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ISPI Innovation Report Series 2

Global Competition for Sustainable AI Chip Innovation Ecosystem

The Importance of Innovation Strategy for Artificial Intelligence (AI) Chip

- In the competition of AI Chip technology, competition has never been so fierce as the demand for large-scale data processing with lower power consumptions has grown fast to support future industry and society such as big data analysis or smart factories.
- The chip industry is transforming from a mass market focused on large-scale production of general-purpose chip processors or memory to a diversified market with various mission-oriented chip processors specialized for different fields of artificial intelligence. Considering such fierce technology competition and market dynamics, the future of the AI Chip market has the potential to change very rapidly. Therefore, this report examines the innovation of AI Chip technology based on patents and scientific papers, analyzing the landscape of AI Chip technology in major countries and providing insights and directions for developing future innovation strategies for the development of AI Chip.

AI Chip Technology Innovation Opens a New Paradigm

- **The impact of AI Chip technology innovation**
  - The demand for AI Chip including GPUs and Neuromorphic processors has been increasing since 2010 when artificial intelligence began to be utilized in various fields.
  - Currently, Mainland China and the United States account for about 80 percent of the global patents in the field of AI Chip. However, the quality of patents filed by Mainland China is relatively low while that by the United States is noticeably high. United States shows that these high qualities of patents are evenly distributed over all sectors including government-funded research institutes, enterprises, and universities, which implies strong technology innovation eco-system built.
  - The qualitative impact of patents filed by Asian countries is relatively low in all sectors such as the university, industry, and government sectors. In contrast, Canada exhibits a high level of patent citation impact that is comparable with the United States. Its university sector has achieved a higher qualitative competitiveness in AI Chip than the United States.
  - For the university sector, the top 10 most innovative universities in AI Chip come from the United States and Mainland China. With Beijing Univ of Tech and Xi'an Jiaotong University at the forefront, Mainland China, is leading the AI Chip technology in both quantity and quality of innovation. In the case of the United States, despite the relatively small number of patents filed by universities such as MIT and the University of California, the patent citation impact is very high. Mainland China's overall low patent quality despite of high innovation quality at university sector implies that not much academic innovative technology has been transferred to industry sector or industry focuses on mass-manufacturing (low price, mass volume) rather than innovative products.
  - As the hardware structure of AI Chip requires innovative ideas that deviate from the existing CPU framework, a number of start-ups with excellent design capabilities around the world are emerging in the field. Furthermore, a number of companies that have not been in the chip industry previously, such as Google, Amazon, and Tencent, are also making inroads into the AI Chip market.
- **The impact of scientific papers in the field of AI Chip**
  - In terms of the impact of scientific papers, the United States is ranked first, followed by Switzerland, Singapore, the Netherlands, the United Kingdom, Australia, Canada, Mainland China, and South Korea. the United States holds a dominant position in both quantity and quality of scientific papers in AI Chip. One thing to note is that although

Switzerland holds only a small number of scientific papers, it has a higher research impact than Mainland China.

- Technology innovation in AI Chip is being led by global R&D collaboration such as industry-university cooperation. Advanced technologies are based on various basic sciences, but companies often face difficulties in securing resources for all basic science internally. This is why international companies cooperate closely with leading global universities when developing advanced technologies.
- United States universities such as Stanford University, UC Berkeley, and MIT have not only a high level of citation impact of their scientific papers and also excellent performance in terms of commercialization of their scientific discoveries. Asian universities in Mainland China and Korea, on the other hand, rank high in terms of the number of scientific papers, but their citation impact and the impact on commercialization (patents) are relatively low.

Suggestions for the Development of AI Chip

National strategies for building a competitive innovation ecosystem

- It is crucial to build an innovation ecosystem where mutual-cooperation among universities, enterprises, and government-funded research institutes is stimulated. To this end, each country needs to establish a strategy for participating in the AI Chip ecosystem by examining their current technological status through comprehensive and objective data analysis. Furthermore, proper science and technology policies as well as industrial strategies must be included.

The acceleration of joint global R&D collaboration

- One of the key success factors of technological innovation is to build an ecosystem that absorbs innovative ideas and trains excellent talent to support a virtuous cycle in cross academic, government and corporate sectors
- The field of AI Chip includes a wide spectrum of technologies. Hence, it is not easy for a company or a university to lead technological innovation in all different fields of AI Chip. Therefore, it is strongly encouraged strategic R&D collaboration among universities and companies to develop innovative AI Chip technologies.

The fostering start-ups in the AI Chip industry

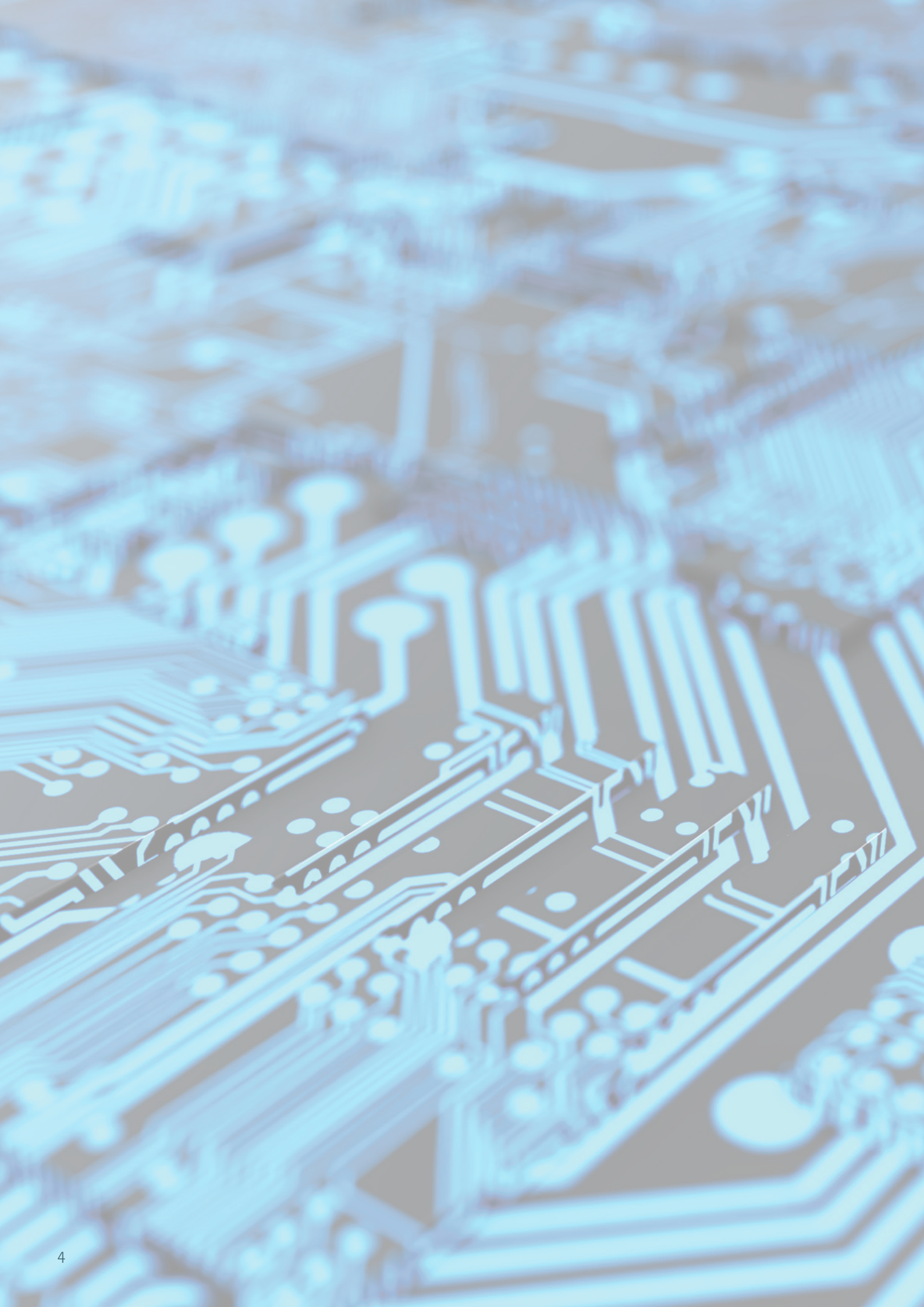
- Start-ups based on basic science and creative R&D attempts in the AI Chip industry should be more actively promoted.
- The start-ups with novel ideas in the university and government research institutions are strategically important for the sustainable growth of the innovative industrial ecosystem.

‘Coopetition’ with non-traditional chip companies

- In the AI Chip market, chip companies and non-chip companies are leading technological innovation. Since the non-chip companies are entering to the market and lack experience while introducing market frontier knowledge, a ‘coopetition’—a blend of competition and cooperation -- with the existing chip companies will be beneficial to innovation.

Discovery of AI Chip application areas that accelerate new growth

- Growth of the AI Chip industry should be prioritized and actively pursued from a national strategic point of view for each country.



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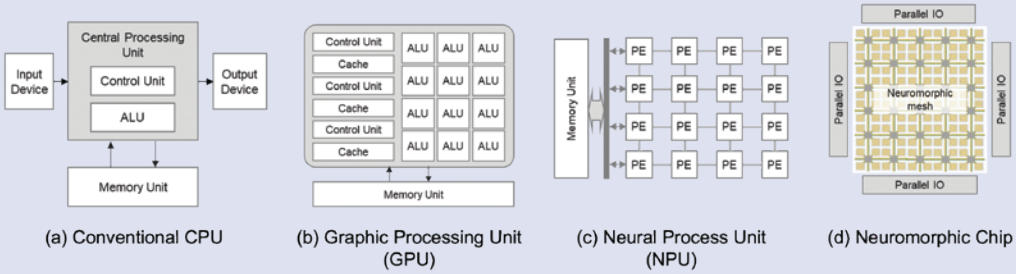
1. Artificial Intelligence (AI) Chip

With the growth of artificial intelligence (AI) systems in various areas, from autonomous driving, big data analysis to smart factories, the demand for AI Chip that are capable of processing massive amounts of data is rapidly increasing. There is no doubt that AI Chip with massive computation capabilities and decision-making abilities are the backbone of the future chip industry.

Figure 1. Example of conventional CPU and AI Chip architecture



(a) Conventional CPU (b) Graphic Processing Unit (GPU) (c) Neural Process Unit (NPU) (d) Neuromorphic Chip

To achieve the ultimate goal of high performance computation, there are several variants of architecture in AI Chip. Since each architecture has strength and weakness, and AI applications also has many different data processing characteristics, it's hard to address which architecture will be dominant for all application cases. This report reviews major architecture type of AI Chip and assess their innovation trend.

In order to lead the future industry, large-scale investments are being made as competition is increasing in AI Chip technology among companies and countries. Currently, non-traditional chip companies are making inroads into the market for AI Chip and about 19 trillion Korean won has been invested in the field of AI Chip by startups since 2021. AI Chip can be classified into five major technologies each in different stages of technological development: conventional processors, central processing unit with AI accelerators, neural processing unit, processing-in-memory based AI Chip, and neuromorphic processors. Accordingly, indiscriminate investment in AI Chip may not ensure global competitiveness in the AI Chip industry. In order to secure the core technology and achieve global competitiveness in the AI Chip market, an innovation ecosystem for AI Chip needs to be created through unique strategies and policies.

This report examines the global trends of AI Chip technology and future direction of the market by analyzing patents and academic papers in the field of AI Chip. It aims to provide implications for the establishment of strategies for the development of AI Chip by analyzing the current development status of AI Chip by major countries from various perspectives.

What is AI (Artificial Intelligence) Chip?

AI Chip is a specially designed semiconductor to process data faster and more efficient than conventional CPU (Central Processing Unit). This emerging technology is due to strong demand for high computation power of various AI applications which process massive data in parallel. By changing the structure of processing, control, memory unit and Input/Output interface of conventional CPU, the internal architecture of AI Chip is optimized for parallel processing, fast memory access and lower power consumption. [Figure 1] shows example of various AI Chip architecture.

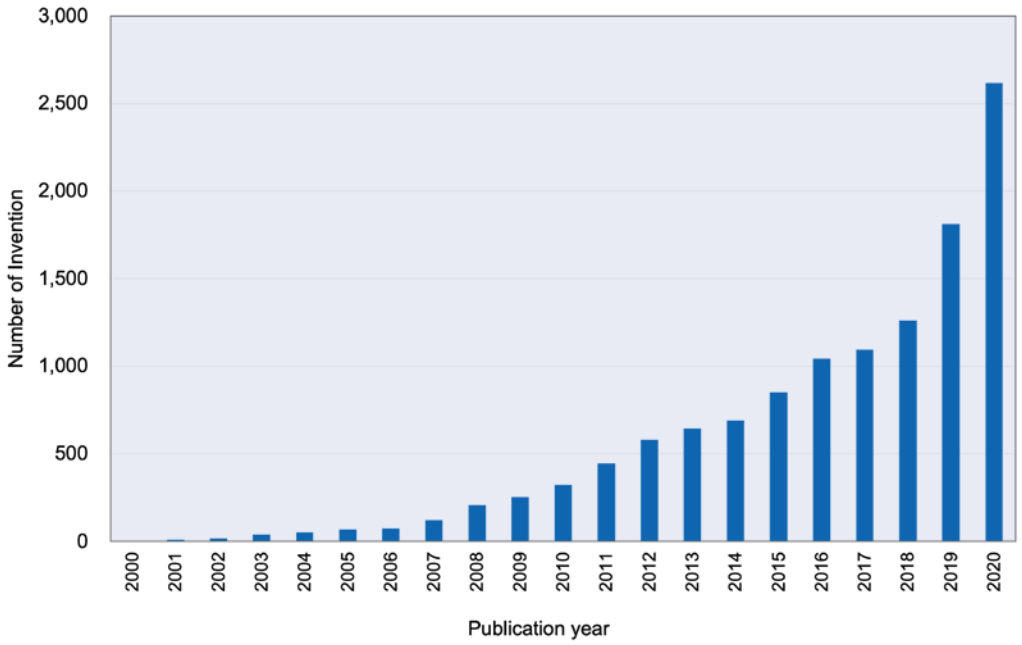
The architects of AI Chip are beginning to overcome the bottleneck problem of von Neumann architecture of existing CPUs (Figure 1(a)). In the von Neumann architecture, the processor and memory are separate components and data move between them via the system bus. The program instructions and data are stored in memory later to be operated. Since the system bus is used to transfer all data between CPU and memory, it created bottleneck as workloads and data transfer become larger. Since AI Chip can compute directly in the memory (PIM(Process-In-Memory) type, one of type of AI Chip), AI Chip can accelerate data processing while using less power.

2. The trend of AI Chip technology innovation

2.1. Global trends of AI Chip technology innovation

The beginnings of AI Chip technology date back to the 2000s, but did not receive much attention due to the existence of traditional CPUs that were capable of basic computations. However, recent advances in AI technology have opened new possibilities for the fourth Industrial Revolution where AI technology has been used in a variety of different areas, from big data, autonomous recognition to pattern recognition. With AI applications gaining traction in various sectors, the demand for AI Chip capable of processing massive amounts of data with low power consumption has rapidly increased. [Figure 2] illustrates the increase in the number of inventions related to AI Chip since 2000. As shown, technology innovation in the field of AI Chip has rapidly increased in the past decade.

Figure 2. The global trend of AI Chip inventions (disclosure of patents)



AI Chip technology is being developed in a variety of different forms, from improving an already existing processor that uses chip technology to be optimized for artificial intelligence computations to having a new paradigm for processor structures. This is a cutting-edge technology where research is being actively conducted in order to meet the demands for large-capacity data processing and lower power consumption in the field of artificial intelligence. AI Chip technology that is currently under research and development can be largely classified into the following five categories.

- **Conventional processors**

  Conventional processors are existing chip processors that are manufactured to be optimized for computation according to the characteristics of its application such as application-specific integrated circuit (ASIC) and field-programmable gate array (FPGA). In addition, the conventional processors such as graphics processing units (GPUs), which process large amounts of data efficiently with computational structures specialized for graphic image processing, and multicore central processing units (CPUs), which process information using several cores, are widely used to process artificial intelligence algorithms.

- **Central Processing Unit (CPU) + AI accelerators**

  A central processing unit (CPU) with AI accelerators is one of the five chip processor technologies developed on the existing CPU by adding AI accelerator chips designed to accelerate artificial intelligence and machine learning. This technology

is developed by integrating GPU or neural processing unit (NPU) modules that can process data at high speed with a central processing unit (CPU) or application processor (AP) inside the chip packages.

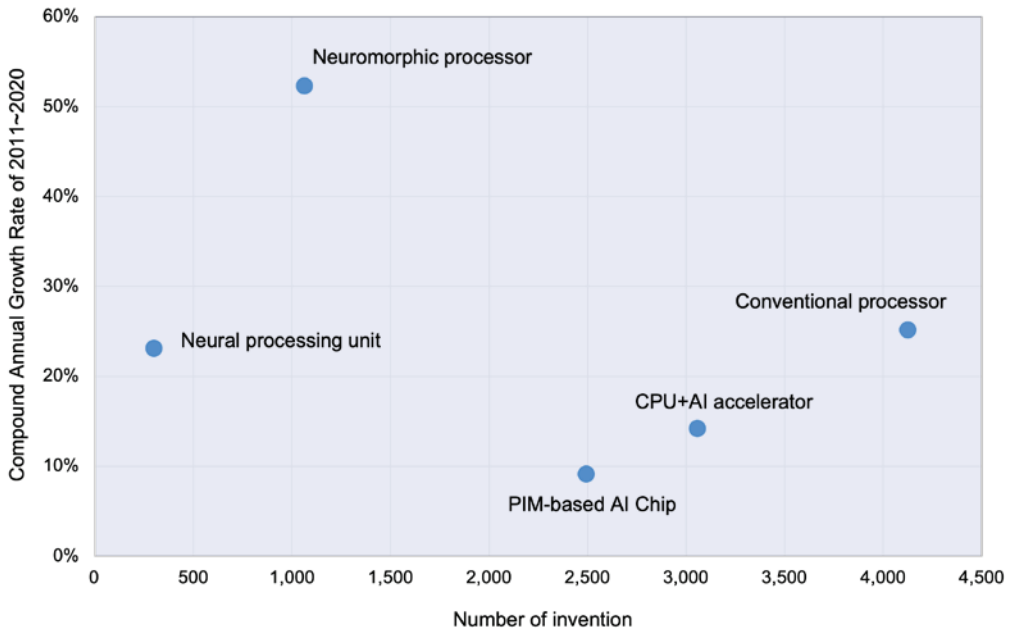
- **Neural Processing Unit (NPU)**
  A neural processing unit (NPU) is a processing unit with a structure that can process data efficiently like the human brain. The development of NPUs has been underway since the mid-2010s. In addition, research in the field of tensor processing units (TPU) specializing in deep learning tasks are actively conducted for the application of the existing memory chip technology in artificial intelligence application fields.

- **Processing-In-Memory (PIM) -based AI Chip**
  Despite the massive amounts of data that need to be processed in the field of artificial intelligence, the computation itself is relatively simple. In order to process the large amounts of data at high speeds while minimizing power consumption, new computational functions are added to the chip memory. Companies with high technical capabilities in chip memory are spurring the development of PIM-based AI Chip in order to advance into the AI Chip industry.

- **Neuromorphic processors**
  Neuromorphic processors, which are inspired by the human brain, are radically different from the existing process structures such as CPUs and GPUs. The neuromorphic processor technologies such as optical neural networks, spiking neural networks, and memristors are being developed based on the idea of how the human brain processes information efficiently using numerous neurons and synapses.

[Figure 3] illustrates each of the five technologies mentioned above and their patent performance. As shown in the figure, most of the technological innovation in AI Chip has been made in the field of conventional processor technology in which GPUs are being rapidly developed. This suggests that GPUs have already been widely applied in various fields of artificial intelligence and is well equipped with a software environment necessary for the development of application systems. Technologies such as FPGAs and ASICs are also being developed into a structure suitable for the application of artificial intelligence. Indeed, AI Chip technologies are continually evolving in which existing chip processor technologies meet new requirements of artificial intelligence through innovation.

Figure 3. Analysis of invention trends by types of AI Chip technologies



On the other hand, chip companies are accelerating the development of neuromorphic processor technology that mimics the computational process of the human brain by integrating memory chips with processors. Although the technology has not yet been commercialized, some prototypes have been introduced to the market. Various efforts have been made to improve the performance of the neuromorphic processors and meet the requirements for commercialization. In contrast, although a significant number of patent applications have been made in the field of PIM-based AI Chip, the pace of technological innovation in this field has not been as active as other technologies.

As seen in the above analysis, various AI Chip technologies are competing to become the next leading processor in the AI Chip industry, and developing into a brain-like technology that can perform both computation and data storage at the same time.

2.2. The trend of technology innovation by major countries

Policy trends of AI Chip in major countries

Technological innovation for AI Chip is rapidly growing across the whole world, and as Table 1 shows, various government-led policies are being announced to secure the leadership in the future AI Chip-related industry.

The United States has selected the chip sector as a core sector and is pushing for the enactment of a bill on the promotion of the chip sector. The European Union is also responding by strengthening industry-university cooperation to secure cutting-edge chip technologies. Furthermore, South Korea is making efforts to secure human resources and build an efficient AI Chip ecosystem by establishing an artificial intelligence development strategy with the goal of realizing an artificial intelligence powerhouse. Indeed, most major countries are preparing to invest heavily into the development of next-generation AI Chip.

Table 1. A summary of AI Chip policies in major countries

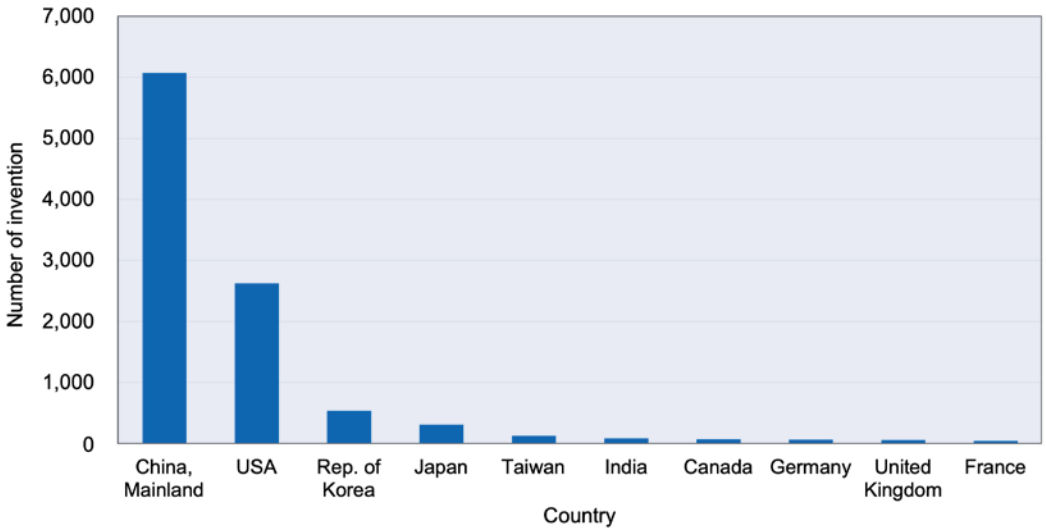
Country	Policy type	Policy
The United States	Chip policy (including artificial intelligence)	The National Defense Authorization Act (NDAA) for Fiscal Year 2021 including 'CHIPS for America Act', and 'American Foundries Act' • Establishment of a legal basis for the promotion of research and development, and fabrication of chips
		U.S. Innovation and Competition Act (USICA) of 2021 • Strengthening R&D investment in high-tech industries including the chip industry
	Specialization in AI Chip	Promotion of research projects by the Defense Advanced Research Projects Agency (DARPA) • DARPA's AI Next program to promote research and development for the development of new artificial intelligence technology (Sep, 2018) • The Real Time Machine Learning (RTML) program with two 18-month research phases: machine learning hardware compiler, and real-time machine learning systems (March, 2019) • The Structured Array Hardware for Automatically Realized Applications (SAHARA) in partnership with Intel that aims to develop custom chips for defense systems (March, 2021)
Mainland China	Chip policy (including artificial intelligence)	Made in Mainland China 2025 (May, 2015) • Promotion of design capabilities and production of core chips with an increase in the Chinese-domestic content of core materials
		Policies to promote the qualitative development of the chip industry and the software industry (August, 2020)
		The 14th Five-Year Plan for National Informatization (2021-2015) (March, 2021) • Securing the stability of supply chains and strengthening the independence of high-tech technologies including chips • Developing chips specialized in artificial intelligence applications
EU	Chip policy (including artificial intelligence)	2030 Digital Compass (March, 2021) • Boosting the EU's share in global production of cutting-edge chips to 20% by 2030
		Industrial Alliance for Processors and Chip Technologies among 22 EU member countries (May, 2021) • Development of 2nm process technology in 2-3 years
		Important Projects of Common European Interest (IPCEI) (2018) • Promotion of projects in 5 major technology fields including energy efficient chips, power chips, sensors, advanced optical equipment, and compound materials
	Specialization in AI Chip	European Processor Initiative (EPI) (Dec, 2018 – Nov, 2021) • Research and development of low-power processors using artificial intelligence technology
		Technology and Hardware for Neuromorphic Computing (TEMPO) (May, 2019 – 2022) • A collaborative research project that aims for the development of low-power chips for the application of artificial intelligence
		Horizon 2020 Research and Innovation Programme for the development of AI Chip (March, 2019 – 2022) • Development of AI Chip that are a billion times faster than biological neurons using chip nanostructures
Japan	Chip policy (including artificial intelligence)	Promotion of innovation for the development of AI Chip (2018 – 2022)
		Development of next-generation computing technology for high-efficiency, high-speed processing AI Chip (2018 – 2027)
	Specialization in AI Chip	Strategy for revival of the Japanese Chip Industry (June, 2021) • Strengthening R&D capabilities and fabrication of chips • Promotion of green innovation
Taiwan	Specialization in AI Chip	Establishment and operation of Taiwan Chip Research Institute (TSRI) (2019)
	Chip policy (including artificial intelligence)	AI Chip Project (June, 2019 – 2022) • Development of artificial intelligence processor chips, next-generation chip design, and process technology
South Korea	Specialization in AI Chip	Strategies for strengthening industrial capabilities and short-term supply and demand response of chips for vehicles (March, 2021) • Development of core chip technology for future mobility (R&D)
	Chip policy (including artificial intelligence)	K-Chip Strategy (May, 2021) • Development of next-generation chip technologies (including power chips, AI Chip, advanced sensors, etc.)

Source: Beyond future growth engines, the emergence of AI Chip as a key technology for national security (IITP, 2021)

The trend of AI Chip inventions by country

As illustrated in [Figure 4], the number of AI Chip inventions from Mainland China has an absolute advantage in terms of quantity, with more than double of the United States. Korea is ranked third in terms of the number of AI Chip inventions, showing a significant gap compared with Mainland China and United States, which are ranked first and second, respectively, among the top 10 countries.

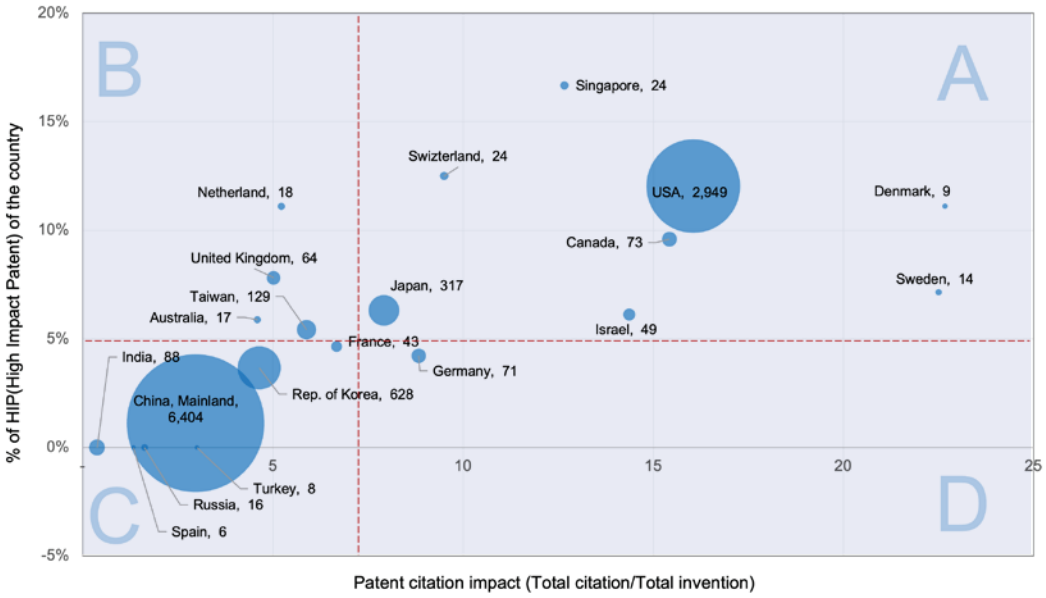
Figure 4. Top 10 countries with the most number of inventions in AI Chip



Mainland China and the United States account for about 80 percent of the global patents filed in the field of AI Chip while Korea holds only 5 percent of the global patents despite its ranking. [Figure 5] illustrates the quality of patents in the field of AI Chip by country. The patent quality is determined by evaluating the technological and commercial values of technological innovation in the field of AI Chip, which is measured using patent citation information. It is clear that the United States leads in the quality of patents in the field of AI Chip. In contrast, Mainland China's patents are low in quality despite being at the forefront of quantity. Besides the United States, countries ranked above the average of the twenty countries in terms of the quality of patents include Canada, Singapore, Switzerland, and Japan. Canada, in particular, shows a high level of quality competitiveness similar to the United States. Among countries with more than a hundred inventions, the United States shows the highest level of qualitative competitiveness, followed by Japan, Taiwan, and Mainland China.

From a national strategic point of view, it seems desirable to set a policy and strategic direction aiming at the positioning of the United States. In addition, Israel has multinational companies such as Intel and Qualcomm while Singapore has Global Foundry. Due to the presence of these international companies, both countries show high quality competitiveness with the support from the government. Furthermore, the United States is promoting joint research for technological innovation with leading universities and companies in the country as well as around the world.

Figure 5. Comparison of patent quality in AI Chip by country



Cross-country comparison of innovation performance by types of AI Chip technologies

As [Figure 6] shows, most countries except for Mainland China and India have invested heavily in the CPU + AI accelerator sector, whereas Mainland China and India have mainly focused on conventional processors.

South Korea holds patents in various fields such as conventional processors, PIM-based AI Chip, CPU+AI accelerators, and neuromorphic processors. In particular, neuromorphic processors account for a relatively large proportion compared to other countries. In the field of PIM-based AI Chip, South Korea owns a number of patents in memory-based AI Chip technologies such as MRAM, PRAM, RRAM, SRAM, and Flash RAM. However, as seen in the previous analysis, the number of patents in AI Chip technologies is significantly small compared to that of Mainland China and the United States [Figure 6].

Figure 6. The proportion of the five major types of AI Chip technologies across countries

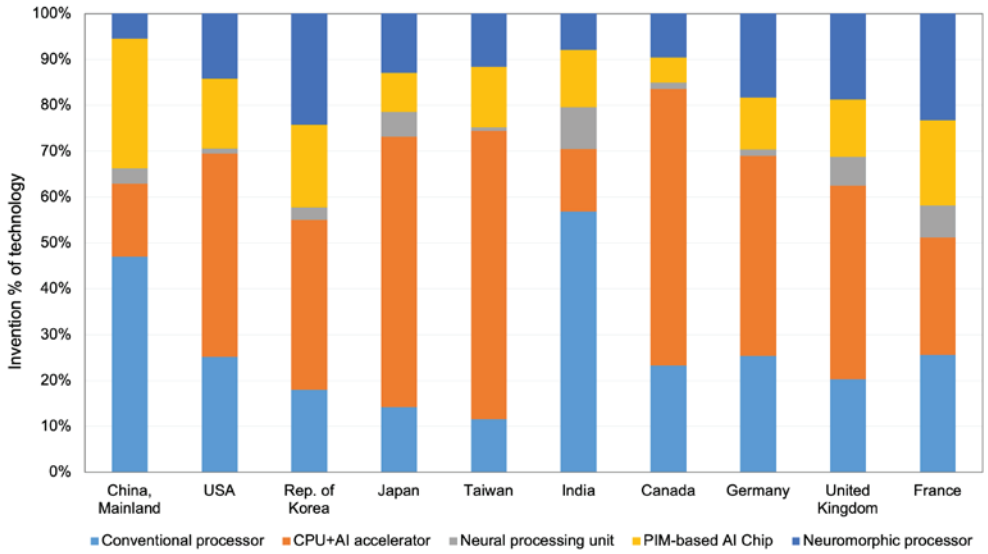
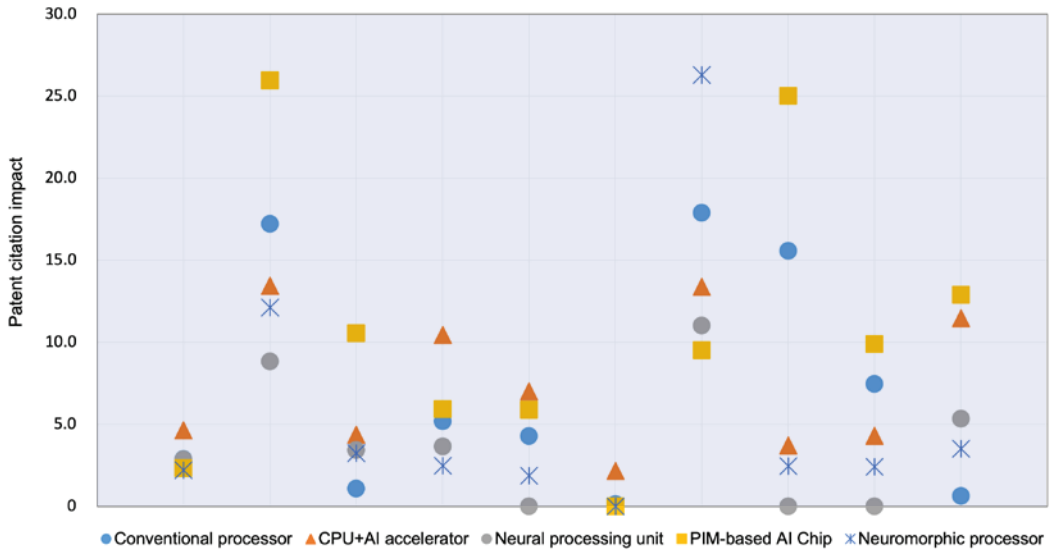


Figure 5: This graph shows the quantitative level of AI Chip technology innovation for each country by illustrating the patent citation impact against the percentage of high impact patents for the top 20 countries based on their number of patents in the field of AI Chip

For instance, the United States holds 4.8 times more patents than Korea in MRAM-based AI Chip technologies, 6.2 times more patents in Flash RAMs, and 2.8 times more patents in Memristor. The impact of patents filed by the United States is significantly higher across the five major types of AI Chip along with Canada while that of Mainland China is relatively small. South Korea shows a higher patent impact in the field of PIM-based AI Chip, but its impact is relatively small in other fields.

The proportions of the five major types of AI Chip is compared between countries in [Figure 6 & Figure 7]. In the field of PIM-based AI Chip, the United States, Germany, France, and Korea are competing for patent application whereas in neuromorphic processors, Korea shows a similar level of patent influence with other countries except for the United States and Canada. The United States, Canada, Germany, the United Kingdom along with Taiwan and Japan have a competitive advantage in the field of conventional processors, accounting for the largest proportion in the number of patents out of the five major technologies.

Figure 7. Comparison of patent quality in the five major types of AI Chip across countries

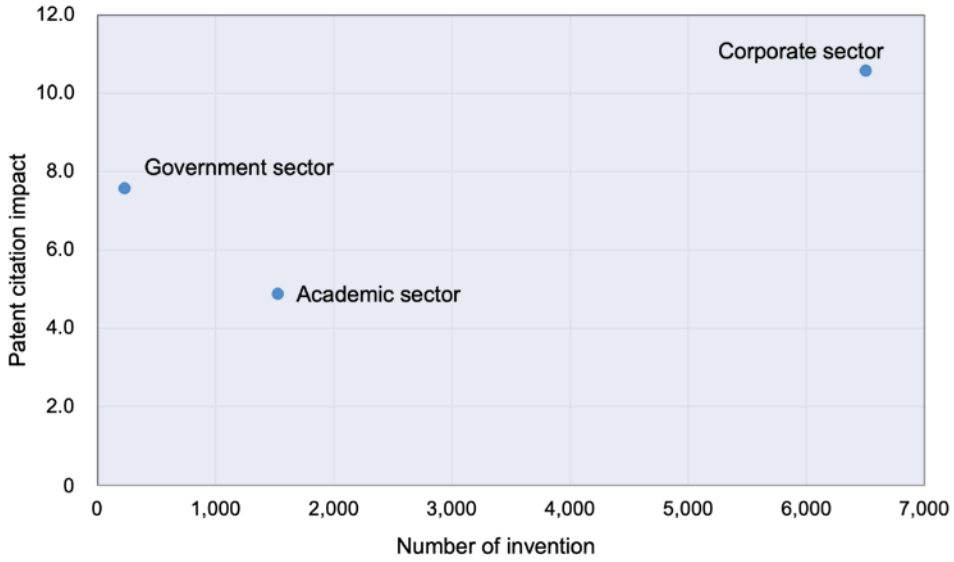


2.3. Performance analysis of technological innovation ecosystems by country

The technological innovation competitiveness of each country is examined by dividing the actors of national technological innovation ecosystem into universities, government-funded research institutes, and enterprises. In general, universities play the role of nurturing basic science and fostering human resources. Government-funded research institutes also focus on basic science research for national development whereas enterprises conduct research and development for commercialization. Efficient national innovation ecosystems lead to the generation of new knowledge, collaboration, and innovation. These are key in driving social and economic development and in promoting the technological competitiveness of a country in the era of a knowledge-based economy.

Looking at the performance of AI Chip technologies by sector worldwide, the amount and quality of patents filed by companies are significantly higher than that by universities and government-funded research institutes. Despite the fact that universities file quite a large number of patents, the quality of patents filed by government-funded research institutes is higher.

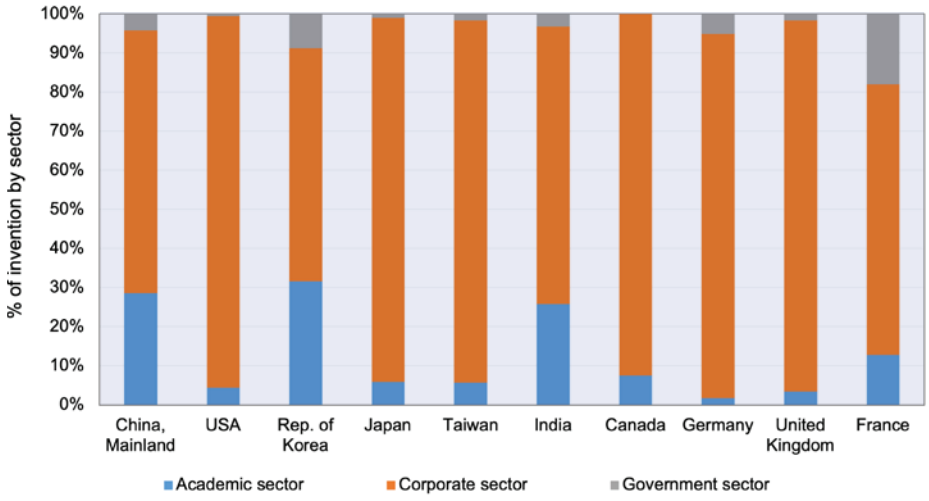
Figure 8. Comparison of the quantitative and qualitative level of patents in AI Chip by three different types of assigneesdifferent types of assignees



[Figure 8] and [Figure 9] show the proportion of AI Chip inventions by the types of assignees. The proportion of AI Chip technology patents filed in the corporate sector accounts for a relatively larger share in Canada, Germany, the United Kingdom, Japan, Taiwan, and the United States than other countries. In Mainland China, Korea, India, and France on the other hand, the proportion of patents filed by the university sector accounts for a relatively larger share. However as shown in [Figure 10], the quality of their patents is lower than the average (except for France).

In addition, although both France and Korea hold a large share of patents filed in the government-funded research sector, the citation impact of patents filed by France is above the average whereas that by South Korea is far below the average of the top 10 countries.

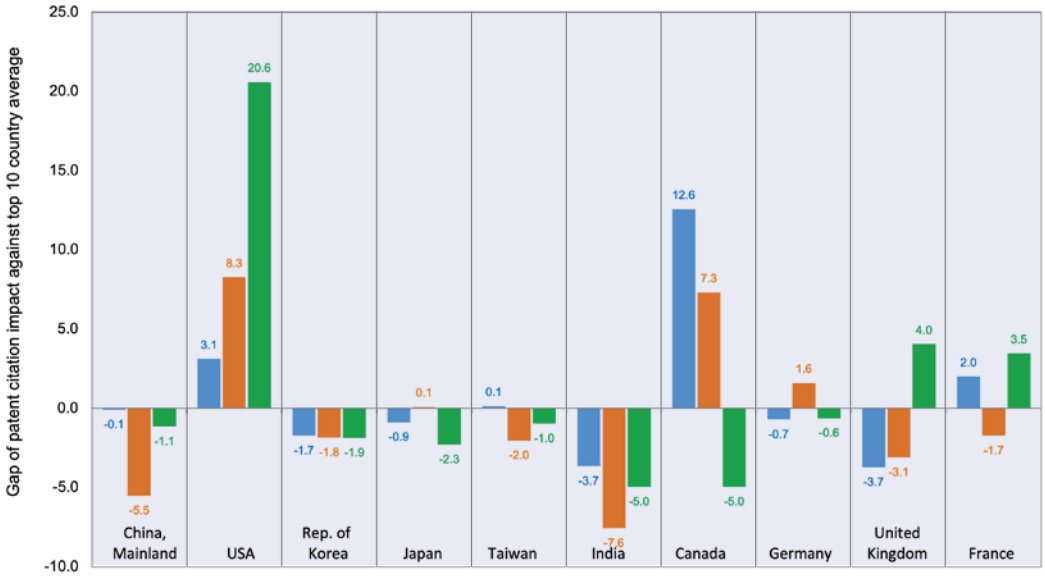
Figure 9. Cross-country comparison of the proportion of technology inventions by sector



Overall, the patent citation impact of Asian countries is considerably lower than that of Western countries. [Figure 10] shows the patent citation impact of each country against the average of the top 10 countries. Mainland China, India, and Korea have lower patent citation impacts than the average in all three sectors. As suggested in [Figure 5], which depicts the patent citation impact against the percentage of high impact patents, Mainland China, India, and Korea are all located in the third quadrant of the graph, implying limitations in technological competitiveness in AI Chip. In particular, the patent citation impact of Korea and India are far below the average of the top 10 countries in all three sectors. On the other hand, the United States has high-quality patents in AI Chip across all sectors and the government-funded research sector in particular shows a high patent citation impact relative to its number of patents.

Furthermore, Canada shows results comparable to the qualitative competitiveness of the United States, and its university sector in particular exhibits a higher patent citation impact than the United States. In addition, France and the United Kingdom exhibit a higher citation impact for patents in the government-funded research sector.

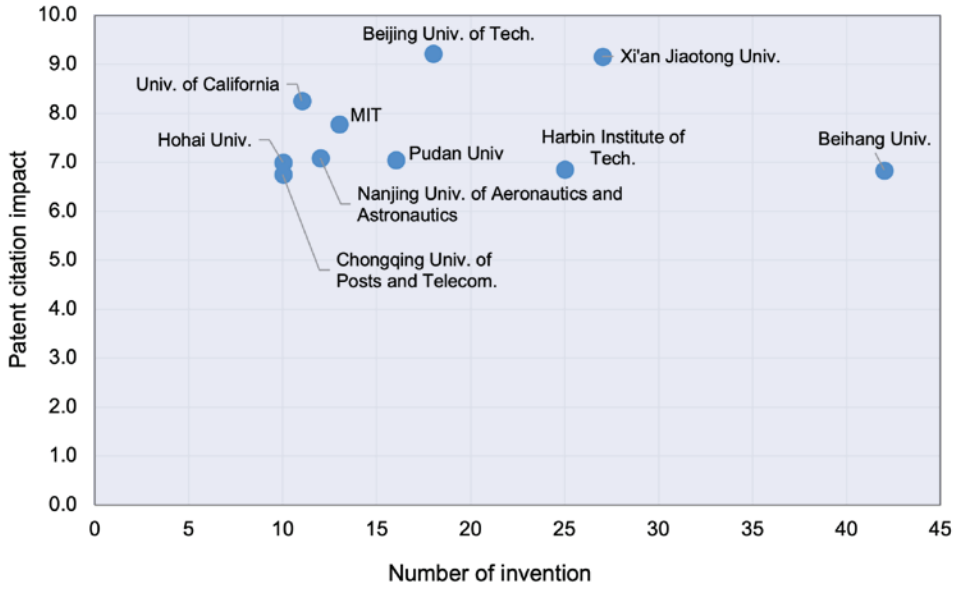
Figure 10. Average patent citation impact of top 10 countries



[The university sector] The global top 10 most innovative universities in AI Chip

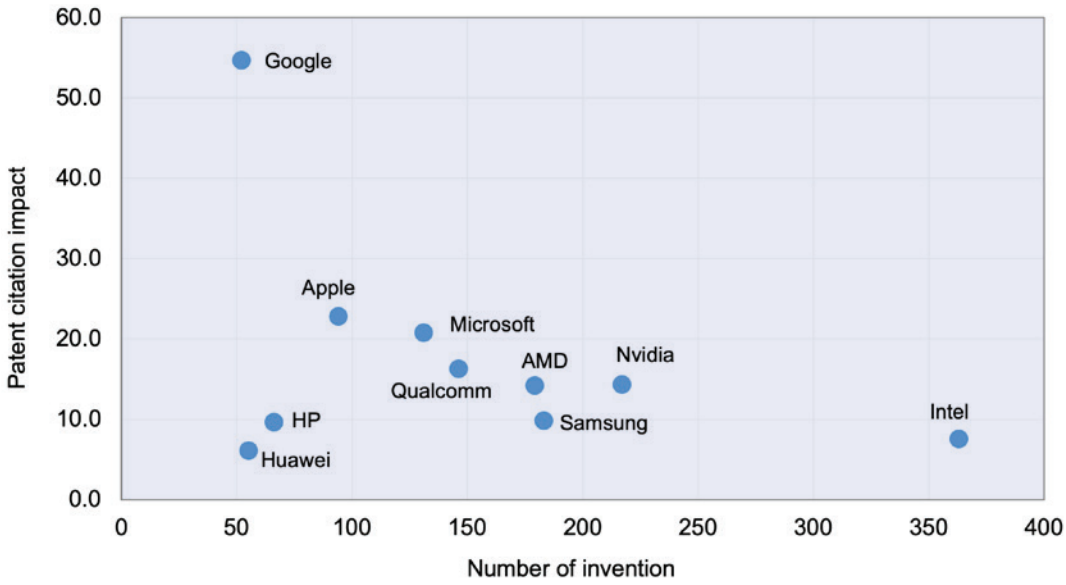
As shown in [Figure 11], most universities listed in the global top 10 most innovative universities in AI Chip come from the United States and Mainland China. In the case of South Korea, Seoul National University is included in the list of global top 10 most innovative universities in AI Chip. One point to note is that Chinese universities with Beijing Univ of Tech and Xi'an Jiaotong University are leading the field of AI Chip in both quality and quantity. Although Chinese universities outperform in terms of the number of inventions, Massachusetts Institute of Technology and the University of California are ranked high in terms of their patent citation impact.

Figure 11. The global top 10 most innovative universities in AI Chip[2]



2 This graph shows the global top 10 universities with the highest patent citation impact that have filed at least 10 patents in the field of AI Chip between 2011 and 2022

Figure 12. The global top 10 most innovative firms in AI Chip[3]

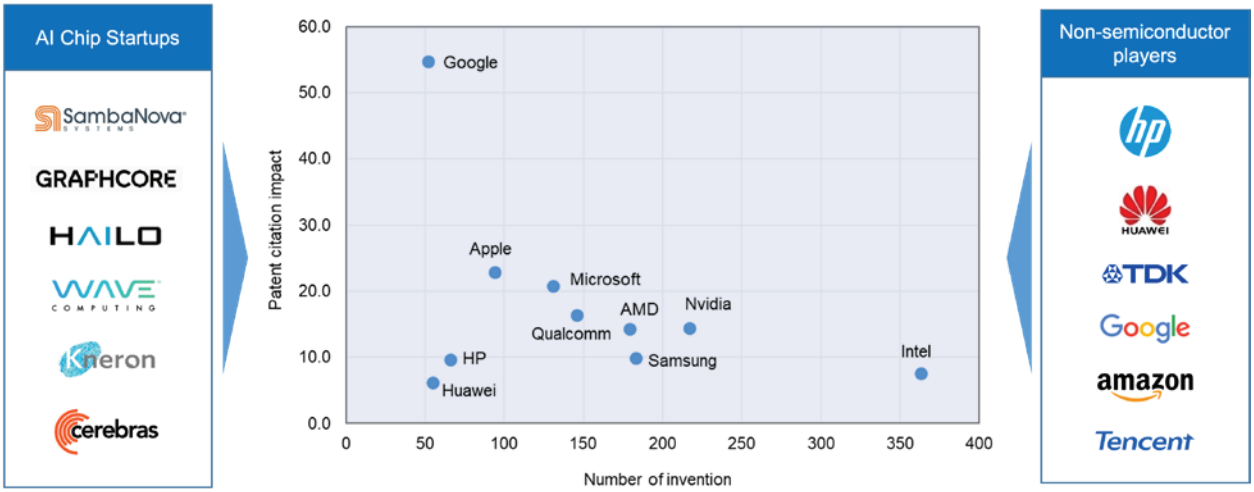


As previously analyzed, companies that do not have large-scale production facilities are also actively entering the AI Chip market. The structure of AI Chip requires innovative ideas beyond the existing structure of CPUs. As shown in [Figure 13], several startups around the world are entering the field of AI Chip with innovative design capabilities. More than 50 startups are already prominent in the field of AI Chip, and various institutions including venture capitalists have made about 14 trillion South Korean won of investment. Some of these startups are producing tangible results, while others are being acquired by existing conglomerates to accelerate technological innovation.

At the same time, a number of companies that have previously not been in the chip industry are entering this field, such as Google, Amazon, and Tencent. These companies have been using AI technologies in a wide variety of ways and are starting to independently develop AI Chip specialized for their application fields. As such, the AI Chip market is expected to be very complex and fiercely competitive due to the already existing large number of chip companies, new startups, and companies expanding their business into the AI Chip market. In the meantime, the mass-market centered on large-scale production of processor chips is transforming into a diversified market with various chip processors specialized for different AI application fields.

Considering such fierce technology competition and market dynamics, the AI Chip market has the potential to change rapidly in the future. In a situation where M&As are recognized as an engine of business growth, start-up acquisitions and mergers between companies have sufficient potential to change the market in a short period of time.

Figure 13. Potential dynamics of the global AI Chip market



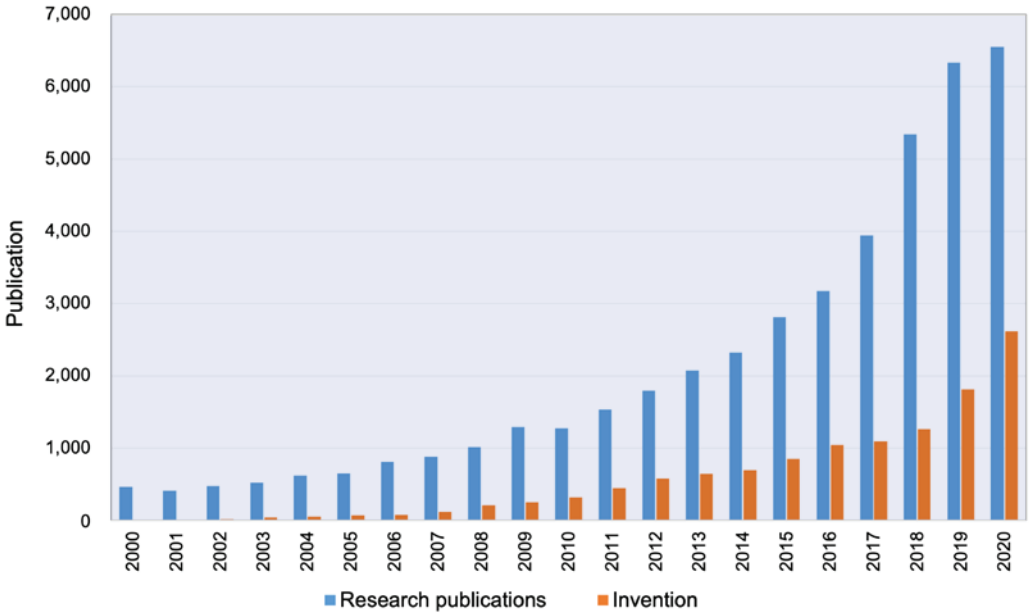
3 This graph shows the global top 10 companies with the highest patent citation impact that hold more than 50 patents in the field of AI Chip

3. Comparison of AI Chip Research Performance

3.1. Comparative trends in research performance

As shown in [Figure 14], there are more scientific papers than technology patents in the field of AI Chip. As the demand for AI Chip has been growing since 2010, R&D for technological innovation in AI Chip is being actively carried out. Considering the rate of increase in the number of scientific papers, it is expected that the number of technology patents will rapidly increase in the upcoming years. Furthermore, if competition for technological innovation in AI Chip begins in earnest between countries and companies, the rate of increase in scientific papers and patents is expected to accelerate.

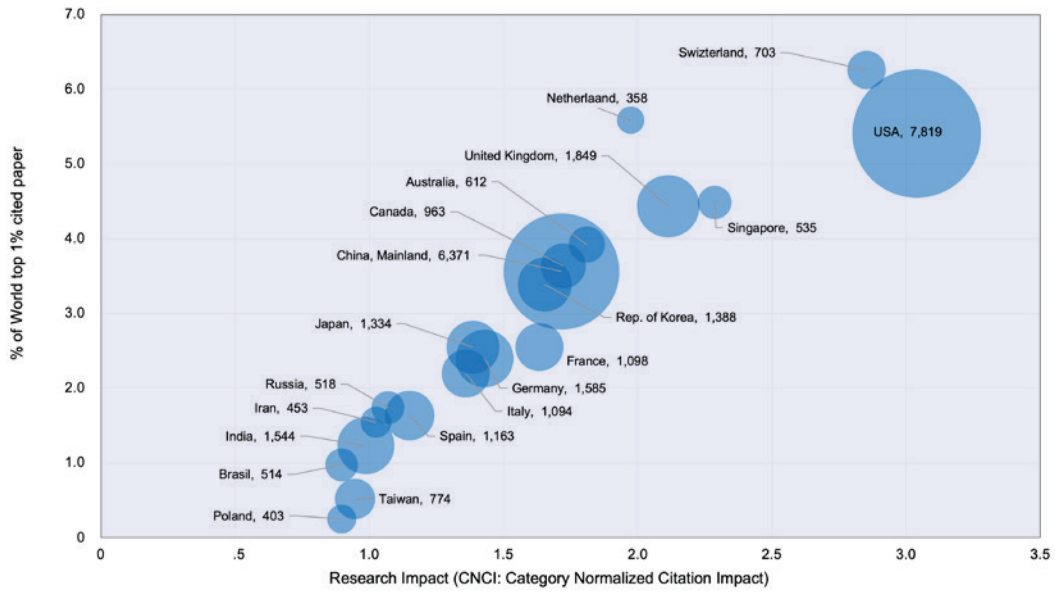
Figure 14. Comparison of trends in scientific papers and patents



3.2. Research trends in AI Chip by country

The foundation for basic science is one of the key requirements for the development of advanced technologies including AI Chip. Therefore, a solid foundation for basic research is required to maintain sustainable technological competitiveness. [Figure 14] illustrates the performance of scientific papers by the global top 20 countries that are selected based on their number of publications. In terms of research impact, the United States is ranked first, followed by Switzerland, Singapore, the Netherlands, the United Kingdom, Australia, Canada, Mainland China, and Korea. Although there is no correlation between quantitative and qualitative competitiveness, the United States holds a dominant position in both quantity and quality of scientific papers in AI Chip. An interesting point here is that although

Figure 15. Comparison of performance in research publications by country



Switzerland holds a smaller number of scientific papers than the United States, it has a higher level of research impact than Mainland China.

In the case of Mainland China, despite its great number of scientific papers that is comparable to that of the United States, its research impact is about the average of the 20 countries. Nevertheless, as previously analyzed, Mainland China's quantitative competitiveness in patents is three times greater than that of the United States, implying that there is a significant difference in the country's quantitative competitiveness between patents and scientific papers. In addition, not only Switzerland but also the Netherlands, Singapore, and the United Kingdom exhibit excellent research performance in terms of quality.

3.3. Research performance of joint R&D in AI Chip

Technology innovation in AI Chip is often promoted through international joint R&D and industry-university cooperation. High technologies are based on diverse basic science, but companies often face difficulties in securing human resources for research. This is why international companies closely cooperate with leading universities when developing cutting-edge technologies.

One of the important strategies in cutting-edge technology R&D is international cooperation. Institutions with excellent research capabilities and differentiated expertise that are essential for the development of cutting-edge technologies are dispersed all around the world. Hence, global cooperation is on the rise in order to carry out R&D for cutting-edge technologies. Therefore, having a global network with overseas research institutes conducting excellent research in their own expertise is one of the important core competencies of recent technological innovation. In other words, conducting industry-university joint research as well as international joint R&D can be viewed as building an external network system for innovation that can absorb innovative ideas from various sources.

[Figure 16] shows the rate of increase in international joint R&D and industry-university cooperation in the field of AI Chip. Switzerland noticeably has the highest growth rate in industry-university cooperation while Iran also shows the highest growth rate in international joint R&D. Countries that have been active in both industry-university cooperation and international joint R&D such as the United States, Japan and Mainland China are also promoting more and more joint R&D in order to spur the development of cutting-edge technologies by absorbing various knowledge and research capabilities from external sources.

Figure 16. The growth rate of R&D cooperation in AI Chip
(including industry-university cooperation and international joint research) [4]

4 A cross-country analysis of the increase in industry-university cooperation and international joint research publications with Korea as the base country

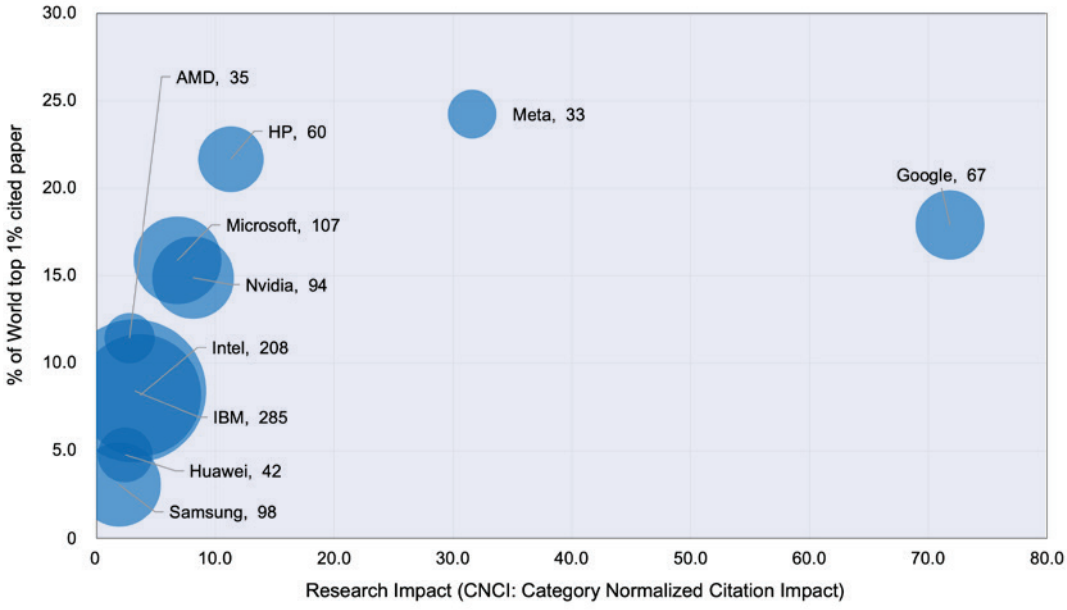
Figure 17. Intel Neuromorphic Research Community

3.4. Comparison of research performance of the global top 10 companies

Apart from technology patents, companies have also published a number of scientific papers related to AI Chip. Although the number of scientific papers published by companies is not large, the quality of their papers is significantly high while non-traditional chip companies such as Google, Facebook, and Microsoft have also published several remarkable papers with a high research impact. The reason these non-traditional chip companies were able to secure research capabilities and develop chips in a very short period of time lies in industry-university cooperation with world-renowned universities that enables the companies to secure core technologies as well as human resources.

[Figure 18] analyzes the research performance of the global top 10 companies based on the number of AI Chip-related research publications. Most of the companies are American firms except for one in Korea and one in Mainland China. Although the number of research papers is lower than that of Intel, IBM, and Nvidia, several non-traditional chip companies are included. Facebook, which has recently changed its name to Meta is also included in the top 10 companies in terms of the quality of research publications in AI Chip. Despite the fact that Meta is not listed in the top 10 companies in terms of the citation impact of the patents, it is clear that the company has excellent research capabilities and is expected to become an excellent company in AI Chip in the near future.

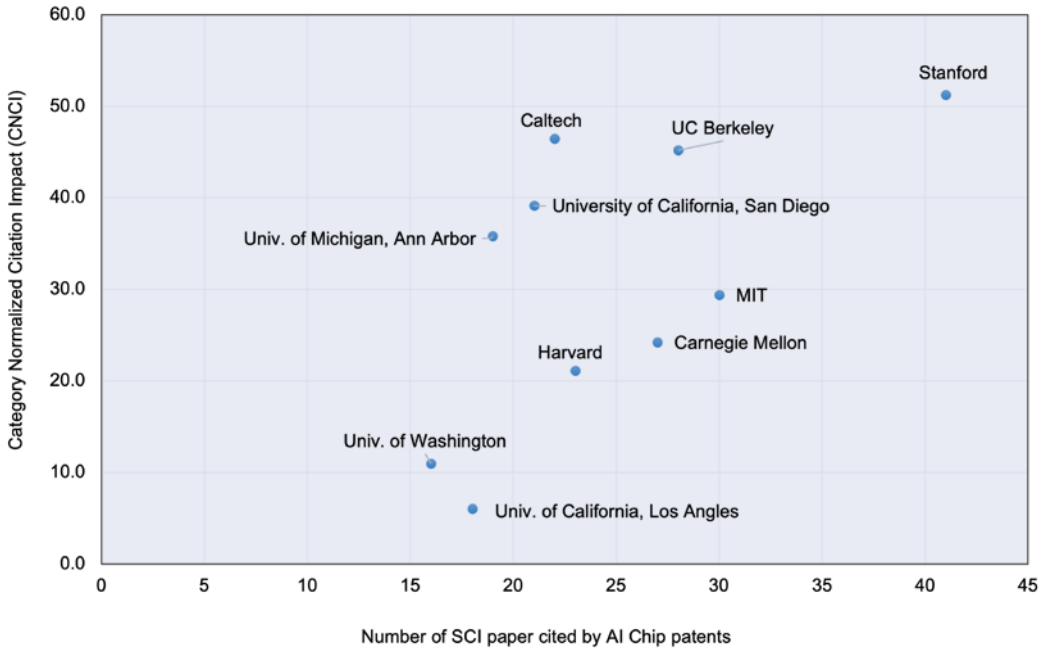
Figure 18. Analysis of research performance by the global top 10 companies



3.5. Analysis of university research publications that are cited by AI Chip patents

Using the citation information in patent documents filed by universities in the field of AI Chip, the impact of research publications is analyzed. Universities are dedicated to making basic science discoveries. Therefore, research papers published by universities with a high citation impact are expected to have a direct influence on technological innovation. In this regard, research publications that are cited for the development of AI Chip are used for analysis. As shown in [Figure 19], research publications that are directly cited by patents in general have a higher level of category normalized citation impact (CNCI). In addition, the top 10 universities with the most number of cited papers in AI Chip patents are all American universities, and their research papers directly contribute to technological innovation of the country. In other words, the innovation ecosystem of the United States is well-connected and efficient, encouraging innovation and stimulating cooperation among innovation actors including universities, enterprises, and government-funded research institutes.

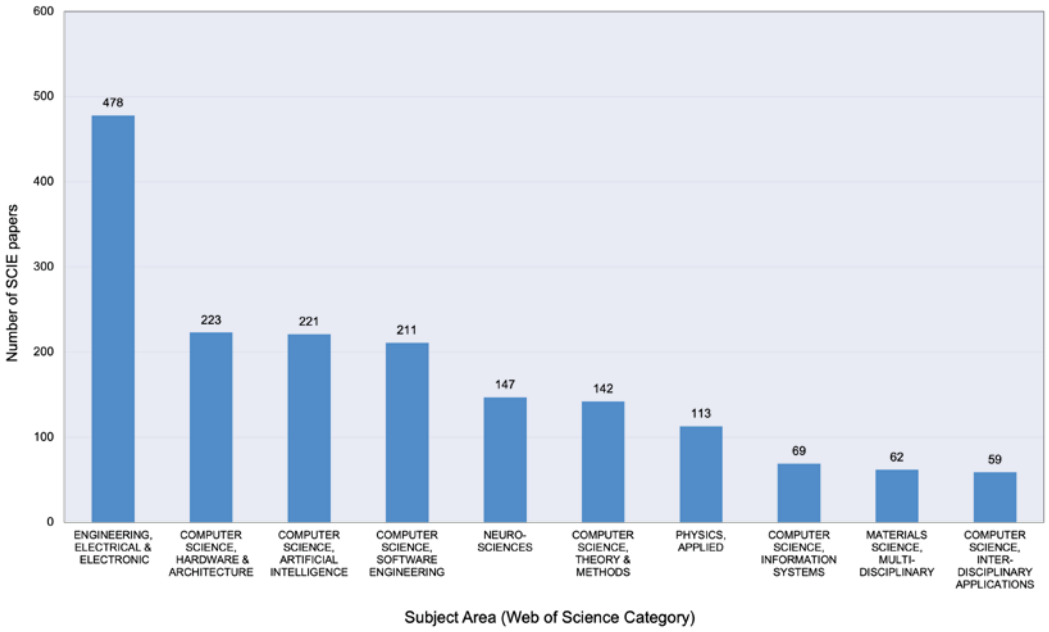
Figure 19. The top 10 universities with the most number of cited papers in AI Chip patents[5]



To be more specific, universities such as Stanford University, UC Berkeley, and MIT have not only a high level of citation impact but also excellent performance in terms of commercialization. Major Asian universities in Mainland China and Korea rank high in the number of research papers produced, but their citation impact and the impact on commercialization (patents) are relatively low. On the other hand, Stanford University and University of California San Diego (UCSD) exhibit excellent performance in both quantity and quality of research papers in AI Chip.

5 The research performance of the global top 10 universities is analyzed based on the number of research papers that are directly cited by AI Chip worldwide

Figure 20. The top 10 research subject area of cited papers in AI Chip patents



The innovation of AI Chip is based on fundamental scientific research. Patent of innovative technology cites various non-patent literature such as research articles or technical papers. The nature of AI Chip is semiconductor, but [Figure 20] shows that scientific research on artificial intelligence, neuroscience, physics and material science contribute the development of AI Chip technology. Multidisciplinary research output empowers the creativeness of technology innovation. Although not shown in top 10 research areas at [Figure 20], nanotechnology, optics and molecular biology also support the development of AI Chip technology. We expect scientific research contributing AI Chip development will continuously grow as research is being conducted how to utilize AI Chip in various applications.

4. Implications for AI Chip technology development

National strategy to build a competitive innovation ecosystem

The overall analysis shows that the United States is at the forefront of the competition for AI Chip technology development qualitatively. In particular, university and industrial sectors in United States are leading the development of AI Chip. In contrast, despite Mainland China's rapid growth in terms of quantity and qualitative growth centered on universities, its industrial sector does not seem to have enough competitiveness yet. Each country is pursuing a different technology in the AI Chip area and hence, it's necessary to review their technology position in the world: what their technology strength is and with whom they are competing. It is crucial to create a sustainable innovation ecosystem where collaboration among universities, enterprises and government-funded research institutes is stimulated. To this end, each country needs to establish a strategy for a seamless integrated and efficient AI Chip ecosystem by examining their technological status based on comprehensive and objective fact analysis. Furthermore, this must be accompanied by proper science and technology policies as well as industrial strategies. The following strategies are suggested for the establishment of an efficient innovation ecosystem.

It is also important for the ecosystem to closely connected to global value chain. To make a final product of AI Chip, there should be many collaborations engaged from chip design to chip production. For example, without ASML's latest EUV machines, it's very difficult to make high performance chip in efficient way.

The acceleration of global R&D collaboration

Sustainable technological innovation of cutting-edge technologies such as AI Chip can be promoted only when there is a solid foundation for basic science. Indeed, basic science is the foundation for competitive technology development. Competing with global companies with fragmented ideas without solid scientific and foundational knowledge will become increasingly challenging in the future. One of the key success factors of technological innovation is to construct an ecosystem that absorbs innovative ideas and excellent human resources, and to actively and continuously nurture the ecosystem. In addition, in the field of AI Chip, technologies are very diverse and complex. It is not easy for a single company or a university to lead technological innovation in all different fields of AI Chip. Therefore, strategic cooperation in R&D with universities and companies devoted to high technologies is strongly encouraged.

As in the case reviewed in this report, leading companies are promoting various R&D projects with universities in various countries. However, although the importance of university-industry cooperation has been widely recognized, it is difficult to find successful cases of strategic university-industry cooperation in many counties. Particularly, government support should be carefully designed to promote the collaboration. For example, the collaborative research efforts need to be supplemented by longer-term research and training activities that can be funded majorly by public resources together with open institutional environment (Grindley, Mowery and Silverman, 1994). The Sematech, a not-for-profit consortium that performs research and development to advance chip manufacturing, can be a good example. While the Sematech has spent five years and $1 billion, benefits to the industry was hard to capture. Therefore, without an efficient university-industry cooperation system, there may be a limit to creating world-class technologies. Companies should consider moving away from the university-industry cooperation system centered on local universities and expand their cooperation system into a more global system where companies cooperate with not only local universities but also leading global universities.

Startups Fostering AI Chip

In recent years, early innovative research in new technologies has been largely initiated by universities and startups. This is linked to the high degree of freedom in research that allows for various new attempts without being constrained by commercial economic feasibility, as

well as the start-up ecosystem that has gradually improved in recent years. On the other hand, corporate innovation often revolves around technological advancement of mature industries. There are several leading companies pursuing new innovations through active M&As and spin-offs. In terms of the degree of freedom of innovation, however, there may be significant restrictions on innovation compared to universities and start-ups.

However, there are also many challenges for start-ups. While start-up CEO establishes a company with innovative idea or technology, but to commercialize it and make business success is tough journey of marketing, business development, fund raising and people management, etc. Lack of skill and experience to run business is one of the biggest obstacles and nurturing business leadership is critical for the successful start-up ecosystem building. It is important to take a comprehensive view and to provide various components of business development in which entrepreneurs could operate rather than providing just capital itself (Lerner, 2010).

From this point of view, it is strongly encouraged for universities and public research institutes to contribute to an industrial ecosystem that encourages innovative R&D attempts and start-ups based on novel ideas. A mature start-up ecosystem can benefit big companies and M&A is another growth engine in the technology innovation area. The emergence of innovative start-ups gives rise to the creation of new industries and the transformation of existing industries, leading to the industrial development of the country in the mid- to long-term. There is a need for more active and strategic programs that facilitate innovative start-ups at universities and research institutes and boost the growth of start-ups. One important point to mention is that the various attempts made by start-ups are also accompanied by a number of failures, but the failure of these start-ups is part of the process of finding innovative technological discoveries while industries also learn from these failures.

Therefore, policy measures that internalize the risks associated with start-ups are also required. In addition, entrepreneurship education can be an important part of the policy since education enhances the understanding of the local markets as well as skill and knowledge about the business development.

Integrated cooperation with non-chip companies

As mentioned above, in the AI Chip market, existing chip companies, new start-ups, and non-traditional chip companies are leading the technological innovation in an integrated manner. This is because development of AI Chip is demand-based and application-optimized. Accordingly, there is a fierce competition between not only existing chip companies but also non-traditional chip companies and new start-up companies. AI Chip technologies are still in the early stages of development, and have very diverse application fields. Therefore, the structure of the market competition may change depending on who develops which innovative technology and dominates the application field. In addition, the entry of non-traditional chip companies is expected to play an important role in the market. Google is the most representative case of non-chip companies that enter the chip market through technological innovation. Although these companies have a relatively small number of patents in AI Chip, their impact is significantly high.

Discovery of application fields that promote new growth

The recent political conflict between countries has had a significant impact on the development of advanced technologies, and global companies that are trying to enter the Chinese market are facing great risks. In addition, decoupling of the technological innovation ecosystem is taking place while the global value chain is also being restructured.

In this situation, AI Chip companies need to prioritize the Economy of Scope strategy to discover new application fields rather than expanding their geographical market for economies

of scale in order to ensure sustainable future growth. In addition, the emerging markets such as the Middle East, South America, and Africa still lack the relevant industrial capabilities to accommodate AI. However, various initiatives such as Industry 4.0 and Intelligent Society have centered around the new application potential of AI Chip. As previously mentioned, Intel, a global chip company, is already advancing the discovery of various application fields where its AI Chip can be utilized through active university-industry cooperation with various organizations around the world.

AI Chip technology is not just confined to the growth of the chip industry, but is a core technology that has had a great impact on strengthening the competitiveness of the national industry as a whole. Therefore, decoupling of the AI Chip innovation ecosystem is expected to hamper technological development, consequently leading to stagnation of a country's overall industry. Countries will increasingly face limitations in competing with global companies due to the decoupled technological innovation ecosystem and localized value chain. Therefore, the development of the AI Chip industry is required to be prioritized and actively pursued from a national strategic point of view.

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5. Appendix

5.1. Choice of taxonomic framework and methodology

An inherent problem within any technology innovation and research data model is that of definition. Deciding upon how individual innovation and research outcome records should be categorized, analyzed output is as varied as retrieved data set by categorization. For this study, we organized AI Chip Advisory Group to identify technology taxonomy and review analysis result. The advisory members are professors and researchers on in the areas of AI Chip, system semiconductors and also have working experience at semiconductor industry.

AI Chip taxonomy has a series of categories put in place so that a definition of what is, and is not. The full taxonomy includes several topics surrounding AI Chip technology.

Within the taxonomy, the analysis focuses on 5 topics: conventional processor, CPU + AI accelerators, Neural Processing Unit (NPU), Processing-in-memory based AI semiconductors, and Neuromorphic processors.

Analysis of innovation and research data

Direct patent search was conducted for each of these five topics to identify the patented inventions specific to these technology areas. We also applied same search criteria to retrieve research articles to analyze research performance. With these two set of records, we compared the performance and landscape of technology innovation and research for AI Chip. From the patent data records, we further retrieved cited research articles to assess the background research of technology innovation.

Multi-level analysis to assess AI Chip innovation landscape

The analysis resolution was structured in multi-level: starting with top-level analysis is focused on country performance. The analysis result and national policy/strategy information helps to understand leading country and its competitive position among others. The next level is to assess sector level: academic, government and corporate sector. This is to understand the performance of innovation eco-system of a country. The last level is for organization level: identifying specific leading organizations at each sector. In this report, we exclude organizations of government sector because the analyzed result showed the innovation contribution of government organization was quite limited relative to academic and corporate sector.

KAIST-ISPI conducted this analysis and identified the findings of this report based on a data partnership with Clarivate.

5.2. Further background

We harnessed the power of our industry-leading patent and research data and used the following data sources from Clarivate for this study:

Derwent World Patents Index™ (DWPI™): A database built around ideas, DWPI records where and when inventions are patented across 60 patent-issuing states and authorities.

DWPI rewrites these patents into English-language invention summaries and categorizes their intended use, why they are needed and what is novel about them – 3.5 million times a year.

Derwent Patents Citation Index™ (DPCI): A sister database to DWPI, the Derwent Patents Citation Index focuses on inventions that have been referenced by applicants and examiners in later, downstream patent applications.

Emulating the DWPI invention-level structure, the Derwent Patents Citation Index automatically remove double, triple (or more) counting of citation events between the same patented ideas.

Web of Science™: The Web of Science is the world's largest publisher-neutral citation index and research intelligence platform. It organizes the world's research information to enable academia, corporations, publishers and governments to accelerate the pace of research.

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