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Material Modification Machine for Mass Production, KYOKA

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Nisshin Ion Equipment Co., Ltd. has pioneered the development of “KYOKA,” the world's first mass-production material modification equipment for semiconductor device manufacturing. By combining our high-current large-area ion source technology with advancements in low-energy ion beam transport efficiency and the development of stable metal ion sources, we have successfully developed this innovative equipment. The use of this equipment is expected to advance semiconductor microfabrication technology and enhance device performance. This paper provides an overview of the demand for material modification, the structure and features of the equipment, and presents experimental results utilizing the equipment.

Keywords: material modification, mass production, ion beam, semiconductor

1. Introduction

In December 2023, Nissin Ion Equipment Co., Ltd. (hereinafter, “Nissin Ion”) announced that it had developed KYOKA, the world’s first equipment capable of making the material modification process suitable for mass production. Material modification is a process that is useful for the manufacture of cutting-edge semiconductor devices. Making the process fit for mass production had long been desired. Since 2017, to meet this and other market demands, we had analyzed beam paths by means of simulations and continuously implemented mechanical, electrical, and software improvements by leveraging the company’s original high-current ion beam technology. The ion implanter used in the semiconductor device manufacturing process is one of Nissin Ion’s flagship products. It was then strategically planned to develop new products based on this ion implantation technology and to spread the company’s activities into markets other than the implanter market. This ambition came true with the equipment KYOKA.

While the name of the equipment “KYOKA” is associated with several concepts, it directly comes from the phrase *kyoka suigetsu*, which means flowers in a mirror and the moon’s reflection on water. The name represents our desire to create things that are beautiful and valuable by modifying the surfaces of materials. The Japanese word *kyoka* also means “to enhance (materials).” Moreover, “Kyo” in KYOKA can mean Kyoto, the birthplace of the Nissin Electric Group. Furthermore, 京, the first character of Kyoto (京都) is also used as the very large number equal to 10 to the power of 16. Thus, the equipment name subtly represents the equipment’s capability to generate a large number of ions required for material modification.

2. Semiconductors and Material Modification

Modern society is sustained by semiconductors. It is no exaggeration to say that the evolution of semiconductors is a kind of motive power that drives the creation of a new future. If there were no semiconductors, even cellular telephones would not be possible, let alone smartphones, and today’s advanced information-oriented society would not have been built. As a result of the COVID-19 pandemic, a semiconductor shortage occurred around 2021, which in turn led to chaotic situations throughout the world. These incidents were enough for people to have a renewed awareness about the importance of the semiconductor. Taking a lesson from that period, there are signs of moves in many countries towards having semiconductor production sites at home as an effort to prepare for emergencies. Take the example of the Creating Helpful Incentives to Produce Semiconductors and Science Act, (commonly known as the “CHIPS Act”), under which a huge amount of subsidies worth 39 billion US dollars will be spent to invite semiconductor manufacturers to the United States.(1)

The semiconductor market has been growing steadily since its emergence and is expected to continue to grow into a super-large market worth one trillion US dollars by 2030, driven by demand in sectors such as 6G telecommunication, artificial intelligence (AI) technology, Internet-of-Things (IoT), and data centers. It is unlikely for the semiconductor to lose its importance in the future.

The history of the evolution of semiconductors overlaps the history of their moves towards smaller design rules. The cutting-edge devices manufactured by a Taiwanese semiconductor device manufacturer have moved to a 3 nm process node. (The process node is an indicator of generations of semiconductors towards smaller design rules. In recent years, this indicator has no longer been referring to the actual size of some feature on the semiconductor chip.) Given that the lattice constant of silicon is 0.54 nm, how much semiconductor design rules have advanced is evident. In addition, to meet characteristic requirements for the state-of-the-art chips, three-dimensional structures have come into use as the structure of semiconductor transistors, while planar structures are traditionally in use for them. As their structure has become increasingly microscopic and complex, use of the existing semiconductor processing process alone has been facing limitations in processing accuracy, and a breakthrough in the processing technology has been desired. One of the candidate techniques is to use ion beams for material modification. By irradiating the materials—such as silicon and silicon oxide—that make up semiconductor devices with a large amount of carbon, silicon, or other ion beams, it is possible to modify the characteristics of the original material to be more preferable, thereby enabling hitherto impossible processing to be achieved or making the following processing process easier. For example, by boosting or reducing the rate of material removal in the nanoscale process known as "etching," it becomes possible to improve processing accuracy, and by utilizing the characteristic that the modified material's surface retards film deposition on it, it becomes possible to form a film of a desired material selectively and locally.

As described above, material modification is expected, as a new means available for the semiconductor device manufacturing process, to help processing technology evolve, to enable devices to move towards smaller design rules, and to help devices benefit from performance improvements such as miniaturization and low power consumption owing to the smaller design rules. But on the other hand, radiation of a large number of ions in the material modification process requires a large amount of time, which has long remained a challenge. As a solution to this challenge, it is conceivable to use high-current ion beams. However, this solution faces the technical barrier that the low-energy ions used to modify materials are difficult to form a high-current beam. Against this backdrop, although many results of material modification have been published,(2)-(11) they are no more than experimental results, so hopes have been placed on the realization of a low-energy, high-current ion beam system that is suitable for mass production and commercialization.

3. Mass Production-Compatible Material Modification Equipment KYOKA

Under the circumstances described in the preceding chapter, low-energy, high-current ion beams were produced and the material modification process was made suitable for mass production and commercialization for the first time in the world by KYOKA. KYOKA is a system intended for 300 mm wafers. Its most notable feature is the capability to process over 30 or more wafers per hour despite the fact that the material modification process requires a large number of ions for irradiation per unit area at $1\times10^{16}/\mathrm{cm}^2$.

This achievement is due to success in developing a large ion source capable of producing super high-current ion beams and, as described later, success in maximizing the ion beam transport efficiency in the low-energy region used for material modification owing to optimized components of the equipment. The equipment's design incorporates the company's super-high-current ion beam technology and beam transport technology developed for smartphone display manufacturing ion implanters—a market dominated by Nissin Ion for over 10 years. The equipment is very difficult for competitors to imitate. Photo 1 shows the exterior of KYOKA. Figure 1 presents a schematic diagram of the mechanism working from ion generation to wafer irradiation. Super-high-current ion beams (height > 300 mm) generated by the large ion source arrive at the inside of the mass separator magnet, where a magnetic field is present, which bends the beams, allowing only the required ion species to selectively pass through the slit provided at the magnet exit. After this passage, the beams are regulated to have a uniform density distribution by the uniforming mechanism and reach the wafer, with unwanted ions deviating from the predetermined energy level being removed by an electrostatic filter. Uniform ion irradiation over the entire wafer surface is achieved by repeated horizontal reciprocating motion of the wafer in the beams. Because the ions are positively charged, the wafer will be positively charged by continuous irradiation of ion beams, causing in some instances electrostatic breakdown of the semiconductor devices formed on the wafer. To avoid this, an electron supply mechanism known as the plasma flood gun (PFG) is provided to supply electrons to the wafer in order to neutralize the positive charge with negatively charged electrons. Since various types of ions are used in material modification, the equipment is capable of radiating carbon, silicon, and metal element ions, as well as boron and phosphorus ions used generally with ion implanters.

Photo 1. Exterior of the mass production-compatible material modification system Kyoka

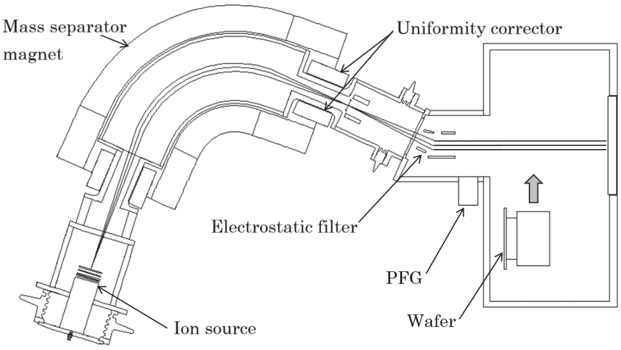

Fig. 1. Schematic top view of KYOKA beam transport system

4. Results of Material Modification with KYOKA

This chapter presents the results of material modification with this equipment.(12),(13) Figure 2 illustrates how the rate of film etching using hydrofluoric acid changed when silicon or phosphorus ions were used for irradiation at 1×10^{16} or 3×10^{16} ions/cm^2 over a 30 nm thick silicon oxide film formed on a silicon wafer, along with the results of a case in which no ions were irradiated. The etching rate, which was originally 7.5 nm/min, decreased to less than 20% after silicon ion irradiation, while conversely the rate increased to more than 200% after phosphorus ion irradiation.

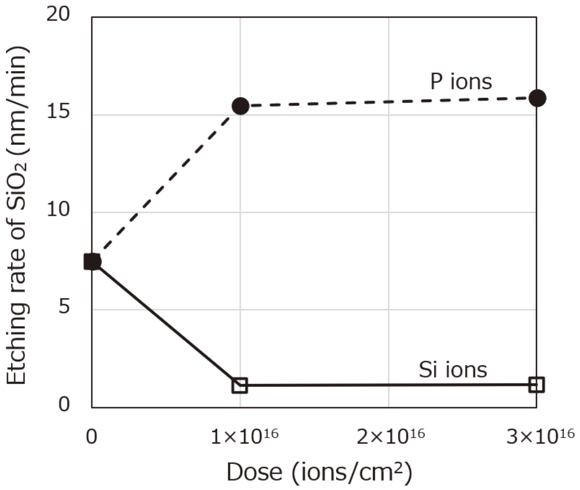

Fig. 2. Etching rate of silicon dioxide films modified by ions

To understand the reason for these changes, the state of chemical bonds of the silicon oxide film before and after modification was investigated by X-ray photoelectron spectroscopy (XPS). The results are shown in Fig. 3. The amount of ion irradiation was 1×10^{16} ions/cm^2 with both silicon and phosphorus. Modification of silicon oxide with phosphorus ions resulted in a decrease of the peak attributable to SiO_2, suggesting breakage of SiO_2 bonds due to ion irradiation. In contrast, modification of silicon oxide with silicon ions caused a peak to be observed at a position away from that of SiO_2, revealing the presence of SiO_x as a result of excessive silicon atoms due to silicon ion irradiation. It is highly likely that the film's resistance to etching with hydrofluoric acid changed due to the difference in the state of bonds, causing changes in the etching rate.

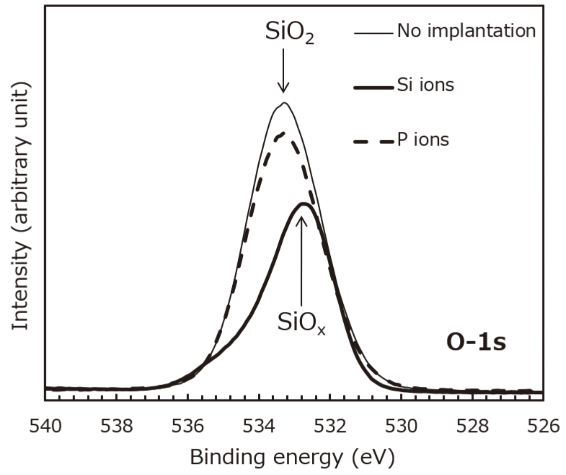

Fig. 3. XPS spectra of silicon dioxide films before and after material modification

Next, an example of partial, selective etching of silicon oxide films formed on silicon trenches is presented below. A sample was prepared, which had 30 nm thick silicon oxide films formed on a structure featuring a row of 200 nm deep silicon trenches provided at regular intervals. The sample was modified with silicon ions at a rate of 1×10^{16} ions/cm^2. Importantly, ion beams have very high directivity, which means that while the trench bottom surfaces and the top surfaces between trenches are irradiated with a large number of ions, the trench side walls are irradiated with the least number of ions. After the material of the sample had been modified, the sample was etched with hydrofluoric acid; then, the resultant structure was such that the silicon oxide on the bottom surfaces and the top surfaces made to have a reduced etching rate due to modification was not etched but remained, and the silicon oxide on the side walls was selectively removed (Photo 2).

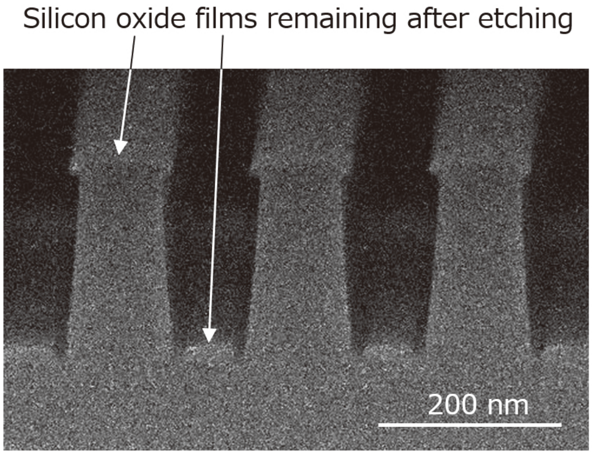

Photo 2. Electron microscope image of silicon oxide films on silicon trenches having undergone material modification and etching

5. Conclusion

Since our announcement of the development of KYOKA in December 2023 and the subsequent SEMICON Japan 2023 exhibition held in Tokyo, we have received many inquiries about the equipment. In April 2024, a demonstration system was installed at the Nissin Ion Shiga Plant to prove that the material modification process will help customers realize their desired semiconductor devices.

Beginning with KYOKA, Nissin Ion intends to promote its entry in markets other than the ion implanter market and, at the same time, deliver innovative manufacturing equipment to the market to meet global demand in order to contribute to its customers' growth and the creation of a sustainable society continuously in the future.

6. Acknowledgements

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- KYOKA is a trademark or registered trademark of Nissin Ion Equipment Co., Ltd.
- SEMICON is a trademark or registered trademark of SEMI, an international association for semiconductor equipment and materials.

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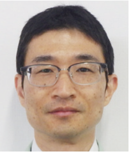

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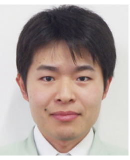

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