Running title：What makes a successful industry-level catch-up?

What makes a successful industry-level catch-up? General framework and case study of China's LED industry

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Abstract

How latecomers from emerging countries catch up on technological innovation is an important topic for industrial practitioners, policymakers, and academic researchers. This study systematically reviews 43 empirical studies on the precursors of industry catch-up in emerging countries. A general framework on what makes a successful catch-up in latecomer industries is suggested based on literature review. The framework comprises six generic determinants, including technological capability, business ecosystem, government roles, market condition, technological regime, and windows of opportunity. In addition, this framework is applied to the Chinese LED industry, and a case analysis of the catch-up is performed in Chinese LED

firms.

Keywords framework of catch-up, LED industry, emerging countries

1 Introduction

What determines catch-up outcomes in emerging economies is a long standing question in the innovation field. Given the importance of catch-up for latecomer economies, substantial research was launched and yielded many thought-provoking achievements. With highly diverse research foci, previous works highlighted several factors, such as the roles of government (Sung and Hong, 1999; Mu and Lee, 2005; He et al., 2006; Hu and Hsu, 2008; Whang and Hobday, 2011; Choung et al., 2012; Wang et al., 2012; Hu et al., 2015; Kiamehr et al., 2015), the effort of latecomers' technology capability building (Sung and Hong, 1999; Lee and Lim, 2001; Mu and Lee, 2005; Hu and Hsu, 2008; Li et al., 2010; Park, 2012; Chuang and Hobday, 2013; Lee et al., 2014; Chen and Chen, 2015; Hu et al., 2015), the favorable market conditions (Mu and Lee, 2005; Li et al., 2010; Whang and Hobday, 2011; Hwang and Choung, 2014; Kiamehr et al., 2015; Liu et al., 2015), the influence of technological regime (Mu and Lee, 2005; Whang and Hobday, 2011; Chen and Chen, 2015; Hu et al., 2015), the support of the local business ecosystem (He et al., 2006; Hu and Hsu, 2008; Li, 2008; Li and Kozhikode, 2008; Whang and Hobday, 2011; Park, 2012; Zhang et al., 2013; Lee et al., 2014; Chen and Chen, 2015; Liu et al., 2015), and the utilization of windows of opportunity (Li and Kozhikode, 2008; Whang and Hobday, 2011; Wang et al., 2012; Lee et al., 2014; Hu et al., 2015).

Despite providing an informative understanding of the determinants of catch-up, extant studies may have two potential gaps. First, prior literature predominantly focused on catch-up processes in a specific industry sector and discussed a set of limited and industry-specific determinants. Hence, their findings may not be generalizable in analyzing catch-up in other industries. Second, identified factors are somewhat confused at the analyzing levels. For example, certain firm- or national-level factors are mixed with industrial factors. In short, the catch-up factors identified in prior studies did not fall into proper categories and were not yet integrated in a coherent framework.

Thus, we attempt to fill in these gaps in the present study. We conduct this research using the case study method and propose a general analytical framework to identify what determines a successful catch-up for latecomers. Specifically, we first review and summarize various driving factors in the existing studies to form a general framework for analyzing the catch-up process across different industries. We then apply our proposed framework to the LED industry for validating our framework.

We are motivated by three questions for choosing China's LED industry as our case subject. First, this industry has a complex value chain with various participants so that almost all driving forces of catch-up can be tested. As such, the LED industry provides an ideal context for us to validate our comprehensive framework. Second, China's LED industry may realize catch-up in terms of market and technology development. Furthermore, this industry has a relatively comprehensive and internationally competitive industry value chain in the past decade. Therefore, the catch-up process of China's LED industry is compatible with the aim of the present study. Third, China's LED industry is growing, with many interesting characteristics in the catch-up process, but it receives limited attention from scholars. People commonly assume that the leaders of such a technological-intensive industry should be firms from developed countries. This assumption may be true in terms of "technological capabilities." However, Asia is catching up with the western leaders in terms of market shares (Lee and Lim, 2001). In fact, Asia is not only an early adopter of LED, but it also leads the global LED market. According to a lighting report from McKinsey (2012), Asia remains the largest general lighting market which accounts for 24% of the total market share in 2011; by contrast, Europe and North America only represent 15% and 16% of the total market share, respectively. In other words, latecomers in Asia significantly realize market share catch-up, even though they still have a long way to go for technology catch-up. However, such an industrial catch-up pattern already challenges the traditional thinking about the catch-up process and thus calls for further studies to explain the underlying logic behind this predicament.

The remainder of the paper is organized as follows. In Section 1, we will introduce the general framework of driving factors for the catch-up process, including the six dimensions of government role, technology capability, market condition, technological regime, business ecosystem, and windows of opportunity. In Section 3, we will present the case of Chinese LED industry to validate our framework. Finally, in Section 4, we discuss our main findings and conclusions as well as the study’s policy implications.

2 The general framework

2.1 Research method

To summarize the common driving forces of catch-up, we used the ISI Web of Science to select relevant articles from the literature. This database provides bibliographic information for over 12,000 academic journals and covers the mainstream journals in the social sciences. Specifically, we performed data collection in the following four steps.

First, we performed a search using the keywords “catch-up” and “latecomer,” by which we obtained 64 articles. Second, two researchers simultaneously read all these articles to validate if they discuss the factors determining catch-up. We then categorized the key arguments of the selected studies and identified six dimensions, namely, government role, market condition, technological regime, technology capability, business ecosystem, and windows of opportunity. Third, we expanded and complemented the first round of article collection with a second review of articles in the ISI Web of Science. As catch-up and latecomer may describe a similar phenomenon, we combined each of the keywords “catch-up” and “latecomer,” with each of the identified six dimensions summarized in the second step. We obtained another 60 articles. After deleting repetitive articles, 115 articles remained. To obtain the most relevant articles, two researchers rechecked the remaining articles and identified the ones that should be deeply analyzed for the present study. Specifically, we retained articles that discuss catch-up phenomena of industries and firms in latecomer economies. In case of disagreement between the two researchers in article categorization, a third expert specializing in innovation management would join in the group discussion. Finally, we identified 43 articles for our case study. The main arguments of the 43 articles are listed in Table 1.

Insert table 1 about here

After data collection, two researchers analyzed and summarized every article separately. They then cross-checked each other’s analysis. First, each researcher read the first article in the list of the 43 articles. Second, each researcher extracted the main arguments about the determinants of focal catch-up phenomenon. Third, each researcher disintegrated those arguments into phrases representing the determinants of the catch-up phenomenon. Fourth, each researcher clustered all phrases into formal concepts according to the theoretical meaning and relationships among all phrases. Fifth, the other two experts examined the clustering processes and, if necessary, integrated those formal concepts identified in the previous step into general concepts. Lastly, all researchers discussed how to establish a framework using the formal concepts identified in the previous step. Subsequently, each of the remaining articles was analyzed by following the aforementioned steps. The original framework will be updated by supplementing new information extracted from the remaining articles. Through an iterative process of reading articles, summarizing constructs, forming analytical framework, returning to the articles to check for inconsistencies, and emerging with refreshed constructs and an analytical framework, we finally came to a general framework of industry-level catch-up, which is described in Fig. 1. Table 2 reports the summarization of the percentages and representative arguments of each determinant in the 43 articles.

Insert Table 2 about here

In this study, industry-level catch-up refers to the phenomenon wherein firms in the focal industry averagely show an obvious trend of reducing the gaps between themselves and the leading firms in terms of technological or market performance. Therefore, industry-level catch-up can be rooted in the interplays of firms' internal (e.g., research and development (R&D) investment) and external factors (e.g., favorable policies of the government). In our framework, the catch-up process in an industry is directly determined by agent factors, including industry players' technology capability and business ecosystem. Latecomers' technology capabilities are endogenous in nature. In other words, these capabilities are developed or originated within those firms. While business ecosystem represents an exogenous capability accessible to latecomers, latecomers can obtain support from other partners within the same business ecosystem. In addition, if the industry encounters a favorable context, strong support from government, favorable market condition, munificence of technological regime, and good windows of opportunity of core technology development, then the catch-up process of the industry will be efficient and successful. However, as the saying goes, “To forge iron, the body must itself be strong.” Contextual factors help firms survive and compete with their foreign rivals. However, a firm with undeveloped technology capability is likely to fail in the long run.

Insert fig. 1 about here

2.2 Technological capability

Schumpeterian economists argue that innovation and technological capabilities are important driving forces for catch-up (Lee et al., 2014). The accumulation of technological capabilities gradually overweighs traditional physical capital and becomes the fundamental factor for catch-up (Mazzoleni and Nelson, 2007). In our framework, a firm’s technological capability mainly consists of absorptive capacity and the strategy of technological learning.

If firms had sufficient absorptive capacity, then they would tend to understand and grasp the external advanced technology. However, a firm’s absorptive capacity depends on its prior knowledge base (Sung and Hong, 1999; Hu et al., 2015) and the existing knowledge base (Chuang and Hobday, 2013), which requires long-term accumulation of resources and capabilities (Lee and Lim, 2001; Park, 2012; Chen and Chen, 2015). Under such conditions, employing talents is critical. For example, many scholars emphasize the importance of huge cheap skilled manpower resource for the catch-up of India’s IT service sector (Arora et al., 2001; Athreye, 2005; Madhani, 2008; Lee et al., 2014). Similarly, several scholars identify the important role of the ethnic Indian top managers in US high-tech firms in the catch-up process (Madhani, 2008). To comprehend the advanced technology thoroughly, a firm also needs to increase and conduct in-house R&D intensity (Li et al., 2010; Park, 2012). For example, Samsung Electronics expanded from 12,000 R&D engineers in 1997 to 27,000 in 2005, while its R&D spending of revenue increased from 5.86% in 2000 to 10.08% in 2005 (Hu and Hsu, 2008). As the saying goes, “practice is the sole criterion of truth,” which is also true for technology learning. Therefore, learning from trial and error is common among latecomers

(Chuang and Hobday, 2013).

An effective strategy for technology learning is critical for latecomers. This strategy may be hampered by forerunners resisting licensing or transferring technology. Effective strategies of technology learning may include acquiring of technology externally (Sung and Hong, 1999; Li and Kozhikode, 2008); seeking chance to access external knowledge or knowledge diffusion (Mu and Lee, 2005; Li and Kozhikode, 2008; Chen and Chen, 2015; Hu et al., 2015); obtaining technological support from foreign firms (Sung and Hong, 1999; Chuang and Hobday, 2013); cooperating with public research institutes (Mu and Lee, 2005), foreign firms, and related organizations (Hu et al., 2015); and fully utilizing technology spillovers from relevant industries and firms (Chuang and Hobday, 2013). In addition, firms can establish joint ventures, absorb advanced technology from foreign firms, or learn through informal learning, licensing, co-development, strategic alliance with foreign firms (Mu and Lee, 2005), and OEM (Chuang and Hobday, 2013). Innovation clusters formed through foreign inward direct investment and export activities (Li et al., 2010; Lee et al., 2014) may also be a source of new technologies.

2.3 Business ecosystem

The development of an industry is never isolated from the global value chain and environment as well as the local industry and environment. A business ecosystem can be actively created by firms themselves. For example, firms can combine international relations with local capacity in local systems (Chen and Chen, 2015). They will then benefit from the "network" access to knowledge and the source of capital. However, business ecosystems also arise with the breakthrough of technology and management mode. For instance, firms used to complete all R&D internally. However, this arrangement decreased efficiency, and only giant companies could afford such heavy investments. However, the modularization of technologies offers opportunities for latecomers. A good example is the revolution in molecular biology. The modularization of biopharmaceutical industry disintegrates the vertically integrated process of developing new drugs into different segments (Wang et al., 2012), which provide latecomers with additional opportunities and a friendly industry ecosystem for catch-up.

To create a beneficial business ecosystem, latecomers usually form business organizations or alliance with other firms (Li and Zhou, 2008; Lee et al., 2014). As to the potential partners, latecomers may ally with local firms as well as foreign firms, even with the international standardization work group (Park, 2012). Amsden and Hikino (1994) argued that firms joining a business group have many chances to obtain scarce and crucial resources like technological expertise and that the knowledge diffusion in business groups is faster than in individual firms. Guillén (2000) also hold the same opinion that business groups are superior and convenient in obtaining resources in contrast to individual firms. Similarly, Khanna and Palepu (2000) conclude that emerging economies suffer from institutional voids, and business groups can mitigate this problem by creating convenient access to scarce and crucial resources for the members. They believe that business groups create neo-institutions and act as an alternative for the weak institutions in emerging economies (Khanna and Palepu, 2000; Peng and Delios, 2006).

However, business groups are not purely altruistic. On the contrary, the basic rules for forming business groups is complementarity, reciprocity, and mutual benefit among members. Only firms that contributed to the network can obtain support from the network (Narula, 2006). In other words, the foundation to form a business group is the complementary assets from different firms, which may include competitive manufacturing, distribution, service, and complementary technologies (Teece, 1986). In fact, latecomers usually prefer to ally with firms that have incumbent complementary assets (Zhang et al., 2013; Chen and Chen, 2015).

In addition, firms can also catch-up through an interactive and competitive ecosystem. Interactions among different stakeholders in the ecosystem can form a standardized product and generate a competitive environment for innovation. In the study of South Korea’s cellular phone ecosystem, Hu and Hsu (2008) find that South Korea’s cellular phone vendors have interactive cooperation with operators; by contrast, in Japan, Japanese operators have great control and influence over the whole industry chain, while cellular phone vendors in Europe and America are independent of the carriers. Although cellular phone makers must gain support from operators, brand cellular phone companies still have the most power in terms of product development, channel management, pricing, and promotion. In this way, South Korea created an innovative environment full of competition. As an example of a business ecosystem, in the Indian IT service sector, many scholars emphasize the importance of innovation clusters

(Dayasindhu, 2002; Chaminade and Vang, 2008; Madhani, 2008; Lee et al., 2014), such as Software Technology Parks.

Industry modularization and value chain evolution also formalize business ecosystems. Industry modularization propels latecomers' innovations in two ways. First, modularity enables local firms to break the technological barrier to technology-intensive industries. As technological innovations are too complicated to be imitated by latecomers (Baldwin and Clark, 2000), the modularization of products, which separates a product into multiple modules, significantly reduces the difficulty of developing an individual module. Through breaking down the complex systems into various modules, the modularization of products allows firms to innovate modules rather than the whole product and create new products efficiently by making novel combinations of existing modules (Schilling and Steensma, 2001). In the case of the Shanzhai mobile phone market in China, firms have limited resources for R&D and are technologically inferior. The modularization in such industry reduces difficulties in R&D and enables firms to source available modules readily from developers. As a result, several advanced firms focus on developing core technologies, such as chipsets, whereas latecomers with good sense of local markets' demands can focus on designing or developing other parts of phones (Liu et al., 2015). In doing so, Chinese firms can easily combine self-developed parts with outsourced parts and quickly introduce them to the market. Secondly, modularity prompts the evolution of the industrial value chain, which in turn speeds up the innovation process to respond to the highly changing market. In the conventional mobile phone industry, vertical integration of the value chain consumes considerable time due to in-house R&D as well as the coordination and development of all parts of a complex product. In facing highly changing and segmented markets in latecomer countries, electronic suppliers gradually turned themselves into module developers who form loose cooperation to produce the final products. In this way, they create a horizontal value chain in which certain members are responsible for developing chips; others are responsible for hardware design; and Shanzhai firms take charge of manufacturing project management. Consequently, the time required in the development of a new mobile phone is substantially reduced (Liu et al., 2015). Hu and Hsu (2008) also confirm that Samsung also benefits from the integrated value chain, wherein the key parts of cellular phone can be supplied by domestic vendors.

2.4 Government role

Emerging economies are associated with the weakness of capital and other important resources for the development of the economy. Therefore, governments in emerging economies have to use limited resources to create output as much as possible. A typical form of which fosters several crucial industry sectors. The most common strategy of governments is to enact supportive policies, including fiscal and tax policy, to facilitate crucial industry sectors, or to modify the existing state policies to cope with the demands of crucial industry sectors (Wang et al., 2012). For instance, Choung et al. (2012) study the strong role of policy design and implementation by the state in influencing the ICT standard setting in South Korea. They suggest that technologies and standards policies should be clearly focused in the early phase, which allows a high level of institutional flexibility in the later phase; moreover, they find that the significance and role of state intervention and control alters the catch-up because the government can raise public interest and awareness for use of standards and provide commercialization support to firms and strengthen regional and international connections for domestic firms (Choung, Hameed, and Ji, 2012). The government also sets protective policies to ensure the initial growth of local firms and reduce reliance on foreign companies. In the case of Iran's thermal electricity generation systems, the government announced a local content law that expected firms to manage the projects and generate local sources (Kiamehr et al., 2015).

Governments also play an important role in creating a favorable environment of technology spillover, which is helpful for firms' technology learning and catch-up. In emerging economies, the government commonly builds technology zones (Wang et al., 2012), where business infrastructures are complete and ample (Hu et al., 2015). These governments also establish institutional platform that can attract knowledge-creation players (Wang et al., 2012), initiate public research institutes to help local firms absorb the advanced technology (Mu and Lee, 2005), or negotiate with industry leaders for technology transfer. Hu and Hsu (2008) find that the South Korean government's decision to cooperate with Qualcomm, the biggest CDMA IC design house, helped firms capture large market shares of CDMA in the world. Hu and Mathews (2005) argue that latecomer countries tend to rely more on public R&D expenditures than on private R&D expenditures in the early stages of their industrial development. Thus, government support for public R&D increases innovative capabilities for latecomer countries.

Thirdly, governments often create market demand for local firms to accumulate capital and capabilities. If the market is too small to support the development of an industry, then the government will establish utility or state-owned firms to fulfill the market vacancy (Sung and Hong, 1999). To face the growing demand for electricity and high costs of equipment in power plant projects, the Iranian government established Mapna, which aims to provide an inexpensive solution for public investments in power generation, support the growth of feasible local content, and facilitate technology transfer to local manufactures in Iran. After establishing Mapna, the state client awarded six projects that were aggregated into a package to Mapna without running competition to create appropriate conditions for technology transfer to the local firms (Kiamehr et al., 2015).

The role of the government is crucial in East Asian countries and the regions' catch-up process, such as the Chinese telecommunication equipment industry (Mu and Lee, 2005), the Korean and Taiwanese semiconductor industries (Lee and Lim, 2001; Mathews, 2002), and the Indian pharmaceutical industry (Guennif and Ramani, 2012). The Indian government's proactive support plays an important in role IT service industry; it aids in obtaining tariff and tax relief or exemption, attracting foreign investors and investments, fostering educational institutions, constructing telecommunications infrastructures, and building techno parks (Arora et al., 2001; Madhani, 2008; Lee et al., 2014). According to Linsu (1997), South Korean firms benefit from the intellectual property regime established by the South Korean government because they are unconstrained to imitate the technologies from multinational firms in the initial stages of the catch-up process (Mahmood and Rufin, 2005).

2.5 Market condition

The destiny of an industry is to satisfy the needs of customers. Therefore, the market condition determines the prospect of an industry. Market condition is depicted by market size, market segmentation, and market concentration. First, a large market is better than a small one. Certain emerging economies, such as South Korea and Taiwan, heavily rely on the export market because of their small domestic market (Whang and Hobday, 2011). The overreliance on exportation exposes emerging economies to the volatility of the international market. However, emerging economies with large domestic demand will enjoy superiority (Mu and Lee, 2005). For example, China has a large domestic market, which provides Chinese firms with innate advantage and breeds many great firms such as Huawei and Lenovo which accumulate managerial experience and narrow the technology gap with industry leaders during their domestic operations. Using their prior experience and capability accumulated in the domestic market, latecomers in China compete with industry leaders in global markets. This case is also true for the Shanzhai mobile phone industry in China, which was also boosted by huge Chinese domestic demand, especially in low-end markets (Liu et al., 2015).

Secondly, a segmented market is good for latecomers' survival, even when catching up with forerunners. In the initial stage of the catch-up process, latecomers struggle for survival and are inferior to forerunners. A highly-fragmented market provides latecomers with a low-end and niche market, where latecomers earn their first pot of gold and accumulate managerial experience for further development. Shanzhai firms in China enjoy a large segmented market, which offers a low-end market to satisfy with inexpensive and sound quality mobile phones (Liu et al., 2015). Moreover, latecomers can avoid competing directly with multinational incumbents. Within a highly fragmented market, latecomers will have a chance to find many market spaces, which multinational incumbents often neglect but can be served with latecomers' limited resources (Xie and Wu, 2003; Li and Kozhikode, 2008). As latecomers develop, the highly fragmented market also offers latecomers chances to challenge the market leaders in high-end market. Thirdly, market concentration is measured by Herfindahl, which uses firms' market sales to describe industry structure. In highly concentrated industries, latecomers may have more resources for product innovations than forerunners, but the former may also have less competitive pressure for conducting innovative activities (Li et al., 2010).

2.6 Technological regime

The specific pattern by which an industry's innovative activities are organized is the result of disparate technological regimes indicated by the essence of technology (Lee and Lim, 2001).

Technological regimes, such as appropriability, entry barrier, trajectory, cumulativeness, and technological cycle time, will influence the innovative activities of latecomers in their catch-up process. The appropriability of technology (i.e., patents) influences R&D activities and technological advancement (Klevorick et al., 1995). That is, if technology appropriability is well protected, then latecomers would not be worried about their innovations being imitated. In addition, latecomers will increase their willingness to invest in R&D. Furthermore, upon making technology breakthroughs, latecomers can create a window of opportunity in catching up through claiming technology appropriability (Hu et al., 2015). Entry barrier is the result of technological complexity (Whang and Hobday, 2011; Hu et al., 2015) and economy of scale (Chen and Chen, 2015). Generally, an industry with a high entry barrier is unfavorable for latecomers to catch-up with the forerunners. However, if latecomers enter the industry and keep a foothold in the industry, then they would also enjoy the benefit derived from the entry barrier. In addition, if the dominating technology of an industry has a predictable technological trajectory or low uncertainty of the technological trajectory, latecomers can ascertain the further direction of technological development, enabling them to reduce the risk of R&D investments.

Cumulativeness is measured by the frequency of innovations (Lee and Lim, 2001). If an industry has a low frequency of innovations, then technology change is slow. As such, latecomers will have additional time and chances to catch-up with forerunners. In the same vein, technological cycle time is closely related to cumulativeness. If technological cycle lasts for a long time, then latecomers would have chances to absorb and grasp the technology before the existing technology undergoes a breakthrough.

2.7 Windows of opportunity

In general, windows of opportunity are derived from entry timing and technological opportunity. When a brand-new technology comes out, it is a good entry moment created by technological opportunities for latecomers to set foot in the industry. When the paradigm shifts, all firms face the new technology and have a similar start. As such, entry barriers become relatively low. A new techno-economic paradigm provides latecomers with windows of opportunity to catch-up with the forerunners if latecomers adopt a new techno–economic paradigm faster than the incumbent firms, which usually are reluctant to give up old technologies (Perez and Soete, 1988).

In comparison with commercialized technology, the licensing of the brand-new technology may be obtained by latecomers more easily. A technology without enough commercial tests comes with great risks. Meanwhile, forerunners often lose interest in a new technology and rather select other commercialized technology. Therefore, latecomers can create new catch-up path by adopting the brand-new technology. A typical case is the South Korean mobile handset industry (Whang and Hobday, 2011). At first, Korea's R&D institute, ETRI, looked for a partner to license the GSM technology, which was already commercialized in Europe. However, foreign firms resist to license GSM technology. ETRI then turned to the CDMA technology of Qualcomm, which is an emerging and untried technology even in the developed countries. Qualcomm was eager for find a party to realize CDMA's commercialization. Hence, ETRI obtained not only the CDMA technology but also substantial favorable support from Qualcomm. Presently, telecommunication firms in South Korea are the forerunners in CDMA.

Business-cycle downturns can create a window of opportunity because downturns impair incumbents and make resources cheaper than before. Consequently, the difficulties for latecomers are reduced (Mathews, 2005).

3 Catch-up of Chinese firms in LED Industry

The LED industry is a technology- and capital-intensive industry with a relatively long and modularized industry chain, including substrate, epitaxial wafer, LED die in upstream, encapsulation in midstream, and various LED applications in downstream. One of the core technologies of LED is material technology, which is still dominated by powerful international corporations from US, Japan, and Europe, such as Cree, Lumileds, Nichia, Toyoda Gosei, and Osram. However, Chinese firms yield outstanding results of catch-up in the global LED industry. In 2012, the Chinese LED output value reached 200 billion RMB, and 70% of the total output is for export; hence, China is already the manufacturing bases for global LED application products (Wang and Li, 2013). Chinese firms are not only catching up in the production processes, such as encapsulation and applications, but they are also reaching the production of core chips. Chinese firms even record great technology breakthroughs in the production of epitaxial wafers, which requires the most advanced technology. In 2012, the localization rate of Chinese lighting application chips was as large as 72% (Zhao et al., 2013). To be specific about the catch-up process of LED firms, we collected supportive data for LED firms located in China. Description of the main foreign and Chinese firms in the LED industry chain in China are listed in Table 3.

Insert table 3 about here

Following Lee and Lim (2001), catch-up is divided into two types, namely, market and technological catch-up, which are measured in terms of market shares and technological capabilities, respectively. We will apply the catch-up framework introduced in the first part of this study to explain these two types of catch-up of the LED industry in China. We will not demonstrate the effect of technology capability on market catch-up as well as the effect of market condition on technological catch-up for the following reasons. A large degree of overlaps exist between the effects of technology capability on market and technological catch-up as well as between the effects of market condition on market and technological catch-up. Thus, we only illustrated the effect of technology capability on technological catch-up and the effect of market condition on market catch-up to avoid redundancy.

3.1 Market catch-up of LED industry in China

3.1.1 Roles of the government

Latecomers from emerging economies face shortage of capital and resources in the catch-up process. Governments from emerging economies play an active role in supporting domestic firms' catch-up as they prioritize industry developments. Prior studies argue that the government can install supportive policies (like favorable fiscal policies), modify existing state policies, or establish an effective platform for industry development (Wang et al., 2012). During the catch-up of Chinese firms in the LED industry, the Chinese government also played an important role in realizing catch-up in the local and the global markets. This circumstance is illustrated by the considerable attention and commitments of the Chinese government to develop the semiconductor lighting industry. In June 2003, the Chinese government took the lead in uniting the Ministry of Science and Technology, the Ministry of Information Industry, the Chinese Academy of Sciences, the Ministry of Education, the original Ministry of Construction, and the China National Lighting Industry Associations to establish semiconductor lighting engineering coordination and leading groups. In October of the same year, the Ministry of Science and Technology started to launch a "Semi-conductor Lighting Engineering Project" and committed a 35 million RMB special fund to identify solutions for the recent difficulties of critical technologies in the industry (Zhao et al., 2013).

Market demand is crucial in the beginning of industry development or when a new product is introduced. Firms can only realize product value if the market accepts the products. Selling products is a premise for the follow-up development of firms. However, at the initial stage of industry development, latecomers lack capital and technology. The quality of product from latecomers is much lower than that of large competitors, and firms are at a disadvantage to compete with global leaders. Under this condition, the government's role in creating market demand is essential for latecomers' survival (Sung and Hong, 1999). Satisfying the original market demand will help latecomers increase the accumulation of capital. Latecomers can afford to expand the scale of production and make numerous R&D investments, a beneficial approach for the firm's long-term success (Cohen and Levinthal, 1990). In the early years of Chinese firms' catch-up in the LED industry, the Chinese government introduced numerous policies to stimulate domestic demand, thereby helping Chinese firms overcome the "cold start" stage. For example, in 2009, the Chinese Ministry of Science and Technology (CMST) formulated the "Demonstration City Plan for Semiconductor Lighting Application" called the "Urban LED project" covering Hangzhou, Shanghai, Shenzhen, and 18 other well-developed cities mainly for street lights. In 2011, the CMST planned for the second stage of the "Urban LED project" on a larger scale covering 50 cities. Until the end of 2012, the government applied 7 million LED lights and saved 2 billion kilowatt-hours of electricity per year, which is a remarkable outcome (Zhao et al., 2013). The Chinese government then introduced new regulations to develop consumption behaviors of buying LED products and expand the LED market for local firms. In 2011, the Chinese National Development and Reform Commission, the Chinese Commerce Department, the Chinese General Administration of Customs, the Chinese State Administration of Industry and Commerce, and the Chinese General Administration of Quality Supervision jointly issued a ban on importing and selling ordinary incandescent light bulb gradually. From 2016 onwards, ordinary incandescent light bulbs can no longer be imported and sold in China. This ban will result in a great increase of LED lighting demand.

In addition to market creation, the government also tends to establish a favorable policy environment to help domestic firms' catch-up (Wang et al., 2012). The Chinese government treats the LED industry as a strategic sector and formulated various industrial planning and supportive policies to foster the LED industry. For instance, the Eleventh Five-year Plan, the National Program for Long-and Medium-Term Scientific and Technological Development, and the Planning of Adjustment and Revitalization for the National Electronic Information Industry are explicitly stipulated to support the LED industry, including investment in technology R&D, construction of supporting facilities, and guidance of private capital investment and consumption habits. Apart from these favorable policies, the Chinese government also provided direct subsidies to LED firms, thereby filling the gap of LED firms' capital shortage. Since 2009, many local governments introduced direct subsidy policies for buying imported MOCVD equipment. Typically, cities like Wuhu and Yangzhou offered 10 million RMB subsidies per MOCVD reactor (Fu, 2013). Under such policies implemented until 2012, the total number of MOCVD reactors amounted to 980 in China, for which Wuhu and Yangzhou accounted for 30% of the total MOCVD installed base (Fu, 2013).

3.1.2 Market Condition

The development of the Chinese LED industry is a result of the establishment and success of the domestic LED market. Generally, a huge market size means many business opportunities and the potential for economy of scales to achieve operation efficiency (Mu and Lee, 2005). As discussed, by introducing many specific and supportive LED industry policies at the initial stage of the LED industry, the Chinese government successfully fosters the consumption habit of local markets and thus created a large LED market. The increasing rate of development of rural and urban areas and the enormous population of China also dramatically create a huge demand for LED products.

With regard to the market segmentation of the LED market, the diversified market provides abundant choices for Chinese LED firms to position their products to meet various market demands (Mu and Lee, 2005). Considering the huge market size, even firms engaging in only one market segment can still make profits and develop technology. Therefore, in their initial development, LED firms tend to first target the low-end market or specific market neglected by multinational companies, and they serve markets with cheap products of modest quality. This method enables Chinese firms to avoid direct competition with multinational corporations (Xie and Wu, 2003). When firms have accumulated enough technological capacities, efficient operating experience, and other resources, they can easily move from lower-end markets to the mid and high-end ones. For instance, Elec-Tech International Co., Ltd. used to produce low-end chips. In 2011, the company released a high-power chip, which reached an international leading level; the company then entered the high-end market successfully (China Semiconductor Industry Association, 2011).

Given their superior manufacturing capabilities, Chinese LED firms have a competitive advantage in the export market. Many countries focus on energy saving and emission reduction. Japan, the US, and the EU have all formulated their LED promotion plans. In 1998, Japan announced “the 21th century lighting plan.” In 2000, the US proposed “The Next Generation Lighting Initiative,” which was listed in the Energy Act. In the same year, the EU launched the Rainbow Project to replace conventional bulbs with LED lighting. During the rapid development of the international LED market, Chinese LED firms increasingly started to target the global LED market. China is currently the leading exporter of LED lighting products worldwide.

3.1.3 Technological Regime

As mentioned, the upstream LED industry is a technology-intensive industry. However, this feature of the LED industry becomes a favorable condition for the catch-up of Chinese LED firms.

One of the main technical features of the upstream of the LED industry is that most LED technology is embedded in the production equipment. Chinese LED firms can catch-up with market leaders without mastering core technologies. They can access advanced technologies by purchasing LED production equipment. For example, MOCVD is the core equipment for the production of LED chips. In 2014, global shipment of MOCVD machines was 228—65.79% of which were purchased by LED firms in Mainland China. From 2010 onwards, LED firms in Mainland China re the biggest customer of MOCVD machines. In 2014, MOCVD machines in the Chinese mainland accounted for 31% of the total number of MOCVD machines globally, and Chinese firms were the largest buyers. Initially, Chinese LED firms had no mastery of the underlying design technology, but they could still produce chips with imported MOCVD equipment. As Chinese LED firms gradually accumulated technological know-how, they started to attempt to master the deposition of MOCVD layers and develop chips. During the Fifteen Year Plan, the Institute of Semiconductors of the Chinese Academy of Sciences developed a 3*2″ MOCVD reactor prototype. At the same time, Chinese firms with the Xi'an University of Electronic Science and Technology developed 3*2″ and 6*2″ GaN MOCVD reactors. Moreover, under the support of Guangdong Province, the Chinese Academy of Sciences successfully developed the first MOCVD prototype to handle 48 wafers at a time. Subsequently, many Chinese firms like the Chinese Semiconductors Company and Shanghai Ideal Energy Company introduced their own MOCVD prototypes and started to produce epitaxial wafers (Wang et al., 2013).

3.1.4 Business ecosystem

Traditional wisdom regards business ecosystems as a combination of stakeholders related to an industry, including firms, universities, research institutes, government, and customers, who provides a resource network to its members (Chen and Chen, 2015). Firms in business ecosystems have many opportunities to access knowledge, technology, resources, and capital. In the public LED projects of China, the Chinese government tends to adopt the Energy Management Contracting (EMC) model and proposes many modifications of the EMC according to various local situations, such as Guarantee Energy Management Contracting

(GEMC), Government Guarantee Energy Management Contracting (G2EMC), and Property Energy Management Contracting (PEMC). Actually, the government links LED firms with guarantee companies, banks, and LED consulting agencies and forms an efficient business ecosystem, with the government as the coordinator. Members of this business ecosystem work closely with one another and promote the development of LED lighting projects.

Business ecosystems composed of different industrial clusters enable efficient communication and cooperation within members. Such an arrangement is helpful for formatting interactive cooperation (Hu and Hsu, 2008), which contributes to reduce the costs and promotes cooperation in the entire industry chain, especially the cooperation for innovation and R&D activities. Moreover, business ecosystems facilitate the transmission of market information, thereby helping LED firms reduce risk. Nowadays, the LED industry in China has established integrated industry chains and four industrial clusters, namely, the Pearl River Delta, Yangtze River Delta, Northern China, and Jiangxi and Fujian Provinces. These four industrial clusters cover 85% of the total LED firms and over 90% of the total output value. Thus, they constitute a preliminary completed industry chain. The central government approved Shanghai, Xiamen, Dalian, and Nanchang as the first semiconductor lighting project cities. Such an agglomeration effect derived from the business ecosystem provides an efficient platform for the cooperation and communication among different parts of the LED industry chain. Consequently, the business ecosystem contributes to the cooperation of innovation and R&D activities and the localization of the supply chain. Moreover, such an ecosystem reduces production costs, facilitates the formulation of LED industrial standards, and promotes large-scale production. For instance, the semiconductor lighting industry in the Pearl River Delta is mainly concentrated in Shenzhen, Guangzhou, Foshan, and Dongguan. It has the largest production scale and investment for LED encapsulation. Its significant competitive advantage is the co-location among firms in midstream and downstream. Guangzhou aggregates dozens of firms engaged in LED encapsulation and applications, whereas Shenzhen establishes an integrated LED industry chain from the production of sapphire (AI2O3), substrates, chips, and encapsulation to applications.

Furthermore, the China Solid State Lighting Alliance (CSA) is established as a part of the business ecosystem and plays an important role in improving the catch-up process of Chinese firms. The CSA specializes in R&D, production, and application of semiconductor and LED lighting. It consists of various members, such as companies, universities, research institutions, industry associations, and testing facilities all over the country. The CSA acts as an information platform to release updated information relevant to the LED industry, such as the annual report of the LED industry development, analysis of the government's industrial policies, and updated news of LED firms' dynamics and expertise for protecting intellectual property of Chinese firms. The CSA organizes several international semiconductor lighting exhibitions and workshops (e.g., GHINASSL and Green Lighting), establishes the Chinese semiconductor lighting internet site (i.e., www.china-led.net), and publishes several LED-related journals and the industry development yearbook to encourage communications within the industry (Li, 2013). The CSA is responsible for setting technological specifications and delivering patent service. CSA members have already developed 13 technological specifications and are establishing a "patent pool," which can facilitate cross-licensing and reduce the transaction costs of firms. In addition, the CSA contributes to organizing and executing major application demonstration projects, such as the "Water Cube" in the Olympics and the lighting energy-saving reconstruction project of the Great Hall of the People. Accordingly, the CSA advances the applications of CSA members' technological achievements and improves public awareness of semiconductor lighting technologies, thereby expanding domestic demand and encouraging industrial development (Li, 2013). The CSA substantially contributed to the establishment of a Joint Innovation State Key Laboratory of Semiconductor Lighting to address the technological weakness in the upper part of the industrial chain. The laboratory can integrate different resources from diverse sources and take advantage of diversified strengths to realize joint innovation and overcome technological shortcomings (Li, 2013).

3.1.5 Windows of opportunity

In the market catch-up process of the Chinese LED industry, LED firms mainly encounter two opportunities, that is, market opportunity and business-cycle downturns.

As to market opportunity, Chinese LED firms are faced with an expanding LED market locally and abroad. For energy conservation and emission reduction, Japan, the US, and the EU launched various projects to promote LED lighting products since 1998, a situation which provides Chinese LED firms with an expanding overseas LED market. With respect to the domestic LED market, China also participates in the promotion of LED lighting products and green lighting, thereby creating a stable and expanding domestic LED market for Chinese LED firms.

Certain parts of the LED industry suffer from business-cycle downturns. Such downturns weaken the incumbents and lead to reduced prices of critical components. In turn, such a circumstance creates opportunities for the entry of latecomers (Mathews, 2005). In 2011, the global LED industry suffered from an excess capacity of LED chips. However, that situation benefitted firms engaged in LED applications and motivated the popularization of LED products in China. Although Chinese chip firms suffered much from such excess capacity, most of them survived with the support of the government. The Chinese government adopts a holistic industrial development strategy with the goal of maximizing the interest of the entire LED industry rather than of a specific part of the industry. Although LED chip firms were faced with losses, LED application firms obtained substantial benefits, an outcome which is helpful to the entire LED industry in the long term. Therefore, the Chinese government supports industry from downstream to upstream through its holistic industrial policies and thus helps chip firms to de-stock their excess capacity and overcome economic downturns.

3.2 Technological catch-up of China's LED industry

3.2.1 Roles of the government

For technology-intensive industries, the government takes the lead in building R&D consortia to assist domestic firms in technological catching-up (Mu and Lee, 2005; Wang et al., 2012; Hu et al., 2015). In the initial stage of catching-up, Chinese LED firms had insufficient resources to research the core technologies of LED. Meanwhile, the dominant multinational LED companies were reluctant to transfer these core technologies to Chinese LED firms. Therefore, Chinese LED firms had limited access to advanced LED technology. Accordingly, the Chinese government established R&D consortia by combining universities and research laboratories with LED firms. The government could then concentrate its resources through the industry–university–research cooperation. Once universities or research laboratories gained technological breakthroughs, these research achievements could be smoothly transferred or diffused to LED firms through the technological achievement transformation channel created by the government. In this way, the technological capability of the entire LED industry chain, such as the production of substrates, epitaxial wafers, and LED dies, were promoted. As early as 1986, the Chinese High-tech R&D Program, named '863 Program' listed photoelectron technology as one of the four tasks of information technology. This program, under the collaboration between China Electronics Technology Group 48th Institute and Nanchang University, China produced MOCVD wafers comparable to those of international producers in 2000 (Fan and Ruan, 2013). In 2003, the Chinese Ministry of Science and Technology launched "The National Semiconductor Lighting Project," a milestone in the development of high brightness LEDs. To develop the core technology of LED (such as the production technology of substrates, epitaxial wafers, and LED dies), many universities (e.g., Peking University, Tsinghua University, and Nanchang University) and research institutes (e.g., The Institute of Semiconductors of the Chinese Academy of Sciences, the Institute of Physics of the Chinese Academy of Sciences, and the 13th Research Institute of China Electronics Technology Group Corporation) were all actively involved in technology research. Nanchang University successfully gained its own intellectual property rights by producing GaN on a silicon substrate, and their blue light and green light LED chips are now commercialized (People's Daily Online, 2016). Furthermore, Chinese LED firms also spare no effort to develop LED technology. For example, San'an Optoelectronics Co., Ltd., Epilight Technology Co., Ltd., Elec-Tech International Co., Ltd., Lattice Power Co., Ltd., and Changelight Co., Ltd. made substantial investments in the design of chip structure and improvement of production processes; consequently, they obtained many achievements in increasing the performance and the reliability of products. In 2011, Elec-Tech International Co., Ltd. released a high-power chip, which reached international energy-efficiency leading levels and filled the gap for lighting chips made in China. The cooperation and co-development of industry, university, and research institutes distinctively improved the absorptive capacity of LED firms and accelerated the research and commercialization of LED technology.

3.2.2 Technological capability

The establishment of Chinese LED firms' technological capabilities mainly occurs in two ways, that is, technology decomposition and recombination.

Technology decomposition is defined as the deconstruction of a set of technologies into separate technical modules to learn about the structure functions and principles of each technical module. This method can reduce the barriers for absorbing advanced technology (Sung and Hong, 1999; Hu et al., 2015). In doing so, local firms can forgo the long stage of resource and capability accumulation, and they enter into an industry quickly (Lee and Lim, 2001; Park, 2012; Chuang and Hobday, 2013; Chen and Chen, 2015).

For Chinese LED firms, technology decomposition reduces the entry barrier and resource requirements of the LED industry. In the initial stage of the Chinese LED industry, Chinese LED firms relied on importing LED dies for encapsulation. In comparison with other segments of the LED industry chain, LED die encapsulation is more labor intensive and has a relatively low technological level. At that time, Chinese LED firms acted as the manufacturers of large multinational LED companies. In this process, Chinese LED firms decomposed the production technology and then imitated it to design a product. Through this kind of incremental learning, Chinese LED firms gradually made great breakthroughs from periphery technology to core technology, and they accumulated knowledge and capabilities about LED technology. At the end of the last century, Chinese LED firms moved toward the upstream of the LED industry chain and began to produce epitaxial wafers. With the help of prior accumulation of efficient operation, technology, and R&D capabilities, Chinese LED firms began the development of epitaxial wafer, which is one of the hardest parts of the LED industry chain and requires the most advanced technology. They also tried a small-batch production of such epitaxial wafers.

Technology decomposition enables Chinese LED firms to maximize the technology capacity from related industries, universities, and research institutes. In particular, the R&D consortium of industry–university–research cooperation organized by the Chinese government becomes the main source of learning, absorbing, and decomposing advanced LED technologies. Meanwhile, high modularization of the LED industry chain enables LED firms to absorb the entire complex LED technology and reduce the cost of technology learning. Firms can thus focus on a separate segment of the whole LED technology and then develop it further.

As discussed, technology decomposition enables Chinese LED firms to accumulate upstream technology capacity. Through the recombination of existing technology, firms can then make separate technical modules into new innovations.

Technology recombination refers to the firms' reorganization and recombination of existing technologies to develop innovative ideas and new technologies. Firms will combine various external and internal technologies and then localize them to meet specific market demands. Currently, industry leaders are always reluctant to transfer or license technologies, especially core technologies, to latecomers. Latecomers cannot rely on a single technology source to acquire all technologies. Therefore, latecomers must adopt various strategies of technology learning and obtain technologies from different sources (Mu and Lee, 2005; Li and Kozhikode, 2008; Chuang and Hobday, 2013). In addition to foreign firms, the main technology source of Chinese LED firms involves universities and research institutes in the R&D consortium. In government-led LED projects, the government encourages universities and research institutes to industrialize their technological achievements. Thus, domestic LED firms can readily absorb and make full use of such advancements. Take chips technology for example. After Chinese LED firms possess the chips technology, they can design the structure and production process of chips according to local market demand to increase the performance and reliability of products. Moreover, latecomers could exploit their prior-accumulated know-how for recombination. For firms with prior knowledge in another industry related to the LED sector, their prior technology capacity, operational experience, and social relations lay the foundation for technology recombination. In 2007, the Irico Group Corporation affiliated with the Chinese State-owned Assets Supervision and Administration Commission invested 130 million RMB in LED firm Epilight Technology Co., Ltd. The main business of the Irico Group Corporation is the plasma display panel and liquid crystal display (LCD). Investment in Epilight Technology Co., Ltd. expanded the main business of the Irico Group Corporation into the LED photoelectron field, and they realized the synergetic effects among these three businesses.

Insert table 4 about here

Table 4 summarizes the technology sources of Chinese LED firms. To generate the list of Chinese LED firms, we first reviewed all publicly listed firms in LED-related industries by reading the firms' descriptions. Then, we selected firms whose main business involves LED technologies and products. The codes of industry we reviewed are C38, C39, C40, C41, and I65 in the specification of industry classification of listed companies (version 2012). Firms in those industries mainly engage in manufacturing electrical machinery, computers, and telecommunication equipment. We also supplemented the information of Chinese LED firms by reviewing research reports about the LED industry. Subsequently, we sent the firm list to experts in LED firms (including a Chinese subsidiary of a multinational enterprise and two Chinese firms) and asked them to identify the most influential and important Chinese LED firms. The experts can make selections from the firm list and nominate other firms beyond the firm list. Finally, we determined the firm list covering 32 publicly listed firms and 2 unlisted firms. These firms are the most powerful LED firms in China and can adequately represent the entire Chinese LED industry. We listed 34 such companies in Table 3. In Table 4, the licensees or transferees of technology are the 34 firms in the firm list. Patent licensing and transfer data were drawn from the Incopat patent database, which is a comprehensive and professional database covering global patent information of firms in China and other countries. To obtain Table 4, we searched the Incopat database using the 34 sample firms' names as keywords and obtained all patents relative to sample firms. Then, we filtered the patent information and retained patents whose patent assignees or licensees are our sample firms. Finally, we classified the remaining patent information into two categories, that is, patent licensing and transfer. In each category, we further divided the patent according to the source. As shown in Table 4, the two main sources of technology for Chinese LED firms are domestic firms and research institutes (including universities). We cross-checked the Philips' intellectual property, compared their public licensee information with our firm list and found consistent results as our findings. We also cross-checked these results by interviewing related companies, such as Philips, Crystal Optoelectronic, and Silan Microelectronic. Their responses provide possible explanations for our findings. First, most Chinese LED firms are located in the middle and downstream of the industry value chain, and the existing patents can be generated by Chinese firms easily or at low or modest cost. Thus, Chinese companies may not use the patent licensing from leading foreign LED companies. Second, license programs like those of Philips only disclose companies who sell their finished products (LED based luminaires and retrofit bulbs) under their brand. Thus, tracing licensee information for companies who manufacture intermediate products is difficult.

Moreover, although individuals have their own category, they commonly share patents with their work units in China. Therefore, "patents belong to an individual" can be treated as particular case of "patents belong to a domestic firm" and "patents belong to a university and research institute." Thus, the mode of R&D consortium and the combination of "production, teaching, and research" has a greatly help Chinese LED firms to gradually develop their technological capabilities.

3.2.3 Technological Regime

One of the main features of the LED industry is that the technological trajectory of LED is explicit and predictable. In other words, the uncertainty of the technological trajectory is low, and latecomers can be certain of the technology development direction, which helps latecomers reduce the risks of R&D (Lee and Lim, 2001). In the LED upstream industry, the core technology is substrate technology. Substrate technology is the key to epitaxial wafer production. Different kind of substrates require various production technologies for epitaxial wafers and influence the process of chips and LED encapsulation. Therefore, the development of substrate technology will greatly shape the entire technological trajectory of the LED industry. Extant material which can be used to produce GaN substrate include aluminum oxide, carborundum, silicon, and zinc oxide. However, only aluminum oxide and carborundum are commercialized on a large-scale. Most supplies are still controlled by the most powerful LED firms, such as Nichia in Japan, which monopolizes most aluminum oxide substrate supply, and Cree in United States, which is the dominant supplier of commercial carborundum substrates. Substrate production remains the bottleneck of the LED industry. Therefore, according to the relatively predictable path of LED technology, Chinese LED firms prefer to invest heavily in R&D.

3.2.4 Business ecosystem

The combination of stakeholders (with their resources) related to an industry forms a resource network for its members (Chen and Chen, 2015), thereby enabling market participants to incorporate with others. Such merging is helpful for resolving technical problems. The LED industry is also highly modularized, and every part of it has a mature technological trajectory. As such, the industry lowers the barrier for firms to further master LED technology. More specifically, technology modularization allows firms to deconstruct a complex product and the production process into several simpler modules. Producing or innovating independent parts is much easier than doing so for an integral and complex product (Baldwin and Clark, 2000; Schilling and Steensma, 2001). Therefore, LED firms that achieve technology breakthroughs in any part of the LED industry chain will establish their competitive advantage and thus have a chance to catch-up with the leaders in any part of the LED industry chain. Actually, Chinese LED firms accomplished many technological breakthroughs in certain critical aspects of the LED industry chain. In March 2011, the Wuhan National Laboratory for Optoelectronics and the School of Energy and Power Engineering of Huazhong University of Science and Technology owned the intellectual property right for developing a world-leading encapsulation technology. In June 2011, a sapphire crystal weighing over 100 kilograms was produced in Jiangsu Province, a testament that Chinese LED firms greatly reduce the difficulty of developing GaN substrate material. In November 2011, Elec-Tech International Co., Ltd. released a high-power chip which reached international leading level. All these technological breakthroughs reveal that Chinese firms are catching up in every part of the LED industry chain (China Semiconductor Industry Association, 2011). In addition, many traditional lighting manufacturers like NVC Lighting and Sunshine Lighting are also investing in LED and are engaged in the transformation from conventional to LED lighting (Fu, 2013). At the same time, related industries in business ecosystems are also making large investments in the LED industry. Although applications of LED in the LCD TV industry and general lighting industry differ, the basic technology is similar. Thus, Many LCD TV manufacturers are actively involved in the LED industry. In 2010, Konka invested 22.5 million USD to Yingrui Optoelectronics

Technology Company. As one of the important color TV manufacturers, the Rainbow Group already established plants for epitaxial chips in Shanghai and Hefei. These changes strengthened the R&D of LED technologies and opened up the LED market.

3.2.5 Windows of opportunity

In the technological catch-up process of the Chinese LED industry, LED firms grasp technology opportunities very well. When leading multinational companies transfer the production of midstream and downstream of the LED industry chain to China, Chinese LED firms grasp the opportunity to absorb and imitate LED technologies. In the meantime, Chinese firms also accumulate production and operation capabilities, thereby building the management foundation for technological development in the long run.

3.2.6 Technological performance

By July 2013, Chinese LED companies and institutions already applied over 80,000 innovative patents and utility model patens. As the Chinese LED industry focuses on middle stream and downstream, these patents are primarily distributed in the application (65%) and the encapsulation (25%) fields (Fan and Ruan, 2013). For in-depth analysis of the technology performance of the leading Chinese LED firms, we used the above 34 firms which account for the main proportion of the Chinese LED market share and which are also positioned in different parts of the entire industry value chain. We then summarized the number of patent applications of firms to reflect the technological catch-up performance of the LED industry (See Fig. 2).

Insert fig. 2 about here

In 1985, the first LED patent was approved. The number of patents increased dramatically since 2006. More specifically, the number of innovation patents and utility model patents soared since 2006, while the number of design patents became stable over time.

To describe the technological characteristics of Chinese LED firms in different parts of the LED industry chain, we divided the 34 firms into four groups according to the positions of their main business in the LED industry chain. We also cross-checked with the experts in the LED domain about the differentiation of the LED value chain (Please see the detailed list in Table 3). The four groups include the integrated, upstream, midstream, and downstream firm groups. The main businesses of firms in the integrated firm group cover the entire LED industry chain, whereas those of the upstream, midstream, and downstream firm groups are limited to the upstream, midstream, and downstream of the LED industry chain, respectively.

Figs. 3 and 4 show that the patent applications and innovation patent applications among the four firm groups are increasing. Fig. 5 indicates that firms in the upstream and integrated firm groups have a high proportion of innovation patents.

Insert fig. 3 about here

Insert fig. 4 about here

Insert fig. 5 about here

The feature shown in Fig. 5 also appears in Fig. 6 and depicts the patent intensity of the four groups. Patent intensity equals the number of patents divided by the number of employees. As shown in Fig. 6, firms in the integrated and upstream firm groups have relatively higher patent intensity than firms in the midstream and downstream firm groups.

Insert fig. 6 about here

We also analyzed the technological diversity of the four groups. Technological diversity reflects the extent to which firms can innovate in different technology areas (Rahko, 2016).

To measure technological diversity, we first calculated the Herfindahl index of the diversity of patent types as follows:

$$Herfindahl\ index = \sum_{i=1}^{N} (S_i)^2$$

where S_i is the ratio of the number of patents in the i^{th} patent category to the total number of patents in a firm, and N is the total number of patent types in the firm. As the lower value of the Herfindahl index (*H*) reflects a higher diversity of patent types, we used 1 minus *H* such that a higher value of the Herfindahl index indicates a higher diversity of patent types. To eliminate the effect of the number of patent types on the value of the Herfindahl index, we adjusted the Herfindahl index as follows:

$$adjusted\ H = \frac{1-H}{1-\frac{1}{N}}$$

As shown in Fig. 7, the technological diversity of the four groups of firms are converging gradually. All firms maintain a relatively high technological diversity.

Insert fig. 7 about here

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4 Conclusions and discussion

From latecomers to today's important players in the global LED industry, Chinese LED companies achieved great success. According to a summarization of prior studies about the determinants of successful catch-up, we offer a general framework for systematically analyzing the catch-up outcome of latecomers. We then applied this framework to the Chinese LED industry to demonstrate our general framework.

The general framework on what makes a successful catch-up in latecomer industries contributes to catch-up literature in the following ways. We identified six factors for determining technology and market catch-up, including technology capability, business ecosystem, government role, market condition, technological regime, and windows of opportunity. Numerous studies focused on what determines the catch-up of latecomers (Sung and Hong, 1999; Mu and Lee, 2005; He et al., 2006; Hu and Hsu, 2008; Whang and Hobday, 2011; Choung et al., 2012; Wang et al., 2012; Hu et al., 2015; Kiamehr et al., 2015), but most of them still addressed specific factors in a certain industry. For example, the Indian government's active support plays an important role in the Indian IT service industry (Arora et al., 2001; Madhani, 2008; Lee et al., 2014), whereas grasping the opportunity created by a new technology (CDMA) is critical in the Korean mobile handset industry (Whang and Hobday, 2011). However, the factors for analyzing one specific industry may not be directly applied to others. In addition, we still require general industry-level framework, which can integrate the diverse findings in prior studies. Our general framework identifies the determinants of the catch-up process and also demonstrates the interrelationship of the determinants. As such, our general framework can serve as a fundamental model to analyze the market catch-up and the technology catch-up across various industries.

We also contribute to a comprehensive understanding of the catch-up in the Chinese LED industry. Only few studies addressed this issue, and they offered a limited understanding. For example, Hu et al. (2015) investigated how technological regime enables technology latecomers to shift the oligopolistic structure of the global LED industry. As discussed, the LED industry is a technology- and capital-intensive one, and the entire value chain for such an industry is complex. Thus, in most cases, leading firms are supposed to come from traditional developed countries. However, despite certain technology gaps between Chinese latecomers and foreign forerunners, Chinese firms have already exceeded the forerunners in terms of market shares. By systematically analyzing the underlying factors in determining latecomers' catching up, we validate our general framework and also fill the gap in terms of comprehensive understanding of such a special and important industry.

Insert table 5 about here

In addition, we also checked the top management teams' overseas background for our sample firms. As shown in Table 5, 79.29% of those firms' top management teams have overseas experience. This outcome indicates that top managers with experience either in terms of overseas education or working experience in multinational firms or their joint venture firms may constitute an important knowledge spillover channel. In this way, Chinese LED firms can be exposed to advanced LED technologies and potential markets, which are beneficial for their technology and market catch-up. Moreover, examining the working experience of top management members reveals that many top managers have work experience in large western multinational lighting companies. One of the vice general managers in Elec-Tech International

Company served as a researcher and chief scientist in the Philips Lumileds Lighting Company. A vice general manager in the San'an Optoelectronics company once worked as a senior engineer in the Taiwan Epistar company. The director of Yankon Lighting was a project manager, production manager, and manufacturing manager in the Philips Lighting Company in Asia. Such connections imply that top managers can play an important role in transferring managerial and technological expertise from advanced western companies to Chinese lighting companies and thus facilitate the whole catch-up outcome of Chinese LED companies. Due to limited knowledge about how top management teams influence the catch-up process of latecomers in emerging countries, further research is needed to examine the detailed underlying mechanisms of how the between-firm mobility of top managers affects the catch-up of latecomer industries.

Another interesting direction for future studies is to reveal the dynamics of learning and catch-up in Chinese LED industry. Although Chinese firms are successfully catching up, the dispersed market condition in the Chinese market may lead to inefficient use of resources. Given the fierce competition among LED firms, a possible trend may involve substantial consolidation among existing firms that will result in a high level of market concentration. Thus, future research can track and investigate the evolution of market concentration among Chinese LED firms, as well as the influence of such evolution on the future development of the Chinese LED industry at the firm and industry levels.

This research also has limitations. First, this work selected 34 leading LED firms in China as cases. However, small LED firms make up the majority of LED firms in China and may also play an important role in the catch-up process of China’s LED industry. Future studies may investigate the role of small LED firms in the catch-up process. Second, although we built a generalized framework for determinants of successful catch-up, this research only used the Chinese LED industry as a single case to demonstrate the influences of the catch-up determinants. Future research can take multiple case studies in broader contexts to further validate this framework. Third, China, as the second largest economy in the world, presents unique and different characteristics from many other emerging economies. Hence, future studies can investigate the uniqueness of the Chinese context and its influence on the industry catch-up to identify new and unique determinants.

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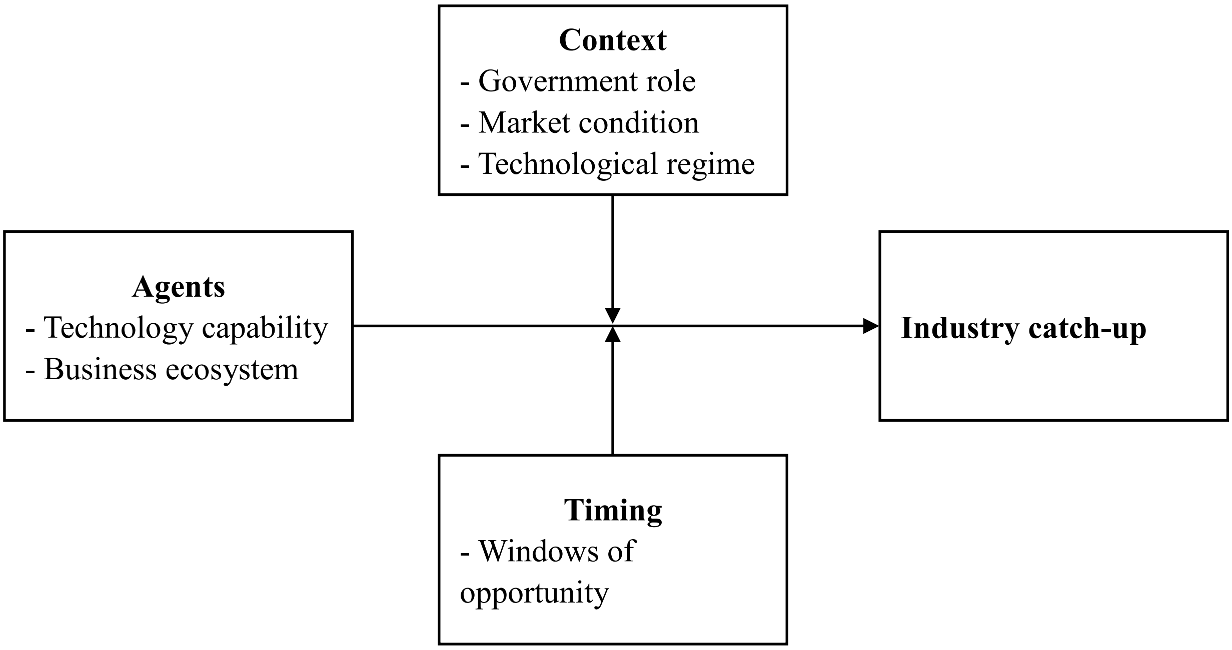

Fig. 1. Framework of technological and market catch-up

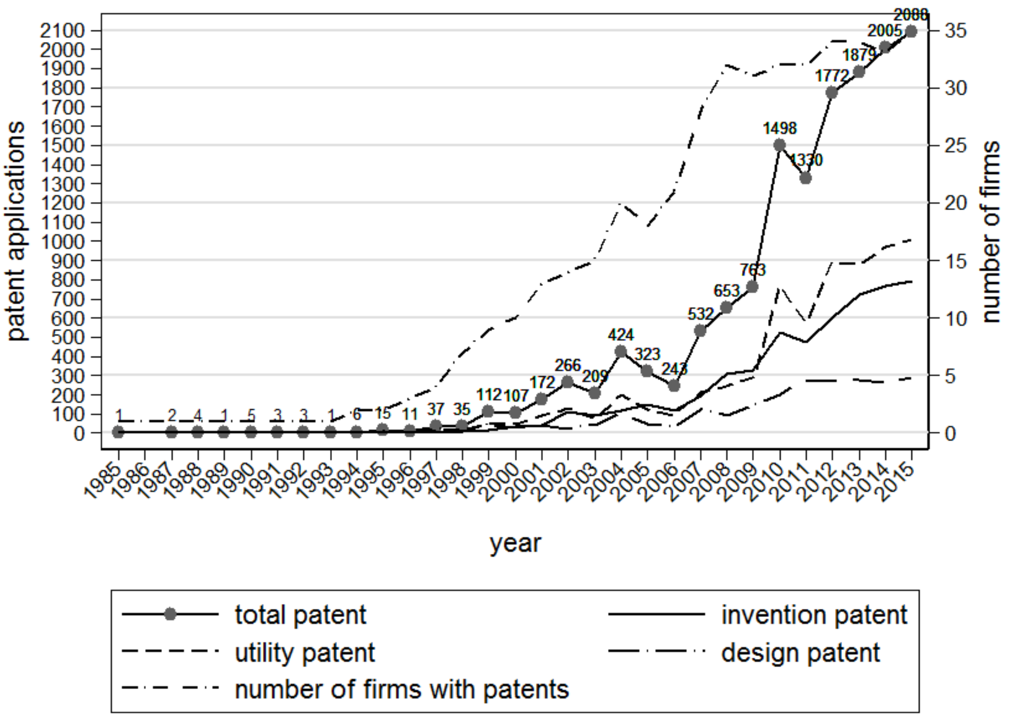

Fig. 2. The number of patent applications in sample firms (n = 34):1985–2015

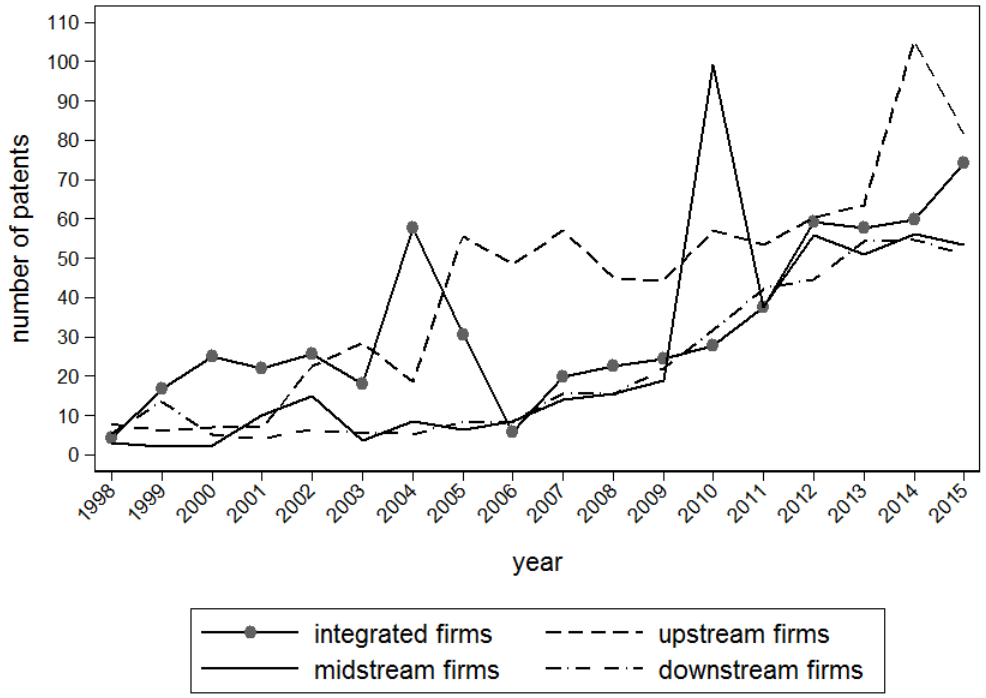

Fig. 3. The number of patent applications for an average firm in four firm groups

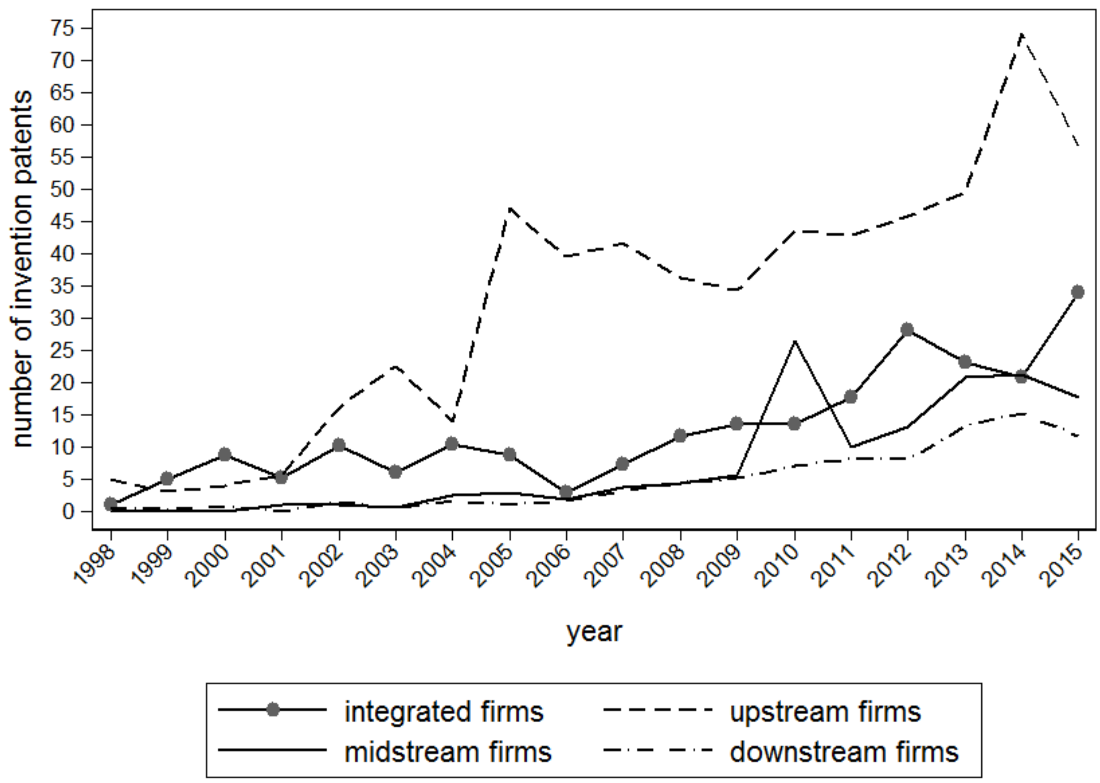

Fig. 4. The number of invention-type patent applications for an average firm in four firm groups

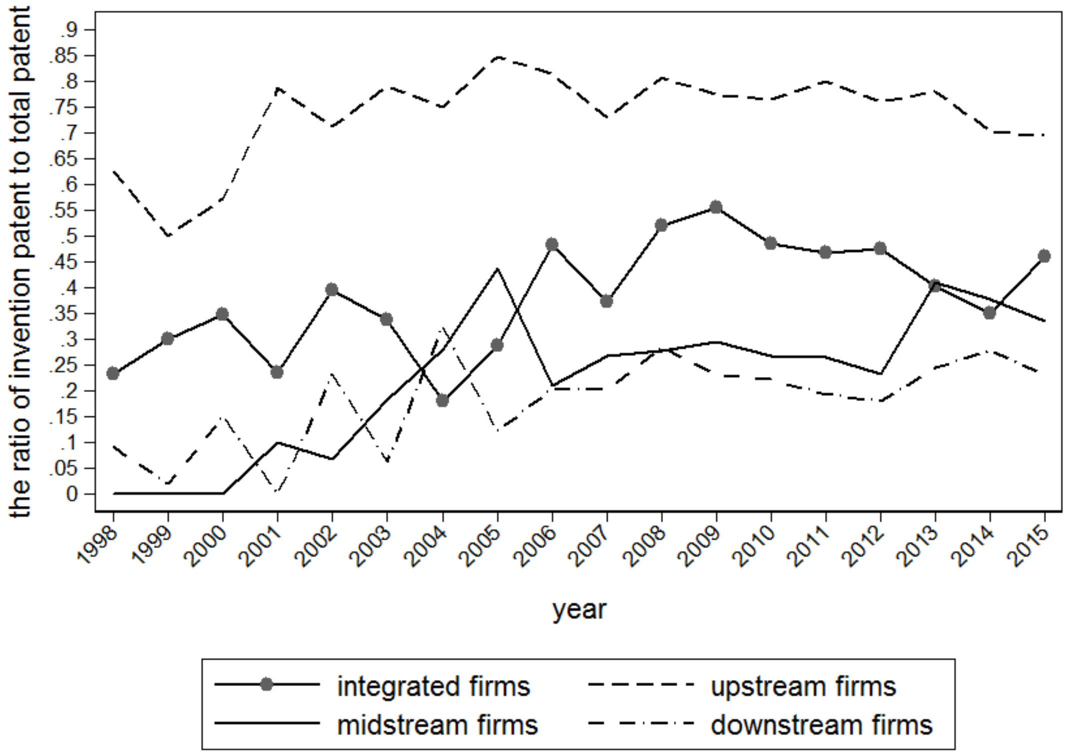

Fig. 5. The ratio of innovation-type patent applications to total patent applications in four firm groups

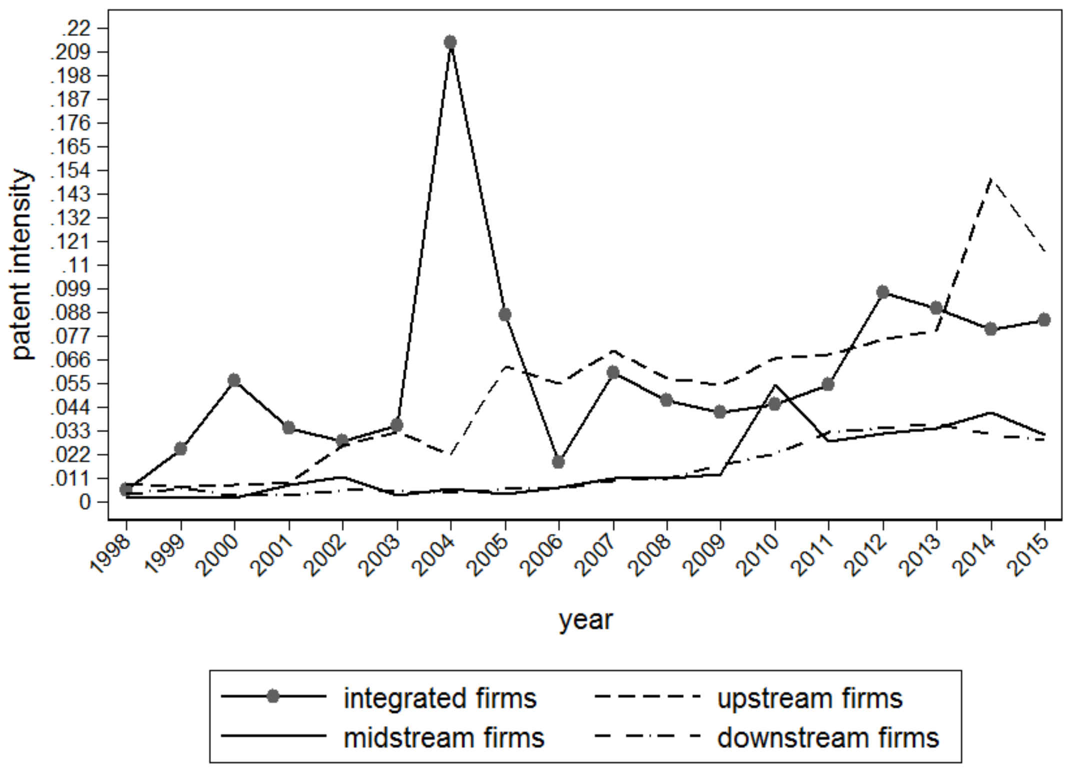

Fig. 6. The patent intensity in four firm groups

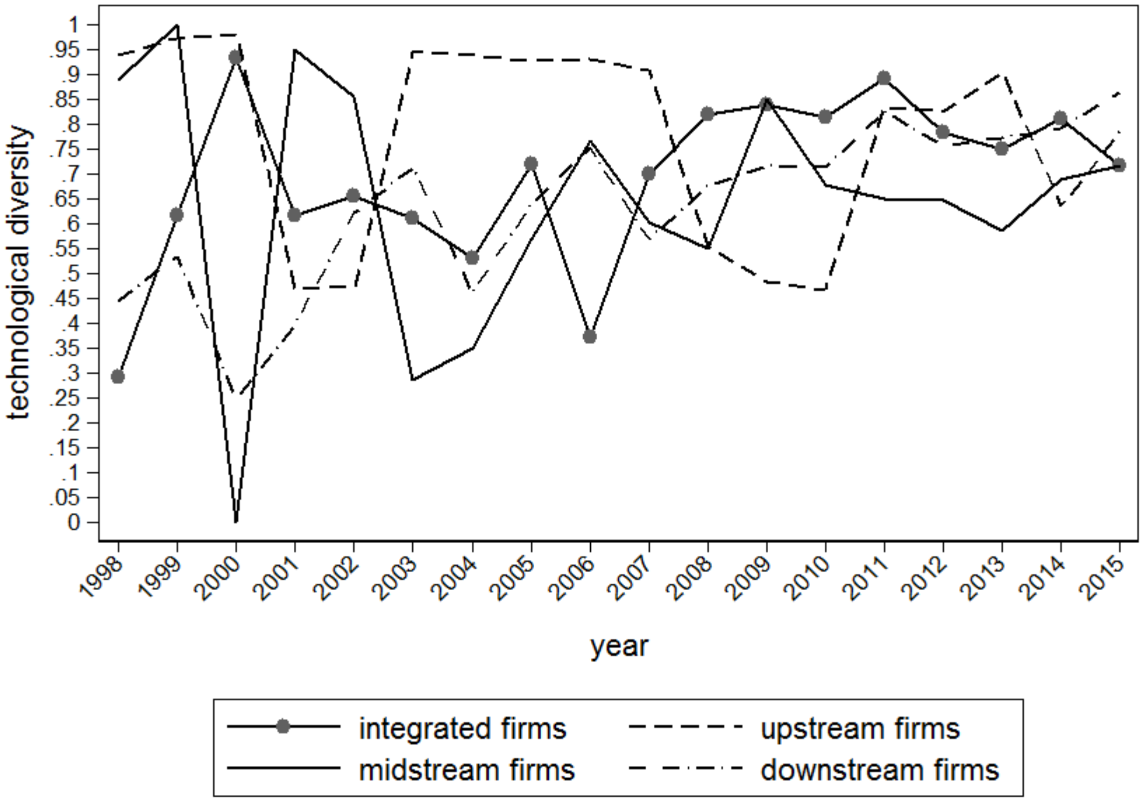

Fig. 7. The technological diversity in four firm groups

Table 1. Articles about reviewed in paper

Year	Journal	Author	Key arguments	TC	BE	GR	MC	TR	WO	Catch-up Type	Country	Industry	Research methods
2001	Research Policy	Lee and Lim	This paper applies technological capability to explain market catching-up of Korea industries, which is defined as a synthesis of technological effort and existing knowledge base. Meanwhile, technological regimes, such as cumulativeness of technical advances, fluidity (predictability) of technological trajectory and the properties of knowledge base, determine technological effort.	√						technological and market catching-up	Korea	multi industry	case study
2014	Development Policy Review	Lee et al.	Indian IT service firms form efficient business ecosystem and accumulate excellent technology capability, which make them well prepared to make full use of windows of opportunity created by techno-economic paradigm shift and government's regulation and support of industry.	√	√	√			√	technological and market catching-up	India	IT Service	case study
2008	Asia Pacific Journal of Management	Li and Kozhikode	Latecomers choose strategies of learning and innovation according to their complementary assets and absorptive capacity.	√	√				√	technological and market catching-up	China	Mobile	case study
2010	Management and Organization Review	Li et al.	FDI and latecomers' export activities are effective channels for acquiring foreign knowledge, which is essential for fostering product innovation. Besides, increasing absorptive capacity by investing in research and development and marketing activities is helpful for utilizing foreign knowledge.	√			√			technological catching-up	China	multiple industry	quantitative analysis
2005	Research Policy	Mu and Lee	Chinese government plays important role in the catch-up of telecommunication industry, who adopts the strategy of "trading market for technology" and other industry promotion policies for knowledge diffusion. Meanwhile, the technological regime of telephone switches characterized by a more predictable	√		√	√	√		technological catching-up	China	Telecommunication	case study

			technological trajectory and a lower cumulativeness also provide telecommunication industry with a favorable environment.									
2015	Innovation: Management, Policy & Practice	Chen and Chen	The catch-up process of latecomers depends on the accumulation of resources and capabilities, as well as their interactions with industrial environments. Besides, public research institutes are helpful for identifying and accumulating resources.	√	√			√	technological and market catching-up	Taiwan Province of China	FPD Industry	case study & SD
2012	Industrial and Corporate Change	Park	Government and large firms plays an important role for Korea telecommunication systems. Meanwhile, acquisition or utilization of major capabilities, taking an active part in global networking, collaboration with international standardization work group and emphasis on in-house research and development are critical factors for catch-up.	√	√				technological and market catching-up	Korea	Telecommunication Systems	case study
1999	Technovation	Sung and Hong	Latecomers depend on their prior knowledge base and effort to develop absorptive capacity of foreign technology in the early age of catch-up. And then, external factors including government, utility firms, other related organizations, foreign donors, human resources, market conditions and social conditions will work.	√		√			technological catching-up	Korea	Nuclear Power	case study
2013	Technology Analysis & Strategic Management	Chuang and Hobday	Accumulation of technological capabilities and the underlying absorptive capacity of each firm explain the technological catch-up of Taiwan's TFT-LCD industry.	√					technological catching-up	Taiwan Province of China	TFT-LCD	case study-fieldwork
2014	The Journal of Develo	Hwang and Choung	The success of catch-up not only depends on firms' export-oriented strategy and a supportive government, but also rely on the interaction between technological characteristics and institutional settings, including corporate organization, industrial structure and the role of public sector.				√		technological and market	Korea and Taiwan	Semiconductor	case study

	Development Studies									catching-up	Province of China		
2015	Innovation: Management, Policy & Practice	Hu et al.	Innovation infrastructure and institutional factors, such as high-quality manpower, state support, legislation, capital inputs and global network connects are critical for successful catch-up of east Asian.	√		√		√	√	technological catching-up	Asia, U.S., Europe and Japan	LED	quantitative study case study
2012	Development and Change	Wang et al.	The segmentation of the value chain has provided industrializing countries with a window of opportunity. Besides, east Asian states establish a more effective institutional platform, for example, biotech parks, to attract knowledge-creation players to the industry.			√			√	technological catching-up	Taiwan Province of China, Korea and China	Biopharmaceutical	case study
2011	World Development	Whang and Hobday	Domestic users, local service suppliers, favorable government policies and strong producer-user links make Korea mobile handsets industry realizing successful catch-up.		√	√	√	√	√	technological catching-up	Korea	Mobile Handset	case study
2013	Chinese Management Studies	Zhang et al.	Institutional elements and market conditions shape and then reshape the development of high-tech industries in large emerging countries.		√					technological catching-up	China	semiconductor	case study
2009	Research Policy	Chu	The second mover of Taiwan rely on accumulated organizational capabilities. However, China and Korea adopt national champion policy, which Taiwan is short of.	√		√				technological catching-up	Taiwan Province of China	IT	case study
2003	Research Policy	Xie and Wu	Chinese government takes a phased approach to liberalization of domestic market, which animates its huge domestic market. Besides, Chinese firms gradually invest in learning.	√		√	√			technological	China	color TV	case study

							catching-up			
2012	Research Policy	Wu and Mathews	Knowledge flow from advanced countries to catch-up follower countries decreases to some degree, and the dependence of the catch-up countries on their own intra-national knowledge generation and flow rises, which indicate catch-up countries' shift from imitation to innovation.	√			technological catching-up	Taiwan Province of China, Korea and China	solar photovoltaic	case study
2010	Research Policy	Motohashi and Yuan	In automobile industry, the innovative activities of multinationals have vertical spillovers to local parts supply firms, while it is not true in electronics industry.	√			technological catching-up	China	multiple industry	quantitative analysis
2015	Research Policy	Nam	Compact organizational space is helpful for technological catch-up, where firms form business group and maintain close proximity through active interactions, collaboration and resource-sharing.	√	√		technological catching-up	China	automotive	case study
2014	Research Policy	Gao	The development of innovation capabilities and new technologies are essential for catch-up. Meanwhile, special capabilities need to be developed to get support from government and stakeholders.	√		√	technological catching-up	China	telecommunication	case study
2008	Research Policy	Cai and Tylecote	Semi-privatized firms with arms-length relationships to government has the most dynamic technological capability.	√		√	technological catching-up	China	mobile telecommunications	quantitative study
2006	Technovation	Fan	Innovation capability and self-developed technologies have been the key to leading domestic firms' catch-up with the multinational corporations. Meanwhile, domestic firms should focus on in-house R&D development to build their innovation capability, supplemented with external alliances.	√			technological catching-up	China	telecom-equipment	case study

2010	World Development	Brandt and Thun	In China, industrial upgrading efforts are often domestically driven, within this domestic market there is intense competition between both domestic and foreign firms.				√		market catching-up	China	multiple industry	case study
2015	Innovation: Management, Policy & Practice	Liu et al.	Modularization and the evolution of value chain significantly lower the technological threshold of entering the mobile phone business, promote disruptive innovations and accelerate latecomers' accumulation of knowledge and technology.		√		√		technological catching-up	China	Mobile Handset	case study
2006	Research Policy	He et al.	An entrant can leverage complementary assets to enter along a new technological trajectory, and then develop appropriability. We illustrate how several mobile telecommunications firms (Ericsson, Nokia and Samsung) pursued this strategy to catch up with the market leader (Motorola).	√	√	√			technological catching-up	Sweden, Finland and Korea	Mobile telecommunications	Case study & patents analysis
2005	Research Policy	Hu and Mathews	Extend and modify the FP&S approach (FP&S frames as a concept of national innovation capacity by Furman, Porter and Stern) applying it to five “latecomer” countries from East Asia, none of which was included in the FP&S study. Results are in broad agreement with the findings of FP&S, but some important differences for latecomer East Asian economies: a smaller number of national factors matter, and there seems to be an important role for public R&D expenditure			√		√	technological catching-up	East Asia	No specific industry	quantitative study
2012	Technological Forecasting & Social Change	Choung et al.	This paper takes stock of Information and Communications Technologies (ICT) policy design, implementations of projects and standards-settings during the Korean catch-up in ICT sectors and attempts at highlighting their commonalities during three different phases: Implementation, Participation, and Definition of standards. The co-evolution of two types of policies and implementations-'generic' and ' targeted'- affect the rate, direction and processes of catch-up.			√			technological catching-up	Korea	ICT standards	case study
2008	Technovation	Hu and Hsu	The gap in R&D intensity between South Korean firm and European and American competitors is closed. South Korean innovative power came from three sources: interaction with operators, getting service information and applications	√	√				technological	Korea	cellular phone	case study

			from service providers, and internal and external competition. After successful experiences in innovating products for the domestic market, South Korean cellular phone makers used customized design with foreign mobile operators and their foreign R&D centers to localize design and make modifications to meet foreign market demand.							catching-up			
2015	Research Policy	Kiameh r et al.	The study shows that the firm was able to exploit its linkages with local clients, favorable government policies and a growing domestic demand to overcome barriers to entry and learn how to manufacture and design complex power generation systems. It highlights the insights differences between strategies of catch-up in the Iranian case with those of Asian electronics and complex goods in Latin America, and the reasons behind an imbalanced progress in accumulation of production capabilities and technological change capabilities.			√	√			technological and market catching-up	Iran	Thermal electricity generation systems	case study
2014	IEEE Transactions on Engineering Management	Chuang	This paper combines the perspectives of the external foreign sources of technology learning for developing countries and the internal sources of organizational learning and routines to examine how latecomers accumulate in-house knowledge bases and assimilate foreign knowledge to create innovation capabilities, and finds that the increasing knowledge bases makes the latecomers benefit form knowledge transfer.	√				√	√	technological catching-up	Taiwan Province of China	FPD	case study
2010	Research Policy	Eom and Lee	This paper utilizes the Korea innovation survey date to analyze the impact of industry-university-government research institute (IUG) cooperation on firm performance, and finds that national R&D project turns out be most significant and IUG cooperation will enhance innovative firms generating more patents.		√	√				technological catching-up	Korea	no specification of industries	case study quantitative study
2011	Asian Journal of Technology Innovation	Kim	This paper applies technological capability, investment and competition strategy, target market and threat types and favorable external circumstances to explain Korea firms' innovation and competition with their Japanese competitors.	√			√		√	technological and market catching-up	Korea and Japan	semiconductor	case study

2012	Research Policy	Hu	This paper analyzes the influence of technological innovation capabilities of one forerunner, Japan, and two latecomers, Korea and Taiwan on their market performance, and finds that firms in Korea and Taiwan expand production by selecting certain technological fields, while Japanese firms strengthen the protection of intellectual property rights to counter the aggressive market expansion of Korea and Taiwan.	√	√			√		technological and market catching-up	Japan, Korea, and Taiwan Province of China	TFT-LCD	quantitative study
2006	Futures	Castellacci	The changes in the techno-economic system are opening up new windows of opportunity for developing countries, and are increasing the scope for a broad range of public policies to sustain the catching up process.			√		√	√	technological catching-up	no specification of countries	no specification of industries	case study
2010	Asian Journal of Technology Innovation	Kim and Seong	The catch-up and post catch-up innovation by latecomer countries and the innovation by advanced countries are different. When Samsung was in the period of catch-up, it focused on accelerating product development speed. However, when Samsung was in the period of post catch-up, its innovation strategy was becoming a fast follower.	√					√	technological catching-up	Korea	Semiconductor	case study
2006	New Political Economy	Mathews	Latecomers are able to exploit their late arrival to tap into advanced technologies, rather than having to replicate the entire previous technological trajectory. Meanwhile, latecomers are faced with new opportunities for linking up with emergent institutions and networks, which makes latecomers easier to acquire knowledge, technology and market access.	√	√	√				technological and market catching-up	no specification of countries	multiple industry	case study
2009	Research Policy	Chen	In low-and medium-technology (LMT) sectors, much knowledge can be acquired by informal means. For example, LMT industries are able to climb the technological ladder through exploiting various local and global informal knowledge linkages.	√	√					technological catching-up	Taiwan Province of China	machine tool	case study
2014	World Development	Choung et al.	This paper distinguishes three archetypes of innovation activities: deepening of the process, architectural and radical innovations. Each route of innovation activities in the transition period of the emerging economies requires corresponding institutional frameworks, different base of capabilities, and	√	√	√				technological catching-up	Korea	multiple industry	case study

			different relationships among innovation actors to facilitate the transition from imitator to innovator.										
2006	World Development	Niosi and Reid	New science-based technologies provide windows of opportunity to less developed countries for catch-up. And the strategies to overcome entry barrier are attracting foreign venture capital and forming innovation cluster and alliance.		√			√	√	technological catching-up	Brazil, China, and India	multiple industry	case study
2011	Asia Pacific Business Review	Zhu et al.	The whole process of catching up should be seen as a dynamic and re-iterative learning process, where the development of existing resources, the learning of new skills and innovation are very crucial.	√						market catching-up	China	television manufacturing	case study
2008	Global Economic Review	Ning	Asian states took a very active role, focusing on fostering indigenous technological and production capability in the creation of their semiconductor industry during globalization and economic liberalization.	√		√				technological and market catching-up	Japan, Korea, Taiwan Province of China and China	semiconductor	case study
2011	Asian Journal of Technology Innovation	Jun	This paper identified the required capabilities for survival and growth of a latecomer's new technological path that are Intra-Path Integration and Inter-Path Reconfiguration capabilities.	√						technological catching-up	Korea and Japan	mobile communications	case study
2012	Review of International	Kim	This paper holds the opinion that the core features of the Korean model have been recombined in creative and unanticipated ways to meet the twin challenges of economic openness and knowledge-based industrialization.			√				technological catching-up	Korea	telecommunications	case study

Political Economy	

Table 2: The percentages and representative arguments of each determinant in the 43 articles

Determinants of catch-up	Percentage of each determinant in 43 papers	Representative arguments of each determinant
Technology capability	69.767%	This paper applies technological capability to explain market catching-up of Korea industries, which is defined as a synthesis of technological effort and existing knowledge base.
Business ecosystem	37.209%	Compact organizational space is helpful for technological catch-up, where firms form business group and maintain close proximity through active interactions, collaboration and resource-sharing.
Government role	46.512%	Chinese government plays important role in the catch-up of telecommunication industry, who adopts the strategy of "trading market for technology" and other industry promotion policies for knowledge diffusion.
Market condition	20.930%	Institutional elements and market conditions shape and then reshape the development of high-tech industries in large emerging countries.
Technological regime	20.930%	The technological regime of telephone switches characterized by a more predictable technological trajectory and a lower cumulativeness also provide telecommunication industry with a favorable environment.
Windows of opportunity	23.256%	The segmentation of the value chain has provided industrializing countries with a window of opportunity.

Table 3: The locations of the primal foreign firms and Chinese firms in LED industry

	Upstream			Midstream	Downstream		
	Substrate	Epitaxial Wafer	LED Die	Encapsulation	Lamps	Luminaries	Systems
Foreign firms							
CREE	■	■	■	■	■	■	■
Toyoda Gosei	■	■	■				


Nichia
Samsung
Seoul Semicounductor
Everlight
Philips Lighting
Philips Lumiled
Osram
LEDvance (Osram spin off)
Chinese firms
Integrated firms
Silan
San'an Optoelectronics Co., Ltd.
Elec-Tech International Co., Ltd.
China Fangda Group Co., Ltd.
Tsinghua Tongfang
Lianovation
Upstream
Grinm Semiconductor Materials Co., Ltd.
ZheJiang East Crystal Electronic Co.,Ltd.
Zhejiang Crystal-Optech Co., Ltd.
Xiamen Changelight Co. Ltd.
Midstream
Jilin Sino-Microelectronics Co., Ltd. (JSMC)
Foshan NationStar Optoelectronics Co.Ltd
GoerTek Inc.
Changjiang Elec. Tech.
Honglitronic
Shenzhen REFOND Optoelectronics

Xiamen Guangpu Electronics Co., Ltd.
Shenzhen Mason Technologies Co., Ltd
Downstream
Ledman Optoelectronic Co., Ltd.
Shenzhen MR Photoelectricity Co., Ltd
SHENZHEN CF lighting Co.,Ltd
Yankon Lighting
Foshan Lighting
CNLIGHT Co., Ltd
Feilo Acoustics
EVERFINE Corporation
Kingsun
Leyard
Unilumin
Shenzhen jufei optoelectronics co.,ltd.
AOTO Electronics
OPPLE
Tospo lighting
Forest Lighting
NVC Lighting Holding Limited

Note: The highlight area means that the focal firm engages in this business.

Table 4. Technology sources of Chinese LED firms

technology sources	the number of technology licenses				
	integrated	upstream	midstream	downstream	total
belong to individuals	2	0	2	10	14

belong to domestic firms	72	1	5	58	136
belong to university and research institute	0	0	0	0	0
belong to foreign firms	0	0	0	0	0
total	74	1	7	68	150

technology sources	the number of technology transfer				
	integrated	upstream	midstream	downstream	total
belong to individuals	14	0	10	186	210
belong to domestic firms	477	83	27	494	1081
belong to university and research institute	59	99	0	4	162
belong to foreign firms	17	0	0	0	17
total	567	182	37	684	1470

Table 5 Top manage teams' overseas background of our firm list

Company name	The number of members in top management team	The number of members with overseas education	The number of members with overseas working experience	The number of members with overseas education and working experience	Total number of members with overseas experience	The percentage of members with overseas experience
Silan	15	0	0	0	0	0
San'an Optoelectronics Co., Ltd.	16	0	3	0	3	0.1875
Elec-Tech International Co., Ltd.	16	0	6	2	8	0.5
China Fangda Group Co., Ltd.	12	1	0	0	1	0.083333333

Tsinghua Tongfang	17	0	0	0	0	0
Lianovation	19	0	1	0	1	0.052631579
Grinm Semiconductor Materials Co., Ltd.	14	0	0	0	0	0
ZheJiang East Crystal Electronic Co.,Ltd.	15	0	0	1	1	0.066666667
Zhejiang Crystal-Optech Co., Ltd.	16	1	0	0	1	0.0625
Xiamen Changelight Co. Ltd.	12	1	2	0	3	0.25
Jilin Sino-Microelectronics Co., Ltd. (JSMC)	13	0	0	0	0	0
Foshan NationStar Optoelectronics Co.Ltd	20	3	0	0	3	0.15
GoerTek Inc.	16	2	3	1	6	0.375
Changjiang Elec. Tech.	17	0	2	0	2	0.117647059
Honglitronic	15	1	0	0	1	0.066666667
Shenzhen REFOND Optoelectronics	13	0	0	0	0	0
Xiamen Guangpu Electronics Co., Ltd. （GOPRO）	12	0	0	0	0	0
Shenzhen Mason Technologies Co., Ltd	13	0	1	0	1	0.076923077
Ledman Optoelectronic Co., Ltd.	11	0	1	0	1	0.090909091
Shenzhen MR Photoelectricity Co., Ltd	17	1	2	0	3	0.176470588

SHENZHEN CF lighting Co.,Ltd	14	0	2	0	2	0.142857143
Yankon Lighting	21	0	1	0	1	0.047619048
Foshan Lighting	20	3	2	0	5	0.25
CNLIGHT Co., Ltd	4	0	0	2	2	0.5
Feilo Acoustics	24	1	6	1	8	0.333333333
EVERFINE Corporation	13	0	0	0	0	0
Kingsun	13	0	3	0	3	0.230769231
Leyard	15	0	1	0	1	0.066666667
Unilumin	12	2	0	0	2	0.166666667
Shenzhen jufei optoelectronics co.,ltd.	10	1	1	0	2	0.2
AOTO Electronics	17	0	0	0	0	0
OPPLE	16	0	6	0	6	0.38
Tospo lighting	17	0	0	0	0	0
Forest Lighting	12	0	3	0	3	0.25
NVC Lighting Holding Limited	18	2	4	5	11	0.61