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Advancing Taiwan's semiconductor industry: Capitalizing on its comparative advantage at the global, regional, and firm levels

El avance de la industria de semiconductores de Taiwán: Aprovechamiento de su ventaja comparativa a escala mundial, regional y empresarial

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ABSTRACT

Taiwan's remarkable growth in the 21st century is largely attributed to its production of critical semiconductors, which are indispensable for the Fourth Industrial Revolution, technological progress, and military advancements. This unique position has established Taiwan as a key player in the global semiconductor industry. This paper contends that Taiwan's semiconductor triumph is not merely a result of its strategic alliances, particularly with Silicon Valley, but also its distinctive comparative advantages in industrial, institutional, and firm-level aspects, forming a part of its catch-up strategy. The study explores Taiwan's trajectory in semiconductor development, analyzing its competitive edge through the lenses of catch-up theories, global production networks and value chains, industrial clusters, and geopolitical factors. It concludes that Taiwan's competitive edge is shaped by state-driven institutional and industrial advantages and firms' fast-follower strategies. These advantages are embedded within the global high-tech division of labor and supported by the regional network of the Hsinchu Science and Industrial Park, which facilitates pooled human resources, technological transfer, collaborative vertical division of labor, and complementary industries. Recent geopolitical tensions have reinforced the semiconductor alliance, pushing TSMC to expand globally. While this expansion enhances collaboration, it also increases competition and challenges. Nonetheless, Taiwan's semiconductor dominance, based on these advantages, remains difficult to replicate elsewhere.

Keywords: *Semiconductor Industry, TSMC, Hsinchu Science and Industrial Park, Industrial Cluster, Clip Alliance.*

RESUMEN

El notable crecimiento de Taiwán en el siglo XXI se atribuye en gran medida a su producción de semiconductores críticos, indispensables para la Cuarta Revolución Industrial, el progreso tecnológico y los avances militares. Esta posición única ha convertido a Taiwán en un actor clave de la industria mundial de semiconductores. Este documento sostiene que el triunfo de Taiwán en el sector de los semiconductores no es sólo el resultado de sus alianzas estratégicas, en particular con Silicon Valley, sino también de sus ventajas comparativas distintivas en aspectos industriales, institucionales y empresariales, que forman parte de su estrategia de recuperación. El estudio explora la trayectoria de Taiwán en el desarrollo de semiconductores, analizando su ventaja competitiva a través de las lentes de las teorías de convergencia, las redes mundiales de producción y las cadenas de valor, las agrupaciones industriales y los factores geopolíticos. Se concluye que la ventaja competitiva de Taiwán se debe a las ventajas institucionales e industriales impulsadas por el Estado y a las estrategias de seguimiento rápido de las empresas. Estas ventajas están integradas en la división del trabajo de alta tecnología mundial y respaldadas por la red regional del Parque Científico e Industrial de Hsinchu, que facilita la puesta en común de recursos humanos, la transferencia tecnológica, la división vertical del trabajo en colaboración y las industrias complementarias. Las recientes tensiones geopolíticas han reforzado la alianza de los semiconductores, empujando a TSMC a expandirse por todo el mundo. Aunque esta expansión mejora la colaboración, también aumenta la competencia y los retos. No obstante, el dominio de Taiwán en el sector de los semiconductores, basado en estas ventajas, sigue siendo difícil de reproducir en otros lugares.

Palabras claves: *Industria de semiconductores, TSMC, Parque Científico e Industrial de Hsinchu, Cluster Industrial, Clip Alliance.*

1. INTRODUCTION

Taiwan has undergone two significant growths in its economic history. The first takeoff can be traced back to East Asian Miracles during the 1960s-1980s. The

second rise is associated with semiconductors, which have been vital in driving the Fourth Industrial Revolution since the second decade of the 21st century. However, they employ diverse development models.
In the 1980s, the four tigers' rise challenged dependency theories and the Kuznet curve by spurring rapid economic growth while reducing inequality. Their unique models, termed by Johnson (1982) as a 'Capitalist Developmental State,' gained worldwide recognition for Meritocracy's sound industrial policies (Johnson, 1982; Evans, 1995). However, Taiwan's economic model also heavily relies on downstream exports to drive a rapid growth engine for facilitating reverse integration, augmented by governments' preferential subsidies and pricing policies close to market benchmarks. Therefore, Johnson (1982) referred to it as "market conforming," while Wade referred to it as a "governing the market" strategy.

Taiwan's economic performance is built on two pillars: the robust exports of SMEs' electrical equipment and components and the global ICT industry. The latter, known worldwide as Hsinchu Science and Industrial Park, is home to many ICT manufacturers, which constitute the backbone of Taiwan's semiconductor industry. Mainly, Taiwan Semiconductor Manufacturing Company (TSMC) produces 51.5% of global foundry wafers in the second quarter of 2020[1] (You, 2021) and more than 90% of critical chips (Tung, 2024), a testament to Taiwan's notable efficiency and managerial ability in the semiconductor industry.

As the world hurtles towards the IC-driven fourth industrial revolution, Taiwan's role in IC production has become increasingly vital. This is especially true in the fierce tech competition driven by 5G and AI innovation. Ferguson (2021) proclaimed, "Whoever controls Taiwan controls the world." This statement highlights the intense competition and Taiwan's strategic position in the global semiconductor market.

The existing literature (Johnson, 1982; Evans, 1995; Amsden, 1985; Amsden & Chu, 2003; Chang, 1999; Deyo, 1987; Wang, 2010; Gereffi, 1989, 1994, 2001) has extensively explored Taiwan's economic miracles and development model, focusing on the government's pivotal role in catching up with the development before the 1980s, and the establishment of the Hsinchu Science and Industrial Park to facilitate the industrial transition from manufacturing to the high-technology industry in the 1980-2000s. However, Taiwan's IC model diverges significantly from the traditional developmental state.

1 The original data came from Clark, 2020.

Taiwan's dominance in global critical chip production heavily relies on OEM and know-how from upstream. This raises one question: Why and how does Taiwan outperform in the semiconductor sector, compared to neighboring countries such as South Korea and Japan? Is this because of the enduring Developmental State model or Neoliberal market-led growth?

This paper delves into Taiwan's semiconductor development model, examining the development trajectory from the mid-1970s onward. It aims to unravel a fundamental question: How did Taiwan forge a new semiconductor industry in the 1980s and progress to its current structural position? How did Taiwan carve out its comparative advantage in the semiconductor industry? What internal and external factors facilitated its formation?

2. THEORETICAL PERSPECTIVES ON TAIWAN'S ECONOMIC MODEL AND IC INDUSTRY DEVELOPMENT

Taiwan's economic miracle is well-documented; however, which theory better captures the essence of Taiwan's experience remains controversial. Three competing theories offer explanations: the Developmental State Theory attributes Taiwan's success to State Intervention (Johnson, 1982; Amsden, 1985; Amsden & Chu, 2003). This approach emphasized meritocracy and sound industrial policies. However, the SME model, which drove exports and capital accumulation before the 1980s, contrasts this view. The second theory, the Liberal Economy theory, posits that Taiwan's miracle relied on the liberal market and robust export competition. This approach highlights the role of the downstream liberal SMEs in driving exports to the East Asian and U.S. markets, creating a rapid growth engine and accumulation mechanism. The robust growth enabled the State to promote industrial upgrades by reverse integration, ultimately driving the economic transition. Despite the Government giving subsidies, their pricing policies were referenced by market price, considering export competitiveness. Therefore, Johnson (1982) referred to it as the "market conforming"; Amsden (1985) called it the "market augmentation" principle, while Wade (1990) denominated Taiwan's model as the State effectively "governs the market" (Wang, 2010:16-17). This critical point diverged the economic performance between East Asia and Latin America during ISI. The third theory, the Dependency Development and World System Theory, argues that Taiwan's insertion into the international division of labor creates external dependence (Crane, 1982). Despite Taiwan's economic take-off, it relies heavily on external markets and upstream technology.

The paper suggests these theories partially explain Taiwan's model but overemphasize one singular dimension. Instead, Taiwan's model should go beyond the dichotomy of State and Market, refocusing on an integral approach to understanding Taiwan's position and upgrading strategies in the international division of labor. The paper argues that from institutional and industrial perspectives, Taiwan's embedded global and regional production chains enable Taiwan to build up a comparative advantage. In addition, the corporate-level strategy is significant for the firm's upscale and upgrading in the value chain. This carves out the two agents: The state's role in comparative institutional advantage and the firm's relations and their catch-up strategies.

Regarding the catch-up development, there are two paradigms: the "innovation" paradigm and the "catch-up" hypothesis. They are also associated with organizational forms and firms' learning patterns to boost growth and competitiveness. Hence, they correspond to two perspectives, i.e., the Hamiltonian school and Jeffersonian schools (Wang, 2010:5-9).

The innovation paradigm describes the development strategies of advanced countries that emphasize their economies, which are propelled by the robust structures of large corporations committed to scientific and technological research and innovation while outsourcing manufacturing to low-cost developing countries for standardized mass production. Large corporations have more resources to improve their technological and organizational innovation capacities. Their internal hierarchical corporate structure replaces the market's mechanism to organize resources and strengthen vertical integration, aiming to reinforce efficiency through internalizing transactions (Wang, 2010; Chandler, 1984, 1992; Schmitz, 1995). This is especially true for producer-driven heavy industries. It enhances and improves efficiency and controls the commanding high of the supply chain through technical rent and patents to maintain growth.

Conversely, the "catch-up" hypothesis accentuates the imperative of "learning" from advanced countries' science and technology and undertaking structure transition by moving upward along the value chain. Gereffi (2001, 2016) identified East Asia's catch-up strategies, initiated by adopting flexible ISI and EOI strategies with buyer-driven Global Commodity Chains (GCCs) in light industries to catch up with development in the 1960s. They gradually increased the value chain by upgrading products, processes, and intra-chain strategies.
Amsden and Chu (2003) argued that countries that arrive late to a mature or semi-mature industry with decreasing marginal profits still possess a "Second-mover advantage" (Amsden & Chu, 2003:2-12). Latecomers can begin

with low-end manufacturing to integrate into the international division of labor and learn from developed countries' mature technologies. They must start cat-cup with upscaling, i.e., mass production and OEM, to accumulate capital while gradually enhancing their technologies and managerial capacities to boost their growth and productivity. Over time, they cultivate the capacity to create new products through partial and gradual reform (Amsden & Chu, 2003:193-211).

Sectoral differences imply diverse strategies for developing countries to catch up by "learning," mainly corporate organizations, and their learning patterns matter. The Jeffersonian school emphasizes the advantages of small and medium-sized enterprises (SMEs) in formulating decentralized, flexible, collaborative networks within geographical proximity, such as Third Italy (Blim, 1990:162). This explains Taiwan's manufacturing SMEs' collaborative networked-based production before the 1980s, particularly the industrial machinery clustering in central Taiwan. However, it is insufficient to describe Taiwan's ICT development, which comprises big and medium-sized corporations rather than SMEs. Furthermore, the state's involvement in the ICT sector is critical but not direct.

According to Evans (1995), the state assumes a central role in developing the ICT industry. The State does not play the role of "Demiurge" but rather "Midwifery or Husbandry" because direct production in a high-tech field cannot be sustained without capital, technology, and human resources. In addition, the State's role is not fixed in one shot but evolves with IT industrial development (Evans, 1995:74-98). Furthermore, informatics must incorporate local cultural and organizational patterns (Evans, 1995:96-98). Breznit (2007) classified the State's role in Taiwan's semiconductor development as a public-private co-evolution. Wang (2010) identified that the State must transform into a "Platform State" or National Innovation System to organize resources, gather data, cultivate human capital, and introduce capital and technology. It aims to create industrial clusters and networks for the exchange of knowledge, technologies, and talent to drive cooperation and virtuous competition (Wang, 2010:7-8).

The National Innovation System emphasized creating a knowledge exchange and innovation platform. It implies geographical concentration and spatial proximity to drive Alfred Marshall's "industrial clusters." Saxenian (2000a) identified how network-based systems boost Silicon Valley's innovation. It is essential to create several networking effects: 1. Dynamic exchanges between manufacturers through formal and informal associations. 2. Technological innovation emerges from the flow of talent, which spreads rapidly in the cluster. 3. Collective learning capacity within clusters and networks encourages competition and cooperation to boost innovation and achieve "collective efficiency" (Saxenian, 2000a: 308-331; Schmitz, 1995). This approach posits that networks create an "external economy" that complements firms' disadvantages. They stimulate collective learning and innovation through cooperation and competition, ultimately achieving collective efficiency. Silicon Valley and Taiwan's Hsinchu Science Park are examples. (Amsden & Chu, 2003:195).

Taiwan's economic transition in the 1980s was associated with the Hsinchu Science Park and firms' catch-up strategies. Amsden and Chu (2003) argued that, compared to advanced countries, "Latecomers" have a relative disadvantage in the knowledge base, technical and production structures, and paths to globalization. Their industrial strategies should focus on "speed" to shorten the product's life cycle and learning curves by upgrading the economy of scale and reinvesting in organizational efficiency and production technologies. These should be accompanied by trinity policies, i.e., Competitive, Research, and Employment (Amsden and Chu, 2003:193-2000).

Since the neoliberal and institutional turn in the 1980s, the State no longer assumes the role of the developmental state; even the WTO rules restrict them from maintaining protectionist policies. Therefore, supporting and fostering science and technology development to enhance competitiveness became imperative (Padilla & Jennifer, 2014:62-65). Developing countries without technical and capital advantages must rely on the State to strengthen R&D and associated complementary institutions, i.e., comparative institutional advantages (Padilla & Jennifer, 2014; North, 1990; Amable, 2000).
Based on the above, the paper explores Taiwan's trajectory in semiconductor development, analyzing its competitive edge through the lenses of catch-up theories, global and regional production networks, industrial clusters, and firm strategies to formulate an integral approach to understanding the subject.

3. THE MAKING OF THE SEMICONDUCTOR INDUSTRY

The comparative advantage of Taiwan's semiconductor industry cannot be separated from its embedded context, i.e., industrial and institutional settings, which dates back to Taiwan's economic miracle. In the early 1960s, when Taiwan sought to catch up with development, the government established an Export Processing Zone (EPZ) to attract FDI. American firm set up the first IC Test and Package factory in 1961. During the first primary Export-Oriented Industrialization (1960-1972), the strong downstream manufacturing exports, mainly private SMEs of light industries, generated a robust growth engine and capital accumulation mechanism. This facilitated economic take-off in the 1960s. Under the KMT military regime's separation of politics and economic principles, Taiwan's economic bureaucracy, the Council for Economic Planning and Development, and the Ministry of Economic Affairs, were aware of catching up with development. According to Gerschendron (1962) and Hirschman (1958), backward countries must emphasize the State-led strategy by creating "an unbalanced growth structure" to foster rapid industrialization. In 1974, Prime Minister Ching-Kuo Chiang (蔣經國) launched "Ten Major Construction Projects" to develop basic infrastructures, the so-called "Social overhead capital (SOC)," such as highways and ports. In the 1970s and 1980s, Taiwan's government used downstream growth forces to organize heavy industries through "reverse integration" to promote chemical, automobile, and industrial machinery industries. The policies, coupled with import-substitution industrialization (ISI) and market-conforming pricing strategies, led to the economic transition to heavy industry in the 1970s-1980s (Chu, 2002:37-63). Therefore, Taiwan's ISI did not create fiscal imbalance and debt.

During the 1960s-1980s, the international market favored Taiwan's industrial upgrading, particularly receiving FDI and technology transfer. This laid the foundation for the semiconductor industry to emerge in the late 1980s-1990s. Specifically, from 1964 to 1979, the Japan-led Flying-Geese Model[2] accelerated the technical transfers from Japan to Taiwan in various sectors such as textiles, consumer electronics, and machinery. Along with this favored environment, the State accelerated the industrial upgrading policies. In 1977, the Precision Machinery Research & Development Center was established. In 1979-1980, a "Ten-Year Economic Construction Plan" was introduced, listing industrial machinery, electronics, information, heavy chemical industry, and vehicles as "strategic industries[3]."

The 1973 and 1979 oil crisis pushed the government to develop a less energy-consuming ICT industry. In 1973, the Industrial Technology Research Institute (ICTR) was founded as a public industrial research entity to promote ICT research and development. In the mid-1980s, neoliberalism swept East Asia; the U.S. forced Japan, Taiwan, and South Korea to appreciate their currencies, increasing production costs and eventually relocating Taiwan's manufacturers to Southeast Asia. Hence, Economic Minister TAO CHIUNG SUN (孫道瓊) insisted on promoting the high-tech industry as a measure to compensate the

2 Kaname Akamatsu proposed this concept to describe the intra-industrial division of labor and technical transfer in East Asia.

3 "Ten-Year Economic Construction Plan," Taiwan Cultural Memory Bank, government's online archive.

economy by using "technology" to upgrade industries (Yang, 1997). Fortunately, the rise of Japan in the digital computer and semiconductor industry in the 1980s challenged the U.S. monopolies in these sectors (Dicken, 2003:13; Miller, 2023:260-261). The U.S. firms were forced to outsource OEM partly to developing countries while re-focusing on value-added innovation. In addition, Japan relocated OEM computer hardware production to Taiwan (Amsden & Chu, 2003:35-47; Wang, 2010:75-77). These moves accelerated the spread of ICT technology to Taiwan, creating an unprecedented opportunity for Taiwan's semiconductor industry to emerge.

State's Role and Industrial Policies in Semiconductor Start-up

Taiwan's comparative advantage in the semiconductor sector relies not on Intel and Samsung's integrated design and manufacture (IDM) but on OEM. This can be attributed to the State's choice to position Taiwan in the global division of labor. Breznitz (2007) indicated that IT development is a consequence of political choice. Compared to Ireland, which was selected to develop software, Taiwan focused on OEM rather than IC design or software. This decision resulted from thoughtful concerns about industrial autonomy and its relationships with foreign firms and investors (Breznitz, 2007:148).

In the 1970s, economic bureaucracy, ITRI, and the high-tech community intensely debated the semiconductor industry's development objective and how to self-position Taiwan in the global production chain. Finally, ITRI, a government-founded ICT research institute, suggested Taiwan focus on OEM because Taiwan could not sustain independent IC development nor compete with developed countries without capital, technologies, and know-how (Chen, 2005, 2008; Breznit, 2007; Yang, 1997; Wu & Shen, 1999).

Since its establishment, ITRI has become the lead agency in promoting ICT development. In 1979, the Act for Establishment and Administrative of Science Parks was launched, providing incentives for business start-ups. The following year, Hsinchu Science and Industrial Park was established. It was considered the pilot program for ICT industrial development. It represented the State's endeavor to create high-tech industrial clusters and the National Innovation System.

In 1982, Economic Minister Sun launched the "Thirty-two-bit Computer Project" and the landmark initiative "Very Large Integrated Circuit Technology Development Plan" (VLSI) to provide unconditional support to boost the industry's development. The precious, successfully strengthened computer giants

MiTac Inc. and ACER to compete internationally; the latter, the VLSI project, was a joint effort of the public-private partnership, leading to the establishment of the "Taiwan Semiconductor Manufacturing Company (TSMC) in 1982." TSMC and TIRI became significant players in Taiwan's semiconductors, especially under the ex-director Morris Chang (張忠謀). Moreover, the Government's policy extended to building infrastructure and institutions, providing resources from research and technology, taxation incentives, and nurturing talent (Lin, 2011:23-25; TSIA, 2024:3).

National Innovation System and ITRI's Role in R&D Development

The government's endeavor to create ICT industries is associated with policies such as establishing ITRI as the lead agent, establishing Hsinchu Science and Industrial Park as an innovative clustering platform, and promoting joint venture firms. Among these policies, recruiting Silicon Valley's engineering talents, primarily Taiwanese migrants, was critical. This decisive move enabled this dynamic clustering network to take form. Compared to Costa Rica, San José's Silicon Valley had a similar recruitment strategy, but it still failed to create networks to bridge transnational ties in innovation, finance, and supply chains (Ciravegna 2012:45-167).

The first critical figure of Taiwan's IC industry was Taiwanese Chintay Shih (史欽泰). He received his PhD at Princeton University and worked at Burroughs Corporation, designing computer memory chips after graduation. In 1976, he returned to Taiwan and was recruited by the ITRI. At that time, he cooperated with ITRI's contract partner, RCA corporate, to facilitate the technical transfer of three-inch wafers. Later, RCA and other firms, such as Phillips and General Instrument, set up factories in Taiwan. The RCA program spun off and became a public-private United Microelectronics Corp (UMC) in 1979-1980 (Miller, 2023:212-218; Lin, 2011:5-17).

Another influential figure is Morris Chang, the father of Taiwan's semiconductor industry. 1981, Chang was a Texas Instrument (TI) deputy general manager. He met Economic Minister Sun and was invited to the Hsinchu Science Park. In 1985, Chang was recruited as ITRI chair and president of UMC while organizing the joint venture of TSMC with Philips of the Netherlands and ITRI. During his mandate, Chang led the R&D in ITRI while pushing TSMC to be aligned with international certification.

When he accepted the interview, Chang recalled, "TSMC's pure-play foundry model was my idea because Taiwan did not possess another advantage, but to manufacture chip according to customer's design and demand (Yang, 1997)." He also led TSMC operations and recommended that Ex-Economic Minister Guoding Lee (李國鼎) invest 48% in TSMC and establish high-tech corporations through public-private partnerships (Chang, 2023). During his mandate as director of ITRI, he promoted industrial R&D, and several corresponding research centers within ITRI were created, such as the Electronic Center and the Artificial Intellectual and Industrial Technology Center. ITRI recruited 5,000 researchers dedicated to industrial R&D, emphasizing their direct application to industrial productions. For example, ITRI invested in automation systems, reticle semiconductors, and carbon textiles, releasing all research technologies and patents to firms (Yang, 1997, 2004). ITRI's independent role, without political influence, made innovation and investments public goods.

The innovation system also involved the academy. ITRI initially associated with two prominent regional STEM universities in Hsinchu, National Chiao Tung University and Tsing Hua University, to conduct R&D. Their research outcomes were open access to all enterprises, fostering a unique division of labor in guiding ICT development, the State (ITRI) cooperate with universities focused on R&D, and the private firms took charge of production. Until the mid-1990s, private firms gradually dominated the semiconductor industry, and ITRI sought to cooperate with private firms to conduct research projects, for example, with ASUS (Yang, 1997). The model that the State takes the lead in R&D continues until today.

Industrial Clustering, Talents, and Collective Efficiency

TSMC, led by Morris Chang, is the leading firm in Taiwan's semiconductor industry. In 1987, Intel considered outsourcing the OEM to developing countries, and TSMC emerged as a potential candidate. Intel visited TSMC, examined 200 production procedures, and provided valuable advice. This led to TSMC securing Intel's OEM contract and becoming an integral part of its production chain, mapping Taiwan into the global division of labor. Under Chang's leadership, TSMC's focus on "efficiency, discipline, and technology" was unwavering. The collaboration with Japan's Filipes to produce a Six-inch wafer foundry further solidified TSMC's position. TSMC's international contracts created the Manifest Effect, a significant boost to the industry's flourishing (Yang 1997, 2004).

In the late 1980s, Silicon Valley's Taiwanese engineers K.Y. Han and Jimmy Lee were recruited by ITRI to help expand the high-tech Hsinchu Science and Industrial Park. With the strong support of ITRI, Han and Lee leveraged their formal and informal ties in Silicon Valley to assist Taiwan in recruiting joint ventures, international engineering talents, and FDI in the computer and state-of-the-art semiconductor sector (Lin, 1998; Saxenian, 2000b:19-21; Frost & Liu, 2023). In 1989, a beacon of international collaboration was lit by establishing the Monte Jade Science and Technology Association. With its mission to strengthen IC cooperation, investment, and technology transfer, this association has catalyzed global networking. It has fostered a strong bond between Taiwan and U.S.-based engineers, venture capitalists, and entrepreneurs. As a result, Taiwan has emerged as the world's leading producer of notebook computers, and the semiconductor sector has grown because of significant capital for start-ups from immigrant entrepreneurs (Saxenian, 2000b:19-21). Therefore, Taiwan's case was a best practice of "brain drain" to "brain circulation (Saxenian, 2000b, 2-6)."

From 1987 to 1994, the ICT sector witnessed a significant increase in private capital and R&D investment. Numerous small-scale IC design companies were established during this period, a development attributed mainly to the TSMC and UMC's demonstration effect. Even after the conclusion of the VLSI project, the Institute of Electronics continued to promote micro-electronics and sub-micron projects. From 1995 onward, international private capital and R&D investment continued to increase, gradually reducing the State's role in the sector and allowing the private sector to lead Taiwan's semiconductor development. At the same time, mutual investment among semiconductor firms proliferated (Chu, 2002; Wang, 2010). The semiconductor foundry invested in IC design and testing, forming a cross-shareholding financial structure and fostering cooperation and development.

Until 2023, there are 238 Fabless IC designers in Hinchui Science Park, 3 Mask firms, 15 Fabrication companies with TSMC taking the leadership, and 37 IC Packaging and Testing companies (TSIA, 2024:4-5). Table 1 shows the top IC firms. Within the Hsinchui Science Park, there are close exchanges between IC manufacturers, IC design and Testing companies, and talents through formal and informal cooperative relationships. It creates a networked-based economy with a vertical and horizontal division of labor that pools talented human resources to interact and attracts professional suppliers and joint ventures to settle in.

Table 1
Taiwan's Semiconductor Industry (2019)

2019 Ranking	Fabless Companies	Fabrication Companies	Packaging and Testing Companies
1	Mediatek	TSMC	ASE
2	Novatek	UMC	SPIL
3	Realtek	Nanya	PTI
4	PHISON	Winbond	KYEC
5	Himax	Powerchip	Chipbond
6	Silicon Motion	MXIC	Chipmos
7	Raydium	Vanguard	OSE
8	Sitronix	Win Semiconductors	Sigure
9	ESMT	Lite-On	FATC
10	Global Unichip	Nuvoton	OSE

Source: TSIA, 2024. "Overview on Taiwan Semiconductor Industry, 2020 Edition," pp. 6-11.

In addition, one engineer can work at Quanta Computer and then shift to semiconductor. Job-hopping among these high-tech talents also facilitates cross-sectoral interactions, stimulating innovation and spreading knowledge within the networks and Science Park. Through local networks of business clusters, connections and interactions between firms and their talents induce the circulation of ideas and expertise within the geographical space. It boosts collective learning and efficiency.

Innovative networking requires recruiting STEM talents. Traditionally, these are graduate students from Taiwan's Big Five universities[4]. Since cultivating talents is imperative, in 1972, the Ministry of Education formulated the "Program to Strengthen the Training and Recruitment of High-level Scientific and Technological Talents" promulgated by the Executive Yuan. Industry-university cooperation and working experience further strengthened their professionalism.

Firms in Science Park compete while cooperating. The demand to deepen their profession and differentiate product specialization speeds up productivity, innovation, and entrepreneurial initiatives, further strengthening industrial synergies. These dynamic networks attract more FDI and enhance their con-

4 Such as Taiwan University, National Chiao Tung University, National Tsing Hua University, National Cheng Kung University and National Taiwan University of Science and Technology.

fidence in Taiwan's capacity, which is attributed to Taiwan's high-tech networking in infrastructure, firms, and talents (Wu & Shen, 1999).

4. ADVANCING TAIWAN'S SEMICONDUCTOR INDUSTRY: COLLECTIVE VERTICAL DIVISION OF LABOR, GRAN ALLIANCES, AND FIRMS' FAST-FOLLOWER STRATEGIES

Taiwan's comparative advantage in the semiconductor sector relies not on IDM but on OEM and IC design. Taiwan's nitch is built on a collective specialized network of vertical and horizontal division of labor among firms within clusters and their cat-up strategies. These have much to do with firms' collaboration patterns and organizational learning strategies.

Amsden and Chu (2003) and Gereffi (2001) recognized organizational learning as a vital mechanism for developing countries to upgrade their position within the industrial chain. Wang (2010) denominated the Taiwanese firms' catch-up strategy as the "Fast-Followers" strategy. It emphasizes the firm's capacity to rapidly follow the latest innovation and absorb new knowledge and technologies in line with the upper stream's move.

Semiconductor production is capital, technology, and human-capital intensive. Producing a chip relies on automated production involving more than 200 processes. Therefore, the managerial capacity is vital. TSMC astonishes the world with its extraordinary managerial and process reform capacity.

The rapid changes in the consumption side of ICT products have accelerated the life cycle and created constant stress. The recent 5G and military race further boosted the demand for high-tech chips. According to Gordon Moore, one of Intel's founders, the number of transistors to be accommodated on each chip will increase according to the law of geometric progression. The number doubles every two years (it is still accelerating), so-called Moor's Law (Miller, 2023:233-234; Ota, 2022:289-290). This creates challenging tasks for OEM. Therefore, OEM Foundry faces a constant challenge: continuously overcoming the enlargement of wafer diameter (accommodating more transistors) and shrinking the production process while speeding up the microprocessor's efficiency (through Nanotechnology). In addition, when the demand for technological content increases, the product life cycle decreases, and the greater the time pressure TSMC faces to generate high-quality chips with continuing costs down. This makes TSMC the master in process reform and systematic managerial controls.

Since Foundry OEMs must correspond to the demand of upper-stream with customized contracts to produce specific-purpose chips or integrate several multi-functional chips on wafers and substrates, the production team must keep up with the pace of the newest technology development. Therefore, "collective learning" among engineers enables them to promptly catch up with the latest innovations. Their expertise and professions have been cultivated and accumulated for years through constant cooperation with upstream firms such as Intel, Apple, and downstream applications.

As TSMC asserts, "TSMC maintains a leadership position in mature technologies by applying the lessons learned in developing advanced technologies and gradually developed its process technology." This leadership is paramount, as it allows TSMC to establish frontend and backend integration capabilities, creating the optimum power/performance to help customers achieve faster production time (TSMC, 2023:19). TSMC also seizes opportunities to move upward to ODM. Driven by gradual procedural and OEM technological innovation, Taiwan's firms are adept at incorporating and integrating several chips with different functions on wafers and substrates to meet the demand while upgrading efficiency. This enables the generation of new patents (Miller, 2023:273-274). For instance, TSMC is launching N3P technology to combine logic chips, memory chips, and MEMS into 2.5 G and 3 G wafers and substrates. This innovation allows the CPU and GPU to be incorporated into tiny chips for small phones, AI, or fighters. TSMC also created the Chips on Wafer on Substrates (CoWas) packaging and testing technology, which allows it to apply directly to the downstream cross-holding firms (TSMC, 2023:19-21).

The paper suggested this strength can be attributed to three factors: Firstly, Cross-sectors' customized chip productions enable the accumulation of knowledge and cultivate integral ODM capacity. Such strengths are accumulated through constantly customized contracts for upstream foreign firms' demand, such as Apple, Nvidia, AMD, and QCOM, that are driven from several high-tech sectors, ranging from air space, the arms industry, small phones, automation vehicles, Internet of Things, to low-earth Orbit, etc. Secondly, the collaboration of Taiwan's robust downstream manufacturing and distribution sectors, including the computer, automation electronics, and machinery sectors. They have factories throughout China and Southeast Asia, and their intra-industrial divisions of labor in supply chains create diverse and robust feedback loops to modify the original design. Based on this, TSMC generates its unique Open Innovation Platform (OIP) (TSMC, 2023:19-21).

Thirdly, skilled and talented engineers can integrate cross-sectoral and multi-functional chips into new integral ICs and make new designs by upgrading nanotechnology and enhancing IC efficiency. Talents' job-looping culture and formal and informal networking strengthen the collective learning and efficiency within the Hsinchu Science Park. The pooled talents contribute to systematic and procedural reforms, second-generation product design, and chips' applications with close collaboration with regional IC designers, such as MediaTek, Novatek Microelectronics, Realtek Semiconductor, etc.

TSMC's success in the OEM Foundry is not just a result of its technological prowess, but also its strategic partnerships. As Morris argued, TSMC has overturned its passive structural dependence on the supply chain to make the world dependent on TSMC's production. This is not only because TSMC is taking the lead in the foundry technology, but also because TSMC is a "neutral participator" that cooperates with all firms and does not compete with them, compared to Samsung (Miller, 2023:273-275). "TSMC learns to dance with more than 400 partners," its customers and partners including Intel, Nvidia, Apple, Altera, etc. (Miller, 2023263-268; Frost & Liu, 2023). This "Grand Alliance" is a testament to the strength of TSMC's alliances, cultivating and facilitating its procedural and product innovation (Frost & Liu, 2023). Since chip production involves more than 200 processes, every step of innovation contributes to the ultimate efficiency and quality. In addition, TSMC's downstream firms cooperate with TSMC in ODM, formulating complementary solid partnerships in the production and application of chips. For example, Taiwan's prominent petrochemical, Chang Chun Petrochemical Co. (CCPG), invested in the"Copper Clad Laminate" technology. At the same time, Taiwan's China Steel Corporation cooperates with Taisil Electronic Materials Corp. through a joint venture to produce silicon wafers, making silicon self-sufficient-rate from zero up to 20%.

The confluent of the national innovation platform with a networked-based economy, downstream industrial complementariness, and their collaborative reverse feedback loop enables TSMC to possess outstanding comparative advantages in OEM and ODM. Wang (2010) denominated the Taiwanese firm-level strategy the "Fast-Follower Strategy" in technology, knowledge, and know-how through collective learning and collaborative vertical division of labor within the clusters. The paper argues that these strengths are embedded in global and regional production networks, reinforced by the firm's cat-cup strategies.

5. TAIWAN'S SEMICONDUCTOR INDUSTRY PERFORMANCE

Although Taiwan lacks an integrated IMD model like Intel and Samsung, its semiconductor industry has outperformed other developing countries for 30 years of catch-up development.

Taiwan's semiconductor industry performs strongly in IC Foundry, IC design, and IC packaging and testing (Table 2). According to the Taiwan Semiconductor Industry Association (2020), Taiwan represented approximately 74.6% of world IC foundry revenue, 56.5% of global package and testing revenue, and 18% of IC design revenue. (TSIA, 2024:3). In addition, research from Foreign Policy revealed that in 2017, TSMC shares 51.5% of the global chip production and 92% of the high-tech chip production market. Both Foundries TSMC and Media Tek are advancing from OEM toward the ODM. Moreover, Taiwan's IC Design and IC Assembly, Testing, and Packaging (ATP) are prominent. Six of the top ten global IC designers are from Taiwan. Despite the total revenue being less than 1/4 of the U.S., it remains in the global top 2. Additionally, Taiwan displays its extraordinary logistics and services capacities in Electronic Manufacturing Services (EMS), i.e., semiconductor distribution, encompassing testing, manufacturing, distributing, and repairing electronic components for OEM manufacturers. Taiwanese firms dominate 75% of the global EMS market, while the U.S. reaches 35.3%. Foxconn is the leading EMS provider, responsible for over half of the worldwide distribution revenue. Chips that can be sold directly to other companies downstream (You, 2021).

According to TSMC, the firm produced 6-inch wafers in its establishment. Currently, TSMC has four 12-inch wafer GIGAFAB fabs, four 8-inch wafer fabs, one 6-inch wafer fab in Taiwan, and two 8-inch wafer fabs at wholly owned subsidiaries, TSMC Washington in the United States and TSMC China Company Limited. In addition, the achievement in nanotechnology (NM) continues to progress. TSMC was the first semiconductor producer of 20nm technology. 2013 TSMC reached 16nm technology mass production; in 2018 with 7nm technology. Moving to 2020, TSMC led the foundry to produce 5nm chips; in 2022, it moved to 3 nm technology production (TSMC, 2024)[5]. With TSMC's 2nm Technology on the track, its yield rate is reported to be around 70% to 80%, compared to Intel's 50% and Samsung's only 20% (Techvedas, 2024). The 2nm technology is ahead of Intel for three years. TSMC remains in the leading position of OEM technology. Furthermore, Taiwan's semiconductor-related patents are substantial because of the innovative material input and procedural technology patents, which upgrade Taiwan to ODM.

5 TSMC, logic technology. Retrieved From https://www.tsmc.com/english/dedicatedFoundry/technology/logic (2024/8/14)

As the Boston Consulting Group (BCG) & Semiconductor Industry Association (SIA) (2021) of the United States identified, “if Taiwan could not produce chips for an entire year, the revenue of the global electronics industry would fall by nearly US$ 500 billion (Tung, 2024:83)”, which underscoring Taiwan’s critical position in the global supply chain.

Table 1

Revenue of Taiwan’s Semiconductor Industry (Unit: Billion NT)

Year	2010	2011	2012	2013	2014	2015	2016
Industrial Revenue (Billion NT)	1,769.3	1,562.7	1,634.2	1,888.6	2,203.3	2,264.0	2,449.3
IC Design	454.8	385.6	411.5	481.1	576.3	592.7	653.1
IC Manufacturing	899.7	786.7	829.2	996.5	1,173.1	1,230.0	1332.4
Foundry	583.0	572.9	648.3	759.2	914.0	1,009.3	1,148.7
Memory and other Manufacturing	316.7	213.8	180.9	237.3	259.1	220.7	183.7
IC Packaging	287.0	296.6	272.0	284.4	316.0	309.9	328.3
IC Testing	127.8	120.8	121.5	126.6	137.9	131.4	140.0
WW Revenue (US$ Billion/Growth%	- 31.8%	- 0.4%	- -2.7%	- 4.8%	- 9.9%	- -0.2%	338.9 1.1%

Year	2017	2018	2019	2020	2021	2022	2023
Industrial Revenue (Billiion NT)	2,662.3	2,619.9	2,665.6	3,222.2	4,082.0	4,837.0	4,342.8
IC Design	617.1	641.3	692.8	852.9	1,214.7	1,32.0	1,96.5
IC Manufacturing	1,368.2	1,485.6	1,472.1	1,820.3	2,280.9	2,920.3	2,662.5
Foundry	1,206.1	1,285.1	1,312.5	1,629.7	1,941.0	2,684.7	2,492.5
Memory and other Manufacturing	162.1	200.5	159.6	190.6	287.9	2356	270.1
IC Packaging	333.0	344.5	346.3	377.5	453.4	466.0	393.1
IC Testing	144.0	148.5	154.4	171.5	203.0	218.7	190.6
WW Revenue (US$ Billion/Growth%	412.2 21.6%	468.3 13.7%	412.3 -12.0%	440.4 6.8%	555.9 26.2%	574.1 3.3%	526.9 -8.2%

Source: Taiwan Semiconductor Industry Association, 2016, 2020, 2024. Overview on Taiwan Semiconductor Industry 2024 Edition (TSIA, 2024), pp. 4-5. Unit: Billion NT.

6. GEOPOLITICS CONFLICT, CLIP ALLIANCE, AND TSMC'S GLOBAL EXPANSION

Since 2018, former U.S. President Donald Trump has initiated a tech war against China, intensifying the G2 global competition. The U.S. launched a de-China supply chain initiative to block the "Made in China 2025" and China's access to high-tech chips. Since the onset of the tech war, a chip alliance under Indo-Pacific Strategy has been consolidated, reinforcing chip monopoly and Taiwan's role in the semiconductor division of labor.

Taiwan specializes in OEM and ODM, producing half the chip and more than 90% of high-tech chips. Chip production involves intricate processes that require highly specialized, capital and technological-intensive equipment, such as Extreme Ultraviolet (EUV) machines for photolithography, which are predominantly supplied by the Dutch ASML (21.6% of semiconductor equipment). Nearly 90% of the components for EUV machines are from four countries—the U.S., Netherlands, Japan (14.8% Electron), and Germany—and involve more than ten suppliers' companies (You, 2021). The Equipment Coalition may successfully restrict Huawei's catch-up in the high-tech industry and reinforce Taiwan's structural position, but not without a cost.

The overconcentration of chip production in Taiwan raises concerns about the risks. China's threat to invade the island disseminates anxiety worldwide and increases the pressure to push Taiwan to partially relocate chip production and its production expertise to other alliances. As geopolitical tensions escalate, controlling AI and military operations hinges on advanced IC algorithms and computing power. War in the Taiwan Strait will affect approximately 70% of global chip production as they pass through Taiwan at certain stages of their life cycles. Therefore, Ferguson argued, "A Taiwan Crisis May Mark the End of the American Empire" (Ferguson, 2021), underscoring a major geopolitical conflict centered on Taiwan's ability to produce high-end logic chips.

To distribute the potential risk of the global economy, TSMC is asked to establish three foundries in Arizona by 2030 to produce 3nm chips. In addition, TSMC in Japan's Kumamoto foundry is in place, and the potential plant in Germany is being negotiated. Relocating TSMC to the alliance's countries enhances TSMC's competitiveness while boosting potential competition in foundry production in the future. TSMC, to rebalance the pressure from the U.S., also actively negotiates with China to set up foundries producing 28 and 16-inch wafers despite being a relatively backward technology (Ota, 2022:90). However, they may not be capable of reproducing TSMC's miracle because Taiwan's miracle is embedded in context-specific regional and local networks and clustering culture, and fast follower strategy.

The positive side is that Taiwan's triple bilateral relations with the U.S., Japan, and India may complement Taiwan's disadvantages. Taiwan can strengthen its memory chips and critical chemical materials from Japanese firms and cooperate with Tokyo University to boost its research capacity in strategic IC materials. Moreover, Taiwan could advance in software development through a strategic partnership with India's IC sector. These bilateral collaborations enable East Asia to block China's catch-up in technical terrain, increasing geopolitical and regional security with a surveillance supply chain. Under the Indo-Pacific Strategy scheme, TSMC, a "trusted foundry" for the Ministry of Defense for the U.S. and Japan, has promised to set up two foundries to produce chips specifically for regional security (Lin 2022; Ota, 2022:280-281).

In addition, geopolitical tension and the de-China industrial chain drive the foreign FDI outflow from China to Taiwan, Japan, India, Singapore, Thailand, Malaysia, and the U.S. Taiwan's FDI has increased in the past few years. For example, in 2023, ASML decided to invest 1 billion USD in Taiwan, while Nvidia announced the set up of two centers (Lin, 2022). Taiwan's government uses the opportunities to launch new R&D regulations to encourage big corporations to establish research centers here, with preferential tax exemption of up to 25% corporate income tax[6]. In sum, this recent development has created push and pull forces that benefit Taiwan. Xi's social control measures and anti-Taiwanese independentist policies have created a push force to trigger the outflow of capital and talent. In contrast, Taiwan is receiving FDI and recruiting international talents worldwide to fill the increasing demand and robust labor shortage.

7. CONCLUSION

Semiconductor development requires technology, capital, and know-how; only some developing countries can achieve or maintain absolute competitiveness. Taiwan's case offers an example of reflection of its long trajectory and cat-up development. However, Taiwan's case showcases that Taiwan's semiconductor achievement relies on the establishment of multi-level comparative advantages, ranging from the structural and friendly position in self-constraint OEM production within the international division of labor to East Asia's intra-industrial regional division of labor, which contributes the critical chip material's inputs and feedback loops to contribute the ODM, as well as Taiwan's

6 Article 10-2 of the Statute of Industrial Innovation provides a strategic layout for Taiwan's future development of the semiconductor industry and can be called the "Taiwan version of the Chip Act." Source: Statute for Industrial Innovation (2023), Law and Regulation Database of the Republic of China (2024).

Hsinchu Science Park's local networking and their industrial complementaries and collaboration based on cooperation and competition. Notably, the firm's fast-follower strategies in the 21st century are critical in converting the comparative advantages into a competitive advantage, above all, by its outstanding procedural and systematic managerial capacity to upgrade and upscale in OEM and ODM. Ultimately, the geopolitical tension pushes alliance networking to take shape, strengthening Taiwan's existing partnership and adding Japan and India's imperative selective affinity partnerships in the Indo-Pacific strategy, consolidating Taiwan's leadership in chip production.

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