The history of miniaturization of semiconductors, which has been supported by Dennard’s theory and developed in accordance with Moore’s law, has entered the new era of Å, and the market is expected to grow explosively beyond the conventional market mechanisms. Semiconductor technology has always faced developing technical challenges, each of which has been overcome by a newly proposed innovation. Even now, a sense of stagnation about the future technology is pervasive. On the other hand, the market is expected to grow explosively due to a shift from single driver technology, including PCs and mobile phones, to multi-driver technology including ICAC5 (IoT, cloud, AI, cars, and 5G). This paper covers a method of development through Enhanced Open Innovation, as a method for overcoming the sense of stagnation about the future technology and responding to the explosively growing market. In preparation for the paradigm revolution of semiconductors that is expected to occur in 2030, CMP needs to be advanced in terms of hardware as well as software. Manabu’s principle “Semiconductor device technology is immortal as long as there are human desires” is about to be proved.

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Enhanced Open Innovation: CMP Innovation to Open New Paradigm

First, in 2014, the author declared that, “2020 will be the year when the miniaturization ends, and this challenge is a true paradigm cliff. (Paradigm Cliff 2020)”. In 2015, the author wrote that, “Taking CMP as an example, pursue the ultimate aim in order to get over the paradigm cliff. (The Way to Zero’s)”, identifying the engineering challenge and the solution. In 2016, the author professed that, “Innovation is essential. (Innovations to Support Semiconductor Technology)”, providing an example of innovation together with serendipity. In 2017, the author stated that, “To make the innovation happen, revisiting the past is also important. (Cherishing Old Knowledge, Acquiring New)”, proposing new CMP technologies into which the conventional technologies are integrated.

Technology Stagnation Viewed from Papers

Figure 2 shows an overview of the flow of the technology taken from several papers previously published by the author.

To summarize the above, the history of miniaturization of semiconductors, which was formerly supported by Dennard scaling law and developed in accordance with Moore’s law, is trying to weather the era of Å with technical innovation despite the severe situation. The market is expected to grow explosively beyond the conventional market mechanisms. Therefore, the paradigm is sure to change revolutionarily by no later than 2030. Manabu’s principle “Semiconductor device technology is immortal as long as there are human desires” is about to be realized.

Technology Stagnation Viewed from Papers

Figure 2 shows an overview of the flow of the technology taken from several papers previously published by the author.

Figure 1. Technology Stagnation and Market Explosion.
Figure 2. Technology View from Several Papers.

**Market Explosion by ICAC5**

As mentioned above, the market is expected to grow explosively beyond the conventional market mechanisms. Figure 3 outlines the market trend with the transition of technology roadmap. Understanding the technology is crucial to achieving a clear view of the future market. From this perspective, road mapping has become a very useful tool.

Device Roadmap was created by SIA (US) in 1992, and changed to International Technology Roadmap for Semiconductors (ITRS) involving Japan, the U.S., Europe, Korea, and Taiwan in 1999. ITRS activity was suspended in 2015. Subsequently, some road mapping activities emerged for applications other than miniaturization.

The following shows an overview of the roles each of the players has played in the semiconductor supply chain. From 1947 to 2015, device manufacturers led the chain and provided development information to set manufacturers and tool and material manufacturers. Since 2015, the question has emerged as to whether set manufacturers and users have begun to collaborate to lead the chain and provide development information to device manufacturers and tool and material manufacturers.

Now, let us have another look at the market. As mentioned above, the market has shifted from single driver technology, including PCs and mobile phones to multi-driver technology, including ICAC5. It inevitably suggests that device technology will become important once again. The author expects that device manufacturers will once again take the lead in 2020 or later.

**What Should We Do Now!?**

Even if the technology stagnates (or seems to stagnate), as long as the market continues to grow explosively and the driving force remains device technology revolution, the tool and material technologies will also contribute to the technology revolution. However, the anticipated technology innovation anticipated there will be dramatically different from conventional technology innovations. What should we do now?

The Enhanced Open Innovation method introduced in this paper is the solution. Differences from conventional Closed Innovation and Open Innovation and expectations of the method are discussed below.

**Various innovation methods.**—Figure 4 shows the differences between Closed Innovation and Open Innovation. Open Innovation has become extremely popular since Chesbrough wrote “OPEN INNOVATION” and this method is still used by many companies.

In the case of Closed Innovation (CI), the variety and volume of research is limited because all research is conducted in-house. Only some is pursued for development, and just a few of a company’s technologies are launched onto the market. Therefore, although the market launch rate and the success rate are high, the scale of innovation is necessarily limited in terms of the level of technology revolution and the level of market explosion.

In the case of Open Innovation (OI), which was a new concept at that time, the variety and volume of research increased dramatically because research from outside the company is extensively pursued. Therefore a company can offer its technology on a research stage outside the company to be merged with another company’s technology and create a new market, or a company can obtain another company’s technology to be merged with its own technology and succeed in the existing market. This implies that research and development no longer have boundaries between companies. High-level technology revolution and potential market explosion are expected, but without engineers who can understand both their own and also other companies’ technologies, success cannot be attained by only widening the range. In
short, the difference between CI and OI can be interpreted as whether
the boundaries between companies are closed or open.

Figure 5 shows Enhanced Open Innovation proposed in this paper.
In this new method, boundaries among companies are open. This
means each companies can use research results mutually with al-
most no restrictions. This circumstance may bring not only much
more creation of innovation itself, but also acceleration of innova-
tion speed. Because, in this new method, a company’s research and
another company’s research can be merged into new research eas-
ily. Furthermore, projects can be merged to produce new projects one
after another in a chain reaction. The advantage is the speed and inno-
vativeness of this chain reaction. The huge amounts of results come
from these researches and projects have the potential to make semi-
 conductor technology advance ahead. The disadvantage: the project
may leave the company’s hands if it fails to keep up with the speed of
innovation. The author therefore believes that this method is advan-
tageous only in fields where the R&D speed is higher than the diver-
sion speed, and is therefore an optimal method for the semiconductor
industry.

Open innovation examples.—Examples of Open Innovation im-
plemented by Ebara are shown below. Figure 6 shows major matured

technologies owned by Ebara.
(1) FEM analysis of H.P. pump: This is an example of structural
analysis of a large diameter high pressure pump, which is one of
Ebara’s specialties. Structural analysis using FEM is required to
design an ordered pump of several meters in size and tens of tons
in weight, and this technology has already been established.
(2) Gas flow analysis of incinerator: This is used to analyze the flow
and heat inside an ordered incinerator of several meters in size
and tens of tons in weight.
(3) Vibration analysis of building: Pumps and compressors can be
a source of vibration in buildings where they are installed, so
vibration analysis is conducted not only on product but also on
the buildings.
(4) Corrosion analysis of pump: Corrosion analysis is conducted on seawater pumps because they are exposed to severe corrosive conditions.

(5) Cavitation corrosion prediction: Cavitation is inherent to pumps, and computer analysis is conducted to prevent cavitation when pumps are designed.

(6) Magnetic technology: Turbomolecular pumps using magnetic bearings to which the magnetic bearing technology is applied.

These existing technologies were applied to the developments shown in Figure 7. In Figures 6 and 7, the same number indicates the same technology field.

(1) FEM analysis of interconnect: FEM is used to analyze the stress on multilayer interconnection during the polishing process. This proves that the meter-order structural analysis can be applied to micrometer- or nano-order structural analysis.

(2) Gas flow analysis of CMP: Flow analysis using FEM is conducted to design CMP so as to prevent contamination because the polishing chamber, which is the most contaminated area, and the cleaning chamber, where cleanliness is most required, are integrated in CMP.

(3) Vibration analysis of CMP: CMP generates vibration due to stick-slip depending on the conditions because the machine applies a heavy load. The occurrence conditions and avoidance conditions are obtained from the analysis.

(4) Corrosion analysis of interconnect: In this example, corrosion of copper wiring is analyzed. This is also successful in analyzing SCC (stress corrosion cracking), which is caused by a change in corrosion rate depending on the degree of stress.

(5) Cavitation jet cleaning: In this example, the cleaning is applied to the non-contact cleaning nozzles to prevent the cavitation phenomenon, which must be avoided in the fluid field.

(6) Magnetic head of CMP: A magnetic bearing is applied to the development of the CMP head that can be freely tilted.

Figure 8 shows an example of polishing analysis using FEM, which is already well-known. The FEM analysis on polish profile published in 1995 is the paper about the first application of FEM analysis to the polishing head. The analysis of CMP for STI (shallow trench isolation), published in 2001, is the first paper to correlate the rigidity of the polishing pad with the planarization characteristic.

Enhanced open innovation.—Figure 9 shows the overview. Ebara’s proprietary technologies include those of Ebara’s three companies: 1 Fluid Machinery & Systems Company’s fluid technology, material technology, and vibration technology, etc.; 2 Environmental Engineering Company’s process technology and incineration technology, etc.; and 3 Precision Machinery Company’s vacuum technology, CMP technology, and plating technology, etc.

The main products of 1 Fluid Machinery & Systems Company, including 4 Pump, 5 Compressor, and 6 Refrigerator, are shown in Product-1. In Product-2 are shown the main products of 3 Precision Machinery Company, including 8 Dry pump, 9 Gas trap, 10 CMP, and 11 Plating, which are based on the rotating machinery technology of 1 Fluid Machinery & Systems Company and the process technology of 2 Environmental Engineering Company. Outside the company boundaries shown with dotted lines, technologies including 12 Weather forecast company’s Data simulation, 13 Aerospace company’s Form optimization technique, and 14 Super computer company’s HPC technology are shown in Other company-1. Technologies, including 15 Electrochemistry company’s Galvanic corrosion, 16 Fluid Machine company’s Visualization technology, and 17 Measurement technology company’s Ellipsometry, are shown in Other company-2.

The arrows show how these technologies are merged with others as Enhanced Open Innovation. For example, from 1 Fluid Machinery & Systems Company, 12 Data simulation, with which 4 Pump has been merged, is applied to 7 Incinerator and 18 Prediction of clearance corrosion. 15 Galvanic corrosion technology, which had been developed for 11 Plating Tool of 3 Precision Machinery Company, and 18 Prediction of clearance corrosion are the same technology, and the technology is merged with 12 Data simulation, thereby making a new connection and evolving into a new technology.

13 Form optimization technique and 14 HPC technology have also evolved in a similar manner.

In the field of 3 Precision Machinery Company, 16 Visualization technology, which started to be applied to 10 CMP, is merged with
Figure 7. Application Examples of Existing Matured Technologies.

Figure 8. Application Examples of CMP Polish Profile.
Figure 9. Structure of Enhanced Open Innovation.

24 CMP cleaning technology. 15 Galvanic corrosion is applied to 11 Plating, and the technology has evolved into 23 Plating analysis. 17 Ellipsometry is applied to 25 Particle analysis (measurement of residual particles on wafer surfaces). These are only some of the examples.

Enhanced open innovation examples.—Figure 10 shows examples of technologies created by Enhanced Open Innovation.

(1) Wafer drying using ME Fluid: This is a technology for visualizing wafer drying created by applying ME (mechanical engineering) technology. The technology, developed in conjunction with a university that excels in fluid technology and visualization technology in the ME field, is used to visualize analysis of the flow on a wafer surface and droplet behavior during the drying process, and contributes to development of post-CMP cleaning.

(2) Brush cleaning mechanism using ME Tribology: The technology, developed in conjunction with a university that excels in fluid technology and tribology in the ME field, analyzed the mechanical characteristics of PVA brushes used for post-CMP cleaning.

(3) Defect measurement using Ellipsometer: The technology for measuring the cleanliness after cleaning using an ellipsometer, which is normally used for thin film measurement, was developed in conjunction with a university that excels in film formation technology and thin film evaluation technology.

(4) Corrosion mechanism using AFM: The technology was developed to observe the potential distribution of copper wiring and predict the progress of corrosion using an AFM, which is normally used for nano-level topography measurement.

New CMP by enhanced open innovation.—Figure 11 shows how CMP can further evolve by applying Enhanced Open Innovation. The clues can be found in “Cherishing Old Knowledge, Acquiring New” on CMP published in 2017. The paper published in 2017 shows how CMP hardware evolved. In that paper, the history of CMP hardware evolving such as introduction of the dry-in/dry-out concept and the most recent CMP system in which polishing, cleaning, monitoring and other units installed at once were described. This paper shows how CMP software (process) can evolve. Virtual Metrology using AI is one of trials in this enhanced open innovation. In preparation for the coming paradigm revolution in 2030, CMP will also enter a new era. To contribute to the revolution in semiconductor devices, hardware needs to be renewed and new software designed for evolving semiconductor devices needs to be proposed.

Conclusions

The history of miniaturization of semiconductors, which had been supported by Dennard’s theory and developed in accordance with Moore’s law, has entered the new era of Å, and the market is expected to grow explosively beyond the conventional market mechanisms.

New technical challenges always arise and each of them has been overcome by a newly proposed innovation. However, a sense of stagnation about the technology has now become pervasive.

The market is expected to grow explosively due to the shift from single driver technology including PCs and mobile phones to the multi-driver technology including ICAC.

The author has introduced a method of development through Enhanced Open Innovation, which is an advanced form of Open Innovation, as a method for overcoming the sense of stagnation about the technology and responding to the explosively growing market.

To contribute to the coming paradigm revolution in 2030, the CMP hardware needs to be renewed through "Cherishing Old Knowl-
Figure 10. Examples of Enhanced Open Innovation.

Figure 11. New CMP by Enhanced Open Innovation.
edge. Acquiring New”, and the software needs to evolve by applying Enhanced Open Innovation.

Manabu’s principle “Semiconductor device technology is immortal as long as there are human desires” is now about to be proved.

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