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Evolution of technology dependence among leading semiconductor companies

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Abstract

Purpose – The purpose of this paper is to examine the characteristics and evolution of the technology-dependence networks of leading semiconductor companies. By comparing and contrasting technology-dependence networks in the 6-, 8- and 12-inch chip eras, this study clarifies the differences among integrated device manufacturers (IDMs) and foundries, and among each company in different eras.

Design/methodology/approach – Leading companies were identified by technological crowdedness and technological prestige to avoid massive actors. Strong ties were extracted to avoid too many relationship ties at the company network level. Strong ties represented directional technology relationships among companies whose citation counts and relative citation rates were higher. The technology-dependence network of leading companies in three chip eras was examined by social network analysis.

Findings – Technology dependence among IDMs was the weakest, and their technology dependence upon foundries decreased in the 12-inch chip era. The highest technology interdependence appeared among foundries and the reduction of their dependence upon IDMs. Technology dependence is expanded primarily by foundries, significant among GlobalFoundries, TSMC, UMC, and VIS.

Practical implications – IDM could invite foundries with technology dependence to form a strategic consortium. That way, the foundries could monitor potential competitors with relationship of technology dependence; in an advanced sense, the foundries could make use of the network to practice commercial maneuvers and create competitive advantage. Scholars may also observe semiconductor manufacturing technology's evolving into the maturity stage of product life cycle by interpreting foundries' highly technology interdependent relationships.

Originality/value – This is the first study to use strong ties in patent citation networks to represent technology-dependence relationships.

Keywords Technology dependence, Strong ties, Semiconductor industry, Consortia, Multinational companies, Patents

Paper type Research paper

I. Introduction

The technology-driven and capital-intensive nature of the semiconductor industry makes it difficult for most companies to conduct independent technology development and innovation. Innovation is an interactive process that requires technological relationships between different agents in manufacturing process. Grant (2000) has identified two inter-organizational factors impacting on a company's agility;

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they were pervasive in knowledge-based industries such as the semiconductor industry. The first factor refers to "competing for standards" so that companies have inclined to do collaborative projects with customers, competitors, and government agencies to achieve a standardization goal. The other refers to "vendor/customer relationships," to the effect that semiconductor companies continue to deploy technical semiconductor design expertise locally to customers throughout the world to ensure collaboration in response to global competition. Therefore, there are often close technological interactive relationships among semiconductor companies.

Watanabe *et al.* (2001) mentioned that effective utilization of technology from the global marketplace gathered from multiple sources has become an important competitive strategy leading to greater concern for assimilation capacity of spillover technology (the ability to utilize this spillover technology). How to effectively utilize this substitution potential has become one of the most crucial R&D strategies for the industry. Before utilizing external technological knowledge, having an insight into technological knowledge spillover (flow or diffusion) is indispensable.

Appleyard and Kalsow (1999) suggested that the ease of knowledge diffusion depends upon the degree of similarity in organizations' technical prowess. They examined knowledge flows in the semiconductor industry through citations to scientific journal articles published by a leading company Intel. Narin (1994) mentioned that knowledge spillover process of technological research and development could be assessed using patents and patent citations. Jaffe *et al.* (2000) suggested that patent citations can be used to trace knowledge spillover, creating a paper trail of the knowledge flows between and among companies.

Jaffe *et al.* (2000) concluded that citations contain important information about technological knowledge spillovers (spillovers accompanied by citations), but with a substantial amount of noise (citations that occur where there is no spillover). For this reason, this study tries to extract strong ties, the effects of technological knowledge spillover, based on patent citation to represent directional technology dependence among leading semiconductor companies. However, analyzing networks based on patents often encounters the following difficulties. First, it is difficult to extract actors/assignees to avoid unrepresentative actor influence analyses. Next, the entire prior art will be included in the patent citation when we observe citation network as technological knowledge flow among assignees. This means most of the assignees will have citation relationships among each other. It is also difficult to determine if a citation is representative or only accidental. These issues must be dealt with to analyze technology-dependence networks at the company level. Thus, this study examines and characterizes the dynamic evolution and characteristics of technology dependence by identifying strong ties in citation networks of the semiconductor industry.

II. Patent citation as a measure of technology spillovers

Since Scherer (1982) originally created an input-output matrix of technological innovation to measure technology-oriented knowledge flows, patents have been used to help generate a technological knowledge flow matrix. Many studies use patent data as an indicator of a company's technological knowledge base (Fleming, 2001; Nerkar, 2003; Nesta, 2008). Patents are the direct outcome of a company's inventive effort, and specifically those inventions expected to have commercial value. The applicant's citations represent the patent's prior technologies, where the cited patents are considered technological knowledge inflows in the invention. Huang (2009) investigated the interaction and technological knowledge spillover between science and technology from citation of journal paper and patent in giant magnetoresistance. Lo (2010) examined co-assignees, reciprocal citation, patent coupling and co-patent to reveal the meanings of the correlations generated via different linkages. It implies the different methods to measure knowledge spillover among applicants.

Verspagen and De Loo (1999) identified two different types of technology spillovers. One was identified as "pure" knowledge spillovers. It is not directly linked to the flow of goods, but operates through various other channels (patent information, reverse engineering, mobility of researchers between companies, etc.). The authors proposed a new method of measuring spillovers between manufacturing sectors over time based on patent citations, and found that the amount of technology spillover peaks two years after R&D was performed, and that it gradually wears off 10 to 15 years later. This implies that the distribution of technology spillovers over time is skewed, with an average time lag of around four-and-a-half years between the spillover and the time of R&D. Deng (2008) quantified the economic value of US semiconductor companies based on patent citations, arguing that the total value of knowledge spillovers a company receives can be half of its actual total R&D expenditures. Li *et al.* (2011) discussed patterns of companies' evolution in the semiconductor industry based on patent citations, and showed that foundries have gradually become technology transferors instead of pure manufacturing capacity providers.

III. SNA to evaluate technology network structure

Researchers have long used social network analysis (SNA) to explore relationships between and among actors. Historically, this method has focused on the relationships among human beings. However, since the underlying algorithms emerging from the field of graph theory have become universally applicable, this method has become a popular way to model various relationships, such as the knowledge/technology flow. Using patent information as a basis for investigation, the node in relationship networks can represent the patent documents, inventors, assignees, or countries. The ties can symbolize the dependence between the nodes from citation links. The common research methods in SNA are network characteristics and actor positions in the network.

A. Network characteristics

The most intuitive network measurement is size, defined as the number of direct links between actors. Previous analyses of network size measure the extent to which a company can access resources (Baum *et al.*, 2000). Another measure of network is centrality; this includes the ability to access (or control) resources through indirect and direct links. Degree centrality measures the ability of actors to reach other actors in their network through intermediaries. Researchers have characterized varying degrees of access to resources by measuring network centrality at the inter-organizational level (Powell *et al.*, 1996). A number of studies on entrepreneurial companies operationalize this construct by assessing network density (McEvily and Zaheer, 1999). Density is calculated as the number of ties in the matrix divided by the number of all possible ties (Knoke and Kuklinski, 1982). In SNA, the tie's strength is a network characteristic; an interpersonal tie is a linear combination of the amount of time, the emotional intensity, the intimacy (or mutual confiding), and the reciprocal services that characterize each tie (Granovetter, 1973). Specifically, more novel information flows to individuals through weak ties rather than strong ties (Granovetter, 2004).

B. Actor position in network

A company's position in a technology network can be determined by the technological crowding coefficient (Podolny *et al.*, 1996) and the power centrality index (Bonacich, 1987). Previous studies apply this method to the semiconductor industry (Stuart, 1998; Breschi *et al.*, 2006; Okamura and Vonortas, 2006). Stuart (1998) developed a network-based mapping of the technological positions of the companies in an industry, and applied this model to a longitudinal study of the formation of alliances between organizations. He identified different roles of companies and positioned each of them accordingly at the four partitions of the graph (leaders, brokers, followers, and isolated companies).

Technological crowding coefficient indicates the similarity between patents in terms of their citation patterns. A company's technological crowding coefficient is the sum of the technology coefficient overlap with all other companies in the network. A large value implies high similarity in technological competencies (Podolny *et al.*, 1996). The power centrality index captures the status of an individual company in the network. This index accounts for both the status of a company in the local network and its status in the global network, and includes indirect connections. Bonacich's (1987) modification of the degree centrality approach has been widely accepted as superior to the original measure (Podolny *et al.*, 1996; Dastidar, 2004; Borgatti, 2005). Bonacich argued that centrality is a function of how many connections one has compared to how many connections the other actors in the neighborhood have. Bonacich proposed that both centrality and power are functions of the connections between actors in one's neighborhood. The more connections one has with actors in the neighborhood, the more central one will be.

IV. Methodology

A. Data source and authority control

This study uses data collected from the USPTO Granted Patent Database. The sample was restricted to utility patents granted during the period 1976 to 2009. The US patents for the semiconductor industry were categorized using the Jaffe *et al.* (2005) classification. They divided the US Patent Classification into six technology categories with 36 subcategories, including semiconductor devices. Based on this method, this study selects the semiconductor device category and divides it into three microchip eras (Li *et al.*, 2011) to analyze the technology dependence between and among assignees: the 6-inch (1976-1991), 8-inch (1989-1999), and 12-inch (1997-2009) eras.

Patent databases do not have any authority control for assignees' names. Therefore, this study uses the authority control to establish unified assignee names which collocate with all versions of an assignee patent even if they were issued under alternative names. The authority-controlled names appearing in this study are the names after companies merged or spun off. For example, Chartered was controlled as GlobalFoundries; Hyundai and LG as Hynix Semiconductor, etc.

B. Sample selection

B-1 Extracting strong ties in a citation network. The thresholds to extract strong ties among companies by citation relationships are set as following:

- the citation count of the tie between a company pair must be higher than the median of citers' citation ties; and
- this link shares a higher proportion of citers' citations than the proportion of citation in the entire industry (activity index (AI) > 1).

Albert (2000) used the AI to measure the concentration of a specific technology in a company's patents. When the value of this index exceeds 1, it means that a company's patent activity in a given technology field is above average. This study uses the AI to measure the concentration of a specific citation tie between a company pair. The index for the tie between company i and j is formally defined as:

$$AI_{i,j} = \frac{\text{Citation of Company}_\text{i}\text{ be cited by Company}_\text{j}/\text{Total citation of Company}_\text{j}\text{ citing to}}{\text{Total citation of Company}_\text{i}\text{ be cited}/\text{Total citation of the Industry}} \quad (1)$$

These thresholds requires that the citation tie be higher than the median of citer's all citation to ensure that this tie is stronger than other ties of the same citer. The AI is more than 1 to assure that this citation tie is significant in the entire industry. When a citation tie fit these thresholds, it is a strong tie and representative of technology dependence. As an example, Table I shows two thresholds of extracting strong ties marked separately. Seven ties fit threshold one and 14 ties fit threshold two, but only six ties fit both thresholds, and are regarded as strong ties and representative of technology dependence. According to equation (1), the calculation of $AI_{A,B} = 0.47$ in Table I is (3/42)/(27/177).

B-2 Extract leading company in the citation network

This study calculates the technological crowding coefficient and the technological prestige for each company in the semiconductor industry. Companies in the top 20 percent of the technological crowding/prestige in the strong ties network were classified as leading companies:

- *Technological crowdedness*. Stuart (1999) proposed an indicator that makes it possible to summarize the position of individual companies within the overall network. The technological crowding index measures the extent to which company i performs research in crowded technological areas, or areas where the research efforts of company i overlap with those of other companies.

	Citation count (AI) of citer					
Patentee	A	B	C	D	E	Sum
A	–	*3 (0.47)*	**11 (2.06)**	**8 (1.05)**	**5 (1.82)**	27
B	**5 (1.02)**	–	**9 (1.69)**	*7 (0.92)*	**6 (2.19)**	27
C	**6 (3.02)**	–	–	**5 (1.61)**	–	11
D	**14 (1.94**	**19 (2.00)**	–	–	**7 (1.72)**	40
E	*7 (0.54)*	**20 (1.17)**	**15 (1.05)**	**30 (1.48)**		72
Median	6.5	19.5	12	7	6	
Sum	32	42	35	50	53	177

Notes: Threshold 1 (italics): citation count higher than median of citer's all citation; threshold 2 (bold): activity index of this tie > 1

Table I.
The example of extracting strong ties

- *Technological prestige (power centrality)*. Bonacich's power centrality or actor's centrality (prestige) is equal to a function of the prestige held by connected companies. Thus, actors who are tied to very central actors should have higher prestige/centrality than those who are not (Bonacich, 1987).

C. Measuring network structure

This study identifies leading companies and the strong ties among them to analyze the characteristics and evolution of technology dependent relationships. The structure of technology dependence network is measured by using network density, degree centrality, and the clustering coefficient of the network.

Network density. The density of a graph is defined as the number of ties it contains, expressed as a proportion of the maximum possible number of ties (Scott, 2000). This measure can vary from zero to one, with the density of a complete graph being one.

Degree centrality. Nodes that have more ties to other nodes may indicate advantageous positions. Thus, degree centrality is a very simple but effective measure of their centrality and power potential. With directed technology dependence based on patent citation relationship in this study, it is important to distinguish centrality as out-degree and in-degree (Freeman, 1979). The out-degree centrality of company *i* refers to the number of targets company *i* is depended upon by other companies. The higher out-degree centrality is, the more targets company *i* is depended upon by others, meaning momentum of technology diffusion from company *i* to other companies. The in-degree centrality of company *i* refers to the number of targets company *i* depends upon other companies. The higher in-degree centrality is, the more targets company *i* depends upon other companies.

Clustering coefficient of network. A clustering coefficient is a measure of the degree to which companies in a network tend to cluster together. The overall network clustering coefficient is the average of the densities of the neighborhoods of all the companies. In assessing the degree of clustering, it is usually wise to compare the cluster coefficient to the overall density (Holland and Leinhardt, 1971). High clustering values – where all of one company's depending targets' depending targets are also the company's own depending targets – imply that it is difficult to reach an unknown target company (to disseminate technology) if this company does not already exist in the depending circle of companies.

V. Results

A total of 20 leading companies in the semiconductor industry were identified as the top 20 percent technological crowded/prestige companies in Table II. Seven leading companies were identified in the 6-inch chip era, with IBM earning the greatest technological prestige. Five leading companies were identified in the 8-inch chip era, with AMD appearing again and SAMSUNG earning lower prestige. Nine leading companies were identified in the 12-inch chip era, with Micron earning the greatest technological prestige. Leading companies from the three eras mentioned above performed higher and higher crowded coefficient, which implies that technology of leading companies overlaps gradually with that of other companies. Furthermore, IBM in the first era and Micron in the third era both obtain the highest prestige obviously, which means the two companies are much technologically connected with other companies. These tied companies also have higher centrality.

Table II.
Technological crowded/prestige of leading companies

Leadings from 6-inch	Technological Crowded	Technological Prestige	Leadings from 8-inch	Technological Crowded	Technological Prestige	Leadings from 12-inch	Technological Crowded	Technological Prestige
AMD[a]	8.47	6.06	AMD[a]	10.95	14.67	Amkor	46.84	2.88
IBM	8.44	112.89	National Semi.	10.83	13.04	GlobalFoundries	25.36	4.39
Intel	8.30	8.29	Samsung	10.64	7.16	Hynix	22.27	3.12
LSI Logic	8.82	4.88	STMicroelectronics	11.75	14.33	Macronix	39.03	3.21
NEC	9.14	4.68	UMC	11.61	12.54	Micron	25.07	149.19
TI	7.77	31.53				Motorola	22.18	10.81
Toshiba	8.46	18.92				Sharp	25.91	2.96
						TSMC	20.05	16.59
						VIS	24.70	6.58
AVG. of others	5.55	2.07		8.12	4.69		16.21	1.50

Note: [a]Continued leading company in 6- and 8-inch eras

A. Network structure and patent trends

To observe the technology dependence among companies, the strong ties were extracted from patent citation network. This study separates original citation ties and strong ties, as Table III shows. The density, average distance, and clustering coefficient of original ties show a closer citation relationship than strong ties. In the original tie, leading companies show network density and clustering coefficient values of 0.69 to 0.99, where maximum values close to 1.0 demonstrate a nearly complete linkage in the citation network. However, if we observe strong ties, it does not matter if the network density or the clustering coefficient is lower than the original ties. In this table, the network density of leading companies drop from 0.17 to 0.11, but the clustering coefficient climbs from 0.22 to 0.45. This demonstrates technology dependence mainly within a neighborhood (increasing clustering coefficient), but the relationships of the entire industry are actually becoming more sparse (decreasing network density).

Figure 1 shows the leading company's high patent quantity and quality performance. The left half shows the patent trends of leading companies and the entire semiconductor industry. In the 6-inch chip era, both grew slowly. They start to grow quickly from the 8-inch chip era until the first half of the 12-inch chip era. Stagnation begins in the 12-inch chip era. Though leading companies exhibit growing tendencies in the earlier 12-inch chip era, they drop in the later 12-inch chip era.

The patent quality achieved by leading companies, the share of patent count, and ratio of average cited times of each patent relative to the entire industry appear in the right half of Figure 1. The relative ratio in patent count changes approximately within the 0.2-0.5 range, but the relative ratio in average cited times of each patent is higher than 1.0 in nearly every year. This demonstrates that though leading companies have only 20-50 percent patent share, they achieved higher patent quality than

Network characteristics	Original ties in era 6-inch	8-inch	12-inch	Strong ties in era 6-inch	8-inch	12-inch
Actors	15	20	20	15	20	20
Ties	155	368	397	39	68	42
Density	0.69	0.92	0.99	0.17	0.17	0.11
Avg. distance	1.23	1.08	1.01	1.80	1.56	2.0
Clustering coefficient	0.78	0.93	0.99	0.22	0.45	0.45

Table III. Network characteristics of leading companies

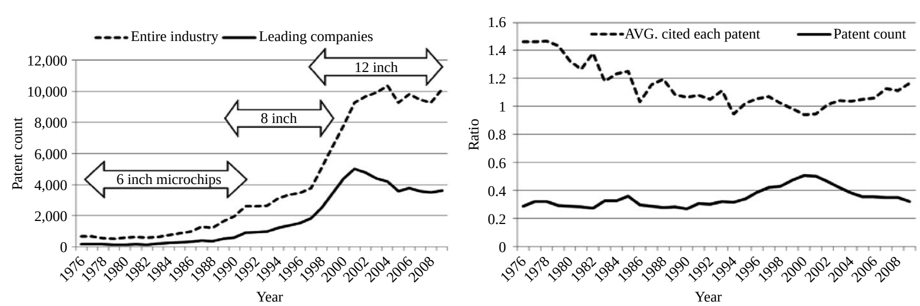

Figure 1. Patent count and cited ratio of leading companies vs entire industry

the entire industry. This implies that these companies support the industry's technological development.

B. Evolution of technology-dependence network

This study examines characteristics and evolution of technology dependence among leading companies in the 6-, 8- and 12-inch chip eras. Network out-/in- degree centrality measures how much technology flows out from or into each company, as Table IV illustrates. Figure 2 maps the technology-dependence network of leading companies using the AI of strong ties.

1. Company actions in each era. The leading companies identified in the 6-inch chip era are seven integrated device manufacturers (IDMs). IBM, NEC, TI, and Toshiba are pure technology suppliers (with technology flow-out) in 6-inch chip era. NEC and TI remain pure technology suppliers in the 8-inch chip era; IBM and Toshiba have become internal patent users without network dependence upon other leading companies in the 8- and 12-inch chip eras. Other 6-inch companies (i.e. AMD, Intel, and LSI Logic)

	Degree centrality in						Correlation coefficient for dependent targets[a]	
	6-inch		8-inch		12-inch			
Leading company	Out	In	Out	In	Out	In	6- and 8-inch	8- and 12-inch
Selected from 6-inch era								
AMD[b] (I)[c]	42.9	7.1	0.0	26.3	10.5	5.3	0	0
IBM (I)	7.1	0.0	0.0	0.0	0.0	0.0	0	0
Intel (I)	35.7	21.4	26.3	0.0	5.3	0.0	−0.068	0.288
LSI logic (I)	28.6	21.4	10.5	0.0	0.0	0.0	0	0
NEC (I)	14.3	0.0	5.3	0.0	0.0	0.0	−0.105	0
TI (I)	14.3	0.0	5.3	0.0	0.0	0.0	0	0
Toshiba(I)	7.1	0.0	0.0	0.0	0.0	0.0	0	0
Selected from 8-inch era								
National Semi. (I)	21.4	21.4	5.3	0.0	5.3	5.3	0	−0.053
Samsung (I)	0.0	21.4	21.1	15.8	5.3	5.3	0	0.484*
STMicroelectronics (I)	0.0	14.3	15.8	0.0	0.0	0.0	−0.105	−0.096
UMC (F)	N/A[d]	N/A	31.6	31.6	15.8	15.8	N/A	0.617**
Selected from 12-inch era								
Amkor (P)	N/A	N/A	0.0	10.5	5.3	10.5	N/A	0
GlobalFoundries (F)	N/A	N/A	21.1	42.1	15.8	21.1	N/A	0.886**
Hynix (I)	0.0	28.6	26.3	21.1	5.3	10.5	0	−0.131
Macronix (F)	N/A	N/A	0.0	31.6	0.0	10.5	N/A	0
Micron (I)	0.0	28.6	15.8	0.0	5.3	0.0	0	−0.096
Motorola (I)	21.4	7.1	5.3	0.0	0.0	0.0	0	0
Sharp (I)	0.0	0.0	10.5	0.0	0.0	0.0	0	0
TSMC (F)	0.0	21.4	31.6	47.4	15.8	21.1	0	0.617**
VIS (F)	N/A	N/A	21.1	26.3	26.3	10.5	N/A	0.892**
Wilcoxon test for expression continued[e]	–	–	0.341	0.479	0.003**	0.008**		

Notes: Significance at: $^*p < 0.05$, $^{**}p < 0.01$ (two tail); [a]Spearman correlation coefficient test for technology-dependent target between eras; [b]continued leading company in 6- and 8-inch eras; [c]company type: (I): IDM; (F): Foundry; (P): Packaging; [d]N/A: company without patent granted in this era; [e]Wilcoxon test of degree centrality expression continued from prior era, **: $p < 0.01$

Table IV. The characteristics of leading companies in tech dependence network

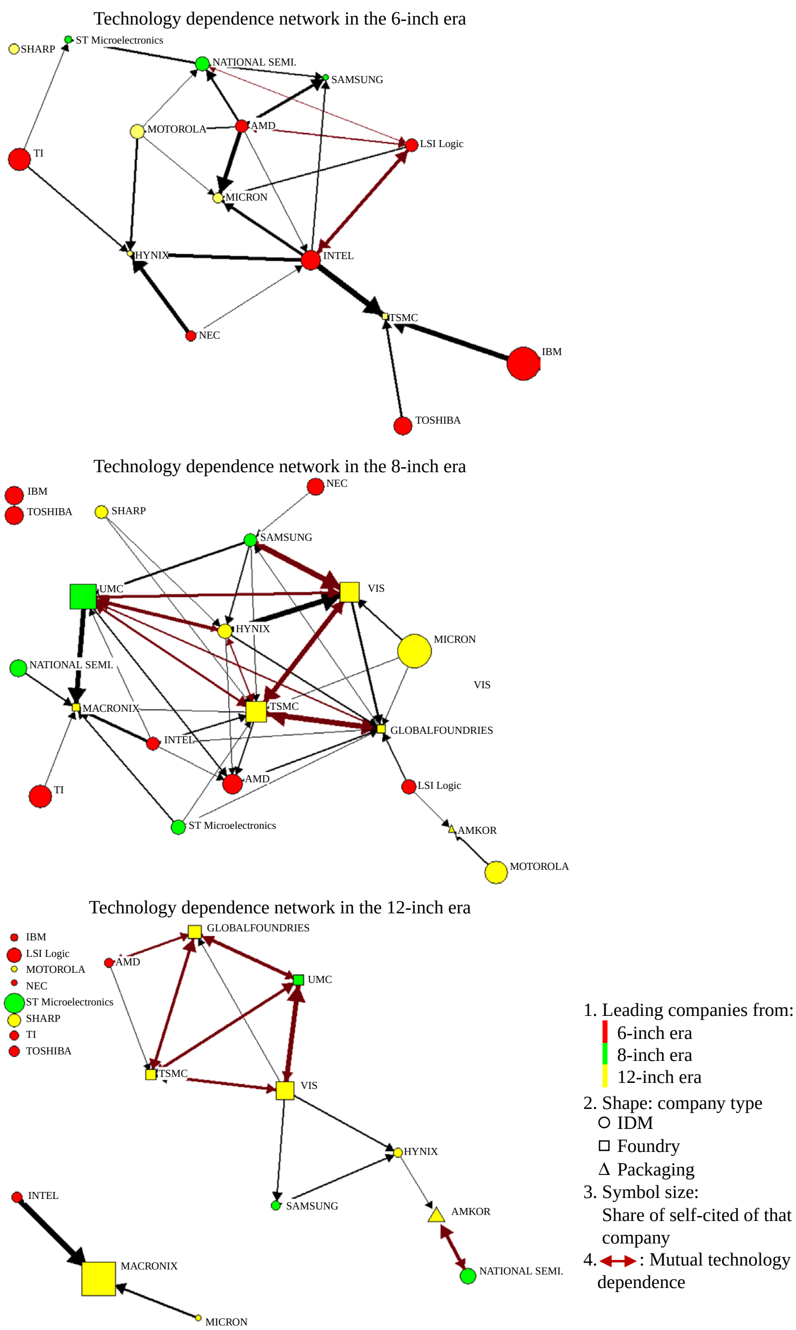

Figure 2.
Technology dependence network in each era

exhibit technology flow-in and flow-out in the first era and are also active in the following eras.

Five companies are identified in the 8-inch chip era, where AMD has already been identified in the 6-inch chip era. The IDMs such as AMD, National Semi and Samsung, are almost technology flow-in and -out companies for three whole eras. Stmicroelectronics, one of the IDMs, receives technology in the 6-inch chip era but supplies technology in the 8-inch chip era. The only foundry coming from the 8-inch chip era, UMC, has no patent output in the first era. However, in the following eras, UMC and other companies are technologically interdependent.

The most leading companies across three eras are selected from the 12-inch chip era, including four IDMs, four foundries and one packing company. The only one packaging, AMKOR, as well as three foundries (Globalfoundries, Macronix and VIS) has no patent grant in the 6-inch chip era. They become active in the following eras. Hynix, Micron and TSMC all are pure technology receivers in the first era. Whereas, Micorn transforms itself into pure technology supplier, Hynix and TSMC become technologically interdependent upon others in the following eras. This indicates these companies are also active in the 8- and 12-inch chip eras. Motorola and Sharp are technology suppliers in the 8-inch chip era but both of them withdraw in the 12-inch chip era. Comparatively Motorola is more active in the first era, but Sharp is not.

2. Technology dependence among companies. The results of Wilcoxon's (1945) signed rank test in Table IV show that the normalized out- and in-degree network centrality of companies in the 8- versus 12-inch chip eras are significant at a two-tailed p-value < 0.01, but they are insignificant in the 6- versus 8-inch chip eras. This means that companies' roles (technology supplier or receiver) changed significantly between the 8- and 12-inch chip eras.

In the 6-inch chip era, IDMs themselves have performed high-technology interdependence. AMD and Intel with higher out-degree centrality are technologically depended upon by other IDMs (National Semi, Samsung, LSI Logic, Micron, Motorola, and Hynix). TSMC is the only Foundry whose technology depends upon IBM, Intel, and Toshiba. Self-citation rates show that the technology suppliers (high out-degree centrality) have higher self-citation rates, while technology receivers (high in-degree centrality) have lower self-citation rates. This indicates that the 6-inch companies were the primary technology R&D actors because they referenced their own technologies, which are also used by other companies.

In the 8-inch chip era, IDMs are significantly technologically depended upon by foundries; foundries themselves are highly technological interdependent. The IDMs – Intel, LSI Logic, NEC, TI, National Semi, STMicroelectronics, Micron, Motorola, and Sharp – all of them are pure technology suppliers and technologically depended upon by the foundries and the packaging. The foundries, including UMC, VIS, and TSMC, perform mutual technology dependence; Macronix depended upon UMC, GlobalFoundries and TSMC are interdependent. In this era, Amkor and Macronix, with lower self-citation rates, are pure technology receivers, the same phenomenon as in the prior era.

In the 12-inch chip era, more IDMs are isolated, and foundries are mutually dependent in the technology dependence network. The IDMs, including IBM, LSI Logic, NEC, TI, Toshiba, STMicroelectronics, Motorola, and Sharp, are wholly isolated from the technology dependence network in this era. Three foundries exhibit closer technology interdependence: TSMC and UMC, respectively, with GlobalFoundries.

VIS continues its technology interdependence with TSMC and UMC as it did in the prior eras. Eventually, they exhibit the closest technical correlation. Macronix depends upon Intel and Micron's technology, and they exhibit an isolated technology-dependent relationship without strong ties connecting to other companies. IBM, Micron, Motorola, and NEC have the lowest self-citation rates in this era. This differs from the previous era when companies with lower self-citation rates were pure technology receivers. Lower self-citation rate companies like Motorola, NEC, and IBM withdraw from the technology dependence network, but Micron becomes a pure technology supplier.

3. Extension of technology dependence. According to Spearman's (1904) rank correlation coefficient in Table IV, no companies get significant correlation for technology dependent targets in 6- and 8-inch chip eras. It means companies almost technology depending upon different targets. But in 8- and 12-inch chip eras, IDM only Samsung gets correlation for technology dependent targets at the 0.05 significance level, and four foundries, UMC, GlobalFoundries, TSMC and VIS, get correlation at the 0.01 significance level. It means these five companies getting higher extension with technology dependent targets.

In advance of Figure 2 shows the extension of technology dependence from the 6- to 8-inch chip eras, and from the 8- to 12-inch chip eras. The only continued relationship from the 6- to the 8-inch chip era is TSMC, which depends upon technology from Intel. The other continued relationships exist from the 8- to the 12-inch chip era, during which Macronix continues technology dependence upon Intel and forms individual technology dependence in the 12-inch chip era. The technology flow continues from the 8- to 12-inch chip eras, from VIS through Samsung to Hynix, and finally to AMD, UMC, and TSMC, demonstrating their continued technology dependence. In addition, TSMC and UMC continue their technology interdependences with GlobalFoundries and VIS, respectively. However, VIS and GlobalFoundries have unidirectional dependent relationships; these four companies have continuous close technology interdependence.

4. Technology dependence based on company types. Leading companies can be classified into IDMs, foundries, and packaging. Because of the scarcity of packaging company, this study focuses on the normalized share rate of strong ties relative to all possible ties between IDMs and foundries in each chip era, with the ratio reorganized in Table V. The technology-dependence phenomenon based on company type shows the closest technology dependence among foundries. There are 65 and 55 percent interdependence rates among foundries in the 8- and 12-inch chip eras, even an 84.6 percent dependent relationship continues across these two eras with correlation at the 0.05 significance level in company type of each foundry company depends upon. The technology dependent rate among IDMs is lower than that of foundries, falling from 14.8 to 1.1 percent across the three eras, and a 20 percent interdependent relationship continues across the 8- and 12-inch chip eras. The rate of IDMs' technology dependence upon foundries is 7.1 percent decreases to 4.3 percent among the last two eras with a continuing 40 percent dependent relationship at the same time. The rate of foundries' technology dependence upon IDMs also descends to 5.7 percent in the 12-inch chip era, with a continuing 4.8 percent dependent relationship at the same time.

VI. Conclusion and discussion

This study examines the characteristics and evolution of the technology-dependence networks of leading semiconductor companies. The strong ties extracted from citation

Table V.
Normalized technology dependent rate between IDMs & foundries

Tech. suppliers	Tech. receivers IDMs in era 6-inch	 8-inch	 12-inch	 Foundries in era 6-inch	 8-inch	 12-inch
IDMs (14 companies)	14.8% (27/182)	2.7% (5/182)	1.1% (2/182)	21.4% (3/14)	30% (21/70)	5.7% (4/70)
Sustained strong ties (correlation coefficient)		0% (0.056)	20.0% (−0.094)		33.3% (−0.135)	4.8% (0.189)
Foundries (five companies)	–	7.1% (5/70)	4.3% (3/70)	–	65% (13/20)	55% (11/20)
Sustained strong ties (correlation coefficient)		0% (N/A)	40.0% (−0.125)		0% (N/A)	84.6% (0.918*)

Note: Spearman correlation coefficient test for company type of sustained technology dependence, $^{*}p < 0.05$ (two-tail) network as the technology-dependent relationships are the first appearance. This method makes it possible to detect whether the ties among assignees are representative or accidental. Comparing and contrasting technology dependence network in the 6-, 8- and 12-inch chip eras reveals the differences among IDMs and foundries, and among each company in all eras. Results show that leading companies lead semiconductor technology development. This study also figures the R&D isolation of IDMs and the interdependence among foundries. Technology interdependence between IDMs and foundries decreased during the 12-inch chip era. This downward trend can be attributed to the change from IDM to the fab-lite or fabless business model. For example, AMD spun off its foundry business, and in 2009-2010, merged with Chartered Semiconductor to form GlobalFoundries in a fabless model to avoid the R&D costs of manufacturing facilities. This finding agrees with Li *et al.* (2011), who found that foundries are expanding beyond the role of the traditional manufacturing capacity provider relying only on its affluent capital resources. Foundries also gradually become technology transferors instead of pure manufacturing capacity providers. Another finding is the foundries' high technical relationship. This study finds that foundries (GlobalFoundries, TSMC, UMC and VIS) form a technology dependence clique and extend their interdependence relationships from 8- to 12-inch chip eras. As for the market share in 2010, TSMC accounted for 48.4 percent, UMC 15.2 percent, and GlobalFoundries 14.0 percent (Industry & Technology Intelligence Service, 2010). These top foundries share 77.6 percent of the foundry market in highly competitive relationships, but all are the IBM consortium partners in cooperative relationships. This study also reveals technology interdependence relationships among these top foundries. A detailed technology flow among them benefits future analysis by revealing their connection in the technology level, and contrasting it with their alliances.

The results of this study show that the proposed research model and findings have important implications for business managers planning to select R&D partner or detect potential competitor of the semiconductor industry. In the 8-inch chip era, IDMs and foundries are more technologically interdependent, but they become technologically isolated in the 12-inch era. It seems that the relation between IDM (more fabless/fab-lite) and foundry is transforming: from vertical to horizontal technology cooperation partnership. One implication is that the IDM could assess the foundry in terms of technology-dependent relationship, and go a step forward to form R&D consortium. For example, in the 12-inch chip era, Intel (IDM) and Micron (IDM)'s technology are depended upon by Macronix (foundry); AMD (IDM)'s technology is depended upon by GlobalFoundries (Foundry) and TSMC (foundry); Samsung (IDM) and Hynix (IDM) depend upon VIS (foundry)'s technology. The technology dependence network as a whole supports IDM to select proper foundries and decide technology partnerships.

Furthermore, as for high technology interdependence, the second implication is that Foundry could find out whether their competitor of higher technology interdependence is possible to be a target for monitoring. For example, in the 12-inch chip era, GlobalFoundries, UMC, TSMC, and VIS have high technology-interdependent relationships, which imply that these foundries' technologies are homogeneous so that commercial competition could be high. It should be noted that technology-dependence network helps to find out potential competitors in the technology level, and its reflection for competitive advantage in R&D would be more meaningful in the commercial level if an extensive research on price study, demand forecast and demand fulfillment planning, capacity planning, capital expenditure, cost structure, customer loyalty, and effect of industrial cluster is added up.

Another implication for academic research could be seen in foundries' highly technology interdependent relationships in the 12-inch chip era. It may be an indicator to observe semiconductor manufacturing technology's evolving into the maturity stage of product life cycle. In this stage, the costs of the production fall dramatically due to standardized production. This ensures mass production of the goods and hence the company receives the benefits of economies of scale (Vernon, 1966). To foundry companies in this era, high technology interdependence means overlap between technologies. Thus, we may infer that the manufacturing technology may be in the maturity stage.

Exploring the positions of other companies (e.g. broker, follower and isolated companies) in the semiconductor technology-dependence network from deeper and wider perspectives is a topic worthy of further research. Contrasting the already-observed weak ties with strong ties among the network to realize their interaction at an all-over/advanced technology level is another endeavor for future research. To be more ambitious, the relationship between technology dependence and alliance, if any, could be forecasted with the help of substantial alliance information. Finally, it would helpful to observe technology alliance from the angle of dependence, or vice versa.

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