from DARPA, financed the construction of a new building and fabrication facility to process VLSI circuits. By the early 1980s, the CIS had the most advanced wafer-processing facility in academia, and could make VLSI devices.[25]

The formation of CIS and its financing by a group of industrial corporations substantially reinforced Stanford's visibility in solid state and computer engineering. They also made its research programmes more attractive to Federal agencies. DARPA was especially interested in the Center's close alliance with industrial corporations. Intellectual inputs from industry also helped staff develop better and more convincing proposals – which, in turn, were funded by the Federal government. As a result, the four main laboratories affiliated with CIS increased their research funding by more than 60 per cent between 1979 and 1981. During the same period, their combined research budget grew from $7.1 million to $11.6 million. The greatest winners were the Computer Systems Laboratory (from $1 million to $2.2 million) and the IC Laboratory (from $3.3 to $5 million). Research funding remained at a high level over the next five years. A large share came from DARPA and other military agencies. But the CIS-affiliated laboratories also received substantial contracts from the National Institutes of Health and the Semiconductor Research Corporation.[26]

This surge in support and the upgrading of the integrated circuits processing facility helped Stanford emerge as a major player in VLSI research. The state-of-the-art facility supported projects in semiconductor physics, integrated circuit processing, CAD tools, manufacturing automation, and computer systems. It also assisted the development of more powerful versions of SUPREM. The facilities supported a much-enlarged experimental programme on key semiconductor manufacturing processes, which, in turn, fed into

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[25] Archives of the *Campus Report* (Stanford University), folder: Center for Integrated Systems, Jim Burke, 'A Facility Introduction to the Center for Integrated Systems', November 1984; 'CIS Equipment/Services Donors', 16 July 1985; and press releases, 7 October 1982 and 13 January 1987; personal communication, Beaudoin to author, 7 December 1995; Richard Reis, interview with author, 27 February 2002.

[26] SASC, presidential papers, PAA 4.4.9, folder: CIS development 9/81–8/82, Linvill, 'Report of the CIS Sponsors Advisory Committee Meeting', 12 November 1981 and Linvill, 'Semiconductor Research Cooperative and Microelectronics and Computer Technology Enterprises', 28 April 1982.

the development of more accurate physical models of processes, such as thermal oxidation, ion implantation, epitaxy, diffusion, and chemical vapour deposition. Through the 1980s, Dutton and his group released greatly improved versions of SUPREM, permitting even more complex simulations. By the end of the decade, SUPREM had emerged as the most powerful simulation tool of semiconductor processes.[27]

The CIS also facilitated innovative projects in the Computer Systems Laboratory. Among these, the most prominent were the geometry engine, the SUN workstation, and Reduced Instruction Set Computing. These projects came within the same DARPA contract on VLSI Computer Systems, whose main objective was the development of 'general purpose programmable systems, design aids, and architecture'. With DARPA funding, Andreas Bechtolsheim, a doctoral student in the Computer Systems Laboratory, designed the SUN workstation. The goal of the project was to build a low-cost graphics terminal for the Stanford University Network (hence its name). To design the SUN workstation, Bechtolsheim used VLSI design tools as well as standard components, including a new Motorola microprocessor. Through its use of integrated systems technology, this workstation was far more powerful than conventional terminals then on the market.[28]

The same DARPA contract also financed two other, related projects: the geometry engine and the MIPS microprocessor. Jim Clark, a research professor in the Computer Systems Laboratory, designed a computer chip: the geometry engine. Clark embedded algorithms fundamental to the generation of 3-D graphics on the chip. In other words, he transferred capability from software to hardware. The geometry engine enabled a terminal to display a three-dimensional object and rotate it every thirtieth of a second. The CIS laboratory fabricated the new chip in 1981. Around the same time, John Hennessy adopted a new concept in computer architecture that had been pioneered at IBM, called Reduced Instruction Set Computing (RISC). Unlike other computer

[27] Jim Plummer, 'SUPREM III: An Important New Tool for the Design of Complex Chips', *CIS Newsletter*, June 1983; Archives of the *Campus Report* (Stanford University), folder: Center for Integrated Systems, 'Research Activities of the CIS Affiliated Faculty', November 1984; Gibbons, interview with author, 30 May 2002; Linvill, interview with author, 25 April and 30 May 2002; personal communication, Linvill to author, 21 August 2002.

[28] SASC, presidential papers, PAA 4.4.0, folder: CIS development, 9/81-8/82, 'List of CIS projects'.

architectures, RISC relied upon a small, highly optimized set of instructions. Building upon IBM's work, Hennessy and his group developed an experimental RISC architecture. The MIPS microprocessor had remarkable performance characteristics. It was five times faster than commercially available microprocessors, but used only a fraction of their transistors. Both the geometry engine and the MIPS microprocessors were important innovations in computer technology.[29]

These and other projects made a substantial impact upon the semiconductor and computer industries – both locally and nationally. During the 1980s, much work on processing and process modelling in the Solid State and Integrated Circuits Laboratories fed into the semiconductor industry through SUPREM. By 1986, Stanford had distributed SUPREM to 500 commercial and academic users. But it was in computing that the research groups affiliated with the CIS were most influential. Research performed at the Center was commercialized by CIS member firms during the second half of the 1980s. For example, H-P introduced its PA-RISC architecture to the market in 1986. Groups of students and staff affiliated with CIS also established their own companies. The main CIS spin-offs were SUN Microsystems, Silicon Graphics, and MIPS Computer Systems. SUN Microsystems, started by Bechtolsheim and two graduates of the Stanford Business School, commercialized the workstation he had designed at Stanford along with the Berkeley version of UNIX. In 1982, Clark set up Silicon Graphics with a handful of students and staff from the Computer Systems Laboratory. The firm exploited his geometry engine, and Silicon Graphics rapidly established itself as the main American supplier of workstations with advanced graphics capabilities. Hennessy also formed his own

[29] Joseph Hughes and Meindl, 'Systems Projects: Key to CIS Effort', *CIS Newsletter*, February 1984; Linvill, 'Progress Toward the Major Goals of the CIS', *CIS Newsletter* (July 1987), 10 and 24; Michael Lewis, *The New New Thing: A Silicon Valley Story* (New York: Norton, 2000); Archives of the *Campus Report* (Stanford University), folder: Center for Integrated Systems, 'First 32-bit Microprocessor Entirely Designed and Made in a University Environment Is Announced by The Center For Integrated Systems', 6 January 1984; "RISC Architecture: Interview with John Hennessy," no date, http://cse.stanford.edu/class/sophomore-college/projects-00/risc/about/interview.html; personal communication, Christopher Rowen to author, 7 January 2003.

company, MIPS Computer Systems, which developed a RISC microprocessor inspired by the original MIPS chip.[30]

This wave of start-ups reshaped Silicon Valley. SUN, Silicon Graphics, and to a lesser degree MIPS became key players in the chip and advanced workstation business. The CIS also helped redirect the flow of Stanford graduates towards Silicon Valley. Electrical engineering graduates, who had turned down job offers from local firms, increasingly accepted positions in the region, especially with corporations that sprang out of CIS. By the mid- to late 1980s, Stanford's solid state electronics programme had become a significant entrepreneurial, technological, and educational centre in Silicon Valley, as well as a force to be reckoned with in the US semiconductor and computer industries.

Conclusion

The rise of the solid state electronics programme at Stanford was made possible by massive transfers of technology from industry. Stanford owed much of its competence in solid state circuit and system design to the Bell Telephone Laboratories. Its processing expertise came from two companies, Shockley Semiconductor and Fairchild Semiconductor. Xerox PARC also supported the transfer of VLSI techniques. These flows of ideas, knowledge, and techniques revolutionized the electrical engineering curriculum at Stanford. They also facilitated major research projects on medical instruments, reading aids for the blind, process simulation programs, and computer architectures. More deeply, these flows shaped the programme's very orientation. They led Stanford to emphasize process research and to couple device and process work with system design. As these transfers fashioned and nourished solid state electronics, the Stanford group made many technological contributions to the semiconductor and computer industries. During the 1970s, Gibbons helped transform ion implantation, an exotic technique used in nuclear physics research, into a major

[30] Hennessy, 'Stanford University: Wellspring of Silicon Valley', no date, http://hennessy-cube.stanford.edu/wellsprings/sld002.htm; Willliam Stallings, *Reduced Instruction Set Computers* (Los Alamitos: IEEE Computer Society Press, 1990); Lewis, *op. cit.* note 29; Gibbons, interview with author, 30 May 2002; personal communication, Gibbons to author, 4 December and 12 December 2001; personal communication, Linvill to author, 21 August 2002; personal communication, Rowen to author, 7 January 2003.

semiconductor manufacturing process. But it was the series of projects in the Computer Systems Laboratory – the geometry engine, the SUN workstation, and the MIPS microprocessor – that were to have the greatest industrial impact.

A number of lessons can be learned from the solid state electronics programme at Stanford. First, contrary to common belief, academic science and engineering were not shaped solely by Cold War pressures. Whilst not underestimating the influence of Defence spending on the development of microelectronics in major American universities, it is clear that industry also played a major role, and not least in the development of research and teaching programmes and in the fashioning of new academic disciplines. Firms such as H-P encouraged the building of the solid state electronics programme at Stanford in the 1950s and 1960s. They also helped establish the Center for Integrated Systems for research on VLSI systems. More important, over a period of thirty years, American electronics corporations provided the knowledge and the know–how that made possible the University's entry into the world of semiconductor technology. Industrial transfers enabled Stanford to systematize and 'normalise' knowledge produced in the corporate world. The University also trained students in innovations already developed by industry. Moreover, it developed these innovations and extended them in areas that industrial firms did not fully exploit. Thus, Linvill, Meindl, and the IC Lab applied the new technology of microcircuits to the design of medical instruments, an area of integrated electronics that few firms had until then cultivated.

Second, it is clear that universities were more beneficiaries than causes of regional growth. The semiconductor industry in Silicon Valley did not spin out of Stanford's solid state electronics programme. Rather, it grew out of Shockley Semiconductor. In the 1960s and 1970s, the semiconductor industry in Silicon Valley owed little to Stanford. With the exception of ion implantation, Silicon Valley did not learn much from the University. Contrary to Shockley's and Packard's expectations, Stanford graduates shunned Silicon Valley corporations for the large electronics firms on the East Coast – thereby funneling knowledge and know–how developed in Silicon Valley to East Coast corporations. However, Stanford did take advantage of its proximity to Silicon Valley, and built its programme on the basis of technology transfers from local firms. Not until relatively late in the history of solid state (following almost twenty-five years of constant flows of knowledge from industry) did the University emerge as a significant player in microelectronics and computing in Silicon Valley. Nonetheless, the case of solid state electronics at Stanford should remind historians that inward flows of knowledge and know–how shape academic engineering, and that transfers enable universities to innovate and foster regional growth. Such factors suggest the need for more close-grained studies that take into account the bi-directional nature of the university–industry relationship, and that examine the industrial antecedents as well as the commercial consequences of academic enterprise.

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