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Development of high-Z sensors for pixel array detectors

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Hybrid pixel detectors using silicon sensors have been successfully applied to experiments with X-rays, such as protein crystallography at synchrotrons. However, silicon has poor quantum efficiency at higher X-ray energies. To apply this hybrid pixel technology to experiments with harder X-rays, for example in materials science and medical imaging, it is necessary to use alternative semiconductors with higher atomic numbers ("high-Z semiconductors"). Currently, there are a few promising options. Cadmium Telluride offers high quantum efficiency at energies of 100keV and above, and the area and uniformity of the material available is improving. Gallium Arsenide is already available in large, uniform wafers, and new compensation techniques are being developed to overcome problems with its high trap concentration. Germanium is already available in large wafers of very high quality; however, it must be cooled during operation, and pixellation and bump-bonding techniques need to be developed for this material. In collaboration with Canberra, DESY is developing germanium pixel detectors using the Medipix3 readout chip. DESY is also developing large-area Medipix3 detector modules, which will be compatible with a variety of high-Z materials and silicon.

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1.Introduction

A hybrid pixel detector consists of a pixellated semiconductor sensor, bonded face-to-face with a pixellated readout chip. Hybrid pixel sensors using silicon photodiode arrays have been successfully applied as vertex detectors in particle physics experiments, and for X-ray detection. For example, the Pilatus hybrid pixel detector is now commonly used for X-ray diffraction experiments at synchrotron light sources [1]. However, silicon sensors have poor quantum efficiency at high photon energies, as shown in Fig. 1, which limits their use in experiments with hard X-rays. By replacing the silicon sensor with a semiconductor with higher atomic number ("high-Z"), high quantum efficiency can be obtained across a wider energy range. Compared to silicon, these high-Z materials often have problems such as poor uniformity, poor material properties or difficult fabrication, which must be overcome in order to produce useful detectors for experiments.

DESY is currently working with Canberra to develop pixellated germanium sensors bonded to Medipix3 [2] readout chips. Additionally, DESY is developing a tilable large area detector module using the Medipix3 readout chip (85mm by 28mm, with 1536 by 512 pixels) which will be compatible with different high-Z materials. These detectors will be used chiefly for high-energy synchrotron light source experiments.

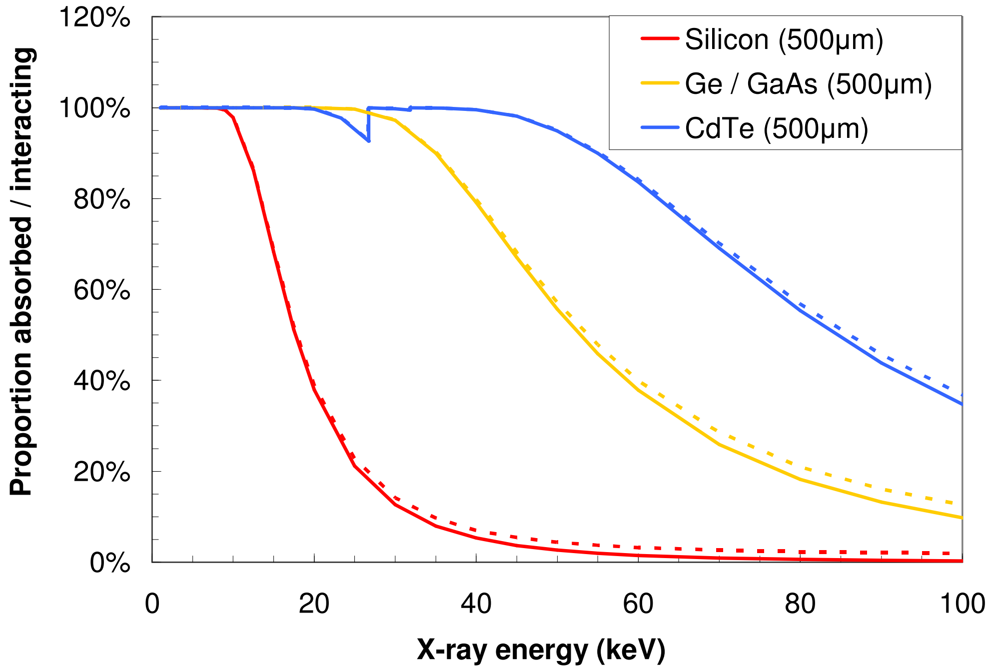

Figure 1: Photon absorption efficiency of different semiconductors. The solid line indicates the proportion of incoming photons absorbed by the photoelectric effect, and the dotted line shows the proportion interacting by photoelectric absorption or Compton scattering. These values are calculated using data from the NIST XCOM database [3].

2. Applications of high-Z detectors

A monochromatic synchrotron X-ray beam with an energy of around 10keV can be used for a range of experiments on small or weakly-absorbing samples, such as proteins. However, a beam of this energy has an absorption length of under 10μm in a heavier element such as iron. So, synchrotron beamlines designed for materials science frequently operate at higher energies. For example, the Petra-III synchrotron light source [4] at DESY, which has recently opened to users, has one beamline which can operate at 150keV, and three others which can produce beams of 50keV and above. These X-ray beams can be focused down to a small volume within a sample, making it possible to determine the material structure at a buried interface (in a fuel cell, for example) or to systematically map the interior structure of a sample (for example, to find the grain structure of a polycrystalline material). Using detectors with higher quantum efficiency will increase the speed and accuracy of these experiments, particularly when working with samples that are sensitive to radiation.

In medical imaging, high quantum efficiency is a particularly important requirement, because this is needed to achieve a high quality image while minimising the X-ray dose to the patient. Since medical imaging is, in most cases, performed at energies above 30keV, replacing silicon with high-Z materials is necessary to make hybrid pixel detectors a feasible technology for medical imaging. Unlike experiments at synchrotron light sources, medical imaging generally uses a polychromatic X-ray source. Hybrid pixel detectors offer the possibility of performing energy measurement on each X-ray photon hitting the detector. This spectral information can improve the distinction between different tissues [5].

High-Z materials are already being used in astrophysics in X-ray and gamma-ray telescopes; for example, the INTEGRAL satellite has a CdTe camera [6]. The requirements for these experiments are often different to synchrotron light source and medical imaging experiments; the photon flux is usually much lower, and accurate spectroscopic measurement is a more important requirement. Additionally, detector systems for use in space face strict limits on mass and power consumption.

3. Requirements for high-Z sensors

As discussed in the next section, different high-Z materials have different strengths and weaknesses. One common problem is that most high-Z materials are compound semiconductors, which means that they typically have much higher defect densities than elemental semiconductors such as silicon.

This section primarily considers the detector requirements for synchrotron light source experiments. Typically, these are X-ray scattering experiments, where a sample is placed in a focused beam and the resulting diffraction pattern must be measured.

Some aspects of the sensor requirements are set by the structure of the hybrid pixel readout chip. The Medipix3 chip has a pixellated area of 14.1mm by 14.1mm, with 256 by 256 pixels of 55μm size. Furthermore, since space is required at the chip edges for wire bonding readout pads, an individual sensor must have a "2 by N" chip layout. While the pixel size may vary in different readout chips, the chip size and wire bonding requirements tend to be similar.

For example, the Pilatus readout chip has a much larger pixel size of 172µm, but a similar area of 17.54mm by 10.45mm [1].

The main material requirements are:

Wafer uniformity and area: To accurately reconstruct the structure of a material from its diffraction pattern, the diffracted intensity must be accurately measured across a wide dynamic range. With monochromatic beam, variations in pixel count rates of a few percent can be reliably compensated by flat-field correction [7] but larger variations and dead or hot pixels will prevent accurate measurement of intensity. So, the uniformity of the sensor material is very important. Since the distance between the sample and source can be varied to change the scale of the projected diffraction pattern at the detector, the Medipix3 pixel size of 55µm is acceptable for most experiments. (However, for certain imaging experiments a pixel size of under 1µm is needed, which simply cannot be achieved with hybrid pixels.) To match existing detector systems such as CCDs and image plates, array sizes of 1k by 1k pixels or greater are required, which would correspond to at least 4 by 4 Medipix3 chips. Since only "2 by N"-chip sensors are possible, these large detector systems must be built from multiple sensors. Although it is possible to compensate for the gaps between the sensors by taking multiple images with different sensor positions, the gaps should be minimised where possible. To achieve these requirements, the detector material should be available in high uniformity single-crystal wafers, with a minimum diameter of 2" needed to obtain 2 by 2-chip sensors. A larger size is preferable, to reduce the number of gaps in a large detector system and to make the wafer processing more cost-effective.

Material properties: In order to successfully operate a detector, it must be possible either to create a diode or Schottky junction and fully deplete the substrate (with a thickness of a few hundred microns or greater), or to use a photoconductor structure with tolerably low leakage current. The maximum acceptable leakage current will be determined by the photon-counting electronics; for the Medipix3 readout chip, the design limit is 25nA per pixel, though in practice the current should be kept well below this [8]. Since hybrid pixel readout chips can count individual photons, and synchrotron X-ray beams are generally monochromatic, energy resolution is a less critical requirement. (The main effect of detector noise is that it limits the minimum detectable photon energy, but at X-ray energies above 12keV these noise requirements can be easily met.) Carrier trapping can tolerated, provided that the majority of the signal is collected. In applications with polychromatic sources such as medical imaging, detector noise and charge trapping may have to meet more stringent requirements, but this will be application-specific.

Physical properties: It must be possible to pixelate and bump-bond the detector without damaging the material. Often, high-Z materials are temperature-sensitive, or physically fragile, and some chemical processes may damage the material, so the processing must be tailored to meet these requirements.

An additional difficulty with high-Z materials is fluorescence. When a sensor absorbs a photon by the photoelectric effect, it will sometimes re-emit a fluorescence photon. In silicon, these fluorescence photons have low energy and do not travel very far in the detector, and will have little effect on the image quality. In higher-Z materials, however, k-shell fluorescence photons can carry a large amount of energy, and may travel far enough to end up in another pixel, or leave the detector altogether. This can blur the image, particularly if the incoming photon energy is immediately above the k-edge. The k-shell energy, fluorescence yield and the mean absorption distance of fluorescence photons all increase with the material's atomic number. So, both quantum efficiency and fluorescence effects need to be considered when choosing the optimum material for a particular energy range.

4. Promising high-Z materials

4.1 Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CZT)

Cadmium telluride is a II-VI semiconductor. As shown in Fig. 1, its X-ray absorption efficiency remains high even at 100keV, which makes it attractive for applications such as medical imaging which operate in a 30-120keV range.

Historically, a major limitation of CdTe has been the difficulty of producing large-area single crystal wafers, and this has limited its use to small arrays. However, cadmium telluride is now commercially available in wafers of up to 3" [9], which is large enough to produce a sensor with an area of 2 by 3 Medipix3 chips. A further problem with CdTe is material uniformity; since CdTe is typically grown under Te-rich conditions, small inclusions of Te may form in the crystal [10].

The bulk material properties of CdTe are generally reasonable. It has a large bandgap (1.44eV) and high resistivity, which means that it can be operated at room temperature while remaining within a readout chip's current limits. As a result, it can be operated as either a photoconductive detector or as a Schottky junction, depending on which metal pixel contacts are deposited on the material. While a Schottky junction will have lower leakage current, using CdTe as a photoconductor avoids certain problems with polarisation which can occur while the detector is in use. Although CdTe has some charge trapping, typical carrier drift lengths are of order centimetres for electrons and millimetres for holes. So, in a 1mm-thick pixel detector with electron readout charge trapping effects should be negligible.

CdTe is a fragile material, which means that it can be broken by rough handling or thermal stresses. Additionally, high temperatures (above 200°C) can degrade the material's transport properties. So, CdTe pixel detector are typically produced by creating metal contacts through low-temperature sputtering or electroless deposition, followed by low-temperature bump-bonding to a readout chip [10].

To date, pixellated CdTe sensors have been bonded to a variety of readout chips, such as Medipix2 [11] and XPAD3S [12]. Due to the increasing availability of 3" CdTe wafers, large-area CdTe detectors are becoming steadily more feasible.

An alternative to CdTe is CdZnTe. This material has a larger bandgap than CdTe (1.57eV) and its lower leakage current can lead to better spectroscopic performance. Currently, the main disadvantage of CdZnTe compared to CdTe is that it is produced in large polycrystalline ingots, with material properties varying from grain to grain. Good single-crystal elements must then be cut from the ingot, and the size of these elements is currently limited to around 20mm by 20mm [9]. So, it would only be possible to produce single-chip Medipix3 devices with CdZnTe, which is a serious disadvantage compared to the other materials discussed in this paper.

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4.2 Gallium Arsenide

Gallium arsenide is a III-V semiconductor. While its quantum efficiency is lower than that of CdTe, it is less strongly affected by fluorescence effects, and so it may give better performance in the 30-60keV range.

Unlike CdTe, GaAs is already available in large, uniform wafers of around 6", which makes it an appealing choice of material. Like CdTe, it has a high bandgap, so it can potentially be operated at room temperature. However, GaAs contains a large number of defects. Shallow defects in GaAs act as dopants, meaning that a standard GaAs wafer cannot be fully depleted or used as a photoconductor. There are two main approaches to producing detector-grade GaAs. Firstly, it is possible to reduce the concentration of defects in the material, by growing it in epitaxial layers. The main challenge of this approach is that it may be difficult to grow and deplete thick epi-layers of material. The alternative approach is to compensate the defects in GaAs. Although it is possible to obtain high-resistivity GaAs simply by growing it under As-rich conditions, the resulting material tends to have very high electron trapping, leading to an electron lifetime of 1ns or less [13] and hence a mean trapping distance of at best 100µm. In a detector thickness of a few hundred microns, this will lead to most of the signal being lost. A more promising alternative is to compensate the defects in GaAs by chromium diffusion [14].

GaAs detectors can either be fabricated as diodes, Schottky junctions or photoconductors. Typically, epitaxial GaAs detectors are fabricated as diodes, for example by growing a thin layer with opposite-type doping onto the top of the sensor and then etching trenches into this to form pixels [15]. Compensated GaAs detectors are typically operated as Schottky junctions or photoconductors by depositing metal pixel contacts. As with CdTe, pixelation and bump-bonding of GaAs is done at low temperature, though GaAs is physically more robust than CdTe. A variety of GaAs pixel detectors have been fabricated and bonded to Medipix2 chips. For example, Ref. [16] shows the first test results from Cr-compensated GaAs Medipix2 sensors, which show that the full depth of the 300µm-thick sensor is sensitive, though there are inhomogeneities in the sensor's response.

4.3 Germanium

Unlike CdTe and GaAs, germanium is an elemental semiconductor, which is available in reasonably large 6" wafers of high uniformity, with a doping concentration as low as $10^{10}cm^{-3}$ and negligible charge trapping [17]. As a result, Ge is widely used for spectroscopic X-ray detectors. However, there are various barriers to using Ge in pixel detectors. DESY is working with Canberra (Lingolsheim) and Fraunhofer IZM (Berlin) to produce germanium pixel detectors on 4" wafers (the largest size that Lingolsheim currently process) and bump-bond them to Medipix3 chips [2].

The first disadvantage of germanium is its narrow bandgap of 0.67eV. This means that it has high leakage current, and cannot be operated at room temperature. Typically, germanium photodiodes for spectroscopy are operated at liquid nitrogen temperature, in order to obtain a very low leakage current and hence achieve high energy resolution. However, photon-counting hybrid pixel detectors are more tolerant of leakage current, for two reasons. Firstly, due to the small volume of each pixel, the leakage current per pixel will be comparatively low. Secondly, photon-counting readout chips such as Medipix3 count the number of signal pulses arriving in each pixel, rather than integrating the total signal seen over the acquisition period, so leakage current will have less effect on their performance. A pixellated germanium detector with pixels of 55µm should have a leakage current of around 1nA per pixel at -50°C, which is safely below the design limit of 25nA. The need for cooling places additional demands on the engineering of the detector system, and will tend to make the system more expensive and bulky. However, in experiments on a synchrotron beamline, this can be tolerated.

Secondly, the technology for fabricating germanium sensors must be modified in order to produce small pixels. This will be done by Canberra. Canberra's fabrication method [18] first uses lithium diffusion to create an ohmic n-type contact on the back surface of high-resistivity n-type germanium. Then, p-doped diode junctions are produced on the front surface using photolithography and ion implantation of boron. The detector is completed by depositing aluminium contacts on the back surface and the pixel contacts, and then passivating the detector. Currently, this approach can be used to create strip detectors with a 50µm pitch; after modification, the process will be used to fabricate arrays of 55µm and 110µm pixels for use with the Medipix3 chip.

To bump-bond these sensors to readout chips, indium must be used [19]. This is for two reasons. Firstly, when the detector is cooled during operation, there will be a mismatch between the thermal contraction of the germanium sensor and the silicon readout chip. For a Medipix3-sized chip and a germanium sensor, and a temperature change of 100K, the difference in contraction at the edge of the sensor assembly will be 3.5µm. This means the bump bond must be composed of a metal which remains ductile at low temperature, so that the bond flows to accommodate this small shift in position rather than cracking. Secondly, germanium is extremely temperature sensitive; heating it to above 100°C for extended periods can allow diffusion of impurities into the germanium, and may also damage the passivation. Due to indium's softness, it is possible to electroplate In bumps on both the sensor and readout chip, then bond them together at less than 100°C using thermocompression. The bump-bonding of these sensors will be done by Fraunhofer IZM (Berlin). Currently, IZM are doing thermal tests on germanium diodes, to establish what effect the bump bonding will have on germanium, and which specific bonding processes and passivation will work best.

5. Developing high-Z detector modules

Although various high-Z materials have been tested with single Medipix chips, to meet the requirements for synchrotron X-ray experiments larger detector areas are required. So, DESY is developing a large-area Medipix3 detector module that will be compatible with a variety of high-Z materials and silicon. For X-ray diffraction and imaging experiments at DESY, the specific detector requirements will vary from experiment to experiment. Since some X-ray scattering experiments require measurement across a wide angular range, it is necessary to develop a tilable detector module that can be built into larger systems. Nevertheless, to reduce the effect of gaps between modules, the sensor size should be as large as possible, within the limits set by the readout chip and sensor materials.

The detector module structure is shown in Fig. 2. Due to the space required for wire bonds, the module must inevitably have a “2 by N” chip structure. An array of 2 by 6 chips was chosen, with an area 28mm*84mm and a total of 512 * 1536 pixels of 55µm size. This module size makes it possible to mount either two smaller high-Z sensors of 28mm*42mm (about the largest size that can be produced with 3” and 4” wafers) or a single large sensor (three of which can be produced on a single 6” Si wafer). The two halves of the module may be read out independently. Three of these detector modules could then be combined to give 1.5k by 1.5k pixel detector, or twelve to give 3k by 3k pixels.

The detector assemblies will be mounted on a heat spreader, which will in turn be mounted on a ceramic circuit board. The input and output pads of the Medipix3 chips will be connected to the board by wire bonding, and then these signals will be routed to a connector on the back surface. A board with signal routing and voltage regulators will then be plugged into this connector, powering the module and allowing it to connect to the rest of the DAQ system. Currently, the ceramic board and voltage regulator board are in production.

During initial testing, the module will be read out by a USB-based readout system developed by Czech Technical University [20]. However, an important aim of the module design is high-speed readout. The module will carry enough signal lines to read out each Medipix3 chip at its maximum rate of 2000 full frames per second with a counter depth of 12 bits per pixel. (The Medipix3 chip allows only full-frame readout, but the counter depth may be reduced to allow readout speeds above 2000 frames per second with reduced dynamic range.) Currently, DESY is collaborating with other institutes to develop a high-speed DAQ system for XFEL [21]. This Medipix3 module will ultimately be read out by a digital board based on these developments, which will incorporate an FPGA and two 10 Gigabit Ethernet connections to allow high-speed data output. The data will then be written to an array of disks.

As mentioned previously, one particular requirement of a germanium pixel sensor is that it will need to be uniformly cooled to around -50°C. The ceramic PCB will be mounted on a cooling frame at this temperature, and the detector assembly will be cooled through thermal vias in the ceramic. The use of a heat spreader underneath the sensor assembly will reduce any temperature variations across the module. Both the graphite-based heat spreader and the ceramic PCB have similar coefficients of thermal expansion to germanium, in order to prevent thermal stresses when the module is cooled.

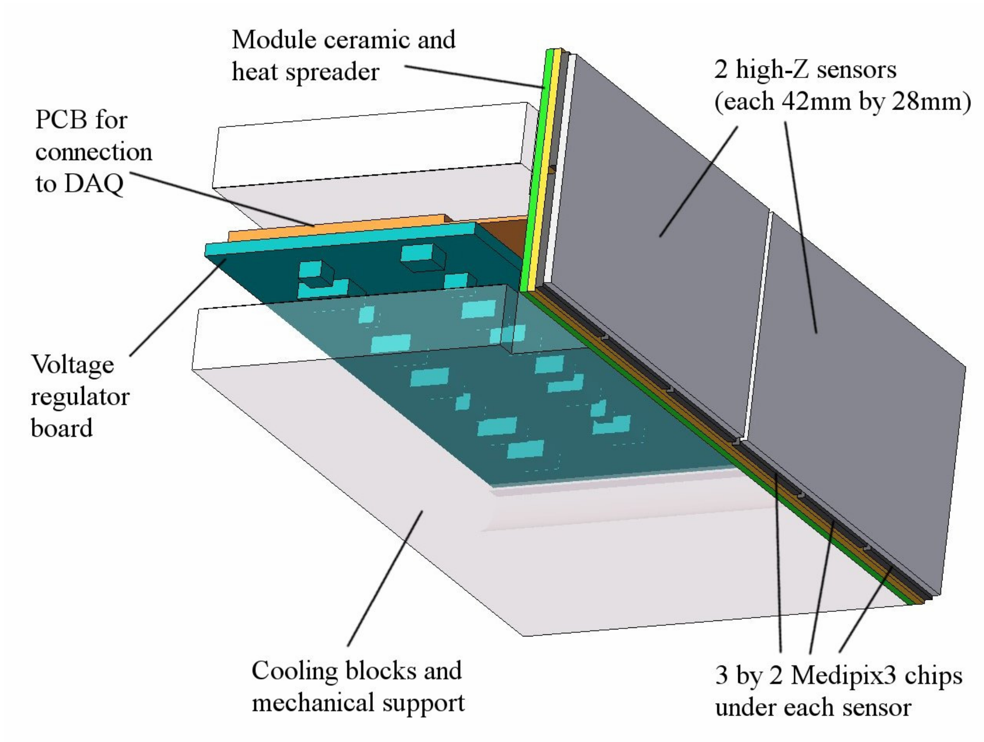

Figure 2 – Design of a large-area Medipix3 detector module compatible with different sensor materials.

6. Conclusions

By developing high-Z hybrid pixel detectors, it should be possible to combine the strengths of hybrid pixel technology with high quantum efficiency at high X-ray energies. This will benefit a range of hard X-ray experiments, such as materials science experiments at synchrotron light sources and medical imaging. Currently, DESY is developing germanium sensors with Canberra, and developing a Medipix3 detector module that is compatible with germanium and a range of other materials such as CdTe and GaAs. While each material has disadvantages, useful high-Z hybrid sensors should be available for experiments in the near future.

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