Innovation Ecosystems and Innovators' Outcomes: How the structure of technological interdependence affects firm performance in new technology generations

Ron Adner and Rahul Kapoor
INSEAD

February 28, 2008

ABSTRACT

The success of an innovating firm often depends on the efforts of other innovators in its environment. How does such external innovation uncertainty affect the focal firm's outcomes? To address this question we first characterize the external environment according to the structure of interdependence. We follow the flow of inputs and outputs to distinguish between upstream components that are to be bundled by the focal firm, and downstream complements that are to be bundled by the firm's customers. We argue that the effect of external innovation uncertainty depends not only on its magnitude, but also on its location relative to the focal firm: greater uncertainty regarding components enhances the benefits that accrue to technology leaders, while greater uncertainty in complements erodes these benefits. We then examine the effectiveness of vertical integration as a strategy to manage external interdependence, and argue that the benefits from vertical integration increase over the course of the technology life cycle. We explore these arguments in the context of the global semiconductor lithography industry from its emergence in 1962 to 2005. We find strong support for our arguments, suggesting that the strategic analysis of technological change needs to be extended beyond its traditional firm-centered focus to include a systematic treatment of the broader innovation environment.

Successful innovation, by definition, requires the innovating actor to change in new ways. These changes are a key source of the uncertainty that accompanies the innovation process. The literature has identified a host of key dimensions along which such changes can be characterized – the degree to which the value of an innovator's existing capabilities is reinforced or undermined (Cooper and Schendel, 1976; Tushman and Romanelli, 1985; Tushman and Anderson 1986), the degree to which an innovator's existing cognitive frame will aid or hinder its ability to change appropriately (Henderson and Clark, 1990; Tripsas and Gavetti, 2000), the degree to which an innovator's existing complementary assets and capabilities will maintain or lose their value (Mitchell, 1989; Tripsas, 1997), and the extent to which an innovator's resource allocation processes and customer focus will support or constrain it's innovation efforts (Christensen, 1997). While multifaceted, the innovation literature has tended to concentrate on the focal innovator's internal challenges, paying less attention to the challenges that reside in the innovator's external environment.

Many innovations, however, depend on accompanying changes in the innovator's external environment for their own success. These required changes, whether technological (Hughes, 1983; Rosenberg, 1976), institutional (Rosenkopf and Tushman, 1998) or social (Black et. al. 2004; Morison, 1966), comprise an ecosystem of mutually dependent innovations that contribute to the overall uncertainty surrounding a given innovation effort.

For example, Airbus's monumental investment in the A380 super jumbo passenger aircraft typifies the interdependencies that characterize an innovation ecosystem. Airbus, as the focal firm, faces significant innovation challenges in designing and manufacturing the core airframe of the plane. It also relies on a host of suppliers for a number of key subassemblies, such as the engine and the navigation system. These suppliers are themselves confronted with significant innovation challenges to meet Airbus' requirements. Airbus needs to successfully integrate these various components in order to deliver an aircraft to its airline customers. For the aircraft to be used productively by airlines, however, a number of other actors in the environment, outside of Airbus's direct supply chain, need to innovate as well. Complementors such as airports need to invest and develop new infrastructure to accommodate the oversized aircraft; regulators need to specify new safety procedures; training simulator manufacturers need to develop new simulators on which aircraft crews can be trained. The A380 innovation ecosystem is thus comprised not only of Airbus as the core innovator, but also its suppliers, its buyers and its complementors, who all needed to resolve their own technology challenges in order for the focal A380 innovation to be used effectively.

In this paper we examine how innovation challenges in a firm's ecosystem affect its outcomes. We explore two interrelated questions: First, how the structure of technological interdependence – the location of challenges relative to the focal firm – affects the benefit that accrues to technology leaders (i.e., firms that pioneer the introduction of new technology generations). Second, how the effectiveness of vertical integration as a strategy for managing technological interdependence changes over the course of a technology's life cycle.

The first mover advantage literature has identified important considerations under which technology leaders gain or lose from early entry into new markets. Both the applied and scholarly literatures are replete with studies, prescriptions, and caveats regarding the merits of pioneering new opportunities (e.g., Leiberman and Montgomery, 1988; 1998; Mitchell, 1991; Golder and Tellis, 1993; Christensen et.al., 1998). Consistent with strong arguments for and against the benefits of leading in the introduction of new innovations, the empirical findings have been decidedly mixed (e.g., Kerin et.al., 1992; VanderWerf and Mahon, 1997).

The debates over technology leadership have tended to overlook the nature of the technology challenges that leaders must overcome. In this paper we move beyond the literature's traditional analysis of firms' positions vis-à-vis their rivals. We explicitly consider the innovation challenges that reside in the firm's environment and need to be confronted by external partners if the focal innovation is to succeed in the market. We develop a simple framework for characterizing the technological uncertainty associated with external innovation challenges.

We draw a key distinction between uncertainty that needs to be confronted by suppliers, and uncertainty that needs to be confronted by complementors. We consider how the impact of this external uncertainty on technology leaders will depend not only on the *magnitude* of the challenges to be overcome, but also on their *location* relative to the firm. We argue that the location of uncertainty impacts the steepness of firms' learning curves, their rate of progress along these curves, and extent of spillovers to rivals. We predict that uncertainty in components increases the performance advantage attributable to technology leaders, while uncertainty in complements decreases this advantage.[1]

We then explore vertical integration as a strategy for managing component uncertainty. We distinguish between technology uncertainty, which is resolved over the natural course of the technology life cycle, and behavioral uncertainty, which need not dissipate over time. We argue that vertical integration helps mitigate contractual risk, but not necessarily technology risk, and therefore predict that the performance advantage from vertical integration will increase over the course over the technology life cycle.

We test our arguments in the context of the global semiconductor lithography equipment industry from its emergence in 1962 to 2005, a period during which the industry transitioned

---

[1] Note that our focus is *not* in specifying whether technology leaders will have a competitive advantage. Rather, our focus is on specifying whether competitive advantage from technology leadership is enhanced or eroded by the magnitude and location of external technology uncertainty.

through nine distinct technology generations. While focal innovators faced significant challenges in each of these generational transitions, the extent to which suppliers and complementors faced innovation challenges varied across these generations, providing us with a unique setting in which to test the impact of ecosystem uncertainty on technology leaders.

Our study makes a number of contributions to the literature. First, it introduces a structure for considering technology interdependence that offers a new perspective for understanding innovators' outcomes during periods of technological change (e.g., Tushman and Anderson, 1986). By using an ecosystem lens to examine the benefits of technology leadership, we expand the scope of inquiry beyond its traditional focus on direct competitors. We identify the underlying mechanisms by which uncertainty in components and complements exercise opposing effects on the performance of technology leaders and laggards (e.g., Lieberman and Montgomery, 1988). By disaggregating the external environment into upstream and downstream constituents, we show that the location of uncertainty matters no less than its magnitude, and offer a finer grained view of the interaction between organizations and their environments (e.g., Lawrence and Lorch, 1967), we show that the location of uncertainty matters no less than its magnitude. To the best of our knowledge, ours is the first study that operationalizes the environment in this way. By linking the flow of activities among partners to the distribution of innovation challenges across the ecosystem shed light on a key mechanism of joint value creation and contribute to the emerging literature on ecosystem strategy (e.g., Moore, 1996; Iansiti and Levien, 2004; Adner, 2006). Finally, by explicitly considering the changing benefits of vertical integration over the course of the technology lifecycle we contribute towards an understanding of how firm's boundary choices affect their performance outcomes over time (e.g., Novak and Stern, 2006; Argyres and Bigelow, 2007).

An Ecosystem Perspective

Individual innovations often reside within broader systems. In such cases, understanding an innovation's consequences requires understanding its relationship to its external context. Hughes' (1983) rich description of the emergence of the electrical power network highlights the obstacles raised when some technological elements of an ecosystem lag behind others in resolving their challenges. He attributes the decline of direct current (DC) generation technologies to bottlenecks in the development of distribution technology for the DC network. Conversely, Henderson's (1995) study of the semiconductor lithography industry (the same industry we examine in this paper) highlights the role that suppliers, customers and complementors played in offsetting bottlenecks in optics technology, thereby extending the dominance of optical lithography over non-optical approaches.

While prior studies have highlighted the importance of external innovations to the success of focal initiatives, they have not given a clear structure in which to assess the impact of these external uncertainties.[2] In the absence of such structure, the literature's characterization of uncertainty in the external environment has tended remained at an aggregated level – distinguishing between stable vs. variable (Lawrence and Lorsch, 1967); low vs. high velocity (Eisenhardt, 1989); smooth vs. abrupt development (Suarez and Lanzolla, 2007). Although these aggregate characterizations have yielded important insights, we believe that a finer grained level of analysis can offer addition insight still.

---

[2] An exception are Afuah's studies (Afuah, 2000, Afuah and Bahram, 1995) which have explored how firm performance is impacted when partners face technology challenges. These studies focus on the overall level of innovation challenges that partners must confront. In contrast, our study explicitly considers the impact of variations in both the level and the location of challenges within the ecosystem. In so doing, we are able to uncover new insights regarding the asymmetric impact of upstream and downstream uncertainty on innovator's outcomes.

Rather than characterizing the extent of environmental uncertainty in the aggregate, we consider its distribution across different roles in the ecosystem. We identify these roles and positions by following the flows of inputs and outputs through the external environment.

Figure 1 shows the schema of our approach. The outputs of upstream suppliers serve as inputs to the focal firm. We refer to such inputs, which are bundled by the focal firm, as components. The focal firm's output serves as an input to its customer. A customer may need to bundle the outputs of other firms alongside the focal firm's output to utilize the focal firm's offer. We refer to such inputs, which are bundled by the customer, as complements. In this simple schema, as in our study, we examine only first-tier components and complements; clearly, this structure can be extended forward and backward along the activity chain to include higher tiered actors (e.g., supplier's suppliers; customer's customers).

(Insert Figure 1 about here)

This framework offers a structure in which to analyze the nature of technology interdependence. Tracing the flow of activities in an ecosystem allows for the simultaneous consideration of firms direct interdependence with suppliers as well as indirect interdependence with complementors. This structure allows us to disaggregate the broad construct of environmental uncertainty to identify both the location and the magnitude of uncertainty that surrounds the focal innovator.

ECOSYSTEM CHALLENGES AND INNOVATORS' OUTCOMES

How do the magnitude and location of technology uncertainty in the ecosystem affect the benefits of technology leadership? Being first to introduce an improved technology to the market is a common managerial aspiration. Successful technology leaders, by virtue of having beaten their rivals to market, enjoy reduced competition when presenting their offer to customers. Whether this temporary exclusivity translates into a sustained competitive advantage over later entrants, however, depends on the leader's ability to exploit its window of opportunity.

Component Uncertainty

A key driver of early mover advantage is the opportunity to exploit production and market experience to progress down the learning curve, increasing the firm's added value through improving the offer's performance or costs (e.g., Spence, 1981; Lieberman, 1989; 1984; Argote, 1999). Empirical studies of learning curves, from the 1930s to the present day, have found significant variance in learning potential, usually defined in terms of the 'progress ratio' parameter. For example, in their review of twenty two learning curve studies, Dutton and Thomas (1984) report progress ratios that vary from 55% (high learning opportunity) to over 100% (no learning opportunity).[3]

The extent to which progress down the learning curve can be a source of advantage is intimately linked to the potential for learning – greater advantage is rooted in greater learning potential. Hence, to understand learning as a source of advantage we must consider what drives differences in the magnitude of the learning opportunity.

The magnitude of the learning opportunity depends on the extent to which the innovating firm needs to change its current approach to problem solving, and has the scope for doing so. It

---

[3] The progress ratio measures the cost reduction associated with a doubling of production. A progress ratio of X% implies that a doubling of production reduces cost of production to X% of the initial cost.

is the emerging mastery of new routines that underlies a firm's progress down the learning curve. If very little change from the status quo is required, it follows that there is not much new for the firm to learn; hence, both the opportunity for, and the relative advantage from, learning will be relatively low. In contrast, when the innovating firm needs to overcome high uncertainty and complexity in order to bring its offer to market, the opportunity for learning will be higher, and so will be the potential for learning to be a source of competitive advantage.

New innovations are often enabled by changes in components. In these cases, both firms and their suppliers may face considerable challenges in developing and integrating these new components into the focal offer (Brusoni et.al. 2001). The uncertainty associated with the integration of new components present additional challenges for focal firms to overcome, and hence additional learning opportunities for the focal firms.

Further, the increased complexity accompanying closer coordination with suppliers (Dyer and Singh, 1998), more frequent iterations through design and development cycles (Clark and Fujimoto, 1991), and increased requirements for organizational flexibility within the focal firm all contribute not only to increasing the benefits to the focal firm from greater experience with the new technology, but also to reducing the ease with which rivals can imitate this progress (e.g., Lippman and Rumelt, 1982; Rivkin, 2000).

Balasubramanian and Lieberman (2006) study the relationship between the complexity of organizational processes and the impact of experience on firms' productivity in 117 industries. They find that greater process complexity is correlated with greater learning potential. They also find greater performance heterogeneity among firms that compete in industries characterized by greater learning opportunities.

Hence, the increased complexity that is associated with increased innovation challenges and technology uncertainty in the creation of new components will increase the potential for learning by the focal firm. For technology leaders, this will contribute to both increased learning potential as well as increased barriers to imitation, which both act to augment the sustainability of competitive advantage associated with their early entry into the market.

Hypothesis 1: Greater technology uncertainty in components will increase the performance advantage of technology leaders.

The degree to which uncertainty in components advantages technology leaders will be tempered by the extent of modularity between the component and the focal product. Two mechanisms stand out when interfaces are well specified: first, with regard to the focal firm, there may be less potential for learning because key developments are undertaken by the supplier. Second, with regard to its rivals, there is the possibility that once the component has been developed for the technology leader, rivals can free ride on these investments and 'plug-and-play' the component directly into their own offers, thereby reducing leader's period of exclusivity in the market.

We note, however, that while these factors can reduce the leader's advantage, they are unlikely to overturn it. While modularity does reduce interdependence, it does not eliminate it. For example, Brusoni and Prencipe (2001) note that while modularity allows for the rise of specialist component suppliers, it also poses greater organizational and knowledge requirements on the focal firms in their role as system integrators. Similarly, Hoetker's (2005) study of outsourcing choices in the notebook computer market supports the argument that organizational coordination challenges exist even when technologies are highly modular.

Complement Uncertainty

We have argued that component uncertainty can increase the potential for learning and hence increase the advantages that accrue to technology leaders. How are the factors that support these advantages affected by uncertainty in complements? The resolution of component uncertainty is required in order for a firm to be able to produce it offer and present it to the market. However, the extent to which the offer can create value for users depends on the availability of critical complements. For example the Airbus A380's ability to create value will be hampered until airports, as key complementors, introduce the new terminals that are required to handle the oversized aircraft.

Many innovations rely on the availability of complements to unlock their full value. Rosenberg (1972) argues that a single innovation rarely constitutes a "complete innovation," and that the opportunities and challenges faced by users in adopting the innovation can be influenced by the state of development of complements. Hughes (1983) described imbalances in the pace of development of complementary innovations as creating "negative salients" on the frontier of technological development. Goldfarb (2005) offers a qualitative examination of how challenges in complements delayed the adoption of electricity in the railroad and printing industries in the early 1900s.

Greater complement innovation challenges result in delays in the availability of the complement as complementors struggle to resolve technology uncertainty. By reducing the value creation of the focal offer, delays in the availability of suitable complements, act to slow the adoption rate of the new offer. These adoption delays impact the advantage from technology leadership in two distinct ways: First, they allow rivals more time to catch up, and possibly imitate the leader, before the market takes off. Second, because lower rates of adoption will reduce the firm ability to gain experience (i.e., lower demand will lead to lower production quantities), the leader will make slower progress down the learning curve during its period of exclusivity. Hence, even without imitation, later entrants will confront a leader with a smaller competitive advantage.

By acting to slow both adoption and the accumulation of experience, greater uncertainty in complements reduces the sustainability of the technology leader's competitive advantage.

Hypothesis 2: Greater technology uncertainty in complements will decrease the performance advantage of technology leaders.

The impact of complement uncertainty on technology leaders is likely to affected by the extent to which complements are open vs. proprietary. When complements are open, such they can be used with the offer of any firm, laggards will benefit from any progress that had been made in the market to advance the leader's offer; that is, spillovers will be higher and technology leaders will be see their advantage eroded. When complements are proprietary, such that they can only work with the offer of a particular firm, spillovers will be reduced. However, the leader need not necessarily be better off: to the extent that there is a new development race to be won in the development of suitable complements, whether the first firm in the market with the focal offer will also win the race to be first to market with the key complement will depend on a number of case specific factors. What is clear, however, is that even when complements are proprietary, high complement uncertainty forces firms to compete in a second race for leadership. Hence, regardless of whether complements are open or proprietary, by putting their leadership into contention a second time, complement uncertainty erodes the benefit of technology leadership in the focal offer.

The changing balance of uncertainty: Technology vs. Opportunism

Our discussion is focused on innovation challenges that arise in ecosystems, in which focal offers need to be combined with components and complements if they are to present a value creating solution to customers. We have argued that, in such contexts, the distribution of technology uncertainty across the ecosystem is an important driver of firms' outcomes. We now consider extent to which the effect of ecosystem uncertainty is moderated by a firm's organizational choices: How are the benefits of technology leadership impacted by whether firms are vertically integrated into components?[4]

A key benefit of vertical integration is the ability to mitigate contractual hazards. These contractual hazards arise when firms and their suppliers make asset specific investments under conditions of uncertainty (Williamson, 1985). When contracting with suppliers for innovative components with high development challenges, the focal firm faces two specific kinds of uncertainty. The first is the technological uncertainty surrounding whether and when suppliers will discover appropriate solutions to their development challenges. The second is what Williamson terms behavioral uncertainty regarding whether and when suppliers will behave opportunistically to renegotiate agreements and reset terms in their favor.

---

[4] Because we define components and complements according to where in the ecosystem they are integrated, complements that the firm chooses to produce and bundle with its focal offer are transformed into components. The choice of which elements of the solution to bundle in an offer and which to leave to external complementors raises important questions regarding the design of ecosystem. Our empirical setting allows us to control for these questions of design. These questions, although fascinating, lie beyond the scope of this paper.

The resolution of technology uncertainty determines value creation – if the supplier cannot produce appropriate components, the firm cannot bring the desired product to market. The resolution of behavioral uncertainty determines value capture – if the supplier renegotiates the contract terms opportunistically, the firm cannot appropriate the expected rents.

Early in a technology's life cycle, technology uncertainty is at its peak. As development takes place, knowledge is accumulated and progress becomes more predictable. Although development continues throughout the lifecycle, and innovation challenges are always present, within a given trajectory the level of technology uncertainty tends to decrease over time (Dosi, 1982; Sahal, 1981).

In contrast to technology uncertainty, the trend for behavioral uncertainty over time is ambiguous. Firms continue to work with suppliers as they improve their offers, such that the level of cospecialization need not decrease. While repeated interactions can allow firms to specify better contracts, such that behavioral uncertainty might decrease over time, it is also possible for behavioral uncertainty to increase over time. Indeed, as the market for the offer grows, so may the opportunity cost to the firm of switching suppliers and, hence, the incentive for suppliers to behave opportunistically.

Vertical integration mitigates the effects of behavioral uncertainty but not of technology uncertainty. As the level of technology uncertainty decreases over time, the relative importance of behavioral uncertainty rises. Hence, the relative benefit from vertical integration will be greater at later stages of the technology life cycle.

Hypothesis 3:The performance advantage from vertical integration will increase over the course of the technology life cycle.

EMPIRICAL CONTEXT

We test our hypotheses in the context of the semiconductor lithography equipment industry. Improvements in lithography tools have been the main driver of progress in semiconductor manufacturing, enabling the production of higher performance chips at lower marginal cost that firms have enjoyed for the past forty years (Moore, 1995). Since its emergence in 1962 to 2005, the semiconductor lithography industry has witnessed no less than 9 different technological transitions. From the beginning, lithography tool manufacturers have regarded technology leadership to be a key source of competitive advantage. Being among the first to introduce a new technology generation offers technology leaders significant learning advantages as well as the opportunity to lock in customers due to high switching costs.

In each of the nine technology transitions the manufacturers of lithography tools had to overcome significant innovation challenges. Although suppliers and complementors were always critical to enabling each new technology generation, the magnitude of their challenges varied significantly across generations – whereas in some generations it was possible to simply reuse existing elements, other generations required suppliers and complementors to completely reinvent their offers.

Semiconductor Lithography

Semiconductor lithography is the process by which a circuit design is imprinted on a semiconductor wafer. The basic principle of lithography is illustrated in Figure 2. After the design of an integrated circuit (IC) is finalized (i.e., the wiring, the gates and the junctions), the circuit blueprint is transferred to a "mask". The lithography process takes place when beams of energy originating from an “energy source” are directed onto the mask. The pattern on the mask allows a portion of the energy to pass through, with or without an optical “lens” system, onto the wafer. The wafer is coated with an energy sensitive “resist”. The resist undergoes a chemical reaction wherever the mask has allowed the energy to pass through. This chemical reaction changes the structure of the resist and allows its selective removal from the wafer. 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 design. A single wafer can go through this process a number of times as multiple layers of circuits are etched on to it. For example, in 2006, a one gigabyte DRAM chip may be etched with as many as sixty circuit layers.

(Insert Figure 2 about here)

The key performance attribute of a lithography tool is its resolution, the smallest geometry on which the tool can focus on the wafer surface. Resolution determines the extent of miniaturization that can be achieved by the semiconductor manufacturer. A semiconductor manufacturer may use scores of lithography tools in a single production line, often one for each circuit layer. With modern tools costing over twenty million dollars each, investments in lithography equipment represent a substantial portion of the cost of a fabrication facility. Lithography “production recipes,” which are customized to specific tool models, masks and resists, are regarded as a key source of advantage for semiconductor manufacturers, who invest significant resources in optimizing their production lines (Iansiti, 1997). To maintain competitiveness semiconductor manufacturers continuously reinvest in their facilities and look to new tool generations to allow them to offer products with higher performance at lower cost.

In this study, our focal firms are the firms that design and assemble the lithography tool. The key components that these tool makers need to integrate into their offers are the energy source and the lens. Their customers are semiconductor manufacturers who use the lithography tool in their fabrication plants. The mask and the resist are the key complements that these customers must integrate with the lithography tool. A schema of the lithography tool ecosystem is presented in Figure 3.

(Insert Figure 3 about here)

The development of a new generation of tool technology poses significant challenges for tool manufacturers to achieve finer and finer resolutions. A new tool generation can also impose significant challenges on other ecosystem elements: the energy source may need to operate at a new wavelength; the lens may need to be manufactured from a new material; the mask, which needs to be etched with thinner lines, may need to be manufactured in a new way, possibly from new materials; the chemical resist may need to be reformulated to allow for greater control of the chemical reactions as energy wavelengths become smaller and geometric resolutions become finer.

Particularly important for the purpose of our study is the fact that, despite undergoing nine generational transitions, the structure of interdependence in the ecosystem – the components that need to be integrated by the focal tool manufacturers and the complements that their customers, the semiconductor manufacturers, need to combine with the tool offer – has remained unchanged throughout the forty-four year period that we study. Moreover, all tool manufacturers have positioned themselves in the same way within this ecosystem; that is, all tool manufacturers integrate the source and lens components and leave it to their customers to integrate the mask and the resist complements. Where firms have differed, is in their strategy for managing their interdependence with components: some firms are vertically integrated into lens production whereas others rely on external suppliers.

Technology Transitions in the Semiconductor Lithography Equipment Industry

The key measure of progress in semiconductor lithography is improvement in tool resolution. Finer resolutions allow the semiconductor manufacturers to use the lithography tool to pack more circuits onto a chip and more chips onto a wafer. These improvements allow semiconductor manufacturers to offer chips with higher performance at lower marginal cost.

For the lithography tool manufacturers this means that improving resolution is a top priority. Tool manufacturers increase resolution using a combination of three levers. The first is to reduce the wavelength of light that is transmitted by the energy source. The second is to increase the size of the lens. The third is to improve the design of the tool itself. The industry distinguishes among technology generations according to the design of the tool and the wavelength of energy that it transmits. Incremental improvements to the tool design and the lens are core drivers of advance within a technology generation. When further improvements become untenable, due to a combination of physical and economic constraints, the industry shifts to a new design or to a smaller wavelength, which heralds the emergence of a new lithography tool generation.

In transitioning across technology generations tool manufacturers always faced significant design uncertainty. Consider the industry's transition from I-line steppers to DUV 248nm steppers. The core approach to increasing resolution in this transition was to decrease the energy wavelength from 365nm to 248nm, which would allow tool resolution to improve from 0.8µm to

0.45µm. The relationship between reduced wavelength and finer resolution is straightforward in theory.[5] Realizing this improvement in a commercial setting, however, requires a corresponding improvements in tool design (e.g., in terms of factors such as alignment, repeatability, reliability, and throughput). Overcoming these design challenges requires tool manufacturers to experiment and iterate, often for years, in order to come up with a suitable offer (Henderson and Clark, 1990).[6]

Beyond the tool manufacturers' own internal, uncertainty, however, the emergence of a new generation can create uncertainty elsewhere in the ecosystem. The transition to DUV 248nm, for example, required fundamental changes in the energy source, the lens, the mask, and the resist. Mercury lamps, which had been used in all earlier generations, were not able to provide sufficient energy at a wavelength of 248nm to cause adequate chemical reactions in the resist. This challenge was overcome by the development of excimer lasers using Krypton Fluoride (KrF) gas. The conventional glass material that was used to make lenses faced absorption problems with 248nm wavelength. The only material that could be used was fused silica, and this required major changes to the lens manufacturing process. These required changes created significant uncertainty in components, which, in turn, served to increase the design and integration challenges that confronted the tool manufacturers.

In order for the new generation tools to be used effectively, significant uncertainty needed to be overcome in the development of the complements as well. Mask makers needed a new

---

[5] The resolution capability of lithography technologies that employ a lens system is given by the Rayleigh criterion:

$$Resolution = k_1 \times (Wavelength/Numerical\ Aperture)$$

where wavelength is the wavelength of the light being transmitted by the source, numerical aperture is the measure of the size of the lens, and k_1 is a process-specific constant.

[6] Henderson's studies of the industry have highlighted that in confronting new technology generations firms may face both engineering challenges in creating new designs, as well as cognitive challenges in recognizing the subtleties of change (Henderson and Clark, 1990; Henderson, 1993). In particular, she highlighted the unique cognitive challenges that confront incumbents when generational changes affect the architectural links among only core design concepts. The focus of our paper is on external uncertainty; however, we account for incumbency effects in our empirical specification.

material that would provide improved transmission of the new wavelength which, in turn, required changes to the mask manufacturing process. Finally, the existing novolac resists could not absorb enough energy from the 248nm wavelength to cause an adequate chemical reaction. To solve this challenge, a new chemically-amplified resist had to be developed.

Table 1 summarizes the major technological changes in the tool, lens, source, mask, and resist in each technology generation. We offer a more detailed overview of each of the technology transitions in Appendix I.

(Insert Table 1 about here)

METHODOLOGY

Data

We used both primary and secondary sources of data for this study. We began by developing a detailed historical understanding of the semiconductor lithography equipment industry during a 20-month field study. We conducted multiple interviews with over thirty industry experts, most of whom have been associated with the industry for more than twenty years. The interviews were semi-structured and lasted two hours on average. We used the information from the interviews to develop an understanding of the challenges that governed the emergence of the different technology generations, paying particular attention to uncertainties in the ecosystem which lay beyond the core design and production challenges of the lithography tool manufacturers. We used this information to construct “ecosystems maps” that identified the structure of the ecosystem for the industry, and the key innovations in components and complements for each of the nine technology generations.

We identified ecosystem structure by asking first, what elements needed to be integrated by tool manufacturers in order for them to produce their offers; and second, what elements needed to be integrated by the tool customers in order for the tool to be used productively. There was unanimous agreement that the energy source and the lens were the key components to be integrated into the tool by the manufacturer, and that the mask and the resist were the key complements to be integrated with the tool by the customer.

For every generation of technology, we then asked whether there was a significant innovation challenge to be overcome in each of these four elements. There was remarkable consensus among our interviewees. While there was some variance in their opinions about whether a given challenge was ‘very big’ or ‘enormous’ there was no disagreement about whether the basic characterization of a challenge should be regarded as minor or major. We consolidated this information in a document that mirrors Table 1 and sent it back to our interviewees for written and verbal comments. We incorporated these comments and then sent the table out for a second review. All the experts agreed with our final characterization.

In parallel, we searched every issue of Solid State Technology from 1961 to 2001 for articles relating to ecosystem innovation challenges. Solid State Technology is a leading industry journal whose mission is to cover the key trends and issues that confront the industry. It has been publishing technical articles on challenges facing the semiconductor industry since its birth. Using this source, we created measures (discussed below) that characterize the extent of uncertainty in the key components and complements for each of the technology generations.

Finally, we obtained detailed market data from the leading industry consulting firm, VLSI Research, which has been following the industry since early 1970’s. The VLSI data included sales by technology generation for every firm that competed in the lithography equipment industry from 1974 to 2005. Rebecca Henderson generously shared her data on the contact printing generation. Our final data set consists of an unbalanced panel of 64 firm-technology generations. The average number of observations per group is 10.4. Our data is comprehensive and includes information on each of the 33 firms that ever sold a semiconductor lithography tool.[7]

Variables

The definitions of the variables used to test our hypotheses are summarized in Table 2 and detailed below.

(Insert Table 2 about here)

Dependent Variable

Our dependent variable, *generation share,* is a firm's market share in a given technology generation. This measure is consistent with prior studies that examine firm performance in new technology generations (e.g., Mitchell, 1991; Henderson, 1993; Tripsas, 1997). Further, industry participants and observers (e.g., VLSI Research, Gartner Dataquest) regularly use market share in a generation as a measure of firm success.

In our main analysis we consider a firm's market share in a given technology generation in a given year. As a test of robustness for hypotheses 1 and 2, reported in Appendix II, we also consider a firm's cumulative market share over the entire life of the technology generation.

---

[7] In our analysis we exclude 2 firms from our sample because, although they produced lithography tools, they were competing in different markets. These firms entered the given lithography generation during its declining phase and were targeting niche markets such as thin film heads, pressure sensors, and biotech applications rather than the mainstream applications of semiconductor manufacturers.

Independent Variables

Our measures of component and complement uncertainty were created using a count of Solid State Technology articles. We believe, and our industry sources confirmed, that a count of published articles that address specific technical challenges is a good proxy for the technological uncertainty that surrounded the development of different lithography generations. We identified a total of 181 lithography related articles that appeared from 1961 to 2001.[8] We then identified articles that discussed ecosystem challenges in a given generation. We used the article titles to identify the match between the generation and the ecosystem element. If insufficient information was available in the title, we read the abstract and the conclusion to ascertain if the article addressed the innovation challenges in the ecosystem for a given generation. This reduced our set to 102 articles.

Finally, since our primary concern was with respect to innovation challenges that confronted technology leaders as they pioneered new technology generations, we further reduced our set to include only those articles that were published no later than 5 years after the commercialization of the first tool in a generation. A second reason to choose 5 year post-commercialization window was to present a balanced view of upstream and downstream ecosystem challenges. The articles that were published after the close of this 5-year window were almost entirely dedicated to discussing complement challenges. This is not surprising, since by the 5th post-commercialization year, much progress would have necessarily been made on the component side. We tested robustness with 3- and 7-year windows and the results are consistent with the ones reported here. A small subset of articles compared the ecosystem innovation challenges for different generations and for these articles, we read the relevant sections for each

---

[8] Our field work provided us with keywords which we used to identify lithography related articles. The keywords were: lithography, microphotographs, mask, photomask, resist, laser, UV, DUV, Deep UV, optical, lens, stepper, aligner, mercury, illuminator, exposure, printer and the names of the different generations

generation in order to create a match. This reduced the set to 56 articles that discussed 78 ecosystem innovation challenges.

We constructed the *Component Uncertainty* measure as the sum of the number of articles that discussed innovations challenges in the lens ($Innov_{lg}$) and the source ($Innov_{sg}$) for technology generation g.

$$Component\ Uncertainty_g = Innov_{lg} + Innov_{sg}$$

Similarly, *Complement Uncertainty* was constructed as the sum of the number of articles that discussed innovation challenges in the resist ($Innov_{rg}$) and the mask ($Innov_{mg}$).

$$Complement\ Uncertainty_g = Innov_{rg} + Innov_{mg}$$

We measure a firm's *Technology Leadership* as the time of its entry into a new technology generation relative to its rivals. We define entry as the first occurrence of revenue for a firm in a given generation. The first firm to enter the generation was assigned a technology leadership value of 1. Subsequent firms were assigned values with reference to the years elapsed since the first entrant (e.g., a firm entering a generation three years after the leader was assigned a technology leadership value of 4).

To assess the effects of vertical integration on firm performance we construct the variable *Vertical Integration.* The variable takes a value of 1 if the firm produced its own lens component in a given technology generation and 0 otherwise. During the history of the industry no tool manufacturer produced its own energy source.

We defined the variable *Technology Maturity* as the number of years in which a given technology generation has been available in the market.

Control Variables

We control for a number of firm and industry level effects. The prior literature (e.g., Henderson and Clark, 1990) has identified important differences between incumbents and entrants during regimes of technological change. We controlled for this effect using the variable *Incumbent*, which takes a value of 1 if a firm had sold lithography tools in an earlier technology generation.

We controlled for firm size through the variable *Conglomerate*, which takes a value of 1 if the firm was active in industries other than semiconductor manufacturing equipment and 0 otherwise. We have two industry level controls. The first is *Generation Sales Growth*, a measure of change in tool sales (in dollars) in a given generation in a given year , which represent the growth opportunities that may influence choices regarding investment in new technology generations. The second is *Number of Firms*, which controls for the competitive density in the generation in a given year.

Statistical Analysis

We use panel data for our empirical analysis. The use of panel data helps to control for potential sources of unobserved heterogeneity and allows us to test how the benefits of vertical integration change over time during the course of a given generation. We use a random effects specification to test our hypotheses. This specification imposes the assumption that the firm specific error component for a given generation is not correlated with the explanatory variables.

Although a fixed-effects approach would require fewer assumptions than the random-effects approach, it cannot be used if the explanatory variables do not vary within the experimental group (Baltagi, 2005; 13). In our analysis component uncertainty and complement uncertainty are the key explanatory variables, but they do not exhibit inter-temporal variation for a firm within a given generation. Hence, we cannot test our predictions using a fixed-effects panel regression specification. We do, however, include firm and year dummies as controls for unobserved firm- and year-specific effects.

As a further test of robustness for Hypotheses 1 and 2, in Appendix II we include a cross sectional OLS specification in which the dependent variable is the firm's cumulative market share in a generation (total firms sales in generation$_i$ / total sales in generation$_i$).

RESULTS

Descriptive Relationships

Figure 4 illustrates the varying degrees of component and complement uncertainty in each of the nine technology generations. As can be seen from the figure, each of the technology generations presented a distinct combination of ecosystem challenges. This is a key source of variance that we exploit in this study.

(Insert Figure 4 about here)

The descriptive statistics and pairwise correlations for the variables used in the study are presented in Table 3. The significant negative correlation between technology leadership and generation share suggests that, as per our expectations, early entry is rewarded with higher market share in the semiconductor lithography equipment market. Since component uncertainty and complement uncertainty are moderately correlated, we enter these variables into separate models to alleviate concerns regarding collinearity.

(Insert Table 3 about here)

Tests of the Hypotheses

Our hypotheses predict the impact of external ecosystem challenges on the performance advantage that accrues to technology leaders, and the impact of vertical integration decisions on this performance over the course of the technology life cycle. We test hypotheses 1 and 2 by interacting firms' technology leadership with measures of ecosystem uncertainty. We mean-center the variables in the interaction terms. The mean-centering of continuous variables helps to reduce potential multicollinearity and facilitates the interpretation of the estimated coefficients (Aiken and West, 1991). We test hypothesis 3 by interacting firms' vertical integration status with the generation's technology maturity. Consistent with prior studies examining market share performance in new technology generations (e.g. Henderson, 1993; Tripsas, 1997), we use a semi-log specification to test our hypotheses.

Table 4 reports our regression results. Model 1 is our baseline model. Consistent with conventional wisdom in the industry, the coefficient for technology leadership is significant and negative, indicating benefits to technology leadership. We find that incumbency has a negative effect, which is consistent with Henderson's (1993) findings in her study of the industry. The coefficient for vertical integration is significant and positive, suggesting that in-house component manufacturing is a source of advantage in this industry. The coefficient for complement uncertainty is significant and positive. While not hypothesized, this finding indicates that high complement uncertainty may increase the market share of an average firm. Since average firms are technology followers, this is consistent with the mechanisms that underlie hypothesis 2. Among the industry level controls, the coefficient of number of firms is negative and significant, confirming the negative effects of competitive density on firms' market share performance.

In Model 2 we interact technology leadership with component uncertainty to test hypothesis 1. In model 3 we interact technology leadership with complement uncertainty to test hypothesis 2. In Model 4 we interact vertical integration with technology maturity to test hypothesis 3. Model 5 is the fully specified model.

(Insert Table 4 about here)

In hypothesis 1 we predicted that greater component uncertainty will increase the performance advantage accorded to technology leaders. The hypothesis is supported in models 2 and 5. The coefficient of the interaction between technology leadership and component uncertainty is negative and significant. Hence, the greater the uncertainty in components, the greater the benefits that accrue to technology leaders.

In hypothesis 2 we predicted that greater complement uncertainty will decrease the performance advantage accorded to technology leadership. The hypothesis is supported in models 3 and 5. The coefficient of the interaction between technology leadership and complement uncertainty positive and significant. Hence, complement uncertainty in the firms' ecosystem erodes the benefits that accrue to technology leaders.

In hypothesis 3 we predicted that the advantage from vertical integration will increase over the course of the technology life cycle. The positive and significant coefficient of the interaction between vertical integration and technology maturity in models 4 and 5 supports the hypothesis.

We tested the robustness of our results in a number a ways. First, as a test of robustness for hypotheses 1 and 2 in Appendix I we include results from a cross sectional specification estimated using OLS regression for a firm's cumulative market share in a given generation. The results are fully consistent with our predictions.

Second, we considered the X-ray and E-beam generations as possible anomalies. These were the only technology generations not to achieve market dominance even in their peak sales years. This however, was only evident ex post. Ex ante, these two generations had garnered very strong interest and support among industry participants, all of whom believed that these generations represented the future of lithography technology. As a robustness test, we present Model 6 in Table 4, which excluded the X-ray and E-beam technology generation and whose results are fully consistent with our predictions.

Finally, we split component and complement challenges into their individual elements of source, lens, mask and resist to make sure that our results are not driven by a specific element. Again, the results are fully consistent with the predictions.

DISCUSSION

Successful innovation depends on a firm's ability to resolve the uncertainties that surround the development and production of its offer. These challenges have long been a focus of both the academic and applied innovation literatures. We note, however, that the literature's focus is largely directed at managing firms' internal innovation uncertainties. In this paper we have explicitly focused on the neglected role of external uncertainty in driving innovators' outcomes.

In considering external sources of uncertainty, we present a structured framework to distinguish between uncertainty whose resolution depends on suppliers and uncertainty whose resolution depends on complementors. We find that, depending on its location, uncertainty in this external ecosystem can either enhance or erode a firm's competitive advantage from technology leadership. Specifically, we find that while technology leadership advantage increases with component uncertainty, it decreases with complement uncertainty. Uncertainty in components increases the technology leader's competitive advantage by increasing the potential for learning and by increasing barriers to imitation. In contrast, uncertainty in complements reduces the technology leader's competitive advantage by slowing its advance down the learning curve and increasing opportunities for rivals to catch up.

Figure 5 uses the estimates from Model 5 to plot the effect of technology leadership on firms' market share performance for different combination of ecosystem uncertainties. The vertical axis is the difference in average annual market share between the technology leader, who enters the generation in year 1, and a follower, who enters in a later year. The horizontal axis is the follower's year of entry. We plot three component-complement uncertainty scenarios, where high (low) corresponds to a +1 (-1) standard deviation above (below) our sample mean. The baseline case, "Low component, low complement" shows a downward sloping curve, indicating that when ecosystem challenges are low the technology leader is advantaged relative to the follower. As discussed above, this is highly consistent with well established industry beliefs. In the case of "high component, low complement uncertainty' we find that the slope is even more negative, indicating that technology leaders enjoy an even greater competitive advantage. To get a sense for the economic magnitude of these differences, consider that in 2004 a 1% market share difference in the DUV 248 generation corresponded to $28.7 million in sales. Finally, in the "low component, high complement uncertainty case we find a weakly upward sloping curve. This indicates that when complement challenges are high, technology leadership is less beneficial; indeed, we find that the leader is at a slight disadvantage to later followers.

(Insert Figure 5 about here)

The implication of Figure 5, as an illustrative summary of our arguments and findings, for the debates regarding early mover advantages is a strong one. Moving beyond the debate of existence vs. non existence of first mover advantages (e.g., Golder and Tellis, 1991; Leiberman and Montgomery, 1988, 1998), we have identified specific contingencies that determine the value of technology leadership. Further, the mechanisms that we identify regarding the opposing effects of component and complement uncertainty expand the analysis of first mover advantage beyond the traditional firm-specific focus to incorporate specific features of the external environment.

Beyond environmental contingency, we also examine vertical integration as a strategy for managing ecosystem uncertainty. We argue that when contracting with suppliers for innovative components, the focal firm faces two specific kinds of uncertainty. The first is the technological uncertainty surrounding whether and when suppliers will discover appropriate solutions to their own development challenges. The second is the behavioral uncertainty regarding whether and when suppliers will behave opportunistically to renegotiate agreements and reset terms in their favor. We note that while technology uncertainty is resolved and reduced over the course of the technology lifecycle, behavioral uncertainty does not necessarily decrease over time. This asymmetry suggests that the balance between technology uncertainty and behavioral uncertainty will tend to tilt towards the latter over time. As such, we argue and find that the benefits derived from vertical integration increase over the course of the technology life cycle. This finding is consistent with recent studies conducted in the context of the automotive industry (Novak and Stern, 2007; Argyres and Bigelow, 2007).

The ecosystem construct, as a way of making external interdependencies more explicit, has gained prominence in business strategy (Moore, 1996; Iansiti and Levien, 2004; Adner, 2006) and practice (e.g., Intel, 2004; SAP, 2006). These approaches have focused on understanding coordination among partners in exchange networks that are characterized by simultaneous cooperation and competition (Brandenburger and Nalebuff, 1997). Studies in this vein explore the challenges that arise when incentives across the ecosystem are not aligned (Casadesus-Masanell and Yoffie, 2005), the role of ecosystem partners in shaping firm's abilities and incentives to compete for different market segments (Christensen and Rosenbloom, 1995), and the activities that focal firms undertake to induce partners to favor their specific technology platforms (Gawer and Cusumano, 2002).

These studies are primarily concerned with the strategic interactions among firms, extending the analysis of bargaining power and leverage from the context of bilateral partnerships (e.g., Teece, 1986) and industries (e.g., Porter, 1980) to the context of ecosystems. Their fundamental focus is on issues of asset *ownership and control.* They largely presuppose the existence of these assets. In contrast, our focus on ecosystem uncertainty is explicitly concerned with the challenges that characterize the *emergence and availability* of such assets. As such, this study answers recent calls in the strategy literature that emphasize the importance of understanding the dynamics of value creation as a predecessor to the dynamics of value capture (Brandenbuger and Stuart, 1996; Adner and Zemsky, 2006).

Our conceptualization of the innovation ecosystem, in which we identify interdependencies between the firm and its environment according to the flow of activities, presents a new way to characterize the organizational environment. The innovation literature has tended to treat the environment as a homogenous construct (Tushman and Anderson, 1986; Eisenhardt, 1989). In contrast, we explicitly consider differences between the firms' upstream and downstream environments and identify their asymmetric effects on the outcomes of focal firms. By distinguishing between the impact of uncertainty that resides upstream and downstream, this paper argues against the perspective that environmental turbulence is necessarily detrimental to firm performance. To the contrary we argue, and find, that upstream environmental uncertainty can act an effective barrier to competition, and so reward those firms whose capabilities have enabled them to overcome these barriers.

This study, of course, has a number of limitations. It explores a single industry, raising questions of generalizability. An important concern remains endogeneity. Although we have included firm and year dummies in our empirical specification, due to data limitations we are unable to control for unobserved differences for a given firm across the different technology generations. While we characterize the locational relationships among ecosystem actors, we have no visibility as to the nature of specific exchange relationships among these actors, or the nature of their strategic interactions. Future studies could address these limitations by incorporating how actors coordinate, through mechanisms such as alliances, and relational contracts, within the context of innovation ecosystems. More broadly, it would be of interest to explore different ways in which firms attempt to construct their ecosystems –choices regarding what should be bundled where, and who should be bundling what – in their attempts to align the processes of value creation and value capture.

This study has presented an ecosystem lens to examine the conditions under which technology leadership yields competitive advantage. We have argued and shown that the benefit of technology leadership depends on both the location and magnitude of uncertainty within the ecosystem. We have examined the effectiveness of vertical integration as a strategy to manage ecosystem uncertainty and have identified the impact of the technology lifecycle in determining its benefits. Ecosystem settings raise a new set of issues for both researchers and managers to consider, such as joint development incentives (Cassadesus-Masanell and Yoffie, 2005), assessing options for positional leadership and coordination (Iansiti and Levien, 2004; Gawer and Cusamano, 2002), the timing of resource commitments (Pacheco de Almeida and Zemsky, 2006), the recalibration of customer expectations (Tripsas, 2006; Adner, 2004), and the evolution of industry architectures (Jacobides, 2005). We hope that our framework and analysis can offer additional avenues through which such questions can be fruitfully addressed.

REFERENCES

Adner, R. 2004. A demand-based perspective on technology lifecycles. Advances in Strategic Management.

Adner, R. 2006. Match your innovation strategy to your innovation ecosystem. Harvard Business Review, 84(4): 98-107.

Adner, R. and Zemsky, P. 2006. "A Demand-Based Perspective on Sustainable Competitive Advantage." Strategic Management Journal. 2006. 27(3): 215-239.

Afuah, A & Bahram, N. 1995. The hypercube of innovation, Research Policy, 24(1): 51-76.

Afuah, A. 2000. How much do your co-opetitors' capabilities matter in the face of technological change? Strategic Management Journal, 21(3): 387-404.

Aiken, L. S., & West, S. G. (1991). Multiple regression: Testing and interpretinginteractions. Newbury Park, CA: Sage.

Argote, L. 1999. Organisational Learning: Creating, Retaining and Transferring Knowledge. Norwell, MA: Kluwer Academic Publishers.

Argyres, N. and Bigelow L. 2007. Does Transaction Misalignment Matter for Firm Survival at All Stages of the Industry Life Cycle? Management Science. 53(8):1332-1344.

Balasubramanian, N. and Lieberman, M.B., 2006, Industry Learning Environments and the Heterogeneity of Firm Performance. Working paper.

Baltagi, B. 2005. Econometric Analysis of Panel Data (3rd ed.). New York: John Wiley & Sons.

Black, L. J., Carlile, P. R., & Repenning, N. P. 2004. A Dynamic Theory of Expertise and Occupational Boundaries in New Technology Implementation: Building on Barley's Study of CT Scanning. Administrative Science Quarterly, 49(4): 572-607.

Brandenburger, A. M., & Nalebuff, B. J. 1997. Co-Opetition: A Revolution Mindset That Combines Competition and Cooperation; The Game Theory Strategy That's Changing the Game of Business. New York: Currency.

Brusoni, S. and Prencipe, A. 2001. Unpacking the Black Box of Modularity: Technologies, Products and Organizations Industrial and Corporate Change. 10: 179-205.

Brusoni, S., Prencipe, A., & Pavitt, K. 2001. Knowledge specialization, organizational coupling, and the boundaries of the firm: why do firms know more than they make? Administrative Science Quarterly, 46: 597-621.

Casadesus-Masanell, R., & Yoffie, D. B. 2005. Wintel: Cooperation or Conflict. Harvard Business School Working Paper.

Christensen, C. M. 1997. Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Boston: Harvard Business School Press.

Christensen, C. M., & Rosenbloom, R. S. 1995. Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. Research Policy, 24(2):233-257.

Christensen, C. M., Suárez, F. F., & Utterback, J. M. 1998. Strategies for survival in fast-changing industries. Management Science, 44(12): S207-S220.

Clark, Kim B., and Fujimoto, T. 1991. *Product Development Performance.* Harvard Business School Press, Boston, MA.

Cooper, A. C., & Schendel, D. 1976. Strategic response to technology threats. Business Horizons, 19(1): 61-69.

Dosi, G. 1982. Technological Paradigms and Technological Trajectories. Research Policy, 11: 147-162.

Dutton, J. and Thomas, A. Treating Progress Functions as a Managerial Opportunity The Academy of Management Review. 9(2): 235-247.

Dyer, J.H. and Singh, H. The Relational View: Cooperative Strategy and Sources of Interorganizational Competitive Advantage The Academy of Management Review, 23(4): 660-679.

Eisenhardt, K.M. 1989. Making Fast Strategic Decisions in High-Velocity Environments." Academy of

Gawer, A., & Cusumano, M. A. 2002. Platform Leadership: How Intel, Microsoft, and Cisco Drive Industry Innovation. Boston: Harvard Business School Press.

Golder, P.N. and Tellis, G.J. 1993. Pioneer advantage: Markeitng logic or marketing legent? Journal of Marketing Research, 30(2): 158-170

Goldfarb, B. 2005. Diffusion of general-purpose technologies: understanding patterns in the electrification of US Manufacturing 1880–1930. Industrial and Corporate Change, 14(5): 745-773.

Henderson, R. 1993. Underinvestment and incompetence as responses to radical innovation: evidence from the photolithographic alignment equipment industry. RAND Journal of Economics, 24(2): 248.

Henderson, R. M. 1995. Of life cycles real and imaginary: The unexpectedly long old age of optical lithography. Research Policy, 24(4): 631.

Henderson, R. M., & Clark, K. B. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of. Administrative Science Quarterly, 35(1): 9-30.

Hoetker, G.. 2006. Do modular products lead to modular organizations? Strategic Management Journal, 27(6):501-518.

Hughes, T. P. 1983. Networks of Power: Electrification in Western Society 1880 – 1930. Baltimore: Johns Hopkins University Press.

Iansiti, M., & Levien, R. 2004. The Keystone Advantage: What the New Dynamics of Business Ecosystems Mean for Strategy, Innovation, and Sustainability. Boston: Harvard Business School Press.

Iansiti, Marco 1997. Technology Integration: Making Critical Choices in a Dynamic World. Harvard Business School Press
Integration. Boston: Harvard University.

Intel Corporation. 2004. “Intel Sees Unified Platform And Ecosystem As Key To Enabling The Digital Home” Press release. Feb. 17.

Jacobides, M. 2005. Industry Change through Vertical Disintegration: How and why markets emerged in mortgage banking. The Academy of Management Journal, 48(3): 465-498.

Kapoor, R. and Adner, R. 2007. Technology Interdependence and the Evolution of Semiconductor Lithography. Solid State Technology 50(11): 51-54.

Kerin, R. A., Varadarajan, P. R., Peterson, R. A 1992. First-mover advantage: A synthesis, conceptual framework, and research propositions. Journal of Marketing, 56(4): 33-52.

Lawrence, P.R., and Lorsch, J.W. 1967. Organization and Environment: Managing Differentiation and

Lieberman, M. B., & Montgomery, D. B. 1988. First-mover advantages. Strategic Management Journal, 9: 41-58.

Lieberman, M. B., & Montgomery, D. B. 1998. First-mover (dis)advantages: Retrospective and link with the resource-based view. Strategic Management Journal, 19(12): 1111-1125.

Lieberman, M.B., 1984. The Learning Curve and Pricing in the Chemical Processing Industries. The RAND Journal of Economics, 15(2): 213-228.

Lieberman, M.B., 1989 The Learning Curve, Technology Barriers to Entry, and Competitive Survival in the Chemical Processing Industries. Strategic Management Journal. 10(5): 431-447.

Lippman, S.A., and Rumlet, R.P. 1982. Uncertain Imitability: An Analysis of Interfirm Differences in Efficiency under Competition The Bell Journal of Economics, 13(2): 418-438.
Management Journal, 32: 543-576

Mitchell, W. 1989. Whether and When? Probability and Timing of Incumbents' Entry into Emerging Industrial Subfields. Administrative Science Quarterly, 34: 208-230.

Mitchell, W. 1991. Dual clocks: Entry order influences on incumbent and newcomer market share and survival when specialized assets retain their value. Strategic Management Journal, 12(2): 85-100.

Moore, G. E. 1995. Lithography and the Future of Moore's Law. Proceedings of the International Society for Optical Engineering, 2438: 2-17.

Moore, J. F. 1996. The Death of Competition : Leadership and Strategy in the Age of Business Ecosystems: Harper Business.

Morison, Elting. 1966. Men, Machines and Modern Times. Cambridge:Mass. MIT Press.

Novak, S. and Stern, S. 2006. How does outsourcing affect performance dynamics? Evidence from the automobile industry. Working paper.

Pacheco-de-Almeida, Goncalo and Peter Zemsky (2006). The Timing of Resource Development and Sustainable Competitive Advantage, INSEAD working paper 2006/13/ST.

Porter, M. E. 1980. Competitive Strategy: Techniques for Analyzing Industries and Competition. New York: The Free Press.

Rivkin, J. W. 2000. Imitation of Complex Strategies. Management Science, 46(6): 824-844.

Rosenberg, N. 1972. Factors Affecting the Diffusion of Technology. Explorations in Economic History, 10(1):3–33.

Rosenberg, N. 1976. On Technological Expectations. The Economic Journal, 86(343): 523-535.

Rosenkopf, L. and Tushman, M. L. 1998. “The coevolution of community networks and technology: lessons from the flight simulation industry.” Industrial and Corporate Change, 7:311-346

Sahal, D. 1981. Patterns of Technological Innovation. Addison-Wesley, Reading, MA.

SAP Corporation. 2006. “SAP Ecosystem Unites to Bring Innovation to Chemicals Industry.” Press release. May 8.

Spence, M. 1981. The Learning Curve and Competition The Bell Journal of Economics. 12(1):49-70.

Suarez, F.F. and Lanzolla, G. 2007. The Role of Environmental Dynamics in Building a First Mover Advantage Theory. The Academy of Management Review. 32(2):377 – 392.

Teece, D. J. 1986. Profiting from Technological Innovation: Implications for Integration, collaboration, Licensing and Public Policy. Research Policy, 15(6): 285-305.

Tripsas, M. 1997. Unraveling the process of creative destruction: complementary assets and incumbent survival in the typesetter industry. Strategic Management Journal, 18(6): 119-142.

Tripsas, M. 2006. "Customer Preference Discontinuities: A Trigger for Radical Technological Change." Managerial and Decision Economics

Tripsas, M., & Gavetti, G. 2000. Capabilities, cognition, and inertia: Evidence from digital imaging. Strategic Management Journal, 21(10/11): 1147.

Tushman, M. L., & Anderson, P. 1986. Technological discontinuities and organizational environments. Administrative Science Quarterly, 31(3): 439-465.

Tushman, M. L., & Romanelli, E. 1985. Organisational evolution: A metamorphosis model of convergence and reorientation. Research in Organisational Behaviour, 7: 171-222.

VanderWerf, P. A., & Mahon, J. F. 1997. Meta-Analysis of the Impact of Research Methods on Findings of First-Mover Advantage. Management Science, 43(11): 1510-1519.

Williamson, O. E. 1985. The economic institutions of capitalis m: firms, markets, relational contracting. New York, London: Free Press, Collier Macmillan.

TABLE 1: Major technological innovations by the lithography equipment ecosystem to overcome the challenges accompanying new technology generations.

Technology Generation (Year of First Sale)	**Resolution (µm)**	**Tool**	**Source**	**Lens**	**Mask**	**Resist**
Initial Solution (pre-1962)			Mercury Lamp	None	Manually cut mask	Negative resist
Contact Printer (1962)	7.00	Circuit design is transferred to wafer by putting mask in direct contact with the resist on the wafer and then shining the light energy from the mercury lamp	-	-	Introduction of Step & Repeat Camera for mask making.	-
Proximity Printer (1972)	3.00	The mask is separated from the wafer by a small gap. Eliminating direct contact reduces defect rates.	-	-	-	-
Projection Scanner (1973)	2.00	A reflective lens system is incorporated into the tool to allow for greater concentration of light energy to be transferred through the mask onto the	-	Development of Reflective lens system.	Use of Electron Beam systems for high quality 1X masks	-
E-Beam Writer (1976)	0.5	Move an electron beam through a preprogrammed path to create the circuit pattern directly on the resist without use of lens or mask.	Development of thermionic and field emission	-	-	New developments with PMMA based resist
X-Ray Printer (1978)	0.3	Change wavelength from 435nm to 10nm and project energy from an x-ray source without use of a lens.	Development of synchrotron for providing a high energy	-	Development of new mask materials such as SiC/Ta.	-
G-Line Stepper (1978)	1.25	Step-and-repeat technology allows a single wafer to be etched through multiple exposures as the mask is shifted across the wafer in steps. A refractive lens system allows for the circuit dimensions on the	-	Development of Refractive lens system.	-	Change in resist from standard Negative resist to Novolac resist to provide low resolution.

I-Line Stepper (1985)	0.80	Wavelength derived from the mercury lamp energy source is reduced from 435nm to 365nm.	-	Development of new lens material for reduced wavelength.	-	-
DUV 248nm Stepper (1986)	0.45	Wavelength is reduced from 365nm to 248nm.	Development of Krypton Fluoride (KrF) excimer laser.	Change in lens material to Fused Silica.	Change in mask material to quartz.	Change in resist to chemically amplified resist.
DUV 193nm Stepper (1996)	0.15	Wavelength is reduced from 365nm to 248nm.	Development of Argon Fluoride (ArF) excimer laser.	Change in lens material to Calcium Fluoride	Introduction of RET Masks for 193nm.	New versions of chemically amplified resist were developed for 193nm wavelength.

TABLE 2: Variable descriptions.

Variables	Description
Dependent Variable	
Generation Share	Firm’s annual market share in a given generation in a given year.
Key Variables in Study	
Technology Leadership	Entry timing for the firm in the new generation. Leadership position is defined as 1 for the first entrant and subsequent entry is measured with respect to the lag in years from the first entry.
Component Uncertainty	Number of technical articles appearing in the industry journal no later than 5 years after the emergence of the new generation that refer to lens and source innovation in the given generation.
Complement Uncertainty	Number of technical articles appearing in the industry journal no later than 5 years after the emergence of the new generation that refer to mask and resist innovation in the given generation.
Vertical Integration	Dummy = 1 for a firm with a separate business unit performing manufacturing of lens component for the generation.
Technology Maturity	Count of number of years between a technology generation’s year of first sale and the given year.
Control Variables	
Incumbent	Dummy = 1 for a firm that sold lithography tools in an earlier technology generation.
Conglomerate	Dummy = 1 for a firm that was active in multiple industries.
Generation Sales Growth	Annual sales growth rate of the generation.
Number of Firms	Number of firms active in the generation in a given year.

TABLE 3: Descriptive statistics and correlations.

Variables	Mean	Std. Dev.	Min	Max													
Ln(Generation Share)	-1.83	1.26	-6.21	0.00	1.00												
Technology Leadership*Component Uncertainty	-0.68	7.67	-29.74	23.29	-0.06	1.00											
Technology Leadership*Complement Uncertainty	1.93	8.81	-22.34	32.71	0.24	-0.20	1.00										
Vertical Integration*Technology Maturity	2.55	5.50	0.00	27.00	0.24	0.10	-0.03	1.00									
Technology Leadership*Ecosystem Uncertainty	1.24	10.46	-41.50	50.45	0.16	0.57	0.70	0.05	1.00								
Technology Leadership [a]	3.54	2.93	1.00	13.00	-0.36	-0.34	0.24	-0.07	-0.05	1.00							
Component Uncertainty [a]	3.53	2.43	0.00	8.00	-0.03	-0.01	-0.37	0.08	-0.32	-0.10	1.00						
Complement Uncertainty [a]	4.12	2.67	0.00	10.00	0.13	-0.39	0.08	-0.15	-0.21	0.25	0.32	1.00					
Vertical Integration	0.23	0.42	0.00	1.00	0.23	0.10	-0.03	0.85	0.04	-0.13	0.13	-0.14	1.00				
Incumbent	0.48	0.50	0.00	1.00	-0.06	0.02	-0.26	0.28	-0.20	0.15	0.39	0.06	0.31	1.00			
Conglomerate	0.49	0.50	0.00	1.00	0.23	0.07	-0.08	0.48	-0.02	-0.34	0.23	-0.11	0.56	0.21	1.00		
Generation Sales Growth	35.47	100.68	-76.54	853.06	-0.06	0.08	-0.04	-0.06	0.02	-0.08	0.15	0.05	0.05	0.12	0.03	1.00	
Number of Firms	4.92	2.39	1.00	11.00	-0.45	0.07	-0.19	-0.03	-0.11	-0.03	0.06	-0.17	0.00	-0.09	0.06	0.09	1.00
Technology Maturity	11.17	6.67	1.00	32.00	0.15	-0.10	0.19	0.22	0.08	0.22	-0.16	-0.12	0.00	-0.12	-0.01	-0.31	-0.24

N=676, Correlations greater than 0.08 are significant at $p<0.05$

[a] pre mean-centered mean, min and max are shown

TABLE 4: Coefficient estimates from panel regression. Dependent Variable = Ln(Generation Share)

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Technology Leadership* Component Uncertainty		-0.0404***			-0.0417***	-0.0438***
		(0.0073)			(0.0073)	(0.0096)
Technology Leadership* Complement Uncertainty			0.0222***		0.0198***	0.0196**
			(0.0065)		(0.0063)	(0.0084)
Vertical Integration* Technology Maturity				0.0338**	0.0412***	0.0286**
				(0.0138)	(0.0134)	(0.0140)
Technology Leadership	-0.1463***	-0.1481***	-0.1635***	-0.1416***	-0.1577***	-0.1562***
	(0.0183)	(0.0178)	(0.0188)	(0.0183)	(0.0183)	(0.0224)
Vertical Integration	0.4062***	0.2451*	0.3981***	0.0470	-0.2053	0.0119
	(0.1547)	(0.1438)	(0.1533)	(0.2127)	(0.2103)	(0.2990)
Component Uncertainty	-0.0361	-0.0452	-0.0008	-0.0517	-0.0330	-0.0354
	(0.0461)	(0.0451)	(0.0469)	(0.0464)	(0.0460)	(0.0942)
Complement Uncertainty	0.1020***	0.0740***	0.0856***	0.1042***	0.0611***	0.0276
	(0.0224)	(0.0225)	(0.0227)	(0.0223)	(0.0226)	(0.0331)
Technology Maturity	0.0028	-0.0252	0.0141	-0.0112	-0.0330*	-0.0294
	(0.0166)	(0.0169)	(0.0167)	(0.0174)	(0.0181)	(0.0309)
Incumbent	-0.6095***	-0.7574***	-0.4229***	-0.6584***	-0.6550***	-0.7686***
	(0.1136)	(0.1141)	(0.1252)	(0.1149)	(0.1272)	(0.1914)
Conglomerate	0.8748	-0.2154	0.3967	2.8453***	2.6973***	2.8117***
	(0.9470)	(0.9901)	(0.9970)	(0.9672)	(0.8854)	(0.9490)
Generation Sales Growth	-0.0005	-0.0006	-0.0005	-0.0003	-0.0005	-0.0003
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Number of Firms	-0.1833***	-0.1806***	-0.1792***	-0.1891***	-0.1839***	-0.1777***
	(0.0206)	(0.0201)	(0.0204)	(0.0206)	(0.0200)	(0.0245)
Constant	-1.0658	0.1938	-1.3932	-3.1905***	-2.4067**	-2.4014**
	(1.1010)	(1.0989)	(1.0955)	(1.0073)	(0.9839)	(1.2233)
Firm Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	676	676	676	676	676	521
Wald Chi-Square	847.03***	919.15***	873.79***	860.15***	966.79***	731.62***

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Figure 1: Generic Schema of an Ecosystem.

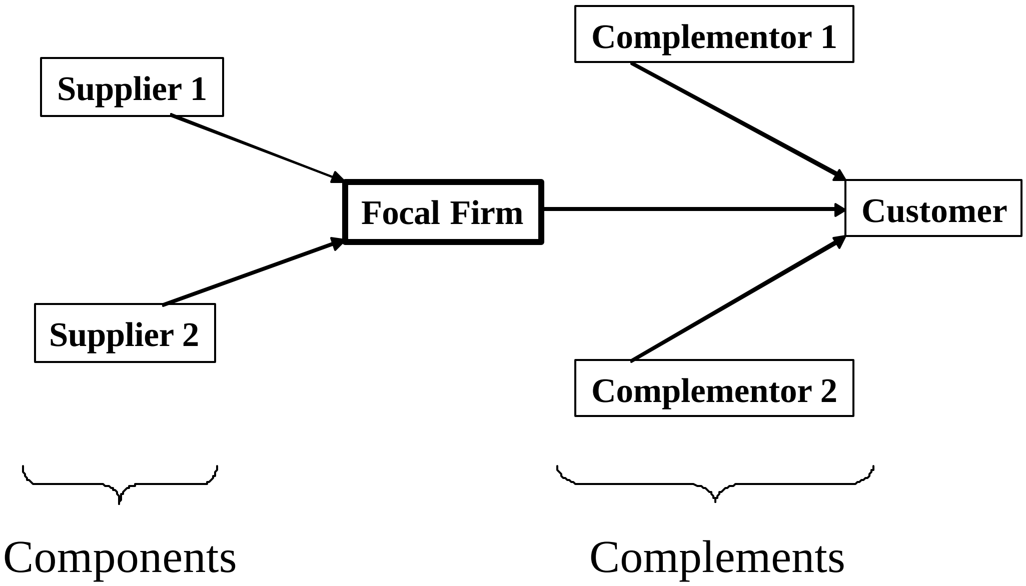


Figure 2: Basic Schema of the Semiconductor Lithography Process.

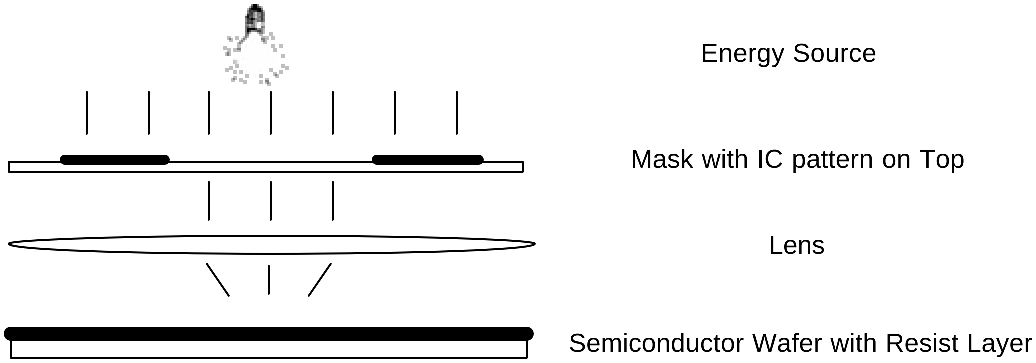


Figure 3: The Semiconductor Lithography Equipment Ecosystem.

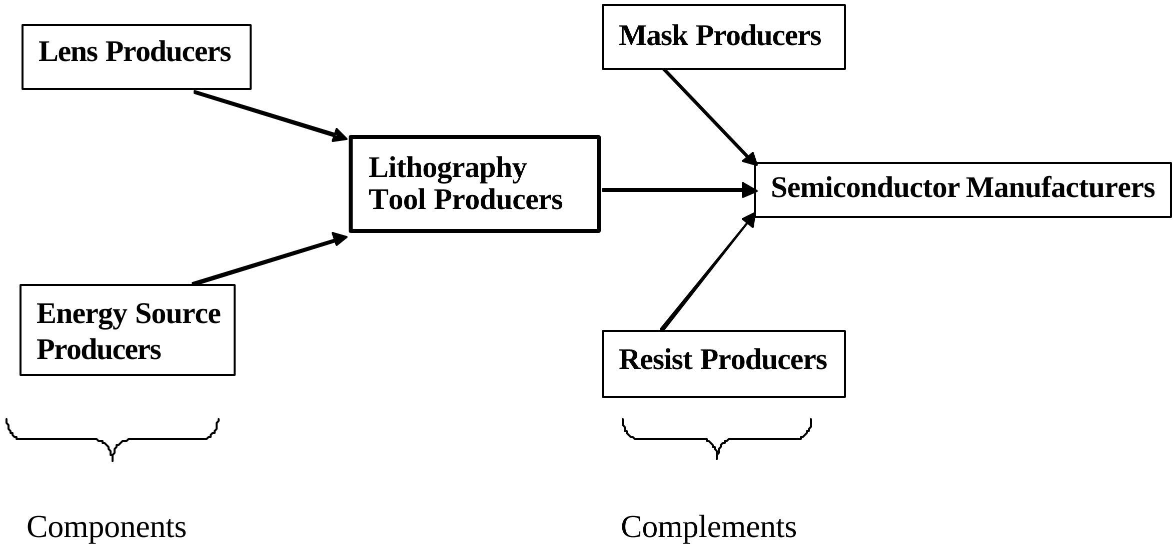


Figure 4: Distribution of uncertainty among ecosystem elements in nine semiconductor lithography equipment generations.

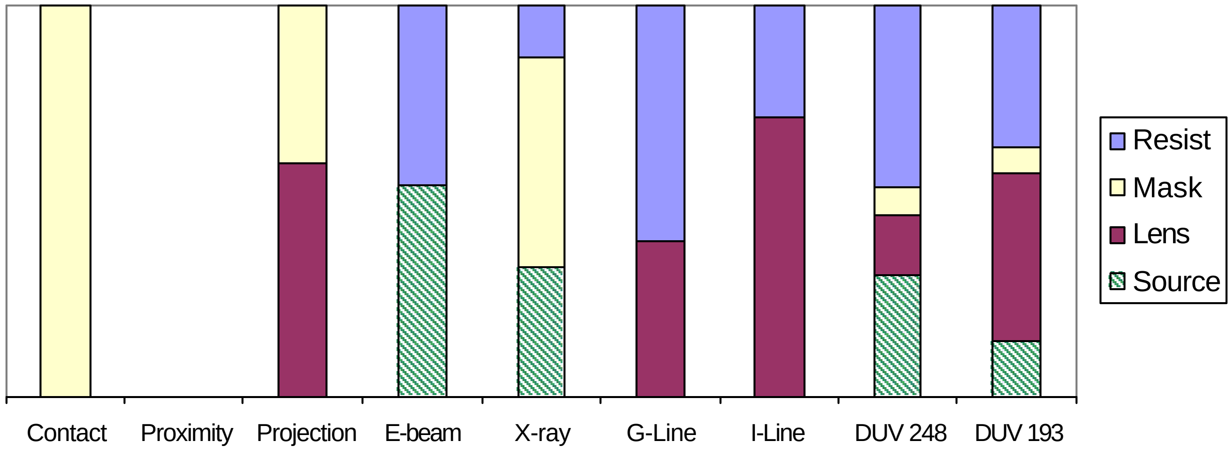
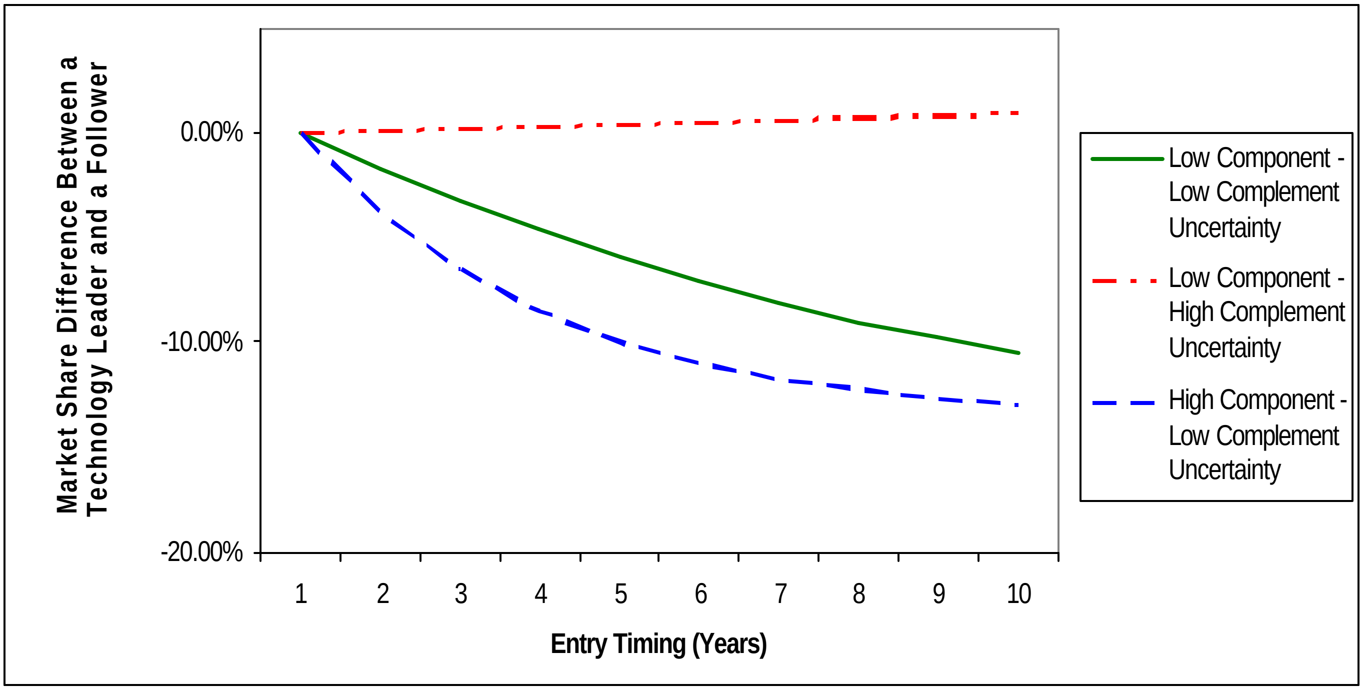


Figure 5: Difference in expected market share between a technology leader and a follower as a function of ecosystem uncertainty and the follower's entry timing.



Appendix I: Technology Transitions in the Semiconductor Lithography Equipment Industry from 1962 to 2004

This discussion is based on the industry history presented in Kapoor and Adner (2007).

Optical Technologies

Optical lithography technologies use light of different wavelengths to create patterns on the semiconductor substrate. These technologies have been dominant in the industry despite repeated expectations for their substitution (see Henderson, 1995 for an intriguing discussion).

Contact Printers – Contact printing was the earliest and the simplest of the lithography technologies to be commercialized. The modifier 'contact' corresponds to the fact that the mask and the semiconductor wafer were in direct contact with each other. The contact printers in the 1960's included a stage system for securing the mask and the wafer, and an alignment unit that ensured that the patterns from the mask were accurately transferred to the wafer. They used a mercury lamp for their energy source, an existing component already used in movie projectors of the time. Contact printers did not incorporate a lens. The resist used by semiconductor firms as a complement to the tool, known as negative resist, was readily available and already being used by Kodak in photography applications.

The main ecosystem challenge to the emergence of commercial contact printers stemmed from difficulties in the manufacture of suitable masks. Masks were made using a three stage process. First the desired circuit pattern was cut from a plastic laminate. This cutting was done using a manually operated tool which could achieve an accuracy of approximately 100µm (0.1mm). Second, the circuit image was etched on to an emulsion plate which became the 'master' mask. Finally, the master mask was used to create copies of itself which served as 'production' masks.

This early mask making process presented two inherent limitations. First, the resolution of the manually cut masks acted to limit the performance achievable by the contact printers. Second, the master mask was highly susceptible to wear during the production mask making process, which led to high manufacturing defects and hence reduced productivity.

To address these challenges, the mask making industry introduced two new innovations during the 1960's. The first was the computerization and automation of the mask making process using high-speed step and repeat cameras. The second was the introduction of master masks made of chrome patterned glass that could be cleaned and reused several times, reducing the defects in the production masks.

Proximity Printers – A primary disadvantage of contact printing was low process yield. This was due to the damage inflicted on the mask and the wafers as they were repeatedly brought in and out of physical contact with each other during the lithography process. Proximity printing, introduced in 1972, offered a way to overcome this problem. With proximity printing the mask and the wafer were separated by a tiny gap in order to reduce the defects that had been caused by their direct contact. This reconfiguration allowed for significant enhancement in resolution, achieving geometries of 3µm. As discussed in detail by Henderson and Clark (1990), this generational transition can be characterized as an architectural innovation and imposed significant innovation challenges on the focal lithography equipment firms. The transition to proximity printing did not, however, present major innovation challenges to any other actors in the lithography ecosystem.

Projection Scanners – The continuous need of semiconductor manufacturers to reduce circuit dimensions and get better manufacturing yields led to the introduction of another architectural innovation in 1974. Projection scanners introduced the use of lens systems as a component in lithography tools. The lens system was composed of a series of reflective mirrors which allowed the image of the mask to be transferred to the wafer. Projection scanners allowed for resolution as low as 2µm. The ecosystem challenges during the development and emergence of this generation were in the lens system, a new component that was developed specifically for the lithography industry; and in the mask, which needed to be etched with correspondingly smaller geometries and greater accuracy. To meet the mask manufacturing challenge, mask makers switched from using step and repeat cameras to using electron beam systems in their production process.

G-line Steppers – Step-and-repeat (stepper) technology was introduced in 1978. The G-line stepper, an architectural innovation, introduced two key modifications. First, light was projected through the mask on to the wafer using a refractive lens system (as opposed to the reflective lens system used in projection scanners). Second, the light was projected on only a part of the wafer at any one time; the mask was shifted across the wafer in steps, such that multiple exposures are made across the wafer to complete the lithography process. G-line steppers operated at a wavelength of 435 nanometer (nm) and allowed users to achieve resolution as low as

1.25µm. The transition to G-line steppers imposed significant challenges on the ecosystem. In terms of components, it required the development of a refractive lens comprised of several precise glass elements that would minimize distortion and transmit light accurately on to the wafer. In terms of complements, the transition to G-line steppers required the development of a resist that would allow for sufficiently small geometries; that is, a resist in which exposure to light energy would trigger a chemical reaction only in the molecules that were directly exposed to the light, without setting off a reaction in adjacent molecules. The negative resist, which had been used to this point in the industry's evolution, was inadequate to the task. The resist challenge was resolved through the development of new novolac-based materials.

I-line Steppers –I-line steppers, introduced in 1985, used light with a wavelength of 365nm to improve over the resolution achievable with the G-line generation.[9] The main ecosystem challenge was to develop a lens that would transmit light at the lower wavelength. This required the development of a new glass material and corresponding changes to the lens production process. The remaining ecosystem elements required only incremental changes for the transition from the G-line generation. I-line steppers allowed for resolutions as low as 0.8µm.

DUV 248nm Steppers – The next step in the industry's technology evolution was the introduction of DUV 248nm steppers in 1988. This generation entailed a further reduction in wavelength into the deep ultraviolet (DUV) spectrum at 248nm. The reduction in wavelength required fundamental changes in the energy source, the lens, the mask, and the resist.

Mercury lamps, which had been used in all earlier generations, were not able to provide sufficient energy at a wavelength of 248nm to cause adequate chemical reactions in the resist. This challenge was overcome by the development of excimer lasers using Krypton Fluoride (KrF) gas. The conventional glass material that was used to make lenses faced absorption problems with 248nm wavelength. The only material that could be used was fused silica, and this required major changes to the lens manufacturing process. The challenges imposed on mask makers were overcome by changing the mask material from soda lime glass to quartz in order to provide improved transmission of the 248nm wavelength. This, in turn, required major changes to the mask manufacturing process. Finally, the existing novolac resists could not absorb enough energy from the new wavelength to cause an adequate chemical reaction. As a result, new chemically-amplified resist had to be developed for semiconductor manufacturers to create fine circuits using the new lithography technology. After the ecosystem challenges were overcome, DUV 248nm steppers could provide resolutions as low as 0.45µm.[10]

DUV 193nm Steppers – The industry's drive towards finer resolutions continued when tools using the DUV 193nm wavelength were introduced in 1996. As was the case for the DUV 248, the very low light wavelength created new challenges in every part of the ecosystem. Since KrF lasers could not produce light with wavelength of 193nm, a new excimer laser that used Argon Fluoride (ArF) gas was developed. New challenges were also posed by light absorption problems with the existing lens materials. The challenges were overcome with the development of a new lens material, calcium fluoride. The resist and the mask also had to

---

[9] The resolution capability of lithography technologies that employ a lens system is given by the Rayleigh criterion:

$$Resolution = k_1 \times (Wavelength/Numerical\ Aperture)$$

where wavelength is the wavelength of the light being transmitted by the source, numerical aperture is the measure of the size of the lens, and k_1 is a process-specific constant. Hence, to improve the resolution of lithography tools, manufacturers can either reduce the wavelength of light or increase the size of the lens. A key source of improvement within the course of a given technology generation has been increases in lens size. When further increases in lens size become untenable, due to a combination of physical and economic constraints on production, the industry shifts to a new, smaller, wavelength which heralds the emergence of a new technology generation.

[10] Firms that entered the DUV 248nm generation employed two different architectures. With the exception of Silicon Valley Group, all firms initially developed step-and-repeat systems for the DUV 248nm generation. Silicon Valley Group entered the new generation with a new step-and-scan architecture (the original step-and-scan technology was developed by Perkin Elmer, which was acquired by Silicon Valley Group). Step-and-scan systems, an architectural innovation, can be considered a hybrid between projection scanners and step-and-repeat steppers. The main benefit was a significant reduction in lens complexity that would provide lower resolution and a larger field size in order to satisfy the growing demand of large size logic IC's. Most firms producing DUV 248nm step and repeat systems eventually moved to the step-and-scan architecture during the course of the generation.

undergo major developments so that this new generation could create value for users. With the change to the 193nm wavelength, the existing resists, which were engineered to react to the 248nm wavelength, were no longer adequate to the task – a new generation of chemically amplified resist needed to be developed. Finally, resolution enhancement technologies (RETs) needed to be developed in order to create masks that could exploit the finer resolution available from the DUV 193nm steppers.[11] Once these challenges were overcome, DUV 193nm steppers were able to provide resolutions of 0.15µm.

Non-Optical Technologies

Since the early 1960's, optical lithography has been the mainstay of semiconductor manufacturing. However, there have been several attempts to introduce non-optical technologies that would offer smaller geometries by using much smaller energy wavelengths outside of the visible spectrum.. Amongst these, the two technologies that attracted the most interest, resources, and market share were X-ray and electron-beam (E-beam) lithography. [12]

X-ray Printers – The use of X-rays for lithography was proposed due to their very low wavelength of less than 10nm. In the early 1970's, X-ray lithography was developed as a simple proximity imaging system. As in proximity printing, the radiation from an X-ray source is transmitted through the mask onto the resist. X-ray lithography's very low wavelength created substantial challenges to the implementation of the technology for semiconductor manufacturing. These challenges included major changes to the source and the mask. Although it was first introduced in 1978 with great fan fare, X-ray printing has never entered the mainstream – as of the time of this writing, its ecosystem challenges have yet to be overcome at a competitive, commercial scale.

E-Beam Writers – Electron-beam (E-beam) technology involves patterning the resist on the semiconductor wafer directly using electron beams the follow a pre-programmed pattern, thereby eliminating the need for a mask. The major concern with this technology has been its throughput. Since a pre-programmed electron beam travels across the wafer to achieve very low resolution, the time required to complete a single wafer can be as high as 10 hrs, which is almost an order of magnitude longer than the alternate optical lithography technologies. This throughput disadvantage has relegated E-beam writers to high-end, low volume niches. The major ecosystem challenges posed by E-beam technology are the development of the E-beam source to increase throughput, as well as new resist chemistries that work with the emitted electrons. At first glance, it might seem that E-beam lithography should be characterized as a radical technological change for producers. In fact, however, every firm that entered with an E-beam tool had already offered E-beam based products to other markets (e.g., electron microscopy). For these firms, E-beam writers for semiconductor lithography presented only incremental innovation challenges. None of the pure optical firms, for whom E-beam would have represented a genuinely radical departure, ever entered the market.

---

[11] RETs control and manipulate the light waves through the mask and the lens, and provide improved contrast of the projected circuit image. This "wavefront engineering" reduces the k_1 of the Rayleigh's criterion to provide lower resolution.

[12] Two additional approaches, ion-beam lithography and e-beam projection lithography have also been experimented with, but neither has ever been commercialized.

Appendix II

Test of Hypotheses 1 and 2 using ordinary least squares regression.
Dependent variable = Ln(firm's cumulative market share in a given technology generation).

	(1)	(2)	(3)	(4)	(5)
	Baseline	Partial 1	Partial 2	Full	Excluding Xray and Ebeam
Technology Leadership* Component Uncertainty		-0.0437*		-0.0487**	-0.0490**
		(0.0228)		(0.0191)	(0.0208)
Technology Leadership* Complement Uncertainty			0.0455*	0.0493**	0.0506*
			(0.0255)	(0.0229)	(0.0248)
Technology Leadership	-0.1248	-0.1531**	-0.1350	-0.1674**	-0.1562*
	(0.0817)	(0.0669)	(0.0830)	(0.0738)	(0.0876)
Component Uncertainty	-0.0920	-0.0922	-0.0608	-0.0584	-0.0837
	(0.1023)	(0.1005)	(0.0992)	(0.0971)	(0.1443)
Complement Uncertainty	0.2755***	0.2547***	0.2615***	0.2373***	0.1790
	(0.0801)	(0.0678)	(0.0771)	(0.0668)	(0.1048)
Vertical Integration	1.7544***	1.8834***	1.6473***	1.7821***	2.1622***
	(0.3314)	(0.3391)	(0.3467)	(0.3603)	(0.4988)
Incumbent	-0.4954	-0.5147	-0.4200	-0.4353	-0.4235
	(0.6816)	(0.6296)	(0.7518)	(0.6941)	(1.0206)
Conglomerate	1.2690*	1.1621*	1.1701*	1.0428	0.8032
	(0.6529)	(0.6636)	(0.6853)	(0.6954)	(0.9666)
Constant	-3.7695***	-3.7670***	-3.7817***	-3.7799***	-3.9284***
	(0.3874)	(0.3911)	(0.3578)	(0.3621)	(0.5868)
R-squared	0.37	0.40	0.41	0.44	0.43
Observations	64	64	64	64	50

Standard errors in parentheses, clustered by firm.
* significant at 10%; ** significant at 5%; *** significant at 1%