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Historical, Entrepreneurial and Supply Chain Management Perspectives on the Semiconductor Industry

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Abstract

This paper studies the semiconductor industry from three perspectives: historical, entrepreneurial and supply chain management. After a brief introduction, the paper begins by tracing the history and evolution of the semiconductor industry including the two seminal enterprises: Shockley Semiconductor Laboratory and Fairchild Semiconductor. Starting from the invention of the transfer resistor (transistor) by three Nobel laureates (John Bardeen, Walter Houser Brattain and William Shockley), the founding of the "most successful failure" in Silicon Valley, Shockley Semiconductor Laboratory and the Fairchild Eight, the paper discusses some earliest entrepreneurial attempts in the industry and how these attempts influenced over seventy semiconductor companies in Silicon Valley, including Intel Corporation, National Semiconductor and Advanced Micro Devices. The paper then examines the industry's developing business models, from the vertically integrated model to the integrated device manufacturing model to the development of the foundry model. Finally, the paper looks at the industry's growing trend of globalization together with its outsourcing/off-shoring and supply chain management developments. The authors believe that such a multi-disciplinary approach to study an industry provides valuable insights into the evolution and development of an entire industry and the approach can be generalized to study other industries to enhance understanding at the industry level.

I. Introduction

According to reports from the Semiconductor Industry Association (SIA), global sales of semiconductors were $255.6 billion in 2007 and $248.6 billion in 2008. The 2008 global sales were negatively impacted by the world-wide economic turmoil, but were with only a 2.8% slight decrease despite the 2008 economic downturn [1]. Prior to the 2.8% drop in 2008, the semiconductor had an impressive seven-year consecutive growth [2]. In today's world, semiconductor has permeated in every part of people's life like nothing did before. From computers, automobiles, office equipment, iPods, iTouch and iPhones, entertainment devices and all home appliances, none can function without integrated circuit semiconductor devices. Just as Intel's corporate publicity literature asserts, "Tiny silicon chips... are changing the way people live, work, and play." [3] Intel's recent announcement that Intel is going to invest $7 billion on state-of-the art chip manufacturing—in the midst of a worldwide economic recession—demonstrates semiconductor industry's continuing vitality and prosperity [4].

From the vantage point of Silicon Valley where the authors are residing and working, this paper studies the semiconductor industry from three perspectives: historical, entrepreneurial and supply chain management. In the following sections, this paper traces the history and evolution of the semiconductor industry including the two earliest companies in the semiconductor industry: William Shockley Semiconductor Laboratory and Fairchild Semiconductor Corporation. Starting from the invention of the transfer resistor (shorted as transistor) by three Nobel laureates (John Bardeen, Walter Houser Brattain and William Shockley), the founding of Shockley Semiconductor Laboratory and its Shockley Eight (aka Fairchild Eight), the paper details some earliest entrepreneurial attempts in the industry and tells how these attempts directly influenced over seventy semiconductor companies in Silicon Valley, including Intel Corporation, National Semiconductor, and Advanced Micro Devices. The paper then examines the industry's developing business models, including the evolution from the vertically integrated model to the integrated device manufacturing model to the emergence of the foundry model. The latter part of the paper looks at the industry's trend of globalization together with its outsourcing/off-shoring and supply chain management developments. Taking advantage of the three authors' interdisciplinary expertise, the paper studies the semiconductor industry from three perspectives: historical, entrepreneurial, and supply chain management. The authors believe that such a multi-disciplinary approach to study an industry, although uncommon in the extant literature of industry studies, provides valuable insights into the evolution and development of an entire industry. This approach can provide a novel paradigmatic way of appreciating an industry and its vicissitudes from the industry's beginnings to ensuing developments. This approach can be generalized to study any other particular industry to enhance understanding of an entire industry, especially in this era of globalization. This paper hopes to stimulate further studies of other industries across the entrepreneurial and business landscape such as telecommunications, networking, biotech, and Internet search engine industries.

II. The Early Days and William Shockley Semiconductor Laboratory

Santa Clara Valley, located south of the San Francisco Bay and surrounded by the Sierra Mountains in the northeast and the Santa Cruz Mountains in the southwest, was nicknamed as "Silicon Valley" by Don Hoeffler, editor of the trade journal *Electronic News,* in 1971 and the nickname quickly caught on as a way to identify the world electronics mecca [5]. Silicon Valley has lived up to its name: throughout human history, the enhanced availability of information has created quantum leaps in human achievement. From microwave radar to laser technology to integrated circuits to disk storage to microprocessors to the Internet and E-commerce, it all started in Silicon Valley [6]. One of the most important industries, which has served as the backbone of Silicon Valley and the indispensable "bread and butter" of all high tech industries, is the semiconductor industry. Modern life and past and future economic development cannot be separated from the semiconductor industry.

How did the silicon-based semiconductor industry ever get started in Silicon Valley? Let us turn the clock back to over half a century ago in the 1950s.

While Leland Stanford and his founding of Leland Stanford, Jr. University in Palo Alto, California might have been the most instrumental in the late twentieth century phenomenon called “Silicon Valley,” and Frederick Terman might well be considered the “Father of Silicon Valley,”[7] William Bradford Shockley (1910-1989) could be considered Silicon Valley’s slightly wacko uncle [8]. Besides his other achievements and quirks, William Shockley has been regarded as the founder of the semiconductor industry. Born in 1910 into a Stanford University professor’s family, William Shockley obtained his Bachelor of Science degree from California Institute of Technology (Caltech) and his Ph.D. in Physics from Massachusetts Institute of Technology (MIT). Working together with John Bardeen and Walter Houser Brattain and other research scientists in the Solid State Physics Group in AT&T’s Bell Labs in the 1940s at Whippany, New Jersey, William Shockley oversaw Bardeen and Brattain’s work when the two scientists co-invented the point-contact transistor. Shockley then independently improved over the point-contact transistor [9]. Shockley, Bardeen and Brattain would soon share the 1956 Alfred Nobel Prize in physics. Meantime, what distinguished William Shockley from his co-researchers Bardeen and Brattain was that Shockley moved to Palo Alto, California and founded in early 1956 William Shockley Semiconductor Laboratory, the world’s first ever semiconductor company to work on silicon-based semiconductor devices.

Located in Mountain View, California, William Shockley Semiconductor Laboratory was funded by Beckman Instruments as a division of Beckman Instruments. The original site for Shockley Semiconductor Laboratory in 391 San Antonio Road, Mountain View, California still bears a historical marker, which reads: “SITE OF FIRST SILICON DEVICE AND RESEARCH MANUFACTURING COMPANY IN SILICON VALLEY. THE RESEARCH CONDUCTED HERE LED TO THE DEVELOPMENT OF THE SILICON VALLEY. 1956.” [10]

William Shockley carefully recruited and assembled for his venture the best team of scientists and engineers at the time. Transistors had already begun to replace bulky vacuum tubes in electronic products, promising new reliability and reduced sizes [11]. However, Shockley's venture did not last too long. As it turned out, the highlight of Shockley Semiconductor's existence may well have been the champagne breakfast to which William Shockley treated his brainy young work force after being informed of his Nobel Prize [12]. In less than two years, he decided that his lab would no longer research silicon-based semiconductors. The group of brilliant scientists and engineers began to defect and start their own company. The most famous of this group consisted of eight prominent figures in the annals of the semiconductor industry, later widely known as the "Shockley Eight" or the "Traitorous Eight" [13], who will be discussed in more detail in the subsequent section.

William Shockley Semiconductor, dubbed as "The most successful failure" in the history of science, technology, and business [14] is a prototype of Silicon Valley entrepreneurship, which, despite falling short of the ultimate goals, left profound effects on the history for the semiconductor industry and on Silicon Valley as a whole. It may not be exaggerating if we say without William Shockley's early entrepreneurial attempt, we would not have had the concentration of U.S. semiconductor industry in Silicon Valley and we would not have had the concentration of the top talent in this industry in Silicon Valley.

In evaluating and summarizing Shockley's early attempt in the semiconductor industry, the following discussion of strengths and weaknesses can be said of this first semiconductor company:

Strengths: Shockley Semiconductor is the result of a watershed event (discovering the transistor) in the field of solid state electronics. It is the first mover in the semiconductor industry and the first company to work on silicon semiconductor devices in a geographical valley the Santa Clara Valley that would come to be known as Silicon Valley. As Gordon Moore quipped, “Shockley brought the silicon to Silicon Valley.” [15] Shockley Semiconductor brought together a remarkable team of top engineers from around the country. The Nobel Prize winning discovery coupled with the best technology constituted the strongest R&D prowess in history of science and engineering. It occurred during the best times to develop such technology with extreme urgency and demand in all electronic gadgetry from military for rockets, missiles, submarines, radar technology to all kinds of civilian use. If Shockley hadn’t come to Palo Alto, there might never have been a Fairchild Semiconductor that in turn spawned over seventy semiconductor companies in Silicon Valley. Overall, William Shockley Semiconductor Laboratory was an important crash course for entrepreneurship, from which the successful Fairchild Semiconductor was forged. For that reason, William Shockley’s contributions continue to be indelible even from today’s perspectives.

Weaknesses: Why did Shockley Semiconductor fail with all these strengths? Here are some of its fatal weaknesses: although William Shockley was a genius in physics, he was a failure in management. Walter Brattain and John Bardeen rated Shockley outstanding at assessing scientific talent and defining a research aim. However, Shockley had never run a company. As some Silicon Valley historians comment, he “didn’t know the first thing” about management [16]. His intense distrust in his employees, his demeaning taskmaster and domineering management style irritated his top engineers including Robert Noyce and Gordon Moore. At a time when the management field was developing in leaps and bounds towards behavioral science and the human relations model with all types of motivation theories as a reaction to Frederick Taylor’s less humane scientific management theory in the mid-1950s, William Shockley was still treating his top scientist team only as mechanisms for pushing forward his scientific research agenda. In addition, Shockley over-emphasized cutting-edge research consistently over commercial productivity. All of these above factors contributed to the doom of his brilliantly founded first semiconductor company. History proves that he would never live to reap any financial rewards from refining his Nobel Prize-wining invention. Later in life, William Shockley devoted his life to being a Stanford professor and to his other endeavors.

III. The Fairchild Eight and Fairchild Semiconductor

If William Shockley Semiconductor Laboratory served to usher in, and also managed to close, the first chapter in the annals of the semiconductor industry, the second chapter started with the Fairchild Eight (aka the Shockley Eight or the Traitorous Eight). When the eight top researchers and engineers realized that William Shockley was abandoning research on silicon-based semiconductors, the eight people group decided to leave the Shockley Lab and start their own company. The famed Fairchild Eight was headed by Robert Noyce, Ph.D. in physics from MIT, who was later to be dubbed as the “Mayor of Silicon Valley.” [17] The other seven included Julius Blank, a mechanical engineer from New York [18]; Victor Grinich, Ph.D. from Stanford, son of immigrant parents from Croatia [19]; Jean Hoerni, an immigrant from Switzerland and a Cal Tech chemist with two Ph.D.s [20]; Eugene Kleiner, an immigrant from Austria and a former manufacturing engineer from Western Electric, who would later become one of the most well-known venture capitalists in Silicon Valley [21]; Jay Last, native Pennsylvanian with a Ph.D. in physics from MIT, who would later become an archeologist and an art writer [22]; Gordon Moore, a native of San Francisco, alumnus of San José State University and of UC Berkeley with a Ph.D. in Physics from Caltech [23]; and Sheldon Roberts, Ph.D. in metallurgical engineering from MIT [24]. In addition to founding Fairchild Semiconductor together, every one of the Fairchild Eight would later on become famous in their respective ways after their collaboration in the Fairchild Semiconductor venture. Their biographies should be written both together and separately one by one to provide further insights to Silicon Valley's entrepreneurship and to render full justice to eight of the most illustrious careers in science, technology and business in American history. That is a subject to be tackled independent of this paper.

Looking for funding on their own project, The Fairchild Eight turned to Sherman Fairchild's Fairchild Camera and Instrument Corporation and formed Fairchild Semiconductor in 1957. According to Fairchild Semiconductor's website:

The Fairchild Eight used $3,500 of their own funds to develop a method of mass-producing silicon transistors using a double diffusion technique and a chemical-etching system. The silicon and germanium mesa allows manufacturers to produce multiple transistors on a single wafer. That was a revolutionary breakthrough. Fairchild Camera and Instrument Corporation invested $1.5 million and on October 15, 1957, Fairchild Semiconductor was born [25]. Once the company was founded, the Fairchild Eight demonstrated entrepreneurial spirit and executed their technical ingenuity with a vengeance. Under that entrepreneurial environment, the Fairchild Eight pioneered new technologies and commercialized what they developed with speed and agility. Robert Noyce developed the monolithic integrated circuit—a miniaturized electrical circuit on a fingernail-sized wafer of silicon. Jean Hoerni took the idea a step further and put a collector, base and emitter all on one plane to form the planar transistor. Hence the modern transistor was born and so was a new industry: the semiconductor industry. Up till today, some fifty years later, the planar process is still the primary method for producing transistors [26]. Just as *San José Mercury News* celebrated, “They [the Fairchild Eight] came, they saw, they conquered. And they created an industry.” [27] In addition to creating an industry, led by Robert Noyce, Fairchild also created what was to become a distinct work environment norm in Silicon Valley and in California: the Silicon Valley style of management, complete with casual dress code, laid back atmosphere [28], and cubicle-size CEO office. Hundreds of high tech companies in Silicon Valley have followed this management style in the last half a century.

While at Fairchild, the eight also made numerous revolutionary inventions in semiconductor manufacturing and processing, resulting in assembly line manufacturing of silicon wafers and semiconductor chips. This process is used widely today by all major semiconductor companies in the world to produce billions of semiconductor chips for today’s use. Fairchild was the first company that introduced the first commercially available integrated circuits and that quickly became one of the major players in the evolution of Silicon Valley in the 1960s.

Although Fairchild Semiconductor Corporation, having gone through several mergers and corporate transformations, has survived even till today with nine thousand employees, its vitality as a major player in the semiconductor industry was long gone. Within a few years of its founding, the Fairchild Eight began to defect. Half of the Fairchild Eight (Hoerni, Last, Roberts and Kleiner) left to form their own company, Amelco, in 1961. The other four also left a few years later. In addition to the eight, many more of the Fairchild employees also left. Those who left Fairchild formed many other companies, known as “Fairchildren.” By 1980, nearly seventy Silicon Valley companies could trace their roots back to Fairchild Semiconductor [29]. In October 2007, Fairchild’s 50th birthday was celebrated in Silicon Valley by Fairchild alumni from all over the country as well as by current semiconductor industry luminaries [30]. True to its advertisement annotation "*We started it all*," Fairchild Semiconductor will be always recognized in history as one of the earliest and most influential entrepreneurial attempts in the annals of the semiconductor industry, which has hence brought immeasurable benefits to humankind.

IV. Fairchildren, Fair-Grandchildren and Some Industry Icons

Former employees of Fairchild directly founded more than twenty semiconductor companies in Silicon Valley, commonly referred to as "Fairchildren," including most of the famous name corporations in the semiconductor industry such as Intel, National Semiconductors, Advanced Micro Devices and LSI Logic. These companies further spawned a few dozen more companies in semiconductor and in other high technology industries. These companies, in their turn, can be dubbed as "Fair-grandchildren." The Fairchildren and Fair-grandchildren together make up a major proportion of the semiconductor industry in Silicon Valley and in the United States.

Among the Fairchild Eight, as mentioned previously, Jean Hoerni, Jay Last, Sheldon Roberts and Eugene Kleiner formed their company, Amelco (Teledyne Technologies Inc), an electronic components, instruments & communications products company. Jean Hoerni also founded Union Carbide Electronics in 1964. Then in 1967, he founded another company: Intersil Corporation, a high performance analog semiconductors company. Julius Blank co-founded Xicor, also a high performance analog semiconductor company which was later merged with Hoerni's Intersil in 2004. After co-founding Amelco, Eugene Kleiner in 1968 together with Hewlett-Packard veteran Tom Perkins formed one of the most influential venture capital firms on Sand Hill Road in Silicon Valley: Kleiner Perkins, later joined by Brook Byers and Frank Caulfield to become the present Kleiner Perkins, Caulfield & Byers. Among the last of the original Fairchild Eight to leave Fairchild were Robert Noyce and Gordon Moore, who took Andrew Grove along in 1968 and founded Intel Corporation in Santa Clara. Wilfred Corrigan, formerly Chairman, President and CEO of Fairchild Camera and Instrument Corporation, founded LSI Logic. Jerry Sanders and Edwin James Turney, both prominent engineers with Fairchild Semiconductors, left Fairchild to found Advanced Micro Devices (AMD), which has remained to be the archenemy of Intel till this day. When former Intel CEO Andrew Grove titled his management book as *Only the Paranoid Survive*, he was partly referring to Intel's continuous and mortal paranoia of AMD [31].

Of all the Fairchild former employees, the most famous are of course Gordon Moore, Robert Noyce and Andrew Grove. They have become the icons and legends of the semiconductor industry. Gordon Moore is truly a visionary in the semiconductor industry. He is credited with the famed industry seminal tenet "Moore's Law." In 1965, Gordon Moore predicted that the number of transistors on a piece of silicon would double every year—an insight later dubbed as "Moore's Law." Intended as a rule of thumb, it has been the guiding principle for the industry to deliver ever more powerful semiconductor chips at proportionate decreases in cost [32]. In 1975, Moore updated his prediction that the number of transistors that the industry would able to place on a computer chip would double about every couple of years [33]. This simple law has inspired Intel and its rival AMD to have kept that pace for almost half a century already since Moore's Law was stated in Moore's 1965 paper. Up till this day, most semiconductor experts continue to uphold this law, although Larry Sumney, CEO of Semiconductor Research Corporation, in a recent discussion, says that around 2018 or 2020, Moore's Law will finally come to an end, because new technical hurdles will make it more difficult for companies to stay on the path of doubling the number of transistors on a computer chip every two years [34]. No matter how long Moore's Law will endure technically, this simple principle and its predicted and realized exponential and exploding phenomenon has played such an important role in changing humankind for almost the last half a century.

Meantime, Robert Noyce, Moore's closest friend and colleague, was credited with the invention of the integrated circuit and the creation of Silicon Valley management style. Not only he was the absolute guru in the budding silicon-based semiconductor technology and innovation, Noyce was considered the nice guy and the employee-friendly executive. He made Intel the first Silicon Valley company with a relaxed working environment, which would become the trademark of high technology companies in Silicon Valley. Today's famed Google organizational culture, characterized by sixteen-hour per day free meals, employees bringing pets to work in pajamas and onsite fitness centers with trainers, can be traced back to Robert Noyce's innovative management style some forty years ago. Today, Intel's worldwide headquarters' gray building with its characteristic blue trims, located in the celebrated address of 2100 Mission College Boulevard in Santa Clara, California was named after its co-founder Robert Noyce.

As the third employee (after Gordon Moore and Robert Noyce), Andrew Grove served as Chairman and CEO of Intel from 1987 to 1998, when the semiconductor industry and the computing industry rapidly developed. Under Andrew Grove's tenure, Intel changed from a manufacturer of memory chips into the world's dominant producer of microprocessors with its market value ballooned from $18 billion to more than $420 billion in 1999 [35], making it, at one time, the world's most valuable company, surpassing even General Electric Corporation and

Wal-Mart. Andrew Grove remained to be the most well-known executive in the entire semiconductor industry until his retirement as Chairman of the Board in late 2004.

V. Evolution of the Business Model in the Semiconductor Industry

In this section, we would like to examine the evolution and development of various business models in the semiconductor industry. Throughout the annals of industry entrepreneurship and changes, the semiconductor industry has witnessed a progression of business models. In general, this progression has resulted consistently in more vertical specialization in the processes of designing, developing, manufacturing and testing semiconductor products. The vertical specialization in the processes further leads to the spatial division of labor at a global scale, which will be discussed further in Section V1 subsequently.

A. The Vertically Integrated Model

In the beginning, the experiments of Bardeen and Shockley at AT&T Bell Labs, which led to the discovery of the semiconductor, were motivated by finding a lower cost and more reliable replacement technology for the vacuum tube. AT&T commercialized its technology entirely through its own products, as semiconductor devices became inseparable parts of AT&T switches, exchanges and later, handset products.

IBM built its highly vertically integrated system 360 mainframe computer around captively manufactured semiconductor devices [36]. Captive manufacturing means that a manufacturing division is created specifically within the same company to provide manufactured products only for the same company. For example, IBM's semiconductor manufacturing division provides semiconductor processors only for IBM's mainframe computers. This was the initial dominant business model for semiconductors. In order to make them, a company had to create a captive subsidiary within a systems company and design the system and the semiconductors, and manufacture the semiconductor chips within the same company at the same time. This vertically integrated systems model pioneered by AT&T and later by IBM was copied by leading Japanese companies such as Hitachi, Fujitsu, NEC and Toshiba and also by leading European companies such as Siemens, Philips Electronics, Groupe Bull and Olivetti.

For a period of time, the vertically integrated model appeared to have its major advantages: the deep knowledge of the design of the system helped in-house producers design products that would work in those systems. Semiconductor design and manufacturing were like an enigmatic form of black art, and having control within one company over all links in the supply chain, that is, over the interactions between the memory chips and the rest of the system was a tremendous benefit. As the semiconductor technology became more diffused and better understood, startup companies began to emerge and grow with newly developed business models, which were different from the vertically integrated model. One of the subsequent models is the integrated device manufacturer (IDM) model.

B. The Integrated Device Manufacturer (IDM) Model

Different from the vertically integrated model, which design and manufacture semiconductor devices for computer systems in-house, the integrated device manufacturer (IDM) business model relies on commercial supplying companies to provide components in semiconductor devices used in the system. The commercial suppliers do not make the final system, but serve as links in the semiconductor industry supply chain, providing semiconductor elements needed by other systems companies. Intel is the most noted example of this newly developed integrated device manufacturer (IDM) model. Its first products were memory products for IBM mainframe computers. Later on, Intel invented the DRAM circuit as a replacement for the core memory that IBM was using in its 360 computers [37]. Different industry players soon followed suit. These commercial suppliers included other smaller companies like Intersil, Mostek, Signetics and National Semiconductor.

The IDM business model competed for many years against the vertically integrated systems model in order to overcome and outweigh the latter's all in-house advantage, as discussed in the previous section. The enigmatic black art of semiconductor design and manufacturing were gradually losing its mystery. Over the subsequent period of time, the knowledge of making semiconductor devices would gradually diffuse and mature, greatly reducing the black art nature of the industry. System architectures also became better understood and de facto interface standards began to develop that would enable customers to plug in memory modules and make them work seamlessly in the system. As these developments took root, the vertically integrated business model's weaknesses became more apparent. Perhaps the biggest weakness was that the high fixed development costs of the capital intensive semiconductors could only be spread over the shipping volumes of the systems of the vertically integrated company.

By contrast, IDM manufacturers could ship their products to a wide range of customers, enabling them to reduce fixed costs. This ability to aggregate volume across the market through serving many customers had another effect as well: IDM companies could justify the addition of new capacity sooner than could many of the vertically integrated companies. This provides IDM companies with access to the latest fabrication technologies, further enhancing their cost advantage. Eventually, the combination of higher market volume and lower costs pushed most systems companies to abandon their captive semiconductor manufacturing efforts or to spin their manufacturing divisions off as independent companies.

The IDM model gradually took over the industry from the vertically integrated model in the semiconductor industry. One particular impetus for this shift was the fabulous success of Intel's microprocessor business. However, just as Intel's microprocessor was reaching enormous volumes, yet another business model was beginning to emerge: the so-called fabless model.

C. The Fabless Design/Foundry Model

The fabless design and foundry model is characterized by the total separation of the semiconductor design process from the semiconductor fabrication. The fabless design firms rely exclusively on external foundries for the manufacturing of their designed integrated circuit chips. The separation of design from manufacturing, or called it the fabless design/foundry model emerged thanks to the ingenuity and tireless efforts of Morris Chang, the Founding Chairman and CEO of Taiwan Semiconductor Manufacturing Company (TSMC) and his colleagues at TSMC. Initially, Chang thought that he could build other companies' semiconductor designs as a stepping stone to developing the scale and capital equipment he would need to develop and manufacture his own designs. Events soon caused him to change his plans. The external fabless customers were lining up at the door, while he and his colleagues were trying to complete their internal designs. Chang soon realized that it was time for TSMC to thrive on a new business model: the foundry model [38]. The following section will discuss this model further in connection with outsourcing and offshoring of the manufacturing functions of the semiconductor industry.

VI. The Foundry Model and the Industry's Globalization: Outsourcing and Offshoring of the Semiconductor Industry

The next chapter in the annals of the semiconductor industry is characterized by the emergence of the foundry model and the industry's globalization.

From the early 1960s, the U.S. semiconductor industry started moving certain supply chain activities to foreign countries in order to take advantage of the relatively inexpensive labor overseas. The success of the initial move, together with the receiving countries' governments' support and the availability of highly skilled labor in these countries have motivated the industry to shift gradually greater number of its supply chain activities overseas. By now the semiconductor industry has formed a fully integrated global supply chain with very high levels of outsourcing and offshoring activities.

Three sequential activities are typically performed in the development and manufacturing of semiconductors: design, fabrication, and assembly/testing. Assembly/testing activities, as the most labor-intensive and least-skilled functions, were moved offshore first, followed by the outsourcing of the capital-intensive fabrication activities to foundries, as was outlined in the previous section. The most skill-intensive semiconductor design activities were the last to be moved overseas.

With Morris Chang's clairvoyance on the foundry model, TSMC experienced an unprecedented booming period in its corporate history. Its foundry model was soon imitated by numerous other companies, including Chartered Semiconductor in Singapore, United Microelectronics Corporation (UMC) in Taiwan, and more recently, Semiconductor Manufacturing International Corporation (SMIC) and Grace Semiconductor Manufacturing Corporation (GSMC) in China.

The foundry model also ushered in the era of semiconductor industry outsourcing, offshoring and full-scale globalization. By now the industry is fully globalized with very high levels of outsourcing and offshoring activities. By definition, outsourcing is the strategy of subcontracting a business process, activity or function, such as product design or manufacturing, to a third-party company and offshoring is the strategy of relocating certain business processes, activities or functions from one's own country to an overseas country. These practices and strategies have allowed semiconductor companies to split manufacturing processes into multiple stages with each stage being performed in the most efficient and cost-effective way. The combined characteristics of high value and light weight made it possible for semiconductors to be offshored to faraway geographic locations with considerable convenience and facility. The semiconductor industry in the U.S. has taken full advantage of these global supply chain management activities, which have enabled the U.S. semiconductor industry to compete effectively in the increasingly competitive global arena, not only based on its superior chip designs, but also based on its low cost leadership strategy.

In the following subsections, we will discuss the three successive stages of offshoring/outsourcing that have occurred in the semiconductor industry: offshoring assembly/testing, outsourcing fabrication, and now offshoring design.

A. Stage One: Offshoring Assembly/Testing

The labor-intensive chip assembly/testing functions were the first semiconductor manufacturing activities to be moved offshore. It was none other than Fairchild Semiconductor that was the first semiconductor company that shifted its assembly/testing overseas in 1961 [39]. Assembly, which typically involves cutting the wafer into chips, requires large amount of less-skilled labor. The abundance of low cost semi-skilled labor in Asian countries motivated Fairchild Semiconductor first to offshore its assembly to Hong Kong. As the assembly process became more and more automated in 1980s, other factors--such as government support, land cost and economic stability--became determinants in the choice of location for semiconductor assembly offshoring. Today, almost all U.S. semiconductor assembly and production activities are shifted offshore, with less than 5% remaining in the U.S. for prototyping and military purposes [40]. The low cost structure achieved by offshoring has enabled U.S. semiconductor companies to sustain their global competitiveness.

B. Stage Two: Outsourcing Fabrication

The second stage in offshoring/outsourcing of semiconductor industry is fabrication which is typically farmed out to overseas suppliers or foundries. Fabrication-- the process used to create chips through a multiple-step sequence of photolithographic and chemical processing, requires substantial capital requirement for building a fabrication plant (commonly referred to as a fab) and acquiring expensive semiconductor equipment.

The emergence of the foundry model can be seen as both a result of emerging fabless semiconductor companies in late 1980s and that of increasing costs of building semiconductor fabrication plants in the U.S. These twin factors caused many integrated device manufacturers (IDMs) which manufactured their own chips previously to outsource their fabrication activities to overseas independent foundries. The foundries were a more cost-effective way to aggregate market volumes to spread the large and increasing costs of semiconductor fabrication over more units than the IDMs could hope to achieve. For example, Elpida Memory, Infineon and Motorola have outsourced to overseas foundries an increasing amount of their chip production [41].

According to IC Insights, a market research firm, fabless sales of IC as a percentage of worldwide sales more than doubled from 6.1% in 1997 to 14.7% in 2003 and the fabless industry has grown from US$9.9 billion in 1999 to US$20.6 billion in 2003. The Fabless Semiconductor

Association (FSA) reported that fabless companies amounted to revenues of over $40 billion in 2005, accounting for nearly 18% of the total semiconductor sales in 2005. In 2006, Fabless IC suppliers secured 20 percent of worldwide IC sales. IC Insights further expects that fabless companies will command at least 25 percent of the total IC market in 2011 [42].

On the other hand, the development of technology has also greatly facilitated the growth of foundries. For example, the widespread adoption in 1980s of the metal-oxide silicon (MOS) manufacturing process enabled the division of labor in the semiconductor industry by providing a more standardized interface between the chip design process and the wafer fabrication process [43]. In the same vein, the growth of third party electronic design automation (EDA) software tools from companies like Synopsys and Cadence Design Systems has also enabled design companies and foundries to coordinate better the transfer of designs into feasible chip layouts that could be manufactured in high volumes with high yields.

The justification for the foundry model is that it is a more efficient use of capital and enables semiconductor companies to concentrate on their core competencies. The total cost of building a new fab has skyrocketed to close to $4 billion. As the fab capital outlay increases, only the largest and most successful semiconductor companies will be able to build new fabs. More and more companies in the industry have decided to outsource the manufacturing portion of their chip products to foundries. As a result they must negotiate for whatever capacity their foundry partner(s) can arrange for them. Having an outside supplier to perform the fab function help U.S. semiconductor companies reduce capital investment and expand sales during periods when such capacity expansion cannot be financed. The resources freed up by outsourcing are invested in company's core competencies, such as design and innovation. This benefit resulted in the rapid growth of fabless semiconductor companies during 1990s [44].

Foundries have also expanded geographically. As the demand increases, IDMs and fabless semiconductor companies have begun to seek alternative foundry suppliers to reduce their reliance on a limited number of foundries. As a result, foundries have mushroomed worldwide. For this capital-intensive process, the incentives for outsourcing are not only the cost of direct labor, but also the proximity to skilled labor, tax advantages, and favorable government regulations. Asia, including Greater China, Malaysia, Korea, Singapore, etc., with the strongest government support, accounts for the lion's share of the worldwide fabrication capacity with the largest two foundries in Taiwan: TSMC and UMC.

1) The Role of Taiwan in the Foundry Model

Taiwan has played a key role in the development of the foundry model. It houses the world's two largest foundries–TSMC and UMC)–which together control over 50% of the global market in 2007 [45].

The establishment of TSMC in 1987 actually marked the beginning of the foundry business on a global scale. According to VISI Research, TSMC was the largest contributor towards the six-year booming of the foundry business between 1995 and 2000, which accounted for more than 66% of the total pretax income of the entire foundry market. TSMC continues to be the market leader and its worldwide share of foundry sales was about 40% in 2007 [46].

Establishing fabs in Taiwan is much less costly than in the United States. As reported by Don Brooks, former CEO of TSMC, it cost about twenty percent more per wafer in the United States than it did in the environment in Taiwan. "The depreciation is the biggest cost. Utilities, (gases, power, etc.) is probably number two. The third big cost is the labor cost (including the management and the engineers), which is less than ten percent of revenue." [47] The Taiwan government has provided preferential policies such as tax holidays to semiconductor firms in the island. These policies are being imitated in mainland China as well in order to lure firms there in the future.

However, the semiconductor industry in Taiwan is more than just these foundries. A varied and rich cluster of semiconductor companies have emerged on the island that represent many specialized firms dedicated to different activities along the entire semiconductor industry value chain. Among them are design houses, foundries, testing houses and packaging companies.

2) The Ascendant Role of China in the Semiconductor Industry

China has experienced phenomenal economic development since it started its economic reform and open-door policy in 1978. Over the past 30 years, it has registered an average annual GDP growth of 9.88%. Hundreds of millions of people have been lifted out of poverty and the overall living standards have improved dramatically. With total foreign trade reaching US$2.55 trillion for 2008 and a foreign exchange reserve of about US$2 trillion, it has emerged as a formidable global power in the world's economic stage [48]. (Please add a cite, numbered [48], even though some popular and well-known data are presented here. right now, there is no [48]). Corresponding to such rapid and sustaining economic development, demand for electronic products such as mobile phones, personal computers, personal digital assistants, DVD players, etc. has increased drastically in this world's most populous country. Such increasing demand provides a major boost to the need for semiconductor devices. This is a critical and unusual feature of the Chinese industry in that its domestic requirements promise to absorb most or all of the new semiconductor capacity in the current decade [49]. According to iSuppli data, the Chinese IC (integrated circuits) industrial revenue increased to $76.5 billion in 2008, from US $19.2 billion in 2003 [50]. China's share of the worldwide IC market increased from 13.7% in

2003 to 29.2% in 2008, according to Gartner's data [51]. This growing demand will require China to rely heavily on the import of semiconductor devices.

The Chinese government has realized the strategic importance of the semiconductor industry for its economic growth. Therefore, it has devoted great resources to support the industry since the late 1990s. With the low production costs, the sizable and fast-growing domestic market and the rising foreign direct investment in China, the Chinese foundry business has also started to flourish. Major industrial players there include Semiconductor Manufacturing International Corporation (SMIC), Grace Semiconductor Manufacturing Corporation (GSMC), Shanghai Hua Hong NEC Electronics Co. (HHNEC) and He Jian Technology and some others. The biggest foundry in China, SMIC, topped Singapore's Chartered Semiconductor Manufacturing Pte. Ltd. for the third place in the worldwide silicon foundry rankings in 2005 after TSMC and UMC in Taiwan, according to the rankings from Gartner Dataquest Inc. [52]. SMIC retained its third place in world foundry ranking in 2007, the latest ranking available [53].

Although Chinese fabs are still making predominantly 4-, 5- and 6-inch wafers, leading companies such as SMIC have started to adopt higher levels of process technologies to build larger wafer manufacturing capabilities. For example, SMIC has built a 12-inch fab in Shanghai, in addition to its two 12-inch fabs in Beijing. The larger wafer fabs are able to provide integrated circuit (IC) manufacturing service at 0.35um to 90nm and finer line technologies than the smaller-wafer fabs.

Emulating the success it has observed in Taiwan with its preferential tax policies and other incentives, the Chinese national and state governments are also offering a variety of favorable policies to entice semiconductor industry-related investment to China. These policies include preferential value-added tax (VAT), preferential enterprise income tax, preferential customs duties and import-related VAT, prolonged periods for the favored policies and limits for depreciation of equipment used in production, among others.

Although much attention has been paid to Taiwan and China since 2000, customers in the semiconductor industry are mainly from North America. For example, about 65% of Chartered's revenue comes from North America and about 75% of TSMC's revenue comes from North America. According to Dr. Kuo from Chartered, “China is still not in the stage using advanced technology yet. After the equipment is fully depreciated in Singapore, then we move it to China to work on legacy business. This reduces both capital cost and labor cost. For foundries in China, their revenue stream is also mainly from outside China.” Echoes of these views are heard from Dr. Rick Wallace, Executive Vice President of KLA Tencor, “China hasn't figured out what they are yet. They are currently playing at the end of the product life cycle, utilizing partially depreciated equipment to service legacy businesses.” [54]

As the trend of globalization of the semiconductor industry looms large and rapid, countries in the Asia Pacific region such as Japan, Taiwan, China and India have identified their key strengths in this space. Taiwan has focused on value added IC design, production and advanced IC manufacturing, while China has relied on low cost manufacturing and regional distribution. India is also a frontrunner in this race with its expertise in the chip design and software development. Over time, each country will make efforts to leverage its advantages to the fullest under ever-changing market and competitive dynamics.

C. Stage Three: Offshoring Design

In recent years, besides offshoring assembly and outsourcing fabrication, U.S. semiconductor companies have also been increasingly shifting chip design jobs offshore. This skill-intensive process has mainly been kept in-house mainly because the U.S.-- especially

Silicon Valley--possesses most of the highly skilled design engineer brain power. However, current trends indicate that, increasingly, several countries in Asia, such as China, Taiwan and India have witnessed growing number of top-ranked design engineers and have offered strong government sponsorship and incentives to design houses. As a result, they have recently been quite successful in attracting semiconductor design processes to their own land.

Outsourcing and offshoring have provided numerous benefits to the U.S. semiconductor industry. They have helped semiconductor companies to focus their core competencies, take advantage of expertise and skills in other parts of the world and further create and sustain competitive advantages in the global semiconductor market. The global supply chain had also provided more opportunities for U.S. semiconductor industry to capture a greater share of the global consumer market. Outsourcing and offshoring practices have also contributed to the high sale growth when domestic revenues do not increase at a desired clip.

Outsourcing and offshoring do have their share of drawbacks as well. A geographically dispersed supply chain is likely to be exposed to different kinds of global risks, including economic, political, and business risks, thus making the management of the supply chain a formidably difficult task. According to a survey by Industry Directions Inc. and the Electronics Supply Chain Association (ESCA), the prevalence of outsourcing in electronics has resulted in companies losing control and visibility across their extended supply chain, creating increased risks to both the outsourcers (original equipment manufacturers and the fabless semiconductor companies) and service providers [55]. Therefore, outsourcing and offshoring, while greatly beneficial to the U.S. semiconductor industry, also present numerous challenges in terms of efficiently managing and controlling the semiconductor supply chain.

Global supply chain management strategies have helped the U.S. semiconductor companies gain their competitive advantage in the intensive international competition. The semiconductor industry, as one of the pioneers to invest in successive stages of outsourcing and offshore activities, has contributed to the development of supply chain management studies. In addition, the semiconductor industry, as the first industry to reply heavily on global supply chain management earlier than other high technology industries, has benefited greatly from the global supply chain management. It has demonstrated a good example of using global supply chain activities and, in its turn, has promoted the development of global supply chain activities for other industries.

VII. Summary

In conclusion, this paper has achieved what it set out to do: presenting 1) two earliest companies in the semiconductor industry: Shockley Semiconductor Laboratory and its characteristics; 2) the Fairchild Semiconductor and the Fairchild Eight; 3) some semiconductor industry icons; 4) the semiconductor industry's evolving models; and 5) the industry's globalization, outsourcing/offshoring and supply chain management. Future research will examine the industry in a more in-depth manner and will provide prognoses of the future of the industry based on the current global economic and industry trends. This paper has taken advantage of the three authors' interdisciplinary expertise and studied the semiconductor industry from historical, entrepreneurial and supply chain management perspectives. It has presented a new paradigm: a multi-disciplinary approach, to study industries in the era of globalization. It is the evolution of the industry increasingly at a global scale that justifies and entails the three perspectives of the approach for the semiconductor industry. It is believed that such an approach can provide valuable insights into the evolution and development of an entire industry. This paper hopes to have stimulated further interest in studies of other industries by using this new approach.

End Notes:

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