XCOL. Low-cost, large area, X-ray colour image sensors

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ABSTRACT

The XCOL project aims at achieving single photon, energy resolving X-ray digital imaging, by pushing the boundaries of large area CMOS image sensors coupled to scintillator screens. The impact of the XCOL technology over our society cannot be overstated. In medicine, it will provide diagnostic of the highest quality, boosting wellbeing across the planet. XCOL will provide protection against terror threats by enhancing the quality of goods and luggage screening and will protect us against food contamination. At light sources or in astronomy, research will greatly benefit from its improved image quality.

Keywords: Single Photon Counting; Wafer-scale; CMOS image sensors; X-ray digital imaging; scintillators

1. INTRODUCTION

X-ray digital imaging is a diagnostic tool which is used in many applications: medicine, security, food industry, semiconductor industry, synchrotrons and astronomy. In most cases, the X-ray beam has a broad energy spectrum and a wealth of information could be available if the energy of every single detected photon were available. Unfortunately, today this is not normally possible. Some single photon counting (SPC) energy resolving detectors are available, but their high cost typically renders them unaffordable.

XCOL intends to bridge this gap and provide a low-cost solution for SPC, thus enabling "colour-like" X-ray imaging. Having X-ray images with a much greater wealth of details than today available will have an impact on society that cannot be overstated. In planar (2D) imaging, contrast of details will be significantly enhanced, by eliminating unwanted background signal (like "structural noise", one of the key limitations of 2D imaging as opposed to 3D approaches), and material discrimination will be provided alongside some degree of material identification. The XCOL CMOS image sensor (CIS) will also give very significant advantages in 3D (Computer Tomography CT and micro CT) imaging, as datasets can be made entirely quantitative, eliminating "beam hardening" artefacts and allowing for more effective scatter reduction strategies.

Our technology is based around innovative, proprietary CIS design coupled to scintillators. The patented design allows the signal from every single photon to be individually identified so that it can be analysed in order to extract energy, and potentially other, information by using sophisticated signal processing techniques. In this first year of the project, we have validated our technology in a laboratory environment using an existing CMOS image sensor, developed by IMASENIC for a different application. Our CIS was coupled to a conventional, off-the-shelf scintillator. These tests demonstrated our technology achieves single photon detection. Further tests, with an improved version of the CMOS camera, will be carried out during the remaining months of the project and beyond its official end.

2. STATE OF THE ART

In the X-ray detector market, the dominant technology is amorphous Silicon (a-Si) flat panels, mainly due to their lower cost. Large panels based on CIS are the technology with the highest growth and, given the ubiquity of CMOS technology and its performance potential, is expected to bring new features and higher performance into X-ray panels as well. However, until now the improvements have been relatively limited to a somewhat better noise and spatial resolution only [1], and a reduction in the number of detector components. Whether CIS or a-Si, the existing panels only give "monochrome" images.

In order to achieve the long-sought goal of single photon detection, three different approaches have been considered so far: 1) direct detection with photon-counting; 2) indirect detection with photon-counting; 3) Bayer-like energy discrimination. Direct detection with photon counting was first proposed in 1988 [2]. A semiconductor detector is usually bump-bonded to a dedicated readout circuit, where hundreds of transistors are integrated in each pixel to provide low-noise analogue processing as well as some digital processing. For the energy of interest for the targeted applications, high Z materials need to be used for efficient detection. This solution provides the highest detection quality, but until now it has not been possible to produce large area detectors at a price which is competitive for the wide medical imaging market. Indirect detection gives a cost advantage and it is used also in both a-Si and CIS commercial products. In these products, the sensor

architecture is simple and does not allow for SPC. Some attempt to achieve this have been published [3], but no product is known to be based on this approach. While the light conversion from X-ray to visible light is essentially linear, the issue here is that the in-pixel electronics remains relatively complicated, with a high number of transistors and control lines, thus producing large area sensors with high yield has not yet been proven possible and the concept has not been developed beyond small test structures. The third method mimics the colour detection done in visible light sensor, where pixels have different filters, typically red, green and blue like in the Bayer pattern [4], and, by interpolation, colour content can be given to every pixel in the image. In front of every pixel, different absorbers are positioned so that the energy content of the beam can be reconstructed for every pixel in the sensor [5]. This method can be implemented at low cost; however, access to additional energy channels can only be achieved at the expense of spatial resolution, as is the case in visible light detectors.

Tab. 1. Comparison of different technologies for X-ray digital imaging.

Technology	SPC	Energy resolution	Large area	High- speed integrating	Integrating	Cost
XCOL	Yes	Medium	Yes	Yes	Yes	Low
a-Si FPD	No	No	Yes	No	Yes	Low
CMOS FPD	No	No	Yes	No	Yes	Low
Hybrid pixels	Yes	High	No	No	No	High
Absorption mask	No	Low	Yes	No	Yes	Low

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In many applications, the cost of the X-ray digital imaging tool is an important parameter. SPC is often considered as a golden goal, but the required energy resolution can often be moderate. With such demanding requirements, a fine balance between cost and performance needs to be found in order to propose a viable product. XCOL technology will provide this fine balance, enabling X-ray images of an unprecedented quality to be obtained, while maintaining the low cost needed for our product to be widely adopted.

This is achieved by combining standard CIS technology with a scintillator material. By innovative design of the CIS and the choice of an optimised scintillator will be able to count every single photon, at the speed required by the applications. As the CIS is standard, the sensor will also be able to work in the more conventional integrating mode, which will make possible to use the sensor in other applications as well.

The evolution of the pixel rate in CIS is shown in **Fig. 1**. A 1Mpixel sensor read out at 1,000 frames per second (fps) corresponds to a pixel rate of 1GPixel per second.

The figure above is based on data for sensors which are fully contained within a microelectronics reticle, i.e. of dimensions of the order of 1 square inch. This is clearly not sufficient for X-ray imaging, where a technique called stitching is used to make sensors as large as a full CMOS wafer, i.e. 200 or even 300 mm in diameter. The speed of wafer-scale CIS as used for X-ray imaging is significantly lower. Probably the fastest sensor of this size achieves 34 frames per second (fps), at 6.7 Mpixel resolution, corresponding to 227 Mpixel per second [6]. With XCOL we aim at moving this limit to be at the same level as smaller sensors.

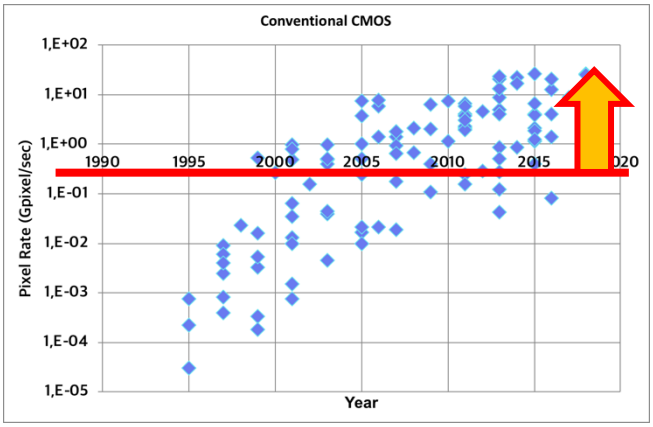

Fig. 1. Evolution of pixel rate in smaller size CIS. The horizontal line shows the limit of speed in wafer-scale CIS and the arrow points to the goal of the XCOL project.

4. PROJECT RESULTS

The project goals are two-fold: 1) demonstrate SPC with unoptimized components; 2) develop and simulate an optimised architecture for SPC, in view of the Phase 2 of the project.

Regarding 1), we used an existing prototype CIS, developed by IMASENIC. Although not suitable for the application, the CIS has large, 60 µm pixels which are suitable for high-resolution X-ray imaging. The CIS was coupled to an off-the-shelf scintillator. Different types of scintillator were used. The CIS coupled with a scintillator was tested at UCL in a conventional X-ray beam (**Fig. 2**). Because of the Covid19 pandemic, only a fraction of the test campaign took place and we are planning to do more tests in the next months. In particular we will have an improved version of the sensor that will enable better detector performance. With this we will repeat flat-field tests as well as performing an imaging test. However, the

initial tests are promising. We used a broad band spectrum, whose estimated energy distribution is shown in **Fig. 3**. From the knowledge of the properties of the detector, we estimated the peak of the spectrum to correspond to around 1,100 DN, and this is confirmed by the measured pulse-height spectrum, which is shown in **Fig. 4**.

We are still working on the data processing algorithm and in the next few months we will have available a detector with better noise, and this should clean the data towards the low energy range. We also estimate that the intensity of the X-ray beam was still generating some double hits in the sensor and this could explain the tail towards higher values.

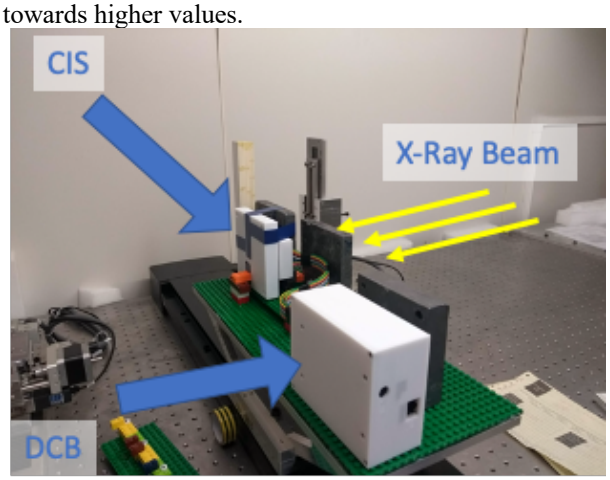

Fig. 2. Setup used for the tests performed at UCL. The prototype CIS coupled to a scintillator is shown. The Data Communication Board (DCB) handles the communication between the sensor and the laptop. The DCB is part of the evaluation platform *Evalima* developed by IMASENIC.

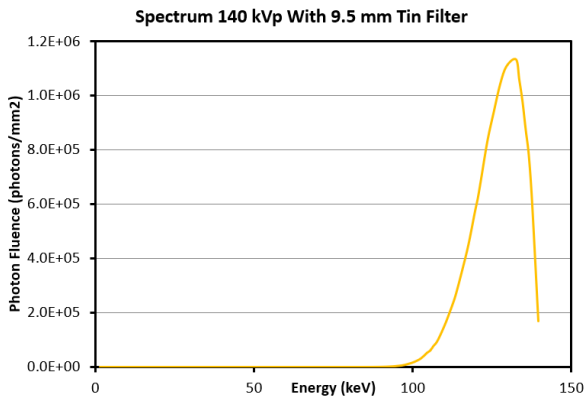

Fig. 3. Estimated pulse height for the broad band spectrum used in the tests

With regard to 2), an important consideration for X-ray digital imaging is that the sensor needs to be large, starting at around 20cmx20cm and up to 40cmx40cm [1]. This is much larger than conventional CMOS chips, which are normally limited to something about or a bit larger than 2cmx2cm. The so-called stitching allows for the sensor to be larger is then required, but still not sufficient as CMOS wafers currently used have a diameter of 200 or 300 mm. Several single-wafer sensors need to be butted together to achieve the desired size, but, as only single defective lines are at most accepted, the gaps between sensors need to be smaller than 1 pixel, or at most ½ a pixel can be lost on each sensor. This forces the designers to put all the electronics on one side only, to make the sensor 3-side buttable. This is a very severe constraint which needs innovative designs to be developed [6, 7]. IMASENIC developed and patented an innovative architecture which will enable 3-side buttable sensors with high yield and high readout speed.

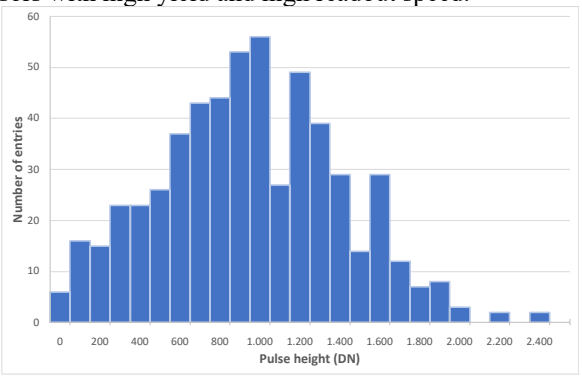

Fig. 4. Pulse height spectrum measured with the prototype XCOL detector

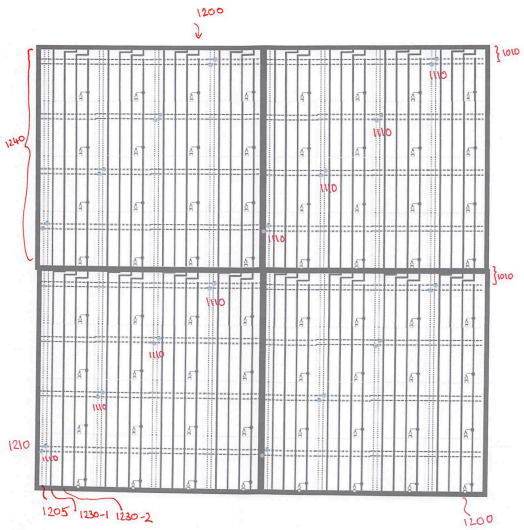

Fig. 5. Patented 3-side buttable architecture developed by IMASENIC.

5. FUTURE PROJECT VISION

The prospective advantage of energy-resolved ("colour") X-ray imaging in healthcare and beyond has been repeatedly proven. In planar (2D) imaging, contrast of details can be significantly enhanced, images can be decomposed in "bases" where specific details are

deliberately enhanced, eliminating unwanted background signal ("structural noise", one of the key limitations of 2D imaging as opposed to 3D approaches), "Z-effective" approaches can be adopted that allow material discrimination as well as some degree of material identification. Very significant advantages have also been identified in 3D (CT and micro CT) imaging, as datasets can be made entirely quantitative, "beam hardening" artefacts can be eliminated, and more effective scatter reduction strategies can be implemented. It is safe to say that, should colour X-ray imaging be readily available, this would be implemented across the board in all medical and non-medical applications of X-ray imaging.

5.1. Technology Scaling

In order to achieve the demonstration of the technology in a relevant and, possibly, in an operational environment, during Phase 2 the XCOL team will design a wafer-scale CIS, based on its patented technology. A matching scintillator, with properties optimised to the XCOL CIS will also be integrated. In phase 1, the scintillator was an off-the-shelf component from a leading manufacturer, but it is possible, see also the next section, that a manufacturer will be invited to join the consortium to optimise the scintillator. The proximity electronics will also be developed within the consortium. The data processing could be integrated in the proximity electronics or included in the computer receiving the data over high-speed link.

5.2. Project Synergies and Outreach

As explained above, the ATTRACT Phase 1 aimed at demonstrating the feasibility of the XCOL within the limited means provided by funding available. An unoptimized CMOS image sensor and scintillator were used. In Phase 2, we are planning to expand the consortium to include strategically important partners in key areas. A potential Phase 2 composition will look like shown in **Tab. 2** here below.

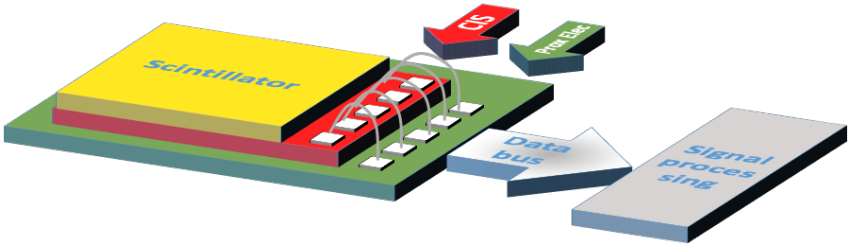

Fig. 6. Phase 2 XCOL system description.

Tab. 2. Possible composition of the ATTRACT Phase 2 XCOL consortium

Role	Partner
CMOS design	IMASENIC
Scintillators	*Partner X*
X-ray characterisation	UCL
OEM	*Partner Y*
End-user	*Partner Z*

IMASENIC will lead the development of an optimised CMOS image sensor, which should already have the characteristics required to demonstrate the system in an operational environment, fulfilling the requirement of TRL7. For the development of a suitable scintillator, a new partner would be added to the consortium. UCL could continue to work on the test of the device with X-rays, analysing the data and developing the most suitable algorithm to obtain good image quality, for which the main parameters would be the measurement of the Modulation Transfer Function (MTF) and Detective Quantum Efficiency (DQE). With respect to the commercial exploitation of the sensor, the XCOL consortium would seek new partners to help with the commercialisation of the device in the X-ray digital market. An original equipment manufacturer (OEM) is likely to be the best choice for this, and we also envisage to add an end-user which would provide further demonstration of the performance of the XCOL product.

5.3. Technology application and demonstration cases

At the moment, save for some implementations based on X-ray filters which, as well as limited flexibility, tend to have field of view and resolution limitations, colour imaging is available only through "hybrid" pixel architectures. This allows the development of chips which are at most a couple of cm in size, and typically two or three-side buttable. This makes it possible to make "long and narrow" detectors but not large area flat panels, the only option for which is through the creation of 4-side buttable structures obtained by means of through-silicon vias, which are still only reliable for small chip areas. Most importantly, detectors created in this way (including without through-silicon vias) are extremely expensive, at least one order of magnitude above devices currently use in e.g. medical imaging, which makes their clinical implementation economically non-viable.

The innovation proposed by our team would make colour X-ray imaging available in large area detectors at affordable costs, therefore enabling their clinical adoption. The possibility to create clinically compatible, large area CMOS-based flat panels at affordable cost has

already been repeatedly proven (see e.g. the success of the UK company Dexela, now part of Varex Imaging, and the emergency of vivaMOS, an award-winning UK company): this proposal would add a key dimension to that technology. Impact would be huge – encompassing the medical imaging industry, the medical community and, most importantly, the patients: a wide availability of colour X-ray imaging would enable the earlier detection of a range of life-threatening diseases like cancer, with obvious consequences on patient management and survival rates. As well as diagnosis, treatment planning, monitoring and assessment would also benefit significantly; for example, most on-board imaging in radiotherapy is based on cone-beam CT which makes use of flat panels and yields largely sub-optimal image quality, and this could be transformed by the contrast enhancement and scatter rejection offered by XCOL.

As well as medicine, several other fields would benefit – for example a large fraction of industrial testing and quality control. As well as image quality enhancement, industrial applications would significantly benefit from the potential for material discrimination/identification, as would other fields such as security screening and food industry.

5.4. Technology commercialization

Already in Phase 1, the XCOL consortium has a mixture of academic and commercial partners. In the 2nd phase, in order to facilitate the commercialisation of the XCOL technology, we partner to expand the consortium to an OEM and/or possibly to an end-user. They could become the lead customer to drive the commercialisation of the TRL7 sensor of the ATTRACT Phase 2 project.

5.5. Envisioned risks

As the initial test have already shown, one of the critical technological factors will be to achieve sufficiently high signal-over noise ratio (SNR) for efficient SPC. In order to overcome this risk, there will be careful design of the CIS together with the scintillator as well as of the analysis algorithms. The addition of a partner specialised in the development of scintillators is our optimum mitigation strategy for this risk, as the other factors are already covered by the existing partners.

The commercial risk is also in the market uptake of the technology. The targeted markets, especially the medical ones, tend to have a slow uptake of new technologies so there is a risk in slow return-on-investment (ROI) for the company involved in the consortium.

5.6. Liaison with Student Teams and Socio-Economic Study

The UCL team, one of the two partners of the Phase 1 project, is world-leading in the field of X-ray imaging, producing internationally leading research as well as integrated hands-on education in the heart of London, with close links to several major teaching hospitals. The academic research includes medical imaging, physiological monitoring, radiotherapy and biomedical engineering. They have a range of accredited BSc, MSc, MRes and PhD degrees and Postgraduate Diplomas. They are then ideally placed to provide materials for explaining the technology as they already have relevant courses in their standard curricula. The founder of IMASENIC; the other member of the Phase 1 Attract and likely to be also the leading team in the Phase 2 proposal, also had the first part of his career spent in academia or research organisations and is still giving invited talks at a number of international conferences. Both Phase 1 partners are then ideally placed to provide MsC level projects during the Phase 2 implementation.

With this excellent background in dissemination of the results, as proven by a wealthy number of publications in internationally renowned journals, the XCOL team will continue this activity through the Phase 2 proposal. We envisage to publish at least one white paper about the technology that we are developing.

6. ACKNOWLEDGEMENT

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