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The PixFEL project: Progress towards a fine pitch X-ray imaging camera for next generation FEL facilities

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ABSTRACT

The INFN PixFEL project is developing the fundamental building blocks for a large area X-ray imaging camera to be deployed at next generation free electron laser (FEL) facilities with unprecedented intensity. Improvement in performance beyond the state of art in imaging instrumentation will be explored adopting advanced technologies like active edge sensors, a 65 nm node CMOS process and vertical integration. These are the key ingredients of the PixFEL project to realize a seamless large area focal plane instrument composed by a matrix of multilayer four-side buttable tiles. In order to minimize the dead area and reduce ambiguities in image reconstruction, a fine pitch active edge thick sensor is being optimized to cope with very high intensity photon flux, up to 10^4 photons per pixel, in the range from 1 to 10 keV. A low noise analog front-end channel with this wide dynamic range and a novel dynamic compression feature, together with a low power 10 bit analog to digital conversion up to 5 MHz, has been realized in a 110 μm pitch with a 65 nm CMOS process. Vertical interconnection of two CMOS tiers will be also explored in the future to build a four-side buttable readout chip with high density memories. In the long run the objective of the PixFEL project is to build a flexible X-ray imaging camera for operation both in burst mode, like at the European X-FEL, or in continuous mode with the high frame rates anticipated for future FEL facilities.

1. Introduction

Next generation free electron lasers (FEL), will deliver X-ray beams of unprecedented brightness, with high repetition rates combined with an ultra-short pulse duration. They will play a fundamental role in many research areas, and in particular in the investigation of the microscopic structure of organic and inorganic materials in many fields (e.g. biology, chemistry, material science, atomic and molecular science) [1–3]. To take full advantage of these unique beam properties, advanced instrumentation for X-ray imaging has to be developed to satisfy the stringent requirements on space and amplitude resolution, input dynamic range, repetition rate and storage capacity.

The INFN PixFEL Collaboration is developing a high performance pixelated X-ray imaging camera for future FEL facilities, deploying new technologies and exploring innovative solutions, with the final goal of obtaining a large area imager composed of tiles made of several layers: the active edge high resistivity pixel

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sensor will be connected through bump-bonding with a two-tiered front-end readout chip realized with 65-nm CMOS technology. Through silicon vias (TSV) will be used to build four-side buttable readout chips with a fine pixel pitch and all the required functionality on board.

The main requirements and challenges of the FEL detectors are summarized below; an extended discussion can be found in [4] while more details on the PixFEL project are presented in [5].

Frame rate: Eu-XFEL uses a bunched 220 ns repetition rate, while next generation FELs are planning on continuous mode operation up to 1 MHz; both continuous and burst mode readout is required for different applications and at different facilities, with local storage to allow exploiting the longer inter-train time for frame readout.

Energy range: 0.25–25 keV.

Dynamic range: Single pulse dynamic range extending from single photon detection up to 10^4 photons is required.

Radiation tolerance: Doses up to 10–1000 MGy over 3 years will be integrated in some part of the detector; in a hybrid system, while the sensor will receive the full dose, the electronics behind is less exposed due to the screen provided by the thick sensor.

Space resolution and area coverage: Typical application requirements call for pixel sizes ranging from 700 to 20 μm and an angular coverage of 60°; this translates in a multi-million pixels large area camera (about 400 cm^2), built with contiguous tiles. The dead area should be kept to the minimum to reduce ambiguities in the reconstruction of the sample image from the diffraction pattern.

In this paper, after an overview of the PixFEL project main features, the design of the readout channel will be presented, along with the preliminary results on the first prototype chips. Active edge silicon sensors, an essential component of the project are described in [6], with the specific edge design optimization introduced to operate them efficiently with very high bias voltage, required for huge signal typical for application at FEL's.

2. PixFEL project overview

Using leading-edge microelectronics developments, the PixFEL project plans to improve the performance of current imaging systems in several areas: pixel pitch reduction combined with high speed readout and large local storage capacity; reach a large dynamic range with high resolution analog-to-digital conversion in-pixel; keep minimal module dead areas allowing large area tiling without missing data issues.

A conceptual sketch of the PixFEL matrix is displayed in Fig. 1 employing several innovative technologies. Thick high resistivity active edge pixel sensors guarantee high quantum efficiency for X-ray conversion. High density dual-tier 65-nm CMOS readout ICs enable the implementation of the needed functionality in a fine pitch of 100 μm, including in-pixel analog-to-digital conversion and data storage. Vertical interconnects of different kinds, also known as 3D integration technologies [7,8], will be adopted to couple the detector to the front-end electronics, the two tiers of the readout chip, and the sensor-chip assembly to the readout hybrid: bump-bonding, through silicon vias, and small pitch vertical integration techniques will be used. The use of active edge sensor and 3D integration will enable the development of four-side buttable modules minimizing the dead area.

The main specifications for the PixFEL demonstrator tile are given below:

- pitch: $100 \times 100\ \mu m^2$; dead area: $< 2\%$;
- photon energy: 1–10 keV; dynamic range: $1–10^4$;
- A/D conversion: 200 ns with 10 bit ADC;
- memory: 1k frame depth;
- burst mode readout: 4.5 MHz frame rate, 1% duty cycle;
- continuous mode readout: 15 kHz frame rate.

The final camera will cover an area of $20 \times 20\ cm^2$, with a matrix of modules of $2.56 \times 5.12\ cm^2$, each made of a single active edge sensor and $4 \times 8 = 32$ readout chips with 64×64 pixels each. The first IC layer will host to the analog front-end channel and the digitization, the second tier will be devoted to the integration of digital memories and readout architecture.

No sparsification is possible in imaging detectors and the resulting data transfer bandwidth can rapidly become unmanageable. The PixFEL readout architecture may include two different readout modes: a direct readout, suitable for FELs operating with a continuous repetition rate, and a store locally & read-out-later mode, compatible with the burst mode operation of the Eu-XFEL.

Present technology can easily cope with the direct readout of a megapixel camera for the low repetition rates of about 100 Hz of current continuous mode FELs. On the contrary instruments to be used at future high rate continuous FELs will require extreme bandwidths and sophisticated designs to deal with the foreseen

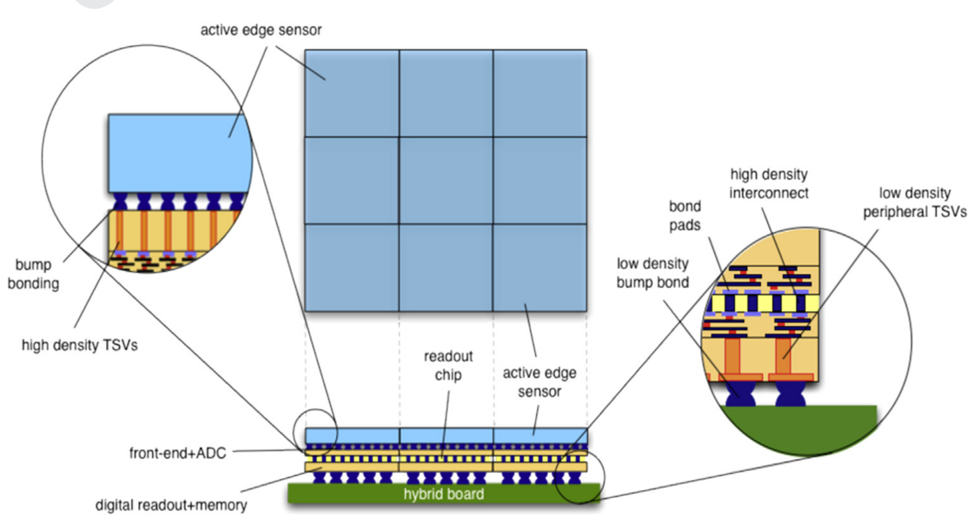

Fig. 1. Conceptual layout of the PixFEL matrix assembled with four-side buttable modules composed of a multilayer device built with sensor, a dual-tier front-end chip and a hybrid board, interconnected with vertical interconnection.

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