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Semiconductor pixel detectors: Si, CdTe, and TlBr

World's First New Technology to Reduce Patient Burden Using High-Performance Hybrid Semiconductor Pixel Detector with Thallium Bromide

Japan Synchrotron Radiation Research Institute[1], Tohoku University[2], Clear-Pulse Co., Ltd[3], Howa Sangyo Co., Ltd[4]
Hidenori Toyokawa[1], Keitaro Hitomi[2], Mitsuhiro Nogami[2], Shin Kubo[2,3], Atsushi Suenaga[4]

Summary

- **The world's first hybrid semiconductor pixel detector have been developed with a high-quality thallium bromide (TlBr) sensor that operates stably at room temperature using thallium electrodes.**

- **The groundbreaking achievement was made possible by deep institutional expertise and experience in developing hybrid semiconductor pixel detectors and by collaborating with joint researchers to harness their technology to produce highly pure thallium bromide crystals.**

- **The high-performance thallium-bromide detector that can operate at room temperature can potentially reduce cancer patients' burden by monitoring irradiated areas in particle radiation therapy and lowering radiation doses. A clinical research plan is currently underway at Gunma University Heavy Ion Medical Center.**

A research group led by Hidenori Toyokawa of the Japan Synchrotron Radiation Research Institute and Keitaro Hitomi of Tohoku University has built a high-performance two-dimensional detector equipped with thallium bromide, having the highest gamma-ray absorption coefficient among semiconductor materials. Radiation imaging allows noninvasive internal observation and is an indispensable technology for medical applications and industrial development; improvements in detector performance will greatly advance these fields. The hybrid pixel detector with the thallium bromide sensor presented in this presentation has already been prototyped and heading for commercialization. This promising technology is the culmination of many years of research by this research group and is expected to be widely used in medical applications to reduce the burden on patients. It will also be available in overseas markets as a Japanese technology.

Detail

Technological innovation of radiation measurements by hybrid pixel detectors

Hybrid pixel detector technology has revolutionized radiation imaging measurement technology, allowing the observation of an object's interior without destroying it, and driving the development of medicine, engineering, and physics. In medicine, observing the internal organs of the human body by radiation has become indispensable for diagnosis and treatment. In industry, radiation transmission testing using X-rays and gamma rays is widely used in the nondestructive observation of the inside of materials.

Hidenori Toyokawa of the Japan Synchrotron Radiation Research Institute (JASRI) is a researcher at SPring-8, a large synchrotron radiation facility generating the world's highest levels of synchrotron radiation. Toyokawa has long been working to improve detector performance by sampling the irradiation of diffracted and scattered X-ray to increase the accuracy of radiation imaging. One of the innovations led by Toyokawa is the hybrid semiconductor pixel detector developed in the 1990s. The name"hybrid" originates from how the sensor and readout integrated circuit are made and assembled separately. Using semiconductor sensors with microelectrodes processed in a two-dimensional array the hybrid detector has both higher spatial resolution and energy measurement, which had been a challenge in previous research.

In 2001, the Pilatus detector using silicon as a sensor was put into practice. This detector later became the standard two-dimensional detector in synchrotron radiation facilities and is now used worldwide. The Pilatus detector was developed at the Paul Scherrer Institute (PSI) in Switzerland, which also developed the CMS pixel detector for the LHC experiment at the European Organization for Nuclear Research (CERN), sharing the same basic technology as the Pilatus detector.

In 2009, a two-dimensional detector with extremely high sensitivity over a wide energy range using cadmium telluride was developed. This work progressed to the Wide Energy Range Pixel Array Detector detector (WERPAD), commercialized in 2018. The readout circuit used a large-scale integrated circuit capable of discriminating wavelengths and extracting their respective diffraction images; the combination of the two functions resulted in a detector capable of simultaneously measuring multiple wavelengths with high precision.

Aiming for even higher-performance detectors, Toyokawa has long dreamed of developing a radiation detector using thallium bromide, a compound semiconductor. The atomic numbers of thallium and bromine are very high, 35 and 81, respectively, and their density is 7.56 g/cm^3, about the same as iron, meaning that the detection efficiency of highly penetrating γ-rays is much higher than other materials (Figure 1). Furthermore, thallium bromide can stably measure the X-ray to γ-ray region at room temperature. This characteristic is useful for practical use as a detector. Compared to cadmium telluride, which requires a cooling system, a thallium bromide detector, which is stable at room temperature, is low-cost and can be installed under any condition, thereby expanding its range of applications.

Meeting the world's leading authority on thallium-bromide research

Thallium bromide is a semiconductor material that was used long ago. In addition to Toyokawa, many researchers aim to develop detectors using thallium bromide. However, the difficulty in growing thallium-bromide crystals has made it challenging to realize this goal because of the difficulty of producing pure crystals, and impurities in thallium-bromide crystals limit the detector's performance. For this reason, developing a thallium-bromide detector at a practical level seemed impossible.

However, Toyokawa's group was still able to develop a thallium bromide detector. This was due to an encounter at the Applied Physics Society of Japan presentation in 2022.

"I had long dreamed of developing a detector using thallium bromide, and when I heard Dr. Hitomi, a world authority on thallium bromide, present his research last year, I was convinced that the detector I was dreaming of could be realized by combining my technology with his work. As soon as the presentation was over, I approached him with an invitation to collaborate with him," said Toyokawa.

Toyokawa's conviction came true in December 2022 when the first thallium-bromide hybrid pixel detector was completed (Figure 2). Only nine months had passed since the day it was approached — an exceptionally fast realization. The research team included Clear-Pulse Co., Ltd, which develops and manufactures radiation measuring instruments, and Howa Sangyo Co., Ltd, which has microfabrication and application technologies for various materials. They have already begun working toward social implementation. Toyokawa expresses his enthusiasm as follows:

"We are also preparing a manufacturing system in collaboration with a semiconductor-manufacture venture company. We hope to develop this technology as a Japanese technology that can compete with the rest of the world through an all-Japan system to reach practical fruition in collaboration with private enterprise."

More effective and less burdensome cancer treatment

Currently, Gunma University Heavy Ion Medical Center, in collaboration with the "RI Imaging Research" project at the Takasaki Advanced Radiation Research Institute of the National Institutes for Quantum Science and Technology (QST), is conducting basic research to visualize the irradiated area of the treatment beam in real-time using the cadmium telluride hybrid pixel detector developed by Toyokawa. Heavy-ion beam therapy is a form of radiation therapy in which carbon beams are focused on the patient, striking the cancerous cells intensively, deep within the body. It is a treatment method that does not use a scalpel; does not damage surrounding normal cells, such as those in front of and behind cancer; and has few side effects. However, if the area to be irradiated with heavy ion beams is outside the cancerous lesion, the desired outcome cannot be reached. Currently, the irradiation area is calculated at the time of treatment planning, but if the arrival position of the treatment beam can be observed, a more patient-friendly treatment method can be developed.

Introducing cadmium telluride detectors has solved this problem because the detector can capture the secondary electron bremsstrahlung generated after heavy particle irradiation. Thus the effectiveness of the treatment can be determined in real-time.

The results of introducing the cadmium telluride detector are already beginning to be seen, but the company is also looking to improve performance with the thallium bromide detector that Toyokawa has now developed.

The thallium bromide detector, which does not require a cooling system, is not only more powerful but also more compact than the cadmium-telluride detector. Eliminating the need for cumbersome equipment reduces the psychological pressure on patients. In addition, since it can be operated at a lower cost than cadmium telluride, expanding its use to general hospitals will be possible in the future," says Toyokawa.

Furthermore, Toyokawa says that if thallium bromide detectors are implemented with X-ray examination and computer tomographic equipment, they may reduce the examination X-ray dose and patient radiation exposure. The range of applications will not *be* limited to the medical field.

“New instruments open up new fields. We believe that the thallium bromide detector we developed will not only improve the performance of existing methods but also trigger the birth of further research and industry. We are at the starting point now, but over the next few years, we would like to expand the scale of the system and further improve its performance,” says Toyokawa.

Figures

Thallium bromide (TlBr)

- High atomic number (81 and 35)
- High density (7.56 g/cm³)
- Wide bandgap (2.68 eV)

Material	Density (g/cm³)	
Si	2.33	←Aluminum (2.7 g/cm³)
NaI	3.67	
Ge	5.32	←LX-57B lead glass (~4.36 g/cm³)
CdTe	5.85	
TlBr	7.56	←Iron (7.87 g/cm³)

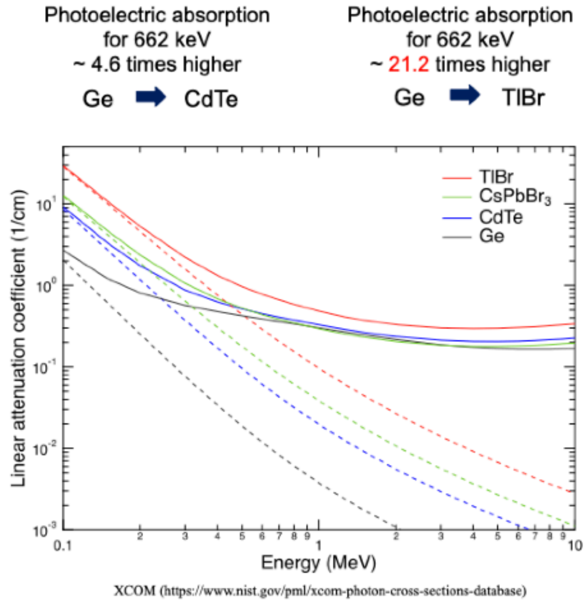

Figure 1: Properties of thallium bromide

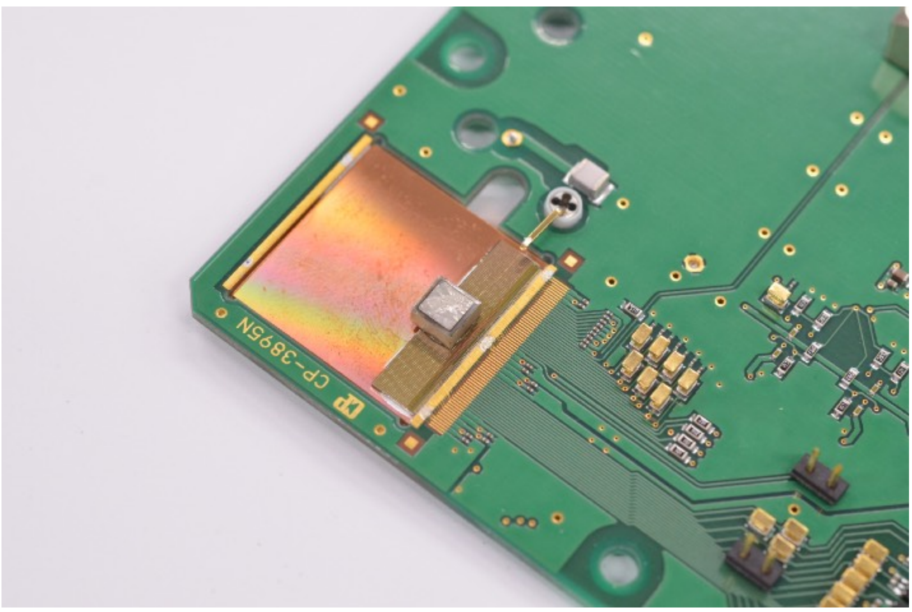

Figure 2 Flip-chip mounted thallium-bromide hybrid pixel detector prototype