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Department of

Business and Management

Unbundling The Ecosystem: How can the European Union fill the technology gap in the semiconductor industry?

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Academic Year 2022/2023

Introduction

The demand for Integrated Circuits (ICs) has soared in the last few years (EE Times). The expansion of technology and the digital revolution have made semiconductors the new oil of the decade (WSJ 2023). The chip market has reached a total value of 634 billion, which will rise to 1124.5 billion in 2032. It is one of the most profitable sectors in the world (Statista 2022).

Every technological device around us contains at least one Integrated Circuit. Their applications are endless; they range from the military to mobile to the medical industry. Endless is also today's society's need for these tiny rectangles of silicon. Growing public attention has led governments worldwide to question where these chips come from, who makes them, and what it means to control their proliferation. While chip technology has been evolving exponentially almost silently for years, at least in Europe, some countries strategically prepared themselves for when semiconductors would become necessary tools for everyone's life. The recent supply chain crisis, triggered by the COVID-19 pandemic and exacerbated by rising inflation, has led semiconductor manufacturers to reflect on the market's health, direction and the challenges it will face. The global focus on semiconductors has created a new mix of private and public interactions, redefining corporate and institutional competition strategies. It has changed market relations and turned chip manufacturing into a political tool. These times are prompting the European Union to acknowledge the importance of semiconductors and to develop a strategy to confront the growing risks this sector will face. To come unprepared into the next decade would mean giving up strategic autonomy in manufacturing any electrical device and indulging in new forms of technological blackmail. **The urgency to exit this impasse calls for a paper able to explain market relations in the semiconductor ecosystem under a policy lens.**

Research question

The ultimate goal of this paper is to develop recommendations on how the European Union can close the technology gap, it has accumulated with other international players, in semiconductor manufacturing. In order to achieve its objective, this paper has identified a roadmap to develop recommendations anchored to a direct empirical study of the chip industry. It is, therefore, necessary to distinguish between two overlapping realities in the semiconductor ecosystem. The first is the notion of the firm as the principal unit within the industry innovation process. The semiconductor's ecosystem is dotted with fewer than 500 companies - of which just over 30 are directly involved in manufacturing. These companies drive a continuous evolutionary process enabling chips to sustain the growth of global technology. It is the interest of this research to explore the relationships that govern the composition of the ecosystem. Specifically, by focusing on firms directly involved in the manufacturing process. This research seeks to understand the characteristics of the firms that have emerged as absolute leaders in this century's most dynamic and risky market race. The second is the role of states and industrial policy in semiconductor manufacturing. This paper will try to achieve two objectives. Firstly, this paper will try to understand which governance modes allow firms to interact and compete profitably with the market and the ecosystem. Then, it will investigate how cutting-edge firms sustain their competitive advantage. The paper aims at interpreting the ecosystem holistically, as a multiform network of actors, to define the relationships that govern its development process. If the paper's ultimate goal is to propose policy strategies, clarifying the inner characteristics of leading firms is essential for the success of this analysis. The semiconductor ecosystem has evolved intensely over the last 50 years. Giants have fallen, and small companies have emerged victorious. Starting with a detailed analysis of the nature of the firm and the relationships that govern the ecosystem is the only way to develop a complete comprehension of this market.

The second objective is to deepen the role that States, and regional Institutions play in chip's development. Public policy has always been a vital component of the semiconductor industry. States have been major stakeholders, helping to finance a substantive part of the industry. The call for productive self-sufficiency, the growing momentum in power-oriented industrial policy strategies must be analyzed in light of the findings of the first part of this paper to understand whether an autarchic production strategy is possible or desirable. Using the example of China and United States of America's efforts to develop a domestic semiconductor market through targeted and intensive financing tactics, it will then be possible to draw parallels with the European Union. At this point, this paper will be able to propose recommendations on how to foster and sustain a future strategic role for European countries within the semiconductor market.

Propositions

This paper starts with three *ex-ante* propositions. The study of the scientific literature and a qualitative interview analysis will try to validate them.

First proposition: In the semiconductor manufacturing business, firms are institutions focused on knowledge creation.

- **a-** Knowledge affects governance modes within the industry.
- **b-** Competitive advantage is generated throughout strategic knowledge management.

Second proposition: In the semiconductor ecosystem, firms can sustain the rhythm of technical development only by sharing knowledge and guaranteeing "competitive parity" to all the members.

Third proposition: States pursuing industrial policies with a focus on self-sufficiency will not be able to develop advanced manufacturing capabilities due to the nature of the ecosystem.

Research gap

This paper is the result of a careful review of the literature, which revealed a gap in research. In the current academic landscape, there are two main types of sources on the topic of semiconductors. The first is the literature that approaches semiconductors by delving into the role of industrial and managerial economics. This type of research focuses on analyzing innovation and manufacturing processes from a technical point of view and reflecting on the importance of the firm and its characteristics. The second is a more policy-oriented approach, widely utilized in the study of the semiconductor market. This approach looks at chips production from a geopolitical point of view, trying to interpret States strategies and, too frequently, reducing the role of firms to passive entities. This stream of literature focus on the role of States in the semiconductor market in terms of global competition reflecting on the challenge for control of resources among great powers. Both research streams have produced exciting and valuable analyses for understanding the industry. Nevertheless, the two streams of literature appear jostled. In particular policy-oriented papers lack a foundation understand of market functioning. It seems that today the two approaches do not influence each other, leaving an important gap for an organic understanding of the topic.

This paper attempts to fit between these two streams of literature. It seeks to take advantage of the latest developments in both fields to create a holistic analysis capable of supporting its findings by uniting the threads of both approach.

Paper structure

The first chapter contains a critical reflection on the nature of the firm in the semiconductor industry. Different theories are considered, namely the Transaction Cost Theory, the Resource Based View, the Knowledge-Based Theory, and the Evolutionary theory. The first objective is to clarify the resonance behind governance modes in the industry. The second is to analyze the deep roots of sustainable competitive advantage strategies in light of the RBV and the KBT. This chapters also includes a brief theoretical review of the cluster literature, needed to introduce the role of geographical heterogeneity in the chips industry.

The second chapter of this paper is designed to provide a complete summary of the semiconductor ecosystem. The first paragraph deepens the technical aspects necessary for a good understanding of the subject. The second paragraph is composed of a summary of all the steps involved in the chip manufacturing process. A brief overview of the players involved in chip production is presented to introduce the different structural manufacturing approaches companies have developed in the market. The fourth section is dedicated to a historical analysis of the ecosystem. The aim is to highlight the ecosystem evolution over time, underlying the high level of dynamism and uncertainty that has characterized this industry. The last paragraph demonstrates the degree of integration that exists in the semiconductor ecosystem. It considers three leads, joint ventures, consortia and standards, to analyze how knowledge is used by competitors as a tool to create advantage but also as the only means to mutually support the fierce and unique technological development in the semiconductor sector. This section demonstrates how the semiconductor ecosystem creates innovation through a unique relationship between rival companies and tries to deepen the reasons behind its self-sustaining nature by ascribing it to a complex system of knowledge transferability.

The third chapter opens the analysis to the role that States play in the ecosystem. Industrial policy literature is used to understand the role of public investment and in particular the application of national champion's subsidies. Strategies and objectives of institutional actors are considered under a political lens to trace a landscape analysis on the influence that the notion of balance dependence have today in industrial policy. The spasmodic quest for semiconductors development of the People's Republic of China and the manufacturing reshoring of the U.S. are used as an example to understand the role of States and international politics within the semiconductor ecosystem.

Then, findings are presented organically. This part, starting from the literature and evidences presented throughout the three chapters, aims at assessing the result of the interviews. An accurate analysis is presented in chronological order as the part's objective is to weight the interviewees responses and to demonstrate the validity of the *ex-ante* propositions.

The paper concludes with an assessment of the state of the semiconductor industry within the European Union. The policy instruments used until known by the European Union are weighted with the findings of the interviews. The last section sum up the research findings with a presentation of key takings and furnish recommendations on the future role the European Union can play in the industry.

Literature review

In order to write this paper, it was necessary to analyze different types of sources. The starting point literature was the one on Complex Products and Systems (CoPS). An example of this stream of literature is the book "Innovation in Complex Products and Systems" by J. A. Franca. The literature on CoPS focused on the analysis of production factors in the manufacturing of complex devices. Prencipe takes an exciting approach to the firm's capabilities and coordination of production factors by firstly introducing the role of knowledge. Another fundamental work concerning the concept of complexity in manufacturing systems is the one of K. Efthymioua and A. Pagoropoulos, who instead focused on the role of production models. The literature on CoPS is completed by the work of Davies and Brady, who used a policy-oriented approach and delved into the role of States in the management of these processes. In an attempt to comprehend the semiconductor segment, the strategic management literature has also made significant efforts. Grant's seminal work "The Nature of the Firm" contained one of the first references to ICs in the KBT application. In that case, many authors have followed in an attempt to explain governance models and competitive advantage in the chips industry. Fascinating the stream of literature that attempt to explain the relationship between the firm and the market by analyzing the firm's application of resources and knowledge. Masterful and fundamental is the work of Heiman and Nickerson, who added the role of interfirm cooperation.

Regarding applications of the Knowledge-Based Theory, fundamental to the development of the literature have been the contributions of Kogut and Zander, particularly those on technology replication and combinatorial capabilities. Coff and Russell, on the other hand, focused on the topic of competitive advantage by rounding the application of this theory under all aspects of strategic resource management. The first debate this thesis sought to explore was the choice of governance mode in the manufacturing process delving into the conflict between hierarchy and market. This debate mainly involved representatives of TCT with those of RBV and, later, KBT. Undoubtedly, Heiman and Nickerson's work provided a reconciling view between TCT and KBT on the nature of the governance modes. Another interesting debate concerned the global nature of innovation in the semiconductor market. Indeed, some literature has found evidence of the diminishing internalization of knowledge in the industry. Another part, on the other hand, considers inter-firm collaboration as one of the essential aspects of the semiconductor ecosystem. The literature on clusters is also very pertinent to this debate. Maskell, in particular, has helped to solidify the relationship between clusters and knowledge by reconnecting it to the issue of knowledge sharing.

A comprehensive introduction to the concept of industrial policy has been developed throughout the work of Christopher Freeman and Luc Soete. Very insightful is the work of Carlo Pietrobelli and Luisa Giuliani on industrial districts and Global Value Chain.

From a political analysis point of view, the literature has produced a consistent amount of work. In particular, the Montagne Institute and the Eurasia Group have done excellent research work, especially concerning the China-US confrontation. Regarding the literature on policy, the work of C. Miller provides an excellent reflection on the evolutionary aspect of the semiconductor ecosystem, tracing a historical reflection on the sector's development. A series of studies by Bruegel about the relationship between government investments and the development of national manufacturing capabilities was particularly useful for the objective of this research.

Chapter 1

Complex Products and Systems (CoPS)

Complex Products and Systems are high-cost, technological-intensive products (Franca 2023). CoPS play a fundamental role in today's economics; they are the foundation of modern technological development. They represent a vital share of the global industrial sector. A product, in order to be defined a CoPS, needs to meet some strict requirements (Hobday 2000). First, CoPS requires a long development phases, where design processes and R&D represent a central share of the companies' efforts. In particular, integration plays a fundamental role. As they are composed of highly technological subparts, CoPS requires the integration of a multitude of suppliers, tenders, and clients. Subsystems complexity, thus, is a fundamental characteristic of CoPS (Davies and Hobday 2005). Another characteristic of CoPS is that they are produced in small quantities as the development phase proceeds through attempts and prototypes. Once they are fully developed and operative, the full-scale production can start. CoPS are distinct from mass production processes for different reasons. Unlike mass products, CoPS production processes take advantage of customized and interconnected elements tailored and developed for specific customers or markets. CoPS operates in extremely uncertain environments with high risk (Franca 2023).

Before dealing with complex product innovation, however, it is important to emphasize the three key characteristics of any innovation process.

The first is the quality and effectiveness of the human resources working on the innovation.

The second key characteristic is specialization. The world specialization synthesizes the ability of each company to produce increasingly high-performance products. In complex production systems, the number of actors involved in production processes grows exponentially along with specialization. The final characteristic of an innovation process is the financing system. In order to be able to innovate and thus create knowledge, research and development phases must be financed with increasing investment (Filippetti and Archibugi 2011).

The possibility of unpredictable or unexpected events characterizes the value chain of CoPS. Uncertainty is one of the reasons for the inherent complexity of these products. The uncertainty in which these products are developed stems from the internal processes involved in production (endogenous uncertainty) and the circumstances and systemic risks of the environment and market in which they operate (exogenous uncertainty) (Franca 2023). On the one hand, complex industrial processes require great precision and care in the production steps, as even small setbacks in the production chain can result in huge losses, both in economic and competitive advantage terms (Davies and Hobday 2005).

On the other hand, the globalization and internationalization required in the production and assembly phases of CoPS expose companies to a wide range of risks, particularly in managing suppliers, raw materials, and machinery. CoPS producers operate in a volatile environment that lacks complete information. As a result, not only risk is systemically high, but strategies and objectives are often unclear and highly dynamic. It is no coincidence that in the production of CoPS, where uncertainty increases, the safeguards normally used in industrial processes do not always pay off. For example, the elements that make up the production of a chip can undergo technological changes that are very difficult to foresee or anticipate. This is why complex production systems require large investments, especially in the research and development phase. Innovations are frequent, and major companies are constantly battling to gain new market shares. The uncertainty resulting from each company's ability to interpret technological market trends is a topic that needs to be addressed to understand the semiconductor market.

The variables are so difficult to predict, and the characteristics of the products are so specific that the company's strategic approach needs to be much more dynamic than in the production of mass products. As explained above, the research and development phase of CoPS begins with the construction of prototypes. This is because CoPS are products from the combination of several related parts developed specifically to satisfy certain standards. Each part is developed to function in combination with the other and to interact specifically with a software and hardware system. Changes or modifications of a single part could lead to radical changes in the final product's structure. This is why development takes a project-based approach rather than being directly launched for large market transactions. The level of interaction between different parts makes the whole system's performance essential to any project's success (Franca 2023).

In the production of CoPS, it is often observable that the system is 'self-supporting' due to its complexity. Hardly any actor can realize the product without the correct market organization, and it is almost impossible for any player to replace all the others. This implies that a strict hierarchy characterizes the production structure of CoPS.

A final characteristic of CoPS is that these products typically do not follow the classic stages described in the product life cycle theory (Franca 2023). This theory presents the stages a product goes through on a timescale once it enters the market. The product life cycle theory states that after an initial phase in which a new product is introduced to the market, there is a growth phase characterized by sales increase and followed by a maturity moment in which the product gains a stable customer base. The final step is marked by the decline in the product and the emergence of other competitors that replace it on the market (Investopedia).

In the case of CoPS, this process does not always seem to happen systematically. The first reason is that the life span of CoPS differ from that of mass-produced products as they have minimal viability. CoPS hardly find new applications on the market or have a commercial "second life"; they are essentially tradable only when they are at the peak of their innovation and technological superiority. For this reason, these products are often introduced on the market for only one year or even much less.

The second reason is that, as highly technological products, they are produced by a handful of companies, the only ones that have accumulated the necessary skills and resources to compete in the market. This is why CoPS producers rarely 'disappear' – at least not in the case of systemically disruptive innovations – but are usually able to sustain their superiority period after period (Franca 2023). The global economy's dependence on these products never makes them obsolete but forces them to evolve into more powerful forms. The architecture of the production system stems as a core characteristic. This encompasses all the capabilities of a company, ranging from the engineering one, to technologies to its human resources, to the intangible ones, such as knowledge, routines, and systems integration capabilities. Product development builds on this architecture and represents the output that the company can deliver. In order to fully understand the dynamics that characterize CoPS, it is necessary to analyze these products through two "lenses." The first is that of the networks, which characterize all the production phases of these products; the second is that of the projects, which are the basic development units of the final product (Franca 2023). In order to develop a comprehensive understanding of how the CoPS ecosystem works, first, it is necessary to analyze the company's management, technology, and innovation processes. Indeed, the question that needs to be asked is how companies that produce complex products generate their competitive advantage. What differences lead companies to establish themselves as industry leaders while others collapse under the heavy weight of investments and competition? The second lens concerns the network. It examines how the ecosystem coexists with hundreds of players and can ensure a continuous innovation process. Complex products can be explained on two levels: the individual level of the company that produces them and the regional or global system in which this company operates, competes, and collaborates. Conducting a comprehensive analysis of the companies involved in these processes without considering the ecosystem in which they operate would not allow to establish a complete view. Normally, the literature on CoPS focuses on products such as smartphones, computers, aviation, and automotive machines. These products easily satisfy the requirements to be classified as CoPS; in particular, they are difficult to assemble and are conglomerates of hundreds of suppliers and producers, even if they are commercialized under a single brand (Franca 2023). This research project will consider chips as CoPS. From a point of view, indeed, semiconductors are not tradable directly to customers – they are only sold to other businesses – and they are a subpart of a more complex final product. Nevertheless, chip production possesses all the intrinsic characteristics described in the CoPS literature. First, semiconductor manufacturing requires great complexity regarding organization and coordination on par with the other industries described above. Moreover, chips represent one of the technological nodes capable of dictating the speed of innovation of every other machine in which they are integrated. Indeed, there can be no innovation regarding software or other hardware components without processors, memories, and GPUs capable of supporting them. Another supporting argument for the thesis that semiconductors belong to the category of CoPS is the one of integration. Chips are products that have different levels of integration. Firstly, they need to integrate a complex network of suppliers. More interesting, however, is the second layer of integration that results in the need for coordinated actions among multiple companies, consortia and the creation of norms and standards for manufacturing. A key characteristic of the semiconductor market is that of uncertainty. Indeed, in this industry, the term "extreme" uncertainty could be used given the number of variables that affect each company's overall scaffolding. In the case of semiconductors, the uncertainty comes from the very complexity of its ecosystem. The ecosystem is characterized by a small number - or even only one actor - capable of offering a given service at the best quality. **The starting consideration of this paper is that semiconductors not only represent an example of CoPS but are the fundamental unit at the core of the realization of any other complex product.**

The manufacturing bottleneck

Although the semiconductor ecosystem is dotted with highly specialized companies, this analysis aims to consider only those directly involved in chip manufacturing. Therefore, all those firms that deal with chip design as Apple, NVIDIA, MediaTek, and Qualcomm, will be left out from this research project. Although these companies are generating huge margins and represent an important share of the market, this analysis wants to focus on the process of the physical creation of chips, as it considers the manufacturing the most critical bottleneck of the industry.

Reducing the analyzed sample makes it possible to avoid a widespread mistake, namely, comparing companies in the semiconductor market involved in very different stages of production. As irresistible as it may seem to compare processor design giants such as Apple and Qualcomm with foundries such as TSMC or GlobalFoundries, this comparison is forced and incorrect. Designers and Pure-Play foundries do not compete but collaborate intensively.

More interesting is analyzing the semiconductor market by looking at the firms that manufacture the final product and are – in most cases – directly competing to create the latest technology. Designers can't expand their capabilities without companies that assure the physical feasibility of the product. For this reason, trying to decode manufacturing challenges and capabilities will help this research develop a comprehensive analysis framework.

Market and hierarchies

In order to understand the semiconductor market, it is important to comprehend the academic debate on market and hierarchies. Indeed, to confirm the first hypothesis of this paper, it is necessary to understand the reasons that lead manufacturing companies to develop certain governance modes.

This intermediate passage will serve the scope of clarifying the logic behind the firm's decision to internalize or not steps within the value chain and will set the theoretical foundation to introduce problems related to knowledge and competitive advantage.

The first scholars to analyze this clivage were the representants of the Neoclassical theory. In the Neoclassical economic theory firms have no reason to exist. Every transaction takes place in the free market and no need arise to internalize production processes. Neoclassical theory assumes that all products are homogeneous and that can therefore be no price difference between them. The other two fundamental assumptions of this theory are that information, within the market, is complete and perfect. The economic man, endowed with perfect rationality, can always choose the best possible option through a complete decision tree. The market, under this double assumption, would be characterized by the total absence of transaction costs. The Neoclassical theory presents the market as a perfect entity, capable of self-regulation throughout relative prices. The market is thus able, in every situation, of achieving equilibrium between supply and demand. However, the Neoclassical theory fails to explain not only the need for firms to arise but also firm’s heterogeneity and the importance of strategic management. If Neoclassical theory were in fact directly applicable to the world's reality, it would be possible to organize market transitions through suppliers at the best price and then assembly the final product without intermediaries. Under the Neoclassical theory specific knowledge is completely irrelevant.

The first criticisms of Neoclassical theory come from Coase, who suggested that there are transaction costs in the market (Coase 1937). Indeed, Coase was able to grasp that every transaction that takes place in the market involves time and resources spent on acquiring information and calculating risks. Furthermore, every transaction in the market is governed by a contract, and in the absence of perfect information, it is impossible to create a perfectly complete contract. This exposes the manager and the firm to additional risks and costs. The attempt to obviate the drafting of perfect contracts, which are impossible by nature, is one of the reasons behind the establishment of the firm (Coase 1937).

Coase also rejects the idea of the firm as a black box. He understood that firms face a choice: whether to rely on a contractually regulated market transaction or to internalize the production process. Coase (1937) recognized that each firm reaches an equilibrium point, relative to its size, when the cost of internalizing a new function equals the price of the same product on the market. Before that point every firm is thus incentivized to produce internally.

The second criticism of Neoclassical theory comes from Simon (1997), who identifies uncertainty and the lack of perfect information as the reason why the “economic man” does not exist in reality. Under Simon’s assumptions the rationality of the manager is therefore limited. Simon's rejection of Neoclassical determinism is replaced by a complex network of individual decisions. Limited rationality is linked to the notion of imperfect knowledge. Simon's innovation stems from the understanding that human beings, by their very nature, are not instinctively prone only to maximization but also to other characteristics as satisfaction (Simon 2013).

Williamson's theory builds on the contributions of Coase and Simon (Williamson 1981). If Coase had identified transaction costs as the reason behind the institutionalization of the firm, Williamson sets out to understand when a certain firm will use the market and when it will decide to internalize production processes. Williamson (1981) sees the market and in-house production as alternative instruments. Williamson makes two important preliminary assumptions: the fundamental role played by bounded rationality and the concept of opportunism. Opportunism is the reason why contracts are not honored; agreements are changed, and uncertainty arise from market transactions. Williamson (1981) identifies three critical dimensions of any transaction: the level of uncertainty, the frequency with which each transaction occurs, and the specificity of the asset. Uncertainty remains a constant point that Williamson inherits from Coase. Uncertainty increases transaction costs, but it does not in itself limit trade. Generic products are steadily accessible throughout the market. The frequency of a transaction becomes relevant the moment it stops being occasional. The firm will start to think about internalizing a production phase as soon as transactions on the market become very frequent. With regard to the specificity of the asset, Williamson suggests the example of a software, to explain this critical passage. In fact, as long as the software is very generic it can easily be acquired on the market at the best price. The problem, Williamson continues, arises when the software becomes unique. At this point it will be necessary to internalize the property over the software by, for example, hiring a specialized engineer. So that a supplier cannot leverage prices, being the only producer, and create a disadvantageous situation for the firm (Williamson 1981). Through this example, Williamson wants to explain how the market is unfunctional when there is a bilateral transaction on a specific asset. This type of transactions needs to be supported by long-term contracts and the price of drafting these contracts and the risk that the buyer takes make the market become less convenient than in the case of transactions on less specific assets.

The development of this theory is particularly interesting in the analysis of the semiconductor market as it pose important interrogatives on the relations between market and hierarchy in the industry. The semiconductor production system flows through nodes and bottlenecks and for this reason uncertainty and risk are endemic. It is also characterized by the production of very specific asset. An example could come from the lithography phase. There is only a company, the Dutch ASML, able to build competitive EUV machines. These machines are incredibly specific assets as they are essential for every foundries and every machine applies specifically for the production of different types of chips. Failures in delivering a single spare part of these machines can stop the entire supply chain of multiple companies. So, in light of what Williamson explained, why has no company like Intel or TSMC yet internalized this function? Another important point can be made regarding the relation between fabless companies and Pure-Play foundries. The nature of their obligation require the drafting of contracts of incredible complexity. Fabless companies put at stake all their work in transaction marked by high level of uncertainty. These transaction are also marked by high level of customization over very specific assets. The relation between Fabless companies and Pure-Play foundries involves hundreds of hour of integration work and require knowledge and resource sharing in considerable amount. Why so Fabless companies find advantageous to outsource their production? One argument could be that it is simple convenient from a cost point of view. As long as the forecasted internal production cost are higher than the cost of the transaction they shall continue their relation. But the response is probably more complex than that. With the incentives Governments are putting in place, willing to subsides every attempt of success, costs seems only to answer partially to the question.

Notions of clusters' theory

The semiconductor market has a strong geographical connotation. Deepening and explaining the evolution of geographical clusters in the semiconductor market remains crucial to providing a complete analysis of its ecosystem. The importance of clusters for regional economics and the dens overlapping of interconnections with political and institutional actors will serve to comprehend the second part of this paper. Firstly, the semiconductor ecosystem needs to be analyzed also throughout its geographical dispersion to develop a complete paradigm of analysis. The industry is concentrated in a few regional clusters spanning three continents.

There have been many attempts in the literature to define the meaning of the word cluster. Alfred Marshall was the first to introduce a clear definition. Marshall believes that industrial cluster are efficient production ecosystems that can exploit the proximity between small and large firms to leverage specialization and lower production costs as a source of competitive advantage (Vicente 2018). Marshall (Vicente 2018) defines industrial clusters as an "organic whole", capturing the ability of clusters to function as a organisms. According to Marshall, the interdependence of production would create better manufacturing dynamics than the one that could be achieved in a large, isolated firm. An important contribution to cluster theory came from the School of Florence, which instead recognized the importance of the concept of "industrial atmosphere" (Vicente 2018). By the end of the twentieth century, Ford's model of firm growth was losing value: the idea of the large firm, capable of transforming simple raw materials into complex machines, began to clash with the phenomenon of globalization and regional specialization (Vicente 2018). The School of Florence added an important feature to the Marshallian academic model: the relationship between companies and the territory in which they operate (Vicente 2018). The cluster thus creates an ecosystem that also includes its people's and institutions' social values. Porter's attempt to sum up the existing research on cluster is considered one of the most complete. Porter (1998) defines clusters as "geographical concentrations of interrelated firms and institutions in a particular field." Porters definition is able to catch the importance of interconnection is between firms and the geographical location where they operate.

The unique historical-geographical development of the semiconductor industry opens the door to a more detailed analysis of the relationship between globalization and regional specialization and between technological development and knowledge. The semiconductor industry is a perfect example of Krugman's thesis that the production of highly specialized technological devices is highly concentrated in determined regions. However geographic concentration and the process of clustering in the semiconductor industry have undergone major changes and are characterized by a unique and fast dynamism.

The Resource-based view

The semiconductor industry is a high-tech sector based on each company's ability to use its resources to create innovation and develop products with better characteristics than its predecessors and competitors. Although it may seem trivial, this sentence leads to the same conclusion hypothesized by Williamson, namely that the existence of a company comes from its ability to produce specific assets.

The first author to underline the critical role of resource management for competitive advantage was Wernerfelt. Wernerfelt (1984) understood that resources within different companies are heterogeneous and are imperfectly distributed in the market and among competitors. Firms must acquire and control valuable, rare, inimitable, and non-substitutable (VRIN) resources and capabilities to produce specific assets, thus obtaining sustainable competitive advantage.

RBV found a complete crystallization in Barney's work. According to Barney (1991), firm resources include all assets, capabilities, organizational processes, firm attributes, information, knowledge, etc., controlled by a firm that enable the firm to conceive of and implement strategies that improve its efficiency and effectiveness. In Barney's view, resources are valuable when they enable a firm to conceive, or alternatively, implement strategies that improve its efficiency or effectiveness. (Barney 1991). A firm is said to have a competitive advantage when implementing a value-creating strategy, not simultaneously being implemented by any current or potential competitor. (Barney 1991). The critical feature of RBV is to consider the resources of a firm immovable and, therefore, very difficult to copy and reproduce. By deepening the meaning of resources, Barney distinguishes between *rare* and *valuable resources*. For Barney, resources must be rare to sustain a competitive advantage. Valuable resources can only generate what is called "competitive parity."

The knowledge-based theory of the firm

A first attempt to integrate the role of knowledge with the theory of the firm was made by Cyert and March. They redefine firms as heterogeneous organizations possessing standard operating procedures and identify knowledge as the main reason for a firm's competitive advantage (Cyert and March 1963). Cyter and March (1963) realize that, although some procedures are generic and easily imitated and identified, others are tacit and difficult to detect. The fact that these operating procedures cannot be easily imitated is the theoretical landmark to explain the heterogeneity and competitiveness of any firm. A company's ability to have inimitable processes is the reason why, according to Cyert and March, sometimes the decision to integrate a production step is more complex than the one provided by Williamson. Another important insight provided by these two authors is the comparison between homogeneous and heterogeneous companies, only those capable of differentiating themselves in knowledge production and skills will be able to develop a competitive advantage (Cyert and March 1963).

Are Nelson and Winter, however, the first to introduce the concept of routines. Routines are described as the genetic material of the firm that influence the firm's adaptation in its environment (Nelson and Winter 1973). Nelson and Winter (1973) identify how routines interact with the stochastic environment and outline the firm's evolutionary path. They sample two types of routines. The first are the static ones, which include all the standardized and repetitive tasks. Although a company must be able to perform these tasks precisely, it is unlikely to gain a competitive advantage from them. Dynamic routines, on the other hand, are related to innovation and development and represent the set of decisions, skills and information that can create new value. These routines are tacit in nature and very difficult to codify and share (Nelson and Winter 1973). In fact, dynamic routines are even difficult to replicate by one company in its other departments and are almost impossible for competitors to copy. In Nelson and Winter's analysis, routines are hierarchical and on the highest step of the pyramid lie those routines that analyze all operational procedures and decide which ones to modify and which ones to eliminate. These routines are capable of guiding the evolutionary path of the company by modifying the lower-level routines. This theoretical introduction rise two points of reflection. The first is that Nelson and Winter's great innovation is to place the firm, understood as a dynamic and evolving element, in a complex, stochastic and uncertain system.

The second is that although routines can be identified as one of the causes of the individuality of each company, they do not necessarily provide a complete answer to governance modes. They are not sufficient to explain why the semiconductor market has developed around different business model and on what basis company decide to outsource production.

To better comprehend the semiconductor market, it is necessary to analyze the theoretical implication of knowledge and its characteristics: transferability and appropriability. Regarding transferability, the difficulties associated with tacit knowledge were codified by Kogut and Zander in 1992. **Since tacit knowledge can only be learned by doing and through practical exercise and repetition, sharing this type of knowledge is very slow, costly, and complex** (Kogut and Zander 1992)**.** Explicit knowledge, on the other hand, can be easily shared and thus learned without losing any information. The transfer of implicit knowledge involves high risks and dangers; its sharing is therefore uncertain, and the possibility of errors is high. The concept of appropriability is also very relevant to knowledge sharing. Teece (2003) defines it as "the ability of the owner of a resource to receive a return equal to the value created by that resource". Both tacit and explicit knowledge present appropriability problems. For tacit knowledge, the problems are due to its learning patterns. The ability to transfer it from one individual to another has high costs due to the inherent absorptive capacity of human beings. For explicit knowledge problems arise when, throughout patents and property rights, firms try to protect their knowledge by reclaiming ownership and excluding competitors.

KBT represents an attempt to introduce organizational knowledge as a theory of the firm. Kogut and Zander (1992) were the first to propose the idea of the firm as a community to maximize the efficiency of knowledge transfer. Together with RBV, KBT shares the concept of the firm as a place of exchange, but in the former, the focus is on resources; in the latter, it is on knowledge. In KBT, hierarchy becomes a way of sharing knowledge to promote values and shared expectations (Kogut and Zander 1992). In Kogut and Zander's vision, the firm aims to bring individuals together to create a flow of knowledge. KBT proposes the idea of a firm as an institution for knowledge application (Kogut and Zander 1993). KBT explains how the costs involving tacit knowledge sharing are more significant than the ones involving explicit knowledge (Heiman and Nickerson 2002). Two factors can increase those costs even more: collaborative activities and production complexity (Heiman and Nickerson 2002). As it was possible to infer, CoPS production involves both of them. CoPS manufacturing processes have many collaborative activities consisting of massive, technologically complex assembly lines. In terms of complexity, the manufacturing process of chips testifies to the precision and difficulty required to create cutting-edge products. As these two factors increase, the costs required to ensure sufficient knowledge transferability increase proportionately.

KBT also opens an essential reflection on the emergence of clusters. Knowledge spillovers contribute to the emergence of regional clusters that specialize in certain products. The transferability of explicit knowledge from universities and consortia and the presence of implicit knowledge among workers lead groups of companies to locate in determined areas (McCann and Arita 2006). In the semiconductor industry, the clearest examples of clusters are Silicon Valley and the small island of Taipei. The relationship between clusters and knowledge is circular. On the one hand, cluster formation attracts investment, research, and attention from different actors, while on the other hand, spatial arrangement is responsible for creating knowledge. Clusters contribute to enhancing knowledge creation horizontally and vertically. In the horizontal dimension, firms in a cluster operate daily under the direct observation of their competitors. On top of that, workers speak the same language, share the same interests, and have a close academic background. This operational closeness increases dialogue and confrontation, resulting in the creation of knowledge. The vertical dimension concerns specialization (Iammarino and MacCann 2006). As the cluster grows, more and more firms become involved in specialized operations. Firms will begin to realize that they perform better in some steps than others and less efficient in other activities. This situation will generate specialization because the firms involved will begin to do what they do best. They will use their capabilities to create a competitive advantage and differentiate themselves. This process eventually leads to a cluster consisting of a constellation of highly specialized players. To summaries, the specialization comes from tacit knowledge arising indirectly within the cluster.

Nelson and Winter (1973) integrated the literature on KBV with an important concept. They understood that the KBV firm's capacity to create sustainable competitive advantage comes from its ability to develop exclusive knowledge from the combination of resources and skills within its workforce. They also added a time component in the firm's capacity, the ability to generate new knowledge before their competitors. The KBT is thus proposed as an alternative to explain the relationship between market and hierarchy in knowledge-intensive industries such as semiconductors. Another important topic is Macher's differentiation of the types of problems that CoPS firms face (2009). According to Macher (2009), the complexity of the problem is directly proportional to the amount of interaction and knowledge required to solve it. Macher (2009) distinguishes between ill-structured and well-structured problems according to the complexity of the knowledge sets from which they are composed. While the former would have high uncertainty and less predictability, the latter would be more linear.

Chapter 2

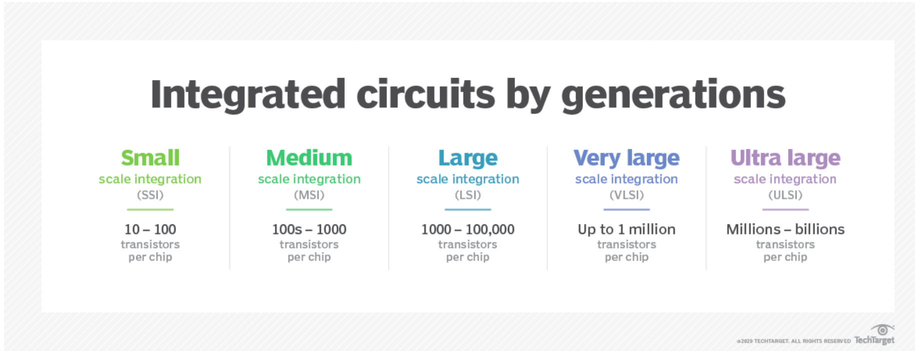
The chip's law

Semiconductors are naturally occurring materials with particular physical properties. Examples of semiconductors are silicon and germanium. Semiconductors have conductivity characteristics, at room temperature, in between insulating and conductive materials. Theirs's properties depend on purity's levels, which positively correlates with conductivity characteristics. Semiconductors also develop unique properties when intersecting with external elements such as light and temperature. Concerning temperature, semiconductors, unlike conducting materials, respond to an increase in temperature by increasing their ability to conduct electricity (Łukasiak and Jakubowski). They are also photosensitive, a characteristic that makes them suitable for the manufacture of microprocessors, and their ability to conduct energy varies according to the amount of electromagnetic radiation they are exposed to; in other words, illumination modifies the conductivity of these products. Semiconductors can be 'doped': they can be mixed with other materials through a doping process to modify their properties, mainly to increase or decrease their conductivity (Łukasiak and Jakubowski). The doping of semiconductor materials leads to the creation of p-type or n-type semiconductors, depending on the material they are mixed with. By appropriately dosing the impurities within a semiconductor and adjusting the temperature, a semiconductor with a fixed number of electric charge carriers can be obtained, thus precisely regulating its conductivity properties (Łukasiak and Jakubowski).

Due to their physical properties, semiconductors are used to construct diodes and transistors. Diodes are one-way current switches consisting of two terminals of different polarity that control the flow of electric energy. They are built by merging n-type or p-type semiconductors. Diodes are used to convert alternating energy into a direct one.

A transistor is a voltage-controlled switch that regulates the flow of electricity in a circuit. A transistor consists of a body made of a semiconductor material to which three terminals are connected. A transistor can act as a switch or as an amplifier by regulating the flow of electrons. As a switch, it regulates the passage of energy, while as an amplifier, it increases the output of electrical current. The invention of diodes and transistors was fundamental as it made it possible to replace cathode ray tubes, which were the ancestor of modern chips but with less efficiency and enormous problems of size and scalability. Transistors paved the way for the construction of integrated circuits.

An integrated circuit is a miniaturized circuit in which numerous components, such as diodes, resistors, and transistors, are assembled. Circuits are composed by directly modifying and applying electrical components to various layers of a semiconductor material. An integrated circuit is built by applying many transistors to a single bar of a semiconductor material called wafer. It is worth remembering that except in these brief lines, where the term semiconductor has been used to define a material, it will be used, in its industrial meaning, as a synonym for chip for the next part of this paper. The number of transistors within an electrical circuit has gradually increased since the 1960s. This process is called *miniaturization* or *integration scale*. The integration scale measures the number of integrated circuits placed within a single microprocessor (Intel).

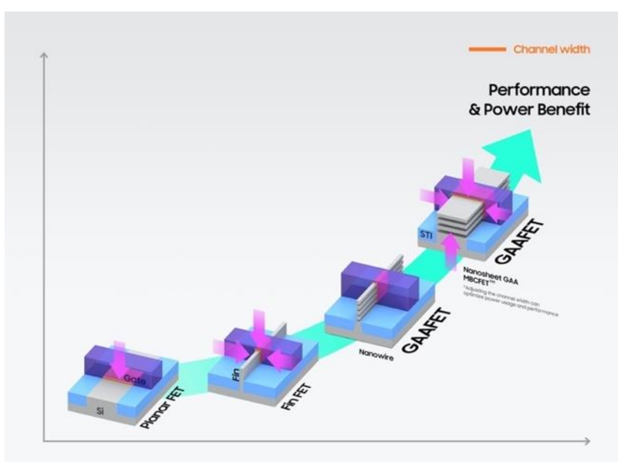


The *scale of integration* has evolved over the decades from MSI - Medium Scale Integration to VLSI - Very Large Scale Integration, which consists of integrating more than 100,000 transistors per chip. The integration process has led to the development of increasingly complex, high-performance microprocessors with ever-increasing computing capabilities. The size of the transistors in the construction process of microprocessors is relevant because the smaller the size of each transistor, the greater the number of transistors that can be integrated into the chip (Foster and Kung 1980). Thus, increasing chip's performance and quality.

The speed at which innovation occurs in chip's production is defined by Moore's law - named after its inventor, one of Intel's founders - . Moore's law states that the number of transistors per chip doubles every 18 months (Intel 2023). The 18 months was initially set at 12 but, during the 1970s, had increased to two years due to the first scalability problems. This figure suggests that while the law has remained valid since the 1950s, it has slightly adapted to the technological capabilities of each decade. Moore's law has been able to describe empirically and at a calculable rate the number of transistors contained in each generation of chips. In the case of CPUs, the transistor's number has gone from just over 2,000, during the 1970s, to 82 billion in a 5 nm AMD CPU chip released two years ago. *Miniaturization* is therefore an essential feature for chips. Leading-edge companies try to develop chips that contain as many transistors as possible. The size of a chip ranges from

200 nm to the most advanced 3 nm. The size of chips depends significantly on the application area. The mobile and computer market drives the *miniaturization* process. The latest generation smartphone mounts a System on a Chip (SoC) with a 4nm CPU. Other markets, such as automotive, need sensors that require heterogenous features. Industrial machineries need chips able to perform advance calculus but have more physical space and less need for chips able to perform different tasks within the same hardware. Therefore, a leading-edge chip in the automotive sector is around 90-70 nm. For this reason, not all foundries necessarily focus on extreme miniaturization processes. Being a cutting-edge firm in the mobile semiconductor industry means developing a product that will be obsolete in less than 18 months.

Nevertheless, little is left of Moore's law today as discussed in Intel's foundries in the 1960s'. If Malthus and the Neoclassical school of economics would reflect today on the relationship between resources and human inventiveness, they would be equally right. From one point of view, the industry has formally maintained a consistent rate of innovation. On the other hand, however, some substantial changes were necessary to the chip structure to make it possible.



The evolution of the FET architecture

The MOSFET is a type of IC commonly identified as the starting point of all electrical circuits. The MOSFET consists of overlapping layers of diodes of n-type or p-type semiconductor materials ("The MOSFET and Metal Oxide Semiconductor Tutorial"). The MOSFET-type transistor had reached its physical limit of miniaturization at 100 nm ("The MOSFET and Metal Oxide Semiconductor Tutorial" n.d.). For this reason, the FinFET architecture was introduced. This new architecture made it possible to create a multi-gate structure by adding a new dimension to the MOSFET. This invention somewhat "cheated" by adding more surface area to the chip but allowed the miniaturization process to be preserved. New technologies are still being developed to manage chip space and speed, including the GAAFET ("Il Futuro dei Microchip" ISPI). It will expand the transistor surface, pushing forward the miniaturization limits.

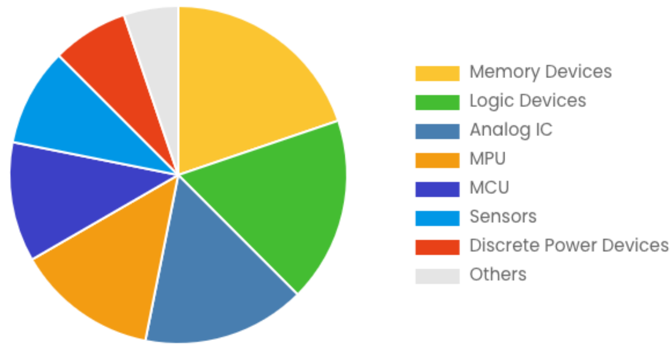
For this reason, cutting-edge firms develop the technology for the next node while still finishing working on the one before. Of course, due to the high costs and risks, a few players can sustain this rigid manufacturing process. The others, however, do business by bringing previous nodes to optimization with a high level of customization.

Rising costs in the miniaturization process

Another essential feature in chip production is the wafer size on which they are manufactured. Producing larger wafers makes optimizing the number of units per lithographic process, but it also requires a state-of-the-art robotic assembly line. Leading edge companies produce 300mm wafers; good quality foundries, on the other hand, use units between 150 and 200mm that are still light enough to be lifted by an operator manually.

Depending on the function they are designed, chips enable all electronic devices to function. Their applications range from everyday machines such as household appliances to complex machines such as cars, computers, and airplanes. Every machine, even the simplest, needs a chip to act as a bridge between hardware and software, enabling it to execute the most basic commands. The most complex machines require numerous chips; a car consists of between 2000 and 5000 chips. Chips are mainly designed for mass-produced industrial products. Often they reach high levels of specialization and customization. A chip designed to work on one machine may not work on another, and the conversion process may be slow and expensive. Semiconductor's manufacturing swings between a complex algorithm involving efficiency, scale, quality and speed.

Chips are not all the same. They are distinguished according to their functionality, the devices on which they are applied, and the industry for which they are developed. The principal types of microchips can be grouped into two large sets. The first set distinguishes the chips based on their functionality; the second set considers the type of integrated circuit.



Different types of chip per market segment.

Depending on the type of integration circuit, a chip can be divided into analog, digital, or mixed. Depending on the type of chip, its application changes. Analog-type circuits use a continuous signal that can take on infinite values in a given range, which is why they are used to process waveforms such as the human voice or music. Their task is to transform these waves into data that digital chips can manipulate. Digital chips, on the other hand, work in binary language, 0 and 1.

Regarding functionality, there are four main categories: logic chips, memory chips, application-specific integrated chips (ASICs), and system-on-a-chip devices (SoCs). Logic chips are those chips programmed to perform operations on data. The primary example is CPUs (Central et al.). GPUs (graphical processing units) are another example of logic chips and are used for the graphical representation of data. ASICs and SoCs are chips designed to perform fewer complex operations; they tend to be simpler but can integrate various functionalities.

Another category of semiconductors is memory chips. Memory chips are divided into two categories: volatile and non-volatile chips. Volatile memory chips, called DRAM (Dynamic et al.), are the 'working memory' chips. They only store data while the device is powered on. DRAM has a large storage capacity and is fast at processing extensive data (“DRAM | Memory” n.d.). Only

DRAM can match the processing power of the CPU. They are used to show the CPU all the information it needs to perform calculations.

Nevertheless, they cannot store data when the device is switched off. Non-volatile memory chips, such as NAND flash, store information when the machine is not running. They are slower and use less power. DRAM memory comprises cells, each comprising a transistor and a capacitor (Samsung Semiconductors 2023). The capacitors convert information, in the form of binary code, into data to be stored (Samsung Semiconductors 2023). DRAM needs to be refreshed so as not to lose any of the information they process, but they cannot store data when the machine is switched off. The smaller the size of each cell, the greater the speed and storage capacity of a DRAM. Innovation in the DRAM market also makes it possible to create products that consume less and less energy. The DRAM market has embarked on a path of remarkable evolution and, like the semiconductor market as a whole, is very dynamic. DDR is the most advanced model of DRAM, having replaced SDRs by doubling the chip's speed (Micron). DRAM memory then evolved from DRAM 2 to DRAM 5, further halving the size of each cell, doubling the speed, and increasing the storage capacity (Micron). There are three main types of DRAM: those for mobile phones, those for PCs, and the HBMs used in artificial intelligence and supercomputers.

Artificial intelligence is pushing the semiconductor market towards new frontiers. Notably the global development of this technology is asking the market for new chips able to support even more complex operations. Seems, in particular, that GPUs are effective for AI applications due to their ability to compute multiple information at the same time, NVIDIA exponential growth is partially connected to this (NVIDIA 2023). The latest chips frontier together with AI, is semiconductors specifically developed for Data Center. Data Center plays a centripetal role in firms and States operations. The centers are essentially powered by a multitude of different chips. Data Centers chip's application remains today one of the most important and critical market.

Semiconductor's manufacturing process

Today's chip manufacturing process is characterized by its complexity and by the heterogeneity of resources required. Although the semiconductor's manufacturing process can vary depending on the type of chip being processed, there is a standard procedure that is generally indicated as the semiconductors basic producing steps. The following process has been created throughout the interviewees explanation and the resources of leading producers available online.

Chipmaking starts form sand.

- Certain types of sand in determined areas contain high levels of silicon dioxide and can be used to extract the silicon crystals needed to make lingots. Silicon is not the only element that can be used in the process; other elements like germanium or silicon germanium have the same properties. Although silicon is one of the most abundant elements in nature, only a few types can provide the level of purity required in the chip-making process. The sand is treated with carbon in a furnace at a high temperature and then crystallized to obtain the silicon crystals. Imperfections and contamination are carefully washed out with chemical reagents, as they cannot exceed one atom per ten million silicon atoms. This process results in ingots of pure silicon, which are cut into circular slices with unique pieces of machinery. Wafers are generally of a diameter between 200 and 300 mm. This step, and all the others that follow, occurs in specialized centers known as *clean rooms*. In addition to particular temperature and humidity control systems, these rooms are essentially dust-free. There can be no more than one atom of dust per 10 liters of air.

- At this point in the process, silicon is still an insulating material that cannot conduct electricity. In the oxidation step, ions – in the "*sputtering process*" – or chemical vapor decisions are used to deposit an oxide film on the wafer. This film serves to shield the wafer by protecting the surface. These layers form the material on which the circuits will be applied.

- The wafer is then coated with a photoresist coat. This step serves to prepare the wafer for etching and deposition. A positive resist is typically used in the semiconductor market, which will make the areas irradiated by ultraviolet energy more soluble.

- At this point, one of the most critical steps in the entire process, photolithography, begins. The film is covered with a photomask containing the circuit design patterns. These patterns are specifically designed at an earlier stage when a 3D copy of the chip is drawn using special software. The wafer is exposed to deep ultraviolet (DUV) or extreme ultraviolet (EUV) light. This step is also very delicate, as the pattern must be represented on the wafer perfectly.

- This is where the etching process begins. A part of the wafer, which was not affected by the previous process, is cut. If a liquid is used, the process is called wet etching; if a gas is used, the process is called dry etching. This procedure removes the thin layer on the wafer to reveal the pattern.

- Now, the deposition phase begins. The photolithography step and the etching part are repeated several times so that several layers are formed. A layer is added each time to protect the wafer and the previous step cycle. Ion deposition consists of bombarding the wafer with ions to activate its conductivity properties. It also involves the addition of impurities so that the ability of the material to conduct electricity can be altered as required.

- The final step is the addition of a metal interconnect, consisting of an aluminum or titanium film, to ensure the passage of the electrical signal.

- In the electrical die testing, the chips are tested to check that they meet standards and are ready to be put on the market or integrated into a machine. Each wafer must meet a yield of at least 90%. Yield is calculated by dividing the number of working chips by the total number of chips on each wafer and multiplying the result by 100. When each wafer has been checked, each chip is cut into the so-called "dies." The chip die is then placed onto a 'substrate,' a baseboard for the microchip die to direct a chip's input and output signals to other parts of a system, while a *'heat spreader'* is placed on the top (ASML). The chip is then marked with the production company's name and the foundry to keep track of its path.

A *package* defines a chip assembled and ready to be integrated into a system, while a *module* indicates a set of packages ready to function in a particular machine. Each chip's manufacturing process can take twelve to twenty-six weeks between the first and last step. Counting the time to conduct tests and functionality checks, it can be as long as twenty-six weeks. Within the semiconductor production chain, particular attention is paid to the total time needed to produce a chip to its optimization as production scale is central. From a manufacturing point of view, the foundries where semiconductors are produced operate continuously 24/7 without ever stopping.

Most of this processes have to be carried out by specialized engineers due to the high complexity of the operations and the cost of the machinery used. Shifts continue all days of the week, day and night to assure the continuity of the production line. This would be the reason for the automotive chip shortage. During the Covid-19 pandemic, car production came to a halt. The foundries, essentially operating on economies of scale, retooled production chains for different types of chips. By the time automakers returned to place orders, the foundries had found other customers, leaving a global void in automotive chip and sensor production.

Averagely the production price for a chip can range from 1$ to more than 100 $. The latest A16 Bionic by Apple has a production cost of 110$. Selling margins can be very high a chip from Intel can cost up to 600$ for a laptop system, while a mobile SoC from Qualcomm can represent almost the 20% of a smartphone price.

A historical analysis of regional clusters

The first semiconductor cluster originated in the United States in the Silicon Valley. Silicon Valley can be defined as the cradle of semiconductors. Silicon Valley chips hub was born in Santa Clara, not far from Stanford University. Today is home to forty of the world's leading digital and technology companies. Shockley Semiconductors Laboratory was the first firm to bring semiconductor manufacturing to California. This company had been a major investor in Bell Laboratories, which is the company that essentially invented the modern concept of transistor (Miller 2022).

Some engineers of Shockley decided to leave the company to found Fairchild Semiconductors in 1957 in Santa Clara. Together with Texas Instruments, it was the first firm able to develop integrated circuits for industrial purposes. The history of Silicon Valley is also closely tied to that of Stanford University. Just before the mid-1950s, Stanford's electrical engineering department had become a national and international benchmark in the research on cathode ray tubes - used before transistors for electrical systems - . It was a partnership between the city of Palo Alto and Stanford that created the first laboratories in the U.S. for academic research on semiconductors (Miller 2022). The U.S. semiconductor hub ruled the market unchallenged for at least twenty years. It reached its zenith by developing consistent semiconductor technology for industrial application without any international competitor. This innovation process led to the birth of Intel in 1960, which would become one of the world's most important players ten years later. In the following years, Silicon Valley became the home of major tech companies such as Google and Apple, but semiconductors' production and manufacturing declined steadily.

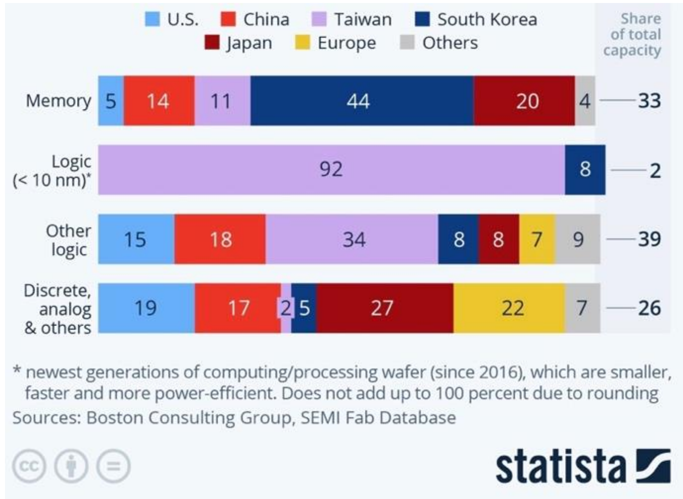
The first regional cluster to challenge Silicon Valley was Japan. The country was the first Asian power to develop a semiconductor industry capable of competing with the United States. Through an industrial policy of massive government support, Japan managed to catch up with the U.S. in terms of technology development and to take over some market, in particular in the memory chips one. U.S. companies responded by withdrawing from competition in the production of chips where Japan seemed to have gained an irretrievable competitive advantage (Japan's Semiconductor Industrial Policy from the 1970s to Today). Japan sovranity was multi-factor. Japan products were more technological advanced, had a lesser production yield and a subsequent cost advantage (Japan's Semiconductor Industrial Policy from the 1970s to Today). The success of Japanese semiconductor manufacturing peaked in the late 1980s when the country's share of integrated circuits accounted for half of the world's total (Japan's Semiconductor Industrial Policy from the 1970s to Today). Between the 1980s and 1990s, six of the top ten companies in the market were Japanese. The Japanese champion was NEC, which surpassed Texas Instrument in production in the mid-1980s.

Then, in the 1990s, the Japanese market started a fast-collapsing path that led country's production below 20 percent (Japan's Semiconductor Industrial Policy from the 1970s to Today). There were two main reasons for the decline of the Japanese semiconductor industry. The first was endogenous; the golden years of Japanese semiconductors coincided with strong economic development and growth. Japan failed to maintain its ecosystem by slowing down on strategic investment and research financing (Japan's Semiconductor Industrial Policy from the 1970s to

Today). Then, when the market stabilized in the 1990s, and the demand for integrated circuits shifted from DRAMs to CPUs - due to the need of processor for computers - the country's system proven not to be as dynamic as the world innovation rate. The second cause was exogenous and connected to a radical change in the ecosystem. The emergence of foundries challenged the model of Japanese integrated companies. For example, in the case of Hitachi, the IDMs failed to come on the market with competitive hardware devices and couldn't find a marketable way to sell its chips separately.

With the collapse of the Japanese ecosystem, the United States regained important market share, especially in chip design, while manufacturing took a different path. By the end of the 1980s, Japan's dominance of the chip market, especially memory chips, had ended. For integrated companies, the manufacturing process shifted to new clusters, including South Korea, Taiwan, Singapore and even Europe. Integrated companies, especially those based in the United States, began to invest in controlled foundries in Asia hoping to gain from the cost advantage. American companies began to make structural investments overseas to regain market share attracted by the low cost of labor and by the tax incentives made available by those countries. These investments were intercepted, for example, by Singapore, which preferred to bring in machineries and knowledge through foreign companies rather than develop its domestic industry (Miller 2022).

In Korea and Taiwan, the situation evolved different. Both countries had a political and entrepreneurial elite focused on improving the country and convinced of the need to collaborate. They invested heavily in national capabilities. South Korea was quick to fill the market void left by Japan when it began to lose competitive advantage (Kim 1998).



Today's manufacturing market is dominated by Taiwan in cutting edge logic chips. South Korea leads the memory market and possess some production capabilities for under 10nm logic chips. Mid to low level chips manufacture has a more heterogenic regional composition.

For several reasons, South Korea is one of the most interesting cases in the global semiconductor market. In the mid-1980s, Korea was not a technologically advanced country, its tech capabilities were basic; and even if it had begun a process of economic recovery, in the semiconductor sector, its contribution among the world's producers was theoretically zero (Kim 1998). However, in 30 years South Korea was able to gain the 14.2 percent of the total production of chips worldwide (Kim 1998). Korea today holds approximately the 77 percent of DRAM memory chip production throughout two integrated companies, Samsung and SK Hynix. The importance of Samsung in the country's technological development is particularly noteworthy (Kim 1998). In less than a decade, the Korean company became the seventh-largest global player in 1993 and it was the first global company by market revenue in 2021, with more than $65 billion sales("DRAM | Memory" n.d.). Samsung fostered the development of a true domestic ecosystem, including SK Hynix and Goldstar, creating a new type of relations between private enterprises and the Government. The case of Korea is fascinating as the country managed to create a cluster in exceptional times and without any technological base. One of the fortunate factors in the Korean experience was probably that the country's companies started producing mainly for the external market, because there was not actually internal market. The country entered the international competition with a positive trade balance that was able to support the initial production effort. However, the Korean ecosystem showed all its limitations when it failed to enter the production of other types of integrated circuits and remined stuck in the limited market of DRAM (Miller 2022).

At the same time, the manufacturing market vacuum created by the emergence of fabless companies was intercepted by the island of Taiwan, where the first Pure-Play foundries were born. In the late 1980s, the island of Taiwan recognized the need to develop a specific technological expertise within the country that would enable it to play a major role in the global economy.

Until then, Taiwan's economy had been based primarily on agriculture and the production of simple, low-quality technological components. Taiwan's history is also linked to the insight of one man, Sun Yun Suan, at the time Minister of Economic Affairs. He was able to understand two things. The first was that to survive, Taiwan would have to develop a major competitive advantage and become a bottleneck for global economy (ISPI). This doctrine was a matter of life and death for the country, becoming economically necessary for the word was the best defense against mainland China.

The second was the importance of applied science research centers in opposition to the classical dichotomy between firms and universities, mainly focused on theoretical research. Taiwan first tried to build competitive advantage in other sectors, such as the chemical industry, but the efforts failed. Then, when it thought of entering the semiconductor market, the Taiwanese government invited an American company, RCA, to bring its knowledge to Taiwan, financing the first operation of knowledge transfer in the history of semiconductors. At the same time, the Institute for Technology Research Institute (ITRI) was created (Miller 2022). Taiwan's first attempt to enter the semiconductor industry went very badly. The first company, United Microelectronics Corporation (UMC), had a traditional structure based on the model exported by the Americans. This company could never establish itself globally and had to close down after a few years of domestic operations. TSMC's success came soon after two adjustments. The first was TSMC's founder Morris Chang. He was called to the island of Taiwan with the specific objective of building a firm able to compete globally. Chang, after a long career in the U.S. chipmaking sector, suggested entering the market with an innovative model. Chang, coming from the U.S., understood before others that the market was shifting towards a new paradigm. Leaving behind the integrated model was the best choice at the best time. The second reason for Taiwan's success was probably a partnership between the island of Formosa and Philips. This time the technology transfer worked perfectly, and TSMC soon became profitable.

However, it is impossible to provide an overview of the historical and geographic distribution of the semiconductor market without discussing the evolution of I.C. manufacturing in the People’s Republic of China. China plays a central role in today's semiconductor ecosystem. First, China's domestic market is one of the largest in the world; Hong Kong is the world's leading importer of semiconductors, accounting for 26 percent of total imports (OEC, 2022). In addition, China, excluding Hong Kong, imports 21 percent of the world's semiconductor production (OEC, 2022). An analysis by CSIS, showed how China in 2020 did spent more money in semiconductor’s imports than in oil.

Given these figures, it is clear how important it is for China's strategy to develop strategic autonomy in this sector. Mainland China has made many attempts to structure domestic production, and while it is certainly a major player in the market today, it has not yet achieved the desired results.

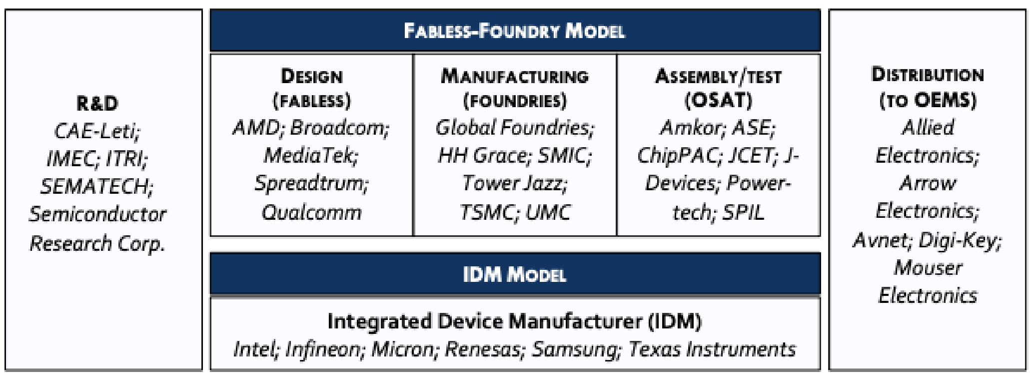
The development of semiconductor manufacturing in China can be described by analyzing this industry's two main historical phases. In 1960s, Communist Party cadres in China were already aware of the importance that transistors, and later integrated circuits, would have played in the future global economy. In light of this awareness, and contrary to what is usually told, Communist China's efforts to bridge this gap began in the late 1950s.

The first plan in China occurred between 1956 and the early 2000s ("Chipping Away: China's Long March toward a Strong Semiconductor Industry" n.d.). Overall, this period was marked by major failures, but it served to build the country's technology and knowledge base for the second phase. China's centralized economy entered the semiconductor sector through five-year plans. In the first period, China focused on developing indigenous innovation. The cornerstones of this innovation included the creation of a skilled workforce and the development of the first factories in the country. However, the period before the Cultural Revolution was marked by the failure of all five-year plans, which never achieved their goals ("Chipping Away: China's Long March toward a Strong Semiconductor Industry" n.d.). The technology developed in China during these years was fifteen to twenty years behind that of the United States during the same period (Miller 2022). When in the seventy Intel was making complex integrated circuits, Chinese companies struggled to produce simple diodes and transistors. The failure of these early industrial plans was probably because China was working on two parallel structures, theoretical research and industry application, without finding a combined approach. The situation changed significantly when, in the 1980s, China began to import semi-new technological equipment from the West and to encourage knowledge transfer with it. Also crucial was establishing the Computer and Large-Scale I.C. Lead Group, the country's first semiconductor research center (Miller 2022). Of particular importance were strategic partnerships with major Western and Japanese companies. These exposed Chinese manufacturing to the global market for the first time. If on the one hand, it highlighted to the world Chinese weaknesses and delays; on the other, it gave a sense of what needed to be done to close the gap. The 1996-2000 five-year plan represented the first real success of the Chinese strategy in its "integrated" version. A Chinese company called Huahong entered the DRAM business through a joint venture with Japan's NEC and was able to operate in the international market. Although Verwey attributes this success to the terms of the partnership, which involved specialized Japanese engineers working in China, this operation demonstrated to the Chinese establishment that the path towards a catch up was theoretically possible. From the early 2000s to the present, the attention and effort in the semiconductor segment in China has grown exponentially. Through ever-increasing investment China funded its industry with billions of dollars in twenty years (Bruegel, 2019) and the country has achieved some successes. The first was to create two industrial clusters in Shenzhen and Shanghai. The second has been the development of some competitive companies, notably SMIC, HiSilicon, and YMTC. The value of China's exports has reached 154 billion, accounting for 19 percent of global production (OEC, 2022). Sales of Chinese integrated circuits have grown by nearly 30 percent per year, demonstrating the international role of the Chinese industry. In addition, China has undergone significant structural changes that have led the country to participate more in the global economy and integrate into the semiconductor ecosystem (“Chipping Away: China’s Long March toward a Strong Semiconductor Industry” n.d.). In particular, China has invested heavily in research and development, increasing by nearly 40 percent per year over the past decade (“Chipping Away: China’s Long March toward a Strong Semiconductor Industry” n.d.). Particular attention has been paid to human resource development and new technologies. Although great strides have been made, China's semiconductor industry faces enormous challenges on the strategic and innovation fronts. First, China still has considerable problems producing next-generation chips, especially CPUs, GPUs, and DRAM for high-performance applications. China still imports almost 100 percent of these products, and the road to domestic production is still challenging (OEC 2022). It is no coincidence that in the list of the most performant CPUs for smartphones, the only Chinese chip producer is HiSilicon, and it has lower yields than three or four years ago models of its competitors. The U.S. ban on chip and machineries export to China was a major setback for the country (Bluhm 2022). The 2022 comprehensive ban comes after the precedent smaller bans over targeted Chinese companies as Huawei and ZTE. It forbids American firms and foreign companies that uses American technologies indirectly to share or sell semiconductor technology with Chinese enterprises (Bluhm 2022).

One point need to be made to conclude this historical-geographical panoramic of the semiconductor ecosystem. Dozens of other countries are collaborating and contributing to the universe of semiconductor manufacturing, including Vietnam, the Philippines, Thailand, Malaysia, and European players such as Sweden and Switzerland. These countries testify to the complexity of the I.C. value chain and, through their relevance, to the fact that **statements that look to oversimplify the semiconductor market in a linear national confrontation between China and the USA do not consider the level of interconnectedness that this industry has achieved over the years.**

The nature of the ecosystem

The term ecosystem defines the entire value chain involved in the complex semiconductor manufacturing process. For two decades, the semiconductor ecosystem has seen critical structural changes. Two different types of business organizations in the manufacturing process have emerged as a result of these changes: Pure-Play foundries and Integrated Design Manufacturers. Pure-Play foundries are firms only involved in the physical manufacturing of the chip. They work on models designed and agreed upon with third parties. Today's biggest Pure-Play foundries are TSMC, Global Foundries, SMIC, and UMC. IDMs are involved in all the phases of chip's creation, from the design steps to the delivery of the final product to clients or its direct implementation in their property hardware. Examples of IDMs are Samsung, Intel, Micron and SK Hynix.



Summary of the two main governance modes within semiconductor manufacturing.

Pure-Play foundries win bid for clients that sought to manufacturer their chips. Primarily these clients are Fabless firms. Fabless companies are responsible for designing the chip architecture, from the patterns to the electrical connections. Fabless companies design chips for their devices, such as Apple, or for third parties, like NVIDIA. Foundries adapt their property technology to fabless companies’ designs and compete to produce chips with the required specifications in the shortest possible time and with the highest quality. In addition, there are companies referred to as fab-lite. Although these companies rely on foundries for most of their wafer production, they keep some strategic foundries under their control, for instance, for research and development or specific product lines. However, the design phase rarely occurs completely in-house, even in fabless companies. Instead, they buy basic design architectures from specialist companies called Design Houses, which are the valid starting point of the chip's value chain. These companies also act as 'conduits' between fabless companies and foundries; they are in charge of adapting the chip to a suitable design to be implemented in a production chain.

Foundries have evolved intensively over the years. Until the 1980s, all semiconductor manufacturing companies were integrated. The market then underwent two significant changes. **The first was that as technology evolved, prices rose, and it became more expensive to produce wafers** (Miller 2022)**. The second was that the ecosystem became more specialized and complex**. As a result, many IDMs started producing fewer chips, specializing in specific segments. Thus, IDMs created a market for trading wafers until some firms realized they no longer needed to produce chips as they could outsource production completely. Margins were growing in the manufacturing segment and some players abandoned the upstream part of wafer development and designing to focus exclusively on manufacturing. This process led to the emergence of the first foundries, culminating in 1987 with the birth of TSMC. It accounts for more than 50 percent of today's global production and intercept the 60% of the total revenues of the foundry business (CNBC 2023). TSMC is the critical bottlenecks of the ecosystem as world chips production relies almost completely on its foundries for cutting-edge technologies.

Foundries are responsible for integrating all the supply chain from the raw materials to machineries, in order to build and assemble the final product and their core business is in the mass production of retail products for large technology companies. Another historical trend in foundries development has been the speed with which companies have risen to the top of production and then gone bankrupt or been taken over by competitors. An estimated 158 foundries are active in the semiconductor ecosystem today, counting integrated companies (Foundry 2022). There are three main reasons behind the survivance of this little number of companies in this market. **The first is the high investment costs required to achieve economies of scale and start production.** The cost of machinery to produce semiconductors is very high, making entry barriers particularly difficult to overcome. **The second is related to the advanced technology required, which is constantly evolving, forcing foundries to invest continuously to keep up with the latest developments in the field.** In addition to these two reasons, **a third possible analysis relates to customer loyalty and integration**. When a fabless company and a foundry work together, they are forced to share large amounts of information, creating a solid convergence between them.

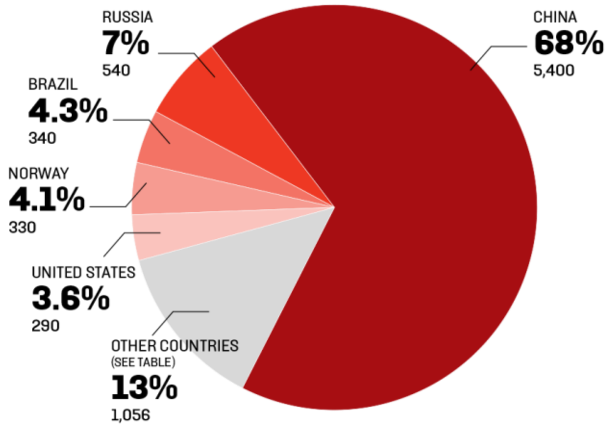
The second business organization model in the semiconductor ecosystem is the Integrated Device Manufacturer (IDM). These companies have internalized all stages of the production process and purchase raw materials and machinery directly from manufacturers. When semiconductor manufacturing was in its infancy, IDM was the only business model that existed, whereas today, only a fraction of companies continue to operate as pure IDMs. Companies' decision to continue to manufacture its semiconductors seems to be related to innovation and R&D. Integrated companies can better protect their trade secrets by not having to share information with foundries. They are also less exposed to market and supply chain uncertainties as they have complete control over their foundries. However, also IDMs have evolved. While in the 1970s, American IDMs produced and designed chips in the same location, in the following years they invested heavily in relocating production and establishing new research and development centers worldwide.

In reality, IDMs and foundries are not as separate as they are normally described. Some IDMs use their foundries for third-party projects, trying to steal business to Pure-Play foundries. This strategy also helps IDMs to keep the production line of their foundries actives in periods when they are experiencing problems in selling their own products. An example could be Samsung producing Google's chips. There are also Pure-Play foundries that try to develop design capabilities for some specific projects. For the sake of the research output, this paper will consider IDMs and Pure-Play foundries as direct competitors and the two industrial organization methods alternatives for chip production.

This brief description has provided a context for the comprehension of the critical nodes in the semiconductor manufacturing ecosystem. However, it is essential to remember that the ecosystem comprises hundreds of other companies involved in supplying raw materials, specialized machinery, chemical materials such as solvents and reagents, logistics, and transport. In particular, the work of the Dutch company ASML should be mentioned for the purpose of this research. ASML manufactures the machines for the photolithography stage. These machines are complex precision instruments and use sophisticated software to function. Photolithography machines are one of the most critical nodes in the entire ecosystem. The wafer size to be used depends on the technological innovation of the EUV lithography machines, which are the most advanced on the market. Only machines capable of printing wafers of 300nm can produce the most advanced five and 3-nm chips. ASML's machines cost between 150 and 250 million and are customized according to the specifications required by clients, IDMs or foundry.

The role of resources

The most important material utilized in the production of chips is silicon. Silicon is used to build wafers. Wafers are the first layer of every chip. Today, silicon is produced in China – that extract more than two-thirds of the eight thousand tons extracted globally – U.S. and Russia (Statista, 2020).



Shares of silicon per country

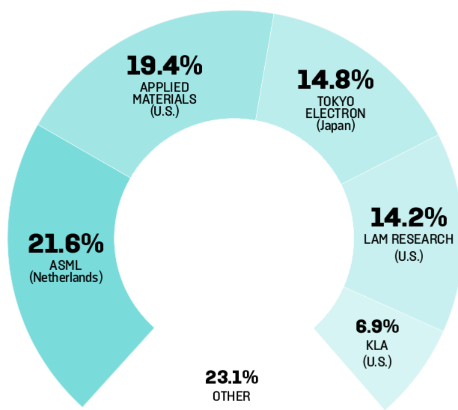
In order to reach precise standards of purity and sleekness, silicon must be chemically treated by specialized companies. There are about ten competitive producers of wafer silicon lingots, equally divided in the U.S., China, Japan, and Europe, specifically in Norway.

Nevertheless, Silicon is also the second most common element occurring in nature, and the chemical processes to transform it in lingots do not involve critical or extreme challenging steps. For this reason, firms do not usually have problems procuring this material. Historically, when silicon was chosen in the 50s for wafer production, its properties were weighed in with its accessibility and malleability. Silicon was very present in the U.S., and still today, the capacity to secure stocks of silicon is acceptable for most companies. Silicon is not the only material used for the production of wafers. Gallium Nitride and Germanium are both alternatives to silicon. For some time, Germanium was seen as the most promising element for chip mass production; germanium's attention shrunk when its characteristics were proven to be less competitive than silicon.

Nevertheless, Germanium and Gallium Nitride are making an essential comeback in the sector. Even though they are still niche products compared to silicon, as Moore's law is approaching its physical limits, critical experiments are being conducted on these materials to exploit their scalability characteristics. Other significant materials used in chip production are chemicals. One foundry averagely uses more than 400 chemicals throughout the process (Williams and Khan, n.d.). Big companies such as TSMC have two or three suppliers for every chemical product, and the most complex objective seems to be the organization of the supply chain rather than the accessibility per se. An important element is the natural resources accessibility in the semiconductor production. Foundries consume massive quantities of water and energy throughout the process. A fab can use up to 18 million liters of water daily to produce a mid-level 30 nm chip. Regarding energy, foundries need the power of a small city to sustain their capacity. A foundry uses up to 100 megawatts of power per hour, which is what 50,000 households consume in a day (Cheng, Gautam and Weig) . The availability of water and energy is one of the reasons behind the chip production migration from the West to the East. A foundry producing in Italy can accumulate during the year a surplus in energy cost of 8 million, compared to the same fab in Asia and 15 million compared to a direct competitor in the U.S.. Energy costs are between 5% and 30% of their total operating costs (Cheng, Gautam and Weig). As noted before, neither chemicals nor energy or water have a per se accessibility problem, but the price of these resources can influence a firm's strategic decisions. On top of that, as foundries usually work on a 24/7 production shift, the continuous need for these resources recalls the notion of uncertainty closely linked to the latest political happenings and the subsequent energy crisis.

Raw materials are not a significant barrier in the production of semiconductors. They pose a logistic challenge to guarantee the smooth continuation of the production chain and are a critical factor to be considered in cost-related strategies. However, in absolute terms, raw materials do not help to identify the reason behind a successful company or a failing one (Hart 1995).

In the semiconductor market, certainly, physical resources play a central role. Between the resources mentioned in Barney's definition, machines and precision instruments, are among the most valuable. The uniqueness of these instruments allows only those with the economic strength to purchase them to produce semiconductors.



Main producers of machineries

ASML collaborate with every firm in the world, except for Chinese companies to which it cannot sell the most modern machines due to a Dutch ban, probably prompted by U.S. indication (Aljazeera, 2023). ASML cooperates with all manufacturing companies and develops independent projects with them. Despite the fact that ASML manages, through its machines, together with its customers, the speed of innovation in the industry, all manufacturers are working simultaneously on very similar nodes. ASML adapts its machines to each company's requirements, but specific projects never differ too much form the technology available to all. This system represents ASML's winning business model. On the one hand, the company can develop the technology every manufacturer needs. On the other hand, it can work closely with the individual needs of each customer, from integrated companies to foundries. The role played by ASML's technologies in semiconductor innovation critically reflects on the role of resources such as photolithography machines among the chips producers. First, if all customers can purchase a photolithographic machine from ASML, then this machine is not a *rare resource* as much as it is a *valuable one*. In Barney's definition, the term *rare* should not be confused with *essential*. ASML machines are in every sense *essential* for semiconductor manufacturing, but by operating freely in the market, ASML does not produce *rare* machines. The ability of a manufacturer to enrich the purchase of a machine with a partnership able to develop the machine's functionality can be pointed to be more related to knowledge than to resources. The example of photolithography machines and, in general, of all resources used in chip production is that **there are no rare resources to date that are not present in the market.** An exception need to be made for China that under U.S. and Dutch bans can't access essential technology.

The current state of the semiconductor ecosystem thus seems to unambiguously demonstrate that "It is not the value of an individual resource that matters, but rather the synergistic combination or bundle of resources created by the firm" (Kraaijenbrink, Spender, and Groen 2010).

Applying the KBT to the semiconductor market

A significant difference lies in the existence of two types of chips: memory and logic. Dynamic memory chips, such as DRAMs, fall into the former category, while other chips, such as processors, fall into the latter. To date, all DRAM producers are IDMs, while all mobile processor companies are fabless, delegating manufacturing to Pure-Play foundries. The reason for this is the nature of the knowledge required to produce these two different types of chips. Memory chips have less coded structures and more difficult variables to control in their evolution over time. Their development creates problems very close to those Marcher defined as ill problems. Logic chips, on the other hand, have miniaturization as a significant goal in their development but follow more coded patterns in their evolution process. In the case of memory chips, an integrated structure has several advantages. First, it avoids the dispersion of knowledge and the need to share inventions with outside manufacturers. Second, combining manufacturing and design in the same company leads to increased knowledge spillovers. If these are linked to routines, values, and the community, then using the same workforce for each project increases the likelihood that the cost of knowledge transfer will decrease over time. IDMs would then have a cost advantage - eliminating transactions involving knowledge - and a security advantage. Through their integrated structure, IDMs would absorb the risks of developing dynamic and risky technologies by being able to manage their production chain directly. This would give IDMs the power to produce at scale and thus optimize each product relatively freely.

On the other hand, logic chips' design firms develop advantages outsourcing production to Pure-Play foundries. As they are more static products with architectures shared by both fabless firms and foundries' proprietary technologies, the knowledge required to solve problems connected to this kind of chips should be lower than for memories one. In this area, Pure-Play foundries have an advantage by having to focus on fewer problems other than optimization and miniaturization. **KBT clearly explains governance modes within the semiconductor industry and underlines the reasons behind the competitive advantage of some companies over others. It is no coincidence that in the mobile microprocessor industry, to date, commanded by Qualcomm, MediaTek, and Apple, all IDMs have been eliminated or absorbed. In the memory chip market, on the other hand, precisely the opposite has happened. The reason stands in how knowledge influence the type of problems firms has to deal with and the solutions they apply.**

Knowledge-based theory could also be a tool for understanding how competitive advantage is created by firms in the semiconductor market. First, knowledge is the basis of all operations performed in a firm. If the business environment is characterized by bounded rationality, then knowledge arise as the main tool for organizing resources and processes. Therefore, creating knowledge-based capabilities in uncertain environments enables firms to differentiate themselves. In manufacturing, tacit knowledge plays a significant role. If resources lead to competitive parity, routines and processes create competitive advantage. They foster innovation and sustain advantage in the long term. History shows that chip's replication is almost impossible (Miller 2022). Despite knowing the theoretical principles behind chip creation and having access to the same technology as competitors, the resulting output has different levels of optimization and accuracy.

The previous chapter has examined Transaction cost theory and the Resource-based view of the firm. Both they have only partially helped to explain the current conformation of the semiconductor ecosystem and have yet to help illustrate the underlying reason that leads some firms to success and others to failure. Both fail to explain the root causes of competitive advantage when applied to the semiconductor ecosystem. **The characteristics that make knowledge a central factor in building competitive advantage can be reduced to three elements. First, because tacit knowledge results from routines and other forms of implicit behavior, it cannot be copied. The inimitability of tacit knowledge implies that there is no market for this type of resource: thus, it is firm-specific. In semiconductor manufacturing know-how is what seems to determine advantage as it leads to a heterogenous usage of machineries that can be found in the market. Second, knowledge is subject to economies of scale; the cost of applying knowledge decrease as know-how and implicit knowledge increase. For this reason, technological catch up are very difficult in the semiconductor market. As it evolves at a lesser**

cost than the initial effort, firms chasing that knowledge are destined to stay behind. Third there is a vital element of chance in the development of knowledge. Sometimes, firms arrive at specific results before others because of a combination of intangibles skills whose composition is random and accidental.

Inter-firm collaboration

Looking at the list of the top ten companies in the semiconductor market, one would be surprised by three pieces of news: Five companies work closely together to make a single chip. Eight of them work indirectly together to realize a SoC, a set of chips that allows our cell phones to make calls, play videos, take pictures, and send emails. All of them are enduring a strategic alliance with at least one partner.

The semiconductor sector is one of the most competitive technology sectors in the world. However, its ecosystem, rather than resembling a bloody battle for monopoly between the top ten companies, is a complex network that oscillates inexplicably between collaboration and competition. Strategic alliances have made the history of semiconductors; some have changed our lives more than we can imagine, like the partnership between ASML and Zeiss for EUV machines. This paragraph will delve into the reason behind this phenomenon.

Supposing that the first proposition has been validated, and companies in the semiconductor industry are institutions focused on knowledge creation. In that case, the goal of strategic alliances will be to share knowledge in specific areas between partners. Knowledge in such complex systems can only be developed through specialization. Therefore, when two companies enter a strategic partnership, they will try to acquire knowledge in complementary areas. A similar phenomenon has been analyzed in the formation of clusters. In alliances, however, the geographical component is lost, so clusters are created without the need for companies to be physically close to each other. A strategic alliance is a formal collaboration between two or more organizations that join forces to pursue common goals or objectives while maintaining their distinct identities and ownership (Investopedia). These alliances are formed to leverage each other's strengths, resources, expertise, and capabilities in order to achieve mutually beneficial outcomes that might be challenging to attain individually (Heck et al. 2011). Strategic alliances can take various forms, such as joint ventures, partnerships, consortia, or cooperative agreements. They can occur across different industries and sectors, ranging from business and technology to research and development, marketing, distribution, and more. The primary purpose of a strategic alliance is to create synergies and competitive advantages by sharing risks, costs, knowledge, and market access. Firms well performing in the semiconductor market, according to Heck et al. (2011), do endure frequently alliances with customers and competitors.

Usually, firms in the semiconductor market interact with three kinds of partners. The first are the suppliers, bidders, and, in general, all the actors on their value chain. For foundries and IDMs, this is on a daily agenda and happens frequently. When a company forms a partnership with a customer or a company that operates in other segments, the benefits are clear. For example, Micron developed a strategic alliance with Intel to integrate its DRAM with Intel chips. This saved Micron significant business development resources while sparing Intel's major market coordination problems. In this type of alliance, knowledge is essential but not central, as both companies continue to focus on their market characteristics. Teece defined the rationale behind this type of alliances as the quest for *complementary assets*.

Acquisitions and investments could also be considered forms of interfirm collaboration. A concrete example of how firms use equity to access knowledge is the acquisition of LFoundry by the

Chinese giant SMIC. There were two main reasons for this acquisition, which reflect widespread practices in the industry. First, SMIC wanted to enter a new market by expanding its physical presence in Europe. The second reason was that SMIC probably wanted to take over LFoundry's manufacturing processes and indirectly absorb the knowledge that Micron had brought to the company. At the time of the acquisition, the two foundries were producing at very similar nodes between 100 nm and 90 nm. It is likely that SMIC needed input to develop its technology and found it in LFoundry.

A more complex example of a strategic alliance is the one involving ASML and different investors, all competitors between them. Although the exact figures are unknown, TSMC, Intel, and Samsung have invested heavily in the R&D of ASML. This strategic alliance have very unique characteristics. First, the companies are all in direct competition with each other: two IDMs and a foundry. All three invest separately to help ASML develop new technologies, and all three get access to them in return. This does not create a competitive advantage but assure the investors with the instrument to build up the opportunity to develop their advantage. This process assures a steady global technological development for all the industry. In fact, although Intel had access to the same ASML technology as TSMC to develop 4nm chips, it missed its targets two years in a row. **Strategic alliances in the semiconductor industry spur knowledge creation and sharing to create the precondition for competition while laying the foundation for innovation development.**

Consortia and standards

Consortia are cooperative relationships between many businesses, usually from the same sector or others close by, that get together to pool resources, share knowledge, and collaborate on tasks that interest both parties (Cambridge Dictionary). Consortia involve collaborative research that brings multiple distribution and manufacturing firms and industry associations across diverse lines of trade together to solve an industry wide challenge (Industry Consortia, Texas A&M University). Consortia can be of different types as pre-competitive, standard-setting, and research consortia. The most prominent example of a successful consortium in the semiconductor industry is SEMATECH. SEMATECH, established in the U.S. in 1987, was created by American semiconductor producers worried and damaged by the threat of the Japanese semiconductor industry (Miller 2022). SEMATECH was created as a space where firms could collaborate together to develop pre-competitive information and technologies and lower expenses and risks. SEMATECH represented the attempt to help businesses overcome obstacles by boosting innovation through knowledge and IP sharing. The consortium was definitely important in helping the American industry to regain market shares.

Standards play another essential process in inter-firm collaboration in the semiconductor sector. As it was possible to confirm through interviews, leading firms in the industry meet numerous times every year to discuss the standard for their next generation of products. This process allows different chip producers to integrate their characteristics with the industry. Developing a cutting-edge chip is a small part of the story; if other complementary chips can't support it, the technology is useless. For this reason, chip makers set the standards for product characteristics and specifics before going to the actual manufacturing process. More interestingly, standards are being set even among companies producing the same chip type.

Brief analysis of the DRAM market

Currently, 45 percent of the DRAM market is controlled by Samsung, and the remained part divided between Micron of the United States and Hynix of Korea (Statista 2022). This market can be considered a perfect sample to analyze the hypotheses validated in the previous chapters empirically. From a historical point of view, it has undergone a steady evolution. In the 1990s, Japan took over almost 100 percent of production from the United States; in the 2000s, South Korea emerged as the leading producer, thanks to substantial public investment, and at the same time, the United States returned to competition. Nonetheless, Asia now accounts for almost all DRAM production, as Micron has relocated its foundries there, due to the almost complete absorption of the Japanese competitors. To date, only IDMs produce DRAMs. This is due to the reasons analyzed in the KBT section. Only integrated companies can handle the evolving dynamics of these chips, and this model is very robust in protecting critical production information. Nevertheless, the three leading companies agree each year on the specifics of their memories. Interestingly, standard setting also takes place between companies that are direct competitors. In a sense, standard setting is used as a way to define the state of competition within the market. Based on these standards, each of the three companies tries to develop its competitive advantage. One is often inclined to think of the semiconductor industry as a race that has just begun; the results of this analysis essentially prove otherwise. Companies in the DRAM market, have no intensive will to gain new market share from the others. The first reason given was that the extreme miniaturization process and the architectures' complexity over the last decade have led manufacturers to develop a very high degree of specialization. This specialization has been reflected in a high degree of interaction between players along the value chain.

On the one hand, this has created an increasing level of loyalty between designers and manufacturers and between IDMs and their customers. Operations such as Apple's abandonment of Intel chips are sporadic because the level of integration inevitably leads to significant problems in changing suppliers. A second point is that there are now generally two or three direct competitors for each manufacturing segment. Since each of these has its value chain, there are only three or four types of next-generation chips in the end market in competition. The market is big enough to satisfy all the producers.

Indeed, chipmaking could have entered a new phase. The market has stabilized, and the race turned into a position war. The focus has shifted to political factors, and the ecosystem reflects these changes.

Chapter 3

The role of States

Governments have been deeply involved in the development of the semiconductor industry since its inception. The first applications of semiconductors were limited to the defense industry. Silicon Valley's chip manufacturers emerged as almost wholly owned subsidiaries of the U.S. Department of Defense. The proliferation of technological consumer devices opened the way for civilian use of the technology. The civilian sector proved more profitable for chip companies and more likely to sustain innovation (Miller 2022). Nevertheless, the military use of chips has remained constant. Government interest in these technologies has grown as geopolitical tensions have skyrocketed in the last decade. Chips find strategic applications in missile systems, navigation devices for airplanes and helicopters, radar, and other military equipment.

The military application of semiconductors overlapped with the most acute years of the Cold War. While the U.S. dominated the chip market, building the technological infrastructure and fostering the academic and industrial ecosystem, the USSR was destined to lag decades behind. Sensing the importance of chips in warfare equipment, the USRR began to develop its own research and industrial program. The Soviet Union made a desperate attempt to copy U.S. chips. Soviet scientists testified to the critic role of tacit knowledge of semiconductors manufacturing (Chips War 2022). Despite being backed by an advanced international espionage program, they failed in their attempt to recreate the leading American technology, reiterating the essential truth that know-how cannot be assimilated by deconstructing an end product (Miller 2022). Economic and world leadership has been steadily in the hands of the U.S. since the end of the Cold War, and semiconductors as well as technology have done the same.

Recently, American leadership in the technology sector has been challenged, in the technology sector, by several Countries. In the chip industry, Japan and Korea are the most prominent examples. Nevertheless, despite the introduction of competition and retaliation measures, the U.S. has never been substantially threatened by these emerging regional powers. Their political ambitions are limited to a specific regional area, and they lack the economic and military resources to challenge the leadership of the United States. Japan and South Korea have been struggling with diverse problems related to difficult post-war recoveries and reconstruction. They emerged as important economic actors, being the 3rd and 13nd world economies for GDP, but for historic reasons both flourished under the *American pax* (Warsaw Institute).

Taiwan's undisputed manufacturing leadership is another example of an industry champion nurtured by positive economic relations with the United States. From the beginning, TSMC's most important partners have been American companies and the small island has historically found an ally in the U.S.. Taiwan has nurtured its relationship with the United States, both economically and politically, since 1949, when Chiang Kay Shek took refuge in Formosa after the final defeat of the Kuomintang by the Communist Party. Taiwan’s sovereignty has been challenged daily by the manifest will of Mainland China to annex it and unify the People's Republic of China (PRC). The U.S. doctrine of military defense has been a solid deterrent over the years and strong balance of power in the region. Taiwan independence is strictly connected to the country’s semiconductor manufacturing industry and by the global economy's dependence on TSMC services.

In the international landscape, the People's Republic of China is the only actor challenging the leadership of the United States and posing a direct threat to its military, scientific and technological dominance (China and the Challenge to Global Order). PRC reached high levels of economic development in the last fifty years, hitting a record GDP of almost $ 8.3 trillion and positioning as the second economy globally (World Bank). The hit of the Covid-19 pandemic slowed down China's rise and the strict sanitary measure weighed on the country's recovery. Nevertheless, PRC has never made a mystery of his willingness to become a great power playing a pivotal role in global governance. Xi Jinping, Secretary General of the China's Communist Party, currently serving throughout his third mandate, developed a clear vision of China's future. China has been constantly challenging international norms and rules (China and the Challenge to Global Order). It has been integrating constant participation into International Organizations (IOs) with the development of new forms of governance as the Belt and Road Initiative (BRI) or the Shanghai Cooperation Organization (SCO). China has consolidated its international presence in multilateral forums as well as with military, economic, academic and humanitarian initiatives in Africa, Asia and Europe. Under Xi's guidance China is repeatedly trying to export and impose its development model that "reflects extensive state control over politics and society, and a mix of both market-based practices and statism in core sectors of the economy" ("Trace China's Rise to Power"). China focused particularly on new technology development and in developing digital self-sufficiency. Technology such as the internet, 5G, AI and therefore semiconductors are the epicenter of China's strategy ("Trace China's Rise to Power").

As the world goes through a period characterized by uncertainty and risky crises, the geopolitical confrontation between the U.S. and China over who will be the future superpower is becoming more tense and concrete. The United States is focused on maintaining the global order, while China is working to challenge it. As the importance of technology in the optic of an economic or military confrontation between the two countries seems fundamental, semiconductors have become a matter of growing strategic interest. The ecosystem found itself at the epicenter of both countries' political agendas.

The call for self-sufficiency has become a key issue for both China and the U.S. They have embraced the notion of semiconductors as a force multiplier and have sought to develop domestic manufacturing capabilities at the highest possible quality. While the chip design segment sees the unchallenged leadership of the U.S., the semiconductor manufacturing market has witnessed the speed of innovation of Chinese state capitalism. Manufacturing is the elephant in the room, Taiwanese expertise leads the global value chain, while Chinese and American capabilities remain limited and imperfect to varying degrees. Attempts to boost national production have led to market distortions in the semiconductor industry. Indeed, the ecosystem is profoundly influenced by the role played by states.

Caught in the middle of the China-US confrontation, the European Union is challenged to define its role in the semiconductor industry. Under the leadership of the European Commission and the efforts of each member state, chips have taken on the importance they deserve. In the light of the propositions of the first part, and with a careful analysis of the race for self-sufficiency between the U.S. and China, what role can the EU play? What features and objectives should its industry pursue to achieve?

Balancing dependence

The Covid-19 pandemic took every government by surprise. Suddenly, the global value chain revealed the limits and dangers of over-exposed international production systems. Starting with medical devices such as oxygen machines and vaccines, the CoPS value chain was quickly disrupted by security measures such as quarantines, mandatory isolation, border blockades and travel restrictions. Governments, under pressure due to overburdened medical infrastructures, called for national lockdowns and started a race for urgent CoPS supplying. Although the harsh effects of the pandemic lasted for a year and a half, the idea of being exposed to the uncertainty of the international environment as a liability is something that governments, scientists, and managers will carry with them for a long time. The theoretical underpinnings of balancing dependence arose as an epiphany and are however strongly influencing the current international narrative.

Balancing dependence can be defined as the sum of state policies that seek to reduce economic dependence on foreign actors, both public and private (Moraes and Wigell 2022).

In the U.S., this theory was first championed by President Trump during his administration, whose narrative built on the notion of dependency by suggesting the intrinsic need for an internal revitalization of American industry. He was very focused on job creation and economic growth and resurrecting the idea of a dangerous and unstable global value chain played along with his internal economic strategy. The slogan "America First" was aimed at a domestic audience and focused primarily on the progress of the U.S. economy in absolute terms. It completely lacked an international economic strategy and had the effect of a clear American global disengagement, both militarily and politically. The notion of balancing dependency evolved under the Biden administration. President Biden spent an important part of his adult life during the Cold War, and his political and industrial agenda seems to recall a flavor of that time as the notion of balancing dependence took the form of global power confrontation during the Biden administration. The American president is urging the development of national production capacities, not because they are generally necessary, but because of the growing risk of confrontation with China and its allies (Moraes and Wigell 2022). Even if the Biden and Trump agendas have some points of contact in foreign and industrial policy, this remarkable difference changes the actual American objectives and, in particular, the desired output of Biden's policy. It marks a breakdown with American long standing liberal tradition. The United States has historically approached international economics under a practical cost-effective framework enriched by multilateral participation (Di Nolfo 2015). The seeds of Biden's policy philosophy could be traced back to Obama's mandates. Differently from its Vice-President, Obama has been nurturing peaceful relations with China focused on finding a common mutual development framework. Indeed, under the Obama presidency, the United States became closest allies of Japan, South Korea and strengthened relations with Modi's India. All of these countries were much more averse to China's rise than the Obama's United States. As Biden was elected President the relations with the Pacific and Asian allies became even stronger and the President embraced a "containment and suppression strategy" (Moraes and Wigell 2022).

China balance dependence theory is the application of a more rooted and substantive strategy anchored into past and recent developments. Xi Jinping's presidency of the Communist Party has been the core resonance behind China's political and ideological transformation over the past decade. Xi's predecessors advocated a low-key approach and intensified China's development efforts. Before Xi, China has balanced high-growth economic outcomes, oriented toward economic openness, with a soft geopolitical approach in an attempt to reassure the West about China's future objectives. Xi's approach has radically changed this paradigm. China's focus has shifted to a more nationalistic view anchored by the ideological necessity to play a global role in the world order (China's Competing Ideological and Economic Policy Objectives in 2023). China's Marxist-Leninist governance has achieved massive results in terms of economic growth, and its development process has consolidated a sense of security and rightness about the Chinese system itself. China seeks to promote an alternative model to the Western world challenging the current global architecture (Can and Vieira 2022). The low-key mantra has been replaced by more aggressive behaviors in business as well as in international relations. The so-called "wolf diplomacy" and "Huawei's corporate wolf culture" are both examples of how China is becoming more assertive (Can and Vieira 2022). They are also evidence of the military-civilian fusion strategy as an instrument of power systematically used by Beijing (Can and Vieira 2022). Another worrying signal is the attention China is devoting to modernizing its military apparatus. During the last Party Congress, Xi predicted a new army to be ready for " actual combat ". China's economic strategy is based on these premises as the Chinese Communist Party (CCP) focuses on the domestic economy primarily as a tool to support the country's political aspirations. The goal of "Made in China 2025" (MIC2025) perfectly reflects the country's balance between dependence and self-sufficiency. The strategy is dated to 2015. It aims to secure, through the combined participation of public and private actors, a complete value chain of strategic sectors such as aerospace, ICs, energy and medical, within national borders. Technology development has been a key feature of Xi Jinping's plans for China's rise and is being fostered by increasing public investment. The “Made in China 2025” plan is strictly connected to the *Dual Circulation* strategy, the ideological epicenter of the contemporary Chinese economy. *Dual Circulation* stands for the interactions between the two parts that make up the Chinese economy, external and internal circulation (Moraes and Wigell 2022). While China has for decades sought to promote its role as a producer of Western and international products, Xi has decided to shift the focus to domestic production and consumption. Xi believes that China's growth should come from the domestic market and domestic consumption rather than from foreign trade. The decoupling strategy, the progressive estrangement of the Chinese economy from the Western hemisphere represent a natural step to allow the country to fulfill its internal market goals.

The process of balancing dependency that is unfolding in both China and the U.S. is particularly relevant for the purposes of this paper. Semiconductor manufacturing is a key sector for both economies. Attempts to create a controlled national value chain are finding massive application in the chip industry. The consequent technological war between China and the U.S. finds a direct implementation in the semiconductor market, which serves as a measure unit and benchmark to assess the progress of both competitors. Both countries are implementing massive measures to stimulate domestic production capacity and slow down the development of competitors. China and the U.S., although thought to be in a race toward a similar goal, have two very different semiconductor industries.

The United States imports 10% of every IC on the market (OEC 2022). Its manufacturing capacity is about 12% of the world's production (OEC 2022). The United States dominates the upstream part of the chip ecosystem as almost all of the major chip designers are American. The U.S. semiconductor ecosystem is, for historical tradition, very structured. It has evolved over several years and includes some of the most advanced research centers and consortia. The role of SEMATECH has already been highlighted in this paper. Another important institution is the Semiconductor Industry Association (SIA). The SIA is a U.S.-based organization that acts as a liaison between the industry, external partners, and political leadership. SIA's lobbying efforts are very relevant in the U.S. Congress and the organization is constantly working to create stakeholder engagement and funding (SIA website). Another very important institution in the American ecosystem is the Defense Advanced Research Projects Agency (DARPA). DARPA is a government agency focused on developing technologies and capabilities for national security reasons (DARPA website). It was one of the first investors in the chip market in the U.S. and is still an important player in bridging the relationship between industry and the Department of Defense. The U.S. semiconductor industry landscape is heterogeneous and dynamic, but it lacks specialized manufacturing capabilities. While the U.S. has fabs, it lacks access to cutting-edge technology. Texas Instrument and Global Foundries are indeed market leaders, but while the former is more focused on a market that requires less miniaturization, the latter has apparently been completely cut out of processors and other core chip manufacturing. Intel, the second largest company in the world by revenue, has had huge problems with EUV technology and is currently buying 4nm chips from TSMC. Micron is one of the few top-tier, truly global competitors making chips in the U.S..

The Chinese ecosystem is much less developed than the American one. China contributes a share of world production between 30% and 45% (OEC 2022). It has specialized in the production of low-value chips used for less complex machines. The vast majority of China's manufacturing capabilities are not indigenous. In China, are located a large number of foundries of foreign companies - including American - due to the fact that the country shares some of the cost advantages of the region. Almost every major Pure-Play foundry and IDM has at least one foundry in the country. These foundries are located in various clusters. The Chinese semiconductor industry is mainly located in the provinces of Jiangsu, Hebei and Guangdong. In terms of national capabilities, the Chinese ecosystem is dotted with companies that produce low-quality chips for domestic use only. It must be emphasized that China's chip consumption is massive, as the country imports chips for a value of 300 billion, Hong Kong region representing 15% of the total internal market consumption (OEC 2022). China is experiencing a large gap between the amount of chips produced internally and the number consumed each year. In addition, China has no capacity to produce ICs below 7nm.

Companies within the semiconductor ecosystem are operating in a fractured and uncertain business environment due to the current geopolitical confrontation. They need to engage with both private and public actors. Regulations, investments, and prohibitions alter the free market and add a layer of complexity to the decision making of companies. Ideology, in the cleavage between Western and other forms of social contracts, seems to be another characteristic that companies need to consider when entering the market. Operating in this environment forces companies to reflect on the consequences of their actions not only in a business logic but also in a political one. As the importance of corporate geopolitics is rising, Moraes and Wigell (2022) have selected three forms of firm's positioning within the balancing dependence political framework.

The first company behavior is "business as usual", when the company tries to resist government interference in the market and tries to leave the political issues aside from its decisions. Market restrictions can lead companies to experience market loss. An example of "business as usual" in the semiconductor market is the case of NVIDIA. NVIDIA has repeatedly criticized the American government's invasive measurement and restriction towards China and has declared that, within its legal limits, it will continue to do business with China. Another example of this firm rationale could be the case of LFoundry. This foundry, owned by a Chinese company, continues to operate in the global market without taking a political stand.

Another type of firm’s behavior is the ‘one company, two systems’, whereby companies seek to adapt in order to play on all sides of the strategic divide (Moraes and Wigell, 2022). Firms by following this approach try to be *super parts* and to specifically follow the political and regulatory characteristics of every market. Companies that decided to continue operating in determined countries such as Russia, Iran or China despite Western criticism due to human rights international law violations embodies this principle. The role and importance of public opinion in business activities has been skyrocketing has been underlined by Malecky (2012). Companies, in relation to different topics ranging from social to environmental topics, are more and more pushed to take a stand.

The ultimate, and far more interesting, approach pinpointed by Foroohar (2018) is the “Patriotic Capitalism”. Under the author definition, companies will have to define their business position by reflection on the American geopolitical positioning - as the terms has been coined for American firms - freely or by imposition (Foroohar 2018). The American call for a politicized capitalism was an important development in both the business and political worlds. Even though it is not clear how American companies will be forced to follow the state's strategic path, some of them, in the semiconductor industry, are already trying to implement this notion. Intel recently called on all companies to support American manufacturing, as did AMD (CNBC). Nevertheless, the Chinese domestic market represents such a fundamental part of operations for American technology companies that no one has taken a more profound stand than the one imposed by the currently unfolding government ban.

The notion of "corporate capitalism" could be compared to the relationship between government and business in China, although there are profound differences. China's business ecosystem is characterized by a massive presence of state-owned or partially state-owned enterprises, which account for more than 50% of the total market (Huang and Véron, 2022). SOEs are under the direct control of the CCP, whose activities are controlled by state officials. SOEs are not publicly listed companies, and for this reason their behavior is particularly shadowy (Huang and Véron, 2022). In particular, the relationship between SOE technology and the military apparatus appears to be close and intertwined. As far as the semiconductor industry is concerned, China's main foundry, SMIC, is a partially state-owned enterprise. Huawei, under U.S. ban due to its founder's close ties to the military establishment, appears to be a fully private and independent company, even though its former subsidiary Honor was acquired by the Shenzhen prefecture in a life-saving operation to avoid market restrictions imposed by U.S. sanctions. As for Chinese private companies, in strategic sectors, they are also under some degree of indirect control. All mobile operators and companies seem to be obliged to share personal data and metadata with the government under the "China First" digital strategy.

While Chinese companies are subject to stricter regulations in the domestic market and there is evidence of less independence, U.S. companies still enjoy a great deal of independence and ownership in R&D and data management. Even though the degree of freedom of the two ecosystems cannot be compared, there is evidence to suggest that the geopolitical confrontation is stressing both governments to expand the government-private relations in the semiconductor market.

Industrial policy

The recent decade has seen a resurrection of industrial policy. Industrial policy is defined as those government policies that explicitly target the transformation of the structure of economic activity in pursuit of some public goal (Juhász, Lane and Dani Rodrik 2023). Industrial policy strategies use a complex set of instruments to achieve economic goals. These goals are generally economic growth, job creation, and technological innovation. Industrial policy has historically focused more on manufacturing than on services. Manufacturing is a sector that is easier for policymakers to monitor and understand. In particular, the development of the manufacturing sector has often been linked to job creation and its physical nature makes it more susceptible to investment.

Industrial policy has always been a complicated business. The literature on the subject is extensive, and economists have been studying the rationale and effects of industrial policy for years. While there is ample evidence and stories of industrial policy successes, there is also compelling criticism of industrial policy's ability to operate positively in a free market environment.

The first argument often used in support of such policies is the benefits of coordination. Coordinating a country's industrial resources could better allocate government ones. Industrial policy would be an important tool for dealing with failures and avoiding market distortions (Juhász, Lane and Dani Rodrik 2023). Another important argument often cited in support of industrial policy is externalities: the creation of positive externalities by the national economy could be maximized by government intervention (Juhász, Lane and Dani Rodrik 2023). Also, national security policies, such as semiconductor manufacturing, could be interpreted as attempts to increase national security and improve the quality of life of citizens (Juhász, Lane and Dani Rodrik 2023).

Arguments against the intensive use of industrial policy relate to a government's ability to understand which sectors or industries deserve intervention and support. The state would not have the capacity or the instruments to make this decision and identify the best options (Juhász, Lane and Dani Rodrik 2023). Critics of industrial policy identify a highly skilled bureaucracy and a permanent policies structure as necessary characteristics and argue that countries such as the US often lack these two characteristics (Juhász, Lane and Dani Rodrik 2023).

Industrial policy can reassume a very large number of operations that states can implement. One of the most important is the infant industry protection: States can subsidize industries in which they believe the country could develop a comparative advantage over time, or that they believe are absolutely necessary for its well-being (Krugman 1987). The investment will support the initial production efforts until the industry is able to achieve economies of scale and become profitable. A second policy example is the regulation of direct technology imports and exports. Governments can finance national firms to acquire advanced machinery or prevent the sale of innovative technology to other countries. Importing innovation and preventing it from becoming a common good is a popular industrial strategy. Tariffs and protectionist policies are other measures that governments can use to protect industries from foreign competition (Krugman 1978). States can promote protectionist policies to ensure the accumulation of protected capital in controlled environments. Industrial policies are not all the same. The degree of risk a country is willing to take is directly proportional to the strategic value of the industry.

The most important policy example is the performance of South Korea, Taiwan and Japan in different sectors. Steel and memory chips in Korea, semiconductor manufacturing in Taiwan, and the Japanese automobile industry are all examples of industrial policy miracles. They are all examples of high-risk investments that were able to drive growth and create competitive advantage.

An important argument in industrial policy is that of selectivity and equality. Does policy need to focus on investments that will benefit the whole industry, such as primary and secondary education, or should it focus on specific sectors and industries, such as strategic ones? Ha-Joon Chang (2017) explained that there isn't an equal industrial policy. The government necessarily needs to focus on specific actors, running the risk of trying to help every industry, which would likely end up not helping any. He also explains that there is no concrete example of "equality" in policy. Education and knowledge have also become increasingly specific. In his example, funding specific engineering departments means choosing a specific industry to support.

National champions

The policy decision to support a specific industry, and in particular one or a small number of firms within the sector, is defined as national champion policy. Strange (1990) refers to champions as “firms given favorable treatment by the state to help them maintain a dominant presence in the home market and a competitive share in the world market”. As this type of policy has become more prevalent in recent years, the concept of championing has grown in interest and importance. When the policy maker has to decide how to increase productivity or stimulate the production of a strategic good, he has three choices. The first is to support a strategy of fair market competition, giving each firm the same help or protection. The second and third are related to the degree of risk the policymaker is willing to take by investing in a national champion (IMF Policy Brief).

Financing a "safe" business ensures financial and fiscal stability, while a bold champion is actually riskier and has a greater chance of failure but has a trade-off: it offers a better chance of growth. The International Monetary Fund (IMF) cites "growth anxiety" as the reason behind policymakers' choices. The chance of generation economic results with a short-term strategy would be preferred by policymakers for political reasons, according to the IMF. Another important argument is that the notion of strategic assets overcomes the difference between safe and bold champions. A strategic asset must be secured even at the cost of financial losses and high costs.

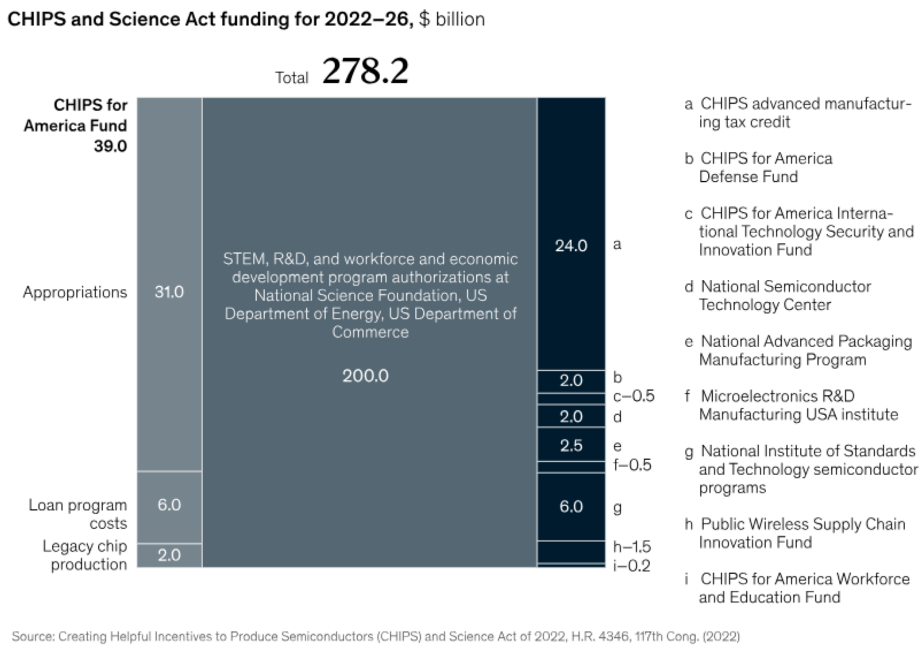
The growth strategy trilemma. Source: IMF

One of the benefits cited by the IMF is that the national champion strategy gives policymakers and public opinion a sense of control over national production capabilities and the economy. The problem lies in how the policy maker decides to sponsor a champion. The notion of "growth anxiety" implies that industrial policy decisions could be driven by heterogeneous factors that are less related to economic rationality and more related to politics. Examples of successful champion strategies exist, such as Samsung in South Korea or Toyota in Japan. However, as the IMF points out in its policy brief, industrial policy is "not a silver bullet”. Examples of unsuccessful planned economies are not only very common, but they all come at a very high price in terms of costs, instability, economic growth and waste of economic resources.

Case Study - The United States: a return to manufacturing

The U.S. industrial policy plan towards semiconductors started under the Trump administration. Trump, for the first time, included 77 Chinese companies in the Entity List, a list of foreign companies under trade restrictions and exports ban. The President also started developing a reshoring manufacturing roadmap starting with a $500 million Foxconn subsidiary in Wisconsin and started out the discussion with TSMC for an American fab (Financial Times). Nevertheless, industrial policy measures started growing aggressively under the Biden administration.

President Biden last summer approved the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act, an investment package focused on reshoring semiconductor manufacturing to the United States. The package consists of $280 billion to be invested over ten years. As explained in the White House presentation document, the CHIPS Act was introduced to address two main issues. The first was the current shortage of chips, which is causing disruptions in the manufacturing of numerous CoPS such as cars and other machines. The second was to address the slight decline in in-house chip manufacturing. Compared to the 1990s, when the U.S. manufactured 33% of the world's semiconductors, this figure has now dropped to 13% (McKinsey, 2022). Within this figure, there are no cutting-edge chips below 7nm.



The CHIPS and Science Act represents an industrial policy attempt to address manufacturing and research capacity in the chip market. As far as manufacturing is concerned, $50 billion will be directly implemented to increase the number of fabs and their capacity. This investment includes funding for the development of new infrastructure and incentives for national champions such as Intel, Micron and Texas Instrument. The CHIPS Act also identifies some specific segments that are important to address. The capacity to develop 5G technologies plays a significant and leading role within the Act as it includes 1.5 billion investment through the Telecommunication Act. It is particularly interesting to highlight the composition of this bill. It is characterized by a heterogeneous combination of private, public and academic institutions. In fact, $174 billion will be invested in the development of new knowledge through science, technology and engineering programs. The act will fund various research centers such as the National Science Foundation (81 billion), the National Institute of Standards and Technology and various state departments such as the U.S. Department of Energy and the U.S. Economic Development Administration. The focus is on developing workforce skills in the STEM field. In order to boost manufacturing, the government will not only invest $50 billion for direct implementations on fabs, but is proposing tax incentives, up to 25% of tax deductions for those who will invest in the sector (Mckinsey 2022). Never before in U.S. history has such a strong and massive investment been made. Although the Act is mainly intended to address the manufacture of semiconductors for civilian use, there is also a presence of military institutions that will benefit from the investments, as the $2 billion intended for the U.S. Department of Defense.

Although it is too early to address the outcome of the investments, which are still in embryonic form, some takeaways can be made from the Act. The first is that the United States is betting like never before on the national semiconductor industry and is implementing a large-scale industrial policy. The scope of the policy is not comprehensive and market-wide but focused on very specific technologies and national champions. From an analysis of the act, it is possible to deduce that the U.S. has understood the importance of knowledge in the industry. The share of investments directly oriented to physical resources, such as factories or machines, represents only 25% of the total. The remaining 75% is knowledge-oriented and focused on know-how generation and research. Another important consideration is the lack of international partners. Manufacturing investment is focused solely on national capabilities and is intended to benefit the internal ecosystem. The Act purposely does not address international partners or promote partnerships with foreign actors.

The only international investment the U.S. are implementing is the construction of the new TSMC's fabs in Arizona. The multi-million investment started two years ago and should have been ready this year. Nevertheless, the fab experienced serious problems and is now one year late on the production roadmap. Recently TSMC announced that it is sending engineers from Taiwan to train local human resources (Reuters).

Although the U.S. has chosen to develop its capabilities without working with the global ecosystem, its policies are aimed directly at influencing it. Export control has been a key feature of U.S. policies, starting from the Trump administration. Recently, the United States could have transformed this practice into an international political instrument involving Western parties and extending the magnitude of the bans. An example could be the sudden decision of the Dutch government to follow the American lead and impose a commercial ban on ASML machines of all categories to China. Considering that the Dutch government had never shown any kind of disagreement with the Chinese government and considered that ASML market in mainland China corresponds to 25% of their business, one could conclude that the United States are lobbying to extend their policies in Europe. Another empirical evidence could be that, as reported by Reuters, the U.S. applied even more stringent sales requirements to NVIDIA and AMD, blocking their export though to the Middle East.

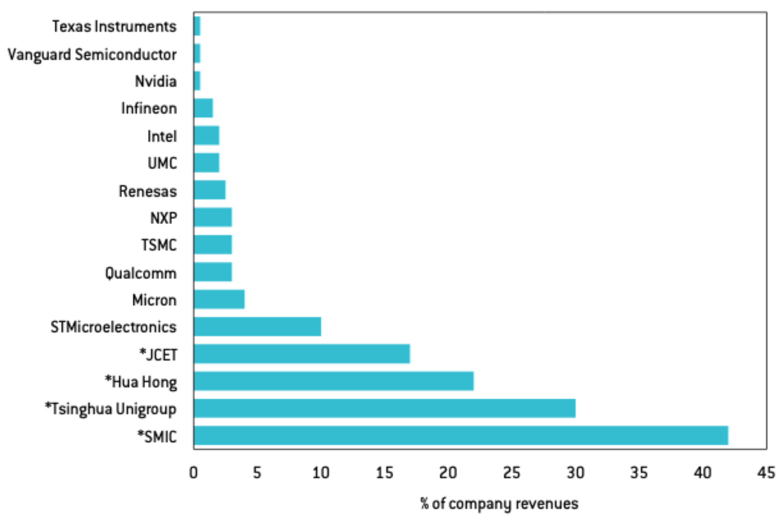
Case Study - China's quest for technological autarchy

Starting in 2015, China has launched a revolutionary industrial policy plan, investing $56 billion to boost the domestic semiconductor industry (Bruegel 2023). Unlike the U.S., China has had to develop and increase capacity in almost every segment of the industry. The only segment along the value chain where it had an advantage and expertise was in assembly and testing.

China's strategy is based on different levels of State participation. While some funds come from the central government, others are provided by provincial and local institutions. China's industrial strategy began with the creation of two Large Public Funds, financed by numerous institutional players, notably the Ministry of Finance and the China Development Bank and the China National Tobacco company (Bruegel 2023). The funds were complemented by the participation of state-owned or, to a lesser extent, private companies. The two funds activated in 2014 and 2018 consisted of $21 billion and $35 billion, respectively (Bruegel 2023).

Beyond the funds described above, government support for the semiconductor sector is also provided through government grants, tax incentives and low interest loans, for an amount estimated to hover around $50 billion (SIA, 2021). Investment has been particularly focused on enhancing the capabilities of some national champions, notably Huawei and its subsidiaries Hisilicon, the country's leading foundry SMIC, and Tsinghua UniGroup.

Figure 3: Estimated total government support provided to semiconductor firms, 2014-2018



Source: OECD (2019). Note: * indicates Chinese firms.

National champions, manufacturers of cutting-edge chips - below 60 nm - enjoyed tax exemptions and favorable loan rates, in addition to having access to most of the funds (Bruegel 2023). As can be inferred from the graph, the State's participation in national championships in China plays a central role. With SMIC receiving subsidies up to 43% of the company revenues (Bruegel 2023).

China's attempt to develop an advanced semiconductor industry sets an unprecedented example for the global economy. According to an analysis by state-run media, China created 58,000 semiconductors firms between January and October 2020 — roughly 200 a day (NYT,2021).

This strategy has produced mixed results, with some successes and some major failures. First, it must be remembered that Chinese semiconductors are mainly developed for the domestic market and for "domestic" use. In the medium to large chip's nodes area, China has developed remarkable manufacturing capabilities and achieved an acceptable level of self-sufficiency, even considering the physical impossibility of overcoming some bottlenecks. Despite this success, many investments have faded and been lost. The most glaring case was certainly that of Tsinghua UniGroup, which, after more than 5 years of concentrated investment from state funds, declared bankruptcy, leaving $200 million in debt (South China Morning Post).

For leading-edge chips, the results of the Chinese strategy have been less impressive. Recently, Huawei, in collaboration with SMIC, succeeded in making the first 7nm SoC with 5G connectivity completely made in China. Although this news was heralded as an absolute success, there are factors to consider. SMIC had actually announced that it had scaled to 7nm two years ago. However, no data could be found on the performance of this chip, let alone some manufacturing data such as Yield, and total units produced. Huawei's move could be mainly political, and the chips used could be modified western models. Indeed, it should be remembered that every other company in the Chinese mobile industry still relies on Western-designed chips manufactured in

Taiwan. Moreover, if Chinese manufacturing capabilities are now at 7nm, it would mean that the country is still 5 to 6 years behind Western competitors.

The manufacturing dilemma

The decision to build domestic manufacturing capacity for the United States and China poses an essential dilemma for policymakers. On the one hand, there is the willingness to achieve high self-sufficiency; on the other hand, this will mean ignoring comparative advantages and cost-opportunity theory. An analysis by Hofbauer and Hogan (2022) shows that the U.S. do not have a comparative advantage in chip manufacturing compared to Taiwan and South Korea. On top of that, as this paper has tried to demonstrate, some firms located in Asia enjoy a competitive advantage in the production of semiconductors due to a complex pattern of lower costs, both natural resources and labor costs, tacit knowledge and specific know-how that led to economies of scale and efficiency. In particular, this paper pointed out that in terms of governance mode, pure-play foundries gain a competitive advantage in the production of logic chips through extensive know-how accumulated over the years, which enables these companies to achieve economies of scale faster than IDMs in the miniaturization process. As explained, China and the U.S., willing to develop high-end logic chips, are boosting the pure-play foundry business through SMIC, Intel, or TSMC Arizona project.

Two problems arise from this strategic choice. The first is to understand if they will be able to produce chips. The second is to consider what the cost will be. Regarding the first problem, the first part of this paper reflected on the role of resources and knowledge in chip manufacturing and the importance of the ecosystem as a dynamic and collaborative environment. Since tacitness has emerged as the main characteristic of knowledge in manufacturing, it would be very difficult for one country to develop manufacturing capacities to compete with Taiwan.

Moreover, as both countries - especially China for endogenous and exogenous reasons - cut their ties with the global ecosystem, less knowledge circulation should lead to a decline in the innovation and production capacity of the closed ecosystem of both countries. Nevertheless, this paper notes that the massive investments implemented by the two countries are starting to pay off. China is already producing chips below 10 nm and that it recently was able to produce, for the first time, a 7 nm chip. Similarly, the U.S. owns and produces most of the explicit knowledge in the field and has successfully accumulated crucial know-how in critical sectors such as design. Furthermore, the most important Asian chip manufacturers have close ties with the U.S. as their political security is part of the American sphere of influence. For this reason, a catch-up in production capacity may be possible for both China and the U.S..

The second problem is that chips produced in China and especially in the U.S., will necessarily have a lower level of efficiency and yield, at least initially. In addition, production costs in both countries are higher than in South Korea and Taiwan, and incentives such as those promoted by Singapore would be costly to sustain in the long run. Therefore, it is not easy to imagine why a chip produced in the U.S. or China should be less expensive than a same-node alternative produced in Taiwan - assuming they can achieve the same quality and performance standards - . Who will buy American or Chinese chips? They are likely to be used only in the domestic market, and fabless and device companies will likely receive further subsidies and incentives to buy these products and sustain the national effort. The problem is that there are no evidence that manufacturing production in these countries - that do not have a comparative advantage - will ever be profitable. China and the United States are challenging the notion of comparative advantage, and by refusing to follow one of the most basic principles of the international economy, they risk transforming billions of investments in a tragic State-led failure.

Policymakers most likely know this as well. If they decide to face this challenge, it is likely because they know that a blockade of Taiwanese production will stop the world economy for a long time. Since China and the United States are polarizing their efforts and risking numerous billion in investments, the conclusion is that they both deem that a sudden stop of Taiwanese semiconductor production is, at best, a probable outcome.

Methodology

The case study follows an explanatory research design based on a qualitative analysis of the semiconductor manufacturing industry from a real-life perspective. It is useful to perform an explanatory case study as the objective of this paper is to reflect on causes and effects within the semiconductor ecosystem and to analyze why and how different phenomena unfold in the chip industry. The explanatory nature of the case study will thus enable the author to assess the validity of the three ex-ante propositions by weighting the theoretical findings with the ideas and perceptions of experienced managers. Interviewing four professionals from the two different business models involved in the chips manufacturing process is the only way to test the reflections on the semiconductor industry performed throughout this paper.

Regarding the sample, a purposive sampling technique was performed. The sample comprehends four experts in the semiconductor ecosystem, selected from two companies: Micron Technology and LFoundry. Two managers from each company were selected.

- Micron Technology is an American-based Integrated Device Manufacturer specialized in producing memory chips. Today, Micron is the fifth-largest semiconductor company in the world, with an annual revenue of more than 30 billion $ ("Micron Technology Revenue 2010-2023 | MU"). Micron is one of the last American companies manufacturing high-level chips on US soil. It was founded in 1978 in Boise, Idaho. Historically, Micron was famous for its precise manufacturing processes and cost-cutting strategies that permitted the company to compete with Korean and Japanese firms. Today, Micron is well known for its innovation processes and retains a global market share of 25% in the memory chip production. Micron has an extensive international presence worldwide, owning foundries and subsidiaries in 17 countries, such as Singapore, Japan, India, China, Korea, and Taiwan, and a presence in Europe.

- LFoundry, located in Italy, specifically in Avezzano, is one of the leading Italian chip foundries specializing in producing sensors and a large variety of chips. Born under the umbrella of Texas Instrument, LFoundry was originally a memory chips foundry. Micron Semiconductors then acquired it. With multimillion investments, Micron transformed it into a state-of-the-art hub in the middle of Abruzzo. When the memory business market started slowly decreasing, Micron sold the ownership of the foundry to a cordate of Italian managers. With the support of Cassa Depositi e Prestiti, they completed a production shift from memory chips to a heterogeneous and dynamic variety of semiconductors, becoming a hybrid client-oriented foundry. They managed to sell the company to Semiconductor Manufacturing International Corporation (SMIC), a partially state-owned Chinese foundry willing to expand its presence in Europe. Then, in 2017 another Chinese investor, Wuxi Xichanweixin Semiconductor purchased the company from SMIC. Today, LFoundry works on wafers at 200 nm and produces chips at 90—110 nm nodes. It collaborates mainly with the automotive sector, but its applications range from medical, industrial, and science industries.

These two companies were chosen because they represent a complete example of semiconductor manufacturing business models operating in the ecosystem. Interviews with Micron managers helped this project learn about the business model of IDMs and gain insights into the memory chip market segment. LFoundry has led this work to delve deeper into the role of Pure-Play foundries. Moreover, the two companies have differences that helped this analysis gaining insight from various levels. While Micron is an international independent leader in the market, managing subsidiaries in different countries, LFoundry is owned by Chinese investors and plays a role more integrated in the national and regional value chain. Through these interviews, it was possible to develop a comprehensive and heterogeneous multi-level view of the semiconductor ecosystem by learning from companies at the epicenter of the most critical bottlenecks in the industry.

All the respondents had a technical background. Three had engineering experience in foundry management and production processes, while the fourth was an industry expert in M&A and finance. While the respondents had homogeneous academic and work backgrounds, all of them accumulated more than ten years of experience in the industry. The respondents were selected via social channels as LinkedIn or via recommendation and contacted through email.

The case study was built throughout a qualitative analysis involving a single in-depth interview per participant. Interviews were formal and semi-structured. An interview sample with open-ended questions was built before the interview process. All interviewees were administered with a homogeneous set of questions - sometimes the questions were adapted to better meet the experience and knowledge of the interviewees - . This paper reports a sample of the interview questions at the end, under the heading Appendix. While, generally, the first part of the interview focused on topics related to resources, knowledge and innovation, the second part deepened the current international scenario, the role of government investments in the chip industry, and recommendations for developing national or regional industrial policies in the sector. All the interviews lasted between one or two hours and were carried out in remote video or phone call. The author decided to conclude the sample with four participants as the scope of the study was reached and data hit the level of saturation. The participants were very talkative due to their experience and the author could accumulate a large amount of usable data. Moreover, the author could also gather numerous shadowed data through the respondents replies. Even though shadowed data regarding experiences of respondent's colleagues could not be completely validated - and thus have not been used systematically - these data helped the analysis indirectly, expanding the sample and the amount of information. In general, the reliability and validity of data was guaranteed by the solid reputation of the two companies, the esteem that the respondents are held in the semiconductor network and the author’s independent research on facts and statements. The author interviewed the respondents alone. To protect the privacy of the interviewees this paper does not directly identify respondents names and specific position or department within the companies.

Regarding the data analysis, interviews have been transcribed in order to perform a thematic analysis. The objective was to code and connect raw data to “theoretical terms” and identify patterns and themes. The interviews were analyzed to try to find commonalities and divergences between the answers offered by the interviewees. In particular, keywords and short opinions were synthesized to identify central topics, compare and cross-examine the information obtained. The results of this analysis have been proposed in the findings. Through a careful analysis it was possible to notice essential differences concerning respondents' answers with the consideration made by the author during the paper and compare the reasons behind their responses.

Although the sample and data analysis achieved their purpose, it is possible to identify some methodological limitations and insights for future analysis. The research sample could have been expanded in terms of different companies - providing experience from at least two of IDMs and foundries - and in terms of industry segment - expanding it to fabless and OSAT firms -. Another limitation is that the two parts that make up this paper would probably need a more specialized sample for each. The author, looking for a manufacturing perspective, focused on experts that could provide real life experience in the sector. In the future, it would be interesting to expand the analysis to scholars in the field of management, public policy and international relations and compare the gap between practice and theory. In the future, it would also be very interesting to develop a longitudinal study to assess the opinion of respondents after witnessing changes and developments in the sector.

Findings

The purpose of this chapter is to present the results of the analysis of the interviews to assess the theoretical resonance made throughout this paper and to demonstrate the validity of the *ex-ante* propositions.

As interviews focused on the manufacturing segment, respondents identified several critical steps. While two managers generally emphasized the importance of reaching a complex diagram of scale, time and quality in production as one of the most dramatic necessities, the other two emphasized the characteristic of developing proprietary technologies capable of adapting to customer needs as fundamental to their business. This difference is related to the governance modes of IDMs and pure-play foundries. Integrated companies manage their entire business based on promptly meeting market needs. Foundries are more customer-focused and must adapt and modify their production structure to meet the client's necessities. All of the interviewees agreed that the chips' characteristics impact the modes of governance. Logic and memory chips trigger different production needs. In the semiconductor ecosystem, while logic chips are generally produced by pure-play foundries, the memory chip market is dominated by IDMs. In this regard, an executive highlighted that intellectual property, innovations and manufacturing processes are better protected and developed in an integrated system. He referred to the value of protecting and creating knowledge in a dynamic environment such as memory chip manufacturing. He confirmed that the development of memory chips involves a high degree of innovation on different parameters, as it is not only focused on miniaturization. This point was also raised by a manager of LFoundry that deepened the role of miniaturization within the industry. While cutting-edge logic chip foundries primarily focus on this process, he specified that the producers of a vast range of medium-dimension products have other priorities, recalling the importance of customization. As it was possible to infer from the application of KBT in the industry, knowledge is essential in determining the market organization as it has contributed to the bifurcation of two primary forms of governance modes. The words they used to describe these characteristics as *customization, intellectual property, and processes*, referred to know-how and knowledge rather than physical resources. The first four questions made it possible to confirm the first assumption and the importance of knowledge creation in governance modes.

Respondents then focused on assessing the deep causes of competitive advantage and the role of knowledge. Finally, respondents were asked to comment on the role of raw materials and natural resources in manufacturing. Two interviewees explicitly stated that raw materials are not a barrier to entry into production, as they are generally available. They mentioned problems related to sourcing, but none cited raw material sourcing as a possible reason behind competitive advantage. Instead, two managers focused on the role of natural resources rather than raw materials. Both interviewees emphasized the importance of the cost of natural resources in the context of the different prices and taxes that apply to different foundries worldwide. Indeed, they both noted that one of the first advantages of Southeast Asian countries is the low cost of water and electricity. One executive also recalled that Singapore has attracted foreign manufacturers by exempting them from paying electricity bills. The answers are perfectly in line with the research in the second chapter.

When the questions focused on critical physical resources, the sample produced more heterogeneous responses. The first part of the paper analyzed the difference between valuable and rare resources and concluded that only rare resources generate a competitive advantage. Since the acquisition of machinery is only subject to the level of investment, physical resources in the industry are more valuable than rare. The respondent highlighted a more complex pattern. All respondents identified physical resources as a competitive advantage source but used different arguments to support their statements. Two respondents emphasized that when their company, for different reasons, found itself with limited access to leading-edge technology, the company was not able to compete anymore. They used this argument to imply that machines were necessary to maintain competitiveness. These two interviews contradict the theoretical analysis of this paper, but only to some extent. The term "essential" had already been used to define physical resources, and the paper had implied that they were critical to production competitiveness. The interviewees confirmed that resources play a critical role by including them among the causes of competitive advantage. The other two respondents completed the framework. They also identified resources as a source of competitive advantage, but for other reasons.

One of them clearly stated that the advantage comes from the relationship between the machine supplier - ASML was quoted directly - and the customer. He believes the advantage is created when the company can innovate the standard model of the product during this relationship and go beyond the linear application of the machine itself. He also explained that his company has developed meaningful relationships with ASML to improve machines and promote innovation. This statement is significant because it implies that the source of competitive advantage will not be the machine itself but rather what he defined as the ability to outperform competitors in their application. This notion is more in line with the second sup-proposition of the paper as the term *capability* is more related to know-how than physical features. The fourth manager also highlighted an important point. He proposed the example of M&A operations within the industry, implying that firms acquire competitors or other companies not only to acquire their physical resources but especially to access their specific characteristics, such as processes and customized technologies.

To summarize the role of resources in semiconductor manufacturing, the interviews revealed that they generate a competitive advantage. Natural resources can be important because of the costs associated with their consumption, but raw materials were not identified as pure sources of advantage. Physical resources such as machinery play a critical role in determining achievable competitive standards. However, it was possible to conclude that even if they are "necessary" to compete in the market, the capacity to develop and integrate them into processes is the added value that contributes to the company's heterogeneity. This argument can support the proposition that the root causes of competitive advantage must also be sought elsewhere.

After this reflection, the interviews started focusing on knowledge. The interviewees spent their replies focusing on the challenges related to maintaining knowledge transmission and circulation within their firms. Two of the interviewees defined the semiconductor industry as knowledge-intensive. They both stressed the importance of know-how in manufacturing processes. This phrase also seems to dovetail nicely with the results of the sector analysis in the semiconductor market that in Chapters One and Two concluded that there are no obstacles to production as critical as processes. The fundamental role of knowledge was emphasized in all interviews at various levels. Theoretical knowledge, explicit knowledge, was cited as very important in terms of research to sustain innovation. Moreover, tacit knowledge was also mentioned by the interviewees. Although none of the interviewees pronounced the term "tacit knowledge", words usually repeated were know-how, processes, skills, abilities and capabilities. These terms can all be synonyms for tacit knowledge, as they imply the same characteristics that the literature uses to define it, particularly inimitability and non-transferability. The interviews confirmed the role of know-how in manufacturing with different examples. One respondent emphasized the role of learning by doing as a centripetal force in R&D to develop innovation.

Another important example was provided by a respondent about human resource management in semiconductor manufacturing. He emphasized that the perfect employee is not necessarily the one who knows more but the one able to share and communicate with his colleagues. Although these examples contribute to a better grasp of the importance of knowledge in the semiconductor ecosystem, one was particularly important. Unlike the previous two, one interviewee explained that there is a learning curve in manufacturing semiconductors. As Moore's Law explains, companies embark on a development process as innovation moves toward miniaturization and performance. Leading companies need follow this process without making mistakes. This is why being behind 3 or 4 nodes behind competition is equivalent to accumulating a 5–6-year delay. Because of the nature of knowledge, companies need to evolve to acquire the know-how, to scale nodes, and because this know-how is complicated to trade, leaps and bounds are very rare. In light of the evidence gathered from the interviews, validating the first proposition in both subparts was possible. However, it is essential to remember that demonstrating the critical role of knowledge in semiconductor manufacturing does not exclude that resources have an essential role in different aspects.

Concerning the second proposition, all the respondents agreed that the ecosystem is organic in sustaining innovation. In particular, the author read the second proposition directly to two interviewees, and both replied that they believed the answer to be “yes”. In particular, the respondents stressed the centrality of relations between firms of different segments to generate innovation. One respondent identified the collaboration and the role of strategic alliances between foundries and designers as central to the ecosystem development. The author was expecting a significant role to be played by consortia, but none of the interviewees cited them or made any reference. One manager talked about the definitions of standards between rival companies as a moment in which competitive firms reflect together on the industry and the "rules" of competition. About this point, the author could not demonstrate other forms of cooperation between rival companies as described in the second chapter. In the aftermath of the interviews, *cooperation* between rival companies should be defined as indirect at best, as the author could not collect proof of forms of direct cooperation between competitors. Even though forms of cooperation, such as strategic alliances, are less extended than the author had forecasted, the second proposition could be acknowledged as accurate because all the interviewees recognized the interconnected nature of the ecosystem. In particular, the interviews highlighted that the semiconductor ecosystem, producing CoPS, needs to evolve organically in every direction.

When the interviewees were asked why the semiconductor manufacturing had been outsourced to Asia, the respondents mainly responded, quoting the cost advantage that the region possesses from a labor force and natural resources point of view. However, one respondent explained that these countries, for example, Taiwan, had also gained a specific expertise in the sector that enabled them to reach high levels of efficiency and scale.

In this regard, one respondent's answer to whether the United States could succeed in their attempt to manufacture high-end chips in-house was surprising. He answered, "Of course, we are already doing that". He argued that the U.S. had all the knowledge needed to produce its chips and relied on Asian foundries only because of lower costs. He continued stating that the American policy attempt will necessarily be a success.

This reply is interesting because, on the one hand, it reiterates the importance of knowledge for chip production. Secondly, the information collected by this paper showed that, to date, no foundries in the United States can produce chips below 7 nm. If it is true that the U.S. has the expertise to manufacture semiconductors domestically, why do companies continue to outsource manufacturing to geopolitically and logistically complex locations? The answer lies in the difference between tacit and explicit knowledge. This differentiation has been widely discussed in the literature, and it lies in its transferability, as proposed by Grant. The former can be easily shared, while the latter is more challenging to transfer. The interviewee refers to the fact that U.S. companies have a high understanding of the chip manufacturing process. Since all the design steps start from American H.Q.s, this reinforces the idea that moving foundries back to home soil would be easy. However, this idea collides with the realization, proposed by other interviewees, that

Asian foundries have accumulated unique know-how over the years that is difficult to duplicate and, more importantly, almost impossible to export. Other evidence comes from the difficulties American companies, such as Intel, are experiencing in producing chips under 10 nm. Another example could be that the TSMC production delays in Arizona obliged the company to send Taiwanese engineers to the U.S.

Nevertheless, the empirical evidence from the other two interviewees suggested that they believed that the U.S. would be able to develop manufacturing capabilities in high-end chips. Thus, the third and last proposition of the paper could not be confirmed as three respondent sustained that Americans company will close the gap as infrastructures, industries, academia and investments will be focused on sustaining the long-term national effort. No reference were made by the respondents about Chinese manufacturing development.

Main Takings

- In the beginning, foundries began to be located in Asia because of cost considerations. American companies funded technology and training to facilitate this process. As Asian countries began to develop domestic manufacturing capabilities, IDMs and pure-play foundries emerged in various countries. TSMC and Samsung captured more than 60 percent of the market for leading-edge chip production. U.S. firms, at the beginning unwilling and then unable, completely lost their expertise in producing chips below 7nm.
- As forecasted by the first proposition, tacit knowledge has indirectly led to two different modes of governance establishing themselves as the leading manufacturing processes in the production of different types of chips.

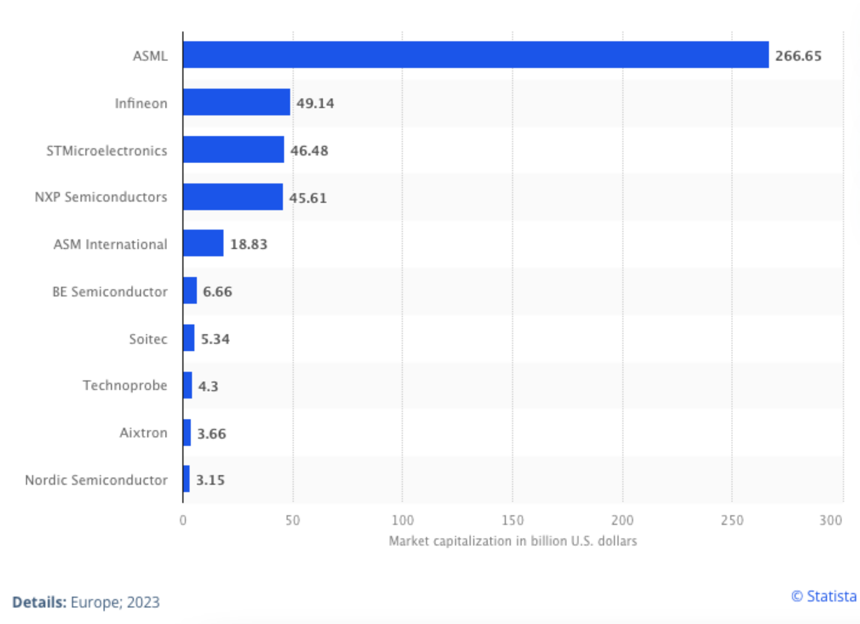
- Semiconductor manufacturing is a knowledge-intensive industry in which routines and tacit knowledge, as rare assets, create competitive advantage, while technology and resources, as essential as they may be, produce competitive parity.
- Despite being a highly competitive sector with two or three leading companies per industry segment, the semiconductor ecosystem is only able to sustain its own law of innovation by fulfilling and sustaining an organic and integrated network of firms.
- A status quo seems to have been reached in the so-called "race" for semiconductor development capabilities. The ecosystem is entering a new phase marked by the presence of few consolidated players with deep entrenched industrial ties.
- The last decade has seen a return to the massive use of industrial policy. The notion of balancing dependence has prompted Mainland China and the United States of America to make multi-billion-dollar investments to achieve a high degree of self-sufficiency in semiconductor manufacturing.
- Critical challenges are posed by the knowledge-based nature of governance modes and production processes. Moreover, the integrated nature of the ecosystem itself makes autarchic industrial efforts targeting national champions less likely to succeed.
- Nevertheless, empirical evidence suggests that the announced efforts are likely to result in the development of manufacturing know-how and capabilities, particularly in the United States. The knowledge gap will therefore be filled as infrastructures, industries, academia and investments will be focused on sustaining the long-term national effort.
- Two interrogatives arise from this evidence. The first is about the degree of competitiveness that manufacturing in the U.S. and China will reach compared to Taiwan. Since costs and efficiencies will be less competitive compared to Asian

manufacturers, there are legitimate doubts about the marketability and competitiveness of U.S. and Chinese cutting-edge chips.

- The second concerns the future of Taiwan's defense, as both China and the United States seek to reduce the global dependence from the small island of Taipei.

Filling the gap: the EU chip industry

Based on the analysis of this paper and the following empirical demonstration, it is possible to proceed with a brief presentation of the European semiconductor market and an overview of the European chip strategy. Some recommendations based on the results of this work are then proposed.

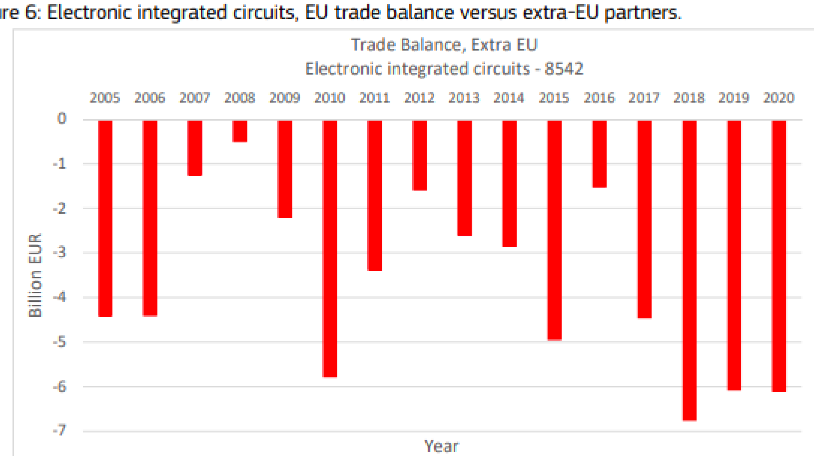


Main European chipmakers for market capitalization

The European semiconductor market is currently worth approximately $3 billion as the EU produces 10 percent of the chips in the market, mainly through three companies: Infineon, NXP

Semiconductors, and STMicroelectronics (OEC 2022). The European market is still dominated by ASML, the first company by market cap and the only able to play a global and pivotal role in the ecosystem. EU semiconductor production is naturally oriented towards the most important sectors in the region. In particular, the automotive, aerospace and healthcare industries. Although European production is already concentrated in these sectors, the EU is still a net importer from the main producers, mainly the US, China, Taiwan and South Korea. The EU's trade balance has always been negative, fluctuating around - $6 billion over the last three years (Bruegel). For what concerns other segments of the chips value chain, Europe is a minimal player also in the design, contributing only 2 percent to the global total. The only segment in which the Union plays a central role is in the production of high-end machineries for chip's manufacturing and assembly. Another segment where the European contribution is significant is in research, both private, through institutions such as IMEC, and public, with polytechnic institutes and applied universities.

Figure 6: Electronic integrated circuits, EU trade balance versus extra-EU partners.



Source: JRC elaboration on Comext Data.

Table 2: Electronic integrated circuits,
leading imported products & leading third-countries exporting to EU

An interesting reflection proposed by Bruegel concerns the extent to which EU-based companies can be considered "European" from an ownership perspective. Before chips became a strategic sector, the European chip market was highly unregulated. EU chipmakers were targeted by American and Chinese competitors between 10 and 5 years ago, often being acquired - as in the case of SMIC for LFoundry - . Many of the fabs and R&D centers operating in Europe today are foreign owned or controlled. Also state controlled enterprises such as STMicroelectronics have the majority of institutional investors from American and Chinese companies.

The European Chips Act has promised €43 billion from national budgets in *“policy-driven investment”* up to 2030 (Bruegel 2022). It is focused on five strategic goals: to strengthen research and technology leadership; to develop and strengthen Europe's ability to innovate in the design, production and packaging of advanced chips and to establish an appropriate framework to increase production by 2030 (European Commission 2023). The Act will indeed address skills shortages and attract new talent to develop an in-depth understanding of global semiconductor supply chains (European Commission 2023).

The reasons behind the birth of the Chips Act are very similar to those of other international players. The semiconductor supply crisis also reminded the European Union of the need to act to lower the risks of depending on an overly complex and integrated value chain. It should be remembered that the European Union is very late compared to other countries. Public policies in the semiconductor field began in the 1960s, and the latest wave, the one described above involving China and the United States, began between 2015 and 2018. The theme of the EU delay in the semiconductors sector emerged in 4 of the 5 interviews that were conducted. Some interviewees pointed out major inattentions at the national and European level in past years toward the sector.

The point that was most expressed was that in an industry characterized by dynamism and speed like the semiconductor one, to lag a few years behind competition is already a huge gap to close.

Recommendations

- In the light of the findings of this research project, it would be unwise for the European Union to try to develop full manufacturing capabilities in the production of cutting-edge chips given the difficulties related to know-how and investments required.
- The European Union has different political balances than China and the United States, for this reason it should aim at balancing a certain degree of self-sufficiency with global market participation.
- The European Union should balance national champions policies with heterogeneous investments emphasizing the role of startups and medium size players and should stay docked in the global ecosystem by increasing the number of partnerships and strategic alliances with leading international companies.
- The European Union should invest in enabling firms to identify new trends in terms of technology innovation and focus on intercepting leading positions in bottlenecks technologies just as ASML did with the EUV technology.

The European Union can address chips shortages by enhancing integration and participation with the ecosystem and could fill the technology gap by specializing in the manufacturing of needed types of chips, technologies and segments rather than aiming for complete self-sufficiency. The European Union could acquire importance in the global ecosystem by becoming essential throughout the process with specific technologies, but it is highly unlike that it could become a leader region by imposing itself as a full integrated manufacturer. The geographical transition of semiconductors manufacturing is too dynamic and fast to think to intercept it in its whole. The investments the European Union is ready to deploy will be an extraordinary opportunities, but they need to be used precisely and with a clear strategy. This paper tries to reflect on the nature of the semiconductor ecosystem and could represent an instrument to chart the course of the future European strategy in the semiconductor industry.

Interview with Wayne Allan

The objective of this interview is to offer an alternative analysis on the topics deepened in this research paper throughout the experience of a leading professional. This interview, considered external the research project itself, wants to offer a comprehensive conclusive view to the reader, independent from the author's analysis.

Wayne Allan is Executive Vice President and Chief Strategic Sourcing & Procurement Officer for ASML. He is also in the ASML's Board of Management since 2023. He joined ASML in 2018 as Executive Vice President of Customer Support. Before he joined ASML, he served as Senior Vice President of Global Manufacturing Operations and as Vice President of Wafer Fabs at Micron Technology, the company where he began his career in 1987 as a production operator.

1) Why in your opinion in the current market configuration cutting edge memory chips are produced only by IDMs while logic chips as SoC or processor are better produced by fabless and pure-play foundries?

I think when it comes to foundries and the growth of the business there has been one major player that has been very successful, and that player is TSMC that has a portfolio capable of dealing with different designs. In relation to driving specific technologies that require your own knowledge to shape processes, you naturally end up going back to do the manufacturing by yourself. It is a question of sourcing for companies. Some companies needs to source manufacturing because they do not have their own fabs. It comes down to the practical reality of what you decide as a user between going to the market or doing it by yourself and if you have the capabilities required. It is a matter of practical choices rather than a structural difference.

2) What is he role of raw materials in chips manufacturing. Are they just part of a complex sourcing chain or there is an ex-ante competitive advantage in their sourcing

When it comes to raw materials it depend on the material. When dealing with new technologies, the need to identify specific materials become a very critical operation. For example, in developing 3D memory chips, the materials used for production are very different and as you continue to shrink the dimension of the node, materials evolve. So, they obviously are very critical but is not only the material itself as much as it is how you are able to use that material in your processes.

3) I would like to ask you about ASML machines, in my work I defined them as source of competitive parity as on the one hand they are essential for production

of cutting-edge chips and generally available on the market for who can invest certain amounts but on the other some manufacturers are successfully using this technology why other don't, in your opinion why?

ASML machines are for sure a very critical technology as they are constantly driving Moore's Law. Of course, there is an entire ecosystem around them but up until now photolithography has been driving innovation in the sector. ASML machines are the most advance tools in any customers fabs and also the more expensive. Nevertheless, there are many things that can lead a manufacturing firm to be successful or not. One of this is the economy of utilizations, when a company has a fab worth 20 billions of tools in it, if you ran at full production with an organization capable of leveraging every minute and good services then you will have better economics even if everything else is equal. Part of the success comes from machines utilization; part is from process knowledge, but it also goes back to process integration and design. Lithography is one piece of the puzzle, a critical one, but by itself you cannot create anything without a design, a process and the rest of the landscape. Is about who is more capable from an operational standpoint to execute and keep the fabs up and running and to achieve a better yield. So, difference in capabilities can come from a lot of different things as operational discipline, process and technology acumen and other things.

4) How does ASML assure a high-level collaboration with its costumers?

We have a strong partnership with our costumer, and we do our best to ensure to help every single one of them. It is important to respond to the needs of everyone. Who has the most open dialogues with us is where the relation is the most successful, but this is something you can apply to any logic relations. Where there are collaborations and challenges there are breakthroughs. ASML is challenged to innovate by its customers, and it is a matter of working in R&D several years in advance to intercept client's needs.

5) Recently I did read that TSMC, Samsung and Intel were investing in ASML to boost R&D, but they are all competitors. Could you elaborate on why the semiconductor ecosystem advance with this peculiar relations of cooperation and competition.

It is a unique relation and when ASML works with its customers, to solve issues, we do not share clients information. There are specific teams that follows specific customers. Rules are very strict and for example no employee that is working on a competitive account can switch to another for a long period of time. We are very careful in compartmentalize information. We do not share IP specific to our customers to others. At the same time there are general things that all customers need, and we work with every customer to address this. We work with all the customer landscape on this problems. This is our IP, and we can use it for every costumer. There is a careful mix, because as a dominant market presence - almost every producers utilize our machines - we need to be extremely careful to preserve customers IP otherwise our business model will fall, and we are extremely careful with that.
Actors in the semiconductor industry cannot work independently because otherwise you will have every companies trying to create their own lithography machines, but common blocks are addressed together because is impossible for every single player do everything on their own.

Companies leverage things in which they have competitive advantage but on other topics they collaborate with the landscape as you cannot do all on your own.

6) In light of the recent call for national self-sufficiency in the chip industry, do you think the United States in particular, will be able to bring back the production of advanced chips? Why?

For many years semiconductor manufacturing was located in lower cost regions. Mostly China, Taiwan and Korea. The trend has been going on for so long, that one could argue that it is natural to get the balance right as manufacturing is a very critical component for a successful economy in differed fields. To see more balance in the supply chain of this process is inevitable. To completely decouple, between the two superpowers in this technology, I cannot see it completely possible, there is too much interdependence between the U.S. and China. The fact that some of this supply chain gets rebalance, I think is not surprising that this is the trend. But to take it all the way to where each country is completely not dependent on the other, I simply not see that happen in my career. Interdependencies are so dramatic in how this countries relies on each other. Completely decoupling, I cannot see it. More realistically we will see a rebalancing so that countries can feel less risk. I do not see complete self-sufficiency being a reasonable outcome. Rebalancing is healthy as everybody has some part of the process and countries do not have to completely rely on others, but it will be a little bit difficult and dangerous if everybody tries to be completely self-sufficient. I do not see that happening on semiconductors in general. I see de-risking going on, but completely decupling I do not think that is possible.

The economics of that would be tragic to the world and I think it will be worst for everybody going for a complete decoupling.

7) Could you asses the state of the European semiconductor market and the challenges it will face in the light of the recent announcements of the European Chips Act.

Is natural going for de-risking and rebalance in the semiconductor market. But I think it takes more than just to put manufacturing in a location, it requires university and infrastructure to work together in innovation. Innovation is really what each country should be focus. Is less about protectionism and is more about innovation as you really eventually only win if you run faster than everybody else. Is natural that the EU wants to have some manufacturing capacity, but the question is how we partner to have the right innovation models, the right technology and the right mindset for coming up with the latest and greatest technology.

Conclusions

In conclusion, the goal of this analysis was to merge economic literature with international politics to develop a full understanding of the manufacturing segment in the semiconductor industry. In terms of its descriptive exercise, this paper could be a valuable tool in bridging the gap between the two bodies of literature. In addition, the paper has attempted to validate three propositions that reflect important questions in the ecosystem from a business and policy perspective regarding modes of governance, competitive advantage, and government intervention. Even if the first two propositions found only a partial answer, as the analysis revealed a more complex network of patterns, and the third one turned out to be false, the paper still achieved its main objective: to demonstrate the critical role of knowledge within the chip ecosystem and to shed light on the relationship between industrial policy and political ideology. This paper, by deepening the role of the semiconductor ecosystem in modern economy, has achieved its basic objective of considering complexity a question and not an answer, always trying to underline the integrated and collaborative nature of chips production.

Appendix

Interviewees were asked the following questions*.

1- Could you describe your professional career in terms of your area of specialization and the companies you have worked with?

2- What do you think are the most critical steps in semiconductor manufacturing?

3- In terms of governance modes, do the characteristics of the chip have an impact on the governance structure of the company?

4- In your opinion, why?

5- How critical is the sourcing and processing of natural resources and raw materials in the semiconductor manufacturing industry?

6- In your opinion, are physical resources such as machinery the reason for the company's competitive advantage?

7- What is the role of knowledge in the industry's innovation process?

8- In your experience, how do companies create competitive advantage in the semiconductor industry?

9-Why do you think semiconductor manufacturing has been outsourced to East Asia?

10- In light of the recent call for national self-sufficiency in the chip industry, do you think Western countries, and the United States in particular, will be able to bring back the production of advanced chips?

11- As a critical technological confrontation between China and the United States unfolds, what is the role of the semiconductor industry?

12- Finally, do you have any suggestions on how the European Union could play a central role in the manufacturing market of tomorrow's chip?

*In order to match the characteristics of the interviewees and to maintain the flow of the interview, minor changes could have been made to the sample.

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