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The many faces of absorptive capacity: spillovers of copper interconnect technology for semiconductor chips

Kwanghui Lim

A case study of copper interconnect technology suggests that absorptive capacity exist in three forms: disciplinary, domain specific and encoded. Each involves different ways of managing R&D and linking internal to external research. Disciplinary absorptive capacity requires a firm to actively engage with the scientific community, while protecting domain-specific knowledge. Domain-specific absorptive capacity depends upon influencing disciplinary research at universities and consortia, then capturing domain knowledge through collaboration and hiring. As technology develops, it becomes encoded, and absorption depends increasingly upon integrating knowledge from suppliers. Hence, absorptive capacity is a multifaceted construct that is heavily shaped by the type and maturity of technology absorbed.

1. Introduction

Knowledge spillovers are important to the productivity of firms (Jaffe, 1986) and to economic growth (Romer, 1990; Griliches, 1992). Cohen and Levinthal (1990) propose that firms can strategically invest in activities that increase their ability to absorb external knowledge. "Absorptive capacity" has become an important and influential theoretical construct, but questions remain about its validity (Lane *et al.*, 2006): while it has become the building block for over 900 academic studies, the nature and determinants of absorptive capacity remain unclear.

In this article, I propose that three forms of absorptive capacity exist: *disciplinary*, *domain specific* and *encoded*. They allow a firm to capture different knowledge types, respectively: general scientific knowledge, solutions to specific technical problems, and knowledge embedded in tools and processes. Each involves different ways of managing a firm's internal R&D and how it links externally. Disciplinary and domain-specific absorptive capacity are needed during the early stages of R&D, while encoded absorptive capacity is applicable at a later stage. Over time, firms may rely upon one or more of these approaches, but it is difficult for a firm to develop disciplinary and domain-specific absorptive capacity simultaneously, as these depend upon divergent organizational practices and incentives.

This conceptualization of absorptive capacity is generated inductively from a case study tracing the diffusion of copper interconnect technology for semiconductors. These "interconnects" refer to conductors through which electricity flows between various circuit elements on a semiconductor chip. The use of copper instead of aluminum for on-chip interconnects is an important innovation. Features of this technology offer a rare glimpse into how firms developed different kinds of absorptive capacity and how they attempted to capture external knowledge.

The main contribution of this article is in offering a better understanding of absorptive capacity. In doing so, it attempts to break the reification of absorptive capacity (Lane *et al.*, 2006), clarifying the different types and mapping each to distinct organizational capabilities and ways in which the firm manage external linkages.

The next section of this article reviews prior research and describes the three forms of absorptive capacity. Section 3 describes the research setting and methodology. Section 4 traces the development of copper technology to illustrate each kind of absorptive capacity in action. Section 5 discusses the key lessons learnt from the case and presents several propositions. Section 6 concludes.

2. Knowledge flows and absorptive capacity

Nelson (1959) and Arrow (1962) characterized knowledge as having the features of a durable public good. The knowledge produced through the R&D of an innovator is easily "borrowed" by another party without compensating the former. The innovator cannot appropriate the marginal value of the knowledge it produces and therefore underinvests in its production, relative to the social optimum.

Departing from the view that knowledge spillovers are easily acquired, Cohen and Levinthal (1990) propose that knowledge spillovers come at a cost to the recipient. Firms must invest resources in order to absorb knowledge spillovers. While Cohen and Levinthal note that various mechanisms exist for building absorptive capacity, the one they emphasize is a firm's prior related R&D. According to Cohen and Levinthal (1990: 135), this relationship between R&D and absorptive capacity arises because knowledge is hard to codify (or tacit) and embedded in the routines of the organization. Thus, R&D has two "faces", or separate roles: it increases a firm's productivity and its absorptive capacity.

There is broad empirical support for the concept of absorptive capacity. Jaffe (1986: 993) found that the interaction between a firm's R&D expenditure and spillovers is strongly correlated with the firm's performance. Additional evidence is offered by Gambardella (1992), Henderson and Cockburn (1996), Arora and

Gambardella (1994), and Zucker and Darby (1995). Absorptive capacity has made a significant impact on theoretical research, with scholars using it as a building block to understand knowledge flows (Szulanski, 1996; Von Krogh and Roos, 1996; Reagans and McEvily, 2003), strategic alliances (Ahuja, 2000), R&D cooperation (Cassiman and Veugelers, 2002), and other areas (Lane *et al.*, 2002 present a review).

Over time, greater attention has been placed on the role of external linkages in building absorptive capacity. A firm's connectedness to external sources of public and private knowledge can help it to acquire knowledge from those sources (Zucker and Darby, 1995; Powell *et al.*, 1996; Cockburn and Henderson, 1998; Todorova and Durisin, 2007). But exactly how does this fit into the framework presented by Cohen and Levinthal? Does the management of external linkages depend upon the type of knowledge being absorbed, and how does it align with the firm's internal management of R&D? A view is emerging that such relationships are path dependent and deeply affect a firm's ability to balance between exploiting existing new knowledge and exploring new areas (Lavie and Rosenkopf, 2006).

Despite its growing importance as a conceptual building block, there has been little theoretical development concerning absorptive capacity itself. Zahra and George (2002) raise concerns about the weak assumptions and inconsistent definitions underpinning the concept of absorptive capacity. While surveying two decades of research in this area, Lane *et al.* (2002) point out that the literature has placed "little attention to the actual processes underlying absorptive capacity." There have been notable exceptions. Lane and Lubatkin (1998) propose the concept of "relative absorptive capacity," in which the efficiency of knowledge absorption between two firms depends upon their degree of similarity and familiarity with one another's practices. Van Den Bosch *et al.* (1999) suggest a coevolutionary framework, providing valuable insights into how absorptive capacity varies according to environmental stability and organization forms. But apart from these studies, we know surprisingly little about absorptive capacity.

The main factor impeding theoretical research is that absorptive capacity is frustratingly difficult to observe. How indeed does one observe a firm in the process of absorbing external knowledge, let alone account for its stock of prior relevant research? Hence, extant theories are often based on deductive rather than inductive logic. Even in empirical studies, absorptive capacity is often not observed directly, but *assumed* to increase with coauthoring behavior, labor mobility, and R&D investment. Because the actual flow of ideas is often hard to trace, it is difficult to separate the "two faces of R&D." Thus, in most studies, it remains unclear whether successful firms were better at capturing spillovers, or whether they were simply more productive at R&D than their rivals.

This article attempts to clarify these theoretical issues by examining a particular technology for which it is possible to account for knowledge flows, along with each firm's attempts at prior R&D and its efforts to access external knowledge. As discussed in Section 3.2, the ability to observe these activities hinges crucially upon features of the technology itself, as well as the combination of qualitative and quantitative research techniques employed.

2.1 *Three distinct types of absorptive capacity*

Before delving into the specifics of the case study, it is convenient to present the typology that emerges from its interpretation. Three distinct types of absorptive capacity appear to exist: disciplinary, domain specific and encoded. These are summarized in Table 1 and discussed in more detail in Section 5. Disciplinary absorptive capacity involves acquiring raw scientific knowledge in key scientific disciplines, and converting that knowledge into a form that is useful for solving practical problems. Domain-specific absorptive capacity refers to the ability to acquire knowledge directly related to solving those problems, so as to produce commercially useful innovations. Finally, encoded absorptive capacity refers to a firm's ability to absorb knowledge that is already embedded in tools, artifacts, and processes.

Disciplinary absorptive capacity is relevant in the early stages of a technology, during which the relevant technical knowledge is tacit and uncertain. Domain-specific absorptive capacity becomes useful at an intermediate stage of development, as solutions to technical problems become more readily available. As the technology matures, knowledge becomes increasingly embedded in tools and processes, and encoded absorptive capacity gains importance. This perspective is consistent with the evolutionary approach suggested by Van Den Bosch *et al.* (1999).

As is discussed in Section 5, I propose that each type of absorptive capacity relies upon different ways of managing internal R&D, as well as different approaches to linking internal and external R&D. To build disciplinary absorptive capacity, a firm

Table 1 Types of absorptive capacity

	Disciplinary	Domain specific	Encoded
Type of knowledge acquired	General scientific knowledge	Solutions to specific technical problems	Knowledge embedded in tools and processes
Stage of technology	Very early	Early to intermediate	Late
Internal R&D	Exploratory (with a focus on autonomy)	Focused R&D	Integration
Linking internal to external R&D	Hire discipline-trained scientists, develop ties with the academic community, encourage scientific publications	Hire people with domain-specific skills, fund external R&D in specific areas, influence the trajectory of external R&D	Collaborate with suppliers possessing the relevant embedded knowledge

must hire scientists who are trained in various scientific disciplines and offer them autonomy to explore possible solutions. The firm has to establish credibility within the academic community (Zucker and Darby, 1995) and actively publish in scientific fields (Cockburn and Henderson, 1998). By comparison, domain-specific knowledge depends upon a combination of approaches, including funding R&D at universities, hiring graduate students from those projects, building strong ties with R&D consortia, and hiring individuals possessing domain-specific skills from other firms (especially those investing in disciplinary absorptive capacity). In order to absorb domain-specific knowledge, a firm does not have to perform as much internal R&D as for disciplinary knowledge; however, the R&D that it performs has to be focused. This helps improve the efficiency of knowledge transfer (Lane and Lubatkin, 1998). Such tuning is less crucial when absorbing disciplinary knowledge, which is of a more general form. As for encoded knowledge, it relies upon integrating relevant knowledge from suppliers and partners that possess that knowledge and have an incentive to profit from disseminating it.

3. Method and data

I conducted an in-depth case study to trace knowledge flows of an important semiconductor technology: copper interconnects. The semiconductor industry is a major one, with shipments worth $227 billion in 2005.[1] Knowledge spillovers are pervasive in this industry (Mowery, 1983; Appleyard, 1996). Much of this knowledge is tacit and deeply embedded in organizational processes. Designing and manufacturing a semiconductor chip involves a great deal of judgment that is difficult to codify. The manufacturing process itself is horrendously complex and requires almost perfect coordination among hundreds of intricate and interrelated steps, each subject to variability from human operators and minor details in the manner and sequence in which it is performed. In short, the semiconductor industry depends upon complex, embedded knowledge. These are the conditions under which prior relevant R&D should enhance absorptive capacity.

A significant recent innovation in the semiconductor industry is the development of copper interconnects to replace aluminum. IBM was largely responsible for creating this technology, devoting three decades of research and millions of dollars. As the semiconductor industry moves to smaller devices, the use of copper will become increasingly important because of its superior electrical properties compared with aluminum. On the day when IBM announced its success at creating this technology in September 1997, its stock price jumped 5%.[2] A year later, the

[1]Source: Semiconductor Industry Association (https://www.sia-online.org/downloads/shares.pdf).

[2]A 5% increase in IBM's stock price in 1997 corresponded to an increase in market capitalization of around $5 billion (source: analysis of CRSP data).

technology went into production and IBM's stock rose an additional 6%. By 2002, approximately two-thirds of semiconductor companies were producing copper-based chips.[3]

3.1 Combining qualitative and quantitative techniques

A case study approach allows me to trace specific ideas that various firms "borrowed" from each other, and from other sources. Spillovers are by nature difficult to observe, so large-scale empirical studies often have to *infer* that spillovers actually occurred. By tracing the actual flow of ideas, this article offers an "inside-the-black-box" view, instead of assuming that spillovers occurred. As discussed below, qualitative and quantitative approaches are combined in order to overcome the limitations inherent in each approach (Yin, 2003). For instance, while concerns over causality in absorptive capacity research are expresed by Knott and Drive (2008), it is not a major issue in this article because we qualitatively trace a chronology of events and validate cause and effect through interviews with industry participants.

The quantitative analysis is based on a data set of patents and publications relevant to copper interconnect technology (see the Appendix). Data on publications were obtained from the Science Citation Index (SCI) and data on patents from the US Patent Office. The data set contains 413 "relevant" articles (1985–1997) and 216 US Patents (1976–1999). The definition of a "relevant" set is necessary because copper has many other uses within and outside the semiconductor industry. Each firm's level of prior relevant R&D is proxied using the number of patents and publications it produced. This data is subject to bias, as not all research results are published or patented (some firms may choose to keep them secret). Also, papers may not meet the standards for publication and patent applications may be rejected. Another issue is that the coverage of the SCI, while excellent, is incomplete. However, the SCI is the best available source, because other bibliographical databases contain only the address of the first author.

I traced knowledge flows using patent-to-patent and patent-to-science citations (the data set contains all cited patents awarded after 1960, as well as all the scientific publications cited by the copper patents of four leading companies). Citation analysis has long been used to measure knowledge spillovers across organizations (e.g., Martin and Irvine, 1983; Henderson *et al.*, 1993; Ahuja, 2000). Patent-to-patent citations indicate spillovers of technological knowledge, while patent-to-science citations indicate spillovers from scientific fields (Narin *et al.*, 1997). There are well-known limitations of patent citation analysis (Jaffe and Trajtenberg, 2002): not all inventions are patented and citations are introduced not only just by

[3]Source: "SEMI Copper Critical Survey 1999."

inventors but also by patent examiners (Collins and Wyatt, 1988; Alcácer and Gittelman, 2006).

Given the limitations of analyzing patent data, there is a need to complement the quantitative analysis with qualitative research. I conducted semi-structured interviews with around 30 scientists, R&D managers, and academics *personally involved* in developing copper interconnect technology. They include two dozen employees and ex-employees from firms involved in developing copper interconnect technology (this includes all but two of the semiconductor firms listed in Table 2 and many of the equipment suppliers and partners listed in Tables 9 and 10). Around two-thirds of these interviewees were research scientists or developers, and the remaining one-third, managers. I also interviewed four university professors and two researchers at consortia who worked on copper interconnect technology during that period. Each interview lasted 45–60 min and included in-depth information about (i) the internal development efforts of each organization; (ii) technological options explored; (iii) sources of internal and

Table 2 Prior relevant R&D for copper interconnect technology versus year of first shipment

Organization	No. of publications on copper interconnects in the SCI (1985–1997)	Start of copper R&D	First shipment	Years elapsed
IBM	40	1960s	Sep 1998	≥30
Motorola	3	1990	Mid 1999	10
TSMC- Taiwan Semiconductors	0	Mid-1998	End 1999	2
UMC- United Microelectronics	0	Mid-1998	End 1999	2
VLSI Technology (USA)	0	1997	End 1999	2
AMD	1	1995	June 2000[a]	5
Texas Instruments	2	Mid-1990	2001[b]	6
AT&T (now Lucent)	7	1993	2001[b]	8
CSM-Chartered Semiconductors	0	July 1997	2001[b]	4
Hitachi	5	1986	End 2000[b]	14
NEC	1	Early 1990s	End 2000[b]	≈10
NTT	8	1990	2000 or later[b]	≥10
Intel	3	1988	2002[b]	14
Sematech (consortium)	2	1988/1993	NA	NA

Sorted by date of first shipment.

[a]AMD demonstrated copper-based microprocessors at the end of 1999 and began shipments in June 2000.

[b]Estimates from interviews and news reports.

external knowledge; (iv) appropriability; and (v) adoption of the technology. Examples of questions asked include:

- Describe your company's attempt to develop copper interconnect technology (including timeline, technical choices explored, structure of team, and management of R&D projects).
- How much did your company invest in copper interconnect technology, in terms of dollars? manpower?
- To what extent have your efforts depended upon information flows from suppliers, research consortia, universities, other firms, and other sources? Please give examples. How did you manage the inflow of external information?
- Did you attempt to protect the ideas created? Did you attempt to share these ideas with others? What was the nature of information protected or shared? What mechanisms did you use in each case (patents, secrecy, conferences, publications, etc.)?

As part of the qualitative research, I visited nine companies and attended several technical conferences to gain a better understanding of the technology as well as to gain access to industry sources. Leveraging my prior technical training in this field, I also analyzed more than 300 related articles from academic journals, newspapers, and trade journals.

The story of how various firms absorbed copper interconnect technology (Section 4) is pieced together from the qualitative research and interviews, but written to protect the anonymity of interviewees. Quantitative analysis of patent and publication data is used to complement the analysis where possible.

3.2 Identifying prior relevant R&D

Several features of copper interconnect technology make it possible to trace knowledge flows. The spillovers occurred from relatively few sources, making them possible to track. Moreover, the trail of evidence was still fresh when I began this project in 1997.[4] But, the most important factor is that it depends upon a novel set of competencies needed to overcome four technical difficulties. These competencies are distinct from the ones needed for making aluminum interconnects, which copper was to replace. This makes it feasible to identify the "relevant prior experience" of each firm in overcoming the four technical problems.[5]

The first technical problem arises because copper is difficult to etch using plasma gases. As such, it is difficult to use the traditional process, in which a layer of aluminum is placed onto the semiconductor chip and the unwanted portions etched away. To solve this problem, IBM developed a technique which it named

[4]For example, I was able to attend an IBM technical presentation at which that firm finally lifted the shroud of secrecy covering its development efforts.

[5]To learn more about the technical details, see Gutmann (1999) and Liu (1999).

the *damascene* process, in which the required pattern is etched onto an underlying material, after which copper is deposited onto that surface. Thus, the damascene process reverses the steps used in the traditional process. Moreover, unlike with aluminum, copper has the propensity to contaminate silicon, destroying the very circuitry it is meant to interconnect. This requires that a special barrier layer be placed between the two materials. The risk of contamination also has organizational implications: it requires careful handling on a production line so as not to contaminate the equipment being used and other wafers being processed. Organizational processes and the production flow must be modified to accommodate copper. Some companies consider the risk of copper contamination so great that they build entirely new fabrication plants for copper.[6]

The second, and perhaps most difficult, technical challenge is how to deposit a uniform layer of copper onto the uneven structures beneath. These structures are deep and narrow, especially the sections connecting vertical layers together. For a long time, researchers struggled to identify a way to deposit copper into these structures without forming air bubbles and imperfections inside. They explored four options: chemical vapor deposition (CVD), physical vapor deposition (PVD), electroless deposition, and electroplating.[7] While the standard aluminum process uses PVD, copper interconnects use PVD only for the barrier and seed layers, and electroplating for depositing the interconnect layer. The use of electroplating was highly counterintuitive at first, as it requires the delicate silicon wafers (which are manufactured in ultra-clean environments) to be dipped into "dirty" electroplating solutions.

The third technical obstacle arises because copper is a soft metal, making it difficult to polish each layer into a flat surface upon which to build the next layer. To do so, IBM developed a process known as Chemical Mechanical Planarization (CMP), in which a rotating disk coated with slurry (a mix of chemicals) is used to polish the surface. As with electroplating, CMP was a highly counterintuitive idea when first proposed. People were opposed to dunking their precious silicon wafers into a cocktail of powerful chemicals while grinding them flat. Moreover, the process is extremely difficult to control, and even today remains somewhat of an art.

[6]For example, AMD built a new factory in Dresden, Germany to produce copper-based Athlon microprocessors, instead of modifying existing factories in Texas (http://www.tomshardware.com, June 2000).

[7]CVD involves suspending copper in a chemical vapor, which then produces a coating of copper on the semiconductor wafer. PVD involves bombarding the target surface with copper atoms that gradually form a layer. Electroplating involves immersing a surface into an electrolytic solution and running an electric current through two electrodes (one of which is the desired pattern on the surface), thereby accumulating copper on one electrode. Electroless deposition is similar to electroplating, but depends on a chemical reaction rather than requiring electrodes.

Once the copper is deposited and polished flat, a final obstacle remains: unlike aluminum, which forms a natural protective coating, copper oxidizes when it is exposed to air. Hence, copper interconnects require a “passivation” coating to protect against corrosion.

Because of these technical difficulties, aluminum has been used instead of copper throughout the history of the semiconductor industry. However, these difficulties also point to relevant technical skills that would have helped adoption. They include prior R&D on: (i) copper deposition techniques—CVD, PVD, electroless, and electroplating; (ii) copper damascene process; (iii) copper CMP; (iv) barrier layers for copper; and (v) passivation layer for copper. Using qualitative and quantitative approaches, I identified each firm’s prior relevant R&D in these technical areas.

4. Tracing the flow of copper interconnect technology

The pattern of R&D on copper interconnects and its adoption by various firms reveals an interesting puzzle (Table 2). IBM pioneered much of the early research on copper interconnects and became the first company to ship copper-based products. This is consistent with the idea that IBM’s prior research helped it to acquire the knowledge needed to create copper interconnects ahead of other firms. However, two surprising facts emerge. First, a very short amount of time elapsed between IBM shipping its first product and other firms (Motorola, TSMC, UMC, VLSI and AMD) shipping their products. In fact, Motorola and Texas Instruments announced their own copper interconnect technologies just weeks after IBM’s announcement. Within a year of IBM, four other companies were also shipping copper-based products. These firms had published far fewer research papers than IBM on the subject, raising the question of how they acquired the relevant knowledge.

The second interesting fact is that several late entrants (including UMC and TSMC) were quick to ship copper-based products relative to the other firms. Astonishingly, TSMC, UMC, and VLSI began shipping copper-based products only 2 years after they began R&D, much shorter than most of the other firms.

In the remainder of this section, I analyze this puzzle using the following logic:

(1) I first provide evidence that firms depended on knowledge spillovers, primarily from IBM (Section 4.1). This rules out the alternative explanation that they did not rely on spillovers, but were simply more productive at R&D than IBM. It also rules out the possibility that copper interconnects involves “obvious” technological solutions that other firms developed independently.

(2) Having established that firms depended upon spillovers, I examine knowledge spillovers among early adopters, prior to 1997 (Section 4.2). Motorola took a domain-specific approach toward absorbing external knowledge, both in its focused approach toward managing internal R&D as well as how it linked its

internal R&D to external knowledge sources. This approach is quite unlike that of IBM, which was geared toward absorbing disciplinary scientific knowledge.

(3) Finally, I trace knowledge flows after IBM's public announcement in 1997 (Section 4.3). By then, absorptive capacity depended mainly on integrating knowledge from companies which already possessed relevant technology.

4.1 The Reliance of other firms on IBM's knowledge

It is tempting to believe that the other firms did not depend on external knowledge (making absorptive capacity irrelevant), but instead caught up with IBM simply because they were more productive at R&D, or perhaps because they independently invented copper interconnect technology. In fact, although other firms performed relatively little research, they depended heavily upon external knowledge from IBM, universities, and research consortia. IBM was the single most important source. The most compelling evidence of IBM's importance is that all commercial copper processes to date *use the damascene process developed by IBM.*[8] As noted above (Section 3.2), the damascene technique involves process steps that were not intuitive at the time of its invention, including reversing the sequence of steps from the traditional etch process and immersing the semiconductor wafers into "dirty" solutions. This makes it highly unlikely that all the firms independently and simultaneously developed the same process. In addition, the other firms followed IBM in *electroplating* copper, instead of depositing the material using some other way (e.g., PVD, CVD, or electroless deposition).

The knowledge dependence of other firms on IBM is consistent with patent citation analysis. As shown in Table 3, the patents on copper interconnect technology by Motorola, TI, AMD, and other firms include a large number of citations to IBM patents. In aggregate, patents for copper interconnects make 265 citations to IBM patents, as shown at the bottom of the first column in the table. This is almost four times more than any other source.[9] The results remain robust if self-citations are eliminated, as shown in the last row of Table 3. It is interesting that two early adopters, Motorola, and AMD, make almost as many citations to IBM patents as to their own, while Texas Instruments cites IBM patents even more than its own. The only firm that did not exhibit knowledge dependence on IBM in the patent-to-patent citations is AT&T, which had access to the bountiful resources of Bell Laboratories. According to interviews, AT&T was self-sufficient in performing in-house disciplinary research on copper technology.

[8]The ubiquity of this technique is apparent from industry interviews, news reports, and descriptions in the patents of various companies. For example, see Proceedings of the IEEE IEDM Conference (1997).

[9]Similar results are obtained if we limit the cited patents to only those on copper interconnects.

Table 3 Citations by copper interconnect patents to other patents

	Reference to															
	Top 10										Not in top 10					Total
Reference by	IBM	Motorola	TI	AT&T	Hitachi	GE	Fujitsu	Blank	MCC*	Micron	Sharp	AMD	Chartered	Toshiba	Other	
IBM	103	16	29	10	18	17	16	10	8	6	2	4		10	187	436
Motorola	20	22		3			3	2		6			2		34	92
Texas Instr	16	2	5	3	4	2		2							8	42
Lucent/AT&T				13											4	17
Hitachi	3					2									0	5
Fujitsu	16		2		2	2								2	5	29
MCC*	22		5	5		3		3	27		2				40	107
Sharp	9	4	5		3		3				9	2		7	31	73
AMD	19	4	3	2	4		2	4		2		21		4	21	86
Chartered Semi.		6			3		5			4			2	4	5	29
Toshiba	3	3	2		2									2	2	14
Other	54	20	19	14	7	15	10	17	3	18	0	5	4	5	147	338
Total	265	77	70	50	43	41	39	38	38	36	13	32	8	34	484	1268
Total excl. self-cites	162	55	65	37	43	28	39	38	11	34	4	11	6	32	439	1104

MCC*, Microelectronics and Computer Technology Corporation of Austin, Texas, an industrial research consortium (http://www.mcc.com).

Patents included are for 1976–1999, while citations to patents are for 1960–1999.

Another interesting result from Tables 3 is the strong knowledge dependence on Motorola, which received the second highest number of citations. As is discussed below, Motorola relied heavily on knowledge spillovers from IBM, and then played a major role in disseminating this technology to other companies.

The knowledge dependence of other firms on IBM existed even though IBM relied heavily on secrecy to protect its technology. IBM was so successful at keeping the project under wraps that many industry experts were surprised when the company made the official announcement in 1997.[10] Publications emerged from IBM on the general ideas relating to the damascene process and copper technology, but process-specific knowledge was kept carefully hidden. At IBM, copper research was deemed a top commercial priority. According to one IBM employee, the firm's researchers were "rewarded internally through other means" (financially and through promotions) rather than given permission to publish their more sensitive research. For example, IBM's work on the CVD of copper produced tangible results around 1983, but was not published till 1990. Some of IBM's research is *still not published* today, including the type of material it uses for the barrier layer and the chemical composition of its electroplating bath.

Only one part of the copper project was not done within IBM: the development of a copper deposition tool, for which IBM, in 1995, signed a top-secret joint-development agreement with Novellus, a small but reputable equipment supplier. Under this agreement, Novellus was not permitted to reveal that it was working with IBM until months after IBM's public announcement, and IBM maintained a list of companies to which Novellus could not initially sell the tool. To mislead competitors, the joint-development project was located in Portland, Oregon—far away from IBM and close to Intel's development facilities.

IBM's secrecy makes the results in Table 3 even more remarkable. By choosing secrecy, IBM withheld from patenting aggressively until the mid-1990s (Table 6). Therefore, the data in Table 3 *understates* the dependence of other firms on IBM, since there were fewer IBM patents to cite than had IBM patented its inventions earlier. An alternative measure of the dependence of other firms on IBM is the number of citations that are made by copper patents to the scientific literature. As Table 4 shows, IBM is the single largest source of publications cited by the copper patents of Motorola, AMD, and by Applied Materials (the world's largest semiconductor equipment supplier).

Table 4 also shows that the copper patents by these companies make a large number of citations to research published by universities and government laboratories. As discussed below, these laboratories and universities were important sources

[10]On the day of IBM's public announcement, The *New York Times* quoted an Intel spokesman: "If [IBM] can move it into production this early, that is certainly more aggressive than we and others had anticipated." Industry experts whom I interviewed echoed this sentiment.

Table 4 Citations by copper interconnect patents to scientific papers

IBM	Motorola	AMD	Applied Materials
Patents by			
IBM (63)	IBM (12)	IBM (10)	IBM (9)
Text Books (16)	RPI(4)	Trade Journals (3)	Applied Mat (5)
AT&T (7)	U.C. Berkeley (4)	Microel Ctr N Carolina (3)	Oki Electric (3)
Unknown (6)	Motorola (4)	Varian Associates (2)	Univ. de Paris-Sud (2)
Toshiba (4)	Text Books (3)	Text Books (2)	Tech. U. Chemnitz Germany (2)
Varian Associates (3)	Sematech (3)	Intel (2)	RPI (2)
Number of references to articles published by			
Mitsubishi (3)	SUNY Albany (2)	Georgia Inst. Tech. (2)	NTT (2)
Univ. Alberta (3)	NTT(l)	Northeastern Univ. (1)	NEC (2)
Oki Electtic (3)	AT&T (1)	Airco Temescal Inc. (1)	Hitachi (2)
Hosei Univ. Tokyo (3)	CalTech (1)		Unknown (1)
Harris Corp. (3)	CNET France (1)		U. New Mexico (l)
CNET France (3)	CNRS, France (1)		Sharp (1)
Carleton Univ. (3)	Intel (1)		Korea Inst. Sci. & Tech. (1)
Philips (3)	Microel Ctr N Carolina (1)		CNET France (1)
Fujitsu (2)	Air Prod & Chem (1)		AMD (l)
Intel (2)	NEC (l)		
Korea Inst. Sci. & Tech. (2)	Samsung (1)		
Hughes (2)	Stanford Univ. (1)		
Motorola (2)	Tech. Univ. Dresden (1)		
Sharp (2)	Tokyo Inst. Tech. (1)		
Siemens (2)	Toshiba (1)		
Spectrum CVD (2)	Taiwan Nat. Chiao Tung U. (1)		
Univ. Uppsala, Sweden (2)			
Others (6)			

Citing patents are for the period 1976–1999.

Citations are to all scientific articles, regardless of date.

of knowledge for companies other than IBM. Unfortunately, their importance is not reflected in the patent-to-patent citations of Table 3. Few universities and government laboratories filed for patents on copper interconnects (Figure 1), although they published a large number of articles on the subject (Figure 2).

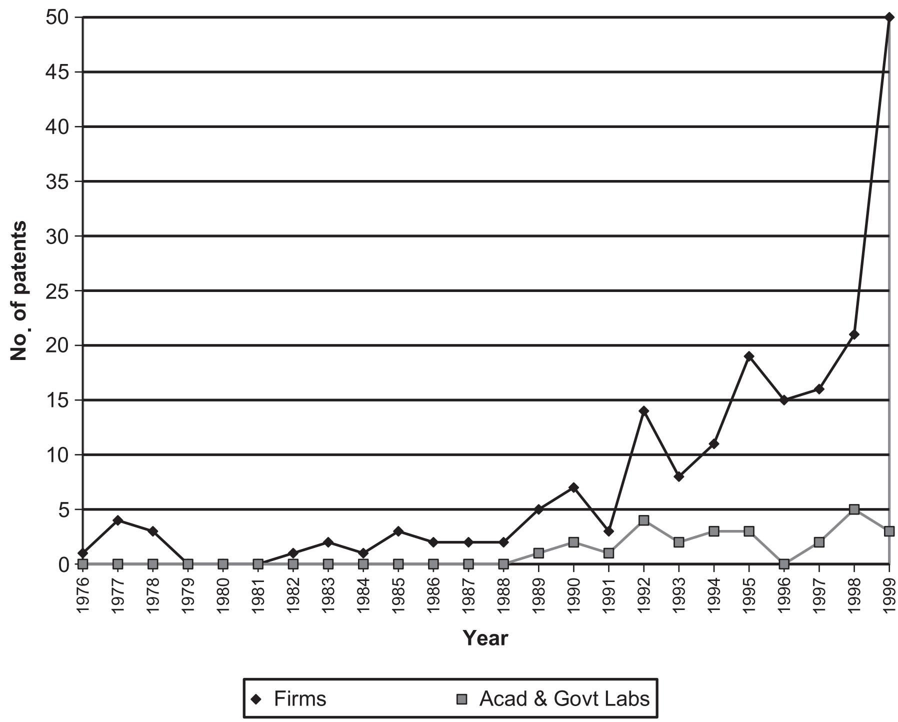

Figure 1 Number of US patents per year on copper interconnect technology.

4.2 Knowledge flows prior to 1997

Published accounts and interviews with IBM researchers show that IBM began researching copper interconnects in the 1960s.[11] By the early 1980s, the company had invented the damascene process and CMP. By the late 1980s, IBM had developed a barrier layer, and in 1989 IBM demonstrated a working chip with copper interconnects using a CVD process. Around 1989, researchers at IBM discovered a way to electroplate copper onto semiconductor chips. For reasons not understood at the time, the electroplated copper did not contain imperfections found using CVD. Moreover, it had electrical properties far superior to that of IBM's CVD process. IBM jealously guarded these secrets for many years. In any case, by 1990 IBM had all the pieces in place for a copper damascene process. In 1991, the firm moved the project into development and, in 1993, announced a prototype that worked although beset with technical issues. In 1997, IBM moved copper interconnect technology into production.

[11]See the IBM *Think magazine* article (1998) and *EETimes* special feature (1998).

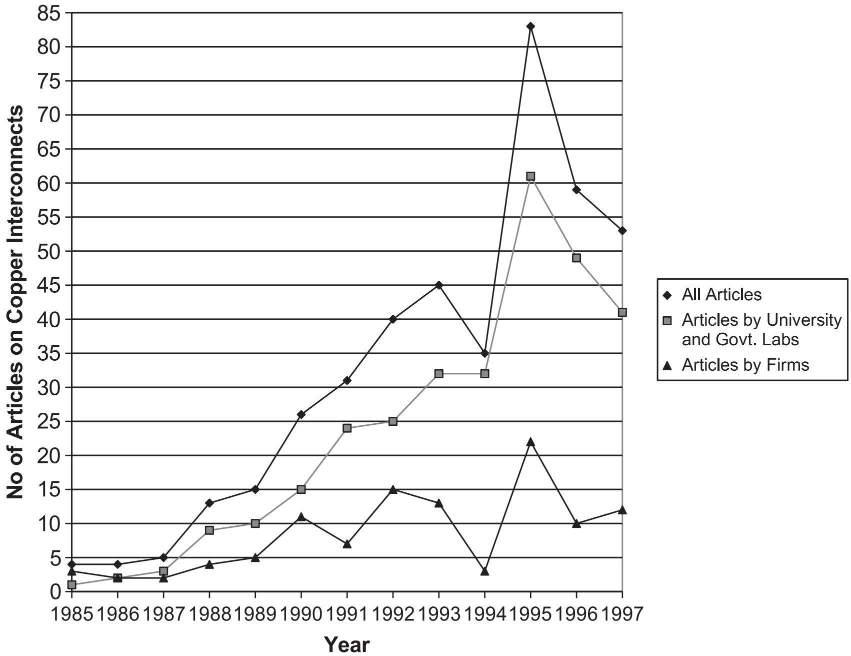

Figure 2 Number of published articles per year on copper interconnect technology.

Tables 5 and 6 show that IBM is the only firm to have systematically investigated copper interconnects prior to 1989.[12] For those familiar with this technology, the scale and depth of IBM's copper R&D is breathtaking. Other firms only began to explore the technology seriously in the late 1980s and early 1990s. Patents and publications began appearing from other companies around 1989 (Tables 5 and 6) and grew at a rapid rate, as shown in Figure 1. Academic research also began to emerge at this time (Figure 2).

Several factors contributed to this expansion of research. There was a growing realization that the industry would not be able to cope with future needs using aluminum. In addition, IBM—although tight-lipped about the details—began to reveal that it was making progress with copper. Momentum grew as technological breakthroughs began to appear from non-IBM researchers. Many of the researchers I interviewed described the emergence of a critical mass of people working on copper, and how this legitimized their own research and their requests for funding.

Intel's effort is noteworthy among the early explorers. In 1989, two Intel researchers published an article on copper interconnects using electroless deposition (Pai and Ting, 1989). One of the authors was a former IBM employee; the other had recently

[12]Scattered efforts were made at Boeing, General Electric, Motorola, and Intel (source: patent and publication data; interviews).

Table 5 Publications on copper interconnect technology per firm

Company	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	Total
IBM	3	1	2	1	3	7	1	6	3	1	8	3	1	40
NTT							2	1	1		2	1	1	8
Lucent/AT&T							1	3	3					7
Hitachi								1	1		2	1		5
Toshiba									1			1	2	4
Intel Corp					1						1	1		3
Mitsubishi										1	2			3
Motorola									2		1			3
National Semicon.								1	1	1				3
Nippondenso							1	1	1					3
Old Electric Ind.											2		1	3
DuPont				1		1	1							3
Applied Materials											2	1		3
Other	0	1	0	2	1	3	1	2	0	0	2	2	7	21
Total	3	2	2	4	5	11	7	15	13	3	22	10	12	109

Source: Analysis of SCI.

Table 6 Patents on copper interconnect technology per firm

Company	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
IBM	1						1	1	1		1	2		1	2		3	1	1	5	4	3	5	5	37
Sharp																				1		1	5	10	17
Motorola														1					1	4	1	1	2	6	16
AMD																					1	2	3	8	14
Texas Instr.													1	1	1		2		1	1		1	1	3	12
Lucent/AT&T		2	1															1	2	2					8
Air Prod & Chem.																	3	1	1						5
Chartered Semicon.																						1	2	2	5
Fujitsu															1	1				2	1				5
Toshiba																	1					1		3	5
Boeing															2		2			1					5
Applied Materials																			1					3	4
LG Semicon.																					1	1	2		4
Hitachi											1			1	1	1									4
Intel																		1	1			1	1		4
Others	0	2	2	0	0	0	0	1	0	3	0	0	1	1	0	1	3	4	3	3	7	4	0	10	45
Total	1	4	3	0	0	0	1	2	1	3	2	2	2	5	7	3	14	8	11	19	15	16	21	50	190

Source: Analysis of US patent data.

completed a PhD on VLSI interconnect technology at Berkeley.[13] The origin of these researchers suggests that Intel absorbed knowledge from those sources. Despite its early lead, Intel did not follow up its research in a serious way and according to industry sources, only began pursuing copper technology around 1997. Meanwhile, other US companies—including Motorola, AMD, AT&T (Bell Labs) and Texas Instruments—began to explore copper interconnects. Motorola's copper program began around 1990 and AT&T's around 1993, but both went into full-scale development only around 1995. AMD did not begin its copper program until 1995, but ramped up quickly and moved into development by 1996. In Japan, NTT and Hitachi began copper R&D in the late 1980s. However, interviewees indicate that most firms outside the United States were slow to explore copper technology and only began in the mid-1990s.

4.2.1 Domain-specific absorptive capacity

How did various companies acquire copper technology so quickly, despite IBM's attempts to keep its knowledge secret? Prior to 1997, this depended primarily upon relationships with Sematech, the consortium of leading American semiconductor companies. According to interviews, firms such as Motorola, Texas Instruments, and AMD took leadership roles at Sematech and actively influenced the trajectory of public R&D, which they then absorbed. In 1989, Sematech began to fund a significant amount of research at universities on copper interconnects, prior to which there was no university program directed specifically at that technology. A Sematech Center of Excellence (SCOE) was initially set up at the Rensselaer Polytechnic Institute (RPI), and later expanded to include Cornell, SUNY, University of Texas (Austin), and Stanford. Table 7 shows that publications began appearing from these universities around 1990. Universities in Japan, Korea, and Taiwan also began to publish articles on copper interconnects, but the Sematech-backed universities led by quite a margin (Table 7).

Researchers at universities and Sematech officials acknowledge during interviews that, during this period, they were "rediscovering" what IBM already knew. A handful of university researchers who attempted to etch copper quickly abandoned the process, and instead began to explore the damascene process. Much of this was directed at copper CVD, driven by IBM's 1989 demonstration of its copper CVD chip (note that by then, IBM had already moved on to electroplating). This pattern of research shows that universities were, in fact, borrowing IBM's ideas. The important difference was that now, it was in the public domain.

At Cornell University, an important Sematech-funded project generated data that helped firms realize that electroplating was feasible (as opposed to electroless plating). The research produced, among others, three patents jointly assigned to

[13]Source: Dissertation Abstracts Online; interviews with researchers.

Table 7 Publications on copper interconnect technology by universities and government laboratories

Company	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	Total
Rensselaer Poly Inst.[a]						5	1		3	4	5	1	1	20
Cornella[a]						2	2		2	2	1	1	6	16
Korea Adv. Inst. Sci. & Tech.								1			2	6	6	15
Univ. New Mexico[a]								3	2	5	2	1		13
Lawrence Berkeley/UC Berkeley							1	3	2		1	1	2	10
SUNY[a]						1		2		1	4	1		9
Univ.-Illinois						1	1	1			2	3		8
Kyoto Univ., Japan						1			1		1	1	3	7
Nat Chiao Tung, Taiwan								1	1	2	1	1	1	7
Ecole Poly Lausanne, Switzerland					1		1	3		1			1	7
Other	1	1	0	3	4	3	4	6	9	8	25	15	12	91
Total	1	1	0	3	5	13	10	20	20	23	44	31	32	203

[a]University affiliated with the Sematech SCOE program on interconnects.

Source: Analysis of SCI.

Cornell, Sematech, and Intel.[14] Interestingly, the inventors of these patents included one researcher originally from IBM, and who had subsequently moved to Intel. This is an indication that the knowledge created at IBM was transmitted to other firms via Sematech.

According to interviewees, the main mechanism used by Motorola and other firms to absorb the knowledge created by Sematech was by recruiting graduate students working on those programs. Academic researchers reported strong demand for graduates with such experience. One professor mentioned how a graduate student had done a less-than-"marketable" PhD, stayed on for post-doctoral research on copper interconnects, and was then snatched up by a company. The companies that recruited these students—unlike AT&T and IBM—were attempting to hire individuals with *domain-specific skills*. According to the R&D director at one company, "The people we hired from universities had the right set of skills. They were familiar with specific technical areas, such as plating, sputtering, etc." Sematech member companies had an advantage in that regular meetings provided them with an opportunity to evaluate students they might recruit. According to one professor:

> In most cases, graduate students went to U.S. industry—especially Sematech companies. This is because Sematech funded the research, and therefore people from Sematech companies were at the annual review, where they had early indications of the quality of the students.

Apart from funding public research, Sematech also performed a series of internal studies to develop copper-capable equipment in conjunction with suppliers (Table 10), and performed benchmarking studies on copper. Except for a handful of publications and patents Sematech filed, the knowledge produced was *made available only to member companies*. Almost all member companies sent assignees on 2-year attachments to the Sematech R&D facility in Austin, Texas. Several firms, including AMD, Motorola, and TI, also located research facilities in Austin. The relationship with Sematech gave US firms a strong advantage over their foreign rivals, who were barred from joining Sematech till 1999.

Apart from Sematech and the universities, IBM was the other major source of knowledge prior to 1997. IBM introduced basic ideas that others explored, such as the damascene process and copper CMP. Around 1994, Sematech paid IBM $1 million for samples and electrical performance data from IBM's copper process. At the time, IBM did not disclose what process was used to create the chips, and it only sent Sematech partially completed wafers. However, the IBM data helped Sematech decide to use electroplating instead of the alternatives. Knowledge also flowed away from IBM due to severe financial difficulties that IBM faced in the early 1990s. The firm was forced to scale back the copper R&D project drastically,

[14] US Patents Nos 5695810, 5824599, and 5891513.

and almost shut it down (IBM Think Magazine, 1998). Interviewees report that as a result, several key individuals left IBM to join competitors and equipment suppliers. At least three members of the core team left, including one who joined Motorola. IBM also suffered from accidental losses. According to one interviewee, "someone at IBM blundered some information and some people [at an equipment company] figured out that with the right [electroplating] bath it would work beautifully. Several plating tools have been developed based on the idea."

Consider the case of Motorola, one of the first companies to ship copper interconnect products. It depended heavily upon domain-specific absorptive capacity. Thanks to its PowerPC alliance with IBM (through which the two firms worked jointly to design a microprocessor), Motorola sensed earlier than other companies that IBM was making progress on copper technology. The alliance did not involve the exchange of process technology, but Motorola was able to draw inferences from the design rules employed by IBM about its progress with copper. According to an IBM source, "Motorola knew more than anyone else what IBM was doing." Motorola absorbed external information by actively recruiting people from IBM and from Sematech-related universities. At Sematech, Motorola was deeply immersed in the copper program. In fact, two consecutive directors of Sematech's interconnect program were Motorola executives. Motorola's relationship with IBM and its strong involvement with Sematech helped the firm to adopt copper technology rapidly, even relative to other Sematech member companies. According to a Motorola employee, the company "operated in tactical mode" to integrate external knowledge with its own talent. They were not out to explore the discipline (as reflected in the low publication counts of Table 5), but organized teams to patent a large number of processes useful for solving the copper problem (Table 6).

While Motorola was clearly dependent on external technology, it was also quite generous about sharing its knowledge. For example, Motorola worked jointly with suppliers from an early stage to develop tools for copper technology. A member of Motorola's copper team remarked that "unlike IBM, we are quite open with vendors. There are vendors down there [on the factory floor]!" Motorola's relative openness made it an important source of information for the rest of the industry. Table 3 shows that citations by copper interconnect patents to those by Motorola rank second only to IBM's. Table 8 also shows that the most highly cited patent on copper interconnect technology belongs not to IBM, but to Motorola.

4.2.2 Disciplinary absorptive capacity

In contrast to other companies and in line with its efforts to preserve secrecy, IBM's efforts depended very much on internal knowledge. As Table 3 shows, IBM's copper patents cite the company's own patents more than they cite patents from any other organization. Likewise, the citations made by IBM patents to the scientific literature make the largest number of references to articles published by IBM itself (Table 4). This is unsurprising, since IBM's Watson Laboratories did much of the fundamental

Table 8 Patents most highly cited by copper interconnect patents (1960–1999)

Patent no.	Patent assignee	Title	No. of citations to this patent
5391517	Motorola	Process for forming copper interconnect structure.	16
4810332	MCC*	Method of making an electrical multilayer copper interconnect.	13
4985750	Fujitsu	Semiconductor device using copper metallization.	12
4789648	IBM	Method for producing coplanar multilevel metal/insulator films on a substrate and for forming patterned conductive lines simultaneously with stud vias.	11
4910169	Fujitsu	Method of producing semiconductor device (including copper).	10
4931410	Hitachi	Process for producing semiconductor integrated circuit device having copper interconnections and/or wirings, and device produced.	9
4944836	IBM	Chem-mech polishing method for producing coplanar metal/insulator films on a substrate.	8
5225034	Micron	Method of chemical mechanical polishing predominantly copper containing metal layers in semiconductor processing.	7
5447599	Cornell & IBM	Self-aligned process for capping copper lines.	7
5071518	MCC*	Method of making an electrical multilayer interconnect (by electroplating copper).	7

MCC*, Microelectronics and Computer Technology Corporation of Austin, Texas, an industrial research consortium (http://www.mcc.com).

research on copper interconnects. There was no need to go outside to acquire such knowledge, and in any case IBM was ahead of everyone else in the field. IBM's closest rivals in fundamental research were RPI and SUNY Albany, both Sematech-funded programs (Table 7). IBM, itself a member of Sematech and in close geographic proximity to these universities, kept track of this research. However, there was no direct transfer of knowledge from IBM to the universities, apart from the papers IBM published in journals and presented at conferences. According to researchers interviewed, IBM's perspective was that although it was ahead in copper R&D, it had nothing to lose by monitoring others.

IBM's dependence upon external knowledge was at a broad, disciplinary level, rather than for knowledge specific to copper interconnect technology. Interviewees at IBM emphasized the company's approach of recruiting top-notch researchers directly from academic programs and allowing them to pursue interesting problems at IBM, rather than hiring people with domain-specific knowledge. In fact, IBM's Watson Laboratories has never hired anyone to work on its copper R&D who had previously worked on copper at other firms, or had written a PhD thesis on the topic. Instead, the IBM team that created the damascene process and CMP technology were specialists in fundamental areas: electrochemists familiar with electrodeposition, a physicist who developed the barrier layer, and materials scientists who understood corrosion and device failure.

4.3 Knowledge flows after 1997

IBM's 1997 announcement of its copper technology triggered a race among other firms to offer copper technology as well (Lineback, 1998). This contest radically changed the dynamics of knowledge flow. Firms could no longer rely on the relatively slow process of converting domain or disciplinary knowledge into a commercial product. Besides, some companies had already done so, including Motorola and the equipment vendors. Alliances and joint ventures formed rapidly between firms that wanted the technology and firms with the expertise (Tables 9, 10). It is interesting that no alliances existed prior to 1998, underscoring the fact that the dynamics had shifted. Even IBM became less secretive and began to seek ways to license or trade its technology. Third-party information traders also materialized, such as a company that began selling reverse-engineering reports of IBM's copper-based chips almost as soon as they were shipped.[15]

It is important to distinguish the relationships that involved true spillovers ("borrowed" ideas) from those that simply reflect inputs purchased below their actual costs (Griliches, 1992). The alliances involving IBM should not be viewed as true spillovers, since IBM probably expected reciprocal benefits. Neither should the manufacturing alliances (e.g., Sun and TI). However, technology-sharing alliances that did not involve IBM should be considered spillovers from IBM's perspective. For example, the alliance between Motorola and AMD did not involve payments by either party to IBM.[16] As for the equipment suppliers, IBM receives an unspecified royalty from Novellus with whom it jointly developed tools. However, IBM receives no royalties from the other equipment suppliers, including Applied Materials, Semitool, and Cutek. Many interviewees reported that equipment vendors "act as conduits through which much more information flows than is embodied in the

[15]"ICE Corp. is excited to announce the immediate availability of a construction analysis report on the recently announced IBM PowerPC 750 . . . This report represents one of the most detailed reports ICE has ever produced . . ." (Source: ICE web site).

[16]Semiconductor companies often trade patent portfolios (Hall and Ziedonis, 2001). IBM may have appropriated some benefit through such bargaining, but it is difficult to monitor and implement such deals. Moreover, Motorola, AMD, and other firms now own many patents, and therefore hold strong bargaining positions.

Table 9 Copper alliances, joint ventures, and acquisitions among semiconductor firms

Date	Companies	Nature of alliance
Pre-1988	NONE	NONE
July 1998	AMD and Motorola	Motorola licenses its copper interconnect technology to AMD. In exchange, AMD licenses Motorola its flash memory processes. This 7-year deal includes the exchange of technology, sharing development costs, and assigning employees to one another's design labs. No money is exchanged.
July 1998	IBM & Sanyo	In a 5-year agreement, Sanyo licenses design methodology from IBM, including ASIC and copper technology. IBM will manufacture the devices.
July 1998	Sun and TI	TI will manufacture Sun's UltraSparc HI using copper in year 2000.
Mar. 1999	IBM and Infineon (Siemens)	IBM gives Infineon access to copper technology (0.18 and 0.13 micron) for joint development of DRAMs.
Dec. 1998	IBM and Pacific Electric Wire & Cable	IBM licensed its technology, including copper, to this new Taiwanese foundry.
Mar. 1999	Lucent (AT&T) and Chartered Semiconductors, Singapore	Lucent and Chartered agree to joint development of 0.18 micron copper technology.
Feb. 1999	Motorola, Hewlett-Packard and Chartered	Motorola licensed its copper technology to a joint venture between Chartered Semiconductor Singapore and Hewlett Packard (0.18 micron copper with low-k dielectrics).
Mar. 1999	UMC Taiwan and Kawasaki LSI Japan	Strategic alliance to develop 0.18 micron copper technology with copper and low-k dielectric.
Jan. 2000	UMC joins the alliance between IBM and Infineon	Joint development of 0.13 micron technology, including copper interconnects.

Sources: News articles, company web sites, and interviews.

tools they sell." Hence, it is reasonable to consider knowledge flows from equipment vendors as externalities.

Perhaps the most viable of the alliances formed after 1997 was that between AMD and Motorola. AMD's copper program began around 1995. However, the firm needed to accelerate its effort to compete with Intel. So, AMD signed a major agreement in July 1998 to trade its flash memory technology for Motorola's copper interconnect technology. Motorola's technology formed the basis for AMD's

Table 10 Copper alliances, joint ventures, and acquisitions involving suppliers

Date	Companies	Nature of alliance
Companies and equipment suppliers		
1997	Intel and Applied Materials	Research on copper etch as an alternative to damascene (IEEE Conference 1–3 June 1998).
July 1998	AMD & Applied Materials	AMD ordered Applied Ion Metal Plasma technology to develop copper interconnects.
1998	AMD & CuTek	Joint venture. Purpose unknown.
1999	TSMC and Applied Materials	TSMC purchases AMAT copper-processing machine.
1999	UMC and the Novellus Alliance	Collaborated on copper interconnect process.
Sematech and equipment suppliers		
1993	Sematech and Semitool	Sematech bought Semitool's electroplating tool for experiments on copper interconnects.
Sep. 1996	Sematech and Varian	Sematech bought a PVD/CVD cluster tool for the Sematech project at SUNY Albany.
May 1998	Sematech and Applied Materials	Second phase of project to etch low-k materials for copper interconnects.
1996	Sematech and CVC (Rochester)	Developed copper deposition tool.
Nov. 1997	Sematech and Lam Research	Developed high-density oxide etch systems.
Jan. 1999	Sematech and Novellus	Sematech selected Novellus' Sabre electrofill tool for its Advanced Tool Development Facility.
Equipment supplier alliances		
1997	Novellus and Varian (thin-films division)	Novellus acquired Varian's thin-films unit, thereby acquiring the PVD expertise it used in developing tools with IBM.
May 1998	Novellus, Lam, IPEC and OnTrak	Novellus announced partnerships with Lam and IPEC to provide a complete copper solution. Novellus offers an electrodeposition tool and a PVD tool (for barrier and seed layers); IPEC is market leader in CMP. Lam produces dielectric-etch systems and Ontrak supplies post-CMP cleaning systems.
Jan 1998	Semitool and Shipley	Semitool partners with Shipley, a electronic chemicals company
Nov. 1998	Semitool and Ulvac, Japan	Semitool (electrochemical deposition) partners with Ulvac (thin-film deposition equipment)
1999	Semitool and ASM (Netherlands)	Semitool (copper electrodeposition tools), forms an alliance with ASMI (CVD tools for low-k dielectric).

Sources: News articles, company web sites, and interviews.

state-of-the-art facility in Germany, and in which Motorola eventually took an equity stake.

Two Taiwanese companies (TSMC and UMC) and an American one (VLSI Technologies) adopted copper interconnect technology with the greatest speed. Both TSMC and UMC began copper R&D programs in mid-1998 and, at the end of 1999, shipped IC chips with the top two metal layers made from copper. According to interviews, TSMC, UMC, and VLSI depended primarily on technical knowledge from equipment suppliers. TSMC worked closely with Applied Materials, while UMC was one of first customers of Novellus (which had jointly developed tools with IBM).[17]

There are several other similarities between TSMC and UMC. Both recruited highly trained personnel, including people who received their graduate-level education at top universities in Taiwan and the United States; some had also worked at US companies. Yet, interviewees at both firms did not perceive a direct relationship between university research and their copper projects. One interviewee characterized university research as being "in the literature and available for years. It's helpful, but they are pure research–basic, fundamental studies. But to make things work is really different [sic]." Hence, although the copper development teams at both the companies had highly talented people, they did not include individuals with extensive prior experience with copper interconnects. Because much of the technical knowledge came from equipment suppliers, the primary role of internal teams was to integrate the knowledge of suppliers into their own manufacturing processes. Thus, while these companies were able to absorb the knowledge for *using* copper technology, they were not building knowledge about copper at a deeper level.

TSMC, UMC, and VLSI are only the first in a larger wave of companies that depend primarily on equipment vendors. The role of equipment suppliers is not an easy one. Each piece of equipment is only a small part of the overall puzzle of putting together a semiconductor manufacturing process. To fill the void in their knowledge, equipment companies have coalesced into alliances that provide complete solutions. The first such alliance was created in 1998 by Novellus, Lam Research, IPEC, and Ontrak (Table 10). It was followed by another alliance led by Semitool. The exception to this pattern of alliances is Applied Materials, which is a very large firm. In 1998, it began offering an integrated set of tools for copper interconnects and opened a service center where customers could "test-drive" this technology.

As a result of the work by equipment companies, much of the technical knowledge had become "unstuck" (von Hippel, 1994) by the end of 1999. These suppliers have turned copper technology into common knowledge (Reagans and McEvily, 2003),

[17]In January 2000, UMC formed an alliance with IBM and Infineon (Siemens) to codevelop process technology, including copper. However, this was after UMC had developed in-house capabilities and shipped copper products the previous year.

at least among industry participants. Adoption has since begun to depend on other issues, such as how to organize a facility to avoid copper contamination and whether to invest in a new facility or deploy copper technology into an existing facility.

5. Analysis and discussion

A close look at the diffusion of copper interconnect technology suggests the existence of three different types of absorptive capacity, as described in Section 2. Pioneering firms (IBM and AT&T) almost exclusively relied upon the disciplinary form. Early adopters such as Motorola shaped the external scientific environment to their own benefit, and tuned their internal R&D efforts toward absorbing domain-specific knowledge, not broad disciplinary knowledge. At a later stage, internal R&D played a secondary role as knowledge became encoded in tools and processes. This leads to the proposition that each kind of absorptive capacity is most relevant at different stages or technological evolution:

Proposition 1: Disciplinary absorptive capacity is most important at the initial stage of a technology, domain-specific absorptive capacity is important at an intermediate stage of technological development, and encoded absorptive capacity is most important when the technology has matured.

Each type of absorptive capacity involves different ways of managing R&D that are difficult for a firm to develop simultaneously. This is because they depend upon different and sometimes conflicting organizational practices (Gittelman and Kogut, 2003; Stern, 2004). Disciplinary absorptive capacity is a costly affair, perhaps affordable only to firms such as IBM, AT&T, and Merck. Laboratories need to be built and filled with special equipment to attract scientists. The organization has to hire and retain scholars, which requires the formation of a conducive internal research environment (Stern, 2004). Long gestation periods are required for the knowledge created to become useful products, thus demanding a degree of patience in the decision to fund R&D. In order to recoup the high cost of participating in science, the firm has to be very careful about protecting the domain-specific knowledge it creates, either through defensible patent positions or through secrecy. At the same time, it has to remain selectively open about the general scientific ideas that it generates, in order to remain connected to the scientific community.

Proposition 2a: Disciplinary absorptive capacity is the most costly, relying upon highly autonomous internal R&D and an academic-like research environment.

Unlike disciplinary absorptive capacity, domain-specific absorptive capacity requires a different set of skills for acquiring solution-specific skills from universities, R&D consortia, and discipline-oriented firms. In a sense, the problem is not really about the tacitness of knowledge *per se*; after all, it is possible to hire people in whose heads lies the tacit knowledge. A real problem is the scarcity of such talent. Hence, the firm may need to actively nurture external talent (such as by influencing research at universities and consortia) and subsequently funnel that talent into the firm through targeted recruitment efforts. In order to spot such talent and bring it in-house ahead of rivals, a firm may need to take leadership positions at R&D consortia, work closely with universities and form strategic relationships with disciplinary firms. Investing in domain-specific absorptive capacity is not costless. It involves expending precious management attention and resources on tuning internal R&D and influencing external research. It also requires direct expenditures to fund research at universities and R&D consortia. Apart from these costs, the firm faces a loss of control over upstream scientific research, as compared with performing it in-house (Aghion and Tirole, 1994). Nonetheless, domain-specific absorptive capacity appears less costly than disciplinary absorptive capacity.

Proposition 2b: Domain-specific absorptive capacity is less costly than disciplinary absorptive capacity, with internal R&D focused on developing solutions to specific technical problems.

As time passes, an increasing amount of the technology becomes encoded and easier to absorb. Encoded absorptive capacity is useful for late-stage entrants. Such firms do not have the luxury of waiting for a scientific discovery to bear fruit, and are mainly interested in using the technical solution already worked out. They seek to acquire knowledge that has been codified by others into portable tools and routines. This may take the form of licensing the technology, forming strategic alliances, and working closely with suppliers. However, effort is needed to ensure that the bundles of routines purchased are carefully integrated into the firm's existing operations. In this case, absorptive capacity mainly involves working closely with the sources of knowledge to assimilate it, and recombining the firm's capabilities where necessary (Kogut and Zander, 1992).

Proposition 2c: Encoded absorptive capacity is the least costly, with internal efforts aimed at rapidly acquiring and integrating knowledge already encoded by others into the firm's own routines and processes.

Being the least costly form of absorptive capacity comes with its own tradeoffs. Several interviewees raised concerns about whether absorptive capacity is sustainable, due to the high dependence on external sources of knowledge and the risk that the relationship might sour.

A third set of propositions concern the different tradeoffs between appropriability and openness inherent in disciplinary versus domain-specific absorptive capacity. For disciplinary knowledge, being an active participant gives the firms direct access into the scientific community and helps it to monitor for breakthroughs. According to interviews, IBM and AT&T scientists were viewed as full members of the invisible college, publishing a significant number of important research papers on copper technology. In fact, between 1987 and 1997, IBM published 40 papers on copper technology (Table 5), twice the number produced by RPI, which had the highest research output among universities (Table 7). While interviewing IBM researchers, I clearly sensed their pride at being scientists. The approach taken by

IBM and AT&T closely resembles the biopharmaceutical firms studied by Cockburn and Henderson (1998) and Zucker and Darby (1995). Such firms establish "connectedness" to the upstream research community, and reward their scientists for collaborating with academics and publishing their research.

However, the heavy cost of participating in scientific exploration creates a strong incentive for the firm to be guarded and closed with its downstream partners, such as suppliers and alliance partners. The more of that knowledge leaks out, the harder it is to recoup the initial investment (Nelson, 1959). As reported above, the domain-specific knowledge created by IBM was jealously guarded, which even went to great lengths to mask its relationship with Novellus. According to researchers at IBM and elsewhere, IBM chose to publish general ideas but kept valuable process-specific information and recipes proprietary: "IBM shared information that didn't fall into their crown jewel capability." Nonetheless, it is extraordinarily difficult to prevent spillovers from happening (Griliches, 1992). Inevitably, the research from IBM spilled out and acted as a focusing mechanism for the efforts of others (Rosenberg, 1969). This accounts for why IBM was so secretive, and at the same time produced research papers that were so highly cited.

Proposition 3a: To develop disciplinary absorptive capacity, a firm should encourage its researchers to be active participants in the scientific community, while protecting the domain-specific knowledge they create.

For domain-specific absorptive capacity, a firm needs to manage external linkages in a manner that helps it to recognize signals in the technological trajectory and to recruit talent. In this case, firms like Motorola took cues from the actions and plans they jointly made by IBM. Alliances with discipline-oriented firms, membership at R&D consortia and financial support for university research gave them priority access to potential hires with the needed domain expertise. An interesting aspect of this case is that it highlights the proactive efforts of such firms to shape public knowledge in their favor (in this case, by influencing the research agenda at Sematech and universities). Such firms have a strong incentive to coevolve with their environment because they are highly dependent upon it for breakthroughs, unlike IBM which had little need or desire to go outside for domain knowledge. Besides, to remain a respected member of the scientific community, it is important for firms like IBM to avoid influencing public science directly.

Another aspect of domain-specific absorptive capacity is that the firm can take a much more open and friendly approach toward downstream partners. Building this form of absorptive capacity certainly takes a significant amount of managerial attention as well as direct monetary contributions (membership fees at consortia, salaries for assignees, funding research at universities). However, it is probably not of the order of magnitude that IBM invested in its 30-year copper program. As such, the firm has less of an incentive to hide its results than a disciplinary firm. As discussed earlier, firms like Motorola and Texas Instruments were much more generous in sharing their knowledge with equipment suppliers and alliance partners than was IBM. They eventually developed into central actors as a web of knowledge formed around them.

Proposition 3b: Firms developing domain-specific absorptive capacity must invest in shaping external R&D and learning from it, but can afford to be more open with their partners.

There remains a question of why disciplinary firms publish their work at all. After all, these publications provide clues for other firms to follow in their footsteps. According to interviews, if IBM had not allowed anything to be published at all, it would have had difficulty getting talented individuals to work on the project. Also, many innovations (e.g., damascene, CMP) were developed within IBM but outside the copper group. To keep everything under wraps probably would have required a firm-wide policy of nonpublication. This would have dampened IBM's ability to build "connectedness." Finally, the emergence of publications by academics after 1989 acted as a catalyst. Had IBM not published its work, some other firm would have done so. According to one professor, "With copper or damascene, when we publish something, IBM starts to publish also." This pattern of behavior could account for why IBM's publication rate increased in the 1990s, after universities and other firms also began to publish (Table 5).

6. Conclusions

The case of copper interconnects offers a rare glimpse into the process of knowledge spillovers, one that is much talked about but seldom observed up close. The case suggests that three different types of absorptive capacity exist, and that each is valuable at different stages of technological evolution. Furthermore, each type of absorptive capacity requires a firm to manage its internal R&D differently, and to use a different approach when linking internal and external R&D. The value of external knowledge changes as a technology evolves, initially as a source of signals that help focus a firm's own efforts (Rosenberg, 1969), then as a source of solutions to specific technical problems, and subsequently as a source of tradable codified knowledge in a "market for ideas" (Gans and Stern, 2003).

An important implication stems from the multifaceted nature of absorptive capacity. In many studies, absorptive capacity is assumed to exist along one dimension, and is therefore high or low depending only upon a firm's cumulative R&D investment. This article shows that one must be cautious about interpreting such figures in isolation. We should view a firm's effort to build absorptive capacity holistically, looking not just R&D figures but also how it manages its own R&D alongside efforts to link internal and external R&D. The efficiency of a firm's efforts is likely to depend upon the kind of knowledge it is attempting to absorb, as well as the stage of technological evolution. Moreover, a firm can actively shape its external knowledge environment, so an evolutionary and dynamic view is necessary (Van Den Bosch *et al.*, 1999).

There is a need for future research to test the propositions generated in this article and to examine whether the insights from this study hold more generally. Further investigation is also needed to better understand the implications for firms' financial performance. Finally, we need to better understand how various types of absorptive capacity are related to knowledge flows *within* the firm, including the role of interfaces and gatekeepers. If we want to confidently use the concept of absorptive capacity as a building block in organizational research, we need to better understand its foundations.

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Address for correspondence

Kwanghui Lim, Melbourne Business School, 200 Leicester Street, Victoria 3053, Australia. e-mail: k@kwanghui.com

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Appendix

A. Construction of data set

The database consists of patents awarded by the US Patent and Trademarks office between January 1976 and December 1999 relating to copper interconnects. It also contains scientific publications in this area between 1985 and 1997.

A.1 US Patents

US patent data is available in electronic format only from 1976, but truncation is unlikely to be a problem given the recency of copper interconnect technology. I searched the database for:

(1) Patents with titles and abstracts containing the keywords ("cu" or "copper") and "intercon*."[18]
(2) Patents with titles and abstracts containing the keyword "damascene."
(3) Patents in the two main semiconductor patent classes (257 and 438) containing the keyword "copper."

Among these patents, I manually identified those directly related to copper interconnects using information from the title and abstract. My field interviews, attendance at technical conferences, and engineering background provided technical knowledge that facilitated this process. Where ambiguity arose, I consulted the "background" section of the patent, which describes the patent's purpose in detail.

[18]An asterisk (*) acts as a wildcard that matches one or more characters.

The database contains 2440 patents, of which 216 are directly related to copper interconnects.

I then generated a cross-reference of citations by copper interconnect patents to all other US patents. To provide an exhaustive analysis, I include all cited patents as far back as 1960. Patents prior to 1976 were obtained from the *Patent Gazettes* printed by the US Patent Office, as these are unavailable in electronic form.

The next step was to create a cross-reference of the scientific publications cited by each copper interconnect patent. I obtained the address of the first author[19] of each cited publication from the SCI, Compendex, INSPEC, and the IEEE Online Library. I then constructed a matrix showing the sources of scientific publications cited by each organization's patents.

A.2 Publications

I searched the SCI for all scientific publications with titles containing ("Copper*" or "Cu"), and at least one of the following keywords: "intercon*," "metalliz*," "ULSI," "VLSI," "damascene," "etch," "planari*," "CMP," "barrier," "deposition," "PVD," "CVD."

The search produced 1017 publications between 1985 and 1997. I manually identified those publications directly related to copper interconnect technology based on their titles (502 publications). I then eliminated all meeting abstracts, review articles, notes, and letters to obtain a final sample of 413 research articles.

I mapped each article to companies, universities, and R&D consortia based on the address field of its authors. The SCI records up to 255 authors per publication. Unfortunately, it does not indicate which authors are associated with each address. Thus, I adopt the following convention: for each distinct address listed in an article, I increment by one the number of articles published by that organization. The rationale is that each publication involves costly research plus the opportunity cost of writing and revising the article. This approach counts articles that are co-authored among organizations multiple times, but this should not be a severe problem: only 32 articles in the sample were coauthored among organizations.

[19]With the exception of the SCI, these databases include only the affiliations of the first author.