# High Resolution Digital Flat-Panel X-ray Detector Based on Large Area CMOS Image Sensor

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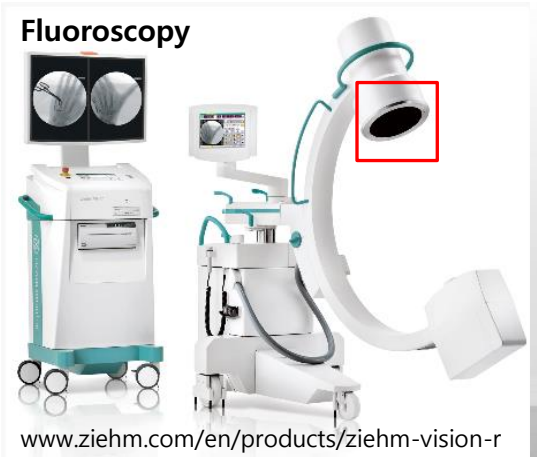
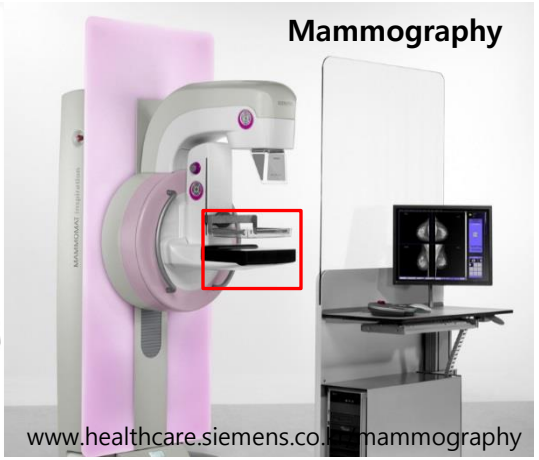
# Outline

- Introduction
- CMOS X-ray detector module
- X-ray characteristics
- Future works
- Summary

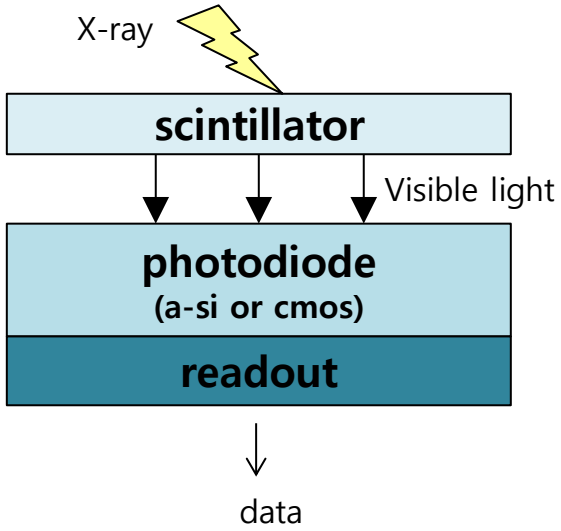
# Introduction (1)

- **X-ray digital flat panel detectors**
  - Digital flat panel detectors are used for clinical applications such as mammography and fluoroscopy.
  - Most flat detectors are based on indirect conversion via scintillator and an active pixel matrix of a-Si photo diodes
  - Recently, CMOS image sensor also studied actively.




Flat detectors




< Indirect Conversion >

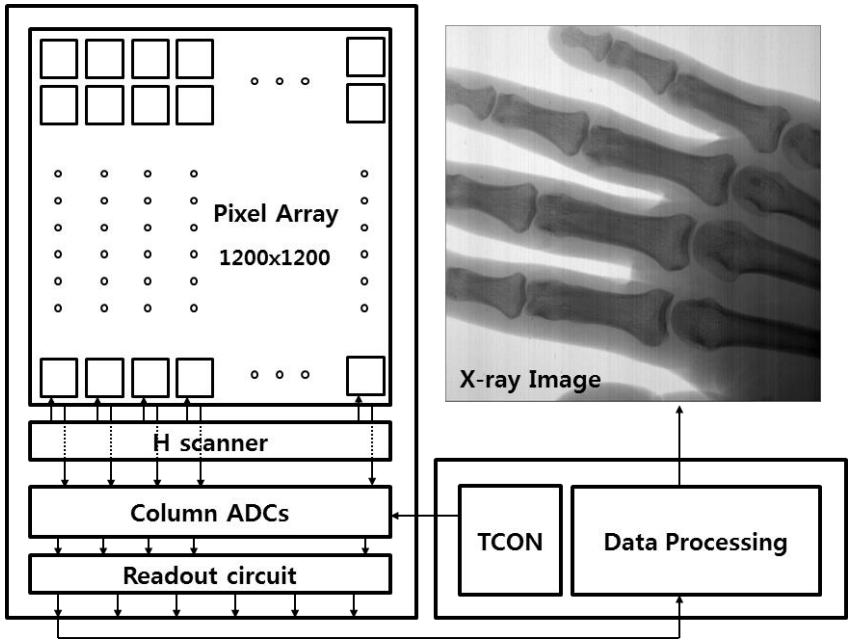
# Introduction (2)

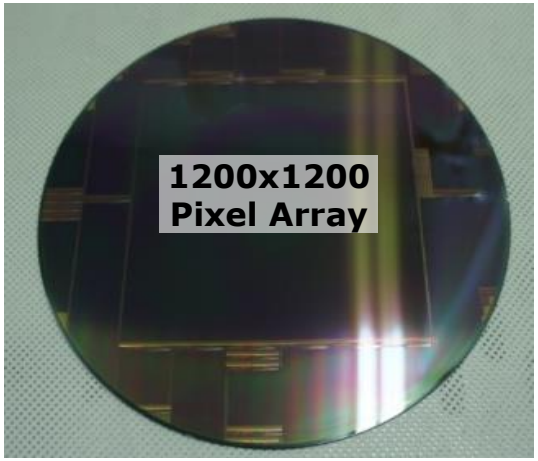
- **Advantages of CMOS process for flat panel detector**
  - **CMOS process enables integration of many additional features.**
    - On-pixel amplification
    - Various pixel circuits from 3 transistors(3-TR) up to 100 transistors per pixel
    - Integrating detectors with CMOS readout circuits
      ( e.g. A/D conversion, Logic)
  - **Electronic shutter**
    - global shutter, rolling shutter, non-destructive reads
  - **Overcome the size limitation through advanced process technology**
    - No more problem with producing large area CMOS image sensor.

***⇒ We study on a high resolution X-ray detector***
***to acquire high quality images for real-time display based on CMOS sensor.***

# Main Features of CMOS X-ray Detector Module

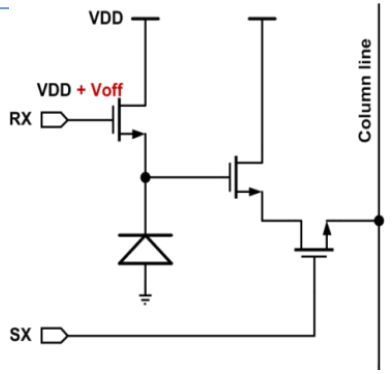
- Detector area : 12 x 12 [cm$^2$]
- Pixel size : 100 x 100 [um$^2$]
- Full well capacity : 4.4 Me-
- Pixel matrix : 1200 x 1200
- TowerJazz 0.35 um CMOS process
- Three-side-tileable structure
- Column-paralleled ADCs
- 14 bit digital outputs
- 2x2 pixel binning
- 30 frame per second in full-resolution
- Rolling shutter method
- Power supply : 3.3 V, 3.9V, 3.0V, 0.6V
- Number of Pads : 752 pads on bottom side

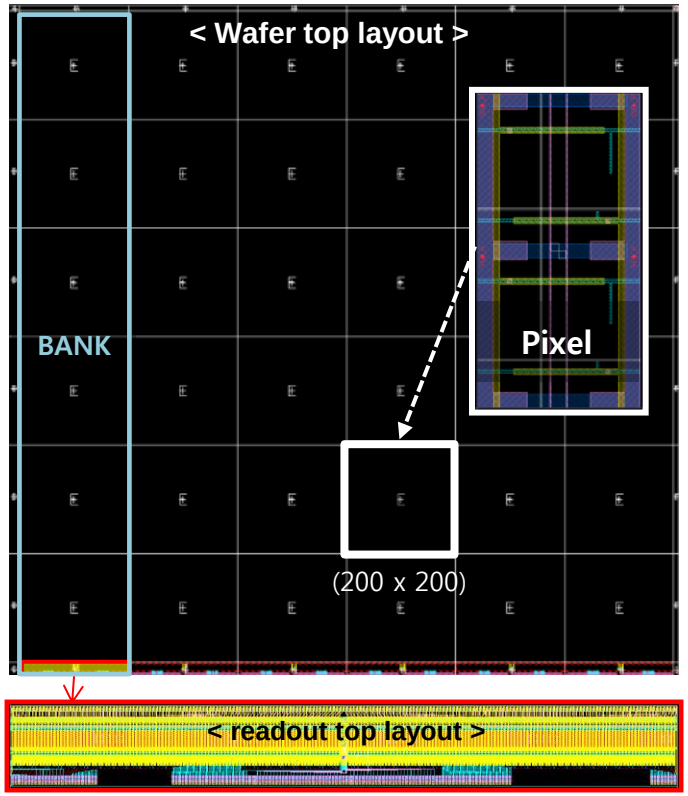


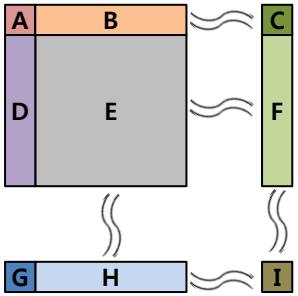



# Large Area CMOS Image Sensor

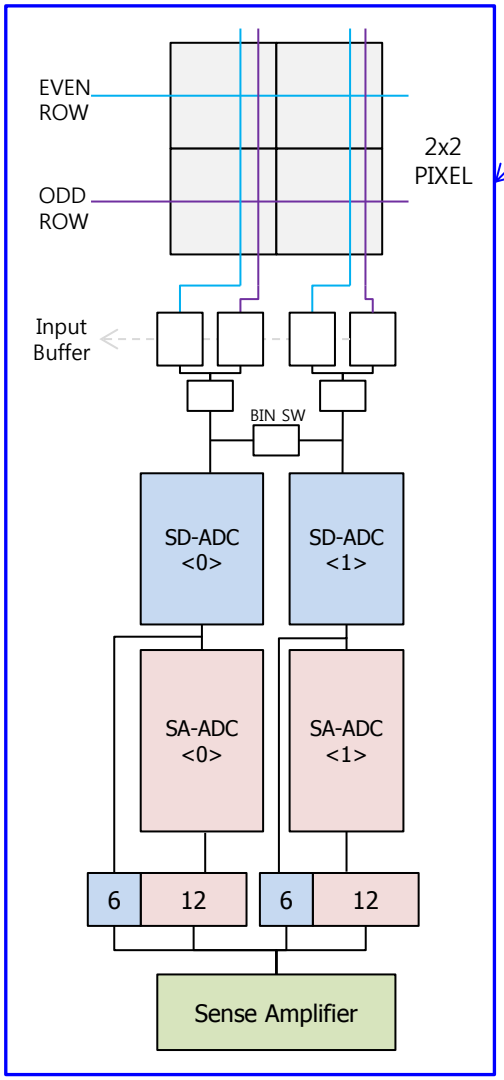
- **Large-area CMOS Sensor with Stitch Process**
  - 3-TR Active Pixel Sensor.
  - Stitch process for large die size
  - Segment Design : 9 segments from A to I
    - **E** segment consists of 200 x 200 pixel arrays. It repeats 36 times to produce 1200 x 1200 arrays.
    - Row driver and column-paralleled ADCs are located in **H** segments. It also repeats 6 times on the bottom side of sensor.
    - Other segments are empty area.
  - According to readout structure, we define 'Bank'; E + H segments.



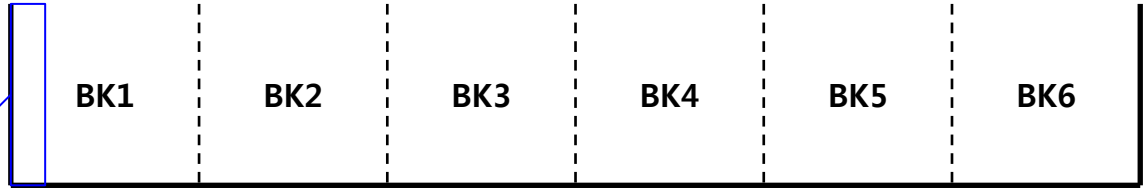



# Readout structure

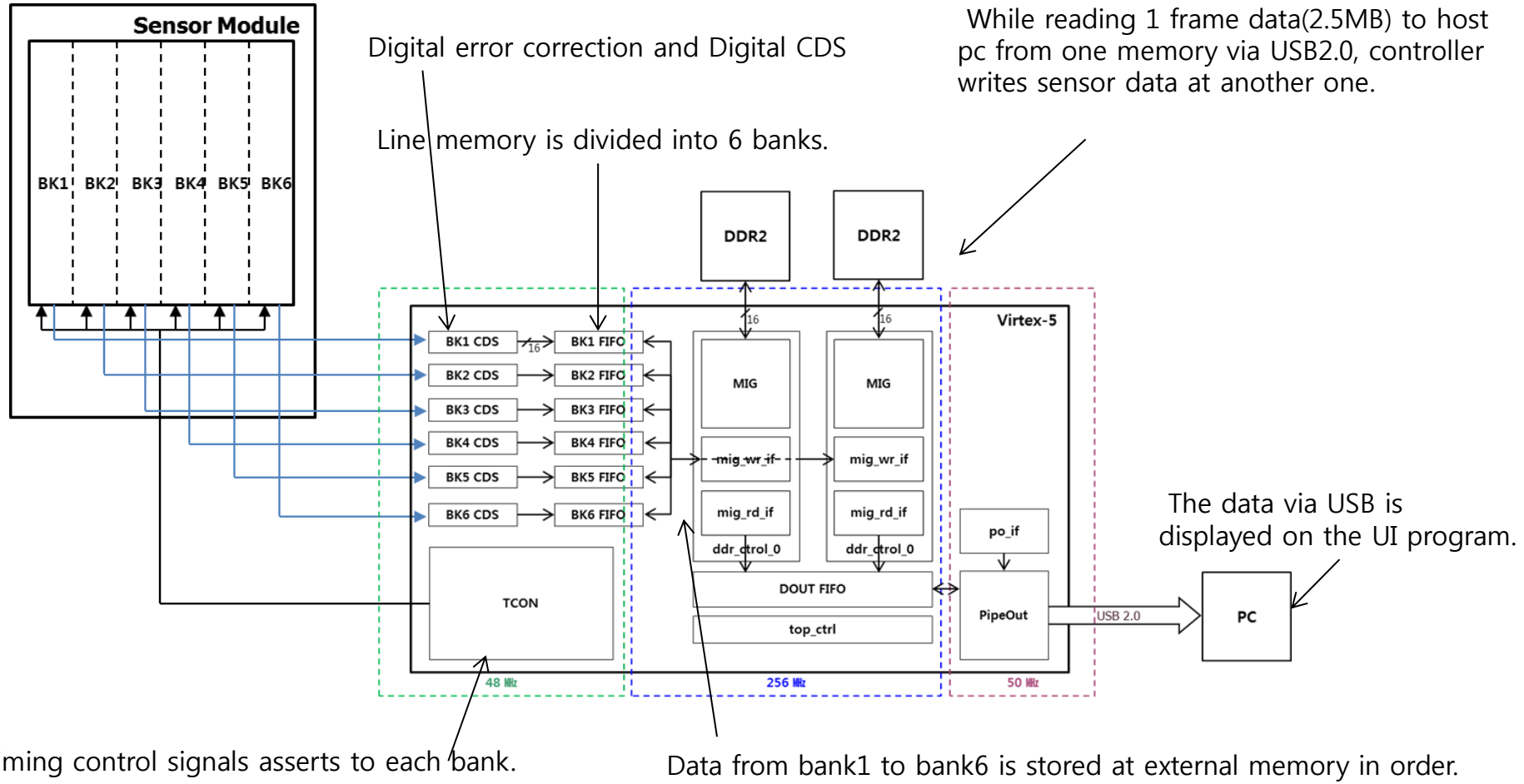



< 2-Channel Readout Structure >

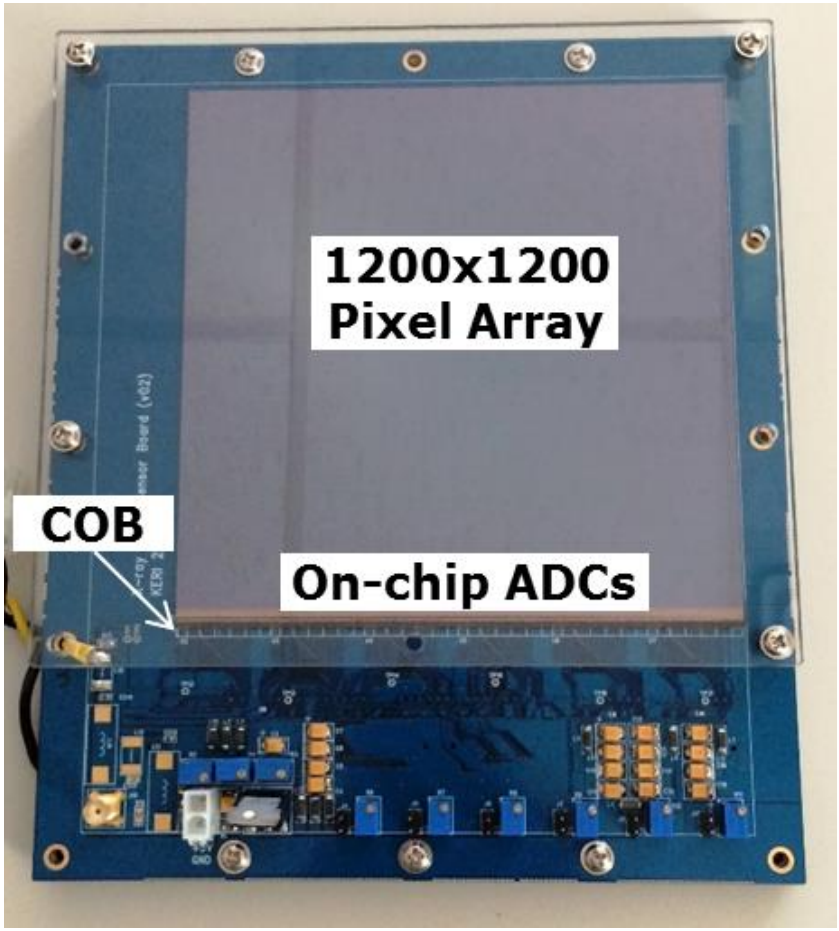



- Basic structure
  - 2 x 2 pixel array and 2 channel ADCs for binning mode.
- The column-parallel Extended Counting ADC(EC-ADC) is used in a large area CMOS X-ray detector to enhance bit-depth.
  - 1st order ΣΔ-ADC(SD-ADC) output upper 3 bit conversion.
  - Residue is converted by 12 bit SAR-ADC.
- In full-resolution mode, each pixel data is converted by each column ADCs.
- In binning mode, 2 x 2 pixel is selected simultaneously and all pixel charge are summed at even column ADC (ADC<0>).
  -> the sensitivity increases four times in binning mode.
- 1 Bank includes 200 channel ADCs and 125 pads are placed per bank. So, 18bit ADC raw data of 6 banks output at the same time.

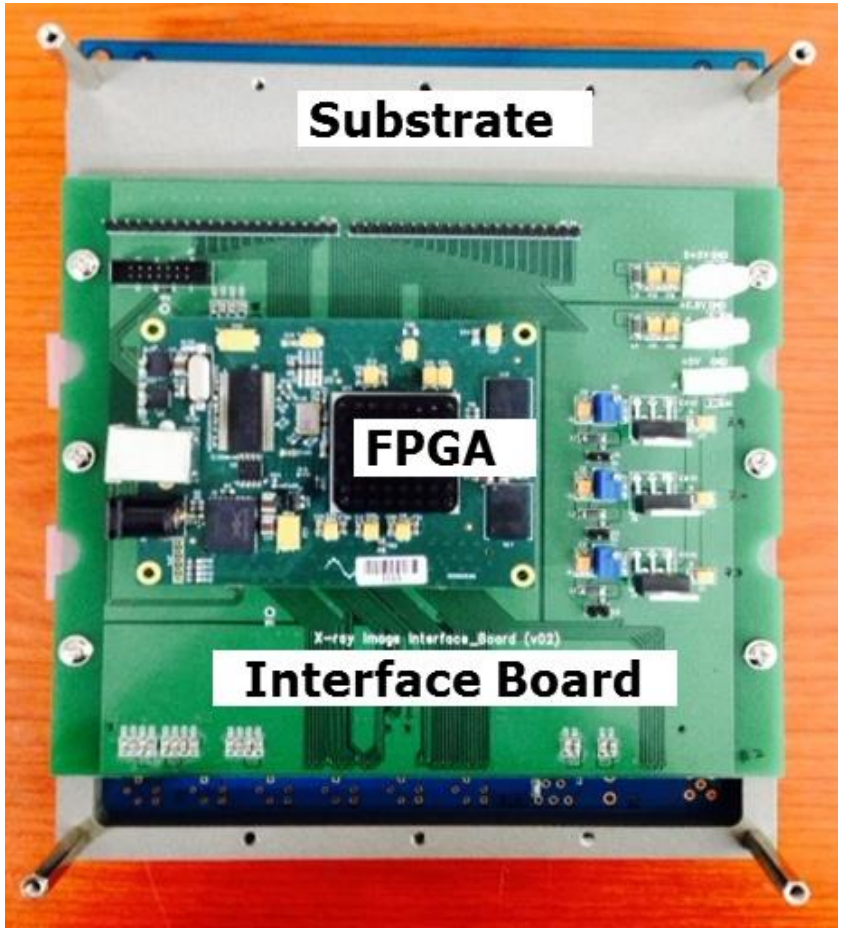
# Sensor Control Logic



# CMOS X-ray Detector Module (1)




< Front >

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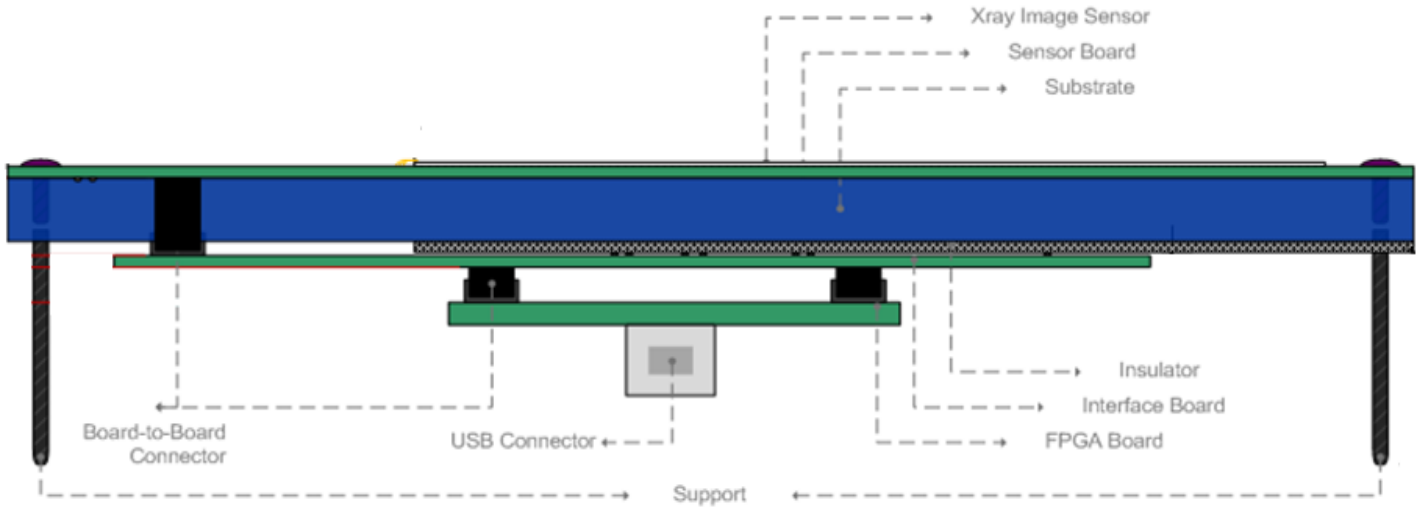
# CMOS X-ray Detector Module (2)

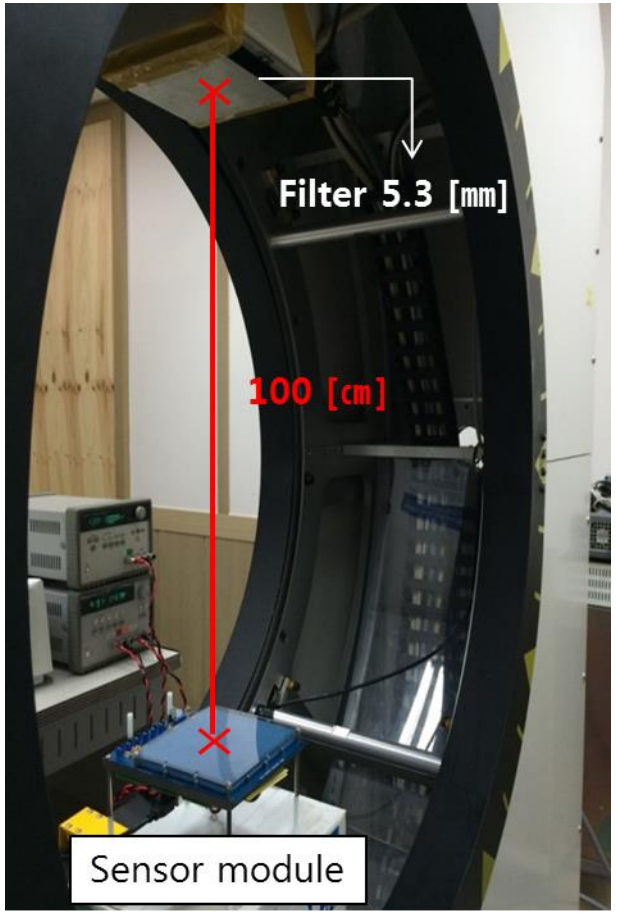



**< Side >**

- After dicing, the sensor is attached to the PCB board using low temperature cure epoxy.
- Sensor board, interface board, and FPGA board are directly connected via board-to-board connector.
- A substrate covered between the sensor and interface board prevents a sensor board from bending, and also insulates.

# X-ray Characteristics (1)

- **Test Conditions**
  - **Distance from focal spot to sensor surface :** 100 [cm]
  - **Filter thickness:** 5.3 [mm]
  - **Tube voltage :** 75 [kVp] (fixed)
  - **Tube current :** 10 to 125 [mA]
    - The intensity of X-ray is linearly proportional to the tube current, not the tube voltage.
    - We can obtain linearly incremented intensities.
  - **On-chip ADC condition setup**
    - Full-Resolution / Binning Mode
  - **Scintillator**
    - DRZ-Standard(GOS)
    - Cut the scintillator to fit the sensor size and place it on the sensor.



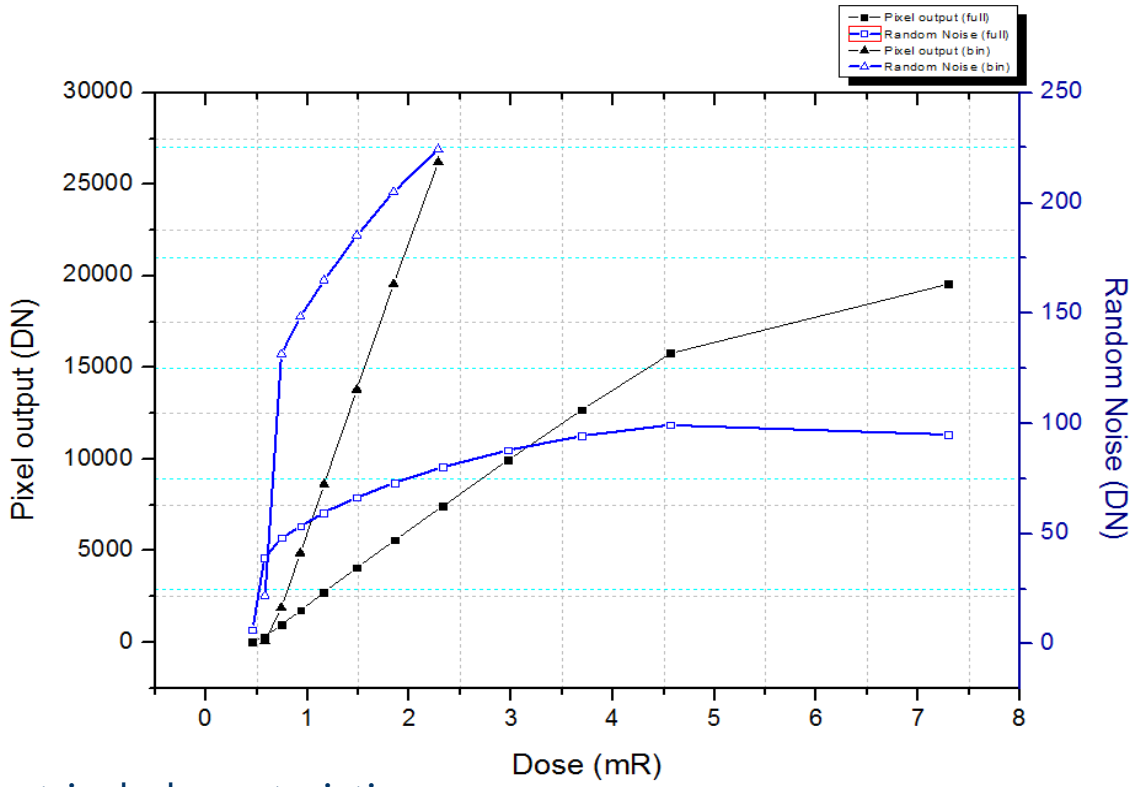
# X-ray Characteristics (2)

- **Dose Measurement**
  - Measured by exposing sensor to x-ray for 1 sec while changing tube current from 10 to 125 [mA].
  - Calculating dose in proportional to x-ray exposure time on the pixel.
    - In full-resolution mode, integration time is 24 [ms].
    - In binning mode, integration time is 12 [ms].

| Tube Current [mA] | Dose [mR] | FULL | BIN |
|---|---|---|---|
| 10 | 19.1 | 0.4584 | 0.2292 |
| 12 | 24 | 0.576 | 0.288 |
| 16 | 31 | 0.744 | 0.372 |
| 20 | 38.8 | 0.9312 | 0.4656 |
| 24 | 48.3 | 1.1592 | 0.5796 |
| 32 | 61.8 | 1.4832 | 0.7416 |
| 40 | 77.4 | 1.8576 | 0.9288 |
| 50 | 96.8 | 2.3232 | 1.1616 |
| 64 | 123.7 | 2.9688 | 1.4844 |
| 80 | 153.9 | 3.6936 | 1.8468 |
| 100 | 190.3 | 4.5672 | 2.2836 |
| 125 | 304.1 | 7.2984 | 3.6492 |

# X-ray Characteristics (2)

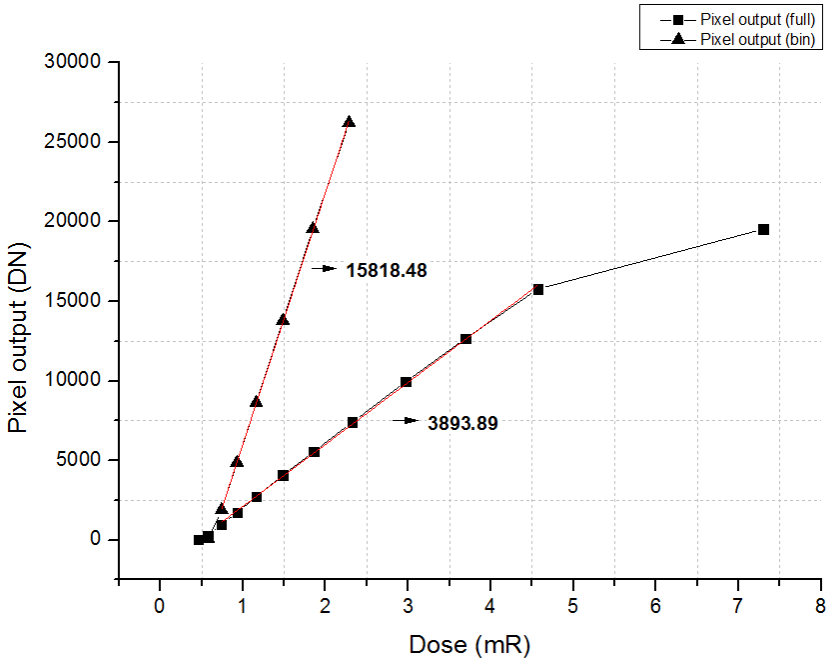
- **Optoelectrical response and random noise of CMOS X-ray Sensor**




- Optoelectrical characteristics
  - full-resolution : the output is linear 0.46 to 4.5 mR
  - binning : the output is linear 0.58 to 2.4 mR
- Random noise
  - full-resolution : 6.38 [DN] at 0.46 [mR]
  - Binning : 21.8 [DN]  at 0.58 [mR]

# X-ray Characteristics (3)

- **Sensitivity of CMOS X-ray Sensor**



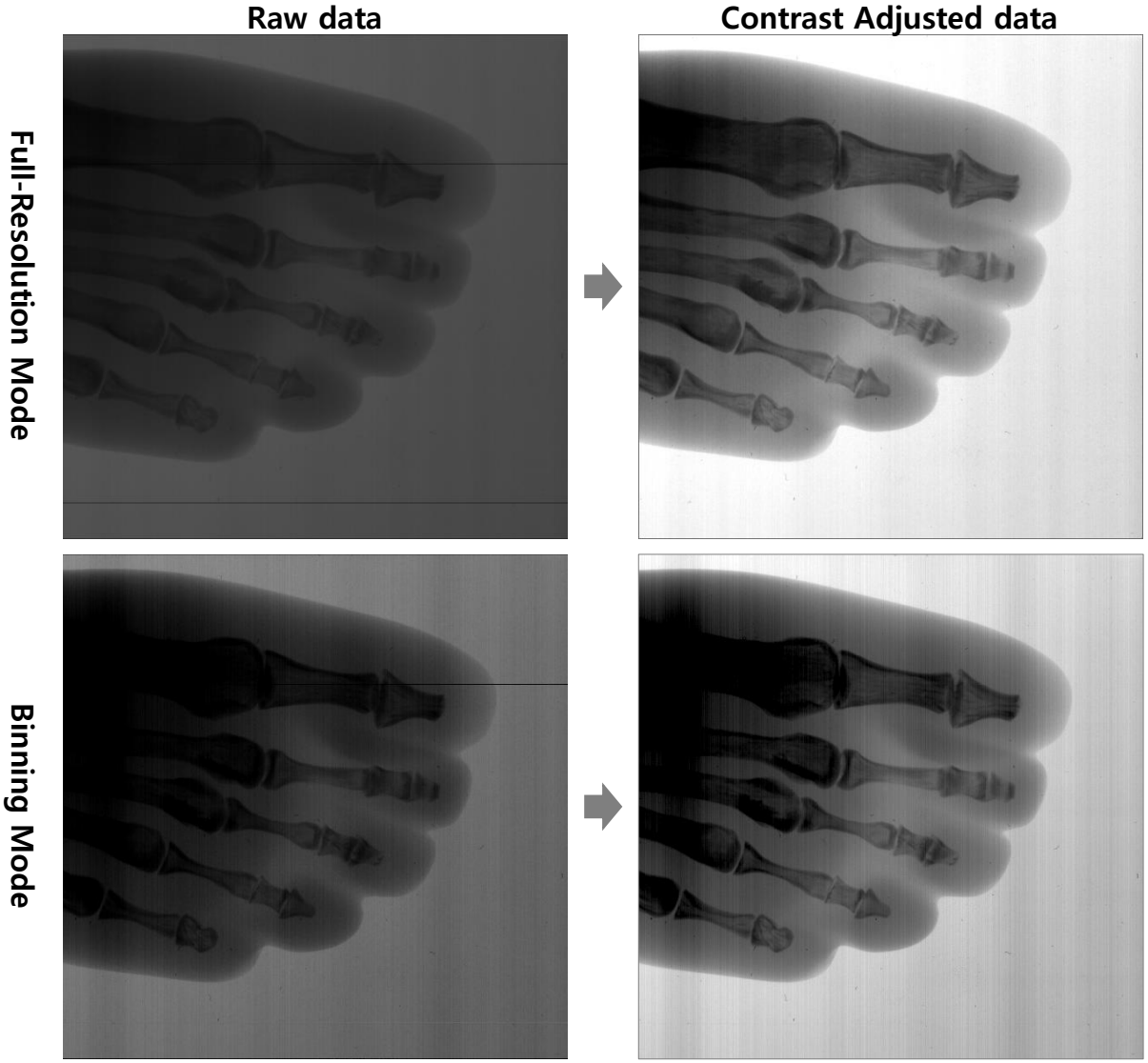

| | [$\mu$V] |
|---|---|
| **1 LSB** | 63.258915 |

- Full-Resolution : 3893.89 [DN/mR] (≒ 0.246 [V/mR] )
- Binning : 15818.48 [DN/mR] (≒ 1.001 [V/mR] )
- The sensitivity in binning mode is the quadruple of that in full-resolution mode.

# X-ray Images (1)

- **Foot Phantom**

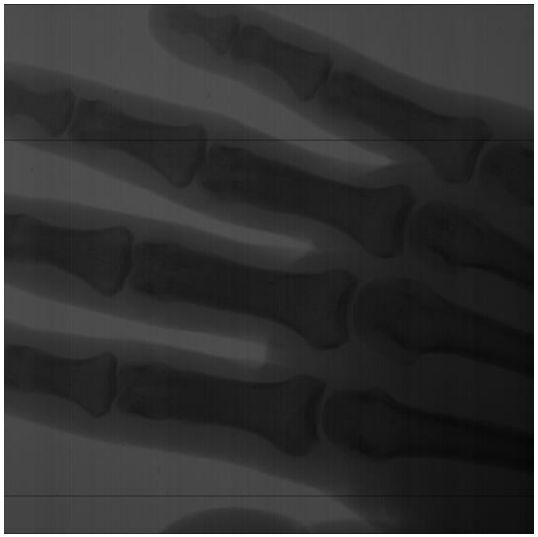
X-ray exposure condition : 75 [kVp] / 64 [mA]



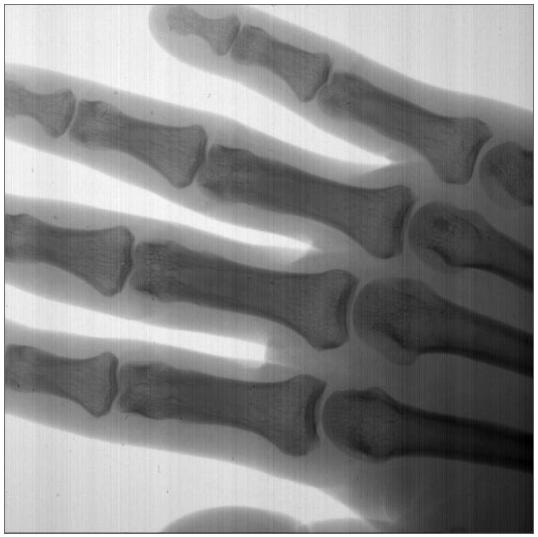
# X-ray Images (2)

- **Hand Phantom**

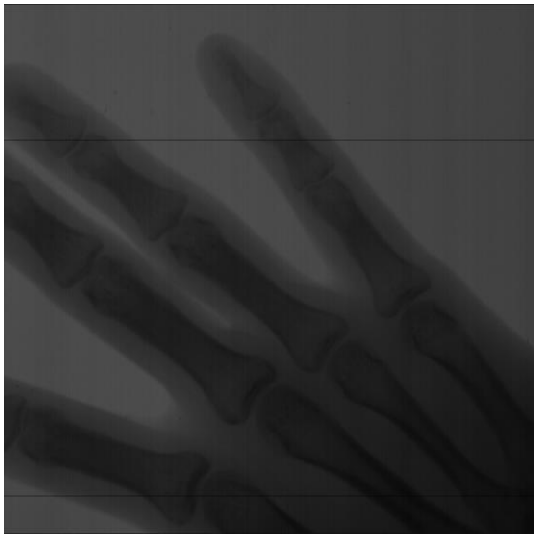
**X-ray exposure condition : 75 [kVp] / 64 [mA]**



**Raw data**



**Contrast Adjusted data**

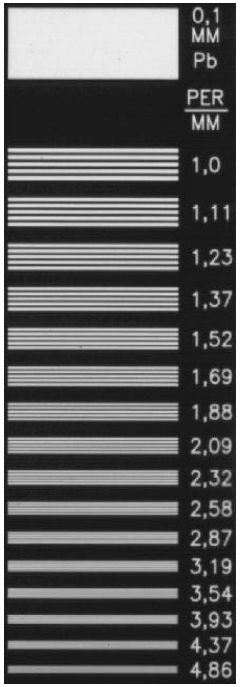


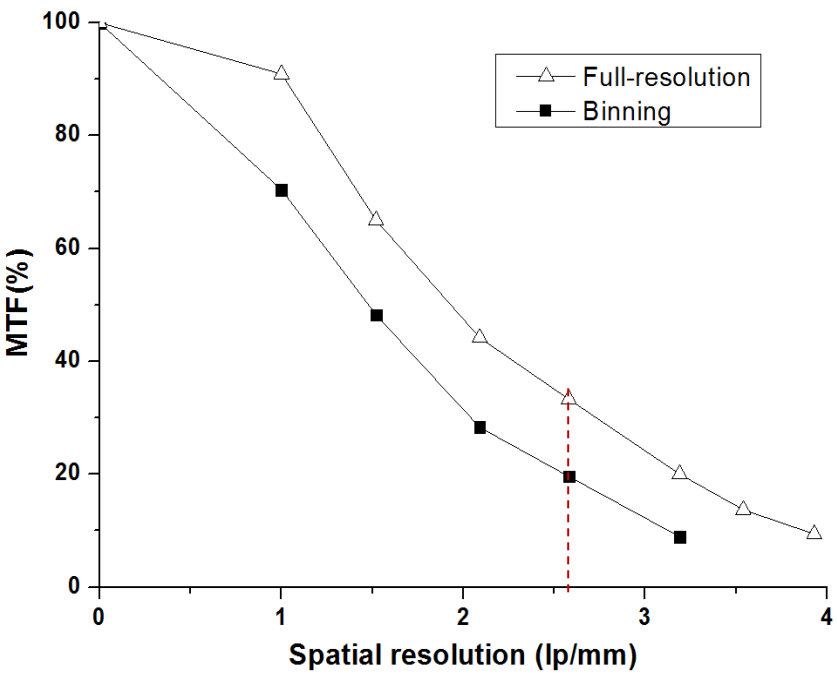
**Shaking hand (16 frame)**

⇒ Based on consecutive images in full-resolution mode, image lag is negligible.

# Spatial Resolution

- **MTF (Modulation Transfer Function)**
  - In full-resolution Mode, MTF at 2.54 lp/mm is 33.3%.
    In binning Mode, MTF at the same lp/mm is 19.6%.
  - Since effective pixel pitch is reduced in binning mode, MTF is also decreased.



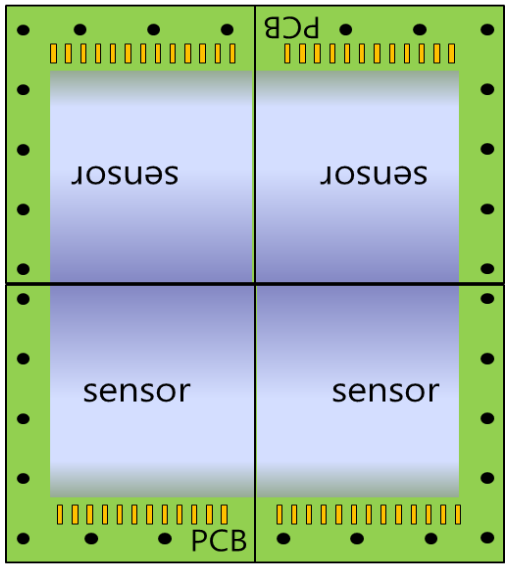




**< Captured images of line pair set and Calculated MTF >**

# Future Works

- **Single CMOS X-ray detector**
  - Optimization of on-chip ADC operation to enhance image quality.
  - Image post-processing
  - Thallium-doped CSI (CSI:TI) scintillator direct deposition on the sensor
    - Scintillators based on CSI:TI have good absorption properties and good light collection.
    - We plan to make a sample to get high spatial resolution.

- **Tiled CMOS X-ray Detector**
  - Four single detectors are tiled to expand detector area. ( 48 x 48 [$cm^2$] )
  - Also, we plan to develop control system that manage each four sensors' operation and data acquisition.



# Summary

- **We developed high-resolution CMOS X-ray detector based on several advantages of CMOS process.**
  - A large-area 1200x1200 array CMOS image sensor with full mode(30fps) and binning mode(60fps) for mammography and fluoroscopic imaging application.

- **Also, we measured results such as X-ray linearity as a function of dose, spatial resolution and X-ray images of the objects for performance evaluation with GOS scintillators**
  - The more detailed characterization of our developed X-ray CMOS image sensor will be evaluated under practical mammography and fluoroscopic application conditions.

- **We plan to enhance the performance of a ingle x-ray detector and to develop tiled x-ray detector process.**

# THANK YOU FOR YOUR ATTENTION !