Impact Objectives

- Fabrication of low-cost, large-area semiconducting diamond wafers
- Fabrication of ultra-low-loss power devices using diamond

Next-generation electronic devices using diamond

***Professor Norio Tokuda** tells us about his work on extending the performance boundaries of current electronic power devices relating to the atomically-precise control of diamond surfaces and wafers for use in field effect transistors and quantum devices*

How did you become interested in developing diamond-based metal oxide semiconductor field effect transistors (MOSFETs)?

I studied atomically-controlled silicon surfaces and interfaces in silicon metal oxide semiconductors (MOS) when I was a PhD student. Atomically-controlled surfaces are those where the precise crystalline structure is controlled, and the position of each atom is pre-planned. Control of the surface texture when making small semiconductor devices is critical because the shape or roughness of a surface can make significant changes to the performance characteristics. Atomic control is usually applied to the etching or growth of very thin layers of crystalline materials.

I found that atomically-controlled silicon surfaces could be easily degraded through oxidation in air and therefore the performance potential of silicon in semiconductor devices had limitations. I became interested in the potential of diamond as a next-generation semiconductor material because its surface is highly non-reactive and stable. In 2009, when I first started working on diamond, no one had managed to create a diamond-based MOSFET with normally off operation using inversion channels. I realised that I could apply my knowledge on the atomic control of surface finishes to this field and that creating a diamond surface without steps or other transitions could be key to making a successful diamond MOSFET.

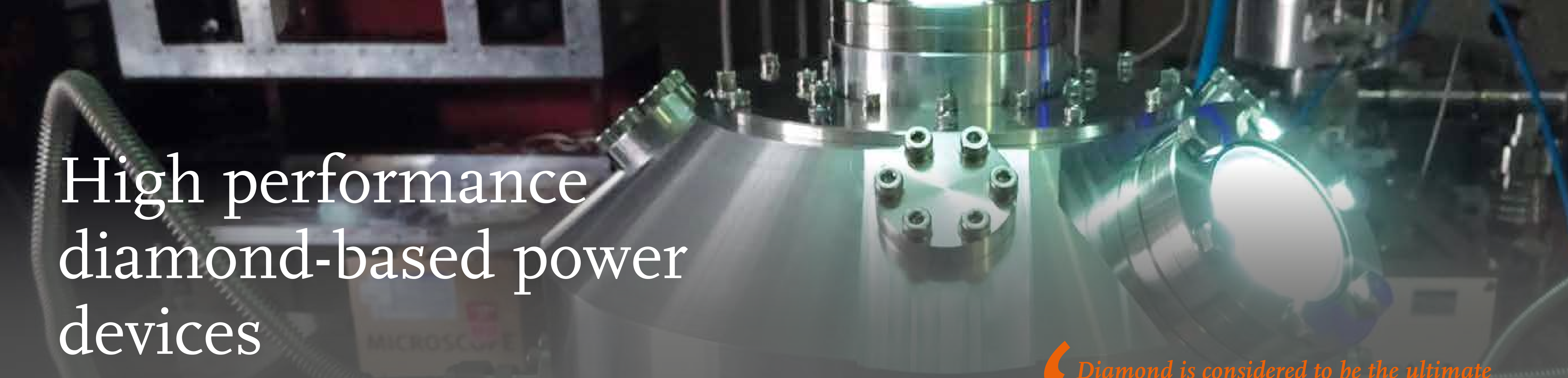
What is a field effect transistor (FET) and why is performance so vital?

A transistor is essentially a switch that either allows or stops the flow of electrical currents. A FET is one of the transistors activated by a transversally-applied voltage differential. The resulting electrical field triggers electron or hole mobility, creating a conductive inversion channel between source and drain electrodes through which current can flow. FETs are made of semiconductor materials that are normally insulators but become conductive through the influence of voltage, heat, light or other energy sources. MOSFETs allow for precise control of voltage flow across them.

MOSFETs are at the heart of every electronic device, whether in our homes, transport or industry. Silicon has become ubiquitous owing to its useful electronic properties and relative cheapness and availability. However, silicon devices are approaching their upper performance limitations and many researchers are looking at different materials that can switch higher voltages, withstand higher temperatures, have lower 'on' resistance, low leakage levels and higher breakdown voltages. To realise Japan's vision of Society 5.0, we need to develop these highly-efficient power devices for use in energy applications and in fast, efficient transportation such as the bullet train. Materials being researched for MOSFETs include silicon carbide, gallium nitride and gallium oxide, but the properties of diamond exceed these materials in every way.

Please tell us about your work, the SAKIGAKE project at Kanazawa University and Society 5.0?

The Japanese Council for Science, Technology and Innovation has developed the concept of Society 5.0 as being the next stage of human development Japan should aspire to. It will move us on from a communication society to one where economic development is balanced and social issues resolved. It requires advanced technology such as energy sources that combat climate change, caregiving robots, sustainable industrialisation, efficient transport solutions and greater automation. In response, Kanazawa University conceived the SAKIGAKE project with multiple aims, including cutting-edge research to suit Society 5.0, greater international collaboration and more integration with education, industry and society. Within this space, I am involved in the SAKIGAKE Project 2018, which aims to develop a next-generation electronics research base to develop innovative devices. Areas of research include fabrication of semiconducting diamond wafers, diamond diodes and MOSFETs, quantum devices using nitrogen vacancy centres in diamond. Such high-performance materials and devices are needed to realise the goals of Society 5.0. ▶

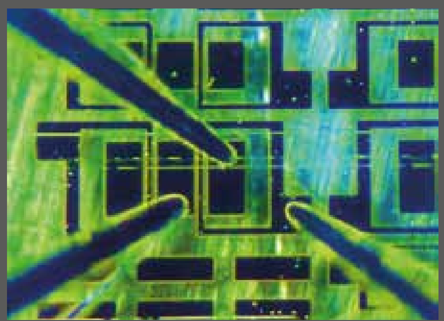


High performance diamond-based power devices

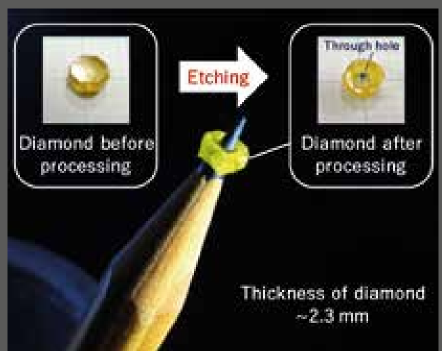
*To meet the demands of Japan's vision for Society 5.0, researchers at **Kanazawa University** and the **National Institute of Advanced Industrial Science and Technology** (AIST) are developing diamond-based power devices with the potential to exceed the performance of silicon devices*

At Kanazawa University, Professor Norio Tokuda, who specialises in research, and fellow researchers are pushing the performance boundaries of current silicon-based power devices. Tokuda notes that to achieve Japan's ambitious national goals for carbon neutral industry and energy supply, plus automation to resolve many social issues such as care for an ageing population; high-performance power devices are vital. Tokuda says: 'The performance of silicon-based devices is thought to be nearing the maximum possible, therefore much research is being devoted to a range of exotic materials, including diamond.'

He explains: 'Diamond is considered to be the ultimate material for power devices. It offers the highest-known dielectric breakdown voltage and carrier mobility as well as high thermal conductivity, low resistance, high-voltage endurance, low losses and the possibility of extreme miniaturisation.' Despite these properties, it has proven hard to fabricate an effective metal oxide semiconductor field effect transistor (MOSFET) based on diamond, not least owing to diamond's hardness and chemical stability. Tokuda says: 'We were the first to create atomically-step-free and hydroxyl-terminated diamond surfaces that enabled us to demonstrate a working diamond MOSFET in 2016. Since then, we have been working to refine this concept and to create other diamond-based power devices.'



Photograph of inversion channel-type diamond MOSFET with normally-off operation that was demonstrated by the group for the first time (T. Matsumoto, N. Tokuda et al., Scientific Reports 6, 31585 (2016))



Yellow diamond with through hole created by the diamond etching process (M. Nagai, N. Tokuda et al., Scientific Reports 8, 6687 (2018))

HIGH PERFORMANCE MOSFETS

FETs are tiny switches that are central to all integrated circuitry, with many millions on a single electronic chip. They are the main enabler for digital technology and hence anything that can extend their performance is useful for the creation of more efficient circuitry. MOSFETs are the most common FET and Tokuda says: 'MOSFETs that use inversion channels enable a high level of control of electrical power and their desired threshold voltage can be obtained by controlling the impurity concentration in the substrate.' An inversion channel is a conductive channel created by the input of energy, usually a voltage, applied to the gate electrode, that allows current to flow between the source and drain electrodes, effectively switching the FET to the 'on' position. The threshold voltage is the minimum voltage required to create this conductance channel. Tokuda continues: 'FETs that use an accumulation channel or the main body of the device as the conductor are less advantageous as it is harder to tune the threshold voltage.'

Tokuda explains: 'The most efficient MOSFETs need to work in extreme environments of temperature and voltage and should preferably have little or no resistance when in the 'on' position.' Diamond offers performance levels that greatly exceed and has a band gap five times that of silicon, meaning it can cope with much higher voltages and faster switching frequencies. One of the most important properties of FETs is the carrier mobility, a measure of how conductive the FET is when activated by an input voltage and how quickly it can be turned from the 'off' to the 'on' position. Tokuda adds: 'Diamond can cope with a much higher voltage than silicon before its dielectric strength ceases to work. In fact, it offers around 30 times the performance of silicon in this regard.'

WET ANNEALING DIAMOND SURFACES

Despite all these potential performance advantages and much research, no working inversion channel diamond MOSFET had been demonstrated before Tokuda and his team first fabricated their proof of concept device in 2016. MOSFETs are layered components comprising a thin doped n- or p-type semiconductor layer between the body or substrate and an oxide layer that is the gate electrode. The conducting channel is formed between the semiconductor layer and the gate oxide when the threshold voltage is applied to the gate. Semiconductors are termed n- or p-types according to whether their mobile carriers are electrons or holes. Holes are positively-charged particles in a crystal lattice into which an electron can move, thus carrying current. Doping, the addition of impurities in precise quantities and distribution patterns in the crystal lattice, creates free electrons or holes in semiconductor materials.

> *'Diamond is considered to be the ultimate material for power devices'*

Tokuda's device started with a standard diamond substrate onto which an atomically-thin n-type phosphorus-doped diamond layer was deposited using wet annealing. Aluminium oxide was then applied using chemical vapour deposition to create a thin gate layer. Tokuda says: 'I realised that it was vital to create an atomically-smooth diamond surface onto which the gate oxide would be applied. Any atomic-scale roughness in the lattice structure would obstruct the channel and create electron traps and therefore prevent a conductive inversion layer forming.'

When a negative voltage was applied to the gate electrode, a p-type channel was created between the doped diamond layer and the gate oxide, thus demonstrating the diamond MOSFET proof of concept. This comprised a major industry breakthrough and the start of Tokuda's mission to refine and improve performance of the device that is expected to be ongoing for many years before commercially-viable devices are perfected.

NON-PLASMA DIAMOND ETCHING

Tokuda says: 'One of the biggest challenges when working with diamond is its hardness and chemical stability. This makes it quite difficult to create desired surfaces and to etch it for device fabrication.' He adds: 'Diamond etching is usually done using a plasma process, but this has the disadvantage of creating rough edges near the etching site, reducing device performance.' Tokuda's team has overcome this problem by developing a high-speed non-plasma anisotropic etching process. The technique uses the thermochemical reaction between nickel and diamond in water vapour at 1000°C, enabling fast, selective etching with extremely high precision. Tokuda says: 'This technology will enable the fabrication of diamond power devices with integral trenched gate structures that will have low transmission losses and high-voltage endurance. In addition, this process could be useful in other industrial diamond applications where the material needs flattening or cutting into precise shapes.'

Tokuda is quick to credit his colleagues, saying: 'All my colleagues at Kanazawa and the National Institute of Advanced Industrial Science have been vital to the progress we have made.' As well as consulting with Japanese experts in semiconductor wafers, power devices and quantum devices, Tokuda has also collaborated with the German Fraunhofer Institute for Solid State Physics, which is also working on diamond devices. In conclusion Tokuda says: 'Only by working together at an international level will the world be able to develop sustainable technologies to address the big challenges facing all our societies. I see high-performance power devices being vital to these new technologies and think that diamond has the necessary properties to realise step-change advancements.'

Project Insights

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BIO
Professor Norio Tokuda received his PhD degree in applied physics from University of Tsukuba in 2005. From 2005-2009, he worked for the National Institute of Advanced Industrial Science and Technology (AIST) as a postdoctoral researcher. In 2009, he joined Kanazawa University as an assistant professor. He is currently a professor (specialising in research) at the Nanomaterials Research Institute. His research interests presently focus on the fabrication of semiconducting diamond wafers and their device applications (power devices, quantum devices).

先魁プロジェクト SAKIGAKE PROJECT Kanazawa University

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