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Next-Generation, Super-Hard-to-Process Substrates and Their High-Efficiency Machining Process Technologies Used to Create Innovative Devices

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SiC, GaN, and diamond are known as super-hard-to-process substrate for next-generation green devices. In this paper, we report on some breakthrough in developing highly efficient processing for such hard-to-process materials, for which we propose improvements in conventional processing, and innovative processing. As part of our project, we developed a "dilatancy pad®" that can efficiently produce high-quality surfaces as well as a high-rigidity, high-speed and high-pressure processing machine. We also designed and prototyped "plasma fusion CMP®," which is an innovative processing technology fusing CMP (Chemical Mechanical Polishing) with P-CVM (Plasma Chemical Vaporization Machining) to machine super-hard diamond substrates that are considered indispensable for future devices. Before the advent of "singularities" by 2045, super-hard-to-process substrates and ultra-precision polishing technology will become more and more essential.

Keywords: hard-to-process materials, SiC, GaN and Diamond substrates, dilatancy pad, high pressure & rotational polishing machine, plasma fusion CMP, singularity

1. Introduction

It is a well-known fact that integrated circuits (ICs) using semiconductor Si substrates have rapidly evolved to LSI and ULSI technologies from their first application in transistors invented by Bell Laboratories in 1947. Currently, however, their physical limitations when applied to LSI devices have become evident, particularly for high-frequency and high-power device systems. Under such circumstances, expectations for wide-gap semiconductor substrates such as SiC and GaN for application to next-generation devices as well as for near-futuristic diamond crystal substrates for application in innovative green devices have heightened (**Fig. 1**). In addition, crystal substrates, having a uniquely excellent resistance to environmental elements such as electromagnetic fields and temperatures, are drawing attention for their application to high-efficiency and long-life blue/green light emitting diodes (LEDs) and laser diodes, white LED illumination, ultra-violet ray LEDs, and ultrahigh-speed electronic devices of low-loss and high-voltage resistance. To apply SiC, GaN, and diamond substrates [1] to sophisticated next-generation devices, it is indispensable to produce ultra-precision surface to an atomic order while taking advantage of the unique characteristics of such crystal substrates. In other words, materials for such devices need to be processed to high precision and high quality of atomic level as being required for silicon devices. Unlike silicon substrates, those crystal substrates are hard to process and mechanically and chemically very stable, which has been a bottleneck in processing before creating innovative devices. If the same processing conditions as silicon substrates are applied to SiC, GaN and diamond substrates, a huge amount of time will be required as shown in **Fig. 2** with poor results.

In the above mentioned context, the extreme difficulty in processing the substrates for application to prospective next-generation devices has thus far created a bottleneck in their dissemination, which calls for some breakthroughs to be found in the processing methods that would match production basis the same way as for Si substrates.

In the development of hard-to-process materials such as SiC, GaN and diamond substrates for next-generation devices, we propose two types of breakthroughs in their high-efficiency processing: (i) improvements in the current processing conditions, and (ii) innovative processing using a totally new method. The former aims to establish balanced high-efficiency processing by improving the current processes using our accumulated knowhow, or by developing a completely new method. The latter adopts a high-efficiency processing method, particularly for diamond substrates, by integrating a plasma processing method into a process regardless of conventional abrasive grain processing method.

In continuation, we present our perspectives on the two types of breakthroughs mentioned above. For the first type of breakthrough, we developed a "dilatancy pad™" that can efficiently produce high-quality surfaces, and a high-rigidity, high-speed and high-pressure processing machinery [2,3]. For the other type of breakthrough, we developed an "innovative CMP and P-CVM fusion processing technology" (called "plasma fusion CMP technology™") aimed at processing diamond sub-

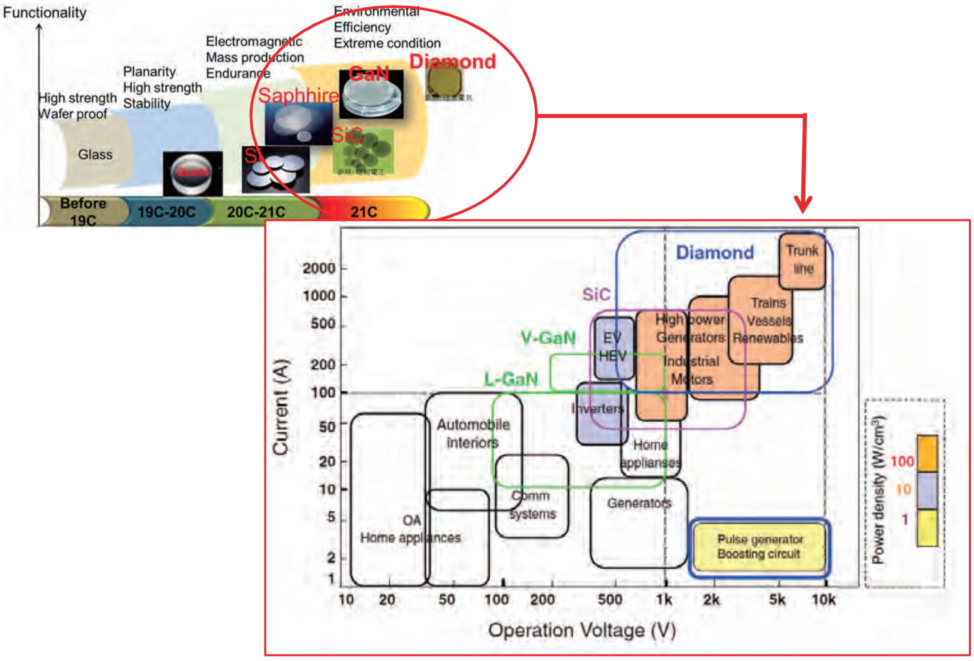


Fig. 1. Next-generation materials and devices.

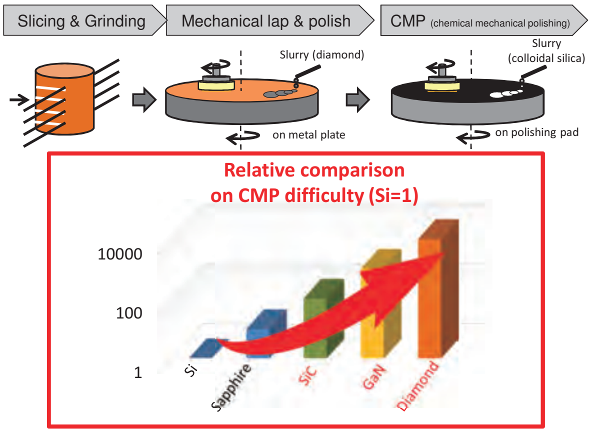


Fig. 2. Hard-to-process materials.

strates, spotlighted as an ultimate substrate for next-generation devices [4]. Finally, with an eye on the singularity, which is expected to reach by 2045, we discuss its future outlook by assuring that novel hard-to-process substrates and their ultrahigh-precision processing technologies will become more and more indispensable in the future.

2. Two Breakthroughs in High-Efficiency Processing of Next-Generation Hard-to-Process Substrates

Unlike chemically active Si substrates, SiC, GaN and diamond crystal substrates, which are extremely hard and mechanically and chemically stable, are difficult to process efficiently with a simple chemical and mechanical polishing (CMP). Processing for such mechanically hard materials usually involves a pre-stage with diamond abrasive slurry, where a grooved surface platen made of copper or tin is used to mirror-finish, which, however, leaves scratches of various sizes on the substrate surfaces. In the final finishing process, pre-processed surfaces are finished to mirror surfaces without defects using colloidal silica which is also used for Si substrates; however, this takes several tens of times longer than for Si substrates, and the final finishing process for diamond substrates takes several hundreds of times longer than for Si substrates as shown in **Fig. 2**. Because the final finishing process for Si substrates (**Fig. 3**) generally determines their processing rates, efforts have been made to reduce this burden on the rate-determining process by improving the colloidal silica slurry or by devising an immediate prior process to minimize rough processed surfaces, deep scratches or damaged layers as much as possible, thus thoroughly reducing the amount to be removed with colloidal silica slurry. The above-mentioned efforts represent a method to improve the processing conditions, based on the current processing methods.

Improvements to the processing conditions alone will not always assure high efficiency, particularly in the ultra-precision processing of diamond substrates. Even more, simple improvements to conventional abrasive grain processing will fall far short in producing the same high-efficiency as in the processing of Si substrates, thus likely impossible to meet their production basis. We have been actively researching and developing a new fusion processing technology incorporating a high-efficiency, physicallydry processing method while making the most of the

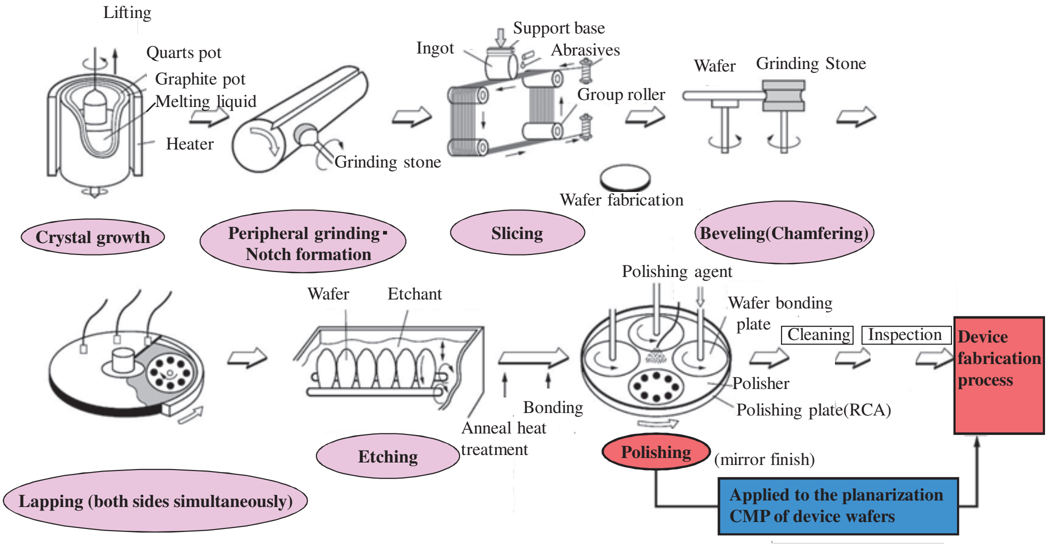


Fig. 3. Fabrication process of bare silicon wafers (the assumed wafer size for slicing is φ 12″).

advantages of CMP technology, which has been proven to be excellent for use in planarization and for achieving a smooth mirror finish. This represents another breakthrough, a challenging processing method for hard-to-process substrates, namely "Plasma-Fusion CMP" [4], an abrasive grain process that is combined with Plasma-Chemical Vaporization Processing (P-CVM) [5].

The two types of breakthroughs mentioned above can be summarized as follows:

A. Breakthrough by improvement in the processing conditions; – based on the current processing –

i) Creation of equilibrium processing involving no limitations in terms of the overall processes:
Because the final colloidal silica polishing/CMP process generally determines the processing rates, the slurry, pad, and mechanical processing conditions for the final processing should be improved to achieve high-efficiency and high-quality processing.

ii) Improvement to any processes that seem to impose a direct burden on the rate-determining final finishing process:
Improve the processing conditions for the process immediately before the final finishing process so that the amount to be removed in the final finishing process can be reduced as much as possible, lightening the burden imposed on the rate-determining final finishing process.

B. Breakthrough using innovative processing

Improvements to conventional processing conditions alone can not assure highly efficient processing, particularly in the processing of diamond substrates. A completely novel processing method, different from a conventional abrasive grain processing, needs to be developed to achieve highly efficient processing that matches the production basis. We are working on the introduction of plasma processing which may be one example of such novel processing methods.

Based on the above two breakthrough concepts, we discuss the highly efficient processing of hard-to-process materials for green devices.

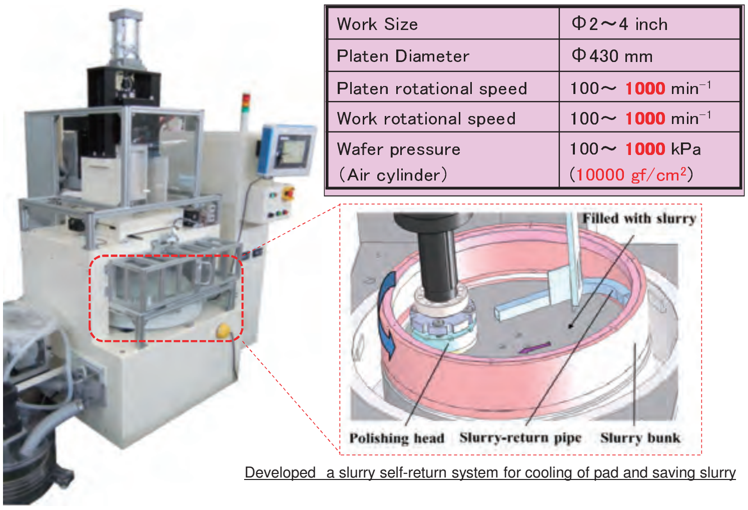
In this paper, we present our studies on the above items "A-ii)" and "B" in particular.

3. Establishment of Processing for Future-Generation Hard-to-Process Substrates

3.1. Proposal of Improved Processing Conditions

From the general processing characteristics, we first seek to enhance the processing pressure p and relative velocity v based on the empirical rule of Preston, namely, $RR = k \cdot p \cdot v / t$ (processing rate; RR, processing pressure; p, relative velocity; v, processing time; t). With a view to develop a processing machine capable of rotating at high pressure and high speed to achieve highly efficient processing of hard-to-process materials, we designed and prototyped a processing machine having around ten-times as large an output load as that of an ordinary processing machine (processing pressure; 100 kPa, number of rotations; 100 min^{-1}). Under generic processing conditions, the surface temperature of the pad will rise when simply increasing p and v during the processing. Thus, we introduced a submerged processing method for cooling rather than simply increasing p and v.

Figure 4 shows a photograph of the developed processing machine and its specifications. Adoption of a highly rigid housing and special belt driving of the ultrahigh-power motor enables very quiet processing under high-speed and high-pressure processing conditions, thereby reducing the influences of machine vibrations on the processing operations, as well as loads on the machine itself, which marks a breakthrough in high-speed, and high-

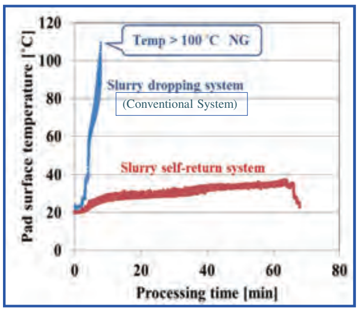


Work Size	Φ2～4 inch
Platen Diameter	Φ430 mm
Platen rotational speed	100～ 1000 min^{-1}
Work rotational speed	100～ 1000 min^{-1}
Wafer pressure (Air cylinder)	100～ 1000 kPa (10000 gf/cm^2)

Developed a slurry self-return system for cooling of pad and saving slurry

Fig. 4. Submerged processing type, "high pressure and high rotation polishing system."

Machine	Developed polishing machine (Fujikoshi Machinery Corp. : SLM-140H)
Work	φ2" SiC substrate (Si-plane)
Polishing pad	Nonwoven fabric pad (FUJIBO Ehime Co.,Ltd. : FPK-7,000C)
Slurry	φ250 nm Diamond slurry (1.0 wt%) (Commercially available)
Slurry amount	6 ml/min (Slurry dropping method)
	250 ml (Slurry self-return method)
Pressure	600 kPa
Rotation speed	200 min^{-1}
Polishing time	1 hr



(Temperature of the pad in a slurry dropping method and in a submerged processing type high-pressure & high-rotation speed polishing machine)

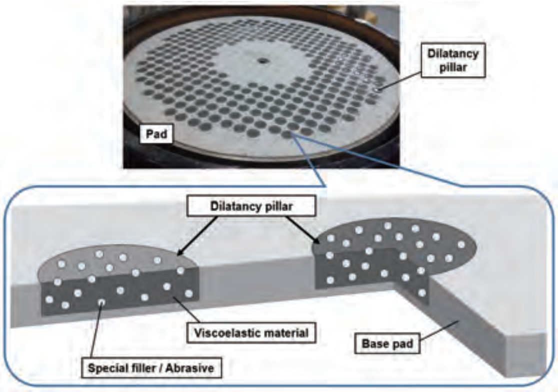
Fig. 5. Cooling effect of slurry self-return method.

pressure processing machines in addition to its high rigidity. **Fig. 5** shows an example of changes in the surface temperature in the developed submerged processing and slurry self-return method, and in a conventional slurry dropping method. We can see from **Fig. 5** that the surface temperature of the pad remains low in the former submerged method: its effectiveness has been well proven. In the developed slurry self-return method, where the distribution of the particle diameters (median grain diameters) within the returning slurry can be changed by moving the slurry return pipe position upward and downward, we can alter the quality of a processed surface (surface roughness) by moving the sample-holding position of the polishing head in the inner circumferential direction of the pad. We checked the processing rate of SiC substrates under high-pressure and high-rotational-speed processing conditions using the developed processing machine and determined that the processing rate increases in accordance with increases in the processing load, as originally designed; thus, concept "A-ii)" above has been partially accomplished.

The most important part of "A-ii)" lies in establishing a processing method immediately before the finishing process that will impose the least burden on the finishing process. To ultimately bring the process immediately before the finishing process close to the finishing process quality, we seek to achieve a high-efficiency and high-quality processing that is able to produce the prescribed shape/size accuracies using new tools/pads in place of conventional metal platen. In fact, we focused on viscoelastic resin to achieve dilatancy, and developed a "dilatancy pad" adopting a completely new viscoelastic resin concept.

We previously reported that when frictional heat or strong shearing stress under high pressure is applied to film colloidal silica, a reversible gelling phenomenon (dilatancy) occurs temporarily, and thus the retention effects of the abrasive grains are increased, thereby accelerating the processing accordingly [6]. With an aim to obtain such a dilatancy on the pad side, we developed a sensitive resin pad for use under high-speed and high-pressure processing conditions. The design concept for the developed pad aims at not only enhancing the processing efficiency but also improving the processed surface quality and shape accuracy, which we call "smart processing." **Fig. 6** shows a schematic diagram of the prototype pad which contains abrasive grains (250 nm diamond grains) kneaded into the viscoelastic dilatancy material along with special filler. Consequently, the pad has sufficient abrasive grains projected onto the surface, which act uniformly and contribute accordingly to the processing. Dilatancy materials with elastically immobilized abrasive grains become hardened instantaneously through the dilatancy when undergoing the shearing stress during a processing operation. The superposition of such effects results in a significantly enhanced processing efficiency as well as mirror surfaces with uniform surface roughness free from deep scratches, which differ completely from the effects of ordinary metal platen.

Figure 7 shows an example comparison of the processing characteristics of SiC substrates between a conventional pad or metal platen and a dilatancy pad. Application of a dilatancy pad can achieve processing rates of



(above: Photograph of prototype Dilatancy Pad, bellow: Schematic diagram of pillar-type Dilatancy Pad)

Fig. 6. Developed "dilatancy pad."

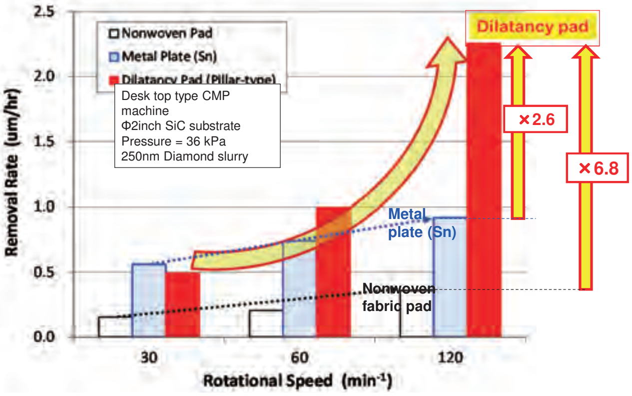


Fig. 7. SiC polishing characteristics with various plate/pads: non-woven pad, metal (Sn) plate, and dilatancy pad.

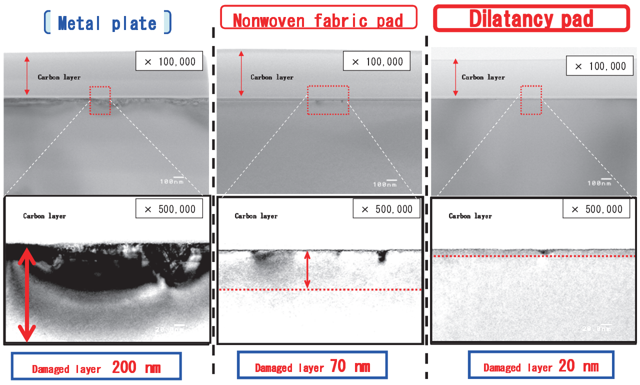


Fig. 8. TEM (cross-section) images of SiC substrate polished using various pads.

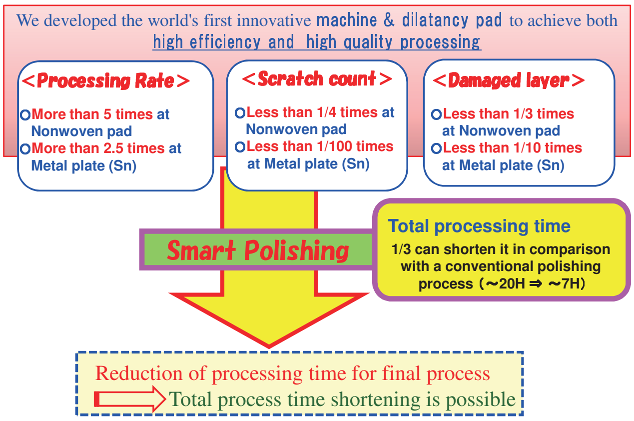


Fig. 9. Capability of smart polishing.

more than three to seven times (even up to twenty times depending on the dilatancy materials) as large as conventional pads, with excellent processed surfaces. In the case of a conventional metal platen, scattered slurry can cause the processing efficiency to lower while no abrasive grains will be scattered during processing with a dilatancy pad because it works for a fixed abrasive grain as well. Therefore, it has more abrasive grains passing the processing area, which contributes to remarkable improvements in the processing efficiency. A dilatancy pad, structured to have a grain-kneaded dilatancy material fused with a non-woven pad to induce dilatancy phenomenon/effects while it moves, can process hard-to-process substrates to high-quality finished surfaces.

We checked the substrate surfaces to determine whether they are processed to a high-quality finish with the level of scratches and also evaluated the depths of the processing damage (damaged layers) using TEM and found that processing using the newly developed dilatancy pad reduces the damaged layers to one-tenth of that with a metal platen, and about one-third of that with a non-woven pad (**Fig. 8**). The development of the dilatancy pad enables high-efficiency and high-quality processing at the same time, and is hence called "smart processing." Such a breakthrough is almost impossible with a conventional processing method, and thus many industries have begun paying attention to the new dilatancy pad.

As described above, by improving the processing conditions immediately before the finishing process, we established an intermediate processing method that will not impose a burden on the finishing process (ultra-precision processing using colloidal silica). As summarized in **Fig. 9**, implementation of smart processing that will reduce the burden placed on the final finishing process has significantly reduced the overall processing time.

3.2. Proposal of Futuristic Processing – Ideas on Innovative Plasma-Fusion CMP Method –

Ultra-precision processing for futuristic hard-to-process materials has been devised based on the following ideas:

(1) Pre-Processing: Micro defects (called pseudo-radical sites) are formed using a femtosecond laser, for example, on only the outermost surface layers (surface layers of several to hundreds of atomic layers) of the substrate. The formation of such pseudo-radical sites makes the mechanical polishing or CMP induce chemical reactions accompanied by frictional

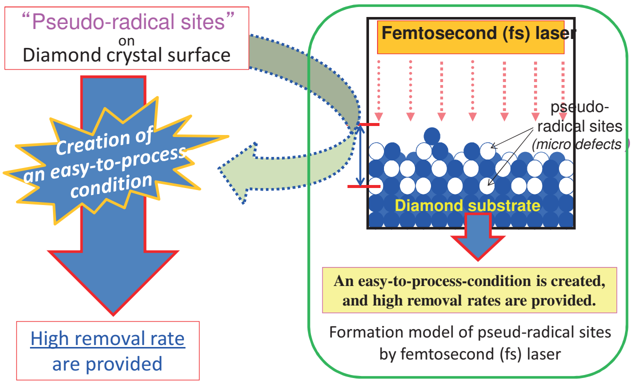


Fig. 10. Diagram of pre-processing: formation of pseudo-radical sites using femtosecond (fs) laser.

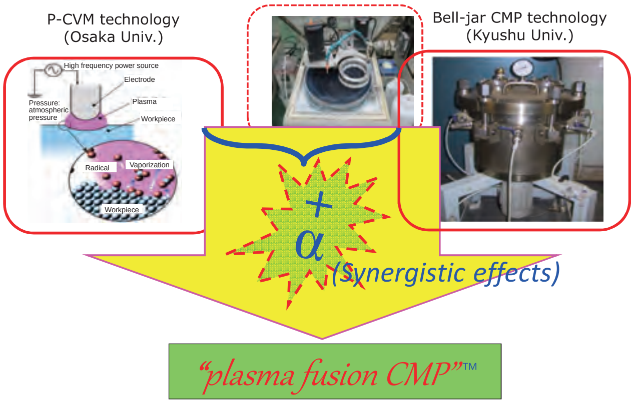


Fig. 11. Concept of novel "plasma fusion CMP$^{\text{TM}}$" machine combining plasma processing (P-CVM) & CMP.

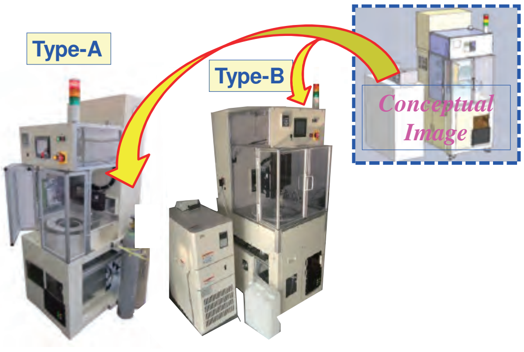


Fig. 12. Novel "plasma fusion CMP$^{\text{TM}}$" machines.

wear, thereby facilitating the polishing or CMP under atmospheric pressure. **Fig. 10** shows the scheme of the above-mentioned idea.

(2) Finishing Processing: A novel CMP/P-CVM fusion processing method ("P-CVM" for Plasma Chemical Vaporization Machining). In the most critical processing part of the machine, effective P-CVM actions are induced through the formation of pseudo-radical sites with a physically acting pad or using slurry or slurry-less tools. We can then also expect superposed effects of high efficiency and high quality owing to the fusion actions of CMP/P-CVM under a gas atmosphere such as oxygen (**Fig. 11**). The proposed processing method is called "Plasma-Fusion CMP."

Of the two proposals mentioned above, the plasma-fusion CMP technology in item (2) above will be discussed here.

The new fusion processing technology concept works such that while pseudo-radical site being formed by polishing or CMP, planarization processing is being performed, and simultaneously no disturbance processing is carried out using P-CVM that is in principle a highly efficient etching processing. We name this concept a fusion processing, capable of generating synergistic effects (**Fig. 11**).

When SiC and GaN substrates formed with pseudo-radical sites (damaged layers) are processed using P-CVM alone, the P-CVM speed is found to increase because the layer with the formed pseudo-radical sites (about 100 nm deep) is chemically unstable. Therefore, while forming moderate pseudo-radical sites (micro defects) through physical actions such as polishing and CMP, processing efficiency is enhanced using P-CVM which keeps removing defective parts preferentially. Depending on the conditions set, CMP can perform smoothing and planarization at the same time. We have thus far developed two types of machines: Type A – Basic Plasma Fusion CMP Machine, and Type B – Challenging Plasma Fusion CMP Machine (**Fig. 12**). Type A has a CMP platen, in the opening of which a linear atmospheric-pressure plasma generator is mounted for P-CVM, thus CMP and P-CVM can be cyclically and alternately performed by reciprocating the sampling stage in the radial direction. As a futuristic processing machine, we focus more on the Type B, a challenging plasma fusion CMP machine.

To fuse P-CVM of the isotropic etching processing principle with the CMP method, which is good at eliminating fine unevenness, plasma needs to be continuously and uniformly generated while the pad platen and the polishing head holding a substrate are rotating. Thus, a number of plasma-generating microelectrodes are built in the platen allowing the high-density plasma to act on the substrate to be processed (**Fig. 13**). To apply CMP while keeping the processing slurry flowing, the microelectrodes were specially structured that can be controlled at a positive gas pressure to avoid slurry from entering into the microelectrodes. The pad platen has an "orbital spiral rotary motion mechanism" with which it can move in a large radius orbit accompanied by a small circular motion rather than a simple circular rotary motion, and thus its highly efficient processing can be assured through superposed plasma actions while maintaining its relative speeds in CMP.

As a preliminary experiment to the Plasma Fusion CMP, we performed the dry polishing of Si substrates with fixed abrasive grains (wrapping tape) and P-CVM separately to confirm the effects and functions of each

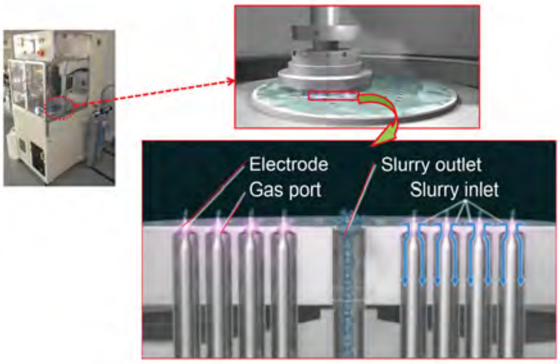
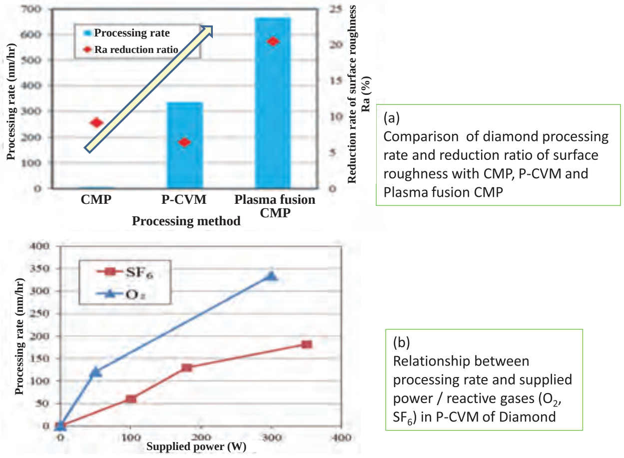


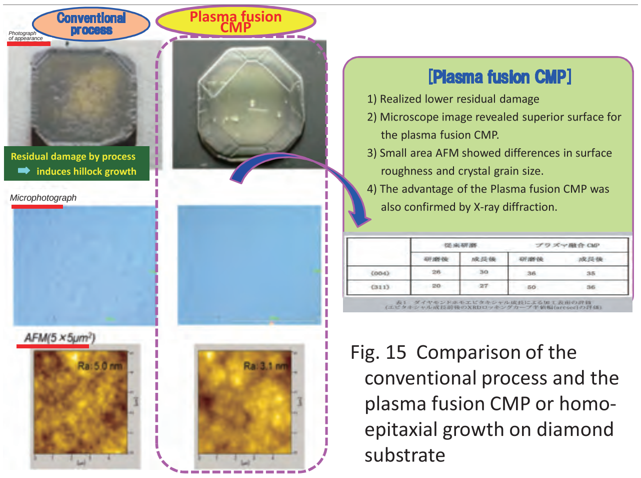
Fig. 13. Mechanism of novel "plasma fusion CMP^{TM}" machines (B-type).



(a)
Comparison of diamond processing rate and reduction ratio of surface roughness with CMP, P-CVM and Plasma fusion CMP

(b)
Relationship between processing rate and supplied power / reactive gases (O_2, SF_6) in P-CVM of Diamond

Fig. 14. Plasma Fusion CMP® of diamond substrate.



[Plasma fusion CMP]

1) Realized lower residual damage
2) Microscope image revealed superior surface for the plasma fusion CMP.
3) Small area AFM showed differences in surface roughness and crystal grain size.
4) The advantage of the Plasma fusion CMP was also confirmed by X-ray diffraction.

	従来研磨		プラズマ融合 CMP	
	研磨後	成長後	研磨後	成長後
(004)	26	30	36	35
(311)	20	27	50	36

表1 ダイヤモンドホモエピタキシャル成長による加工表面の評価
(エピタキシャル成長前後のXRDロッキングカーブ半値幅(arcsec)の評価)

Fig. 15 Comparison of the conventional process and the plasma fusion CMP or homo-epitaxial growth on diamond substrate

Fig. 15. Comparison of the conventional process and the plasma fusion CMP or homoepitaxial growth on diamond substrate.

processing. As a result, we confirmed that fusing dry polishing with P-CVM can improve the processing rate by about two-times that of dry polishing alone, and can improve the surface roughness (*Ra*) to one-third. We then tried to process SiC substrates using the developed "Plasma Fusion CMP Machine" and determined that it can produce a far larger processing rate than the sum of the processing rates by the CMP and P-CVM individually. We also found that it can improve the surface roughness of the substrates through proper adjustment of its processing conditions.

Next, we present an example of the processing characteristics of diamond substrates using CMP and plasma fusion CMP. Comparison of the processing rates is shown in **Fig. 14**, which indicates that the processing rate using CMP is 1.9 nm/h, and the processing rate using plasma fusion CMP, where P-CVM and CMP are simultaneously performed, is 670 nm/h, which is 350 times larger. The above experimental results prove that the developed plasma fusion CMP processing system has processing characteristics that reflect the both advantages of CMP's planarization performance and P-CVM's high-efficiency etching performance, allowing it to process even a super hard-to-process diamond with high efficiency and high quality. This means that Plasma Fusion CMP can produce far larger processing rates than single CMP or single P-CVM owing to its synergistic effects. In processing diamond substrates using P-CVM, the use of O_2 gas as reactant is found to produce larger processing rates and better surface roughness (*Ra*) than SF_6 gas. This suggests that oxygen plasma should be more suitable for processing diamond substrates, and that its processing conditions including O_2 gas and its flow rate should be optimized accordingly in the future [5].

Figure 15 shows a full-picture, a microscopic photo, and an AFM image of a diamond substrate surface with a homo-epitaxially grown diamond thin film on the diamond substrate processed using the plasma fusion CMP [8]. For comparison, the figure also shows those processed using conventional polishing that is based on scaife polishing. We can see from **Fig. 15** that, although a large number of hillocks are observed on the epitaxially grown diamond thin film processed using the conventional method, the substrate surface processed using plasma fusion CMP has an excellent epitaxial growth of the diamond thin film with no hillocks. Because residual damage during processing is deemed to act as a cause of hillock growth, it suggests the possibility that plasma fusion CMP processing has successfully processed and created a diamond substrate surface with no residual damage. Microscopic observations show clear differences in the surface roughness. AFM images of extremely micro areas also show such differences in the surface roughness, as well as in the size of the grown crystal grains. Furthermore, we reconfirmed such differences through X-ray diffraction measurements. This definitely proves the superiority of the plasma fusion CMP processing.

The above-mentioned observations tell us that the advantages of the plasma fusion CMP processing mechanism for diamond substrates may be attributed to the reactants being first formed and then removed by CMP, and the plasma density increasing by the locally closed cells (see the schematic diagram in **Fig. 16**).

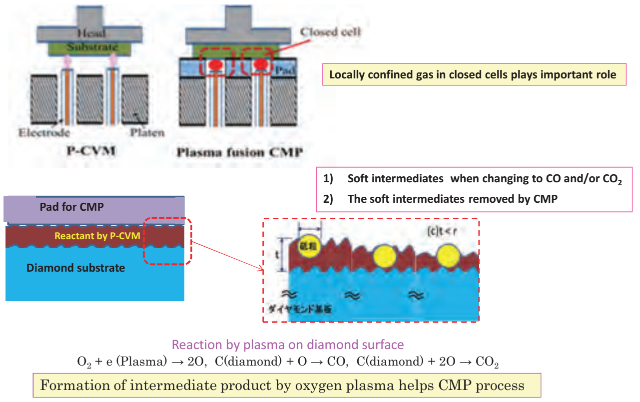


Fig. 16. Processing mechanism of plasma fusion CMP for diamond substrate.

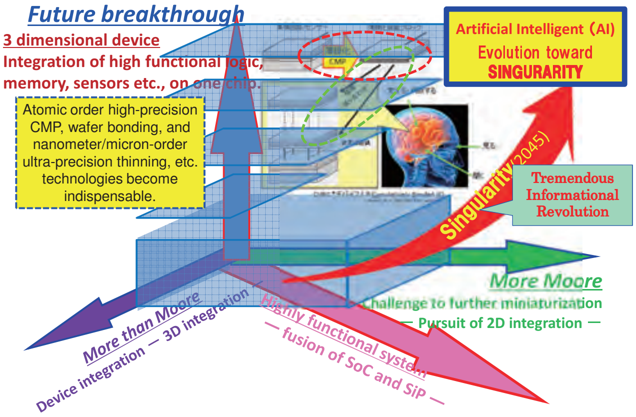


Fig. 17. A schematic of technological evolution towards “singurarity” in 2045.

The proposed plasma fusion CMP method, which is capable of improving both the processing rate and the surface roughness, is drawing attention as a highly promising futuristic technology for the high-efficiency and high-quality processing of hard-to-process materials.

4. Trends in Innovative Devices and Expectations for High-Efficiency Ultra-Precision Processing

The 21st century has seen various remarkable advancements in nanotechnology, as found through the following keywords: 3D devices and implementations, MEMS sensors, automatic operations, 3D printing, and robotic medical equipment, among others. Ultra-precision polishing is indispensable in the manufacturing of innovative opt-mechatronics parts [9]. Taking the semi-conductor industry as an example, it is no exaggeration to say that ultra-precision polishing technology, as represented by planarization CMP, holds the key to creating future high-performance devices.

Looking back on the progress of processing technology, research and development of various functional materials with its processing technologies and integration technologies has formed the basis of the Information Communication Technology (ICT) industry and brought high-performance opt-mechatronics components and systems into the world. To create components helpful for people through technical advantages, they need to be designed and prototyped to be safe in operation, operable at high speed, long life, compact or micro in size, light in weight, and energy saving. Needless to say, they should be manufactured at low costs to make them available to as many people as possible. Moreover, with growing calls for a low carbon society, it will become a big issue in the future to develop opt-mechatronics components and systems that are friendly to the global environment in terms of environmental conservation, and energy and resource savings.

In the future trends of the opt-mechatronics industry, the IT industry will become increasingly spurred on, as it occurred in the industrial revolution in the 18th century, and thus new methods for high-functional systems and components will inevitably emerge such as automatic driving cars packed with numerous MEMS sensors and high-functional semiconductor devices to bring them ultimately close to artificial intelligence. At the same time, new materials and structural components will emerge inseparably; as such new materials emerge, it will become indispensable to study how their unique properties should be used, and to research and develop not only their processing and treatment technologies but also their evaluation and measurement technologies.

As shown in **Fig. 17**, the future will continue evolving from the third time-and-space-transient axis to an artificial intelligent evolution, leading to innovative opt-mechatronics components and systems. In the figure, a schematic diagram of 3D devices and their implementation used to create higher speed, highly functional, and more intelligent devices, closer to human “brains,” is shown. In the course of such technological evolutions, planarization CMP, particularly Silicon Device-Thinning CMP and ultra-precision junction technology for large-diameter substrates, is indispensable in materializing layering of thinned devices with high accuracy. Future opt-mechatronics devices will be materialized around the future breakthrough axis that has ultimately evolved high-functional systems fusing “More than Moore” with “More Moore” [10].

The early 21st century, called the fifth industrial revolution (IoT and AI), has seen a rapid progress in AI research, gaining exponential momentum through the evolution of various technological fusions [11]. Such a revolutionary progress of AI research will reach its singularity in 2045, when AI is expected to surpass the human brain. Because fusion technologies are closely related to not only ultra-precision processing technologies but also precision engineering and semiconductor engineering, we should keep track of their evolution in order to firmly capture their future images and issues to be addressed in anticipation of the advent of their singularity in 2045 (**Fig. 18**) [12].

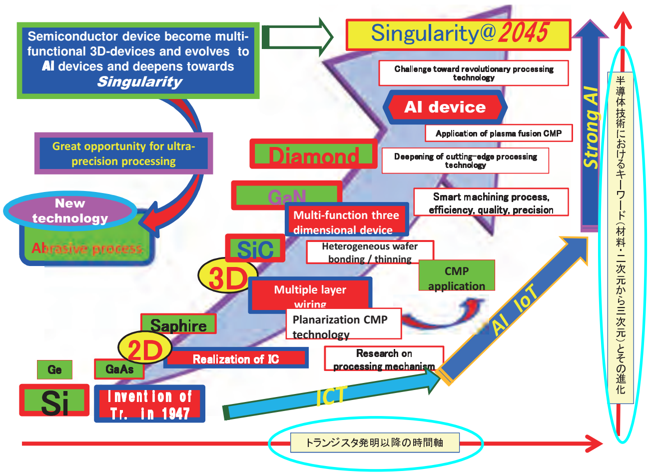


Fig. 18. Evolution of semiconductor device and processing technology.

We duly recognize that, in response to further developments of opt-mechatronics components and systems, it should become crucially important to establish more sophisticated ultra-precision processing methods and develop more breakthroughs.

5. Conclusion

In this paper, we discussed and summarized the transition of precision processing technologies and in particular referred to the designs for highefficiency processing of hard-to-process materials. To contribute to the manufacturing of devices that use wide-gap semiconductors such as SiC,GaN, and diamond substrates, we have mainly presented our research and development projects challenging for the breakthrough for innovative processing technologies aimed at high-efficiency and high-quality processing for such hard-to-process substrate materials. In particular, as a part of developing high-efficiency and high-quality processing for hard-to-process materials, we presented here a high-rigidity, high-speed and high-pressure processing machine, novel dilatancy pads applying a dilatancy phenomenon, and an innovative CMP/PCVM fusion machine ("Plasma Fusion CMP"). In addition, as a part of research and development of processing for substrates used in green devices, we presented an ultra-precision, normal temperature/low temperature junction technology that has now come into the limelight. It is highly expected that a combination and fusion of these technologies will enable innovative devices to be created with high efficiency.

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