New "Biz Tech" by MGSSI

Top 5 Technologies to Watch in 2026

Mitsui & Co. Global Strategic Studies Institute
Technology & Innovation Studies Div.

Introduction

Technologies and innovations are progressing constantly, day by day and moment by moment, and their trends demand continuous attention.

As researchers, we monitor these changes from a global perspective, analyze market developments, and conduct in-depth research to determine where the Mitsui & Co. Group should make its next strategic moves.

In 2026, **New "Biz Tech" by MGSSI**, published by the Technology & Innovation Studies Div., was fully revamped.

First of all, in light of the accelerating pace of technological advancement, we have focused on technologies expected to reach the implementation stage as early as within six months, or at most within the next few years. We have carefully selected five that could serve as near-term milestones and present them as the **Top 5 Technologies to Watch in 2026**.

In addition, as a new feature this year, we have launched **Global Trend to Watch in 2026**. In light of the growing number of technologies that cut across a wide section of society and multiple industries and that cannot be fully covered by a single researcher or discipline, researchers now bring together their respective areas of expertise to jointly analyze and write on a single theme. By examining the fundamental nature and broader implications of technologies from a diverse range of perspectives, we aim to deliver new insights to our readers.

We collectively refer to these initiatives as the renewed **New "Biz Tech" by MGSSI**, for launch in 2026.

Here, we first present the **Top 5 Technologies to Watch in 2026**.

We will continue doing out utmost to create value for society as a whole through the integration of knowledge.

Takuya Kawaguchi
Technology & Innovation Studies Div.

CONTENTS

(1) **Silicon Carbide Power Semiconductors Enter Full-Scale Adoption Phase with Killer App**
— Module Diversification and Expanding Business Opportunities from the "Heart" of Popular Hybrid Vehicles — / Reina Ogawa ······ 2

(2) **Laboratory Automation in the Pharmaceutical Industry**
— Transforming Drug Discovery Through Equipment, Software, and Robotics — / Takako Kato ······ 10

(3) **Lithium Manganese-Rich Cathodes Enabling High-Performance, Low-Cost Rechargeable Batteries**
— China, Europe, the US, and South Korea Taking Divergent Approaches to Application in EV Batteries — / Jian Zhao ······ 15

(4) **Co-Packaged Optics Gain Traction in Data Centers**
— Optoelectronic Integration Enters the Adoption Phase — / Rieko Tsuji ······ 21

(5) **Microgravity Utilization Technology Entering the Industrialization Phase**
— In-Orbit Experiments Opening New Frontiers in Next-Generation Manufacturing — / Hideki Kinjo ······ 27

Silicon Carbide Power Semiconductors Enter Full-Scale Adoption Phase with Killer App

— Module Diversification and Expanding Business Opportunities from the "Heart" of Popular Hybrid Vehicles —

Reina Ogawa
Industry Innovation Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

Toyota's new RAV4, launched in Japan on December 17, 2025, marks the first use of SiC power semiconductors in a Toyota hybrid system. The previous-generation-RAV4 was the world's best-selling passenger vehicle in 2024 in terms of new car sales volume. The installation of silicon carbide (SiC) power semiconductors in hybrid vehicles—considered a real solution for electric vehicles by balancing environmental impact and economic efficiency—as well as in high-volume, popular models is expected to make 2026 an inflection point for the rapid adoption of SiC power semiconductors.

Summary

- Power semiconductors are incorporated into all types of electrical equipment, from home appliances and automobiles through to elements of infrastructure, and they serve as the heart of these devices. The SiC power semiconductor market is projected to reach JPY 2.9034 trillion by 2035, representing 6.4-fold increase over the level in 2025.
- The incorporation of SiC power semiconductors into the hybrid system of the next-generation Toyota RAV4, the world's best-selling vehicle in 2024, signaled the beginning of full-scale adoption in automotive systems.
- As demands for miniaturization, weight reduction, and greater reliability continue, all companies involved in SiC wafer manufacturing, front-end and back-end processes, and modularity in installation stand to benefit from this growth.

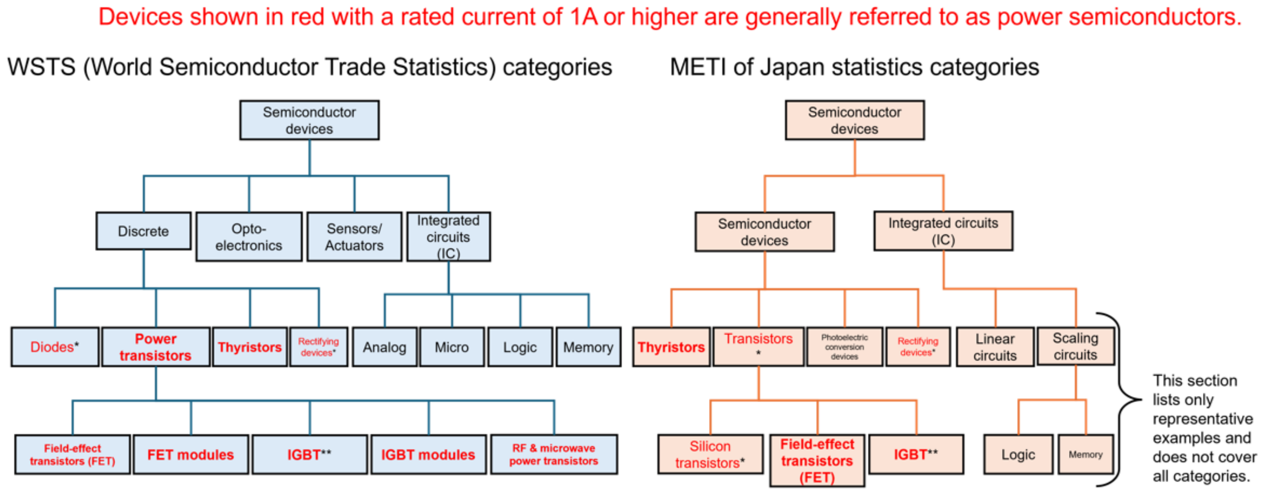
1. What are SiC Power Semiconductors?

1-1. What are Power Semiconductors?

Power semiconductors are capable of controlling large currents and voltages, and they are incorporated into all types of electrical equipment, from automobiles and home appliances through to trains, power transmission facilities, and other elements of infrastructure. Logic and memory can be likened to the human brain because they handle information processing and storage. In the same manner, power semiconductors can be likened to the heart, as they deliver electrical current throughout the entire device in the form required for proper operation. While their classification within semiconductor devices varies depending on the method used, they are categorically not integrated circuits (ICs) like logic and memory, which integrate large numbers of transistors onto a single wafer. The term "power semiconductors" collectively refers to semiconductor devices that handle large currents and voltages, operating as single transistors or combinations thereof (modules). The term also encompasses power transistors and diodes (Figure 1).

The global power semiconductor market is projected to grow roughly 2.2-fold over the next decade,

Figure 1: Classifications of power semiconductors within semiconductor device categories



* Some diodes, rectifying devices, and (silicon) transistors have low rated currents. Among the devices listed on the left, generally only those with a rated current of 1A or higher are classified as power semiconductors.
** An abbreviation of Insulated Gate Bipolar Transistor
Source: Compiled by MGSSI based on JEITA, Green Clean Semiconductor: An Easy Guide to Semiconductors
https://semicon.jeita.or.jp/book/docs/green_clean_semicon_1.pdf (Last accessed on November 5, 2025)

from JPY 3.5285 trillion[1] in 2025 to JPY 7.7710 trillion in 2035. Applications for automobiles, renewable energy, and communications/data centers are expected to be the primary drivers of this growth. More than half of this increase will be accounted for by next-generation power semiconductors. While silicon has traditionally been used as substrates (wafers) for conventional power semiconductors, next-generation power semiconductors are manufactured using wafers with chemical compositions other than silicon.

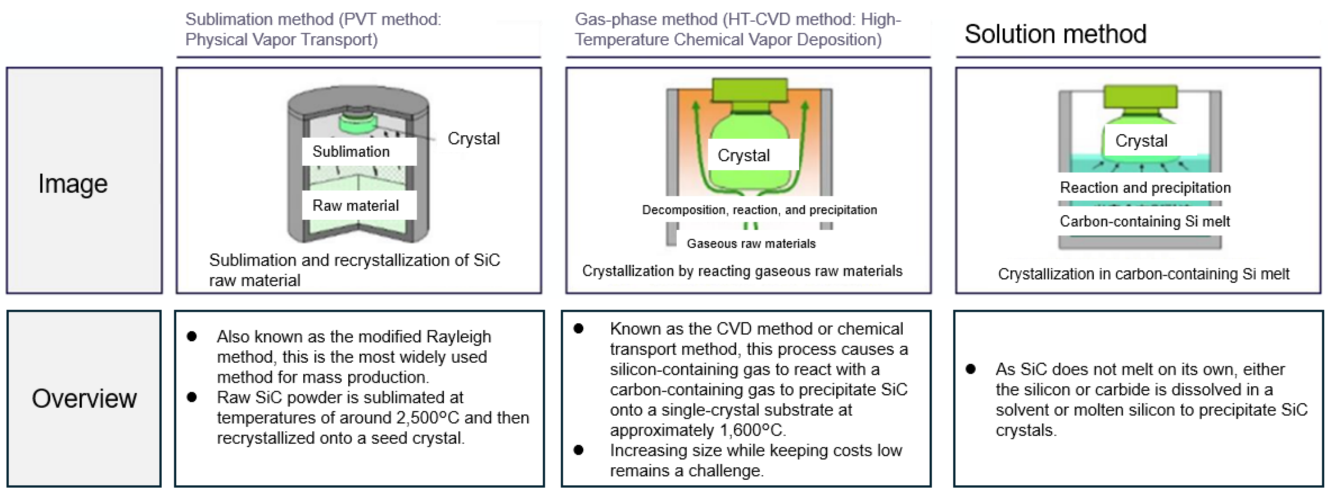
1-2. SiC Power Semiconductors as the Leading Contender among Next-Generation Power Semiconductors

Next-generation power semiconductors that make use of silicon carbide (SiC) wafers are referred to as SiC power semiconductors. As semiconductors are required to provide ever greater energy efficiency and performance year after year, the silicon conventionally used in power semiconductors is now approaching its physical limits in meeting requirements for thermal resistance and dielectric strength. This has led to the full-scale development of next-generation power semiconductors with far superior physical properties. Among next-generation power semiconductors, SiC power semiconductors currently account for the largest share of the market. The global market is expected to have reached JPY 455.8 billion in 2025 and grow to JPY 2.9034 trillion by 2035, representing a 6.4-fold increase over 2025. The greatest advantage that SiC power semiconductors have over other next-generation power semiconductors is their ability to directly apply the technologies for manufacturing power semiconductors that make use of silicon wafers. This enables manufacturers to keep development costs relating to production processes for devices following wafer production lower than those for other next-generation semiconductors, resulting in SiC devices taking the lead in mass production.

[1] Fuji Keizai, 2025 Edition: Current Status and Future Outlook of the Next-Generation Power Device-Related Market

While conventional silicon ingots[2] are produced by dipping a seed crystal into molten silicon, SiC is manufactured using a different process as it does not melt. Mass production primarily makes use of the sublimation method and the solution method (Figure 2). However, because SiC ingots take longer to produce than silicon ingots, the prices of the ingots and of the wafers sliced from them are higher than those of silicon. Accordingly, the shift from silicon to SiC has first begun in applications where the advantages of SiC—such as smaller size, lighter weight, and greater energy efficiency—justify the higher wafer cost, such as in trains, industrial equipment, and electric vehicles, including battery electric vehicles (BEVs) powered solely by batteries and hybrid electric vehicles (HEVs). Figure 3 illustrates the ranges of rated current and rated voltage by application, as well as the areas where the switch from silicon to next-generation semiconductors is progressing.

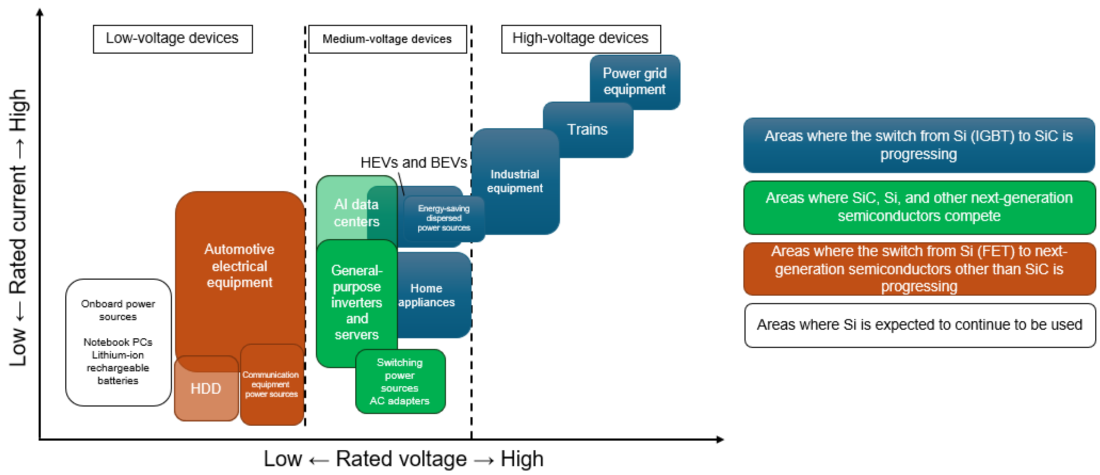
Figure 2: SiC ingot manufacturing methods and overview of the process



Source: Compiled by MGSSI based on "Domestic and International Trends Related to the Construction of Next-Generation Digital Infrastructure" by Ministry of Economy, Trade and Industry of Japan (published in October 2025) for the images, https://www.meti.go.jp/shingikai/sankoshin/green_innovation/industrial_restructuring/pdf/034_03_00.pdf (Last accessed on November 4, 2025) and based on various materials for the overview

[2] A lump of highly pure metal. Wafers used in semiconductor manufacturing are produced by slicing cylindrical ingots into thin discs and polishing them.

Figure 3: Performance requirements for power semiconductor by application and outlook for the switch from silicon to next-generation semiconductors



Source: Compiled by MGSSI based on various sources

2. Noteworthy Trends

2-1. Full-Scale Adoption of SiC Power Semiconductors Begins with Toyota's 6th Generation RAV4

SiC power semiconductors are most commonly applied in inverters, which convert the direct current (DC) supplied from an electrified vehicle's battery into alternating current (AC) to drive the motor. The plug-in hybrid model of Toyota's sixth-generation RAV4, which launched in Japan on December 17, 2025, adopted SiC power semiconductors for the first time in the company's hybrid systems. Due to the smaller size of the module, the height and weight of the hybrid system were reduced by 15% and 18% each, while the battery capacity was increased by 30%. This extended the electric driving range from 95 km of the previous model to 150 km. A driving range of 150 km means that, while still a plug-in hybrid vehicle, everyday driving can be covered using electricity from the battery alone. The previous fifth-generation RAV4 surpassed the US-based Tesla's Model Y[3], which had been the world's best-selling vehicle in 2023, to become the global best-selling vehicle in 2024, and its successor, the sixth-generation RAV4, is also planned for release worldwide. As growth in BEV sales remains slower than expected around the world, there is a growing trend of reassessing the value of HEVs as vehicles that balance environmental impact[4] and economic efficiency across the entire product lifecycle, from manufacturing to disposal, during the transition toward BEVs. In line with this trend, manufacturers are expected to continue adopting SiC power semiconductors.

2-2. Power Semiconductor-Related Companies Making Long-Term Investments in Development and Mass Production

As noted in the previous chapter, although the SiC power semiconductor market is expected to expand over the long term, its short-term growth path will not be smooth due to factors such as weaker-than-

[3] Within the electric vehicle sector, Tesla focuses on developing, manufacturing, and selling BEVs; and the company adopted SiC power semiconductors made by STMicroelectronics for its Model 3 inverter in 2017. The Model Y also makes use of similar SiC power semiconductors.

[4] In some cases, HEVs have a lower environmental impact than BEVs depending on battery manufacturing processes and disposal conditions, power supply configurations in the regions where the vehicles are used and charged, the use of biofuels, and other factors. https://www.jstage.jst.go.jp/article/jsaeronbun/56/4/56_20254372/_pdf

expected BEV sales—previously seen as a primary growth driver—and the rapid rise of Chinese competitors. Some companies, such as the Onsemi (US) and Mitsubishi Electric, have halted or postponed initially planned investments considering the balance between supply and demand, and others such as Wolfspeed (US) have been driven into management crises due to misjudged investment decisions, with Renesas Electronics recording losses as a result. On the other hand, European players including STMicroelectronics (Switzerland) and Infineon (Germany) are steadily investing in development and manufacturing across a broad range of fields, including automobiles, data centers, and renewable energy. What these companies have in common is that they are making investment decisions with the goal of sustaining and growing their businesses over the long term. Figure 4 shows trends in SiC power semiconductor development and manufacturing among power semiconductor-related companies.

Figure 4: Trends in SiC power semiconductors among major power semiconductor manufacturers

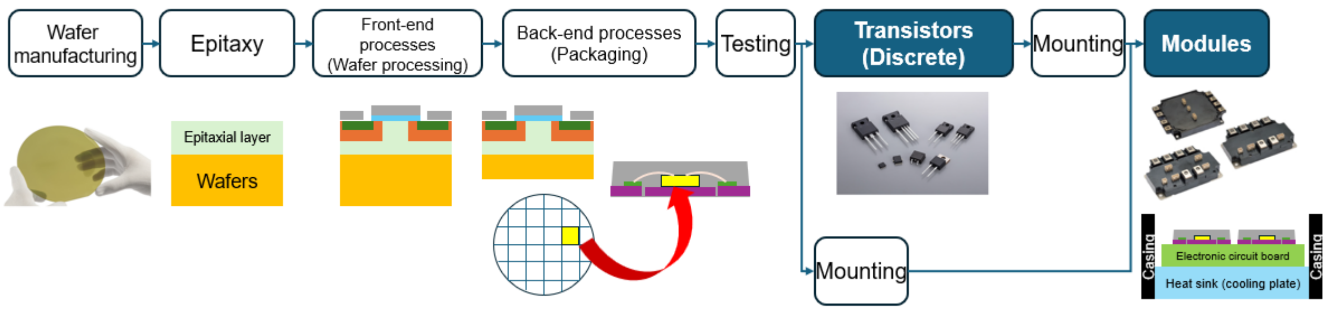
Company	Market share (2025 estimate*)	Overview
STMicroelectronics (Switzerland)	32.5	Has R&D facilities in Italy, mass-produces SiC wafers in Morocco and China, and manufactures devices at its 150 mm SiC wafer fabrication facilities in Italy and Singapore. Currently constructing a factory in China through a joint venture with Sanan Optoelectronics (China). Also constructing a fully vertically integrated facility in Italy, encompassing modules and packaging. This represents a multi-year investment of EUR 5 billion.
onsemi (US) (Semiconductor Components Industries, LLC)	23.6	Established in 1999 as a spin-off from the Semiconductor Components Division of Motorola (US). In 2022, expanded manufacturing capacity in the Czech Republic to 3 million wafers per year. In 2023, expanded its 200 mm SiC wafer manufacturing facility in South Korea, securing an annual production capacity of 1 million wafers. In 2024, announced plans to build a vertically integrated production facility in the Czech Republic with an investment of up to USD 2 billion. Halted additional investment in its South Korean plant in 2025 due to sluggish BEV sales, even though it had announced that its products had been adopted for use in plug-in HEVs by a US-based OEM. Acquired SiC JFET** business from Qorvo (US) in January 2025. Also targeting adoption in power sources for AI data centers.
Infineon Technologies (Germany)	16.5	The world's largest power semiconductor manufacturer. In 2024, opened the world's largest SiC power semiconductor factory in Malaysia. Invested EUR 2 billion in the facility as Phase 1 of the plan. Plans to invest up to EUR 5 billion in Phase 2. Has already secured six automotive OEM customers, along with others in the renewable energy and industrial sectors, and aims to achieve annual SiC revenue of EUR 7 billion and a 30% share of the global market by 2030. Developed CoolSiC JFET for AI data centers. Plans to launch mass production in 2026.
Wolfspeed (US)	11.8	Holds the leading share in SiC wafer manufacturing. Founded as a wafer manufacturer but later expanded into device production. However, filed for Chapter 11 bankruptcy protection under US federal law in June 2025 due to sluggish EV sales and the emergence of Chinese competitors. Announced completion of its restructuring in September.
ROHM (Japan)	8.1	Although sales declined significantly in 2024, its SiC power semiconductor modules were adopted for use in Toyota's EVs for the Chinese market. Announced a partnership with DENSO in this sector. DENSO has acquired a portion of ROHM's shares. In addition, its group company SiCrystal (Japan) has concluded a multi-year contract to supply SiC wafers to STMicroelectronics starting in 2024.
Mitsubishi Electric (Japan)	2.0	In October 2025, completed a new factory building for power semiconductors using 200 mm SiC wafers in Kikuchi City, Kumamoto Prefecture. Aims to transition to full-scale mass production in 2027. However, expansion investments have been postponed until the 2031 fiscal year or later. Aims to transition to mass production in 2027. Has also established a roadmap to reduce costs in cooperation with Coherent (US), a leading SiC substrate manufacturer in which it has invested. Expects to launch mass production of the J3 series for inverters used in electrified vehicles in 2026, while initially focusing on the railway and power sectors, where high performance and reliability are critical.
DENSO (Japan) and Fuji Electric (Japan)	1.8	In 2024, announced a joint investment totaling JPY 200 billion. Expansion is underway at DENSO sites in Aichi and Mie Prefectures, as well as at Fuji Electric's site in Nagano Prefecture. The company, which develops and manufactures power semiconductors for Toyota's BEVs, is expanding its Tsugaru Plant in Aomori Prefecture to bolster its shift toward SiC.
YJ (China) (Yangzhou Yangjie Electronic Technology Co., Ltd.)	0.8	Has decided to launch mass production of SiC power semiconductors featuring next-generation transistor structures around 2027. This follows the successful achievement of a 41% reduction in cell size compared with the previous generation. Working to increase SiC power semiconductor production capacity from the current 5,000 150-mm wafers per month to 20,000 wafers per month by 2027, while also transitioning to 200-mm wafers.
Renesas Electronics (Japan) electronics	-	In 2023, deposited USD 2 billion (approx. JPY 290 billion) with Wolfspeed and concluded a 10-year contract for the supply of SiC substrates. However, recorded losses following Wolfspeed's bankruptcy, and supported the company's restructuring. Suspended development of products and investments in factory facilities for SiC power semiconductors in response to environmental changes, including the emergence of Chinese competitors. The Kofu Factory (Kai City, Yamanashi Prefecture), which had been scheduled to mass-produce SiC devices, will instead be used to produce silicon MOSFETs and gallium nitride (GaN) devices.

* Estimated based on 2025 sales, the 2023 market share (TrendForce), and forecast figures from each company's IR materials and various announcements.
** An abbreviation of Junction Field Effect Transistor. SiC JFETs are expected to enable higher efficiency and performance in power supply equipment for artificial intelligence (AI) data centers, due to their low on-resistance, high voltage tolerance, and high-speed switching capabilities.
Source : Compiled by MGSSI based on various date

2-3. Module Design and Heat Dissipation/Cooling Technologies Growing in Importance for Ensuring Reliability

Figure 5 provides an overview of the power semiconductor manufacturing process. Modules are produced by placing and connecting (mounting) chips or transistors onto circuit boards. For SiC power semiconductors, wafer prices account for a large proportion of the cost of devices, and packaging and mounting technologies have a significant impact on performance. As a result, many companies maintain vertically integrated systems covering everything from wafer manufacturing through to module production, while combining in-house production with procurement from wafer manufacturers for SiC wafers and SiC epitaxial wafers with epitaxial layers.

Figure 5: Manufacturing process for power semiconductors (transistors and modules)



Note: The images are for illustration purposes only and do not reflect actual product dimensions or designs.

Source: Compiled by MGSSI based on various data
ROHM website https://www.rohm.co.jp/news-detail?news-title=2022-04-14_news_sicrystal25&defaultGroupId=false
(SiC wafers)
Fuji Electric website https://www.fujielectric.co.jp/products/semiconductor/power_discrete/index.html
(SiC discrete devices)
Mitsubishi Electric website https://www.mitsubishielectric.co.jp/semiconductors/powerdevices/products/power-module/sic-module
(SiC power modules)

In conventional silicon substrate design, development proceeded sequentially in line with the order of the manufacturing processes. However, as automotive OEMs and other power semiconductor users demand an increasingly higher degree of balance between miniaturization and high-current capability, it is becoming essential to eliminate backtrack in development. To achieve this, it is necessary to consider cooling methods when in module format from the chip and transistor development stages, and to ensure that chip and module designs are aligned. It is of particular note that as SiC power semiconductors are capable of resisting temperatures more than 50°C higher than silicon power semiconductors and handling larger currents, they generate more heat during operation. However, the surrounding materials are not as resistant to heat as SiC, making heat dissipation and cooling technologies increasingly important in preventing the thermal degradation of peripheral materials.

3. Future Prospects

Companies engaged in the development and manufacture of SiC power semiconductors are expected to continue investing in development and mass production in a manner that addresses demand and performance requirements from markets such as HEVs and other automotive applications, data centers, and renewable energy infrastructure.

It is becoming increasingly important to develop modules for HEVs and BEVs, which are seen as key killer apps. To achieve further miniaturization and weight reduction while ensuring reliability—namely, effective thermal countermeasures—the following four trends merit attention as proposals for new modules to replace the general-purpose 6-in-1 power modules, which integrate the devices required for current and voltage control and have traditionally been used for motor drives in electrified vehicles.

(1) Substrate-embedded modules: Designed to save space by embedding SiC power semiconductor chips directly into circuit boards. Europe is leading in this area, and in 2023, Infineon announced joint development with Schweizer Electronic (Germany).

(2) 2-in-1 molded modules: Designed to achieve miniaturization and high performance by integrating two transistors—previously mounted separately on circuit boards—into a single package. ROHM is mass-producing such modules, but its adoption requires advanced bonding technology to attach heat sinks (cooling plates) with fin-like structures for effective heat dissipation.

(3) 6-in-1 multifunctional modules: Designed to integrate various circuits and devices that previously required external components into general-purpose modules, while minimizing package thickness. Mitsubishi Electric and ROHM are both engaged in development.

(4) Multifunctional, dual-sided cooling modules: Designed to balance cost and performance by integrating SiC and silicon power semiconductors into a single package according to drive voltage and other requirements, while ensuring a high degree of heat dissipation by bonding heat sinks to both sides. At the Power Conversion and Intelligent Motion (PCIM) Expo, one of the world's largest power semiconductor exhibitions held in May 2025, ROHM, BASiC Semiconductor (China), and Silan Microelectronics (China) exhibited their products.

In the development of new SiC power semiconductor devices and modules—in addition to the services and solutions needed to accelerate changes in the development process—it will be necessary put forth proposals for new levels of performance and value with regard to manufacturing equipment and component materials. As such, all companies involved in the supply chain could be seen as standing to benefit from this market growth.

Laboratory Automation in the Pharmaceutical Industry

— Transforming Drug Discovery Through Equipment, Software, and Robotics —

Takako Kato
Consumer Innovation Dept.

Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

As drug discovery research becomes more sophisticated and research instruments more diverse, laboratory automation is reshaping the paradigm of experimental research that have traditionally relied on researchers' tacit knowledge and manual skills. Through the integration of equipment, software, and robotics, laboratory operations are evolving from mechanization to automation and ultimately to autonomy. Automation is expected to improve efficiency and reproducibility, while enabling researchers to focus on higher-value tasks such as hypothesis generation and data analysis. Furthermore, advances in AI are driving initiatives in which the exploration, design, execution, and analysis of experimental conditions are conducted autonomously, fundamentally reshaping the nature of drug discovery itself.

Summary

- Pharmaceutical companies are rapidly expanding their adoption of laboratory automation. Driven by advances in generative and other AI technologies, the scope is evolving beyond automation toward autonomous experimentation.
- In the US and Europe, cloud labs are gaining prominence by providing remotely operated automated experiments and 24/7 experimental infrastructure. Collaboration with AI-driven drug discovery companies is accelerating the drug discovery process.
- The introduction of robotics and smart labs is also accelerating in Japan. While addressing issues related to standards, harmonization, and operations, the role of researchers is shifting toward higher value, data-driven domains.

1. What is Laboratory Automation?

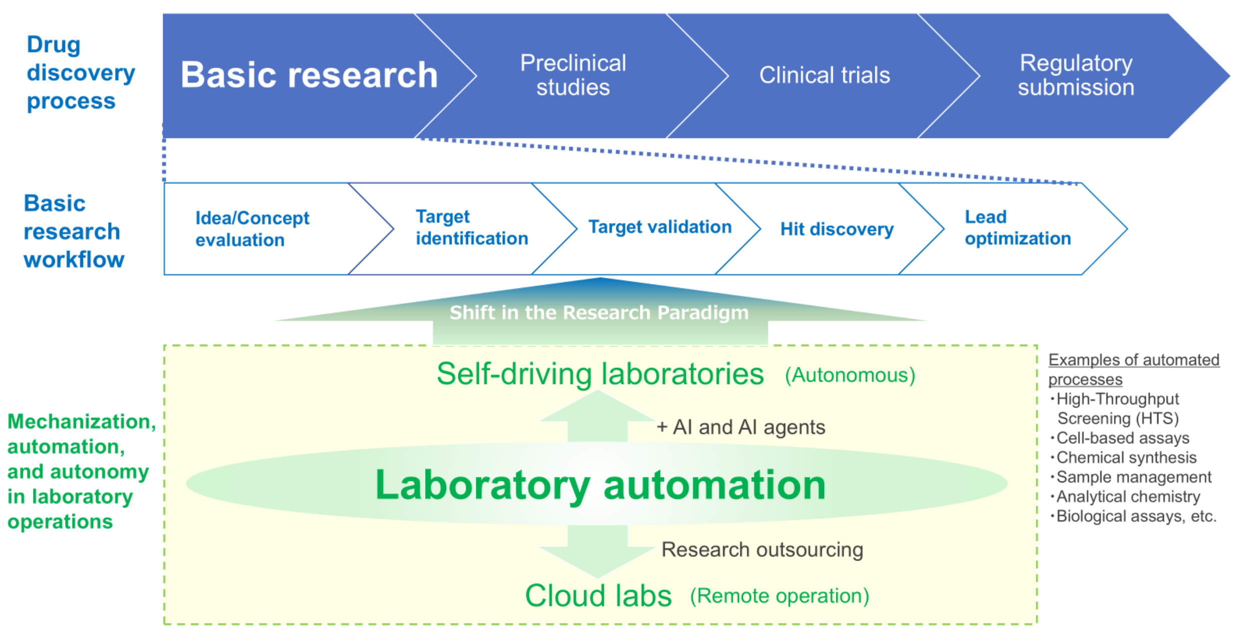
Although the definition of laboratory automation varies by purpose and application, it generally refers to the integration of equipment, software, and robotics that progressively advances laboratory operations from mechanization to automation and ultimately to autonomy. For example, in the screening phase of drug discovery research at pharmaceutical companies, it is necessary to select promising candidates from among a large number of compounds. By linking multiple analytical instruments and automating experimental procedures with robotic arms, processes that previously relied on researchers' experience and technical skills can be performed more efficiently and with greater reproducibility.

This domain also encompasses concepts such as cloud labs—laboratory systems that enable researchers to initiate and conduct experiments remotely—and self-driving laboratories, next-generation laboratories in which AI autonomously explores, designs, executes, and analyzes experimental conditions (Figure 1).

At present, the primary focus is on automating operations that have traditionally depended on human intervention, including high-throughput screening (HTS)[1], cell-based experiments, chemical synthesis, sample management, analytical chemistry, and biological testing. The scope of automation is expanding beyond individual experimental steps to encompass the linkage of multiple processes and the integration of entire workflows, and the approaches adopted are becoming increasingly diverse.

Against this backdrop, this report reviews the latest trends and future outlook for laboratory automation, covering not only initiatives within pharmaceutical research facilities but also the use of external resources such as cloud labs.

Figure 1: The role of laboratory automation in the drug discovery process



Source: Compiled by MGSSI based on various sources

2. Key Trends

2-1. Leading international Examples

As drug discovery research becomes increasingly sophisticated, pharmaceutical companies in the US and Europe are strengthening high-throughput capabilities to conduct large numbers of experiments in parallel and are seeking to standardize processes and improve data quality. As a result, alongside the automation of experiments within research facilities, the use of external resources such as cloud labs is accelerating. In particular, the demand for research systems that allow experiments to be conducted remotely increased sharply during the COVID-19 pandemic.

Against this backdrop, Eli Lilly (US) collaborated with Strateos (US), a pioneer in laboratory automation, to establish an automated laboratory that enables experiments to be initiated and executed remotely. This initiative attracted significant attention both within and beyond the pharmaceutical industry as an advanced effort to

[1] High-throughput screening refers to the rapid identification of novel drug candidate compounds (hit compounds) by biochemically evaluating large numbers of compounds in a short period of time using highly systematized methods. Nikkei Biotechnology & Business website, January 26, 2023, article "Overview: Welcome to the Science of Screening," https://bio.nikkeibp.co.jp/atcl/column/16/052700070/011800014/ (Last accessed December 10, 2025)

streamline and structure experimental workflows.[2] Subsequently, Eli Lilly sold the automated laboratory to Arctoris (UK) in September 2024 (Figure 2). The transaction is understood to have been a strategic decision made after evaluating the potential and scope of automated experimentation.

Figure 2: Arctoris automated laboratory

Source: Arctoris website, press release dated September 12, 2024, https://www.arctoris.com/arctoris-acquires-eli-lilly-life-science-studio-laboratory/ (Last accessed December 19, 2025)

As a partnership research organization (PRO), Arctoris offers a proprietary automated drug discovery platform, "Ulysses," in which robots autonomously conduct drug discovery experiments and generate high-quality data through an end-to-end process. This acquisition expanded the company's research facilities and strengthened its capacity to process large numbers of experiments in parallel. In addition to pharmaceutical companies, Arctoris collaborates with AI-driven drug discovery firms such as Insilico Medicine (US) and 310.ai (US). Under this framework, these companies design drug candidates using supercomputers, while Arctoris automates and performs the experimental processes required for candidate production, purification, and evaluation. For example, Insilico Medicine partnered with Arctoris during the development[3] of a JAK inhibitor[4] for COVID-19 and obtained analytical data on candidate molecules within 24 hours.

Emerald Cloud Lab (ECL) is a leading cloud lab provider in the US and is used as a research outsourcing partner by major pharmaceutical companies such as Biogen (US), Bristol Myers Squibb (US), Amgen (US), and GSK (UK). ECL's laboratory facilities operate 24 hours a day, 365 days a year. Researchers can initiate experiments from anywhere in the world with a single click through the "ECL Command Center" (Figure 3). Through this model, pharmaceutical companies seeking to externalize research functions can seamlessly connect geographically dispersed researchers online and conduct research efficiently using shared experimental infrastructure. ECL operates more than 200 research instruments[5] and focuses particularly on biotechnology and pharmaceuticals, supporting experimental needs across a broad range of fields including analytical chemistry, biology, and materials science.

[2] According to Arctoris's press release dated September 12, 2024, the 11,500-square-foot Lilly Life Sciences Studio operated by Strateos was conceived and designed by Eli Lilly, which invested USD 90 million as part of its plan to expand its research presence in San Diego, US. https://www.arctoris.com/arctoris-acquires-eli-lilly-life-science-studio-laboratory/ (Last accessed January 20, 2026)

[3] Arctoris website, https://www.arctoris.com/arctoris-automated-platform-accelerates-drug-discovery/ (Last accessed January 26, 2026)

[4] A pharmaceutical that inhibits the activity of Janus kinase (JAK), an enzyme involved in signaling pathways that trigger immune responses and inflammation.

[5] HPLC, FPLC, GC, mass spectrometry, NMR, PCR, qPCR, ddPCR, ELISA, SPR/BLI, Western blot, flow cytometer/FACS, etc. https://www.emeraldcloudlab.com/ (Last accessed December 2, 2025)

Figure 3: Emerald cloud lab facility

Source: Emerald Cloud Lab website
https://www.emeraldcloudlab.com/ (Last accessed December 22, 2025)

2-2. Leading Domestic Examples

At present, no companies in Japan have fully commercialized cloud lab services for pharmaceutical companies comparable to those offered by Arctoris or ECL. However, the development of experimental automation leveraging Japan's strengths in robotics and automation technologies is advancing in both the public and private sectors. As part of its *AI for Science* initiative, the Japanese government is planning projects to significantly enhance the efficiency of research data creation and utilization through automation, autonomy, and remote operation, with a budget of approximately JPY 2.6 billion.[6]

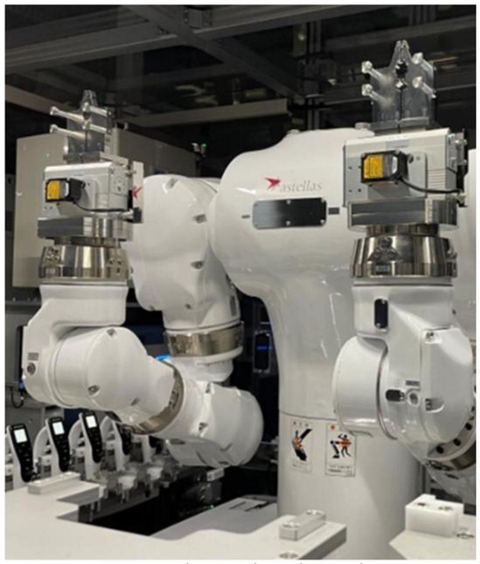
A notable commercialization effort is Cellafa Bioscience (Japan)[7], a joint venture established in September 2025 by Astellas Pharma (Japan) and Yaskawa Electric (Japan). The company aims to develop and provide manufacturing platforms for regenerative medicine products, including those based on iPS cells, by utilizing the general-purpose humanoid robot Maholo[8] (Figure 4). Experiments involving living cells require not only precise manipulation but also stable operation over extended periods, and practical implementation cases remain limited both in Japan and overseas. Cell culture is particularly sensitive to environmental changes, making the assurance of reproducibility a major challenge for automation. Maholo is characterized by its ability to explore optimal conditions for cell culture and obtain target cells with high efficiency.

Chugai Pharmaceutical (Japan) is advancing laboratory automation in drug discovery research at its Chugai Life Science Park Yokohama research center through the use of robots and AI.[9] Automated transport carts move freely within the facility, and efforts are underway to improve efficiency across the entire research process, including automation of experimental tasks using robots. Meanwhile, Daiichi Sankyo (Japan) established a Smart Research Lab in the US in January 2025 and is developing a 24-hour automated drug discovery infrastructure that integrates robots, automated equipment, and cloud platforms.[10]

---

[6] Ministry of Education, Culture, Sports, Science and Technology, Key Points of the FY2026 Budget Request, https://www.mext.go.jp/content/20250826-ope_dev02-000044427_12.pdf (Last accessed December 2, 2025)
[7] Yaskawa Electric press release, https://www.yaskawa.co.jp/newsrelease/news/1424695 (Last accessed December 2, 2025)
[8] A laboratory humanoid robot specialized for life sciences research, developed by Robotic Biology Institute (RBI), a subsidiary of Yaskawa Electric (Japan). In December 2025, the cell culture automation system utilizing Maholo received designation as an Advanced Manufacturing Technology (AMT) from the Center for Biologics Evaluation and Research (CBER) of the US Food and Drug Administration (FDA).
[9] Chugai Pharmaceutical website, https://note.chugai-pharm.co.jp/n/n080d564fbe32 (Last accessed December 2, 2025)
[10] Daiichi Sankyo press release, https://www.daiichisankyo.co.jp/files/news/pressrelease/pdf/202501/20250121_J.pdf (Last accessed December 2, 2025)

Figure 4: Maholo humanoid robot for cell culture automation



Source: Cellafa Bioscience, press release dated October 1, 2025, https://cellafa.com/news/20251001(Last accessed December 22, 2025)

3. Future Prospects

While automation continues to advance, human involvement remains indispensable for tasks such as responding to equipment malfunctions and replenishing reagents. Moreover, the burden of initial investment, changes to operational processes, and the development of standards and harmonization to ensure seamless integration among multiple instruments and software systems remain important challenges.

At the same time, as laboratory automation becomes more widespread, its impact is expected to extend beyond improving the efficiency of drug discovery research. Automation enables the systematic accumulation of vast amounts of experimental data, potentially opening new research areas that were previously difficult to explore. Furthermore, the spread of cloud labs will allow diverse experiments to be conducted without the need for companies to own expensive equipment and facilities, potentially expanding access beyond large pharmaceutical companies to biotech startups.

Looking ahead, the use of AI and AI agents may enable a shift beyond automation to the next stage of autonomy—a research paradigm in which robots autonomously perform processes from experimental design to data analysis. As a result, the roles expected of researchers are likely to expand into higher-value, cross-functional domains, including data-driven hypothesis generation, experimental design, and research conducted with an awareness of connections to clinical development. At the same time, data management and the protection of confidentiality will become increasingly important. If cross-departmental data utilization is achieved, processes spanning research, development, manufacturing, and clinical stages could be organically connected through data. This could enhance the sophistication of decision-making and accelerate development timelines, ultimately driving digital transformation across pharmaceutical companies as a whole.

Lithium Manganese-Rich Cathodes Enabling High-Performance, Low-Cost Rechargeable Batteries

— China, Europe, the US, and South Korea Taking Divergent Approaches to Application in EV Batteries —

Jian Zhao
Industry Innovation Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

Cathodes in lithium-ion batteries (LIBs) are critical components that undergo chemical reactions to generate electrical energy. While lithium iron phosphate (LFP) cathodes currently dominate the low-cost segment, lithium manganese-rich (LMR) cathodes—able to achieve higher energy density at comparable cost—are being developed and adopted worldwide as alternatives to LFP cathodes and for application in all-solid-state LIBs.[1] Depending on the direction and degree of future progress, LMR cathodes could transform existing LIB supply chains and reshape the competitive landscape in all-solid-state LIB development.

Summary

- Practical application of lithium manganese-rich (LMR) cathodes is expected within the next few years for their ability to provide high capacity while using little to no cobalt, making them ideal next-generation battery materials combining high performance with low cost.
- In China, where the development of all-solid-state lithium-ion batteries (all-solid-state LIBs) is accelerating, LMR cathodes are highly regarded as a promising candidate for all-solid-state LIBs, and major companies are actively engaged in development. In Europe, the US, and South Korea, efforts are underway to develop and commercialize LMR cathodes through international collaboration as an alternative to LFP cathodes—a sector dominated by China—with a focus on ensuring a stable battery supply.
- While the share of LMR cathodes for EV passenger vehicle batteries in 2035 is projected to remain low at around 3%, China has placed them under export controls in recognition of their future potential. Japan, which seeks to ensure a stable battery supply and pursue the practical application of all-solid-state LIBs, should also closely monitor these developments.

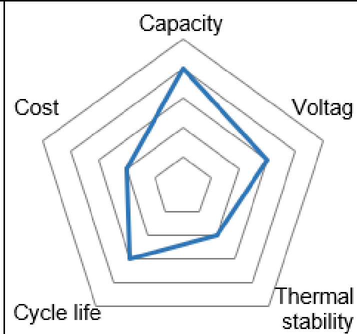
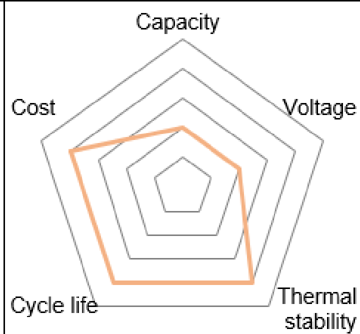
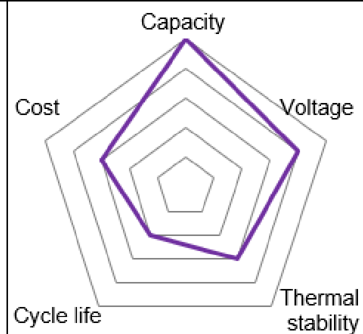
1. What are Lithium Manganese-Rich Cathodes?

1-1. Overview of Lithium Manganese-Rich Cathodes

LMR cathodes make use of a lithium-rich metal oxide cathode material. As it is possible to incorporate a large amount of lithium, they achieve capacities of 250 mAh/g or higher, exceeding that of the current mainstream high-performance cathode materials used in ternary (NMC[2]) cathodes. LIBs using LMR cathodes have the potential to achieve energy densities in excess of 500 Wh/kg, making them suitable for high-performance applications such as in EVs with extended driving ranges. Manganese, an abundant resource, accounts for 30 to 40% of the material composition of LMR cathodes, making it possible to keep material costs at a level comparable to LFP cathodes, which are currently the mainstream low-cost yet lower-performance cathodes. As they require little to no cobalt—

[1] A type of lithium-ion battery in which all components, including cathodes, anodes, and electrolytes, are made of solid materials.
[2] Cathodes primarily composed of nickel, manganese, and cobalt.

Figure 1: Performance comparison between LMR cathodes and current mainstream cathode materials

Cathode material	High-nickel ternary NMC811 (Note)	Lithium iron phosphate LFP	Lithium manganese-rich LMR
Main components	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	$LiFePO_4$	$xLi_2MnO_3 \cdot (1-x)LiMO_2$ (M=Ni、Co、Mn、$0<X<1$)
Capacity (mAh/g)	Up to 200	Up to 170	250 or higher
Performance comparison	 The farther from the center, the higher the corresponding performance.		
Advantage	High energy density, compact, and suitable for high-capacity applications	・Delivers high thermal stability and excellent safety. ・Inexpensive due to the absence of expensive metals such as cobalt.	・Delivers high capacity and a wide operating voltage range. ・Inexpensive due to little or no use of cobalt.
Disadvantage	・Thermal stability and safety are inferior to LFP. ・Uses expensive and geographically concentrated rare metals such as cobalt, resulting in high costs and concerns over stable supply.	Its lower energy density requires more space and weight than ternary batteries for the same capacity.	Numerous charge and discharge cycles leads to continuous decline and a shorter cycle life.
Main applications	Used in batteries for mid- to high-priced EV passenger vehicles, drones, and similar applications.	Used in batteries for low- to mid-priced EV passenger vehicles, electric buses, stationary energy storage, and similar applications.	Used in batteries for low- to high-priced EV passenger vehicles, drones, and similar applications.

Note: A type of high-nickel NMC with a nickel-manganese-cobalt ratio of 8:1:1
Source: Compiled by MGSSI based on various public data

an element associated with uneven resource distribution, environmental damage from mining, child labor, and other concerns—LMR cathodes also enable responsible sourcing by battery manufacturers. LMR cathodes are regarded as a promising next-generation cathode material capable of delivering both high performance and low cost (Figure 1) as they combine the advantages of both NMC cathodes and LFP cathodes.

However, practical application still faces challenges. Over the course of numerous charge and discharge cycles, some of the metal oxides in LMR cathodes transition from a layered structure to a spinel structure.[3] As a result, continued use leads to a decline in the battery's operating voltage, ultimately shortening its cycle life compared with the various other LIBs already in practical use. To address this issue, companies around the world have researched measures such as coating the surfaces of material particles with metal oxides, metal doping, and improving manufacturing processes. Of particular note, since 2025, multiple companies have announced technological breakthroughs and plans for mass production, bringing the practical application of LMR cathodes into clearer view.

[3] This spinel structure is represented by the general formula AB_2O_4 and is a crystal structure in which metal ions at tetrahedral (A-site) and octahedral (B-site) positions are bonded to oxygen ions.

1-2. The Future of R&D and Anticipated Applications

In addition to their low cost and high performance, LMR cathodes—with their broad operating voltage range of 2 to 4.8 volts—are being developed with a variety of applications in mind.

Developers are seeking a cathode material for use with the current liquid-based LIBs that delivers higher performance while maintaining costs at a level comparable to existing LFP cathode products. Its use may also be combined with existing cathode materials to complement their performance. For instance, blending it with NMC cathode materials is expected to extend the cycle life and reduce costs per kWh.

For higher voltage ranges, research and development are underway to incorporate LMR cathodes into high-performance batteries. Many first-generation all-solid-state LIB products, likely to be released around 2027 to 2028, are expected to adopt high-nickel NMC cathodes with an operating voltage of 3.7 volts. However, solid electrolytes offer an innately high voltage performance of up to 5 volts, and this feature is not fully utilized when paired with NMC cathodes. Replacing them with LMR cathodes, which can support a maximum operating voltage of up to 4.8 volts, makes it possible to better leverage the solid electrolyte's inherent high-voltage performance of up to 5 volts, while also costing less than NMC cathodes. For this reason, LMR cathodes are regarded as a leading candidate for use in next-generation all-solid-state LIBs.

Chinese companies that hold a significant share of the LIB industry and Western companies that are still in the process of building their battery supply chains are each charting different paths forward for LMR cathode research, development, and commercialization based on their respective positions in the battery industry, as well as on their corporate strategies and national policies. The details are discussed in the next chapter.

2. Noteworthy Trends

2-1. China Pursues Application in All-Solid-State LIBs

China produces the majority of the world's liquid-based LIBs and is also stepping up development of all-solid-state LIBs as they continue to conduct research and development on LMR cathodes as a candidate. As shown in Figure 2, numerous manufacturers of battery materials, batteries, and EVs in China are working to develop LMR cathodes. More than half are focusing on the development of high-voltage, high-capacity LMR cathodes for application in all-solid-state LIBs. Some companies are developing high-performance all-solid-state LIB prototypes that make use of LMR cathodes and next-generation lithium metal as anodes.

Figure 2: LMR development and production trends among Chinese companies

Industry	Company	Timing of announcement	LMR development and production trends
Battery materials	Ningxia Hanyao	April 2023	Has commenced test production. Developing multiple products across the low-, medium-, and high-voltage categories, with the high-voltage (4.45 volt) variant achieving a capacity of 220 to 230 mAh/g.
	Ronbay Technology	December 2024	Engaged in small-scale production of sample products, and has commenced shipping to battery manufacturers and other customers for testing purposes.
	BTR	May 2025	Announced a prototype sulfide-based all-solid-state battery using LMR cathodes with a high voltage (4.8 volts) and a capacity of 300 mAh/g.
	Ningbo Fuli	July 2025	Successfully developed an LMR cathode with a capacity in excess of 300 mAh/g. Developing LMR cathodes for all-solid-state batteries with energy densities of over 450 Wh/kg.
	Chuangneng Huitong	September 2025	Announced several cutting-edge products, including low-voltage, long-life variants and high-voltage, high-capacity variants (4.8 volts, 300 mAh/g).
	Easpring Material Technology	October 2025	Achieved capacities of 280 to 305 mAh/g in tests with all-solid-state batteries, and has commenced shipping samples on the scale of tens of tons.
Batteries	Tailan New Energy	April 2024	Announced a prototype all-solid-state battery using LMR cathodes with a cell energy density of 720 Wh/kg. The anode makes use of lithium metal.
	China Automotive New Energy Technology	July 2025	Announced an LMR cathode battery with an energy density of 366 Wh/kg and 2,000 life cycles, with plans for installation in EVs offering a driving range of over 1,000 km to be launched before the end of 2026.
	Farasis	September 2025	Plans to announce a second-generation sulfide-based all-solid-state battery using LMR cathodes in 2026. The battery has an anticipated energy density of 500 Wh/kg.
EV	Guangzhou Automobile	February 2025	Announced that it will consider adopting LMR cathodes for all-solid-state EV batteries over the long term.
	Chery	September 2025	Announced an all-solid-state battery using LMR cathodes with a cell energy density of 600 Wh/kg. Aims to install the battery in prototype vehicles in 2027 and launch mass production by 2030.

Source: Compiled by MGSSI based on various publicly available materials.

Easpring Material Technology, a leading cathode material manufacturer, has shipped more than a dozen tons of LMR samples to customers in China as well as in Europe, the US, South Korea, and other regions. It is also developing halide-based solid electrolytes compatible with LMR cathodes. While CATL, China's largest battery manufacturer, has yet to announce any prototypes, it is thought to hold the world's largest number of patents related to LMR cathode materials and is actively engaged in developing the technology. Since 2023, CATL, Ningxia Hanyao, Ningbo Fuli, and other startup companies have been carrying out a public-private partnership project to develop low-cost mass production technology for LMR cathodes under the leadership of the Ministry of Industry and Information Technology (the Chinese government ministry equivalent to Japan's METI).

In September 2025, mid-sized automaker Chery Automobile announced a prototype all-solid-state LIB using LMR cathodes. The battery offers a driving range of 1,300 km and has demonstrated a high degree of safety by passing nail penetration tests that evaluate resistance to heat generation and ignition during internal short circuits. It is scheduled to be installed in EVs for launch in 2030. It will be worth watching whether this prompts other Chinese EV manufacturers to follow suit.

2-2. Europe, the US, and South Korea Seek Low Cost and Stable Procurement

In Europe and the US, where there are concerns about dependence on China for battery supply chains, attention is focused on the potential of LMR cathodes to reduce reliance on China due to their low cost and ready availability. In particular, efforts to develop and commercialize LMR cathodes are being accelerated with the aim of replacing LFP cathodes, for which Chinese companies account for 90% of global production (Figure 3).

Figure 3: LMR development and production trends among companies in Europe, the US, and South Korea

Industry	Company	Timing of announcement	LMR development and production trends
Battery materials	Umicore (Belgium)	February 2023	Plans to launch mass production for EV applications in 2026. Potential production sites include existing cathode material plants in South Korea and Poland, as well as a planned facility in Canada.
	POSCO FUTURE M (South Korea)	May 2025	Completed development and prototyping in 2024 in collaboration with EV manufacturers, and has commenced verifications for mass production. Aims to cathodes in the EV sector with LFP cathodes.
	FIREBIRD METALS (Australia)	July 2025	Announced the commencement of in-house development of LMR cathodes, with completion targeted within 18 months. Leverages its expertise in high-purity manganese sulfate (HPMSM).
	Stratus Materials (US)	August 2025	Has commenced shipping samples of second-generation products. In October, announced the joint development of next-generation cathode materials for EVs, together with Ampere in the Renault Group (France).
EV	Ford (US)	April 2025	Achieved a breakthrough in research and development, with installation in actual vehicles anticipated by 2030.
	GM (US)	May 2025	Successfully completed joint development with LGES (South Korea), and the joint venture plans to launch mass production in North America in 2028.

Source: Compiled by MGSSI based on various publicly available materials.

In May 2025, GM announced plans with LG Energy Solution (LGES) to jointly develop and produce LMR prismatic battery cells for EVs, including electric trucks and large SUVs. The two companies, which hold numerous patents related to LMR technology, plan to begin prototyping by the second half of 2027 and gradually commence mass production by 2028 at Ultium Cells, their North American battery joint venture. At the 15th The Battery Show North America, held in Detroit in October 2025, LMR batteries developed by GM and LGES were recognized as the Battery Innovation of the Year, underscoring the high expectations that the North American battery industry has for the technology.

Europe and the US—unlike China—have yet to fully develop domestic supply chains, making cross-border collaboration crucial for companies in these regions for raw material procurement, research and development, and production. It is of particular note that South Korea, which possesses an established battery manufacturing base, is attracting attention as a hub for research, development, and production outside of China.

3. Future Prospects

According to the research firm BloombergNEF[4] (US), the adoption of LMR cathodes is expected to begin after 2027, primarily for use in EV passenger vehicle batteries, and they are projected to account for roughly 3% of all cathodes used in EV passenger vehicle batteries by 2035. Although its projected share is not particularly high at present, further technological advances could make the technology far more important in the future, further increasing its share of the market.

On November 8, 2025, China placed materials and technologies related to high-performance LFP cathodes, NMC cathodes, and LMR cathodes under export controls.[5] It is unusual to impose export controls at the research and development stage or during small-scale pilot production. This suggests the Chinese government's intention to preemptively block the outflow of next-generation battery technologies that could potentially transform the existing battery supply chain.

Further progress in the development of LMR cathodes may also affect the global race to commercialize all-solid-state LIBs. A company's ability to reduce costs—one of the major barriers to the widespread adoption of all-solid-

[4] Source: BloombergNEF「Lithium-Ion Batteries State of the Industry 2025」
[5] Source: Announcement No. 58 [2025] of the Ministry of Commerce and the General Administration of Customs

state LIBs—and ensure high performance is directly linked to its ability to develop competitive products and widen the scope of adoption. While LMR cathode research, development, and commercialization efforts in Japan have not been as active as in China or the US, Japan is working to secure a stable supply of storage batteries (under the Act on the Promotion of Ensuring National Security through Integrated Implementation of Economic Measures) and to promote the practical application of all-solid-state LIBs. In light of this, Japan should closely monitor global trends in LMR cathode development, which could impact the competitive environment.

Co-Packaged Optics Gain Traction in Data Centers

— Optoelectronic Integration Enters the Adoption Phase —

Rieko Tsuji
Consumer Innovation Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

2026 will mark the year when co-packaged optics (CPO), a form of optoelectronic integration, enters the full-scale mass production and practical roll-out phase. As power consumption continues to surge with the rapid expansion of AI data centers, expectations are high that CPO will dramatically improve power efficiency and curtail energy usage. A wave of product launches is underway, led by companies such as Broadcom (US) and Nvidia (US). While in Japan, NTT (Japan) has begun providing commercial samples based on its IOWN concept[1]. With major players moving to release products simultaneously, 2026 is likely to become a critical inflection point marking the start of competition for leadership in the next-generation AI infrastructure sector.

Summary

- CPO technology places electro-optical conversion functions—traditionally located away from the processor—in close proximity to the processor. By shortening the distances that electrical signals must travel, the technology significantly reduces power consumption, boosts data transmission capacity, and lowers latency.
- Fully realizing CPO requires advanced packaging technology. As such, silicon foundries and OSAT companies such as TSMC (Taiwan) are increasing in importance, driving the formation of an ecosystem that encompasses these companies.
- While challenges including heat management and the complexity of maintenance remain, Japanese companies possess advantages in optical packaging technologies and the component material sector, which present the keys to resolving these issues. Japanese companies are therefore expected to play central roles in next-generation AI infrastructure through active collaboration with major manufacturers in Japan and overseas.

1. What is CPO?

With the widespread use of generative AI, enhancing the computing capacity of data centers has become an urgent priority. Increasing communication speeds is a critical factor in boosting computing performance, alongside semiconductor miniaturization and other factors. However, under conventional methods in which most signals are transmitted electrically across server circuit boards[2], higher speeds exacerbate signal attenuation and noise, and compensating for these effects results in substantial power consumption. As optical transmission incurs far less energy loss during transmission than electrical signals, replacing electrical signal transmission with optical signal transmission is expected to resolve these power consumption challenges, and the collective term for such technologies is optoelectronic integration. In recent years, CPO, a type of optoelectronic integration technology, has attracted particular attention.

[1] An abbreviation of Innovative Optical and Wireless Network. The IOWN concept, put forth by NTT, is a next-generation communications infrastructure initiative that seeks to transform the entire information infrastructure—from networks through to computing—with a focus on optical technology to achieve ultra-high capacity, ultra-low latency, and ultra-low power consumption.
[2] Circuit boards are substrates with wiring on its surface or interior, onto which chips, capacitors, connectors, and numerous other electronic components are soldered.

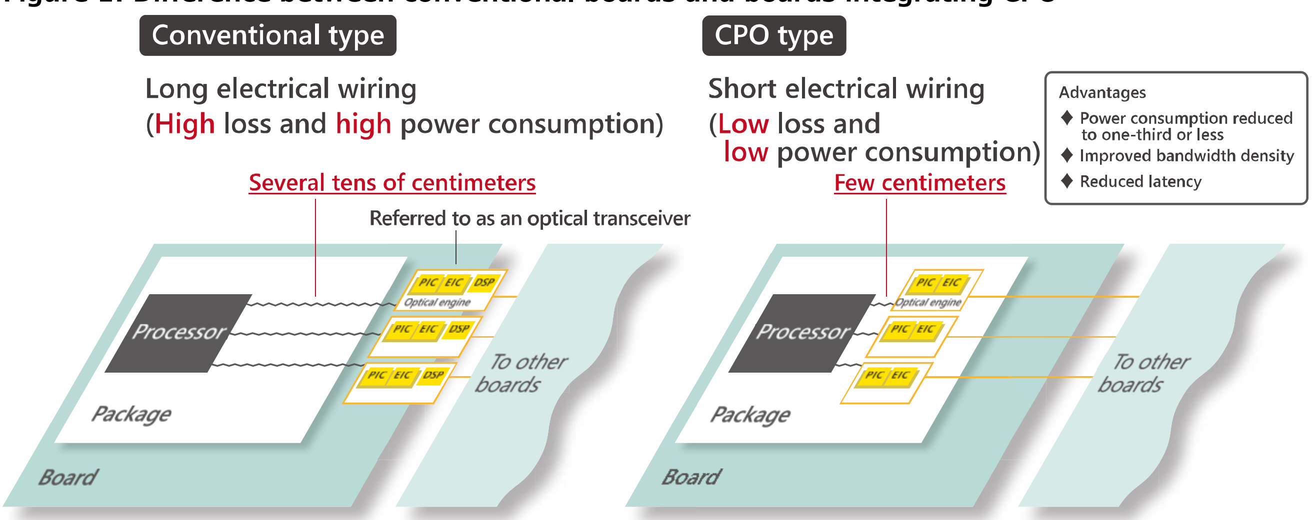
1-1. Technology

Optoelectronic integration progresses in stages depending on where electrical signals are replaced with optical signals. It is expected that, ultimately, even extremely short-distance inter-die[3] connections will be made optical, and as an intermediate step toward that goal, CPO technology places electro-optical conversion functions in very close proximity to the processor (e.g., CPU, GPU, ASIC) within communication devices that link together boards. In recent years, adoption of switch ASICs[4] used in power-intensive network equipment has progressed particularly rapidly, and around 2025, some data centers also began to incorporate the technology.

Conventionally, optical transceivers (modules detachable from the board) that convert electrical signals to optical signals were placed at the edge of the board, away from the processor. In CPO, the optical engine[5]—the core component of the optical transceiver—is integrated onto the same package[6] as the processor, enabling electrical-to-optical signal conversion within the package itself. This shortens distance that electrical signals must transverse from several tens of centimeters to just a few centimeters, minimizes losses resulting from the electrical wiring, and reduces power consumption to roughly one-third or even lower (Figure 1).

Research into CPO technology proceeded gradually through discussions and studies beginning in the late 2010s. However, at the time, few users were demanding higher communication speeds, and technologies for optical integration and implementation had not yet matured. For on-board transmission[7] of electrical signals, conventional copper wiring remained more advantageous in terms of

Figure 1: Difference between conventional boards and boards integrating CPO



Source: Compiled by MGSSI based on various sources

---

[3] Dies are small components, typically only a few millimeters in size, in which microscopic electronic circuits (such as transistors) are integrated onto a substrate such as silicon.
[4] An abbreviation of Application Specific Integrated Circuit. It refers to an integrated circuit (IC) designed and manufactured for a specific purpose or application. Switches connect communication equipment within a network and manage data transfer and routing. Switch ASICs are ASICs designed specifically for use in switches.
[5] Optical engines include photonic integrated circuits (PIC), which generate and manipulate optical signals, and electronic integrated circuits (EIC), responsible for electronic control, both of which are core components of an optical transceiver. While digital signal processors (DSP), responsible for correcting degraded electrical signals, are incorporated in conventional optical transceivers, they are generally not included in CPO.
[6] Packages protect semiconductor devices (including chips) from external elements and provide external terminals for electrical connections. They are typically black, square-shaped objects with leads extending outward in four directions.
[7] Even now, some argue that copper wiring remains more advantageous in terms of cost and reliability for short-distance communication, such as between GPUs rather than on-board.

both cost and reliability. In recent years, as data centers become faster, losses resulting from transmitting signals electrically have reached the point where they can no longer be ignored. However, advances in silicon photonics[8] and packaging[9] technologies have made it possible to increase the degree of integration between electrical and optical circuits, making implementation a realistic possibility.

1-2. Benefits and Challenges

The adoption of CPO offers the following technological and commercial benefits.

1. Significantly reduced power consumption: Replacing long electrical wiring on circuit boards with optical wiring can reduce power consumption to approx. one-third or lower in comparison with conventional optical transceivers.

2. Improved bandwidth[10] density: Large, detachable optical transceivers have conventionally been mounted on the front panel at the edge of the board, creating physical space constraints that limit the number of optical fiber connections. In CPO, optical fibers are drawn directly from the package, allowing for connections in higher density and a dramatic increase in data transmission capacity.

3. The potential for lower latency: Drastically shortening the distance between the processor and the optical engine either simplifies or eliminates complex DSP processing and related functions. This has the potential to lower transmission latency by tens to hundreds of nanoseconds[11] compared with conventional approaches.

Conversely, however, CPO technology also requires advanced mounting technologies and faces the following challenges.

1. Heat management: Sophisticated thermal countermeasures are required as heat-sensitive optical components (such as lasers) are placed in close proximity to heat-generating ASICs. The external laser source (ELS) approach, which places the failure-prone laser light source outside of the package, is becoming the mainstream solution.

2. Complexity in manufacturing and maintenance: With optical components and semiconductors integrated into a single package, replacing individual components becomes difficult once packaged. As components are no longer detachable, a failure in internal optical components may necessitate discarding the entire expensive processor, requiring extremely high levels of reliability.

2. Noteworthy Developments

CPO technology and optoelectronic integration are developing along two distinct paths: (1) application in switches that handle network connections between data center racks (board-to-board), and (2) realization of optical I/O technologies that use light for inter-package connections and for connections between chips and dies within packages. Figure 2 summarizes the approaches taken by major companies.

[8] Silicon photonics technology makes use of silicon semiconductor manufacturing processes to build large-scale optical circuits—such as optical waveguides and optical modulators—on silicon wafers.
[9] Packaging generally refers to back-end processes in semiconductor manufacturing. For CPO, it refers to integrating optical components and semiconductor chips into the same package, as well as the technologies that enable this integration.
[10] Bandwidth refers to the range of frequencies used in communication. In other words, it indicates the amount of data that can be transmitted and received within a given period of time.
[11] A nanosecond is equal to one billionth of a second. In other words, 100 nanoseconds correspond to one millionth of a second. It is sometimes abbreviated as "ns."

Figure 2: Trends among CPO-related companies

Company	Product shipment and supply status (as of January 2026)	Areas transitioning toward an optical approach ◎ Commercial shipments/sample supply confirmed ○ Plans confirmed – Outside scope/no public disclosure			Approach
		Board-to-board	Package-to-package/chip-to-chip	Die-to-die	
Broadcom	Has already shipped ethernet-ready CPO switches.	◎	○	–	・The company's strategy focuses on incorporating CPO for long-distance rack-to-board connections. ・Plans have also been announced for a conversion to optical short-distance connections (processors, HBM, etc.). ・The company has adopted TSMC's optoelectronic integration packaging technology, COUPE.
Nvidia	Market launch of CPO switches for InfiniBand scheduled for early 2026, and CPO switches for Ethernet scheduled for the second half of 2026.	◎	–	–	・The company's strategy focuses on incorporating CPO for long-distance rack-to-board connections. ・For short-distance connections (chip-to-chip/GPU-to-GPU), the company remains committed to using copper wiring (NVLink) wherever possible from the standpoint of cost and reliability. ・The company has adopted TSMC's optoelectronic integration packaging technology, COUPE.
Marvell Technology	Information on product shipments has yet to be disclosed. (Contributions to revenue from optoelectronic integration products are expected to begin in the second half of FY2028.)	–	○	○	・The company replaces electrical connections between chiplet-integrated packages with optical connections. Note: In December 2025, the company acquired the optoelectronic integration startup Celestial AI for USD 3.25 billion, and the optoelectronic integration-related technologies described here are those of Celestial AI.
Ayar Labs	Currently providing customers with optical I/O evaluation kits.	–	◎	○	・The company offers a general-purpose optical I/O chiplet, and aims to replace electrical wiring between packages with optical wiring. ・Collaboration is underway with Nvidia. ・Manufacturing is outsourced to GlobalFoundries.
Lightmatter	Announced that products will become available in summer 2025.	–	○	○	・Through a highly integrated approach, the company seeks to fully eliminate communication bottlenecks within packages and between dies by enabling optical data input and output directly beneath the die.
NTT (IOWN)	Market launch of CPO samples scheduled for 2026.	○	○	○	・In the process of developing optoelectronic integration devices for IOWN, the company aims to pursue joint design and mounting in collaboration with semiconductor vendors and materials manufacturers.

Source: Compiled by MGSSI based on various sources

2-1. Developments among Major Companies

Broadcom and Nvidia are leading the way in CPO technology.

• Broadcom: Drives the CPO switch market. Provides AI data centers with CPO switches that make use of TSMC's advanced processes and packaging technologies, with large-scale roll-out anticipated from 2026 onward.

• Nvidia: Pursues a unique strategy as the leader in the AI infrastructure sector. Announced products featuring CPO technology for use in switches, and considers CPO technology to be a core technology that underpins AI factories. Works to build a silicon photonics ecosystem that includes TSMC, Fabrinet (US), Senko Advance (Japan), Sumitomo Electric Industries (Japan), and similar companies. However, the company remains committed to using copper wiring wherever possible in GPU-to-GPU (NVLink) connections. This reflects the view that, in terms of cost and reliability, copper wiring still holds the advantage in short-distance connections.

• Startups: Ayar Labs, Celestial AI, and Lightmatter—all of which are US-based startups—are developing chiplets and light sources that leverage CPO technology in optical I/O solutions, with the goal of eliminating communication bottlenecks between processors and memory, as well as between multiple linked processors. This overcomes a longstanding challenge facing generative AI, which required increasingly significant expenditures of time and energy to transfer data between chips and memory as AI models grew larger.

• TSMC: Works to enhance its presence as the center of the ecosystem, as a contract manufacturer of optoelectronic integration products. Develops proprietary optoelectronic integration packaging technologies and provides major players such as Nvidia and Broadcom with 3D lamination technology. Also, together with the OSAT[12] company ASE (Taiwan), co-leads the Silicon Photonics Industry Alliance (SiPhIA) proposed by the international industry association SEMI to strengthen the supply chain for silicon photonics technologies, including CPO.

2-2. Developments in Japan

In Japan, NTT is researching optoelectronic integration under the IOWN concept and has published research findings on CPO devices. The government has also long promoted optoelectronic integration technologies, with the Ministry of Economy, Trade and Industry (METI) of Japan and NEDO playing central roles. In a NEDO project focused on enabling optical inter-chip communication invested a total of JPY 22.8 billion between 2014 and 2022. Recently, optoelectronic integration was identified as a priority technology in a document released by METI titled Current Status and Future of the Semiconductor and Digital Industry Strategy, which describes collaboration with the IOWN concept as a national-level vision. In addition, the Photonics-Electronics Integration Research Center was established at the National Institute of Advanced Industrial Science and Technology (AIST) in April 2025.

The incorporation of CPO technology requires alignment technology capable of connecting PICs and optical fibers with an extremely high degree of precision—to within a single micrometer (micron)[13]—as well as specialized connector links associated with the ELS approach. Japanese materials manufacturers, including Sumitomo Electric Industries, Senko Advance, and Fujikura (Japan), possess large shares of the global market along with the advanced technological capabilities required to supply these critical components.

3. Future Prospects

According to forecasts by the research firm IDTechEx, the overall CPO market is expected to exceed USD 20 billion (approx. JPY 3 trillion) by 2036. Along the timeline of adoption, 2026 is expected to be a transitional period in which CPO technology becomes increasingly incorporated into switches for hyperscalers while conventional optical transceivers remain in use. From 2027 onward, the scope of adoption is expected to expand as the manufacturing technologies mature. It is anticipated that optical I/O technologies will gain significant traction during the same period, with the market projected to rapidly expand at a compound annual growth rate of over 20%.

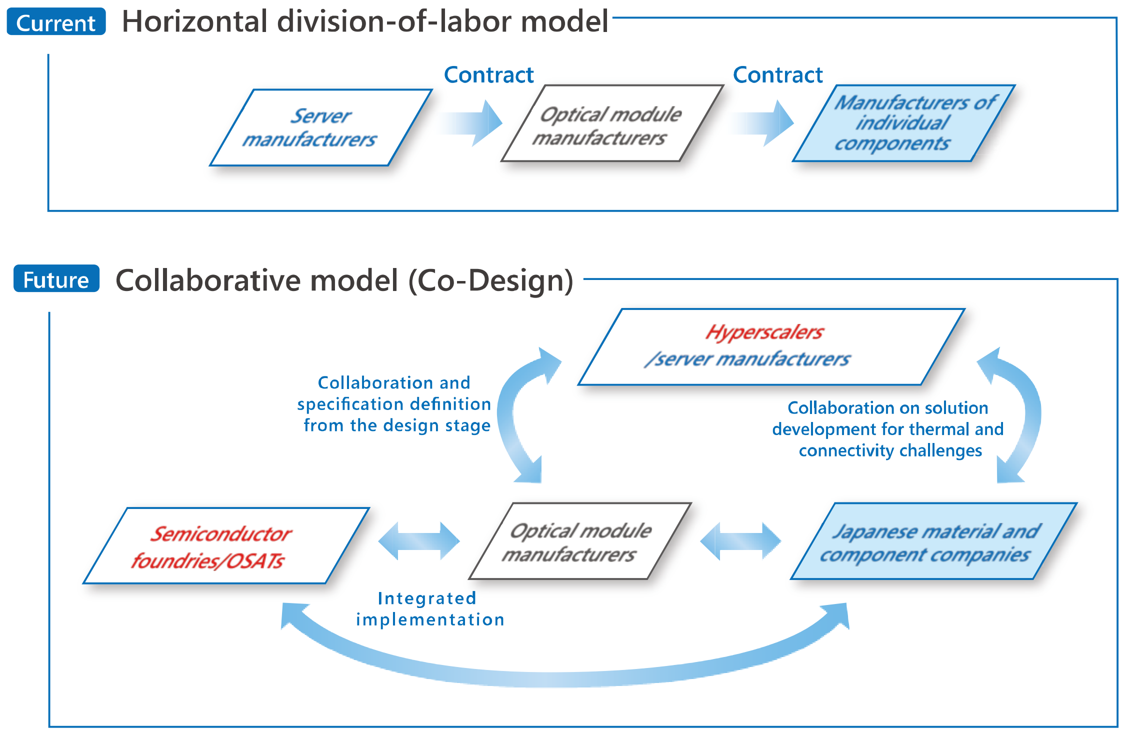
With CPO shifting the technology paradigm from individually inserting optical modules to integrating optical functions into semiconductor packages, semiconductor foundries (such as TSMC) and OSAT companies (such as ASE) now play critical roles within the supply chain. Optical module manufacturers (such as Broadcom) and component manufacturers (such as Sumitomo Electric Industries) that previously designed and developed optical transceivers will be required to collaborate more closely with foundries and OSAT companies.

Japanese companies are well placed to succeed in the particular materials and equipment sectors that present bottlenecks for CPO, including optical fiber mounting (alignment) technology, high heat-

[12] An abbreviation of Outsourced Semiconductor Assembly and Test, which refers to companies that specialize in providing semiconductor back-end processes such as packaging and final testing. As previously noted, packaging technology is also required in CPO.
[13] A micrometer (micron) is equal to one-thousandth of a millimeter. It is occasionally denoted by the symbol μ.

resistant materials, and glass substrates. The key to success in the next-generation data center market will likely be whether companies can deeply integrate into the ecosystems formed by optical module manufacturers and other players—not merely as suppliers, but as joint development partners addressing technical challenges (Figure 3).

Figure 3: Changes in business model



Source: Compiled by MGSSI based on various sources

Microgravity Utilization Technology Entering the Industrialization Phase

— In-Orbit Experiments Opening New Frontiers in Next-Generation Manufacturing —

Hideki Kinjo

Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

Outer space has long been regarded as a domain limited to a small number of researchers and national projects. In recent years, however, it has begun to attract attention as a new foundation for research and industry. Against the backdrop of declining launch costs and the growing participation of private companies, innovation across the space sector is accelerating. Of particular note are in-orbit experiments that leverage the unique microgravity environment of space, along with the commercial applications of the results. This environment, distinct from that on Earth, can lead to the creation of new products and manufacturing processes and may influence the formation of new markets and supply chains in the future. This report reviews these trends and considers future prospects.

Summary

- In a microgravity environment, the effects of natural convection and sedimentation/buoyancy are minimal, allowing processes such as crystallization to be observed and controlled with a high degree of precision. Leveraging these characteristics, applications are expanding primarily in the pharmaceutical, biotechnology, and materials fields.
- Each partner country has developed its own utilization model on the International Space Station (ISS), and a wide range of experiments, including research on the crystallization of pharmaceutical compounds, have been conducted. The ISS is now maturing as a platform for commercial use as well.
- In-orbit experiments technologies using "free flyers," in which experimental equipment is mounted on small satellites, have reached practical application. In addition, private space station projects are advancing in anticipation of the ISS's retirement, and a new ecosystem for in-orbit experimentation is expected to take shape.

1. What Is Microgravity Utilization Technology?

1-1. Why Does Microgravity Enable High-quality Crystal Growth?

Microgravity utilization technology is an umbrella term for initiatives that use platforms such as the International Space Station (ISS)[1] to precisely observe and control processes that are difficult to evaluate in isolation from gravity on Earth. Suppressing gravity-driven effects such as natural convection, sedimentation, and buoyancy, enables isolation of the phenomenon itself in a purer form, deepening fundamental understanding and enabling process optimization.

On Earth, gravity causes natural convection within liquids (including concentration convection and thermal

[1] The International Space Station (ISS) is an international space research facility orbiting at an altitude of approximately 400 km above Earth. It is operated jointly by five space agencies from the United States, Japan, Europe, Russia, and Canada. Construction began in 1998 and was completed in 2011. At present, experiments utilizing the microgravity environment, external exposure experiments leveraging the space environment, and life sciences research conducted under space conditions are being carried out onboard.

convection). Differences in concentration or temperature create regions with different densities, causing lighter (lower-density) fluid to rise and heavier (higher-density) fluid to sink. In crystallization, this convection disrupts concentration and temperature distributions in the solution during crystal growth, leading to non-uniform crystal growth and surface defects. In addition, crystal nuclei and impurity particles can become unevenly distributed due to sedimentation or buoyancy, causing microscopic strain and other distortions within the crystal.

By contrast, the ISS orbits in a continuous free-fall state, moving forward at high speed while being pulled by Earth's gravity. From the perspective inside the ISS, objects experience gravity that is balanced by apparent centrifugal force, resulting in a microgravity state. In this environment, objects receive almost no supporting force from floors or walls, and the sensation of being pressed upward or downward is extremely weak, inhibiting sedimentation or buoyancy-driven movement. As a result, natural convection is suppressed, and conditions within liquids become gradually uniform through diffusion alone. Under these circumstances, crystal nuclei tend to form uniformly, and crystals can grow slowly and evenly without disturbance. Applications of this technical effect are shown in Figure 1.

Figure 1: Applications of microgravity utilization technologies

Field	Application	Effects
Pharmaceuticals/ biotechnology	Protein crystallization	・Suppression of convection and sedimentation under microgravity makes it easier to obtain more uniform crystals with fewer impurities than on Earth. ・Considered useful for pharmaceutical structural analysis and formulation design.
	Formation of regenerative medicine tissues	・Cells naturally aggregate three-dimensionally without settling, facilitating the formation of vascular networks and complex tissue structures.
	Development of probiotics	・Changes in microbial metabolism and properties are expected to lead to the emergence of new functionalities. ・Changes in stress responses and gene expression have been reported.
Materials	Uniform crystal growth (wafer manufacturing)	・Greater temperature difference stability may reduce crystal defects. ・Expected to lead to the realization of high-performance materials.
	High-strength polymers and nanocomposites	・Particles do not settle and disperse more uniformly, potentially enhancing material strength and other properties.

Source: Compiled by MGSSI based on various sources

1-2. Diversifying Microgravity Platforms

Platforms capable of utilizing microgravity environments are rapidly diversifying (Figure 2).

Figure 2: Comparison of microgravity platforms

Category	Platform [primary operator]	Microgravity duration	Features/applications
Ground-based	Drop tower [ZARM Institute (Germany)]	Up to approx. 9 s	・Dropped through a vacuum tube from a tower approx. 146 m high. ・Lowest-cost and high-precision option for short-duration microgravity experiments. ・Suitable for materials, fluids, etc.
	Aircraft [Novespace (France), etc.]	Approx. 20 s × multiple runs	・Parabolic flights conducted at altitudes of approx. 9 to 10 km. ・Enables repeated experiments; widely used for life sciences, pharmaceutical development, and educational purposes.
Suborbital	Suborbital rocket [Blue Origin (US), etc.]	Approx. 3.5 to 4.5 min	・Ascends to approx. 100 km near the edge of space and goes into free fall. ・Used for short-duration space experiments and equipment validation.
	Sounding rocket [NASA Note and other space agencies]	Approx. 6 to 10 min	・Flies in space at altitudes of approx. 100 to 300 km. ・Provides a space environment for several minutes for technology demonstrations and material experiments.
Orbital	International Space Station (ISS) [NASA and other space agencies]	Months to 1 yr or more	・Orbits at approx. 400 km altitude. ・Provides the most stable microgravity environment; widely used for pharmaceuticals, biotechnology, and materials research.
	Free flyer (small satellite) [Varda Space Industries (US), etc.]	Several days to weeks	・Orbits at approx. 450 to 550 km altitude. ・Experiments conducted onboard small satellites. ・Recovery capsule reenters the atmosphere, and experimental results are retrieved on Earth.
	Commercial space station [Axiom Space (US), etc.]	Months to 1 yr or more	・Orbits at approx. 400 to 500 km altitude. ・Scheduled to begin operations sequentially from 2028.

Note: National Aeronautics and Space Administration (NASA)
Source: Compiled by MGSSI based on various sources

In addition to traditional drop towers and parabolic-flight aircraft, a variety of experimental platforms are being developed and utilized. These include suborbital rockets that reach the edge of space (approximately 100 km in altitude), the ISS orbiting at roughly 400 km, free-flyers (small satellites) that autonomously conduct experiments in orbit, and future private space stations under development. An ecosystem is emerging in which the optimal experimental method can be selected based on research objectives, cost, and duration. Free-flyers and private space stations are discussed further in "2. Noteworthy Trends."

1-3. ISS Utilization Models Differ by Country

The US, Japan, and Europe have each established distinct utilization models for the ISS, and researchers and companies can access these platforms regardless of nationality (Figure 3). The US has developed an advanced commercial model in which private experiment service providers permanently install their own equipment and continuously operate research programs for multiple companies. The Japanese experiment module "Kibo" allows users to access facilities operated by the Japan Aerospace Exploration Agency (JAXA) under established safety standards, and is characterized by its ease of use. In the European laboratory module "Columbus," private experiment service providers offer a flexible system that accepts compact experimental units brought in by customers. These diverse frameworks ensure experimental opportunities that meet a wide range of testing needs. Utilization fees depend on the scale of the experiment but range from several tens of millions to several hundreds of millions of yen.[2]

Figure 3: ISS laboratory module utilization models

Item	US Laboratory Module	Japanese Laboratory Module (Kibo)	European Laboratory Module (Columbus)
Technical strengths	Cell and biotechnology research, manufacturing applications, materials science	Electrostatic levitation furnace, crystallization research, high-temperature materials	Fluid science, plasma crystallography, life sciences
Utilization point of contact	Center for the Advancement of Science in Space (CASIS) (US)Note 1	・Mitsui Bussan Aerospace ・Japan LEO ShachuNote 2 ・Space BD ・Kanematsu / DigitalBlast / Japan Manned Space Systems	Space Applications Services (SAS) (Belgium)
Users (customers)	Companies and research institutions worldwide; no nationality restrictions	Primarily Japanese companies; also available to overseas companies	Primarily European companies; no nationality restrictions
Entity conducting experiments	NASA-certified commercial experiment service providers	・Astronauts conduct experimental operations ・In some cases, private operators or JAXA perform remote operations from the ground	・SAS oversees primary operations ・Astronauts conduct experimental operations ・In some cases, ground control teams are responsible
Owner of experimental equipment	Commercial experiment service providers	JAXA	European Space Agency (ESA)
Items prepared by users	・Samples and materials ・Experimental units inserted into commercial service providers' ISS experiment racks as needed	・Samples and materials ・JAXA-provided equipment used in general	・Samples and materials ・Experiment units inserted into ISS experiment racks

Note 1: A nonprofit organization entrusted by NASA with the operation and management of the utilization allocation U.S. National Laboratory within the U.S. on-orbit segment (USOS) of the ISS.
Note 2: Japan LEO Shachu, Inc. was initially established as a subsidiary of Mitsui & Co., with Mitsubishi Heavy Industries and Mitsubishi Electric later joining as equity participants.
Source: Compiled by MGSSI based on various sources

2. Noteworthy Trends

2-1. ISS Becoming an Orbital R&D and Manufacturing Demonstration Hub for Private Companies

The ISS is evolving from a facility for state-led fundamental research into a hub for commercial utilization by private companies. Since the mid-2010s, the number of experiments conducted in the US segment has expanded to more than 100 in FY2024[3], of which approximately 80% were projects undertaken by private enterprises.[4]

Private-sector experiments on the ISS can be broadly classified into (1) ground-application-oriented research (knowledge feedback) and (2) in-space manufacturing demonstration. Under (1), pharmaceutical companies are advancing crystallization research and increasingly applying the resulting insights to product development on the ground. Under (2), NASA is promoting In Space Production Applications (InSPA)[5], an initiative to utilize space as a manufacturing site, with demonstration projects underway for products such as artificial retinas and medical

[2] NASA, Commercial and Marketing Pricing Policy; JAXA, Fee Structure and Reduction Program for the Paid Utilization System (Non-Standard Services)
[3] October 1, 2023, to September 30, 2024
[4] "2024 ISS National Lab Annual Report Highlights Momentum in Space-Based R&D", ISS National Lab, January 2025.
[5] InSPA is a NASA program designed to promote manufacturing demonstrations in space by utilizing the ISS experimental environment and to apply the results to product development for terrestrial applications. Its policy objectives are to secure US leadership in the space manufacturing sector and to foster a sustainable low Earth orbit economy.

materials. Figure 4 shows examples of both (1) and (2). In addition, Figure 5 organizes experimental themes undertaken by private companies, focusing mainly on cases from the 2020s. Applications are expanding into more familiar domains, including food, consumer products, and lifestyle infrastructure.

Figure 4: Examples of private-sector experiments utilizing a microgravity environment

Category	Lead company	Experiment overview and key results	Period
Ground application	Merck & Co. (US)	・Conducted an experiment to generate a crystalline suspension[Note 1] of the anti-cancer immunotherapy Keytruda. ・Obtained a crystalline suspension with higher particle size uniformity under microgravity. ・Indicated potential contributions to formulation design and administration methods for antibody therapeutics.	2017
Ground application	MicroQuin (US)	・Conducted 3D cultures of breast and prostate cancer cells. ・Indicated potential changes in mechanisms related to cell survival maintenance.	2022
Ground application	Colgate-Palmolive (US)	・Analyzed the effects of microgravity on skin aging, hydration, and collagen production. ・Detailed experimental data have not yet been publicly disclosed.	2022
Space manufacturing demonstration	Flawless Photonics (US)	・Manufactured ZBLAN (heavy metal fluoride glass) optical fiber. ・Confirmed production of fiber exceeding 11 km in length. ・Indicated potential improvements in layer uniformity and reductions in crystal defects compared with terrestrial manufacturing.	2024
Space manufacturing demonstration	LambdaVision (US)	・Repeatedly validated the manufacturing process for protein thin films used in artificial retinas. ・Indicated potential improvements in film uniformity and defect reduction under microgravity conditions.	Ongoing since 2018
Space manufacturing demonstration	United Semiconductors (US)	・Conducted growth experiments of semiconductor-semimetal composite bulk crystals[Note 2]. ・Analysis and evaluation of effects on crystal size and defect reduction currently underway.	Launched 2024 / analysis 2025

Note 1: A liquid formulation in which fine crystalline particles of an active pharmaceutical ingredient are uniformly dispersed in a liquid. Such formulations offer properties that contribute to formulation stability and expanded administration options.
Note 2: A novel high-performance material that combines semiconductor properties enabling current control with semimetallic properties allowing high-speed current flow within a single crystal.
Source: Compiled by MGSSI based on various sources

Figure 5: Private sector experiment themes

Field	Lead company	Experimental theme
Pharmaceuticals / biotechnology	Eli Lilly (US)	Evaluation of novel drug candidates targeting muscle atrophy (loss of muscle mass) in microgravity environments
	PeptiDream (Japan)	Support for crystal generation and three-dimensional structural analysis of drug discovery targets
	Yakult (Japan)	Evaluation of stability and functionality of probiotics (lactic acid bacteria) in a microgravity environment
Materials	adidas (Germany)	Analysis of structural and rebound property changes in foam materials to enhance cushioning performance and durability
Food	Kirin Holdings (Japan)	Lettuce cultivation experiment using a bag-type culture tank
	AB InBev (Belgium)	Evaluation of barley germination and growth characteristics to improve grain quality and explore future applications in space food research
Consumer products and lifestyle infrastructure	Procter & Gamble (US)	Evaluation of detergent component degradability and cleaning performance for application in the design of water- and energy-efficient laundry processes
	Delta Faucet (US)	Analysis of droplet and bubble behavior mechanisms to develop water-saving shower designs that maintain comfort with low water usage
	Kao (Japan)	Demonstration of hair-washing and laundry solutions in microgravity environments where water use is extremely limited

Source: Compiled by MGSSI based on various sources

The activities of private experiment service providers, represented by Redwire (US) and Space Tango (US), which support these experimental initiatives, are also drawing attention. Using its proprietary crystallization device, PIL-BOX[6], Redwire has continued joint research with multiple pharmaceutical companies[7] and has built a track record in generating high-quality crystals. In 2025, the company launched a new business model under which it licenses seed crystals[8] grown on the ISS to pharmaceutical companies. Space Tango has conducted more than 150 experiments and is also pursuing in-space manufacturing demonstrations of materials for regenerative medicine.

2-2. Free-flyers: The Emergence of Rapid and Flexible In-Orbit Experiments Platforms

One alternative to conducting experiments on the ISS is the use of free-flyers. A free-flyer is a small satellite equipped with experimental payloads that autonomously conducts experiments in orbit over a period of several days to several weeks. The resulting materials are returned to Earth using a reentry capsule[9] . In some missions, only experimental data are collected, without recovery of physical samples.

The key advantages lie in speed and flexibility. Free-flyers do not depend on ISS operational constraints or astronaut work schedules, enabling (1) completion of the entire cycle from launch to recovery within a matter of months, and (2) the continuous execution of multiple missions over short intervals. This allows companies to accelerate PDCA cycles for experimentation and significantly reduce lead times from test initiation to results acquisition.

A leading company in this field is Varda Space Industries (US). Using its proprietary small satellites, the company is conducting in-orbit manufacturing demonstrations for pharmaceuticals. In its first orbital mission in 2023, it successfully generated crystals of the HIV treatment drug ritonavir, which were recovered on Earth in 2024.[10] In Japan, ElevationSpace plans to launch its first mission in the second half of 2026, marking what is expected to be the country's first free-flyer business, and is drawing attention as a domestic entrant in this area.

The key to the competitiveness of free-flyers lies not only in their in-orbit experiments capabilities but also in the atmospheric reentry capsule that safely and reliably returns experimental results to Earth. In particular, when targeting pharmaceuticals and other high-value materials, the reliability of the recovery process becomes a decisive factor in commercial viability. Figure 6 summarizes each company's approach to recovery.

---

[6] To date, 28 PIL-BOX units have been deployed on the ISS, successfully achieving crystallization of 17 different compounds.

[7] The company has conducted joint research with Bristol Myers Squibb (US) and Eli Lilly (US), among others.

[8] Seed crystals are small crystals that serve as the starting point for crystal growth and enable highly reproducible crystallization. Obtaining high-quality seeds is challenging due to the extremely delicate formation conditions, making them a highly valuable research resource.

[9] A heat-resistant capsule designed to return samples or manufactured products obtained in orbit to Earth. It is equipped with thermal protection materials that shield the interior from heating of several thousand degrees Celsius during reentry and autonomously performs functions required for deceleration and landing.

[10] The second satellite was launched in January 2025 and recovered in Australia in February of the same year. The third spacecraft was launched in March and successfully recovered in May.

Figure 6: Free flyer operators and companies involved in reentry recovery capsules

Company	Business model	Development status and achievements
Varda Space Industries (US)	・Provision of integrated experiment-to-recovery services ・Creation of proprietary products through in-space manufacturing	・Successfully manufactured crystals of the HIV treatment drug ritonavir in orbit and recovered them in 2023 to 2024. ・Has been conducting consecutive missions and transitioning to commercial operations since 2025. ・Strengthening its business foundation in both experimentation and manufacturing through expanded contracts with the US Department of Defense.
Space Forge (UK)	Creation of proprietary products through in-space manufacturing	・Aims to manufacture high-performance materials such as gallium nitride (GaN) used in semiconductors for power electronics as proprietary products. ・Succeeded in generating plasma required for the manufacturing process in orbit in 2025, establishing the foundation for manufacturing demonstration. ・Supported by the UK government and the European Space Agency (ESA).
ElevationSpace (Japan)	Provision of integrated experiment-to-recovery services	・Plans to launch its first mission in 2026. ・Formed a partnership with Exobiosphere[Note 1] (Luxembourg) in September 2025. ・Exploring an operational model linked to future commercial space stations in collaboration with Axiom Space (US).
ATMOS Space Cargo (Germany)	Primarily focused on the design and manufacture of recovery capsules	・Conducted orbital demonstration of the recovery capsule Phoenix 1 in 2025. Plans to launch Phoenix 2 in 2026. ・Collaborating with multiple experiment operators[Note 2] as one of the few recovery technology providers in Europe. ・Planning capsule operations at a frequency of around once a month.

Note 1: Exobiosphere is a contract research organization (CRO) specializing in drug discovery and biotechnology experiments that utilize the microgravity environment.
By offering in-orbit experiments as a CRO service, the company significantly lowers the barriers for pharmaceutical and biotechnology firms to access in-orbit experimentation.
Note 2: In November 2025, the company announced a partnership with Space Cargo Unlimited (Luxembourg), which develops experimental equipment for installation on spacecraft.
Source: Compiled by MGSSI based on various sources

2-3. Commercial Space Stations: Building Core Infrastructure to Support the Low-Earth Orbit Economy

With the anticipated retirement of the ISS around 2030, efforts to develop commercial space stations are gaining momentum. These stations are positioned as essential core infrastructure for sustaining and expanding commercial activities in orbit over the medium to long term. At present, there are four representative examples of commercial space station projects supported by NASA.

(1) Axiom Space (US) (station name: Axiom Station) is constructing commercial modules to be attached to the ISS, with plans to detach them in the future and operate them as an independent station. The company aims to establish a multipurpose commercial platform that can support research and manufacturing, crewed stays, and even orbital data centers.

(2) Starlab Space (US) (Starlab) is developing an integrated small space station jointly with European partners. In collaboration with the European Space Agency (ESA), it seeks to create a research and industrial hub open to international customers, including those in Europe.

(3) Blue Origin (US) / Sierra Space (US) (Orbital Reef) is building a multipurpose platform accessible to companies, universities, and government agencies under the concept of an industrial park in space.

(4) Vast (US) (Haven-1) plans to begin with a small station capable of accommodating approximately four people for short stays, with the vision of developing it into a station suitable for extended habitation through the introduction of artificial gravity generated by a rotating structure.

These developments are also extending to Japan. Japan LEO Shachu is advancing the development of the Japan Module, envisioned as a successor to the Kibo module on the ISS. The participation of Japanese companies is expected to further accelerate the expansion of the orbital utilization ecosystem.

3. Future Prospects

The commercial utilization of microgravity is expanding primarily in the pharmaceutical, biotechnology, and materials sectors. Examples are beginning to emerge in which outcomes are translated into terrestrial industries, including applications in new drug development by pharmaceutical companies, manufacturing demonstrations of regenerative medicine devices such as artificial retinas, and the licensing of seed crystals grown in space. In the free-flyer domain, Varda Space Industries has presented a new service model that integrates in-orbit experimentation with payload recovery, offering a concrete vision for commercialization. Looking ahead, the addition of commercial space stations is expected to give rise to a new in-orbit experiment ecosystem encompassing R&D, manufacturing validation, and recovery. These developments are likely to become more closely linked with terrestrial value chains, accelerating the social implementation of results.

What benefits might these technologies bring to everyday life? In the pharmaceutical and biotechnology sectors, they are expected to advance the development of more effective medicines with fewer side effects, thereby reducing both the physical and economic burden on patients. The further advancement of cutting-edge medical devices, such as artificial retinas, also holds strong potential to help restore lost human functions and improve quality of life. In the materials sector, the practical application of lighter, stronger, and more efficient materials will advance energy savings, miniaturization, and longer product lifespans. In the food sector, the development of high-value functional foods is anticipated to contribute to the maintenance and enhancement of consumer health.

On the other hand, several challenges remain in moving toward industrialization. First, reducing launch and recovery costs continues to be critical, as it significantly influences business sustainability. Second, reliable autonomous operation technologies[11] capable of functioning over extended periods in the space environment are essential. Third, it is necessary to establish co-creation R&D frameworks with terrestrial companies in sectors such as pharmaceuticals, materials, and food. Fourth, progress must be made in developing quality standards and certification processes to commercialize and bring to market products derived from results obtained in orbit.

The market for microgravity utilization is already showing clear signs of expansion. Opportunities for corporate participation span a wide range of areas, including contract experimentation, in-orbit manufacturing support, materials supply, recovery logistics, use of data and intellectual property, and applications of materials derived in space. Achievements gained in orbit are helping address challenges faced by terrestrial enterprises, creating new markets. A new wave of manufacturing that connects space and Earth is beginning to take shape as a tangible industrial reality.

[11] Here, autonomous operational technologies refer to those that enable systems to independently assess current conditions, plan, carry out, and respond to anomalies without continuous human intervention.