Combining high resolution and sensitivity in X-ray detectors using perovskites ESSENCE

Albert J.J.M. van Breemen[1*], Bart Peeters[1], Joris Maas[1], Hylke B. Akkerman[1], Eric A. Meulenkamp[1], Gerwin H. Gelinck[1], Sarah Deumel[2], Judith E. Huerdler[2], Sandro F. Tedde[2]

[1] Holst Centre-TNO The Dutch Organization for Applied Scientific Research, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands; [2]Siemens Healthineers, Technology Excellence, Guenther-Scharowsky-Str. 1, 91058 Erlangen, Germany
*Corresponding author: albert.vanbreemen@tno.nl

ABSTRACT
Higher sensitivity and resolution enables medical X-ray diagnostics at lower dose and higher confidence. Here we report on advances in sensitivity and resolution of flat panel X-ray detectors enabled by combination of a high resolution oxide TFT backplane and a direct X-ray-to-charge conversion perovskite based frontplane. A lowest detectable X-ray signal of only 1µGy/frame at a low electrical field of 0.04V/µm is shown with an outlook toward 20 nGy/frame. Good imaging capabilities of the detector were demonstrated with an MTF of 0.7 at 1 lp/mm. These results are paving the way for low-dose mammography systems, without compromising on image quality.

Keywords: direct conversion X-ray detector, metal halide perovskite, mammography

1. INTRODUCTION

Nowadays, mammography screening is the most effective tool to fight breast cancer. Still, more than 30% of cancers are not detected, in particular in case of dense breast tissue. Today, X-ray detectors for mammography are optimized for resolution but still lack in sensitivity if compared to angiography systems. Reason is the different technology they rely on. Mammography is based merely on direct converters, *e.g.* amorphous Selenium (a-Se), while angiography on indirect converters like Cesium Iodide (CsI) scintillator coupled with an amorphous silicon (a-Si) photodetector. Furthermore, at comparable detecting area, mammography detectors are up to 5 times more expensive.

In this paper we report on advances in sensitivity and resolution of flat panel X-ray detectors, in particular for mammography applications, by combining the high sensitivity of a-Si/CsI indirect converters with the high specificity of a-Se direct converters (Fig. 1).

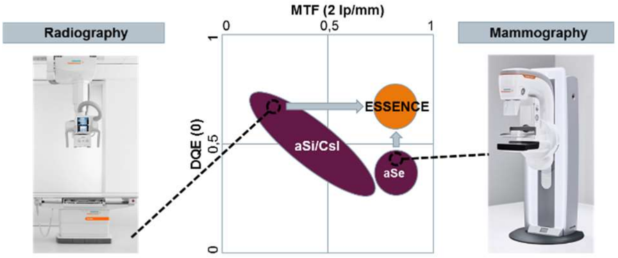

Fig. 1: (left) Radiography X-ray system; (middle) Objective of ESSENCE: combining the high sensitivity of aSi/CsI indirect converters with the high specificity of a-Se direct converters; (right) Mammography system.

2. STATE OF THE ART

The measures for the sensitivity and the resolution of flat-panel X-ray detectors (FPD) are the detective quantum efficiency (DQE) and the modulation transfer function (MTF), respectively. State-of-art FPDs consists of 1) indirect converters (*e.g.* a-Si backplane and photodiodes stacked with CsI:Tb scintillators) which achieve high sensitivity, but suffer from poor resolution due to optical crosstalk and 2) direct converters (*e.g.* a-Se detectors on a-Si backplane) which enable high resolution but suffer from poor sensitivity and robustness, especially temperature stability and requires high applied electrical fields (up to 10V/µm).

The X-ray dose reduction discussion gets more and more important in recent years were it has been clinically proven that breast tomosynthesis screening improves diagnostic performance[1] by better visualization and reduced false positives, generating less recalls which in turn result in unnecessary additional costs and less patient anxiety. The high number of X-Ray projections raises of course a dose debate and gives pressure to make low dose imaging without a need of a balance between dose and image quality mandatory.

In recent years, the introduction of Complementary Metal-Oxide Semiconductor (CMOS) based X-Ray detectors, enabled the era of ultra-low-dose imaging. However also in CMOS X-Ray detectors, DQE is limited by the sensitivity of the converting material (direct or indirect).

Recently, lead halide perovskites, in particular methylammonium lead triiodide (MAPI), revealed to be an excellent X-Ray absorber with a 10-fold sensitivity in comparison to a-Se detectors, showing a performance on par with the best available direct conversion technologies, such as HgI_2 and Cd(Zn)Te[2]. The possibility to use MAPI in FPD has recently been proven by Samsung.[3] Printing of thick MAPI films (more than a few hundred micrometres) over large areas is reported.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In the ESSENCE project we aim to demonstrate breakthrough advances in specificity and sensitivity of flat panel X-ray in particular for mammography applications.

Higher sensitivity and resolution enables medical X-ray diagnostics at lower dose, lower cost, and higher confidence. Lower dose results in a lower probability of DNA damage and a lower risk of inducing cancer. Lower cost makes X-ray diagnostics more affordable for everybody and helps to cure diseases and lengthen life expectation. Higher confidence, *e.g.* in mammography screenings, would mean less false positives, less emotional harm, less unneeded therapies, resulting in lower burden for the people and the health associated cost. ESSENCE will bring mammography to the next level of medical X-ray diagnostics imaging. In particular we envision the combination of breast tomosynthesis and an approach similar to the one Google reported recently in the Google AI blog[4] by applying deep learning to metastatic breast cancer detection. We believe that the detection of micro-calcification with diameter smaller than 100µm combined with effective artificial intelligence algorithms, will support physicians in fighting breast cancer earlier and with a higher accuracy, generating a better outcome for the patients.

Tab. 1: State-of-the-art and ambition of ESSENCE.

Objective	State-of-the-art	Ambition in ESSENCE
Resolution TFT backplane	Resolution TFT backplane: • a-Si/CsI: 170-200 ppi • a-Se: 300-500 ppi	Resolution TFT backplane: 500 ppi
specificity of FPD X-ray detectors	• a-Si/CsI: MTF[1]: 0.3 • a-Se: MTF 0.8	This work: MTF 0.8
Sensitivity of FPD X-ray detectors	• a-Si/CsI: DQE[2] 0.7 • a-Se: DQE 0.4	This work: DQE 0.6

[1] 2lp/mm. – [2] at 0 lp/mm

4. PROJECT RESULTS

The ESSENCE direct conversion FPD is enabled by the disruptive combination of new technologies: a) a high resolution metal oxide TFT backplane and b) an integrated direct X-ray-to-charge conversion MAPI perovskite based frontplane realized with a soft-sintering approach as previously reported.[2, 5] The backplane is a self-aligned dual-gate oxide thin-film transistor array, described and characterized elsewhere.[6] The sensor array has a resolution of 500 pixels per inch (ppi). It comprises 640x480 pixels, resulting in a total sensor area of 2.4x3.2 cm². The entire FPD stack and X-ray detector are shown in Fig. 2. The thickness of the MAPI layer is 230 µm with a density of 88% if compared with a MAPI single crystal. This will result in an effective bulk thickness of ~202µm.

The applied bias for all measurements presented hereafter is -10 V on the top electrode thus resulting in an electron integrating mode and an extremely low applied electric field of ~0.04 V/µm.

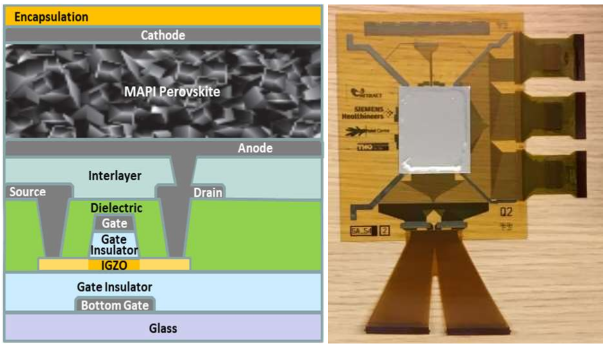

Fig. 2: (left): ESSENCE direct conversion FPD stack: (right): ESSENCE X-ray detector.

X-ray characterization has been performed using a mammography X-ray tube. Video sequences have been acquired with an integration time of 35ms corresponding to a frame rate of ~28.6 fps.

The X-ray photon *X(E)* spectrum (green circles), corresponding absorbed X-ray photon spectrum (red line) and percentage of absorbed photons *Aq(E)* (blue line) are shown in Fig. 3a. The total absorbed energy in the MAPI layer is ~93%. Fig. 3b shows the percentage of absorbed energy, for different MAPI thicknesses.

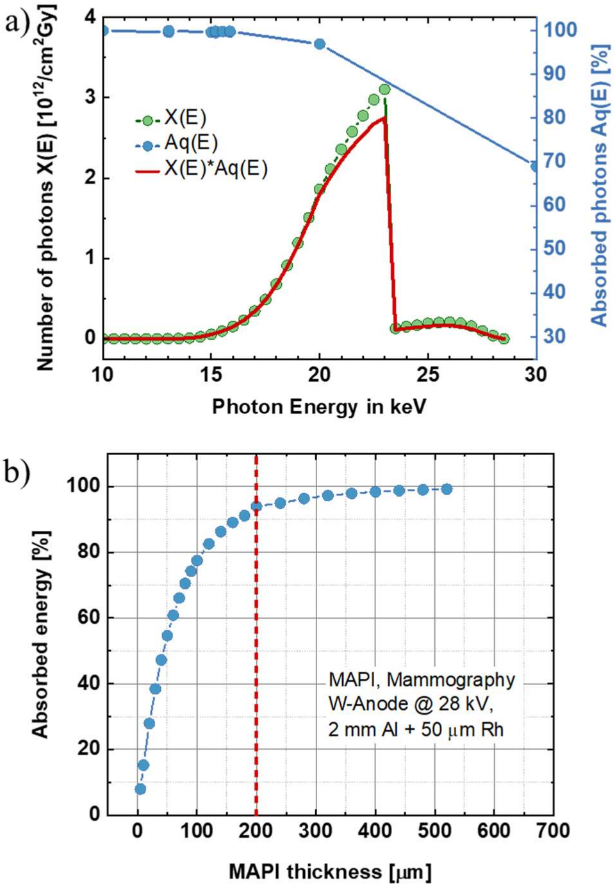

Fig. 3: a) X-Ray spectra from the source tube with a W anode, 28 kVp voltage and 50 µm Rhodium plus 2 mm Aluminium as filters and the corresponding absorbed X-ray photons (spectrum in red and percentage in blue) b) Calculated energy absorbance for different MAPI thicknesses.

The MAPI FPD has been exposed to X-ray pulses with different dose rates and a pulse length of 500 ms. 100 frames have been offset corrected (OC) and the response in least significant bit (LSB), the smallest unit of the readout electronics, to different dose rates is shown in Fig. 4a.

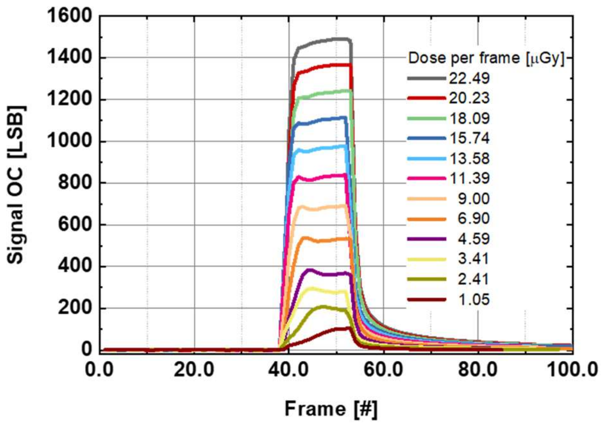

Fig. 4: X-Ray response in least significant bit (LSB) of the MAPI FPD to an X-ray pulse of 500 ms at different dose rates.

The dose per frame varied between 22.49 and 1.05 µGy/frame. Higher and lower dose rates were not possible without changing the pulse length and beam quality due to limitation of the X-ray source. At low dose per frame (<3.41 µGy/frame) the shape of the MAPI FPD X-ray response is heavily affected by the pulse shape of the X-ray tube.

By taking the signal value at the end of the pulse for each of the single pulses in Fig. 4 it is possible to evaluate the linearity of the detector (Fig. 5a). Given the low noise of the system (only a few LSB) we estimate that the lowest detectable signal (indicated with the orange star in Fig. 5a) is at only 20 nGy/frame.

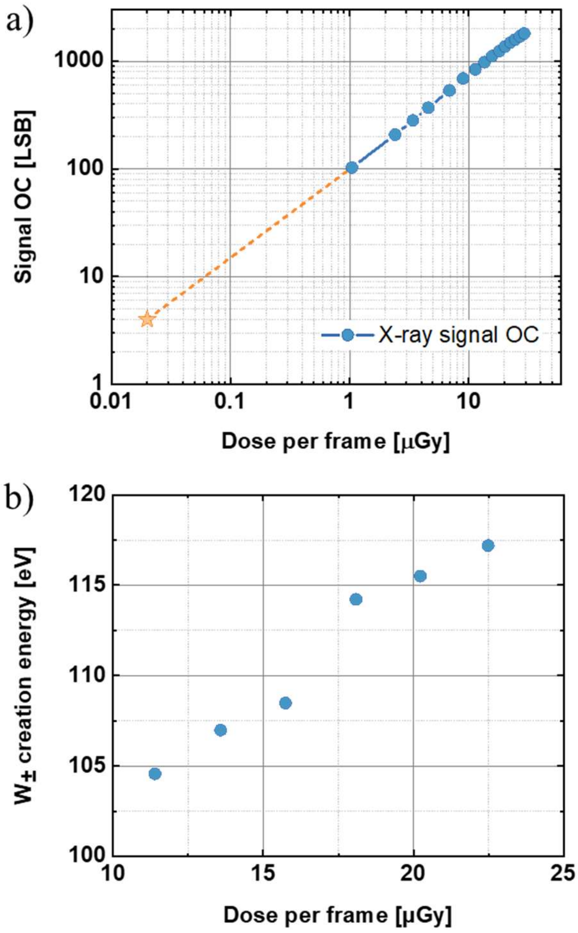

Fig. 5: a) Linearity plot: X-ray signal taken at the end of the 500ms X-ray pulse for the different doses. b) Sensitivity plot: electron-hole-pair (EHP) creation energy vs. dose per frame.

The electron-hole-pair (EHP) creation energy $W_{\pm}$ which is the ratio of the absorbed energy and the number of extracted charges is a good figure of merit to compare sensitivities for different direct-converting materials with different thicknesses. $W_{\pm}$ in MAPI (Fig. 5b) at ~0.04 V/µm is in the range 104 eV - 117 eV, which is more than one order of magnitude larger than the theoretical limit determined by the Que and Rowlands' relationship.[7] For a-Se, $W_{\pm}$ at 10 V/µm is about 40–50 eV.

Fig. 6a shows an X-Ray image (detail) of a resolution phantom with 4.3, 4.6 and 5.0 lp/mm structures. These structures are still visible, showing the good imaging capabilities of the MAPI FPD. The MTF plot (Fig. 6b) shows that our MAPI FPD is still far away from the theoretical resolution expected for a 500 ppi backplane having a Nyquist frequency at 10 lp/mm. This gap is attributed to the low electrical field applied, combined with a large charge carrier diffusion and the accumulation of ions at the interfaces with the electrodes. Further research is necessary to completely understand these phenomena and exploit the detector to its maximum resolution.

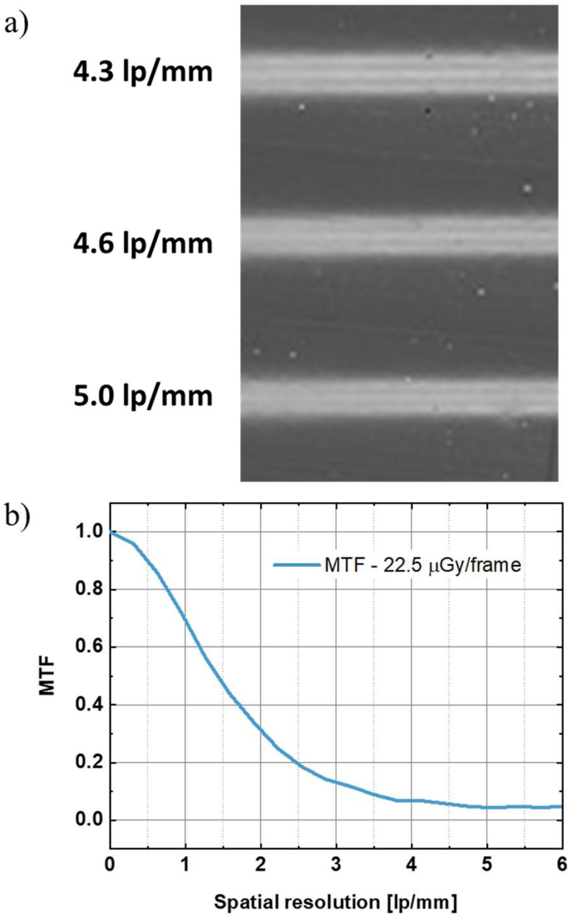

Fig. 6: a) X-Ray image of a resolution phantom with 4.3, 4.6 and 5.0 lp/mm. b) MTF calculated using an X-ray image of a slanted edge.

5. FUTURE PROJECT VISION

ESSENCE has confirmed the potential of perovskites as direct converter in flat panel X-ray detectors, showing outstanding sensitivities of only 1µGy/frame (envisioned potential 20 nGy/frame) at relatively low electrical fields (0.04V/µm), paving the way for low-dose mammography systems, without compromising on image quality.

5.1. Technology Scaling

Scale-up of ESSENCE technology to large area flat panel X-detectors (20x20 cm^2), as well as improving the lack of resolution as observed in ESSENCE, is addressed in the EU-project PEROXIS.[8] The TRL level will be increased from 3 in ESSENCE to 5 in PEROXIS.

The future of X-ray imaging is in “color”. This can be achieved with spectral sensitive imaging (Fig. 7) either by:

1. Less cost intensive dual energy detectors by stacking of different flat panel perovskite detectors (TRL 6)
2. High end counting technology based on integration of single crystals with a counting backplane (TRL 4)

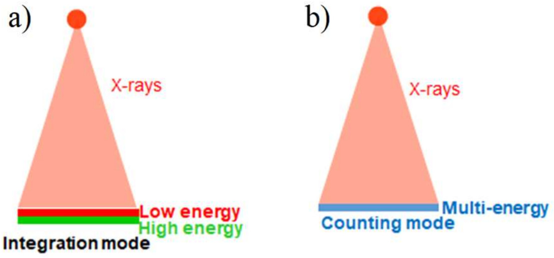

Fig. 7: Spectral sensitive imaging by a) stacking of different flat panel perovskite detectors that can generate low and high energy images in integration mode; b) technology based on integration of a perovskite single crystal detector with a counting backplane.

All key performance indicators (*e.g.* DQE, MTF) of perovskite based X-ray detectors in the two tracks will be evaluated. We expect that for track 1 a TRL of 5-6 and for track 2 a TRL of 4 can be realized at the end of an ATTRACT Phase 2 project. For both tracks a substantial effort is needed in backplane development, front plane upscaling to large area, including adhesion between backplane and front plane, and system integration. From a technical point of view, the next step would require competences in the field of materials chemistry, physics and processing as well as readout circuit (TFT or CMOS backplane) and system integration.

5.2. Project Synergies and Outreach

We envision to team-up with other ATTRACT Phase-1 consortia dealing with similar high energy detection technologies to fully exploit the potential of perovskites in medical X-ray detectors. A complementary consortium should be composed of industrial (potential investors), Research and Technology Organisation (RTO) and academic partners in the field of radiation detection. These complementary partners are present within the ATTRACT Phase 1 project PerXI and the EU-project PEROXIS, which include European industrial partners Siemens Healthineers, Philips and Trixell.

The main results of an ATTRACT Phase 2 project will be available via public deliverables that will be on the project website. The scientific results are planned to be published in high impact factor journals and presented at national and international conferences. Other outreach activities will include production of promotional material like project flyers, press releases and newspaper articles.

5.3. Technology application and demonstration cases

Perovskite based large area spectral sensitive X-ray detectors, promise concrete benefits for society and citizens in the area of health, demographic change and wellbeing:

- Multi-energy radiography will provide new clinically relevant information, improving patient diagnosis using cost-effective and highly accessible radiography exams instead of currently used Computed Tomography exams.
- High-precision medical imaging based on chemical contrasts will improve the detection of atherosclerotic plaques and the identification of kidney stones. Associated with injected contrast agents, it will enhance the visualization of blood vessels imaged in the chest even behind the spine.
- On a longer term, new high-resolution functional images could be produced with the use of markers linked to molecules with specific affinity for pathological organs. Also, direct detection could be a key technology for phase contrast imaging systems.

5.4. Technology commercialization

The commercialisation of perovskite based medical X-ray detector technology should be done in partnership with European industrial investors that have interests in this technology: Siemens Healthineers (Ge), Philips (NL), Trixell (Fr).

5.5. Envisioned risks

A preliminary risk analysis has identified both technological and commercial risks. Both will be briefly elaborated below.

Technological risks:

- Limited stability, homogeneity and process reproducibility of perovskite detector frontplane. A limited stability can be mitigated by the use of lower electrical fields. Process reproducibility will be controlled by a strong interaction between perovskite suppliers and detector suppliers building on a high level of quality control.
- Limited resolution of the detector. This can be mitigated by adapting the electrical field and introduction of charge selective contacts in the frontplane.
- Integration of two perovskite based X-ray detectors

Commercial risk: a high CAPEX might hamper the market introduction of perovskite based medical X-ray detectors.

5.6. Liaison with Student Teams and Socio-Economic Study

The ATTRACT Phase 2 project will continue the preliminary mapping of a series of studies on socio-economic value that was started in the ATTRACT Phase 1 workshop held in December 2019. Hence novel methods, tools, and approaches to measure the accountability of scientific research infrastructures, as well as normative policies and platforms to engage new actors or contributors in the innovation ecosystems surrounding research infrastructures will be further explored and detailed. To reach this goal, interested scholars will be invited through a dedicated workshops. Active participation of early-stage Ph.D. students will also be encouraged and supported, inviting them to visit and study different ATTRACT project partners.

6. ACKNOWLEDGEMENT

A.v.B. would like to thank the process engineers of Holst Centre’s R&D TFT Pilot Line for the realization of the TFT backplanes. This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222. This work is partly financed through the Flexlines project within the Interreg V-programme Flanders-The Netherlands, a cross-border cooperation programme with financial support from the European Regional Development Fund, and co-financed by the Province of Noord-Brabant, The Netherlands.

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