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Strong ties and weak ties of the knowledge spillover network in the semiconductor industry

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A B S T R A C T

This study aims to analyse knowledge spillovers across semiconductor companies through two channels with time evolution. Depending upon the wafer diameters, this study divided the technological development into three periods: 6 in. (1976–1991), 8 in. (1989–1999) and 12 in. (1997–2011). R&D cooperation and patent citations were used to measure the strong ties and weak ties of knowledge spillover networks. Adopting patent bibliometrics and social network analysis, this study examined main companies' network structures and channels of knowledge spillovers. Results showed that semiconductor-related knowledge spilled over more efficiently through weak ties than through strong ties. Furthermore, it was found that strong ties could be used to monitor the development of shared technologies, and weak ties could be used to monitor the development of specific technologies. During the period of the 6-inch wafer diameter, companies that had high degrees of centrality in both strong and weak ties of knowledge spillovers included: Toshiba, Mitsubishi, NEC, Hitachi and National Semi. During the period of the 8-inch wafer diameter, such companies included: STMicroelectronics, Mitsubishi, NEC, TI, Toshiba, Siemens and Philips. During the 12-inch wafer diameter, such companies included: Samsung, Toshiba, NEC and STMicroelectronics.

1. Introduction

Facing the fast-changing business environments in the age of knowledge-based economy, companies are continuous innovation and opening up their organisational boundaries to tap into external knowledge (Berchicci, 2013). The conventional paradigm of organisational core R&D activities is exclusively in-house and becomes less critical, while recent research of innovation has suggested companies open up their R&D borders to tap into external sources of knowledge (Chesbrough et al., 2006). Tapping into external technology sourcing alleviates some challenges companies face such as shorter product life cycles, faster product renewals and increasing R&D costs (Rigby and Zook, 2002).

Early innovation models in companies were an internally controlled process. The company was just an innovation locus and the innovation process kept away from competitors and other external actors to ensure that the knowledge was kept in-house. Instead of closed innovation, an open innovation paradigm is suggested, where the R&D structure should be seen as an open system (Chesbrough, 2003; Chesbrough et al., 2006). This paradigm assumes that "*firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as firms look to advance their technology*" (Chesbrough, 2003, p.24). Companies are no longer the exclusive locus of innovation. In fact, external and internal knowledge is equally important. How to obtain external knowledge has become an important issue for running a company (Berchicci, 2013).

Companies in open innovation alliances through knowledge spillovers can benefit the rivals of participating companies (Han et al., 2012). Knowledge spillovers are regarded as the process where the knowledge transfers from producers (knowledge sources) to users (knowledge receivers), which can also be seen as a learning process (Griliches, 1992; Smith, 1995). A knowledge spillover is defined as a phenomenon that "*the existence of technologically related research efforts of other firms may allow a given firm to achieve results with less research effort than otherwise*" (Jaffe, 1986, p.984).

Similar to measuring knowledge spillovers, a number of different approaches have been used to measure the degree of open innovation across companies' borders. These metrics include: pecuniary (e.g., investment in collaborative R&D), time (e.g., time for licensing), industrial property rights and market (e.g., the number of patents and joint patents), collaborative projects and human resources (e.g., the number of R&D employees involved in collaboration), sources of knowledge (e.g.,

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Table 1
Characteristics of the network structure of knowledge spillovers between semiconductor companies in different wafer diameter periods.

	Strong/weak ties		
	6-in.	8-in.	12-in.
Number of companies	129	194	292
Number of ties	338/804	580/1402	1298/3305
Network density	0.02/0.05	0.02/0.04	0.02/0.04
Average path length	3.39/2.28	3.24/2.35	3.11/2.42
Clustering coefficient	0.54/0.21	0.23/0.22	0.25/0.24

the number of external sources of knowledge), and practices (e.g., R&D outsourcing and alliances) (Michelino et al., 2015). As implied in the variation of metrics, different channels of knowledge spillovers among companies can be measured.

Network analysis is a commonly-used method for observing relationships of knowledge spillovers among companies, including identifying the contributors in direct and indirect research collaboration network (Fershtman and Gandal, 2011); understanding how ties in the knowledge spillover network are used and activated for business activity (Jack, 2005); investigating the structure of international technology diffusion (Shih and Chang, 2009); and examining how the competencies and resources are transferred to another actor that uses them to enhance transactions with a third actor (Uzzi and Gillespie, 2002).

Many studies have investigated knowledge spillovers among companies. Although the flow channels and flow intensity of knowledge spillovers have been changing over time, related topics remain scarcely investigated. In this respect, identifying different knowledge spillover channels may help expand spillover networks, and tracking the process of network growth may inform further knowledge transfer, which in turn helps expand the knowledge spillover network (Xiang et al., 2013). This paper addresses this issue by investigating how the knowledge spillovers between companies in the semiconductor industry. In this paper, R&D cooperation is regarded as a channel of knowledge spillovers as strong ties between companies, and patent citations as another channel of knowledge spillovers as weak ties. Through different spillover channels, the authors investigate network structures of knowledge spillover channels and main actors in knowledge spillover networks in each wafer diameter periods. Findings of this study could help semiconductor companies grasp the characteristic and function of knowledge spillover channels.

In terms of studies on interfirm networks, the uncertain environment and abundant resources have an impact on the differences of company networks. If a comprehensive investigation of the evolution of interfirm networks within a field is to be achieved, the field needs to have a long history of development and possess complete information for use (Koka et al., 2006). Knowledge spillover network is defined as a group of nodes and their connections, which implies an assumption of the “stability” of the network. However, the “dynamics” of the network remain unexplored (Degenne and Forsé, 1999). To this end, this study analyses knowledge spillovers between semiconductor companies for the past 36 years, which is divided into three time periods depending upon the wafer diameters (including six inches, eight inches and 12 in.). Specifically, this study adopts patent bibliometrics, social network analysis and statistical tests to examine main companies' network structure (including strong and weak ties) and channels of knowledge spillovers in the semiconductor industry.

For the purpose of analysing knowledge spilled over across companies through different channels with time evolution. The rest of this paper is organized as follows. In Section 2, we review the literature and propose a method for constructing strong and weak ties in knowledge spillover networks. Section 3 provides a detailed procedure of

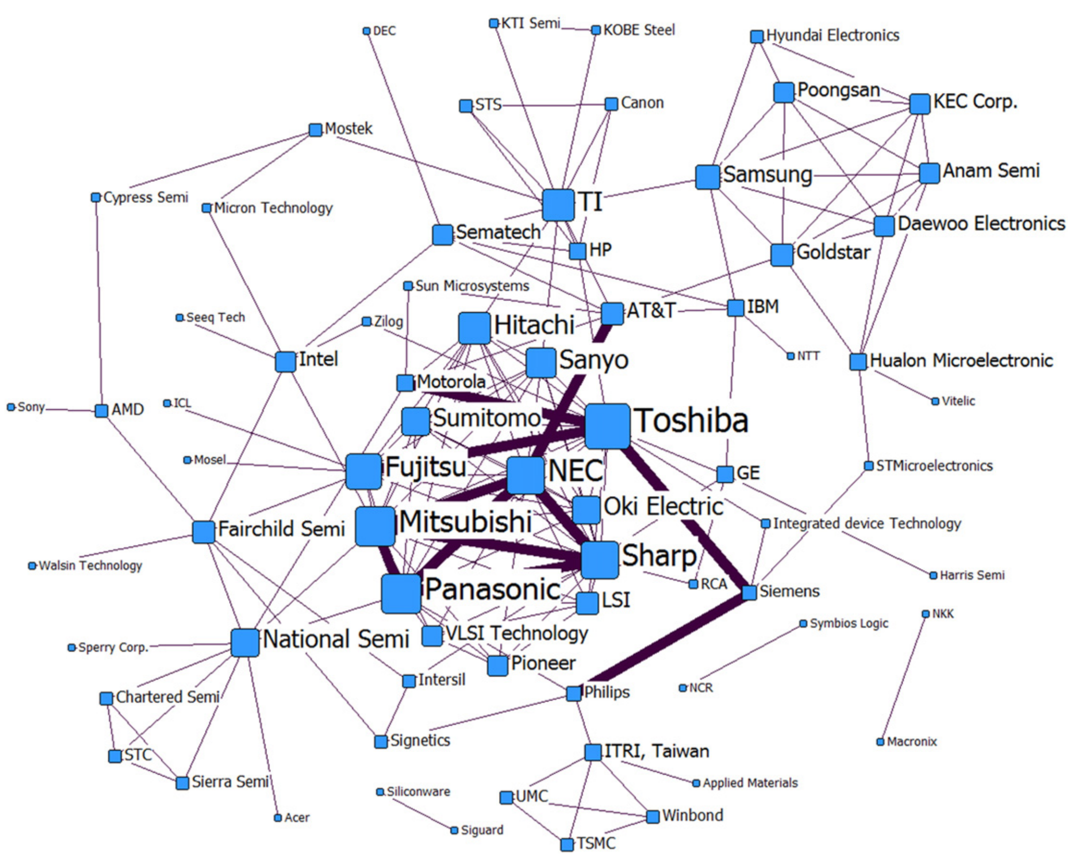

Fig. 1. Network diagram of semiconductor companies in the strong ties during the 6-in. wafer diameter period (Note: Nodes and sizes of companies' names: degree centrality; thickness of lines: frequency of R&D cooperation).

our method on how to construct and measure R&D cooperation as the strong ties and patent citations as the weak ties data in knowledge spillover networks. In Section 4, we apply the procedure to construct strong and weak ties of knowledge spillover networks in three periods based on our selected sample dataset. We discuss our results and analyse various structural properties and characteristics of actors in the constructed networks. Then, the last section summarizes our main findings and lists the implications as well as the limitations of this research.

2. Literature review

Firstly, the definition and measuring indices of knowledge spillover network are introduced. Second, we illustrate the definition of strong ties and weak ties in the knowledge spillover network. Finally, R&D cooperation is considered as the proxy variable of strong ties and patent citations as the proxy variable of the weak ties in the knowledge spillover network.

2.1. Knowledge spillover network

The concept of knowledge spillover was first proposed by Schmookler (1966). Since then, knowledge spillover has as a result of some companies' research findings been used by other companies without permission (Spence, 1984). The term, 'knowledge spillover', refers to the sharing, interaction and exchange of knowledge, which is the process where the knowledge transfers from producers (knowledge sources) to users (knowledge receivers) (Smith, 1995). The phenomenon that "*the existence of technologically related research efforts of other firms may allow a given firm to achieve results with less research effort than otherwise*" was an effect of knowledge spillovers (Jaffe, 1986, pp.984).

Knowledge spillovers would be influenced by five key factors: the value of knowledge possessed by subsidiaries, motives of subsidiaries for sharing knowledge, the existence and abundance of channels for transferring knowledge, motives of subsidiaries for receiving knowledge, and the absorptive capacity of subsidiaries for receiving knowledge (Gupta and Govindarajan, 1991). Furthermore, the evaluation of firms' knowledge value depends upon how much the firm possess highly-valued knowledge which is difficult for competitors to imitate. It is argued that it is only meaningful if the knowledge shared by subsidiaries has high relevance to knowledge receivers (Gupta and Govindarajan, 1991).

Research about knowledge spillovers based on Social Network Analysis is common. Network structure properties: the number of nodes, the number of ties, network density, average path length, and cluster coefficient were used to depict knowledge spillover across countries separated to embodied and disembodied technology networks (Xiang et al., 2013), across institutions and technology fields (Choe et al., 2013), and across individuals/inventors (He and Fallah, 2009). Centralities of nodes were also the common indices used to evaluate importance of actors in the knowledge spillover network. Centrality indices were used to identify the important or prominent countries (Shih and Chang, 2009); the degree centrality of the inventor/assignee network is a key indicator to measure innovation performance in two periods (He and Fallah, 2009). These network structure indices (the number of nodes, the number of ties, network density, average path length, and cluster coefficient)

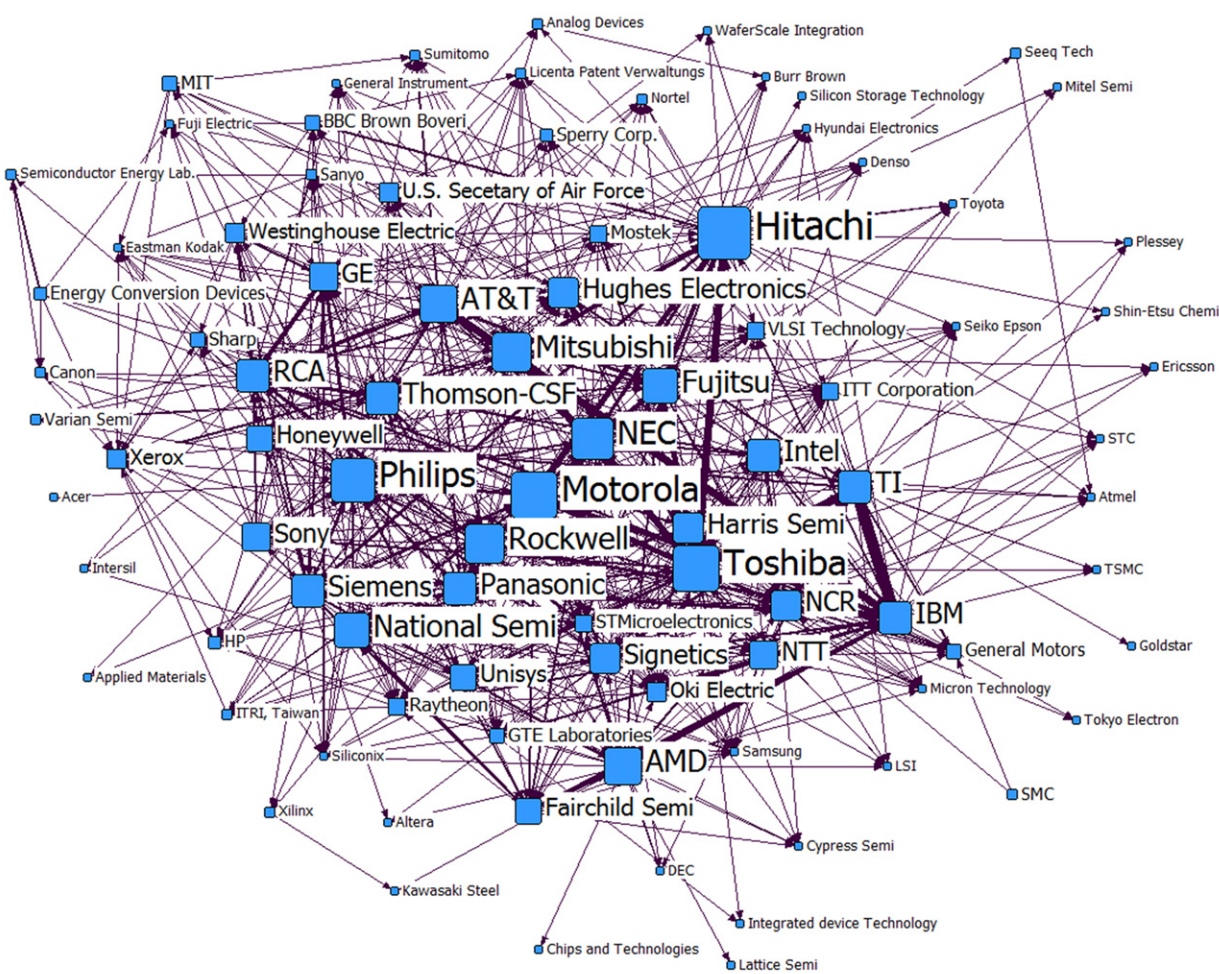

Fig. 2. Network diagram of semiconductor companies in the weak ties during the 6-in. wafer diameter period (Note: Nodes and sizes of companies' names: outward degree centrality; thickness of lines: frequency of patent citations; directions of arrows: directions of knowledge flows).

and actor position indices (degree centrality) all measured in this study to compare differences between two channels of knowledge spillover networks in three periods.

2.2. Strong and weak ties in the knowledge spillover network

This study aims to analyse the evolution of knowledge spillovers across semiconductor companies based on the strong and weak ties of social network theory. In terms of the strength of the ties between nodes in a network, the relationships of the ties were considered either one-way or reciprocal (Granovetter, 1973; Hansen, 1999; Marsden and Campbell, 1984; Mitchell, 1969). Strong ties and weak ties can also be distinguished based on the strength of the ties. Scholars found different advantages for using the strength of dyadic ties to investigate strong ties and weak ones. For example, weak ties are often more important than strong ties (Granovetter, 1973). This proposition rests on the assumption that strong ties tend to bond similar, well-defined people together, where the information obtained is more likely to be redundant, and thus not useful for innovation. In contrast, a weak tie more often constitutes different parts of the social system that are not easily defined, where new information is more likely to be obtained from disparate parts of the system. Echoing this proposition, weak ties are considered helpful for looking for different ideas (Granovetter, 1983; Rogers, 2003). However, strong ties are more important than weak ties, because both parties connected by a strong tie would be more willing to help each other and disseminate information (Krackhardt, 1992), and useful knowledge is more likely to be gained through strong ties (Ghoshal et al., 1994; Szulanski, 1996; Uzzi, 1997). Both strong ties and weak ties show different advantages (Hansen, 1999; Hansen, 2002). Strong ties between groups request more investment to maintain but weak ties do not. In this respect, the costs of codified knowledge transfer through weak ties tend to be lower, and therefore more efficiently.

In this study, R&D cooperation, which involves reciprocal, longitudinal interactions and concrete written agreements, is regarded as strong ties of knowledge spillovers between companies. The R&D cooperation relations between semiconductor companies collected in this study include: co-funded research companies, research collaboration agreements, technology exchange agreements, direct investment in technology, technology licensing agreements, and subcontracting agreements (including co-production, research associations, government-funded research collaboration projects, and joint patent applications), as defined by Freeman (1991). Joint patent applications involve more than one assignee or applicant for a patent granted. This study regards patent citations that are asymmetric, one-way and involving temporary interactions as weak ties of knowledge spillovers. Patent citations recorded in the U.S. patent documents can be collected to construct patent citation relations between companies. However, this study, drawing upon patent citations to observe knowledge spillovers between companies, asserts that not all citation relations can be used to represent spillovers of knowledge. Thus, the researchers used patent indicators (i.e. patent citation count and activity index) to gather patent citation relations that are representative of knowledge spillovers.

2.3. R&D cooperation and patent citation as knowledge spillover channels

This study aims to analyse strong and weak ties in knowledge spillover networks. R&D cooperation is used as the proxy variable of strong ties and patent citation used as the proxy variable of weak ties.

2.3.1. R&D cooperation as a knowledge spillover channel

R&D cooperation can be defined as "*the union of two or more parties, institutions or individuals, who pursue a distinct assignment together*" (Arranz and Fdez de Arroyabe, 2008, p.89). In other words, two or more parties work in collaboration and under cooperative agreement to develop specific technology or products (Narula, 2004; Yasuda, 2005). The cooperative relationships between companies have been termed differently in the literature, e.g. 'cooperation' and 'collaboration' (Spekman et al., 1996); 'inter-firm cooperation' (Mowery et al., 1996; Singh, 1997); and 'strategic network' (Gulati, 1995, 1999). All the terms imply the cooperative relationship between companies based on strategic considerations. Information concerning co-application, co-assignee, joint patenting or co-patenting retrieved from patent documents can be seen as outputs of R&D cooperation between companies and indicate R&D partnering of the companies. Joint patenting by companies indicates two or more assignees engage in co-application and co-ownership of patents, which can be seen as concrete outputs of R&D cooperation among companies (Hagedoorn, 2003).

R&D cooperation has become an increasingly important channel for companies to acquire technology knowledge (Archibugi and Coco, 2005; Daim et al., 2006; Hagedoorn, 1996; Narula and Hagedoorn, 1999). When companies look for complementary technologies and knowledge, asymmetric partnerships are likely to be formed, which involve heterogeneity in terms of the company size, knowledge assets, market positioning, and product types. When companies intend to internalise external knowledge spillovers or increase market power, symmetric partnerships are more likely to be formed, which are characterised by horizontal collaboration with virtual or potential competitors (Röller et al., 2007).

Furthermore, the extant studies that employ co-patenting as a means of analysing R&D cooperation and knowledge spillovers among regions tend to focus on European cities. Based on data of co-patenting, the technological knowledge of a region and the pattern of cooperative behavior of the innovative actors within that region in Germany was investigated by Cantner and Graf (2004). They found that "*technologically moderately specialized regions show the highest number of research cooperations, and the higher a regions specialization, the more cooperations*

Table 2
Centrality performance of main companies in the knowledge spillover network during the 6-in. wafer diameter period.

Company	Degree centrality	
	Strong tie	Weak tie
Toshiba	12.50	25.00
Mitsubishi	10.94	19.53
NEC	10.16	21.09
Hitachi	8.59	28.91
National Semi	7.03	17.97
Panasonic	10.94	15.63
Sharp	10.16	4.69
TI	8.59	16.41
Fujitsu	9.38	17.19
Oki Electric	7.03	7.03
Sumitomo	7.03	0.78
Sanyo	7.81	1.56
Motorola	3.91	25.00
Philips	3.13	22.66
Rockwell	0	20.31
AMD	2.34	18.75
AT&T	5.47	18.75

Note: Grey shading indicates top ten companies by degree centrality in strong ties and weak ties respectively.

take place with partners inside that region" (Cantner and Graf, 2004, p.543). In summary, R&D cooperation and co-patenting among companies are treated as the agent of strong ties in the knowledge spillover network, the data about R&D cooperation between semiconductor companies will be obtained and compiled from Semiconductor Industry Yearbook. The data about co-patenting between semiconductor companies will be obtained and compiled from the United States Patent and Trademark Office (USPTO) database.

2.3.2. Patent citations as a knowledge spillover channel

In the application and review process of the U.S. patents, applicants must identify citations to prior art or reviewers will add relevant references in order to show novelty of the patents (Huang and Yang, 2013). Applications of the citation analysis to patents could be conducted using citations and references in patent gazettes or instruction books, e.g. the 'references cited' in the U.S. patents. Similar to the citation analysis of academic articles, that of patents builds upon the co-citation relationship between patents. Through the relationship between citing and cited patents, the inter-substitution, inter-supplement, and evolution of technologies can be observed. Different from the citations in scientific literature, citations can only be incorporated into the patent documents when the citations are determined by reviewers to be related to the applications. Patent citations referred to by previous patents implies that knowledge of the prior art is helpful for developing new knowledge (Jaffe et al., 1993).

In 1993, patent citations were used to investigate knowledge spillovers because of the value of previously existing knowledge upon which later patents built (Jaffe et al., 1993). Topics of studies on knowledge spillovers through patent citations include: university-corporation R&D spillovers (Jaffe et al., 1993); strategic alliances and interfirm knowledge transfer (Mowery et al., 1996); international knowledge flows (Jaffe and Trajtenberg, 1999; Shih and Chang, 2009); and the diffusion of knowledge between basic science and industrial technology (Chen and Hicks, 2004; Sorenson and Fleming, 2004).

In summary, it is worth noting that previous research on knowledge spillovers tended to focus on one period. No research has examined issues related to the evolution of knowledge spillovers in different channels across different time periods. In knowledge spillover measuring, network structure properties: the number of nodes, the number of ties, network density, average path length, and cluster coefficient were used to depict knowledge spillovers; and centralities of nodes were also the common indices used to evaluate importance of actors in the knowledge spillover network. Scholars found different advantages for using the strength of dyadic ties to investigate strong ties and weak ones. R&D cooperation, which involves reciprocal, longitudinal interactions and concrete written agreements, is regarded as strong ties in the knowledge spillover networks. Patent citations are asymmetric, one-way and involving temporary interactions as weak ties in the knowledge spillover networks.

Would the knowledge spillover network tend to stabilise as time goes on? Characteristics of the network structure of knowledge spillovers could change at different time points. Also, the position of a company within the network could change the control of knowledge spillovers within the network. Such issues as the evolution of

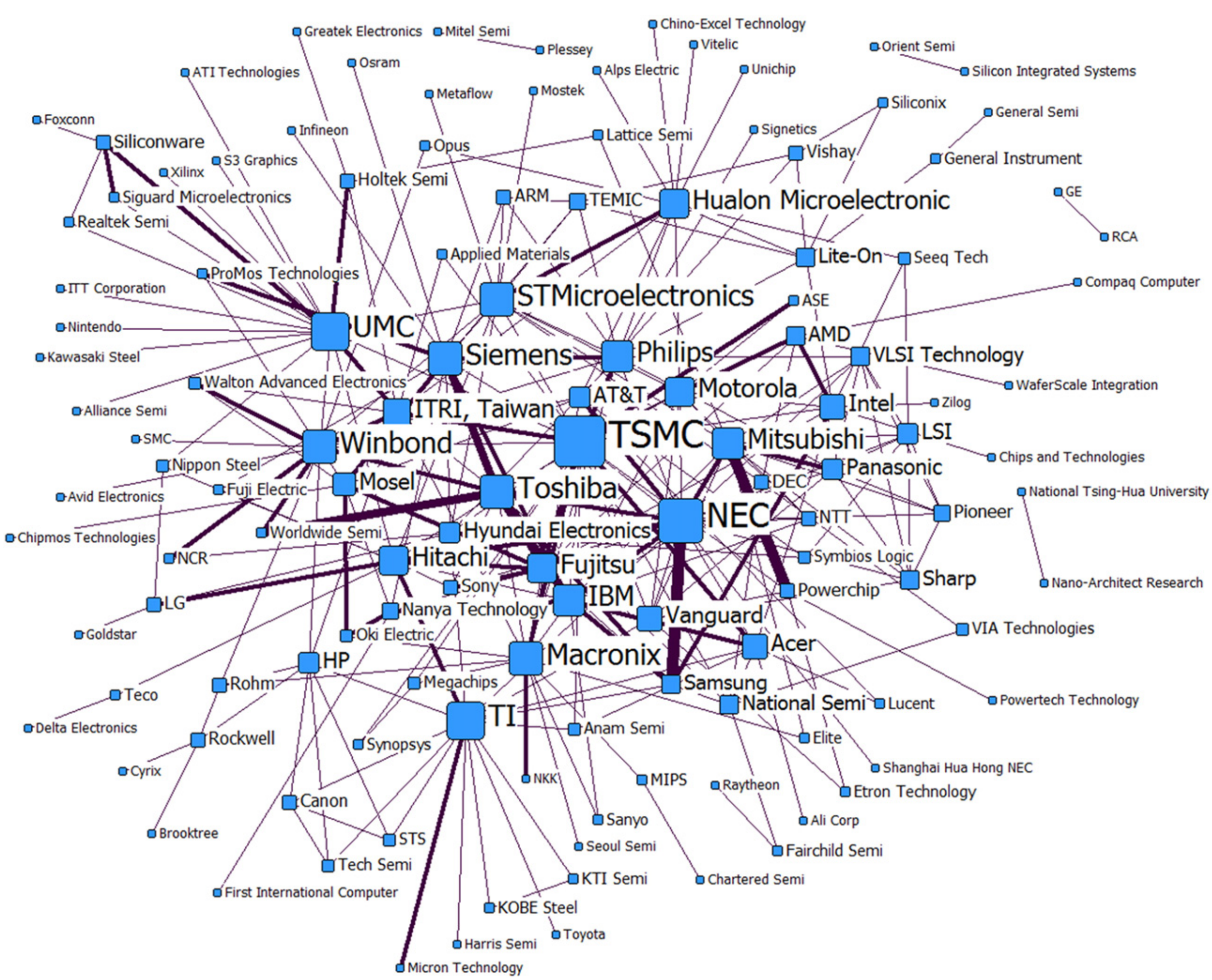

Fig. 3. Network diagram of semiconductor companies in the strong ties during the 8-in. wafer diameter period (Note: Nodes and sizes of companies' names: degree centrality; thickness of lines: frequency of R&D cooperation).

characteristics of the network structure and channels of knowledge spillovers and as the changes of a company's position within a network have rarely been explored.

3. Methodology

This study analysed strong ties and weak ties of knowledge spillovers. Data on knowledge spillovers were obtained from patent data and Semiconductor Industry Yearbook. This study used patentometrics and social network analysis as research methodologies.

3.1. Data collection

This study collected data pertaining to patents and patent citations in the semiconductor industry. All the patent data were collected solely from the United States Patent and Trademark Office (USPTO) database. US Patent Classification (USPC) was used to help identify patents that possess technologies related to semiconductor devices. According to Hall et al. (2001), the four USPC codes, 257, 326, 438 and 505, are classified under the sub-category of Semiconductor Devices. Data regarding R&D cooperation between semiconductor companies was obtained and compiled from *Semiconductor Industry Yearbook*, published by Industrial Economics & Knowledge Center (IEK) in Industrial Technology Research Institute in Taiwan. The Yearbook has published 21 volumes until 2011. It mainly documents the development trajectories and major issues in the semiconductor industry every year in main countries and Taiwan and presents industry dynamics and major changes in a neutral way, which provides authoritative references. In this study, patents issued by the USPTO between 1976 and 2011 were gathered for analysis. In addition, data related to R&D cooperation was gathered from *Semiconductor Industry Yearbook* published between 1999 and 2011.

3.2. Patent bibliometrics

Patent bibliometrics, or patentometrics, is a theoretical method of mathematics, statistics and logic, which studies and analyses the quantity, quality and application of patent literature, e.g. patent counts and patent citations (Narin, 1994). Patent bibliometrics helps understand the development of patented technologies (including individuals, organisations and countries), and understand, through citation relations, the links between researchers, organisations and countries. Based on the selected units of analysis (e.g. country, company/organisation, inventor and technology), calculating patent counts shows the frequency distribution of patents for different analysis units and helps identify main activities. Patent citation analysis focuses on the references cited in the patents (including patents and non-patent references) as the units of analysis. Potential links could be established through calculating patent citation counts and analysing citation relations. This study used citation analysis techniques in patent bibliometrics to measure weak ties of knowledge spillovers between semiconductor companies during the three time periods of different wafer diameters. The indicator, activity index, was used to select representative patent citation relations.

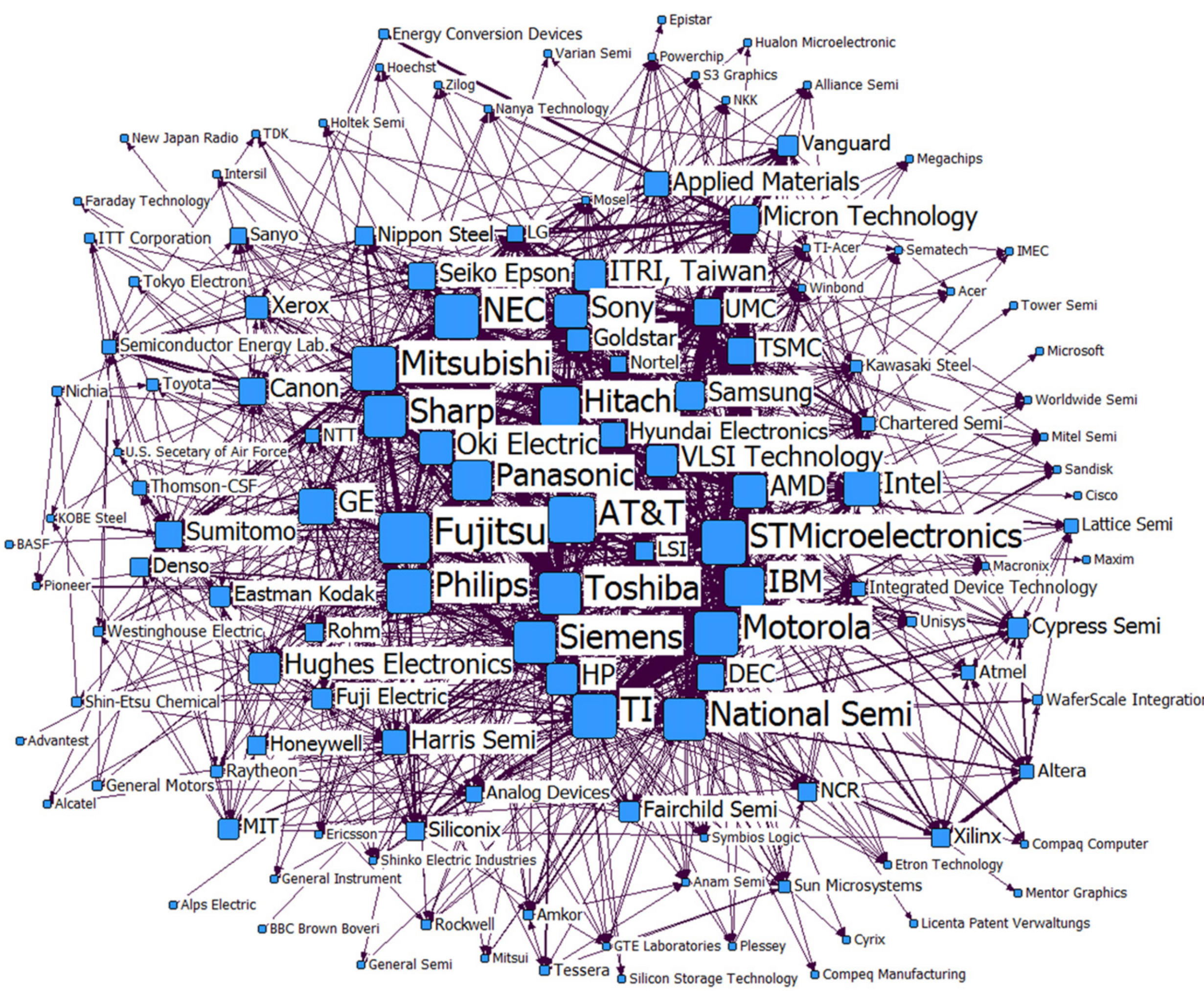

Fig. 4. Network diagram of semiconductor companies in the weak ties during the 8-in. wafer diameter period (Note: Nodes and sizes of companies' names: outward degree centrality; thickness of lines: frequency of patent citations; directions of arrows: directions of knowledge flows).

3.2.1. Activity index

The indicator, activity index (AI), was originally defined as the share of a given technological field in a company total of patents, divided to the share of the given field in the U.S. patents, this indicator also showed the relative activeness of a company in different technological fields in order to identify what technological fields the company specialised in (Pavitt and Soete, 1980). This study adjusted the indicator and applied it to measure the activeness of a company indicated by the ratio between the percentage of the patent citations between two companies and the percentage of the patent citations between whole citing companies and cited companies. It is worth noting that the activeness, in this case, is not 'absolute' but 'relative'. 'Relative' means that the company is more active compared with the given technological field, which does not indicate that the company has more absolute technical advantages than other companies. The AI value ranges from 0 to $+\infty$. It indicates whether the company is relatively less active ($AI < 1$) or relatively more active ($AI > 1$). The formula for AI is shown below:

$$\text{Activity Index (AI)} = \frac{\text{patent citation counts between two companies}/\textit{total patent citation counts of the citing company}}{\textit{total patent citation counts of the cited companies}/\textit{total patent citation counts by all companies}}.$$

3.2.2. Data sampling

This study, drawing upon patent citation relations, analysed knowledge spillovers between companies. However, the number of a company's patent citations varies according to the number of its patents, which increases the likelihood of being cited for companies with more patents. In terms of patent citation counts, does one citation count represent the weak ties of knowledge spillovers between two companies? In order to select representative patent citation relations among companies, this study adopted not only citation counts but also the activity index (a patent indicator) for data sampling, as explained below:

Condition 1: The number of patent citations between two companies must be higher than the median of the citing company that cites all companies.

Condition 2: The ratio between the patent citation count between two companies and the total citation count of the citing company must be higher than the citation count of the cited company by all companies in the industry. In other words, the AI values of the two companies must be higher than 1.

In the aforementioned sampling process, patent citation relations that meet condition 1 were regarded as high 'absolute' citation relations among citing companies. Those meet condition 2 were regarded as high 'relative' citation relations. Therefore, results derived from analysing the patent citation relations selected from the sampling process are considered representative for measuring knowledge spillovers between companies.

Table 3
Centrality performance of main companies in the knowledge spillover network during the 8-in. wafer diameter period.

Company	Degree centrality	
	Strong tie	Weak tie
STMicroelectronics	7.77	18.65
Mitsubishi	7.25	19.17
NEC	10.88	18.65
TI	8.81	18.65
Toshiba	7.77	18.14
Siemens	7.77	18.14
Philips	7.25	18.65
TSMC	12.44	9.85
UMC	8.81	10.36
Winbond	7.77	0.51
Macronix	7.77	0
IBM	7.25	17.10
Fujitsu	6.22	22.28
AT&T	4.15	19.69
Motorola	6.22	18.65
Sharp	3.63	18.14

Note: Grey shading indicates top ten companies by degree centrality in strong ties and weak ties respectively.

3.3. Social network analysis

Social network analysis (SNA) is a quantitative technique based on graph theories in mathematics. The network constitutes nodes and lines that connect the nodes. Nodes can be individual actors, groups of people, events or organisations. Lines between nodes can be used to indicate the existence of the relationships as well as the direction, strength, content and formats of the relationships. Quantitative indicators can be used to analyse the relationship, length and density of the lines between nodes (Freeman, 1977, 1979). Network theories were first employed to analyse the relationships or interactions between actors in social sciences. According to Freeman (1979), relationship structures of individual roles in a network and positions of individual roles help provide information regarding behaviours, perceptions and attitudes of individuals and offer an overview of the whole system.

In term of the network formed by knowledge spillovers between semiconductor companies, both strong ties and weak ties of knowledge spillovers (as indicated by R&D cooperation and patent citations respectively) were the focuses of analysis in this study. Commonly-used indicators in social network analysis (e.g. network density, average path length and clustering coefficient) were used to measure the characteristics of network structures. Furthermore, this study employed another indicator in social network analysis, degree centrality, to investigate the control-power of knowledge flows indicated by the positions of companies in the network. A company positioned in the central place in a network represents that it has strong connections with or powerful control over other companies, which then forms the concept of centrality. Therefore, network positioning can be used to investigate the performance of knowledge spillovers between companies. To this end, this study used degree centrality to measure the centrality of a company in a network.

3.3.1. Network density

Network density was defined as "*the proportion of present dyadic ties to all potential ties*", indicating the percentage of ties between actors in a network (Kenis and Knoke, 2002, p.279). A complete network implies that all potential ties exist, where the density equals 1. In other words, there exist direct ties between each actor and all other actors. The formula for Density (N) is shown below:

$$\text{Density (N)} = \frac{|Edge(N)|}{Max|Edge(N)|} \tag{1}$$

3.3.2. Average path length

The average path length refers to the average number of steps along the shortest paths that connect all potential pairs of nodes in a network. Paths refer to the steps from s_i to s_j that are necessary for connecting a dyad. The shortest path is also called the length between the two nodes, noted as dist (i,j). The formula for the average path length is shown below:

$$\text{dist}_c = \frac{2}{N(N+1)} \sum_{j \geq i} dist(i,j) \tag{2}$$

N is the number of nodes, and the shortest length between a node and itself is defined as 0. If such a length is excluded from calculation, then a different formula for the average path length is defined as below:

$$\text{dist}_c = \frac{2}{N(N-1)} \sum_{j > i} dist(i,j) \tag{3}$$

3.3.3. Clustering coefficient

A clustering coefficient is a measure for characteristics of networks, which value is used to indicate the degree to which a node and other adjacent nodes cluster together. Because a clustering coefficient shows the relationships of lines that connect adjacent nodes, the value is also related to the network structure. The higher the value is, the higher the degree to which the node and other adjacent nodes cluster together; and vice versa. When a node and adjacent nodes form a clique (i.e. all the nodes are connected), the clustering coefficient of the node is 1. The clustering coefficient for Node i is the ratio between the number of real lines that connect adjacent nodes and that of potential lines. The formula for the clustering coefficient (cc) is shown below:

$$\text{cc}_i = \frac{E_i}{k_i(k_i-1)/2} = \frac{2E_i}{k_i(k_i-1)} \tag{4}$$

E_i is the number of real lines that connect adjacent nodes of Node i, and k_i is the number of adjacent nodes of Node i. The degree of Node i, $\frac{k_i(k_i-1)}{2}$, shows the number of lines in a complete graph of adjacent nodes of Node i. The clustering coefficient mentioned above is to be used for individual nodes. An overall level of clustering in a network is measured as the average of the clustering coefficient of each node,

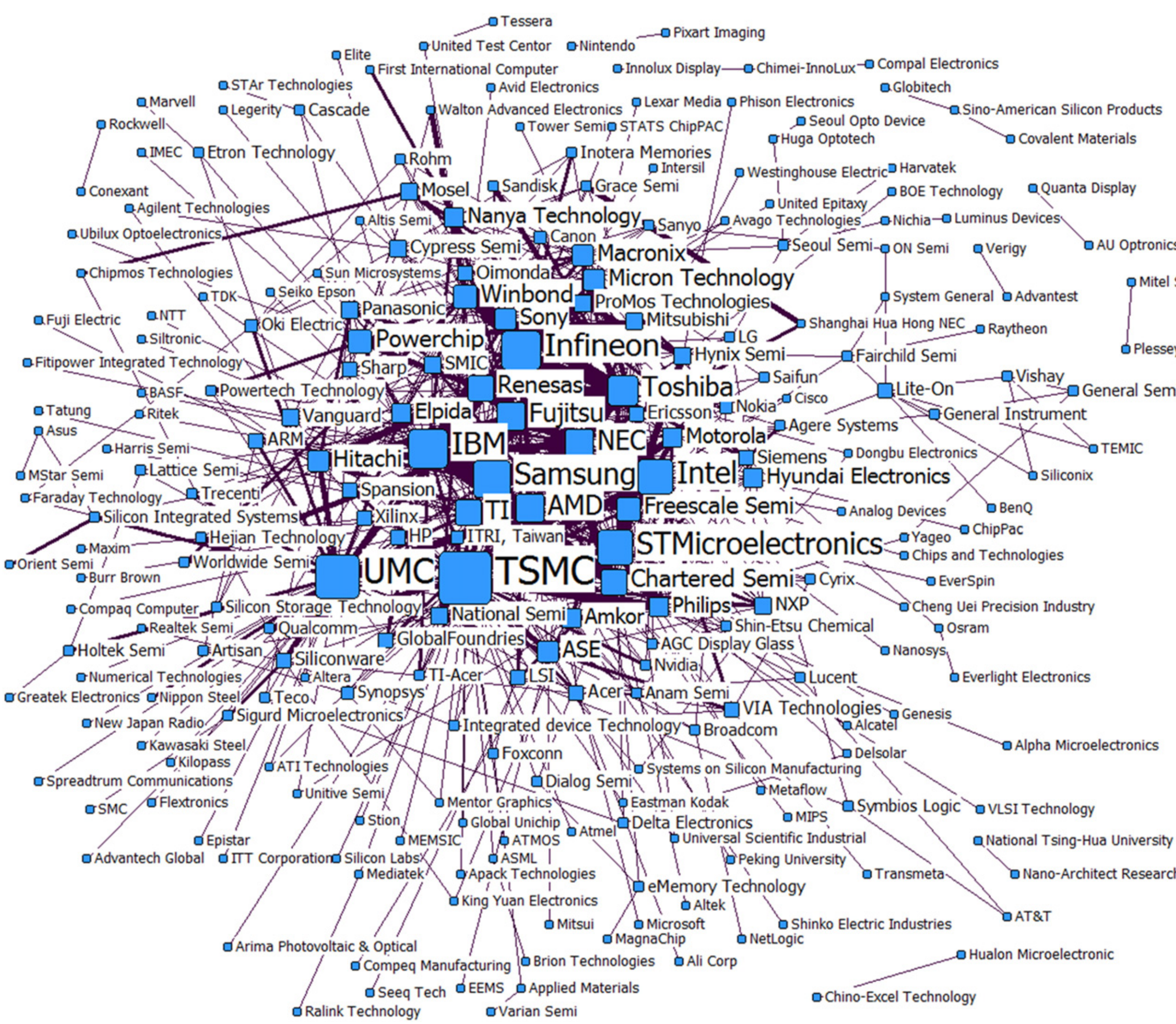

Fig. 5. Network diagram of semiconductor companies in the strong ties during the 12-in. wafer diameter period (Note: Nodes and sizes of companies' names: degree centrality; thickness of lines: frequency of R&D cooperation).

which is called network average clustering coefficient. The formula for the network average cluster coefficient (CC) is shown below:

$$CC = \frac{\sum_{i=1}^{n} CC_i}{n} \tag{5}$$

n is the number of nodes. The CC value indicates the strength of the connection in a network. The higher the value is, the stronger the connection of the overall network structure is; and vice versa.

3.3.4. Degree centrality

Degree centrality is to measure the total number of links between an actor and other actors. When the centrality of an actor is high, it means that the actor plays a vital role as an information channel in the overall network, has advantages of dominating the network, and shows more innovation in outputs and a higher speed of product development when compared with other actors (Ahuja, 2000; Deeds and Hill, 1996). Freeman (1979) defined the centrality as:

$$C_{in}^{i} = \sum r_{in} \tag{6}$$

$$C_{out}^{i} = \sum r_{out} \tag{7}$$

When $r_{in} = 1$, it means that the knowledge spillovers from other companies to Company i are significant. In contrast, when $r_{in} = 0$, it means that the knowledge spillovers from other companies to Company i are not significant. When $r_{out} = 1$, it means that the knowledge spillovers from Company i to other companies are significant. In contrast, when $r_{out} = 0$, it means that the knowledge spillovers from Company i to other companies are not significant. Comparing the relative values of the in-degree and out-degree centrality shows the position of a company in a knowledge spillover network, e.g. the sender, transmitter or receiver of the knowledge.

4. Results

This section reports findings derived from this study, including network structures of knowledge spillovers, and major actors in knowledge spillover networks.

4.1. Characteristics of the network structure of knowledge spillover channels

Table 1 shows the characteristics of the network structure from the perspective of strong ties and weak ties of knowledge spillovers, through indicators such as network density, average path length and clustering coefficient, and during the periods of 6-, 8- and 12-in. wafer diameters. It is observed that with the evolution of the wafer diameters, the number of companies and the number of strong/weak ties between companies increased in the network. In terms of the network density, the strength of the connection between companies was not high in either strong ties or weak ties. However, the network density of weak ties of knowledge spillovers was higher than strong ties, meaning

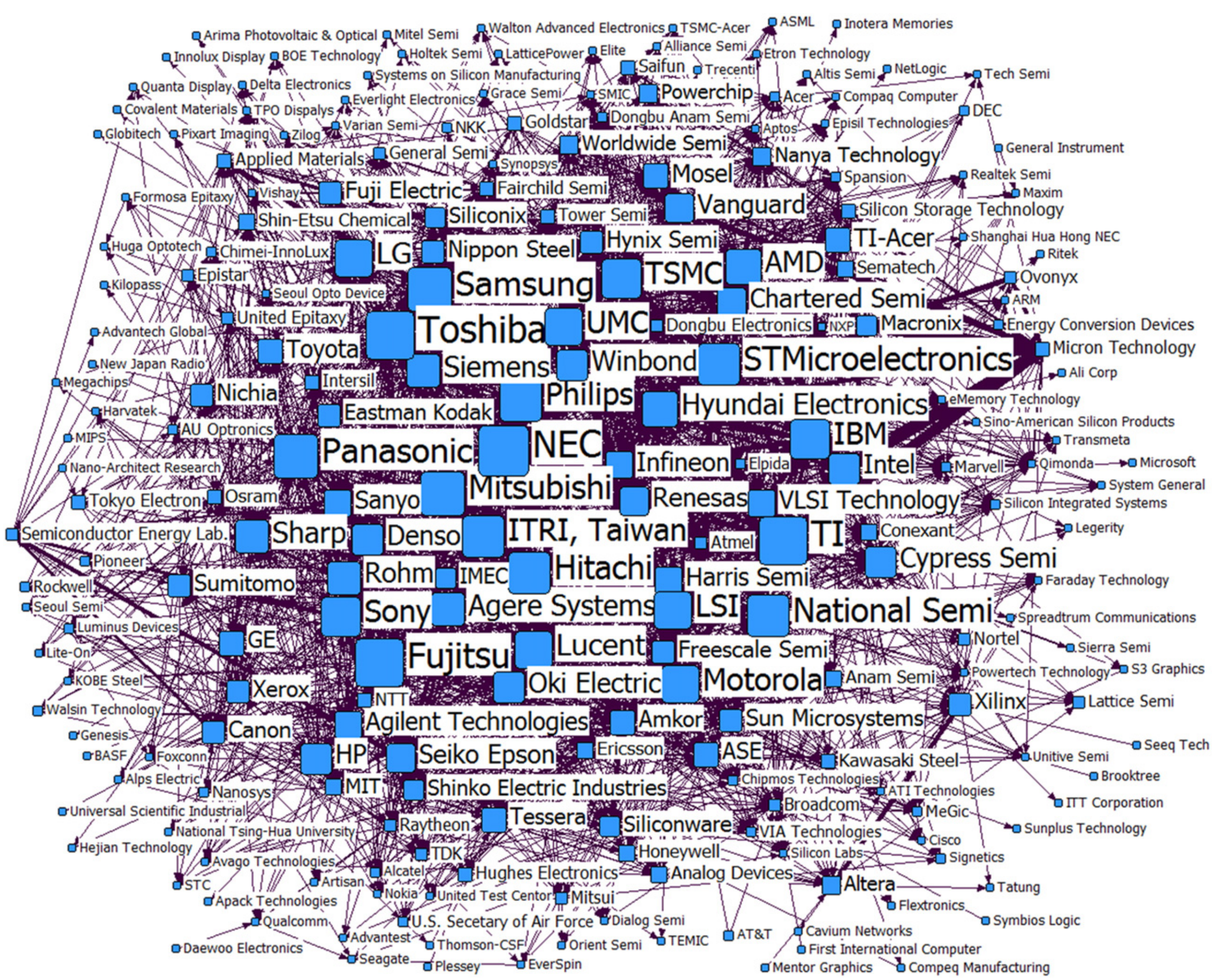

Fig. 6. Network diagram of semiconductor companies in the weak ties during the 8-in. wafer diameter period (Note: Nodes and sizes of companies' names: outward degree centrality; thickness of lines: frequency of patent citations; directions of arrows: directions of knowledge flows).

knowledge spilled over more efficiently through weak ties than through strong ties.

In terms of the average path length, the value for strong ties gradually decreased, whilst that for weak ties gradually increased. This means that with the evolution of the wafer diameters, the length that a company's strong ties of knowledge spillovers to other companies was shorten, but the length that a company's weak ties of knowledge spillovers to other companies increased. Despite this, the average path length of weak ties of knowledge spillovers was shorter than that of strong ties, which indicates that the efficiency of weak ties of knowledge spillovers was higher than that of strong ties. In terms of the clustering coefficient, only the value of the strong ties of knowledge spillovers during the period of the 6-in. wafer diameter was 0.54, which was clearly higher than that of the weak ties (0.21). In the following periods of the 8- and 12-in. wafer diameters, the value of clustering coefficient for strong ties was higher than that for weak ties (0.01). This means that the degree of strong ties of knowledge spillovers within the clustering was slightly higher than that of weak ties, the efficiency of weak ties of knowledge spillovers was higher than that of strong ties.

In summary, the network efficiency of weak ties of knowledge spillovers was higher than that of strong ties. In other words, semiconductor knowledge spilled over to other companies more efficiently through weak ties than strong ties.

4.2. Main companies in knowledge spillover networks

In the network of strong/weak ties of semiconductor knowledge spillovers, the degree centrality can be used to measure the position of a company in the network. If a company is placed in a central position in a network, it tends to have more opportunities to access resources, which also indicates that the company has an important role in accessing knowledge or controlling the path of knowledge spillovers in the network. This study measured the degree centrality of strong/weak ties of knowledge spillovers between semiconductor companies during the periods of 6-, 8- and 12-in. wafer diameters. Top ten companies were regarded as main companies for knowledge spillovers.

4.2.1. Main companies for channels of knowledge spillovers during the period of the 6-in. wafer diameter

The positions of semiconductor companies in the strong ties and weak ties of knowledge spillovers during the period of the 6-in. wafer diameter are shown in Figs. 1 and 2 respectively. Fig. 1 shows that the companies that were placed in central positions in the strong ties of knowledge spillovers with high centrality tended to be Japanese companies, such as Toshiba, NEC, Sharp, Mitsubishi, Panasonic and Fujitsu. Furthermore, these companies frequently conducted R&D cooperation with each other. Those Japanese companies were therefore regarded main companies in the strong ties during this period. Fig. 2 shows a different phenomenon from the strong ties, where the companies positioned in the centre of the weak ties did not tend to be Japanese ones. In addition to Hitachi, Toshiba and NEC, which were still Japanese companies, companies positioned in the centre of the network also included Motorola, Philips and Rockwell. This means that those companies had more intensive knowledge spillovers with other companies in the weak ties.

A further analysis was conducted, using degree centrality, to measure the positions of companies in the knowledge spillover network. Table 2 shows the main companies by degree centrality in the strong/weak ties of knowledge spillovers and 17 companies were identified. It was found that Toshiba, Mitsubishi, NEC, Hitachi and National Semi were the top five companies that built R&D cooperation with the majority of companies in the strong ties of knowledge spillovers during the period of the 6-in. wafer diameter, and they also involved in a high degree of knowledge spillovers to other companies in the weak ties, which indicates that those five companies had high participation through such channels of knowledge spillovers as strong ties and weak ties. Companies, such as Panasonic, Sharp, TI (Texas Instruments), Fujitsu, Oki Electric, Sumitomo and Sanyo, had high degree centrality only in the strong ties of knowledge spillovers, which indicates that knowledge spillovers occurred between those seven companies and other companies in the strong ties. Furthermore, companies, such as Motorola, Philips, Rockwell, AMD (Advanced Micro Devices) and AT&T, had high degree centrality only in the weak ties of knowledge spillovers, which indicates that knowledge spillovers occurred between those five companies and other companies in the weak ties.

4.2.2. Main companies for channels of knowledge spillovers during the period of the 8-in. wafer diameter

The positions of semiconductor companies in the strong ties and weak ties of knowledge spillovers during the period of the 8-in. wafer diameter are shown in Figs. 3 and 4 respectively. Fig. 3 reveals that the companies that were placed in central positions in the strong ties of knowledge spillovers with high centrality include TSMC (Taiwan Semiconductor Manufacturing Company), NEC, Toshiba, IBM (International Business Machines), Macronix, STMicoelectronics and UMC (United Microelectronics Corporation), which were regarded as main companies in the strong ties during this period. Fig. 4 shows a different phenomenon from the strong ties, where the companies positioned in the centre of the weak ties included not only NEC, Toshiba, IBM and STMicoelectronics (which were also regarded as main companies in the strong ties) but also Fujitsu, AT&T, Motorola, Philips, TI and Mitsubishi. This indicates that those companies had more intensive knowledge spillovers with many other companies in the weak ties.

A further analysis was conducted, using degree centrality, to measure the positions of companies in the knowledge spillover network.

Table 4
Centrality performance of main companies in the knowledge spillover network during the 12-in. wafer diameter period.

Company	Degree centrality	
	Strong tie	Weak tie
Samsung	12.37	20.96
Toshiba	9.97	24.06
NEC	9.28	24.74
STMicroelectronics	11.68	19.59
TSMC	19.24	18.90
Infineon	13.75	11.68
IBM	13.40	18.21
AMD	9.28	16.15
UMC	15.46	17.87
Intel	11.68	13.06
Fujitsu	8.59	23.71
TI	8.25	23.02
Panasonic	4.12	21.31
Mitsubishi	3.78	20.62
National Semi	4.47	20.28
Hitachi	6.19	19.93

Note: Grey shading indicates top ten companies by degree centrality in strong ties and weak ties respectively.

Table 5
Cross analysis of companies' linkage in the strong/weak ties of knowledge spillovers during the 6- and 8-in. wafer diameter periods.

		8-in. wafer diameter period				
		Existence of the strong ties only	Existence of the weak ties only	Existence of both ties	Disappearance of both ties	Total
6-in. wafer diameter period	Company pairs with the strong ties only	72	37	24	120	253
		28.5%	14.6%	9.5%	47.4%	100.0%
	Company pairs with the weak ties only	18	168	17	454	657
		2.7%	25.6%	2.6%	69.1%	100.0%
	Company pairs with both ties	14	30	22	19	85
		16.5%	35.3%	25.9%	22.4%	100.0%
Total		104	235	63	593	995
		10.5%	23.6%	6.3%	59.6%	100.0%

X^2 (6) = 239.308, p = 0.000.

Table 3 shows the main companies by degree centrality in the strong/weak ties of knowledge spillovers and 16 companies were identified. It was found that STMicroelectronics, Mitsubishi, NEC, TI, Toshiba, Siemens and Philips were the main companies that built R&D cooperation with the majority of companies in the strong ties of knowledge spillovers during the period of the 8-in. wafer diameter. In the meantime, the seven companies also involved in a high degree of knowledge spillovers to other companies in the weak ties, indicating that they had high participation through such channels of knowledge spillovers as strong ties and weak ties. Companies, such as TSMC, UMC, Winbond, Macronix and IBM, had high degree centrality only in the strong ties of knowledge spillovers, which indicates that knowledge spillovers occurred between those five companies and other companies in the strong ties. Furthermore, companies, such as Fujitsu, AT&T, Motorola and Sharp, had high degree centrality only in the weak ties of knowledge spillovers, which indicates that knowledge spillovers occurred between those four companies and many other companies in the weak ties.

4.2.3. Main companies for channels of knowledge spillovers during the period of the 12-in. wafer diameter

The positions of semiconductor companies in the strong ties and weak ties of knowledge spillovers during the period of the 12-in. wafer diameter are shown in Figs. 5 and 6 respectively. Fig. 5 reveals that the companies placed in central positions in the strong ties of knowledge spillovers with high centrality included TSMC, UMC, Infineon, IBM and Samsung. These semiconductor companies were regarded as main companies because they showed the high frequency of R&D cooperation, indicating that they had closer R&D cooperation relations in the strong tie during this period. Fig. 6 shows a different phenomenon from the strong ties, where the companies positioned in the centre of the weak ties included NEC, Toshiba, Fujitsu, TI, STMicroelectronics and Panasonic, indicating that those companies had more intensive knowledge spillovers with many other companies in the weak ties.

A further analysis was conducted, using degree centrality, to measure the positions of companies in the knowledge spillover network. Table 4 shows the main companies by degree centrality in the strong/weak ties of knowledge spillovers and 16 companies were identified. It was found that Samsung, Toshiba, NEC and STMicroelectronics were the main companies that built R&D cooperation with many other companies in the strong ties of knowledge spillovers during the period of the 12-in. wafer diameter. In the meantime, the four companies also involved in a high degree of knowledge spillovers to other companies in the weak ties, indicating that they had high participation through such channels of knowledge spillovers as strong ties and weak ties. Companies, such as TSMC, Infineon, IBM, AMD, UMC and Intel, had high degree centrality only in the strong ties of knowledge spillovers, which indicates that knowledge spillovers occurred between those six companies and other companies in the strong ties. Furthermore, companies, such as Fujitsu, TI, Panasonic, Mitsubishi, National Semi and Hitachi, had high degree centrality only in the weak ties of knowledge spillovers, indicating that knowledge spillovers occurred between those six companies and many other companies in the weak ties.

4.3. The transition of knowledge spillover channels

This study used Pearson's chi-square test to conduct a cross analysis of the semiconductor companies' performance at the early and later stages of the strong ties and weak ties of knowledge spillovers. Specifically, company pairs' performances at an early stage were compared with those at a later stage. Table 5 shows the cross analysis during the 6- and 8-in. wafer diameter periods. Results show significant correlations (χ^2 (6) = 239.308, p = 0.000) between the early and later stages of knowledge spillovers. As indicated in Table 5, if company pairs conducted knowledge spillovers only through the strong ties during the 6-in. wafer diameter period, as high as 47% of the company pairs' knowledge spillovers disappeared during the 8-in. wafer diameter period. 28.5% of the company pairs continued the knowledge spillovers only through strong ties. Only 9.5% of the company pairs' knowledge spilled

Table 6
Cross analysis of companies' linkage in the strong/weak ties of knowledge spillovers during the 6- and 8-in. wafer diameter periods.

		12-in. wafer diameter period				
		Existence of the strong ties only	Existence of the weak ties only	Existence of both ties	Disappearance of both ties	Total
8-in. wafer diameter period	Company pairs with the strong ties only	185	29	59	185	458
		40.4%	6.3%	12.9%	40.4%	100.0%
	Company pairs with the weak ties only	32	423	61	671	1187
		2.7%	35.6%	5.1%	56.5%	100.0%
	Company pairs with both ties	16	30	60	16	122
		13.1%	24.6%	49.2%	13.1%	100.0%
Total		233	482	180	872	1767
		13.2%	27.3%	10.2%	49.3%	100.0%

χ^2(6) = 727.908, p = 0.000.

over through the weak ties at a later stage because of its strong ties at an early stage, where there existed both the strong and weak ties of knowledge spillovers.

During the 6- and 8-in. wafer diameter periods, if company pairs conducted knowledge spillovers only through the weak ties at an early stage, as high as 69.1% of the company pairs' knowledge spillovers disappeared at a later stage. 25.6% of the company pairs continued the knowledge spillovers only through the weak ties. Merely 2.6% of the company pairs' knowledge spilled over through the strong ties at a later stage because of their weak ties at an early stage, where there existed both the strong and weak ties of knowledge spillovers. Furthermore, for company pairs who had both strong and weak ties of knowledge spillovers during the 6-in. wafer diameter period, as high as 35.3% of the company pairs' knowledge spillovers remained only through the weak ties during the 8-in. wafer diameter period, which was followed by 25.9% maintaining both the strong and weak ties of knowledge spillovers.

During the 6- and 8-in. wafer diameter periods, for company pairs who conducted knowledge spillovers only through either the strong ties or the weak ties at an early stage, there was a higher proportion of the company pairs whose channel disappeared at a later stage, which was followed by the company pairs whose knowledge spillovers took place only through one channel (either the strong ties or the weak ties) at both stages. There was a low proportion of company pairs whose establishment of the strong ties affected that of the weak ties, and vice versa. For company pairs who had both strong and weak ties of knowledge spillovers at an early stage, a higher proportion of the company pairs were survived only by the weak ties at a later stage, which was followed by the company pairs whose original channels of knowledge spillovers remained or disappeared.

Table 6 shows the cross analysis during the 8- and 12-in. wafer diameter periods. Results show significant correlations (X^2 (6) = 727.908, $p = 0.000$) between the early and later stages of knowledge spillovers. As indicated in Table 6, if company pairs conducted knowledge spillovers only through the strong ties during the 8-in. wafer diameter period, 40.4% of the company pairs' knowledge spillovers disappeared during the 12-in. wafer diameter period. Similarly, 40.4% of the company pairs continued the knowledge spillovers only through strong ties. Only 12.9% of the company pairs' knowledge spilled over through the weak ties at a later stage because of its strong ties at an early stage, where there existed both the strong and weak ties of knowledge spillovers.

During the 8- and 12-in. wafer diameter periods, if company pairs conducted knowledge spillovers only through the weak ties at an early stage, as high as 56.5% of the company pairs' knowledge spillovers disappeared at a later stage. 35.6% of the company pairs continued the knowledge spillovers only through the weak ties. Merely 5.1% of the company pairs' knowledge spilled over through the strong ties at a later stage because of their weak ties at an early stage, where there existed both the strong and weak ties of knowledge spillovers. Furthermore, for company pairs who had both strong and weak ties of knowledge spillovers during the 8-in. wafer diameter period, as high as 49.2% of the company pairs maintained both the strong and weak ties of knowledge spillovers during the 12-in. wafer diameter period, which was followed by 24.6% whose knowledge spillovers remained only through the weak ties.

Similar to the performances of company pairs during the 6- and 8-in. wafer diameter periods, for company pairs who conducted knowledge spillovers only through either the strong ties or the weak ties at an early stage, there was a higher proportion of the company pairs whose channel disappeared at a later stage, which was followed by the company pairs whose knowledge spillovers took place only through one channel (either the strong ties or the weak ties) at both stages. There was a low proportion of the company pairs whose establishment of the strong ties affected that of the weak ties, and vice versa. For company pairs who had both strong and weak ties of knowledge spillovers at an early stage, a higher proportion of the company maintained both ties of knowledge spillovers at a later stage, which was followed by company pairs that were survived by the weak ties only.

To sum up, in accordance with the evolution of characteristics of the network structure and channels of knowledge spillovers at different time periods, there was an increase in the number of companies and their connection (as indicated by the number of the lines) within the network. The calculation of indicators (i.e. network density, average path length and clustering coefficient) revealed that semiconductor-related knowledge spilled over more efficiently through weak ties than through strong ties. Different main companies were identified during different time periods. During the 6-in. wafer diameter period, companies such as Toshiba, Mitsubishi, NEC, Hitachi and National Semi built R&D cooperation relations with more companies, conducted knowledge spillovers through strong ties, and at the same time showed high participation in the weak ties of knowledge spillovers. During the 8-in. wafer diameter period, such companies included: STMicroelectronics, Mitsubishi, NEC, TI, Toshiba, Siemens and Philips. During the 12-in. wafer diameter period, such companies included: Samsung, Toshiba, NEC and STMicroelectronics. An observation of the degree of participation of the main companies in knowledge spillovers during the three time periods indicated that companies such as NEC, Toshiba, Fujitsu, TI, Samsung, STMicroelectronics, IBM, UMC and TSMC showed high participation in both strong ties and weak ties of knowledge spillovers. A cross analysis of companies' participation in the strong/weak ties of knowledge spillovers revealed significant correlations between the early and later stages during both periods of the 6- and 8-in. wafer diameters and the 8- and 12-in. wafer diameters. For company pairs who conducted knowledge spillovers only through either the strong ties or the weak ties at an early stage, there was a higher proportion of the company pairs whose channel disappeared at a later stage, which was followed by the company pairs whose knowledge spillovers took place only through one channel. There was a low proportion of company pairs whose establishment of the strong ties affected that of the weak ties, and vice versa. For company pairs who had both strong and weak ties of knowledge spillovers at an early stage, a higher proportion of the company maintained both ties of knowledge spillovers at a later stage, which was followed by company pairs that were survived by the weak ties only.

5. Conclusions

This study found that semiconductor knowledge spilled over through weak ties more efficient than through strong ties. Strong ties can be used to monitor the development of shared technologies and weak ties can be used to monitor the development of specific technologies. Suggestions for future research are provided.

5.1. Semiconductor knowledge spillovers through weak ties more efficient than through strong ties

The network density of weak ties of knowledge spillovers was higher than strong ties, meaning knowledge spilled over more efficiently through weak ties than through strong ties. Furthermore, the average path length of the strong ties of knowledge spillovers decreased gradually but that of the weak ties increased gradually, which indicates that with the evolution of the wafer diameters the path length of knowledge spillovers through the strong ties decreased whilst that through the weak ties increased. Despite this, the average path length of weak ties of knowledge spillovers was shorter than that of strong ties, indicating that the efficiency of weak ties of knowledge spillovers was higher than that of strong ties. Companies' linkages were compared during the periods of 6-, 8- and 12-in. wafer diameters using the calculation of network density, average path length and clustering coefficient; results showed that the network efficiency of weak ties of knowledge spillovers was higher than that of strong ties. In other words, semiconductor knowledge spilled over to other companies more efficiently through weak ties than strong ties.

Despite the network efficiency of weak ties of knowledge spillovers was higher than that of strong ties, weak-ties knowledge spillovers as external knowledge acquisition channels are easily ignored by companies. Patent citation was considered as weak ties of knowledge spillover networks in this study. It could be a way to forecast technological similarity between competitors and the determinants for the choice of partners among small and medium enterprises that cooperate in R&D.

5.2. Using strong ties to monitor the development of shared technologies and using weak ties to monitor the development of specific technologies

In accordance with the evolution of the wafer diameters, the strong ties of knowledge spillovers between semiconductor companies were built as a whole and on the basis of a decrease in the average path length and an increase in the clustering coefficient. On the contrary, the weak ties of knowledge spillovers were built between individual semiconductor company groups and on the basis of a decrease in the network density, and an increase in the average path length and clustering coefficient. It can be inferred that the strong ties of knowledge spillovers formed by the R&D cooperation relations between companies could be seen as channels of knowledge spillovers for the technology co-invention and the establishment of market technical standards, and therefore there exited a tendency toward closer knowledge spillovers between the majority of companies. The weak ties of knowledge spillovers formed by the patent citation relations between companies could be seen as channels of knowledge spillovers for the specific technology invention, and therefore there appeared cluster development in knowledge spillovers between the minority of companies.

Furthermore, main companies were identified in the strong ties of knowledge spillovers during the three time periods of different wafer diameters. During the 6-in. wafer diameter period, companies that had high centrality in the strong and weak ties of knowledge spillovers included: Toshiba, Mitsubishi, NEC, Hitachi and National Semi. Those five companies also built R&D cooperation relations with more companies and showed high participation in the weak ties of knowledge spillovers. During the 8-in. wafer diameter period, companies that had high centrality in the strong and weak ties of knowledge spillovers included: STMicroelectronics, Mitsubishi, NEC, TI, Toshiba, Siemens and Philips. During the 12-in. wafer diameter period, such companies included: Samsung, Toshiba, NEC and STMicroelectronics.

Our findings would be helpful for managers who need to develop effective R&D strategies by external knowledge acquisition. We provide a methodology to construct R&D cooperation and patent citation networks that are relevant to their strong and weak ties in knowledge spillover networks. The visualised network shows the strong ties network of R&D cooperation relationships could be used to forecast the development of shared technologies from the strong ties network. A cause that encourages R&D cooperation or technology alliance is to share technical achievements instead of technology licensing negotiation. Thus the more actors in the R&D cooperation network, especially the main companies in the industry, involve, the more likelihood their technical achievements become standard-essential patents. The weak ties network of patent citation relationships could be used to forecast the development of specific technologies from those patents with direct citations. Patent citations are based on direct technology linkage. The evolution of weak ties networks represents this specific technology continuous improvement or continuous utilised by companies.

5.3. Suggestions for future research

A limitation of this study is that the limited samples could not cover all types of knowledge spillover channels such as the knowledge spillover channels through inventor turnover. Built upon this study, it is suggested that future research further investigate differences in knowledge spillovers of various types of companies using technology positioning of companies and the role of the industry chain. Specifically, analysis could involve differences of the degree of participation of various types of companies in the strong and weak ties of knowledge spillovers and their evolution in accordance with different periods of wafer diameters. Furthermore, whether changes in the type of a company affect the degree of spillovers of knowledge through the strong and weak ties and where the knowledge spillovers could also be investigated.

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