Paper presented in the VI Globelics Conference at Mexico City, September 22-24 2008

Globelics

Explaining Variations in Semiconductor Catch-up Strategies in China, Korea, Malaysia and Taiwan

Rajah Rasiah [1]
Xinxin Kong[2]
Yeo Lin[3]
Jaeyong Song[4]

1 Introduction

The evolution of semiconductor manufacturing was very much driven by precision control demands in the United States military but because of its complementary and enabler properties it is increasingly diffusing into the manufacture and use of many different products and processes. It is therefore very common to find semiconductor chips driving central panel control systems in the manufacture of steel and cement, cad-cam machines in garment making, monitoring of captive salmon, storing of graphic memory in digital cameras, powering computers and providing control to computer numeric control (CNCs) and electronic device machines (EDMs). Although the processes of manufacturing semiconductor chips varies in sophistication – from simple transistors that replaced cathode ray tubes (CRT) in the transfusion of picture in televisions to sophisticated microprocessors that power supercomputers – the design and fabrication of chips remains high technology. Hence, catch up attempts in the industry has required lumpy investments in large physical plants, machinery and equipment, human capital and its requisite matching demand. Scale economies have not fallen despite continued miniaturization and the decomposition of semiconductor manufacturing vertically into chip design, chip fabrication, assembly and test. Even in Taiwan Amsden and Chu (2003) and Rasiah and Lin (2006) have argued that scale requirements has driven up firm size. Despite similarities the sources of learning and innovation in the industry as articulated by Malerba and Nelson in this volume are expected to be different from the routes taken by firms in the other industries in the volume.

Governments in the four countries, *viz*., China, Korea, Malaysia and Taiwan, have all taken serious steps to promote semiconductor manufacturing and therefore offer a unique set of experiences to examine variations in the catch up process. These countries also

[1] University of Malaya
[2] National Research Center for Science and Technology for Development
[3] Zhejiang University
[4] Seoul University

provide enough diversity to examine variations. China with a population of 1.4 billion in 2006 has a large domestic market and has since 1978 been integrating an essentially centrally planned economy into the capitalist world system. With a population of 47 million in 2006 Korea is the next biggest and in Samsung the country has a shaper of the technology frontier in dynamic random access memory (DRAM) and Nand flash chips. Malaysia and Taiwan with populations of 25 and 19 millions respectively in 2006 are smaller economies where domestic demand never acted as the major stimulant of rapid manufacturing growth. Taiwan is the smallest of the four economies but Taiwan Semiconductor Manufacturing Corporation (TSMC) is not only the first contract manufacturer of semiconductor chips that has separated chip design from chip fabrication but has caught up swiftly to join Samsung at the DRAM frontier.

This chapter aims at explaining the key drivers among the four late-comers of China, Korea, Malaysia and Taiwan, in the origin of semiconductor manufacturing and in the pace of catch up achieved in the four economies using the framework of sectoral system of innovations (SSI) proposed in the introduction of this volume by Malerba and Nelson.

2 Historical Backdrop

Unlike in the pioneering economy of the United States where the government-led military and later the domestic market were critical in the origin and spread of semiconductors using silicon (the prime material used in semiconductor devices) and gallium arsenide (see Marsh, 1981),[5] the main drivers of demand in China, Korea, Malaysia and Taiwan have largely been export markets. China is the only one among the four that had a military plan targeted at the computer and semiconductor industry during Chairman Mao's administration. The government created the Ministry of Electronics Industry (MEI) but the subsequent growth in semiconductor production from the 1980s has had little link with both instruments.

Large-scale foreign-driven semiconductor assembly emerged in Taiwan and Korea, Malaysia and China in the 1960s, 1970s and 1980s respectively following the opening of export processing zones. Multinationals seeking low wage, literate and disciplined workers in locations with good basic infrastructure and security relocated assembly and later test operations in these countries. Special export processing zones were created and coordinated in these countries to attract semiconductor firms. Employment creation started as the prime policy aim of the host governments in the initial phase.

[5] Gallium arsenide technology is sometimes still preferred over silicon owing to the higher frequency and light emitting functions it allows government financed research in the military labs (e.g. Bell Laboratory), key universities such as MIT, University of Chicago and Purdue University were instrumental in the development of diodes and transistors in the United States. Fairchild was the first private semiconductor firm created to fabricate and manufacture transistor chips following the transfer of technology from the Bell laboratory in 1948 (see Marsh, 1981).

Among the four countries Korea was the first to attempt integrated semiconductor production operations when Samsung acquired a local firm in 1975 to venture into chip manufacturing. Wafer fabrication subsequently began to mushroom outside the developed economies when leading semiconductor firms started to outsource fabrication owing to rising production costs, quick technological obsolescence and falling profit margins from the 1980s (Rasiah, 1993; Zook, 1999). Apart from microprocessors where only Advanced Micro Devices (AMD) has fabrication facilities outside the United States in Leipzig since 2003 the fabrication of most other integrated circuits, diodes and transistors are increasingly being outsourced. Intel has one memory wafer fab plant and announced plans in 2007 to build another in China. Taiwan's United Micro Electronics (UMC) has contract fabrication operations in Singapore. Infineon started power chip fabrication in Kulim, Malaysia in 2006. Osram is the other foreign firm having fabrication operations in Malaysia.

The historical evolution of the semiconductor industry in China, Korea, Malaysia and Taiwan can be summarized as follows:

China Semiconductors got strategic status when computers and semiconductor devices were made a national industry for research during Mao Ze Dong's leadership when the Ministry of Electronics Industry (MEI) was also created. The initial stage development of IC industry in China could be traced from the middle of 1960s. The first semiconductor integrated circuit device called digital logic (DTL) circuit was developed successfully in 1965, which led to the successful development of TTL, ECL, PMOS, n-type metal oxide semiconductor (NMOS) and complementary metal oxide semiconductor (CMOS) technologies. The basic R&D elements related to materials, equipment, manufacturing and techniques were largely developed before the 1980s and occurred in the MEI, Chinese Academy of Social Sciences and the Ministry of Spaceflights. Apart from microprocessors, it can be argued that prior to 1980 Chinese IC technology was close to that of the world. However, in the period 1980-95, IC industrial development began to fall behind that of the firms at the technology frontier. The domestic products were mainly middle or low level products above 0.8 micron. Most of the high technology products such as central processing unit (CPU) for civil usage and DSP for mobile telecommunication were imported from foreign countries.

There are many explanations on the stagnant development in this period. One explanation is that government focus on semiconductor R&D declined as foreign semiconductor firm s relocated assembly and test operations in China from the 1980s. China enjoyed its first large scale manufacturing of semiconductors following the relocation of American plants in export processing zones (EPZs). Flagship firms such as Intel, National Semiconductor (Fairchild now), Motorola (Freescale now), Chippac relocated operations in China but regulations requiring that non-joint ventures must export all output meant that these firms had to target export markets rather than the domestic market. China's share of global IC and electronic components exports rose from 1.7 percent in 2000 to 5.9 percent in 2005 (computed from Table 1).

While a strong FDI-led platform was evolving from the 1980s, the Chinese government also launched instruments to encourage R&D in semiconductors and to assist the opening of local firms in strategic industries that included semiconductors, computers and telecommunication equipments. The acquisition of the computer manufacturing division of IBM worldwide by Chinese firm Lenova, and the expansion of Taiwanese owned Acer, American owned Dell and HP into China heralded a major breakthrough for Chinese semiconductor firms, which now have the market potential to sell chips to major users. IBM was already manufacturing computers in China before the Lenova takeover.

Korea The early EPZ-type assembly operations that began in the 1960s was superseded by the opening of the first local semiconductor firm in Korea in 1974. This firm was subsequently bought by Samsung in 1975 to start off the catch up process in the semiconductor industry. The launching of the Heavy and Chemical Industries (HCI) by the government in 1975 was pivotal in attracting Samsung's entry into semiconductor chip manufacturing, though, the firm was also motivated by its own self-expansion plans to supply its consumer electronics subsidiaries (Kim, 1997: 88).

Imports and adaptation of machinery and equipment and the absorption of process technologies, acquisition of ailing foreign firms, and gradually in-house development through the hiring of Korean engineers and scientists carrying tacit and experiential knowledge from in foreign firms helped Samsung to reach the technology frontier in DRAM chips in1984 (see Edquist and Jacobssen, 1987; Kim, 1997). Samsung has since been shaping the technology frontier in DRAM and Nand flash chips. Samsung, Hyundai, and LG Electronics back-integrated from consumer and telecommunication products.

Malaysia National Semiconductor relocated operations in Penang in 1971 to start the industry in Malaysia. This firm was followed by Advanced Micro Devices (AMD), Mostek (sold later to Thomson CSF in 1986 which later sold the plant to International Device Technology in 1989), Hewlett Packard, Monolithic Memories (acquired by AMD in 1989) and Intel by 1976. A parallel relocation of American semiconductor firms also occurred in Kuala Lumpur and Petaling Jaya: Texas Instruments, Motorola,[6] Western Digital, MEMC and Harris Semiconductor relocated operations in Kuala Lumpur and Petaling Jaya in the 1970s. Hitachi and Siemens were the first Japanese and European semiconductor firms respectively to relocate operation in Malaysia in 1973. All the firms began with front-end assembly operations using labour-intensive technology. NEC, Motorola, Fujitsu (Senawang and Seremban) and ST Microelectronics (formerly known as SGS-Thomson) (Muar) subsequently started operations in Malaysia from the 1980s. Korean and Taiwanese semiconductor firms such as Samsung and ASE began assembly and test operations from the 1990s in Senawang and Johor respectively. Whereas test activities were incorporated by the early semiconductor firms in the Malaysian operations by the MNCs from 1976 firms that relocated after 1976 were integrated assembly and test operations. The subcontract firm of Carter Semiconductors opened operations in Ipoh in 1979.

Local involvement with semiconductor manufacturing also started in assembly and test

[6] Motorola sold its semiconductor division to Freescale in 2002.

operations when Carsem (owned by Hong Leong) acquired Carter Semiconductors during the mid-1980s industry-wide crisis. Subsequently Unisem (Ipoh) and Globetronics (Penang) started similar operations in the early and mid-1990s respectively. Whereas venture capital from the government owned Malaysian Technology Development Corporation (MTDC) has been used to support Globetronics none of these firms have connected in any significant way with government labs (including MIMOS and public universities).

Motorola was the first to start wafer fabrication in Malaysia (in Seremban) – but its scope was limited to old transistor technology – and the plant closed down in the late 1990s. The government managed to attract Infineon to start an 8 inch wafer fabrication plant in Kulim to produce power chips in 2005. Government efforts to attract a similar plant from Samsung failed as the plant eventually went to India in 2006. The government subsequently acquired VLSI in the Silicon Valley, and assisted the founding of Silterra (Kulim) and First Silicon (Sama Jaya) and a wafer lab at MIMOS. By 2001 the labs at VLSI and MIMOS had already closed down, and the 1st Silicon plant in Sama Jaya in 2007 was only engaged in the fabrication of application specific integrated circuits using 4 inch wafers. Infineon is still ramping up production while Silterra are engaged in supplying fabricated wafers to consumer electronics manufacturers –e.g. Sharp-Roxy. Despite these developments almost 100 percent of fabricated wafers used in assembly and test operations in Malaysia are imported. Only Infineon's back-end plant in Kulim has plants to supply wafers to its front-end plant in Malacca.[7]

Semiconductor manufacturing was not targeted as a strategic industry in the 1970s and early 1980s when foreign-driven assembly operations expanded sharply. Instead it fitted a typical neo-liberal hands-off strategy of inviting labour-intensive low value added manufacturing and hence semiconductors were targeted along with other export-oriented light manufacturing activities such as garments, consumer electronics and industrial electronics. All these industries were offered tax exemptions and tariff-free operations at export-processing zones on the basis of investment and employment generation, and export intensities. The focus from 1986 following the First Industrial Master Plan (IMP1) identified semiconductors as a strategic industry but no targeting was established for a systematic catch up. The Malaysian Institute of Microelectronics Systems was established in the Prime Minister's department in 1985 – which was eventually corporatized following directions given in the Action Plan for Industrial Technology Development (APITD) in 1990 – whose focus was to drive learning and innovation in the industry.

Taiwan Like in Malaysia, foreign firms relocated back-end assembly operations in export processing zones in the 1960s to start semiconductor manufacturing in Taiwan. Government policy was instrumental in making the shift from simply assembly and test activities into front-end activities when the Electronic Research and Service Organization (ERSO) was established among the Industrial Technical Research Institutes (ITRI) in

---

[7] Infineon acquired the semiconductor division of Siemens in the 1990s. This firm uses both Infineon and Qimonda names.

1974.

However, the initial creation of the Industrial Technical Research Institute (ITRI) in 1974 did not produce significant results as no grants were given to stimulate participation in R&D activities. In addition to the science and technology project (STP) funds that were disbursed from 1979 ITRI also started to develop incubators to stimulate the birth of high tech firms. The Electronic Research and Service Organization (ERSO), the division within ITRI involved in supporting R&D in electronics activities became a key driver of incubation from 1979 (Rasiah and Lin, 2005).

Leading firms such as TSMC, which is the world's leading contract manufacturer of semiconductor wafers, have subsequently forged strong collaboration with foreign technology R&D labs, universities and purchasers to move up the technology trajectory. In 2006 TSMC was fabricating cutting edge 12" inch wafers using 0.13 micron chips using nanotechnology with R&D support from a range of foreign collaborators providing the design support. The firm also announced plans to fabricate microprocessors in 2008 (Shilov, 27/7/07).

It can be seen that the history of catch up in the semiconductor of the four East Asian economies are different from the path taken by the United States. Although differences in the distance reached in the technology ladder, organization structures and product types manufactured, Figure 1 provides a rough ecology of firms – semiconductor and buyer-supplier firms, and organizations that constitute an industrial cluster showing the industry.

Table 1: World IC and Electronics Component Exports, Selected Economies, 1990-2005

	Value (US$millions)					Share in Total Exports	
	1990	2000	2003	2004	2005	2000	2005 a
World	...	307528	278694	330198	345195	4.9	3.4
Australia	20	132	171	217	232	0.2	0.2
Belarus	-	33	34	35	36	0.4	0.2
Brazil	79	234	213	212	169	0.4	0.1
Bulgaria	...	7	20	23	44	0.2	0.4
Canada	...	3459	1782	2074	2609	1.3	0.7
China b	128	5352	10401	16184	20413	2.1	2.7
Costa Rica b	...	51	95	258	813	0.9	11.6
Croatia	...	3	46	58	51	0.1	0.6
European Union (25)	-	58742	51478	61801	60412	2.4	1.5
intra-EU (25) exports	-	36212	30454	36304	35997	2.2	1.3
extra-EU (25) exports	-	22530	21024	25497	24415	2.8	1.8
Hong Kong, China	2562	14046	19832	26277	30590	6.9	10.5
domestic exports	550	2520	801	1138	1522	10.7	7.6
re-exports	2012	11525	19031	25139	29068	6.4	10.7
India c	39	86	175	227	242	0.2	0.2
Indonesia	18	739	721	762	738	1.2	0.9
Israel c	143	1782	1067	1269	1139	5.7	2.7
Japan	13391	42454	35256	40653	39885	8.9	6.7
South Korea	5364	24688	19111	24446	27488	14.3	9.7
Macao, China	...	3	3	5	...	0.1	0.2
Malaysia b	4321	18729	22406	23500	23759	19.1	16.9
Mexico b	...	3064	2172	2523	2220	1.8	1.0
Morocco b	110	480	601	630	621	6.5	5.8
New Zealand	1	17	28	47	58	0.1	0.3
Norway	11	30	86	84	122	0.1	0.1
Philippines b, c	1053	16663	15900	15186	15002	41.9	36.4
Romania	...	45	19	45	49	0.4	0.2
Russia	-	102	121	182	131	0.1	0.1
Singapore	3675	34436	37039	48459	53866	25.0	23.5
domestic exports	2844	15433	14450	18357	19380	19.6	15.9
re-exports c	830	19003	22589	30102	34486	32.2	31.9
South Africa	...	25	74	107	130	0.1	0.3
Sri Lanka	...	...	3	3	4	...	0.1
Switzerland	231	677	569	768	838	0.8	0.6
Taiwan	2435	21767	20270	26922	30086	14.7	15.9
Thailand	901	5876	6307	6322	6538	8.5	5.9
Tunisia	0	19	19	21	...	0.3	0.2
Turkey	1	11	15	19	25	0.0	0.0
Ukraine	-	10	41	17	23	0.1	0.1
United Arab Emirates c	...	46	129	169	...	0.1	0.2
United States	13991	62824	47769	49274	48240	8.0	5.3
Viet Nam c	...	85	114	151	...	0.6	0.6

a Or nearest year; b Includes significant exports from processing zones; Includes Secretariat estimates.

Source: WTO (2007)

3 Catch Up Trajectories

In this section we examine the trajectory paths of process and product technologies taken by semiconductor firms in China, Korea, Malaysia and Taiwan. The catch up started in these economies with entry into the assembly manufacturing of memories by foreign multinationals in export-processing zones in all four countries: 1960s in Korea and Taiwan, 1970s in Malaysia and 1980s in China. Whereas multinationals began assembly and test operations of memory chips, the entry into chip fabrication and chip design started with government supported programmes. China had the first government programme in the 1950s but the development of the industry from the 1980s has little link with that programme. Taiwan and Korea followed next launching formal programmes to develop semiconductor manufacturing through the establishment of the Electronics Research and Service Organization (ERSO) among the Industrial Technical Research Institutes (ITRI) in 1974 and 1975 and the Heavy and Chemical Industry (HCI) programmes respectively (Mathew and Cho, 2000; Amsden and Chu, 2003; Kim, 1997; Rasiah and Lin, 2005). Malaysia earmarked semiconductors among its strategic industries in 1986 when launching its first Industrial Master Plan (IMP) in 1986 (Malaysia, 1988).

Unlike foreign affiliates already in possession of the requisite intellectual property rights (IPRs) local firms bought licenses or firms to access both product and process technologies. The regulatory framework on IPRs first became pronounced with the 1989 Washington Treaty that legalised industrial layouts in addition to industrial designs and patents The governance regime of IPRs were included in the 1995 World Trade Organization's (WTO) Trade Related Intellectual Property Rights (TRIPs) agreement. Local firms' first access to most product technologies in the four countries first came through licensing and acquisition of the firms. Korean firms wre the leading acquirers of technology through such a route followed by Taiwanese firms. For a long time microprocessor manufacturing was dominated by Intel until AMD won a legal suit to enter production in the 1990s. It appeared that American firms will not contract out microprocessor fabrication until in 2008 when TSMC announced plans to manufacture its first output by the end of the year (Shilov, 2008).

Unlike foreign assemblies that started operations in the 1960s local Korean and Taiwanese semiconductor firms went directly into integrated operations from the late 1970s. UMC was started in 1980 (see Mathew and Cho, 2001; Cheng, 1995) following the acquisition of the semiconductor division of RCA in the second half of the 1970s (see Rasiah and Lin, 2005). RCA offered UMC ASICs, diodes and transistor technology. TSMC (49%) and Phillips (51%) merger in 1987 gave the Taiwanese firms access to more sophisticated memory chips such as DRAMs.

Foreign and local Malaysian firms are largely specialized in assembly and test operations. Local assembly and test firms are engaged in assembly of second and third generation transistors and memory chips while foreign firms are largely manufacturing first and second generation memories and microprocessors. Four firms were engaged in wafer fabrication in Malaysia in 2007. Although assembly and test dominated semiconductor manufacturing when the first waves of operations expanded operation in the 1980s semiconductor firms in China have embarked more extensively into wafer fabrication.

Horizontal user-producer links grew between semiconductor firms and suppliers and buyers in the United States, Japan and Germany. Several machinery technology semiconductor firms coevolved as strong interactions helped machinery firms automate, refine, remodify and manufacture more efficient and effective machinery and equipment. Taiwan's world class machinery industry facilitated similar transition. In Malaysia the machine tool industry coevolved alongside the semiconductor industry owing to quick demand changes that forced even multinationals such as Intel, AMD, Texas Instruments and National Semiconductor to seek proximate sourcing.

Process Technology

Process technology refers to the processes that are undertaken to process or assembly products. It refers to machinery and equipment, layouts, inventory and quality control systems, production organization and firm-structures. Lead firms in process technology are able to drive creative destruction as they are able to lower defects, delivery times and costs while raising quality levels. Falling profit margins often drive latecomers lacking product innovation rents typically to either drive out high cost incumbents or fill up the vacuum left behind them. Apart from industrial layouts of chips and chemical processes, cutting edge machinery and equipment and materials most process technologies are not subjected to IPRs and hence its diffusion is far quicker and easier than product technologies.

Rapid growth of user-producer driven product and process specifications, defect-free output and delivery times, also drove closer interface and technology coordination between semiconductor firms and buyer firms (e.g. computers, avionics, consumer electronics and mobile phones) in all four countries.

Semiconductor firms in all the four countries are engaged in state of the art development of process technologies. Taiwan and Korea led in the take up of process patents in semiconductor devices issued by the US patent office over the period 2002-2006 with 2,907 and 2,503 patents. Malaysia and China followed next with 39 and 27 patents each over the same period.

China Foreign owned multinationals in China relocated significant aspects of process technology including just in time systems through their subsidiaries to facilitate better coordination between them and buyers.

China has both the Malaysian-type MNC operations and a strongly emerging local base resembling Taiwan (Xinxin, 2006). Intel, Freescale, National Semiconductor, Texas Instruments and Chippac have largescale assembly and test of semiconductors in China targeting export markets. These firms also have backend designing and other operations that are important for improving production performance.

Foreign firms were the initial transmission channel for the movement of process technologies to Chinese semiconductor firms. Because the first wave of semiconductor firms to China relocated in the 1980s when flexible production systems, automation and continuous improvement benchmarks were absorbed by European and American firms these techniques were already carried to from the outset among export-oriented firms.

Although the main machinery and equipment in assembly, test and fabrication are still imported considerable adaptations have already started in China. By the end of the 1990s Chinese firms have already started supplying robotics and automated machinery to foreign and local semiconductor firms.

Korea Korean semiconductor firms had initially relied on embodied knowledge in human capital hired as well as training provided by machinery and equipment suppliers from Japan, the United States and Germany. However, as the Japanese firms became more reluctant to transfer process technology once Korean firms reached sufficient levels maturity they decided to invest on in-house developments (see Kim and Amsden, 1985; Kim, 1997; Amsden, 1989).

Integrated manufacturing spreading into consumer and telecommunication products and the development of the chemical industries also facilitated the diffusion of low cost machinery and equipment, chemical materials, inventory control systems and space utilization skills to help Korean firms lower production costs. Integrated operations enabled cross transfers of process technology.

Incremental engineering through the absorption of Japanese JIT and kaizen practices were instrumental in the rapid diffusion of flexible specialization practices (6-sigma, TPM, SGA, teamworking, QCC and TPM) in semiconductor assembly and test in all four countries from 1980. Duplicative imitation and later creative imitation (Kim, 1997) dominated catch up in process technology practices. These developments took place both in local and foreign firms. Extensive improvements (including in-house modifications) in machinery and equipment (e.g. fully automated machinery and integration of die attach and die bonding), materials (e.g. changes in use of sticky tape, shipping tubes and epoxy) and layouts helped reduce cost, eliminate defects and shorten throughput time. These developments largely diffused from automotive manufacturing in Japan. Volatile fluctuations in demand drove firms to keep inventories low and production changes swift.

The emphasis on yield management spread from Samsung to the other semiconductor firms such as Hynix in the 1990s. Yield management at the corporate level included continuous R&D to improve process technology. Samsung invested huge amount of capital in purchasing high-end equipment and machinery, and Hynix focused on R&D of new process technology. Korean engineers were highly regarded for their deft skills and meticulousness to detail. R&D projects were also conducted at the government level. An example is the project conducted by the Ministry of Science and Technology between 1994 and 1996, the purpose of which was to develop production and process management system.

Despite heavy emphasis by the government to stimulate the fabrication and manufacture of machinery and equipment local capabilities – including the opening of the Cheon-an semiconductor equipment complex – the development of local capabilities have been slow so that in 2005 foreign manufacturers and imports still accounted for 80 per cent of the machinery bought by semiconductor firms (Song ref?).

Malaysia Foreign assembly plants first transferred semiconductor assembly and test as well as related process technologies to Malaysia from 1971. Semiconductor assembly and test firms in Malaysia subsequently enjoyed significant transformation in process technologies from the late 1970s with the proliferation of automation, flexible production systems and its consequent impact on skill training (see Rasiah, 1988, 1994).

Whereas NS (Micro-Machining) and Intel (Intel Automation) started their own machinery subsidiaries, Texas Instruments, HP, Hitachi, AMD, Harris Semiconductor (renamed as Intersil and finally as Chippac) and IDT created in-house machinery workshops in Malaysia. However, by the mid-1980s Intel, closed its machinery subsidiary while AMD, HP and Chippac reduced theirs to emergency solutions (see Rasiah, 1987, 1987, 1996).

Intel in Penang started prototype development from 1980 to facilitate technology transfer to local supplier firms to support its own flexibilization and use of JIT operations (see Rasiah, 1988, 1994, 1995). Indeed rapid technological obsescelence driven by shortening product cycles and miniaturization forced semiconductor firms in Malaysia to establish strong interface with machinery suppliers.

Organizational change and a rise in productivity helped reduce real output-fixed capital and output-labour ratios in semiconductor firms. Indeed, Intel expanded its output twice while reducing its workforce from 8,000 employees to 4,000 employees in 1984 (the plants in Barbados and Puerto Rico were closed down to appropriate production synergies from these gains) (see Rasiah, 1988).

Driven initially by American firms to absorb cutting edge Japanese and American inventory and quality control systems, kaizen practices were introduced in both foreign and local firms manifesting in different forms – e.g. small group activities, just-in-time, quality control circles and six-sigma – were developed in these firms to raise efficiency levels by eliminating defects, downtime and coordinating production flexibly to meet volatile fluctuations in demand and prices.

Growth of experiential knowledge in MNCs and the American open framework helped the use of Malaysian employees to ramp up new operations, provide expert training and process systems in the semiconductor value chain. Indeed, Malaysian engineers and managers played an important role in the ramping of manufacturing in Intel in Shenzen and Manila, Motorola in Shenzen and AMD in Bangkok in the 1980s.

The local firms of Carsem, Unisem and Globetronics managed to reduce production costs in semiconductor assembly and test so much so that they had started to capture demand from incumbent American, Japanese and German firms – creative destruction.

Local owned Silterra, by far the most advanced Malaysian local fabrication plant, took up 5 process patents issued by the US Patent Office in the period 2002-2006. The foreign owned Intel and National Semiconductor subsidiaries in Malaysia led patent take up issued by the US Patent Office over the period 2002-2006 with 21 and 20 patents each.

Taiwan The initial source of process efficiency improvements was recorded through technology transfer by employees gaining experiential knowledge working in American and Japanese consumer electronics firms and training provided by machinery and equipment suppliers. Taiwanese firms then internalized training and inventory and quality control systems in-house once the suppliers became reluctant to supply the laest technologies. Like in the other countries kaizen practices manifesting in different forms – e.g. small group activities, just-in-time, quality control circles and six-sigma – were developed in these firms to appropriate throughput efficiency and make production agile and flexible to meet volatile fluctuations in demand and prices.

The domestic machinery industry adapted strongly in Taiwan to the needs of semiconductor manufacturing, including wafer fabrication to manufacture cutting edge machinery and equipment, and to support modifications in firms. Kaizen practices to lower throughput time, reduce defects and meet customer requirements (the OEMs who achieved global service provider (GSP) status faced added pressure to remain innovative) among Taiwanese firms – part of Schumpeterian Mark I system (creative destruction) (see Malerba, 1992; Rasiah and Lin, 2005).

Taiwanese domestic firms – e.g. UMC, ASE, TSMC, Windbond, Asus and Vanguard – upgraded and relocated supply base at all major buyer locations, and also introduced and refined their capacity to anticipate changes in demand from buyer firms. Network cohesion facilitated strong differentiation and division of labour in Taiwan to support large scale manufacturing of OEM computers (only Acer is a major local OBM computer manufacturer in Taiwan), scanners, monitors, motherboards and components.

Product Technology

Unlike in process technology, the catch up process in product technology is much more difficult owing to the introduction of intellectual property rights, huge investment and the leaps in path dependent knowledge required sustain participation in the development of products facing rapidly shortening product cycles. Semiconductor firms in the four countries have managed to move up the product technology trajectory of semiconductor chips.

China Both **f**oreign and local firms in China are engaged in assembly, test, fabrication and R&D activities on non-optical, optical, discrete, analog, logic, memories, ASSPs and ASICs. While much of the R&D is confined to ASICs, some firms undertake DRAM fabrication and R&D (e.g. Intel, Freescale and Qimonda). Government funded R&D labs in China's high tech parks are working on DRAM R&D.

Xinxin – more info required here

Korea Korean companies started with memory products as their specialization memory products have large and fast growing market, and provide benefits of mass production (see Kim, 1997). Since the competitive advantage in the memory market lies in the production technology and equipment, late entrants can also catch up in short time if provided with sufficient capital and human resources. Also, the microprocessor industry is dominated by Intel with stringent patent laws shielding against new entrants.

Through a series of hiring of Korean human capital embodied with tacit knowledge working in foreign firms, acquisition of ailing but strategic foreign firms and licensing agreements Samsung started fabricating and manufacturing 64K DRAM chips in 1982 and by 1984 had reached the frontier of DRAM technology to manufacture 256K DRAM chips (see Edquist and Jacobssen, 1987; Kim, 1997). LG Electronics, Hyundai and Hynix followed similar patterns of acquiring product technology.

The product technology trajectory of Samsung is shown in Table 2. Samsung's strategy of seeking its human capital, technology and markets globally alongside its own internalized development facilities – which included R&D labs and its own university - drove the firm to quicken the process of integration so that Hwang's (the CEO of Samsung) law enabling the doubling of memories every 12 months replaced Moore's (CEO of Intel) law that achieved this only in 18 months. By the mid-1980s Samsung had become a driver of creative accumulation in semiconductor memory chips. Table 2 shows Korea enjoying the highest position in the product technological trajectory of semiconductor firms among the four countries.

Malaysia Foreign and local Malaysian firms are largely specialized in assembly and test operations – the former in the latest product lines. The local firms of Carsem, Unisem and Globetronics are engaged in contract assembly and test of low end microchips. Carsem was acquired from foreign owned Carter Semiconductor in 1984, Unisem was started new by a group of Malaysians who left American semiconductor firms in 1990, and Globetronics was started by Intel's local managers in 1992. Semiconductor multinationals acted as training ground to expand experiential knowledge.

In 2007 there were 2 foreign (Infineon and Osram) and 2 local (Silterra and 1st Silicon) fabrication houses in Malaysia. These firms are engaged in low end 4 and 8 inch wafer technology. Infineon fabricates power chips while the local firms are engaged in the fabrication of complementary metal oxide semiconductors (CMOS) and application specific integrated circuits (ASICs) respectively both using silicon wafers.

At least 7 semiconductor firms seeking to relocate ASIC and DRAM fabrication in Malaysia chose not to after negotiations with MITI, Malaysia. Prime reasons – lack of human capital and insufficient capitalization.

After a long dialogue and attempts by the government between the corporatization of MIMOS in the early 1990s and Silterra, Southeast Asia's second largest fabrication factory in 2006, started manufacturing operations in late 2000 to fabricate 0.25 micro CMOS chips. There were a number of management changes over this period until 2004. It was in 2004 when the government-linked investment company, Khazanah, acquired control of Silterra providing the much need capital for expansion. Being still new to the industry Silterra forged strategic alliance with IMEC which is one of Europe's leading independent research centre which led to the successful fabrication of 8MB SRAM chips using 0.13 micron CMOS technology in 2005 (Silterra, 2006) (see Table 2).

Silterra then established a strategic partnership with Key ASIC in 2006 to provide mutual customers access to the latter's IP portfolio and design services on the former's 0.18- and 0.13-micron CMOS process technologies. The firm reported having expanded market shares following the acquisition of access rights to Key ASIC's design facilities, and is seeking to expand its size to appropriate scale economies.

Taiwan Local Taiwanese semiconductor firms went directly into integrated operations when UMC was started in 1980 (see Mathew and Cho, 2001; Cheng, 1995) from the acquisition of the semiconductor division of RCA in the late 1970s (see Lin, 2002). RCA offered UMC ASICs, diodes and transistor technology.

The merger between TSMC (49%) and Phillips (51%) in 1987 gave the Taiwanese firms access to DRAM technology. ERSO helped the incubation and creation of several high tech firms – including with R&D and wafer fabrication capabilities – e.g. Windbond, ASUS, Vanguard and ASE from 1983.

The collapse of RCA coincided with the acquisition of the company's semiconductor division by ERSO in the late 1970s. ERSO gave birth to United Microelectronics Company (UMC) in 1980, which started producing ASICs for consumer electronics firms (see Ernst, 2000; Mathew and Cho, 2000; Mathew, 2004). Taiwan Semiconductor Manufacturing Corporation (TSMC) started subsequently in 1987. TSMC was the first contract semiconductor chip manufacturer to separate chip design from chip fabrication to specialize on the latter. From wafer fabrication with strong R&D support from industrial technical research institutes of ERSO led to the starting of eventually front-end operations such R&D and wafer fabrication. Front-end did not integrate with the old back-end firms in Taiwan as the companies were different. In the more integrated Taiwanese semiconductor companies such as UMC and ASE the back-end activities of assembly and test were eventually relocated in China and Malaysia. UMC has also relocated wafer fabrication abroad in Singapore and the United States.

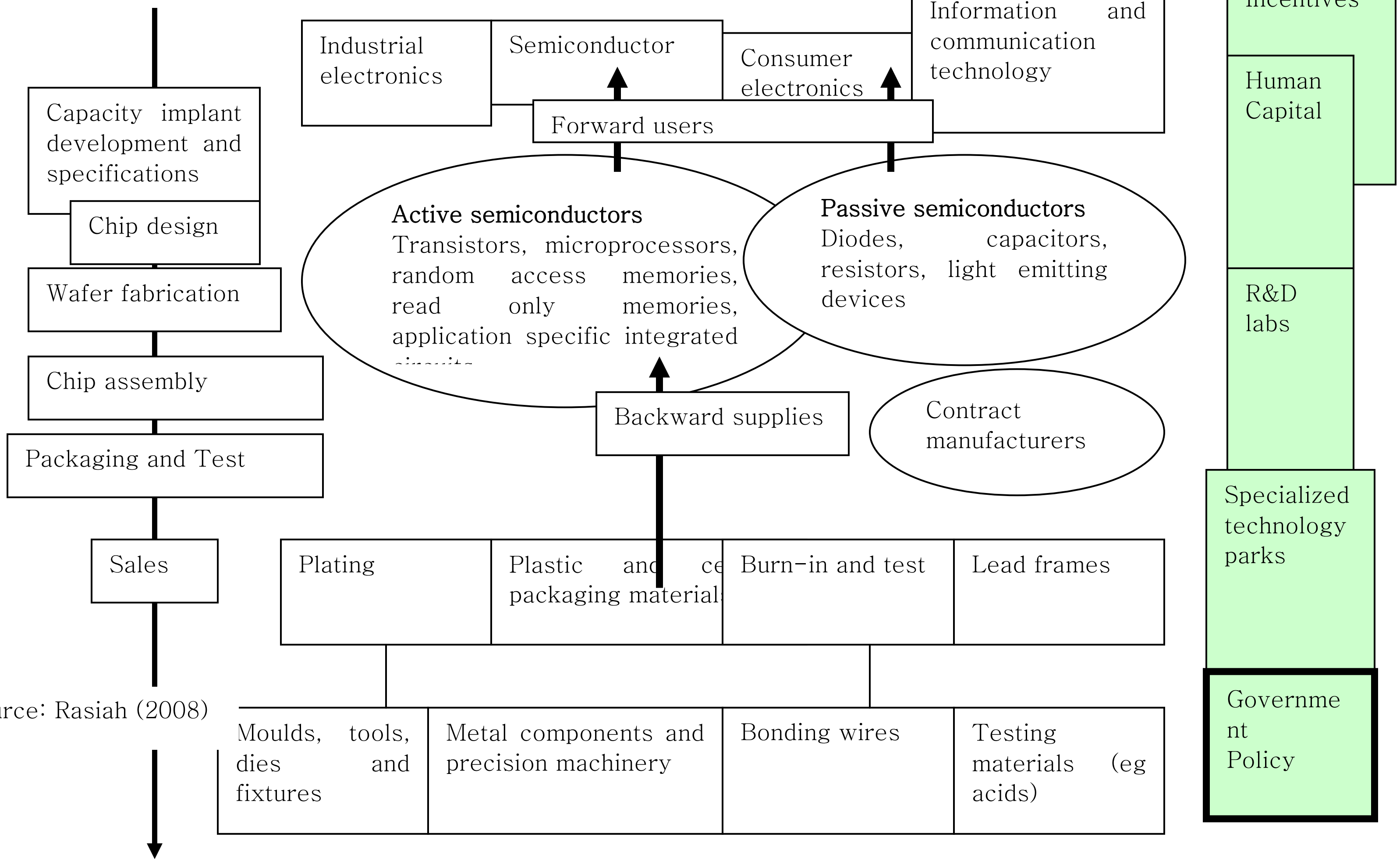
Although UMC was the first Taiwanese fabrication plant to open in Taiwan TSMC has become the leading Taiwanese fabrication house since the 1990s and hence the focus here is on the latter. Once the government successfully negotiated a joint venture with Philips holding 51 per cent of the share Maurice Chang who had gained tacit and experiential knowledge working in American firms and left Texas Instruments as its Senior Vice President was appointed as its founding CEO. Using his knowledge and linkages with R&D centres, universities buyers, suppliers and rivals played a key role in charting the direction of the firm.

Not only that the leading local semiconductor manufacturers in Taiwan (UMC, TSMC, ASE and Winbond) and China have linked with R&D and wafer fabrication that is targeted towards sale of important manufacturers – especially computers (e.g. Acer and Lenova and the contract manufacturing firms such as Tatung, Vanguard and Asus) as well as exports (see Mathews and Cho, 2000; Amsden and Chu, 2003; Rasiah and Lin, 2005). Some large American multinationals have also set up R&D and wafer fabrication plants in China and Taiwan. Especially in Taiwan considerable R&D off-shoring has occurred from the late 1990s – something that began with TSMC – a joint-venture between Phillips and Taiwanese capital that was started in 1986. The top three leading semiconductor manufacturers in Taiwan are also in the top ten DRAM producers in the world. Taiwan's world class machinery industry has also helped the complementary development of semiconductor machinery and equipment.

By 2007 TSMC had become completely Taiwanese owned. From being the world's first independent contract manufacturer of memories entering the manufacturing of 12" wafers using nanotechnology the firm announced plans to fabricate through contract arrangements microprocessors in 2008 (TSMC, 2008 February 20). TSMC was the first to specialize in IC fabrication separating it from IC design.

Overall, semiconductor firms are at the technology frontier in process technology in all the four countries examined. However, only firms in Korea and Taiwan are at the product technology frontier. Although semiconductor firms in Taiwan are not involved in integrated operations and are still heavily but horizontally reliant on strategic alliances for markets and technology, they are engaged in cutting edge product technologies in the segments they have entered. Korean semiconductor firms are dominated by fairly independent access to markets and technological capabilities. Chinese firms come after that followed by Malaysia where fabricating firms are heavily reliant on foreign markets and technology and are still far from the technology frontier (see Table 3).

Figure 1: Semiconductor Cluster, East Asia, 2008



Source: Rasiah (2008)

Table 2: Technology Trajectory of Lead Local Firms

	China	Korea	Malaysia	Taiwan
	Hua Hong	Samsung	Silterra	TSMC
1975		Started		
1976-1981		Acquisitions, Hirings and Licensing		
1982		64K DRAM		
1984		256K DRAM		
1986		1M DRAM		
1987				Incorporated
1988		4M DRAM		Hiring personnel and contract fabrication
1990		16M DRAM		
1992		256M DRAM		
1996		1G DRAM		
1997	Founded			
1999	DRAM	256MB Nand		
2000		516MB Nand	Started with 0.25CMOS	
2001		1G Nand	0.22 CMOS	Range of DRAMs
2002	Foundry	2G Nand	0.18 CMOS	
2003		4G Nand		
2004		8G Nand		12” wafer
2005		16G Nand	8MB SRAM	Nand
2006	Plans for 12” wafer	32G Nand	0.13 CMOS	

Source: Compiled from Kim (1997: 88); Authors’ interviews (2007); Samsung website; TSMC website; Silterra website.

Table 3: Product Technology Capabilities of Lead Firms, Selected Economies, 2007

Closeness to frontier	Capabilities of Firms
Frontier operations	Korea: OBM R&D and fabrication of DRAM/Nand flash
Frontier operations	Taiwan: OEM fabrication capability of frontier DRAM/Nand
Previous generation	China: OEM fabrication capability in 0.13 and 0.18 micron CMOS, NMOS and DRAMs
Previous generation	Malaysia: OEM fabrication capability in 0.13 0.18 CMOS

Source: Compiled from Kim (1997: 88); Authors' interviews (2007); Samsung website; TSMC website; Silterra website.

4. Building Blocks

Having established the technological paths, this section analyses the drivers behind them using the broad net expounded in the introduction in this volume by Malerba and Nelson. The unfolding of these paths will help explain the differences, if any, of the catch up patterns of firms in China, Korea, Malaysia and Taiwan. The technological regime of semiconductors can be characterized by high velocity high frequency devices using light emitting devices that are expensive (using gallium arsenide material base) that are used in mobile phones and related products, and low frequency devices that do not require much light emitting functions and are also cheap and abundant (silicon as the base) that are used to fabricate memories and microprocessors. TSMC is engaged in all categories, Samsung is engaged in memories and nand flash.

Access to Foreign Knowledge

Semiconductor assembly and test began with the transfer of technology by multinationals to their subsidiaries in Korea and Taiwan since the 1960s, Malaysia from 1972 and China from the 1980s. Flagship semiconductor firms such as Intel, AMD, National Semiconductor, Hitachi and HP relocated the assembly and test of the cutting edge production technology to Malaysia. This early phases were associated with employment generation in export processing zones with little focus on catch up.

Two major and more minor routes to accessing foreign sources of knowledge in the semiconductor catch up track can be identified from the four countries. In the first route all four countries foreign firms as training grounds to access tacit knowledge. Malaysia and China have attempted to use this route with less success. In the first major route, Korean, Taiwanese, Chinese and Malaysian firms accessed foreign technology through licensing. In the second major route Taiwanese and Chinese firms merged or acquired foreign firms to access technology and markets. Among the minor routes, Korea and Taiwan used

Korea and Taiwan led the way among the four countries in driving a catch up in the semiconductor industry. The Korean government encouraged local firms to license technology from foreign companies and to invest abroad to access technology from foreign labs. Foreign direct investments made by Korean companies in the U.S mainly include setting up local R&D lab to learn cutting-edge technology such as ASIC design technology. Samsung and Hyundai set up R&D labs in Silicon Valley in 1983, which helped the development of DRAM technology.

Korean and Taiwanese semiconductor companies established strategic alliances with leading foreign companies. The purpose of Korean alliances with Japanese firms was to learn memory–related technologies and capture the market, whereas alliances with the U.S and European companies were mainly intended to learn non-memory technologies and capture the market share. UMC grew from ITRI's acquisition of RCA in 1979 while TSMC started as a joint-venture with Philips in 1987. Dependence on foreign firms fell in the 1990s in Korean firms but Taiwanese firms such as TSMC, UMC, ASE and Winbond remained strongly linked to strategic alliances with foreign firms.

Technological partnerships between foreign companies and Korean and Taiwanese companies has taken place since 1970s. Unlike in automobiles Korean electronics firms did not merge with foreign firms in Korea. The early fabrication houses of UMC and TSMC merged first with RCA and Philips before acquiring them. Korean firms signed cross-licensing, royalty and technological alliance agreements with foreign companies that filed lawsuit against Korean firms' infringing on the patent right. Between 1983 and 1988, Korean semiconductor firms entered 101 technology licensing agreements – 66 cases of these were with US firms. However, whereas Korean firms have reduced their dependence on strategic alliances by the mid-1990s the highly de-verticallized Taiwanese firms remain strongly but horizontally attached their strategic partners.

Korean and Taiwanese firms too advantage of the mid-1980s downswing in the industry: prices of 64K DRAM chips had fallen from US$50 to US50 cents in 1980-85, and the EPROM from US$18 to US$4 in three months in 1985. This Schumpeterian (1912) Mark I entry – the displacement of ailing incumbents (see Malerba, 1992; Mathews, 2006) such as Mostek (sold subsequently at a low price to Thomson CSF before International Device Technology acquired it) and the phasing out of old product lines in AMD, Intel, Texas Instruments and National Semiconductor – coincided with the entry of Taiwanese contract semiconductor manufacturers. Whereas Korean firms licensed technology from foreign firms directly, much of the early Taiwanese forays into foreign technology was done through ERSO. The early acquisitions in Taiwan and licenses in Korea allowed a key point of entry, which has then been transformed to drive frontier research especially in memories – *a la* the Schumpeterian Mark II development of creative accumulation (see Malerba, 1992).

Chinese and Malaysian firms have also accessed foreign technology through licensing agreements but with less success. However, whereas the focus in Korea and Taiwan has been on accessing foreign technology by local firms moving up the product technology trajectory, in China and Malaysia foreign firms still dominate but largely in the low value added production stages of assembly, packaging and test operations. Initiatives to follow the Taiwanese framework started in Malaysia and China. The same approach was used in China first in the 1980s but the huge labour force of China was unrivalled by other countries. The Chinese government allowed total foreign equity when all output was exported. The focus in China shifted subsequently in the 1990s as technological deepening became important. Hence, both local and foreign firms have managed to attract incentives to start R&D operations and wafer fabrication. Attempts to move up the value chain in Malaysia have again benefited from two foreign wafer fabrication subsidiaries of Infineon and Osram that relocated their technology from abroad significant efforts are made to evolve it using in-house expertise. Silterra and 1st Silicon established strategic tie-ups with design technology from foreign technology suppliers and purchasing firms, R&D labs and universities. The acquisition of of VLSI technology in the Silicon Valley in 1997 however did not materialize because the management then at MIMOS did not have a strategy to use the knowledge for designing and fabrication wafers. The plant was sold in 2001.

More from Xinxin

Demand Conditions

Export markets were the critical initiator of large scale semiconductor manufacturing in Korea, China, Malaysia and Taiwan and remain important (see Table 1; Figure 1). China's semiconductor market nevertheless has become the third largest in the world by the end of the 1990s. Ownership regulations in electronics required that foreign controlled firms to export most of their output. These regulations were the same in Malaysia – at least 80 percent of output had to be exported for firms to hold 100 percent foreign equity (see Rasiah, 1995). Although the initial efforts to acquire semiconductor manufacturing operations was motivated by the desire to ensure quality support for its consumer electronics plants fabrication and manufacturing by Samsung and other Korean semiconductor firms relied extensively on export markets. Whereas the local firms are also important buyers in Korea, Taiwan and China, foreign firms remain the main purchasers in Malaysia.

Taiwanese consumer and IH electronics firms purchase the bulk of their ASICs and DRAMs from Taiwanese semiconductor firms. User-producer relations strong in wafer fabrication in all four countries as lock-ins play a key role in the wafer fabrication start-ups. Booking-billing ratios are important in low margin fabrication where yield is critical because of the lumpy nature of investment involved. The bulk of semiconductor chips are sold to lock in contractors, the rest in open markets. Strong interface between semiconductor firms and electronics firms that use chips have been an important element driving and shaping the flow of knowledge between them. However, 1st Silicon in Malaysia have been losing buyers. Silterra has managed to reverse its fortunes in export markets since 2003 and has shown a steady rise from then on.

The acquisition of IBM's computer manufacturing division has also expanded Chinese owned Lenova market share in computers and with that demand for Chinese semiconductor firms. In Korea, as of 1990, the export demand accounted for 92.5% and the domestic demand accounted for the rest. Since the size of the domestic market was negligible, companies focused on the export market. Strong export demand has led to the trade balance involving the industry to reach positive figures in Korea and Taiwan (see Table 4).

Malaysia and China are still faced a negative balance, though, the ratio is close to zero for the former. China's deficit remains very high owing to heavy imports of components by consumer and industrial electronics firms. The relocation of consumer electronics firms from Malaysia since the mid-1990s to China, Philippines and Vietnam helped improve its trade balance.

Whereas semiconductor firms have largely remained in assembly and test activities in Malaysia, their counterparts in Korea and Taiwan and China have in addition upgraded strongly to wafer fabrication and R&D activities. In addition to export demand the OEM contract manufacturers – especially in export-oriented computers and peripherals – provide considerable demand for the sale of high value added chips in Taiwan. Hence, domestic demand (including in Taiwanese firms that have relocated front-end activities in China) have since the second half of the 1980s become major buyers of Taiwanese DRAMs and ASICs. Both the Malaysian type and the Taiwanese types of activities and demand conditions have evolved in China.

The lack of upgrading has driven Malaysia's export shares in world exports of integrated circuits down in the period 2000-2005 when those of Taiwan and China have continued to rise. Exports as a share of world integrated circuits exports from China rose from 1.7 percent, 3.7 percent and 5.9 percent in 1990, 2000 and 2005 respectively (see WTO, 2006: Table 4.59). The commensurate figures for Taiwan were 7.1 percent, 7.3 percent and 8.7 percent respectively. The Malaysian share rose from 6.1 to 8.0 percent in 1990 and 2000 respectively, but fell to 6.9 percent in 2005. The latter is expected to fall further following a hollowing out taking place currently in the semiconductor industry in the country.

Export markets have been the prime catalyst in driving semiconductor demand in all four countries, though the Chinese market was the world's third largest in 2007. Semiconductor assembly began in all four countries to supply global markets. As shown in Figure 2 and Table 1 the four countries are among the leading exporters of integrated circuits in the world.

While export markets essentially provided the demand for semiconductor firms in Malaysia, China and Taiwan, access to sell fabricated wafers or assembled and tested semiconductor devices from domestically fabricated wafers relied extensively on connecting with buyers. In Malaysia the two local wafer fabrication plants enjoy market access through a lock-in agreement with consumer and telecommunication electronics firms located abroad. Indeed, the wafer fabrication plants were begun after the lock-in deals were struck. These demand arrangements are similar to the experience of Taiwan and China. Despite the presence of flagship downstream firms such as Intel, Motorola and Dell in Malaysia Silterra exported all the wafers it fabricated in 2006 with 70 per cent going to North America and the remainder to Asia and Europe.

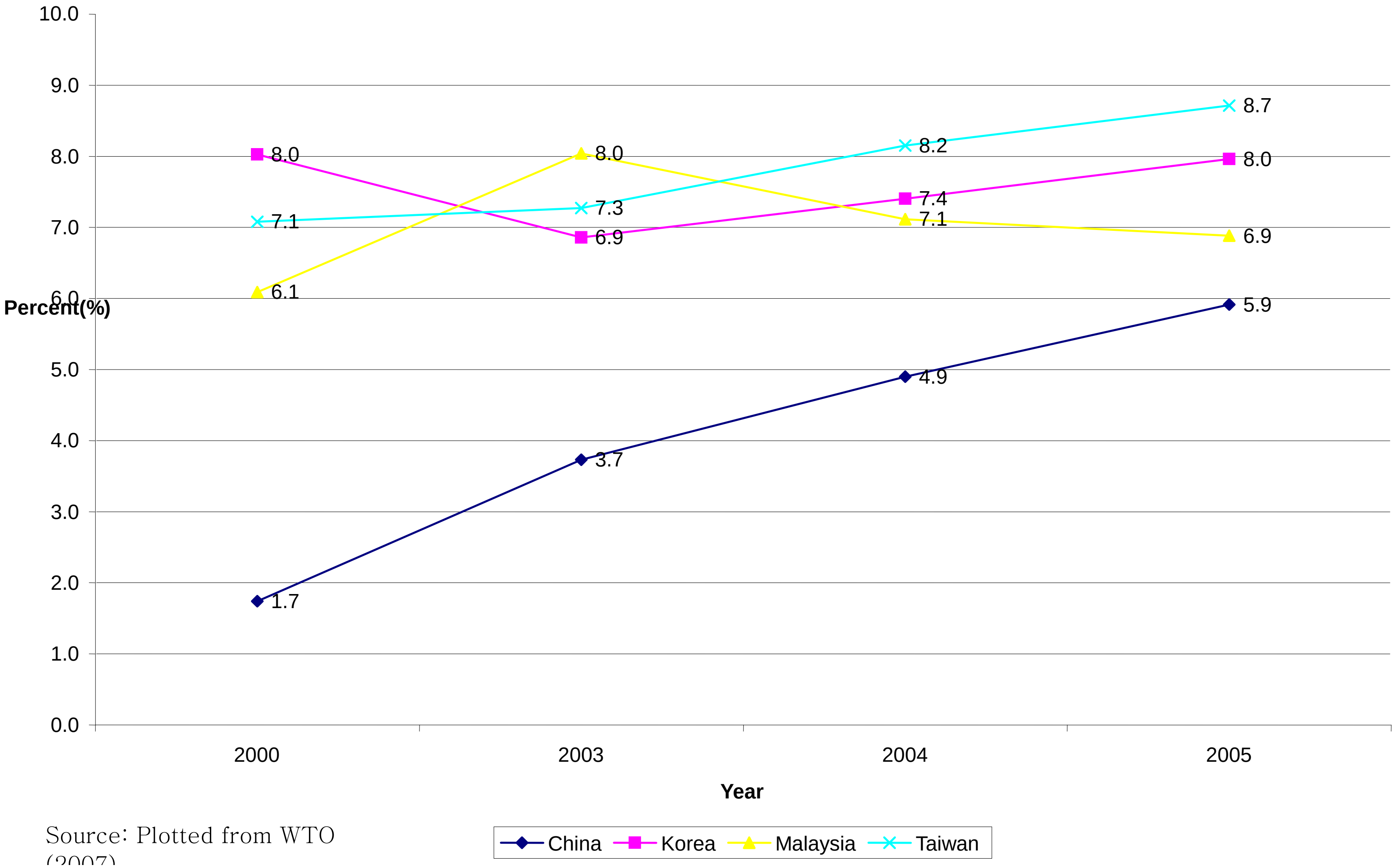
Table 4: World Exports, Imports and Trade Balance, IC and Electronics Component, Selected Economies, 2005

	Value (US$billion)		Trade Balance
	X	**M**	**(X-M)/(X+M)**
European Union (25)	60.4	68.4	-0.062
extra-EU (25) exports	24.4	32.4	-0.141
Singapore	53.9	41.7	0.127
United States	48.2	26.7	0.287
Japan	39.9	21.3	0.304
Hong Kong, China	30.6	41.9	-0.156
Taiwan	30.1	28.5	0.027
Korea, Republic of	27.5	23.9	0.070
Malaysia a	23.8	27.9	-0.081
China a, b	20.4	95.3	-0.647
Philippines a	15.0	14.4	0.021
Thailand	6.5	9.5	-0.186
Canada	2.6	4.4	-0.252
Mexico	2.2	11.5	-0.676

a Includes significant shipments through processing zones.
b In 2005, China reported imports of integrated circuits and electronic components from China amounting to $7.4 billion. For further information, see the Technical Notes.
c Includes Secretariat estimates.
d Imports are valued f.o.b.
e Excludes retained imports of Hong Kong, China.

Source: WTO(2007)

Figure 2: World Share of IC Exports, Selected Economies, 2000-2005



Source: Plotted from WTO (2007)

The Role of Government

Government policy in the promotion of semiconductor manufacturing has also differed. From simply offering incentives to attract MNCs direct operations in the 1960s and early 1970s, the Korean and Taiwanese governments promoted directly the growth of local firms. While the human capital gained tacit knowledge, government research institutes failed to assist technological catch up in Korea (Kim, 2001). In Taiwan, the government-led industrial technical research institutes (ITRI) that were started in 1974 (and the electronics labs under the electronics research and service organization (ERSO) have been a central anchor in driving R&D to local firms. The heavy and chemical industries programme offered Samsung and LG Electronics subsidized credit and support for seeking licenses from foreign firms , while in Taiwan the STP grants in 1979 (particularly after it was turned into matching grants with the private sector in 1983) and the Hsinchu Science Park that offered tremendous R&D synergies.

Korea's and Taiwan's technology transfer agreements also actively screened ex ante, monitored the use and diffusion and undertook ex post appraisal to ensure licensing fees were brought down, diffusion occurred and mistakes were not repeated. Government in Taiwan launched an active education policy – at one level driving expansion in human capital supply from technical schools and universities and at another level imposing levies on unskilled labour imports to pressure firms to upgrade (Tseng, 1994).

China, national S&T plan has been starting to play important roles to enhance the linkage s of the industry and academia. For instance, the main S&T plans like 863, 973 and suppo rting plan, within the industrialization relating contents began to encourage firms, researc h institutes and universities taking on together. Especially, since 2000, China has issued 1 2 significant S&T specific projects, which includes super large scale IC and software. Thi s project not only adopted the modes that industrial academic collaboration with governm ental funding as the leading funding, but also tried to established industrialization base. U p to now, 7 national IC industrialization bases have been established, including Shanghai, Xi'an, Beijing, Wuxi, Chengdu, Hangzhou, Shenzhen etc. Within those bases, different modes through industrial funding and market information exchanges, training and agenci es have been adopted to enhance the network.

China has an FDI attraction policy as well as one following Taiwan in the semiconductor catch up. Its large labour force supports assembly and test MNC operations in locations such as Pearl River Valley and Shenzen, and local integrated firms in high tech parks such as GanSu, Shanghai and Tianjin. Public R&D labs play an important role in supporting the knowledge base of local firms in China. The acquisition of IBM's computer manufacturing division by Lenovo has given strong horizontal learning opportunities to semiconductor firms in China.

Although the government initiated the semiconductor and computer industry in the 1960s with the MEI driving R&D, from the 1980s this route was essentially abandoned. Labour-intensive low value added assembly and test operations became dominant from the 1980s – initially from the relocation of foreign multinationals. Assembly and packaging has remained the main semiconductor production activity in China.

The government introduced market protection and incentives to promote domestic producers. IC manufacturing – assembly and test enjoyed the first large domestic expansion. Several domestic IC manufacturing plants were launched through the national seventh, eight and ninth five year plans. By the end of 1999, there were 5 large domestic and joint-venture companies – e.g. Huajing, Huayue, Beiling, Xianjin and Shougang NEC Electronics. In addition, there were also 10 specialized and 871 electronics factories in GanSu province enjoying support from the Microelectronics Industrial Centre of Chinese Academy of Sciences. IC manufacturing industry developed rapidly since late 1990s. Shougang NEC Electronics Co., Ltd started production of 0.56 64M DRAM in 1996. Huajing started production in its 0.96 CMOS line in 1998. Shanghai Huahong started production of 0.58 MOS line in 1999. Comparing with the IC manufacturing industry and IC design industry, IC packaging and testing industry was much larger in China.

Huada IC Design Centre, the first IC design company in China, was set up in 1986. IC design became important in China from the 1990s (see Table 5). Document 18 issued by the State Council in 2000 has been an important institutional development that has driven IC design development in China. IC design output rose from US$0.2 billion in 1996 to US$10billion in 2000 – expanding by around 50 times. By the end of 2003, the number of IC design firms in China reached 463. The share IC design industrial sales in overall IC industrial sales exceeded 10 percent in 2003. IC design human capital also increased in numbers from less than 5000 to 20 thousand in 2003. IC designing occupied 10th place in overall market share of sales in 2003 (see Table 5).

Table 5: IC industry structure dynamics, 1996-2004 (US$billion)

Year	IC design	IC manufacturing	IC packaging and testing	In total
1996	0.2	16	22.8	39
1997	0.3	18	33.5	51.8
1998	0.8	21	41	62.8
1999	3	24	84	111
2000	10	44	130	184
2001	1.48			
2002	2.16	4.72	19.96	26.84
2003	5.76	9.54	24.6	39.9
2004	11	18.12	28.26	57.38

Source: Digital times, Industrial Trends of Semiconductor industry and components indus try, industrial values on mainland semiconductor industry, CCID-MRD, P43; Editing com mittee of China Industrial Maps, China Economy Booming Inspection and Foresight, Chi na Industrial Maps 2004-2005, Social Sciences Academic Press.

The Korean government formulated a six year plan to develop semiconductor manufacturing within the heavy and chemical industries (HCI) programme that was launched in 1975 (Kim, 1997: 88). The chaebols were reluctant to initially to enter semiconductor manufacturing owing to the heavy dependence on a foreign technology that experienced shortening product cycles. Hence, Samsung only entered semiconductor manufacturing when it acquired Korea's first local semiconductor firms. The acquisition of this firm which opened in 1974 not only helped Samsung acquire its operational facilities but also add the tacit and experiential knowledge embodied in its founder who obtained his doctorate in from Ohio State University and gained experience working in Motorola (Kim, 1997: 88).[8]

Since 1986, the private and public sector have invested intensively in R&D, and Korea's Samsung has become the shaper of the globe's DRAM technology. In order to promote balanced development of both memory and non-memory semiconductors and to improve the technological competence of equipment and materials industry, the Korean government put forward the System IC Development Project in December 1998. In order to strengthen the design field and the non-memory sector, the Korean government and local companies ran the IC Innovation Partnership Program from 2001 till 2005. However, infrastructure-related investment especially in the non-memory sector is still quite low compared to competing countries.

While strong governmental support dominated semiconductor manufacturing until the early 1980s, mainly in the DRAM sector, support for integrated circuit manufacturing by the 1990s had been limited to three types.. The first type of support is offered directly for systems IC development, while the second to finance venture companies, and the third for the construction of infrastructure building and training system designers. Examples of such governmental support include the System IC 2010 Project and the "ASIC Joint Development Project" and "IT Core Parts Development Project" run by the Ministry of Science and Technology and the Ministry of Commerce, Industry and Energy. Owing to the failure of government research institutes (GRIs) (see Kim, 2003), Samsung internalized the development of DRAM chips with strong links to R&D centres and other firms. Hence, the Korean semiconductor industry has relied strongly on private enterprise for its growth.

The Malaysian government provided generous incentives from especially 1971 (following the Free Trade Zone Act) to attract export-oriented firms, in which semiconductor firms such as National Semiconductor, AMD, Motorola, HP, Intel, Hitachi and Texas Instruments were among the pioneers. The objective then was simply to create jobs. The Malaysian government then initiated through the Industrial Master Plan of 1986 to promote upgrading in manufacturing, including in semiconductors. The Malaysian Institute of Microelectronics Systems (MIMOS) was created in the Prime Minister's Department in 1985 to spearhead catch up and innovation in semiconductors and related devices. Unlike the experience of Taiwan, China and Korea, MIMOS failed to incubate

[8] Ki-Dong Kang's firm failed to weather the first oil crisis of 1973-75 and hence sold the firm to Samsung.

any successful high tech firms in the industry. Its attempts to seek direct participation by the multinational firms failed as these firms were only engaged in assembly and test activities in the 1980s. The ethnic coloured New Economic Policy (NEP) that targeted largely Bumiputera participation in government run firms discouraged any possibility of giving special incentives to Chinese controlled firms such as Carsem and Unisem – both of which had successfully entered semiconductor assembly and test in the mid-1980s and early 1990s. Although Globetronics eventually enjoyed capitalization from the Malaysian Technology Development Corporation (MTDC), the government appeared reluctant to engage in lumpy investment to drive the introduction of wafer fabrication in these firms.

The Malaysian government did acquire VLSI in the Silicon Valley, which opened opportunities for a Mark I entry as the firm was ailing in the mid-1990s. However, instead of using it as a vehicle to acquire technology for catch up lacking in a clear strategy MIMOS quickly sold the plant. MIMOS was to spearhead the opening of two local wafer fabrication plants – Silterra in Kulim in 1999 and 1st Silicon in Sama Jaya in 2000 – both of which operated without a clear catch up plan and made losses until 2007. Nevertheless, Silterra has shown signs of TSMC-type catch-up as the firm has established a clear roadmap since and has identified other firms to acquire and partners to establish collaboration with since MIMOS has indeed closed down its own fabrication plant at Bukit Jalil in 2003. Hence, with the possible exception of Silterra, government policy effectively failed to provide the impetus for a catch up to take place in the semiconductor industry in Malaysia.

The government shifted its framework of coordinating MIMOS activities in 2005 when it hired the former vice president of Motorola to head it. This development along with the hiring of human capital with experiential knowledge in the industry - Bruce Guy and subsequently Jalaludin Jarjis to lead Silterra through an expansionist capital financing to drive up its designing support and scale capabilities helped turn around the firm by 2006.

Foreign multinationals were attracted initially with incentives in the late 1960s to undertake export-oriented assembly and test activities. These firms provided jobs that were important during the 1960s. RCA was one of the firms to relocate operations in Taiwan. The government then targeted the semiconductor division of RCA for the acquisition of strategic technology. Government was also involved in the development of incubators at ERSO to undertake wafer fabrication activities which started semiconductor manufacturing in Taiwan. UMC was the first to be launched by ERSO. ERSO subsequently helped the incubation and creation of several high tech firms – including with R&D and wafer fabrication capabilities – e.g. Windbond, ASUS, Vanguard and ASE from 1983.

Grants initiated through incubators in the Hsinchu Science Park – started originally in 1979 but became successful after a 1:1 matching condition was attached from 1983 and the hiring of professionals brought back under the brain gain programme from the United States - were instrumental in the launching of TSMC, Winbond, Vanguard, Asus and UMC. Hence, in Taiwan front-end wafer fabrication and R&D eventually took over from the original assembly and test operations undertaken by foreign multinationals from the late 1960s. TSMC had become the fourth largest seller of semiconductor devices in the first half of 2006 rising from 8th place in 2005 (see Table 6).

Mathews (2006) argues that the government also timed its intervention to enter the semiconductor industry during an industry-wide global crisis when incumbent firms were facing severe downswings in the mid-1980s. The government subsequently in 1991 formally approved relocation of labour intensive low value added assembly and test activities to mainland China (Rasiah and Lin, 2005).

Korea, Taiwan, China and Malaysia also launched the talent attracting programme, which has been very important in the management of high semiconductor firms, and connecting them with buyer-supplier firms and foreign R&D centres. However, while Korean, Taiwan and China managed to attract a critical mass of human capital with tacit knowledge to lead or work for local semiconductor firms the Malaysians have not been very successful on this. Some Malaysians returned to work in local firms but they have either been overshadowed by ethnic policies or have left because of restrictive management practices.

Table 6: World Market Share of Top 15 Semiconductor Firms Based on Sales, 2005-2006

1H2006	2005	Firm	Headquarters	1Q2006	2Q2006	1H2006	2005
1	1	Intel	United States	8,040	7,215	15,255	35,395
2	2	Samsung	South Korea	4,365	4,581	8,946	17,838
3	3	TI	United States	3,260	3,505	6,765	11,300
4	8	TSMC	Taiwan	2,389	2,522	4,911	8,217
5	6	Infineon	Germany	2,395	2,477	4,872	8,297
6	5	ST	Italy	2,363	2,491	4,854	8,870
7	4	Toshiba	Japan	2,317	2,154	4,471	9,045
8	7	Renesas	Japan	1,963	2,050	4,013	8,266
9	10	Hynix	South Korea	1,522	1,635	3,157	5,599
10	11	Freescale	United States	1,465	1,535	3,000	5,598
11	11	Philips	Netherlands	1,465	1,534	2,999	5,598
12	12	NEC	Japan	1,386	1,381	2,767	5,593
13	13	Micron	United States	1,242	1,328	2,570	4,954
14	16	AMD	United States	1,332	1,216	2,548	3,936
15	18	Qualcomm	United States	1,018	1,133	2,151	3,457

Source: Global Sources, http://www.globalsources.com

Human Capital

Semiconductor manufacturing became knowledge-intensive from the late 1970s. Hence, minimum statistical numeracy, communicative, cognitive and judgemental skills are important before firms hire even operators. Intel's super-operators in all four countries enjoy a wage premium. The use of JIT and kaizen type practices has raised the demand for skilled workers. Schooling in Korea, Taiwan, China and Malaysia provide such labour. In addition, participation in wafer fabrication and new product development requires strong supplies of R&D engineers and technicians. However, labour markets for skilled labour tightened in Taiwan and Malaysia from the 1980s and 1990s respectively. Taiwanese and Korean firms relocated labour-intensive assembly and test in Southeast Asia since the 1980s and China since the 1990s. Malaysia has suffered a slowing down in upgrading because of both a tightening labour market as well as lack of R&D human capital.

China's conversion from centrally planned economy to markets has also provided enough human capital to drive catch up in both product and process technologies. The engineering intensity of GanSu High Tech Park in China is reported to exceed that of Hsinchu Science Park in Taiwan in 2005. China had the largest numbers of R&D scientists and engineers among the four countries with 800 thousand in 2000 and 1 million in 2004. Government institutions and

Among the four Korea and Taiwan launched first a formal policy to attract their own national human capital from abroad to provide especially the tacit knowledge to run high tech firms. However, whereas well-trained human resources were scattered across different industries in Taiwan, the Korean semiconductor industry, backed by the investment of chaebols, hired a pool of well trained graduates from science and engineering majors. Since the enactment of the Immigration Law in 1965, Korean engineers have been working in the United States. Korean chaebols hired them back in the 1980s, offering salaries even higher than those of CEOs. To hire those who did not wish to come back to Korea, Korean companies established R&D labs in the United States to tap their resources.

For example, SSI, Samsung's R&D lab in Silicon Valley, played a key role in assimilating 64K DRAM designs and production processes just 6 months after Samsung's announced entry in 1983 into the DRAM business. In a peak year, SSI hired 260 local engineers, including a substantial number of Koreans. Hyundai set up an R&D lab in Santa Clara in 1983 and at one time employed 430 local engineers. LG established a relatively small-scale R&D outpost in Sunnyvale in 1984 and roped in 115 local semiconductor engineers.

Wafer fabrication and R&D – the two going strongly going together – is highly knowledge-intensive. Engineers, scientists, and R&D scientists and engineers are a critical drivers of these operations. Taiwan supplemented demand for such human capital by stepping up their supply as well as through talent attracting programmes. Taiwan is by far the most successful here has it has managed to attract Taiwanese specialists who had gained tacit and experiential knowledge working in especially American multinationals, R&D labs and University R&D centres back. TSMC, ASUS, Vanguard and Winbond are examples of high tech firms run by these experts. Maurice Chang has been the CEO of TSMC from its founding until now.

In Malaysia automation under conditions of productive and innovation-driven flexibilization helped raise demand for skills. Semiconductor firms – especially American owned – were the first to use their connections with the state government of Penang to canvass for the starting of skills development centres. MNCs funded the Penang government's move to open the Penang skills development centre in 1989 to conduct off-firm training.

While skilling through in-house learning by doing and utilization of the PSDC) has been a success, Malaysia has faced severe demand-supply shortfalls that have restricted upgrading in the industry. Indeed, Malaysia's universities have failed to supply the requisite numbers and quality of scientists and engineers to firms such as Intel, AMD, Hitachi, Motorola (freescale), HP, ST Microelectronics, Texas Instruments and Chippac who reported being keen on hiring more engineers and scientists to undertake R&D activities since the 1990s. Seven multinationals reported dropping Malaysia when considering to relocate wafer fabrication in Malaysia over the period 1997-2007. Foreign owned Infineon embarked on an ambitious programme to train engineers and scientists in its fabrication plant in Kulim in 2007 while the local owned Silterra has scouted since 2000 the globe to seek human capital to participate in its expansion plans.

Networks, Alliances and Consortiums

Consortiums and strategic alliances have been important in the development of a number of firms in these countries. The independent local fabrication and assembly plants of China, Malaysia and Taiwan have relied extensively on formally registered strategic alliances with foreign firms and R&D centres for key technologies and markets. Enjoying large scale and integrated consumer and industrial electronics Korean attempted to work together on accessing joint R&D but intense competition in product markets often derailed these agreements.

Strategic alliances with foreign firms and labs were critical in the catch up stage of integrated Korean firms, and have remained important in the de-verticallized Taiwanese firms. Strategic alliances are also critical in Chinese and Malaysian firms but it is too early to predict their direction.

The government has been the chief architect ere helping to establishing a consortium to pool R&D efforts. Samsung, Hyundai, LG Electronics and Hynix participated in this consortium to coordinate their R&D and production internalization efforts until the late 1990s when intense competition in product markets broker down this relationship. Korean firms have since internalized R&D and marketing efforts thereby reproducing what Kim (1997) classified as the old Japanese Zaibatsu framework. Large vertically integrated firms such as Samsung and LG Electronics manufacture a large share of the chips they use in their consumer and industrial electronics plants.

Hence intermediary organizations have largely been insignificant in the development semiconductor firms in Korea. Hence, three Korean chaebols organized the Consortium of Semiconductor Advanced Research in 1986. Collaborative R&D activities by Samsung, Hynix and Hyundai and active governmental support were the main driving force of catching-up in the initial stages. By the 1990s cooperation in R&D broke down owing to intense competition between these firms in product markets. Hence each firm started to develop its own R&D facilities.

Since the semiconductor industry requires huge initial investment, with the life cycle being very short, market players need to take bold risks and make swift decisions and reactions. One of the biggest advantages of Korean firms lay in the owner-management system in which the decision making responsibility was solely given to the owner-CEO to facilitate swift market reaction. Thus, the chaebol-driven development strategy was especially effective in Korea because CEOs had both the strong initiative and power to make swift decisions at critical times.

Korean companies chose standard memory products as their strategic target, in order to capture the large and fast growing memory market, and also to enjoy the benefit of mass production. Since the competitive advantage in the memory sector comes from the manufacturing technology embedded within equipments, late entrants can relatively easily catch up the leaders, as long as they are supported by sufficient capital and well-trained human resources. Koreans firms never feared to make large-scale investments in order to rise as the leader in the future market. Samsung Electronics is building the second semiconductor complex in Hwa-Sung with the investment of 33 billion USD, which will be finished by 2012. Ki-Heung Hwa-Sung Cluster will become the world’s largest semiconductor complex, and will facilitate swift decision making and market reaction.

The establishment of TSMC's Design Center Alliance has been highly strategic in attracting access to new technology, which is vital for it to specialize in foundry-based fabrication. For example Accent joined this alliance in 2004 to supply complex customer designs for TSMC's process technologies. Membership in TSMC's Design Centre Alliance allows Accent to service companies wishing to utilise TSMC’s foundry operations. Accent supplies design support for OEM, fabless and chipless small-to-medium sized enterprises (SMEs), as well as start-ups.

Recent projects by Accent for TSMC include the analog-mixed signal IC, capacitive interface sensors, a multi-million gate integrated circuit for wireless applications, the hardening of an ARM CPU, systems with large memories and analog blocks and a very complex IC for networking applications, which include 0.13μm, 0.18μm, and 0.25μm technologies. Accent also supplies its very deep submicron (VDSM) design for the delivery of incoming 90 and 45 nanometer designs.

TSMC announced in February 2008 to establish production lines to start fabricating central processing units on a 45 nanometer high end process for low cost personal computers with a target of start sales by the second half of the year. AMD is widely believed to have given the contract to TSMC to develop a low cost method to produce microprocessors. This declaration opens the way for catch up from Asian firms without which the stringent copyright and patent laws have for long threatened to restrict new entrants in the product line. Entry into microprocessors also for the first time offers Taiwanese firms the opportunity to leapfrog Korean semiconductor firms have dominated in the production of DRAM and Nand flash chips.

Malaysia's Silterra and 1st Silicon and Chinese local firms remain strongly linked with foreign technology suppliers and markets for wafer fabrication activities – though the large local market has given the latter less dependence on foreign firms.

Co-evolution – driver and driven

Taiwanese firms have by far benefited most from the co-evolution of industries. Machinery and chemicals had emerged on a large scale from 1980 in Taiwan. The co-evolution of these industries as well as the plastics industry through support from ITRI helped provide the complementarities essential for process and product technology improvements in Taiwan's semiconductor firms. Indeed a number of latest technologies that were developed at ERSO quickly found their place in the chips fabricated by Taiwanese firms. One such example is the thin membrane developed to separate transistors in wafers.

In Taiwan the semiconductor industry has been simultaneously, the driver as well as is being driven, by other industries. On the one hand major developments in chemicals and plastics, and machinery and equipment have enhanced semiconductor product technologies and process technologies respectively. On the other hand, the proliferation of semiconductor technology as the driver has benefited enormously the development of automotive parts, computer numeric control (CNCs) and electronic device machinery (EDMs), and fish tracking equipment. Microchips fabricated by Taiwanese firms also power the industries that manufacture chemicals and plastics.

None of the remaining countries have actually appropriated significant synergies from the coevolution of other industries. Local machine tool and plastic injection moulding firms co-evolved with upgrading and flexibilization in semiconductor firms in Penang from 1980s, and in Shenzen, China from the 1990s. Korea and Malaysia remain major importers of inputs to the semiconductor industry. However, whereas semiconductor firms provide significant fabricated wafer supplies to consumer and industrial electronics firms in Korea, firms in Malaysia import all their fabricated wafers. The existing wafer fabricators in Malaysia export all production.

Conclusions and Implications

Of the four countries Korean firms are at the global frontier of product technology in DRAMs and Nand flash products. Despite acquiring the OEM capability to fabricate cutting edge DRAMs, Nand flash and other CMOS products on 12" wafers, Taiwanese firms still rely on R&D and designing support from abroad. Chinese firms are in the same situation but have not acquired the OEM capabilities to fabricate the latest chips. Malaysian foreign and local semiconductor fabrication firms are still engaged in second and third generation power chips and CMOS technology on "4" and "8" wafers. Korean and Taiwanese firms have relocated much of their assembly and test activities in China and Southeast Asia while Chinese and Malaysian firms still largely specialize in these activities.

While multinationals started the first large scale assembly and test of semiconductor devices, local firms spearheaded the first critical mass of fabrication activities in all the four countries. China's initial experience with the spawning of semiconductor technology within computer industry in the 1950s did not trigger subsequent manufacturing for export markets. Despite the similarities, the evidence amassed in this chapter using the lenses provided by Malerba and Nelson in the introduction of this volume show significant differences in the channels that drove catch up in the four countries. The one major similarity across the four countries is the role government played in the initial regulatory environment as well as investment – either through direct ownership or subsidized credit - to fabricate wafers and support technological catch up.

The paths taken by firms in the two leading countries on the manufacturing of semiconductor chips - i.e. Korea and Taiwan - are very different. Whereas the Korean firms eventually became independent through zaibatsu-type integrated operations back-integrating from consumer and telecommunication electronics manufacturing into semiconductors and internalizing R&D activities Taiwanese firms have remained highly specialized in wafer fabrication or vertically integrated operations within semiconductors while continuing to depend strongly on R&D support from ERSO and foreign firms. Taiwanese firms also continue to enjoy strong collaboration in particularly participation in R&D activities among themselves as well as foreign research labs and designing companies. In addition, some Taiwanese firms such as TSMC and UMC have continued to specialize in contract wafer fabrication foundries without participation in assembly and testing. These firms have also continued to rely extensively on strategic alliances for both technological support and markets. Being highly vertically integrated Korean firms have gradually reduced their dependence on strategic alliances as they moved to the technology frontier.

The nature of state intervention in all four countries differed. Whereas Korean firms relied on licenses the firms internalized much of the R&D activities because of the failure of the GRIs Taiwanese firms have successfully access R&D labs directly from ERSO and the other ITRI labs for complementary technologies. The lack of human capital and performance standards has undermined the capacity of subsidized local wafer fabricators in Malaysia to upgrade. Chinese wafer firms demonstrate better capacity to upgrade because of large reserves of human capital and better coordination with performance standards.

Unlike in Korea and Taiwan where rising production costs have driven out assembly activities, in China and Malaysia foreign firms still largely specialize on such activities. The lion's share of semiconductor manufacturing in China and Malaysia is still specialized in assembly and test activities. With 497 local designing plants in 2006 China enjoys very strong capacity to expand designing and fabrication activities. Government participation – both federal and provincial – has been crucial in the establishment of design parks and in the forging of links between firms, R&D labs and universities. Some firms have taken the Taiwanese path by specializing in foundries while others have attempted to integrate computer, telecommunication and industrial electronics with semiconductor chip manufacturing. Local firms in Malaysia are either confined to assembly and test or in the fabrication of second and third generation semiconductor chips. Silterra is the most promising of these firms and is seeking to follow the TSMC path. This firm has forged alliances with foreign purchasers and technology suppliers and is seeking to expand scale operations and purchase design firms to complement its activities. Lacking in technology support from the short pool of engineers and poor facilities in R&D labs and local universities this firm is expanding its hiring of foreign human capital and forging ties with foreign R&D labs and universities to pursue its catch up path.

REFERENCES

Amsden, A. (1985) “The division of labor is limited by the rate of growth of the market: The Taiwanese machine tool industry”, *Cambridge Journal of Economics*, 9(4), pp. 271-284.

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

Ariffin N. & Figueiredo P.N. (2004) “Internationalisation of Innovative Capabilities: Counter-evidence from Electronics Industries in Malaysia and Brazil”, *Oxford Development Studies*, 32(4), pp 559-583.

Bhagwati J. (1979) “International Factor Movements and National Advantage”, *Indian Economic Review*, 14(2): 73-100.

Bell, M. & Pavitt, K. (1995) “The Development of Technological Capabilities”, in: I.U. Haque (ed), *Trade, Technology and International Competitiveness*, (Washington DC., World Bank)

Becattini G. (1990) The Marshallian Industrial District as a Socio-Economic Notion”, Pyke F., Becattini G. and Sengenberger W. (eds), *Industrial Districts and Inter-firm Cooperation in Italy*, Geneva: International Labour Organization.

Bell, M. & Pavitt, K. (1995) “The Development of Technological Capabilities”, in: I.U. Haque (ed), Trade, Technology and International Competitiveness, (Washington DC., World Bank).

Best, M. (2001) *The New Competitive Advantage*, (Oxford, Oxford University Press).

Brusco S. (1982) “The Emilian Model: Productive Decentralisation and Social Integration, *Cambridge Journal of Economics*, 6(2): 167-84.

Burchell, B.J. and Wilkinson, F. (1997). 'Trust, Business arrangements and contractual environment'. *Cambridge Journal of Economics* 21(2), pp 217-237

Cantwell J. and Mudambi (2001) “MNE competence-creating subsidiary mandates: an empirical investigation”, International Investment and Management Discussion Paper, No. 285, Reading University.

Cooke P. and Morgan K. (1998) The Associational Economy: Firms, Regions, and Innovation, (Oxford, Oxford University Press).

Darwent D. (1969), "Growth poles and growth centers in regional planning--a review," Environment and Planning, 1, pp. 5-32.

Dosi, G. (1982) "Technological Paradigms and Technological Trajectories", *Research Policy*, 11(3), pp. 147-162.

Dosi G. (1997) "Opportunities, Incentives and the Collective Patterns of Technical Change", *Economic Journal*, 107, pp 1530-1547.

Dunning J. (1974) Economic Analysis and the Multinational Enterprise, London: Allen & Unwin.

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

Edquist C. (2004) "Systems of Innovation: Perspectives and Challenges", Fagerberg J., Mowery D.C. and Nelson R.R. (eds), *The Oxford Handbook of Innovation*, Oxford: Oxford University Press.

Ernst, D., Ganiatsos, T. & Mytelka, L. (eds) (1998) Technological Capabilities and Export Success: Lessons from East Asia, (London, Routledge).

Ernst D. (2006) "Innovation offshoring: Asia's Emerging Role in Global Innovation Networks", East-West Center Special Report 10, East-West Center, Hawaii.

Figueiredo, P.N. (2002) "Learning processes features and technological capability accumulation: explaining inter-firm differences", *Technovation*, 22, pp. 685-698.

Figueiredo, P.N. (2003) "Learning, capability accumulation and firms differences: evidence from latecomer steel", *Industrial and Corporate Change*, 12(3), pp. 607-643.

Fransman, M. (1985) "International Competitiveness, Technical Change and the State: The Machine Tool Industries in Taiwan and Japan", *World Development*, 14(12), pp. 1375-1396.

Freeman, C. (1989) "New Technology and Catching-Up", European Journal of Development Research, 1(1), pp. 85-99.

Friedmann, J. (1972) "A General Theory of Polarized Development," in N.M. Hansen (ed.), Growth Centres in Regional Economic Development, Free Press, New York.

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

Gerschenkron A. (1962) *Economic Backwardness in Historical Perspective: A Book of Essays*. Cambridge: Belknap Press of Harvard University Press

Hamilton, A. 1791, "Report on Manufactures", December 5, http://www.oberlin.edu/~gkornbl/Hist258/ReportMfres.html, downloaded on 13 December 2005.

Hirschman A. (1958) *The Strategy of Economic Development*, New Haven: Yale University Press.

Hirschman A. (1970) *Exit, Voice and Loyalty: Responses to Decline in Firms, Organizations, and State*, Cambridge: Harvard University Press.

Hirst P. and Zeitlin J. (1991) *Reversing Industrial Decline? Industrial Structure and Policy in Britain and Her Competitors*, Oxford: Berg Publishers.

Hobday, M. (1995) *Innovation in East Asia*, (Cheltenham, Edward Elgar).

Humphrey J. and Schmidt H. (1996) "The triple C approach to local industrial policy", *World Development*, 24(12), pp. 1859–1877

Johnson C. (1982*) MITI and the Japanese Miracle*, Stanford: Stanford University Press.

Katz, J. & Berkovich, N. (1993) "National Systems of Innovation Supporting Technical Advance in Industry: The Case of Argentina", in: R.R. Nelson (ed*)*, **National** *Innovation Systems: A Comparative Analysis*, (New York, Oxford University Press).

Kaldor, N. (1957) "A Model of Economic Growth", *Economic Journal*, 67, pp. 591-624.

Kim, L. (1997) *From Imitation to Innovation*; Cambridge, Harvard Business School Press

Lall, S. (1979) "The International Allocation of Research Activity by US Multinationals," *Oxford Bulletin of Economics and Statistics*, 41(4), pp 313-331.

Lall, S. (1992) "Technological Capabilities and Industrialisation", *World Development*, 20(2), pp. 165-86.

List, F. (1885) *The National System of Political Economy*, London, Longmans, Green & Company

Lundvall, B.A. (1988) "Innovation as an Interactive Process: From User-producer interaction to the National System of Innovation", in: G. Dosi, C. Freeman, G. Silverberg & L. Soete (eds), *Technical Change and Economic Geography*, London, Frances Pinter

Lundvall, B.A. (1992) *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*; London, Frances Pinter

Malerba F. (1992) “Learning by Firms and Incremental Technical Change”, Economic Journal, 102(413): pp 845-859.

Malerba F., Nelson R.R., Orsenigo L. and Winter S. (2001) Competition and industrial policies in a 'history friendly' model of the evolution of the computer industry, International Journal of Industrial Organization, 19(5): 635-664.

Marshall A. (1890) *Principles of Economics*, London: Macmillan.

Marshall A. (1920) *Industry and Trade*, London: Macmillan.

Marsh H. (1981) *Silicon Chip Book*, London: Pelican Press.

Marx, K. (1853) “The British Rule in India”, New York Daily Tribune, June 10.

Marx, K. (1956) *Capital: The Process of Circulation of Capital*, Volume II, Moscow: Progress Publishers.

Mathews, J.A. & Cho, D.S. (2000*) Tiger Technology: The Creation of a Semiconductor Industry in East Asia*, (Cambridge, Cambridge University Press).

Mills J.S. (1848*) Principles of Political Economy, with some of their Applications to Social Policy*, (London: John W. Parker & West Strand).

Myrdal, G. (1957).. *Economic Theory and Under-Developed Regions*. New York: Methuen.

Mytelka, L.K. (ed) (1999*) Competition, Innovation and Competitiveness in Developing Countries*, (Paris, OECD).

Nelson, R.R. and Winter, S.G. (1982) *An Evolutionary Theory of Economic Change;* Cambridge, Harvard University Press

Nelson, R. (ed) (1993) *National Innovation Systems*; New York, Oxford University Press

Nelson, R. (2007) “Economic Development from the Perspective of Evolutionary Theory”, paper presented at the Sanjaya Lall Memorial Conference, UNCTAD, 8-9 March, Geneva.

Pavitt, K. (1984) “Sectoral Patterns of Technical Change: Towards a Taxonomy and a Theory”, *Research Policy*, 13(6), pp. 343-73.

Penrose E. (1959) *The Theory of the Growth of the Firm*, New York: John Wiley.

Piore, M. & Sabel, C. (1984) *The Second Industrial Divide: Possibilities for Prosperity*; New York, Basic Books

Porter, M E. (2001) ”Regions and the new economics of competition”, A. J. Scott (ed), *Global City-Regions: Trends, Theory, Policy*, (Oxford: Oxford University Press).

Rasiah R. (1988) The Semiconductor Industry in Penang: Implications for the New International Division of Labour Theories, *Journal of Contemporary Asia*, 18(3): 44-69.

Rasiah, R. (1992) *Foreign Capital and Industrialization in Malaysia*; Doctoral thesis approved by Cambridge University, Published in 1995 (Basingstoke: Macmillan).

Rasiah, R. (1994) “Flexible Production Systems and Local Machine Tool Subcontracting: Electronics Transnationals in Malaysia”, *Cambridge Journal of Economics*, 18(3), pp. 279-298.

Rasiah, R. (2002) Systemic Coordination and the Knowledge Economy: Human Capital Development in MNC-driven Electronics Clusters in Malaysia, *Transnational Corporations*, 11(3), pp. 89-130.

Rasiah, R. (2004) “Technological Capabilities in East and Southeast Asian Electronics Firms: Does Network Strength Matter?”, *Oxford Development Studies*, 32(3), pp. 433-454.

Rasiah, R. (2005) “Foreign ownership, technological intensity and export incidence: a study of auto parts, electronics and garment firms in Indonesia”, *International Journal of High Technology and Globalization*, 1(3/4), pp 361-380.

Rasiah, R. (2006) “Technological intensities and Economic Performance: A Study of Foreign and Local Manufacturing Firms in South Africa”, *International Journal of Technology Management*, 36(1-3), pp 166-189.

Rasiah, R. & Lin Y. (2005) “Learning and Innovation: The role of market, government and trust in the information hardware industry in Taiwan”, *International Journal of Technology and Globalization*, 1(3/4): 400-432.

Reinert E.S. (1994) “'Catching-up from way behind: A Third World Perspective on First World History”, Fagerberg, J., Verspagen B. and Tunzelmann N.V. (Eds), *The Dynamics of Technology, Trade and Growth;* Aldershot: Hassocks.

Richardson G.B. (1960) *Information and Investment*, Oxford: Oxford University Press.

Richardson G.B. (1972) “The Organisation of Industry”, *Economic Journal*, 82: 883-96.

Rosenstein-Rodan P.N. (1984) "Natura Facit Saltum: Analysis of the Disequilibrium Growth Process", Meier G.M and Seers D. (eds), *Pioneers in Development*, New York: Oxford University Press.

Sabel C. and Zeitlin J. (1997) *World of Possibilities: Flexibilities and Mass Production in Western Industrialization,* New York: Cambridge University Press.

Saxenian A.L. (1994) *The Regional Advantage: Culture and Competition in Silicon Valley and Route 128*, Cambridge: Harvard University Press.

Saxenian A.L. (1999) *Silicon Valley's New Immigrant Entrepreneurs*, San Francisco: Public Policy Institute of California.

Scherer, F.M. (1980) *Industrial Market Structure and Economic Performance*, (Chicago, Rand McNally).

Scherer, F. (1992) *International High Technology Competition*, (Cambridge, Harvard University Press).

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

Scott A.J. (1988) *New Industrial Spaces: Flexible Production Organization and Regional Development in North America and Western Europe*; London, Pion

Sengenberger W. and Pyke F. (1991) "Small Firms, Industrial Districts and Local Economic Regeneration", *Labor and Society*, 16(1).

Shilov A. (27/7/2007) "TSMC confirms entering microprocessor manufacturing business", http://www.xbitlabs.com/news/cpu/display/20070727063402.html

Smith, A. (1776) *The Wealth of the Nations*; London, Strahan and Cadell

Storper M. (1995) "The resurgence of regional economies, ten years later: The region as a nexus of untraded interdependencies," *European Urban and Regional Studies*, 2(3), pp. 191-221.

Swann G.M.P. and Preverzer M. (1998) "A comparison of the dynamics of industrial clustering in computing and biotechnology", *Research Policy*, 25: pp 139-157.

Taiwan (2004) Investment Statistics, unpublished, (Taipei, Central Bank of Taiwan).

UNU-MERIT, World Bank & DFID (2004) "*Survey data on Malaysian industrial firms*", compiled by the Institute for New Technologies (MERIT), DCT and Pemm Consultants..

Vernon, R. (1966) “International Investment and International Trade in the Product Cycle”, *Quarterly Journal of Economics*, 80: pp 190-207

Vernon, R. (1971) *Sovereignty at Bay: The Multinational Spread of U.S. Enterprises*, (New York, Basic Books).

World Bank (2003) World Development Indicators, (Washington DC: World Bank).

Young, A. (1928) “Increasing Returns and Economic Progress”, *Economic Journal*, 38(152), pp. 527-542.