Institutions and Economies
Vol. 7, Issue 1, April 2015, pp. 52-79

Sticky Spots on Slippery Slopes: The Development of the Integrated Circuits Industry in Emerging East Asia

Rajah Rasiah[a] , Yap Xiao Shan[b] , Yap Su Fei[c]

Abstract: *This paper draws from an evolutionary study of 36 integrated circuit (IC) production firms to examine the role of institutions and intermediary organizations in supporting technological upgrading in the integrated circuit industry in emerging East Asia. The evidence shows that IC firms in Korea and Taiwan have reached the technology frontier to show that they are deeply rooted on the slope of competition. IC production has also become sticky in Singapore and China where the provision of grants and government-industry coordination have attracted participation in the high value added activities of wafer fabrication, IC design and supportive R&D activities. Although IC production in Malaysia has enjoyed functional upgrading, particularly since 2005, its capacity to follow the path of Singapore and China will depend heavily on the dismantling of ethnic considerations by the government in the promotion of the industry. IC production is not sticky at all in the countries of Philippines, Thailand and Indonesia because of a lack of institutional deepening. Consistent with the global production network approach, the successful experiences examined in this paper show that the development of institutions and intermediary organizations through effective coordination between governments and industry is critical to stimulate technological upgrading in the IC industry.*

Keywords: East Asia, Integrated Circuits, Institutions, Technological Upgrading

JEL Classification: 033,L63, L52
Article Received: 21 February 2014; Article Accepted: 14 September 2014

1. Introduction

The decomposition of production and its dispersal to connect developed sites with less developed sites have been welcome as a boon from where a number of poor countries have enjoyed the opportunity to break in and move

[a] Corresponding Author. Department of Development Studies,University of Malaya. *Email*: rajah@um.edu.my

[b] Department of Development Studies, University of Malaya. *Email*: xiaoshan0605@gmail.com

[c] Department of Economics, University of Malaya. *Email:* g1sufei@yahoo.com

up global value chains (UNIDO, 2009). The immediate division of labor of such cross-border spread of production has been driven by resource endowments (natural resources and low wage labor) along what Froebel *et al.* (1980) had argued to depict the Babbage Principle. Babbage (1835) had conceived the first computer through his efforts to use mathematical, engineering and manufacturing knowledge to design a mechanical structure that could be decomposed by knowledge capabilities. Similarly, mainstream economists claim that the geographical differentiation of production would occur on the basis of relative prices (Helleiner,1973; Collier,2007). However, whereas Baran (1973) and Froebel *et al.* (1980) contend that such a geographical extension of the division of labor will lead to the underdevelopment of the periphery, Collier (2007) argued that it will provide the opportunity for these sites to develop. These one-directional flows of international investment have been transformed in particular industries so that knowledge asset seeking MNCs have begun relocating from emerging to the developed economies (see Rasiah et al., 2012).

The locus of technological change has also shifted in some product niches with firms from the emerging economies dislodging the incumbents from the developed economies to play technological shaping roles. For example, at a time when Moore's law predicting the minimum line width of IC nodes to half with transistor implants doubling every 24 months was increasingly being questioned following soaring costs of photolithography (Brown and Linden, 2009), Samsung managed to lower the period to 12 months in the less complicated memory chips (Rasiah *et al.,* 2012). Also, the Taiwanese pioneered independent wafer fabrication plants in the 1980s to engineer horizontal specialization in the relocation of MNC subsidiaries (Tsai and Cheng, 2006).

While a focus on global value chains is important, we argue that institutional development at host-sites helps explain why technological upgrading has occurred at some rather than other sites. Markusen (1996) had provided arguably the most robust argument on institutional development as being central to stimulate technological upgrading.[1] We attempt to take on the views of Nelson (2008) to include a rigorous account of the embedding institutional framework to capture the role of national actors in driving technological upgrading.

ICs make an excellent laboratory to examine the importance of institutional development as the volume of IC trade from developing and newly developed East Asia grew from US$36.5 Billion in 1990 to US$566.4 Billion in 2010 (WTO, 2011: Appendices Table 11.55 and 11.56). China enjoyed the most dramatic expansion in which trade in ICs grew from US$0.9 Billion in 1990 to US$243.9 Billion in 2010. As a consequence emerging East Asia's share in world IC trade rose from 32.8% in 1990 to 59.0% in 2010 (see Table 1). China's expansion is the most dramatic as its share rose from 0.8% in 1990 to

25.4% in 2010. Hence, this paper examines the development of the industry in emerging East Asia, and analyses the influence of institutional development on technological upgrading at host-economies. Following Markusen's (1996) lucid exposition of the role of institutional development, we develop a typology by taxonomies and trajectories to evaluate the influence of institutional support on technological upgrading achieved by IC firms in emerging East Asia.

The rest of the paper is organized as follows. Section 2 reviews the key theoretical arguments relevant for investigating technological upgrading in IC firms. Section 3 presents the methodology and data used. Section 4 analyses the technological upgrading experiences of IC firms against the supporting institutional infratructure efforts in emerging East Asia. Section 5 presents the conclusions.

2. Theoretical Considerations

There is a wide range of papers that focus on the globalization of production but only a few examine incisively its impact on technological upgrading at host-site locations using empirical evidence. In some cases the decomposition of production is undertaken entirely by MNCs so that the firm retains command of the whole value chain. Foreign direct investment is the basis of such a globalized division of labor, which spreads across borders. There has been a shift toward outsourcing production abroad in industries, such as clothing, electronics and shoes since the 1980s whereby the firm in control of the global value chain (GVC) focuses on the high value added activities of new product development, designing and brand promotion (Gereffi, 2002; Sturgeon, 2002). Exponents of GVCs have analysed the drivers of value chains (see Gereffi 2002; Gereffi *et al.,* 2005), which has helped the mapping of the value chain, and to identify opportunities within the dynamics of the chain (including the drivers within them) that host-site firms could expand into. Whereas in the first mode, MNCs keep ownership and control of the value chain through internalized command, control in the second mode is defined by the relative strength of suppliers in value chains though ownership structures are independent. Flagship firms, such as, Intel, Samsung and Texas Instruments still largely operate as integrated device manufacturers undertake all activities within their internalized value chain but distributed across the world, though, some operations are outsourced. However, some brand-less original equipment manufacturers have emerged strongly to define the knowledge base of IC value chains. For example, Taiwan Semiconductor Manufacturing Company (TSMC) undertakes frontier R&D activities so that it provides buyers the most advanced fabricated wafers for the production of logic chips (Yap and Rasiah, 2013). Nevertheless, technological upgrading at host-sites through both types of routes is influenced by the presence, level of development and connectivity of host-site institutions and intermediary organizations. It is in this context, Markusen (1996) had referred succinctly to 'sticky places' on 'slippery space' when explaining why some locations experience industrial deepening while others have remained as shallow low end sites.

The sources of stickiness that explain industrial deepening in particular regions can emerge from interrelationships between local, provincial and federal governments and intermediary organizations, regional trading regions, and global organizations (e.g. MNCs, and the World Trade Organization) (Rasiah, 2004). These relationships can be viewed as networks in which firms engage in flows of knowledge and transaction of goods and services within particular locations and integrated internationally through either internalized MNC production chains or driven by particular outsourcing or marketing links (Sturgeon, 2002; Gereffi, Humphrey and Sturgeon, 2005). However, where upgrading involves high tech activities that require constant innovation the institutions and actors must also have access to the critical inputs of human capital and R&D support to support knowledge-creating activities.

Mainstream economists have focused on economic development as a process of transforming physical resources without much discussion on the importance of institutions and institutional development to ensure technological upgrading. North (1994) articulated the important role of institutions by referring to it as the 'rules of the game' that define the conduct of the players, i.e. the entrepreneurs and organizations. Whereas Schumpeter (1934) called for the need to provide productive rents to attract investment into risky and uncertain activities to support innovation spurts, it is also critical that the macro instruments and intermediary organizations targeted at solving collective action problems are created and connected to firms at the micro level to ensure that the interface between them is smoothly coordinated to stimulate firms movement to the technology frontier so as to enable them to appropriate economies of scale and scope (Nelson, 2008). Companies in such activities may crumble rather than compete if exposed early to unbridled currents of competition, especially to sudden external shocks from volatile fluctuations in exchange and interest rates (Katz, 2006). Where the pursuit of the firm is confined to creative destruction activities (Mark 1) the focus is on incremental innovation - product adaptation, and new and more effective ways of producing and delivering products and services (Schumpeter, 1934). At the catch up stage latecomers can quicken the period of learning by looking at the leader and skipping stages and avoiding errors (Veblen, 1915; Gerschenkron, 1952; Abramovitz, 1956). Where firms engage in the generation of new stocks of knowledge to benefit from innovation rents that come with new product launches, large firms or small firms networked with external R&D labs participate in creative accumulation (Mark 11) (Schumpeter, 1943). In a knowledge-intensive industry such as ICs, three variables are critical in driving innovation leaps, i.e. lumpy investments, knowledge absorption and eventually the production of new stocks of knowledge, and large markets to appropriate scale economies (either at the firm or at the industry level). The depth of integration and potential for technological upgrading in particular host-sites in value chains depends very much on the embedding institutions and intermediary organizations as articulated by Markusen (1996) and Nelson (2008). As firms switch strategies from late mover to first mover roles heavy investment into R&D becomes critical as evidenced by the paths of Samsung and TSMC, both of whom dislodged incumbents to take leadership of memory and logic chips respectively (Rasiah *et al.,* 2012; Yap and Rasiah, 2013). Rodrik (2007) and Acemoglu and Robinson (2012) provided econometric evidence over the significance of institutions in economic development, though, their references to and quantification of the institutions leaves serious questions over measurement issues.

Table 1: Share of R&D-Performing and Innovating Firms,Thailand, 1999-2011(%)

Country	**1990**	**2000**	**2010**
China	0.9(0.8)	26.5(4.3)	243.9(25.4)
Indonesia	0.2(0.2)	0.8(0.1)	3.1(0.3)
Korea	9.9(8.9)	45.2(7.3)	71.9(7.5)
Malaysia	8.1(7.3)	43.2(7.0)	62.3(6.5)
Philippines	2.1(1.9)	27.3(4.4)	29.2(3.1)
Singapore	6.5(5.8)	27.0(4.4)	40.8(4.3)
Taiwan PC	6.6(5.9)	45.5(7.4)	92.4(9.6)
Thailand	2.2(2.0)	14.2(2.3)	21.4(2.2)
Vietnam	0.0(0.0)	0.6(0.1)	1.4(0.1)
Total	**36.5(32.8)**	**230.3(37.3)**	**566.4(59.0)**

Note: Trade is measured by adding exports and imports.
Source: Calculated from WTO (2011: Appendix Tables 11.55 and 11.56)

3. Methodology and Data

This evolutionary study traces the institutional support elements to distinguish why there has been stronger technological upgrading in the IC industry in some countries rather than other countries in emerging Asia. Officials from selected firms were interviewed to identify the drivers of technological upgrading and economic synergies. A ledger with a checklist of critical generic questions was used in the interviews. Consistent with Keynes (1890) notion of inductive theorizing, evidence was compiled along a generic trajectory of IC production (see Figure 1):independent R&D, chip design, R&D support, wafer fabrication, and assembly and test,[2] though some integrated device manufacturers

IDMs (e.g. Intel, Texas Instruments and Samsung) firms undertake all three stages. In an attempt to examine the critical drivers of initiation (whether through relocation or greenfield investment), three important need to be scrutinized in each of the IC stages involved, namely, economies of scale and scope, relational contracting (Macneil, 1974; Massey, 1973), and regional, sectoral and national institutions (Malerba and Nelson, 2012).

We combined the data used by Rasiah and Yap (2013) to explain the motives behind relocation abroad by 14 IC MNCs from emerging East Asia, and another 5 American (Intel, Texas Instruments, Advanced Micro devices, Fairchild and International Device Technology), 2 Japanese (Renesas and Panasonic Semiconductor), 2 German (Infineon and OSRAM) and 1 Italian-French (but headquartered in Switzerland) (ST Microelectronics) parent IC firms interviewed at the same time in 2012, and in addition what these firms sought or were offered to upgrade at host sites. Interestingly, the responses of the non-East Asian firms matched the responses of the East Asian firms. The motives from responses of the 24 MNCs are reported in Table 2.

A stylized framework of technological upgrading is depicted in Figure 1. In the functional category, IC firms evolve to integrate front- and back-end operations without significant increases in value added, while some relocate or upgrade to participate in R&D, IC design and wafer fabrication. Whereas the former refers to horizontal integration the latter refers to functional upgrading. We do not consider horizontal integration activities as functional upgrading if they are limited to the merging of lower value added activities – e.g. the addition of assembly to test activities, or wafer bumping to wafer fabrication.

In the second dimension, IC firms absorb best practices, including cutting edge inventory and quality control systems, and introduce adaptive engineering and R&D support to upgrade assembly and test activities to raise plant-level productivity, which qualify as Mark 1 activities that entrepreneurs can easily undertake (Schumpeter, 1934). Because of the public good nature of knowledge, the extent of government support required to promote upgrading to include R&D, IC design and wafer fabrication will be higher than simply the promotion of upgrading in assembly and test activities. R&D is also integral to firms carrying out independent R&D, IC design, R&D support and wafer fabrication, and hence, they can be classified as Mark 11 activities (Schumpeter, 1943). Rasiah (2010) offered a typology by taxonomies and trajectories of the knowledge-intensities within IC firms. Of the six levels of knowledge-intensities used, the first involves no incremental innovation, while the second, third and fourth generate incremental innovation with the engineering intensity rising from 2 to 4. Levels 5 and 6 involve participation in R&D activities. Level 6 refer to firms successfully shaping the technology frontier to enjoy product innovation rents.

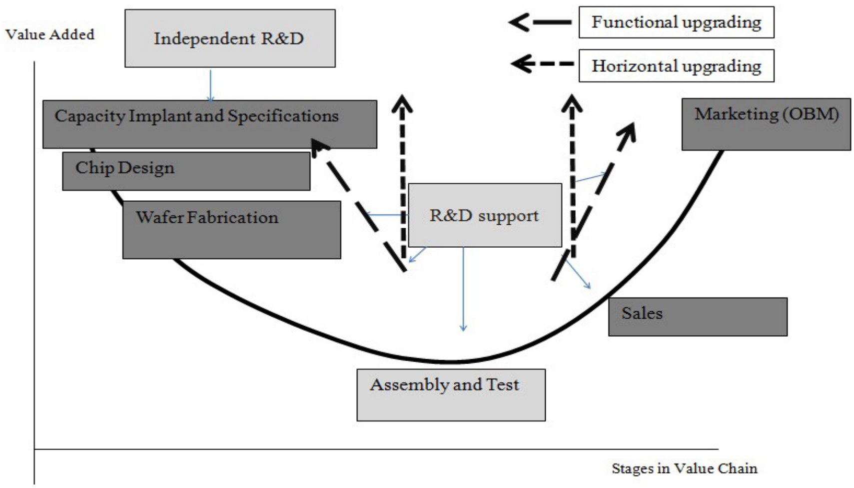
Table 2: Taxonomy of IC production by stages, 2014

	Infrastructure	Human Capital	Markets	Incentive
Assembly and Test	Excellent basic infrastructure	Large reserves of literate labour	Buyers essential in developed economies; Not essential in developing economies	Tariff-free operations (because of low margins), Tax exemption to attract relocation
Wafer fabrication	Excellent high tech infrastructure; Uninterrupted uniform band power supply; Excellent environment –friendly infrastructure	Large pool of engineers and scientists	Buyers important motive	Tariff-free operations;Tax exemption to attract relocation; Capital grants critical
Support R&D	Excellent high tech infrastructure; Strong presence of process engineers	Large pool of process engineers	Mainly to support own operations	Tax exemption
Chip design	Excellent high tech infrastructure; Strong presence of design engineers	Large pool of software engineers	Buyers important motive	Tax exemption to attract relocation; grants if human capital needs to be developed.
Independent R&D	Excellent R&D infrastructure, frontier R&D labs and research universities in IC technology	Large pool of R&D scientists and engineers	First-mover buyer firms important	Tax exemption and tariff-free operations; Capital grants

Source: Authors

The evolutionary study of 24 MNCs with operations in East Asia, both their national operations and foreign operations to capture the characteristic institutional support firms look for starting or relocating the different stages in the IC value chain. Because the responses were unanimous we present them in Table 3.

Figure 1: Value Chain of ICS, 2012



Source: Authors

Table 3: IC Firms Interviewed, 2009-2012

	MNC	Ownership	Locations in East Asia
1	Advanced Manufacturing Devices	United States	Singapore, Malaysia, China
2	ASE	Taiwan	Taiwan, Japan, South Korea, China, Singapore, Malaysia
3	Alterra	United States	Malaysia, China
4	Avago	Singapore	Singapore
5	Carsem	Malaysia	Malaysia, China
6	Chartered Semiconductor	Singapore	Singapore
7	Fairchild Semiconductor	United States	South Korea, Philippines, Malaysia, China
8	Freescale	United States	Malaysia, China
9	Globetronics	Malaysia	Malaysia, China (closed)
10	Hynix Semiconductor	South Korea	South Korea, China
11	Infineon	Germany	Singapore, Malaysia, China, Indonesia
12	Intel	United States	Malaysia, China, Vietnam
13	International Device Technology	United States	Malaysia, Philippines

Table 3 (continued)

14	Marvell Technology	United States	South Korea, Taiwan, Singapore, Malaysia, China
15	Osram	Germany	Malaysia
16	Panasonic Semiconductor	Japan	Japan, Singapore, Malaysia, China
17	Qimonda	Germany	China (closed)
18	Renesas	Japan	Japan, Singapore, Malaysia, China
19	Samsung	South Korea	South Korea, China
20	ST Microelectronics	Italy/France	Singapore, Malaysia, Philippines, China
21	Taiwan Semiconductor Manufacturing Company	Taiwan	Taiwan, China, Singapore
22	Texas Instruments	United States	Japan, Taiwan, Malaysia, Philippines, China
23	United Microelectronics Company	Taiwan	Taiwan, Japan, Singapore
24	Unisem	Malaysia	Malaysia, Indonesia, China

Source: Authors

Frontier R&D

IC firms undertake frontier R&D focusing on node miniaturization and wafer diameter that relate to capacity implant and specifications. Although a few firms undertake research at the frontier in the three main IC products of memory chips, logic chips and microprocessors, the firms that have been shaping the technology frontier by bringing out the most novel inventions in these segments are Samsung, TSMC and Intel respectively (see Yap and Rasiah, 2013). As reported by Rasiah and Yap (2013), IC firms locate frontier R&D in sites endowed with R&D scientists and engineers, research labs and universities where advanced IC research is carried out. Given the uncertainty associated with such R&D, firms also look for capital grants to underwrite the risks. Hence, the United States, Israel, Japan, Germany, South Korea and Taiwan were identified in this study as locations where frontier IC R&D is carried out.

Chip Design

Designing firms cluster around wafer fabrication plants as the fabrication process is often defined by the designs supplied to meet buyers' demand. Flagship IDMs, such as Intel and Samsung often develop the next generation chips, and hence, internalize this activity by owning designing plants. Smaller fabless IC firms attract designers to work closely with contract fabrication houses to ensure the smooth coordination of IC fabrication. Also, small orders often attract small design firms that offer their designing services to fabrication plants and fabless firms by relying on a blend comprising relative prices and cooperation. Relational contracting is very strong especially when the IC buyers, designers and the fabrication houses are independently owned. The highly diversified software design firms in India export considerably their services to, inter alia, IC firms located abroad that is because of strong relational contracting fostered through the involvement of a large diaspora abroad engaged in such activities in the absence of wafer fabrication (Saxenian 2006; Parthasarathy 2010). The internet has played an important role here. Specialized designing firms seek grants in the formative years to scale up operations, relocate at new sites or are engaged in R&D to introduce new designs. Being knowledge-intensive, designing firms also take up considerable number of patents.

Wafer fabrication

Wafer fabrication is generally deployed as the anchor around which firms specializing on the stages of assembly and test, and designing locate. Fabrication plants seek uninterrupted supply of uniform band power and water at competitive prices and infrastructure support that prevents the emission of hazardous effluents.[3] All three require institutional governance from intermediary organizations to generate adequate and uninterrupted supplies of power and clean water. Fabrication plants also require excellent communication infrastructure, high security and political stability.

Also, because wafer fabrication is highly engineering-intensive firms seek locations where large numbers of engineers (particularly in electrical engineering) are available. Where national supplies are inadequate the immigration regulations should be supportive of their import. While proximate locations to buyers and suppliers are important it is not essential as production can be globally organized and flights and internet help reduce physical distances.

Wafer fabrication plants whether characterized by the internalized mode of MNC value chains or independent mode of contract manufacturing rely on economies of scale. Investments in fabrication houses are lumpy, and hence, firms only break even when production is close to installed capacities. Hence, unless national governments finance the creation of infant wafer fabricationplants, IC firms seek grants upfront as an inducement to locate such activities. Even in the developed countries, such as, the United States, New York's Public Authorities Control Board approved a US$650 million grant to AMD in 2006 to locate a wafer fabrication plant (AMD 2006).[4] Also, being at the frontier of the miniaturization process and defining the durable and functional characteristics of the dies that make up the brain in chips, fabrication houses undertake new knowledge creating R&D facilities that is reflected in high take up of patents.

R&D Support

Following the introduction of kaizen and just-in-time practices in American and European IC firms to compete with Japanese firms since the 1980s (Rasiah, 1988), competitive firms have established R&D activities to support innovation throughout the value chain. Hence, it is the trend since to have R&D support to quicken the knowledge intensity of chip design, wafer fabrication and assembly and test. Non-brand holder firms in previously low value added activities, such as Advanced Semiconductor Engineering (ASE) have introduced R&D activities to support assembly and test.

R&D support activities - whether undertaken wholly in-house or jointly with other firms and R&D labs and universities – are often carried out by large firms who amortize their investments by pooling enough demand to meet economies of scale. Investments in R&D support are less risky, and flagship firms that are highly reliant on knowledge-intensive production activities have started such activities without capital grants. Intel and AMD are two good examples in which their operations in China and Malaysia incorporated such R&D support activities from the 1990s before grants were offered.

Assembly and Test

Assembly and test are the least knowledge-intensive of the IC production stages (UNCTC, 1986). Under the internalized structure mode, subsidiaries of MNCs generally relocated assembly and test in locations endowed with excellent basic infrastructure, security, large reserves of literate low wage labor (Sciberras,1977). Interviews with the 24 MNCs show that they also also sought tariff and tax free incentives when initially relocating to reduce the risks of relocation. In the presence of small de-verticallized independent assembly and test stages, firms often cluster around wafer fabrication plants so that they can rely on strong relational contracting bonds to access fabricated wafer supplies, and at the same time offer production feedback targeted at raising yield, eliminating defects and shorten delivery times.

The rapid rate of technological obsolescence in the IC industry arising from the intensification of the miniaturization process and shortening product cycles has also driven independent assembly and test plants to locate around machinery and tooling suppliers. Although less intensive, frontier assembly and test plants occasionally take up process and utility patents. Relational contracting within user-producer relations[5] is extremely important to ensure the self- expansion of the connected firms.[6]

Overall, wafer fabrication is the most capital-intensive. Although frontier R&D is the most knowledge-intensive (targeted at the creation of new stocks of knowledge), the intensification of knowledge use in IC production has led to the introduction of R&D support in all stages of IC production. Assembly and test is more capital intensive but is less knowledge-intensive than chip design. Apart from flagship firms such as Intel and Samsung, most IC firms do not support basic research on ICs. The bulk of the R&D by IC firms is carried out in supporting production activities – wafer fabrication, chip design, and assembly and test.

Overall, wafer fabrication is the most capital-intensive. Although frontier R&D is the most knowledge-intensive (targeted at the creation of new stocks of knowledge), the intensification of knowledge use in IC production has led to the introduction of R&D support in all stages of IC production. Assembly and test is more capital intensive but is less knowledge-intensive than chip design. Apart from flagship firms such as Intel and Samsung, most IC firms do not support basic research on ICs. The bulk of the R&D by IC firms is carried out in supporting production activities – wafer fabrication, chip design, and assembly and test.

Data

Table 4 presents the distribution of all IC firms in emerging East Asia in 2012. There were 414 IC firms with a breakdown of 182 national and 232 foreign registered firms. The largest number of firms was found in China, Korea and Malaysia. National and foreign firms accounted for 44.0% and 56.0% respectively of the total IC firms. The concentration of national IC firms was highest in Taiwan (72.6%) and Korea (54.8%), while the concentration of foreign firms was highest in Indonesia (100.0%), Malaysia (81.4%) and Philippines (75.9%). Foreign firms also accounted for over half of IC firms in Vietnam (75.0%), Thailand (71.4%), Singapore (70.6%) and China (56.1%). The analysis in the next section attempts to link the different stages in the value chain with the institutional strength of the host-site country locations.

Table 4: IC Firms by Ownership, Emerging East Asia, 2011

Country	**National**	**Foreign**	**Total**
China	65	83	148
Indonesia	0	5	5
South Korea	23	19	42
Malaysia	8	35	43
Philippines	7	22	29
Singapore	10	24	34
Taiwan	61	23	84
Thailand	6	15	21
Vietnam	2	6	8
Total	**182**	**232**	**414**

Source: Firms' list obtained from Gartner (2011a), Gartner (2011b); Confirmed through website search for all firms.

4. Technological Upgrading

This section analyzes the upgrading experiences of IC firms in emerging East Asia. As we have noted earlier, both modes of technological upgrading –internalized MNC value chains and as independent exporters to buyers - require strong government support because of the publicness of the knowledge processes involved. ICs therefore present an excellent example to distinguish the 'sticky places on the slippery space' to use Markusen's (1996) argument. The extent of technological upgrading shown through both the modes shown in Figure 1, i.e. upward within the stages to higher value added activities, and by moving onto or integrating higher value added stages in the value chain) as reflected in functional upgrading, has had direct consequences in the take up of IC patents by emerging East Asian firms in the United States.

Three broad groupings of countries can be discerned from the way IC firms have experienced technological upgrading in emerging East Asia. The first group of Korea and Taiwan has been shaping the globe's technology frontier through stimulating national IC firms in memory and logic chips respectively. The second group of Singapore, China, Malaysia and Vietnam attracted foreign MNCs to relocate assembly and test operations first before following it up with incentives and capital grants to encourage upgrading with varying degrees of success. Singapore is by far the most successful but IC firms are engaged only in chip design, R&D support, wafer fabrication and assembly and test activities. The final group comprising of Philippines, Thailand and Indonesia have remained confined to assembly and test activities with little upgrading.

The classification of the three categories of countries is also reflected in the IC patent take up in the United States. No firm from all the three category of countries had any IC patents at all registered in the United States in 1985. IC firms in Korea, Taiwan and Singapore were the only ones to register patents in the United States in 1990. Although IC firms from Singapore, China, Malaysia, Thailand and Philippines began to register IC patents in the period 1990-2005, registrations from Korea and Taiwan began to dominate those from emerging East Asia. Firms from Korea and Taiwan firms accounted for 98.6% all IC patents taken up in the United States in 1990 and 1995 (see Table 5). Although this share fell slightly thereafter it was still a massive 94.2% in 2010. The share of IC patents taken in the United States from the second category of countries, i.e. Singapore, China, Malaysia and Vietnam rose from 3.3% in 2000 to 5.7% in 2010. The last category (Indonesia, Philippines and Thailand) only accounted for 0 0.1% of the patents taken up by IC firms located in emerging East Asia in the United States.

Table 5: Patents Filed in the US, IC Firms in East Asian Developing Economies, 1985-2011

Year	**1981-1985**		**1986-1990**		**1991-1995**		**1996-2000**		**2001-2005**		**2006-2011**	
Country	**N**	**F**	**N**	**F**	**N**	**F**	**N**	**F**	**N**	**F**	**N**	**F**
China	0	0	0	0	0	3	0	27	11	52	177	436
Indonesia	0	0	0	0	0	0	0	0	0	0	0	0
Malaysia	0	0	0	0	0	1	0	5	4	39	3	270
Philippines	0	0	0	0	0	0	0	5	0	40	0	70
Singapore	0	0	0	1	0	14	0	36	4	216	290	545
South Korea	1	0	103	2	1526	1	5095	11	8049	139	25014	409
Taiwan	0	0	2	0	278	5	3063	124	4826	43	5223	107
Thailand	0	0	0	0	0	0	0	3	0	45*	0	3
Vietnam	0	0	0	0	0	0	0	0	0	0	0	0

Note:*The 45 patents were taken by AMD subsidiary in Thailand within 2001-2005. There is no patent taken-up after 2005.
Source: USPTO (2012)

4.1 Korea and Taiwan

Table 6 shows the number of existing IC centers or plants according to the specific production stages as of 2011 in South Korea and Taiwan. South Korea's Samsung and Taiwan's TSMC dislodged the incumbents to dominate the memory chip and logic chip markets since the early 1990s and late 1990s, respectively.

From the evidence shown in Table 6, it is obvious that South Korea and Taiwan had the largest number of IC R&D centers in emerging East Asia in 2011, and all of them are nationally owned.[7] Extensive government support in the development of technological capabilities through subsidized credit, grants and incentives was instrumental in the development of IC firms in South Korea and Taiwan (see Amsden, 1989; Kim, 1997; Mathews and Cho, 2000; Amsden and Chu, 2003). Korean and Taiwanese plants enjoyed grants to launch wafer fabrication activities and R&D, and subsidized capital to expand assembly and test activities in the formative years (Kim, 1997). While the focus in Korea was on supporting a few chaebols, Taiwan developed the Electronics Research and Services Organization (ERSO) to spin out national IC firms. National firms grew into vertically integrated firms in Korea, while they pioneered specialization by stages in Taiwan.

The South Korean government supported the IC industry in Korea in a number of ways. The acquisition of Zenith, and the creation of the institutional conditions for technology transfer to Samsung by the Korean government before approving imports from Micron and Sharp since the late 1970s and early 1980s (Edquist and Jacobbsen, 1987) were among the initial government initiatives to stimulate technological catch up by Korean firms. The government also supported growth of high-technology industries through the introduction of national banking regulations, low-interest loans, tax incentives, and duty-free import of selected capital goods (WTEC 1997). To promote education and R&D for high-tech industry, the government provided direct financial support to public and non-profit institutes, universities, and other educational institutions, primarily through the Ministry of Science and Technology (MOST); the Ministry of Trade, Industry, and Energy (MOTIE); and the Ministry of Information and Communication (MOIC).

The government's Highly Advanced National (HAN) program was designed to last for 10 years, from 1992 through 2001, which enjoyed an expenditure of US$ 4.7 billion on R&D programs focused at strategic technologies and linking many disciplines and technologies together for synergistic advancement (WTEC 1997). The DRAM project was started in the early 1980s, but was absorbed into the HAN program as the government began to fund such ventures directly. Typically, the government accounted for 50% of the overall costs incurred in developing new technologies (WTEC 1997).

In Taiwan, the Hsinchu Science Park (HSIP) Administration established the Guidelines Governing Grants for Innovative R&D at the Science Park to encourage R&D and innovation. At the end of 2009, the HSP received a total of 240 applications qualifying for approximately US$ 19.6 million (NT$574 million) of subsidies to conduct IC R&D, which accounted for 23.2% of total R&D spending of approximately US$ 84.41 million (NT$ 2.472 billion) in HSP (Hsinchu Science Park 2011). In addition, the HSP sought to enhance technological competence and management capabilities of human capital through talent cultivation and training programs. In 2010, approximately US$ 83, 660 (NT$ 2.45 million) and US$ 116, 441 (NT$ 3.41 million) were allocated by the administration for semiconductor design courses and semiconductor manufacturing process courses respectively (Hsinchu Science Park 2011).

The National Science Council also approved approximately US$ 13.2 million (NT$387 million) toward the establishment of an exclusive zone complete with all infrastructures required for carrying out System-on-Chip (SoC) design under its SoC Innovation Product Partnership (SIPP)) program. The objective is to foster the world's first model zone for SoC design services - a cluster of value-adding ventures, especially those who are ready to channel creativity and innovative technologies towards IC design (Hsinchu Science Park 2011). The first two stages of the program were completed in February 2007 and October 2008 respectively, which involved the development of a model zone for SoC design services at the SiSoft SIPP Center and the installation of an R&D platform for design services and technologies related to innovative SoC products. The center attracted tenants who filled up 89% of office space by 2010, including 30 IC design firms.

Foreign sources of knowledge were critical in both experiences as acquisitions, licensing and the hiring of national human capital rooted in American education and working experiences supported the upgrading of national firms to participate in frontier R&D, designing and wafer fabrication activities (see Vogel 1991; Saxenian and Hsu 2001; Saxenian 2006). Assembly and test too enjoyed technological upgrading as process and production R&D were introduced by national firms such as ASE. Both countries have retained the promotion of R&D through grants for new firms but stringent performance standards have been used to keep unproductive rents low. The frontier nature of IC operations by national firms in both countries is reflected in the massive take up of IC patents in the United States (see Table 5). In fact, Korean and Taiwanese firms have dominated the memory and logic IC technologies respectively since the 1990s.

Governments ensured the supply of subsidized water, uninterrupted uniform-band power supply and since the 1990s laid the infrastructure to prevent hazardous effluents from hitting the groundwater. The 3 Korean and 5 Taiwanese IC firms interviewed were unanimous in the importance of these endowments in supporting wafer fabrication activities. These are costs that governments met so as to remove obstacles facing national firms' quest to reach the technology frontier.

The contrasting structure of Korean and Taiwanese IC firms meant that firm strategies varied between the two. The highly vertically integrated structure of Korean firms meant that strategic decisions were made in-house. Samsung's large size, including in-house markets from its industrial and consumer electronics firms, offered massive agility to act on investment and technological decisions (see Lall 1996). Nevertheless, there were 112 small IC design firms that considered relational contracting with wafer fabrication and assembly and test plants as important for their performance (EE Times Korea 2007). In contrast, the highly de-verticalized Taiwan firms appropriated their historically strong cultural and social bonds to strengthen relational contracting with buyer-supplier firms, government agencies and other private organizations. The basis for technological upgrading in Taiwan was laid out by the Industrial Technical Institute (ITRI) that was started in 1974 (Huang 2006). In fact, if the smaller non-specialized designing firms were included, Lin (2009) reported that there were 250 such firms in Taiwan in 2008. The Hsinchu Science Park acts as the nucleus in the molding of social relations connecting it with the Silicon Valley in the United States to hold together the physical and social technologies in supporting technological upgrading in IC firms (see Mathews and Cho 2000; Saxenian and Hsu 2001).

Governments also strengthened the intermediary organizations, especially on science and technology education in schools and universities (Vogel 1991). As the technological capabilities of intermediary organizations grew the large pool of human capital helped attract foreign firms to participate in IC design, and assembly and test activities in Korea and Taiwan. Although foreign direct investment was unimportant in the formative years of upgrading, national IC firms in Korea and Taiwan benefited considerably from flows of knowledge from multinationals located abroad through licensing, acquisitions, and movement of human capital and flows of knowledge through interactive learning across the globe (see Cohen and Levinthal 1990; Mowery et al. 1996; Saxenian and Hsu, 2001; Song et al. 2003).

Also, in the initial stages Korean and Taiwanese firms worked with their respective national ministries to attract back their national human capital and connected interactively to circulate knowledge exchange to smoothen patent filing in the United States (see Cohen and Levinthal 1990; Song et al. 2003; Saxenian and Hsu 2001). Also, continuous improvements have taken place in the evaluation of R&D grants in Korea and Taiwan with recipients having to show patents as one of the performance standards when applying for new grants since the 1980s (Lin 2003). The imposition of such performance standards helped both governments to steer the rents towards productive activities.

Table 6: Countries with Most Advanced IC Firms, Emerging East Asia, 2011

	National					Foreign					
	RD	**CD**	**RDS**	**WF**	**AT**	**RD**	**CD**	**RDS**	**WF**	**AT**	**Total**
South Korea	4	2*	2#	6	9	0	7	6	2	4	38*#
Taiwan	5	3*	2	17	34	0	7	5	2	9	84*
Total	**9**	**5***	**4#**	**23**	**43**	**0**	**14**	**11**	**4**	**13**	**122*#**

Note: RD, CD, SRD, WF, AT and N refer to R&D, chip design, support R&D, wafer fabrication and assembly and test respectively; Firms are defined by the registration status, and hence, some subsidiaries of the same firm are counted more times; * firm has both R&D and chip design in the same registration premises;# firm has both R&D and other supportive R&D in the same premises.
Source: Firms' list obtained from Gartner (2011a), Gartner (2011b); Confirmed through website search for all firms.

4.2 Singapore, China, Malaysia and Vietnam

Singapore, China and Malaysia have enjoyed functional upgrading to include wafer fabrication, R&D support and chip design activities (see Table 7). Although Avago has independent R&D in Singapore it is not at the technology frontier. Also, it does not have a critical mass of R&D scientists and engineers to support frontier research. Singapore, China, Malaysia and Vietnam have through grants attracted firms into chip design, R&D support and wafer fabrication. Assisted by strong leveraging policies, Singapore has been the clear leader in this group (Mathews and Cho 2000; Wong 2001). Driven by the relocation of assembly and test operations by foreign MNCs since the 1960s, 1970s and 1980s respectively, IC production and export from Singapore, Malaysia and China is still dominated by foreign MNCs. Government provision of investment grants helped attract wafer fabrication by the foreign MNCs since the late 1980s in Singapore, since the 1990s in China, and since 2005 in Malaysia. Governments in Singapore and China offered R&D grants and R&D laboratories to foreign MNCs to support wafer fabrication, IC design and assembly and test activities. The Malaysian government offered investment grants to the foreign firms of Infineon, OSRAM and ON Semiconductor to start wafer fabrication in Malaysia since 2005. [8] R&D grants were also offered to MNCs seeking to introduce R&D support and IC design activities. In addition, the government approved the import of unlimited foreign human capital to support high value added activities from 2005 (Rasiah, 2010).

The Economic Development Board (EDB) of Singapore invested in Chartered Semiconductor Manufacturing by taking an initial stake of 90% of shares (METI, 2003). Other examples of investments made by EDB include Chartered Silicon Partners - a joint-venture company of Chartered Semiconductor Manufacturing, Hewlett-Packard and EDB that was started in 1987, Hitachi-Nippon Steel Semiconductor - an amalgamation of Hitachi, Nippon Steel and EDB with an initial investment of US$ 1.07 billion (S$1.33 billion) in 1996, and TECH Semiconductor engaged in wafer fabrication that was opened in 1991 through a joint-venture between Micron Technology, EDB, Canon and Hewlett-Packard (METI, 2003). EDB established a joint venture with Philips Semiconductors and TSMC by subsidizing Systems-on-Silicon Manufacturing Company (SSMC) and building its fabrication plant in 2000 with the capacity to produce 30,000 wafers monthly (TSMC, 2000). The Singapore government also built and hosted 4 wafer fabrication parks over 260 hectares by 2002 at Woodlands, Tampines, Pasir Ris and near Senoko. These wafer fabrication parks offer advantages of special and dedicated infrastructure support and services (METI 2003), which were augmented by the launching of the Integrated Circuit Design Centre of Excellence (VIRTUS) costing US$ 40.1 million (S$50 million) investment in 2009, which was funded jointly by Nanyang Technological University (NTU) and EDB (EMT WorldWide, 2009). National firms in Singapore had 1 R&D center, 2 chip design centers and 3 wafer fabrication plants in 2011. Foreign firms in Singapore had 7 chip design centers, 1 R&D support facility, 10 wafer fabrication plants and 13 assembly and test plants. The 1 national firm, and 2 foreign IC firms interviewed in Singapore reported that they enjoyed strong capital grants upfront to undertake wafer fabrication, designing, and R&D support activities, and to upgrade assembly and test activities. If non specialized design houses are included, there were 40 in Singapore in 2003 with the 7 foreign owned ranked among the top 10 in the world (EE Times, 2004). Both foreign and national firms in Singapore undertook R&D support to upgrade assembly and test activities. Avago had a R&D and designing center in Singapore, while Chartered Semiconductor, another national firm, carried out IC design activities.

Like Singapore, governments in China, Malaysia and Vietnam also offer high tech support in designated high tech parks. However, IC firms in China, Malaysia and Vietnam are engaged in both high and low value added activities. Semiconductor Manufacturing International Corporation (SMIC), a national IC firm in China, carried out R&D and wafer fabrication activities. Among the foreign IC firms in China, 16 undertook IC design, and 12 R&D activities to support assembly and test activities. Overall, there were 468 fabless design houses in China, though, they only accounted for 1.5% of demand in the country (Saxenian, 2006). In Malaysia, foreign MNCs had 4 chip design centers, 1 R&D support facility, 5 wafer fabrication plants and 28 assembly and test plants. National firms had 2 wafer fabrication plants and 7 assembly and test plants.

All three countries show varying degrees of relational contracting. Excellent policy coordination through strong interactions between the EDB of Singapore, and the firms has helped IC MNCs coordinate their actions in line with their self-expansion plans – including production, R&D and labor. Without the full support of a critical mass of nationals, Singapore's success in stimulating upgrading to higher value added activities is only inferior to Korea and Taiwan whose firms shape the technology frontier in IC production. Despite lacking the same coordination capacity as Singapore, the key locations designated to stimulate high technology operations in China, Malaysia and Vietnam have achieved reasonably high levels of upgrading. China in particular demonstrates the capacity of significant expansion in wafer fabrication and designing activities (Kong, 2009). However, interviews show that the extent of cooperation (institutional thickness) was much less in these countries as global pull and push forces with significant considerations centripetally emanating from home locations of MNCs compared to Singapore. In addition, interviews also show that ethnic policies by the government has restricted the use of human capital endowed with tacit knowledge to run the Malaysian Institute of Microelectronics Systems (MIMOS), which was targeted to play the role of ERSO of Taiwan. Loh Kin Wah, the former chief executive officer of Qimonda who enjoys a performance record comparable to some of the leading performers of Taiwan,[9] was bypassed when the past chairmen of MIMOS were named. Negotiations by the Malaysian government to forge an alliance between the highly successful Phison of Taiwan (led by a Malaysian) and the national fabrication plant of Silterra in 2010-11 will have to avoid ethnic considerations if it is to stimulate upgrading into higher value added activities.

By giving capital grants, Singapore, China and Malaysia managed to stimulate patent take up from the foreign wafer fabrication and IC design plants, and supportive R&D facilities by 1990, 1995 and 2005 respectively. National firms in Singapore and China have followed these practices to increase their take up of patents in the United States from the turn of the millennium. National firms' take up of patents from Malaysia went up from 2 in 2005 to only 3 in

2010 as the government slashed R&D funds granted to Silterra. Nevertheless, the approval of grants to start fabrication and designing operations, and unlimited import of engineers from abroad to foreign firms since 2005 has helped raise the take-up of patents by foreign firms, which went up from 3 in 2000 to 26 in 2005 and 66 in 2010. Vietnam's experience with IC production only began after 2000 but its emphasis on upgrading suggests that firms from the country are poised to take up patents in the United States soon.

Table 7: Countries with IC Firms Facing Upgrading, Emerging East Asia, 2011

	National					**Foreign**					
	RD	**CD**	**RDS**	**WF**	**AT**	**RD**	**CD**	**RDS**	**WF**	**AT**	**Total**
China	1	3*	2#	25	34	0	11	8	6	58	148*#
Malaysia	0	0	0	2	6	0	4	1	5	25	43
Singapore	1	1	1	3	4	0	7	1	4	12	34
Vietnam	0	1	0	1	0	0	3	1	0	2	8
Total	**2**	**5**	**3**	**31**	**44**	**0**	**25**	**11**	**15**	**97**	

Note: RD, CD, SRD, WF, AT and N refer to R&D, chip design, support R&D, wafer fabrication and assembly and test respectively; Firms are defined by the registration status, and hence, some subsidiaries of the same firm are counted more times; * firm has both R&D and chip design in the same registration premises;# firm has both R&D and other supportive R&D in the same premises.
Source: Firms' list obtained from Gartner (2011a), Gartner (2011b); Confirmed through website search for all firms.

4.3 Philippines, Thailand and Indonesia

Driven by efforts to attract low end labor-intensive activities to generate jobs, Philippines, Thailand and Indonesia focused on attracting assembly and test activities from abroad. Consistent with calls by mainstream economists to leave the relocation process to be determined by factor endowments (World Bank, 1993), Indonesia, Philippines and Thailand provided security, good basic infrastructure and tariff exemptions on imports to foreign MNCs seeking to relocate assembly and test activities to utilize labor. Foreign IC firms began relocating in Philippines, Thailand and Indonesia in the 1970s, 1980s and 1990s respectively. Whereas Philippines and Thailand had in place favorable foreign investment policies comparable to Malaysia, Indonesia had in place a pribumi policy that discouraged American IC firms who preferred owning equity completely. Hence, foreign IC firms only began to relocate in the 1990s when Singapore's Temasik Holdings obtained the lease of Batam Island to manage foreign production operations. All foreign IC firms in these countries were only engaged in low value added assembly and test activities (Table 8), though the knowledge-intensive characteristics of the industry drove even assembly and test, the absorption of best practices.

However, although these firms have absorbed best practices in inventory and quality control systems and continuous improvement practices, none had in place R&D activities to support technological upgrading. The Philippines had 29 foreign IC firms in low value added assembly and test activities, while there were 15 foreign firms in Thailand and 5 foreign firms in Batam (Indonesia) engaged in similar low end assembly and test activities. Philippines have demonstrated the capacity to supply knowledge-intensive human capital with considerable numbers of people undertaking education and training in the United States. There is also evidence of this potential following the opening of one designing firm in the Philippines. However, the reluctance of the government to offer grants at least in the formative years has restricted its capacity to stimulate functional and horizontal upgrading into R&D support and wafer fabrication activities.

Philippines, Thailand and Indonesia are endowed with labor reserves that are significantly larger than those of Singapore and Malaysia. Yet, foreign MNC operations have remained confined to low value added assembly and test operations without much upgrading. The 1 foreign MNC in Philippines engaged in chip design took advantage of the returning diaspora to support activities of firms located abroad rather than stimulating economic synergies through the host-country networks. These countries have not succeeded in stimulating upgrading, and hence, have remained potentially vulnerable to threats of a hollowing out in future.

Table 8: Countries with IC Firms Facing Little Upgrading, East Asia, 2011

	National					**Foreign**					
	RD	**CD**	**RDS**	**WF**	**AT**	**RD**	**CD**	**RDS**	**WF**	**AT**	**Total**
Indonesia	0	0	0	0	0	0	0	0	0	5	**5**
Philippines	0	0	0	0	7	0	1	0	0	21	**29**
Thailand	0	0	0	0	6	0	0	0	0	15	**21**
Total	**11**	**10**	**7**	**52**	**100**	**0**	**40**	**22**	**19**	**151**	**412**

Note: RD, CD, SRD, WF, AT and N refer to R&D, chip design, support R&D, wafer fabrication and assembly and test respectively; Firms are defined by the registration status, and hence, some subsidiaries of the same firm are counted more times; * firm has both R&D and chip design in the same registration premises;# firm has both R&D and other supportive R&D in the same premises.
Source: Firms' list obtained from Gartner (2011a), Gartner (2011b); Confirmed through website search for all firms

Despite the take up of some patents, largely a consequence of long production experience that helped generate problem-solving process engineering adaptations to be patented, all three countries are clearly entrenched at the bottom of the technology ladder in emerging East Asia. In short, these locations are certainly not the 'sticky places in slippery space' that Markusen (1996) had observed. . Unless efforts are taken to evolve the requisite institutions and intermediary organizations, firms in Philippines, Thailand and Indonesia are unlikely to achieve technological upgrading into higher value added activities.

5. Conclusions

In attempting to answer the question we began with, it is obvious that IC production in Korea and Taiwan has experienced the deepest rooting to show that they will remain sticky for a long time. IC production have also become sticky in Singapore, China, Malaysia and Vietnam where the provision of grants has attracted participation in wafer fabrication, IC design and R&D support activities. IC production is not sticky at all in the countries of Philippines, Thailand and Indonesia.

The evidence offers implications for the theories we considered at the outset. Collier's (2007) argument over breaking in and moving up value chains is obviously overly simplistic as it does not explain why some places enjoy upgrading while others do not. While helping out with the identification of opportunities in the value chain, the GVC approach also falls short in trying to explain why some host-sites have enjoyed more upgrading than others almost implying that host-sites are only capable of appropriating benefits left behind by the drivers of value chains whereas the evidence from South Korea and Taiwan shows that active institutional development at host-sites helped domestic firms restructure their relationship against developed country firms. The arguments of Markusen (1996) and Nelson (2008) explains the sticky spots on the slippery slopes of competition facing firms from emerging East Asia. IC production is most sticky and indeed highly rooted in Korea and Taiwan, both of which have evolved the institutions and intermediary organizations to drive firm-level upgrading to the globe's technology frontier. Taking account of its peculiar small base, Singapore has done well to stimulate upgrading with foreign MNCs as the drivers with China, Malaysia and Vietnam pursuing similar but less extensive leveraging strategies. However, Malaysia's capacity to reach Singapore's level of upgrading will depend very much on its political conviction to drop ethnic-based considerations in government policy. Philippines, Thailand and Indonesia have the endowments to stimulate the creation of a broader base with more national firms, but have not focused on institutional development to stimulate upgrading. IC operations in Philippines, Thailand and Indonesia are not sticky at all because of a lack of emphasis on institutions and intermediary organizations beyond simply providing the basic infrastructure, security and tariff free operations at export processing zones.

The evidence shows that governments have the opportunity to target IC production through either inviting foreign MNCs or supporting the launching of national firms by raising the quality of infrastructure and administering tariff-free operations in particular locations where trainable labor can been pooled. It is obviously easier to pursue the MNC invitation for the poor economies as it is extremely expensive to promote national firms in such knowledge-intensive fields. However, this is the easy first step in the development of the industry.

The more difficult steps require the creation of the conditions for technological upgrading to support the transformation of the operations to higher value added activities to quicken economic development. The successful experiences examined in this paper shows that the development of institutions and intermediary organizations through effective coordination between governments and industry is critical to stimulate technological upgrading in the IC industry.

Acknowledgments

We wish to thank the late Alice Amsden who so constructively commented on an earlier piece of this paper. We also like to thank the officials of the IC firms who graciously gave the time to be interviewed. We wish to acknowledge funding support that allowed the compilation of information on the conditions IC firms seek to relocate and continue operations at host-sites that was awarded by the University of Malaya High Impact Research Grant (HIR) (2012-13). We are grateful to Gabriela Dutrenit and Fukunari Kimura and two other anonymous referees for their comments. The errors that remain are ours.

Notes

1. Ernst (2006) had provided evidence of the off-shoring of R&D in Asia, but as Rasiah (1996) and Amsden and Tschang (2003) have shown they are not in frontier R&D activities.
2. Some IC firms located assembly and test operations separately before the 1980s but developments in production technology within the industry drove the integration of these stages into single assembly and test plants since the 1980s (Rasiah, 1988; see also UNCTC, 1986).
3. The Montreal Protocol prohibits firms originating from the OECD countries from discharging toxic waste in any part of the world (UNEP, 2009).
4. IBM received incentives, including a US$13 million in training grants from New York state in 1999 for locating a 300-mm wafer fab plant in East Fishkill, New York (Solid State Technology, 1999).
5. See Lundvall (1992) for a lucid account of the importance of user-producer relations.
6. See Sabel (1994) for an incisive account of a blend of competition and cooperation in driving the performance of cluster firms.
7. Because of the wide range of R&D activities carried out by IC firms, we have only included those undertaking exclusively R&D in separate centers as R&D centers. Other firms that undertake R&D to support assembly and test, or engineering or process technology improvements are placed separately as supportive R&D.
8. Authors' interview conducted in Penang on June 21, 2009.
9. The chairman of the Taiwan Semiconductor Manufacturing Association, Dr Wu Tai Yuan, acknowledged this with an interview with the authors on 21 November 2009 at Hsinchu Science Park.

References

Abramovitz, M. (1956) "Resource and Output Trends in the United States since 1870", *American Economic Review*,46:5-23.

Acemoglu, D., and Robinson, J. (2012) *Why Nations Fail: The Origins of Power, Prosperity and Poverty,* New York: Crown Publishers.

AMD - Advanced Micro Devices (2006) *AMD Signs Grant Disbursement Agreement for New Fab Option,* available online: http://www.amd.com/us/press-releases/Pages/Press_Release_115424.aspx. Accessed 15 April 2012.

Amsden, A. (1989) *Asia's Next Giant: South Korea and Late Industrialization*,New York: Oxford University Press.

Amsden, A., and Chu, W.W. (2003) *Beyond Late Development: Taiwan's Upgrading Policies*,Cambridge: MIT Press.

Amsden, A. and Tschang, T. (2003) "A New Approach to Assess the Technological Complexity of Different Categories of R&D (with Examples from Singapore)", *Research Policy*, 32(4):553-572.

Babbage, C. (1835) *On the Economy of Machinery and Manufacture,*London: Charles Knight, Pall Mall East.

Baran, P. (1973) *The Political Economy of Growth*, Harmondsworth: Penguin Books.

Brown, C., and Linden, G., (2009) *Chips andChange: How Crisis Reshapes the Aemiconductor Industry*,Cambridge: The Massachusetts Institute of Technology (MIT) Press.

Cohen, W., and Levinthal, D. (1990) Absorptive Capacity: A New Perspective on Learning and Innovation", *Administrative Science Quarterly*, 35:128-52.

Collier, P. (2007) *The Bottom Billion: Why The Poor Countries Are Falling and What Can Be Done About It*,Oxford: Oxford University Press.

EE Times Korea (2004) *Fabless Industry in China to Quadruple by 2008, says iSuppli*, available online: http://www.eetimes.com/electronics-news/4050694/Fabless-industry-in-China-to-quadruple-by-2008-says-iSuppli, accessed 15 April 2012.

EE Times Korea (2007) *IC design house survey 2007: Korea,* available online: http://www.eettaiwan.com/ARTICLES/2007MAY/PDF/2007_IC_Survey_Korea.pdf?SOURCES=DOWNLOAD, accessed 20 April 2012.

Edquist, C., and Jacobssen, S. (1987) "The Integrated Circuit Industries in India and South Korea in An International Techno-Economic Context", *Industry and Development*, 21: 1-62.

EMT World Wide - Electronics manufacture and Test (2009) *Singapore launches S$50 Million IC Design Research Centre 23 December*, available online: http://www.emtworldwide.com/article.aspx?ArticleID=30466, accessed 15 April 2012.

Ernst, D. (2006) "Innovation Offshoring: Asia's Emerging Role in Global Innovation Networks", *East-West Center Special Report No. 10*, East-West Center, Honolulu.

Froebel, F.; Heinrich, J.; and Kreye, O. (1980) *The New International Division of Labor*, Cambridge: Cambridge University Press.

Gartner (2011a) Fab Database: Worldwide, Fourth Quarter 2011 Update. Gartner Database.

Gartner (2011b) Semiconductor Packaging, Assembly and Test Facilities: Worldwide, Fourth Quarter 2011 Update. Gartner Database.

Gerschenkron, A. (1952) Economic Backwardness in Historical Perspective, in Hoselitz, B.F. (ed.) *The Progress of Underdeveloped Areas*, Chicago: University of Chicago Press, pp. 3-29.

Gereffi, G. (2002) "The International Competitiveness of Asian Economies in the Apparel Commodity Chain", *Economics and Research Department Working Paper No. 5*, Manila.: Asian Development Bank,

Gereffi, G.; Humphrey, J.; and Sturgeon, T. (2005) "The Governance of Global Value Chains", *Review of International Political Economy*,12:78-104.

Helleiner, G.K. (1973) "Manufactured Exports from Less Developed Countries and Multinational Firms", *Economic Journal*, 83:21-47.

Hsinchu Science Park (2011) 2*010 Annual Report*, available online: http://www.sipa.gov.tw/english/home.jsp?serno=201006140013&mserno=201006140012&menudata=EnglishMenu&contlink=include/menu03.jsp&level2=Y., accessed 15 April 2012.

Huang, M.P. (2006) The 'Cradle of Technology': The Industrial Technical Research Institute, in T. Tsai and B.S. Cheng (eds.) *The silicon dragon: High tech industry in Taiwan*, ,26-49. Cheltenham: Edward Elgar. Kim, L. (1997) *From Imitation to Innovation*, Cambridge: Harvard Business School Press.

Katz, J. (2006) "Structural Change and Technological Capabilities", *Cepal Review 89*, Santiago.

Kim, L. 1997. From imitation to innovation. Cambridge: Harvard Business School Press.

Kong, X.X. 2009. The semiconductor industry in China, mimeo.

Keynes, J.N. (1890) The Scope and Method of Political Economy, Cambridge: Batoche Books.

Lall, S. 1996. Learning from the East Asian Tigers. Basingstoke: Macmillan.

Lin, Y. 2003. Industrial structure, technical change and the role of government in development of the electronics and information industry in Taipei, China. Economics and Research Department Working Paper No. 41, Asian Development Bank, Manila.

Lin, Y. 2009. Taiwan's brain gain program. In Brain drain, brain gain and brain circulation experiences of India, Malaysia and Taiwan, ed. R. Rasiah and K. Thiruchelvam, pp. 123-143. Putrajaya: Ministry of Science Technology and Innovation.

Lundvall, B-A. 1992. National systems of innovation. Towards a theory of innovation and interactive learning. London: Pinter Publishers.

Macneil, I.R. 1974. Restatement (Second) of Contracts and Presentation. Virginia Law Review 60:589-610.

Malerba, F.; Nelson, R. 2012. Economic development as a learning process: Differences across sectoral systems. Cheltenham: Edward Elgar.

Markusen, A. 1996. Sticky places in slippery space: A typology of industrial districts. Economic Geography 72:293-313.

Massey, D. 1973. Towards a critique of industrial location theory. Antipode 5:33-39.

Mathews, J.A., and Cho. 2000. Tiger technology: The creation of a semiconductor industry in East Asia. Cambridge: Cambridge University Press.

METI – Ministry of Economy, Trade and Industry. 2003. Singapore semiconductor industry report. Available online: http://www.meti.go.jp/english/apec/apec-isti/ISTI/abridge/sgz/zsgzic.htm. Accessed 15 April 2012.

Mowery, D.; Oxley, J.; and Silverman, B. 1996. Strategic alliances and interfirm knowledge transfer. Strategic Management Journal 17:77-91.

Nelson, R. 2008. What enables rapid economic progress: What are the needed institutions? Research Policy 37:1-11.

North, D. 1994. Economic performance through time. American Economic Review 84:359-68.

Parthasarathy, B. 2010. The computer software industry as a vehicle of late industrialization: Lessons from the Indian case. Journal of the Asia Pacific Economy 15:247-70.

METI – Ministry of Economy, Trade and Industry (2003) *Singapore Semiconductor Industry Report*, available online: http://www.meti.go.jp/english/apec/apec-isti/ISTI/abridge/sgz/zsgzic.htm., accessed 15 April 2012.

Mowery, D.; Oxley, J. and Silverman, B. (1996) "Strategic Alliances and Interfirm Knowledge Transfer", *Strategic Management Journal*,17:77-91.

Nelson, R. (2008) "What Enables Rapid Economic Progress: What are the Needed Institutions?", *Research Policy*,37:1-11.

North, D. (1994) "Economic Performance Through Time", *American Economic Review,* 84:359-68.

Parthasarathy, B. (2010) "The Computer Software Industry as a Vehicle of Late Industrialization: Lessons from the Indian Case", *Journal of the Asia Pacific Economy*, 15:247-70.

Rasiah, R. (1988) "The Semiconductor Industry in Penang: Implications for the New International Division of Labor Theories", *Journal of Contemporary Asia,* 18: 44-67.

Rasiah, R. (1996) "Institutions and Innovations: Moving Towards the Technology Frontier in the Electronics Industry in Malaysia", *Journal of Industry Studies*, 3(2): 79-102.

Rasiah, R. (2004) "Technological Capabilities in East and Southeast Asian Electronics Firms: Does Network Strength Matter?", *Oxford Development Studies*, 32(3): 433-54.

Rasiah, R. (2010) "Are Electronics Firms in Malaysia Catching Up in the Technology Ladder?", *Journal of Asia Pacific Economy*, 15(3): 301-319.

Rasiah, R., Kong, X.X., Lin, Y., and Song, J.Y. (2012) Variations in the Catch Up Experience in the Semiconductor Industry in China, Korea, Malaysia and Taiwan", Malerba, F. and Nelson, R. (eds), *Economic Development as a Learning Process: Differences Across Sectoral Systems,* Cheltenham: Edward Elgar, pp. m113-156.

Rasiah, R., and Yap, X.-S. (2013) *Motives of IC EMNCs Relocating Abroad from East and Southeast Asia*, mimeo.

Rodrik, D. (2007) *One Economics, Many Recipes: Globalization,Institutions, and Economic Growth*, Princeton: Princeton University Press.

Sabel, C. (1994) Flexible Specialization and the Re-Emergence of Regional Economies, in A. Amin (ed.) Post-Fordism: A Reader, Oxford: Blackwell Publishers, pp.101–56 .

Saxenian, A.L. (2006) *The New Argonauts: Regional Advantage in a Global Economy*, Cambridge: Harvard University Press.

Saxenian, A.L., and Hsu, J.Y. (2001) "The Silicon Valley-Hsinchu Connection: Technical Communities and Industrial Upgrading", *Industrial and Corporate Change*,10:893-924.

Schumpeter, J. (1934) *The Theory of Economic Development*, Cambridge, Mass.: Harvard University Press.

Schumpeter, J. A. (1943) *Capitalism, Socialism and Democracy,* London: Allen & Unwin.

Sciberras, E. (1977) *Multinational Electronics Companies and National Economic Policies*, New York: Jai Press.

Solid State Technology (1999) *IBM Plans 300-mm fab at East Fishkill Site,* available online: http://www.electroiq.com/articles/sst/print/volume-41/issue-1/departments/tech-news/ibm-plans-300-mm-fab-at-east-fishkill-site.html, accessed 15 April 2012.

Song, J.Y.; Almeida, P.; and Wu, G. (2003) "Learning-by-hiring: When is Mobility more likely to Facilitate Interfirm Knowledge Transfer?", *Management Science*, 49:351-65.

Sturgeon, T. (2002) "Modular Production Networks: A New American Model of Industrial Organization", *Industrial and Corporate Change*,11(3):451–96.

Tsai, T., Cheng, B. (2006) *The Silicon Dragon: High-tech Industry in Taiwan*,London: Edward Elgar Publication.

TSMC 2014 "Company Profile", Taiwan Semiconductor Manufacturing Corporation, accessed from http://www.tsmc.com/english/default.htm on June 9 2013.

UNCTC (1986) T*ransnational Corporations in the International Semiconductor Industry*, New York: United Nations Center for Transnational Corporations.

UNEP - United Nations Environment Programme (2009)*Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer,* Nairobi: UNEP.

UNIDO - United Nations Industrial Development Organization (2009)Breaking in and Moving Up: New industrial challenges for the bottom billion and the middle-income countries. Vienna: UNIDO.

USPTO (2013) "Calendar Year Patent Statistics", United States Patent Office, data accessed from http://www.uspto.gov/web/offices/ac/ido/oeip/taf/reports.htm on May 12, 2014.

Veblen, T. (1915)Imperial Germany and the industrial revolution. New York: A. M. Kelley, 1964.

Vogel, E. (1991)The four little dragons: The spread of industrialization in East Asia, Cambridge: Harvard University Press.

Wong, P.K. (2001) "Leveraging Multinational Corporations, Fostering Technopreneurship: The Changing Role of S&T Policy in Singapore", *International Journal of Technology Management,* 22:539-67.

World Bank (1993) *The East Asian Miracle: Economic Growth and Public Policy,* New York: Oxford University Press.

WTEC - World Technology Evaluation Center (1997) WTEC report on the Korean electronics industry, available online: http://www.wtec.org/loyola/kei/welcome.htm.,accessed 15 April 2012.

WTO (2011) *International Trade Statistics*,Geneva: World Trade Organization (WTO).

Yap, X.-S., and Rasiah, R. (2013) Outplay and Outlast: TSMC's First-mover Strategy to Catch Up in the Logic Integrated Circuit Industry, mimeo.