Toward a Photon Counting Detector for X-ray Imaging by Direct Deposition of Scintillator on 32x32 CMOS SPAD Array

Yao-Lun Liu[1], Meng-Hsuan Lu[1], Chun-Hsien Liu[1], Yu-Hsun Wu[1], Sheng-Di Lin[1], Chia-Ming Tsai[1], Jin-Cherng Hsu[2], Yu-Cheng Syu[3], and Jau-Yang Wu[4*]

[1]*Institute of Electronics, National Yang Ming Chiao Tung University, 1001 University Road, Hsinchu 300, Taiwan*
[2]*Graduate Institute of Applied Science and Engineering, Fu Jen Catholic University, New Taipei City 242062, Taiwan*
[3]*Department of Physics, Fu Jen Catholic University, New Taipei City 242062, Taiwan*
[4]*Department of Electrical Engineering, Yuan Ze University, Taoyuan 32003, Taiwan*
**Corresponding Author: judewu13@saturn.yzu.edu.tw , telephone: +886-3-4638800 ext. 7520*

***Abstract*—We develop a low cost and high performance X-ray imager by directly depositing the CsI material on the 32x32 CMOS single photon avalanche diode (SPAD) array as a scintillator. From the effective dose calculation, our imager performs more sensitive compare to a photomultiplier tube (PMT) with scintillator which is often used in the X-ray diffractometer (XRD). So we believe that the SPAD array imager with direct deposition of CsI could be a better candidate for digital radiography systems.**

I. Introduction

Combining scintillator materials with silicon based photon detector can make up a low cost digital radiography image system as a replacement of the traditionally radiographic films. The scintillator can convert the incident X-rays to optical light in the detection wavelengths range (420-600 nm) of silicon photon detectors. However, the indirect detection method has low detection efficiency because of the low transfer efficiency of the scintillator materials [1], leading to long integration time and poor spatial resolution in the applications such as dentistry, surgery, positron emission tomography (PET) [2], and mammography [3]. The CMOS SPAD array is a kind of imager which possess ultra-high photon sensitivity and easy to be integrated with digital signal processing circuits, so a scintillator deposited on COMS SPAD array can realize digital radiography systems with high frame rate and low cost [4].

II. The Device Fabrication and Testing Methods

For the traditional method that uses crystalline (slab) scintillators coupled to the imager, the light transferred from scintillator will experience multiple reflections between several interfaces, causing laterally spread of light and resulting in poor spatial resolution and lower optical efficiency [5]. In this work, differing from the conventional method, we deposit an undoped cesium iodide (CsI) films as the scintillator directly on a 32x32 SPADs array to perform better spatial resolution and photon coupling efficiency [6]. The CsI film is prepared by thermal vacuum evaporation technique. The cross sectional structure of SPAD array with CsI coating is shown in Fig. 1(a), and the top view picture of final chip is shown in Fig. 1(b). From the cross-sectional image of dual-beam focused ion beam (FIB) microscope as shown by Fig 2(a), the coating of CsI has the thickness of

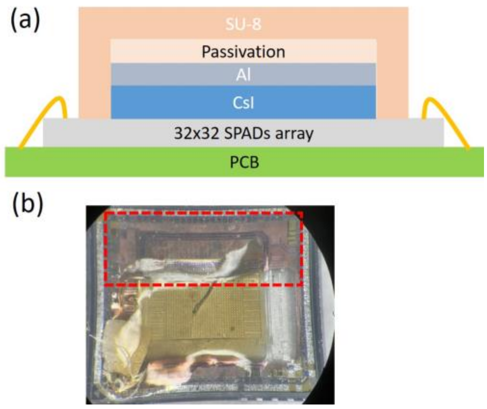

Fig. 1. Cross-section structure of 32x32 SPAD array chip with directly deposited CsI layer (a) and the top view picture of chip. The red dotted region indicates the area without CsI coating.

about 14 µm. The image shown in Fig. 2 (b) clearly shows that the microcolumn width is about 0.5 µm for the deposited CsI of microcolumns array type. A columnar-structure with needle-like tips is also observed for CsI films. The size and shape of deposited CsI depends on the temperature and

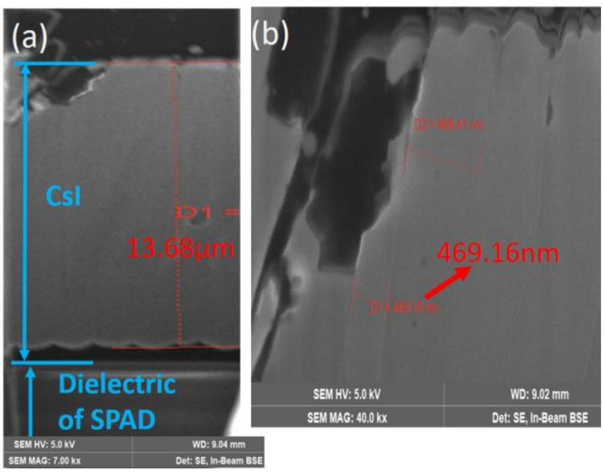

Fig. 2 (a) Cross-sectional picture of CsI from focused ion beam microscope. (b) Magnification of cross-sectional picture.

pressure during the thermal vacuum evaporation. Note that the cross-sectional FIB picture shown here is taken from the device different with the one under investigation. The passivation and SU-8 layer are used for preventing CsI layer from hydrolysis. For examining the effect of CsI layer, we purposely designed a region without CsI coating as shown by the red dotted frame in Fig. 1(b) [7, 8]. The 32x32 SPAD array is fabricated by TSMC 0.18 um BCD HV process, with a breakdown voltage of 48.5 V. The SPAD array is integrated with time gated quenching circuit [9].

The chip readout is controlled by a FPGA (kintex-705). The dark count rates (DCRs) of the chip are almost unaltered after the CsI coating, where it is plotted in Fig. 3(a). There is an aluminum film upon the CsI coating for blocking the light other than the emission from CsI layer. Fig. 3(b) shows that there is higher photon counts of SPADs for the area without CsI coating when the chip is under illuminated.

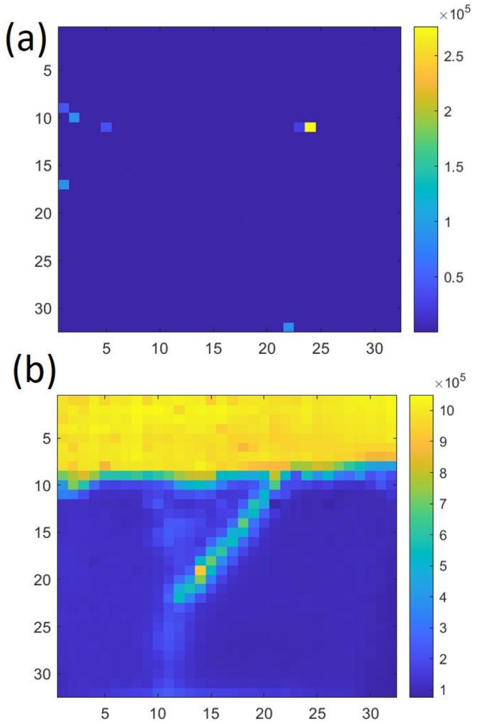

Fig. 3 (a) Measured dark count rates of 32x32 pixels (b) and the photon count rate under ambient light.

The measurement system setup in the X-ray diffractometer (XRD) instrument is shown in Fig. 4. First a lower SPADs bias voltage (51.4 V) was used for the preliminary test. The DCRs of chip before and after X-ray irradiation has no obvious difference, so the chip was not damaged by the irradiation. Fig. 5 shows that there is obvious photon counts of SPADs with the CsI coating when X-ray gun was turned on, where the photon counts were measured with integration time of 0.1 second. A higher bias voltage (52.5 V) is used to achieve higher photon detection efficiency of SPADs for the following measurements, acquiring much higher photon

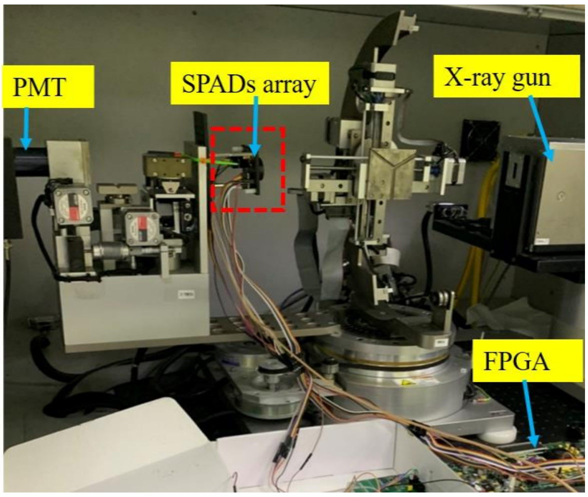

Fig. 4. Picture of measurement system setup in the X-ray diffractometer (XRD).

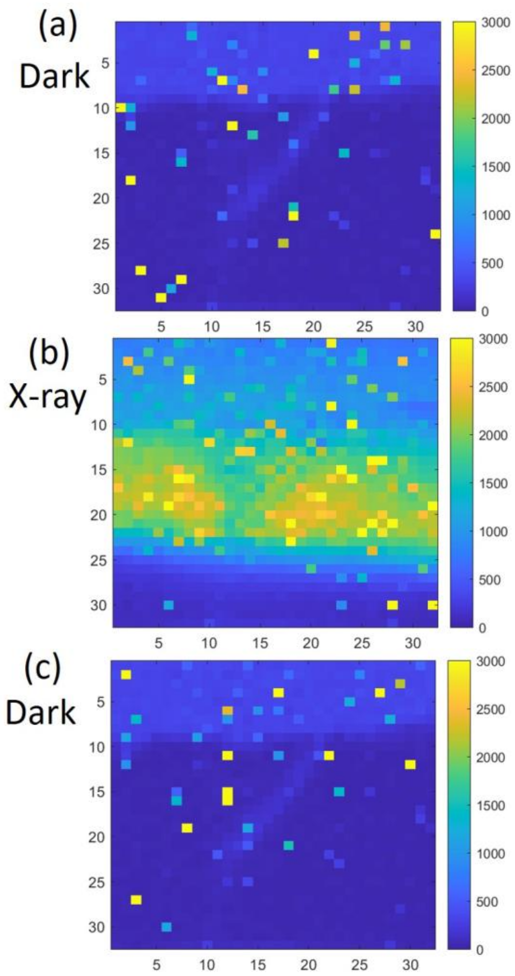

Fig. 5. The dark count rate of SPAD array under the bias voltage of 51.4 V and 0.1 second integration time (a) before X-ray irradiation, (b) under X-ray irradiation and (c) after X-ray irradiation

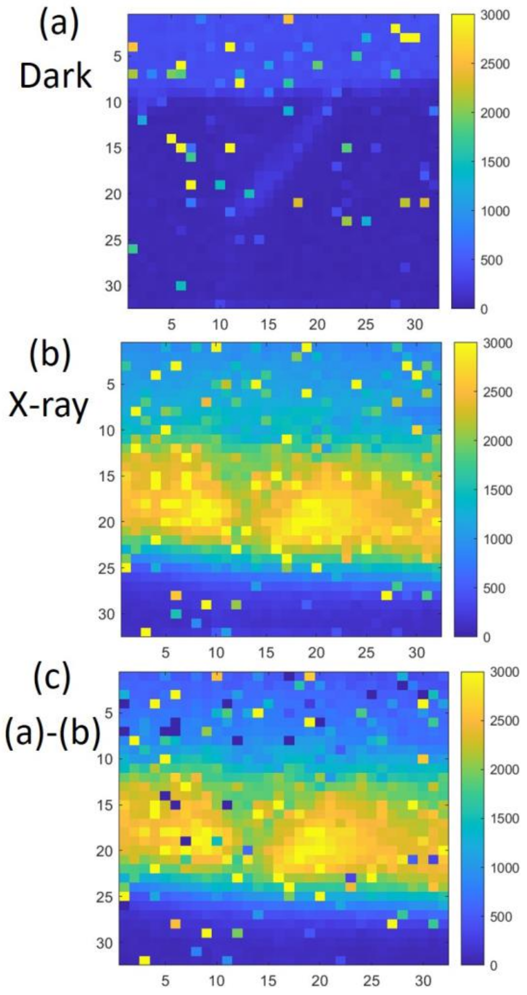

Fig. 6. The dark count rate of SPAD array under the bias voltage of 52.5 V and 0.1 second integration time (a) before X-ray irradiation and (b) under X-ray irradiation. (c) The net photon counts with counts of (b) subtract from the counts of (a).

counts in the X-ray irradiation measurement as shown in Fig. 6. The highest net photon counts are over 3000 counts during the integration time of 0.1 second as shown in Fig. 6 (c).

To examine the effect of CsI film on the performance of our chip for the X ray detection measurement, we replace the detector by our chip to perform X ray detection. Then we compare the effective photon counts of our chip to that of the PMT detector with scintillator which is used in the original XRD system. The PMT detector with an opened window of 2.5 x 1 cm^2, as shown in Fig. 7(a), can detect about 600 counts per second (cps) with a detection area of 20-µm diameter, where we normalize the photon counts to the area size same as that of our device for better comparison. As shown in Fig. 7 (b), under the same condition, our chip can detect over 30000 cps averaged from 9 pixels of our chip. The photon counts detected by PMT is much lower than the that detected by our chip.

To demonstrate a digital radiography system, we use a stainless shutter with various multi-silts width pattern ranging from 50 µm to 200 µm, as shown in Fig. 8 (a), and put the shutters in between the chip and X-ray gun. The 130 µm width of multi-slit is used for radiography. Although the stainless shutter was not aligned well with the SPAD, the

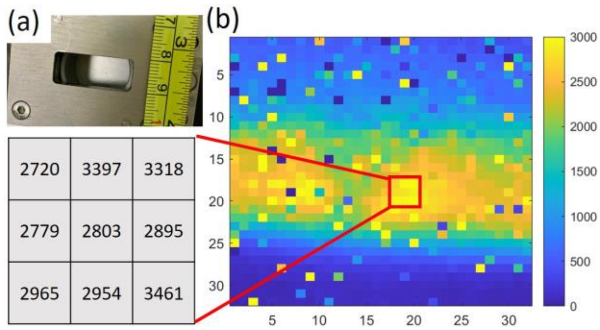

Fig. 7. (a) Picture of the PMT detector in XRD with an opened window of 2.5 x 1 cm^2. (b) Photon counts of 9 pixels of our SPAD array, measured in 0.1 s integration time.

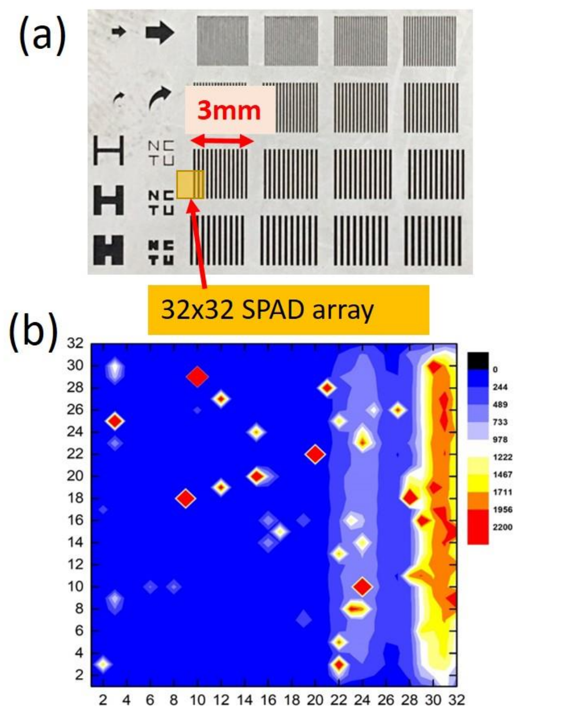

Fig. 8. The picture of stainless shutter with multi-slit patterns and the position of 32x32 SPAD arrays under the multi-slit of 130 um width (a), the radiography of the measurement in XRD.

multi-slit. radiography can still be clearly measured as shown in the Fig. 8 (b). The digital radiography picture shows good spatial resolution due to the benefit of direct deposition of scintillator on SPAD array.

III. CONCLUSION AND DISCUSSION

From the measurement results and effective dose calculation, our imager performs much higher sensitive detection comparing to a photomultiplier tube (PMT) with scintillator which is used in the X-ray diffractometer (XRD) , thanks to the highly photon sensitive of 32x32 pixels CMOS SPAD array. We also demonstrate a high spatial resolution radiography with our imager, verifying the benefit of directly depositing the CsI material as the scintillator on the SPAD imager. So we believe that the SPAD array imager with direct deposition of CsI could be a better candidate for digital radiography systems.

Furthermore, in order to develop a digital radiography imager with timing information, the luminescence lifetime information of our deposit CsI is an ongoing task. Our chip with high speed operation is suitable for the high X-ray dose application, though the X-ray induced damage of scintillator should be prevented [10].

IV. ACKNOWLEDGMENT

We thank the financial support from NSTC in Taiwan, the National Center for High-Performance Computing for their assistance with TCAD licensing and ITRI for their help on chip fabrication.

V. REFERENCES

[1] Wang, Wenzhen, et al. “Approaching the theoretical light yield limit in CsI (Tl) scintillator single crystals by a low-temperature solution method.” Crystal Growth & Design 20.5 (2020): 3474-3481.

[2] Xu, Chen, et al. “Comparison of digital and analog silicon photomultiplier for positron emission tomography application.” 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC). IEEE, 2013.

[3] Patt, B. E., et al. “High resolution CsI (Tl)/Si-PIN detector development for breast imaging.” IEEE Transactions on Nuclear Science 45.4 (1998): 2126-2131.

[4] Prekas, G., et al. “Direct Deposition of Microcolumnar Scintillator on CMOS SSPM Array: Toward a Photon Counting Detector for X‐Ray/Gamma Ray Imaging.” AIP Conference Proceedings. Vol. 1412. No. 1. American Institute of Physics, 2011.

[5] Venialgo, Esteban, et al. “Time estimation with multichannel digital silicon photomultipliers.” Physics in Medicine & Biology 60.6 (2015): 2435.

[6] Hsu, Jin-Cherng, and Yu-Shen Ma. “Luminescence of CsI and CsI: Na films under LED and X-ray excitation.” Coatings 9.11 (2019): 751.

[7] Nagarkar, V. V., et al. “Structured CsI (Tl) scintillators for X-ray imaging applications.” IEEE transactions on nuclear science 45.3 (1998): 492-496.

[8] Nikl, Martin. “Scintillation detectors for x-rays.” Measurement Science and Technology 17.4 (2006): R37.

[9] C. C. Hsu, et al. “CMOS Single-photon Avalanche Diodes using Gated Reset Circuit with On-chip Pulse Width Modulation,” P09, IISW 2019.

[10] Tremsin, A. S., et al. “X-ray-induced radiation damage in CsI, Gadox, Y2O2S and Y2O3 thin films.” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 459.3 (2001): 543-551.