The LAMBDA photon-counting pixel detector

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Abstract. The Medipix3 photon-counting detector chip has a number of novel features that are attractive for synchrotron experiments, such as a high frame rate with zero dead time and high spatial resolution. DESY are developing a large-area Medipix3-based detector array (LAMBDA). A single LAMBDA module consists of 2 by 6 Medipix3 chips on a ceramic carrier board, bonded to either a single large silicon sensor or two smaller high-Z sensors. The readout system fits behind the carrier board to allow module tiling, and uses a large on-board RAM and multiple 10 Gigabit Ethernet links to permit high-speed readout. Currently, the first large silicon modules have been constructed and read out at low speed, and the firmware for high-speed readout is being developed. In addition to these silicon sensors, we are developing a germanium hybrid pixel detector in collaboration with Canberra for higher-energy beamlines. Canberra have produced a set of 256-by-256-pixel planar germanium sensors with 55 µm pitch, and these are currently being bonded to Medipix3 readout chips by Fraunhofer IZM (Berlin).

1. The Medipix3 photon counting chip and high-Z pixel sensors

In recent years, photon-counting hybrid pixel detectors such as Pilatus [1] and Medipix2 [2] have become the cutting-edge technology for many X-ray scattering and imaging experiments. In these detectors, a signal pulse is produced whenever an X-ray photon hits a pixel, and this pulse is counted if it exceeds some user-defined threshold level. This means the detector is effectively “noise free”, giving an excellent signal-to-noise ratio, and also makes it possible to exclude lower-energy background photons. These detectors can also have a high frame rate, so they can be used to exploit the high brilliance of modern synchrotrons, for example to perform time-resolved experiments or fast scanning of a sample.

The Medipix3 chip [3] is a new generation of photon-counting readout chip, which combines the relatively small pixel size (55 µm) of its predecessor with a range of new features which are attractive for synchrotron experiments. It can operate in a continuous read-write mode: there are two counters in each pixel, and while one is accumulating photon hits the other one can be read out, meaning that there is negligible dead time between frames. The maximum frame rate of the chip has also been increased to 2000 frames per second with 12-bit counter depth, and the counter depth can be decreased to allow proportionally higher rates. A new “charge summing” feature also improves the image quality by correcting for charge-sharing effects in the sensor [4].
Although hybrid pixel detectors typically use silicon sensors, readout chips can also be bonded to sensors with higher atomic numbers (high-Z semiconductors) to greatly improve their quantum efficiencies at higher energies. This is particularly important for synchrotrons such as PETRA-III where most of the beamlines can operate at energies above 20 keV. The Medipix3 chip is particularly well-suited to working with a range of high-Z materials [5]. Firstly, the charge summing feature will be particularly valuable when working with these sensors, since they are typically thick (increasing charge sharing effects) and they also have additional charge spreading due to fluorescence within the sensor. Secondly, the preamplifier in Medipix3 allows both hole and electron collection, and it also has leakage current compensation circuitry, so it can be used with materials with poor hole transport or higher leakage currents.

Most synchrotron experiments require a larger detector area than can be provided by a single Medipix3 chip. So, DESY are developing the LAMBDA (Large Area Medipix3 Based Detector Array) system, which consists of large, multi-chip modules which can be tiled to cover a large area. This system is designed to take advantage of the high-speed readout capability of Medipix3, and to be compatible with a range of high-Z sensor materials such as germanium, GaAs and CdTe. DESY are collaborating with other institutes to investigate different sensor materials, but the majority of our work focuses on a germanium detector development as described in Section 4.

2. The LAMBDA module
A single LAMBDA module consists of a detector head plus a readout system, as shown in Fig. 1. The readout system fits immediately behind the detector head, so that multiple modules can be tiled together to cover a large area.

2.1. Detector head
The detector head consists of a ceramic board on which an array of 2 by 6 Medipix3 chips can be mounted. In turn, these Medipix chips can either be connected to a single large silicon sensor (1536 by 512 pixels of 55 µm pitch) or two smaller high-Z sensors. This particular arrangement was chosen for two reasons. Firstly, the Medipix3 chip, much like other photon counting chips, requires free space at one edge so that it can be wire-bonded to the ceramic board. This naturally means a “2 by N”-chip layout is needed. Secondly, the sensor size of 84 mm by 28 mm for silicon, or 42 by 28 mm for high-Z sensors, is a convenient match to typical sensor wafer sizes.

The input and output pads on each Medipix3 chip are wire-bonded to the ceramic board. These signals then pass through the board to a 500-pin high-density connector on the back side. A large number of pins are needed because each Medipix3 chip has many data output lines to...
allow a high frame rate.

The ceramic board is designed to allow effective cooling of germanium and other high-Z sensors. The ceramic provides a good match to the coefficient of thermal expansion of germanium and other semiconductors, and also has silver-filled thermal vias to improve its thermal conductivity. The board is mounted directly onto a cooling block.

2.2. Readout electronics

While developing the LAMBDA detector, a prototype data acquisition system with USB2 readout was built, as described in Ref. [6]. This was used to test a prototype detector head (with a smaller silicon sensor read out by 4 Medipix3 chips) and develop firmware control for Medipix3.

The final readout electronics make use of a mezzanine high-speed readout board, which will also be used by other detector projects at DESY. This board has four 10 Gigabit Ethernet links, which will be sufficient to read out the detector continuously at its maximum frame rate (2000 frames per second with 12 bit counter depth). It also has a large onboard RAM (8GB) which will allow the detector to take images rapidly, store them to memory, and read them out using a single 10GE link. This will make it possible to do high-speed measurements with less computing infrastructure. (With a single 10GE link, a continuous rate of up to 500 frames per second should be possible.)

The mezzanine board is mounted on a “signal distribution” board which plugs into the detector head. This board routes signals between the mezzanine and the detector head, provides voltage regulators to power the detector, and also has analog-to-digital and digital-to-analog converters that are used for additional monitoring and control of the detector. A vacuum barrier can be glued onto this board, meaning that the detector head can be in vacuum while the voltage regulators and mezzanine board are kept outside of the vacuum.

The high-speed readout electronics were recently manufactured. Currently, the firmware for high-speed readout control is being developed.

3. Large-area silicon sensors

A set of large area silicon sensors (1536 by 512 pixels) have recently been bonded to Medipix3 chips by Fraunhofer IZM (Berlin), as shown in Fig. 1. In the first module assembled, all the chips are functional and there are no major errors in the bump bonding. 0.25% of the pixels were found to be bad—the majority of these appear on a single chip in the bottom-right corner, and are due to errors in its column readout circuitry. Fig. 2 shows an X-ray image of some pine cones taken with the first assembled module; the layered structure is clearly visible. The image was taken using a Mo target X-ray tube at 40kV, and the image has been flat-field corrected.

![Figure 2. (a) Optical picture of a single pinecone. (b) X-ray image of 4 pinecones taken with LAMBDA using a Mo target tube at 40kV.](image-url)
4. Germanium detector development

As mentioned previously, building detector modules using high-Z sensors would make it possible to achieve high quantum efficiency with hybrid pixel detectors even at high photon energies. Most high-Z materials are compound semiconductors, which means that their crystals often contain many defects which degrade their performance. However, germanium is already available in relatively large crystals of excellent quality, which makes them a promising option. DESY are collaborating with Canberra to build germanium hybrid pixel detectors with Medipix3.

There are a few obstacles to using germanium with hybrid pixel detectors: firstly, germanium must be cooled during operation to reduce its leakage current; secondly, germanium detectors are usually produced with strips or much larger pixels, so small-pixel fabrication methods must be developed; and thirdly, a bump bonding process must be developed that does not damage the sensor.

Typically, germanium detectors have large volumes, and must be cooled to cryogenic temperatures to achieve optimal spectroscopic performance. However, in this case the germanium only needs to be cooled to the point where the leakage current from each pixel is low enough not to significantly degrade the photon counting performance. In electron collection mode, Medipix3 is designed to compensate for up to 30 nA leakage current per pixel, but the noise performance steadily degrades above typical settings of 2 nA, so this should be the target. (This corresponds to 60 μA/cm².) Germanium diode structures were tested after undergoing the thermal steps required for detector processing, and it was found that this leakage current requirement was reached around -70°C.

After modifying their fabrication process, Canberra have produced a set of 700 μm thick high-purity germanium wafers, each of which has 16 Medipix3-compatible sensors (256 by 256 pixels, 55 μm pitch). One of these wafers is shown in Fig. 3. These sensors are currently being bump bonded by Fraunhofer IZM (Berlin) using indium bonds. Since indium is an extremely soft and ductile metal, the bonding can take place at temperatures below 100°C to prevent damage to the sensor, and when the sensors are cooled the bonds will flow slightly to compensate for the mismatch in thermal contraction. To optimise the bump bonding process, a series of germanium diodes with different passivation were put through a range of thermal and chemical processes, to determine a process that would not damage the sensors. Additionally, a set of dummy sensors made from low-quality germanium were used to optimise the flip-chip process.
5. Conclusions
The first LAMBDA detector module with silicon has been produced and works successfully. Combined with high-speed readout electronics, the system will provide a small pixel size, excellent signal-to-noise performance and a high frame rate for X-ray scattering experiments. The first germanium detectors are being bump bonded, and will be tested soon.

References
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