2024

QUANTUM INFORMATION SCIENCE ENGINEERING TECHNOLOGY

WHITE PAPER

(SUMMARY)

Ministry of Science and ICT
NIA NATIONAL INFORMATION SOCIETY AGENCY
미래양자융합포럼 Future Quantum Convergence Forum

2024

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Comprehensive Trends in Quantum Technology

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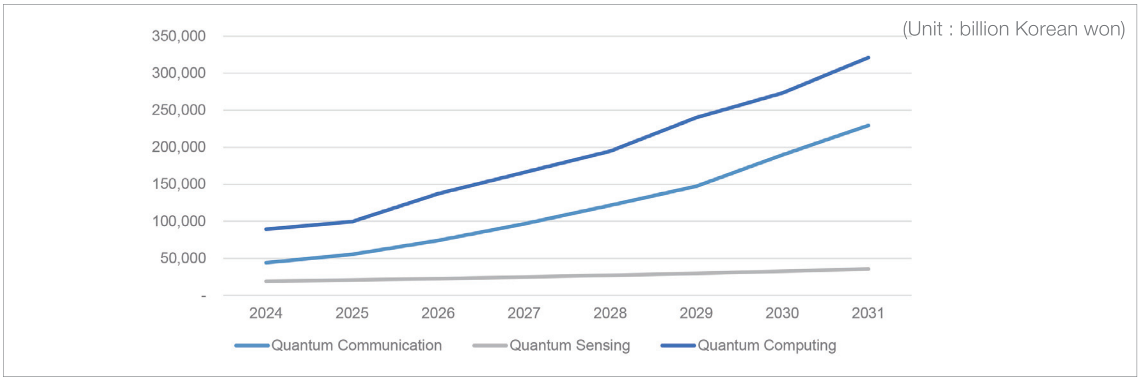
I. Comprehensive Trends in Quantum Technology

Domestic and International Market Trends

Quantum technology is emerging as a key next-generation technology with applications in defense, energy, healthcare, and other industries. Market research indicates that quantum communication and sensing are likely to be commercialized soon, while quantum computing is expected to expand through integration with these technologies. With major firms like McKinsey forecasting rapid market growth, governments and companies are increasing their investments.

The global quantum technology market is estimated at approximately 15.1848 trillion Korean won (about 11.2 billion dollars)* in 2024 and is projected to reach 58.6055 trillion Korean won (43.2 billion dollars) by 2031, with a 21.3% annual growth rate. By sector: quantum communication is expected to grow from 4.3831 trillion Korean won (3.2 billion dollars) in 2024 to 22.9333 trillion Korean won (16.9 billion dollars) in 2031 (26.7% annual growth); quantum sensing from 1.8862 trillion Korean won (1.4 billion dollars) to 3.5520 trillion Korean won (2.6 billion dollars) (9.5% annual growth); and quantum computing from 8.9155 trillion Korean won (6.6 billion dollars) to 32.1202 trillion Korean won (23.7 billion dollars) (20.1% annual growth).

Figure I-1 Global Quantum Technology Market Forecast by Sector



※ Source(s): McKinsey (2024), Mind Commerce (2024)

* The exchange rate of 1 USD = 1,357 KRW was applied.

Table I-1 **Global Quantum Technology Market Forecast by Sector**

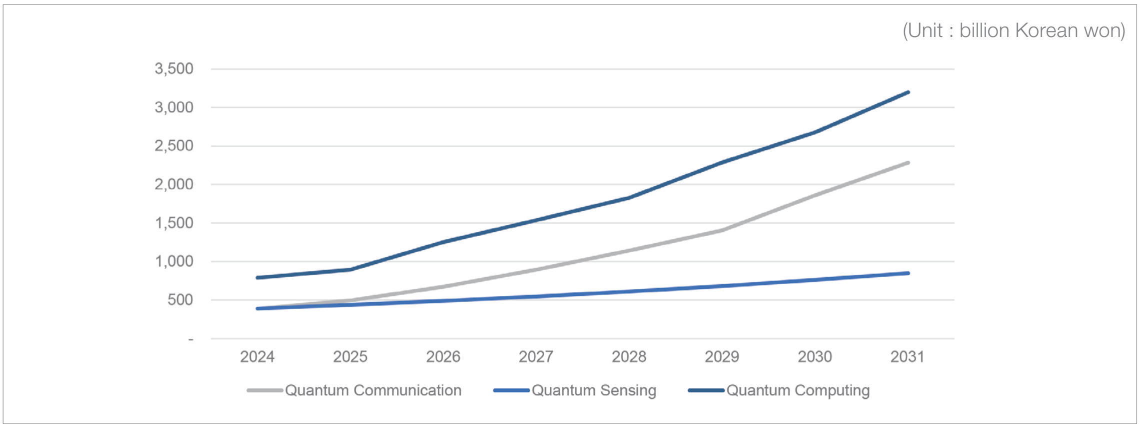
(Unit : billion Korean won)

Category	2024	2025	2026	2027	2028	2029	2030	2031	CAGR
Quantum Communication	43,831	55,230	73,957	96,618	121,587	147,235	189,709	229,333	26.7%
Quantum Sensing	18,862	20,633	22,576	24,707	27,045	29,611	32,427	35,520	9.5%
Quantum Computing	89,155	99,604	137,328	165,961	194,730	239,918	273,164	321,202	20.1%
Total	151,848	175,467	233,861	287,286	343,361	416,763	495,300	586,055	21.3%

※ Source(s): McKinsey (2024), Mind Commerce (2024)

The Korean quantum technology market, while starting from a relatively small scale, shows strong growth potential. In 2024, the market is estimated at 156.8 billion won (115.5 million dollars), with quantum communication at 38.8 billion won (28.6 million dollars), quantum sensing at 39.1 billion won (28.8 million dollars), and quantum computing at 78.9 billion won (58.1 million dollars). Quantum communication is expected to industrialize rapidly with a 28.8% annual growth rate, and quantum computing to expand at 19.1%. Quantum sensing should see stable 10.2% growth, with quick adoption in specialized areas like defense and healthcare.

Figure I-2 **Domestic Quantum Technology Market Forecast by Sector**



※ Source(s): IQ4I (2022), McKinsey (2024), Mind Commerce (2024)

Table I-2 Domestic Quantum Technology Market Forecast by Sector

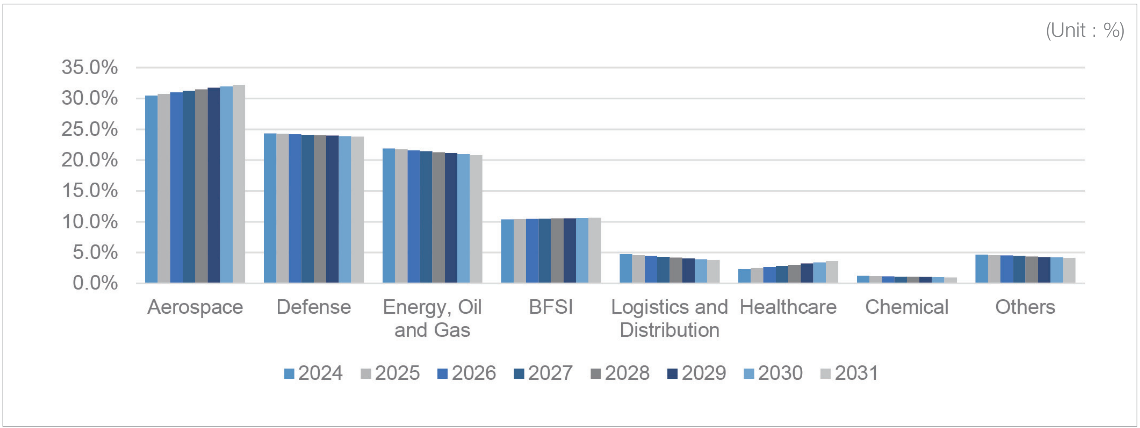
(Unit : billion Korean won)

Category	2024	2025	2026	2027	2028	2029	2030	2031	CAGR
Quantum Communication	388	496	674	894	1,142	1,404	1,860	2,282	28.8%
Quantum Sensing	391	440	489	547	611	680	761	849	10.2%
Quantum Computing	789	895	1,252	1,536	1,829	2,287	2,679	3,197	19.1%
Total	1,568	1,830	2,416	2,977	3,582	4,371	5,300	6,328	22.1%

※ Source(s): IQ4I (2022), McKinsey (2024), Mind Commerce (2024)

The industrial ripple effects of quantum technology are expected to be prominent in areas such as aerospace, defense, and energy. From 2024 to 2031, the aerospace industry is expected to account for approximately 30% of total revenue, followed by defense (24.1%) and energy, oil and gas (21.4%). The BFSI (Banking, Financial Services and Insurance) (10.5%), logistics and distribution (4.2%), and healthcare (2.9%) sectors also show growth potential based on quantum technology.

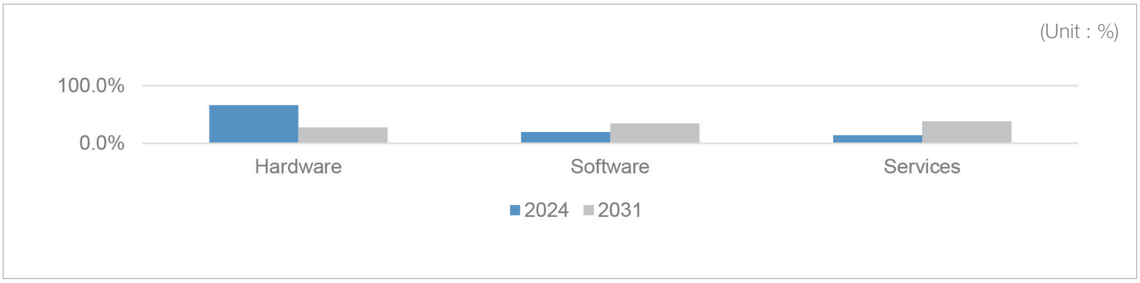
Figure I-3 Industrial Composition of Global Revenue Based on Quantum Technology



※ Source(s): IQ4I (2022)

In terms of product type, hardware revenue is expected to be high initially, but the proportion of software and services is expected to increase over time. In 2024, hardware accounts for approximately 66.5% of revenue, but is expected to decrease to 27.3% by 2031. On the other hand, software (34.6%) and services (38.2%) are expected to continuously increase their market share.

Figure Ⅰ-4 Composition of Global Revenue Based on Quantum Technology by Product Type



※ Source(s): IQ4I (2022)

In South Korea, growth in the quantum communication market and the expansion of quantum sensing — especially in the defense and medical sectors — are drawing attention, with quantum computing software developmentt emerging as a major trend. Quantum sensing, with its high potential for rapid commercialization in specific industries, requires technical innovation and continuous investment amid global competition. Government support, deregulation, and private collaboration are necessary for quantum technology's industrial expansion; infrastructure development and technical standardization are core market growth factors.

02

I. Comprehensive Trends in Quantum Technology

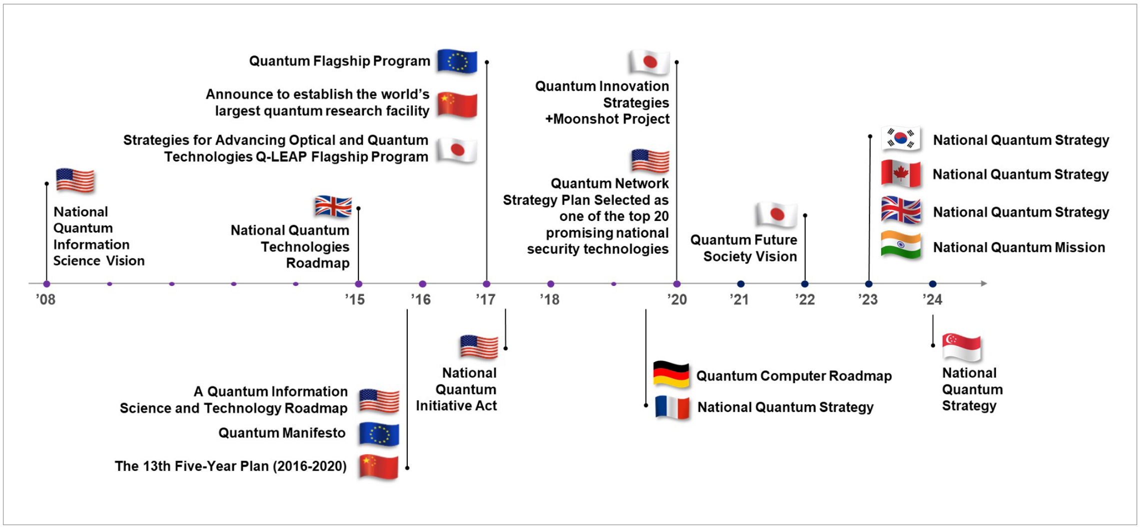
Domestic and International Policy Trends

Major countries are designating quantum technology as a national strategic technology, establishing legal and institutional frameworks, and making large-scale investments in research and development (R&D) while supporting industrialization. The United States became the first in the world to enact the National Quantum Initiative Act (NQIA) in 2018, and in 2023, it introduced the reauthorization bill to accelerate the industrialization of quantum technology. The White House has set short-term goals, such as developing quantum repeaters and memory, to strengthen national security and economic competitiveness. Meanwhile, the National Semiconductor Technology Center (NSTC) is emphasizing the cultivation of quantum technology talent and the establishment of industry-academia-research collaboration networks. Additionally, the National Quantum Initiative Advisory Committee (NQIAC) provides policy recommendations and supports technology development in parallel.

The EU supports research focusing on networking, sensing, communication, and computing technologies through the €1 billion 'Quantum Flagship' project. Notably, in 2024, the EU released the 'Strategic Research and Industry Agenda 2030', providing an integrated roadmap for technology commercialization. The UK is expanding the application of quantum technology to healthcare, transportation, and energy sectors through its National Quantum Strategy announced in 2023. Germany, with its 2023 action plan, has set a goal to develop a quantum computer capable of controlling 100 qubits by 2026. France is pursuing the development of a quantum computer prototype with 128 logical qubits by 2030 through the PROQCIMA program.

China is showcasing remarkable achievements in quantum communication and computing technologies, leading the quantum network field by establishing a 2,000 km quantum communication network and successfully conducting quantum key distribution and teleportation experiments using satellites. Japan has designated quantum technology as a core national technology alongside AI and bio, accelerating technology development and commercialization with a goal of 10 million technology users and 50 trillion yen in production value by 2030 through its 'Strategy of Quantum Future Industry Development'

Figure Ⅰ-5 Status of Quantum Policy and Legislation in Major Countries



※ Source(s): Ministry of Science and ICT (2023)

South Korea is accelerating the development of quantum technology by announcing the 'National Strategy for Quantum Technology Research and Development' in 2021, followed by the 'National Quantum Strategy' in 2023, and the 'Quantum Initiative' in 2024. The Act on the Promotion of Quantum Science, Technology, and Industry, which took effect on November 1, 2024, has laid the institutional foundation for securing global competitiveness. The government has set a goal to lead the global quantum economy by 2030, with investment expansion, talent development, global cooperation, and industrialization as core strategies. In particular, starting in 2025, the government plans to strengthen mission-oriented R&D and investment expansion to secure quantum science and technology capabilities and promote corporate participation. Short-term priorities include the commercialization of quantum sensing and communication and the systemization of quantum computing, while mid-to-long-term priorities involve discovering and supporting globally competitive quantum technologies.

Figure Ⅰ-6 Current Status of Major Domestic Quantum Policy Initiatives (2021-2024)

※ Source(s): Ministry of Science and ICT (2025)

Organizations under South Korea's Ministry of Science and ICT are driving various projects to establish foundations for the research, development, and commercialization of quantum technology. The National Information Society Agency (NIA) is conducting projects to establish quantum cryptography communication infrastructure, build foundations for quantum technology commercialization, and create quantum testbeds. The Institute for Information & Communications Technology Planning & Evaluation (IITP) is pushing forward with the development of quantum sensors and quantum cryptography communication technology, as well as core quantum internet technology research and development. Additionally, the National Research Foundation of Korea (NRF) is carrying out various projects to develop and lead quantum computing technology, consistently striving to enhance domestic quantum technology competitiveness.

The Ministry of Science and ICT has built various support systems to boost domestic quantum technology R&D and the industrial ecosystem. In 2021, the 'Future Quantum Convergence Forum (FQCF)', involving industry, academia, research institutions, and government, was launched to strengthen R&D and industry linkages. In 2022, the NIA was designated as the dedicated agency, and the 'Korea-Quantum Industry Center (K-QIC)' was opened in Pangyo to support quantum technology industrialization. Furthermore, the 'Quantum Information Research Support Center (Qcenter)' was established at Sungkyunkwan University in 2020 to support research activities and education, and the 'The Korean Association of Quantum Information Science and Technology

(QuIST)', launched in 2019, was incorporated as the 'Quantum Information Society of Korea (QisK)' in 2022, further solidifying the academic ecosystem.

Table I-3 Committees and Subgroup Roles of the FQCF

Committees	Subdivisions	Main Roles
Industrial·Utilization Committee	Commercialization Models	· Produce quantum ICT service models and develop policies to create markets
	Industrial Ecosystem	· Build an open quantum ICT ecosystem for testing prototypes and developing standards
	Joint Research	· Develop joint projects on industry and user
	Security Policy Cooperation	· Coordinate with private sectors, domestically and internationally, and improve on the legal system and our industry performance
Academic · Personnel Committee	Quantum Communication	· Focus on matters of fundamental quantum communication technologies, and ensure development of their research projects
	Quantum Sensing	· Focus on matters of fundamental quantum sensing technologies, and ensure development of their research projects
	Quantum Computing	· Focus on matters of fundamental quantum computing technologies, and ensure development of their research projects
	Enabling Workforce	· Coordinate the building of quantum workforce by designing programs for schools, colleges, industry and partners
Standardization Committee		· Conduct domestic and international standardization activities and cooperate with standardization experts

※ Source(s): Future Quantum Convergence Forum

Table I-4 Websites of Major Quantum Technology-Related Institutions in Korea

Organization Name	Website
Future Quantum Convergence Forum (FQCF)	fqcf.org
Korea-Quantum Industry Center (K-QIC)	kqic.kr
Quantum Information Research Support Center (Qcenter)	qcenter.kr
Quantum Information Society of Korea (QisK)	qisk.or.kr

03

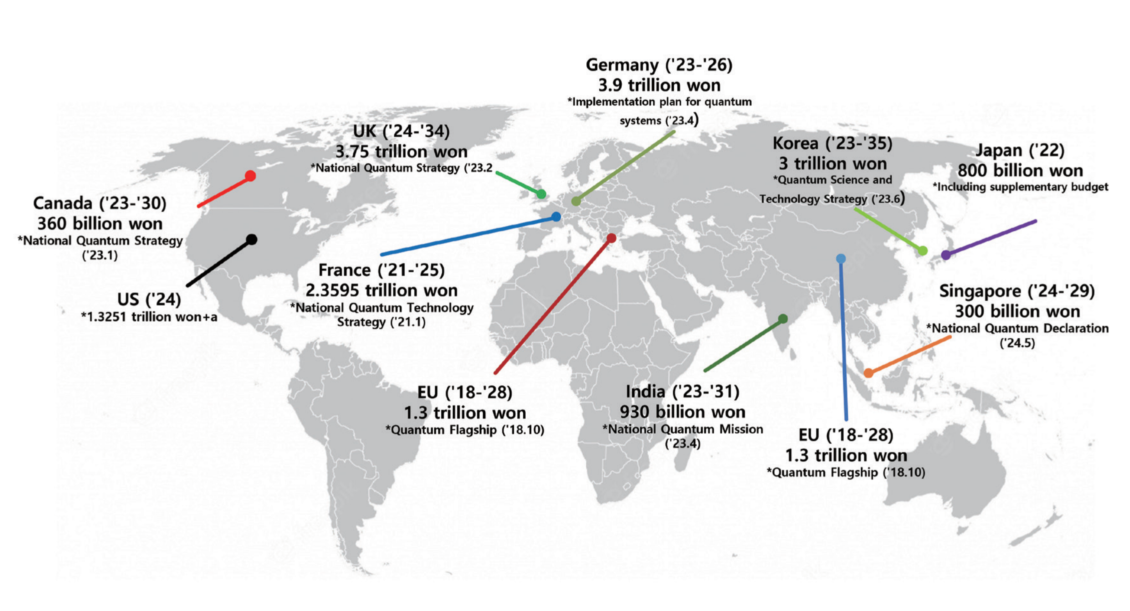
I. Comprehensive Trends in Quantum Technology

Domestic and International Investment Trends

Major countries are competitively allocating large-scale budgets and expanding long-term investments to secure the initial market for quantum technology. The U.S. federal government and its agencies have requested approximately 1.3251 trillion Korean won (about 968 million dollars) for the 2024 quantum technology budget. The European Union (EU) has invested approximately 1.3 trillion Korean won (1 billion euros) in its Quantum Flagship project over 10 years, starting in 2018. The UK announced its National Quantum Strategy in 2023, stating it will invest approximately 3.75 trillion Korean won (2.5 billion pounds over 10 years from 2024. Germany announced in its 2023 action plan that it will invest approximately 3.9 trillion Korean won (3 billion euros) in quantum technology by 2026. France is investing approximately 2.3595 trillion Korean won (1.8 billion euros) from 2021 to 2025 under its National Quantum Technology Strategy.

Canada is investing approximately 360 billion Korean won (360 million Canadian dollars) over 7 years through its National Quantum Strategy in January 2023, and China is focusing on quantum communication and quantum computing by increasing its R&D budget by more than 7% annually under its 14th Five-Year Plan. Japan invested approximately approximately 800 billion Korean won (80 billion yen) in the 2023 fiscal year alone, including supplementary budgets. Singapore and India have also allocated approximately 300 billion Korean won (300 million Singapore dollars) and approximately 10 trillion Korean won (600 billion rupees), respectively, for quantum technology research and commercialization.

Figure Ⅰ-7 Quantum Industry Investment Scale in Major Countries Worldwide



South Korea announced its 'National Quantum Strategy' in 2023, planning to invest 3 trillion Korean won (about 2.2 billion dollars) jointly with the public and private sectors by 2035. In 2024, a budget of 125.8 billion Korean won (92.7 million dollars) is being invested to create a quantum technology ecosystem, strengthen industry-academia-research cooperation, and promote startup support and quantum technology commercialization.

Worldwide, private investment in quantum technology is also rapidly increasing. In particular, startups are becoming a major investment target. In the U.S. and Europe, the industrialization of quantum technology is being accelerated through government and private sector cooperation, and this model is gradually spreading to other countries.

Table Ⅰ-5 Policy and Investment Scale of Major Countries in the Quantum Field

Country		Highlights	Budget
US		· Based on the world's first "NQIA" (Dec. 2018), the country supports quantum R&D, coordinates cross-ministry plans & links federal programs led by the White House, and supports public-private cooperation for 10 years. · With its “Strategic Vision for America's Quantum Networks” (Feb. 2020, Jul. 2020), the country aims to integrate quantum information networks by establishing a nationwide quantum network in 10 years. · Designated quantum computing as one of the top 10 high-tech areas under the Innovation and Competition Act (Jun. 2021). · Set short-term goals for the industrialization of quantum sensors based on the “Bringing Quantum Sensors to Fruition” (Mar. 2022). · Established the “NQIAC” under the White House and signed the “National Security Memorandum” to mitigate cybersecurity risks relating to quantum computers (May 2022). · Gave the NIST authorization to establish up to 3 centers for quantum sensing, under the NQI Act Reauthorization proposed in Nov. 2023 (up to $54 million grant per year between 2024 and 2028).	National Quantum Initiative Act: maximum $1.2 billion (2019-2023)
Europe	EU	· Under the mid to long-term quantum technology roadmap, the EU launched its “Quantum Technology Flagship” project for the next 10 years with a budget of €1 billion. · The “2030 Digital Compass” aims to develop Europe's first quantum computer by 2025 (Mar. 2021). · Large enterprises, SMEs, investors, and startups established the European Quantum Industry Consortium to enhance the competitiveness of their quantum technologies, quantum economy, and related industries (Apr. 2021). · Announced ‘Strategic Research Industry Agenda 2030,’ integrating roadmaps and visions from the research and industry sectors (Feb. 2024).	Quantum Flagship: €1 billion (2018-2027)
	UK	· Announced its “National Quantum Strategy” to encourage long-term investments in quantum technology R&D. · Announced 38 new investment projects to industrialize quantum-related fields and support the commercialization of quantum computers (Jun. 2019). · Announced the “National Quantum Strategy Missions” (Mar. 2023).	National Quantum Strategy’s hub deployment budget: £270 million (2014-2018)
	Germany	· The federal government established the Framework program for quantum technologies, improving the research environment and industrial competitiveness. · The “Quantum Technology Conceptual Framework” was presented, led by the German Federal Ministry of Education and Research, to secure world-class technology leadership (Apr. 2023).	Federal government’s Framework program: €650 million (2018-2022)

Country	Highlights	Budget
Europe / France	· Launched the “National Quantum Strategy” to secure technological supremacy with the development of quantum computers (Jan. 2021). · Established its national strategy for quantum technology and selected R&D projects (Mar. 2022).	-
Canada	· Concentrate research efforts in aerospace, national defense, and security that can create synergy effects with quantum technologies. · Provide full support to foster universities as a center of innovation in quantum fields. · Established the “National Quantum Strategy” to develop quantum technology, related enterprises, and manpower (Feb. 2023).	Federal government: $100 million a year
China	· Prepare to become a quantum powerhouse by designating quantum control and information as national strategic areas and building the world's largest research center. · Local governments established quantum industry clusters to build quantum ecosystems. · Under the 14.5 plan, quantum information was designated as a strategic science and technology project (Oct. 2020).	National Laboratory for Quantum Information Science: ¥100 billion (2018-2022)
Japan	· Promote commercialization and industrialization based on basic research conducted under its cutting-edge research program. · Established its “Quantum Technology and Innovation Strategy” (Jan. 2020). · Support not only its areas of strength but also related technologies to realize Society 5.0. · Announced its “Quantum Future Society Vision” (Mar. 2022). · Announced the “Strategy of Quantum Future Industry Development” (Mar. 2023).	Q-Leap program: ¥2.2 billion (2018), ¥2.2 billion (2019)
Australia	· Expand investment to foster quantum-related industries. · The “National Quantum Strategy” set out the goals of creating A$4.6 billion in value and large-scale job opportunities by 2045 (May 2023).	Australian Research Council: AU$130 million
South Korea	· Expand investment based on its R&D investment strategy while promoting quantum industries, especially by conducting pilot projects for quantum cryptography communication infrastructure. · Announced its “Quantum Technology Roadmap” and “Vision for Quantum Science & Technology” to lead the global quantum economy (Jun. 2023). · Enacted the Act on Fostering Quantum Science & Technology and Quantum Industries (approved by the National Assembly, Oct. 2023). · Announced the “National Quantum Strategy” (Jun. 2023). · Enforced the Act on the Promotion of Quantum Science, Technology, and Industry (Nov. 2024).	National Quantum Strategy: 3 trillion Korean won (2023-2035)

※ Source(s): IITP (2022)

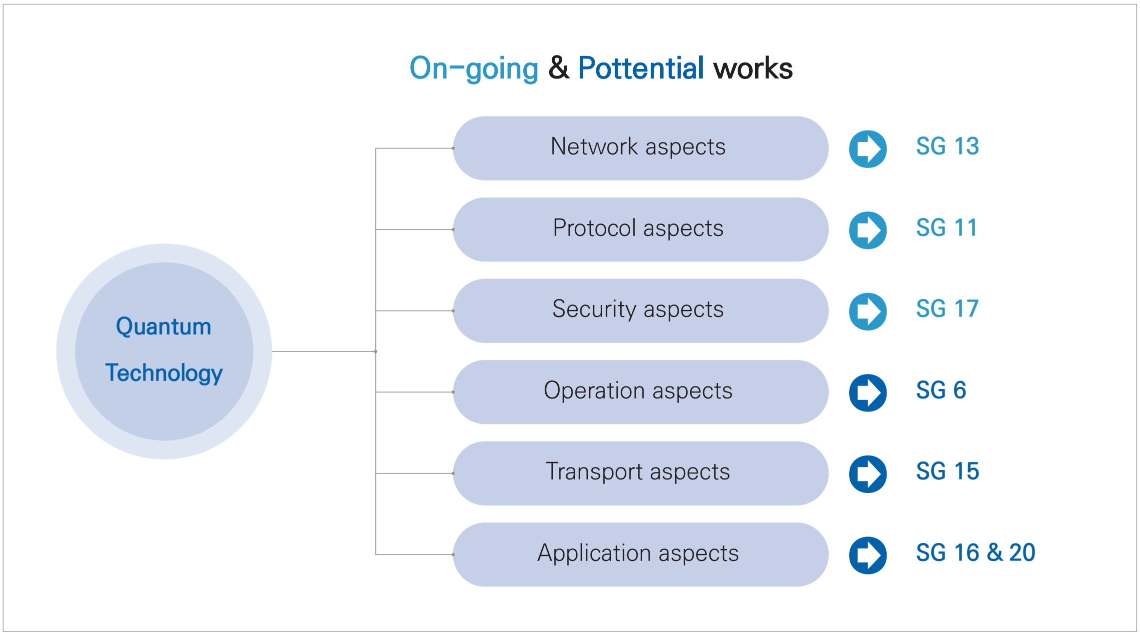
04

Domestic and International Standardization Trends

Standardization in quantum technologies is primarily focused on the quantum communication sector, with a gradual expansion into quantum computing and quantum sensing. Major international standardization organizations such as ITU-T, ETSI, and ISO/IEC, along with de facto standardization bodies like IETF/IRTF, are taking leading roles. South Korea, in particular, has established itself as a leading nation in international standardization, notably in areas like quantum-cryptographic networks and quantum key distribution technology standardization.

The ITU-T (International Telecommunication Union – Telecommunication Standardization Sector) is actively engaged in standardization activities, including the development of technical standards for commercialization as well as quantum-cryptographic network architecture. Here, South Korea is effectively guiding ITU-T's quantum technology standardization by consistently proposing core standard agendas.

Figure I-8 ITU-T Quantum Technology Standardization Study Group



ETSI (European Telecommunications Standards Institute) was the pioneering organization in standardizing quantum key distribution technology, playing a critical role in the implementation and interoperability of quantum cryptography systems. In particular, the QKD ISG (Industry Specification Group), established in 2008, is an industry specification group with participants from quantum cryptography communication equipment manufacturers, telecommunications operators, universities, and research institutions. This group has been developing functional, interface, and security requirements for quantum key distribution systems. To date, this group has published over 20 industry specification documents.

ISO/IEC (International Organization for Standardization/International Electrotechnical Commission) is advancing quantum cryptography security standardization based on traditional security evaluation criteria (Common Criteria), and is fully promoting standardization across all quantum technologies through the newly established JTC3 (Joint Technology Committee 3) in 2024. JTC3 was established under South Korea's leadership, and is expanding international standardization of quantum technologies by organizing various ad hoc groups and working groups.

Europe's CEN/CENELEC (European Committee for Standardization/European Committee for Electrotechnical Standardization) JTC22 is strengthening European-centered leadership in quantum technology standardization. IETF (Internet Engineering Task Force)/IRTF (Internet Research Task Force) is responsible for standardizing next-generation networks such as the quantum internet. Standardization of quantum computing is being conducted by ISO/IEC JTC1 and IEEE (Institute of Electrical and Electronics Engineers), and is in its early stages.

In South Korea, standardization for quantum technology, which had been dispersedly handled by various project groups within the TTA (Telecommunication Technology Association) standardization committee, is now overseen by the newly established PG225 (Quantum Communication) in 2022. Additionally, RRA (National Radio Research Agency) has established a quantum technology expert committee in 2024, leading national standards, and is proposing numerous national standards, including service quality standards for quantum key distribution networks.

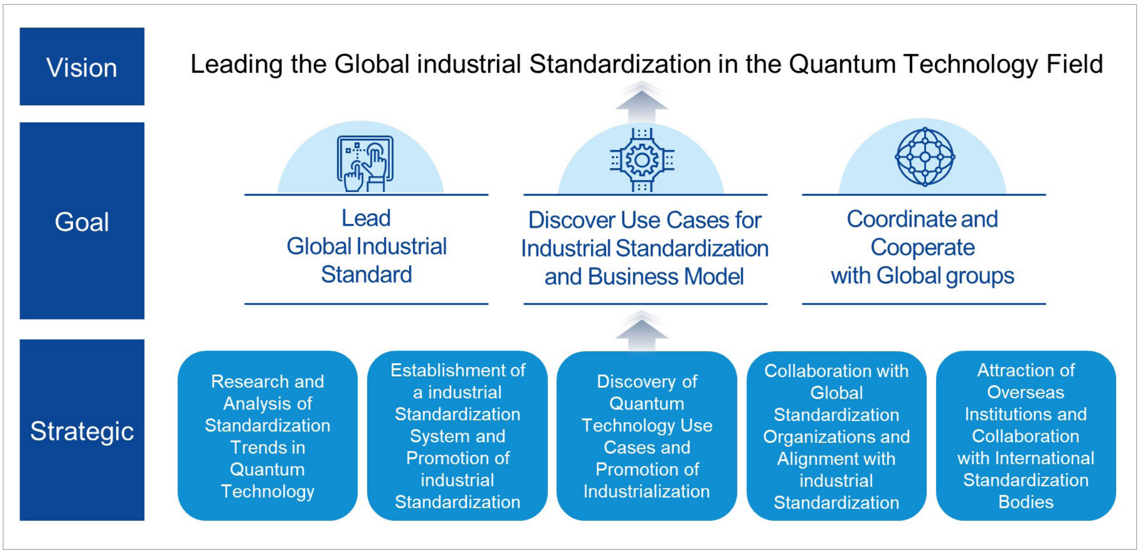
Table Ⅰ-6 Status of Standards Development by TTA PG225 and RRA

Classification	Organization Name	Standard Documents	Completion (Scheduled) Year
1	TTA PG225	TTAE.ET-GS QKD 003, Quantum Key Distribution: Components and Internal Interfaces	2017
2		TTAE.ET-GS QKD 004, Quantum Key Distribution Network: Application Interfaces	2017
3		TTAE.ET-GS QKD 011, Quantum Key Distribution (QKD); Component Characterization: Optical Component Characterization of QKD Systems	2018
4		TTAE.ET-GS QKD 008, Quantum Key Distribution (QKD); Module Security Specifications	2018
5		TTAE.IT-Y.3800, Quantum Key Distribution Network Overview	2020
6		TTAE.IT-Y.3804, Quantum Key Distribution Network - Control and Management	2021
7		TTAE.IT-Y.3802, Quantum Key Distribution Network - Functional Architecture	2021
8		TTAE.IT-Y.3801, Quantum Key Distribution Network Functional Requirements	2021
9		TTAR-01.0021, Use Cases for Machine Learning-Based Quantum Cryptographic Distribution Network (QKDN) Interworking Control and Management (Technical Report)	2021
10		TTAR-01.0022, Use Cases of Quantum Cryptography Network (Technical Report)	2021
11		TTAK.KO-01.0230, Quantum Key Distribution (QKD) Terminology Definition	2021
12		TTAK.KO-01.0225/R1 [Revised] QKD Network (QKDN); Interface between QKD System and Quantum Cryptographic Key Management System and YANG Data Model	2021
13		TTAK.KO-01.0214/R1 [Revised] Functional Architecture of Quantum Cryptographic Transmission Network	2021
14		TTAE.IT-Y.3807 Quantum Key Distribution Network – Service Quality Parameters	2022
15		TTAE.IT-Y.3806 Quantum Key Distribution Network – Service Quality Assurance Requirements	2022
16		TTAE.ET-GS QKD 018 Quantum Key Distribution (QKD); Orchestration Interface for Software Defined Networking	2022
17		TTAE.IT-Y.3805 Quantum Key Distribution Network - Software Defined Networking Control	2022
18		TTAE.IT-Y.3808 Framework for Integration of Quantum Key Distribution Network and Secure Storage Network	2023
19		TTAK.KO-01.0235 Guidance and Use Cases for Introduction and Operation of Quantum Key Distribution Network	2023
20		TTAE.IT-Y.3813 Quantum Key Distribution Network Interconnection - Functional Requirements	2023
21		TTAE.IT-Y.3810 Quantum Key Distribution Network Interconnection - Framework	2023
22		TTAE.ET-GS QKD 014 Quantum Key Distribution (QKD); Protocol and Data Format of REST-Based Key Supply API	2023
23		TTAK.KO-03.0026 Application Plans and Framework for Post-Quantum Cryptography in Optical Transmission Networks	2024

Classification	Organization Name	Standard Documents	Completion (Scheduled) Year
24	RRA	KS X ITUTY3800, Quantum Key Distribution Network Overview	2024
25		KS X ITUTY3807, Quantum Key Distribution Network – Service Quality Parameters	2017

As the demand for quantum technology standardization continues to increase in domestic and international industries, QuINSA (Quantum INdustrial Standard Association) was established as a global de facto standardization organization in August 2024, and its secretariat is currently located in South Korea. The standardization scope includes general quantum technology classifications such as quantum communication, quantum computing, and quantum sensing, and it is expected to contribute to the revitalization of the global quantum industry ecosystem through industry networking and testing/certification.

Figure I-9 Vision and Goals of QuINSA



Quantum Technology R&D Trends

01

II. Quantum Technology R&D Trends

Domestic and International Quantum Communication R&D Trends

Quantum communication is a technology that leverages single photons and the principles of quantum mechanics to revolutionize information security. In wired networks, the commercialization of quantum key distribution (QKD) technology and certification systems is becoming more tangible both domestically and internationally, while in wireless networks, experiments using satellites and drones are actively underway. There is a strong focus on developing next-generation security technologies, such as quantum random number generators (QRNG) for secure key generation, as well as quantum authentication, digital signatures, and secret sharing to ensure data integrity and authentication. Additionally, efforts are being made to establish quantum key distribution networks and repeaters for long-distance communication, integrate wired and wireless technologies, develop error correction and entanglement purification for stable data transmission, and validate technologies through testbeds to prepare for commercialization. This chapter examines domestic and international R&D trends in quantum cryptography, quantum networks, quantum communication protocols, and their applications.

Table II-1 Core R&D Trends in Quantum Communication

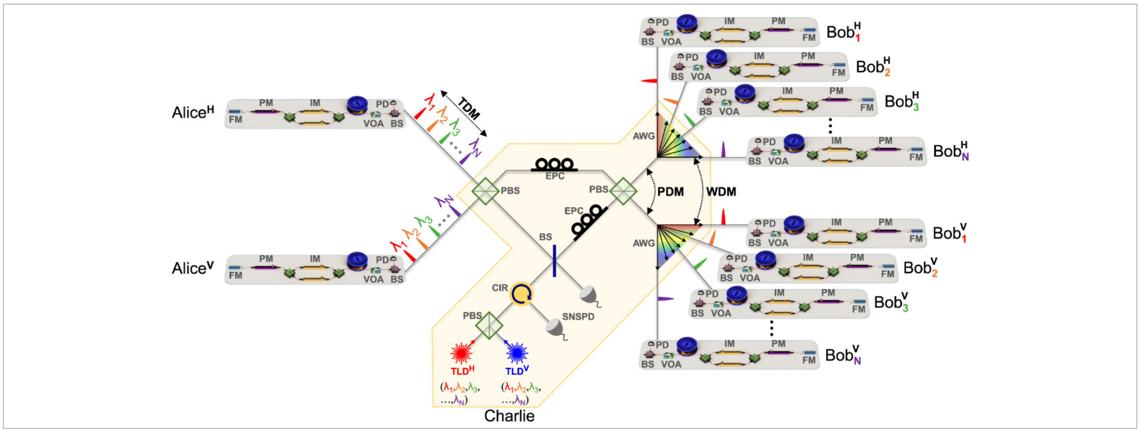
Category		Detailed Contents
Quantum Cryptography	Quantum Cryptography Concepts	· Concepts of quantum cryptography
	Wired Quantum Key Distribution	· R&D trends in Prepare and Measure (P&M) quantum key distribution (including BB84 QKD, distributed-phase-reference protocol, continuous-variable QKD, high-dimensional QKD, passive QKD), and measurement-device-independent protocols (including measurement-device-independent QKD, twin-field QKD, mode-pairing QKD)
	Wireless Quantum Key Distribution	· R&D trends in satellite quantum key distribution, drone quantum key distribution, and underwater quantum key distribution
	Quantum Key Distribution Implementation Technology	· Technology and research trends of quantum key distribution implementation technology, and application areas

Category		Detailed Contents
Quantum Cryptography	Quantum Random Number Generator	· Technical trends in optical quantum random number generators and non-optical quantum random number generators · R&D trends in high-speed quantum random number generators, continuous-variable-based quantum random number generators, device-independent quantum randomness, and quantum random number generators in quantum computers
	Quantum Authentication	· R&D trends in quantum identity authentication (QIA), and application areas
	Quantum Electronic Signature	· Technical trends in classical electronic signatures, Gottesman-Chuang electronic signatures, and quantum electronic signatures using quantum key distribution · Research trends in electronic signatures using OTP, and application areas
	Quantum Secret Sharing	· Technology and research trends in quantum secret sharing, and application areas
	Quantum-Based Encryption	· R&D trends in quantum-based stream encryption, quantization of public key cryptography, and quantization of homomorphic encryption
Quantum Networks	Quantum Key Distribution Network	· Technical trends in international standardization by ETSI and ITU-T, software-defined networking (SDN), multi-vendor interoperability, quantum key services, and service continuity · Case studies of DARPA, SECOQC, Tokyo UQCC, Indian, Cambridge, and Chinese satellite-fiber integrated broadband quantum key distribution networks, and the Berlin quantum key distribution testbed construction
	Quantum Repeater	· R&D trends in quantum repeaters
	Quantum Communication Network	· R&D trends in quantum communication networks
Quantum Communication Protocols and Applications	Quantum Error Correction	· Technology and research trends in quantum error correction technology (quantum error digitization, quantum error types, quantum error correction procedures) and related algorithms (Shor code, stabilizer code, Steane code, Bacon-Shor code, surface code) · Trends by application area, such as quantum key distribution, quantum repeaters, the impossibility of cloning quantum states and error correction, quantum communication network coding, and error correction in multi-user quantum communication networks
	Entanglement Purification	· R&D trends in basic theory and entanglement purification
	Quantum Communication Test Network	· Technical trends in OpenQKD (Berlin, Madrid, Poznań, Vienna testbeds), China's quantum communication network (wired, wireless), Washington Metropolitan, LiQuiDNET, IEQNET, UKQN testbeds · Research trends in quantum communication networks such as OpenQKD, EU QLA, QuaNeCQT, and Chinese and domestic open quantum testbeds.
	Quantum Cryptographic Communication Test Verification	· R&D trends in quantum cryptographic communication test verification

Quantum cryptography is being researched in various fields, including quantum key distribution (QKD), random number generation, authentication, signatures, and secret sharing, and is particularly applied in the financial, IoT, and military sectors. In wired communications, QKD technologies based on protocols like BB84 and MDI-QKD are notable, while in wireless communications, satellite, drone, and underwater quantum communication technologies are gaining attention. Quantum authentication technology, combined with QKD, prevents public channel message tampering, and authentication methods utilizing Bell states and quantum direct communication through Quantum Identity Authentication (QIA) have been proposed. This technology provides a security foundation as a core element of the quantum internet, and it is expected to enhance the security and efficiency of encryption and public key cryptography technologies in the future. Domestically, academic institutions such as Korea Institute of Science and Technology (KIST), Electronics and Telecommunications Research Institute (ETRI), Korea Institute of Science and Technology Information (KISTI), and Korea University, and industrial entities like SK Telecom, KT, WooriNet, FISYS, and Coweaver have independently developed and tested wired QKD systems. In particular, KIST and KT, through joint research, introduced time, wavelength, and polarization multiplexing technologies into the QKD system and announced the results of a 1×64 network expansion experiment and a 1×4 network operation.

Additionally, KIST succeeded in expanding a 2×N network by converting TF-QKD into a Plug&Play method to reduce implementation difficulty and applying multiplexing technology. Since June 2022, NSR has been developing quantum encryption protocols utilizing quantum entanglement, KRISS is researching high-quality quantum state generation devices and high-efficiency measurement technology, and joint real-environment application tests with KISTI are being conducted. Thus, the development of quantum authentication and signature technology for quantum internet security is being pursued. Meanwhile, research on quantum repeaters is being conducted under the leadership of ETRI with the participation of KT, SKT, WooriNet, Korea Advanced Materials (formerly PPI), and Chemoptics. Since 2022, they have been developing wired quantum repeaters and have implemented quantum entanglement distribution between two nodes over 50 km and multiple nodes over 20 km. Currently, research is underway with the goal of developing a system capable of stably distributing quantum entanglement in real environments over 100 km.

Figure II-1 Overview Diagram of Plug&Play TF-QKD Network Experiment

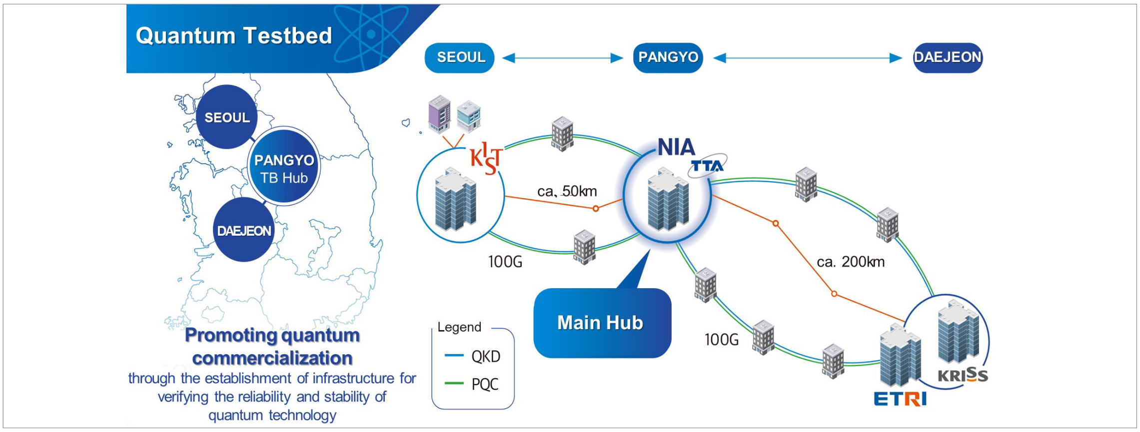


※ Source(s): Park, C. H. et al. (2022)

Quantum networks are being developed under the leadership of international standardization organizations (ETSI, ITU-T) in terms of software-defined networking (SDN), multi-vendor interoperability, quantum key services, and service continuity. There are confirmed cases of wide-band quantum key distribution network construction by major countries and institutions such as DARPA (Defense Advanced Research Projects Agency), SECOQC (Secure Communication based on Quantum Cryptography), Tokyo UQCC (Updating Quantum Cryptography and Communications), China's satellite-fiber integrated network, and the Berlin OpenQKD testbed.

Additionally, research on quantum repeater technology and quantum communication networks as a whole is actively underway to overcome the distance limitations of quantum communication. Looking at relevant major domestic trends, several institutions, including telecommunication companies (SKT, etc.) and major base institutions (KIST, ETRI, KRISS, TTA) including the National Information Society Agency (NIA), are cooperating to build a quantum communication network, an important infrastructure for commercialization and demonstration of quantum cryptographic communication technology, in the Seoul-Pangyo and Pangyo-Daejeon sections in 2024. Based on this, an open quantum testbed will be operated for testing and verifying interworking technology between quantum cryptographic communication, post-quantum cryptography, and heterogeneous QKD systems. This test network is expected to play a crucial role in building quantum communication infrastructure in the public and private sectors through security and performance verification of quantum cryptographic communication equipment and software, and long-distance transmission tests.

Figure II-2 Configuration Diagram of Quantum Communication Testbed



In the quantum communication protocols and applications field, the content regarding quantum error correction (QEC) technology, an essential technology to ensure the reliability of quantum computers, was newly covered this year. Quantum error correction technology, which detects and corrects errors caused by the sensitivity of quantum states, also plays an important role in quantum communication by correcting errors that may occur during information transmission, thus ensuring reliability. In particular, it was confirmed that active development of technologies is being carried out to enhance reliability and efficiency through various algorithms such as Shor code and surface code for quantum error correction, and real-time error detection and resource optimization in quantum key distribution, repeaters, and multi-user networks. In addition, entanglement purification theory and related research are also receiving attention.

Following the establishment of major domestic and international quantum communication testbeds, such as OpenQKD, China's wired and wireless quantum communication network, Washington Metropolitan, LiQuiDNET (The Long Island Quantum Information Distribution Network), IEQNET (The Illinois-Express Quantum Network), UKQN (The UK Quantum Network), network technology research is also expanding through projects such as OpenQKD, EU QIA (Quantum Internet Alliance), and QuaNeCQT (Quantum Networks to Connect Quantum Technology). Furthermore, test and evaluation research for verifying the reliability of quantum cryptographic communication technology is being conducted in various regions.

02

Domestic and International Quantum Sensing R&D Trends

Quantum sensors are sensor systems in the form of quantum systems that measure physical quantities with high sensitivity using phenomena such as quantum coherence, interference, entanglement, and squeezing. Representative examples include quantum clocks, quantum gyroscopes and accelerometers, gravimeters, magnetometers, radio wave receivers, and imaging sensors. These can be used in various fields such as navigation, underground structure detection, early detection of natural disasters, medical diagnosis, healthcare, semiconductors, and defense. This section examines domestic and international R&D trends in each sensor area.

Table II-2 Core R&D Trends in Quantum Sensing

Category	Detailed Contents
Quantum Inertial Sensors	· R&D trends in quantum gravity sensors in major countries such as the United States, Europe, the United Kingdom, France, Germany, and China · R&D trends in acceleration and rotation sensors, such as atom interferometer-based gyroscopes, NV center-based gyroscopes, and atomic spin gyroscopes, in major countries such as the United States, Europe, the United Kingdom, France, Japan, and China · R&D trends in quantum gravity sensors conducted jointly by KRISS, KIST, Chonnam National University, and NNFC etc.
Quantum Time · Frequency	· R&D trends in various quantum time/frequency sensors, such as high-precision small atomic clocks and ultra-small chip-scale atomic clocks · R&D trends in quantum time/frequency sensors at standards-related institutions in major countries such as the US NIST, UK NPL, German PTB, French SYRTE, Chinese NIM, and Japanese NICT · R&D trends in application fields such as EU's smart networks for energy and communication · R&D trends in quantum time sensors through KRISS-centered university cooperation, and mobile/satellite-mounted optical clock development, etc.
Quantum Electric Field · Magnetic Field Sensor	· R&D trends such as US GHz/THz sensors and images, Rydberg atom-based gas sensors, and R&D trends such as Europe's non-destructive band electric field imaging technology · R&D trends such as Canada's new quantum LiDAR technology using time-frequency entanglement · R&D trends in NV center-based magnetic field sensors in the US, UK, Germany, China, Japan, etc. · R&D trends in quantum electric/magnetic field sensors at KRISS, ETRI, KIST, Pusan National University, etc.

Category	Detailed Contents
Quantum Optical Sensors	· R&D trends such as imaging in the mid-infrared based on Germany's quantum nonlinear interferometer · R&D trends in spy satellites detecting fighter jets in China's defense sector · R&D trends in quantum optical applications in countries other than China, such as the US, UK, Germany, Italy, Austria, Australia, and Singapore · R&D trends in optical sensors at Pusan National University, ETRI, Agency for Defense Development (ADD), KIST, KAIST, etc.
Quantum Measurement	· R&D trends in quantum measurement fields in countries such as the US, China, Italy, Austria, and France · R&D trends in multi-phase sensing and distributed quantum phase sensing at KIST, ADD, KRISS, etc.

Quantum inertial sensors utilize quantum phenomena such as atoms, matter waves, and optomechanical systems to measure physical quantities like gravity, acceleration, and rotation. They are increasingly being used in various fields such as defense, autonomous vehicles, disaster preparedness, and resource exploration. In particular, quantum gravimeters and gravity gradiometers are useful for underground structure detection and early detection of volcanoes and earthquakes, and research on miniaturization and airborne development is underway. The US Sandia National Lab is developing high-sensitivity quantum gravimeters, and the Department of Defense emphasizes the importance of gravity navigation in GPS-denied environments. In addition, M Squared has commercialized quantum gravimeters, and recent trends show that France's Exail has developed quantum gravimeters for monitoring volcanoes and underground structures. In 2024, Boeing successfully tested an atom interferometer-based inertial sensor mounted on an aircraft, and China achieved the feat of developing a space-based atom interferometer gyroscope and mounting it on the ISS. It is also confirmed that Imperial College and Exail are strengthening cooperation for the development of quantum accelerometers and gyroscopes.

Domestically, quantum gravity sensor research is actively being conducted at KRISS, KIST, National Nanofab Center (NNFC) and Chonnam National University. In particular, KRISS has been developing atom interferometer-based quantum gravity sensors since 2011, and through core foundational technology research from 2019 to 2022, it has secured mobile and miniaturization technology, achieving world-class performance. Since 2023, KRISS and KIST have been jointly developing a cesium atom-based atomic fountain type quantum gravimeter with sub-μGal accuracy. In addition, for acceleration and rotation sensor technology, Agency for Defense Development (ADD) has been researching atomic spin gyroscopes with KRISS and Pusan National University since 2014, developing a prototype with a bias stability of 0.2 deg/h, and producing and technology transferring xenon-based atomic vapor cells.

Figure II-3 Quantum Gravity Sensor Under Development at KRISS

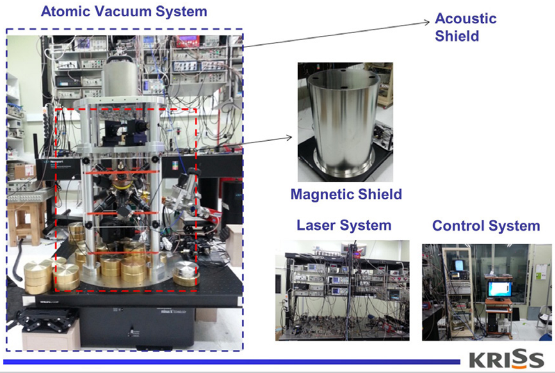


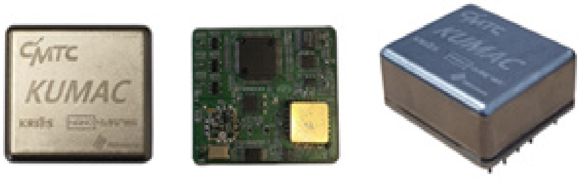
Table II-3 Comparison Table of Performance Levels of World-Class Quantum Gravimeters

Item (Unit)	France (SYRTE)	Germany (Braunschweig)	USA (Stanford)	China (NIM)	China (CNS)	Korea (KRISS)
Accurav (nm/s²)	20 Wave front	30 Wave front	30 No wave	50 Wave front	30 Coriolis	27 Wave front
Sensitivity ($nm/s^2 \cdot Hz^{1/2}$)	60 Vibration	96 Vibration	80 Vibration	440 Vibration	20 Detection	56 Vibration
Stability	2 nm/s^2 @1000s	0.5 m^2/s^2 @1day	N/A	2 nm/s^2 @30000s	3 nm/s^2 @200s	0.7 nm/s^2 @1day
Interrogation Time T (ms)	80	260	160	70	300	80
Repetition Rate (Hz)	3	0.7	1	0.8	1	2
Method	Free-fall	Atom Interferometry	Atom Interferometry	Free-fall	Atom Interferometry	Free-fall

Quantum time/frequency sensors utilize quantum phenomena to generate, synchronize, and measure time and frequency with high accuracy and stability. Research requiring precise reference time and frequency sources is actively being conducted in advanced industries, defense, and broadcasting/communication fields. Research is being conducted on quantum clocks based on optical frequency transitions, nuclear clocks using nuclear transitions, ultra-small atomic clocks, and satellite-mounted clocks. High-precision clocks play an important role in improving the accuracy of navigation systems based on quantum inertial sensors. Major national standards organizations, the EU, and domestic KRISS and universities are leading the development of quantum time sensors and optical clocks. Particularly in 2024, JILA and NIST are developing next-generation atomic clocks using ^{229}Th nuclear transitions, while Germany has reported research measuring frequency differences according to altitude using portable optical clocks. Additionally, Japan has developed

Cs, Sr, and Yb optical clocks at NMIJ, NICT, and RIKEN, and conducted long-distance frequency comparison studies using portable optical clocks. China has developed various optical clocks and portable optical clocks, and is confirmed to be conducting experiments to measure gravitational redshift in space stations. In Korea, KRISS is developing ultra-high precision atomic clocks such as the optically pumped atomic clock (KRISS-1), atomic fountain clock (KRISS-F1), and optical clock (KRISS-Yb1) in collaboration with universities and industries. From 2014 to 2020, KRISS also worked on developing ultra-small Chip-Scale atomic clocks with National Nano Fab Center and NEPCORES Co., Ltd.

Figure II-4 Developed Ultra-Compact Chip-Scale Atomic Clock



Size : 25cm³, Power Consumption : 370mW

※ Source(s): KRISS, National Nano Fab Center, NEPCORES Co., Ltd.

Quantum electric field sensors, with sensitivity exceeding classical technology, can measure electric fields from DC to THz bands in a wide frequency range, attracting attention as a promising technology specialized in defense and communication fields. Research is actively conducted in the US, Europe, and China, driven by the development of Rydberg atom technology. The US NIST and the University of Colorado lead research in the communications field, and DARPA and the US Army conduct research for defense technology. In addition, NASA has started research for satellite mounting, and China is developing rapidly, announcing results that exceed the performance of existing sensors. NIST demonstrated the possibility of high-quality video streaming by detecting guitar playing, TV, and game console signals using quantum electric field sensors and demodulating them, and announced research results using Cs and Rb atom-based sensors.

In addition, the University of Warsaw, Poland, announced that broadband microwave-optical conversion technology using room temperature Rydberg atoms can be applied to quantum computers and quantum electric field sensors. Domestic KRISS, ETRI, and Pusan National University jointly conducted electromagnetic wave measurement research based on quantum electric field sensors that can measure electric fields in a wide band from 1 GHz to 1 THz from 2021 to 2023. In 2016, Pusan National University announced a study that measured electromagnetic induction transparency and Autler-Townes Splitting frequencies using a Rydberg atom spectroscopy system, and in

2023, KRISS demonstrated and reported electric field measurement technology by fabricating its own atomic devices necessary for quantum electric field sensors.

Research on quantum magnetic field sensors using atomic vapor cells and solid-state point defects has been actively conducted recently. Quantum magnetic field sensors can operate at room temperature and are easy to miniaturize, so their application in various fields such as defense, industry, and medicine is expected. In particular, they have high potential for applications in measuring geomagnetic field distortion, precision measurement of target magnetic fields, wearable magnetoencephalography imaging, and 3D MRI. Overseas, industrialization research is being conducted mainly by small and medium-sized enterprises and startups based on university research teams. In the United States, Twinleaf, Quspin, and Fieldline are developing and selling small atomic magnetometers, and Quspin and Fieldline are also using them in wearable magnetoencephalography and MEG systems. Quantum Diamond Technology and Lockheed Martin are developing biomarker detection and GPS-denied navigation systems using diamond NV center-based magnetometers. In Europe, Switzerland's Qnami and Qzabre are producing and selling diamond-based nano magnetic field imaging scanners, and China's CiQTEK is developing and selling room temperature-operated nano magnetic field imaging scanners using diamond NV centers.

In Korea, atomic vapor-based quantum magnetic field sensors have been studied at KRISS, ADD, Seoul National University, Korea University, and Pusan National University for more than 10 to 15 years, and diamond NV center-based quantum magnetic field sensors have been studied at KRISS, KIST, Korea University, Seoul National University, GIST, and UNIST for more than 5 years. Korea University is developing micro-magnetic field imaging and compact magnetometers using single NV centers and ensemble NV centers, and is researching applications in industrial and medical fields in collaboration with LG Electronics. KRISS possesses high-level technology, having transferred SQUID-based magnetoencephalography/magnetocardiography measurement systems to overseas (Australia's Compumedics) and domestic companies (AMCG). KRISS is also jointly conducting diamond-based quantum magnetic imaging research with KIST and Korea University, and is performing current distribution imaging studies of lithium-ion batteries.

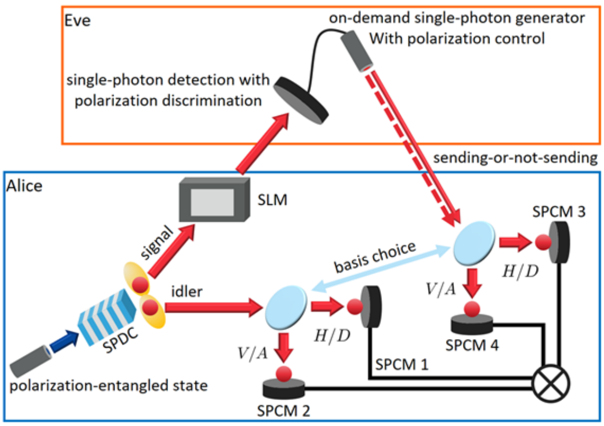
Quantum optical sensors are technologies that overcome classical measurement limitations by utilizing quantum light sources such as entangled states. Research is actively being conducted in various fields such as quantum illumination, quantum LiDAR, quantum radar, quantum imaging, and quantum gas sensing. By using the quantum gain of quantum light sources, it is possible to achieve high-sensitivity measurements that exceed classical resolution and sensitivity limitations, and the possibility of measurement without interacting with the object through techniques such as ghost imaging is also being reported. In particular, these technologies are expected to play an important role in areas such as bio fields and stealth aircraft detection countermeasures. Germany is developing mid-infrared imaging technology based on quantum nonlinear interferometers, and China is researching fighter jet detection technology through spy satellites. The University of Toronto in Canada developed a quantum LiDAR technology protocol using time-frequency entanglement, suggesting the possibility of improving the sensitivity of quantum LiDAR technology by improving the signal-to-noise ratio by 43 dB. In addition, Kyoto University in Japan and Zhejiang University in China announced technologies to improve the signal-to-noise ratio through quantum light source development using a wide wavelength band and unobserved photon imaging, respectively.

In Korea, quantum light source technology is being researched by KRISS, ADD, ETRI, Pohang University of Science and Technology, and Pusan National University as nonlinear-based technology such as spontaneous parametric down-conversion and spontaneous four-wave mixing, and atomic vapor cell-based technology is secured by Pusan National University and KRISS. In addition, research is actively being conducted at UNIST, ETRI, KIST, and KAIST to generate deterministic quantum light sources and develop high-efficiency light sources using semiconductor quantum dots and point defects. Recently, ETRI has secured single-emitter-based quantum light sources and nonlinear-based quantum photon pair technology, and is conducting research on quantum imaging, quantum microscopy, and measurement technology that exceeds classical optical sensitivity limitations and quantum microscopy research for biological tissue measurement.

Quantum metrology is a technology that exceeds classical measurement limitations by using entangled states or vacuum squeezed states, focusing on quantum parameter estimation and quantum hypothesis testing. In quantum parameter estimation, measurement precision is improved by utilizing entangled states or vacuum squeezed states, and accuracy exceeding classical measurement limitations can be achieved with fewer photons. Active research is being conducted in the field of quantum metrology in the United States, China, Italy, Austria, and France, focusing particularly on quantum parameter estimation and high-precision measurement technology. In 2024, Shenzhen University of Science and Technology in China not only succeeded in an experiment approaching the Heisenberg limit with 40 photon number states using a programmable photon number filter method in a superconducting microwave cavity, but also proved that high-resolution 3D imaging is possible in a wide area even during the day by mounting a single photon LiDAR system on an airplane. In addition, it can be seen that the University of Rome La Sapienza in Italy has developed a variational quantum algorithm that efficiently optimizes quantum multi-phase sensors, improving precision and noise resistance.

Domestically, KIST, ADD, KRISS, etc. are conducting R&D on multi-phase sensing and distributed quantum phase sensing technology, and efforts are being made to commercialize quantum measurement technology and develop high-precision measurement systems. Meanwhile, ADD is researching quantum illumination theory and measurement methods, conducting research considering quantum memory performance limitations and quantum channel effects, and conducting single-pixel security imaging experiments using entangled photon pairs.

Figure II-5 Quantum-secured Single-pixel Imaging



※ Source(s): Optica 10, 1461 (2023)

03

II. Quantum Technology R&D Trends

Domestic and International Quantum Computing R&D Trends

Quantum computing technology, which goes beyond the limitations of existing computer systems, can process problems that are impossible to solve with existing computing based on quantum theory, and can have a significant economic impact on various industries such as defense, finance, medicine, and artificial intelligence. Accordingly, countries around the world are actively conducting research and development for the practical use and generalization of quantum computing through government-led R&D investment and private sector cooperation. This section analyzes domestic and international R&D trends for the six hardware platforms of quantum computing, and covers the development status of software and algorithm development, especially in the field of quantum AI.

Table II-4 Core R&D Trends in Quantum Computing

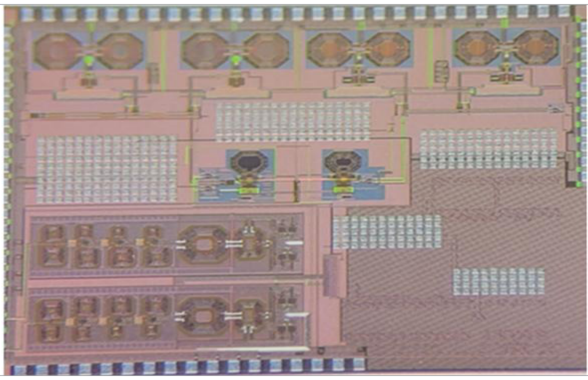
Category	Detailed Contents
Superconducting Quantum Computing	· R&D trends in superconducting qubit technology, such as process improvements for enhancing transmon qubit performance, novel qubits, Al-InAs-Al, 2DBG, and graphene-based qubits · R&D trends in high-performance, multi-qubit, and high-dimensional superconducting quantum gate technology · R&D trends in superconducting quantum computer application technology, such as VQE performance improvement, many-body quantum system simulation, and quantum error mitigation techniques · R&D trends in quantum error correction technology, such as demonstrations of quantum error correction technology and novel qubits for efficient quantum error correction · R&D trends in element technologies for scaling up superconducting quantum computers, such as cryogenic cooling technology for superconducting quantum computing, hardware technology for measurement and control of superconducting quantum processors, packaging technology for scaling up quantum processors, and quantum processor module connection technology
Semiconductor Quantum Dot Quantum Computing	· R&D trends in spin qubit host quantum materials, multi-qubit control technology, and scalable integrated quantum processor technology
Ion Trap Quantum Computing	· R&D trends in ion trapping technology, quantum gate and quantum algorithm implementation technology, and qubit scaling technology
Photonic Quantum Computing	· R&D trends in quantum light generation technology, quantum light measurement technology, quantum computation space expansion technology, quantum error correction technology, and photonics-based quantum simulators

Category	Detailed Contents
Diamond NV Center Quantum Computing	· R&D trends in diamond growth and NV center formation, electron spin and nuclear spin control, qubit state measurement, and multi-qubit connection technology
Rydberg Atom Quantum Computing	· R&D trends in neutral atom rearrangement technology, 3D qubit systems, Rydberg quantum line technology, quantum simulation of Rydberg atoms, and 3D atom imaging technology
Quantum Computing Software	· R&D trends in quantum algorithms, NISQ technology-based quantum algorithms, quantum software for hardware interfaces, and quantum algorithm cloud platforms
Quantum Machine Learning· Quantum AI	· R&D trends in early research on quantum machine learning query/sample complexity, machine learning technology utilization in quantum information processing, quantum support vector machines, quantum random-access memory, and NISQ era quantum machine learning/quantum artificial intelligence research

Superconducting qubit-based quantum computing platforms boast high scalability due to their manufacturability using existing semiconductor processes and have the advantage of being able to define desired frequency bands by designing energy levels. Superconducting qubits are classified into various types such as charge, phase, flux, transmon, and fluxonium, and based on their different characteristics, various companies are building their own platforms. In this field, research on enhancing transmon qubit performance, developing novel material-based qubits, and high-performance multi-qubit quantum gate technology is actively underway, and VQE performance improvement, quantum error mitigation, and error correction technology development are being carried out. Additionally, research on cryogenic cooling technology, hardware technology, packaging, and module connection technology for scaling up superconducting quantum computers continues to advance. In 2024, Google announced research results that successfully performed quantum error correction by implementing a distance-7 surface code with 101 qubits using 105 qubits. According to this, qubit performance has been significantly improved, recording a T_1 time of 68 μs and a T_2 time of 89 μs, and not only has the survival time of logical qubits been greatly improved with real-time decoding function, but also important achievements have been made, such as implementing a distance-29 repetition code, further advancing the feasibility of fault-tolerant quantum computing.

In Korea, a joint research team from the Korea Research Institute of Standards and Science, Korea University, and Sungkyunkwan University has developed the country's first frequency-tunable superconducting transmon qubit on a silicon substrate. Additionally, researchers at the Korea Research Institute of Standards and Science have designed transmon qubits and state measurement resonators on a two-dimensional substrate, developing a 5-qubit quantum processor capable of individual qubit control. A research team from Pohang University of Science and Technology has developed a CMOS-based quantum processor control chip, implementing technology that can generate and analyze RF signals at extremely low temperatures of 4 K, aiming to solve performance degradation issues in superconducting quantum computers.

Figure II-6 4K Cryogenic Quantum Control Chip



※ Source(s): Kang (2022)

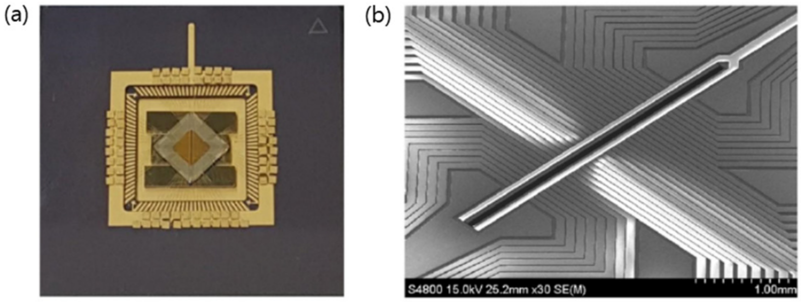
The second quantum computing platform, semiconductor quantum dots, forms an energy well with a structure similar to a field-effect transistor, and uses the spin state of electrons or holes trapped there as qubits. It is showing a rapidly developing aspect due to recent advancements in silicon substrate isotope purification and spin noise minimization technology, and is characterized by high compatibility with CMOS processes, which is advantageous for manufacturing large-scale quantum processors. In addition, hole spin qubit technology using P-type semiconductors such as germanium is also opening up new possibilities. In the field of semiconductor quantum dot quantum computing, research on spin qubit host quantum materials, multi-qubit control technology, and integrated quantum processor technology is actively underway. As a major research trend in 2024, the TuDelft-Qutech group demonstrated single gap tuning of 16 quantum dots using germanium material, and the Dutch quTech group derived basic results for 2D qubit expansion through high-fidelity spin shuttling. RIKEN group in Japan achieved 99.9% measurement fidelity for silicon spin qubits, and the UNSW group in Australia developed a 4-qubit processor and high-fidelity 2-qubit gates. In addition, Silicon Quantum Electronics and Diraq announced plans to develop quantum processors with more than 1 million qubits by 2030.

In Korea, the KRISS has secured quantum devices and basic technology infrastructure and possesses the technology to grow III-V based semiconductor quantum dots and AlGaAs and InGaAs HEMTs with high electron mobility. In addition, Seoul National University, KIST, KAIST, Pohang University of Science and Technology, and the Korea Research Institute of Standards and Science possess quantum material property evaluation technology and have been researching since 2019 with the goal of securing 5-qubit gate fidelity through the National Research Foundation of Korea's 'Semiconductor Quantum Dot Programmable Quantum Computing System' project. Domestic researchers have succeeded in demonstrating 4-qubit operation and CPHASE type 2-qubit gates for GaAs spin qubits, successfully implementing 5-qubit addressing of silicon 5-qubit devices with domestic technology, and are working to develop automatic tuning technology for spin qubits and quantum dot devices.

Third, ion trap quantum computing technology performs quantum calculations by capturing individual ions using laser cooling and electromagnetic potential and using them as qubits. The trapped ions maintain long quantum coherence times by being well separated from the external environment and can perform initialization, measurement, and quantum gates with high fidelity. In addition, high-reliability quantum entanglement is possible using the quantum motion between ions, and high connectivity acts as an important advantage of ion trap-based quantum computers. Active research is being conducted in the field of ion trap quantum computing on ion trapping technology, quantum gate and algorithm implementation technology, and qubit expansion technology, which greatly supports performance improvement and scalability enhancement. As a newly added trend, IonQ and Quantinuum plan to apply high-fidelity ion qubit manipulation technology to next-generation ion trap quantum computers, and Oxford University has developed a technology that can implement individual ion qubit manipulation and quantum entanglement gates without lasers. Tsinghua University captured 512 ions using a two-dimensional array and experimented with Ising model interactions with 300 ions, and Duke University compared quantum error correction methods with ion qubits. In addition, the Innsbruck group succeeded in implementing the quantum entanglement state of ion-photon pairs over a distance of 101 km.

Domestically, Seoul National University and Sungkyunkwan University are conducting barium ion research to overcome the limitations of optical loss and detection performance due to the use of ultraviolet wavelengths of ytterbium ions, and Sungkyunkwan University has succeeded in capturing barium ions. Each university independently develops capture devices and uses them for experiments. Macro capture devices include 4-rods, blades, and partitioned devices, and in micro capture devices, Seoul National University and Sungkyunkwan University are developing chip-based devices, and Pohang University of Science and Technology is developing multi-layered micro capture devices.

Figure II-7 (a) Photo of the Semiconductor Chip-Based Ion Trap Device Developed at Seoul National University
(b) Close-up Image of the Chip Trap Device with Multiple Electrodes

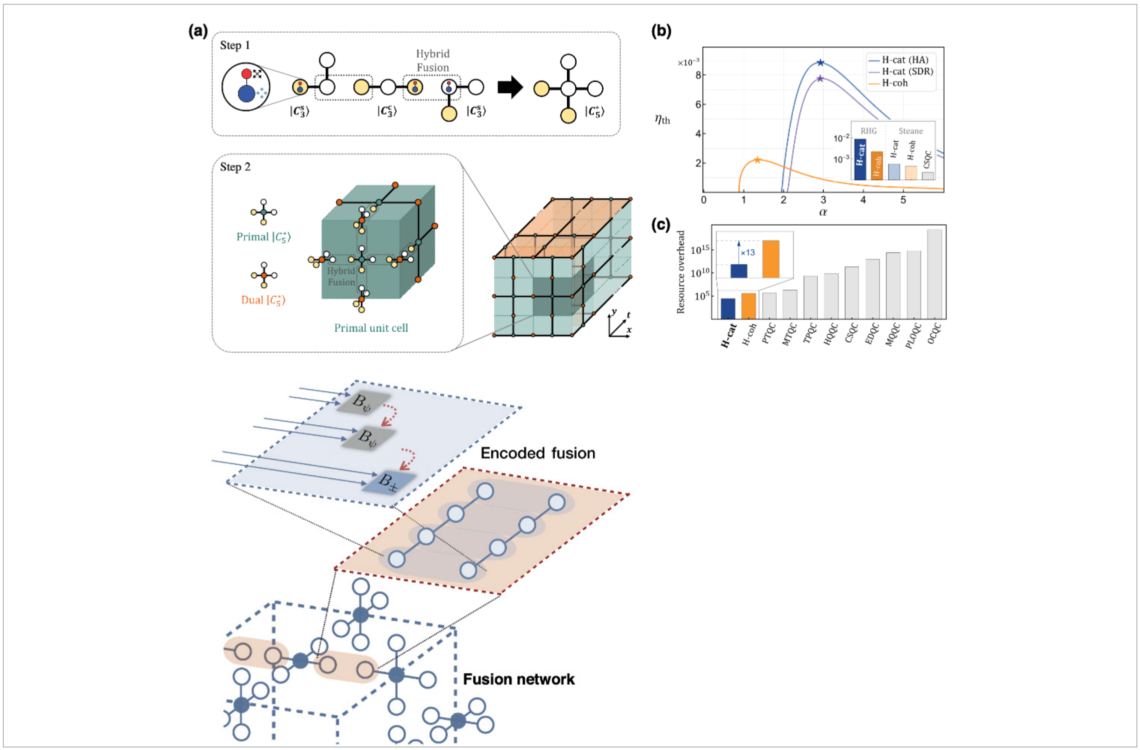


※ Source(s): Kang (2022)

Fourth, photonic quantum computing is attracting attention as a technology suitable for quantum communication and quantum network expansion by utilizing the mobility of photons and their robustness against decoherence. To implement this, technologies for generating, controlling, and detecting quantum light sources have greatly advanced, and recently, quantum advantage experiments have been conducted that successfully perform computations impossible with existing supercomputers using photonics-based quantum simulators. In addition, research using integrated photonics technology is actively underway, and by combining it with quantum computation space expansion technology and quantum error correction technology, the performance and feasibility of quantum computers are greatly improved. Recently, studies that have led to important progress in photonic quantum computing research have been conducted one after another. In 2023, US research teams developed PNRDs that can accurately measure the number of photons up to 100, and research teams from the Technical University of Denmark and the University of Tokyo, Japan, demonstrated the possibility of universal quantum computing by generating large-scale 2D cluster states through continuous-variable quantum photonics systems. In addition, Quandela developed a 6-qubit quantum computer, and PsiQuantum announced a photonic quantum computing platform based on silicon photonics, stating that it aims to develop a practical fault-tolerant quantum computer.

In the case of Korea, the KAIST research team succeeded in generating a 3D cluster entangled state using time-frequency modes, making significant progress in fault-tolerant quantum computing, and ETRI, in joint research with the University of Trento, Italy, developed a 4-photon entangled silicon photonic integrated circuit to implement a high-purity and visibility quantum entangled state. Recently, the KAIST research team designed a fault-tolerant architecture that significantly improves the photon loss threshold and resource efficiency by proposing a DV-CV hybrid qubit that combines a bosonic cat quantum error correction code with single photons. In addition, a new quantum error correction encoding method applicable to fusion-based quantum computers was developed to significantly improve the loss threshold and resource efficiency. Furthermore, meaningful results were achieved in quantum simulator research through the implementation of 4D quantum states using single photons and the experimental implementation of variational quantum eigensolvers.

Figure II-8 **Schematic Diagram and Threshold of the DV-CV Hybrid Qubit Proposed by KIST & New Fusion-Based Quantum Computing Encoding Scheme Proposed by KIST**



※ Source(s): Lee (2024), Song (2024)

Fifth, diamond NV centers are materials that are attracting attention in quantum information technology due to their long coherence time and excellent optical properties. Diamond growth, NV center formation, spin state control, and coherence time extension technologies are required for the development of quantum computing. To utilize the electron spin and surrounding nuclear spins of NV centers, it is essential to have technologies that stably read and control spin states, increase the number of qubits, and secure connectivity. To this end, active development is underway in technologies such as high-quality diamond growth, precise NV center formation, electron spin and nuclear spin control, qubit state measurement, and connecting multiple qubits to increase system scalability.

Domestic research teams are conducting research to grow high-quality single-crystal diamonds and improve the quantum quality of NV centers using chemical vapor deposition (CVD) and ion implantation technology. The KIST Quantum Information Research Division is improving photon collection efficiency through diamond nanostructures and is conducting research on 5-qubit quantum computers and quantum algorithms using NV centers operating at room temperature. The Korea University research team has developed a 5-qubit quantum register that controls ^{13}C nuclear spins around NV centers and is researching nuclear spin search and initialization technology. In addition, domestic researchers are conducting research on quantum entanglement and computation implementation between NV centers, quantum interference experiments between electron spins and nuclear spins, and solving light crosstalk problems at room temperature.

Figure II-9 **5-qubit Diamond NV Center-Based Quantum Computer Unveiled at Quantum Korea 2023**

※ Source(s): KIST Quantum Information Research Division

Sixth, Rydberg-based neutral atom quantum computing is rapidly advancing as a technology that performs highly complex calculations using the Rydberg state of neutral atoms and implements arbitrary qubit connection structures by arranging atoms at intervals of several micrometers. Proof-of-concept for solving NP-complete problems using quantum adiabatic methods has been achieved, and since 2023, there has been a trend of transitioning to research on universal quantum computers based on quantum circuits. In particular, quantum error correction was successfully demonstrated for the first time, and research on qubit scale expansion, such as mid-circuit measurement and erasure conversion technology and trapping more than 10,000 atoms, is actively underway. In addition, precise rearrangement of neutral atoms to implement 3D qubit systems, quantum wire (neutral atom chain) technology using Rydberg states, quantum simulation, and 3D atom imaging technology are contributing to performance and scalability improvements. In 2023, Harvard and QuEra ushered in the era of quantum error correction (QEC) by implementing quantum error correction for the first time by configuring 40 logical qubits with 280 atoms. Pasqal successfully demonstrated trapping 1,000 atomic qubits in a cryogenic environment, along with rearrangement technology and fast qubit control based on FPGA. Princeton and Caltech achieved 1-qubit fidelity of 99.9% and 2-qubit Bell state fidelity of 99.85% using Yb and Sr atoms, respectively, securing high-fidelity quantum computing technology. Neutral atom qubits are evolving by comparing the efficiency of error correction algorithms based on surface codes and qLDPC codes through free rearrangement of atom arrays and the possibility of long-range operations. QuEra and Atom Computing are accelerating the development of scalable quantum computers by improving laser technology to trap and rearrange more than 1,000 qubits.

Domestically, in 2024, a research team at KAIST solved the Maximum Independent Set (MIS) problem and prime factorization problem using a Rydberg atom array platform and released the data for this. In addition, Rydberg interactions were used for many-body physics research such as implementing asymmetric Heisenberg systems and observing spin transport, and the Korea Research Institute of Standards and Science is conducting research on developing a neutral atom quantum computer platform and improving qubit control quality using Yb atoms.

In the field of quantum computing software, quantum algorithms, NISQ-based algorithms, software development for hardware interfaces, and quantum algorithm cloud platforms are being actively researched, greatly contributing to increasing the practicality and accessibility of quantum computing. Quantum AI utilizes the superposition and entanglement characteristics of quantum computing to quickly and efficiently process complex problems that are difficult to solve with existing AI technology, and improves the performance of AI algorithms through quantum machine learning (QML), quantum reinforcement learning (QRL), and quantum Boltzmann machines. In addition, research on query/sample complexity and applying machine learning technology to quantum information processing is actively being conducted in the field of quantum machine learning and quantum artificial intelligence, and technologies suitable for the NISQ era are being developed. These technologies focus on improving the performance of existing machine learning technology by utilizing the advantages of quantum computing. In particular, goal-oriented quantum advantage can be expected in the short to medium term in chemistry, new materials, and complex system analysis, and it is expected to expand to models that directly learn and predict quantum data when transitioning to the fault-tolerant quantum computing era.

Industrial Ecosystem Trends in Quantum Enabling Technology

01

III. Industrial Ecosystem Trends in Quantum Enabling Technology

Key Technologies and Materials, Components, and Equipment in Quantum Communication

The quantum industry is composed of materials, components, equipment, and services, including high-purity single crystals, single-photon detectors, and quantum computing clouds. If successful in securing the market early in the quantum industry, it is possible to stabilize the supply chain and pioneer overseas markets, but if it fails, there is a risk of falling into a vulnerable structure that relies on overseas for key materials, components, and equipment. In particular, in preparation for quantum technology export regulations in each country, diversification of the global supply chain and internalization of key technologies are essential. This section covers the status and supply chain information of materials, components, and equipment related to key technologies in the fields of quantum communication, sensors, and computers.

Table III-1 Definition of Materials, Components, Equipment, and Services

Category	Materials	Components	Equipment	Services
Definition	Materials that form the basis for making quantum components, etc.	Can operate independently and constitute part of the equipment	Instruments or environment maintenance instruments capable of providing services using quantum technology	Providing tangible and intangible products with quantum technology
Example	High-purity single crystal quantum materials, semiconductor materials, dielectric materials, superconducting materials, etc.	Single photon detector, QRNG chip, optical splitter, etc.	High vacuum chamber, cooling instrument, QKD instrument, etc.	Quantum cryptography services, quantum computing cloud, etc.

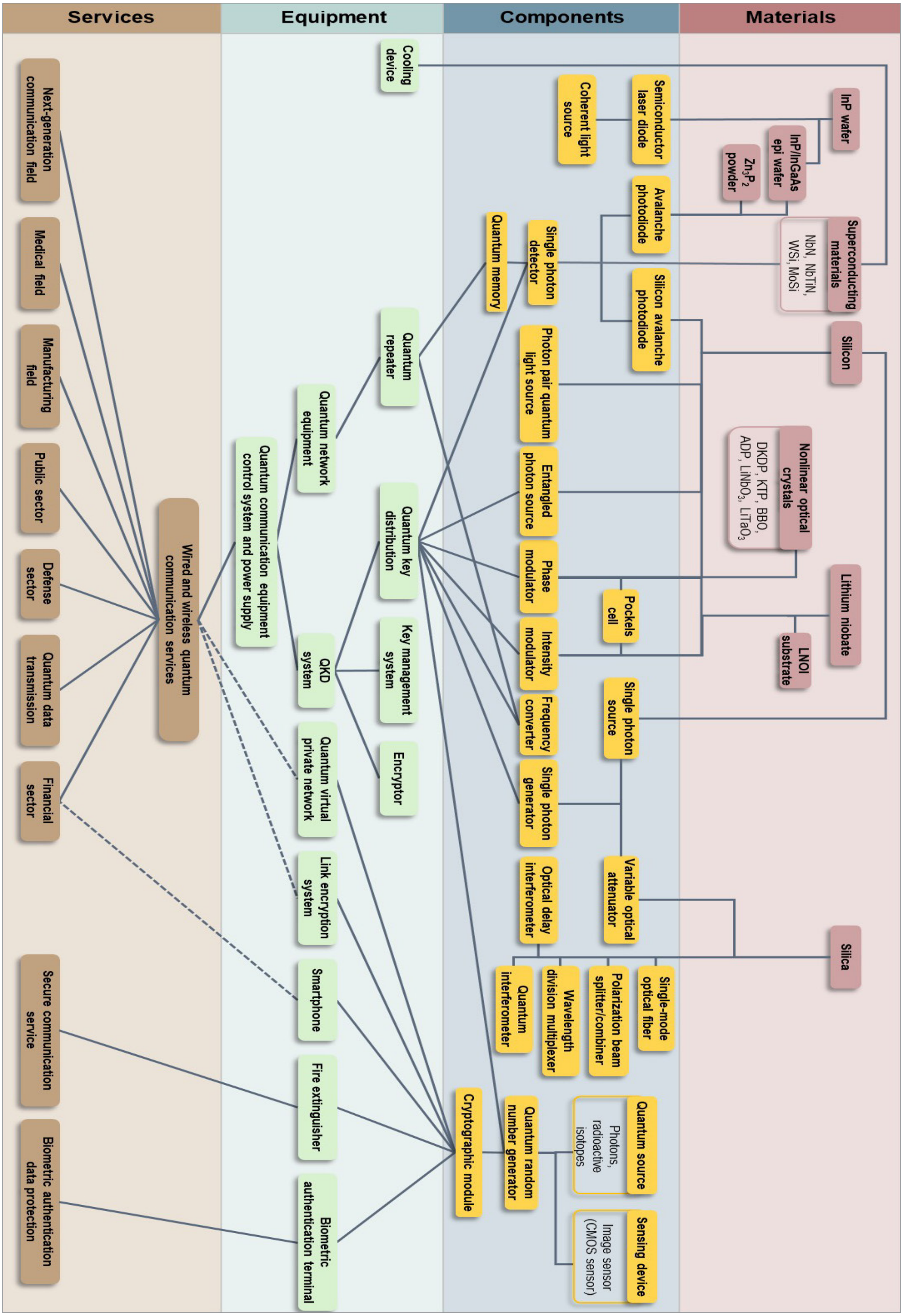
The materials required for quantum communication technology include indium phosphide, silica, and lithium niobate, which are key materials for high-speed electronic and optical devices, and superconducting materials also play an important role. In particular, lithium niobate is a material with strong electro-optic and nonlinear optical effects and is used as a key material for quantum photonics and high-speed optical modulation devices. In particular, lithium niobate on insulator (LNOI) wafers are advantageous for implementing optical integrated circuits and exhibit high performance in highly nonlinear devices such as entangled photon pair generation through periodic poling. LNOI wafers are being actively researched worldwide, and KAIST, ETRI, KIST, etc. are also conducting related technology development in Korea.

The key components of quantum communication technology include single-mode optical fibers, laser diodes, and avalanche photodiodes for quantum key distribution, as well as quantum random number generators and encryption modules, which are crucial components. The performance improvement of these components determines the efficiency of quantum communication systems. Additionally, quantum key distribution instruments and management systems, along with quantum random number-based security equipment, are essential instruments that enhance the security and reliability of quantum communication. Domestic representative suppliers of quantum communication components include LS Cable & System, DIMES, Dream Security, FISYS, Woorinet, Coweaver, EYL, and Korea Advanced Materials. The integration module technology for the transmitter and receiver of quantum key distribution systems is expected to play an important role in industrial revitalization through cost reduction and miniaturization. Internalizing domestic technology and leading in the global market are essential factors in enhancing the competitiveness of quantum communication technology.

Table III-2 List of Quantum Communication Materials, Components, and Equipment

Category 1	Category 2	Category 3	Product Name
Quantum Communication	Materials	Quantum Key Distribution	Indium Phosphide (InP) Wafer
			Epitaxial Wafer
			Zinc Phosphide (Zn_3P_2) Powder
			Silica (SiO_2)
			Silicon (Si)
			Lithium Niobate ($LiNbO_3$)
			Superconducting Materials (NbN, NbTiN, WSi, MoSi, etc.)
	Components	Quantum Key Distribution	Single-Mode Optical Fiber
			Laser Diode
			Avalanche Photodiode
			Phase Modulator
			Intensity Modulator
			Variable Optical Attenuator
			Quantum Random Number Generator
		Quantum Random Number Generator-Based Products	Quantum Random Number Generator
			Cryptographic Module
	Equipment	Quantum Key Distribution	Quantum Key Distribution Instrument
			Quantum Key Management System
		Quantum Random Number Generator-Based Products	Quantum Virtual Private Network
			Smartphone
			Secure Terminal
			Link Encryption Instrument
			Biometric Authentication Solution

Figure III-1 Quantum Communication Value Chain



02

III. Industrial Ecosystem Trends in Quantum Enabling Technology

Key Technologies and Materials, Components, and Equipment in Quantum Sensing

Quantum sensors are classified into quantum inertial sensors, quantum time/frequency sensors, quantum electric/magnetic field sensors, and quantum optical sensors depending on the physical quantity, and each sensor uses specialized materials, components, and equipment according to the measurement target. However, the principles used are often similar depending on the physical quantity, so some sensors can operate by sharing the same materials and components. As a result, various types of sensor technologies are developing in an interconnected manner.

Table III-3 Major Materials, Components, and Equipment for Implementing Quantum Gravimeters

Quantum Gravimeter Components	Required Materials, Components, and Equipment
Atomic Source	· Rubidium (Rb), Cesium (Cs), Ytterbium (Yb), Strontium (Sr), etc.
Magnetic Shielding Alloy	· Metal alloy for magnetic field shielding
Optical Components and Equipment	· Lasers and optical components and equipment for atomic cooling and manipulation
Vacuum Components and Equipment	· Vacuum components and equipment for atomic cooling and manipulation
RF Components and Equipment	· Components and equipment required for generating and synthesizing RF or microwaves

First, looking at the materials required to implement each quantum sensor, atomic sources and magnetic shielding alloys are used for quantum inertial sensor technology, and atomic vapor cells with buffer gas and MEMS-based ultra-small atomic vapor cells play an important role in quantum time/frequency sensors. The atomic source/sink component instrument currently under development uses alkali metal alloys and performs the function of supplying or collecting atoms depending on the direction of current by configuring electrodes and structures. This instrument has the advantage of extending the lifetime of the atomic source by controlling the atomic vapor pressure in vacuum and allowing the atoms to be reused. Type 1b single crystal diamond, high-purity single crystal diamond, quantum grade NV diamond, and atomic vapor cells are used for quantum magnetic field sensors, and various bulk nonlinear crystals and semiconductor quantum dot materials are used as main materials for quantum optical sensors.

Figure III-2 Fabricated MEMS Vapor Cell Structure and Photograph

Various components such as laser diodes, atomic vapor cells, cooled atomic beam sources, and acousto-optic modulators are essential for quantum gravity sensor technology, and these components support high-precision measurement. In addition, vertical cavity surface emitting lasers play an important role in implementing quantum time/frequency sensors. Also, various components such as atomic vapor cells, gain-adjustable detectors, magnetic shielding chambers, and photodiodes are used to implement quantum electric/magnetic field sensor technology, and commercial nonlinear-based quantum light sources, single photon light sources, and additional components are used for quantum optical sensors. For commercial nonlinear-based quantum light sources, Quantum Computing Inc.'s EPR-XX-YY series generates entangled photon pairs at C-band communication wavelengths based on SPDC in PPLN waveguides and has a brightness of 5 MHz/μW in the 1534.3 nm to 1566.4 nm range with a 775 nm pump laser. AdvR, Inc.'s photon pair source generates photon pairs of 10 MHz/mW and 3 MHz/mW or more at 810 nm and 1550 nm, respectively, based on Type 0 and Type II SPDC. Representative domestic suppliers of quantum sensor components include ATOVAC, Alpha-VS, and KVC.

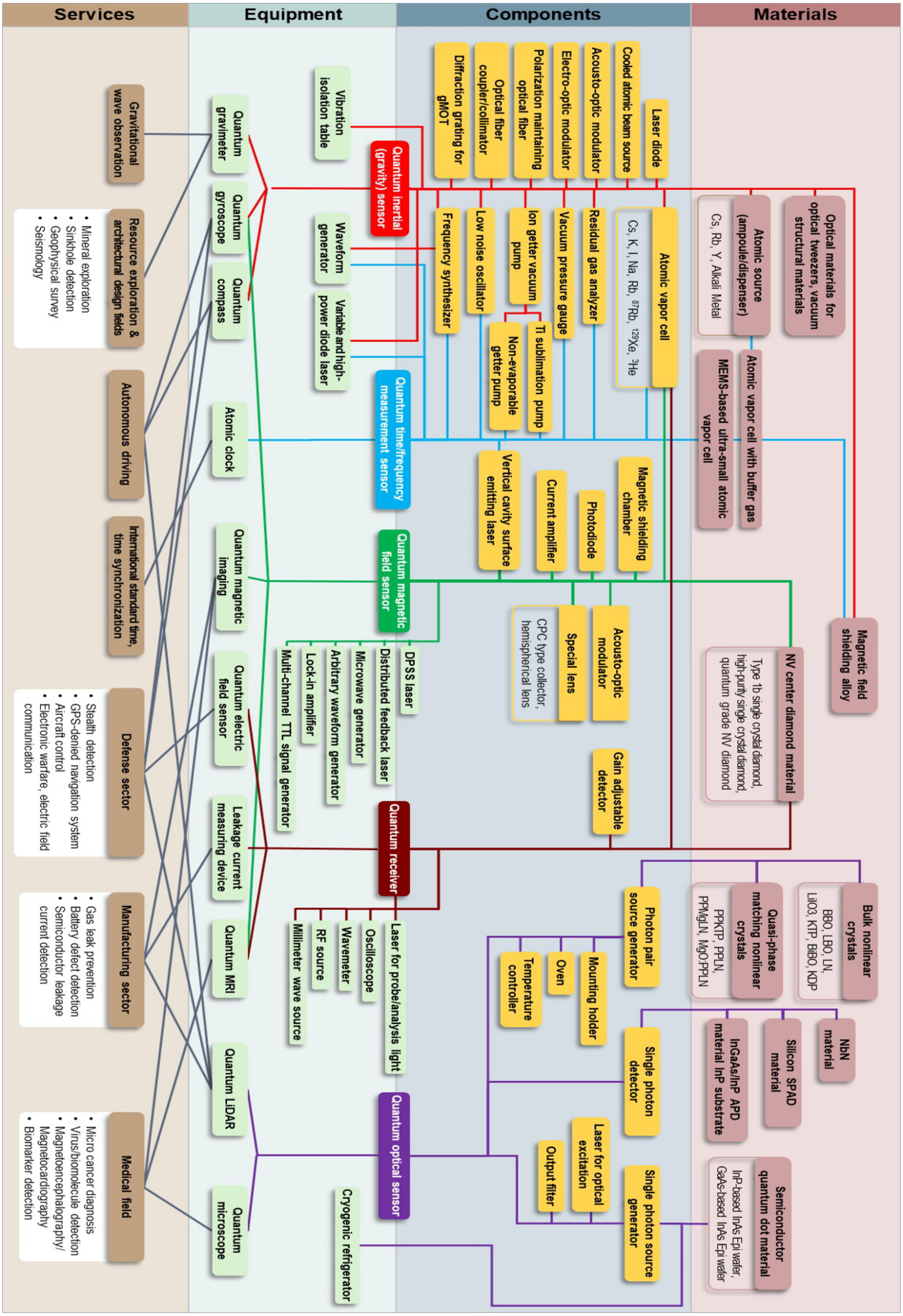
The equipment required to implement quantum gravity sensor technology includes tunable and high-power diode lasers, waveform generators, and vibration isolation tables to support high-precision gravity measurement. For the implementation of quantum electric field sensor technology, lasers for probe and analysis light, oscilloscopes, wavemeters, RF and millimeter wave sources are essential to provide the accuracy required for electric field measurement. In the case of quantum magnetic field sensors, various equipment such as diode-pumped solid-state lasers, distributed feedback lasers, microwave generators, arbitrary waveform generators, and lock-in amplifiers are used. For the development of quantum sensor technology, it is important to localize and miniaturize core components such as high-purity diamonds and nonlinear materials, and focus should be on MEMS-based miniaturization and performance improvement of quantum light sources. In addition, investment in equipment efficiency improvement and software and system integration technology is required for the commercialization of quantum sensors, which will enable not only the revitalization of the domestic market but also securing global competitiveness. Strategic investment and policies for research and development support and technological independence are needed at the national level, which will play an important role in commercializing and industrializing quantum technology.

Table III-4 **List of Quantum Sensing Materials, Components, and Equipment**

Category 1	Category 2	Category 3	Product Name
Quantum Sensing	Materials	Quantum Gravity Sensor	Atomic Source
			Magnetic Shielding Alloy
		Quantum Time/Frequency Sensor	Atomic Vapor Cell with Buffer Gas
			MEMS-Based Ultra-Small Atomic Vapor Cell
		Quantum Magnetic Field Sensor	Type 1b Single Crystal Diamond
			High-Purity Single Crystal Diamond
			Quantum Grade NV Diamond
			Atomic Vapor Cell
			Bulk Nonlinear Crystal (BBO, LBO, LN, KTP, BiBO, KDP)
			Quasi-Phase Matching Nonlinear Crystal
			Semiconductor Quantum Dot Material
	Components	Quantum Optical Sensor	Laser Diode
			Atomic Vapor Cell
			Cooled Atomic Beam Source
			Acousto-Optic Modulator
			Electro-Optic Modulator
			PM Optical Fiber

Category 1	Category 2	Category 3	Product Name
Quantum Sensing	Components	Quantum Optical Sensor	Optical Fiber Coupler and Collimator
			gMOT Diffraction Grating
			Residual Gas Analyzer
			Vacuum Pressure Gauge
			Ion Getter Vacuum Pump
			Low Noise Oscillator
			Frequency Synthesizer
	Components	Quantum Time/Frequency Sensor	Vertical Cavity Surface Emitting Laser (VCSEL)
		Quantum Electric Field Sensor	Atomic Vapor Cell
			Gain Adjustable Detector
		Quantum Magnetic Field Sensor	Magnetic Shielding Chamber
			Photodiode
			Current Amplifier
			Special Lens
		Quantum Optical Sensor	Commercial Nonlinear-Based Quantum Light Source
			Commercial Single Photon Light Source
			Additional Components for Nonlinear Crystal Light Source
	Equipment	Quantum Gravity Sensor	Variable and High-Power Diode Laser
			Waveform Generator
			Vibration Isolation Table
		Quantum Electric Field Sensor	Laser for Probe and Analysis Light
			Oscilloscope
			Wavemeter
			RF Source
			Millimeter Wave Source
		Quantum Magnetic Field Sensor	Diode-Pumped Solid-State Laser
			Distributed Feedback Laser
			Microwave Generator
			Arbitrary Waveform Generator
			Lock-in Amplifier
			Multi-Channel TTL Signal Generator

Figure III-3 Quantum Sensing Value Chain



03

III. Industrial Ecosystem Trends in Quantum Enabling Technology

Key Technologies and Materials, Components, and Equipment in Quantum Computing

Various approaches are being researched for implementing quantum computers, including superconducting, semiconductor quantum dot, ion trap, quantum photonics, NV center, and Rydberg-based methods, and each method requires specific materials, components, and equipment. This section examines the current status of suppliers of materials, components, and equipment for each implementation method, identifies dependence on foreign countries and limitations of domestic technology, and presents the overall quantum computing ecosystem.

Various platforms for implementing quantum computing require specialized materials. Superconducting quantum computing aims to maintain stable qubit states at low temperatures using highly controlled substrates, sputtering targets (materials for thin film deposition), and liquefied gases. Semiconductor quantum dot quantum computing utilizes high-precision GaAs HEMT, silicon (^{28}Si) raw materials and wafers, and germanium (Ge)-based wafers to control electronic structures and optimize interactions. For ion trap quantum computing, atomic materials and special wafers for microtrap fabrication, which require high precision, are essential. Quantum photonics-based systems use materials with excellent optical and electrical properties, such as silicon (Si), silica (SiO_2), lithium niobate ($LiNbO_3$), silicon nitride (SiN), and lithium tantalate ($LiTaO_3$), to maximize optical control and interference effects, enabling the generation and manipulation of quantum states. Despite rapid technological advancements, lithium niobate still faces challenges in thin film uniformity and mass production, while lithium tantalate is considered a promising candidate for quantum device development by providing better thermal stability and electrical properties. Both materials are expected to have increased commercialization potential in quantum computing and optical applications with future technological advancements. NV center-based quantum computing requires materials that can maintain high coherence, such as single-crystal diamond, nitrogen ions, and diamond nanostructures. NV centers must operate in the negatively charged state (NV^-) for use in quantum sensing and quantum computing, and this is achieved by injecting electrons into the NV^0 state to convert it to the NV^- state. Typically, electron beam irradiation is used on CVD diamond to increase the density of NV^- states, and in Korea, the Korea Atomic Energy Research Institute provides electron beam irradiation services. Finally, Rydberg quantum computing requires specialized materials related to atoms, which are utilized as a key technology for qubit manipulation using inter-atomic interactions. Representative domestic suppliers of quantum computing materials include BMI Tech, NNFC, Seoul National University, Sungkyunkwan University, Korea Tech, and KIST.

Components for each quantum computing platform require unique technologies tailored to the characteristics of each system. Superconducting quantum computing requires low-noise amplifiers at room and low temperatures, quantum-limited Josephson parametric amplifiers, circulators, isolators, low-temperature semi-rigid coaxial cables, and magnetic shielding. As the number of qubits in superconducting quantum processors has recently expanded to hundreds to thousands, the installation of hundreds of RF cables has been required, but conventional semi-rigid coaxial cables have had difficulty supporting this due to space constraints. To address this, Bluefors and Delft Circuits have released high-density coaxial cables. Bluefors' product supports up to 1,008 RF lines, and Delft Circuits provides Cri/oFLEX io tape-type coaxial cables, enabling the installation of more cables and bandwidth integration. Semiconductor quantum dot systems use cryogenic signal amplifiers and high-frequency superconducting cables for signal amplification and transmission, while ion trap systems use optical fibers, acousto-optic modulators, electro-optic modulators, and radio frequency/microwave switches to support signal control and precise qubit manipulation. Optical fibers, nonlinear crystals, and optical components play a key role in quantum photonics-based systems for advanced optical control, and NV center systems use microwave amplifiers, RF/microwave switches, and acousto-optic modulators for quantum state control and measurement. Finally, Rydberg systems use high-precision optical and electronic equipment, turbomolecular pumps, ion pumps, getter pumps, optical instruments, and laser frequency stabilization servos to achieve atomic control and precise measurement. Representative domestic suppliers of quantum computing components include Withwave, Coream Tech, and Fiberpia.

The equipment required for each quantum computing platform varies depending on the characteristics and implementation method of the platform. For superconducting quantum computing implementation, cryogen-free dilution refrigerators, arbitrary waveform generators, quantum control and analysis systems, and high-frequency signal generators are used to provide the environment necessary for controlling and measuring the state of superconducting qubits. Recently, Bluefors and FormFactor have released cryogenic wafer probe equipment that can automatically evaluate cryogenic characteristics at the wafer scale without instrument packaging for the characterization of superconducting quantum processors. In addition, electron beam lithography systems are used for precise patterning of Josephson junctions, which are essential for manufacturing high-performance quantum processors, and various electron beam lithography equipment is provided by RAITH, JEOL, ELIONIX, etc. Semiconductor quantum dot systems use high-stability constant voltage generators, multi-channel quantum controllers, and multi-channel arbitrary function generators to enable precise signal control and distribution. Ion trap systems utilize diode lasers, pulsed lasers, and single/multi-channel single-photon detectors to efficiently manipulate and measure atoms, while quantum photonics-based systems use photon pair generation equipment, superconducting nanowire single-photon detectors, and quantum dot-based single-photon sources to achieve optical control and detection. For the implementation of NV center quantum computing, external cavity diode lasers, single-photon detectors, and vector signal generators are used to support quantum state control and measurement, while Rydberg quantum computing utilizes high-power diode lasers, optical frequency comb equipment, and narrow linewidth lasers to precisely perform atomic manipulation and laser frequency analysis. Representative domestic suppliers of quantum computing equipment include Wooriro.

The materials, components, and equipment technology required for quantum computing varies depending on the platform, but most core components and equipment still rely on imports. Accordingly, superconducting quantum computing requires localization of dilution refrigerators, quantum control and analysis systems, low-temperature coaxial cables, and low-noise amplifiers, while semiconductor quantum dot and ion trap-based quantum computing are experiencing delays in the development of qubit control technology. Although Photonics-based quantum computing is rapidly developing, it also relies on imports for most of its materials and equipment, so reliability and compatibility issues of domestic products need to be addressed. NV center and Rydberg atom quantum computers have different technological requirements, but localization of related components and equipment through domestic technology development is emerging as an important task. To solve this, industrialization through startups is necessary, including expanding investment in basic technology. In particular, in the case of laser technology and electronic control circuits, since the domestic technology base has already been established, international competitiveness can be achieved if rapid response is made.

Table III-5 List of Quantum Computing Materials, Components, and Equipment

Category 1	Category 2	Category 3	Product Name
Quantum Computing	Materials	Superconducting Quantum Computing	Substrate
			Sputtering Target
			Liquefied Gas
		Semiconductor Quantum Dot Quantum Computing	GaAs HEMT
			^{28}Si
			^{28}Si -Based Wafer
			Ge -Based Wafer
		Ion Trap Quantum Computing	Atomic Material
			Wafer for Microtrap Fabrication
		Photonic Quantum Computing	Silicon (Si)
			Silica (SiO_2)
			Silicon Nitride (SiN)
			Lithium Niobate ($LiNbO_3$)
			Lithium Tantalate ($LiTaO_3$)
			Aluminum Nitride (AlN)
			Tantalum Pentoxide (Ta_2O_5)
		NV Center Quantum Computing	Single Crystal Diamond
			Nitrogen Ion
			Diamond Nanostructure
		Rydberg Quantum Computing	Atom
	Components	Superconducting Quantum Computing	Room/Low Temperature Low Noise Amplifier
			Quantum-Limited Josephson Parametric Amplifier
			Circulator
			Isolator
			Filter
			IR Filter

Category 1	Category 2	Category 3	Product Name
Quantum Computing	Components	Semiconductor Quantum Dot Quantum Computing	Coaxial Cable
			Low-Temperature Semi-Rigid Coaxial Cable
			Low-Temperature Magnetic Shielding
			Cryogenic Signal Amplifier
			Cryogenic High-Frequency Superconducting Cable
			Cryogenic Signal Generator
			Cryogenic Directional Coupler
		Ion Trap Quantum Computing	Signal Amplifier
			Optical Fiber
			Acousto-Optic Modulator
			Electro-Optic Modulator
			Radio Frequency/Microwave Switch
		Photonic Quantum Computing	Optical Fiber
			Multi-Channel Optical Fiber Bundle Component
			Optical Component
			Nonlinear Crystal
			Nonlinear Optical Module
		NV Center Quantum Computing	Pinhole
			Objective Lens
			Dichroic Mirror
			Optical Filter
			Microwave Amplifier
			RF & Microwave Switch
			Acousto-Optic Modulator
			Electro-Optic Modulator
		Rydberg Quantum Computing	Atomic Cell
			UHV Glass Cell
			Turbo Pump
			Ion Pump
			Getter Pump
			Electron Multiplying CCD Camera
			sCMOS Camera
			Liquid Crystal Device
			Fabry-Perot Cavity
			Phase-Locked Loop Servo

Category 1	Category 2	Category 3	Product Name
Quantum Computing	Components	Rydberg Quantum Computing	Acousto-Optic Modulator
			Electro-Optic Modulator
			Optical Instrument
			Precision Imaging Photonics
			Laser Frequency Stabilization Servo
	Equipment	Superconducting Quantum Computing	Cryogen-Free Dilution Refrigerator
			Arbitrary Waveform Generator
			Quantum Control and Analysis System
			Wire Bonder
			High-Frequency Signal Generator
			Cryogenic Wafer Probe System
		Semiconductor Quantum Dot Quantum Computing	Electron Beam Lithography System
			Cryogen-Free Dilution Refrigerator
			High-Stability Constant Voltage Generator
			High-Frequency Signal Generator
			Multi-Channel Arbitrary Function Generator"
			Multi-Channel Quantum Controller
			Multi-Channel Up-Down Converter
		Ion Trap Quantum Computing	Diode Laser
			Pulsed Laser
			Single/Multi-Channel Single Photon Detector
			Wavelength Meter
			Imaging Instrument
			Signal Generator
			ARTIQ
		Photonic Quantum Computing	Photon Pair Generation Equipment
			Superconducting Nanowire Single Photon Detector
			Single Photon Counter
			Avalanche Photodiode
			Communication Wavelength Laser
			Near-Infrared Laser
			Photon Pair Generation Equipment
			Quantum Dot-Based Single Photon Source
			Waveguide-Based Superconducting Nanowire Single Photon Detector

Category 1	Category 2	Category 3	Product Name
Quantum Computing	Equipment	Photonic Quantum Computing	Ion Beam Etcher
			Multi-Channel Electrical Signal Supply Instrument
			Multi-Channel Quantum Optical Processor Interferometer
		NV Center Quantum Computing	Diode-Pumped Solid-State Laser
			External Cavity Diode Laser
			Single Photon Detector
			TTL Pulse Generator
			Vector Signal Generator
			Arbitrary Waveform Generator
			Piezo Stage
			Pulse Counter
		Rydberg Quantum Computing	Diode Laser
			Diode Laser Servo
			High-Power Diode Laser
			Spectroscopy Laser
			Diode Laser Oscillator
			Diode Laser Second Harmonic Generator
			Current Supply Instrument
			Digital/Analog I/O Instrument
			Optical Frequency Comb Equipment
			Narrow Linewidth Laser
			Laser Frequency Analyzer
			Laser Intensity Noise Analyzer

Figure III-4 Quantum Computing Value Chain

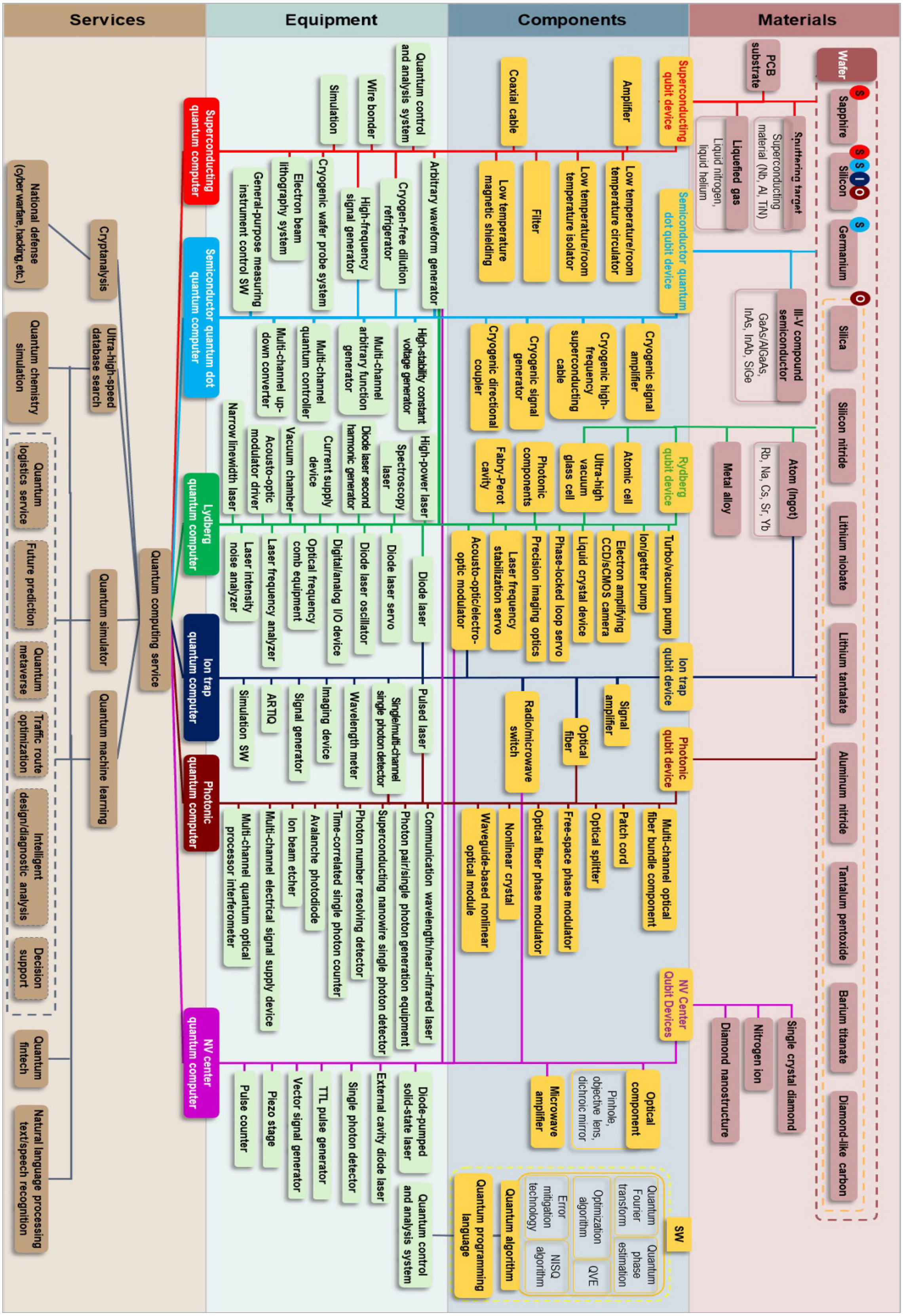
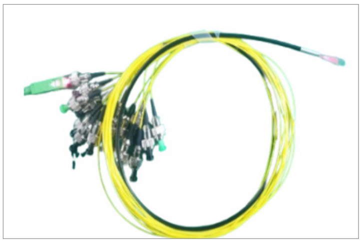


Figure III-5 **List of Representative Domestic Companies' Quantum Materials, Components, and Equipment**

Wooriro Co., Ltd. Single Photon Detection Device



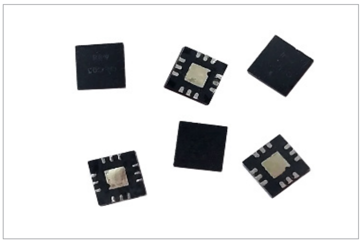
Fiberpia Co., Ltd. Optical Fiber

Korea Advanced Materials Co., Ltd. Mach-Zehnder Delay Line Interferometer

Woorinet Co., Ltd. QKD

Coweaver Co., Ltd. QKD

KVC Co., Ltd. Vacuum Pressure Gauge



EYL Co., Ltd. Ultra-Small Chip Providing Quantum Entropy

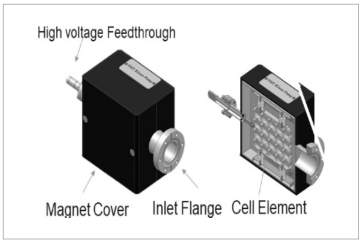
EYL Co., Ltd. Secure Terminal

SDT Co., Ltd. Quantum State Precision Measurement Device (CCU)

Octaco Co., Ltd. Quantum Random Number Fingerprint Security Key

Korea Advanced Materials Co., Ltd. Silica PLC Wafer

Atovec Co., Ltd. Vacuum Pressure Gauge



Alpha-EVS Co., Ltd. Vacuum Ion Pump

Korea Spectral Products Co., Ltd. Optical Diagnostic Sensor

Withwave Co., Ltd. Amplifier

Quantum Technology Statistics

IV

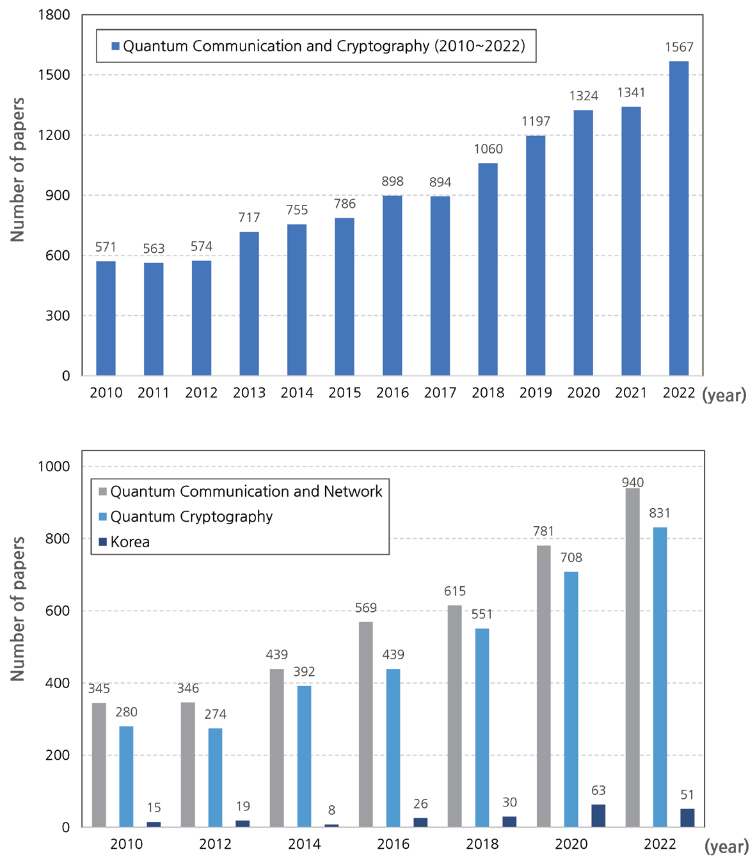
01

IV. Quantum Technology Statistics

Domestic and International Journal Paper Statistics

According to KISTI (2023), in the field of quantum communication, 12,247 papers were published from 2010 to 2022, with a Compound Annual Growth Rate (CAGR) of 8.78%. Korea maintains a share of about 2-3% of total papers. China accounts for more than 40% of the 11 major countries, showing overwhelming dominance in the number of papers, but its excellence index is relatively low. On the other hand, the United States, Germany, and the United Kingdom maintain both high market share and excellence index, ranking at the top.

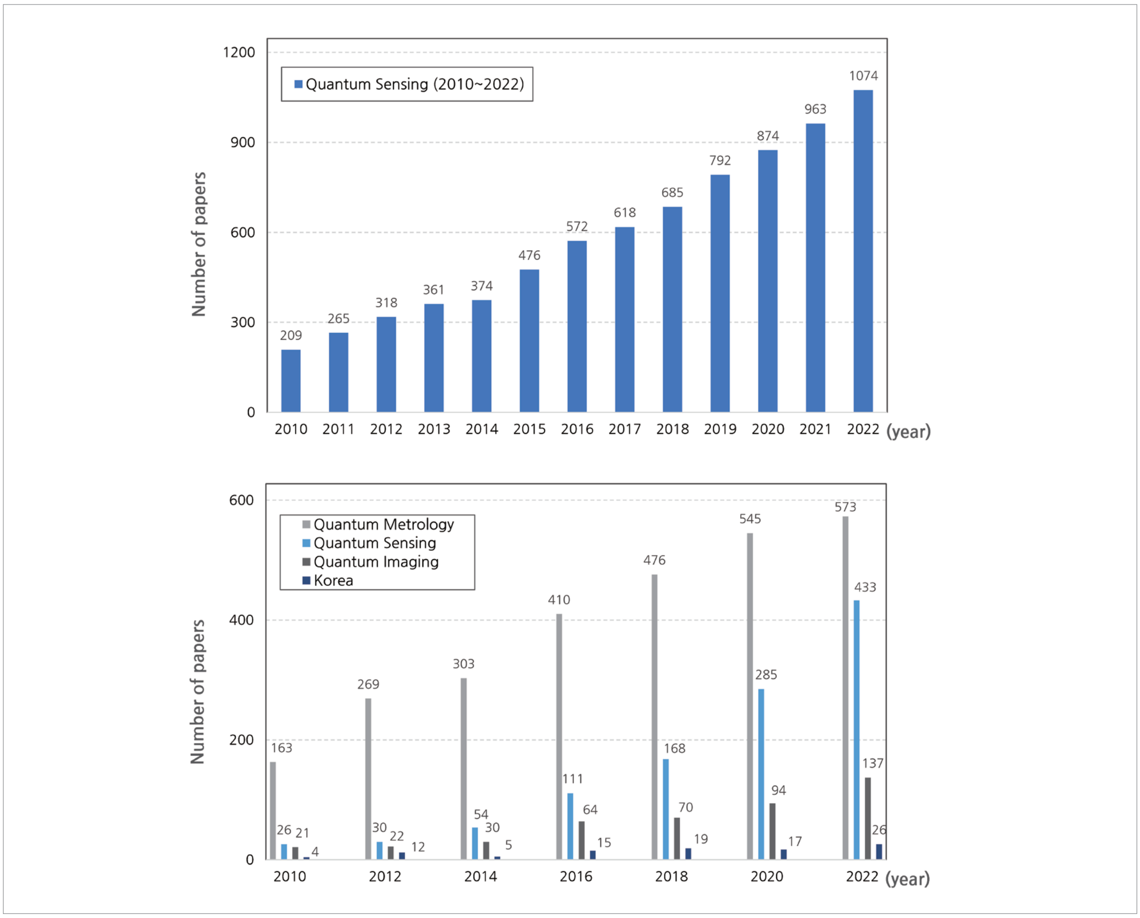
Figure IV-1 Number of Papers on Quantum Communication by Year (2010-2022)



※ Source(s): KISTI (2023)

In the field of quantum sensing, 7,581 papers were published from 2010 to 2022, showing the fastest growth rate with a CAGR of 14.61%. Korea recorded a market share of about 2%, with the number of papers increasing or maintaining a certain level every year, and its excellence index is steadily improving. Since 2016, China has been leading the field, surpassing the United States in the number of published papers.

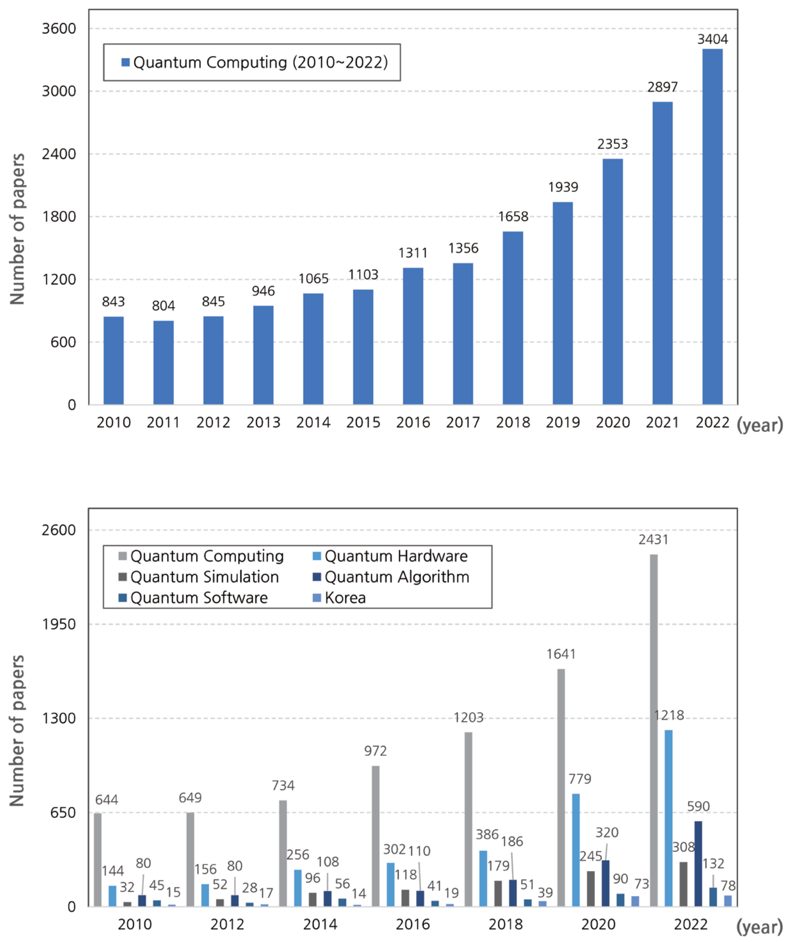
Figure IV-2 Number of Papers on Quantum Sensing by Year (2010-2022)



※ Source(s): KISTI (2023)

In quantum computing, 20,524 papers were published during the same period, with a CAGR of 11.33%. Korea accounted for about 2% of the total number of papers, publishing more papers than in quantum communication and quantum sensing. The United States maintained the top market share for a long time, but with China's rapid growth, China published the most papers as of 2022.

Figure Ⅳ-3 Number of Papers on Quantum Computing by Year (2010-2022)



※ Source(s): KISTI (2023)

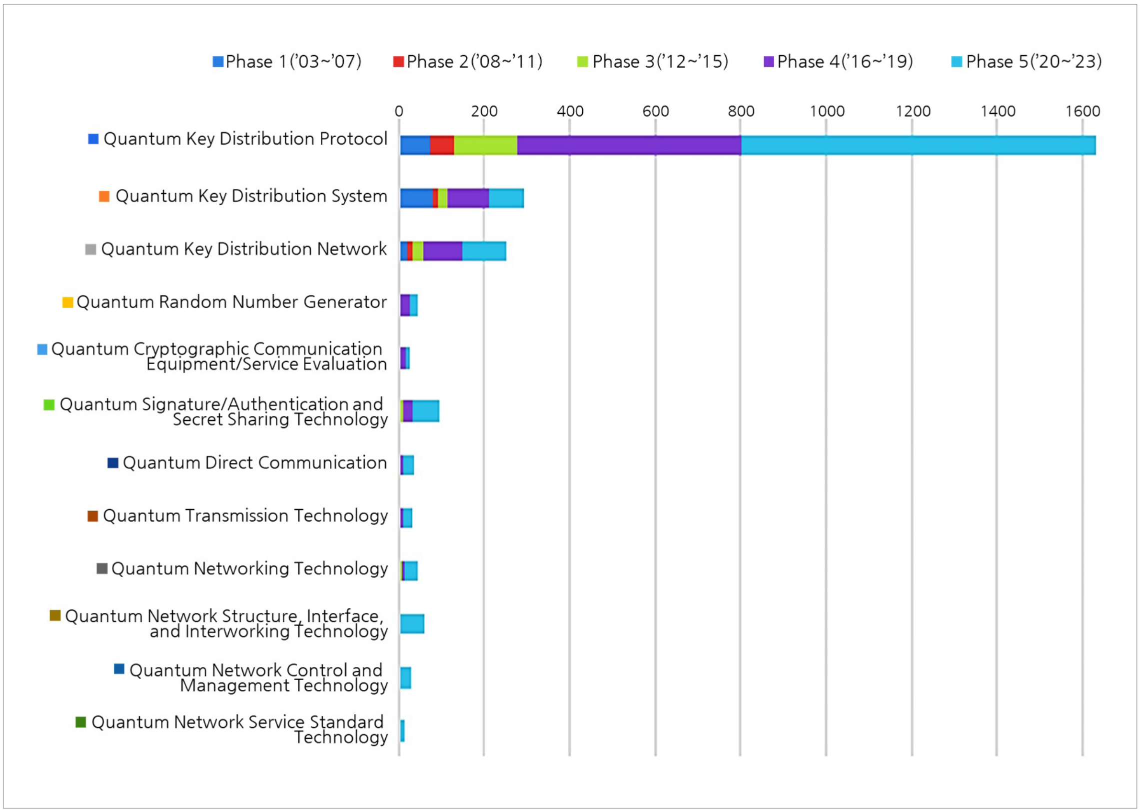
02

IV. Quantum Technology Statistics

Domestic and International Patent Statistics

According to the analysis of KISTA (Korea Intellectual property STrategy Agency) (2023), patent applications related to quantum key distribution protocols are the most active among quantum communication technologies, and patent applications for quantum communication and network technologies have been steadily increasing between 2020 and 2023. Korea stands out with a high concentration in quantum key distribution protocol technology compared to other countries. Major applicants include Magiq in the US, Toshiba in Japan, and Alibaba and Huawei in China, and they are also focusing on quantum key distribution-based technologies.

Figure IV-4 **Patent Application Trends by Section for Quantum Communication Technology (2000-2023)**



※ Source(s): KISTA (2023)

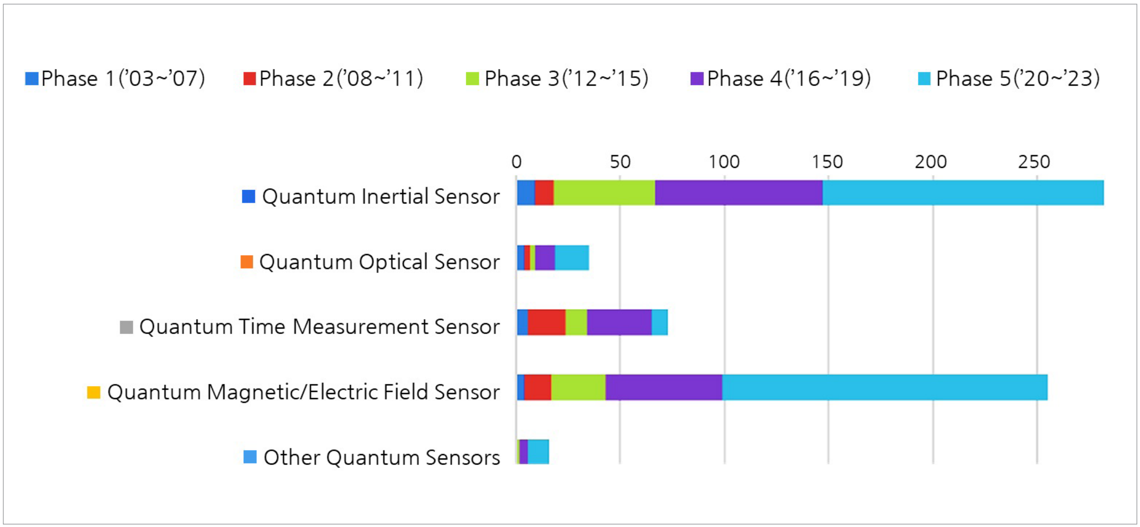
Table IV-1 Patent Application Trends by Multiple Applicants for Quantum Communication Technology (2000-2023)

Category	Quantumcteck	Magiq	Toshiba	Alibaba	Huawei	ID Quantique
Quantum Key Distribution Protocol	87	36	39	58	31	29
Quantum Key Distribution System	27	68	6	1	16	15
Quantum Key Distribution Network	34	6	32	10	17	7
Quantum Random Number Generator	2	0	0	0	0	2
Quantum Cryptographic Communication Equipment/ Service Evaluation	1	0	1	2	0	0
Quantum Signature/ Authentication and Secret Sharing Technology	1	0	1	0	0	0
Quantum Direct Communication	2	0	0	0	1	0
Quantum Transmission Technology	0	0	0	0	2	0
Quantum Networking Technology	2	0	0	0		0
Quantum Network Structure, Interface, and Interworking Technology	0	0	2	0	1	1
Quantum Network Control and Management Technology	0	0	0	0	0	0
Quantum Network Service Standard Technology	1	0	0	0	0	0

※ Source(s): KISTA (2023)

In quantum sensing technology, patent activity is most active in the implementation and performance evaluation technology of quantum inertial sensors and quantum magnetic/electric field sensors, especially in the field of quantum magnetic/electric field sensors, recent applications stand out. Korea has been confirmed to have a high proportion of applications in quantum magnetic/electric field sensor implementation and performance evaluation technology compared to other countries. Major applicants include Honeywell, Lockheed Martin, Northrop Grumman, and Texas Instruments in the US, Beihang University in China, and KRISS in Korea, and they are mainly focusing on quantum inertial sensor and quantum magnetic/electric field sensor technology.

Figure IV-5 Patent Application Trends by Section for Quantum Sensing Technology (2000-2023)



※ Source(s): KISTA (2023)

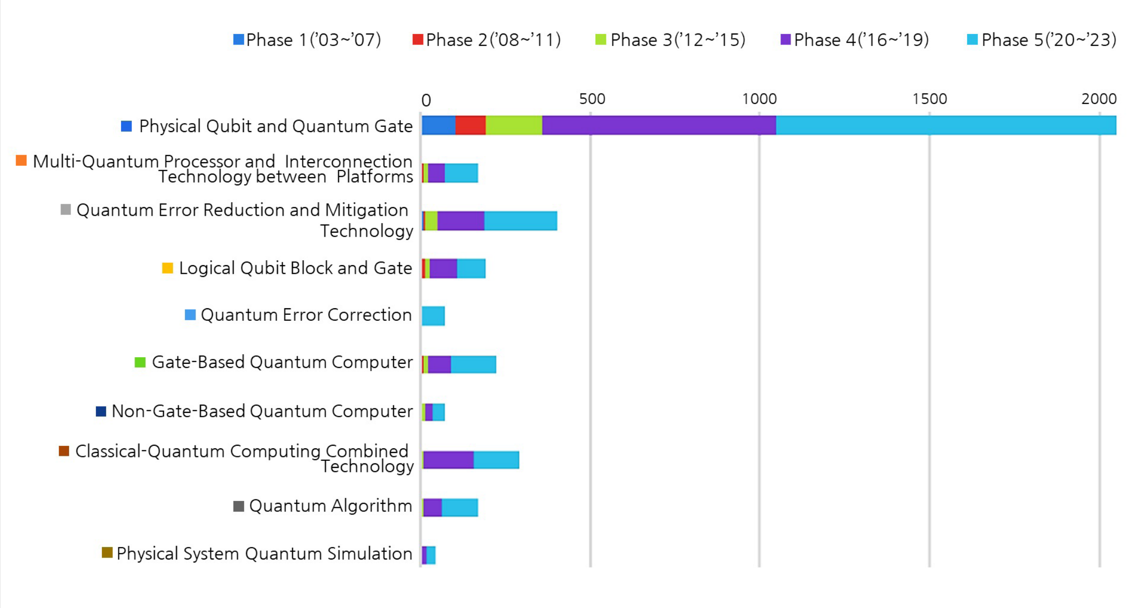
Table IV-2 Patent Application Trends by Multiple Applicants for Quantum Sensing Technology (2000-2023)

Category	Univ. Beihang	Honeywell	KRISS	Texas Instrument	Northrop Grumman	Lockheed Martin
Quantum Inertial Sensor	21	13	1	0	4	1
Quantum Optical Sensor	0	0	0	0	0	0
Quantum Time Measurement Sensor	0	24	5	12	0	0
Quantum Magnetic/Electric Field Sensor	25	3	8	3	10	0
Other Quantum Sensors	0	0	2	0	0	0

※ Source(s): KISTA (2023)

Among quantum computing technologies, physical qubit and quantum gate implementation and performance evaluation technology were the areas with the most active patent applications from 2016 to 2023, and Korea showed a relatively high proportion in error reduction and mitigation technology. Major applicants include IBM, Google, Microsoft, and IonQ in the US, and D-Wave in Canada, and they are focusing on physical qubit implementation, quantum error reduction and mitigation, and logical qubit gate technology. The portfolios of IBM, Google, and Microsoft show similar patterns, and D-Wave and IonQ also show similar trends.

Figure IV-6 **Patent Application Trends by Section for Quantum Computing Technology (2000-2023)**



※ Source(s): KISTA (2023)

Table IV-3 **Patent Application Trends by Multiple Applicants for Quantum Computing Technology (2000-2023)**

Category	IBM	Google	Microsoft	D-Wave	IonQ	Northrop Grumman
Physical Qubit and Quantum Gate	348	149	118	119	85	74
Multi-Quantum Processor and Interconnection Technology between Platforms	46	4	5	25	2	0
Quantum Error Reduction and Mitigation Technology	62	50	46	6	3	5
Logical Qubit Block and Gate	22	32	30	2	0	10
Quantum Error Correction	0	6	1	0	1	0
Gate-Based Quantum Computer	22	12	3	0	1	1
Non-Gate-Based Quantum Computer	10	5	5	10	0	0
Classical-Quantum Computing Combined Technology	52	67	30	7	10	0
Quantum Algorithm	43	14	9	15	10	0
Physical System Quantum Simulation	0	13	5	0	0	0

※ Source(s): KISTA (2023)

V Quantum Technology Industrialization Model

V. Quantum Technology Industrialization Model

Industrial demand for quantum technology is increasing worldwide, and more than 200 companies are focusing on quantum technology development and commercialization. Major quantum technology fields such as quantum communication, quantum sensing, and quantum computing are actively developing through testbed construction and initial commercialization. In particular, industrialization is accelerating as quantum technology is being combined with various industries such as defense, security, space, semiconductors, automobiles, medicine, and pharmaceuticals.

Major industrial sectors where quantum technology is applied are divided into a total of 8 categories: defense·security·space, telecommunications, manufacturing·semiconductors, medicine·-pharmaceuticals, materials, finance, transportation·logistics·aviation, and others. A total of 106 industrialization models have been derived from these sectors. Specifically, 19 models are being considered in the defense·security·space sector, 13 in telecommunications, 10 in manufacturing·semiconductors, 16 in medicine·pharmaceuticals, 3 in materials, 7 in finance, 18 in transportation·logistics·aviation, and 20 in other sectors. In the defense·security·space sector, information security and ultra-precision sensing technology are important, and in the manufacturing·semiconductors sector, sensor development and process optimization are dealt with as key technologies. In the medicine·pharmaceuticals sectors, research is focused on precision diagnostics and new drug development.

In the short term, 49 industrialization models that can produce visible results within 5 years have been reviewed, and the telecommunications sector, in particular, is highly likely to be industrialized quickly through achievements such as the launch of B2B rate plans. In the medicine·pharmaceuticals sectors, new drug development using quantum computing is accelerating, and in the manufacturing·semiconductors sectors, quantum sensing technology development is urgent to secure global competitiveness. In the medium to long term, 57 industrialization models aim for industrialization after 5 years based on technological proficiency, security, and institutional complementation. In particular, in the defense·security sector, the combination of quantum sensing and quantum computing technology is important and requires multifaceted consideration.

Looking at each technology field, quantum communication, quantum sensing, and quantum computing technologies are contributing to industrialization in a complementary manner. 36 industrialization models have been discovered for quantum communication in 7 industrial sectors, 34 for quantum sensing in 5 industrial sectors, and 36 for quantum computing in 7 industrial sectors. In the short term, rapid results are expected in the telecommunications sector, and in the medium to long term, technology application in the defense·security sector is expected to be dealt with importantly. It is expected that the achievements of each technology will lead to remarkable industrialization results through mutual cooperation.

Figure Ⅴ-1 Overview of Industrialization Models by Key Sector

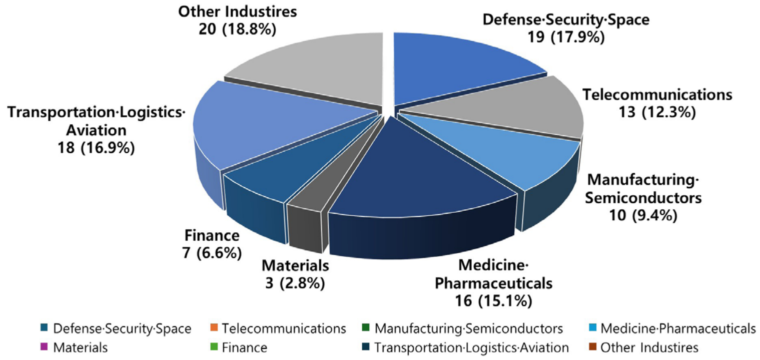


Table Ⅴ-1 Overview of Industrialization Models by Key Sector

Industry Sector	Technology Field	Industrialization Model
Defense·Security·Space	Quantum Communication	① Satellite-based quantum key distribution (QKD) network security service ② Free space quantum communication service ③ Quantum communication satellite service for space security ④ Drone quantum cryptographic module security service ⑤ Military communication encryption service
	Quantum Sensing	① Geomagnetic quantum navigation service ② Quantum magnetometer underwater surveillance service ③ Gravity quantum navigation service ④ Quantum inertial navigation system service ⑤ Quantum gyroscope navigation service

Industry Sector	Technology Field	Industrialization Model
Defense·Security·Space	Quantum Sensing	⑥ Quantum radio frequency (RF) sensing service ⑦ Long-range target surveillance service using quantum radar ⑧ Real-time 3D spatial information provision service using quantum LiDAR ⑨ Space dark matter signal detection service ⑩ Small object surveillance service using quantum sensor-equipped satellites ⑪ Military quantum laser service ⑫ Quantum imaging service
	Quantum Computing	① Defense scenario generation service ② Cryptosystem development service
Telecommunications	Quantum Communication	① Small encryption system supply service ② Quantum cryptography-enhanced quantum internet service ③ High-frequency band optical wireless communication service ④ Wireless quantum cryptographic communication network service ⑤ Wired quantum cryptographic communication service ⑥ 6G communication service ⑦ Quantum internet service ⑧ Communication encryption service ⑨ Quantum cryptographic system application service for performance and entertainment fields ⑩ Hybrid/multi-cloud environment quantum cryptographic communication service ⑪ Quantum secure networking service ⑫ Quantum security-based IP camera surveillance service ⑬ Quantum memory service
Manufacturing·Semiconductors	Quantum Communication	① Smart factory communication network service ② Production line equipment monitoring service ③ Remote facility management service for semiconductor processes
	Quantum Sensing	① Building material defect detection service ② Battery defect detection service ③ Gas sensing and monitoring service ④ Quality control service through particle detection
	Quantum Computing	① Battery material optimization service ② Chemical mass production service ③ Manufacturing process optimization service
Medical·Pharmaceuticals	Quantum Communication	① Quantum cryptography-based medical cloud service ② Medical data transmission service ③ Medical cyber security service
	Quantum Sensing	① Biomagnetic measurement service ② Non-destructive biological structure observation service using quantum microscopes ③ Room temperature MRI diagnostic service ④ Cancer diagnosis and surgery support service ⑤ Disease infection diagnosis service
Medical·Pharmaceuticals	Quantum Computing	① New drug design service ② Protein structure analysis service ③ Cancer diagnosis and treatment service ④ Brain disease diagnosis and treatment service ⑤ Personalized medicine service ⑥ Radiation therapy service ⑦ Quantum imaging platform service ⑧ Insurance premium calculation and risk analysis service

Industry Sector	Technology Field	Industrialization Model
Materials	Quantum Computing	① New material development service ② Development of automotive battery and fuel materials for transportation ③ Quantum engine service
Finance	Quantum Communication	① Cryptocurrency-based financial security service ② Financial security service ③ Payment system security service
	Quantum Computing	① Risk analysis and management service ② Portfolio optimization service ③ Financial platform service ④ Customer targeting and prediction service
Transportation·Logistics·Aviation	Quantum Communication	① Quantum cryptography applied autonomous delivery service ② Quantum cryptography applied aviation security service ③ Automobile electronic control unit encryption service
	Quantum Sensing	① Manned·unmanned aerial vehicle integration service ② Aircraft visual flight rules guidance service ③ Aircraft system monitoring and maintenance service ④ Autonomous driving service using quantum LiDAR ⑤ Driving accuracy and safety improvement service
	Quantum Computing	① Traffic management service ② Urban air mobility transportation network control service ③ Aircraft design service ④ Flight gate allocation service ⑤ Air cargo loading optimization service ⑥ Air operation system optimization ⑦ Context-based customized service ⑧ Airline network optimization service ⑨ Automobile production supply chain and logistics network operation service ⑩ Logistics resource optimization service
Other Industries	Quantum Communication	① Personal assistant security service ② Quantum electronic voting service ③ Quantum cryptography-based virtual private network (VPN) provision service ④ Quantum support technology commercialization support service ⑤ Remote data center data protection service ⑥ Lottery and online game services
	Quantum Sensing	① Climate change indicator tracking service ② Underground communication facility location identification service based on quantum gravity sensors ③ Geophysical survey and resource exploration service ④ Oil and gas exploration service ⑤ Volcanic activity monitoring service ⑥ Energy infrastructure monitoring service ⑦ Communication line disconnection detection service ⑧ Public safety service using brain waves
	Quantum Computing	① Artificial intelligence enhancement service ② Power grid operation service ③ Other services in the energy sector ④ Underground resource exploration service ⑤ Weather forecasting service ⑥ Quantum robot service

VI Quantum Consortia Trends

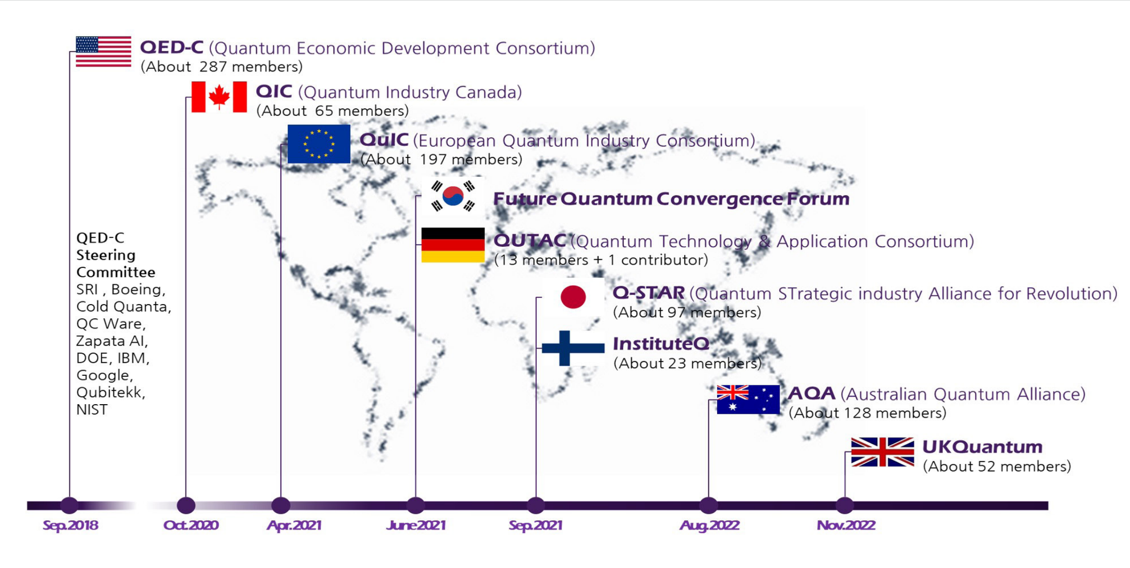
01

VI. Quantum Consortia Trends

North America

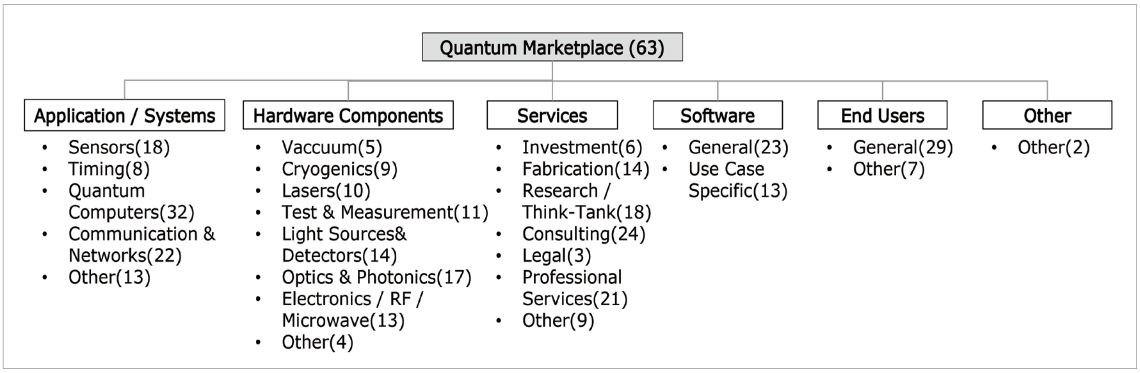
Various quantum collaboration platforms have been launched worldwide from 2018 in the United States to 2024. In 2021, Europe's QuIC, Korea's Future Quantum Convergence Forum, Germany's QUTAC, Japan's Q-STAR, Denmark's Danish Quantum Community, and Finland's InstituteQ were established, and in 2022, AQA and UKQuantum were newly formed.

Figure VI-1 Global Quantum Consortia (as of Sep. 2024)



The US QED-C (Quantum Economic Development Consortium) is a consortium established in accordance with the NQI Act in 2018 and is managed by SRI International under the commission of NIST. QED-C aims to build a strong quantum ecosystem and revitalize the industry supply chain, and as of September 2024, it has 294 member organizations. The membership consists of 185 companies, 40 universities, and 61 government agencies and research institutes. Its main activities include proposing federal R&D investment priorities, establishing standards and regulations, educating the quantum workforce, and promoting cooperation between industry and government, focusing on establishing standards and performance criteria for the commercialization of quantum technology and resolving technology gaps. Futhermore, the Quantum Marketplace, provided by QED-C, enables the dissemination of information on the technologies and capabilities of its members and participants to potential customers. It also facilitates information exchange between customers and suppliers to support the development of quantum-based products.

Figure VI-2 Number of Member Companies by QED-C Quantum Market Classification



Canada established QIC (Quantum Industry Canada) in 2020 with the goal of commercializing quantum technology and achieving economic prosperity. QIC's mission is to preemptively occupy the early market based on world-class basic research in quantum technology, and as of September 2024, it has 65 member companies. Member companies cover all areas including quantum communication, quantum sensing, and quantum computing, and support the commercialization of quantum technology in their country in cooperation with provincial and federal governments. QIC focuses on raising global awareness of Canadian quantum technology and promotes talent development and attracting new businesses. It also supports early commercial paths through infrastructure development and provides expertise and strategic support for the global success of startups as well as mature companies.

VI. Quantum Consortia Trends

Europe

The European QuIC (European Quantum Industry Consortium) is a non-profit association established in 2021 with the goal of strengthening the competitiveness of the European quantum technology industry and promoting economic growth. Large companies, small and medium-sized enterprises (SMEs), startups, and investors participate to revitalize the ecosystem, and through support for the Quantum Flagship project, standardization, intellectual property protection, workforce development, and strategic roadmap development, it is strengthening sustainability and global competitiveness. As of September 2024, QuIC, with 197 member companies, plays a central role in the development of the European quantum technology ecosystem.

Finland's InstituteQ aims to strengthen the preparedness of Finnish society for the impact of quantum technology on society and the economy as a whole. It aims to secure competitiveness in the quantum era through research, education, and innovation, and promote scientific discovery, technology adoption, and commercial opportunities through infrastructure development and resource integration. InstituteQ consists of three sub-organizations: ResQ focused on research, EduQ focused on education, and BusinessQ focused on business. Aalto University, the University of Helsinki, and VTT Technical Research Centre of Finland are responsible for its operation. More than 20 institutions and companies participate and cooperate.

Germany's QUTAC (Quantum Technology and Application Consortium) is a consortium of 13 major companies and Airbus as an external contributor, aiming for the commercialization of quantum computing and securing digital sovereignty in Germany and Europe. It is developing a quantum computing ecosystem through building an industrial application portfolio, realizing reference applications, and collaborating, and is showing potential to solve complex optimization problems in various industries such as logistics and finance. In addition, it focuses on discovering industrial use cases, strengthening cooperation, and market incubation to accelerate technological development.

UKQuantum, established in the UK in 2022, is a consortium that aims to develop the UK quantum industry and provides policy advice and industry advocacy to the government. As of September 2024, it has 52 member companies, with major members including IBM, Google Quantum AI, Quantinuum, and Q-CTRL. Members participate in regular webinars and committees, contributing to the UK's quantum technology policy and priority setting. Working groups are composed of various stakeholders, including computing, sensing, communications, supply chains, and research institutions, covering all aspects of quantum technology.

03

VI. Quantum Consortia Trends

Asia

Japan's Q-STAR (Quantum STrategic Alliance for Revolution) is a quantum technology consortium established in 2021 with the goal of creating new industries and businesses based on quantum technology. Q-STAR researches the commercialization of major technologies such as quantum cryptography, quantum computing, and quantum sensors, and carries out various tasks such as material/component/equipment development, workforce development, intellectual property protection, and standardization. The organization consists of a board of directors and steering committee led by major companies such as Toshiba, Fujitsu, and NEC, and six subcommittees, focusing on activities for quantum technology application and industrialization. As of September 2024, the number of member companies has increased to 97, with companies from various industries participating to promote the diversified development of Japan's quantum technology ecosystem.

Australia's AQA (Australian Quantum Alliance) is a quantum industry consortium established in 2022 with the support of the Technology Council of Australia (TCA), aiming to promote, strengthen, and connect Australia's quantum ecosystem. Leading local companies such as Quintessence Labs, Q-CTRL, and Quantum Brilliance, as well as global companies such as Google and Microsoft, participated as founding members, and as of September 2024, it has 128 member companies. AQA cooperates with the government and businesses for quantum technology innovation, job creation, and economic prosperity, and actively encourages cooperation and technology utilization between companies through supporting early-stage startups and operating pilot programs.

VI. Quantum Consortia Trends

Other Small Consortia

The Chicago Quantum Exchange (CQE) in the United States serves as a hub for quantum information science, centered around the University of Chicago, connecting universities, research institutes, and industry to support the development and commercialization of technologies such as quantum communication, quantum sensing, and quantum computing. Seven major institutions, including the University of Chicago, Argonne National Laboratory, and Fermi National Accelerator Laboratory, participate in the CQE. Through various projects, including network and qubit research, the CQE aims to foster the quantum economy and develop a skilled workforce.

Canada's Quebec Quantique is a consortium that strengthens the quantum ecosystem by connecting 125 companies and institutions in the Quebec region. Members collaborate in various fields such as research, finance, and computing, and promote network construction and technology commercialization. Some members have overlapping memberships with global consortia, expanding their international network.

The German Quantum Alliance is a consortium of eight quantum clusters and research centers in Germany, conducting research and commercialization in various fields such as quantum computing, sensing, and materials research. Each cluster connects academic achievements with industrial applications and cooperates with the goal of quantum technology development and practical application.

The UK QCA (Quantum Computing Application Cluster) aims to develop a quantum computing and simulation ecosystem centered on the central belt of Scotland. Major participating universities such as the University of Strathclyde, the University of Edinburgh, and the University of Glasgow conduct research on quantum technologies such as neutral atoms and superconducting circuits, and cooperate with the UK National Quantum Technology Programme to strengthen education and industrial applications.

The Swiss Quantum Economy Network is a collaborative global community of business leaders, technology innovation experts, researchers, and policymakers for the development of the quantum economy, with 125 member institutions from 28 countries as of 2024.

Denmark's Danish Quantum Community consists of more than 37 partners as of 2023 and aims to achieve a global advantage in quantum technology research and applications. By presenting use cases of quantum technology, it contributes to building a strong quantum ecosystem and accelerating the development of quantum technology.

Table VI-1 Trends of Major Global Quantum Consortia

Category	Consortium Name	Year of Establishment	Number of Member Companies (as of Sep. 2024)	Main Activities
North America	US QED-C	2018	294	Revitalizing the industrial supply chain, standardization
	Canada QIC	2020	65	Commercialization of quantum technology, talent development
Europe	Europe QuIC	2021	197	Strengthening the competitiveness of the European quantum industry
	Finland InstituteQ	-	20+	Quantum research·education·innovation
	Germany QUTAC	-	13	Industrialization of quantum computing
	UK UKQuantum	2022	52	Advising on UK quantum policy
Asia	Korea FQCF	2021	184	Supporting quantum industrialization and policy development
	Japan Q-STAR	2021	97	Industrialization of quantum technology in Japan
	Australia AQA	2022	128	Quantum technology innovation, startup support

References

1. C. H. Park, M. K. Woo, B. K. Park, Y.-S. Kim, H. Baek, S.-W. Lee, H.-T. Lim, S.-W. Jeon, H. Jung, S. Kim, and S.-W. Han, 2×N twin-field quantum key distribution network configuration based on polarization, wavelength, and time division multiplexing, *npj Quantum Information* **8**, 48 (2022)

2. https://quantum.kist.re.kr/

3. https://www.kriss.re.kr/

4. https://www.nnfc.re.kr/

5. J. Lee, N. Kang, S.-H. Lee, H. Jeong, L. Jiang, and S.-W. Lee, Fault-tolerant quantum computation by hybrid qubits with bosonic cat code and single photons, *PRX QUANTUM* **5**, 030322 (2024)

6. J. Heo, J. Kim, T. Jeong, Y. S. Ihn, D. Y. Kim, Z. Kim, and Y. Jo, Quantum-secured single-pixel imaging with enhanced security, *Optica* **10**(11), 1461 (2023)

7. W. Song, N. Kang, Y.-S. Kim, and S.-W. Lee, Encoded-fusion-based quantum computation for high thresholds with linear optics, *Physical Review Letters* **133**(5), 050605 (2024)

QUANTUM INFORMATION SCIENCE ENGINEERING TECHNOLOGY
WHITE PAPER

SUMMARY

* This Summary serves as a condensed overview of the '2024 Quantum Information Science Engineering Technology White Paper', and the act of quoting is strictly forbidden.
* We kindly request that you consult the '2024 Quantum Information Science Engineering Technology White Paper' for comprehensive details and proper citations.
* For inquiries regarding the '2024 Quantum Information Science Engineering Technology White Paper', please contact the Secretariat of the Future Quantum Convergence Forum.

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