

## 論文の内容の要旨 (summary)

論文題目     Development of X-ray imaging system using silicon strip detector  
(シリコンストリップ検出器を用いたX線撮像システムの開発)

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Although reactors in Japan have been stopped after the great nuclear accident on 11 March 2011, some operable reactors will be restarted in the future because of the serious energy situation of Japan. Reactors can only be restarted on the major premise of ensuring safety. Special care has to be taken with steel structures in these reactors, such as reactor vessel, pipes, turbine, et al. On the other hand, a large number of concrete based infrastructures, such as highways, bridges, tunnels, et al. were built in the past 50 years with little consideration of the long term safety aspects. It is important to reliably assess the health of aging concrete structures and test new concrete structures to determine whether they satisfy safety criteria.

X-ray radiography is the most suitable technique for nondestructively detecting internal feature in thick components. Conventional detectors for imaging applications include array detectors with many pixels or line-up detector elements with large thickness. The array detectors usually have low efficiency for high-energy photons because of their small thickness, and they are generally used in medical applications or low-energy industrial applications. A system with line-up detector elements is used for scanning the sample to be tested, and a full image of the sample is realized with a series of scans. It takes a long time to imaging the sample and the dose to the sample and environment is high. Besides, traditional X-ray radiography systems are working in energy-integrating mode. They suffer from limited dynamic range and sensitivity to dark current and electronic noise which degrades the spatial resolution.

We are now developing a photon-counting X-ray imaging system with stacked edge-on silicon strip detectors for nondestructive testing of steel pipes in nuclear facilities and concrete structures in infrastructures. Compared with conventional energy integrating imaging systems, the stacked edge-on silicon strip detectors provides high detection efficiency to high-energy photons and electronics working in photon-counting mode helps to improve spatial resolution of images and fit the system for testing

thicker samples.

We performed Monte Carlo simulations to study and optimize the imaging system working with 3.95 MeV LINAC X-ray source. It is validated that "edge-on" 50 mm-thick silicon strip detectors have high detection efficiency for high-energy photons (about 30% for 4-MeV photons). Scattering contribution of photons incident on silicon detectors inside the 5-cm-long detector module is severe. The scatter-to-primary ratio is about 6.3. Tungsten sheets parallel and match detectors can improve image contrast, and they should be placed close to object and apart from the detectors. Tungsten sheets inside the detector module even enhances scattering other than reducing scattering, and the scatter-to-primary ratio increases to be about 12.5 when a 0.5-mm-thick tungsten sheet is placed under each strip detector. On the contrary, the scatter-to-primary ratio decreases to be about 4.3 when a collimator module composed of 2-cm-thick tungsten sheets is placed in front of the detector module. An energy threshold of about 200 keV further improves image quality of the designed system.

We fabricated 50-channel strip detectors with the a-Si/c-Si heterojunction technique. The a-Si/c-Si heterojunction process with PECVD technique is greatly simplified compared with conventional normal process and is suitable for mass production at low cost. The 50-channel detector has quite homogenous leakage performance when the bias voltage is lower than 120 V, and the leakage current density of the detector was measured to be  $0.06 \text{ nA/mm}^2$  at 120 V bias. A bias voltage of 120 V also guarantees depletion of over 90% of the whole wafer. The fabricated detector has energy resolutions of 2.8 keV FWHM at 59.5 keV and 2.9 keV FWHM at 122 keV. The spatial resolution of the 1-mm-pitch strip detector was measured to be lower than 2 mm (FWHM) with face-on geometry. Cathode pattern of the a-Si/c-Si heterojunction can be easily fabricated by common lithography process to meet the demands of different applications, e. g., 2D pads for low energy X-ray imaging or Compton imaging (as scatter).

ToT method was chosen to readout signals of the silicon strip detectors. The ToT circuit converts analog signals to digital signals with only one comparator. Such a simple structure is beneficial to decreasing circuit complexity and is suitable for imaging systems with more than thousands of channels. Based on the 48-channel ToT ASIC, we built continuous-mode edge-on modules for gamma-ray or low intensity X-ray imaging and a pulse-mode edge-on module for LINAC X-ray imaging.

We used a  $^{137}\text{Cs}$  gamma-ray source to scan images of sample objects with continuous-mode prototypes consisting of one strip detector and two stacked strip detectors. The central right angle can be identified from the scanned image of an iron object. However, because the distance from the detector to the source was more than twice the distance from the object to the source, the right angle was distorted because the object was too close to the  $^{137}\text{Cs}$  source. Another cylinder iron object with holes filled with soil was also

scanned, and soil parts can be identified from the main iron cylinder. Though the image was not as clear as the previous image because the thickness was smaller and the density difference between soil and iron is much smaller than that between air and iron, the distortion of the image was slighter than the previous one because the object was placed relatively closer to the detector. A tungsten cylinder with a conical hole was imaged with two stacked silicon strip detectors. The central hole and the outer edge of the tungsten cylinder were clearly visible in the two scanned images. A wider region of the sample can be seen after joining the two images. However, because photons were not incident parallel to the detectors, the images scanned by two detectors were not perfectly joined.

A pulse-mode module consisted of 6 stacked strip detectors were constructed. The module was evaluated with the  $^{137}\text{Cs}$  gamma-ray source. The module had efficiency of about 20% for the 662 keV photons with a threshold of about 180 keV and without anticoincidence filter. Spatial resolution of the module was measured to be about 1 mm (rms). One-scan and six-scan images of a 2-cm-thick tungsten sample and a 1-cm-thick iron sample were obtained. Each scan lasted for about 3600 s with the 1 MBq  $^{137}\text{Cs}$  source for accumulating acceptable statistics. The module was also evaluated with the 0.95 MeV LINAC X-ray source. Spatial resolution of the module was measured to be about 1 mm (rms). Six-scan images of the same tungsten sample and iron sample were obtained. Each scan lasted for about 180 s. The images measured with the LINAC X-ray source reproduced the samples better without distortion and amplification compared with scan images measured with the  $^{137}\text{Cs}$  source.

The six-layer module was also used to scan a 20-cm-thick concrete. Another 1.2-cm-thick lead was inserted to simulate a thicker concrete, reinforcing bars inside the concrete were observed. A flat panel detector working in energy-integrating mode was also used to imaging the concrete, however, the reinforcing bars were invisible when the setup was the same with the measurement proceeded with our silicon strip detectors, validating that the newly developed imaging system is capable of imaging thicker samples.

Scans with prototypes validated the imaging capability of the proposed system, and higher-quality images can be obtained with a complete system when a more intense source is applied. We are planning to use 4 (2×2) modules for X-ray imaging. Each module has more stacked silicon strip detectors with about 1-mm pitch, and region of interest can be as large as 10 cm × 10 cm by using the 4 modules. In addition, tungsten collimator module will be applied in the following experiments.

We are planning to proceed on-site NDT of steel structures in NPPs and concrete in infrastructures with both the 0.95 MeV and 3.95 MeV LINAC X-ray sources. Dynamic ToT ASIC will be optimized and implemented in the imaging system.