EXCALIBUR: a small-pixel photon counting area detector for coherent X-ray diffraction - Front-end design, fabrication and characterisation

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Abstract. Coherent X-ray diffraction experiments on synchrotron X-ray beamlines require detectors with high spatial resolution and large detection area. The read-out chip developed by the MEDIPIX3 collaboration offers a small pixel size of 55 microns resulting in a very high spatial resolution when coupled to a direct X-ray conversion segmented silicon sensor. MEDIPIX3 assemblies present also the advantages of hybrid pixel detectors working in single photon counting mode: noiseless imaging, large dynamic range, extremely high frame rate. The EXCALIBUR detector is under development for the X-ray Coherence and Imaging Beamline I13 of the Diamond Light Source. This new detector consists of three modules, each with 16 MEDIPIX3 chips which can be read-out at 100 frames per second in continuous mode or 1000 frames per second in burst mode. In each module, the sensor is a large single silicon die covering 2 rows of 8 individual MEDIPIX3 read-out chips and provides a continuous active detection region within a module. Each module includes 1 million solder bumps connecting the 55 microns pixels of the silicon sensor to the 55 microns pixels of the 16 MEDIPIX3 read-out chips. The detection area of the 3-module EXCALIBUR detector is 115 mm x 100 mm with a small 6.8 mm wide inactive region between modules. Each detector module is connected to 2 FPGA read-out boards via a flexi-rigid circuit to allow a fully parallel read-out of the 16 MEDIPIX3 chips. The 6 FPGA read-out boards used in the EXCALIBUR detector are interfaced to 6 computing nodes via 10Gbit/s fibre-optic links to maintain the very high frame-rate capability. The standard suite of EPICS control software is used to operate the detector and to integrate it with the Diamond Light Source beamline software environment. This article describes the design, fabrication and characterisation of the MEDIPIX3-based modules composing the EXCALIBUR detector.

1. Introduction
Coherent X-ray diffraction is a powerful tool for the structural analysis of nano-materials. Imaging samples in the reciprocal space with highly coherent synchrotron X-ray beam overcomes the resolution limit of direct imaging techniques and provides information on the strain distributions in materials at the nanoscale [1]. The beamline I13 at the Diamond Light Source consists of two branches, one of which is dedicated to coherent X-ray diffraction and ptychography [2]. Two-dimensional detectors covering a large angular range with a high angular resolution are necessary to resolve the speckles produced in coherent X-ray diffraction images. X-ray detectors with a pixel size...
smaller than 50 µm and operated in direct-X-ray detection mode are typically used. On I13 beamline, the high angular spatial resolution is achieved by mounting the detector at a long distance from the sample (up to 5 m) and using an industrial robot in the large experimental hutch to cover the angular range required. Recently, small-pixel single-photon counting X-ray detectors have been used for coherent X-ray experiments. These detectors are direct-X-ray conversion hybrid pixel detectors based on the 55 pixel size MEDIPIX2 chip [3] and offer the advantage of high dynamic range and noiseless imaging capability compared to more traditional 2D detectors. I13 beamline is equipped with one of these detectors (MAXIPIX) developed by ESRF. In order to cover a larger active area and to benefit from the small pixel size, high frame rate, high radiation hardness, continuous read/write and charge-summing-mode of operation of the latest version of the MEDIPIX read-out chips, a joint project between Diamond Light Source and the Science and Technology Facilities Council (STFC) has been set-up to produce the EXCALIBUR detector described below.

2. EXCALIBUR detector

The EXCALIBUR detector consists of three modules, each with 16 MEDIPIX3 chips which can be read-out at 100 frames per second in continuous mode or 1000 frames per second in burst mode. In each module, the sensor is a large single silicon die covering 2 rows of 8 individual MEDIPIX3 read-out chips and provides a continuous active detection region within a module. The detection area of the 3-module EXCALIBUR detector is 115 mm x 100 mm with a small inactive region between modules. Each detector module is connected to 2 FPGA read-out boards via a flexi-rigid circuit to allow a fully parallel read-out of the 16 MEDIPIX3 chips. The 6 FPGA read-out boards used in the EXCALIBUR detector are interfaced to 6 computing nodes via 10Gbit/s fibre-optic links to maintain the very high frame-rate capability. The standard suite of EPICS control software is used to operate the detector and to integrate it with the Diamond Light Source beamline software environment [4].

3. EXCALIBUR front-end module design

An EXCALIBUR module consists of four principal elements: the hybrid pixel detector itself, a cold-finger, a hybrid-carrier PCB and a pair of flexi-rigid adaptor PCBs as shown on Figure 1. The maximum power dissipated by the 16 MEDIPIX3 read-out chips of the hybrid pixel detector is around 16W and is dissipated via the cold-finger which is in thermal contact with a water-cooled heat-sink. Molybdenum was selected as the cold-finger material since its coefficient of thermal expansion is close to that of the silicon chips. In addition, a thermoplastic adhesive film with high thermal conductivity is used to bond the hybrid pixel detector onto the cold-finger. A 10-layer PCB was designed to interface signals from the 16 read-out chips to two 300-way connectors carrying power and control signals. High track density is necessary since the hybrid carrier PCB has to fit behind the hybrid pixel detector and also because a large central region of the PCB is not available for routing due to an 8 mm x 10 mm slot provided in the PCB to allow direct thermal transfer between read-out chip, cold-finger and heat-sink. Electrical connections between read-out chips and hybrid carrier PCB

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are provided by aluminium wire-bonds. Two parallel rows of pads were necessary on the hybrid carrier PCB to interface all the signals and ensure that the minimum pad-to-pad distance was more than 80 µm in order to stay within standard PCB design rules. The interfacing between the two 300-way connectors at the back of the hybrid carrier PCB and two FPGA boards is done via two flexi-rigid adaptor PCBs. The flexible part of this board allows the fan out of the signals to match the large FPGA boards (FEM boards) which were initially developed for a different detector project (LPD [5]) where modules are wider and higher than EXCALIBUR modules.

4. EXCALIBUR front-end module fabrication

This project uses version 3.1 of the MEDIPIX3 read-out chips which were designed by the CERN-based MEDIPIX3 collaboration and produced at IBM on 8-inch wafers using 0.13 µm CMOS process. The 100 chips in each wafer were probe-tested and classified before being deposited with solder bumps and diced at VTT Technical Research Centre, Finland. Silicon sensors were produced by the company CANBERRA, on 6-inch high-resistivity silicon wafers, allowing placement of two 115 mm x 30 mm sensors at the centre. Electrical characterisation was performed by means of IV measurements on test structures around the large sensors. Wafers were sent to VTT where wafer flatness was checked before solder bump deposition and sensor dicing. The silicon sensor and the MEDIPIX3 chips were hybridized using a FC150 flip-chip bonder at VTT. Each module includes 1 million solder bumps connecting the 55 microns pixels of the silicon sensor to the 55 microns pixels of the 16 MEDIPIX3 read-out chips. Hybrids are sent to DIAMOND clean-room where they undergo another probe-testing procedure in order to assess the quality of the hybrid. This assessment is done by exposing the hybrid with X-rays while acquiring data with one chip of the hybrid via a probe-test card connected to a MERLIN single MEDIPIX3-chip read-out system developed at DIAMOND [6]. Scanning detector threshold and acquiring data with or without exposing the hybrid with X-rays provides a map of pixels insensitive to X-rays. The test is repeated for the 16 chips of the hybrids in order to determine whether bump-bonding quality is high enough or whether rework is necessary. After probe testing, hybrids are aligned onto the cold-finger under a microscope and bonding is achieved by means of a heating assembly shown in Figure 2 which takes the temperature of the

Figure 2. Photographs showing the EXCALIBUR module at various phases of assembly or testing: (a) alignment of hybrid on cold-finger, (b) wire-bonding, (c) wire-bonded hybrid under inspection, (d) bonded hybrid on adapter board tested with an X-ray source.
thermoplastic adhesive film above 100°C. The hybrid carrier PCB is fitted at the back of the cold-finger and bonded using an electrically isolating and thermally conducting epoxy resin so that wire-bonding pads align with the pads of the MEDIPIX3 chips. After this bonding procedure, hybrids are transferred to STFC were they are wire-bonded using a HESSE&KNIPPS BondJet715 ultrasonic bonder shown in Figure 2. After a final visual inspection of the wire-bonds, flexi-rigid adaptor PCBs are mounted on an aluminium supporting bracket connected to the hybrid PCB to form a front-end module of the EXCALIBUR detector.

5. EXCALIBUR front-end module characterisation
After wire-bonding, modules are tested using a MERLIN single-MEDIPIX3 read-out system developed at Diamond [6]. An adaptor board shown in Figure 2d was manufactured in order to interface one MEDIPIX3 chip of an EXCALIBUR sensor module to the MERLIN read-out. A high voltage bias of 120V is applied to the whole sensor and X-ray images are obtained using the 8 parallel data lines of the chip read-out at 120MHz. The discriminator thresholds of the pixels are equalized on the noise edge using MATLAB scripts communicating with the LabVIEW-based MERLIN system using a TCP/IP connection. Figure 3 shows some image samples extracted from a sequence of X-ray images of a rotating chopper taken at a frame rate of 1000 images per seconds. These images were obtained with one chip of the EXCALIBUR module. Full-module X-ray images will be achievable by reading the 16 chips in parallel with the multiple-MEDIPIX3 read-out system under development for the 3-module EXCALIBUR detector.

A total of five silicon sensors were bump-bonded to MEDIPIX3 ASICs to form five EXCALIBUR hybrids. Four of the five sensors were tested with X-rays using the probe-testing procedure described in the previous section. A bump-bonding yield higher than 99% was achieved for two hybrids. A bump-bonding yield of 92% and 87% was measured for two other hybrids. For these measurements, detection thresholds were equalized in a crude way and threshold scans with and without Fe^{55} X-rays were compared for each pixel in order to establish the sensitivity to X-rays. Since threshold dispersion and energy resolution are strongly dependent on the threshold equalization methods which are still being developed for the EXCALIBUR system, it is not yet possible to give a definite value for the threshold dispersion and energy resolution achieved with these hybrids. However initial measurements performed with X-rays suggest that the performance in terms of energy resolution will be close to the one obtained with standard single MEDIPIX3 chip assemblies [7].

6. Conclusion
EXCALIBUR is a 55µm pixel photon counting area detector system developed for coherent X-ray diffraction on I13 beamline at Diamond Light Source. Hybrid-pixel-detector modules based on 16 MEDIPIX3 chips have been produced. High frame-rate X-ray images were obtained during partial module characterisation using a single-chip read-out system. A detector read-out system based on 6 FPGA boards is under development to allow the full parallel read-out of the 48 MEDIPIX3 chips composing the three modules of the EXCALIBUR detector.
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