The Emergence of Tools Suppliers in the Semiconductor Industry

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Abstract

While the R&D intensive semiconductor tools industry has become pivotal to the advancement of technology and the growth of the downstream semiconductor chip manufacturing industry, this was not always the case. In the early stages of the industry, the chip manufacturers made their own tools in-house. Using data at the initial stages of the industry and a wealth of publicly available information from interviews with industry pioneers conducted as part of oral history projects, I examine how (i) market size (ii) intellectual property protection (iii) geographic proximity to downstream firms, influenced the process of emergence of the tools suppliers.

1. Introduction

An extensive literature spanning many decades has identified a diverse array of factors that influence why a firm might buy an input or component from an outside supplier rather than make it in-house. The factors include market size, geographical concentration of downstream firms, economies of scale in production, transaction costs, asset specificity, complexity of the product, the extent of intellectual property protection, product and market uncertainty, strategic control of input market, technological change, among others.[1] Although the literature has made definite progress in furthering our understanding of the determinants of vertical structure, much work remains to be done in putting forward a tractable and comprehensive theory that can explain when and why each of these factors become relatively more important than others. While a number of econometric studies using firm and industry level data have examined the empirical relevance of these factors, Bresnahan and Levin (2015) point out that testing theories of vertical integration (or vertical specialization) runs into many problems associated with data and

[1] Smith (1776) emphasized the role of market size, and Stigler (1951) build upon Smith's idea to argue that market size plays an important role in determining vertical structure because of the presence of economies of scale in production. Coase (1936) pointed to the central role of transaction costs in determining vertical structure, and Williamson (1971) argued that vertical integration was a way to overcome market failures arising from asset specificity.

measurement. Under these circumstances, detailed historical studies at the industry level, like Rosenberg (1962) and Mowery and Macher (2004), have provided a valuable counterpart to econometric studies. This paper follows that tradition and uses historical accounts of the emergence of specialized suppliers of process tools in the semiconductor industry to shed light on some questions that have been raised in the voluminous literature on vertical specialization.

The semiconductor industry is an ideal industry to study the emergence of specialized suppliers, because production in the semiconductor industry is a combination of well-defined engineering tasks, or processes (see Section 2 for details). Each of these processes requires specialized tools. In the early years of the industry, the pioneering semiconductor firms like AT&T/Bell Labs, Fairchild Semiconductors and Texas Instruments made the tools themselves, but specialized suppliers began entering the industry in the 1960s (see VLSI Research, 1990**)**.

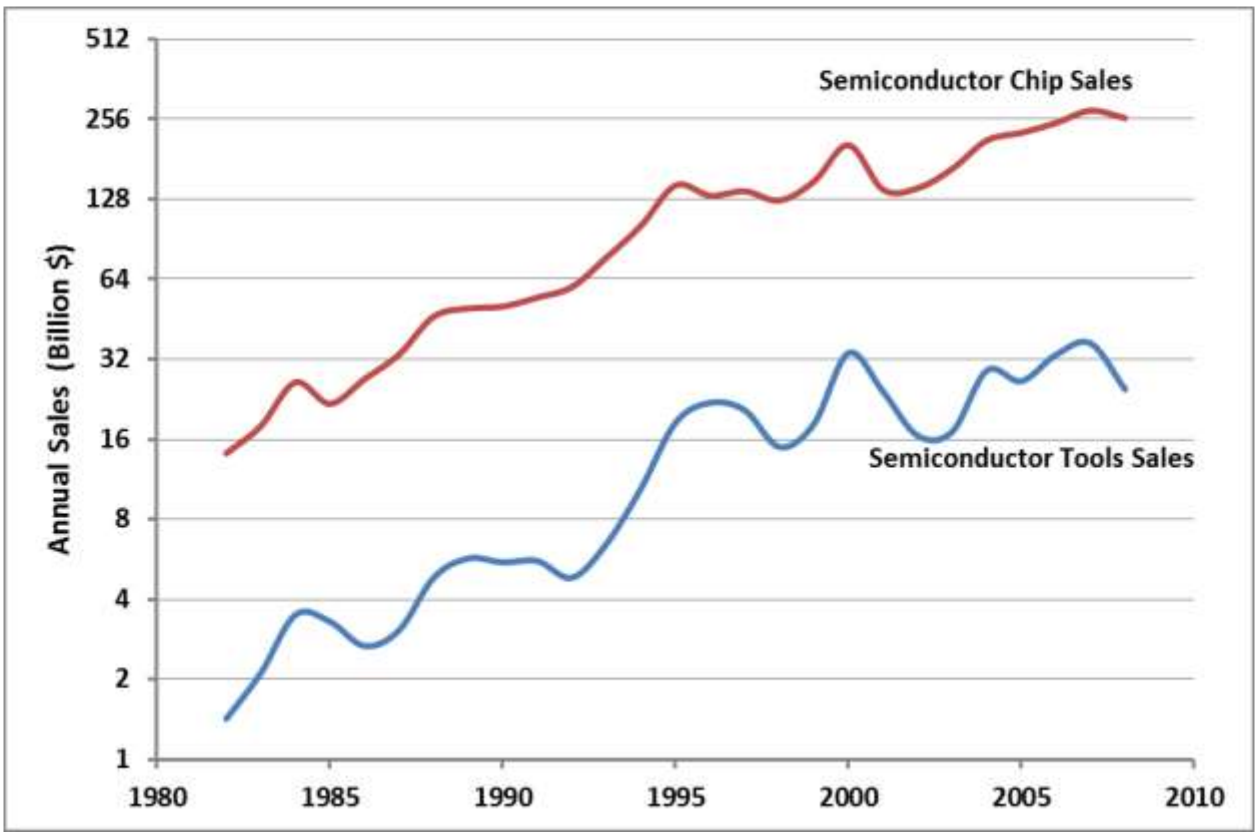

Figure 1: Annual Sales of Semiconductor Chip Companies and Semiconductor Tools Suppliers (Source :Gartner)

Over the years, the semiconductor industry has evolved from being fully vertically integrated in the production of the tools, to being fully vertically specialized. Downstream semiconductor chip manufacturing firms like Intel, AMD, Texas Instruments or Toshiba have completely withdrawn from the manufacture of the process tools, and instead rely on a large eco-system of tools suppliers who develop and manufacture these tools. None of the tools suppliers manufacture chips, and instead confine themselves to the production of tools only. While the mix of tools suppliers show substantial churning, the tools industry itself has grown substantially over time (see Figure 1), with the total industry revenue increasing from around $0.3 billion in 1974 to $34 billion in 2013.[2]

I delve into historical accounts of the evolution of semiconductor tools suppliers to look at three questions that have occupied a central place in the discussion on causes and effects of vertical integration (or vertical specialization). First, I examine the claim originally made in Smith (1776), and more carefully laid down in Stigler (1951), that the level of specialization is limited by market size. Second, I evaluate the argument by a number of authors, including Teece (1986), that the possibility of loss of intellectual property can be factor motivating firms to vertically integrate. Third, I look at the proposition, first made in Marshall (1920), that specialized suppliers are more likely to emerge (and firms are more likely to be vertically specialized) in locations close to downstream firms.

While a quantitative analysis of these questions would require historical data that are perhaps impossible to get, and would run into many of the problems mentioned in Bresnahan and Levin (2015), there is a wealth of anecdotal documentation on the origins of the different supplier companies in the industry. Since the semiconductor industry has become the poster child for rapid technological progress, various institutions that were associated with the industry (including universities, trade associations and professional scientific associations) have put in a great deal of effort to document the industry's history, and their individual roles in this history. These historical accounts provide a multi-faceted and in-depth account of the early years of the industry. In this paper, I rely primarily on information available in the transcripts of interviews conducted with pioneers of the industry, collected and made publicly available by the Silicon

[2] The estimate of $0.3 billion in 1974 is from VLSI Research (1990), and the estimate for 2013 is from a press release published by Gartner, available here http://www.gartner.com/newsroom/id/2701117.

Genesis Project at Stanford University, the Semiconductor Equipment and Materials Industry (SEMI) Oral History project, the AVS Historical Interviews prepared by the American Vacuum Society and the Chemical History of Electronics prepared by the Chemical Heritage Foundation.[3] I complement the information from these interviews with data collected from a number of sources, including Compustat, Gartner, and online articles and press releases.

Although not quantitative, the information in the interviews tell a surprisingly coherent narrative on the three issues raised above regarding the emergence of specialized process tools suppliers. For the first question, I present evidence that in the case of the semiconductor industry, market size was indeed a factor limiting the entry of suppliers in the initial stages of the industry. Second, I find that fear of loss of intellectual property was not a major concern of the chips firms with regard to whether or not outsource the manufacturing of tools, and chip firms in fact actively supported the diffusion of innovations that they had developed by providing these innovations to the tool suppliers. Finally, the role of geographical proximity to downstream firms varied across equipment categories, with the level of technical sophistication playing a crucial role. While the effect of being close to the downstream firms was evident in the emergence and growth of suppliers for some of the less scientifically advanced tools, distance was not an inhibitor for the more sophisticated tools, where superior technical proficiency allowed suppliers to sprout and flourish far away from the downstream firms.

There a number of industry studies that has focused on the causes and consequences of the emergence of specialized suppliers. One of the earliest of these studies is Rosenberg (1963), who documents the emergence of specialized suppliers of machine tools in the U.S in the 19th century, and the role played by the machine tool suppliers in promoting technological development in a number of industries like textiles, railroads and guns. Macher and Mowery (2004) examine the emergence of specialized suppliers in the computer, semiconductor and chemical industries, and the differences in the pattern of vertical specialization across different stages of the industry lifecycle. Langlois (2000) studies the same industry studied in our paper,

[3] Silicon Genesis Project is available at http://silicongenesis.stanford.edu/. The SEMI Oral history project is available at http://www.semi.org/en/semi-oral-history-interview-archive. The American Vacuum Society's Oral History Project is available at https://avs.org/About/History/Historical-Interviews. The Chemical History of Electronics is available at http://www.chemheritage.org/research/institute-for-research/oral-history-program/projects/chemical-history-of-electronics.aspx.

the semiconductor tools industry, and examines how the emergence of standards and modular architectures can affect firm competitiveness in the presence of vertical specialization. Arora and Gambardella (1999), in their study on the evolution of the chemical industry, document the emergence of Specialized Engineering Firms in the industry, and the role played the firms in the growth of the industry. Our paper complements the above papers and focuses on some key questions that have been raised in the literature on vertical structure using historical information from the semiconductor industry[4]. The next section provides a brief outline of the manufacturing process in the semiconductor industry, and the important role of process tools in the production of semiconductor chips.

2. Semiconductor Manufacturing and its Constituent Processes

Semiconductor chips (or integrated circuits) have emerged as the linchpin of modern electronics because a semiconducting material has the attractive property that it is not a good conductor of electricity (an *insulator*) in its pure state, but it can be turned into a conductor by introducing impurities (also called *dopants*) into it. The property of being able to transition from being an insulator to a good conductor of electricity makes semiconductors attractive in making switches (*transistors*), the basic component of most modern electronic devices. The process of controlled introduction of dopants involves a series of processes, a stylized representation of which is shown in Figure 2.

[4] The semiconductor industry has been used by other authors to investigate questions on a variety of topics. Tilton (1971) uses the semiconductor industry to study the diffusion of technology across countries. Malerba (1985) uses the industry to study the causes of differences in industry evolution across countries. Flamm (1996), Macher and Mowery (1998) and Langois and Steinmueller (1999) use the industry to study the impact of different factors (e.g. government policies), on the evolution of competitiveness, both among firms and among nations. Macher and Mowery (1998) and Irwin and Klenow (1994) use the industry to study the causes and effects of learningby- doing and technology spillovers. Aizcorbe (2005), Aizcorbe and Kortum (2005) and Aizcorbe, Oliner and Sichel (2008) examine the factors determining the rate of price declines and the rate of technological progress in the semiconductor industry.

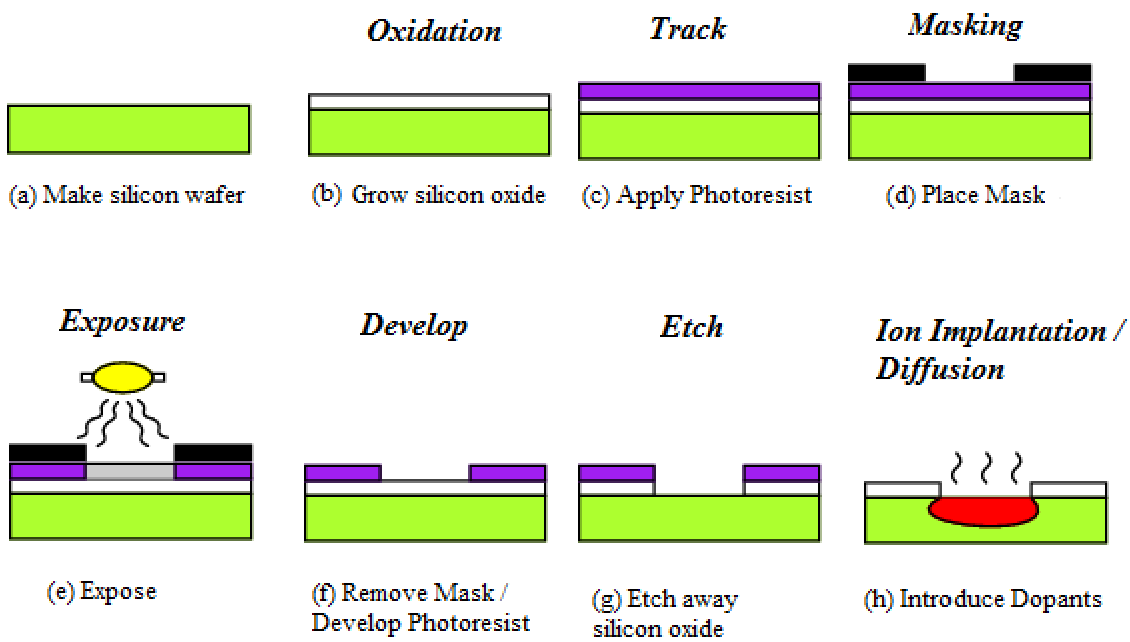

Figure 2: Semiconductor Processes

Notes: Each of the above processes require specialized tools, and downstream chip firms depend on a large eco-system of tools suppliers to perform the R&D and manufacture of the tools.

The semiconducting material, silicon, is first refined to have a crystal structure amenable to making transistors (process a), the resulting silicon disks (called *wafers*) forming the substrate for the subsequent processes. The pure silicon wafers are made to react with oxygen in a furnace to form a layer of silicon oxide, which is an insulator (process b, *Oxidation*). To introduce the impurities that make the silicon conduct electricity, very small windows have to be made on the insulating silicon oxide layer. These windows are made using the lithography process, which is very similar to photography. First a material that is sensitive to light called photoresist is spun on to the insulating layer (process c, *Track*). Then a mask which contains the pattern of windows is placed above the photoresist (process d, *Masking*), and the photoresist is exposed to a light source through the mask (process e, *Exposure*). When light falls on the regions of the photoresist exposed through mask, it alters the photoresist, and the altered regions are removed using chemical processes (process g, *Develop*), a process similar to developing a photograph. Next, the insulating silicon oxide is etched away from under the exposed windows (process h, *Etching*). Finally, the dopants are bombarded into the substrate through the exposed windows (*Ion

Implantation) and are pushed further in (process j, *Diffusion*). During these processes many intermediate layers have to be put on the surface, and this is done through the *Deposition* process. The manufacturing steps above - *Oxidation*, *Track*, *Masking*, *Deposition*, *Exposure*, *Etching*, *Ion Implantation* and *Diffusion* form the backbone for making semiconductor chips.

In a semiconductor manufacturing plant, each of the processes above is implemented using a tool developed specifically for implementing the process. Figure A1 shows a picture of process tools used for exposure, deposition, etching and track. Modern semiconductor tools are technologically sophisticated and incorporate discoveries at the cutting edge of scientific fields like optics and materials science. The tools are also very expensive, with the prices for some tools reaching up to tens of millions of dollars per tool. The tools industry is a fairly large industry, with revenue reaching billions of dollars since the early 2000s (see Figure 3).

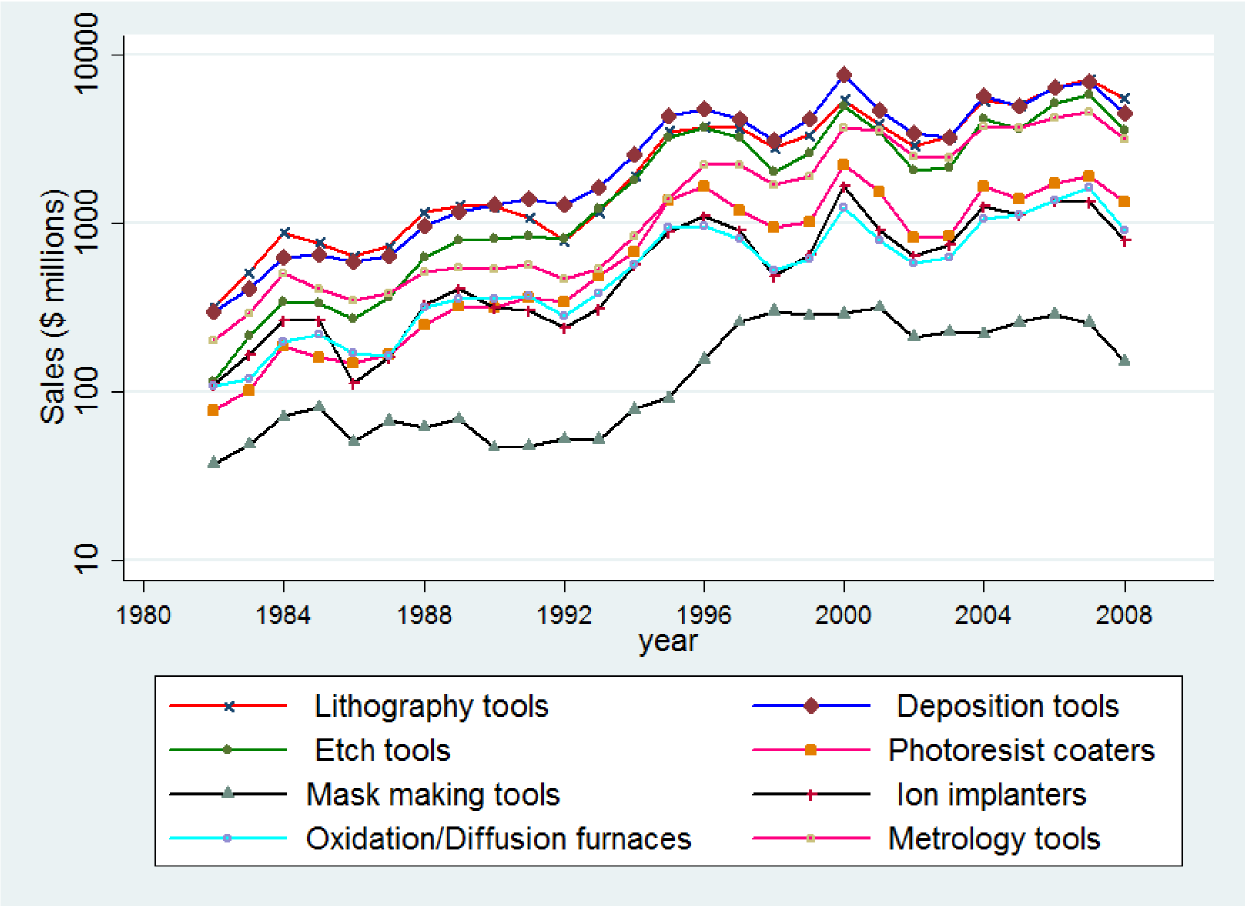

Figure 3 : Annual Sales of Tools Suppliers for each Process (Source: Gartner)

The specialized suppliers of tools are central to the growth of the semiconductor industry. As Pillai (2013) shows, the march to smaller transistor sizes is the driving force behind Moore's Law, and the growth of all technological and economic variables in the industry. The transitions to smaller transistors require improvements in the processes described above, and the tools suppliers play the critical role in undertaking the R&D and the making the outcomes of the R&D, embodied in new vintages of tools, available to the downstream chip manufacturing firms.

The semiconductor tools industry was non-existent in the 1950s, and the next section traces the gradual emergence of the industry during the 1960s and 1970s.

3. The Emergence of the Tools Suppliers

The evolution of the semiconductor tools suppliers is tightly connected with the evolution of the downstream semiconductor chip manufacturing industry. The chip manufacturing industry has its origins in the invention of the transistor in 1947 at Bell Labs, which was co-owned by AT&T and its manufacturing concern, Western Electric.[5] In 1956, William Shockley, one of the inventors of the transistor at Bell Labs, set up Shockley Semiconductor Laboratories to commercialize the invention.[6] In 1957, eight engineers at Shockley Semiconductors left to start a new company, Fairchild Semiconductors, which subsequently generated a number of spin-off companies.[7] In 1953, another Bell Labs employee, Gordon Teal, left the company to join Texas Instruments, taking with him the knowledge of making transistors. The early years of the semiconductor chip industry, as well as the upstream tools industry, was heavily influenced by the decisions of these three companies – AT&T-Bell Labs-Western Electric, Fairchild Semiconductors and Texas Instruments.

[5] Several improved versions of the transistor have been developed since its invention at Bell Labs - point contact, grown junction, alloyed junction, surface barrier, the diffused transistor, and the planar transistor.

[6] See Riordan (2007) for an account of the role that AT\&T-Bell Labs, Shockley Semiconductors and Fairchild Semiconductors played in the development of the industry. Shockley Semiconductors played less of a direct role when compared to the other two, but provided the founders of Fairchild the learning experience from which they build successful semiconductor devices. Shockley set up the company in California, thus igniting the process that led to the development of the Silicon Valley. Shockley Semiconductors was founded as a part of Beckman Instruments, a leading instrumentation company at the time.

[7] Some of the prominent spinoffs include Intel, AMD, Signetics, Amelco and National Semiconductors.

In the early 1950s, there was very little known about how to carry out the processes described in Section 2 in a manner that could be scaled up for manufacturing. The three pioneering companies, AT&T-Western Electric-Bell Labs, Fairchild Semiconductors and Texas Instruments not only developed industrial versions for these processes which had until then been done only in labs, but they also developed initial versions of many of the tools, setting the stage for the emergence of the tools suppliers. A few other chip manufacturers also played a role in developing and improving the tools, especially Hughes, Sylvania, Westinghouse, General Electric, Transitron and Sprague in the 1960s, and IBM and Motorola in the 1970s.

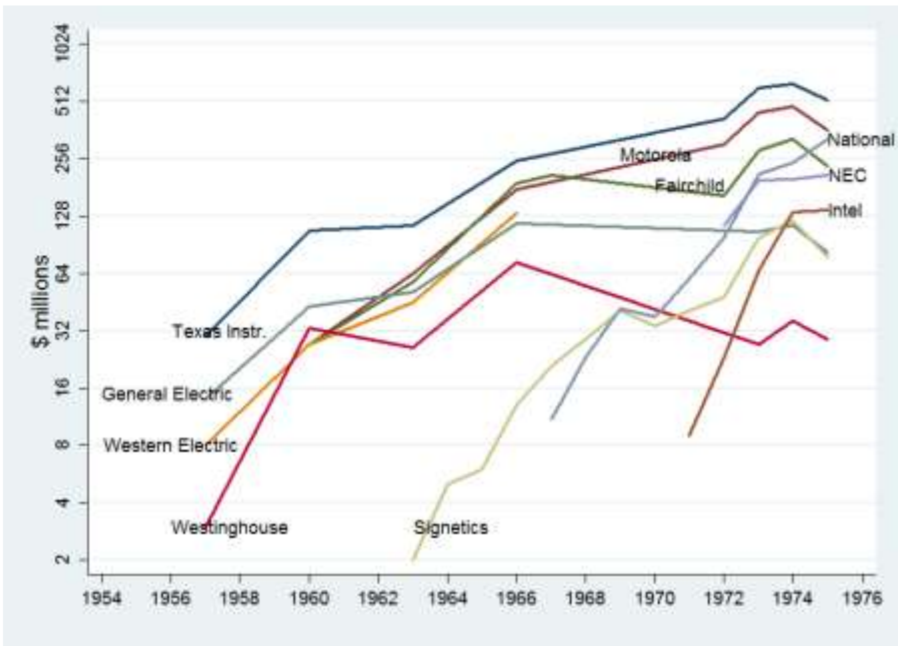

Figure 4: Leading Semiconductor Chip Manufacturing companies

Notes: Western Electric (AT&T/Bell Labs), Texas Instruments and Fairchild were three of the pioneering companies who played an important role in the development of the transistor and different processes required to manufacture semiconductor chips. Source: Compustat, Tilton (1971) and Gartner.

Our approach is to use information from interviews with industry leaders who were at the helm of these companies during the early years, as well as with those who were involved with the starting up the supplier companies. These interviews reveal surprisingly consistent answers to the three questions raised in the introduction. I start with the role that market size played in the emergence of specialized tools suppliers.

4. Factors Affecting the Emergence of Semiconductor Tools Suppliers

4.1 Vertical Structure and Market Size

Smith (1776) and Stigler (1951) argue that the extent of vertical specialization in an industry is limited by the extent of the market. Stigler contented that vertical specialization is a result of economies of scale, and hence limited by the extent of the market. In the initial stages of an industry, firms in the industry would have to make all the capital equipment and materials themselves, because specialized suppliers would not find it profitable to enter the market, given its small size. Stigler’s contention finds support in the emergence of the semiconductors tools suppliers.

There are significant economies of scale in the tools industry, arising from the upfront R&D that invariably has to be done to develop the next generation of each tool. As Figure 2 shows, the tools companies spend between 10% and 20% of their revenues on R&D, with individual R&D expenditures running to hundreds of millions of dollars annually. These large R&D sunk costs that have to be incurred suggest that potential tools suppliers would be hesitant to enter if market size is not large enough to generate revenues that can pay for these sunk costs. This was indeed the case, and founders of leading downstream chip manufacturing firms like Fairchild and Texas Instruments recount occasions when they were rebuffed by potential suppliers, citing the small size of the market.

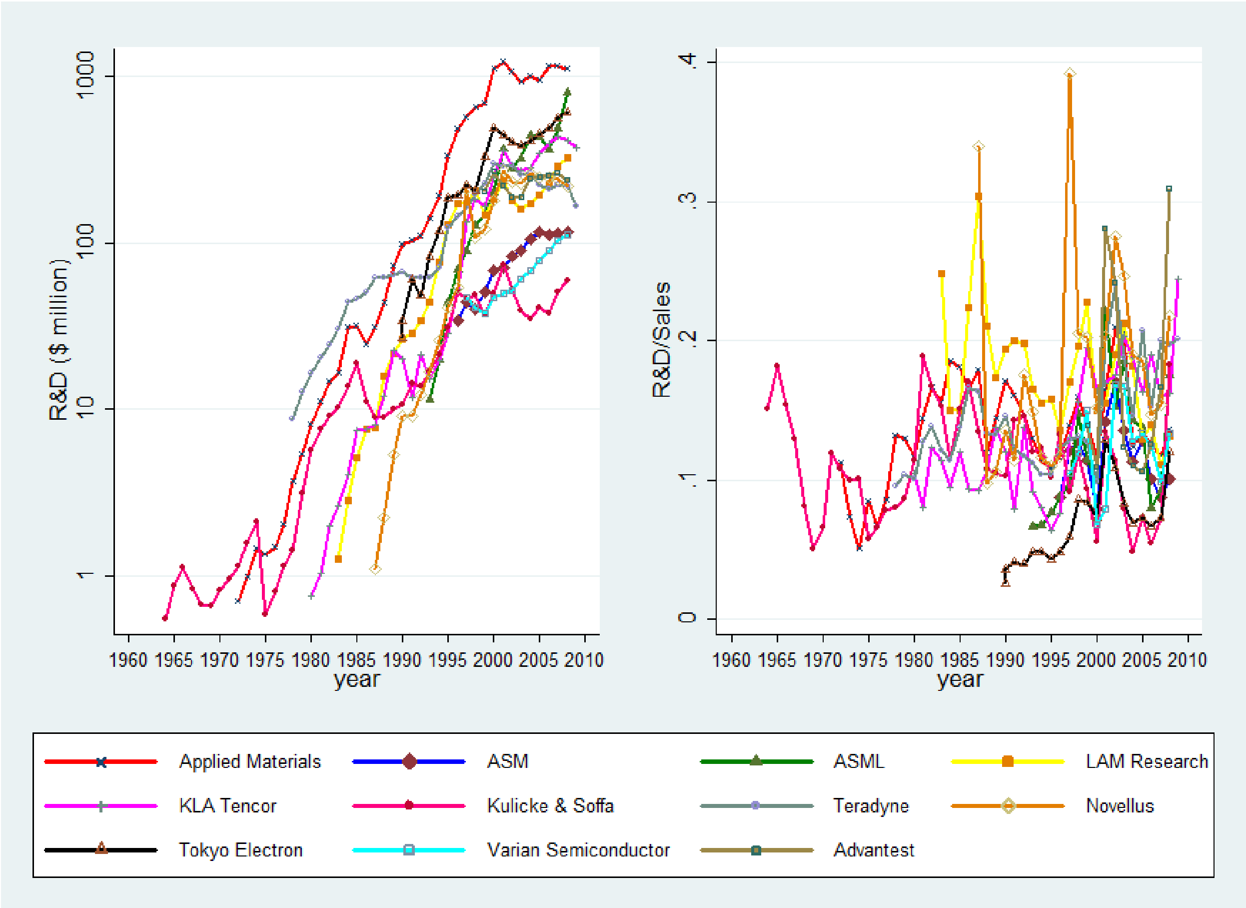

Figure 5: Annual R&D expenses and R&D/Sales ratio of leading semiconductor tools suppliers.

Notes: The suppliers were the eleven of the top fifteen suppliers in 2010. The remaining four (Canon, Nikon, Hiatchi Heavy Engineering and Dainippon Screen) were left out because they are large conglomerates who do not reveal their R&D expenditures on semiconductor tools. (Source: Compustat)

Julius Blank, an engineer at Shockley Semiconductors and later a founder of Fairchild Semiconductors, describes his futile attempts to purchase diffusion equipment from outside suppliers:

> *"Well, we had to make everything because nothing was available. We were using furnaces that were basically laboratory type furnaces for diffusion. And, you know, these were clearly too small... And you really have to have a sturdy, robust*

furnace with very good controls to make sure that over a long period of time nothing changes. I couldn't get anybody to build one for me. I went around personally to a number of manufacturers trying to get them to do it. And they just [said] the market's not big enough. Well, they were right. At that time it wasn't. But we were sort of forced into doing this. We made our furnaces for a long time."
- Blank (2008).

The situation was similar at Texas Instruments. In the words of Jay Lathrop, who was a member of the team that made the first integrated circuit at Texas Instruments:

"At that point you couldn't buy equipment to make ICs (integrated circuits). We made our own diffusion furnaces, deposition equipment, mask making facilities, photo resist exposure stations, etc. Everything had to be made from scratch" - Lathrop (1996).

Given the reluctance of potential suppliers to build the required equipment, the path followed by these pioneering firms was to hire scientists who had knowledge in the scientific fields related to each of the processes. Jay Last, one of the initial hires at Shockley Semiconductors, and later a founder of Fairchild Semiconductors, recounts the situation at Fairchild:

"There were eight of us. We all had different skills but among the group we had all the necessary skills and it was a completely cooperative effort.... Bob Noyce and I were involved with a step-and-repeat camera (mask making and exposure)... Jean Hoerni was involved with diffusion and he had a great deep, physical insight into a lot of things about the physics of semiconductors. Gordon [Moore] also was involved with diffusion. He made a great contribution, he was the only one that knew how to blow glass so he was making all the jungles for the diffusion and he also was involved with metal evaporation. Sheldon Roberts just went off and got us right into the silicon crystal business. Vic Grinich was the one that really knew what transistors were and what they were used for and he set up all the testing facilities. Julius Blank was in charge of the facilities and also making

equipment. Gene Kleiner was a magnificent equipment manufacturer, great machinist" - Last (2007).

Thus, one man made the silicon crystal, another made the diffusion furnace, yet another made the exposure tool, and the important business of making the chip was accomplished by putting together the skills of a number of scientists, reminiscent of Adam Smith's famous description of the pin factory in eighteenth century Britain. These engineers had background knowledge in the processes, but they had no equipment available to implement these processes, as potential suppliers rebuffed requests to make the tools, citing the small size of the market. Hence, they were forced to develop their own equipment, quite in line with the argument made in Stigler (1951).

4.2 Vertical Structure and the Protection of Intellectual Property

The inability of firms to protect their innovations from diffusing to potential competitors, especially under weak intellectual property protection regimes, has often been cited as a reason why firms might prefer to make the inputs in-house rather than depend on external suppliers. In contrast to this hypothesis, the interviews with industry pioneers reveal a surprisingly different perspective, where the consistent pattern that emerges is one of the downstream chip firms working actively transfer the technology to potential tools suppliers, to facilitate the entry of these suppliers into the market.

The downstream chip firms aided the emergence of the tools suppliers in two ways. First, they encouraged the formation of the new firms by their own technicians and engineers who had gained knowledge of the relevant processes. Second, they actively worked with companies who possessed expertise that was closest to what was required to implement each process, and imparted to them the additional knowledge required to build the tool for each process. These companies ranged from industries as disparate as photography, nuclear engineering and industrial furnace manufacturing. The chip manufacturing companies provided these potential suppliers with the know-how and training necessary to transition into semiconductor tool production.

Gordon Moore, the proponent of Moore's Law and one of the founders of Intel, explains the rationale of semiconductor companies through an example of his support for Electroglas, one of the first tool suppliers founded by Arthur Lasch, who was a technician working with Moore, at Fairchild Semiconductors:

> **Gordon Moore***: Art Lasch was my technician for a good part of the time there. He helped me build the furnaces. And then when we developed the gold ball bonding technology... we had a problem that the capillaries kept getting plugged. So we had to have a significant supply of these. Art became very good at making these things. So he was encouraged by our production people – Gene Kleiner in particular, who was in charge of that – essentially to moonlight and make glass capillaries on the outside and deliver them to us. Well, that business grew, and Art next upgraded the design of the furnaces we'd built at Fairchild and started supplying furnaces also from his company, Electroglas. And that was really the first company I know of that was specifically set up to deliver equipment to the semiconductor industry...*
> **Interviewer***: So you started buying from Electroglas eventually and stopped making your own?*
> **Gordon Moore***: Yes. And other people got into the furnace business also. But that's been repeated over and over again, that a company dedicated to supplying the equipment that has a broad market ends up doing a better job than an in-house equipment supply capability can. So, when we set up Intel, we decided we'd do nothing on equipment internally, we'd work with the vendors, and* ***even if this resulted in technology we developed getting transferred to the rest of the industry, it would be the most effective way for us to continue to grow****"* - Moore (2008).

Pillai and Kim (2017) develops a model that brings out the underlying mechanism behind the motivations of the chip manufacturers in supporting the emergence of specialized suppliers. Suppliers undertake the responsibility of doing research that is common across all firms, and in that way serve as an alternative to joint research ventures. Each chip manufacturing firm's net benefit from doing this common research in-house gets less as the number of firms in the industry increases, since increased competition hinders the firm from reaping the full rewards of its research. On the other hand, a common supplier's benefit from doing the same research gets higher as the number of downstream firms increase, because the supplier can now sell more units of the tool embodying the outcomes of the research. Given this, the supplier will invest more in R&D than an individual downstream firm would, and hence produce a better quality tool. It is thus in downstream firm's interest to encourage the formation of specialized suppliers, even if buying tools from these suppliers would not have been the lowest cost way of getting the tools in the beginning. Note that this effect is not dependent on any learning effects in production.

There are many more examples in the interviews that support the argument above, and show that Moore's view was a commonly accepted one among the industry pioneers. In 1974, AT&T developed a novel technology (called EBES) for making masks (used in process d in Figure 2) using electron beams, which significantly reduced the number of steps involved in mask making. Although AT&T-Western Electric was still producing semiconductor chips, and anticipated considerable use of new electron beam tool in its production, it chose to license the enabling technology to two potential suppliers, ETEC and Extrion. Alles and Thomson (1987) from AT&T-Bell Labs recount the thinking behind AT&T-Bell Lab's decision:

> *"The commercial EBES-like electron-beam pattern generators have displaced all of the optical pattern generation systems in AT&T Technologies Systems (formerly Western Electric) mask shops... Their performance and acceptance have surpassed both our original goals and best expectations. The long-term need for more of these pattern generators to meet our mask making needs was recognized in the late 1970s when the EBES design was licensed to ETEC and Extrion. We at AT&T Bell laboratories realized that ETEC and Extrion would pursue an aggressive program of evolutionary development and that we could be assured of a supply of compatible (although probably better and faster) EBES-like systems from these vendors in the near future."*

A similar instance occurs in the emergence of diffusion furnace suppliers (process h, in Figure 2). In the manufacture of diffusion furnaces, one of the earliest suppliers was Thermco Systems, the inventor of the Pacesetter diffusion furnace which found widespread acceptance among the chip companies. Thermco developed the product, and its successors in the Pacesetter series, in close collaboration with Texas Instruments and Motorola. The founding president of Thermco, Karl Lang and one of the initial employees Alfred Giese, recall the role played by Texas Instruments and Motorola in the development of Thermco's diffusion furnaces:

> ***Giese****: They (Texas Instruments) more or less designed their own custom furnace and we built it for them, they directed us how to build it for them... Double thermocouples was another thing, if the first set burned out the second set took over. That was all TI (Texas Instruments) designed stuff.*
> ***Interviewer****: Were you able to use that for your other customers?*
> ***Giese****: For those companies that wanted to pay for it, yes, we used those features for other semiconductor guys.*
> ***Interviewer****: And Texas Instruments didn't mind?*
> ***Giese****: No, not at all. In those days it was like ... they were quite helpful as a matter of fact. There was no, "don't tell anybody else." It was also when Motorola helped us build the first laminar flow load station because none of that existed before... Motorola helped develop that one"* - Lang (2006).

Another example is from the Ion Implantation equipment segment, and the role played by Sprague Electric, in the emergence of the ion implanter suppliers. Sprague was a company that had entered semiconductor chip production in 1950s, but was not as successful as Texas Instruments or Fairchild. As Lecuyer and Brock (2009) describes, Sprague had difficulties in perfecting the diffusion process that was essential to introducing the dopants. Driven by this weakness, Sprague focused on developing better ion implantation techniques to introduce the dopants into the silicon substrate. After having developed better designs, Sprague did not pursue and manufacture the tool, instead approached a smaller company in Texas, Accelerators Inc, which was a spinoff from Texas Nuclear Corporation looking to leverage their expertise in nuclear engineering. Sprague provided its implanter design to Accelerators Inc., and also allowed

Accelerators Inc. to sell the implanters based on the design to other companies. Accelerators became an important supplier of ion implanters to semiconductor firms in 1970s.

As these example demonstrate, the downstream chip firms were not only not worried about how intellectual property might leak out through suppliers, they were quite happy to let the suppliers have that technology and use it to make equipment that was subsequently sold to other competing downstream firms. What was more important to them was to ensure that the supplier had the incentive to enter the industry and to continue to invest in R&D to make the next generations of these tools.

4.3 Vertical Structure and Geographic Proximity to Downstream Firms

Marshall (1920) argued that suppliers are likely to emerge in places where the downstream firms are concentrated. Subsequent authors have argued that geographical proximity not only facilitates the easy transport of components and parts, but also the flow of ideas. How important was geographical proximity to downstream firms for successful entry by suppliers in the semiconductor tools industry?

In the very early stages of the industry, the role of proximity to downstream firms, and the flow of information and ideas that proximity facilitated, was clearly evident in the emergence of many suppliers. As the technical sophistication of the tools grew, technical competency clearly dominated over geographical proximity and suppliers sprouted in places far from where the downstream firms were located.

The role of geographical proximity in the early years is perhaps best illustrated by the entry of Kulicke and Soffa into the semiconductor tools industry in 1956. Kulicke and Soffa was perhaps the first outside supplier (not a spinoff from a downstream firm) to enter the tools industry. Below is an excerpt of an interview with Scott Kulicke, a former president of the company and the son of one of the founders, Fred Kulicke:

> *"And the company (Kulicke and Soffa) started making special machinery for anybody who walked in the door. Initial equipment included machines for putting*

> *string handles on paper bags. I don't know if they're still in existence, but there's a company called the Metal Edge Box Company, making metal edge boxes, all kinds of odds and ends. And along the way…Bell Labs was in the process of building the first commercial transistor and they needed all kinds of special fixtures. Allentown [Bell Labs' headquarters] was just up the road. They would come down and say, "Fred, can you make me a thing to do this, or make me a thing to do that." They'd build it for them and then they went on to the next project. But then Bell Labs started to license transistor technology to companies that also built transistors. On the way back from Allentown they'd stop in Philadelphia [Kulicke and Soffa headquarters] and say, "We saw you had this, and this, and this in Allentown, we'd like one too. So the company backed into what became the first commercially available semiconductor production gear."*- Scott Kulicke (2004).

Being down the road from Bell Labs, and on the route of engineers from other companies who traveled to Bell Labs to learn about the transistor technology that they had licensed from Bell Labs, was the principal reason why the two-man, odd-jobs engineering firm of Kulicke and Soffa managed to enter the semiconductor tools business. Sixty years after its entry, Kulicke and Soffa still operates as a tools supplier, with over a half a billion dollars in revenue in 2015.[8]

The manufacture of deposition tools was another instance where the pioneering semiconductor chip companies utilized the capabilities existing in the region that grew to be Silicon Valley, the predominant geographical cluster for downstream semiconductor chip manufacturing firms. In 1950s and 1960s, the region had a number of companies involved in radio and vacuum tube engineering with expertise in vacuum coating of materials (see Lecuyer (2007)). Because of the pre-eminence of these companies, such as Eitel-McCullough, Linton and Varian Associates, a number of small companies had sprung around the region, with expertise in vacuum coating of materials. Many of these companies, leveraged their vacuum coating experience and proximity to

[8] See Kulicke and Soffa Annual Report for the year 2015.

the chip manufacturers to enter the deposition tools industry.[9] Varian Associates, for example, remained a leading supplier of deposition tools to the semiconductor industry for many decades.

Geographical proximity was also crucial for the entry and growth of the most successful deposition tool supplier, Applied Materials, in 1967.[10] Applied Materials was founded by Michael McNeilly, who used his expertise at Union Carbide Electronics in Buffalo (New York) to set up Apogee Chemicals, supplying silane gas and other chemicals to budding semiconductor companies in the Silicon Valley region. He subsequently started Applied Materials, forging a close working relationship with Fairchild, who played an important role in developing the initial products at Applied. In the words of McNeilly:

> *"Very early on at Apogee, I became involved with Fairchild which was really the fountain head of the leading edge of IC technology at the time. And that's where I got to know Gordon Moore and Bob Noyce and a lot of the guys that were working on the line. I wound up playing basketball for Fairchild. That's how I really got to know the production process guys. The Wagon Wheel, basketball, silicon precursors. Fairchild did a lot of the work for me. I'd bring samples in the back door and go around to the front door. If it was fine, they've give me a purchase order and I'd write an invoice and we'd have a transaction in one day. And from that it became obvious to me that the industry was populated by guys that were very, very smart -- the EEs, a lot of physicists, device and electronic guys. But they really didn't understand chemistry. They didn't understand the handling of chemicals for processing semiconductors. And it became obvious very quickly that the future of semiconductor device manufacturing was going to be based on their ability to utilize a variety of hazardous chemicals and other*

[9] The early deposition tool companies that supplied Farichild and its spinoffs in 1960s included Davis and Wilder Manufacturing (see Oral History at American Vaccum Society, DavidWaits) and Varian Associates.

[10] The company started by making deposition tools which used chemical reactions to deposit materials (called CVD, or Chemical Vapor Deposition), in contrast to most other companies at that time who were using physical methods (vacuum coating, evaporation) for deposition.

materials for device production and that that was not in place at that time."- McNeilly (2004).

The entry of Applied Materials, and its closeness to Fairchild, illustrates the role that geographical proximity played, not only in facilitating the flow of components and ideas, but also in identifying market opportunities available for suppliers. Applied Materials has grown tremendously since its inception, and is currently the largest firm in semiconductor tools industry, with annual revenue of $9.6 billion in 2015.[11]

As semiconductor manufacturing technology advanced, however, geographical proximity became less important. Suppliers whose technical capabilities were more advanced began to displace many of the incumbents. This was perhaps most striking in the market for Exposure tools (process e, in Figure 2). The two early entrants in the market were two suppliers whose entry was described earlier - Electroglas and Kulicke and Soffa. Electroglas was a spinoff from Fairchild and maintained a close working relationship with, and geographical proximity to, Fairchild. Kulicke and Soffa, as we have seen earlier, came into the business of semiconductor tools, primarily because of geographical proximity to AT&T-Bell Labs. The initial exposure tools (or lithography tools as they are often called) were more of mechanical devices, with a level of technology that could be handled by firms like Electroglas and Kulicke and Soffa.

As semiconductor technology advanced however, it became imperative for exposure tool companies to have cutting edge knowledge in the scientific field of optics. Advances in semiconductor technology was essentially driven by reduction in size of transistors, and to make smaller transistors it was necessary to make exposure tools that can produce and manipulate components of light with smaller and smaller wavelengths. As such, successful suppliers were ones who were established in the field of optics. Perkin Elmer, an optical instruments company based in Norwalk, Connecticut, dominated the exposure tools industry in the 1970s (see Figure 6). Henderson and Clark (1990) provide a good description of technological differences that allowed other new entrants to displace many incumbents in the exposure tools industry.

[11] See Applied Materials Annual Report for 2015.

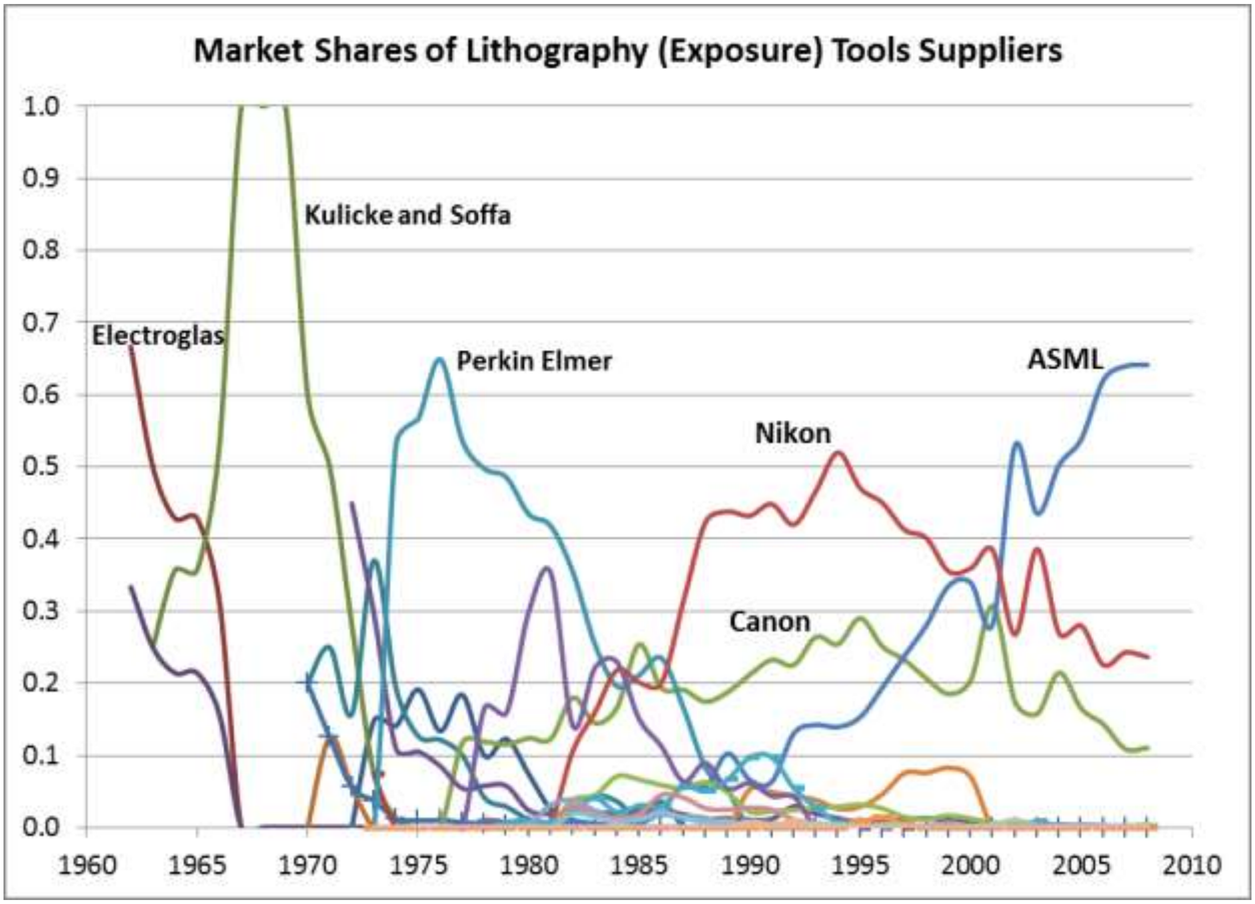

Figure 6: Market shares of leading lithography (exposure) tool suppliers

Notes: The leading lithography tools suppliers in the early years were companies like Electroglas and Kulicke and Soffa, who were located near leading semiconductor companies (Fairchild and AT&T-Bell Labs). Later entrants like Perkin Elmer, Nikon, Canon and ASML relied on their expertise in optical technology (microscopes, cameras, lenses) to become market leaders. (Source: Data for 1962-1982 is from Henderson (1993), and data for 1982-2008 is from Gartner[12]).

As semiconductor technology advanced, and transistor size become even smaller, the reliance on technical sophistication in optics has become even more striking. For the last two decades, for instance, there have been no manufacturers of exposure tools in the U.S Instead, the whole industry worldwide has come to rely just on three suppliers – ASML, Canon and Nikon - whose expertise in cameras, lenses and optical technology has given them an unassailable advantage that could not be substituted by geographical proximity.

[12] The Henderson (1993) data is available at http://five.dartmouth.edu/datasets.

Even at the beginning stages of the industry, one could see that for the more technically sophisticated tools, distance was not an important limitation. A telling example is the case of the Ion Implantation (process h, in Figure 2) tools. The research into the development of ion implanters was helped by the ongoing research in nuclear engineering on particle accelerators, and the initial ion implanter suppliers were spin offs from nuclear research laboratories. The most prominent among them was the High Voltage Energy Corporation, a startup that was founded to commercialize the nuclear research done at the Van de Graff Research Laboratory at MIT (see Yarling (2000) and Rose (1985)). In 1965, HVEC shipped its first ion implanter to Fairchild, marking the emergence of the ion implantation tools industry. Although HVEC did not become very profitable in the semiconductor industry, it spawned many spinoffs, including Ion Physics Corporation, KeV, General Ionex and Extrion. Many of these spinoffs were established along the North Shore area close to Boston, which became the hub of the ion implanter industry.[13] The suppliers of ion implanter tools thus clustered around Boston, far away from Silicon Valley, sticking close to the nuclear laboratories that spawned them rather than the semiconductor companies that used the machines they produced.

5. Conclusion

I have put forward some observations on the emergence of a key component of the semiconductor supply chain, firms who supply tools that enable companies to manufacture semiconductor chips. The most salient observation is that this first level of vertical specialization in the industry was midwifed by the chip manufacturers themselves, who supported the suppliers by providing them technological know-how, and by working closely with them to develop and improve the early versions of externally manufactured tools. The chip manufacturers were aware that the technology developed in their labs would diffuse out to their competitors through the suppliers' sale of tools to their competitors. Even then, they thought it in their best interest to actively support the formation of the supplier companies.

[13] The most successful descendent was Extrion, whose Model DF4 implanter was one among the most popular ion implanters in the industry.

Geographical proximity often helped potential suppliers, but was not an insurmountable hurdle. Many of the pioneering semiconductor companies clustered around the Silicon Valley region, and local firms with existing know-how in deposition of materials were able to tap the geographical proximity and emerge as important suppliers of deposition tools. But the suppliers of ion implanter tools clustered far away around Boston, sticking close to the nuclear laboratories that spawned them rather than the semiconductor companies that used the machines they produced.

The contention by Smith (1776) and Stigler (1951) that the degree of specialization is limited by the extent of the market finds support in the emergence of the tools suppliers, as industry pioneers were often rebuffed by potential suppliers in the initial stages of the industry, citing the small size of the market. But there seems to also have been a more nuanced pattern of entry, with suppliers entering the different segments at different points in time. While diffusion furnaces and photorepeaters for mask making were available for purchase at least as early as 1961, suppliers for etching tools entered only around 1968. Whether this happened because of technical differences across tools, differences in market sizes across tools, or because of some other reason, is an interesting topic of further study.

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Appendix

Photoresist Coat/Develop Tool made
by Tokyo Electron
Clean Track Lithius Pro Z

Lithography Exposure Tool made by
ASML - Twinscan 190i

Deposition Tool made by Applied
Materials

Etching Tool made
by LAM Reserach

Figure A1 : Sample semiconductor tools made in modern semiconductor fabrication plants.