Overview of GaAs und CdTe Pixel Detectors Using Medipix Electronics

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GaAs and CdTe pixel detectors have been developed over the last few decades. The applications of these detectors include X- and gamma-ray detectors working at room temperature. Fundamental properties such as detection efficiency and noise are determined by the material properties of the sensor material. Different materials have been evaluated over the years in search of the best choice for different types of radiation. This article describes the properties of GaAs and CdTe materials for single photon processing pixel detectors using the Medipix electronics.

1. Introduction

When a high-energy photon is captured in a semiconductor a charge cloud is generated in a limited space at the position of interaction. The amount of charge depends on the photon energy, the capture process and the energy required to generate an electron–hole pair in the semiconductor. For Compton scattering, only part of the photon energy is deposited at the primary interaction site. If the capture results in X-ray fluorescence, part of the energy is transported to a different site by the fluorescent photon.

If a sufficient electrical field exists in the semiconductor the charges are separated and drifted to the corresponding readout electrodes. The charge cloud will at the same time be spread out by diffusion. This leads to charge sharing in a pixelated detector. Charge sharing and incomplete charge deposition will lead to distorted spectra in single photon processing devices.

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Several high-Z semiconductors show low hole mobility. The signal is then essentially generated by the electrons. According to Ramos theorem[1,2] and revisited[3] the signal is induced when the charge travels through the electric field. For a thick detector with small pixels, most of the signal is induced when the charge is close to the pixel contact. This is called the "small pixel effect"[4,5] and gives excellent spectral properties even if only one charge carrier contributes to the signal.

X-ray absorption in matter is strongly dependent on the electron density of the material and the photon energy. Silicon detectors can be used for photon energies up to 20 keV. Higher energies require high-Z materials. The most common materials are GaAs and CdTe or CdZnTe. Some attempts have been made to develop detectors from low doped epitaxial GaAs[6] but in most cases compensated material is used in order to get sufficient sensitive thickness.[7] In a compensated semiconductor the electric field is essentially uniform through the material and the concept of the depletion region is no longer valid. Charge transport in a compensated semiconductor is usually affected by trapping of charges causing additional noise. If the material is not a perfect crystal, grain boundaries and dislocations might cause spatial distortion by deviating the charges from their normal transport pattern.[8]

2. Overview of Detector Materials

This section gives a brief overview of potential semiconductor materials for X-ray pixel detectors. The common feature of such detectors is the strong dependence of the efficiency on the thickness of the sensor. The active detection volume is the equivalent to the thickness of the detector. The radiation detector is a bulk device.

The required properties are the following:

- High resistivity ρ for low leakage current ($\rho > 10^8$ Ω cm)
- High mobility-lifetime product $\mu\tau$ for both charge carriers for an optimum of mean free path length ($\mu\tau > 10^{-3}$ cm^2 V^{-1})
- High structural quality
- Low defect concentration
- Homogeneous distribution of properties
- Reliable contact and interconnection technology
- High-Z for high absorption of X- and gamma-rays

In the last 50 years, several semiconductors were tested for the use as radiation sensors.

Table 1. Comparison of semiconductor materials for pixel detectors.

Material	Si[31]	Ge[31]	GaAs:Cr[32]	epi-GaAs[31]	CdTe[33]	$Cd_{0.9}Zn_{0.1}Te$[34]	TlBr[35]
Growth method a)	CZ	CZ	CZ	CVD	THM	THM	BM
Atomic number	14	32	31, 33	31, 33	48, 52	48, 30, 52	81, 35
Density [g cm^{-3}]	2.33	5.33	5.32	5.32	5.85	5.78	7.56
Band gap [eV]	1.12	0.67	1.43	1.43	1.44	1.57	2.68
Resistivity [Ω cm]	10^4	50	10^9	10^7	10^9	10^{10}	10^{12}
Pair creation energy [eV]	3.62	2.96	4.2	4.2	4.43	4.6	6.5
$\mu_e \tau_e$ [cm^2 V^{-1}]	>1	>1	10^{-5}	10^{-6}	10^{-3}	10^{-1}	10^{-4}
$\mu_h \tau_h$ [cm^2 V^{-1}]	1	>1	10^{-6}	10^{-6}	10^{-4}	10^{-5}	10^{-5}

a) The growth methods are: CZ: Czochralski (liquid encapsulated for GaAs); CVD = chemical vapor deposition; THM = travelling heater method using tellurium solution; BM = Bridgman method. The data were collected from Del Sordo,[31] Veale,[32] Toyokawa,[33] Zappettini,[34] and Nogami.[35]

Table 1 summarizes the different materials and the related properties. Silicon is the first choice for excellent detector homogeneity and stability, but for higher X-ray energies, CdTe, Cd0.9Zn0.1Te CZT, and GaAs offer the best combination of the required material properties and reliable technology.

3. Medipix Readout Chips

Medipix and Timepix are pixelated photon counting semiconductor detectors chips. The family of Medipix readout chips is under continued development by the Medipix2, Medipix3, and Medipix4 Collaborations at CERN since 1999 and includes Timepix chips. The Medipix chips feature adjustable energy thresholds and the Medipix3 even the so-called charge summing mode for compensation of charge sharing effects. For each registered event, the charge that was spread to neighbored pixels is summed up into the pixel with the highest charge. This way, the energy information can be restored and charge-sharing problems overcome. The Timepix chips feature time of arrival information and spectroscopic energy information for each registered photon.

The currently newest Medipix chip is the Medipix3RX, fabricated in a CMOS 130 nm process, as well as the Timepix3 chip. The Medipix2 and Timepix1 chips are fabricated in a CMOS 250 nm process. The electronic of the Medipix chip family has 256 × 256 pixels with a pixel pitch of 55 μm and can be bump bonded to different sensor materials. All Medipix chips are three-side-buttable allowing the assembly of larger detector modules with monolithical sensors. More detailed information about Medipix and Timepix chips can be found in ref. [9].

4. GaAs

Applications with higher X-ray energies (>20 keV) require semiconductor materials with high absorption, that is, high-Z. Only two material systems have a combination of high absorption and available technology for the production of detector systems. These are CdTe or CdZnTe and GaAs. The latter is very well suited for use at energies below 80 keV.

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Simon Procz has been in charge of the development of computer tomographs with photon-counting Medipix/Timepix detectors at the Freiburg Materials Research Centre (FMF) in the University of Freiburg since 2014. His areas of responsibilities include applied research with semiconductor detectors, the guidance and supervision of master's students and doctoral students, teaching the "Sustainable Materials" and "Crystalline Materials" courses and the acquisition of third-party funds.

In the research projects GALAPAD and GALAPAD II of the German–Russian Joint Research Program, between DESY Hamburg, University Freiburg, the Karlsruhe Institute of Technology, State University Tomsk and the Joint Institute for Nuclear Research JNIR Dubna, the material system GaAs was intensively investigated, the detector properties characterized and the first systems tested on synchrotron beamlines. Detectors with an active detector area of 84 × 28 mm^2 and 800 000 pixels were successfully manufactured and used at DESY. **Figure 1** shows a corresponding detector system and an acquired X-ray image.

These results were achieved on GaAs wafers, which were processed and delivered by the Russian project partners. At DESY, the detector systems LAMBDA were assembled and tested based on the Medipix3 readout electronics. The intensive material characterization at the KIT was a decisive step in the production of the large-area detector modules from 100 mm diameter wafers.

The GaAs sensors were manufactured in Tomsk using Cr compensation. In contrast to the usual EL2 compensation for the production of semi-insulating GaAs, Cr compensation is applied to n-type LEC GaAs wafers. The coating with chromium and the subsequent heating process lead to overcompensated material, that is, the transport properties are reduced.

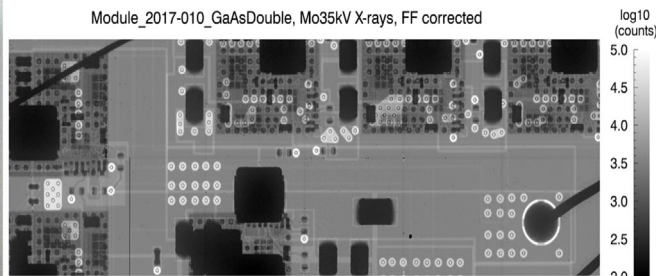Analyses at the TOPO/TOMO Beamline at KIT[10] on the structural defects at the Cr-compensated wafers from Tomsk

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Figure 1. Image of a GaAs double hexa module 84 × 28 mm² and an X-ray image of a PCB board. Reproduced with permission.[34] Copyright 2019, Elsevier.
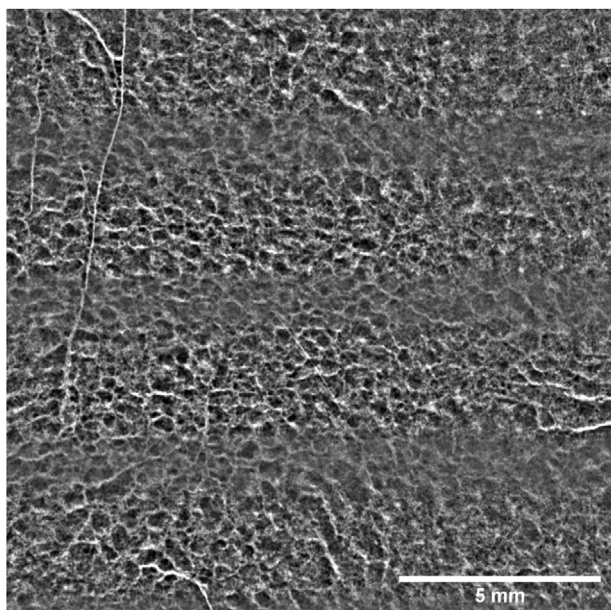

Figure 2. Synchrotron radiation white beam topography of a GaAs(Cr) wafer.

prove the very high defect density as shown in **Figure 2**. The topography of the GaAs(Cr) wafer was performed by using synchrotron radiation white beam and shows a 15 × 15 mm² detail of a 40 mm diameter wafer.

The processing of the electrical contacts, the passivation of the sensors and the under-bump metallization UBM are also carried out exclusively by the team of Tomsk. The sensors were connected to the Medipix3 readout chips in Freiburg by flip-chip bonding. For this purpose, a corresponding low-temperature bonding with In–Sn solder bumps was further developed.[11] This method provided the best results for hybridizing the detector modules and achieved a high yield regarding working pixel connections.

The greatest challenge for the use of modern photon sources is the high photon flux. To exploit the advantages of a synchrotron or the XFEL, images must be taken form more than 10^8 photons s^{-1} and mm^{-2}. The latest measurements on GaAs detectors show, however, that these high fluxes lead to a saturation effect due to the high charge carrier density in the material. The generated charge can no longer be dissipated, the counting rate decreases

for high fluxes. This was recorded during measurements at the KIT and is shown in **Figure 3**.

GaAs sensors are also used in applications for Ultrafast Imaging. The latest publications by Becker et al.[12] show that the combination of charge-integrating electronics requires significantly higher stability and homogeneity requirements for each individual pixel. Dislocations and intrinsic defects such as those present in Cr-compensated GaAs have an even greater influence on the reduction of efficiency and spatial resolution. This is shown **Figure 4**.

The achieved results demonstrated the strong potential of the GaAs-based photon counting detectors and their application in beamlines with higher photon energies. It could be proved that the developed technology and the designed detector systems are working very efficiently and open the possibility for new and future application at the beamlines PETRA III, XFEL, and ESRF.

5. CdTe and CdZnTe

The earliest scientific publications of CdTe are dated from 1955.[13] The most interesting property of the material group is the sensitivity to many kinds of radiation. The major interest is concentrated in the field of radiation detectors for IR, X-, and γ-rays. The applications of CdTe and related compounds are summarized by Triboulet and Siffert.[14] The commercial potential is huge but the crystal quality of CdTe and especially CdZnTe was a limiting factor. The growth of high resistivity ($\rho > 10^9$ Ω cm) CdTe and ($\rho > 10^{10}$ Ω cm) CdZnTe, which are required for the most applications, is quite complex as presented by Szelecs et al.[15] and by Fougeres et al.[16] In the past, high detector grade material had to be selected and prepared out of large crystals by complicated and extensive preparation. The breakthrough was achieved by the growth from tellurium solvent called travelling heater method (THM) by Acrorad for CdTe and by Redlen for CdZnTe. THM is based on the growth of CdTe and CdZnTe from a solvent zone, with the advantage of a lower growth temperature.[17] Well homogenized crystals have been obtained. THM yield single crystals for both materials with diameters up to 3 in. (75 mm). The difference between CdTe and CdZnTe are related to the resistivity and the mobility-lifetime of the charge carriers. Several companies are now growing detectorgrade CdTe and CdZnTe by THM like Eurorad,[18] Acrorad,[19] EV Products Kromek,[20] and Redlen.[21]
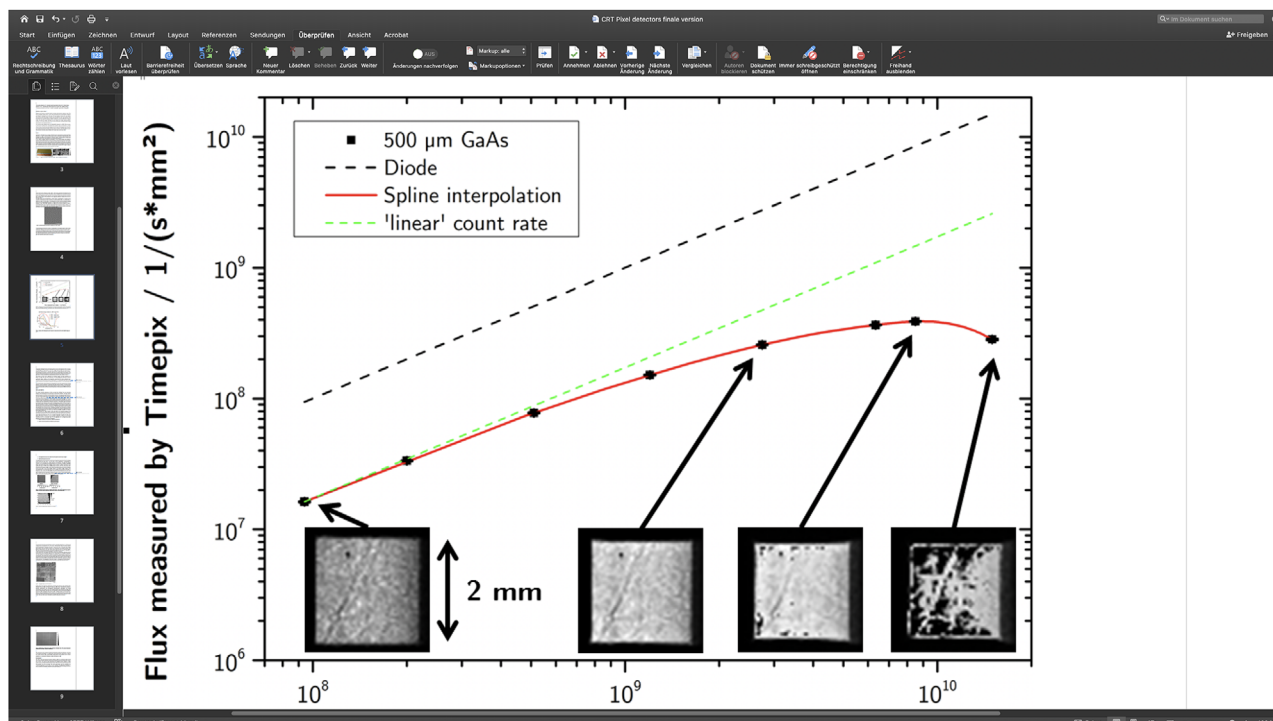
Figure 3. Measured count rates versus input photon flux. The insets are showing details of frames at the respective flux. At very high fluxes of around 10^{10} $(s\ mm^2)^{-1}$ the current of the generated charge carriers is too high for the leakage current compensation of the Timepix detector ASIC, therefore the count rate is decreasing. Reproduced with permission.[36] Copyright 2015, IOP Publishing.
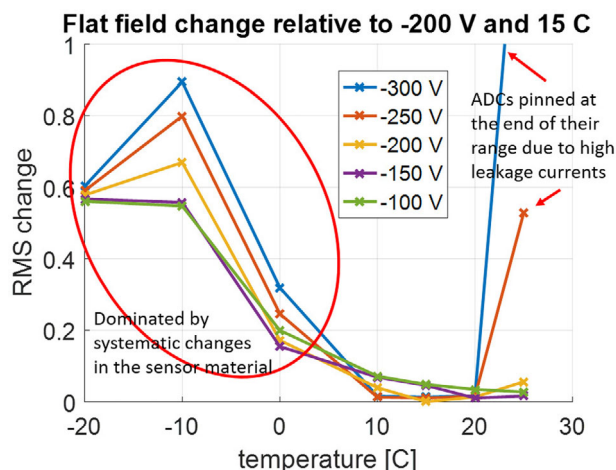

Figure 4. Analysis of the inhomogeneity of pixel response by measurements of the relative flatfield changes per pixel. Reproduced with permission.[12] Copyright 2018, IOP Publishing.

The requirements for single crystals of CdTe and CdZnTe are constantly growing by the development of new prototypes and the exploitation to new fields of applications of radiation. The need for pixel detectors is more and more toward large, high quality single crystals, which means high purity (less than 10^{15} cm^{-3} of residual impurities), no grains nor twins, low dislocation density ($< 10^4$ cm^{-2}), and homogeneous distribution of dopants and residual impurities as well in a micrometer scale. For the applica-

tion of X- and gamma-ray pixel detectors, the following requirements are defined:

- detector volume up to several cm^3 (200 keV and above)
- uniform material properties and detector performance
- inhomogeneities have to be smaller than the spatial resolution (μm-range)
- stable performance over time

The applications of CdTe and CdZnTe crystals have the general requirement that the leakage current should be lower than 1 nA per pixel at room temperature, corresponding to 33 μA cm^{-2}. This is necessary for the stable operation of the detector. The higher the leakage current is, the more the electrical properties of the sensor are changing with time. While the today's best CdTe sensors have a leakage current of about 1 μA cm^{-2}, previously it was significantly higher. In 2004, the first Medipix2 pixel detectors with CdTe sensors were presented by Chmeissani et al.[22] The CdTe material was delivered by Acrorad and the leakage current was high at low bias voltage already. The flatfield image showed some inhomogeneities in the pixel performance and an unstable interconnection technology as presented in **Figure 5**. Due to the high leakage current and bump bonding issues, the count rate significantly decreased in the upper left corner within 1 month. The characterization of the sensor material was also done using resistivity mapping as shown in **Figure 6**. The resistivity distribution is quite homogeneous in the range of 3×10^8 to 6×10^9 Ω cm.

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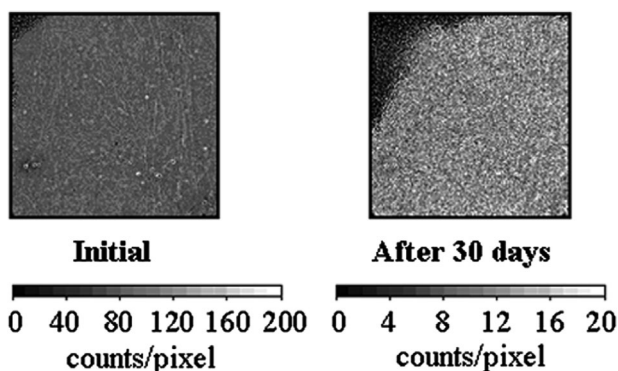
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Figure 5. Comparison of pixel response in a Medipix2 CdTe detector. The count rate significantly decreased in the upper left corner within 1 month due to high leakage current and bump bonding issues. Reproduced with permission.[27] Copyright 2011, Elsevier.
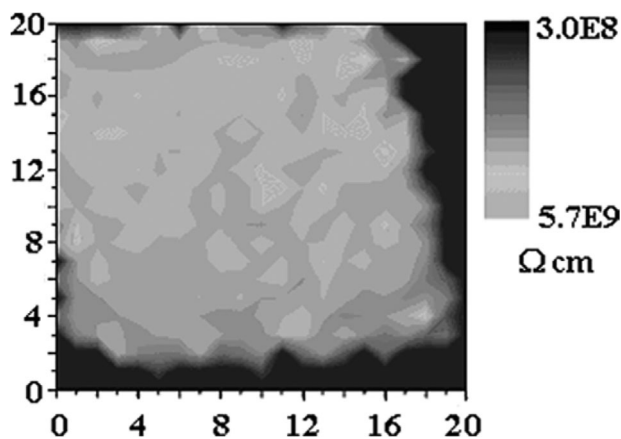

Figure 6. Resistivity mapping using CoReMa for a CdTe sensors. Reproduced with permission.[27] Copyright 2011, Elsevier.

Figure 7. Topography map of CdTe 004 reflection. Reproduced with permission.[30] Copyright 2017, IOP Publishing.

Figure 8. Flatfield image of CdTe detector module 42 × 48 mm^2 with Medipix3 chips. The count rate homogeneity presented here is very high. Courtesy of X-Spectrum. Courtesy of X-ray Spectrum GmbH, Germany.[36]

A consequence from the required leakage current is a resistivity higher than 1×10^9 Ω cm and a charge carrier concentration of 10^6 cm^{-3} or lower. The theoretical values for intrinsic material for the resistivity are 10^9 Ωcm for CdTe and 10^{11} Ωcm for $Cd_{0.9}Zn_{0.1}Te$. The only way to obtain high resistivity CdTe and CdZnTe crystals is by compensation of the shallow acceptors. The growth of high resistivity CdTe and CdZnTe can be achieved by the use of different dopants. The choice of the dopant depends on the field of application the material is dedicated to. Chlorine and indium are the favored dopants for pixel detector material.

In the recent years, the quality of the CdTe crystals was consequently improved and the interconnection was successfully adjusted to the requirements of CdTe-based compounds. This was possible by the intensive material and detector characterization carried out by several groups. The scientific focus was the correlation of reduction of detector performance and material defects as presented by Greiffenberg et al.,[7] Guni et al.,[23] and Cecilia et al.[24] The analysis of structural defects was performed at the KIT synchrotron source for a former Timepix detector. The topography is illustrated in **Figure 7**, showing the CdTe 004 reflection.[35] The significant reduction of detection signal could be correlated with dislocation lines.
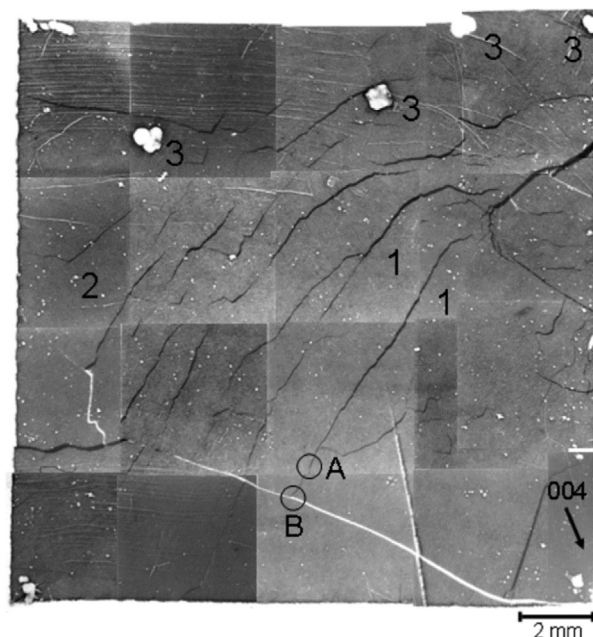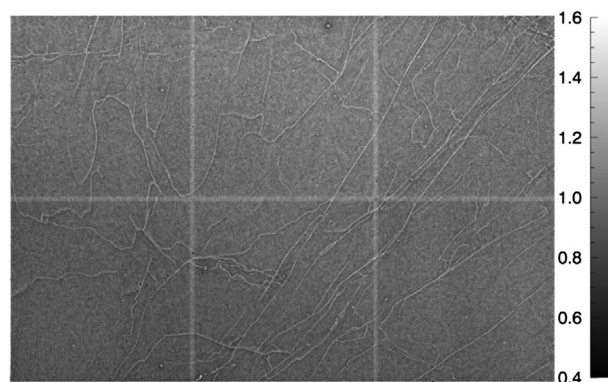
Further data of the detector performance of CdTe pixel detectors were published with Medipix3 (Procz et al.[25]) and Timepix3 (Trojanova et al.[26]) chips. These detectors showed an excellent performance and well-defined interconnection technology. The strong improvement of the quality of the CdTe material allowed the production of larger area, monolithic pixel detectors with more than 350.000 pixels for 55 μm pixel pitch with Medipix2 (Koenig et al.[27]) and Medipix3 (Pennicard et al.[28]). A flatfield image of a CdTe 42 × 28 mm^2 detector module with Medipix3 is shown in **Figure 8**. A very high bump bond connection yield of more than 99% could be achieved, as well as a high uniformity of sensor efficiency. For this reason, the count rate was very homogenous except for dislocation structures.

The actual topics in the research of material development and detector technology is focusing on the high-flux performance. The applications require photon fluxes larger than

10^8 photons s^{-1} and mm^{-2}. This requires further improvement of the material and the contact technology, for example, presented by Prokesch et al.[29] and Thomas et al.[30]

6. Conclusions

Promising results were obtained in the research of materials for the development of pixel detectors beyond silicon. CdTe, CdZnTe, and GaAs are the favorite candidates for large area detectors for energies above 20 keV. The achieved results demonstrate the availability and the reliability for high spatial resolving and highly efficient detector systems. There have been great improvements in both materials over the last decades. The recent achievements open the possibilities for commercial applications in several fields. The next challenge is the application for high-flux X-rays in computed tomography and photon sources applications. Several challenges have to been met but the research is still continuing in this important field.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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