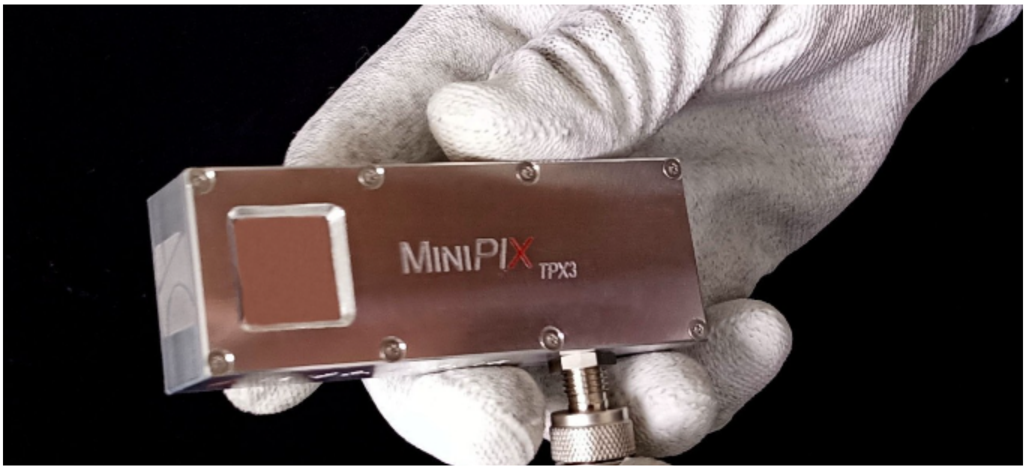
PREPARATION



Spectroscopic radiation hard imaging detector for observation, astronomy and space dosimetry

Executive Summary

Channel: **EISI - Early Technology Development Activity Proposals**
Innovation Area: **Discovery**
[EISI - Early Technology Development Activity Proposals]

Affiliation(s): **Advafab Oy**

Activity summary:

Comprehensive research in semiconductors, nanostructures, photoelectronics, and microelectronic engineering has led to the development of novel, space-proof prototype imaging detectors sensitive to energy ranges above Si- and below CdZnTe-based sensors. Advanced chemical, plasma, and laser techniques, along with various electrode metals, were employed to detector-grade GaAs wafers obtained through an elaborated annealing process. GaAs pixel sensors with high flux tolerance, degradation resistance, and stability under severe γ-ray radiation, operating effectively in the mid-spectral range, were used to manufacture MiniPIX TPX2/TPX3 detectors, designed for space applications, including gamma-ray spectroscopy, dosimetry, particle detection, X/γ-ray imaging, space telescopes, and planetary exploration.

Publishing Date: 22.1.2025
Contract Number: 4000142816
Implemented as Early Technology Development

1. Introduction

The ***purpose*** of the project research activity was to develop a space-proof prototype MiniPIX TPX2/TPX3 imaging detector with a novel GaAs sensor that is efficient for the mid-energies higher than those of Si and lower than those of CdZnTe sensors. The ***scope*** of research and technical work focused on the following key innovations: (i) the preparation of radiation-sensitive detector-grade GaAs through Cr-compensation using an advanced high-temperature annealing process; (ii) the creation of the efficient electrical contacts by selecting the most appropriate electrode metal and optimal techniques for semiconductor crystal surface processing, including chemical, plasma and laser treatments; (iii) the use of thicker (> 0.5 mm) GaAs wafers to manufacture sensors with higher detection efficiency; (iv) the formation of pixel patterns using lithography and non-lithography methods; (v) the replacement of traditionally used Si sensors in MiniPIX TPX2/TPX3 detectors with novel GaAs pixel sensors, which exhibit remarkable distinctive features of the semiconductor: a direct band gap, a wider forbidden band gap, and higher effective atomic number, density, resistivity, and charge carrier mobility compared to Si.

The ***objectives*** of this report are to provide an overview of the context, relevance, and state of the art of the project activity; summarize the applied approaches and methods; highlight the developed insights and the most significant results, emphasize the key achievements and conclusions; propose the next steps for further research; demonstrate the potential applications of GaAs pixel sensors in MiniPIX TPX2/TPX3 space detectors and other spectroscopic imaging and radiation monitoring instruments; and discuss how they can be effectively implemented in both space and on Earth.

2. Project Background

The project activity focused on the development of advanced direct-conversion detectors for X/γ-ray systems, which are critical for applications requiring reliable detection of radiation, ranging from single photons to high fluxes within the broad mid-energy spectrum. Traditional materials such as Si and Ge have limitations, particularly in detecting higher energy ranges, which motivates the search for semiconductors with a wider band gap, higher X/γ-ray absorption efficiency, and favorable electrical characteristics. GaAs stands out as a strong candidate, owing to its optimal properties, particularly having high detection capability in the energy range above the Si sensor's operating range and below that of CdZnTe-based sensors. However, despite its potential, significant challenges exist in creating GaAs-based sensors, such as obtaining high-quality, structurally perfect GaAs crystals and optimizing fabrication processes for pixel sensors.

The project has addressed these challenges by leveraging advanced approaches and innovative techniques to prepare GaAs-based pixel sensors for spectroscopic and imaging applications, especially in demanding environments such as space and high-energy research.

GaAs semiconductors have been studied for over 30 years as materials for ionizing radiation detection, with recent advancements in Cr-compensation enabling high-resistivity crystals for improved charge carrier collection and higher bias voltages. While Si detectors dominate the market, GaAs offers superior radiation sensitivity, energy resolution, and detection efficiency, especially for high-energy X-rays. Advafab is introducing advanced GaAs-based hybrid pixel detector modules with these advantages, making them ideal for applications such as spectroscopic measurements, radiation-hard imaging, high-resolution observation, and X/γ-ray and charged-particle dosimetry.

3. Methodology

The project activity was planned and carried out according to six Work Packages (WP):

WP1: Proof of concept space detector with TPX3/TPX2 GaAs pixel sensors.
WP2: Improved spectroscopic performance by reducing the leakage current of the GaAs sensor.
WP3: Improved detection efficiency by manufacturing thicker GaAs sensors.
WP4: Reducing the cost of GaAs sensors using non-lithographic pixel patterning.
WP5: Game changer detector with optimized TPX3/TPX2 GaAs sensor.
WP6: Management and dissemination.

The concepts, methods and technologies used for the creation of GaAs-based sensor modules for imaging applications can be briefly described as follows. (i) Special long-term annealing and Cr compensation of 0.5 mm thick GaAs wafers with Cr ensured uniform detector-grade material with optimal electronic properties. (ii) Various metals were used for electrical contacts on GaAs:Cr samples, and different treatments were applied to the crystal surface or the metal-semiconductor interfaces. Subsequently, *I-V* characteristics were monitored. (iii) The use of thicker GaAs wafers (1 mm) for sensor fabrication would increase absorption efficiency from 40 keV to 120 keV and beyond. (iv) An efficient lithography technique was developed to form a high-spatial pattern on the GaAs wafer surface, and a lithography-less patterning technique was employed to create 55 µm pitch pixel sensors. (v) Following the comparative study of imaging detectors based on TPX2 and TPX3, it was decided to use the MiniPIX TPX2 GaAs detector, which demonstrated an acceptable detection response and efficiency to γ-rays, neutrons and charged particles and has provided spectral tracking results similar to the radiation observed in LEO.

GaAs pixel sensors that were flip-chip bonded to the TPX2/TPX3 modules were tested using the X-ray probing system before assembling of the final detector.

4. Key Findings

The main project goal of the project, i.e. elaboration of novel GaAs pixel sensors effectively operating in the mid-spectral range has been achieved. The GaAs sensors were deliberately developed for the manufacturing of the MiniPIX TPX2/TPX3 space detectors, as well as for other spectroscopic imaging and radiation monitoring instruments that have been designed for use in space areas: gamma-ray spectroscopy, space dosimetry, space-based particle detection, X/γ-ray imaging, space telescopes for cosmic astronomy, and planetary exploration.

The MiniPIX TPX2 GaAs detector was prioritized over TPX3 due to following benefits: (1) TPX3 data driven mode fills up the memory due to noisy pixels and uses more power to operate than TPX2; (2) TPX3 has commercial limitation for space applications; (3) TPX2 is more stable and commercially usable in space; (4) TPX2 does not have the volcano effect and is thus able to detect the full charge of the absorbed radiation; (5) TPX2 is twice as fast, having a half the dead time between acquisitions; (6) Frame-based power consumption is same for TPX2 and TPX3.

The MiniPIX TPX2 GaAs detector was evaluated by Carlos Granja from Advacam s.r.o. at Czech Metrology Institute's MT-25 Microtron electron accelerator and Nuclear Physics Institute Light Ion Cyclotron to demonstrate the detector's detection capabilities for Low Earth Orbit radiation. The MiniPIX TPX2 GaAs detector's position and energy sensitivity, combined with software clustering, enable particle discrimination and identification in a mixed radiation field. The figures 1.a-1.d below represent the mixed radiation field tracking capabilities of the MiniPIX TPX2 GaAs detector.

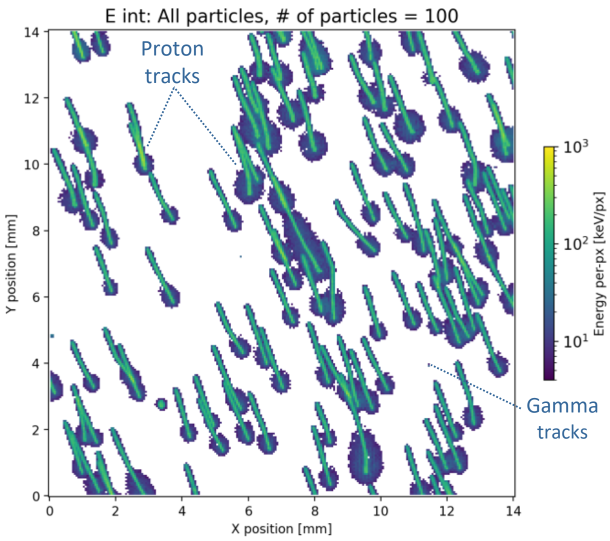


Fig. 1.a. Protons 31 MeV @ 60° angle to the sensor's surface.

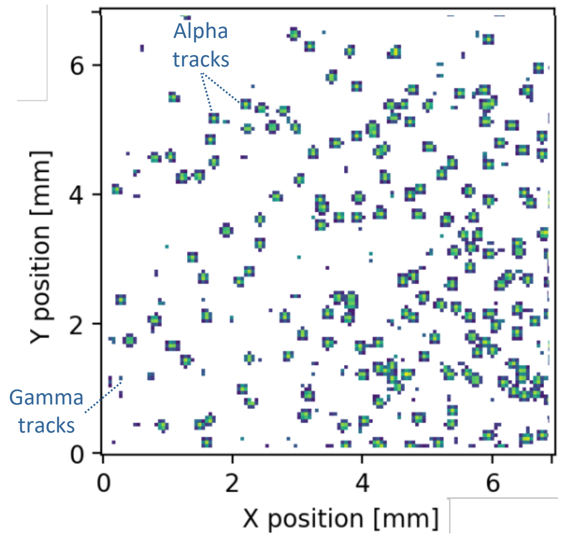


Fig. 1.b. Alpha particles 1 MeV @ 0° = perpendicular the sensor's surface.

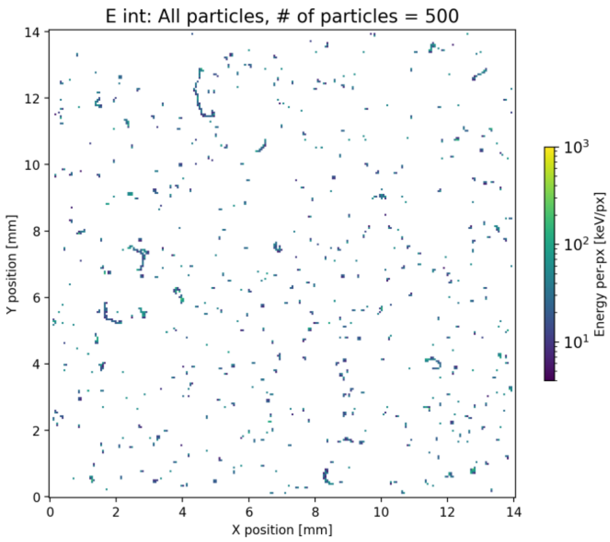


Fig 1.c. γ and Fast neutrons, $^{241}Am^{9}Be$ radionuclide source.

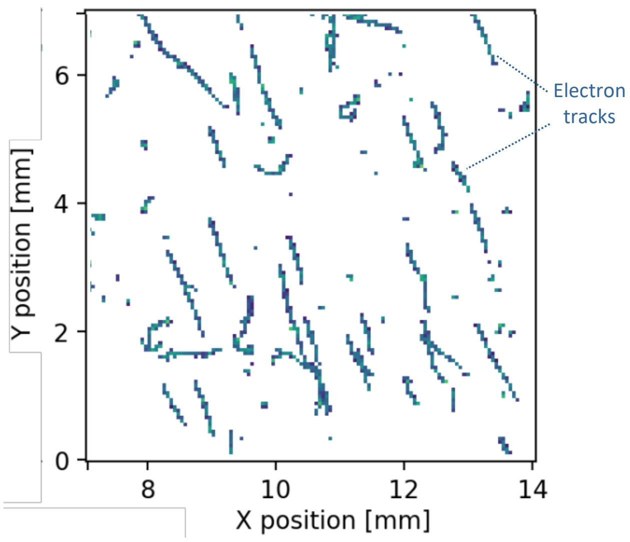


Fig. 1.d. Electrons 22 MeV @ 60° angle to the sensor's surface.

The spectrum of each measured particle was recorded with excellent energy resolution and discrimination using the novel MiniPIX TPX2 GaAs detector. Figures 2.a-2.d represent the spectrums of the detected radiations of Figs 1.a-1.d, respectively. The recorded spectrums demonstrate that it is feasible to discriminate different types of radiations in the mixed radiation field.

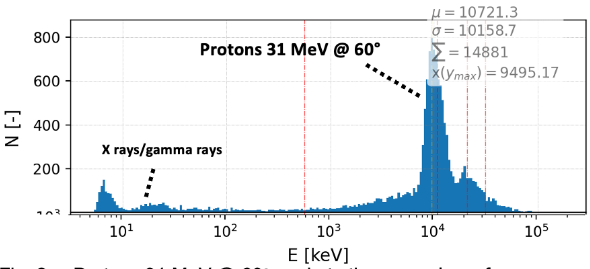


Fig. 2.a. Protons 31 MeV @ 60° angle to the sensor's surface.

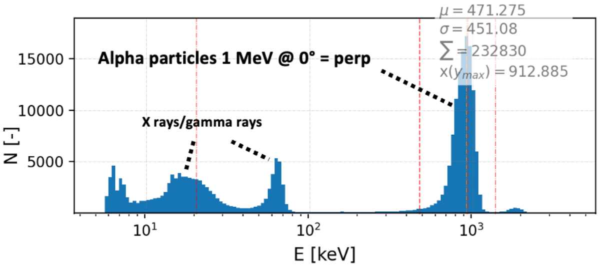


Fig. 2.b. Alpha particles 1 MeV @ 0° = perpendicular the sensor's surface.

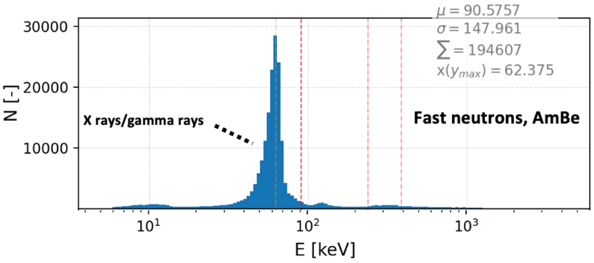


Fig 2.c. γ and Fast neutrons, ^{241}Am^{9}Be radionuclide source.

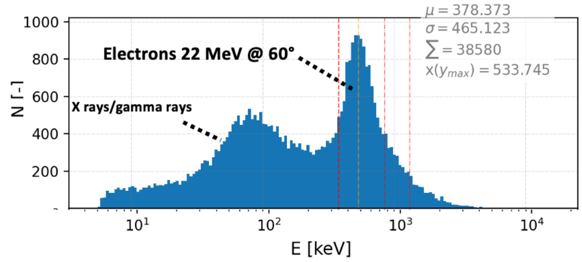


Fig. 2.d. Electrons 22 MeV @ 60° angle to the sensor's surface.

During the project, it was also demonstrated that the GaAs sensor is more than several thousand times more effective in protecting the readout ASIC electronics from the radiation compared to Si sensors.

The project has demonstrated that the novel MiniPIX TPX2 GaAs detector has the following benefits compared to similar Si-sensor-based detectors.

- Higher stopping power for both γ-rays and charged particles,
- Enhanced particle discrimination capability,
- Extremely high flux operation capability,
- More than a thousand times better radiation hardness.

Combining all the demonstrated capabilities from the project, the MiniPIX TPX2 GaAs detector is an excellent candidate for space weather monitoring, astronaut dosimetry, satellite early warning systems, and radiation spectroscopy.

The fabricated GaAs pixel sensors were able to detect high fluxes, in particular, the measurements were carried out up to 0.72 Gcount/s/mm^2, as shown in Figure 4.a. Since the detector count rate was limited by the TPX2 ASIC but not the GaAs sensor, we are investigating the use other ASICs. The results obtained from the GaAs pixel sensor coupled with a customer ASIC with 330 um pitch proved that its successful operation under extremely high radiation fluxes (up to 1.5 Gcount/s/mm^2). The high-count rate NDT imaging was demonstrated with a transillumination of a computer CPU at 0.37 Gcount/s/mm^2 providing an extremely sharp high-resolution image acquired in less than a second, as shown in Figure 4.b. A high through put NDT imaging is feasible with the TPX2 GaAs detector.

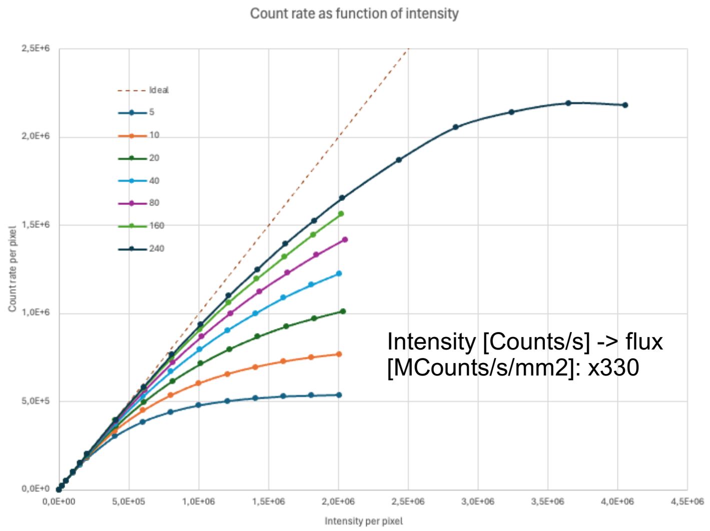


Fig. 4.a. MiniPIX TPX2 GaAs detector's count rate dependence of incoming X-ray flux.

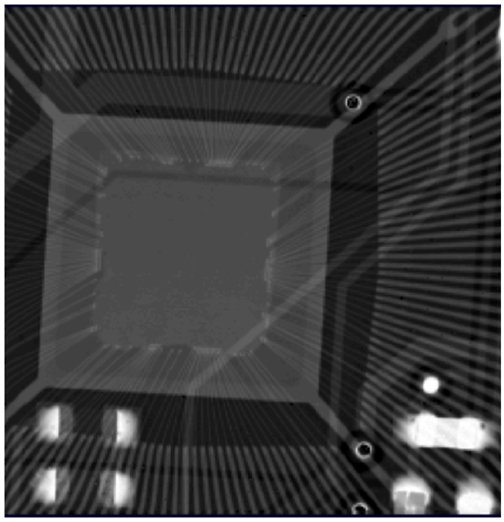


Fig. 4.b. X-ray image of a CPU measured in 1 s at 0.37 Gcount/s/mm^2 X-ray flux.

During the project implementation, research findings on the fabrication of GaAs X-ray pixel sensors, as well as technical achievements in the creation and evaluation of GaAs TPX-based modules and MiniPIX TPX2/TPX3 GaAs imaging detectors, were obtained and presented in 8 abstracts at 5 international conferences and workshops, as listed below.

1. J. Kalliopuska, D. Nalyvaiko, V. Gnatyuk, S. Vähänen, J. Jakubek, S. Polansky, E. Maddox, E. Hogenbirk, J. Lange, Y. Tsujita, M. Kuribayashi, S. Mikusu, K. Matsushita, O. Baussens, P. Smolyanskiy, **Evaluation of chromium compensated gallium arsenide sensors using photon counting detectors,** *7th Workshop on Medical Applications of Spectroscopic X-ray Detectors (SPECXRAY-2024), Program*, Abstract (15-18 April 2024, CERN, Zurich, Switzerland).
2. J. Kalliopuska, D. Nalyvaiko, V.A. Gnatyuk, S. Vähänen, J. Jakubek, S. Polansky, E. Maddox, E. Hogenbirk, J. Lange, Y. Tsujita, M. Kuribayashi, S. Mikusu, K. Matsushita, O. Baussens, P. Smolyanskiy, **Chromium compensated gallium arsenide sensor evaluation using photon counting readout electronics**, *The 25th International Workshop on Radiation Imaging Detectors (iWoRiD2024), Book of Abstracts*, 2024, Abstract 27, 9-10. (30 June - 4 July 2024, Lisbon, Portugal).
3. M. Bezak, V. Gnatyuk, M. Kalliokoski, J. Kalliopuska, P. Luukka, D. Nalyvaiko, R. Turpeinen, M. Vähänen, **Charge transport dynamics studies of planar GaAs:Cr sensors by laser excitation**, *The 25th International Workshop on Radiation Imaging Detectors (iWoRiD2024), Book of Abstracts*, 2024, Abstract 191, 104-105. (30 June - 4 July 2024, Lisbon, Portugal).
4. J. Jakubek, J. Kalliopuska, **Optimization of energy resolution and/or stability for Timepix type photon counting detectors: 130 eV rms and/or images with SNR=1000 taken at 760 MCounts/mm^2/s**, *The 25th International Workshop on Radiation Imaging Detectors (iWoRiD2024), Book of Abstracts*, 2024, Abstract 207, 116. (30 June - 4 July 2024, Lisbon, Portugal).
5. J. Kalliopuska, D. Nalyvaiko, V.A. Gnatyuk, S. Vähänen, J. Jakubek, S. Polansky, E. Maddox, E. Hogenbirk, J. Lange, Y. Tsujita, M. Kuribayashi, S. Mikusu, K. Matsushita, O. Baussens, P. Smolyanskiy, **Chromium compensated gallium arsenide sensor evaluation using photon counting readout electronics**, *The 15th International Conference on Synchrotron Radiation Instrumentation (SRI 2024), Programme and Abstracts*, 2024, Abstract MS4/3, 318-319. (26-30 August 2024, Hamburg, Germany).
6. D. Nalyvaiko, J. Kalliopuska, S. Vähänen, V. Gnatyuk, **Development of GaAs-based X/γ-ray sensors in Advafab**, *The International Workshop with Research Institute of Electronics, Shizuoka University, and ANSeeN Inc. Program*, 2024, Abstract. (15 October, Hamamatsu, Japan).
7. J. Kalliopuska, D. Nalyvaiko, V.A. Gnatyuk, S. Vähänen, J. Jakubek, S. Polansky, E. Maddox, E. Hogenbirk, J. Lange, Y. Tsujita, M. Kuribayashi, S. Mikusu, K. Matsushita, O. Baussens, P. Smolyanskiy, **Evaluation of chromium compensated gallium arsenide sensors using photon counting readout electronics**, *2024 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-*

Temperature Semiconductor Detector Conference (2024 IEEE NSS/MIC/RTSD), Program*, 2024, Abstract No R-0203 (#1581). (26 October - 2 November 2024, Tampa, Florida, USA).

8. K. Sykorova, J. Jakubek, D. Doubravova, D. Hladik, J. Ingerle, J. Kalliopuska, J. Pivec, **Radiography image quality and stability with Timepix-family detectors**, *2024 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Conference (2024 IEEE NSS/MIC/RTSD), Program*, 2024, Abstract No R-0601 (#1567). (26 October - 2 November 2024, Tampa, Florida, USA).

5. Conclusion

Using a prototype such as a commercial MiniPIX TPX2/TPX3 space detector with a Si pixel sensor, we replaced Si pixel sensor by the novel GaAs pixel sensor developed using our original techniques, which include high-uniform Cr-compensation of the semiconductor wafer, efficient surface processing, multilayer contact deposition, and fine pixel patterning. The distinguishing features of the newly created GaAs imaging sensor have a more comprehensive radiation sensitivity range compared to Si, higher energy resolution and detection efficiency, particularly for higher-energy γ-rays. Additionally, it offers high flux tolerance, radiation hardness, and greater stability under severe irradiation.

The novel GaAs X/γ-ray sensors have a unique energy sensitivity range of 40-120 keV where traditional Si- or CdZnTe-based sensors are not optimal. This makes GaAs sensors ideal for applications in spectroscopy, imaging, and radiation monitoring on Earth and in space. The MiniPIX TPX2/TPX3 GaAs detector excels in: (i) *γ-ray spectroscopy*: Its superior energy resolution enables precise identification and characterization of radioactive isotopes and γ-ray sources. (ii) *Space dosimetry*: Enhanced dose measurement accuracy, radiation resistance, and stability under severe irradiation ensure reliable performance. (iii) *Particle detection*: The sensor tracks individual particles and measures their energy levels, aiding the study of space weather, particle interactions, and radiation impacts on spacecraft and astronauts. (iv) *X/γ-ray imaging*: With fine pixel structure and high energy resolution, it captures detailed radiation images, crucial for studying black holes, neutron stars, supernova remnants, and other astrophysical phenomena. (vi) *Space telescopes and astronomy*: Its high flux tolerance and radiation hardness support high-resolution imaging of cosmic-ray sources, γ-ray bursts, and other high-energy phenomena, advancing our understanding of the universe. (vii) *Planetary exploration*: It identifies surface elements on planets, moons, and asteroids, revealing geological histories and potential habitability.

GaAs-based imaging detectors deliver exceptional energy resolution, radiation hardness, stability, and spatial resolution, making them invaluable for space-based scientific investigations. The MiniPIX TPX2/TPX3 GaAs detector is a significant breakthrough in spectroscopic imaging and radiation monitoring, helping to advance our understanding of Earth, space, and the fundamental processes of the universe.

6. Future Work

Advafab Oy will continue the development of GaAs-based pixel sensors, including the optimization of Cr-compensating annealing of the semiconductor, the search for more efficient electrical contacts to provide ultra-low leakage current. There is great interest in exploring 1 mm or thicker GaAs wafers especially in the medical, security and non-destructive testing imaging applications.

ADVACAM s.r.o. will continue TPX3 and TPX2 GaAs detector evaluations for space dosimetry and other applications.

The application of the developed techniques and elaborated technologies of manufacturing GaAs pixel sensors, image modules and MiniPIX TPX2/TPX3 imaging detectors will ensure game-changer for spectroscopic imaging and radiation monitoring on Earth and in space

Advafab Oy together with ADVACAM s.r.o together might pursue for an opportunity to apply a GSTP follow up project in case supported by ESA and the national delegates.