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The Chicken Game and the Amplified Semiconductor Cycle: The Evolution of the DRAM Industry from 2006 to 2014*

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Abstract

Industry fluctuations in the supply of DRAM chips relative to demand have been characterized by what is called "the silicon cycle." In the period between 2006 and 2008, the DRAM industry experienced an unusually sharp transition from a shortage of DRAM products to an extreme oversupply, culminating with the crash of DRAM prices in 2008. The industry's overcapacity was preceded by a mad race to expand capacity; this race has been dubbed as the "chicken game" in the media. Even in the time of plunging DRAM prices, players preferred not to reduce their output. The amplified industry cycle accelerated the exit of financially vulnerable firms. I argue that the combination of the amplification of cycle and rising entry barriers fosters the transition of an industry to an oligopoly, in which cyclicality is curbed and the positions of market leaders are solidified.

Keywords: Cycle, DRAM, Technology, Innovation

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INTRODUCTION

Since Intel created the dynamic random access memory (DRAM) industry by introducing the world's first commercially successful DRAM chip in 1970, industry competition has been fierce. Occasionally, newcomers have entered the market, and changes in leadership have occurred. Industry fluctuations in the supply of DRAM chips relative to demand have been labeled "the silicon cycle," the booms and busts of which have been irregular and unpredictable.

In the midst of the 2008 financial crisis, an unprecedented level of oversupply occurred in the DRAM industry, with prices plummeting below the chipmaker's material costs. The industry's overcapacity was preceded by a mad race to expand capacity; this race has been dubbed as the "chicken game" in the media (e.g., Wang 2009). Even in the time of plunging DRAM prices, players preferred not to reduce their output; as a result, cutback decisions came too late, leading to a major shakeout in the industry. Two major competitors, Qimonda and Elpida Memory, left the industry. Other DRAM manufacturers experienced mounting losses and financial pressures, and were driven to marginal positions. Eventually, the industry evolved into an oligopoly with three main players: Samsung Electronics, SK Hynix, and the Micron Group. Burning questions raised in this paper are: Under what conditions do unstable industry cycles persist or stabilize? How do such industry cycles affect the position of market leaders?

In many capital-intensive industries, industry cycles, which affect the competitive positions and survival of firms, can often be observed. In the shipping industry, investment in ships at the ends of up cycles can lead to the loss of those ships or even the exit of firms (Theotokas and Harlaftis 2009). For example, a debt crisis blew the STX Group onto the rocks when the shipping and shipbuilding industries experienced an unprecedentedly severe downturn in the wake of the 2008 financial crisis. In the boom period prior to the crisis, the STX Group expanded aggressively based on the belief that the rapid economic growth in China would continue to provide growth opportunities for their shipping and shipbuilding businesses. When the market swung against the group, it was not able to sustain its business activities.

In the DRAM industry, boom-and-bust cycles triggered changes in leadership, which often resulted in the exits of former industry leaders. During the downturns of the 1970s, American firms reduced capacity investments and lost their leadership positions as Japanese rivals aggressively added capacity and subsequently increased their market shares (Angel 1994; West 1996). Eventually, most of the American firms including Intel left the industry. Another leadership change happened during the downturn in the late 1980s and the early 1990s. Samsung Electronics overtook the Japanese DRAM manufacturers, whose demise in the industry occurred at the turn of the new millennium.

In the absence of industry cycles, it is much easier for firms to manage their growth and plan their capital investments. For example, a utility firm may rely heavily on debt, but such high financial leverage in the absence of industry cycles does not increase its exposure to the risk of default. When irregular industry cycles persist, however, it becomes difficult for firms to formulate their growth strategies. Poor timing of capital investment may lead even industry leaders to lose their competitive advantage. Down cycles can be fatal, particularly when firms rely heavily on debt financing in making investments.

The limited research that is available suggests that many firms do not fully understand the implications of these cycle effects, and, as a consequence, they do not cope with them effectively (Hambrick and Schecter 1983). In contrast, the long-term success of Greek ship owners in the shipping industry has been largely attributed to their deep understanding of the cycles of their industry and their development of dynamic strategies to cope with those cycles (Theotokas and Harlaftis 2009). However, the issue has been neglected in strategy research (Mascarenhas and Aaker 1989; Mathews 2005). Given the paucity of prior research, this paper is exploratory in nature; its modest aim is to lay the groundwork for future research by providing historical details and sketching some observed regularities in the DRAM industry without formalizing them.

A long-term goal in this stream of research may be to develop a full-blown theory of the creation, persistence, and disappearance of industry cycles. The mechanism for the creation of industry cycles was partly hinted at by Schumpeter (1927). An exogenous technological shock, or what he called "creative destruction," often spawns industry cycles, as many firms jump into a burgeoning industry to seize opportunities associated with the shock. The history of the DRAM industry shows no such exogenous shock. Although some touted the commercial possibilities of alternatives to DRAM chips (e.g., PRAM), nothing has replaced them thus far. Given this fact, the present paper focuses on the persistence and disappearance of industry cycles. In particular, I explain why cycles occurred in the DRAM industry in the past and why they may not persist in the future. I seek an answer to these questions from two angles: (1) amplification of industry cycles (2) rising barriers to entry.

The combination of cycle amplification with rising barriers to entry is described in this study as a mechanism that accelerates the transition of an industry to an oligopoly, where cyclicality diminishes or vanishes altogether. In the DRAM industry, amplification of the industry cycle from 2006 to 2008 accelerated the exit of financially vulnerable firms. The seeds of this situation had been sown by debt-financed capital investment during the industry upturn around 2006. Without entry barriers, however, future upturns can attract newcomers, whose arrival will disturb industry stability, after which the cycle may repeat itself. In a similar vein, entry barriers without cycle amplification may not completely eliminate industry cycles. High entry barriers may deter future entry, but they may not reduce the number of existing firms to the point of oligopoly. In such circumstances, it may be difficult for industry participants to coordinate capacity investments. This implies that with a non-zero probability, an industry will build up overcapacity. The historical details of the DRAM industry demonstrate that both rising barriers to entry and amplification of industry cycles jointly led to price stability and the disappearance of cyclicality in that industry.

THE NATURE OF COMPETITION AND RISING BARRIERS TO ENTRY

Before exploring the two factors involved in the transition of the DRAM industry, I first describe a characteristic feature of industry competition, which provides a glimpse of the reason as to why the cycle was amplified in the first place. On the surface, the amplification stemmed from the massive buildup of overcapacity in the upturn of 2006. The unusual profitability (along with other triggering events, which will be described later) encouraged DRAM manufacturers to build up capacity. Even in the face of mounting losses in 2007, most industry participants were reluctant to stop expanding their capacity and investing in advanced process technologies. These industry participants should have known that this sort of excessive buildup would eventually result in a pernicious downturn. It does not take a rocket scientist to predict the consequence of this sort of mad race. Why, then, did they choose to expand their production capacity and to invest in new process technologies? To understand this seemingly reckless decision-making, the details of competition within the DRAM industry must be scrutinized.

The DRAM industry, over the past four decades, has been characterized by exponential increases in bits per dollar of cost. This characteristic is associated with Moore's Law, which predicts that integrated circuits will double in power and halve in price every 18–24 months. Recently, Intel (2015) noted:

> The insight, known as Moore's Law, became the golden rule for the electronics industry, and a springboard for innovation... Performance—aka power—and cost are two key drivers of technological development. As more transistors fit into smaller spaces, processing power increased and energy efficiency improved, all at a lower cost for the end user. This development not only enhanced existing industries and increased productivity, but it has spawned whole new industries empowered by cheap and powerful computing.

Shih and Chien (2013: 3) noted: "Indeed, the number of DRAM bits shipped per dollar of cost showed an exponential improvement over the last 36 years." Since industry participants have largely competed based on price, they have been willing to move quickly to whatever state-of-the-art, process technology (often possible with the latest manufacturing tools) that minimized the cost per bit, or the per-unit cost of computing power. As a consequence, DRAM manufacturers have continuously pushed the frontiers of technological possibility, and the DRAM business has long been viewed as a technology driver.

What would happen if a DRAM manufacturer chooses not to follow this cost reduction game? Once the industry starts the mass production of the new generation chips, their price tends to drop dramatically within a few years. For example, the price of a 4-megabit DRAM chip was around $40 when industry leaders first began producing chips in large volumes. Within four years, however, the price dropped to about $2. Unless DRAM manufacturers matched such dramatic cost reduction at a later stage of the industry cycle, they were unable to survive (West 1996; Shin and Chang 2008). Even industry leaders were not exceptions to this ruthless selection process. For example, Intel exited the industry when it could not narrow the cost gap with Japanese DRAM manufacturers in the 1980s. In the 1990s, the Japanese leaders followed in the footsteps of Intel, as Samsung overtook the industry leadership, aggressively driving down the cost per bit.

DRAM manufacturers should have learned that the name of the game in order to survive in the industry is to drive down the cost per bit faster than the competition. Cost reduction can be achieved by increasing capacity to realize economies of scale or by reducing the cost per bit with the latest process technology. As a consequence, the pressure to survive appears to have led DRAM manufacturers to develop an obsession with economies of scale and process innovation, which, in turn, resulted in a massive buildup of products leading to overcapacity and aggressive migration to new process technologies in the face of mounting losses.

Rising Barriers to Entry

Now I examine the historical context of rising barriers to entry. In the early period of the DRAM industry, entry barriers were relatively low; occasionally newcomers were attracted. The intensity of capital investment was much lower than it is now. The cost of building a minimum-efficient-scale semiconductor factory skyrocketed over time. For example, it increased from $4 million in 1971 to $3 billion in 2004. In the beginning, when Intel entered the industry, it was a start-up company. Nowadays, start-up firms cannot enter this industry, primarily because the amount of capital investment required for entry goes beyond the reach of venture capitalists.

Examining the history of the industry further, one can see that there were frequent changes in leadership prior to 1992 (Shin and Chang 2006). Chang Gyu Hwang, the former head of Samsung's

Memory Division, noted:

> In the past, the number one player changed at every generation. For example, it was NEC for 256-kilobit DRAM, Toshiba for 1-megabit DRAM, Hitachi for 4-megabit DRAM, and so on. Since many firms compete in the DRAM industry, it is important to become number one. Otherwise, you will suffer losses. (Joongang Monthly Magazine 2004: p. 11)

This leadership instability reflects the absence of strong barriers to entry (Gort and Klepper 1982; Klepper 1996). Weaker entry barriers imply that the number of firms in an industry could be larger than the level at which industry participants can coordinate capacity investments. In such circumstances, there is a positive probability that industry participants will collectively build up overcapacity, which will be followed by downward-spiraling prices. Indeed, the persistence of industry cycles in the DRAM industry for more than three decades could be explained by the large number of firms in the industry and the entry of newcomers. Unless the number of firms drops to a level at which oligopoly is possible, coordination among industry participants may be difficult, triggering irregular industry cycles.

Rising barriers to entry in the DRAM industry have been observed over time. First, intensification of capital investment over time is an indication of the rising entry barriers. As mentioned above, capital investment in the DRAM industry steeply increased over time. Second, the theory of industry evolution considers declining entry as a sign of industry maturity, which is associated with high entry barriers (Gort and Klepper 1982; Klepper 1996). In the new millennium, no new firms have entered into the DRAM industry up to the year 2014. Furthermore, DRAM prices have been stable since 2013, and three industry survivors, Samsung, SK Hynix, and the Micron Group, have enjoyed mushrooming profits by restraining capacity expansion. These facts suggest that the industry has transformed into an oligopoly. Third, the disappearance of leadership instability is another indication of the rising entry barriers (Gort and Klepper 1982; Klepper 1996). Since 1992, Samsung Electronics has occupied the leadership position in the DRAM industry and has stood out in terms of profitability (West 1996).

The rising entry barriers become more evident through an examination of the industry leader's growing competitive advantage over time. Samsung's persistent outstanding performance since 1992 has been attributed to cost leadership (Shin and Chang 2006). As discussed earlier, the name of the game in the DRAM industry is to drive down the cost per bit ahead of the competition. To achieve this cost reduction faster, Samsung outspent its rivals. For example, the average amount of capital investment per year in Samsung's DRAM division from 1993 to 2000 was $134 million, which is 4.7 times the average amount of annual investment among the four largest Japanese DRAM makers (Shin and Chang 2006). It has been widely known that Samsung was able to overtake leadership from the Japanese DRAM makers primarily because the company was the first mover to the 8-inch process technology. When the 12-inch process technology became available in the late 1990s, Samsung was, again, the first mover.

The strategy literature has addressed the diverse sources of first-mover advantage (Lieberman and Montgomery 1988; Mitchell 1991). In the DRAM industry, the source of the first-mover advantage has been identified as learning-by-doing, as follows:

> [P]roduction yields—a key drive of semiconductor manufacturing costs—would fall dramatically with the introduction of new processes. Yields would only rise as the plant gained experience with the new process, identified and resolved trouble-spots, and exploited opportunities for process optimization and improvement.... Fujitsu's higher market share translated into higher cumulative production volumes, which in turn, gave the company a manufacturing cost advantage. This scenario was repeated again in 1982. (Casadesus-Masanell, Yoffi, and Mattu 2004: 2–3)

Spence (1981) formalized the learning curve effects on cost reduction competition. The implication is that a firm should go beyond the short-run profit maximizing level of output to improve its cost position in the future. In other words, an increase in market share is more important than profit maximization in the long run. Samsung's aggressive efforts to achieve cost leadership and increase its market share over the last two decades can be understood in this light. Repeatedly, Samsung Electronics moved faster to the latest technology. This strategic behavior allowed the firm to learn diverse ways to reduce its unit cost dramatically ahead of its rivals (Shin and Chang 2006). In this way, Samsung was consistently better prepared and less vulnerable to price crashing in downturns than its rivals.

In addition to cost leadership, Samsung Electronics developed the capability to differentiate its products from those of its rivals, who mostly focused on commodity DRAM chips—due to limited resources, they usually had no choice but to do so. Toward the end of the chicken game, from 2010 to 2012, for example, Samsung was still able to make profits, while all of its rivals lay bleeding. Samsung's profitability in this period was largely due to differentiation of its products, such as mobile and server DRAM chips. Unlike the commodity segment, these niche segments attract customers who are willing to pay higher prices for improved quality or functionality (e.g., faster clock speed or lower power consumption).

A positive feedback process, also known as the winner's virtuous cycle, was additionally responsible for Samsung's dominant position over time. In evolutionary economics, rising entry barriers are theorized in the form of a positive feedback process (Nelson and Winter 1978, 1982; Lee et al. 2010). If firms compete for innovation, some may become more successful over time as a result of their R&D activities than others. Even when all industry participants are equal in size at the start, firms can grow larger as a result of the positive feedback process because "growth confers advantages that make further success more likely" (Nelson and Winter 1982: 325). This literature has highlighted the importance of the positive feedback loop between investment and return. Lee et al. (2010) numerically showed that an industry leader can accumulate substantially more retained earnings than its rivals when the winner's virtuous cycle naturally emerges from the positive feedback between R&D investment and successful innovation. The widening gap between market leaders and followers has been observed in the pharmaceutical industry (Lee 2003) and the aircraft industry (Phillips 1971).

In the DRAM industry, Samsung Electronics as a pacesetter appears to have enjoyed this sort of positive feedback process, accumulating a large amount of cash on its balance sheet. This, in turn, made the firm less vulnerable to downturns. Furthermore, in the last two decades, the firm's strong cash position facilitated its aggressive investment in additional capacity and migration into the latest process technology during downturns, at times when its rivals were cutting back their capital investments. Samsung Electronics' growing market share and profitability over the last two decades can therefore be partially explained by this positive feedback process.

THE AMPLIFIED INDUSTRY CYCLE

In this section, I elucidate the details of the catastrophic downturn of 2008 and how it affected cyclicality in the DRAM industry. In this paper, the silicon cycle (or semiconductor cycle) is defined as a transition from a shortage of DRAM chips to an oversupply, or from an oversupply to a shortage, with no identifiable periodicity. Profits tend to fluctuate wildly with semiconductor cycles. For example, for the first three quarters of 2008, a record loss of 8 billion U.S. dollars accumulated to the industry. Like other semiconductor cycles in the past, the most severe downturn in the new millennium started with a shortage of DRAM chips in the 2006 upturn.

Strong Demand Meets Supply Shortage in 2006

To explore the circumstances of this shortage, I first describe the factors affecting demand and supply. Numerous factors boosted the demand for DRAM chips in 2006. One of these was increasing demand in emerging markets. The Christmas period is a hot selling season for PCs; after this period, demand usually drops substantially. At the beginning of 2006, however, there seemed to be no end to the demand for these chips. The extended demand was in part due to Chinese New Year. In the 1990s, PC sales were mostly focused in the U.S., Europe, and Japan. China's demand was minimal compared to that in these three regions. In 2006, however, China became the second-largest PC market in the world. In addition, Chinese New Year became another hot selling season for DRAM chips. Besides China, other emerging markets also showed double-digit growth in PC sales. Furthermore, the extended PC sales continued stronger than expected throughout 2006. This situation set the scene for the shortage of DRAM chips and partially explains why the DRAM industry could not keep up with the rising demand. PC manufacturers simply failed to forecast the stronger demand in 2006, misguiding DRAM manufacturers and resulting in the shortage of chips.

In addition, an increase in demand for NAND Flash memory products contributed to the shortage. Samsung, the largest DRAM chipmaker, converted its DRAM production line to accommodate NAND Flash memory chips and other niche products. Samsung built its semiconductor plants with flexible operationalization capacity, which allowed the firm to switch from the production of DRAM chips to NAND Flash memory products. The firm exercised this option in response to plunging DRAM prices in September 2005. In addition, Samsung made a secret, long-term deal with Apple to supply them with Flash memory chips. To introduce the iPod Nano, Apple needed Flash memory chips in large volume, and it chose Samsung as its supplier. At this point, Samsung may have switched to production of Flash memory chips for Apple before building additional production lines dedicated to their manufacture. In any case, Samsung's conversion contributed to the shortage later in 2006.

Capacity Expansion in 2006 and 2007

An important consequence of the mismatch between demand and supply in 2006 was similar to that in other boom periods. DRAM prices became high and bullish during 2006. Furthermore, Microsoft's announcement of the launch of its new operating system, Vista, which was scheduled for the end of January in 2007, encouraged DRAM manufacturers to increase capacity. Industry players collectively learned that demand for DRAM chips had dramatically increased when Microsoft introduced Windows 95. Industry experts and the media expected that a similar surge in demand would occur for two reasons. First, the new operating system would accelerate the replacement cycle from old PCs to new ones. Second, the PC's average DRAM content per box would at least double because Vista would allow heavy use of graphics. Some industry experts optimistically predicted that the average might even quadruple, suggesting that DRAM manufacturers should increase their capacity substantially to keep up with the expected increase in demand.

Another important reason for the aggressive increase in output was associated with upgrading plants from 8-inch wafer to 12-inch wafer process technology. According to DRAMeXchange (2007a), manufacturers with a higher ratio of plants using the 12-inch

Table 1. Operating Margin of DRAM Manufacturers in the 4th Quarter of 2006

Manufacturer	Samsung	Micron	Qimonda	Elpida	Powerchip	Nanya
Operating Margin	31%	12%	18%	19%	43%	28%

Source: DRAMeXchange, January 2007.

wafers performed better than the average. Moreover, firms with mostly 8-inch plants generated much lower profits. In the past, most of them could not afford the more efficient plants. In 2006, however, all DRAM manufacturers made unusual profits. This profit-making momentum continued until the first quarter of 2007. With surplus cash on the balance sheet, they rushed to invest in the more cost-effective 12-inch process technology. In particular, encouraged by the industry's highest operating margin, Powerchip of Taiwan invested aggressively in 12-inch wafer capacity. As shown in Table 1, Powerchip enjoyed the highest operating margin in the fourth quarter of 2006 of all DRAM manufacturers.

DRAMeXchange attributed the high margin to the company's more unified DRAM production lines, its higher ratio of 12-inch wafer plants, and the company's pure-play manufacturing strategy, which required no R&D expenditure (DRAMeXchange Weekly Research 2007a). Powerchip's aggressive strategic move was followed by those of Hynix and others, as the momentum of cash inflow boosted their morale. This herd behavior turned into a mad race to expand capacity (to be discussed in detail later).

Another factor that further encouraged aggressive strategic moves was the formation of strategic alliances to match Samsung. Samsung's major rivals learned that they could not compete with the juggernaut individually. This realization made them forge strategic alliances with latecomers in Taiwan or China. An immediate strategic benefit from the perspective of these major rivals was that they could rely on their local partners' additional capacity without incurring substantial costs. Elpida forged alliances with Powerchip in Taiwan and SMIC in China. Their joint market share was 21% in 2006. Quimonda partnered with another Taiwanese DRAM maker, Nanya, by creating a joint venture, Inotera. Their joint market share was 21% in 2006. Hynix partnered with Promos in Taiwan. Their joint market share was 22%. By 2006, each group roughly matched the size of Samsung, whose market share dropped from 27% in 2004 to 24% in 2006. Encouraged partly by strong performance and cash position and partly by its alliance with Powerchip, Elpida publicly announced that it intended to beat Samsung Electronics and overtake its leadership position in the DRAM market after 2010. Elpida allocated a large portion of its resources to the expansion to 12-inch wafer capacity (DRAMeXchange Weekly Research 2007b). In addition, its joint venture with Powerchip involved construction of four new 12-inch plants. DRAMeXchange reported:

> Moreover, [Elpida's] joint venture with Powerchip in constructing 4 new 12-inch fabs, along with the increased yearly capex of US $1200M for 2007, evidently reveals its intentions in grabbing a bigger market share than Samsung after 2010... The "12-inch wafer battle" is expected to become more intense between the DRAM players in the future. (DRAMeXchange Weekly Research 2007b)

This event alone appeared to be sufficient to stimulate Samsung's demise. In the wake of a decreasing market share, Samsung responded to its rivals' aggressive strategic moves by expanding its production capacity (to be discussed in more detail later).

Prior to the 2008 financial crisis, there was a liquidity glut worldwide, which also seemed to contribute to the overcapacity in the DRAM chip market. For example, it was reported that the Taiwanese financial sector funded Taiwanese DRAM manufacturers in the amount of U.S. $25.14 billion (DigiTimes 2009b). In retrospect, such a high level of speculation is quite surprising when one considers the limited capabilities of these latecomers. They did not build up R&D capabilities to keep up with changes in products or process technologies. Therefore, they relied almost completely on their global partners to aid in the transition to new products and new process technologies. Furthermore, these local firms did not build up their own downstream capabilities to sell their products directly to major PC manufacturers outside Taiwan. International sales were done mostly through the business-to-business channels of their global partners. Along with their limited capabilities, production capacity was a key bargaining chip for these local manufacturers to strike deals with their global partners, driving the local firms to increase capital expenditures (DRAMeXchange

Weekly Research 2009b). Had it been more difficult for these local DRAM manufacturers to raise funds for their capital expenditures, the situation in 2008 might have been better. As easy money became available worldwide, bankers and investors seemed to be too optimistic about the potential outcomes of these ventures. The consequence of this speculative bet will be discussed later.

In sum, because of the complexity of expectations related to all the future consequences of the aforementioned factors, which simultaneously affected demand and supply of DRAM products, it seemed too challenging for the industry to reach a balance between demand and supply. Given this level of complexity, pessimists may contend that the DRAM industry is doomed to perennial cycles of shortage and oversupply (Hardy 2013).

Subsequent Downturn and the “Chicken Game”

Now, let us examine the subsequent downturn in 2007 and 2008. Contrary to expectations, the introduction of Vista in 2007 did not boost demand sufficiently to upset the imbalance between the oversupply and modest demand; therefore, DRAM prices were pushed downward. There was no substantial evidence supporting the increase in DRAM sales after the Vista launch, perhaps because many consumers and companies delayed or avoided the adoption of Vista. By the beginning of April 2007, contract prices had dropped close to the cost structure or cash cost (DRAMeXchange Weekly Research 2007c). Among the companies with plunging DRAM prices, Micron, which had a high cost structure due to its lower ratio of 12-inch wafer plants, was the first to incur a net loss for the period from December 6 in 2006 to February 7 in 2007. This loss was followed by others. By the second quarter of 2007, DRAM contract prices had plunged sharply, and most firms incurred losses – except Samsung Electronics (DRAMeXchange Weekly Research 2008c). Even in the summer, a hot selling season for PCs, the demand did not match the oversupply.

Surprisingly, most chipmakers decided to stick with their capital investment plans in early 2007 despite the unfavorable prices (DRAMeXchange Weekly Research 2007f). This strategy may look absurd to outsiders. In the media, this mad race to expand capacity is dubbed a “chicken game” (e.g., Wang 2009). In this game, players refuse to yield to one another, and the worst possible outcome occurs when neither player gives way. Apparently, the industry was marching toward this worst possible outcome unless some DRAM makers showed themselves to be willing to pull back from their original capital investment plans. DRAM makers, however, had various reasons not to do so. As mentioned previously, they should have learned that the name of the game is to drive down the cost per bit faster than the competition. In previous years of competition with Samsung Electronics, they learned that average cost is a function of size. The largest firm almost always had positive profits, whereas its smaller rivals suffered frequent losses. This lesson seemed to motivate most DRAM makers to stay in the mad race, hoping that this decision would enhance their competitiveness in the long run.

Another seemingly absurd decision in a time of tumbling prices was to join the upgrading bandwagon by converting manufacturing plants to advanced process technologies. Although the upgrading reduced average costs from the individual chipmaker's viewpoint, this herd behavior contributed to the increase in the industry's total output. In general, to reduce costs, manufacturers had to increase the number of good chips cut from a single wafer. This goal can be achieved in two ways. First, the switch can be made to a larger wafer size. All DRAM makers rushed to move from the 8-inch to the 12-inch wafer technology because the latter allowed them to reduce their costs by reducing waste and cutting more chips in one production step. Second, smaller design rules can be accommodated by migrating to a smaller nanometer technology, which allows more electronic circuits to fit on chips of smaller sizes. Given that the wafer size was held constant, cost savings occurred when more chips were cut from wafers of the same size. DRAMeXchange reported estimates of actual cost savings from migration to smaller nanometer technologies as follows:

> With new process migration, the closer the line distance is, the larger gross die number a single wafer gets, and the cost is lower and the vendors gain more competitiveness. The average DRAM output increased about 30% during the process migration from 70 nm to 60 nm. With the improvement of process design and die shrink in the same generation of process technology, the output can once again increase 20%. In the 50-nm generation, the output will increase almost 40% to 50%, compared to the 60-nm process and the number of gross die increases to 1500 to 1700 per 12-

> inch wafer with another 30% cost down. (DRAMeXchange Weekly Research 2009d)

In 2007, DRAM makers believed that the migration to these advanced process technologies was a shortcut to escape from losses during difficult economic times. For example, DRAMeXchange reported: “Micron is currently working very hard to raise the output ratio from its 12-inch fabs, and further drive down its costs by accelerating its migration to the 78-nm manufacturing process” (DRAMeXchange Weekly Research 2007c). DRAM manufacturers’ obsession with a larger market share and cost efficiency is revealed in DRAMeXchange’s report as follows:

> With DRAM manufacturers continuously increasing their output, the contract price is not expected to rebound soon, and they are forecast to tumble further in May. In response to the persisting DRAM glut, manufacturers are still mostly trying to increase their 12” fab output, in lowering their costs and expanding their market share. The significant DRAM pricing corrections do not appear to be having much of an effect on DRAM makers, as they do not have any plans on scaling back on their production. This can be seen by Qimonda’s recent decision in constructing a new 12” fab in Singapore. The increasing capacity is believed to be this year’s most worrisome factor to the DRAM industry. (DRAMeXchange Weekly Research 2007d)

Another factor that intensified the race was Samsung’s unwillingness to give up its leadership position. Samsung showed that it would defend its position in the DRAM market at all costs by aggressively increasing output. When DRAM prices had plunged in the past, Samsung had exercised its option of switching from production of DRAM chips to production of NAND Flash chips. However, Samsung chose not to do so in 2007. Instead, the firm’s output of DRAM chips in the second quarter of 2007 jumped 31% year over year (DRAMeXchange Weekly Research 2007e). The chicken game did not end despite further declines in price in 2008. In particular, Samsung and Elpida continued to increase output in the first half of 2008.

The 2008 Financial Crisis

In the beginning of the second half of 2008, the industry began to make the transition from capacity race to cutbacks, signaling that the chicken game was ending. In particular, Powerchip, Elpida, and Hynix announced cutbacks in September (DRAMeXchange Weekly Research 2008a). However, the industry as a whole incurred a loss of U.S. $8 billion for the first three quarters of 2008. As DRAM makers realized that they were in a life-and-death situation, they seriously considered cutting production as a way to conserve cash and survive.

The DRAM industry faced the worst-case scenario with the outbreak of the financial crisis in 2008. Demand was frozen and unprecedented excess capacity lingered. PC manufacturers repeatedly lowered their shipment target, reducing their DRAM purchases along with high levels of their own DRAM inventory (DRAMeXchange Weekly Research 2008a). DRAM prices collapsed further in the fourth quarter of 2008. The highest price in 2008 for a DRAM chip with 667 megahertz and 1 gigabyte was $2.29, but the price nosedived to a low of $0.58 in the last quarter. The price of the DDR2 512 megabit chip was lower than the chipmaker's material cost; it continued to plummet to almost the packaging and testing price. DRAMeXchange noted that with chips in this price range, there would be "no cash inflow, but only cash outflow" for DRAM manufacturers (DRAMeXchange Weekly Research 2008b). As prices continued to fall, DRAM manufacturers could no longer tolerate losses. Thus, they lowered output again and again (DRAMeXchange Weekly Research 2008d).

However, these cutback decisions came too late. DRAM makers with heavy debt were already stuck in a vicious cycle. These firms had borrowed money to increase their production volume in the boom period. With the continually plunging prices, they suffered losses for seven consecutive quarters. This continuous net cash outflow caused an operating crisis. As these companies ran out of cash, they faced the problem of covering interest payments on loans. Furthermore, in the midst of the 2008 financial crisis, liquidity risk for these firms suddenly turned into reality as a credit crunch hammered banking systems globally, pushing banks to tighten the terms of their loans. The difficulty of obtaining funding from the capital market eventually drove them to bankruptcy. The worst-case scenario, the most negative possible outcome of the chicken game, had turned into reality. Two major industry competitors were forced to leave the industry. On January 23, 2009, Qimonda was the first to declare bankruptcy.

On the other hand, Elpida had survived for additional three years since the Japanese government decided to rescue the firm by injecting public funds in 2009 (The Yomiuri Shimbun 2012b). The Development Bank of Japan bought 30 billion yen's worth of Elpida shares (AFP 2012). The Yomiuri Shimbun (2012a) disclosed the details of this capital injection as follows:

> In June 2009, Elpida received 30 billion yen of public loans via the Development Bank of Japan (DBJ) under the Law on Special Measures for Industrial Revitalization. Elpida later received another 10 billion yen from the DBJ and 100 billion yen from 14 private banks, including three megabanks, as syndicated loans.

However, the government rescue program did not save the firm. In February 2012, with $5.6 billion in debt, it was pushed to file for bankruptcy protection from creditors. In Japan, the government's rescue program was criticized for wasting public resources in vain (The Yomiuri Shimbun 2012b). The media attributed one of the crucial strategic mistakes on the part of Elpida to its bold commitment to heavy capital spending to keep pace with the cash-rich market leader, Samsung Electronics (Kubota and Uranaka 2012). In July 2012, Micron agreed to acquire Elpida. This acquisition process ended in 2013 (Tibken 2012).

Problems in the Taiwanese DRAM Industry

One can gain additional insight into the chicken game by examining what happened to Taiwanese DRAM manufacturers after the crisis. They were among the hardest hit by the worst downturn. According to DRAMeXchange, the DRAM industry had taken a total loss of $10 billion for almost seven consecutive quarters since the beginning of 2007. The portion of loss of the Taiwanese manufacturers was 42% of the total industry loss (DRAMeXchange Weekly Research 2009a).

As explained earlier, in the chicken game, no one wants to be the

Table 2. DRAM Manufacturers' Utilization Rate in March 2009

Firm	Fab Type	Capacity	Utilization Rate
Samsung	12 Inch	350	89%
Hynix	12 Inch	240	71%
Micron	12 Inch	75	100%
Elpida	12 Inch	115	87%
Powerchip	12 Inch	130	23%
Rexchip	12 Inch	80	81%
Nanya	12 Inch	30	40%
Inotera	12 Inch	120	42%
Promos	12 Inch	100	15%
Windbond	12 Inch	30	70%

Source: DRAMeXchange, March 2009

first to yield. The endgame looms when some players cannot tolerate the cost of staying in the game. As DRAM prices fell, Taiwanese producers, who continued to bleed losses under mounting financial pressure, were among the first to reduce output. The utilization rates of semiconductor plants in the first quarter of 2009 reflect this harsh reality (DRAMeXchange Weekly Research 2009c). As shown in Table 2, the utilization rates for Powerchip, Nanya, and Promos were 23%, 40%, and 15%, respectively. On the other hand, the rates for Samsung, Hynix, Micron, and Elpida were 89%, 71%, 100%, and 87%, respectively.

Besides cutting back their output, the substantial decline in market shares for Taiwanese manufacturers stemmed also from the drop in sales of their products to PC manufacturers. This happened because their global partners, who were struggling to utilize their own plants as much as possible, had to stop outsourcing from Taiwanese DRAM makers. For example, Hynix pulled the plug on Promos for sourcing chips. Powerchip also had a similar problem with their contract manufacturing deal with Elpida; as a result, Powerchip had to sell chips under its own brand (DRAMeXchange Weekly Research 2009e). Qimonda's bankruptcy also dramatically decreased revenues for its Taiwanese partners, Windbond and Nanya. This situation compounded the problems for the financially distressed Taiwanese DRAM makers. All these unexpected events contributed to a sharp decline in cash flow for these firms, resulting in operational problems and financial pressure related to interest payments. Despite all these imminent problems, the Taiwanese

DRAM makers also faced a dilemma of whether they should upgrade to the next generation of technology, 50-nm process technology, as Samsung Electronics planned to do. If they chose not to follow the leader, they risked going from bad to worse in terms of cost competitiveness.

In 2009, the imminent collapse of the entire DRAM supply chain in Taiwan pushed the Taiwanese government to seek a solution in the form of injecting bailout funds into troubled firms. Immediately, two issues attracted public attention. First, some questioned the sustainability of the Taiwanese DRAM makers' business model. Was it worthwhile to inject tax money into these seemingly failing companies? Taiwanese DRAM makers may have tried to emulate the success of TSMC, a world-class foundry in Taiwan, whose focus is on manufacturing chips for clients like Qualcomm. TSMC has maintained a policy of not developing and producing its own chips. This foundry business model has proven to be quite successful and sustainable primarily because it involves fabless semiconductor companies that do not build their own plants, instead relying on manufacturing service companies like TSMC or UMC. The question was whether this model could also apply to the DRAM industry, in which major competitors design and produce their own chips. Furthermore, the industry has been characterized by Schumpeterian competition, where new products and new processes constantly replace existing ones (Nelson and Winter 1978, 1982; Lee et al. 2010). In the strategy literature, capacity to survive in such an endlessly changing technological environment is called dynamic capabilities (Teece, Pisano, and Shuen 1997). It was rather evident that these local DRAM makers lacked dynamic capabilities to sustain themselves in this tough environment. Government officials in Taiwan realized that local chip makers lacked their own technology and could not survive without developing it (Wang 2009). Naturally, their concern was that capital injection would only delay their exit rather than enhancing business sustainability. The following quote reflects this concern:

> Practically speaking, the government makes no commitment to helping local DRAM makers avoid bankruptcy, said Chen [administrator of Taiwan's Ministry of Economic Affairs bureau]. If the makers are unwilling to consider investing in self-developed technologies, the government will not necessarily inject any rescue

> aid, Chen reiterated. (DigiTimes 2009a)

Another key issue was industry consolidation. Government officials also recognized that economies of scale mattered in the industry and that the Taiwanese DRAM makers were too small to compete with the juggernaut, Samsung Electronics. In the following news article, the two necessary conditions that the government imposed for injecting any rescue aid were reported:

> Fundamentally, Taiwan's government intends to inject bailout funds into the local DRAM industry under two conditions – some industry consolidation should occur and makers must show their commitment to home-grown technological development. (DigiTimes 2009a)

The Taiwanese government proposed a plan for industry consolidation by creating the Taiwan Memory Corporation (TMC), a substantial portion of which was owned by the government. The government then encouraged the Taiwanese DRAM manufacturers to sell their shares to TMC. However, conflicts of interest among stakeholders undermined this plan. Taiwanese DRAM manufacturers managed to prolong their survival by raising capital mainly through selling common stocks. In the absence of dynamic capabilities, however, their competitiveness eroded over time, and they could not keep up with the constant pressure of the race for process and product innovation.

Some recovery occurred in the second half of 2009, but it did not last long. From 2010 to 2012, the industry was characterized by chronic oversupply, primarily because of the industry's efforts toward continuous transformation from a 60-nm process in 2009 to a 30-nm process in 2012. Furthermore, PC shipments during this period declined due to the weak global economy. In addition, the rapid growth of smartphones and tablet PCs changed demand for PCs as well as commodity DRAM chips. While Samsung benefited from this rapidly growing market segment by developing and introducing mobile DRAM chips, the Taiwanese DRAM makers lacked the dynamic capabilities to respond to these new opportunities. Stuck with only manufacturing capabilities and obsolete commodity DRAM chips, most Taiwanese DRAM manufacturers eventually decided to exit the industry. The Taipei Times (2012) described the industry transformation as follows:

> In the latest shake-up in the global DRAM industry, it is evident that Taiwanese firms are reduced to playing a marginal role. Specifically, local firms that survived a severe industrial slump have wound up as bench players on Micron Technology's team to challenge industry leader Samsung Electronics…

Industry experts expect that the dramatic price fluctuations that characterized the DRAM market for decades will eventually subside. Recently, some signs of reduced price fluctuations have been visible, as three survivors, Samsung, the Micron Group, and SK Hynix, have been cooperative in restraining their capacity.

Summary

In this case analysis, I examine how such a catastrophic cycle was possible in the DRAM industry. With the supply shortage in the cyclical upturn of 2006, DRAM manufacturers expanded their production capacity. Then, competition was escalated for upgrading process technologies. All these efforts contributed to the development of a mad race to increase output despite plunging prices and mounting losses. From an individual firm perspective, the switch to advanced process technologies may have seemed like a reasonable action to avoid loss and to survive in the long run. Ironically, these efforts collectively served only to lower the chances of survival for most firms in the industry. No one anticipated how their individual choices would collectively influence supply so catastrophically. The subsequent DRAM price crash in conjunction with the credit crunch accelerated the exit of firms in financially vulnerable positions.

A MECHANISM FOR INDUSTRY TRANSITION TO STABILITY

The dynamics in the DRAM industry have changed; price behavior and profitability have moved from unstable cyclicality to relative stability. In the early period, the industry was characterized by what Winter (1984) called an "entrepreneurial regime," in which newcomers challenged incumbents with occasional changes in leadership. Now, the industry has transformed into a "routinized regime," where the market leader's technological capacity is beyond the reach of any challenge from entrants.

Based on the case study above, I propose one hypothesis with two explicit boundary conditions. In the long run, the strategy field may build a full-blown theory encompassing the creation, persistence, and disappearance of industry cycles. At the moment, I propose a piece of this grand theory in the form of a hypothesis: The higher the amplitude of the boom and bust in an industry, the larger the leader's market share will become in the long run, and the cycle will vanish eventually as the industry becomes more concentrated. The validity of this hypothesis depends on two necessary conditions outlined below.

The first condition is rising barriers to entry over time. Industry fluctuations alone may not drive the outcomes predicted above. In the absence of entry barriers, economic booms may continuously attract newcomers who may disturb industry stability in the future. Under such circumstances, there is no guarantee that industry participants will coordinate their activities to achieve a good balance between demand and supply. In the shipping and shipbuilding industries, where entry barriers are limited, for example, this sort of coordination has proven difficult, industry profitability has fluctuated dramatically, and cyclicality has continued.

Gort and Klepper (1982) proposed that as an industry moves from early stages to later stages, the cumulative stock of innovations may begin to favor incumbents, operating as an entry barrier. This is a defining characteristic of a routinized regime (Winter 1984). Indeed, product and process innovation in the DRAM industry has been crucial for competitive advantage, as mentioned earlier. For a long time, the possibilities for improving products and processes seemed endless, and Samsung Electronics was able to widen the gap between itself and laggard firms. On the other hand, innovation possibilities in the flat panel industry have been more limited, leaving room for latecomers to catch up with the market leader by increasing capacity and undercutting prices. The "crystal cycle", as it is known in this industry, is unlikely to generate the predicted outcomes in the near future, and the cyclicality associated with shortage and oversupply of flat panels is likely to persist much longer.

The second condition for the prediction above is the absence of technological change outside the industry, which often helps entrants challenge incumbents (Schumpeter 1934; Winter 1984; Tushman and Anderson 1986; Cohen and Levin 1989; Anderson and Tushman 1990; Tripsas 1997). Schumpeter (1927) conceptualized creative destruction of this kind as a trigger of industry fluctuation. For example, in the automobile industry, major changes may happen in the future in the form of alternative designs, such as electric or fuel cell vehicles, which may potentially replace vehicles with internal combustion engines, the industry's dominant design for more than half a century (Abernathy and Utterback 1978). If such a major change does indeed happen, it will disturb industry stability as entrants jump into the fray to take advantage of opportunities. In the DRAM industry, however, no such major change has happened over the last three decades. Some touted the commercial possibilities of alternatives to DRAM chips (e.g., PRAM), but no viable alternative has been realized, nor will there be one in the near future. In the absence of such exogenous creative destruction, industry fluctuations stemmed from mismatches between supply and demand, as industry participants were not able to coordinate capacity investments. In the case described here, the amplified fluctuations accelerated evolution of the industry to a stable state.

Now, let us consider why higher amplitudes in an industry cycle accelerate firm exit, leading to industry stabilization. The evolution of the DRAM industry indicates that firms with high cost structures or those with prior capital investment based on heavy debts may be vulnerable to the effects of amplified cyclicality. More specifically, the crisis for these firms stems from their exposure to risk from both operating and financial leverage. Operating leverage measures a firm's fixed costs as a percentage of its total costs. In cases of high operating leverage, a firm is exposed to higher risk because small fluctuations in sales magnify fluctuations in profit. When a price goes below its average cost, the firm begins to bleed a loss. On the other hand, financial leverage means the use of borrowed money to increase production volume. It is measured as the ratio of total debt to total assets. In cases of high financial leverage, the firm is exposed to risk of bankruptcy during economic downturns when sales go down, cash reserves to cover interest payments are inadequate, and external financing is not possible.

The crisis of Corning after the burst of the dot-com bubble illustrates the ramifications of these two types of leverage. At the turn of the new millennium, Corning sold off its cash-producing businesses and expanded its fiber optics business, which was growing rapidly prior to 2001. This strategic choice changed the underlying nature of risk in the company's business portfolio such that its operating leverage increased dramatically. Lacking understanding of this change, Corning added financial leverage in order to acquire a fiber optics company, Pirelli's U.S. subsidiary, and to benefit from the fast growth in this market. The combination of high operating leverage and financial leverage almost led to bankruptcy for Corning during the severe downturn caused by the meltdown of the dot-com bubble.

Firms in the DRAM industry tend to allocate a large portion of their expenditures to fixed costs, such as investment for increasing capacity or investment for product and process innovation. This tendency naturally exposes firms to risk from high operating leverage. However, this is a necessary condition to stay in the DRAM business. Unless a firm invests in capacity in anticipation of rising demand, it will lose its market share and any cost advantages associated with economies of scale. Unless the firm invests in product innovation, it will be stuck with existing products, which will eventually be replaced by rivals' new products in the next round of the race. Unless DRAM firms invest in process innovation, their average costs will be higher than those of their rivals. When the price goes below a firm's average cost, the firm will incur a loss. In addition, the DRAM industry has witnessed a trend toward increased fixed costs, primarily due to the steeply rising costs of production equipment for accommodating larger wafers and almost yearly migration to smaller design rules (West 1996). Rising fixed costs result in use of financial leverage. In the case presented here, most DRAM manufacturers could not rely on internal financing alone. In sum, the factors discussed above contributed to the increased risk from financial leverage during the 2008 downturn for DRAM firms. This, in turn, explains why the amplification of an industry cycle hastened the exit of less competitive firms.

CONCLUSION

In the midst of the 2008 financial crisis, the DRAM industry witnessed an unprecedented level of instability, with DRAM prices plummeting below the chipmaker's material cost. The amplification of the industry cycle accelerated the exit of vulnerable firms with heavy financial leverage, transforming the industry into an oligopoly with three main players, Samsung Electronics, SK Hynix, and the Micron Group. In general, the presence of irregular industry cycles makes it difficult for firms to formulate their strategies. Poor timing of capital investment may lead even industry leaders to lose their competitive advantage. Indeed, many firms do not fully understand the implications of these cyclic effects; as a consequence, they do not cope with them effectively (Hambrick and Schecter 1983). Exacerbating the situation, the issue has long been neglected in strategy research (Mascarenhas and Aaker 1989; Mathews 2005).

The present paper explores under what conditions industry instability with irregular cycles persists or evolves to a stable state. Empirical research on industry evolution (Abernathy and Utterback 1978; Gort and Klepper 1982; Klepper and Graddy 1990; Klepper 1996) identified the inter-temporal pattern of industries, which move through well-defined stages over time to a stable state with maturity. Yet, previous studies cannot explain why unstable industry cycles sometimes persist in mature industries, such as shipping and shipbuilding. The term "maturity" comes from biology; it invokes the image of a living organism following a predetermined path until its death. This biological analogy may not be unambiguously applicable to industries characterized by the perennial gale of creative destruction, which often resets the cycle of an industry (Schumpeter 1927, 1934). What is missing in the literature is articulation of the boundary conditions under which an industry evolves or does not evolve to stability.

The case study in this paper sheds light on why the cycle in the DRAM industry was amplified in the first place and how the amplification transformed the industry into an oligopoly. The nature of competition (characterized by Moore's Law) has constantly pushed industry participants to reduce the per-unit cost of computing power by (1) moving quickly to the latest process technology and (2) expanding capacity. This competition, over time, steeply increased the costs of staying in business in the DRAM industry; as a consequence, most industry participants had to use heavy financial leverage.

The intensity of the mad race or "chicken game" between 2006 and 2008 stemmed partly from industry participants' obsession with size and process innovation for cost effectiveness and long-term survival. From the individual firm perspective, the decision to expand capacity and to adopt the latest process technology may have seemed like a reasonable action to reduce average costs and avoid loss, but the industry as a whole suffered from the oversupply of an unexpectedly large volume of DRAM chips. A sharp transition from the boom to the bust devastated the majority of firms with high levels of financial leverage. However, in industries where barriers to entry are weak, as is the case in the shipping and shipbuilding industries, future booms will continue to attract newcomers, which will block the transition to stability. I predict that this is less likely to happen in the DRAM industry because barriers to entry are now beyond the reach of most entrants.

The mechanism of industry transition to stability identified in this paper is primarily based on observation of the evolution of the DRAM industry. This mechanism may not be at work in other industries. More systematic theoretical work is needed to deepen our understanding of the conditions under which industry cyclicality persists or evolves to a stable state. Future studies may analyze and validate the aforementioned mechanism more systematically through use of computational modeling tools. In addition, case studies from other cyclical industries will enrich our understanding of industry cycles. We still do not fully understand why firms engage in overinvestment to increase capacity, which is a key precursor of industry cycle amplification. Some of the details observed in the DRAM industry may be specific to the industry; others may be applicable to other industries. Additional case studies in this direction may enrich our understanding of motives for overinvestment and its relationship with industry cyclicality.

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