Patent Rights and Innovation:
Evidence from the Semiconductor Industry

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1. Introduction

"If you tried to build an Android phone today using the chips available in 1971, it would be the size of a parking space." -- Weise 2015

Gordon Moore, co-founder of Intel Corporation, predicted in 1965 that the number of computer chips etched onto a silicon wafer would double roughly every two years. More than fifty years later, the rate of technological progress in the semiconductor industry remains astonishing. According to Intel estimates, modern transistors are 60,000 times cheaper on a per-unit basis than they were in 1965. Equally impressive, they are 3,000 times more powerful and 90,000 times more energy efficient. Although "Moore's Law" appears to be slowing down and hitting technical limits (Markoff 2016), few deny that these historic advances in the design and manufacture of semiconductor devices underpin the modern information economy.

In the United States alone, the semiconductor industry employs approximately a quarter of a million people (SIA, 2016). In 2015, U.S. semiconductor companies invested $34 billion in research and development, representing the highest share of revenue of any U.S. industry (SIA, 2016). This industry is a fascinating context in which to explore how patent rights affect the innovative activities of firms. State of the art changes quickly, with firms racing to move the frontier forward. Semiconductor devices—including the integrated circuits that power modern smartphones and servers—typically embed thousands of potentially patentable inventions. And the manufacturing process is complex and costly. These conditions naturally lead to concerns about inadvertent infringement and patent "hold-up." Indeed, some credit compulsory licensing restrictions in the 1950s with the early diffusion of semiconductor know-how and the subsequent development of a standalone industry of chip design companies and manufacturers (e.g., Levin 1982; Grindley and Teece 1997).

Innovation in the semiconductor industry was also highly cumulative prior to a "pro-patent" shift in the U.S. legal environment in the 1980s, thus setting a natural stage for investigating how stronger patent rights affected the incentives of firms in the industry. According to the USPTO (1995), for example, over 20,000 U.S. patents were issued from 1969 through 1980 on inventions pertaining to semiconductor devices and manufacturing processes. In contrast, few software or biotechnology-related patents were issued prior to 1980 due to differences in patentable subject matter at the time (Graham and Mowery 2003; Merges 1997), which makes it difficult to ascertain before-and-after effects in these settings.

This chapter describes empirical findings from studies that examine the relationship between patent rights and innovative activity in the U.S. semiconductor industry. How important are patent rights as a stimulus to innovation investment in this sector? What strategies do firms adopt to navigate the patent landscape and access technologies? To what extent, if at all, do patent rights deter follow-on innovations?

Even in a single industry setting, answering these questions poses non-trivial measurement and methodological challenges. In early phases of the industry's development, pioneering semiconductor companies such as IBM and AT&T engaged in semiconductor R&D and production primarily for in-house use in their downstream product markets. Since diversified companies rarely report R&D expenditures at the technology level, much of the evidence on the relationship between patenting and innovation is based on specialized firms that primarily compete in semiconductor-related markets. Similarly, detailed information about the timing of patent license negotiations and the terms of license agreements is not reported on a systematic basis, leading to a reliance on indirect litigation-based measures in studies of conflict and settlement among patent owners.

A second, more challenging issue relates to the simultaneous determination of many economic and innovation outcomes. Suppose, for example, that we are interested in whether entry of new firms in the semiconductor industry affects the propensity of incumbent firms to litigate their patents. One may consider addressing this research question by comparing patent litigation rates before and after a new competitor enters. But this is challenging because unobservable factors may drive both market entry and patent litigation. An increase in market demand may spur entry of new firms in the industry, for example, and simultaneously increase the incentives of incumbent firms to enforce their patent rights. In addition to reviewing descriptive findings in the field, we highlight recent methodological advances that help address these types of challenges.

The chapter is organized as follows. Section 2 discusses the "pro-patent" shift in the United States in the 1980s, and its effects on the patenting strategies and organization of innovative activity within the industry. Section 3 describes the added insights the role that patents play in appropriating returns to R&D based on managerial surveys. In Section 4, we elaborate on the fundamental economics of patent "hold-up" problems, discuss the challenges of measuring such problems directly, and highlight indirect evidence based on patterns of legal conflict and license agreements. Although we discuss selected evidence from the literature on standards setting organizations (SSOs), we refer readers interested in multi-party institutional arrangements to the more extensive discussion on that topic in the chapter by Contreras in this volume.

2. The "Pro-Patent" Shift in the 1980s: Implications for Patent Strategies and the Organization of R&D[1]

The modern semiconductor industry stems from the invention of the point-contact transistor at Bell Labs in late 1947 and the subsequent licensing of this invention by Bell Labs in the 1950s (Holbrook et al. 2000). In their 1959 book, Scherer and co-authors describe the patent landscape during the early phase of the industry's development as follows:

> During the past two decades a pronounced change has taken place in the policies of governmental bodies towards patents owned by corporations…

[1] This section draws on material in Ziedonis (2003).

> The courts have become increasingly critical of patent validity, and cases in which the exercise of patent rights conflicted with antitrust statutes have been prosecuted by denying the exclusiveness of the patent grant. Since 1941, more than 100 judgments have been entered that required corporations to license their patents to all applicants at reasonably royalties or no royalties at all. This trend was brought sharply to the public's attention in January 1956 when two of the nation's foremost leaders in industrial technology, the American Telephone and Telegraph Co and International Business Machines, Inc., entered into decrees requiring them to license all of their more than 9,000 patents, in most cases without receiving royalties in return." (p. 2-3).

From the 1950s through the early 1980s, AT&T and IBM—technological pioneers with large portfolios of semiconductor-related patents—licensed their inventions widely in return for access to subsequent inventions by licensees. Levin (1982) and Grindley and Teece (1997) credit this liberal licensing scheme with the early growth and development of an industry of firms specializing in semiconductor design and manufacturing. Based on an analysis of citations to Bell Labs inventions, Watzinger et al. (2017) similarly conclude that the consent decree stimulated follow-on innovation during this vital stage of the industry's development, particularly by young and small firms. While intuitive, determining whether the stimulus is explained by the consent decree alone is challenging due the interplay between antitrust and patent policies. When describing AT&T's open licensing of Bell Lab inventions, for example, Tilton (1971, p. 76) observes:

> Certainly the great probability that other firms were going to use the new technology with or without licenses is another reason for the liberal licensing policy. Secrecy is difficult to maintain in the semiconductor industry because of the great mobility of scientists and engineers and their desire to publish. Moreover, semiconductor firms, particularly the new, small ones, have demonstrated over and over again their disposition to infringe on patents. The prospect of lengthy and costly litigation in which its patents might be overturned could not have been very attractive...

von Hippel (1988, p. 52-53) makes a similar observation when describing competitive dynamics within the industry in the early 1980s:

> Since patents challenged in court are unlikely to be held valid, the result of high likelihood of infringement accompanying use of one's own patented—or unpatented—technology is not paralysis of the field. Rather, firms in most instances simply ignore the possibility that their activities might be infringing the patents of others. The result is what Taylor and Silberston's interviewees in the electronics components field

> termed 'a jungle' and what one of my interviewees termed a 'Mexican standoff'… The usual result is cross-licensing, with a modest fee possibly being paid by one side or the other."[2]

As numerous scholars in law and economics have observed, the legal environment in the United States changed dramatically in the decade of the 1980s, both overall and for firms in the U.S. semiconductor industry (Merges 1997; Jaffe 2000; Gallini 2002). Driven by concerns about increased international competition and growing belief that stronger intellectual property rights were needed to stimulate innovation investments, Congress passed a series of laws that improved the functioning of the U.S. patent system and relaxed antitrust constraints on firms. The 1984 National Cooperative Research Act (NCRA), for example, reduced the antitrust penalties for collaboration among firms in "pre-commercial" research, paving the way for the formation of research consortia such as SEMATECH in the semiconductor industry (Grindley et al. 1994; Ham et al. 1998). The 1984 Semiconductor Chip Protection Act provided legal protection for the layout of chip designs, although technological changes soon eroded the value of this *sui generis* form of protection (Samuelson and Scotchmer 2001).

The 1982 formation of the Court of Appeals for the Federal Circuit (CAFC) was particularly important (Jaffe 2000; Gallini 2002).[3] Although the driving force of this centralized appellate court was a unification of U.S. patent doctrine, the Federal Circuit put in place a number of procedural and substantive rules that collectively favored patent owners. As Merges (1997) explains, the new court interpreted patent claims more broadly, increased evidentiary standards to make it more difficult to invalidate the rights of patent owners and was more willing to sustain large damage awards and thereby penalize infringing parties more severely. The plaintiff success rates in infringement cases also increased substantially during this period (Lerner 1995).

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2 To reduce the risk of disruptions in supply, large customers of chips (e.g., IBM and the U.S. government) typically required a semiconductor supplier to transfer to a competing firm know-how and patent rights. These "second source" agreements further promoted cross-licensing in the industry but declined in use over the decade of the 1980s as the industry built up capacity and matured (Grindley and Teece 1997).

3 Until 1982, patent appeals were primarily heard in the court of appeals of the district in which the case was tried, leading to "forum shopping" among firms (Jaffe, 2000). Adelman (1987, p 983) argues that the CAFC's establishment also represented "dissatisfaction with the functioning of both the Supreme Court and the federal appellate courts" and a "realization by Congress that a uniform and more reliable patent system was necessary for sustained economic growth and to rise to the challenge of Japanese and German industrial competition."

The Federal Circuit also induced a dramatic increase in the use of preliminary injunctive relief (Merges, 1997). Prior to 1982, such injunctions were only granted when the validity of the patent was 'beyond question', the infringement was clear, and recovery through ex post award of damages was not possible ('irreparable harm'). The CAFC adopted a less stringent standard requiring the patentee to prove only that there was a 'reasonable likelihood' of prevailing at trial (Atlas Powder Co. v. Ireco Chemicals, 773 F.2d 1230, Fed. Cir. 1985), and it held that irreparable injury can be presumed (Smith International v. Hughes Tool Co., 718 F.2d 1573, Fed. Cir. 1983). Galasso and Schankerman (2010) document how the effect of this change is confirmed by data on the use of preliminary injunctions by lower courts. The proportion of requests for preliminary injunctions that were granted by the district courts increased from about 32 percent before 1982 to 53 percent after the establishment of the Federal Circuit.

Not surprisingly, firms with important portfolios of semiconductor patents responded to the "pro-patent" shift by adopting more aggressive licensing and litigation strategies—both by seeking licenses from a larger number of firms and by charging higher royalty rates for rights to use their inventions (Ziedonis 2003). Soon after the CAFC's formation, for example, Texas Instruments (TI) launched an assertive licensing program targeted against Japanese and Korean competitors in memory chip markets. After litigating its patents successfully, TI earned almost $2 billion between 1986 and 1993 from licensing rights to its semiconductor patents and used the funds to re-invest in the development of new product markets (Grindley and Teece, 1997).

Based on archival evidence and interviews with former IBM executives, Bhaskarabhatla and Hegde (2014; "BH2014") provide an in-depth case study of the internal management practices and rewards systems that IBM put in place in the late 1980s to seize opportunities in the new regime. The authors document that, reversing its open-science norm of publishing unpatented discoveries in IBM's Technical Disclosure Bulletins (TDB), IBM executives tied employee bonuses more tightly to patent filings, established an internal "patent factory," and created a new business development group to increase revenues from out-licensing IBM knowhow and inventions.

Jack Kuehler, IBM's president between 1989 and 1993, explained the shift in internal practices to IBM employees as follows:

> "A series of new laws in the [United States]—plus a much-improved court system for handling disputes [the CAFC]—are helping patent holders protect their rights better than before…From a simple means of protecting inventions patents have evolved into competitive weapons. Recent cases before the courts have resulted in multimillion dollar settlements affecting product line and even corporate profitability in what are now high-stakes battles…Being a world-class manufacturer and marketer is not enough. You need to own the right to compete. That's why IBM is encouraging more patenting of inventions" (as quoted in BH2014, p 1749).

Bhaskarabhatla and Hegde (2014) further show that in the decade following the adoption of its pro-patent management practices, IBM increased its successful U.S. patent applications by 492%—from 637 in 1988 to 3,777 in 1998. The share of IBM technical disclosures unprotected by patents fell sharply in turn, from 82% in 1988 to 15% by 1998, the last year that the TDBs were published. The authors find that these pro-patent practices improved IBM's financial bottom line, but led to a gradual reduction in others' citations to IBM inventions.

Hall and Ziedonis (2001) investigate the effects of the pro-patent shift on 95 U.S. semiconductor firms using a combination of quantitative and qualitative research methods.[4] Consistent with the case study of IBM by Bhaskarabhatla and Hegde (2014), Hall and Ziedonis (2001) find that semiconductor manufacturers started "ramping up" their patent portfolios in the mid-to-late 1980s. As one interviewee noted, there were "a lot of patentable inventions around," but the firm "not taken the time and incurred the cost" to patent those inventions in the past (Hall and Ziedonis 2001, p. 109).

Managers interviewed by Hall and Ziedonis (2001) suggested that the upsurge in patenting was a strategic response to the more favorable judicial treatment of U.S. patents. Although the CAFC was established in 1982, several interviewees commented that CEOs at

[4] For the quantitative analysis, it was important to track annual R&D investments related to semiconductors. The sample in Hall and Ziedonis (2001) therefore is based on publicly traded U.S. firms whose primary business is semiconductors and related devices. The approach unfortunately excludes from the estimation sample large US "systems" manufacturers such as IBM, AT&T and Motorola and non-US firms (e.g., Toshiba, Samsung or Siemens) that are important owners and users of semiconductor-related patents.

their companies first "woke up" to the new power of patents in 1986, when Kodak was forced to halt production of instant cameras and pay almost $1 billion in damages to Polaroid due to a patent infringement lawsuit. As a licensing director from a semiconductor manufacturer noted, the threat of injunction is a powerful lever when it is costly to halt production and difficult to invent around inventions. Others noted the cascading effects of TI's successful litigation strategy and the more assertive stance of industry leaders (e.g., AT&T, IBM, and Motorola) in earning licensing revenues from their inventions.

Overall, the evidence suggests that patents became more valuable for use as bargaining chips in negotiations with other patent owners. As Hall and Ziedonis (2001, p. 109-100) conclude: "a firm lacking a strong patent portfolio of its own with which to negotiate licensing or cross-licensing agreements could face a more rapid erosion of profits in an era when the costs and risks associated with infringement had increased." Consistent with this view, they document a dramatic upsurge in patenting between 1979 and 1995 that outpaced R&D spending in the industry and was unexplained by other factors. Hall (2005) reports a similar upsurge in the propensities of firms to patent in other segments of the information computing and technology (ICT) sector after the CAFC's formation.

In addition to triggering "patent portfolio racing" by capital-intensive firms, Hall and Ziedonis (2001) find that the pro-patent shift had a distinctive—and separable—effect on firms that specialize in the design of semiconductor devices but contract out the manufacture of their products to others. Managers from these semiconductor design (or "fabless") firms emphasized the importance of obtaining strong "bullet proof" patents to protect proprietary technologies against competitors in niche product markets and to attract venture capitalist funding. Indeed, when asked to consider a hypothetical abolishment of the patent system, representatives from both design firms and manufacturers in the Hall and Ziedonis (2001) study voiced concerns about potential chilling effects on entry by innovative design firms that relied on external sources of financing.

These latter insights are consistent with theoretical models linking stronger patent rights to increased specialization in the organization of R&D (e.g., Arora, Fosfuri, and Gambardella 2001). In line with that view, Hall and Ziedonis (2001) provide quantitative evidence that the rate of entry by semiconductor design firms increased sharply following the pro-patent shift. They were unable, however, to specifically pinpoint the increased entry to the strengthened patent regime due to simultaneous advances in technological platforms that facilitated vertical disintegration within the industry. Put differently, the counterfactual world—of entry rates and organization forms in the industry had the legal environment remained unchanged—was unobservable.

In summary, there is considerable evidence that the shift in the U.S. legal landscape in the 1980s significantly affected incentives to patent within the semiconductor industry and that specialized design firms relied heavily on strong patents both to secure financing from venture capitalist and to safeguard proprietary technologies in niche product markets. Even within one industry, the effects of the pro-patent shift were multi-faceted and wide-ranging.

3. Survey Evidence on the Value and Use of Patents

Additional insights about the value and use of patents in the U.S. semiconductor industry can be gleaned from surveys of practicing managers. Such surveys provide insights about managerial perceptions, and often allow for useful cross-industry comparisons. The main drawback is that most surveys seek to obtain representative views from many industries, which can limit within-industry coverage. Large-scale surveys can also be costly to administer, making it difficult to track changes in viewpoints and practices over time.

Of particular importance, the 1983 "Yale" and 1994 "Carnegie Mellon" Appropriability Surveys (Levin et al. 1987; Cohen Nelson and Walsh 2000) asked managers of R&D labs in U.S. manufacturing firms to rate the relative effectiveness of patents in appropriating the returns to R&D investments. Despite the fact that the Carnegie Mellon Survey was administered in 1994, well into the pro-patent regime, the findings for the semiconductor industry were consistent with those reported in the earlier Yale Survey: R&D lab managers ranked patents among the *least* effective mechanisms for profiting from innovation overall and relative to other industries. Instead, semiconductor R&D lab managers emphasized the importance lead-time, secrecy, and superior manufacturing and/or design capabilities as means for recouping returns to R&D investments.

Importantly, the Carnegie Mellon Survey asked follow-up questions about the motives for patenting. Similar to interview evidence in Grindley and Teece (1997), Hall and Ziedonis (2001), and Bhaskarabhatla and Hegde (2014), R&D lab managers from semiconductor firms emphasized the strategic value of patenting for both defensive (reduce litigation risks) and offensive (gain superior access to external rights and know-how) reasons. As Cohen et al. (2000) report, similar views were espoused in other "complex products" industries where the value of a single patent is inherently tied to that of other patented and unpatented technologies.

Contributing more systematic evidence from entrepreneurial firms, the 2008 Berkeley Patent Survey asked CEOs of technology-oriented startups a series of questions about patents (Graham, Merges, Samuelson, and Sichelman 2009). The authors received responses from CEOs of 1,332 companies in the biotechnology, medical devices, computer software, and information technology (IT) hardware industries. Graham et al. (2009) subsume semiconductor startups in the broader "IT hardware" industry, which also includes communications and computer hardware companies. Overall, CEOs from health-related and IT hardware companies ranked patents (along with first-mover advantage) to be among the most important means for "capturing competitive advantage". This emphasis on the importance of patents as means for profiting from innovation for IT hardware startups contrasts sharply with the more lackluster views expressed by larger IT companies represented in the earlier Yale and Carnegie Mellon Surveys.

The Berkeley Patent Survey also asked the CEOs of startups to rank on a 1 ("not at all important") to 4 ("very important") scale which factors drove the decision to seek U.S. patent protection (Graham et al. 2009). The top-ranked reason (at 3.59 on average) was to prevent others from unauthorized use of the invention, which is not surprising. The next-highest reasons were arguably finance-related, including to "improve changes of securing investment" (at 3.30), "to improve changes/quality of liquidity" (3.24), and "to enhance the company's reputation" (3.13). These findings call into question whether patents serve a meaningful signaling function in the market for entrepreneurial financing, as suggested by Long (2002) and tested in Hsu and Ziedonis (2013).

In combination, this survey evidence suggests that patent rights are important for the financing and development of early-staged companies, including semiconductor startups. The survey findings in Graham et al (2009) suggest, however, that software startups may be an exception to this more general rule.

4. Patent Hold-up and Its Resolution

In policy debates, the semiconductor industry is often heralded as a context rife with patent "hold-up" problems (e.g., USFTC 2003, 2011). Given the ongoing controversy surrounding this topic, we elaborate on the fundamental "patent hold-up problem" below and discuss the challenges of measuring such problems directly.

4.1. The Hold-up Problem

In the economics literature, "hold-up" refers to a situation where one party is able to expropriate rents from another typically due to investments specific to a relationship. Hold-up can generate economic inefficiencies that both courts and contracting parties often try to avoid. "Bad" behavior (such as deception) is not required to generate losses of economic surplus, but deception and concealment may magnify the impact of hold-up (Farrell et al. 2007).

The basic idea is that simple market contracts insufficiently safeguard against expropriation when assets cannot be redeployed to the next best use (or user) without significant loss of value (Klein et al. 1978). Asset-specific investments are pervasive. A famous example is the supply of automobile body parts by Fisher to General Motors at the beginning of the 20th century. Fisher Body made investments in machines highly specific to General Motors and of little use to other car manufacturers. These specific investments allowed General Motors to hold-up Fisher by threatening to change suppliers unless Fisher reduced its prices (Klein 1998). A natural way to minimize the hold-up problem is to design contracts prior to making the investment. Even then, "ex-ante" contracts are an imperfect solution given the difficult and cost of covering every contingency. Moreover, some elements of performance cannot be measured or described unambiguously (e.g. the taste of a soft-drink or the effort a contractor puts toward a task).

A large body of literature in "transactions cost economics" shows how this imperfect nature of contracts induces agents to underinvest in areas with high risks of expropriation (Williamson 1985). In these environments, there is also a strong incentive to internalize transactions involving highly specific assets by performing economic activities within a firm instead of relying on the market. In other words, severe risk of hold-up may lead to integration and mergers among firms.

Patent licensing negotiations are a natural setting where the hold-up problem may arise. A valid patent grants a patentee the right to exclude others from using the patented invention. This exclusionary right thus allows the patentee to extract rents through licensing deals from firms using the patented technology. The magnitude of these rents depends on the bargaining power of the patentee, which in turn depends on the timing of investments and the feasibility and costs of ex ante contracting.

The issue of patent hold-up has recently appeared in prominent public debates on patent policy in the US and Europe (National Research Council 2004, US FTC 2011, European Commission 2011). There is substantial agreement among academic scholars and policy makers that the patent system can be a powerful policy tool to increase research and development incentives and to promote follow-on innovation. However, there are growing concerns that patent rights may also be an impediment, rather than an incentive, to innovation if the increasing proliferation of patents and the fragmentation of ownership rights among firms have raised transaction costs and exposed firms to ex-post hold-up through patent litigation (Heller and Eisenberg 1998).

4.2. Hold-up in the Semiconductor Industry

The semiconductor vertical chain includes a large number of production steps. While a variety of companies (e.g., Intel) complete the entire process in-house, other industry players frequently outsource part of their production activities (Turley 2005). At the extremes of the vertical chain spectrum, the "fabless" companies discussed earlier specialize in chip design and "pure-play" foundries manufacture chips without designing them. While most of the semiconductor companies position themselves at intermediate levels of vertical specialization, the industry has moved toward organizational separation of semiconductor design from chip manufacturing (Monteverde, 1995). There are also cases of firms that specialize in the acquisition and licensing of IP such as Rambus and ARM. Others companies like Qualcomm and Xilinx combine licensing with specialized component sales (Simcoe et al., 2009, Serrano, 2010, Galasso et al., 2013).

A key feature of the manufacture of semiconductor devices is the use of "clean rooms," where airborne particles are minimized and temperature, humidity and pressure are strictly monitored. Manufacturing equipment consists of two broad kinds: front-end equipment - installed in clean rooms and used to produce silicon wafers and semiconductor chips - and back-end equipment - used to assemble, package and test the devices (U.S. International Trade Commission 2006). Typically, front-end equipment is installed and arranged to accommodate the production of a specific semiconductor device. Because minor changes in clean room operations may impact the sensitive equipment and result in product damage, reconfiguring front-end equipment to accommodate changes in product manufacturing is very expensive, to the extent that construction of a new fabrication facility is often a cheaper alternative (Turley 2005; Theron et al. 1999).

Fabrication facilities are not only expensive but also have a short lifespan. By 2006, for example, a typical new manufacturing facility had an economic life of about three years and cost $3 billion (SIA, 2006). In addition, there is a steep learning curve associated with the production of semiconductor devices (Macher and Mowery 2003). Most of the chips produced during the first weeks of operation of a new fabrication facility are usually damaged. Over time the quality of the production improves, but it may take more than twelve months of non-stop operations to have production yields above 90 percent (Turley, 2005).

In short, clean rooms and front-end manufacturing equipment are difficult to redeploy, expensive and involve steep learning curves. These characteristics of the semiconductor industry imply that halting or altering production processes will be more costly for firms that own and operate manufacturing facilities compared to firms that do not own such facilities. In turn, this explains why patent litigation and preliminary injunctions are viewed as more costly by firms with large investments in fabrication facilities. This idea is supported by the findings of Hall and Ziedonis (2001), Ziedonis (2004) and Galasso (2012) that document how capital intensive semiconductor firms tend to react to the risk of patent litigation by amassing large patent portfolios to improve their ex-post bargaining position in the event of settlement negotiation.

These features of the semiconductor manufacturing environment exacerbate the risk of hold-up for firms working in the industry. To see this, consider - as in Ziedonis (2004) - the problem of a semiconductor firm. Suppose the manufacturer could easily invent around a patent at the initial stages of the production process (e.g., while designing new chips or when specifying the layout of new fabrication facilities). In this case, the licensing fees the patentee could obtain from the firm would be small, ex ante, because of the manufacturer's ability to invent around the patent (Levin et al. 1987; Teece 1986). The bargaining power of the manufacturer would be far weaker, however, if it learns about the patent after embedding the technology in designs or production processes that are expensive to redeploy. At this stage, these investments specific to the patented technology allow the patentee to extract more rents from the firm since the cost to invent around the patent is much larger at this point.

To illustrate more formally how the hold-up problem can affect licensing negotiations for semiconductor firms, consider the following stylized model. There is one firm with production facilities generating product market profits equal to V. A patentee holds a patent that the firm is allegedly infringing. In the absence of a license agreement, the parties resolve the dispute in court, each incurring a litigation cost of L. We assume that the court will find the patent infringed with probability ρ. If the patent is found infringed, the infringing firm sustains a loss equal to K to halt the production and design around the infringed patent. Let us indicate the profits of the firm in case of litigation as:

$$\pi^{Lit} = V(1-\rho) - \rho K - L = V - \rho(K+V) - L.$$

Now consider the licensing option. If we indicate with f the (fixed) licensing fee requested by the patentee, the profits of the licensee will be:

$$\pi^{Lic} = V - f.$$

From the above formulas it follows that the maximum license fee that will be accepted by the licensee—the fee that renders the licensee indifferent between accepting or rejecting the offer—is equal to:

$$f = \rho(K + V) + L. \tag{1}$$

Equation (1) highlights a variety of features that determine the outcomes of licensing negotiations in the semiconductor industry. First, it shows that the rents that can be extracted by patentees are larger, the larger the cost of litigation of the alleged infringer, L. Intuitively, this suggests that firms that have a comparative advantage in litigation (e.g. because of "deeper pockets" or access to superior legal counsel) will be able to access technologies at better terms. One may expect small firms to have a larger value for L. Lerner (1995) provides evidence that small firms avoid investing in technology fields where the threat of litigation from large firms is high. Lanjouw and Lerner (2001) show that the use of preliminary injunctions by large firms can discourage small firm innovation. Simcoe et al (2009) illustrate how small private firms are particularly litigious after disclosing their patents to standard setting organizations. Finally, Lanjouw and Schankerman (2004) show that the probability of being involved in a suit is higher for patents owned by small firms than for patents owned by large firms.

A second intuitive insight from equation (1) is that the licensing fee depends on the strength of the patent, ρ. Such parameter implies that a strengthening of patent protection, as the one experienced in the 1980s with the establishment of the Federal Circuit, is likely to have increased the cost of accessing patented technology and the rent extracted by patentees. Third, the fee is larger for technologies generating greater profits in the product market, V.

Finally, equation (1) shows that the licensing fee is likely to be larger the greater the cost of halting production, *K*. This idea is consistent with the interviews summarized in Hall and Ziedonis (2001) and Ziedonis (2004): losses incurred when halting or altering production processes are more detrimental for firms investing intensively in product-specific manufacturing facilities. Notice that when investments in clean rooms and front-end manufacturing equipment are substantial (i.e. K is very large), the patentees can extract a large rent holding-up the alleged infringer even when the patent protecting the technology is weak (i.e. ρ is small).

A related stream of transactions-costs research emphasizes that hold-up problems may also surface due to fragmented ownership rights (Heller and Eisenberg 1998). This literature suggests that granting "too many" exclusionary rights to "too many" parties can reduce the use of economic resources. In the patent context, this view implies that bargaining failure can arise when a technology user requires licenses from numerous disparate patentees. In this case, uncoordinated negotiations among the parties can generate 'royalty stacking' that reduces the licensee's profit and, in extreme cases, can prevent downstream development (Heller and Eisenberg 1998; Lemley and Shapiro 2006; Galasso and Schankerman 2010).

To clarify the point, consider a hypothetical example of a semiconductor firm that is considering an investment of $10 billion in a new fabrication facility. Assume the manufacturer identifies 1,500 patents potentially infringed in the design or manufacture of its products and is still unsure of the effective scope and validity of those patents. Will the investment in fabrication facility take place?

For simplicity, consider two extreme scenarios. In Scenario 1, one firm owns all the patents. In scenario 2, the patents are assigned to 1,500 different patentees. If patent negotiations are costless, as in a Coasian setting with zero transactions costs, ownership of patent rights would not matter and the fabrication facility investment would take place as long as it is efficiency-enhancing (Coase 1960). But once we assume nontrivial transactions costs, there are substantial differences in the bargaining environment across the two scenarios that may influence the investment decision of the firm. As explained in Ziedonis (2004), in scenario 2 the costs and potential delays involved in bargaining <u>sequentially</u> with a large number of fragmented rights holders may render patent negotiations infeasible for the manufacturer. In other words, the costs and potential delays associated with patent negotiations depend on the concentration of ownership of rights and the 'industrial organization' of the technology field (Galasso and Schankerman 2015a, 2015b).

4.3 Empirical Evidence of Hold-up

Despite the substantial theoretical work developing the idea of patent hold-up and characterizing settings where the problem is likely to be more pervasive, an empirical analysis of patent hold-up is inherently challenging. Ideally, the researcher would like to observe the details of patent licensing negotiations, including the ex-ante alternatives, the rents extracted by the patentee as well as the specific investments made by licensees/infringers. These data are typically unavailable since both the terms of patent licensing agreements and the details of negotiations leading to a contract are kept confidential[5]

Moreover, the fear of patent hold-up may lead firms to vertically integrate, avoid innovation investments, or design institutions such as patent pools or FRAND commitments to mitigate the problem. These strategic responses in turn affect the licensing data available to researchers.

4.3.1 Patent Litigation

The challenges involved in collecting direct evidence of patent hold-up lead the law and economics literature to study indirect evidence of the problem. The most common approach has been to collect data on patent disputes and their resolution. Litigation and delays in the settlement process would typically be associated with hold-up and high transaction costs for the negotiating parties.

Ziedonis (2003) provides the first comprehensive analysis of patent cases filed in U.S. District Courts and the U.S. International Trade Commission (USITC) from January 1, 1973, through June 30, 2001, that involve 136 dedicated U.S. semiconductor firms as defendant or

[5] Anand and Khanna (2000) discuss the scarcity of licensing data and contrast it with data availability in other areas of economics.

plaintiff. Sample firms include the universe of publicly traded U.S. firms during 1973-2000 that either (a) list semiconductors and related devices (SIC3674) as their primary line of business or (b) were identified by industry sources as dedicated U.S. semiconductor firms. In 2000, sample firms collectively generated over $88 billion in revenues, spent $12 billion in R&D, and had been awarded roughly 31,000 U.S. patents. The sample does not include non-U.S. firms (e.g., Samsung, or Siemens) and large U.S. "systems" manufacturers (e.g., IBM or AT&T) because it is not possible to identify R&D investments targeted to semiconductor technologies for these large diversified companies.

The empirical analysis follows over time this sample of semiconductor firms and focuses on the patent acquisition and enforcement histories at the level of individual firms. This approach allows examining changes in the litigation propensity of firms over time. The sample includes both semiconductor "manufacturers" (i.e., firms like Intel, Texas Instruments, and Micron Technologies, which design and manufacture the majority of their products in-house) and "design" firms (i.e., firms like Altera, Xilinx, and SonicBlue). Even though most of the design firms in the sample commercialize and sell products of their own, they are typically much smaller in size (in terms of number of employees or sales revenues) than manufacturing companies in the sample and they invest more heavily in R&D.

Several interesting albeit descriptive trends emerge from this study. First, the analysis shows that roughly 56 percent of the sample firms are involved in at least one reported patent case filed in U.S. District Courts and the USITC between January 1, 1973, and June 30, 2001. On average, semiconductor firms involved in patent cases tend to be larger (in terms of sales or number of employees), invest more in R&D (in absolute terms and per employee) and own larger patent portfolios than semiconductor firms not involved in patent litigation during the sample period.

Second, the data show a sharp increase in the number of annual cases filed involving semiconductor firms around the mid-1980s that continued throughout the 1990s. This trend suggests that legal disputes over intellectual property became more common in semiconductors— despite the widespread use of cross-licenses in this industry. More importantly, while the litigation rate per R&D dollar increased dramatically in the semiconductor industry during 1986-2000 from that in the preceding decade (by as much as 93 percent), the number of cases filed per 1,000 patents slightly declined between the two periods.

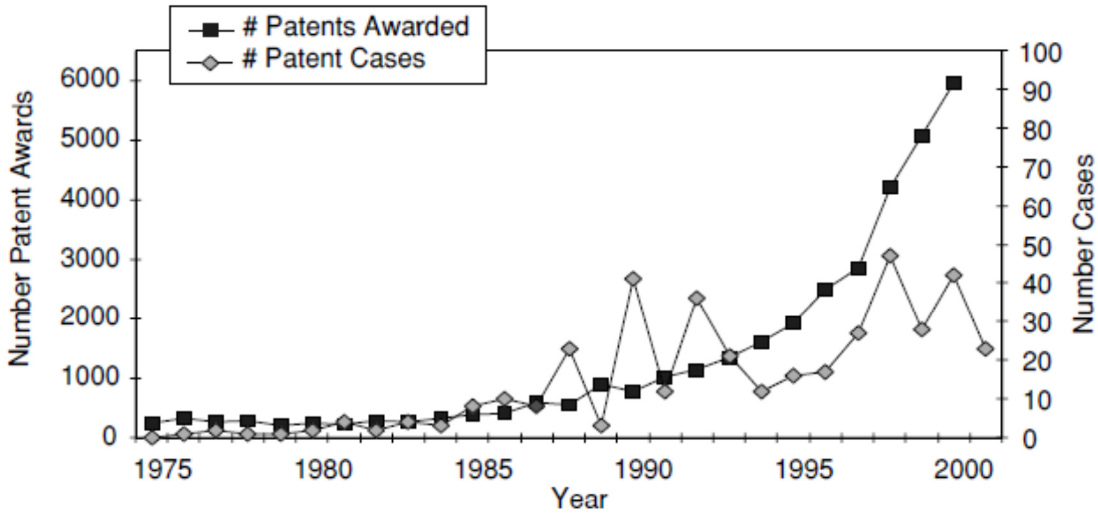

FIGURE 3 Number of annual patent awards v. patent case filings (U.S. semiconductor firms, 1973-2001).

This asymmetric effect is driven by the dramatic rise in patenting by semiconductor firms since the mid- 1980s because of the "patent portfolio races" of U.S. semiconductor manufacturers documented in Hall and Ziedonis (2001). The figure above (from Ziedonis, 2004) provides evidence of this impressive growth in patenting.

Finally, the paper shows that the average litigation rate of specialized design firms in the sample is high and is more than twice that of manufacturers in the sample. On average, semiconductor manufacturers litigate with a more diverse set of parties and enforce patents that are almost 4 years older than the average patent in their portfolios. In contrast, design firms typically litigate against other design firms and enforce patents that are roughly the same age as the average patent in their portfolios.

Somaya (2003) studies the determinants of patent litigation and settlement in a sample including firms from two distinct industries: research medicine (which includes biotechnology, drug delivery systems, assays, and dental innovations) and technology research (which includes semiconductors, data storage, computer systems, I/O devices, computer applications and networking technologies). His analysis provides evidence of substantial differences between litigation in the technology sector and medical research in the period 1983-1993. The paper shows that the litigation propensity is consistently lower for research medicine patents compared to technology patents. In the technology sector, patent cases are more likely to include more than one patent, and counter-suits are much more frequent. Finally, litigation involving individual inventors is more likely in the technology sector, whereas litigation by universities is less likely.

Taken together, the results in Somaya (2003) are consistent with the idea that patents have different uses across industries. The evidence for the semiconductor field, in which the propensity of countersuits is very high, suggests that mutual hold-up between firms is quite frequent in this sector.

Galasso and Schankerman (2015a) exploit patent litigation at the Court of Appeal for the Federal Circuit to quantify the extent to which patent rights impede the cumulative innovation process, and to identify whether their impact differs across technology fields and firms. To study empirically the impact of patent protection on innovation incentives is challenging for two reasons. The first problem is that comparable technologies with and without patent protection need to be identified. The second issue is that it is hard to measure innovation activity related to a specific patent. To address these problems, Galasso and Schankerman (2015a) exploit patent invalidation cases litigated at the US Court of Appeal for the Federal Circuit. Their dataset comprises 1357 Federal Circuit decisions from 1983 to 2008, with information on whether each patent was invalidated. About 40% of the decisions in their sample are associated with loss of patent protection for the technology.

To estimate the effect of patent rights on follow-on innovation, Galasso and Schankerman (2015a) look at citations received by patents in a five year window following the Federal Circuit decision and compare those invalidated with those which are upheld. Measuring cumulative innovation with citations by later patents is a common practice in the economics of innovation literature where a large number of empirical studies exploit citations as a way to trace knowledge spillovers (see Griliches 1992 for a survey). It is important to note that citations can either under- or over-estimate the extent of follow-on innovation. This happens when inventors develop improvements that are not patented (or patentable), or when a citing inventor does not actually build on a cited patent. While using product level information is clearly desirable, citations are often the only practical measure for studies that cover a wide range of technology fields.

A fundamental challenge with litigation data is that invalidated patents may differ from not-invalidated patent and that such differences may also affect patent citations. For example, a positive shock to the commercial value of the underlying technology may increase citations to a patent and, at the same time, induce the patentee to invest heavily in the case to avoid invalidation. It is crucial to address this 'endogeneity' issue in order to test whether the impact of patent protection on cumulative innovation is causal.

The empirical strategy followed by Galasso and Schankerman (2015a) exploits the fact that judges are assigned to patent cases through a computer program which randomly generates three-judge panels. Essentially, their empirical methodology is equivalent to comparing citations received after Federal Circuit decisions by patents that are invalidated because they were randomly assigned to judge panels with high propensity to invalidate with citations received by similar patents that are not invalidated because they were randomly assigned to judge panels with low propensity to invalidate. In conducting this exercise, they also control for a number of confounding factors such as the age of the patent, the technology field and the number of citations received before the Federal Circuit decision.

Galasso and Schankerman (2015a) find that patent invalidation is followed by a 50% increase in subsequent citations to the litigated patent, on average. This evidence suggests that, on average, patents block follow-on innovation. More importantly, they also show that the impact of patent invalidation differs substantially across broad technology areas. Their empirical analysis shows that patent invalidation has a large and statistically significant impact on cumulative innovation in the fields of semiconductors, computers and communications, electronics, and medical instruments. However, they find only a small and statistically insignificant effect in the chemical, pharmaceutical, or mechanical technology field. Moreover, they find that the impact of invalidation is predominantly driven by the invalidation of patents owned by large firms, which increases the number of small innovators subsequently citing the focal patent. This suggests that invalidation of a particular patent is unlikely to affect strategic interaction between large semiconductor firms, but it may affect innovative investment by small entrepreneurial firms.

In a companion study, Galasso and Schankerman (2015b) study the impact of patent invalidation on subsequent innovation and exit by the patent holder. They show that patent invalidation leads to a 50 percent decrease in patenting by the patent holder, on average, but the effect is entirely driven by small innovative firms in technology fields where they face many large incumbents. In addition, the loss of patent rights significantly increases the likelihood of exit for small firms.

The findings in Galasso and Schankerman (2015a; 2015b) help understanding the role of patents in the semiconductor industry. They support the idea that semiconductor firms face patent hold-up and that the economic trade-offs generated by patents in this industry are different from those faced by firms in other innovation environments. Moreover, these two studies show that patent rights affect innovation by small and large firms very differently.

4.3.2 Hold-up in Semiconductor Standard Setting

In a variety of industries compatibility standards outline key technical criteria for shared technology platforms. Compatibility standards define key formats and interfaces for shared technology platforms (Simcoe 2012). By coordinating firms toward technological specifications, standards generate a variety of economic benefits (Shapiro, 2001). First, by reducing incompatibility problems, standards increase users' willingness to pay for a technology. Second, by attracting a greater number of users compatibility standards generate incentives to entry and innovate in the technology space.

Standard Setting Organizations (SSOs) are forums where interested companies see consensus and endorse specific technologies to develop industry standards (Simcoe 2012). SSOs play an important role in semiconductors where compatibility and interoperability induce coordination in choice of components, packaging, test methods and materials. The

Joint Electron Device Engineering Council (JEDEC) founded in 1958 is the most prominent organization developing standards for semiconductor devices.

In principle, the risk of hold-up can be substantial when SSOs include patented technologies in a standard. Before an industry standard is chosen, the bargaining power of a patentee is quite weak because SSOs compare alternative technologies that have the potential of becoming a standard. After the adoption of a standard, alternative technologies become less attractive and patents covering the standard become much more valuable. The change in patent value may induce members of standard committees to withhold information about their patent applications when they vote for the inclusion of technologies in a standard. The magnitude of these inefficiencies is at the center of a recent growing literature on patent hold-up in standard settings. Research on the topic has been primarily theoretical and provides contrasting views on the severity of the problem. At the heart of these divergent opinions, there is the inherent difficulty of conducting empirical research on patent hold-up and the confidentiality of licensing deals.

Epstein, Kieff and Spulber (2012) argue that private solutions implemented by SSOs (such as licenses, reputation through repeat play and RAND commitments) are likely to curb substantially the severity of patent hold-up problems. Intuitively, because the objective of SSOs is to maximize the market success of commercial standards, they are likely to take actions to limit potential threats of hold-up. For example the Institute of Electrical and Electronics Engineers Standards (IEEE) has been very proactive by clarifying and strengthening the FRAND licensing commitments it requires from participants.

Other scholars have come to different conclusions. Among others, Farrell et al. (2007), Lemley and Shapiro (2013) and Lerner and Tirole (2014) propose regulatory actions arguing that market mechanisms are not sufficient to alleviate the negative impact of patent hold-up on innovation incentives. These papers are motivated by anecdotal evidence from companies such as Wang Laboratories and Rambus that have been found guilty of deceptive actions as members of JEDEC. In Wang Labs, Inc. v. Mitsubishi (2007) the Federal Circuit asserted that Wang, by failing to disclose to JEDEC its patent applications, created an implied license from Wang to Mitsubishi to practice the invention. In Rambus v. FTC (2006), the FTC found Rambus guilty of monopolization for not revealing its patent applications while a member of JEDEC.

These studies show that strategic deception by patent holders not only impacts the licensing process, but can also generate antitrust concerns and harm competition. In discussing remedies to restore competition and compensate injured parties, these papers emphasize that the focus should be the increment to market power compared to the competitive environment that would have appeared with an open and well informed technology competition. This line of research spurred various actions taken by courts and policy makers to mitigate the concern of patent hold-up in complex industries (Shapiro, 2016). First, in a 2006 landmark case the Supreme Court greatly reduced the threat of patent hold-up by limiting the availability of injunctions to patent holders (*eBay Inc. v. MercExchange, L.L.C., 547 U.S. 388, 2006).* Second, in *Ericsson v D-Link* the Court of Appeals for the Federal Circuit clarified that the determination of "reasonable royalties" for patents essential to a standard should reflect the ex-ante incremental value of the technology (i.e. prior to its inclusion in the standard).

4.4 Hold-up Resolution: Licensing and Cross-Licensing

The high risk of unintentional infringement in the semiconductor industry induces firms to develop IP strategies aiming to mitigate the risk of being held-up and halting production. One way to reduce hold-up risk is to enter a license agreement "ex-ante", or before investments in new manufacturing facilities or product designs take place.

Siebert and von Gravenitz (2010) provide empirical evidence of ex-ante licensing strategies in the semiconductor industry. The authors compile a dataset of licensing contracts involving semiconductor companies signed between 1989 and 1999. They obtain this information from Thompson Financial and other publicly available sources such as business reports, filings published in the National Cooperative Research Act, and announcements made in the public press. The data, summarized in Table 1 below, show that licensing remains widespread in the semiconductor industry.[6]

Table 1
Number of licensing contracts and patents (1989–1999).

Year	Licensing	Ex ante licensing	Ex post licensing	Semiconductor patents
1989	43	22	21	4,063
1990	74	38	36	4,521
1991	110	83	27	5,276
1992	115	77	38	5,313
1993	117	86	31	5,688
1994	135	103	32	7,554
1995	85	58	27	9,250
1996	34	22	12	10,390
1997	67	40	27	13,507
1998	37	12	25	13,080
1999	30	8	22	12,624
Total	847	549	298	91,266

The table displays the total number of licensing contracts as well as ex ante licensing and ex post licensing contracts signed between semiconductor firms (Data source: Thompson Financial). The table also shows the number of semiconductor patents filed (Data source: NBER database). Note that the technological classes defining the semiconductor industry are mentioned in the text.

After examining the details of each licensing contract, the authors manually classify each deal in an 'ex-ante' or 'ex-post' contract. Their data show that ex-ante agreements are much more common than ex-post deals. Moreover, while the frequency of ex-post deals appears constant during the sample period, ex-ante contracts follow an inverse-U shape over time with a peak in the mid-90s. Siebert and von Gravenitz (2010) also find that ex-ante licensing deals between two firms are more likely when firms have high technological similarity (measured exploiting cross-citations of patents of the two firms).

A special case of ex-ante deals are cross-license contracts, which are bilateral agreements in which two firms choose not to enforce intellectual property rights against each other. Galasso (2012) studies broad cross-licensing deals that are agreements covering the entire patent portfolios or patents in some extensive technology class. Broad cross-licensing is a common IP strategy in industries like computers and semiconductors, where products combine many patentable technologies and where it is easy to unintentionally infringe on a patent (Grindley and Teece 1997; Shapiro 2001). Press releases and companies' annual reports clearly reveal that broad cross-license deals are indeed widespread in the industry. Galasso (2012) shows that, of the ten semiconductor companies with the largest R&D expenditure in the period 1990-1995 (carrying out more than sixty percent of the R&D

[6] Many licensing deals are not disclosed by firms, so these data may under-estimate the market for technology in the industry.

expenditure of the industry), eight entered at least one cross-licensing deal between 1990 and 2000.

To illustrate the economic incentives that lead to broad cross-licensing, Galasso (2012) develops a game theoretical model in which two firms are involved in a series of infringement disputes. In the absence of a broad cross-license agreement, these disputes are litigated and the infringing firm stops producing if the court finds it liable. The cost that a firm sustains when halting production increases with its capital intensity. Firms negotiate cross-licensing contracts through a bargaining procedure in which they learn the value of each other patent portfolios.

The Galasso (2012) model shows that both the decision to cross-license and the timing of the agreement depend crucially on firms' capital intensities. Specifically, it shows that two firms will sign a cross-license agreement only if their capital intensities are large enough. The intuition for this result is the following. A broad cross-license agreement is costly to a firm because it involves sharing patented technologies with a rival firm. On the other hand, a firm benefits from such a cross-license because it avoids the loss associated with discontinuing production. Because this benefit increases with firms' capital intensities, a cross-license agreement is profitable only for firms with high capital intensities. In addition, the model predicts that broad cross-license negotiations will have shorter duration for firms with high capital intensities and for firms facing a low frequency of infringements. This occurs because firms have an incentive to delay the agreement in order to obtain additional information on the value of the rival's patent portfolio. However, waiting is costly because it involves litigation that is particularly detrimental for firms with high capital intensities. Finally, the model predicts greater broad cross-license agreements between firms with complementary technologies in their patent portfolios.

Galasso (2012) tests the predictions of the model using a unique dataset that combines information on broad cross-license agreements and patent litigation in the semiconductor industry. Specifically, the sample includes 218 publicly traded U.S. firms whose principal line of business is semiconductors and related devices (SIC 3674), for which Compustat has data for at least three years between 1985 and 2005. Broad cross-license contracts were identified from the SEC annual filings (10-K) and company press releases.[7]

The empirical findings are consistent with the theoretical model and can be summarized as follows. First, high capital intensity increases the likelihood that firms will sign broad cross-license agreements and decreases the duration of licensing negotiations. Second, broad cross-license agreements take longer to negotiate when firms patent in similar technology areas. Finally, the analysis shows that firms are more likely to enter broad cross-license agreements when their patent portfolios are complementary, as indicated by a high frequency of cross-citations between the patents of the two firms.

Harhoff, von Gravenitz and Wagner (2015) study challenges to patent validity as a strategy to mitigate the risk of hold up. Their analysis uncovers the public good nature of patent invalidation. That is, invalidation reduces the risk of hold-up not only for the firm that litigated the patent, but also for all firms operating in the technology space covered by the invalidated patent. This positive effect on competing firms reduces the incentives to challenge patent validity especially in a crowded technology area as semiconductors. Using data on opposition against patents at the European Patent Office, Harhoff, von Gravenitz and Wagner (2015) show that in fields with a large number of mutually blocking patents the incidence of opposition is sharply reduced, particularly among large firms.

5. Conclusion

The past fifty years have witnessed remarkable improvements in the speed, size, and power of semiconductor devices, providing a vital underpinning for the modern information economy. Both before and after fundamental shifts in U.S. patent and antitrust policies during the 1980s, semiconductor companies devised ways to move the technological frontier forward. It might be tempting to conclude from this fact that patent rights fail to shape technological progress in this industry. Overall, the empirical evidence is at odds with this

[7] For example Micrel Inc.'s 10-K filing for 2003 states that "on May 23, 2002, the Company entered into a Patent Cross License and Settlement Agreement with National Semiconductor which settled all outstanding patent disputes between the companies and cross licensed the entire patent portfolio of each company."

view. Instead, the evidence calls for a more nuanced interpretation: even within a single industry, patent rights play multi-faceted roles that can alter the innovative activities of firms. Within this industry, the ability to secure strong and enforceable protection for patented inventions seems particularly important for new companies that rely on external sources of financing and for smaller firms. Although patent "hold-up" is difficult to observe directly, indirect evidence and interview insights suggest that capital-intensive firms in the industry are particularly vulnerable to such problems. These companies also, however, find ways to help mitigate such problems, whether through increasing their bargaining positions with larger portfolios of patents, through ex-ante licensing and cross-licensing agreements, or through participation in standards-setting organizations.

There are several useful directions for further research on patent rights and innovation in the semiconductor industry. First, more empirical and survey evidence on the actual timing and structure of patent licensing negotiations would be extremely useful in assessing the impact of patent thickets, royalty stacking and hold-up on technology diffusion and innovation incentives. Second, there is the need for an investigation of patent assertion entities operating in the semiconductor space. Specifically, it would be very valuable to understand whether non-practicing firms play a key role as patent intermediaries or, instead, they exacerbate hold-up problems through patent-trolling behavior. Third, the recent decades have witnessed an internationalization of the semiconductor production process that currently spans many countries (Breznitz, 2005). Exploring the link between international patent law and global fragmentation of the semiconductor manufacturing and commercialization process is a promising avenue for future research.

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