

From Silicon to Donkey Kong: A Case Study in the Use of Semiconductors in Video Game Consoles

March 2023

Nathan Lotze

Disclaimer: Office of Industries working papers are the result of the ongoing professional research of USITC staff and solely represent the opinions and professional research of individual authors. These papers do not necessarily represent the views of the U.S. International Trade Commission or any of its individual Commissioners.

Abstract

Two of the latest generation video game consoles were released in November 2020: Microsoft's Xbox Series X and Sony's PlayStation 5. However, due to surging demand for electronic devices and supply chain shortages during the COVID-19 pandemic, retailers struggled to maintain inventories. One of the most notable supply chain chokepoints experienced by the industry has been the semiconductor shortage. Using these gaming consoles as a case study (along with the 2017 Nintendo Switch), this paper analyzes the various semiconductors used by electronic devices, explains what their functions are, and explores the global market for their production.

From Silicon to Donkey Kong: A Case Study in the Use of Semiconductors in Video Game Consoles

Nathan Lotze

Office of Industry and Competitiveness Analysis
U.S. International Trade Commission (USITC)
March 2023

This paper represents solely the views of the author and is not meant to represent the views of the U.S. International Trade Commission or any of its commissioners. Please direct all correspondence to Nathan Lotze, Office of Industry and Competitiveness Analysis U.S. International Trade Commission, 500 E Street, SW, Washington, DC 20436, telephone: 202-205-3231, email: Nathan.Lotze@usitc.gov.

The author would like to thank Gwenetta Duvall and Trina Chambers for their production support.

Introduction

In 2020, schools and businesses around the world closed in response to the COVID-19 pandemic, ushering in an era of remote work and distance learning. Corporate board meetings and 8 am economics lectures were now being attended from spare bedrooms and living room couches instead of in person. However, school and work were not the only activities upended by the pandemic. With movie theaters, bowling alleys, and gyms closed, entertainment and leisure activities were also confined to people's place of residence. One industry in this sector that saw a surge in demand was the gaming industry.

Microsoft (United States), Nintendo (Japan), and Sony (Japan) are the world's largest video game console manufacturers. Nintendo's Switch was released in 2017, while Microsoft's Xbox Series X and Sony's PlayStation 5 were introduced in the fall of 2020. But instead of spending their 2020 holiday season fighting dragons in *Demon's Souls* or leading a Viking raid in *Assassin's Creed Valhalla*, many consumers simply struggled to find retailers who had these consoles in stock. This shortage of video game consoles was a symptom of one of the most notorious supply chain shocks of the COVID-19 pandemic: the semiconductor shortage.

Figure 1 Current generation gaming consoles

Source: Patel, Nav, "PS5 vs Xbox Series X: Console and Game Sales Numbers – Jan2021," Hooked On Tech, <https://hookedontech.com/ps5-vs-xbox-series-x-console-and-game-sales-numbers-jan2021/>.

Note: From left to right: the Nintendo Switch, the Xbox Series X, and the PlayStation 5.

While the semiconductor shortage has been widely discussed, much of the commentary surrounding it gives the impression that semiconductors are a single commodity. In reality, the term "semiconductor" refers to a broad range of microelectronic devices, each with unique functions. This paper discusses the three major categories of semiconductors, explains what their functions are, and highlights examples present in the current generation of video game consoles. It also analyzes their market for production by detailing the companies and countries involved in their design and manufacturing.

Background

What are Semiconductors?

Semiconductors are an essential input to electronics. Technically, a semiconductor is a substance that can act both as a conductor of electricity or an insulator (a substance that does not conduct electricity).¹ In the case of electronics, semiconductors (also referred to as "integrated circuits," "IC's," or "chips") are devices, typically made out of silicon, containing electronic circuit components such as transistors and wiring.² These transistors act as switches that can turn an electric current on or off.³ Semiconductor devices can range from simple temperature sensors used in digital thermometers to cutting-edge central processing units (CPU) used in high-end computers.

Semiconductor devices and components can be broken down into three broad categories: logic, memory, and DAO (discrete, analog, and other). Logic chips process information and execute software, while memory chips store information. DAO components are designed to perform specific tasks ranging

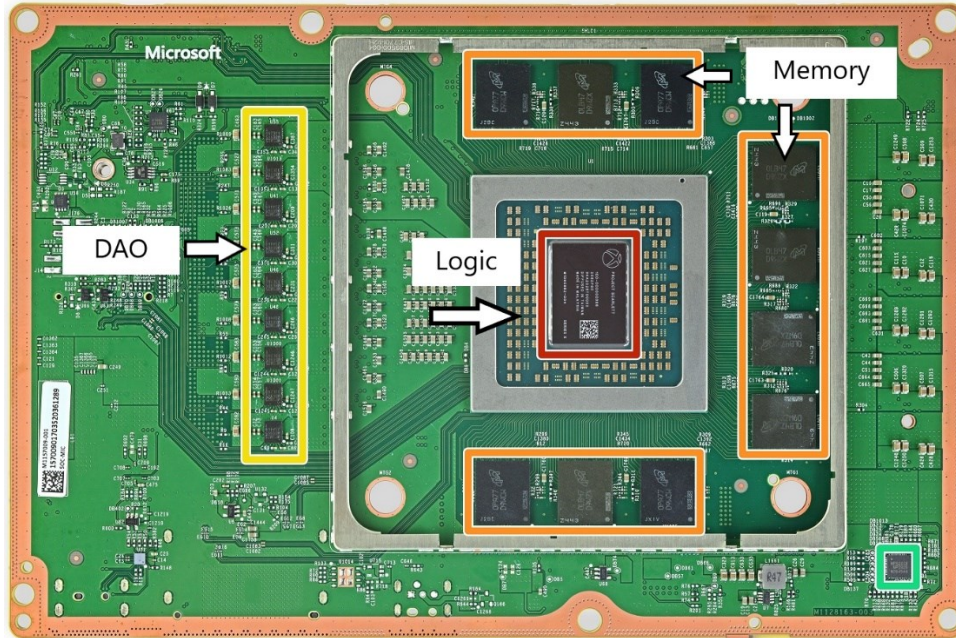
¹ Hitachi High-Tech Corporation, "What Are Semiconductors?," accessed December 1, 2022.

² Loveday, "What the Semiconductor Chip Shortage Means For You," March 25, 2022. Silicon is the commonly used semiconductive material in commercial chips.

³ ASML, "The Basics of Microchips," accessed December 1, 2022.

from power management to light sensing. Figure 2 shows an example of a video game circuit board with the three categories of semiconductor devices and components.

Figure 2 Circuit board example



Source: iFixit, “Xbox Series X: Teardown.”

Note: This circuit board from the Xbox Series X contains examples of logic, memory, and DAO chips. The image was modified to add labels.

Semiconductor Production

The production of semiconductors can also be divided into three main categories: design, front-end manufacturing, and back-end manufacturing. Design refers to the overall design of a semiconductor device and its underlying circuitry. Front-end manufacturing refers to the actual fabrication of the integrated circuit onto a silicon wafer, while back-end manufacturing refers to assembly, testing, and packaging activities.⁴ This paper will focus on design and front-end manufacturing, which are primarily concentrated in the United States and East Asia.

Global Semiconductor Demand

The shift to remote work, school, and leisure caused a surge in demand for devices such as computers and video game consoles, placing a strain on the supply of semiconductors. In 2021, global semiconductor sales totaled \$555.9 billion, a 26.2 percent increase from 2020.⁵ With semiconductor manufacturers unable to keep up with demand, many consumer electronics companies struggled to

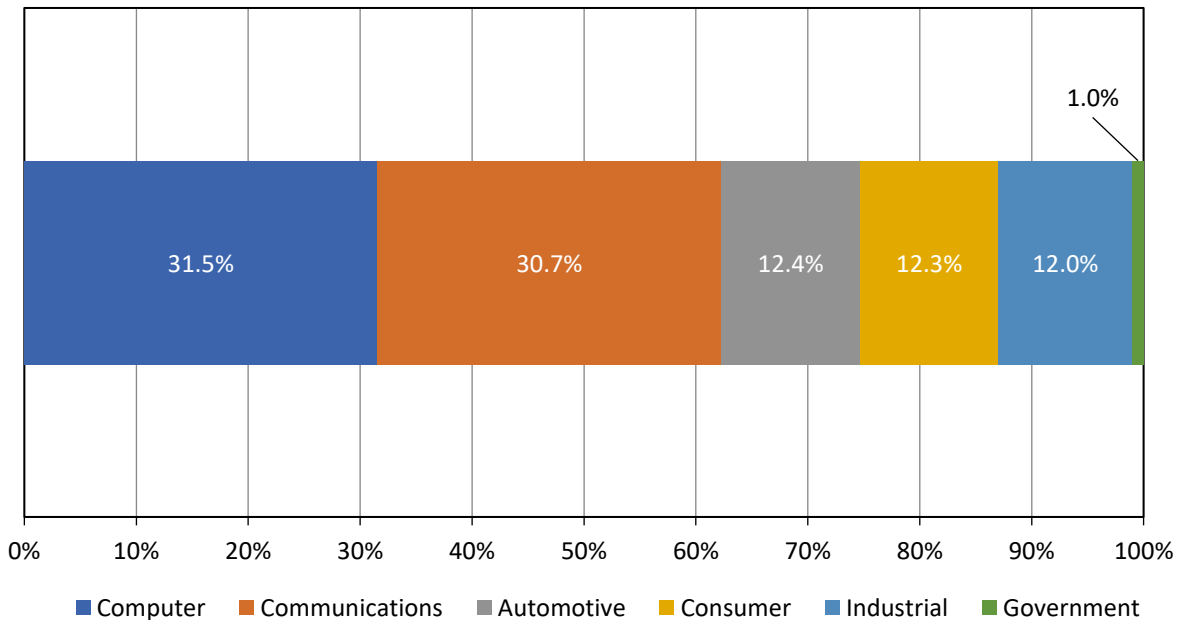
⁴ Varas et al., *Strengthening the Global Semiconductor Supply Chain*, April 1, 2021, 19.

⁵ Semiconductor Industry Association, “Global Semiconductor Sales,” February 14, 2022.

obtain an adequate supply of chips needed for their products. According to the U.S. Department of Commerce, the chips in shortest supply were microcontrollers, analog chips, and optoelectronics chips.⁶

Figure 3 below depicts 2021 sales by end-use industry. Computers and communication devices, such as cell phones, made up the largest share of market demand at roughly 32 percent and 31 percent of total sales, respectively. Automotives, consumer electronics (which includes video game consoles), and industrial machinery each accounted for about 12 percent of the market, while government purchases accounted for the remaining 1 percent.

Figure 3 Global semiconductor sales by end-use, 2021



Source: SIA, 2022 State of the U.S. Semiconductor Industry, p. 19.

Despite consumer electronics not being the leading industry in chip sales, video game consoles are an ideal product to survey the landscape of semiconductors. Gaming consoles use a wide variety of chips also seen in products from other industries, such as computers and mobile devices. Also, the chips found in these consoles are sourced globally, primarily from the United States, Taiwan, Japan, South Korea, and China.

Figure 4 represents the global share of sales for each semiconductor chip type, with logic and memory chips leading the market at 27.9 and 27.7 percent of sales overall, respectively. Using product teardowns of the PlayStation 5, the Xbox Series X, and the Nintendo Switch, the following section of the paper will

⁶ U.S. Department of Commerce, “Results from Semiconductor Supply Chain Request for Information,” January 25, 2022.

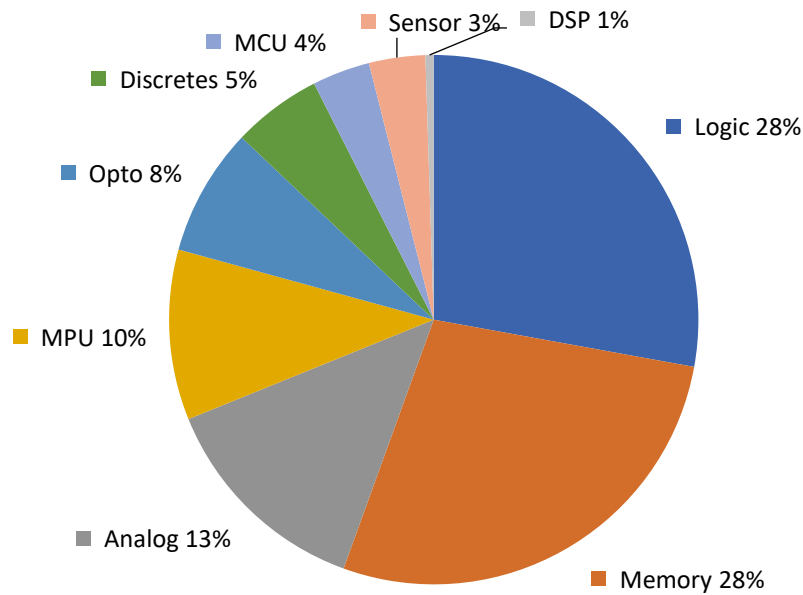
discuss these major semiconductor categories, examples present in the three consoles, and the global market for their production.⁷

Types of Semiconductors: Gaming Console Case Study

Logic Chips

Logic chips accounted for the largest share of global semiconductor sales in 2021 (figure 4).⁸ These chips receive input signals, perform logical operations, and produce output signals.⁹ Simply put, logic chips process information. The two primary logic chips in video game consoles are central processing units (CPUs) and graphical processing units (GPUs).¹⁰ Microprocessors (MPUs) and microcontrollers (MCUs) are related categories of chips that also process information and perform logic functions.

Figure 1 Global semiconductor sales by type, 2021



Source: SIA, 2022 Factbook, p. 12.

⁷ Teardowns are dissections of consumer electronic products, often used to analyze underlying technology and assess how repairs and modifications can be made. iFixit, “Nintendo Switch Teardown,” March 3, 2017; Tech Insights, “Nintendo Switch Teardown,” March 3, 2017; iFixit, “PlayStation 5 Teardown,” November 5, 2020; iFixit, “Xbox Series X Teardown,” November 11, 2020.

⁸ SIA, 2022 Factbook, April 21, 2022, 12.

⁹ Toshiba Electronic Devices & Storage Corporation, “What Is a Logic IC?,” accessed December 1, 2022.

¹⁰ CPUs and GPUs are specialized logic chips. Another type of specialized logic chip are neural processing units (NPUs), which are used for deep and machine learning. ASML, “The Basics of Microchips,” accessed December 1, 2022.

CPUs and GPUs

CPUs are considered the brains of computers, running their operating system and executing software instructions.¹¹ CPUs today typically have multiple processors, known as cores, which can each focus on unique tasks.¹² The more cores a CPU has, the more efficiently it can process information. In video game consoles, CPUs manage the operating system, execute software, and manage in-game functions such as combat, collision mechanics, and “non-player character” (NPC) interactions.¹³

GPUs, also referred to as graphics cards, are processors that specialize in the rendering of graphics and videos.¹⁴ By performing these functions, the GPU frees up the CPU to focus on other tasks. GPUs play a vital role in video game consoles by rendering high resolution graphics and textures. The more powerful the GPU, the more frames per second a video game console will be able to render.¹⁵ High frame rates are especially important for competitive players in games known as first-person shooters (FPS).¹⁶

The United States accounted for 67 percent of the global value added in logic chip design in 2021 (figure 5), with two U.S.-headquartered firms, AMD and Nvidia, leading the market for video game console CPUs and GPUs. Both are “fabless” semiconductor companies, focusing on chip design while contracting out manufacturing activities to companies known as foundries.¹⁷ The PlayStation 5 and Xbox Series X use customized versions of AMD’s Ryzen (“Zen”) 2 CPU and AMD’s RDNA 2 GPU.¹⁸ The Nintendo Switch on the other hand uses Nvidia’s Tegra 210 CPU and GPU.¹⁹

¹¹ Arm, “What Is a Central Processing Unit?,” accessed December 2, 2022.

¹² Jolene, “GPU vs CPU,” February 24, 2019.

¹³ Intel, “How the CPU Affects Your Gaming Experience,” accessed December 2, 2022; NPCs are computer/AI controlled characters within games. CPU’s perform tasks related to the artificial intelligence functionality of NPCs. Jolene, “GPU vs CPU,” February 24, 2019.

¹⁴ Intel, “What Is a GPU?,” accessed December 2, 2022.

¹⁵ Jolene, “GPU vs CPU,” February 24, 2019.

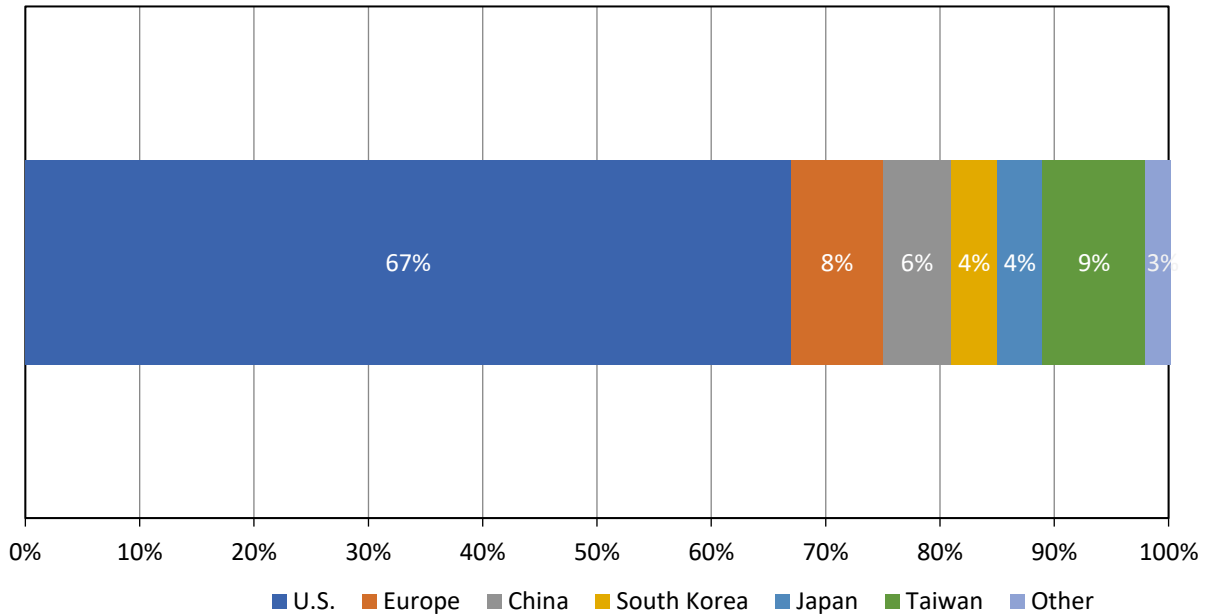
¹⁶ FPS include popular franchises like *Call of Duty*, *Overwatch*, and *Apex Legends*.

¹⁷ SIA, “What Is a Semiconductor?,” accessed December 2, 2022. In contrast, companies like Intel that both design and manufacture semiconductors are known as “integrated device manufacturers” (IDMs).

¹⁸ iFixit, “PlayStation 5 Teardown,” November 5, 2020; iFixit, “Xbox Series X Teardown,” November 11, 2020.

¹⁹ Tech Insights, “Nintendo Switch Teardown,” March 3, 2017.

Figure 5 Share of value added in logic chip design, 2021



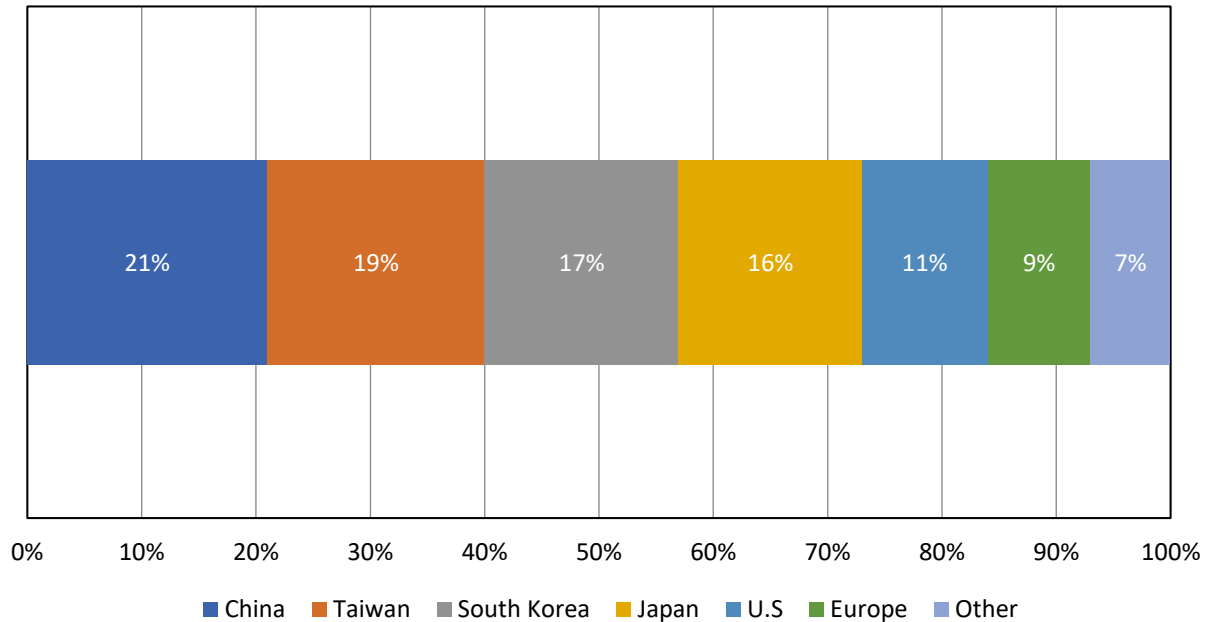
Source: SIA, 2022 State of the U.S. Semiconductor Industry, p. 21.

While the United States is the market leader in logic chip design, over 70 percent of total chip manufacturing is in East Asia (figure 6). AMD has foundry arrangements with Taiwan Semiconductor Manufacturing Company (TSMC) for the fabrication of chips with node sizes²⁰ of 7 nanometers or less and arrangements with Global Foundries (United States) for chips with node sizes between 12 and 14 nm.²¹ Both the Zen 2 and RDNA 2 have 7 nm node sizes, suggesting they are produced by TSMC. Nvidia also utilizes TSMC for chip production.²²

²⁰ Node size, also known as process size, refers to the size of the transistor elements within a chip. Smaller node sizes correspond to greater computing power because more transistors can be fit into a given area, with each transistor requiring less energy to operate. PCMag, “Definition of Process Technology,” accessed January 12, 2023; Fox, “What Is a Processor’s Process Size and Why Does It Matter?,” January 26, 2017.

²¹ Advanced Micro Devices Inc, *Form 10-K 2021*, February 3, 2022, 10.

²² Nvidia Corporation, *Form 10-K 2022*, January 30, 2022, 9. In a breakdown of the Switch, “Taiwan” is clearly labeled on the Nvidia CPU/GPU, though it does not say TSMC specifically. iFixit, “Nintendo Switch Teardown,” March 3, 2017.

Figure 6 Share of value added in semiconductor manufacturing by country, 2021

Source: SIA, 2022 State of the U.S. Semiconductor Industry, p. 21. Note: The source refers to manufacturing as “wafer fabrication”.

TSMC is the largest semiconductor foundry company in the world, accounting for nearly 54% of the foundry firm revenues in Q1 2022.²³ In 2021, it was one of only three companies capable of producing advanced microchips (node sizes at 10 nm and below). Due to TSMC’s advanced manufacturing capabilities, Taiwan is home to 92 percent of the world’s manufacturing capacity for leading-edge chips.²⁴

MPUs and MCUs

MPUs and MCUs are categories of semiconductors that perform logic functions but are also sometimes presented separately from logic chips (as shown in Figure 4). Additionally, the terms MPU, CPU, and logic chip are often used interchangeably, leading to further confusion. MPUs are single-chip implementations of CPUs, therefore meaning all CPUs are MPUs.²⁵ But because MPU’s can perform additional functions, and devices like GPUs are considered MPUs, not all MPUs are CPUs.²⁶

MCUs are considered a computer on a chip, containing a microprocessor and other components such as memory.²⁷ MCUs however cannot perform multiple tasks like an MPU and are designed to run specific

²³ Alsop, “Leading Semiconductor Foundries Revenue Share Worldwide from 2019 to 2022,” accessed December 2, 2022.

²⁴ Intel (United States) and Samsung (South Korea) were the other two companies capable of producing advanced chips. South Korea was home to the remaining 8 percent of advanced logic chip manufacturing capacity. Varas et al., Strengthening the Global Semiconductor Supply Chain, April 1, 2021, 35.

²⁵ Munoz, “CPU vs. Microprocessor,” June 26, 2020.

²⁶ Munoz, “CPU vs. Microprocessor,” June 26, 2020.

²⁷ Knerl, “Microcontroller vs Microprocessor,” November 11, 2019.

tasks without a sophisticated operating system.²⁸ MCUs found in these gaming consoles manage components like memory storage devices, USB-C and ethernet connections, as well as optical drives.²⁹ However, due to uncertainty surrounding the MCU category, some controller devices are included in subsequent sections, while others are excluded entirely.

Memory Chips

Memory chips accounted for the second largest share of semiconductor sales in 2021.³⁰ Memory chips store information and come in two basic varieties: **volatile and non-volatile**.

Volatile memory is the working memory used by the CPU to temporarily store and quickly access data.³¹ The information stored there is fed to the CPU for processing. This type of memory is considered “volatile” because information is only held temporarily while the device is powered on.³² The most common type of volatile memory is **dynamic random-access memory (DRAM)**.³³ A notable variant of DRAM used in video game consoles is synchronous graphics random access memory (SGRAM), which contains specialized functions for efficiently rendering graphics.³⁴

Non-volatile memory is used for long-term data storage.³⁵ While non-volatile memory is slower to read from and write to than volatile memory, it does not require the device to be powered on in order to retain data. Non-volatile memory chips are typically housed in a solid-state drive (SSD). SSDs are data storage units that function without moving parts, compared to a traditional hard-disk drive storage.³⁶ The most common type of non-volatile memory is flash. There are two types of **flash memory**, NAND and NOR, named after the logic gates their structures resemble.³⁷ However, the flash memory found in the three video game consoles is predominately of the NAND variety because its high-density structure allows for greater storage capacity.³⁸

Video game consoles use a variety of memory chips. The PlayStation 5 contains SGRAM from Micron (United States) and SDRAM from SK Hynix (South Korea).³⁹ Its SSD primarily uses flash memory from Kioxia (Japan) and Winbond (Taiwan).⁴⁰ The Xbox Series X contains SGRAM from Micron and a Western

²⁸ Knerl, “Microcontroller vs Microprocessor,” November 11, 2019.

²⁹ iFixit, “Nintendo Switch Teardown,” March 3, 2017; iFixit, “PlayStation 5 Teardown,” November 5, 2020; iFixit, “Xbox Series X Teardown,” November 11, 2020.

³⁰ SIA, *2022 Factbook*, April 21, 2022, 12.

³¹ Knerl, “What Is DRAM,” April 2, 2021.

³² Knerl, “What Is DRAM,” April 2, 2021.

³³ ASML, “The Basics of Microchips,” accessed December 1, 2022.

³⁴ PC Mag, “Definition of SGRAM,” accessed December 2, 2022.

³⁵ ASML, “The Basics of Microchips,” accessed December 1, 2022.

³⁶ Pavlovic, “What Is a Solid-State Drive (SSD)?,” July 11, 2018.

³⁷ A NAND (not-and) contains an AND gate followed by a NOT gate. Therefore, if both inputs are true, then the output is false. Otherwise, it is true. A NOR gate (not-or) combines an OR gate and a NOT gate. Therefore, if both inputs are true, then the output is false. Otherwise, it is true. Aravindan, “Flash 101,” July 23, 2018; TechTarget, “Logic Gate (AND, OR, XOR, NOT, NAND, NOR and XNOR),” accessed January 17, 2023.

³⁸ Marko, “Choose between NAND vs. NOR Flash Memory,” April 2, 2020.

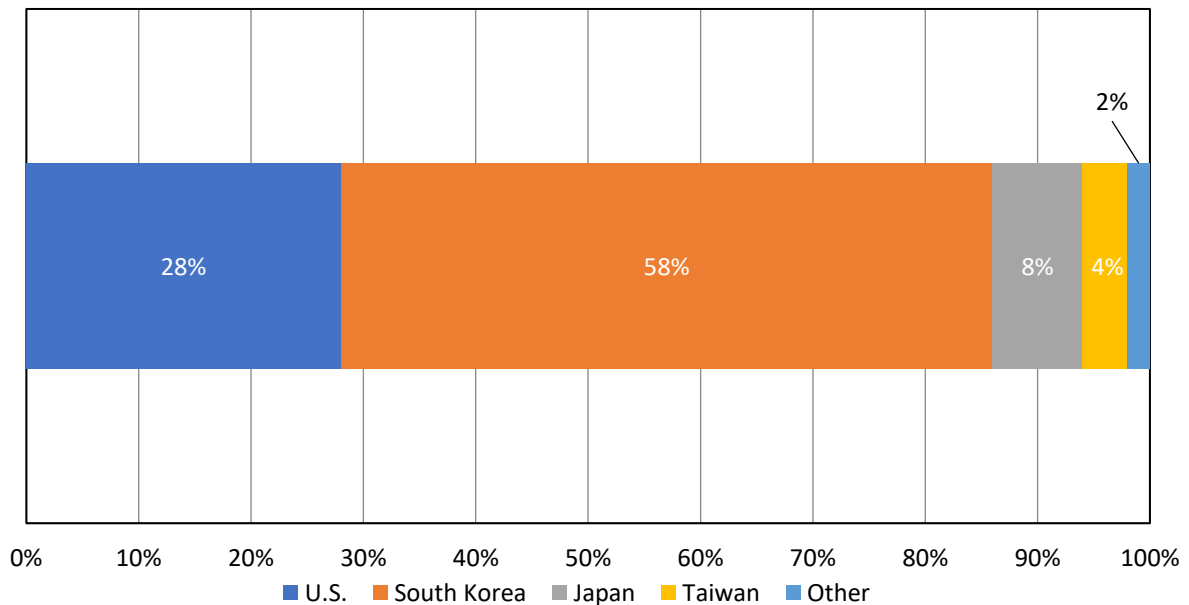
³⁹ iFixit, “PlayStation 5 Teardown,” November 5, 2020.

⁴⁰ iFixit, “PlayStation 5 Teardown,” November 5, 2020.

Digital (United States) SSD using SanDisk NAND Flash memory for storage.⁴¹ Nintendo's Switch contains serial flash memory from Macronix (Taiwan), SDRAM, and NAND flash from Toshiba (Japan).⁴²

As described above, the United States is the global leader in logic chip design. However, South Korea is the market leader for design in memory chips. South Korea accounts for 58 percent of the value added in memory chip design, compared to only 28 percent for the United States (figure 7). Samsung (South Korea) is the market leader in DRAM manufacturing with a 43.5 percent market share in Q1 2022.⁴³ The other two major players are SK Hynix and Micron with 27.4 and 24.5 percent, respectively.

Figure 7 Share of value added in memory chip design, 2021



Source: SIA, 2022 State of the U.S. Semiconductor Industry, p. 21.

Those three companies also accounted for about two-thirds of the market for NAND memory in Q3 2020.⁴⁴ Samsung has semiconductor manufacturing centers located in South Korea, China, and the U.S.⁴⁵ SK Hynix, another South Korean firm, has production sites in South Korea and China.⁴⁶ Micron (United States) has manufacturing locations in the United States, Japan, Malaysia, Singapore, Taiwan, and China.⁴⁷ Kioxia, the second largest NAND producer, operates a manufacturing facility in Japan.⁴⁸

⁴¹ iFixit, "Xbox Series X Teardown," November 11, 2020.

⁴² iFixit, "Nintendo Switch Teardown," March 3, 2017.

⁴³ Alsop, "DRAM Manufacturer Market Share," accessed December 5, 2022.

⁴⁴ Stice, *High Volume - Mainstream Memory*, 2021, 6.

⁴⁵ Samsung Semiconductor Global, "Location of Our Offices," accessed December 5, 2022.

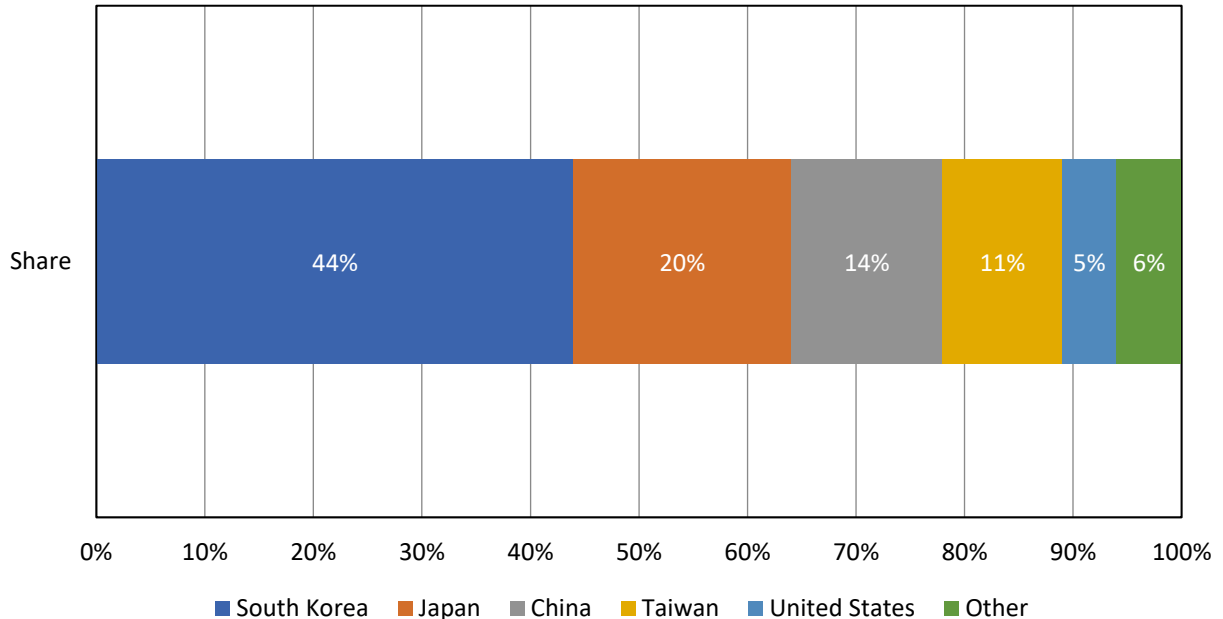
⁴⁶ SK hynix Newsroom, "SK Hynix Story: Company Overview," accessed December 5, 2022.

⁴⁷ Stice, *High Volume - Mainstream Memory*, 2021, 7.

⁴⁸ Kioxia, "Yokkaichi Plant," accessed December 14, 2022.

Figure 8 below depicts the memory chip fabrication capacity by country, with South Korea accounting for 44 percent of the global capacity.

Figure 8 Global memory chip manufacturing capacity by country, 2019



Source: SIA, *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era*, p. 35.

Discrete, Analog, and other (DAO) Chips

DAO stands for discrete, analog, and other. It is an umbrella category for a variety of semiconductor devices and components, typically with a specific function.

Discrete Devices

Discrete devices are simply a single device with a single function (as opposed to an integrated circuit, which contains multiple elements on a single chip).⁴⁹ Examples of discrete devices are diodes, transistors, rectifiers, and thyristors. On a circuit board, discrete devices are microelectronic components not built directly into an IC.⁵⁰ However, it appears that most discrete devices were likely excluded from mention in the teardown analyses.

Analog Chips

Analog chips use analog signals, as opposed to digital ones. They function by representing a continuous real-world signal (in the form of a wave), with a proportional electronic voltage current.⁵¹ Analog chips

⁴⁹ Toshiba, *Basic Knowledge of Discrete Semiconductor Device*, February 2022.

⁵⁰ PCMag, "Definition of Discrete Component," accessed February 9, 2023.

⁵¹ Semiconductor Engineering, "Analog Circuits," accessed December 5, 2022.

can perform functions like power management, audio and video conversion, audio amplification, and can include certain sensors.

Some of the most common analog chips seen in the three consoles relate to **power management**. These include DC voltage converters, power management IC's, step-down converters, and low dropout regulators. Broadly speaking, these chips regulate voltage and supply power to components throughout the console. The most prominent suppliers of power chips seen in these consoles include Texas Instruments (United States) and Richtek (Taiwan).⁵² Texas Instruments was the leading analog IC manufacturer in the world in 2021.⁵³ Texas Instruments operates wafer fabrication facilities in the United States, China, Germany, and Japan.⁵⁴ There is limited available information on the manufacturer for Richtek, but it appears TSMC is the predominant foundry used by its parent company, MediaTek.⁵⁵

Another common set of chips found in these consoles pertain to **audio and video**. Each console has a semiconductor responsible for video output: a Megachips (Japan) Mobility DisplayPort to HDMI converter in the Switch, an ON Semiconductor (United States) HDMI/DisplayPort level shifter/linear redriver in the Xbox, and a Panasonic (Japan) HDMI redriver in the PlayStation.⁵⁶ In order to maintain signal integrity at high speeds from the console to the video output device (usually a television or monitor), a redriver is used to boost the signal.⁵⁷ Level shifters allow compatibility between IC's operating at different voltages.⁵⁸ MegaChips is a fabless Japanese company whose primary manufacturer is Macronix International (Taiwan).⁵⁹ ON Semiconductor has manufacturing facilities in the United States, Belgium, the Czech Republic, Japan, South Korea, and Malaysia.⁶⁰ Panasonic transferred its semiconductor business to Nuvoton Technology (Taiwan) in 2020.⁶¹

Chips relating to audio include Realtek (Taiwan) audio signal converters (codecs)⁶² and Nuvoton audio amplifiers.⁶³ Realtek is a fabless semiconductor firm with foundry agreements with TSMC, United Microelectronics Corporation (Taiwan), and others.⁶⁴ Nuvoton is a Taiwanese chip manufacturer, with

⁵² iFixit, "Nintendo Switch Teardown," March 3, 2017; iFixit, "PlayStation 5 Teardown," November 5, 2020; iFixit, "Xbox Series X Teardown," November 11, 2020.

⁵³ Alsop, "Top Analog IC Suppliers Worldwide 2021," June 23, 2022.

⁵⁴ Texas Instruments, "Worldwide Manufacturing," accessed December 5, 2022.

⁵⁵ MediaTek, "Better Chipset Fabrication," accessed December 8, 2022.

⁵⁶ iFixit, "Nintendo Switch Teardown," March 3, 2017; iFixit, "PlayStation 5 Teardown," November 5, 2020; iFixit, "Xbox Series X Teardown," November 11, 2020.

⁵⁷ Diodes, "Linear Redrivers," accessed December 8, 2022.

⁵⁸ Tech-Box.io, "Level Shifter," accessed December 8, 2022.

⁵⁹ MegaChips Corporation, MCC Report 2021, 20, accessed December 6, 2022.

⁶⁰ On Semiconductor Corporation, *Form 10-K 2021*, December 31, 2021, 11.

⁶¹ Panasonic Industry, "Notice of Discontinuation of Posting of Semiconductor Products," accessed December 9, 2022.

⁶² A codec is a combination of "encode" and "decode." In order to transmit audio and video signals, they must be converted into bit information, and then converted back. MiniTool, "What Is a Codec?," accessed December 5, 2022.

⁶³ iFixit, "Nintendo Switch Teardown," March 3, 2017; iFixit, "PlayStation 5 Teardown," November 5, 2020; iFixit, "Xbox Series X Teardown," November 11, 2020.

⁶⁴ Realtek, Realtek Semiconductor Corp 2021 Annual Report, April 28, 2022.

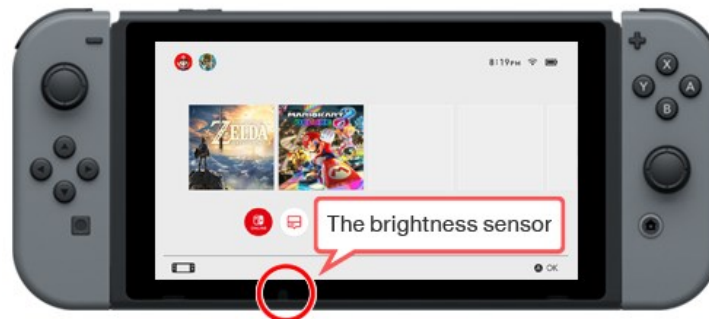
offices in Taiwan, China, Israel, India, Japan, South Korea, Singapore, and the U.S., but the locations of its fabrication facilities are not publicly available.⁶⁵

Optoelectronics

Optoelectronics are semiconductor devices that transform electrical energy into light or light into electrical energy.⁶⁶ Optoelectronics can be broken down into two broad categories: light sensing devices and light emitting devices.⁶⁷ An example of a light sensing device is a photodiode, which converts light into an electrical current. These are commonly used in smoke detectors.⁶⁸ Light emitting diodes (LEDs) are an example of a light emitting device.

The Nintendo Switch includes multiple optoelectronic devices. One is a Rohm (Japan) **ambient light sensor** on the main console.⁶⁹ This is a photodetector that adjusts the brightness of the devices screen based on the sum of nearby ambient light.⁷⁰ This is present in the Switch because of its handheld mode display and is common in smart phones and laptops. Rohm has manufacturing facilities in Japan, South Korea, Malaysia, Thailand, the Philippines, and China.⁷¹

Figure 9 Switch ambient light sensor



Source: Nintendo, “[Switch] When using my console in Handheld Mode, the brightness suddenly changes. Why does this happen?” <https://www.nintendo.com/my/support/qa/detail/33808>.

Another optoelectronic device in the Switch is the **infrared motion camera**.⁷² The camera and its sensors allow the handheld controller to detect object shapes, distances, and even record video.⁷³ Among its many uses, this camera can read a player’s heart rate in *Ring Fit Adventure*, detect a player opening and

⁶⁵ Nuvoton, “World Wide Location,” accessed December 8, 2022.

⁶⁶ Geeks for Geeks, “Optoelectronic Devices,” November 2, 2022.

⁶⁷ Circuits Today, “Optoelectronic Devices,” July 9, 2014.

⁶⁸ Abasolo, “A Complete Guide to Optoelectronic Devices - Circuit Basics,” accessed December 6, 2022.

⁶⁹ iFixit, “Nintendo Switch Teardown,” March 3, 2017.

⁷⁰ ELPROCUS, “Ambient Light Sensor,” accessed December 6, 2022.

⁷¹ Direct Industry, “ROHM Semiconductor,” accessed December 13, 2022.

⁷² Tech Insights, “Nintendo Switch Teardown,” March 3, 2017.

⁷³ CMOS (complementary metal oxide semiconductor) sensors convert photons to electrons and are used to create images in digital cameras. They are also commonly found in scanners and barcode readers. Tech Insights, “Nintendo Switch Teardown,” March 3, 2017; TechTarget, “What Is CMOS Sensor?,” accessed December 8, 2022.

closing their mouth in a 1,2, *Switch* eating contest, and act as a night vision camera or motion detector in several independently produced games.⁷⁴

Sensors and Actuators

Sensors and actuators are devices used to measure things like temperature, pressure, velocity, acceleration, or stress. Sensors containing optoelectronics, however, are typically categorized under optoelectronics. The Switch contains four non-optoelectronic sensors: a Texas Instruments (United States) remote/local temperature sensor and three STMicroelectronics (Netherlands) accelerometer/gyroscopes (one in the console and one in each controller).⁷⁵ **Accelerometers** are sensors used to measure vibrations or changes in motion.⁷⁶ **Gyroscopes** are used to sense and maintain direction.⁷⁷ These sensors are necessary for motion controls, for example when returning a tennis serve in *Nintendo Switch Sports* or aiming an Ancient Bow in *Legend of Zelda: Breath of the Wild*. No sensors were cited in the PlayStation teardown and there was no available teardown of the Xbox controller.

The PlayStation's DualSense wireless handheld controller's **haptics technology** operates by using Foster Electric (United States) voice coil actuators.⁷⁸ Haptics technology creates a more realistic gaming experience by digitally recreating the sense of touch.⁷⁹ Nuanced vibrations generated by haptics attempt to convey feelings like riding a bumpy New York subway car in *Spider-man: Miles Morales*, running across a glass surface in *Astro's Playroom*, or the recoil of firing off a burst pistol in *Ratchet and Clank: Rift Apart*. Voice-coil actuators create the vibrations and are the same kind of device that speakers use to create vibrations and sounds.⁸⁰ The Nintendo Switch Joy-Cons use a similar form of haptics technology, though the manufacturer is unknown.⁸¹

Others

The consoles contained a few other notable types of chips, which may not be part of the previously mentioned subcategories. These chips allow for wireless connectivity to both the internet and external devices. The Switch contains a Broadcom (United States) 5g **Wi-Fi** chip with integrated Bluetooth in the console, as well as Broadcom **Bluetooth transceivers** in the Joy-Con controllers.⁸² The PlayStation contains a Sony Wi-Fi chip. No Bluetooth chips were identified in the Xbox teardown.

The Switch also contains a chip for wireless **near-field communication (NFC)**.⁸³ NFC chips enable short-range wireless communication between devices.⁸⁴ These chips are commonly used in credit cards and

⁷⁴ Nintendo, "Frequently Asked Questions," accessed January 13, 2023; Carter, "I Forgot the Right Switch Joy-Con Has an IR Sensor: Here's What Uses It," accessed January 13, 2023; Totilo, "The Switch Joy-Con's Infrared Sensor Is Cooler Than We Thought," February 2, 2018.

⁷⁵ iFixit, "Nintendo Switch Teardown," March 3, 2017.

⁷⁶ Omega, "Accelerometer: What Is It & How It Works," accessed December 8, 2022.

⁷⁷ Utmel, "What Is a Gyroscope Sensor?," September 11, 2020.

⁷⁸ iFixit, "PlayStation 5 Teardown," November 5, 2020.

⁷⁹ Konishi, "Taking on New Challenges with Haptics," December 2, 2020.

⁸⁰ Jones, "PS5 Controller: What Haptic Feedback Does," April 13, 2020.

⁸¹ iFixit, "Nintendo Switch Teardown," March 3, 2017.

⁸² iFixit, "Nintendo Switch Teardown," March 3, 2017; Tech Insights, "Nintendo Switch Teardown," March 3, 2017.

⁸³ iFixit, "Nintendo Switch Teardown," March 3, 2017.

⁸⁴ STMicroelectronics, "What Is an NFC Chip?," accessed December 8, 2022.

smart phones for contactless payment. The NFC chip located in the right Joy-Con controller enables use of Nintendo’s amiibo. Amiibo are figurines of video game characters, such as Mario or Pikachu, which contain an embedded NFC chip (also known as a “tag”) in their base. Information stored in the amiibo’s chip can be read by placing one of the figurines on top of the Joy-Con. This can unlock in-game features like special items and power-ups or can even add the character to the game.⁸⁵

Figure 10 NFC tag



Note: Modified to focus on the tag. Source: Blue Bite, “The Complete Guide to NFC,” <https://www.bluebite.com/nfc>.

Figure 11 Amiibo



Note: An NFC tag in the base of the figurine can be read by the NFC chip in the Joy-Con. Source: Nintendo, “Amiibo.”

DAO Global Production

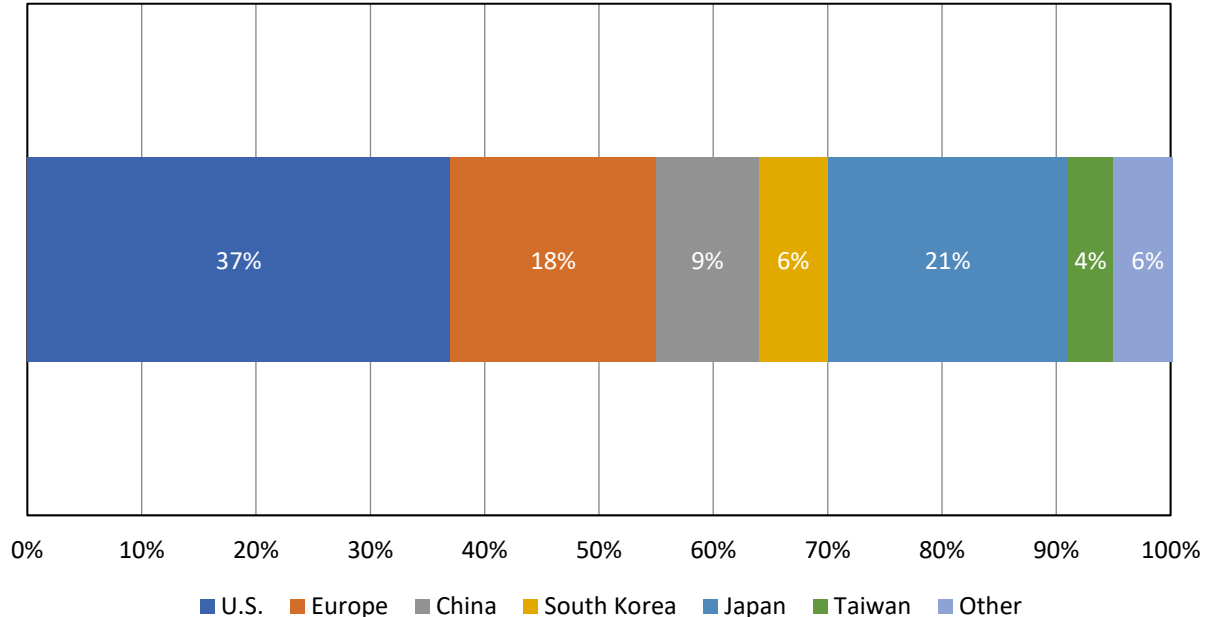
Compared to logic and memory chips, DAO design and front-end manufacturing is more evenly distributed among the major semiconductor-producing nations. Figure 12 depicts the 2021 global share of value added in DAO design, with the United States, Japan, and Europe leading the market.⁸⁶ These

⁸⁵ Nintendo, “Amiibo,” accessed December 8, 2022.

⁸⁶ SIA, 2022 State of the U.S. Semiconductor Industry, 21, accessed November 22, 2022.

three were also the market leaders in global DAO manufacturing capacity in 2019, with Japan accounting for 27 percent, Europe 22 percent, and the United States 19 percent.⁸⁷

Figure 12 Share of value added in DAO chip design, 2021



Source: Source: SIA, 2022 State of the U.S. Semiconductor Industry, p. 21.

Conclusion

Semiconductors are a critical input to electronic devices. Surging demand for consumer electronics during the COVID-19 pandemic strained the supply of semiconductors, creating shortages of many downstream electronic products. Partially due to the 2020 launch of two next-generation consoles, the video game console industry was particularly affected. These consoles are ideal products to analyze the market for semiconductors, the variety that exist, and their use in consumer electronics.

Much of the dialog and reporting on the semiconductor shortage fails to explain that semiconductors are not a single commodity, but a broad range of devices. Using the example of video gaming consoles, this paper highlights the three main categories of semiconductors: logic, memory, and DAO. It also analyzes many of the individual semiconductors found in these consoles and their function. Despite varying levels of sophistication, all play important roles in the function of a gaming console, whether it is the rendering of high-resolution graphics by the GPU, the storage of software in flash memory chips, or the enabling of motion controls with gyroscope sensors.

The list of semiconductor devices cited in this paper is not comprehensive. Some were excluded by choice in order to not overwhelm the reader with excess examples. For others, such as discrete devices, there may have been a gap in available information. Additionally, the semiconductors contained in these

⁸⁷ Varas et al., *Strengthening the Global Semiconductor Supply Chain*, April 1, 2021, 35.

devices may change overtime as manufacturers make upgrades or alter their sourcing. Moving forward, categorization of semiconductor devices remains a challenge. Some terms are used interchangeably for devices that are technically distinct or multiple terms are used for devices that seem to overlap, such as logic chips, MCUs, and MPUs. This leads to uncertainty when analyzing aggregate statistics. Certain devices in this paper may be miscategorized as a result. Balancing technical accuracy and granularity with definitions and groupings that are analytically useful remains a challenge.

The supply chain for semiconductors is complex, with design and manufacturing activities often performed by separate companies and across borders. U.S. firms have the largest market share for the design of both logic and DAO chips, whereas South Korean firms account for the largest share of design in memory chips. However, the primary location of semiconductor manufacturing is East Asia, in countries like Taiwan, Japan, South Korea, and China. Much of this is the result of market segmentation where fabless U.S. design firms like AMD and Nvidia contract out their manufacturing to foundries in Asia, such as TSMC.

Bibliography

- Abasolo, Louvil. "A Complete Guide to Optoelectronic Devices - Circuit Basics." Circuit Basics. Accessed December 6, 2022. <https://www.circuitbasics.com/optoelectronic-devices/>.
- Advanced Micro Devices Inc. *Form 10-K 2021*. Advanced Micro Devices Inc, February 3, 2022. <https://www.sec.gov/Archives/edgar/data/2488/000000248822000016/amd-20211225.htm>.
- Alsop, Thomas. "DRAM Manufacturer Market Share by Quarter 2022." Statista. Accessed December 5, 2022. <https://www.statista.com/statistics/271726/global-market-share-held-by-dram-chip-vendors-since-2010/>.
- Alsop, Thomas. "Leading Semiconductor Foundries Revenue Share Worldwide from 2019 to 2022." Statista. Accessed December 2, 2022. <https://www.statista.com/statistics/867223/worldwide-semiconductor-foundries-by-market-share/>.
- Alsop, Thomas. "Top Analog IC Suppliers Worldwide 2021," June 23, 2022. <https://www.statista.com/statistics/555200/worldwide-analog-integrated-circuit-suppliers-by-revenue/>.
- Aravindan, Avinash. "Flash 101: NAND Flash vs NOR Flash." Embedded, July 23, 2018. <https://www.embedded.com/flash-101-nand-flash-vs-nor-flash/>.
- Arm. "What Is a Central Processing Unit?" Accessed December 2, 2022. <https://www.arm.com/glossary/cpu>.
- ASML. "The Basics of Microchips." Accessed December 1, 2022. <https://www.asml.com/en/technology/all-about-microchips/microchip-basics>.
- Carter, Chris. "I Forgot the Right Switch Joy-Con Has an IR Sensor: Here's What Uses It." Destructoid. Accessed January 13, 2023. <https://www.destructoid.com/right-switch-joy-con-has-an-ir-sensor-heres-what-uses-it/>.
- Circuits Today. "Optoelectronic Devices," July 9, 2014. <https://www.circuitstoday.com/optoelectronic-devices>.
- Diodes. "Linear Redrivers Make Visible Difference in DisplayPort Connections." Accessed December 8, 2022. <https://www.diodes.com/design/support/technical-articles/linear-redrivers-make-visible-difference-in-displayport-connections/>.
- Direct Industry. "ROHM Semiconductor." Accessed December 13, 2022. <https://www.directindustry.com/soc/rohm-semiconductor-13683.html>.
- ELPROCUS. "Ambient Light Sensor Working and Applications." Accessed December 6, 2022. <https://www.elprocus.com/ambient-light-sensor-working-and-applications/>.
- Fox, Alexander. "What Is a Processor's Process Size and Why Does It Matter?" maketecheasier, January 26, 2017. <https://www.maketecheasier.com/processors-process-size/>.

From Silicon to Donkey Kong: A Case Study in the Use of Semiconductors in Video Game Consoles

Geeks for Geeks. "Optoelectronic Devices," November 2, 2022.

<https://www.geeksforgeeks.org/optoelectronic-devices/>.

Hitachi High-Tech Corporation. "What Are Semiconductors?" Accessed December 1, 2022.

<https://www.hitachi-hightech.com/global/en/knowledge/semiconductor/room/about/>.

iFixit. "Nintendo Switch Teardown," March 3, 2017.

<https://www.ifixit.com/Teardown/Nintendo+Switch+Teardown/78263>.

iFixit. "PlayStation 5 Teardown," November 5, 2020.

<https://www.ifixit.com/Teardown/PlayStation+5+Teardown/138280>.

iFixit. "Xbox Series X Teardown," November 11, 2020.

<https://www.ifixit.com/Teardown/Xbox+Series+X+Teardown/138451>.

Intel. "How the CPU Affects Your Gaming Experience." Accessed December 2, 2022.

<https://www.intel.com/content/www/us/en/gaming/resources/how-cpus-affect-your-gaming-experience.html>.

Intel. "What Is a GPU? Graphics Processing Units Defined." Accessed December 2, 2022.

<https://www.intel.com/content/www/us/en/products/docs/processors/what-is-a-gpu.html>.

Jolene, Dobbin. "GPU vs CPU: What Matters Most for PC Gaming?" HP, February 24, 2019.

<https://www.hp.com/us-en/shop/tech-takes/gpu-vs-cpu-for-pc-gaming>.

Jones, Camden. "PS5 Controller: What Haptic Feedback Does & How It Works." Screen Rant, April 13, 2020. <https://screenrant.com/ps5-controller-what-haptic-feedback-actually-does/>.

Kioxia. "Yokkaichi Plant." Kioxia. Accessed December 14, 2022. <https://www.kioxia.com/en-jp/about/yokkaichi.html>.

Knerl, Linsey. "Microcontroller Vs Microprocessor." HP, November 11, 2019. <https://www.hp.com/us-en/shop/tech-takes/microcontroller-vs-microprocessor>.

Knerl, Linsey. "What Is DRAM (Dynamic Random Access Memory)?" HP, April 2, 2021.

<https://www.hp.com/us-en/shop/tech-takes/what-is-dram-dynamic-random-access-memory>.

Konishi, Yukari. "Taking on New Challenges with Haptics - A Technology That Stimulates the Sense of Touch, One of the Five Senses." Sony, December 2, 2020.

<https://www.sony.com/en/SonyInfo/technology/stories/Haptics/>.

Loveday, Steven. "What the Semiconductor Chip Shortage Means For You." U.S. News, March 25, 2022.

<https://cars.usnews.com/cars-trucks/features/semiconductor-shortage>.

Marko, Kurt. "Choose between NAND vs. NOR Flash Memory." TechTarget, April 2, 2020.

<https://www.techtarget.com/searchstorage/feature/Choose-between-NAND-vs-NOR-flash-memory>.

- MediaTek. “Better Chipset Fabrication = Better Performance and Efficiency.” Accessed December 8, 2022. <https://www.mediatek.com/technology/fabrication-process-technology>.
- MegaChips Corporation. *MCC Report 2021*. Accessed December 6, 2022. <https://megachips.com/2022/06/2021-annual-report/>.
- MiniTool. “What Is a Codec? Why Is It Important? What Are the Types of It?” Accessed December 5, 2022. <https://www.minitool.com/lib/what-is-a-codec.html>.
- Munoz, Stefani. “CPU vs. Microprocessor: What Are the Differences?” TechTarget, June 26, 2020. <https://www.techtarget.com/searchitoperations/tip/CPU-vs-microprocessor-What-are-the-differences>.
- Nintendo. “Amiibo.” Accessed December 8, 2022. <https://www.nintendo.com/amiibo/>.
- Nintendo. “Frequently Asked Questions.” Accessed January 13, 2023. <https://www.nintendo.com/my/switch/al3p/faq/index.html>.
- Nuvoton. “World Wide Location.” Accessed December 8, 2022. https://www.nuvoton.com/about-nuvoton/company-profile/world-wide-location/?_locale=en.
- Nvidia Corporation. *Form 10-K 2022*, January 30, 2022. <https://www.sec.gov/Archives/edgar/data/1045810/000104581022000036/nvda-20220130.htm>.
- Omega. “Accelerometer: What Is It & How It Works.” Accessed December 8, 2022. <https://www.omega.com/en-us/resources/accelerometers>.
- On Semiconductor Corporation. *Form 10-K 2021*, December 31, 2021. <https://www.sec.gov/Archives/edgar/data/1097864/000162828022002416/on-20211231.htm>.
- Panasonic Industry. “Notice of Discontinuation of Posting of Semiconductor Products.” Accessed December 9, 2022. <https://industrial.panasonic.com/ww/business-transfer-of-semiconductors>.
- Pavlovic, Dwight. “What Is a Solid-State Drive (SSD)?” HP, July 11, 2018. <https://www.hp.com/us-en/shop/tech-takes/what-is-an-ssd>.
- PC Mag. “Definition of SGRAM.” Accessed December 2, 2022. <https://www.pcmag.com/encyclopedia/term/sgram>.
- PCMag. “Definition of Discrete Component.” Accessed February 9, 2023. <https://www.pcmag.com/encyclopedia/term/discrete-component>.
- PCMag. “Definition of Process Technology.” Accessed January 12, 2023. <https://www.pcmag.com/encyclopedia/term/process-technology>.
- Realtek. *Realtek Semiconductor Corp 2021 Annual Report*. Realtek, April 28, 2022. https://www.realtek.com/images/ar/-2021_20220518.pdf.

From Silicon to Donkey Kong: A Case Study in the Use of Semiconductors in Video Game Consoles

Samsung Semiconductor Global. "Location of Our Offices." Accessed December 5, 2022.

<https://semiconductor.samsung.com/about-us/locations/>.

Semiconductor Engineering. "Analog Circuits." Accessed December 5, 2022.

https://semiengineering.com/knowledge_centers/integrated-circuit/ic-types/analog-circuits/.

Semiconductor Industry Association. *2022 Factbook*, April 21, 2022.

<https://www.semiconductors.org/resources/factbook/>.

Semiconductor Industry Association. *2022 State of the U.S. Semiconductor Industry*. Accessed November

22, 2022. <https://www.semiconductors.org/state-of-the-u-s-semiconductor-industry/#:~:text=Despite%20an%20historic%20year%20in,the%20second%20half%20of%202023>.

Semiconductor Industry Association. "Global Semiconductor Sales, Units Shipped Reach All-Time Highs in 2021 as Industry Ramps Up Production Amid Shortage." SIA, February 14, 2022.

<https://www.semiconductors.org/global-semiconductor-sales-shipped-reach-all-time-highs-in-2021-as-industry-ramps-up-production-amid-shortage/>.

Semiconductor Industry Association. "What Is a Semiconductor?" Accessed December 2, 2022.

<https://www.semiconductors.org/semiconductors-101/what-is-a-semiconductor/>.

SK hynix Newsroom. "SK Hynix Story: Company Overview." Accessed December 5, 2022.

<https://news.skhynix.com/sk-hynix-story/company-overview/>.

Stice, Craig. *High Volume - Mainstream Memory*. OMDIA, 2021. https://www.semiconductors.org/wp-content/uploads/2021/02/Highest-Volume-Mainstream-Memory_Omdia.pdf.

STMicroelectronics. "What Is an NFC Chip?" Accessed December 8, 2022.

https://www.st.com/content/st_com/en/support/learning/essentials-and-insights/connectivity/nfc/nfc-chips.html.

Tech Insights. "Nintendo Switch Teardown," March 3, 2017.

<https://www.techinsights.com/blog/nintendo-switch-teardown>.

Tech-Box.io. "Level Shifter." Accessed December 8, 2022. <https://tech-box.io/blogs/keywords/level-shifter>.

TechTarget. "Logic Gate (AND, OR, XOR, NOT, NAND, NOR and XNOR)." Accessed January 17, 2023.

<https://www.techtarget.com/whatis/definition/logic-gate-AND-OR-XOR-NOT-NAND-NOR-and-XNOR>.

TechTarget. "What Is CMOS Sensor?" Accessed December 8, 2022.

<https://www.techtarget.com/whatis/definition/CMOS-sensor>.

Texas Instruments. "Worldwide Manufacturing." Accessed December 5, 2022.

<https://www.ti.com/about-ti/company/ti-at-a-glance/manufacturing.html>.

- Toshiba. *Basic Knowledge of Discrete Semiconductor Device: Chapter 1 Basis of Semiconductors*, February 2022. https://toshiba.semicon-storage.com/content/dam/toshiba-ss-v3/master/en/semiconductor/knowledge/e-learning/discrete/discrete-basic-chap1_en.pdf.
- Toshiba Electronic Devices & Storage Corporation. "What Is a Logic IC?" Accessed December 1, 2022. <https://toshiba.semicon-storage.com/us/semiconductor/knowledge/e-learning/cmos-logic-basics/chap1/chap1-1.html>.
- Totilo, Stephen. "The Switch Joy-Con's Infrared Sensor Is Cooler Than We Thought." Kotaku, February 2, 2018. <https://kotaku.com/the-switch-joy-con-s-infrared-sensor-is-cooler-than-we-1822669059>.
- U.S. Department of Commerce. "Results from Semiconductor Supply Chain Request for Information," January 25, 2022. <https://www.commerce.gov/news/blog/2022/01/results-semiconductor-supply-chain-request-information>.
- Utmel. "What Is a Gyroscope Sensor?," September 11, 2020. <https://www.utmel.com/blog/categories/sensors/what-is-a-gyroscope-sensor>.
- Varas, Antonio, Raj Varadarajan, Jimmy Goodrich, and Falan Yinug. *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era*. Semiconductor Industry Association, April 1, 2021. <https://www.semiconductors.org/strengthening-the-global-semiconductor-supply-chain-in-an-uncertain-era/>.

