What Firms Make vs. What They Know: How Firms' Production and Knowledge Boundaries Affect Competitive Advantage in the Face of Technological Change

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ABSTRACT

Product innovation often hinges on technological changes in underlying components. We examine how firms' success in managing such component-enabled innovation is impacted by their knowledge and production strategies with respect to key components. We further consider how this relationship depends on whether the innovation is incremental or architectural. Using data on all firms in the DRAM industry across 12 technology generations from 1974 to 2005, we find that vertical integration into component production improves firms' success in managing technological change. Although non-integrated firms have lower performance, their disadvantage is muted by the extent of their component knowledge. We find that the relative advantage of extending production vs. knowledge boundaries is determined by two factors. The first is the nature of the innovation: integrated firms have a greater advantage over non-integrated firms when the change is architectural than when it is incremental. The second is the degree of integration: non-integrated firms derive greater benefit from their knowledge of external components than do integrated firms. Our results clarify the conditions under which extending knowledge boundaries can be a substitute for extending production boundaries during in managing technological change.

INTRODUCTION

New product innovations are often enabled by changes in components within existing and new architectures (Rosenberg, 1976; Hughes, 1983; Henderson and Clark, 1990; Christensen, 1992; Fine, 1998). Scholars have uncovered important mechanisms by which new innovations affect the performance advantage of firms. These examinations include the roles of firms' existing competencies (Tushman and Anderson, 1986), cognitive frames and information filters (Henderson and Clark, 1990), complementary assets (Tripsas, 1997) and resource allocation processes (Christensen, 1997). While multifaceted, these studies have tended to concentrate on how the characteristics of an innovation interact with firms' *internal* resources and product development routines to affect performance. In so doing, they have tended to overlook the interaction with firms' *external* dependencies.

Specifically, the literature on technological change has tended to assume that all components are produced and integrated by the focal firm (e.g., Henderson and Clark, 1990: 10). Firms, however, often rely on external suppliers for their components. Indeed, as numerous studies have highlighted (e.g., Monteverde and Teece, 1982; Walker and Weber, 1984; Argyres, 1996; Novak and Eppinger, 2001; Leiblein and Miller, 2003), whether firms produce components internally or source them externally is a choice that depends on firms' capabilities, economies of scale and scope, and the transaction costs associated with the development of components. In this paper, we examine how firms' performance in the face of technological change depends not only on the nature of the change, but also on the extent of their involvement in *both* the production as well as the knowledge of key components.

Transaction cost economics (TCE) has been a key theoretical lens used by scholars to evaluate how firms manage coordination problems in the vertical chain. According to TCE, the choice of vertical integration is based on the characteristics of transactions between two contracting parties (Williamson, 1985). In the context of innovation, such transactions may occur during the development and integration of components into the final product. Scholars in innovation have suggested an important link between firms' governance mode and their ability to manage new innovations (Teece, 1996; Chesbrough and Teece, 2002; Afuah, 2001). The uncertainty coupled with transaction specific investments that accompany an innovation creates contracting problems and hence, makes governance critical to the success of firms' innovation efforts.

While the dominant focus of firm boundary choice has been on the make-or-buy decision, recent evidence suggests that firm's vertical scope decision also encompasses choice with respect to integration of knowledge; i.e., instead of investing in production, firms may invest in knowledge of activities even if the activities are outsourced (Fine and Whitney, 1996; Patel and Pavitt, 1997; Brusoni et al., 2001). This knowledge may help firms to better manage the coordination challenges in the vertical chain by selecting suitable suppliers and by improving the governance in the vertical chain through crafting of superior contracts and more effective monitoring mechanisms (e.g., Mowery, 1983; Mayer and Salomon, 2006; Argyres and Mayer, 2007).[1]

In this paper we examine how vertical scope, measured through both production and knowledge of key components, affects firms' abilities to manage technological change. We evaluate effectiveness according to the speed with which firms' commercialize new technology generations. We consider how the decision to vertically integrate is determined not only by transaction costs but also by firms' capabilities and production economies. We argue that under conditions of high transaction costs vertically integrated firms are likely to gain advantage from extending their *production boundaries* to encompass component production; whereas non-integrated firms can offset their disadvantage by investing in the knowledge of components i.e., by extending their *knowledge boundaries*.[2] Finally, we predict that the magnitude of the performance difference between vertically integrated firms and non-integrated firms depends on the nature of technological change: non-integrated firms will be more disadvantaged when technological change is *architectural* than when it is *incremental*.

We test our predictions in the dynamic random access memory (DRAM) industry from 1974 to 2005, a period during which the industry transitioned through 12 distinct technology generations that were critically enabled by changes in components. The 12 technology transitions can be clearly classified as either incremental or architectural (Henderson and Clark, 1990), such that the interactions between transition types and firm strategy are well characterized. Also, because DRAMs of a given technology generation are homogenous goods (Irwin and Klenow, 1994), comparisons between firms time to

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[1] Our analysis focuses on the impact of knowledge on the firms' ability to coordinate technological changes with component suppliers. Thus, we are not examining cases in which firms invest in knowledge in order to internalize component development (Clark, 1989) or to make and buy the same component (Harrigan, 1984).

[2] Our conceptualization is consistent with prior research that has examined firms' knowledge in the context of activities in the vertical chain (e.g., Fine, 1998; Brusoni et al., 2001; Takeishi, 2002). However, we note that firms' knowledge boundaries may encompass broader domains than those considered here.

commercialization offer a particularly crisp measure of performance. Hence, the DRAM industry is an especially good context in which to test our arguments.

We find that vertically integrating into component production improves firms' ability to manage transitions across technology generations. Although non-integrated firms have lower performance, this effect is muted by the firms' component knowledge. Moreover, the relative advantage of extending production vs. knowledge boundaries is determined by two factors. The first is the nature of technological change: integrated firms have a greater advantage over non-integrated firms when innovation is architectural than when it is incremental. The second is the choice of vertical integration: non-integrated firms derive greater benefit from their knowledge of external components than do integrated firms.

Prior research in innovation has emphasized internal challenges that firms face during periods of technological change. Firms, however, often depend on external suppliers for their innovation, and coordination of technological changes across firm boundaries may play no less a role in shaping firms' performance. Our examination of such coordination challenges across 12 different technology generations sheds important light on how firms' production and knowledge strategies within the vertical chain affect their ability to commercialize new innovations. Our results also extend the emerging literature that integrates transaction cost economics with competence based perspectives (e.g., Leiblein and Miller, 2003; Mayer and Salomon, 2006). We show that while knowledge of external activities may improve firms' governance capabilities, its effect may be muted for partially integrated firms that have a lower reliance on external suppliers. Finally, we contribute to the emerging literature of innovation ecosystems by explicitly recognizing that the success of firms' innovation efforts depends on other innovations in the firms' environments (e.g., Afuah and Bahram, 1995; Adner and Kapoor, 2006; Adner, 2006; Gawer and Henderson, 2007), and by showing how firm strategies interact with technological changes in the environment to influence performance outcomes.

THEORY AND HYPOTHESES

Technological Change and Firm Performance

Technological progress in an industry is characterized by long periods of incremental improvements punctuated by radical changes (Sahal, 1981; Tushman and Anderson, 1986). Radical changes occur when core technological concepts underlying a given product are transformed, and followed by the emergence of a new dominant design (Abernathy and Utterback, 1978). Incremental changes are more subtle, such that core technological concepts are reinforced and progress takes place along continuous technological trajectories (Dosi, 1982). Historically, the innovation literature has focused on differences between entrants and incumbents during periods of technological upheaval, paying particular attention to the internal challenges that firms face in managing these transitions (e.g., Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1997). While such episodes are critically important, by far the bulk of economic activity is characterized by incumbents competing with other incumbents during periods of non-radical change. The successful commercialization of such non-radical innovations plays a vital role in extending the firms' competitive advantage over their rivals. In this study, we complement the earlier literature by focusing on this more common form of competition in technology based industries, paying particular attention to coordination challenges in the vertical chain..

Firm's Vertical Scope and Management of Non-Radical Technological Change

We conceptualize product as composed of components that are themselves arranged in an architecture (e.g., Baldwin and Clark, 1999), and then examine how a firm's production and knowledge boundaries with respect to key components affect its ability to make technological progress. In this discussion, we only consider technological changes in which core technical concepts are reinforced, not overturned. Hence, we constrain the type of innovations to either incremental or architectural (Henderson and Clark, 1990). Such innovations are enabled by technological changes in components along pre-existing trajectories (e.g., Henderson and Clark, 1990; Christensen, 1992).

From the point of view of an innovating firm, managing technological changes in components requires close coordination between activities that underlie the development of components and their integration into the final product. This is especially true when such components advance at non-uniform rates (Rosenberg, 1976; Hughes, 1983) or have technological interdependencies that require experimentation and learning for their potential to be realized (Iansiti, 1998; Loch and Terwiesch, 1998).

Transaction cost economics (TCE) has been a key theoretical lens used to explain how firms could manage coordination between upstream and downstream activities through a make-or-buy choice. TCE views the make-or-buy decision by the firm as a solution to minimizing transaction costs. Hence, the efficient form of organization for a particular transaction is deduced based on key properties of the transaction: asset specificity, uncertainty and frequency (Williamson, 1985). Of the different transaction characteristics, asset specificity has received the most attention in the empirical literature as it plays a central role in the transaction cost approach to vertical integration (Williamson, 1985, p. 56). Asset specificity refers "to the degree to which an asset can be redeployed to alternative uses and by alternative users without sacrifice of productive value". Williamson (1991, p. 281) has identified at least six different types of asset specificity: site specificity, physical asset specificity, human asset specificity, brand-name capital, dedicated assets and temporal specificity.

In the context of innovation, beyond physical asset specificity, the iterative process of component development and integration often requires extensive interactions between employees from the firm and the upstream component suppliers resulting in high human asset specificity (e.g., Monteverde and Teece, 1982; Monteverde, 1995). In addition, such transactions are also typically characterized by high degree of temporal coordination between component and product development and hence, subject to temporal specificity (Wheelwright and Clark, 1992).

Vertical integration of key technological components characterized by high asset specificity would facilitate the commercialization of new innovation by mitigating contractual hazards associated with the asset specificity. Such hazards may result in poor product quality or delays in new product introductions where suppliers operating under different incentive conditions may behave opportunistically (Masten, 1996; Teece, 1996). Hence, we expect that firms' vertical integration of component characterized by high asset specificity would provide superior coordination of activities during the commercialization of the new innovation:

> *Hypothesis 1: Vertical integration of a component characterized by high asset specificity will improve a firm's performance in a new product technology.*

Even if the likelihood of contractual hazards in the vertical chain may suggest internalizing production, firms may not be able to do so. First, firms may not enjoy production economies and hence, have higher production costs than their suppliers (e.g., Walker and Weber, 1984). Second, firms may not have the capability associated with the development and production of key technological components (e.g., Argyres, 1996; Leiblein and Miller, 2003). Finally, the possibility of technological obsolescence associated with components may also dissuade vertical integration (e.g., Balakrishnan and Wernerfelt, 1986). Such constraints to internalizing the production are especially relevant in industry contexts in which innovations are created through the combination of multiple, rapidly advancing, component technologies.

While the strategic choice of firm's production boundaries is important, it is not the only dimension along which firm component strategies may be evaluated. For example, Patel and Pavitt (1997) provided comprehensive evidence that the production boundaries of the world's largest corporations are significantly narrower than their knowledge boundaries. They found that many firms develop competencies in a given technological field (as measured by patents) even though they do not actively participate in the relevant product market. Similar findings have been reported in the aerospace and the automotive industries i.e., firms invest in knowledge of components even if the components are fully sourced through the market (Fine, 1998; Brusoni et al., 2001; Takeishi, 2002; Ahmadjian and Lincoln, 2001).

Firm's investment in knowledge of components may facilitate the governance of activities in the vertical chain by reducing information asymmetry. More specifically, component knowledge is likely to influence governance through at least three different mechanisms. First, component knowledge may allow firms to select superior suppliers and avoid problems of low quality or longer development times. Second, component knowledge may also help firms to craft better ex ante contracts. Such contracts would clearly identify roles and responsibilities of the partners, detailed project milestones, monitoring mechanisms, contingency planning and knowledge sharing between parties. Finally, component knowledge may allow firms to monitor upstream activities more effectively by evaluating supplier investment and progress during development and identifying detailed specifications to asses the quality of the inputs. For example, Ahmadjian and Lincoln (2001) provide evidence of how Toyota's investment in knowledge of electronics improved its governance of activities with its key supplier, Denso:

> Some supporting evidence comes from our interviews with Toyota engineers who stated that the quality of Toyota's discussions with Denso about parts design and manufacturing had risen since Toyota's investment in electronics learning began. Before, they said, Toyota people sometimes asked silly or naive questions in procurement negotiations with Denso. Now that Toyota was acquiring a solid knowledge base in the technology, the communication between the companies has improved (pp. 689).

Hence, we expect that a non-integrated firm's component knowledge will facilitate its governance of the vertical chain and offset the negative impact of under-integration i.e., not internalizing the production of component with high transaction cost.

Hypothesis 2: In the absence of vertical integration, a firm's knowledge of the external component characterized by high asset specificity will improve its performance in a new product technology.

Innovation within a product architecture requires not only the integration of individual components but also the coordination of interactions between different components. While technological progress in components along pre-existing trajectories allow for new innovations, these innovations may vary in their extent of changes in interactions between components (e.g., Henderson and Clark, 1990; Christensen, 1992). According to Henderson and Clark, "architectural innovation is often triggered by a change in a component – perhaps size or some other subsidiary parameter of its design – that creates new interactions and new linkages with other components in the established product" (p. 12). Business and technology historians have provided numerous instances in which changes in a given component technology create "disturbances" which are eventually resolved through modifications in other parts of the architecture (Rosenberg, 1976; Hughes, 1983). These modifications may be through changes in other components as well as through changes in the interactions between components.

The architecture of a product may include components that are produced by the firm or its suppliers. Henderson and Clark (1990) only considered product innovations in which the components are designed, engineered, manufactured and integrated by a single firm (p. 10). Hence, their arguments with respect to coordination routines to commercialize new innovations were directed at units within an organization. However, these arguments may also be applied when components are produced by the firm's suppliers. Just as the interactions within a firm are characterized by communication channels, information filters and problem solving strategies, so too are the interactions between the firm and its suppliers (e.g., Dyer and Nobeoka, 2000; Takeishi, 2002) which may require greater adaptation during an architectural innovation.

While Henderson and Clark (1990) provided convincing evidence from the semiconductor lithography alignment equipment industry that architectural innovation was a major reason for incumbent's failure during technology transitions, subsequent research in other contexts has provided mixed findings. For example, Christensen and Rosenbloom (1995) showed that in the disk drive industry, incumbents were successful in commercializing new architectural innovations as long as the innovation was developed and deployed within the same value network. However, as Chesbrough (2001) notes, incumbents in the semiconductor lithography alignment equipment industry were operating in the same value network and were still adversely affected by the architectural innovation.

We suggest that this inconsistency in findings can be resolved through closer examination of the interaction between firms' production boundaries and the nature of technological change. In the semiconductor lithography alignment equipment industry, three of the four architectural transitions changed the relationship between the lens and other components of the system (Henderson and Clark, 1990, p. 23). Incumbent firms who relied on external lens suppliers to commercialize the new innovation exited the industry when confronted with architectural innovations.[3] However, the one firm that produced its own lens (Canon), despite facing significant challenges due to architectural innovation continued to be an important industry participant during and after the transition. Similarly, in the disk drive industry, the two technology innovations in which existing value networks were preserved and incumbents were able to successfully commercialize architectural innovations were the change from removable disk-pack drives to 14 inch Winchester drives and the transition from 3.5 inch to 2.5 inch drives. In both of these cases, vertically integrated incumbents such as IBM, Control Data, Toshiba, Hitachi and Fujitsu, which manufactured their own key components of magnetic disk and drive heads were successful (Christensen, 1993; Christensen and Rosenbloom, 1995; Christensen et al., 2002). Hence, it does seem that across both industry settings, firms that were vertically integrated in the production of key components performed better with architectural innovations. This observation is in line with Teece's (1996) proposition that integrated firms fare better in commercializing innovations that require "coordinated adjustment" throughout the technological architecture:

> What is needed to successfully develop and commercialize systemic innovations are institutions with low-powered incentives, where information can be freely shared without worry of expropriation, where entities can commit themselves and not be exploited by that commitment, and where disputes can be monitored and resolved in a timely way. This is precisely what multi-product integrated firms achieve. (p. 219)

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[3] An incumbent firm, GCA, acquired a lens maker, Tropel, in 1982 but continued to rely on an external supplier for most of its technical and commercial needs (Henderson, 1988: 227).

The above discussion suggests that vertically integrated firms may be able to better coordinate technological changes that underlie an architectural innovation. This prediction is consistent with TCE. The changes in interactions between components during an architectural innovation are likely to increase the uncertainty associated with the coordination of various tasks. An increase in uncertainty coupled with greater asset specificity would exacerbate the transaction cost and hence, further increase the advantage of hierarchy over markets as a preferred organization mode to minimizing contractual hazards (Williamson, 1985).

Hypothesis 3: A vertically integrated firm will have a greater advantage over a non-integrated firm when the technological change is architectural than when it is incremental.

INNOVATION IN THE DRAM INDUSTRY

The context for our study is the global dynamic random access memory (DRAM) industry. This industry is an ideal setting to test the hypotheses. Technological progress in the DRAM industry during the period of study has been enabled by changes in components along existing technological trajectories. This resulted in DRAM innovations being either incremental or architectural, providing us with a natural control to test our hypotheses. Throughout the industry's history, the key component technologies have been characterized by high asset specificity during commercialization of new innovations, such that the setting provides a valid test for TCE predictions. Finally, DRAMs represent homogenous goods (Irwin and Klenow, 1994). Therefore, each firm introduces the new innovation with essentially the same product characteristics. Hence, comparing differences in firm performance for a given product innovation is less likely to suffer from biases from unobserved differences in product quality and attributes.

Data

We used both primary and secondary data for this study. The primary data was collected through a series of interviews with over twenty industry experts over a period of 18 months. The secondary data was collected from semiconductor industry analysis firms, industry publications and the US Patent and Trademark Office (USPTO). Appendix I provides the details of the sources of secondary data that we used in the study to carry out the quantitative analysis. Our sample includes every firm that ever sold a DRAM on the open market.[4] We identified a total of 36 firms in the DRAM industry that competed in 12 distinct DRAM generations ranging from 4 Kilobit (4K) to 1 Gigabit (1G) memory density from 1974 to 2005. In this study, we only consider the performance of incumbent firms (that is, we include firms as of their second generation of DRAM production). We note that incumbent firms have been the leading innovators in the industry, consistent with the presence of significant learning curve effects and the total absence of successful radical (Cooper and Schendel, 1976) and disruptive (Christensen, 1997) innovations.

Component Technologies and Technological Change in the DRAM Industry

Since its emergence in the late 1960s, the DRAM industry has been viewed as a main engine of growth for the entire semiconductor value chain. Due to advances in computing applications, DRAM firms are faced with a continuous need to introduce new generations that increase the memory density of the DRAM chip. The memory density of the DRAM chip is defined based on the number of "bits" of binary data that the chip can store. For example, the 1 Megabit (1M) DRAM chip can store 1 x 10^6 bits of data. Each bit on the chip is stored in a memory cell - a simple electric circuit of transistor and capacitor. The 1M generation was succeeded by the 4M generation, which increased memory density, and could store 4 x 10^6 bits of data on the chip. The increase in the density of the DRAM is achieved by increasing the number of cells in the chip. However, the increase in the number of cells per chip can only be economically viable if the size of the cell is reduced. This reduction is constrained by the design of the integrated circuits, the materials from which the chip is composed, and the process used to manufacture the circuits.

The core capabilities of the DRAM firms encompass product design, process technology and manufacturing engineering (Burgelman, 1994). The process technology and the manufacturing engineering groups can be considered as part of the DRAM firm's manufacturing capability. The successful commercialization of a new DRAM generation requires co-development of product design and process technology to achieve the required DRAM density. Once the new product is developed and commercialized, the focus moves to manufacturing engineering to scale up the process to achieve large volumes with high yields. Among the many processes required to manufacture a DRAM, the lithography

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[4] We do not have data on the small number of firms that produced DRAMs exclusively for their own in-house use.

process plays the most critical role in reducing the cell size and allowing for the introduction of new DRAM generations (Moore, 1995).

The lithography process used in semiconductor manufacturing is illustrated in figure 1. There are three key component technologies that are integrated in the lithography process - the mask, the alignment equipment and the resist.[5] The lithography process takes place when beams of ultraviolet (UV) light from the alignment equipment are directed onto the mask. The mask bears the blueprint of the DRAM chip design. Since the DRAM chip is made up of several stacked layers with each layer characterized by a unique circuit design, several unique masks are used to create a single DRAM chip. The mask allows a portion of the light to pass through, onto the semiconductor substrate. The substrate, a DRAM wafer, is coated with an energy sensitive chemical resist. The resist undergoes a chemical reaction wherever the mask has allowed the light to pass through. This chemical reaction changes the structure of the resist and allows its selective removal from the wafer through a developing process. Another chemical process is then initiated in which the exposed parts of the wafer are etched. Finally, the remaining resist is removed, creating a final circuit that replicates the initial DRAM design. A typical DRAM chip goes through this process a number of times to sequentially build the integrated circuits with different mask designs. For example, the recent 128M DRAM chip went through as many as 120 lithography process steps.

(Insert Figure 1 about here)

The alignment equipment, the resist and the mask are key component technologies in the DRAM manufacturing vertical chain. The DRAM firm’s commercialization of new generation depends in large part on progress in these component technologies. While all these technologies have been progressing at fast rates, their progress has not been uniform leading to the rise of technological bottlenecks (Kapoor and Adner, 2007). Moreover, the integration of these component technologies during the commercialization stage requires extensive experimentation and firm-specific learning. For example, a manager from a supplier of mask technology commented:

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[5] Note that components can be either physical elements within the product architecture (e.g., Henderson and Clark, 1990) or, as is the case here, inputs to the production process (e.g., Henderson and Cockburn, 1994).

> “We can offer our technology to our customer but how that technology works in the customer’s facility is very much a function of how the customer integrates the different technologies, and we typically go back and forth until the technology is implemented in production.”

Hence, DRAM firms are faced with significant challenges in coordinating the technological changes in the lithography components in order to commercialize the new generation.

Component Technologies and Asset Specificity

The commercialization of a new DRAM generation requires close collaboration between personnel in the product design, process technology and manufacturing engineering groups within the DRAM firm. This close collaboration has been referred to as “unstructured technical dialog” which creates human asset specificity between the design and manufacturing activities (Monteverde, 1995). Since the mask represents the blueprint of the firm’s product design and is used to develop and scale up the manufacturing process, it is the bridge through which this unstructured technical dialog takes place. The mask activity is normally located in very close geographic proximity to the semiconductor manufacturing. This is due to the combination of intense pressure to be early to market with a new DRAM innovation, and the complex iterations between DRAM firms and their mask suppliers. The required coordination between mask making activity and DRAM production is therefore also characterized by temporal specificity (Masten et al., 1991). Our interviews with industry experts confirmed this aspect of coordination. For example, a technical manager with a leading semiconductor manufacturer commented:

> “From lab to production, there are typically three to four mask redesigns…..Your designers come to you and say we are going to change the chip design and you should be able to implement it [the new mask design] very quickly.”

The commercialization process also includes extensive experimentation with different types of resist. The suitability of resist is evaluated based on its coating uniformity on the semiconductor substrate, its interaction with the alignment tool as well as its stability during the chemical processes of developing and etching. A DRAM manufacturer invests significant amount of effort and resources extending over many months in finalizing a resist for the new DRAM process. Once a particular resist is finalized in a firm’s process “recipe”, any changes are time consuming and extremely costly. In addition, DRAM firms invest in dedicated equipment for downstream processes in their manufacturing lines which may be specific to a given resist chemistry.

The alignment equipment is the final component technology within the lithography architecture. As with resist, firms invest significant resources in selecting the alignment equipment from a limited number of suppliers. In addition, firms incur dedicated investments to integrate the equipment into their manufacturing lines and to create the infrastructure for maintenance.

Component Technologies and Firm Boundaries

The above discussion suggests that all three lithography component technologies exhibit a high degree of asset specificity for a DRAM firm during the commercialization of new generation and hence, DRAM firms may be subjected to contractual hazards from the suppliers of the respective components. While transaction cost considerations may suggest that an efficient organization of activities would constitute firms internalizing all three components, firm's choice may also depend on consideration of production costs and firm capabilities (e.g., Walker and Weber, 1984; Argyres, 1996). During the time period that we studied, some DRAM firms integrated the production of mask, no firm integrated the production of resist, and only one firm (Hitachi) integrated into the alignment equipment. The development and production of resist requires large R&D and production investments, and a deep knowledge of chemical compounds and processing. Therefore, only large specialized chemical suppliers such as Kodak, Hoechst and Shipley have manufactured resist for semiconductor manufacturing. These specialized chemical firms also enjoy large economies of scope through participation in other chemical markets. Similarly, the development and production of alignment equipment also require enormous R&D expenditures, and advanced knowledge of optics and mechanics. Hence, firms such as Perkin Elmer, Nikon and Canon with superior optics and mechanics capabilities, and participation in multiple photo-imaging markets have supplied alignment equipment to DRAM firms.

While DRAM firms did not integrate the production of key components, we found that they invested in the knowledge of such components. As discussed later, our examination of patents filed by DRAM firms showed that these firms invested in the knowledge of components even when they outsourced their production. This finding is consistent with prior examination of knowledge boundaries (Patel and Pavitt, 1997; Brusoni et al., 2001; Takeishi, 2002).

DRAM Innovation and the Nature of Technological Change

The capability of the lithography process is defined based on the minimum feature size - the smallest circuit dimension that can be patterned on the semiconductor. Figure 2 plots the introduction of different DRAM generations and the minimum feature size in microns (µm = 10^{-6}m) that is achieved through improvements in the lithography process. Since the emergence of the DRAM industry with the introduction of 1K DRAM, there have been a total of 12 new generations from 1974 to 2005. Moreover, each generation is enabled by the DRAM firm's reduction of the minimum feature size. This reduction is largely attributed to progress in the alignment equipment, the resist and the mask.

(Insert Figure 2 about here)

While the new DRAM generations were commercialized through improvements in the alignment equipment, the resist, and the mask, there were differences in the nature of the technological changes across these generations. Table 2 lists the different DRAM generations, the minimum feature size and the key changes in the lithography technology that enabled the commercialization of the new product. From the table, it can be seen that certain changes within the lithography technology represented incremental innovations whereas others represented architectural innovations (Henderson and Clark, 1990). For example, in the 64K DRAM innovation, there was a change in the lithography technology from the proximity printing method to the projection printing method. While projection printing technology promised smaller feature size and higher yield, it shifted the emphasis on the process yield from the alignment equipment to the mask. The change also altered the relationship between the mask and the alignment equipment as the optical energy from the alignment equipment was gradually scanned across the wafer after being projected through a lens system. In contrast, the commercialization of 1M DRAM was achieved through incremental changes in components within the same technology architecture as the previous generation of product.

(Insert Table 2 about here)

The classification of these generations as being either incremental or architectural is a key aspect of this study and presented us with a major challenge. To obtain this classification, we discussed the details of each technology transition with a number of industry experts, read technical articles from the annual lithography conference organized by The International Society for Optical Engineering (SPIE) since 1976, and read articles written by industry analyst firms such as Integrated Circuit Engineering, VLSI Research and IC Knowledge. For each technology transition we characterized the changes in lithography technology that enabled the new DRAM generation. We also characterized the changes in the relationship in the linkages between the key components of aligner, mask, and resist. We tabulated these descriptions, circulated them among our industry experts, and made changes based on their feedback. All the experts agreed with our final characterization of the different DRAM generations. Consistent with the description of architectural innovation in Henderson and Clark (1990) and on the construct items developed by Gatignon et al. (2002), we identified the DRAM innovations being either incremental or architectural according to whether a technological generation entailed changes in the critical relationships among key components (coded architectural) or not (coded incremental).

While the successful DRAM generations have been either incremental or architectural, there have also been attempts to introduce radical innovations to replace the conventional integrated circuit technology based on the metal-oxide-semiconductor (MOS) technology.[6] However, none of the radical innovations have ever entered the mainstream of DRAM markets and hence, this setting provides us with a natural control for innovations that are, exclusively, either incremental or architectural.

Measures

Dependent Variable

Our measure of firm performance is based on the firm's timing of commercialization of the new DRAM generation. Research in strategy has considered firm's time of entry into new markets as an important driver of competitive advantage (Lieberman and Montgomery, 1988). In addition, studies on innovation have used firm's timing of new innovation as a key measure of its performance (e.g., Schoonhoven et al., 1990; Brown and Eisenhardt, 1995; Gatignon et al., 2002). The sharp price erosion and intensive rivalry in the DRAM industry creates a significant early mover advantage within a given DRAM generation (Methe, 1992; Enz, 2003). These advantages are largely a result of learning by doing

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[6] These include the development of various magnetic memory products such as the bubble memory and the magnetoresistive random access memory (MRAM) that required very different processing technologies and materials.

(Hatch and Mowery, 1998; Irwin and Klenow, 1994). As a result, DRAM firms are continuously striving to be first to introduce the new generation with improved lithography technology. The measure is also appropriate for testing the firm's ability to coordinate technological changes in its vertical chain so as to minimize delays in the commercialization of new innovations.

We measure the firm's *Timing of Innovation* as one plus the difference in the number of quarters (3-month periods) between the first shipment by the firm and the first shipment in the industry for a given DRAM generation. Hence, the first firm takes the value of 1 and a firm that commercializes the generation three quarters after the first firm takes a value of 4. We used the logarithmic transformation of the dependent variable in our analyses.[7]

Because no firm in the industry has ever 'skipped' a technology generation, strategic non-participation is not an issue in our context. Since we examine all firms that have participated in the industry, we do not face any left censoring issues. We are also confident that right censoring is not a problem in our data given the dynamics of the industry. In the DRAM industry, product life cycles are short and entry into older generation of products is not economically viable once a new product has taken root; that is, firms begin their production in the newly introduced generation, not the older ones).

The only generation for which we have potentially incomplete observations is the 1G generation that emerged in 2003, into which a number of incumbents had yet to enter by 2005. We performed robustness test by excluding the 1G generation. We performed an additional test to ensure that our reported results are not sensitive to the chosen measures. It is possible that the first shipment may represent delivery of samples that may not be fully qualified by the customers. Hence, the quarter in which the first shipment is recorded for the new DRAM innovation may inappropriately characterize an early "sampler" as a full-fledged market pioneer. In order to check for this bias, we also tested two alternative commercialization thresholds in which the timing of innovation was measured as the first quarter in which the firm shipped 100,000 and 250,000 units of the new DRAM generation. The results are consistent with the ones reported here.

Independent Variables

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[7] As a test of robustness, we also used a linear specification and the results are consistent with those reported here, but with a lower R-squared.

Among the three component technologies – the mask, the resist and the alignment equipment – we focus on the firm's make-or-buy decision for the mask technology and the firm's investment in knowledge for both the mask and the resist. As discussed earlier, none of the DRAM firms internalized the production of the resist due to the high cost of development and production and hence, we do not consider the governance choice for the resist. We also exclude the alignment equipment from the boundaries' analysis as there was only a single instance in which a DRAM firm (Hitachi) also manufactured alignment equipment, and it did so in a standalone business unit. Further, because alignment equipment knowledge draws on a multitude of scientific domains (e.g., optics, mechanics, software) that overlap with many of the firms' other businesses it was not possible to measure specific knowledge investments in alignment equipment using the patent data.

The industry has treated the mask and the resist as key component technologies for semiconductor manufacturing, as demonstrated by numerous annual dedicated conferences such as Photomask Japan, the Annual BACUS Symposium, the European Conference on Mask Technology, and Advances in Resist Technology and Processing in which new technological developments are presented and discussed. The variable *Mask Governance* takes a value of 1 if the DRAM firm outsourced the production of mask technology and takes the value of 0 if the firm is vertically integrated into the mask technology in the year prior to its commercialization of the new DRAM innovation. We measured the firm's knowledge in the mask and resist technology using patent data. We asked industry experts who have been associated with the mask and resist R&D to provide us with the most prominent technology subclasses associated with the two components.[8] We identified the patent subclass 430/5 as the key technology subclass for the mask technology, and patent subclasses 430/270.1, 430/191a, 430/192a, 430/326, 430/325, 430/281.1, 430/190, 430/311 as key technology subclasses for the resist technology. We also confirmed the validity of the subclasses as proxy for knowledge underlying the components by examining the patents granted to specialized mask and resist manufacturers. The subclasses mentioned above dominated the patents for all specialized firms. The variables *Mask Knowledge* and *Resist Knowledge* are operationalized as the number of successful mask and resist related patent applications filed by the DRAM firm in the 3 years preceding the firm's commercialization of the new DRAM generation. Similar patent based measures have been

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[8] These experts included industry veterans such as Marc Levenson, who worked for IBM during the 1980's and is the inventor of perhaps the most important innovation in the mask technology – the phase shift mask, that allowed for feature sizes to be smaller than 0.25μm.

used in prior studies to examine firm's knowledge in a given technology (e.g., Patel and Pavitt, 1997; Cattani, 2005).

As a test of robustness we also included a 5-year window for the patent based measures of component knowledge. Also, because the primary subclass may under-represent the knowledge underlying the patent granted to the firm, we included component knowledge measures using patents where the mask or the resist subclass is not restricted to only the primary subclass. The results using these alternative measures were consistent with the ones reported in the paper.

We defined the variable *Architectural Innovation* for a DRAM generation based on whether the generation entailed major changes in the critical relationships among the key components as indicated in Table 2. The variable takes a value of 1 if the DRAM innovation is architectural and 0 if it is incremental.

Control Variables

We controlled for *Firm Size* as measured by the log of firm's annual sales (in millions of dollars) in the year prior to its commercialization of the new generation. Firms in our sample vary in their degree of dependence on the DRAM market. Besides DRAMs, these firms may also be active in other semiconductor markets. Burgelman's (1994) account of Intel's participation in both the DRAM and the microprocessor markets suggests that firm's market scope may influence its resource allocation towards the development of new innovations. We controlled for this effect using the variable *Firm Scope*, defined as the percentage of firm's sales in non-DRAM markets in the previous year. Finally, we accounted for variations in the complexity of the DRAM generation (e.g., Macher, 2006). The variable *DRAM Feature Size,* the smallest dimension of the circuit, is a widely used measure of the sophistication of the product and the process technology required to create these miniaturized DRAM products.

As a robustness check, we also controlled for Japanese firms and the results are consistent with the ones reported in the paper. Evidence, primarily from the automotive industry, have shown that Japanese firms use greater degree of relational governance that increases trust and decreases opportunism (e.g., Womack, Jones and Roos, 1990; Dyer, 1997). However, as noted by Williamson (1985) and more recently by Ahamdjian and Lincoln (2001), Japanese auto firms use a combination of formal and relational contracts to manage governance in the vertical chain. While Japanese firms may face reduced opportunism, governance of supplier activities is certainly a key determinant of their success and this governance capability has been shown to increase with their knowledge of supplier activities (e.g., Takeishi, 2002).

To ensure that our results are not biased by temporal effects, we created dummy controls for each of the four decades in our study. Although we would have preferred to use finer grained temporal controls, we are constrained by the degrees of freedom in our data. The results with time controls are consistent with the ones reported here.

Statistical Method and Analysis

Firms self-select into their governance mode. Unobserved factors can influence both firms' governance forms as well as their performance. This can create a selection bias such that normative implications drawn from the estimation may be incorrect. We follow the Heckman procedure (1979) to address this self-selection problem. This procedure includes a first-stage probit model to specify a selection equation and then calculates the inverse Mill's ratio (?) that is used as a control variable in the second stage performance model (c.f., Shaver, 1998). The first stage selection equation is given by:

$$Prob\ (Y_i = 1|X_i)\ =\ ?(d'X_i)$$

where Y_i is governance choice variable that takes the value of one if a firm outsources the production of mask and zero if it vertically integrates into the mask. The set of independent variables includes measures for firm's production economies and knowledge in mask, the extent of new technology investment required in the mask to commercialize the new DRAM generation, and the contractual hazards associated with the existing mask supply. Firm characteristics include production scale measured through firm size, production scope measured through firm scope and mask knowledge. We also consider the extent of new technology investment that firms may incur in mask for the new DRAM generation. The need for new investment may prevent firms from vertical integration (Balakrishnan and Wernerfelt, 1986). The DRAM feature size is a useful proxy to measure the degree of new investment as smaller feature size significantly increases firm's investments in the mask making facility (Trybula and Grenon, 2003). Finally, we use the number of mask suppliers as an instrument in the first-stage estimation. Prior research has identified small numbers bargaining hazards due to the number of suppliers as being an important source of contractual hazards that firms may consider in choosing their governance mode (Pisano, 1990;

Leiblein et al., 2002). We account for this hazard by measuring the number of mask suppliers in the given year of observation.

After the first stage estimation for firm's governance choice and the calculation of the inverse Mill's ratio (?), the second stage performance model is estimated using ordinary least squares (OLS). Since firms participate in multiple DRAM generations, we account for the possibility that residuals for a given firm may be correlated across innovations by using STATA's "cluster" option.

RESULTS

First-Stage Governance Choice Results

Table 3 presents results from the first stage governance choice models for mask (Buy=1, Make=0). In Model 1, we include the direct effects of firm attributes - firm size, firm scope and mask knowledge. In Model 2, we test the effect of new technology investment by also including DRAM feature size, and in Model 3, the full model, we test the effects of small numbers bargaining hazards by adding the number of mask suppliers. The decision to internalize the production of mask technology is based on firms' consideration of both production and transaction costs (Williamson, 1985: 93). The coefficient for firm size is negative and significant suggesting that large firms are more likely to vertically integrate into mask. Vertical integration is a costly strategy in terms of initial capital outlays, costly ongoing investment in required upgrades, and risks associated with guaranteeing sufficient mask quantities to operate past the minimum efficient scale. As expected, the coefficient for firm scope is negative indicating that firms that are also active in other non-DRAM markets have a greater propensity to vertically integrate. Firms are more likely to undertake large investments in mask production if they can leverage this strategic asset for DRAMs as well as for other markets. However, this effect is significant for only models 1 and 2. The effect of mask knowledge is positive and weakly significant for models 1 and 3 suggesting that firms with greater mask knowledge are more likely to use external governance. This result is consistent with findings in Mayer and Salomon (2006) in the context of information technology outsourcing. The coefficient for DRAM feature size is negative and significant suggesting that as the degree of investment in mask production increases, firms tend to rely on external suppliers for their masks. Finally, the positive and significant coefficient for number of suppliers is consistent with the expectation that firms internalize the production of mask when small numbers bargaining hazards are likely (Pisano, 1990; Leiblein et al., 2002). We use the results from model 3 to calculate the inverse Mill's ratio for the second-stage performance model.

(Insert Table 3 about here)

Second-Stage Performance Results

Industry incumbents pioneered all new technology generations in our study sample, regardless of whether the innovation was incremental or architectural. Moreover, in 10 out of 12 generations (the exceptions are 4K and 128M), the pioneering incumbents were vertically integrated with respect to the mask technology. Therefore, vertical integration of mask seems to facilitate early commercialization of the DRAM generation. The descriptive statistics and correlations for variables used in the second stage model are reported in Table 4.

(Insert Table 4 about here)

Table 5 provides results from the firm's performance model. Model 1 includes the controls and the firm's knowledge and governance choice for mask. In Model 2, we account for the potential self selection bias in the choice of governance mode by including the inverse Mill's ratio. In Model 3, we relax the assumption that the coefficients for firms that are vertically integrated are the same as the firms that outsource the mask technology. Controlling for self selection, we split our sample between vertically integrated and non-integrated firms and estimate their effects separately. In Model 4 we include the effect of firm's resist knowledge and in Model 5 we include the covariate for architectural innovation.

A comparison of the results of Model 2 with those of Model 1 indicates that the coefficients are broadly similar in signs and magnitude except with generally larger standard errors. The statistically significant coefficient for the inverse Mill's ratio justifies the use of the Heckman procedure in our performance estimation. The coefficient for mask governance is positive and significant suggesting that firms that do not integrate into mask production tend to commercialize new generations later than their vertically integrated rivals, even after controlling for the unobserved characteristics that may influence both the firm's governance choice and performance. Hence, these results support Hypothesis 1.

(Insert Table 5 about here)

In Model 3, the coefficient for mask knowledge is negative and significant not only for firms that integrate into mask production but also for firms that outsource the mask. This implies that firms that do not integrate into mask production can offset their disadvantage by investing in mask knowledge to improve their ability to coordinate technological changes in the vertical chain (Hypothesis 2). The difference in the mask knowledge coefficient for the firms that vertically integrate into mask and those that do not was statistically insignificant (p=0.644).While both integrated and non-integrated firms benefit from their knowledge of masks, the estimated coefficient for resist knowledge is negative and significant only for firms that do not integrate into mask. Whereas non-integrated firms benefit from their knowledge of both the resist and the mask, firms that integrate into mask do not benefit from their knowledge of resist. Hence, the effect of resist knowledge on the firm's timing of innovation provides mixed support for Hypothesis 2. Moreover, the difference in the resist knowledge coefficient between the two subsamples is significant (p=0.039) suggesting that non-integrated firms benefit more from their knowledge of resist than do firms that integrate into mask.

In Model 5, the coefficient for architectural innovation is negative but insignificant for integrated firms. The effect is positive and significant for non-integrated firms. Hence, non-integrated firms tend to commercialize the new DRAM generation later when the change is architectural than when it is incremental. In contrast, vertically integrated firms seem unaffected by the nature of the transition. We also find that the difference between the two coefficients is significant (p=0.025). The findings from Model 5 support Hypothesis 3 that vertically integrated firms have a greater advantage over non-integrated firms during an architectural change than during an incremental change.

In order to better interpret the above findings, Figure 3 plots the expected timing of innovation for an average firm as a function of the firm's mask and resist knowledge for the different governance choices and the transition types. We generate the figure by multiplying the coefficient estimates with the average firm attributes for the respective integrated and non-integrated sub-samples. At the mean levels of mask and resist knowledge, a firm that integrated into mask commercializes the new generation 2.31 quarters after the first introduction, and this timing is independent of whether the technological change is incremental or architectural. At the mean level of mask and resist knowledge, the non-integrated firms commercialize the new generation 4.76 quarters after the first introduction when the change is incremental and 7.32 quarters after the first introduction when the change is architectural. A one standard deviation increase in the non-integrated firm's mask and resist knowledge reduces the lag to 2.74 quarters in the case of an incremental change and 4.39 quarters in the case of an architectural change. In assessing the economic significance of these commercialization lags, consider that the average quarterly market size during the first two years of the 64M DRAM was US$497m. In addition to extracting greater share of this revenue, early commercialization may also provide a firm with a significant competitive advantage through learning by doing which carry over into later time periods (Irwin and Klenow, 1994).

(Insert Figure 3 about here)

Lastly, we comment on the results for the control variables. After accounting for governance selection, the estimated effect for firm size is insignificant. The effect of firm scope is positive and significant for both the integrated and non-integrated firms suggesting that broader firm scope could compromise the speed of the firm's new DRAM technology development as resources get shared across multiple product lines. As expected, the effect of DRAM feature size is negative. However, it is significant only for non-integrated firms. Greater complexity of the DRAM (smaller feature size) is correlated with greater delays in the non-integrated firms' commercialization of the new DRAM generation. The difference between the coefficients for integrated and non-integrated firms was insignificant (p=0.956).

DISCUSSION AND CONCLUSIONS

This study examines how firms' vertical scope, measured through both production and knowledge boundaries, affects their performance during periods of technological change. While prior research on innovation has focused on the internal challenges faced by firms, we explicitly add consideration of the external challenges in coordinating technological changes in the vertical chain. We suggest that in the context of interdependent component technologies being integrated by the innovating firm, governance of activities in the vertical chain is a key determinant of the firm's ability to commercialize new innovations.

We find support for prior research on production boundaries that firms' decision to integrate activities in the vertical chain is jointly determined by their capabilities, production and transaction costs.

After taking into account the determinants of firms' governance choices, we find that firms that integrate into components with high asset specificity are able to commercialize new innovations earlier than their non-integrated rivals. We also find that while high production costs may deter firms from internalizing the production of components with high transaction costs, firms' knowledge of such components can serve as an imperfect substitute to improving their commercialization of new innovations. This finding was validated in our conversations with industry participants who emphasized the importance of knowledge of the key lithography components in managing suppliers. For example, a technical manager with a large DRAM manufacturer remarked:

> "If we were to just get the resist from the market without having any expertise, it will be a disaster for developing the new technology……this knowledge is not just useful, but essential, and an important source of competitive advantage."

The knowledge of upstream components is likely to facilitate the firm's governance of activities in the vertical chain during their development and integration into the firm's product. We discussed this result with a manager in a non-integrated firm and he commented:

> "The expertise in resist and mask helps us to select suppliers but more importantly, it helps us to manage the ongoing process of evaluation and feedback with the supplier during technology development iterations… expertise in mask and resist helps you to design contracts….in most companies, the actual people that do purchasing work very closely with engineers to create specifications when they create contracts….the last two [monitoring and writing of contracts] are more important aspects and gives more bang for your buck for investment in expertise."

A surprising result from the study was that firms' knowledge of external components with high asset specificity seems to play a more significant role for lean firms – those that do not vertically integrate into either of the components, but does not affect the performance of firms that vertically integrate into the mask. Why is it that a firm that does not integrate into any of the components of lithography technology benefits more from knowledge of external components than a firm that "partially" integrates into the technology? We asked this question of our industry experts and the following quote captures the essence of the difference:

> "Firms that outsource critical technologies have more incentive to develop supplier capabilities than firms that own technologies….You do see [in the industry] that certain firms are much better in managing technology development with suppliers than others. These are the firms that rely on suppliers for most of their technology needs."

This finding certainly warrants future research in understanding how the scope of firm's vertical integration in a multi-component technology interacts with its knowledge of components to influence governance capabilities and competitive advantage. It is possible that non-integrated firms may build superior capabilities to manage suppliers and enjoy greater benefits from their knowledge of external components. The increasing diversity of component technologies and their rapid rate of change are making it increasingly difficult for all critical components to be produced within a single firm (e.g., Fine, 1998). Hence, firms' governance capabilities are likely to play a critical role in their successful commercialization of new innovations.

The final result of the study shows that within the existing vertical chain of activities, incremental changes in component technologies result in changes in the interactions between components, and such architectural changes seem to create significant delays in the commercialization efforts of non-integrated firms. Hence, vertically integrated firms seem better suited for architectural innovations. This finding suggests an important boundary condition for firms pursuing non-integrated "lean" strategies that they may be significantly disadvantaged if new innovations are architectural. A corollary of this finding is that the lack of vertical integration in an industry may induce technological progress primarily through incremental innovations until a new radical innovation is introduced.[9] Hence, architectural innovations which have a potential to extend the technology life-cycle may not be pursued due to coordination problems.

While we have taken care in this empirical examination, there are several limitations. The sample is restricted to a single industry and there is a need to explore the generalizability of our findings in other contexts. Our use of patent data to measure firm's component knowledge assumes the firm's propensity to disclose such knowledge. It is possible that certain DRAM firms may choose to keep this knowledge as a trade secret. However, there is strong evidence that semiconductor firms aggressively patent to use their knowledge as bargaining chips (Hall and Ziedonis, 2001), such that our context at least partially controls for this concern. Although our measure of innovation performance as firm's timing of DRAM innovation is particularly suitable to our context, it would be of interest to explore our hypothesized effects using

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[9] Economic historians have documented a relationship between the extent of vertical integration in an industry and its rate and direction of technological advance. For example, see Frankel's account of innovations in the British textile and iron and steel industries (1955) and Marx's account of the diesel-electric locomotive industry (1976).

additional measures of performance. Finally, we are unable to identify differences in the ways in which firms manage their relationships with external suppliers. In future work it would be interesting to explore how firms' abilities to manage different types of technological change are impacted by the interaction between their supplier capabilities (Dyer, 1997) and their investments in component knowledge (Fine, 1998; Takeishi, 2002; Brusoni et. al., 2001). It would also be interesting to explore how performance is impacted by the interaction of production choices with design choices (Ulrich and Ellison, 2005).

This study examines how firms' production and knowledge strategies within the vertical chain affect their ability to manage technological change. We show that governance issues play a critical role in the successful commercialization of new innovations. We hope that our results encourage researchers to expand their examination of governance strategies beyond the make-or-buy decision to also firms' their knowledge profiles, and to consider how these strategies interact with changes in technology. This study extends the emerging literature that integrates transaction cost economics with competence based perspectives (Argyres, 1996; Leiblein and Miller, 2003; Mayer and Salomon, 2006). We show that while firms' knowledge of external activities may facilitate the development of governance capabilities, its effect may be muted for firms that are integrated into a subset of activities and have a lower reliance on external suppliers.

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Figure 1: Schema of the Semiconductor Lithography Technology

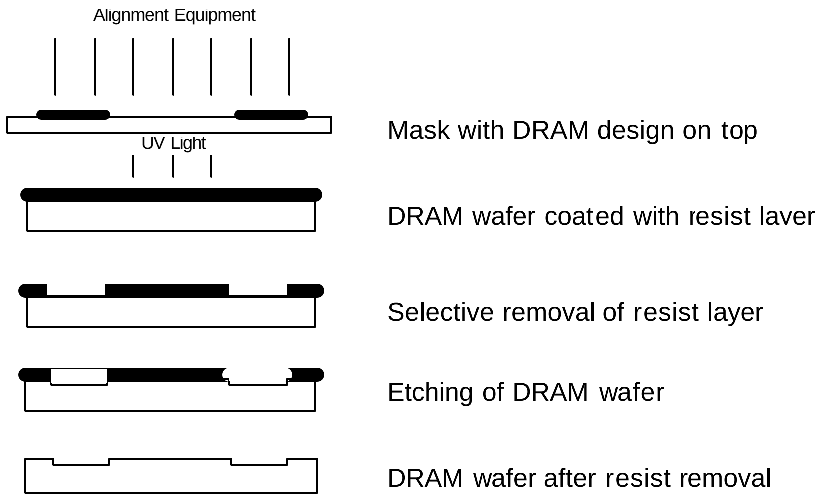

Figure 2: Introduction of New DRAM Generations, the Minimum Feature Size and Market Growth.

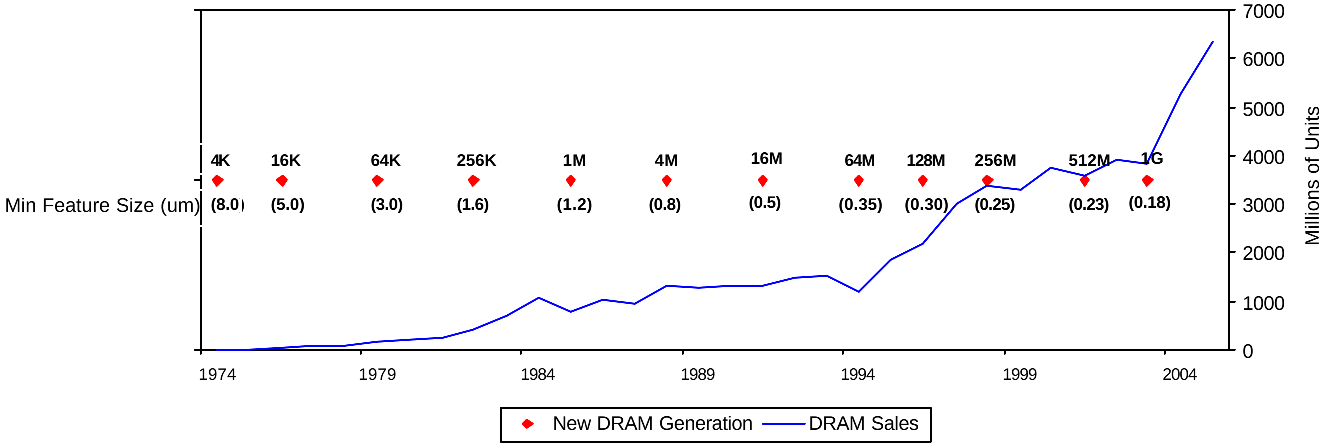

Figure 3:Firm's timing of DRAM innovation as a function of its governance strategy for mask, its knowledge of mask and resist, and the nature of technological change.

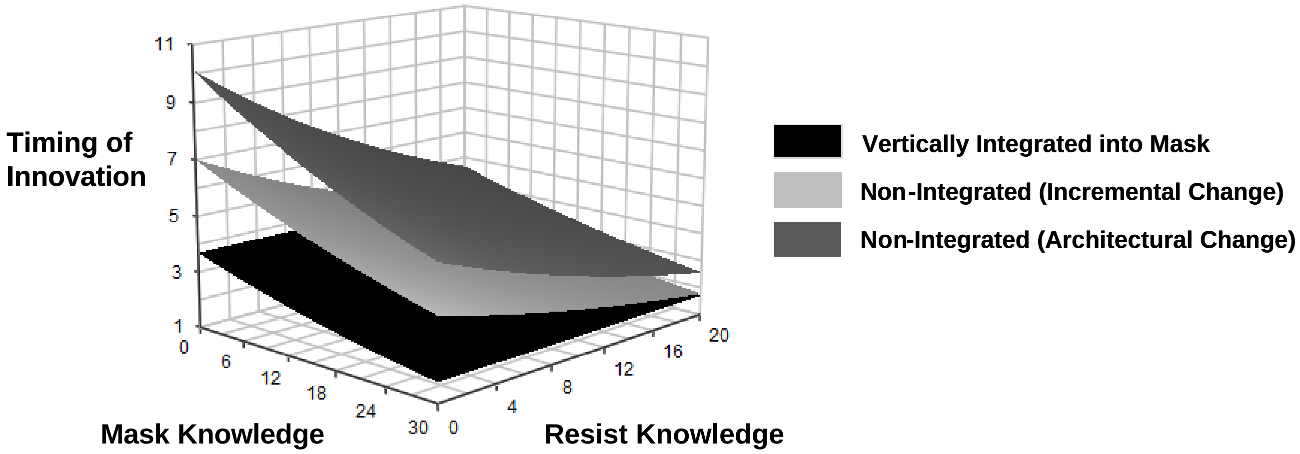

Table 2
Changes in Lithography Technology for Each DRAM Generation and the Nature of Technological Change

DRAM Generation (Year)	**Minimum Feature size (μm)**	**Description of Changes in Lithography Technology that Enabled the New DRAM Generation**[a]	**Major Changes in Critical Relationships Between Components**	**Type of Innovation**
1K (1970)	>8	N.A.		N.A.
4K (1974)	8.0	Mask is now separated from the wafer with a tiny gap to improve the process yield.		Incremental
16K (1976)	5.0	Improvements in mask making process and resist chemistry to print smaller circuits.		Incremental
64K (1979)	3.0	UV light is passed through reflective lens system of the alignment equipment and through the mask on to the wafer.	Interaction between mask and alignment tool. Manufacturing performance is now driven by mask as compared to the alignment equipment.	Architectural
256K (1982)	1.6	UV light is projected through refractive lens system on only a part of the wafer at any one time; the mask is shifted across the wafer in steps, such that multiple exposures are made across the wafer to complete the lithography process. The pattern on the mask is 5-10 times the DRAM circuits.	Interaction between the mask and the alignment equipment changes from scanning to stepping. Minimum feature size is now driven by the interaction between the tool and the resist.	Architectural
1M (1985)	1.2	Improvement in resist chemistry to achieve smaller feature size.		Incremental
4M (1988)	0.8	An increase in the size of the lens in the alignment equipment and improvement in resist material.		Incremental
16M (1991)	0.5	Reduction in the wavelength of UV light from 435nm to 365nm accompanied by changes in the resist material to absorb lower wavelength light.	Relationship between the alignment equipment and the resist due to change in wavelength from 438 to 365 nanometers (nm).	Architectural
64M (1995)	0.35	Increase in the size of the lens of the alignment equipment; improvement in mask making process and resist material.		Incremental
128M (1998)	0.30	Increase in the size of the lens and improvement in mask and resist components.		Incremental
256M (2000)	0.25	Reduction in the wavelength of UV light from 365nm to 248nm accompanied by changes in the resist and mask material to absorb lower wavelength light.	Absorption of the low wavelength light by the mask and the resist becomes a key bottleneck to reducing the feature size. New mask techniques such as phase shift mask (PSM) and optical proximity correction (OPC) are employed to get smaller features.	Architectural
512M (2001)	0.23	Increase in numerical aperture of the lens; improvement in mask making process and resist material.		Incremental
1G (2003)	0.18	Increase in numerical aperture of the lens, improvement in mask and resist materials.		Incremental

[a] For details of changes in lithography technology, please refer to Kapoor and Adner (2007)

Table 3: Probit Estimates for First-stage Governance Choice Model for Mask (Buy=1, Make=0)

	(1)	(2)	(3)
Firm Size	-0.522***	-0.923***	-0.997***
	(0.100)	(0.162)	(0.174)
Firm Scope	-2.280***	-1.165**	-0.843
	(0.372)	(0.511)	(0.550)
Mask Knowledge	0.032*	0.020	0.033*
	(0.017)	(0.015)	(0.017)
DRAM Feature Size		-0.783***	-0.964***
		(0.194)	(0.214)
Number of Suppliers			0.244***
			(0.076)
Constant	4.541***	6.362***	5.504***
	(0.710)	(0.924)	(0.974)
Log-likelihood	-71.60	-62.81	-58.32
Incremental ?^{2}		17.58***	8.98***
Observations	166	166	166

Robust standard errors in parenthesis. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 4: Descriptive Statistics and Correlations for Second-Stage Regression

	Timing of Innovation	Mask Knowledge	Resist Knowledge	Architectural Innovation	Firm Size	Firm Scope	DRAM Feature
Entire Sample (N=166)							
Mean	1.58	4.84	3.66	0.40	6.73	0.64	-0.29
S.D.	0.92	9.28	7.43	0.49	1.55	0.35	1.19
Min	0.00	0.00	0.00	0.00	3.58	0.00	-2.41
Max	3.14	46.00	45.00	1.00	9.35	0.99	2.08
Correlations							
Mask Knowledge	-0.31						
Resist Knowledge	-0.32	0.52					
Architectural Innovation	0.15	-0.14	-0.15				
Firm Size	-0.48	0.48	0.45	-0.10			
Firm Scope	-0.09	-0.33	-0.23	0.05	-0.05		
DRAM Feature Size	0.06	-0.53	-0.47	0.11	-0.58	0.56	
Make Mask (N=99)							
Mean	1.28	4.24	4.68	0.41	7.20	0.78	-0.07
S.D.	0.91	7.24	8.54	0.50	1.32	0.22	1.09
Min	0.00	0.00	0.00	0.00	4.09	0.00	-2.21
Max	2.94	27.00	45.00	1.00	9.35	0.99	2.08
Buy Mask (N=67)							
Mean	2.03	5.73	2.15	0.37	6.04	0.42	-0.61
S.D.	0.73	11.66	5.10	0.49	1.62	0.40	1.28
Min	0.00	0.00	0.00	0.00	3.58	0.00	-2.41
Max	3.14	46.00	20.00	1.00	9.00	0.99	2.08

All correlations above 0.2 are significant at $p < 0.05$

Table 5: Second-Stage Regression Results for the Firm's Log (Timing of Innovation) [a]

	(1)	(2)	(3)		(4)		(5)	
			Make Mask	Buy Mask	Make Mask	Buy Mask	Make Mask	Buy Mask
Mask Governance (Buy)	0.404**	1.568***						
	(0.188)	(0.472)						
Mask Knowledge	-0.026***	-0.031***	-0.026*	-0.036***	-0.026**	-0.024***	-0.026**	-0.020***
	(0.009)	(0.008)	(0.012)	(0.007)	(0.012)	(0.007)	(0.012)	(0.006)
Resist Knowledge					0.004	-0.039**	0.004	-0.039***
					(0.017)	(0.014)	(0.017)	(0.012)
Architectural Innovation							-0.016	0.367***
							(0.132)	(0.090)
Firm Size	-0.297***	-0.055	-0.224	0.092	-0.231	0.055	-0.230	0.023
	(0.080)	(0.127)	(0.254)	(0.115)	(0.247)	(0.108)	(0.250)	(0.087)
Firm Scope	0.367	0.822***	1.646**	0.626**	1.676**	0.578**	1.677**	0.510*
	(0.228)	(0.279)	(0.683)	(0.257)	(0.708)	(0.269)	(0.711)	(0.249)
DRAM Feature Size	-0.310***	-0.116	-0.210	-0.126	-0.204	-0.176*	-0.203	-0.188*
	(0.101)	(0.117)	(0.237)	(0.100)	(0.243)	(0.096)	(0.245)	(0.102)
Inverse Mill's Ratio (?)		-0.753**	-0.702	-0.844**	-0.669	-0.707**	-0.672	-0.589*
		(0.309)	(0.602)	(0.307)	(0.559)	(0.328)	(0.568)	(0.298)
Constant	3.220***	0.910	1.472	1.741***	1.494	1.908***	1.493	1.905***
	(0.511)	(1.083)	(2.323)	(0.612)	(2.310)	(0.574)	(2.329)	(0.477)
R-squared	0.37	0.40	0.32	0.47	0.32	0.51	0.32	0.57
Observations	166	166	99	67	99	67	99	67

[a] Lower value of dependent variable implies superior performance i.e., earlier timing of innovation.
Standard errors in parentheses, clustered by firm.
* significant at 10%; ** significant at 5%; *** significant at 1% (two-tailed t-test).

Appendix I: Description of the Secondary Data Used for the Study

Secondary Data Sources	Data
Gartner Dataquest	Quarterly DRAM shipment by firm, Quarterly DRAM price.
VLSI Research	DRAM firm annual sales.
US Patent and Trademark Office	Patents granted to DRAM firms.
Rose Reports	DRAM firm's participation in mask production.
Reynolds Consulting	DRAM firm's participation in mask production.
Grenon Consulting	DRAM firm's participation in mask production.
IC Knowledge	DRAM feature size
SPIE Conference Proceedings (Technical Articles)	Changes in component technologies of alignment equipment, resist and mask for DRAM generation. Changes in relationships between different components.
Industry Articles by Analysts	Changes in component technologies of alignment equipment, resist and mask for each DRAM generation.

[a] We had to use multiple sources for the firm's make-or-buy decision for the mask technology as industry analysts providing such services operated at different time periods of the study. We used the overlapping years to check that the data between different sources is consistent. We found no discrepancy between the three sources. This is expected as internal mask production was a "commonly" known fact in the industry.