Impact Objectives

- Investigate novel electronic devices that have high radiation resistance and are capable of high-temperature operation in imaging devices
- Develop a silicon carbide charge-coupled device

Silicon carbide (SiC): An extremely tough semiconducting material

*Physicist **Professor Yasuto Hijikata** introduces his innovative work to develop a charge-coupled device with an array of exciting potential applications*

Could you first provide an overview of some of the research underway at the Division of Mathematics, Electronics and Informatics at the Graduate School of Science and Engineering, Saitama University?

Some of the topics we are conducting research on include: electric energy control fields, such as robotics (both with and without artificial intelligence), high-voltage or plasma science; electronics fields such as microwave technologies, superconductors and opt-electronics; as well as information communication technology fields, such as intelligent control and the automation of electronics design.

What is your role at the University, and can you discuss your background?

I received my Engineering PhD in light-wave sensing technology from Tokyo Institute of Technology, Japan, in 1999. I then joined Saitama University as an Assistant Professor, becoming an Associate Professor in 2006. I previously worked at the national research institute (CNR) in Italy as a guest researcher. I am now an Associate Professor of electrical and electronic systems engineering at Saitama University.

What research are you currently involved in and why is this work important?

We are working on the first ever attempt to develop a silicon carbide (SiC) charge-coupled device (CCD). SiC is a very unique material as it has the advantages of both silicon (Si) and diamond (C). This has the potential to realise an extremely radiation-resistant image sensor. In recent years, there has been a growing need for electronic devices that can maintain a long life with high reliability, even in harsh environments such as high radiation fields and extreme temperatures. It is said that the development of electronic devices that have high radiation resistance and are capable of high-temperature operation in imaging devices is indispensable in order to reduce human exposure.

From your perspective, what gaps in knowledge about electronic devices that can maintain a long life with high reliability even in harsh environments are you seeking to fill?

There are a few unknowns such as: knowledge about the mechanism of device degradation due to radiation irradiation; the establishment of a CCD fabrication technique for the SiC semiconductor; and gaps in knowledge about the photo-response properties of SiC.

Who do you hope will benefit from your work?

If a SiC CCD with radiation-hardness and high-temperature durability is created, it will be very useful for the decommission of TEPCO Fukushima Dai-ichi Nuclear Plants and will also have applications in space developments performed by JAXA or NASA.

Have you faced any challenges in this work? How have you overcome these?

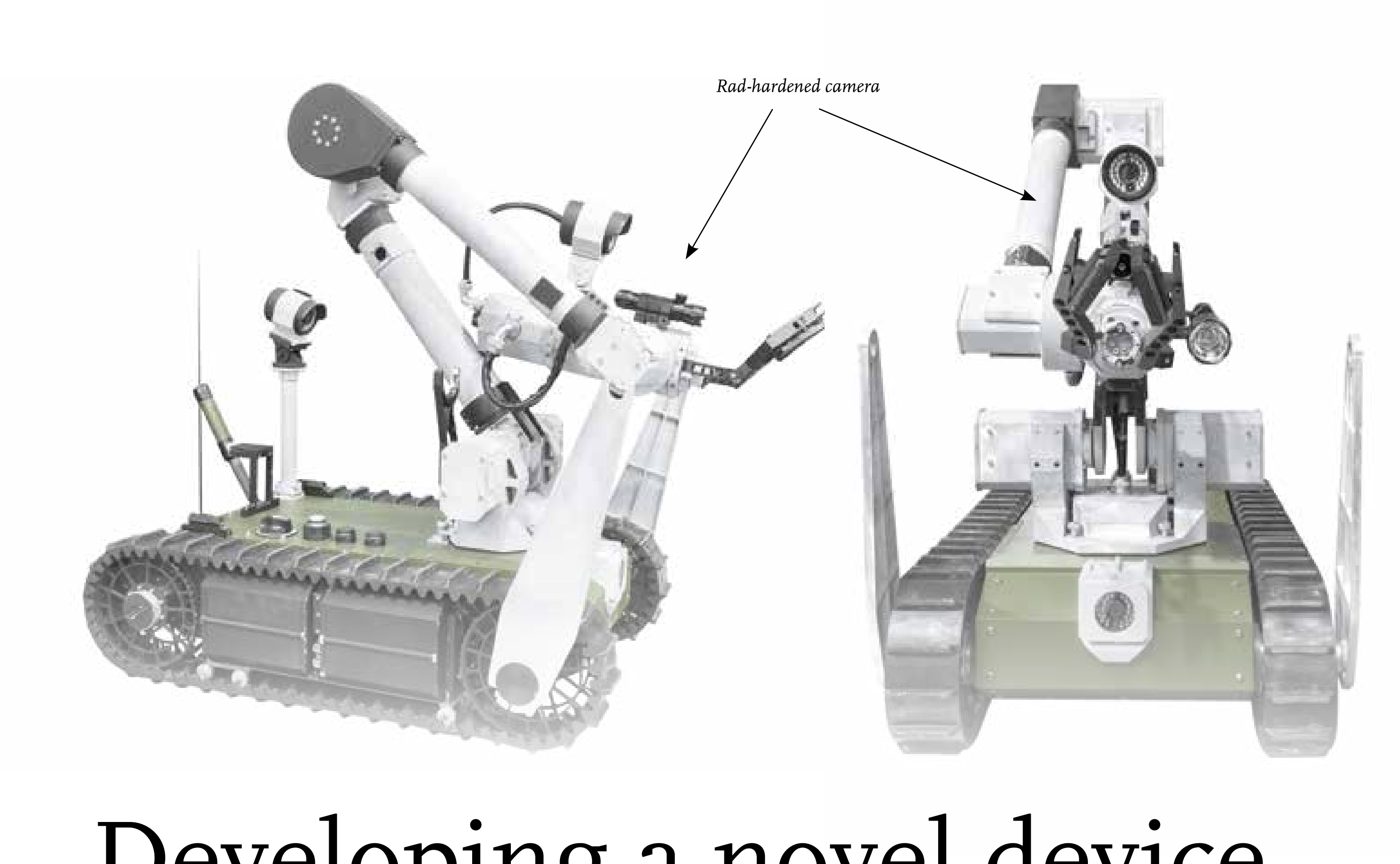
Because SiC MOS interface trap states are normally very high density, various device processes were attempted to reduce the trap states. A normal SiC semiconductor is not responsible for visible light because of its wide bandgap. Accordingly, we selected another polytype SiC substrate to extend the response wavelength region.

How do you validate or test your results?

We performed photo-response measurements, charge transfer verification with MOS capacitor array, and gamma-ray irradiation tests.

What are the next steps for your studies?

So far, only the fundamental properties relevant to SiC CCD have been evidenced. Next, we will work on developing the device manufacturing processes. ▶



Developing a novel device

*At the Division of Mathematics, Electronics and Informatics at **Saitama University**, scientists are working to develop a novel device able to withstand high temperatures and high radiation. It could prove to be invaluable*

There is a growing need for electronic devices that can maintain a long life with high reliability even in the harshest of environments, such as in high radiation fields and extreme temperatures. One tangible example of this is the Fukushima Daiichi nuclear disaster that occurred on 11 March 2011. A nuclear accident took place at the Fukushima Daiichi Nuclear Power Plant in Ōkuma, Fukushima Prefecture, that is known as the most severe nuclear accident since the 25 April 1986 Chernobyl disaster. If electronic devices with high-radiation resistance and the ability to operate at high temperatures can be created, human exposure to high radiation fields can be reduced or even prevented and lives saved.

This is the premise of investigations being conducted by an intrepid group of Japan-based researchers. In a world first, a team in the Division of Mathematics, Electronics and Informatics at Saitama University, Japan, is attempting to fabricate a charge-coupled device (CCD), also known as an image sensor, by replacing silicon carbide (SiC) semiconductors that can operate at high temperatures with silicon (Si) semiconductors with high radiation resistance.

They are collaborating with the National Institutes for Quantum and Radiological Science and Technology (QST) on this work, which is where the gamma-ray irradiation facilities the team is using are based. Professor Yasuto Hijikata, who is leading the team, says that if the researchers are successful in their work, not only can human exposure to high radiation be reduced but will have a range of other valuable applications. 'For example, we believe that the CCD we are developing could have applications in space research, because such a device could prove invaluable in the harsh conditions found in space.'

SIC SEMICONDUCTORS

Hijikata is an Associate Professor of electrical and electronic systems engineering at the University, where he has worked for the past 19 years. He is interested in three key topics. 'Firstly, I am studying SiC MOS interface characterisations and SiC thermal oxidation mechanism to develop a high-performance and ultra-low loss SiC MOSFET with high reliability,' he outlines. 'I am also interested in the development of radiation-hardness devices using SiC semiconductors for use in nuclear facilities or aerospace, as well as the characterisation and functionalisation of single photon sources in SiC crystals for quantum information communication, quantum computing and quantum sensing applications.' One of his research interests is to realise high-performance (ultra-low power-loss or high radiation-hardness) SiC MOSFETs. 'These developments on the MOS device have been transferred to developments of CCD image sensor,' Hijikata explains.

The team is employing a number of methods and tools in this work. 'We are using capacitance to voltage (C–V) measurements for MOS interface trap state evaluation and to test photo-response,' Hijikata highlights. 'Transient capacitance (C–t) measurements for the tests of charge transfer between MOS capacitors are also being performed, as well as photo-conductivity measurements to test photo-response and gamma-rays irradiation tests against SiC MOS capacitors.'

PUTTING METHODS INTO PRACTICE

This process, applied by the researchers, has enabled the creation of a novel CCD. The first step was to prototype a MOS capacitor using a SiC semiconductor. 'We fabricated a SiC MOS capacitor with a gate electrode made of a transparent metal material, and then verified the photoelectronic response and charge accumulation by examining the optical response of RF and QS C–V characteristics,' Hijikata confirms. 'This enabled the researchers to surmise that by using an inversion layer of minority carrier excitation, photo response in the ultraviolet region can be obtained by using 4H-SiC substrate, and photo response in both visible and ultraviolet regions can be obtained by using 3C-SiC.' Furthermore, they also found that the interface state density was reduced in the MOS capacitor using the 3C-SiC substrate compared to the 4H-SiC substrate. 'We observed the capacitor transient response, which enabled them to garner the results of the minority carrier response speed and discharge time,' continues Hijikata.

The team used photolithography to fabricate a 1 x 3 3C – MOS capacitor array and then examined the optical capacitance response characteristics. 'Through this work we found that the change due to the capacitance inversion showed a small value because the light receiving part also shrank but we were able to confirm the optical response using a UV laser and green laser as the source of light,' notes Hijikata.

The researchers also verified the charge transport between MOS capacitors by observing the capacitor transient response. 'In this case, we found that the capacitance increased in both cases using UV lasers and green lasers as the source of light, and we were able to confirm the charge transport in the SiC MOS capacitor array for the first time,' Hijikata explains. The team measured the time constants for the light turn-on/-off and found that the charge accumulation/holding time was 0.19s/0.32s respectively. 'Several MOS capacitor arrays with different electrode gap lengths were produced, and the research obtained the gap length dependence of the applied voltage required for charge transport as part of their basic data.'

> *We are using capacitance to voltage (C–V) measurements for MOS interface trap state evaluation and to test photo-response*

EXPLORING EFFECTS

Hijikata and the team also investigated the effects of gamma-ray irradiation on Si and SiC MOS capacitors and discovered that the SiC MOS structure has a gamma ray resistance. 'In fact, we found it to be three orders higher in magnitude than Si, which suggests the MGy resistance of CCD,' he points out. They attempted to suppress the photo charge trapped in the interface state and improve the optical response speed by using the MOS capacitor inversion layer embedded in the channel structure. 'When the interface state density was evaluated from the S-factor measurement of the SiC MOSFET and the gamma ray absorption dose dependency was measured, there was no significant difference in the unirradiated S-factor with or without the embedded channel structure, however, when the embedded structure was introduced, it was found that the S-factor (interface state density) decreased with a small dose of irradiation and then took a constant value up to a high dose,' Hijikata highlights.

A photograph of the gamma-ray irradiation room in QST

INTO THE REAL WORLD

The team removed the oxide film and electrodes of the SiC DMOSFET and observed damage to the crystal due to gamma irradiation using Raman imaging. 'As such, there were no changes due to the damage observed in the n-type epitaxial layer, but the Raman line tends to increase in the p-type A1 ion-implanted layer due to excess in carbon,' states Hijikata. The researchers are now confident that they have forged a path that will enable them to develop an image sensor with high radiation resistance.

The next stage is to develop a prototype which means that this work is closer than ever before to achieving significant real-world applications. ●

Project Insights

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BIO
Professor Yasuto Hijikata is currently an Associate Professor of electrical and electronic systems engineering at the Saitama University, Japan, where he has taught for 19 years. Hijikata is the co-author of over 200 technical papers and conference presentations and has received several awards, including the 'Outstanding research achievement and contribution award' from the Asian Pacific Society for Computing and Information Technology. He is a reviewer of various journals and a member of the Japan Society of Applied Physics.