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Toward a Theory of Industrial Development and Vertical Disintegration:

The Case of the Semiconductor Industry

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Abstract

The semiconductor industry has accomplished surprising growth, and its production base has extended from the United States to Japan, Europe, and other Asian economies. One of the factors of this phenomenon is the progress of vertical disintegration in the semiconductor industry. The boundaries of firms are discussed within a transaction cost framework. However, to identify the process of long-term vertical disintegration at an industrial level, a dynamic theory rather than a static theory is necessary.

In this paper, the process of vertical disintegration in the semiconductor industry is explained, and then a consideration is made of a static theory versus a dynamic theory. A tentative view of a dynamic theory of vertical disintegration is presented based on the case of semiconductor industry. Vertical disintegration of the semiconductor industry has strongly been affected by the frequency of technological innovation, the speed of market expansion, the degree of competition, the existence of interface, and the amount of the transportation costs. When vertical disintegration is analyzed, it is necessary to take such factors into consideration.

Key Words: industrial development, vertical disintegration, semiconductor industry

Introduction

After the invention of the transistor, the semiconductor industry has kept growing at a rate of about 20–30%. Moreover, its production base has extended from the United States to Japan, Europe, and other Asian economies such as South Korea, Taiwan, and China. One of the factors of this phenomenon is the progress of vertical disintegration in the semiconductor industry.

The boundaries of firms have been discussed over many years through the transaction cost approach. Transaction and coordination costs have played an important role with this. However, this theory of firms assumes a stable market structure and doesn't address the situation when the market structure changes as the industry develops. In this sense, it can be said that the theory is static.

When discussing a long-term process of industrial development, it is necessary to include the assumption that the market structure is changed by technological innovation and market scale. Stigler (1951) and Baldwin and Clark (2000) have discussed the progression of vertical disintegration in the long-term process of industrial development.

However, vertical disintegration in industrial development is not commonly recognized. Moreover, vertical disintegration might not be so advanced depending on the industry, and the process of vertical disintegration might be different according to the age. Therefore, it is not easy to construct a dynamic theory of vertical disintegration. This paper contributes to the development of a dynamic theory of vertical disintegration by theoretically considering vertical disintegration in the semiconductor industry.

The composition of this paper is as follows. First of all, the process of vertical disintegration in the semiconductor industry is explained. Secondly, the ability of a static theory of vertical disintegration in explaining the process of vertical disintegration in the semiconductor industry is examined. Thirdly, some views about a dynamic theory of vertical disintegration are considered. Fourthly, a dynamic theory of vertical disintegration is presented based on the case of the semiconductor industry.

Ⅰ. The Process of Vertical Disintegration in the Semiconductor Industry [1]

In the early days of the semiconductor industry, device makers were both processing raw materials and producing manufacturing equipment. In time, the various processes involved in semiconductor manufacturing came to be done by firms other than the device maker. In this section, the progression of vertical disintegration involved with silicon wafers, manufacturing equipment, assembly and testing processes, electronic design automation (EDA), fabless, and foundries is clarified.

Around 1950, device makers refined germanium of high purity and manufactured the refinement equipment themselves.[2] As silicon replaced germanium, a very advanced chemical treatment was needed, and other firms began to supply high-purity polysilicon. At first, device makers manufactured single crystals and wafers occasionally, and after that production moved completely to silicon manufacturers because of the efficiency of production.

At the beginning, device makers also made the manufacturing equipment. However, the planar process was developed and special manufacturing equipment was needed, so small-scale device makers did not have room to develop manufacturing equipment. Therefore, the number of firms that specialized in the manufacturing equipment began to increase, and the manufacturing equipment industry of the semiconductor was formed in the 1970's. Some major device makers kept making the manufacturing equipment by themselves, but the proportion of device makers that depended on other firms increased due to the speed of technological innovation and the load of the development cost.[3]

The device makers in the United States came to do the assembly and testing processes in developing countries like those in Asia in 1960's.[4] Because the process needed quite a lot of workers, developing countries where cheap laborer existed were very attractive at that time.[5] The device makers in the United States often established subsidiary companies and built a lot of plants in developing countries. As time went on, outsourcing to firms in developing countries increased, in part due to the policies of the developing countries.

As device integration proceeded, circuit design took a considerable amount of time and

1 This section is based on Suenaga (2007).
2 At that time, germanium was primarily used as the material for semiconductors.
3 About this paragraph, see Stowsky (1987; 1989).
4 At first assembly lines were also built in places such as Mexico and El Salvador, but the production capacity has been reduced related to the influence of political and social uneasiness. See Brown and Linden (2005).
5 The labor cost of the assembly process occupied more than half of the manufacturing cost when the assembly process was done in the United States. Comparing wage levels in 1970 with those of the United States, Singapore was 1/11, and Hong Kong was 1/10. See U. S. Department of Commerce (1979).

the need for design automation tools rose. At first, device makers made such tools, but these were only able to be used within their companies and the development costs could not be recouped from selling the tools to other companies. With further increases in device integration, making the tools became more difficult. Venture companies that specialized in making EDA appeared at the end of 1970's, and the EDA industry became independent in the latter half of 1980's.[6]

In 1980's, the number of fabless companies specializing in the design of devices increased. Various factors are thought to have brought about the appearance of these companies.[7] The division of labor between device design and manufacturing engineering became possible because the making of complementary metal oxide semiconductors (CMOS) became the superior manufacturing process, and the technology of the device manufacturing was standardized. Moreover, the amount of investment necessary to manufacture devices became enormous, and new start-up firms were able to enter only in areas other than the manufacturing process. Additionally, the increased demand for application specific integrated circuits (ASIC) and the increase of EDA firms and intellectual property (IP) were also factors.

The number of fabless companies increased, allowing pure foundries to be born because an enormous investment was necessary to manufacture the devices. A particular "silicon cycle" in the semiconductor industry also existed, and it was technically and financially difficult for device makers to manufacture everything by themselves. As a result, the number of companies that outsourced manufacturing to the foundries increased. The foundries were able to deal with problems in the technological and silicon cycles because the foundries were able to respond at a wide technological level and produce various devices.[8]

Data about the degree of vertical disintegration follows. The rate of device makers producing silicon wafers fell to about 11% in the United States, about 4% in Japan, about 2% in Europe, and about 2% in other countries in Asia and elsewhere in 1992, and these rates have further decreased after that. Concerning manufacturing equipment, the tendency to depend on equipment makers also has become strong. In case of photolithography machines for which the most advanced technology is needed, a greater part of device makers are procuring the machines from specialist firms. The proportion of fabless chip producer sales increased to 10.9% of world production, and the proportion of manufacturing foundries in the world reached 25% in 2001. Independent contractors account for 26.7% of the assembly processes in the world in 2003.[9]

Ⅱ. The Static Theory of Vertical Disintegration

According to the static theory of vertical disintegration, whether a firm produces inputs by itself or procures them from other firms basically depends on the cost. That is, if producing by itself is cheaper, it will produce, and if production by other firms is cheaper, it will entrust this to other firms. Through self-production it is also possible to use economies of scale and scope, reduce the transaction costs, and expand market control. Conversely, motivation to work efficiently weakens and management costs rise. Milgrom and Roberts (1992: 556) describe the conditions under which a firm should outsource to other firms. These conditions

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6 About the history of EDA, see Miwa (2001) and Hobday (1991).
7 See Macher *et al.* (1999: 268), Macher and Mowery (2004: 331), and Hobday (1991).
8 About foundries, see Sato (2000).
9 See Takekoshi (1994: 24) about silicon wafers, Arensman (2003) about the fabless, Leachman and Leachman (2004: 212) about foundries, and Anonymous (2004) about assembly processes.

include the following:

> the use of standard inputs, the presence of several competing suppliers, economies of scale in the supply firms that are too large to be duplicated by the buyer, economies of scope that would force the vertically integrated firm into unrelated businesses, and the absence of specific investments on the part of either the buyer or the seller.

How is such a view effective when thinking about the vertical disintegration of the semiconductor industry? As a matter of course, when thinking about cost, it is necessary to consider not only the immediate circumstances but also the long-term perspective. When a device maker chooses between internal production versus procurement, it is necessary to consider which is cheaper from a long-term viewpoint. It is necessary to examine from a long-term viewpoint whether the act of entrusting other firms with important equipment will become a disadvantage in negotiations. In a realm where the technological innovation is active, costs might rise relatively over time if an important technology is controlled by other firms. Moreover, because device production and manufacturing equipment production are very closely related in the process of achieving state-of-the-art quality, cooperation between device makers and equipment makers is indispensable. Therefore, a company entrusting its equipment to other firms risks having its own technology and know-how flow out.

It is not impossible to convert all such aspects into the cost. However, in the semiconductor industry, technological innovation is vast, competition is active, and demand has expanded rapidly. In this case, it is not easy to forecast long-term cost because the uncertainty is large. Although economies of scale and scope have become major factors in stimulating vertical disintegration, factor such as efficiency and management costs were not the major factors influencing the selection of integration versus disintegration.

Moreover, the situation that Milgrom and Roberts have pointed out does not apply to the entire semiconductor industry as it was. The inputs used with semiconductors were not standard at all. Silicon of ultra-high purity was needed, and specialized technology was necessary for the other raw materials and the chemicals. In addition, the manufacturing equipment and EDA were very specialized, and the specifications of such products were unique in each company.

To what extent was the degree of competition between suppliers? The oligopoly is very advanced under the present situation. The market share of the three highest ranked companies of silicon wafers and various manufacturing equipment is extremely high. There was no buyer purchasing the cheapest products from among many suppliers. The supplier could not help but invest a large sum of money in research and development because the inputs were not standard and new technology was needed. Technological competition was more important than price competition.

The economies of scale on the supplier side became a major factor in selecting vertical integration or vertical disintegration. For a device maker producing both the silicon wafers and the manufacturing equipment itself, the load of the development cost became heavy. Therefore, a device maker was not able to shoulder the development cost when limiting it to use within its company. Moreover, selling manufacturing equipment to a rival was not desirable for both the company making the equipment and the rival firm because there was a possibility of spillover of technological know-how for the equipment maker and the rival company would have to depend on another company for its technology. As a result, a market for independent suppliers has developed.

Economies of scope have also played a major role in the process of vertical disintegration in the semiconductor industry. Advanced expertise was often needed to resolve technical bottlenecks when device makers developed new devices. Although device makers were theoretically able to develop the needed technology through R & D investment and purchases, these were often practically impossible under intense competition because of time and unavoidable costs. So, firms with special technology that was developed in other industrial fields often entered a related area of the semiconductor industry. For example, some firms were able to enter the business of silicon refinement by using their chemical technology, other firms were able to enter the lithography market by using their lens technology, and still other firms were able to enter the sputtering market by using their vacuum technology.

In turn, suppliers and buyers also often had a specific investment in each other. A device maker had to order equipment and special materials from another supplier to resolve technological bottlenecks. Suppliers often received support for the development costs from device makers because it was not clear that these special orders could be sold to other buyers.

In the case with the semiconductor industry, the proportion of procurement from other firms has expanded, though there have been a lot of situations different from the situation that Milgrom and Roberts described. The static theory of vertical disintegration is also effective to some degree when considering the process of vertical disintegration in the semiconductor industry. However, discussing a long-term process of industrial development centering on cost is futile, and the reason why vertical integration has changed is hardly discussed. Thus, in the next section a dynamic theory that considers the dynamic process of industrial development is discussed.

Ⅲ. The Dynamic Theory of Vertical Disintegration

Though the static theory concerning vertical disintegration was examined in the foregoing section, there is some research that discusses vertical disintegration with the assumption of a dynamic process. The three research papers are taken up in this section. The pioneering research of Stigler (1951) paid attention to the relation between the life cycle and vertical disintegration of an industry. The second paper is a research by Langlois (2003) and discussed the relationship between the development of institutions and the vertical disintegration of an industry. The third is a research on the computer industry by Baldwin and Clark (2000) that paid attention to the relationship between modulation and vertical disintegration.

Stigler (1951) described the relationship between the developmental stage of an industry and the tendency toward vertical disintegration of that industry. Generally, vertical integration is predominant in an early stage of an industry, and vertical disintegration advances when it enters a stage of growth. The tendency toward vertical integration is brought about again when the industry enters a stage of decline.

A new industry is often outside the norm for an existing economic system and the needed raw materials are often uncommon, so a firm in the new industry has no choice other than to choose self-production. Moreover, special manufacturing equipment might be necessary, along with its design and production. Even more, the necessity to look for skilled workers who are well-versed in special tasks might arise. It is often necessary to solve technical problems when a product is being used and to persuade users to switch to the new product from older ones. However, it is also difficult to find agencies to take charge of such persuasion work.

As this new industry reaches a steady state and its prospects are clear, other firms enter with their specific businesses. Various companies individually focus their business practices, and vertical disintegration of the industry advances. For example, some firms specialize in the production of special raw materials and manufacturing equipment, other firms specialize in marketing and agency, and some other firms specialize in worker training.

Thereafter, when this industry decline, companies that have played a supplementary role will begin to decrease. When independent firms go under, the firms that remain will have to carry out the business.

Langlois (2003) presented the hypothesis of the “vanishing hand” as opposed to the hypotheses of the “invisible hand” (Smith, 1976) and the “visible hand” (Chandler, 1977). According to Langlois, Smith thought that the division of labor was advanced by the invisible hand of the market as market expanded, though Chandler thought that the visible hand took the place of the invisible hand. However, Langlois pointed out that the view of Chandler was only valid for a specific historical environment.

The “vanishing hand” hypothesis of Langlois is as follows. As the population and their incomes increase and the barriers of exchange decrease, the division of labor that Smith indicated progresses. Each role becomes more specialized, and coordination through the market increases. However, the speed is various at which the technology, organizations, and institutions that form the basis of this process are changed. The “management revolution” that Chandler described is a result of this unbalance. That is, although technology with high productivity makes for the necessity of new coordination, the unbalance increases when the development of the market and institutions that fill such a necessity is delayed. This unbalance causes the “management revolution” that Chandler described. However, as the market expands and the institutions that support exchange develop, centralized management of the process of production decreases gradually, and vertical disintegration advances again.

Baldwin and Clark (2000) discussed the process of vertical disintegration of the computer industry while paying attention to the concept of modulation. In their view, the modules are units in a larger system that are structurally independent of one another, but work together (Baldwin and Clark, 2000: 63). The first type of computer to appear as a true module type computer is system/360 of IBM launched in 1964. Before then, computer products were incompatible with each other. If customers wanted to change the systems they had, they could not help but completely rewrite the application software and buy new peripherals. To maintain compatibility between products, IBM adopted the module design, and the series was great success in the computer market.

It was the quality of the architecture and the establishment of the design rules that made it important to work in this mode of modulation. Because the parameters had been clarified enough, the developer of each module was free to make the effort to improve the functioning of that module.

However, firms that manufactured modules compatible with IBM products appeared, and they made the products highly competitive by specializing in specific areas. The industry was changed from a substantial monopoly by IBM to a huge module cluster. As printers, terminals, memory, software, and CPUs came to be produced by special firms, the position of IBM has decreased.

Ⅳ. A Dynamic Theory of Vertical Disintegration Based on the Case of the Semiconductor Industry

When technological innovation, especially radical innovation, frequently develops, it is very difficult for a company to judge whether to take charge of the specific input and production process by itself or to entrust it to other firms. The cost might be able to be reduced for the short term when entrusting it to other firms. However, costs might increase due to the market control of other firms over the long term. In the realm where technological innovation frequently occurs, it might be difficult to enter the target area again later. Although the suppliers in the semiconductor industry might have been competing at first, a small number of firms came to occupy a high market-share in some realms with the passage of time.

Therefore, in order to analyze the dynamic processes of an industry like the semiconductor industry, a dynamic theory is more useful than a static theory. The frequency of technological innovation, the speed of market expansion, the degree of competition, the existence of the interface and the height of the transportation cost are factors that have influenced vertical disintegration in the semiconductor industry.

Although the semiconductor appeared to be taking the place of the vacuum tube originally, it had the potential to exceed the performance of the vacuum tube greatly. As the semiconductor came to be manufactured at a low cost, the market expanded rapidly. The market expanded not only to radio and television but also to calculators, computers, personal computers, cellular phones, and cars. Moreover, semiconductor technology was a new technology using the solid state of semiconductors, and it had significant potential. As a result, new technological innovations arose one after another. These technological innovations brought about the decline of the price and extended the market, and this brought further technological innovation. Thus, the virtuous circle of technological innovation and demand has greatly developed the semiconductor industry.

Under such a situation, the anti-trust policy of the United States enabled small-scale firms to enter the market, and active competition was brought about. The existence of venture capital and vigorousness of independent spirit also had a big influence. Moreover, high profits and big markets came to cause intense competition and press not only the United States but also Europe, Japan and Asia.

The speed of technological innovation and market extension was fast and competition was active, so it was difficult for device makers to produce everything by themselves. Therefore, device makers could not help but depend on other firms even if it was understood that their position in the market might weaken.

Whether the interface between the processes became easily clear and whether the transportation costs were relatively cheap were factors influencing vertical disintegration. The existence of interface and the cheapness of transportation cost pressed vertical disintegration in the semiconductor industry. However, the semiconductor industry was a different from the computer industry, and vertical disintegration in the semiconductor industry did not advance under a clear architecture, and it progressed under the path dependence.

Although at first the interfaces among device production, silicon refinement, manufacturing equipment, and EDA were not clear, the interfaces became clear with competitiveness among the various firms and the promotion of standardization by industry associations. The fact that the interface between device design and manufacturing processes became clear was a great factor for the birth of the fabless and the foundries. Moreover, the assembly and testing process was easily separated at first. Thus, the entry of new firms became technically and financially possible due to the clarification of the interfaces. As the entry of such firms pressed for further clarification of the interface, vertical disintegration then progressed further.

Langlois (2003) pointed out that the management revolution was brought about because the market and its institutions were underdeveloped. Nonetheless, the existence of the interface and the problem of the transportation cost are important. In heavy industries like the steel industry and chemical industry, it was originally undesirable to divide the processes, and the corporate scale could not help but grow. On the other hand, because the semiconductor and the computer are both lightweight, it was not comparatively difficult to complete portions of the work in different places (or among different corporations) considering the transportation costs.

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