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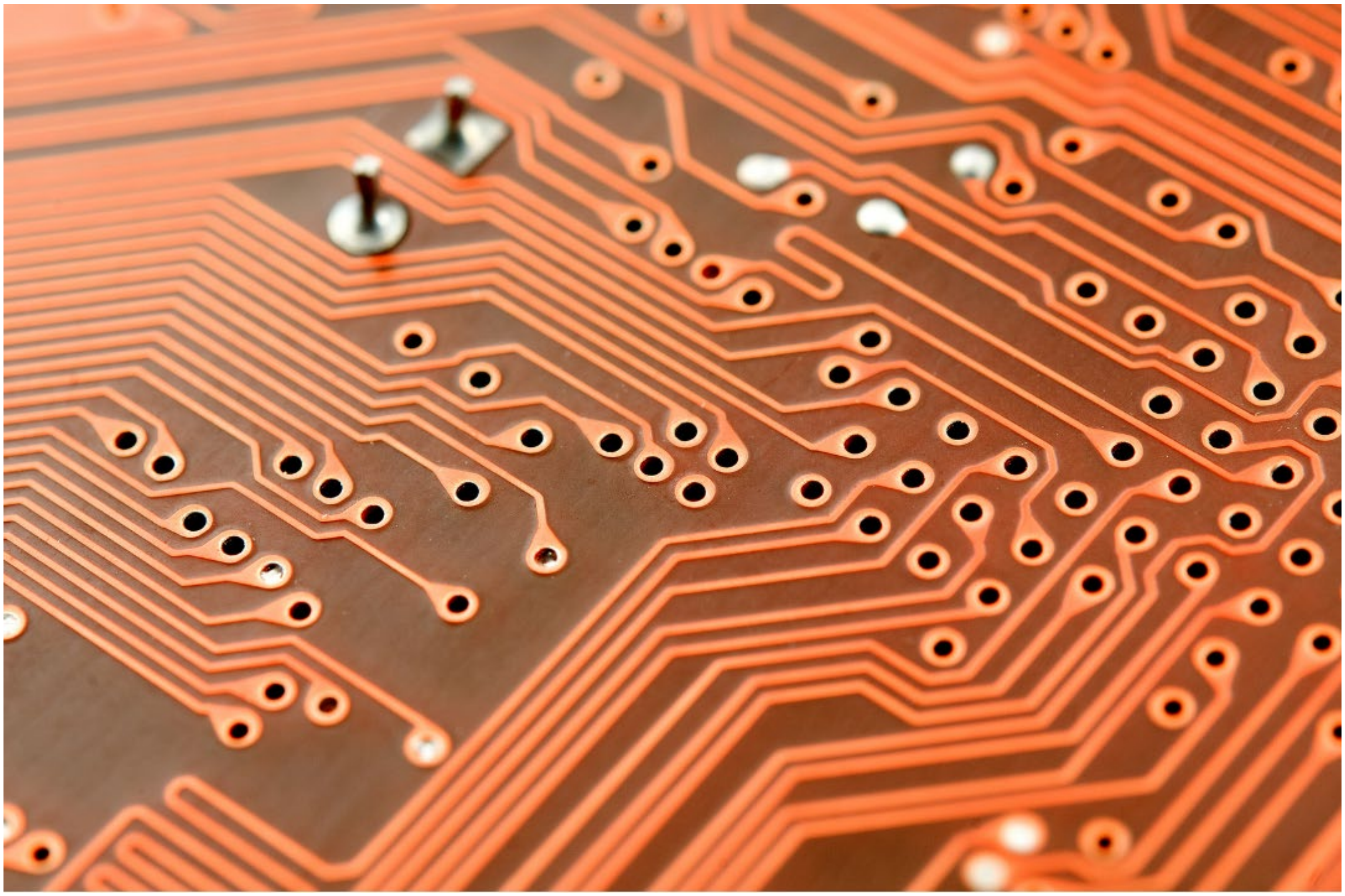
JANUARY 2024

TRENDS IN INTELLECTUAL PROPERTY

Global Semiconductor Alliance

Intellectual Property Interest Group



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1. Executive Summary

Intellectual Property (IP) is a crucial aspect of the semiconductor industry. It refers to the legal rights that protect the creations of the mind, such as inventions, literary and artistic works, designs, and symbols used in commerce. In the semiconductor industry, IP is used to protect the value created by companies that invest massive amounts of money in research and development. The laws on IP, including its transfer between suppliers and buyers, are the tools by which the investments and their value are protected.

The semiconductor industry is vast and complex, with many fields requiring IP protection. These fields include materials, manufacturing processes and tools, processors and engines, memory, security, sensors, analog systems, systems integration and packaging, communications, software, test, and verification. Although some of these fields may not seem connected to each other, they are part of a network that is indispensable for creating a full solution.

Innovation is a key aspect of the semiconductor industry. The need to process an ever-growing amount of data from a larger field of sources drives the industry. When boundaries are reached in one field of semiconductor technologies, solutions emerge in different and adjacent areas to create systems processing ever-larger data streams. Without the creativity of scientists and engineers, the industry would quickly come to a standstill.

Governments worldwide are heavily involved in policies driving the semiconductor industry in their countries. They fund universities to train talents that will drive innovation in the industry.

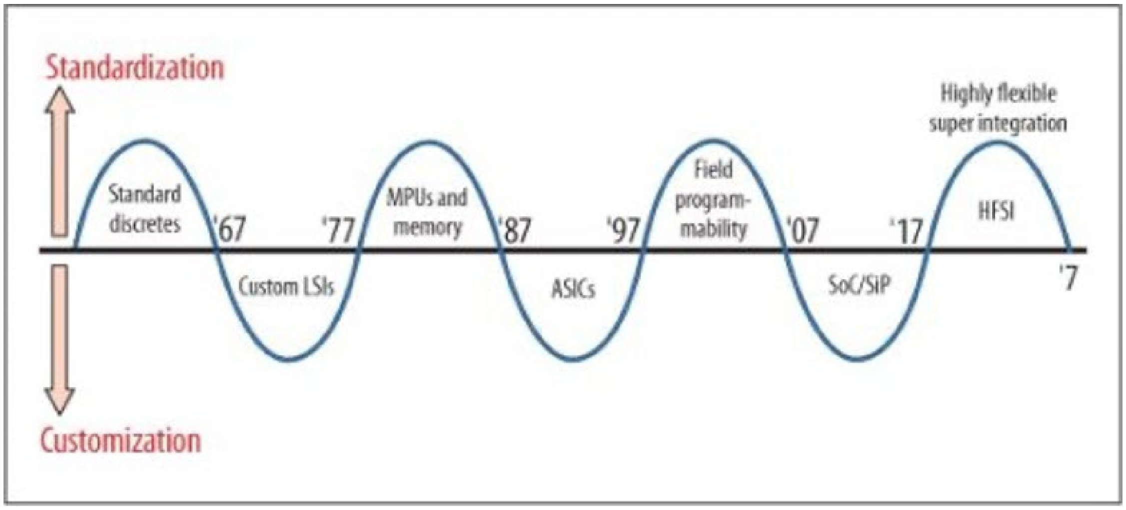
The objective of this document is to cover the trends of Intellectual Property in the semiconductor industry. At the same time, we recognize that this document only offers an overview. In follow-up papers, we will offer descriptions of specific segments of the industry such as Materials IP and Manufacturing Processes IP.

2. Megatrends

The ITRS (International Technology Roadmap of Semiconductors) once postulated that “design cost” is the single biggest challenge to the progression of semiconductors. The Semiconductor IP (SIP) industry was born because of the need to reduce the cost of designing semiconductors. SIP involves designing pre-verified building blocks such as processors, peripherals, interconnects, and memories that can be included in someone else’s design. This approach has become the leading mechanism of cost control for chipset vendors, and industry analysts estimate that the percentage of IP reuse in Systems-on-Chips exceeds 80% and that the average number of re-used blocks exceeds 200. The business model for SIP is typically a license fee combined with a royalty.

The Semiconductor IP industry has become essential for the creation of large and complex devices as it is difficult for any single company to develop all the necessary IP. Over the years, the industry went through cycles, from specialization to generalization and back again to specialization as outlined in Makimoto’s wave.

In the very early days, the industry was populated by integrated device manufacturers (IDMs) that would build the product from silicon to the full device (e.g., Motorola). Proprietary inventions were the key differentiators to drive growth. The IP was generated internally. As the industry grows and achieves maturity, EDA companies, foundries, and fabless vendors enter the market. “Standard” functions (e.g., pads, logic libraries, oscillators, ...) become a source of efficiency for the designers and developers. It becomes cost-effective to buy the building blocks rather than develop them in-house. Foundation IP was born.



Makimoto's wave

The functional requirements of chipsets increase to the point where it becomes difficult to complete chip implementations without external IP of increasing complexity. The development of products is based on a few key building blocks such as CPUs and GPUs, enabling an era of designs based on "Star IP" with their supporting ecosystems. Product differentiation increasingly trends towards software applications. Prominent ecosystem examples include the CPU ecosystems around Instruction Set Architectures (ISAs) from Arm, MIPS, and more recently RISC-V. These hardware Architectures led to the formation of software and hardware eco-systems around them. In addition, GPUs, and DSPs – with companies such as Imagination, ARC, Tensilica, and CEVA – emerged as additional building blocks. Embedded FPGA IPs are the latest configurable digital IPs to emerge, with providers such as Menta and Flex Logix. The evolution of digital chip interfaces such as USB, PCI, and UCIe enabled the Design IP industry which includes digital controllers and analog mixed-signal PHYs, with Synopsys, Rambus, Alphawave, and Cadence as key providers.

The limits to Moore and Denard's laws refocus the innovation on silicon value. Differentiation becomes based on creative architectures. Neural architectures create a disruptive shift. Analog neural networks become valuable. Analog computation based on neural networks and highly differentiated architectures become a source of major advances. New SIP categories like AI/ML accelerators emerge, and the most recent trend towards chiplets bears the potential to elevate the reuse of IP to chiplets.

Most markets where computing is expanding are data driven. The processing of information is based on training models to recognize and act upon patterns in data sets. Most new markets that are expanding fast and picking up steam such as IoT, Automotive, and Smart Devices are data driven. Existing markets are also dealing with upsurges of data for which they must adjust their operational models and their computing systems: data centers, and hyperscalers with Large Language Models.

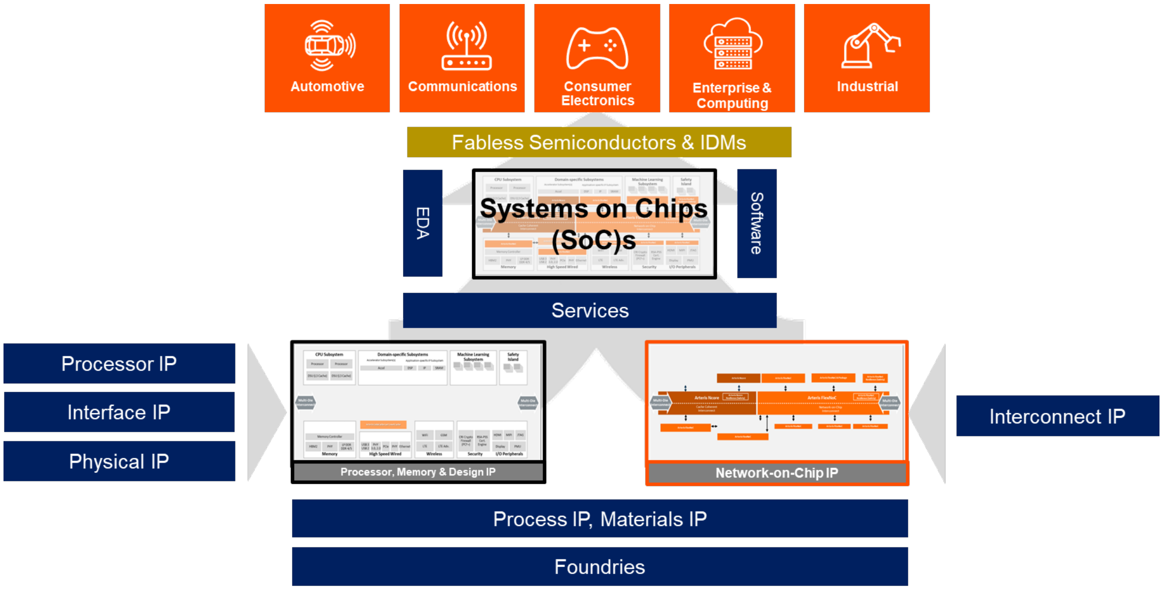
To keep up with the required performances of data driven systems, specialized AI/ML models get integrated with traditional computing systems, causing many changes in the architecture of systems. The industry is experiencing a migration away from CPU-based computing running algorithms tailored for one application, to systems where a combination of AI/ML and CPU-based systems offer advances in performances and the ability to handle ever larger amounts of data.

Consequently, markets and industries require specialized hardware systems to handle their unique data and the models behind this data. Little by little, there is a verticalization of solutions for specific markets.

The actors within vertical solutions feel the need to own more of the solutions. We observe SoC vendors moving up the stack and delivering solutions and services providers, especially the hyperscalers, developing specialized hardware for the markets that they target.

3. Structure of the industry

The semiconductor IP Industry is a challenging business. It has typically been the field of companies that focus on specific technologies (e.g., wireless, CPUs, GPUs, Memory, Interfaces, ...). Successful companies solve key latent needs of the industry, whether it is technical or business challenges. They optimize sectors of the semiconductor industry by solving difficult underlying technical problems.



This figure illustrates the industry structure as part of the design flow from the various types of IP to the Systems on Chips (SoC) they enable. We have come to a point that the end industries – like automotive – can have a significant impact on the underlying IP decisions as vendors decide what IP to license.

3.1. Centers of expertise

Over time, specific geographical areas have been the centers of IP development. These areas evolved, spurred by pioneers coming from industry or academia.

Here are examples of geographical areas where IP development takes place:

- California and the West Coast: CPUs, Wireless, System IP, Memory interface IP, Cryptography, AI/ML
- Texas and the Austin area: CPUs, System IP
- UK: CPUs, GPUs,
- France: System IP, Security and Cryptography
- China: AI/ML

- Taiwan: CPU, Memory
- Israel: CPU, DSP, AI/ML

3.2. Worldwide developments

Over time the need for specialization made it paramount for semiconductor developers to differentiate their developments and focus their efforts on their blocks – differentiating in hardware and software – and rely on acquiring non-differentiated IP from commercial vendors. With the rising complexity of semiconductor designs following Moore's law, the Foundation IP and Design IP eventually required Co-optimization of SIP and design tools, and as a result, EDA vendors took on a fair amount of SIP development. According to industry experts, today, Arm, Synopsys, and Cadence make up almost 70% of the SIP market share.

3.3. Role of Academia

Academia plays a key role in the development of the semiconductor industry. Multiple surveys indicated that the top challenge of CEOs in the 2020s is finding and retaining talent. Foundries scheduled to be rolled out in Arizona within the framework of the CHIPS Act are being delayed because of the lack of talent. The development of talent is a long and challenging process that starts with universities attracting and educating the best and brightest minds. We see that the regions with a strong high education system in electronics and materials offer advantages to the semiconductor companies. Hence, we see the West Coast, the Northeast of the USA, the UK with the Cambridge area, the Grenoble region of France, Israel, Korea, Japan, Taiwan, and China as the leaders in semiconductor development. All these regions are supported by leading universities in the field of semiconductor technologies.

Academia plays a role in innovation. Professors and students are involved in startups, or they work with established vendors on the development of leading-edge technologies. The meshing of academia with industry enables research and innovation. New concepts emerge from academia. Research in models and data processing enables the development of new advanced systems. Academia seeds research with talent and fundamental IP that will become the basis for commercial systems. We often see professors working with companies with the encouragement of the leadership of universities. This collaboration plays a key role in the development of advanced technologies.

3.4. Vertical design chains and their impact on IP

Traditionally, the decision to use a SIP was made by the semiconductor companies. With the changes in various design chains, the influence from OEMs on the design chain grew substantially, especially for CPUs and GPUs as software ecosystems depend on it. For instance, Nokia and Ericsson worked with their suppliers to influence processor IP in the mobile market. See Figure 1 in "A Design Chain for Embedded Systems":

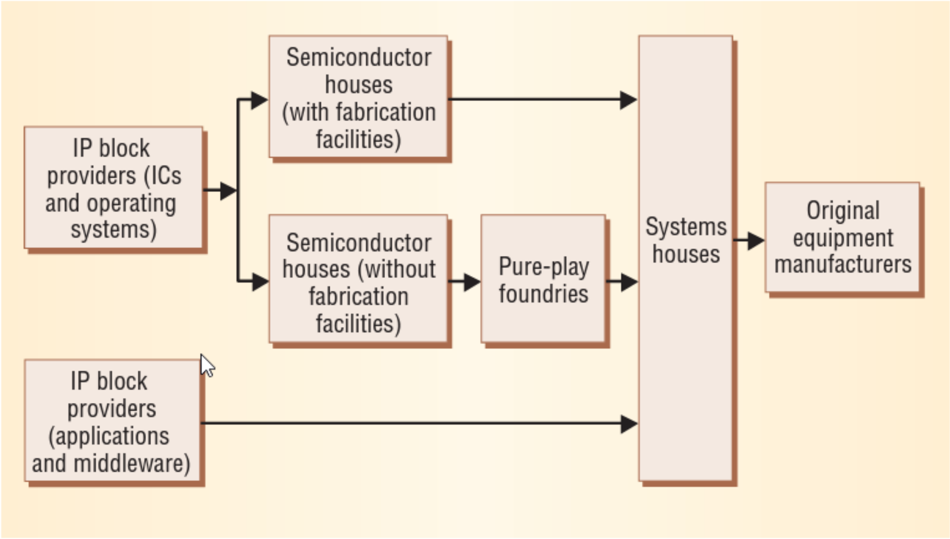


Figure 1. The embedded SoC provider-integrator design chain. What used to be a vertically integrated process within each product company has become significantly fragmented. Platform-based design can accelerate the flow in this chain.

The mobile design chain has been restructured a few times, with leading-edge OEMs often designing their chipsets in-house and influencing IP features early in the design cycle to drive the software ecosystem. The same trends occurred in the data center industry, with, for example, Arm's (Server Base System Architecture) SBSA certification process for server architectures. The automotive design chain is restructuring in similar ways, with OEMs heavily influencing the decisions within the design chain of Tier 1s, Semiconductor, and IP companies.

3.5. Open-Source and Open Standard IP

The industry has been working with Open-Source software for quite a few years. Netscape started this trend. It is now an established business practice in the software industry. Open source in the field of hardware development is a new concept which has not seen adoption beyond a few areas such as the ISA of RISC-V which is an open standard managed by the RISC-V International organization. RISC-V International (riscv.org)

In certain fields like security and AI, the transparency brought by open-source software and hardware IPs is mostly welcomed. Public examination could help to identify threatful bugs or intentional backdoors, which can eventually bring more trust to open-source designs than proprietary ones. While making the IP design open-source is not yet a clear trend for IP vendors, many open-source projects have been already initiated by some big industrial players, which will certainly have impacts on the IP design ecosystem.

3.5.1. RISC-V

RISC-V is an open standard Instruction Set Architecture (ISA) enabling processor innovation through open collaboration. The RISC-V ISA specifications and its extensions are an open standard that is developed and ratified by the RISC-V International organization. This standard is provided royalty-free, and it is open. It is the basic building block for anyone to build their solutions and services on. The RISC-V ISA specifications and ratified extensions are provided under globally accepted open licenses that are permanently open and remain available for all. Any company licensing this technology can build its own proprietary solution with a CPU core that will implement the RISC-V specifications.

In the realm of computer architecture, the RISC-V instruction set architecture (ISA) has emerged as a groundbreaking and open architecture. RISC-V pronounced as "RISC-Five," represents a departure from the conventional proprietary instruction sets, offering a new paradigm for designing efficient and customizable processors. RISC-V combines a modular technical approach with an open, royalty-free ISA — meaning that anyone, anywhere can benefit from the IP contributed and produced by RISC-V. As an open standard, anyone may leverage RISC-V as a building block in their open or proprietary solutions and services. With its modular and extensible design, RISC-V has gained significant attention from both academia and industry, fostering innovation, collaboration, and diversity in the world of computing.

The genesis of RISC-V can be traced back to the late 2000s when a team of researchers and engineers at the University of California, Berkeley, led by Prof. David Patterson, recognized the need for an open and free ISA that could drive research and development without the limitations imposed by proprietary architectures. The project sought to build an instruction set that would facilitate experimentation in processor design, enabling a wide range of applications from embedded systems to supercomputers. The RISC-V Foundation (www.riscv.org) was founded in 2015 to build an open, collaborative community of software and hardware innovators based on the RISC-V ISA. The Foundation, a non-profit corporation controlled by its members, directed the development to drive the initial adoption of the RISC-V ISA.

The foundation of RISC-V is rooted in the Reduced Instruction Set Computer (RISC) principles, which advocate for a simplified and streamlined instruction set to achieve higher performance and energy efficiency. RISC-V embraces these principles while introducing modularity and extensibility. Its base ISA consists of a minimal set of instructions that can be expanded upon through standard and custom extensions. This allows system designers to tailor the instruction set to match the requirements of their applications, optimizing performance and energy consumption.

One of RISC-V's defining features is its modular design, where various standard extensions can be added to the base instruction set to meet specific needs. These extensions include integer and floating-point arithmetic, cryptography, vector processing, and more. This modular approach encourages innovation by enabling the creation of new instructions without fundamentally altering the core architecture. Furthermore, the open nature of RISC-V fosters collaboration among hardware and software developers, resulting in a diverse ecosystem that contributes to the evolution of the ISA.

RISC-V's open ISA nature has had a profound impact on the computing industry. Traditional proprietary ISAs often require licensing fees, limiting accessibility to small companies, startups, and academic institutions. The base RISC-V ISA and extensions provided through RISC-V International are open standards and allow freedom to design implementations in combination with open or proprietary IP. This accessibility has spurred the development of custom processors, accelerators, and specialized hardware for a wide range of applications, from Internet of Things (IoT) devices to data centers.

While RISC-V has gained significant momentum, it is not without its challenges. Achieving widespread adoption requires overcoming the inertia associated with existing architectures that dominate the market. Additionally, ensuring compatibility and standardization across the diverse set of extensions and implementations can be a complex task. Looking ahead, RISC-V holds the potential to reshape the landscape of computing. As it continues to evolve, collaborations between academia, industry, and the open-source community will play a crucial role in shaping the ISA's trajectory.

4. Patent Filing Trends, Impact of M&As

4.1. Macro-level analysis of patent filing trends in the SIP industry

Patents provide a window into innovation around the world. Companies file patents to protect their market position and to add value to their businesses. As most semiconductor IP ("SIP") companies do not sell products, patents are mainly used to increase the value of technology licenses. There are different approaches to patent filing strategies. Some companies prefer to keep innovation confidential by relying on trade secrets. This approach may be more popular amongst SIP companies because they don't sell products and therefore often can't be sued for direct patent infringement. Other companies prefer to flood the market with patents to build up solid protection to increase the value of their semiconductor IP. Furthermore, while patents roughly correlate to acts of invention, they rarely accurately map to product portfolios. Given these points, patent filings are only ever a proxy for innovation, and patent filing data should be weighted accordingly.

Chart 1 shows the total number of granted patents worldwide owned by SIP companies[1]:

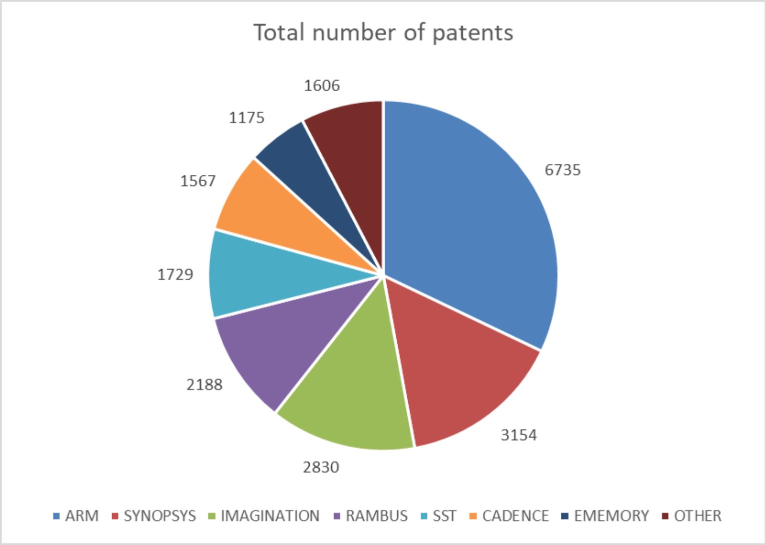


Chart 1

Arm, Imagination, Synopsys, and Cadence dominate patent ownership in the logic domain, and Rambus, SST, and eMemory dominate in the memory domain. These companies own over 90% of patents amongst SIP companies, with Arm alone owning over 32%. The total number of SIP patents owned by these companies is just under 21,000. This can be compared to semiconductor patents generally (covering equipment makers and foundries) for which there are presently over 600,000 patent families in force[2]. Taiwan Semiconductor Manufacturing Corporation ("TSMC") alone has over 46,000 granted patents worldwide, showing that SIP patent filings are relatively low compared to the broader semiconductor industry.

Chart 2 shows the patent filing trend for SIP companies from the 10 years from 2012 to 2021:

[1] We compiled a list of some of the most well-known SIP companies that file patents. The list does not include SIP companies whose primary business is manufacturing or fabless design. Some well-known SIP suppliers are therefore excluded from this assessment.
[2] A patent family is the group of patents relating to a particular invention, and may include multiple patents in different countries.

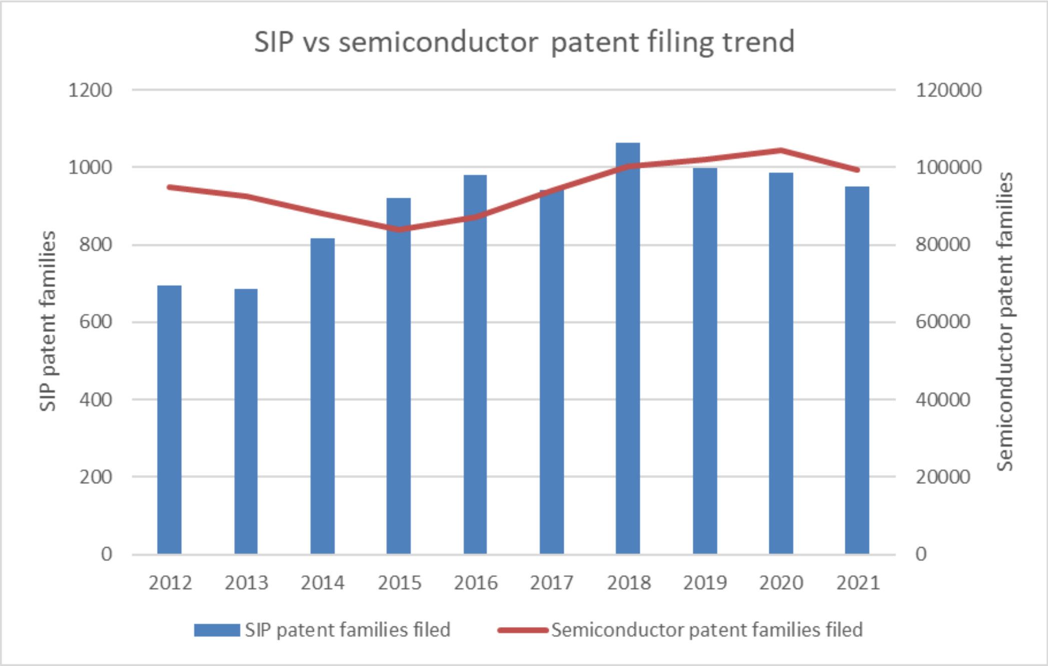


Chart 2

Chart 2 also shows the patent filing trend for semiconductor filings more generally[3] over the same timeframe. In terms of growth, SIP patent filings have achieved an average CAGR of ~3.5%. This outperforms semiconductor patent filings generally which only achieved a CAGR of ~0.5%.

Chart 3 shows the countries where SIP companies file patent applications:

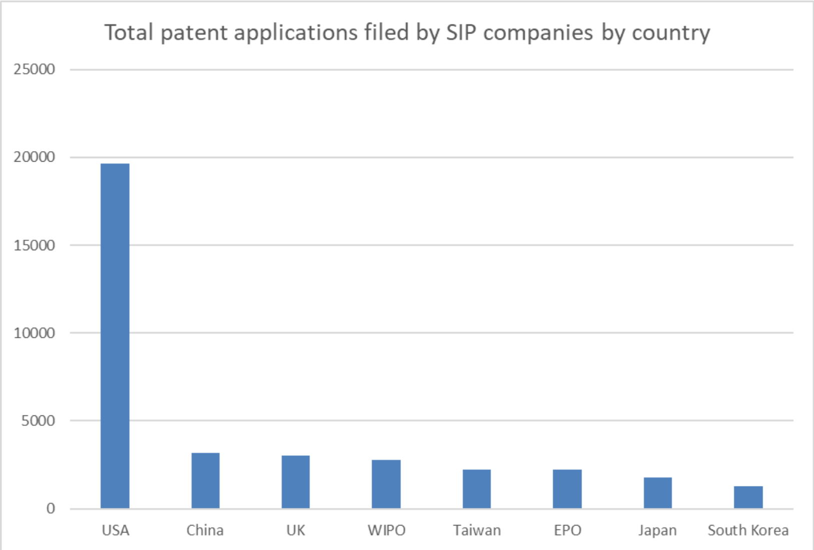


Chart 3

The US dominates with significantly more patent applications filed with the United States Patent and Trademark Office ("USPTO") than in other countries. This is likely a reflection of the fact that the main market for licensing SIP is the US, with most of the main chip designers being based here. China is the

[3] This data uses the patent classification H01L which is often used as a proxy for semiconductor patent filings.

second most popular filing destination with the UK and WIPO (the international patent filing system) a close third and fourth. Taiwan, the European Patent Office ("EPO"), Japan, and South Korea also feature.

It is worth comparing this to semiconductor patent filings more broadly. Chart 4 shows the trend over the last 20 years:

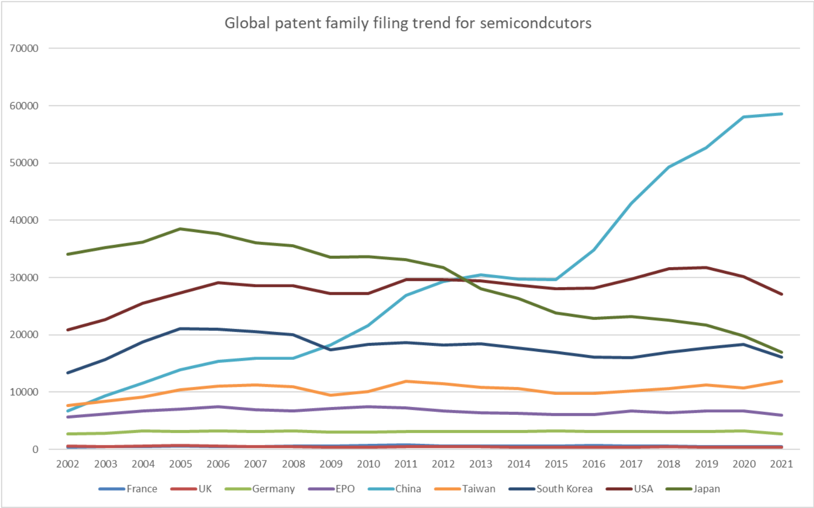


Chart 4

This graph shows a very different picture of SIP industry patent filings. The story shown is one of the changes in the fortunes of Japan and China. Japan led patent filings significantly until 2011. After this, filings in Japan dropped heavily. Filings in China have risen significantly from a standing start in 2000 to a position where almost twice as many patents are filed here as in the US[4]. Patent filings in the US, South Korea, Taiwan, and Europe have remained relatively flat over the same period. This shows that most semiconductor companies are either filing in their local jurisdiction or the main markets for manufacturing and sales. This is a very different picture from SIP patents, where the destination market for licensing is key.

Turning back to patents owned by SIP companies, Chart 5 shows the patent filing trend for the "Other" companies identified in Chart 1:

[4] It should be noted that the rise in patent filings in China is seen in many industries. Many of these filings are by universities or research organisations. Furthermore, it is frequently observed that Chinese companies favour filing many incremental patents. As such, the number of patents in China may not necessarily be taken to reflect actual levels of innovation or sector dominance.

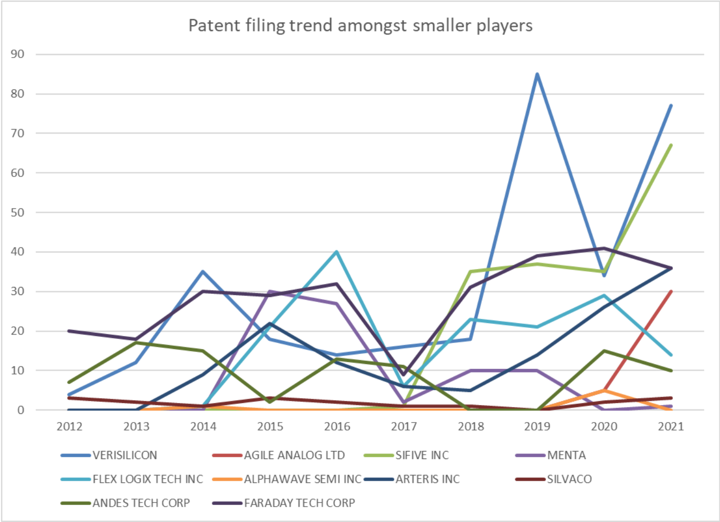


Chart 5

Verisilicon and SiFive have shown the greatest number of filings in recent years. Verisilicon (China) is a silicon platform-as-a-service provider that offers a range of IP cores including processors, analog and mixed signals, and RF. SiFive (US) is a RISC-V processor IP company whose patent filings have risen steadily since being founded in 2015.

The chart also shows Menta (France) and Flex Logix (US), both active in the embedded FPGA space, as well as Agile Analog (UK), who are analog IP specialists. Also shown are design and system IP companies Faraday Technology (Taiwan), Arteris (US), Silvaco (US), and processor IP company Andes Technology (Taiwan). This profile suggests that beyond the main UK-based processor IP companies, the US is the leader in IP cores, at least in terms of patent filings. Overall, the investment in R&D appears to be very healthy, with the total number of patent filings increasing by 805% from 34 in 2012 to 274 in 2021.

Technology and process IP is amongst the most widely licensed, and yet, as noted below in Section 6, it is often invisible to the semiconductor design community. Much of this IP belongs to the IDMs, the pure-play foundries, and the equipment manufacturers. As such, it does not appear in any assessment of SIP patent filings. In this regard, it is worth looking at the patent filing trends for TSMC.

Chart 6 shows TSMC’s patent filing trend over the last 20 years:

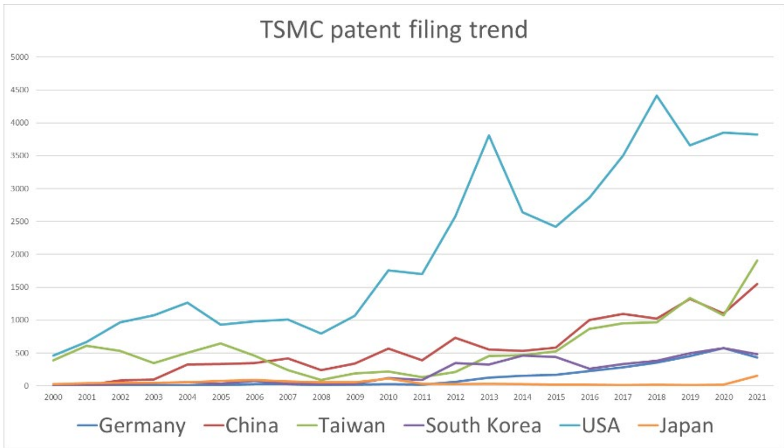


Chart 6

Twenty years ago, TSMC only filed patents in Taiwan and the US as they made products in Taiwan for customers in the US. As they sell no products themselves, filing patents made no sense. Over time, TSMC has dramatically increased its patent filings in the US. They are now the number one filer of semiconductor patents with the United States Patent and Trademark Office ("USPTO"). They have also begun filing in China, Germany, and South Korea. Very recently, they have also started filing in Japan. This might simply be a result of a very successful company having more resources to file in more countries. However, it may also be more tactical. While the US has always been an important market, their huge portfolio will become much more valuable now they are expanding their manufacturing capacity in Arizona. Furthermore, TSMCs decision to invest in the European Semiconductor Manufacturing Company in Germany, with Infineon, NXP, and Bosch, suggests their decision to invest in patent filings here was, if not strategic, highly valuable.

As we have seen, there is going to be a shift in manufacturing away from Taiwan and China and towards the US and Europe. This is happening for commercial strategic reasons, and because of Government incentives like the US and EU CHIPs Acts. Semiconductor IP companies will have to consider these shifts carefully and decide what impact they are likely to have on their and their competitors' patent filing strategies.

4.2. Impact of Mergers & Acquisitions

The semiconductor landscape has rapidly evolved, with the past couple of years proving to be a pivotal period marked by significant merger and acquisition activity. These transactions have reshaped the competitive dynamics and technological advancements in the semiconductor industry, providing the acquiring entity access to a broader range of technologies, innovations, and intellectual property. The following discussion highlights a few significant semiconductor mergers and acquisitions—and the subject technologies—over the past couple of years.

In 2021, Analog Devices, Inc. closed its $21 billion acquisition of Maxim Integrated Products, Inc., an integrated circuit design company. The transaction broadened Analog Device's analog and mixed-signal, power management, radio frequency, and digital and sensor product capabilities—thus leading to a more comprehensive and diverse patent portfolio. The transaction also expanded Analog Device's reach in more markets, such as the communications, automotive, industrial, and consumer markets.

Also, in 2021, Marvell Technology Group closed its $10 billion acquisition of Inphi Corp., a provider of high-speed data movement and interconnect solutions. This strategic move aimed to combine Marvell's expertise in semiconductor infrastructure solutions with Inphi's strengths in data center connectivity and optical networking. The transaction provided Marvell with a comprehensive patent portfolio of semiconductor solutions for cloud data centers and 5G networks—which are key growth areas in the semiconductor industry.

Further, in 2021, Intel Corp. sold its solid-state drive (SSD) business to SK Hynix Inc. for $7 billion. As one of the largest memory chipmakers and largest semiconductor companies in the world, SK Hynix bolstered its presence in the NAND flash memory and SSD markets with this acquisition. As part of the sale, Intel transferred certain NAND SSD-associated intellectual property and a memory manufacturing facility in Dalian, China to SK Hynix. To handle its new SSD business, SK Hynix formed a new subsidiary, called Solidigm.

In 2022, Advanced Micro Devices, Inc. closed on its record-setting acquisition of Xilinx Inc. From the nearly $50 billion acquisition, AMD boosted its high-performance computing expertise with Xilinx's programmable logic solutions and adaptive computing technology. This combination of technologies significantly expanded AMD's opportunities in data centers, embedded computing, and telecommunications.

In 2022, Broadcom Inc. announced its plans to acquire VMware, Inc.—a cloud computing and virtualization technology company—for over $60 billion. The acquisition of VMware would significantly boost Broadcom's software portfolio—particularly in virtualization software—and would give Broadcom a significant foothold in the cloud computing market. Currently, the transaction is in process—with Broadcom receiving legal merger clearances in Australia, Brazil, Canada, South Africa, and Taiwan. In July 2023, Broadcom received conditional approval from the European Commission.

While the above mergers and acquisitions have been successfully completed or are in the process of being completed, not all transactions have gone as smoothly. For example, in 2022, Nvidia Corp. called off its attempt to acquire Arm—a leading semiconductor company and intellectual property company known for its central processing unit designs—for $40 billion. Due to regulatory challenges in the United States and Europe, the parties agreed to terminate their agreement. In another example, in August 2023, Intel Corp. and Tower Semiconductor Ltd.—a manufacturer of analog semiconductor solutions—agreed to terminate their agreement for Intel to acquire Tower Semiconductor for over $5 billion. After Chinese regulators failed to approve the deal, the parties mutually agreed to terminate the deal due to an inability to obtain regulatory approvals in a timely manner.

In conclusion, semiconductor merger and acquisition activities and consolidation have been significant trends, shaped by market expansion, regulatory considerations, and intellectual property consolidation. While mergers and acquisitions often aim to combine complementary technologies and provide access to specialized expertise, intellectual property consolidation strengthens competitive positions through a broader and diverse portfolio of patents, designs, and technologies. These dynamics highlight the intricate interplay between business strategy and the strategic management of intellectual property.

5. Types of IP

5.1. Design IP

Logic Design IPs are reusable units of logic, cell, or integrated circuit layout design that are the intellectual property of one party. They are building blocks of SoC/ASIC design.

Different types of logic design IPs can be categorized into Soft IPs, Hard IPs, Analog and/or Mixed Signal IPs.

Soft IPs are IPs that are delivered as synthesizable RTL in a hardware description language such as Verilog or VHDL. This logic can be modified by RTL Designers at a functional level and can be compiled for any process technology.

Hard IPs are IPs that are delivered as a lower-level physical description that is specific to a particular process technology. They offer better predictability of chip timing performance and area for their technology, but they cannot be significantly modified by chip designers. Analog and mixed-signal logic are generally available as Hard IPs.

To classify logic design IPs, one possible approach is to use the following criteria:

- The level of abstraction: whether the IP core is at the RTL level or the physical level.
- The degree of customization: whether the IP core can be modified by chip designers or not.
- The type of functionality: whether the IP core is digital, analog, or mixed signal.

Using these criteria, we can create a table to classify logic design IPs as follows:

Level of abstraction	Degree of customization	Type of functionality	Example of IP
RTL	High	Digital	Soft
Physical	Low	Analog	Hard
Physical	Low	Mixed-signal	Hard

The market analyst IPNest defines several categories for IP, including processors making up about half the market in 2023, and interface IP with about a quarter of the market. Physical IP and others, including eFPGA and other System IP that includes infrastructure components and Networks-on-Chips (NoCs), make up the remaining quarter.

5.1.1. Processor IP

Processor IP is a reusable unit of logic that implements a processor core. Processor IP can be used to create custom processors for a wide variety of applications, including embedded systems, microcontrollers, personal computers, servers, and high-performance computers (HPC).

Processor IP is typically offered by semiconductor companies to accelerate the development of custom processors. Processor IP can save developers significant time and money, as it does not need to be designed from scratch.

There are two main types of processor IP: soft IP and hard IP.

1. Soft IP is implemented in software and can be delivered to downstream customers for implementation into a physical design. Soft IP is typically less expensive than hard IP. It needs to be "hardened" into a physical design but offers more implementation flexibility.
2. Hard IP is implemented in hardware. Hard IP is more expensive than soft IP, as it involves turning the design into a specific implementation that is dependent on the technology process and physical libraries.

Processor IP typically includes the following features:

- Instruction set: The instruction set defines the set of instructions that the processor can execute.
- Register file: The register file stores the processor's data and program counter.
- ALU: The ALU performs arithmetic and logical operations.
- Control unit: The control unit fetches instructions from the instruction memory and executes them.
- Memory interface: The memory interface connects the processor to the system memory.
- Interrupt controller: The interrupt controller handles interrupts from external devices.
- More advanced features include out-of-order processing, multi-processor design, multi-threaded design, hierarchical cache architecture, intra-cluster, and inter-cluster cache coherency.

There are several benefits to using processor IP:

- Time to market: Processor IP can help to shorten the time to market for custom processors. This is because processor IP does not need to be designed from scratch.

- Cost savings: Processor IP can help to save costs on the development of custom processors. This is because processor IP is typically less expensive than designing a processor from scratch.
- Risk reduction: Processor IP can help to reduce the risk of developing custom processors. This is because processor IP has been extensively tested and validated.
- Versatility: Processor IP can be used to create a wide variety of custom processors. This is because processor IP is typically highly configurable.

There are a few cost items associated with using processor IP:

- Licensing fees: Processor IP is typically licensed from semiconductor companies. This can be a significant cost for small companies or startups.
- Royalties: Processor IP may also require royalty payments. This can be a significant cost for companies that produce a large volume of products.
- Technical expertise: Processor IP can be complex to integrate into a system. This requires technical expertise that may not be available in-house.

Processor IP is a powerful tool that can be used to accelerate the development of custom processors. Processor IP can save time, money, and risk, and it can be used to create a wide variety of custom processors. However, processor IP can also be expensive and require technical expertise to integrate.

5.1.2. System IP and eFPGAs

Among IPs used on-chip, embedded FPGAs usage has recently been growing up. The integration of such an IP allows reserving a piece of silicon that can be reconfigured, at the hardware level, postproduction, and within the field, at the price of extra silicon area. It allows for product evolution and differentiation during the whole lifetime of the ASIC/SoC. An eFPGA IP also acts as a design insurance, making sure that a brand-new chip, which took years of design and tens if not hundreds of millions of dollars to bring to the market, is not stillborn because the algorithms and protocols it is using have evolved dramatically in the meantime. eFPGA IP usage is nowadays moving from Aerospace & Defense toward IoT and IIoT, cloud/data center, telecommunication, and mobility.

The category defined by IPNest as System IP includes infrastructure building blocks and Networks-on-Chips (NoCs) responsible for the connection of the SIP blocks within SoCs. Since the introduction of (Advanced Microcontroller Bus Architecture) AMBA in 1996, various protocols have been introduced (OIP, TileLink), The protocols involved in managing data transfers have grown significantly in complexity and today pose a make-or-buy decision for development teams. For instance, AMBA is today in its 5th generation supporting complex protocols with cache coherency, now extending into the chiplet domain. As a result of this growth of complexity in the last two decades, several vendors – Sonics, Netspeed, Arm, Arteris, and others – emerged during the last two decades, offering reusable solutions for Networks-on-Chips (NoCs). OEMs Meta and Google have acquired some of the vendors at this point.

5.1.3. Interface IP

Interface IPs are specific IP blocks designed to handle data communication between components within an SoC (System on Chip) or between the SoC and external devices. Interface IPs are integrated into SoC to provide the required connectivity for different applications.

Common interface IPs include:

- PCIe (Peripheral Component Interconnect Express): A high-speed interface standard for connecting high-speed devices like graphics cards, SSDs, etc.

- USB (Universal Serial Bus): Used for connecting peripherals to computers and transferring data.
- DDR (Double Data Rate): Used for interfacing with memory devices.
- MIPI (Mobile Industry Processor Interface): A set of interfaces (like CSI for cameras, DSI for displays) designed for mobile devices. Speeds can range from a few hundred Mbps to several Gbps.
- Ethernet: For wired LAN connections. Common speeds are 10/100 Mbps (Fast Ethernet), 1 Gbps, 10 Gbps, and even 100 Gbps.
- SerDes (Serializer/Deserializer): High-speed serial interface.
- General-Purpose I/O (GPIO): Simple digital signals for basic I/O functions.
- I2C (Inter-Integrated Circuit): A serial communication protocol used for low-speed communications between ICs.
- SPI (Serial Peripheral Interface): A faster serial communication protocol than I2C, commonly used for interfacing with flash memories, sensors, and other low-speed peripherals.
- UART (Universal Asynchronous Receiver-Transmitter): Used for asynchronous serial communication.

Trends in Security Requirements on Interface IPs

Security is becoming a critical concern in the design of SoCs, especially for applications where data protection and integrity are crucial, such as IoT devices, automotive systems, and industrial control systems. Here are some key trends in security requirements for interface IPs:

- Hardware Root of Trust (HRoT): HRoT is a secure hardware module embedded within an SoC that provides secure storage of keys and certificates, secure execution of cryptographic operations, and a secure boot process. Recently, the use of PUF technology has become a popular approach in the implementation of HROT to establish a secure system.
- Encryption/Decryption: Most interface IPs are now required to support data encryption and decryption to ensure that data transmission and reception are secure. This is achieved using cryptographic algorithms like AES, RSA, or ECC.
- Authentication and Access Control: Ensuring that only authorized devices can connect to an interface IP is critical. This is achieved using techniques like public-private key cryptography or device authentication using certificates.
- Secure Boot: Secure boot ensures that an SoC only executes trusted code by verifying the digital signature of the bootloader and operating system before executing them. This prevents unauthorized or malicious code from running on the device.

5.1.4. Physical IP

Physical IPs are widely adopted in SoCs whereas designing the analog circuits and embedded memory blocks is infeasible of design automation and typically requires domain-specific expertise. Integrating physical IPs into the SoC design is therefore a straightforward approach to omit the massive efforts of designing them in-house.

Some of the physical IPs have been popular for a long time, such as A/D converters and high-speed front ends. Recently, due to the growing demand for power efficiency, the power management unit has become increasingly important. Given the same reason, analog computing has regained attention to improve the computation efficiency of AI. The demand for embedded memory IPs is also increasing for various reasons, such as the need for trimming data and code patches to improve time to market, the need for secure storage, and the need for higher throughput and lower latency. From the hardware security perspective, the requirements for physical randomness and resistance against physical attacks have brought the demands for security-related physical IPs.

While the market for physical IPs has increased due to these new demands, there is another trend toward using open standards for IP interfaces. In the past, the interface of these physical IPs was mainly proprietary, resulting in more integration efforts and less reusability. Nowadays, it has become more common for physical IP developers to adopt standards like AMBA in their design, which could help reduce the integration efforts and time to market for their customers.

5.2. Technology IP

Technology IP is a set of proprietary process recipes and/or materials that enhance an existing semiconductor process or enable the creation of an entirely new one. Although very widely practiced, it is often invisible to the semiconductor design community. The licensor of such technology is typically a semiconductor manufacturer, either a foundry or an IDM, but occasionally fabless semiconductor companies will license such technologies to create a proprietary "have made" manufacturing process at their partner fabs which can only be run for the licensing company.

5.2.1. Process IP

Process IP is by far the most widely licensed semiconductor technology IP.

The predominant form of these transactions is when one semiconductor manufacturer licenses to another manufacturer a portion or the entirety of one of its process nodes. Such a license may or may not be in conjunction with a second-sourcing agreement.

Another model that has been growing over time is that of semiconductor equipment companies providing process module recipes in conjunction with their tool sales. These recipes are typically licensed for free but can only be used on the manufacturer's tools.

A smaller but growing model is the emergence of independent companies developing and licensing technology IP as their primary business. These companies generally focus on niche, high value-added technologies which complement the processes developed by manufacturers and equipment companies. Multiple companies have pursued this model in the specialty memory (MRAM/ReRAM) space, and other licensing examples include an entire 2nm gate-all-around manufacturing process, an oxygen-insertion process to enhance semiconductor performance, and a strain engineering process.

5.2.2. Materials IP

Materials IP is typically only licensed when customers demand a second source. Advanced substrates are a well-known example.

6. Government policies and their impact

The global semiconductor industry is spread among various countries, both vertically along the components of the value chain (e.g., from raw materials, IP/design, processing equipment, wafer fabrication, OSAT, etc.) as well as horizontally for each of the components. In terms of wafer fabrication, analysts have estimated global supply shared among Taiwan (~21%), Korea (~20%), Japan (~16%), China (~15%), North America (~13%), Europe (~6%), and rest of world (~9%) [source: IC Insights]. The spread of semiconductor production activities was propelled in part by a drive to efficiency and specialization within the industry, but also by the policies of various governments.

Following the disruptions in the semiconductor supply chain during the COVID-19 pandemic and recently heightened economic and national security considerations, many governments have taken a renewed interest in policies to promote and guide their respective domestic semiconductor industries. A sampling of such policies is provided below.

6.1. Impacts of Government Policies on the Semiconductor Industry

The impact of government policies on semiconductor activities is difficult to quantify, considering that such policies operate alongside semiconductor companies' plans and investments. However, there has been a recent increase in the number of new semiconductor fabrication facilities starting construction around the time of the announcement of many of these policies, with an estimated 33 fabs starting construction in 2022 and 28 in 2023, versus 17 in each of 2019 and 2020 [Source: SEMI, World Fab Forecast Report]. In the U.S., fabs have been planned by major vendors, including Intel (2 fabs in Ohio and 2 in Arizona), Micron (Idaho), Samsung (Texas), and TSMC (Washington and Arizona).

The impact of government policies on innovation is also difficult to quantify, though unsurprisingly there is a correlation between the level of semiconductor activity each year and the number of patents granted a few years afterwards. Based on such correlation, the number of patent filings could be expected to increase as the impact of these policies spreads through the industry in the coming years. In addition, the value of existing semiconductor portfolios, including those addressing currently mature technologies, could be expected to grow and to represent an increasingly valuable asset for enterprises with significant portfolios and the resources to generate returns from them, leveraging in-house or professional outsourced expertise.

In alphabetical order, here are inputs on the various countries and regions where the government is deeply involved in the semiconductor industry.

6.2. China

China's semiconductor industry played a central role in the government's "Made in China 2025" strategic plan, issued by the Chinese Communist Party in May 2015. The government's goals were updated in 2018, setting an objective to expand domestic production of semiconductors to be able to supply 80% of domestic demand by 2030. The central government has used a variety of approaches to support the industry, including subsidies, tax preferences, and trade and investment policies.

The government also created the China Integrated Circuit Industry Investment Fund in 2014 to "invest in chip manufacturing, boost industrial production, and promote mergers and acquisitions." The first financing round was followed by a second fund in 2019, with an estimated capitalization of ~$30B.

6.3. Europe

With the European Chips Act, the EU will address semiconductor shortages and strengthen Europe's technological leadership. It will mobilize more than €43 billion in public and private investments and set measures to prepare, anticipate, and swiftly respond to future supply chain disruptions.

The European Chips Act proposes:

- Investments in next-generation technologies
- Access to tools and pilot lines for the prototyping, testing, and experimentation of cutting-edge chips
- Certification procedures to guarantee quality and security for critical applications
- An investor-friendly framework for establishing manufacturing facilities in Europe

- Support for innovative start-ups, scale-ups, and SMEs in accessing equity finance
- Fostering skills, talent, and innovation in microelectronics
- Tools for anticipating and responding to semiconductor shortages to ensure the security of supply
- Building semiconductor international partnerships with like-minded countries

6.4. Japan

In June 2021, Japan's Ministry of Economy, Trade, and Industry (METI) outlined a strategy to sustain Japan's market share within the global semiconductor industry as well as to develop new semiconductor technologies and capabilities. Along those lines, in November 2021 the Japanese government approved $6.8B to support domestic semiconductor manufacturing, including ~$3B toward the development of a TSMC/Sony foundry in Kumamoto prefecture.

The Japanese government has taken further steps to support the domestic industry. For example, it provided subsidies worth up to $320M to produce DRAM at a Micron Hiroshima facility and $640M to expand production of NAND flash at a Western Digital / Kioxia Mie Prefecture facility. METI has also worked on providing ~$2.3B to support the development of an advanced foundry in Hokkaido run by Rapidus, a semiconductor company established in August 2022 with the support of 8 leading Japanese companies.

6.5. South Korea

The South Korean government also has a history of supporting the country's semiconductor industry, particularly in the field of memory chip fabrication. In August 2022, the government passed the "Special Measures Act on Strengthening and Protecting Competitiveness of National High-Tech Strategic Industry"; under this act, companies manufacturing semiconductors and other high-tech items receive tax benefits, regulatory exemptions, and other benefits to encourage business growth and development. In March 2023, the South Korean Parliament passed the "K-Chips Act", an amendment to the "Act on Restriction of Special Taxation" to expand tax credits for investments in semiconductor manufacturing and other high-tech activities.

6.6. Taiwan

The government of Taiwan has supported its domestic semiconductor industry for nearly 50 years, such as by providing nearly half the startup capital for TSMC in 1986. Currently, the country accounts for nearly 90% of the world's high-volume leading-edge semiconductor chip production, and the government provides ongoing support for the sector. For example, in January 2023, the Legislative Yuan amended the country's "Act for Industrial Innovation" to allow semiconductor producers to claim 25% of R&D expenses as tax credits, as well as 5% of capital expenditure for advanced processing equipment.

6.7. United States

In August 2022, the U.S. "CHIPS and Science Act" was signed into law by President Joe Biden. The law was intended to catalyze semiconductor manufacturing activity in the U.S., support R&D and commercialization of advanced technologies, create regional technology hubs, support the development of the STEM workforce, and provide other such benefits to the nation's economic competitiveness and technology security.

Among the provisions, $39B was directed to subsidies for semiconductor fabrication, assembly, testing, packaging, and R&D, and a further $11B was allocated to advanced semiconductor R&D by the Department of Commerce. The law also provided for an estimated $24B for a 25% tax credit for investments in semiconductor manufacturing and processing equipment.

7. Evolution of Technologies and their impact

7.1. End of Moore's law and Dennard's law

Moore's law and Dennard's law are two empirical observations that have guided the development of semiconductor electronics for decades. Moore's law states that the number of transistors on a chip doubles approximately every two years, while Dennard's law states that the power density of a chip stays constant as the transistors shrink, allowing for higher performance and lower power consumption.

However, both laws have faced significant challenges in recent years, as the physical limits of transistor scaling have been reached. The end of Moore's law and Dennard's law means that the performance and efficiency gains from shrinking transistors have slowed down or stopped, and new approaches are needed to overcome the technical and economic barriers.

Some of the factors that have contributed to the end of Moore's law and Dennard's law are:

- The leakage current and threshold voltage of transistors, which do not scale proportionally with size, increase the power consumption and heat generation of chips, creating a "power wall" that limits the clock frequency and performance.
- The cost and complexity of chip fabrication, which increases exponentially with smaller feature sizes, makes it less profitable and feasible to produce chips with more transistors.
- The interconnect delay and bandwidth between transistors, which do not improve with scaling, limit the communication and data transfer within chips.

The end of Moore's law and Dennard's law has profound implications for the future of computing, as it requires new innovations in hardware design, software optimization, and computing paradigms. Some of the possible directions are:

- Exploiting parallelism and heterogeneity in chip architectures, such as multicore processors, GPUs, FPGAs, neuromorphic chips, etc., to increase performance and efficiency for different types of workloads.
- Developing new materials and devices for transistors, such as carbon nanotubes, graphene, nanowires, quantum dots, etc., to overcome the limitations of silicon-based technology.
- Leveraging emerging technologies such as quantum computing, optical computing, molecular computing, etc., to enable new modes of computation that surpass the capabilities of classical computers.

The end of Moore's law and Dennard's law is rather an opportunity for creativity and innovation.

7.2. Emergence of AI/ML

The emergence of Artificial Intelligence has ushered in a new era of technological advancement, with profound implications for various industries, and none more so than the semiconductor sector.

AI's impact on the semiconductor industry is two-fold. Firstly, AI applications are driving the need for more powerful and energy-efficient hardware, typically via an NPU (Neural Processing Unit) or GPU (Graphics Processing Unit). The complex algorithms and data-intensive processes inherent in AI require processors with higher processing speeds, larger memory capacities, and efficient power consumption. This demand has spurred semiconductor manufacturers to innovate, pushing the boundaries of Moore's Law and prompting the development of cutting-edge architectures.

Secondly, AI is influencing how semiconductors themselves are designed, manufactured, and tested. AI-driven design automation tools are helping engineers optimize chip layouts for enhanced performance and energy efficiency. Moreover, AI is being utilized to identify defects during manufacturing and to improve yield rates through predictive analytics. This integration of AI in semiconductor production is streamlining processes and reducing costs, ultimately benefiting both manufacturers and consumers.

Along with the predicted benefits of the rise of AI, every technological revolution also comes with risks. One of the biggest risks is that without security that is specifically designed for AI systems, we will soon face problems with the quickly growing AI adoption. AI systems require a different security approach than traditional IP systems. In addition to traditional security threats such as counterfeiting, IP theft, and eavesdropping on communications, AI systems also must be protected from other types of attacks, which include:

- **Attacks to influence data models:** If attackers can corrupt the models on which AI systems are based, for example through data poisoning, decisions from these systems can no longer be trusted.
- **Attacks making use of data models:** An attacker can try to use the behavior of an AI data model to learn more about the IP that is running on a system. This could allow attackers to create counterfeit devices.
- **Supply chain and lifecycle management:** In a modern supply chain, many parties are involved in creating systems. The many stages and different parties involved can all have a (negative) influence on the behavior of AI IP and models. After manufacturing software updates have an impact as well.

Many new security threats need to be considered for AI systems. With the importance of AI clear, most companies are rushing their AI products to market to capture a time-to-market advantage, which makes it even more difficult to address these security requirements properly.

As AI continues to evolve, the semiconductor industry faces challenges and opportunities. The race to develop specialized AI hardware has intensified competition among semiconductor companies, spurring research, and investment in next-generation technologies. Nowhere is this more evident in the IP industry, where a wealth of start-ups are challenging legacy chipmakers for supremacy.

7.3. Emergence of Chiplet Business

In recent years, the semiconductor industry has been undergoing a transformative shift with the emergence of a groundbreaking technology known as chiplets. Chiplets represent a departure from the traditional monolithic approach to semiconductor design and manufacturing, offering a more modular and flexible solution to building advanced electronic systems. This new paradigm is poised to reshape the industry landscape and has the potential to revolutionize the way electronic devices are developed, leading to significant changes in the semiconductor market.

At its core, the concept of chiplets involves breaking down complex monolithic silicon into smaller, individual components, or "chiplets," that can be designed, manufactured and tested independently. These chiplets, which are generally specialized for specific functions such as processing, memory, connectivity, or power management, are then interconnected and packaged together. This modular approach offers several advantages that address some of the challenges faced by traditional monolithic semiconductor design.

The flexibility offered by chiplets can lead to better resource utilization and reduced waste. Manufacturers can mix and match chiplets from different suppliers, selecting the best components for each function. This approach also enables greater customization, catering to the specific requirements of diverse applications without needing to completely redesign the entire system. As a result, chiplets can contribute to reducing electronic waste and improving sustainability in the industry.

The emergence of chiplets also has far-reaching implications for the semiconductor market. Traditional vertically integrated companies that design, manufacture, and assemble their monolithic chips may find themselves adapting to a more horizontally integrated ecosystem. This shift could give rise to specialized chiplet design companies that focus on developing highly optimized components for specific tasks. These chiplet providers could then collaborate with assembly and packaging partners to create complete solutions.

Moreover, the adoption of chiplets has the potential to foster innovation and competition. With different vendors offering specialized chiplets, the market could see a more diverse range of options for customers. This could stimulate faster advancements in various domains as chiplet providers compete to offer superior performance, energy efficiency, and reliability.

However, the transition to a chiplet-based approach is not without challenges. Interconnecting chiplets efficiently and reliably demands advances in packaging and interconnect technologies. Ensuring high-speed data transfer, low latency, and minimal power consumption across interconnected chiplets requires new design considerations and materials. Standardization efforts will be crucial to ensure compatibility and interoperability among different chiplets, preventing fragmentation in the market.

8. Evolution of development and verification technologies

The evolution of verification technologies has been marked by several significant advancements over the years. In hardware, the shift from manual design and testing to automated tools has improved efficiency and accuracy. Electronic Design Automation (EDA) tools have played a crucial role in designing and verifying complex ICs.

Digital simulation, Logic simulation, Formal verification, and virtual prototyping are a few areas that have shown significant growth in recent years in terms of software development for design verification. Digital simulations allow engineers to model and simulate hardware designs to verify functionality and behavior. Logic simulation simulates digital circuits at the gate or transistor level providing insights into timing, propagation, and logic correctness. Formal verification methods such as model checking and theorem proving have been used to mathematically verify hardware correctness. Formal applications such as connectivity checking, x-propagation, unreachability checking, etc. have decreased the time and effort required in signing off a verification while giving more reliable results. Virtual prototyping has enabled the parallel development of embedded software development thereby improving the time to market of a product. Coupled with these trends, the transition to Integrated Development Environments (IDEs) and the usage of version control systems like GIT have revolutionized collaboration, while automated regression tools have enabled quicker testing and deployment. While System Verilog is still the most used language in design verification- usage of Python is on the rise.

The adoption of emulation techniques has helped alleviate the speed and performance limitations of the software techniques mentioned above for very large designs.

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