Development of X-ray/Gamma-Ray Imaging System Based on Hydrogenated Amorphous Silicon/Crystalline Silicon Heterojunction Strip Detector

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A high-energy X-ray/gamma-ray imaging system based on a hydrogenated amorphous silicon (a-Si : H)/crystalline silicon (c-Si) heterojunction strip detector was developed. The imaging system will be applied in nondestructive testing of concrete structures. We fabricated 50-channel heterojunction strip detectors with a 1 mm pitch on 500 μm thick p-type silicon wafers. The average leakage current was 2.9 nA per channel at 120 V reverse bias. Energy resolutions of 2.8 keV FWHM at 59.5 keV and 2.9 keV FWHM at 122 keV were obtained at 18°C. The position sensitivity of the strip detector was measured by edge-on irradiation with a 137Cs gamma-ray source. Edge-on gamma-ray imaging of a tungsten object using the prototype was performed. A module consisting of 20 stacked silicon strip detectors is being constructed.

Key Words: amorphous silicon/crystalline silicon heterojunction, silicon strip detector, X-ray imaging, gamma-ray imaging

1. Introduction

Owing to the aging and deterioration of nuclear facilities and infrastructures, nondestructive testing (NDT) of reinforcement bars and defects in the concrete structures (e.g., containments, reactor buildings, highways, bridges, and tunnels) is becoming increasingly important. X-ray/gamma-ray imaging techniques have been widely employed because they are capable of producing high-quality images of the concrete interior nondestructively. However, traditional X-ray/gamma-ray imaging systems have a low penetration capability, large time consumption, and emit high radiation doses to the surrounding environment1,2. Advanced X-ray/gamma-ray imaging systems that can be developed at low costs for imaging thick structures in shorter time and with lower radiation doses are required. We are now developing a high-energy (~MeV) X-ray/gamma-ray imaging system based on stacked hydrogenated amorphous silicon (a-Si : H)/crystalline silicon (c-Si) heterojunction strip detectors.

Widely used detectors for imaging application include flat panel detectors. However, flat panel detectors are usually built on thin scintillator screen and are poorly efficient for high-energy photons. For example, commercially available Perkin Elmer XRD0822 flat panel
detector has 200 μm thick GOS scintillator, and its efficiency for 1 MeV photon is 0.23%. N. Estre et al. developed a new 2D scintillator screen made of 1.5 mm thick GOS scintillator with Ta intensifier, and its efficiency for 1 MeV photon is 7%.

Although silicon detectors are generally considered to be only efficient in the detection of low-energy photons or charged particles, the signal amplitude of a silicon detector is about one order of magnitude higher than that of a normal high-Z scintillator coupled with a photodiode. This is because of the direct conversion of deposited energy to electron-hole pairs in the depletion region. If strip detectors are used and the strips are oriented parallel to the incident beam (called “edge-on”), one can benefit by stacking edge-on strip detectors in high-energy X-ray or gamma-ray imaging. Each strip functions as a pixel of the imaging device, and the edge-on configuration greatly increases the detection efficiency for high-energy photons compared with traditional films or flat panel detectors. Efficiency of a 5 cm long silicon strip detector for 1 MeV photons is calculated to be as high as 52%. Compared with other room-temperature semiconductors (e.g., CdTe and CZT), the higher mobility of the charge carriers in silicon makes it possible to operate at a much higher count rate in photon-counting imaging applications, which is performed on a LINAC platform with a duty pulse width of only a few microseconds.

a-Si:H is suitable for large area fabrication at low cost; however, it is difficult to produce an a-Si layer thick enough for minimum-ionizing particle detection. Instead, the a-Si/c-Si heterojunction detector can be easily fabricated using the plasma-enhanced chemical vapor deposition (PECVD) technique at around 200 – 250°C. The relatively low-temperature PECVD technique also helps reduce the risk of degrading the carrier generation life in high-purity silicon wafers. However, a heterojunction detector with both low leakage current and position-sensitive capability has not been realized so far. M. Yabe et al. fabricated a large-area a-Si/c-Si heterojunction detector by DC plasma deposition process, and the detector showed energy resolution of 8.3 keV FWHM for 59.5 keV at room temperature. Y. Chiba et al. fabricated heterojunction detector by the plasma CVD method, and they realized position-sensitive by evaporating segmented electrodes on the a-Si film, however, their detector suffered from high leakage current ranged from 10⁻⁶ to 10⁻⁵ A at 20°C and they didn’t find out the solution to decrease this high leakage current.

We fabricated 50-channel strip detectors with an a-Si/c-Si heterojunction structure. The average leakage current of each channel was 2.9 nA when a reverse bias of 120 V was applied. The detector had energy resolutions of 2.8 keV FWHM for 241Am 59.5 keV and 2.9 keV FWHM for 57Co 122 keV at 18°C. We scanned two-dimensional (2D) images of a tungsten object with a 137Cs source and two stacked edge-on silicon strip detectors. A compact module, which consists of 20 stacked silicon strip detectors, is being constructed.

2. System design

2.1 Detector module

Fig. 1 shows the configuration of the detector module. The size of one module is 5 cm × 5 cm × 5 cm. One unit consists of one silicon strip detector and one tungsten sheet. One unit is 2.5 mm thick, and the whole module is formed by stacking 20 units. Each silicon strip detector is mounted on a printed circuit board (PCB) and
48 channels are connected to 48 inputs of a readout application-specific integrated circuit (ASIC, not shown) by wire bonding. Tungsten sheets are used to absorb scattered photons in the module. X-ray/gamma-ray photons are incident parallel to the strip as shown on the left in Fig. 1.

2.2 Detector structure

The wafers employed for fabrication were p-type silicon, each with an area of 52.5 mm × 52.5 mm and a thickness of 500 μm. The resistivity of the wafers was 10 kΩ·cm. We deposited a 1 μm thick undoped a-Si: H film on the wafer by decomposing SiH₄ in hydrogen using PECVD. Fifty electrodes were formed on the a-Si: H layer by masked deposition of aluminum using the electron beam evaporation technique. Each electrode was 0.5 mm × 49.5 mm, and the electrodes were 0.5 mm apart. An aluminum anode was also evaporated on the other side of the silicon wafer. The thickness of the aluminum cathodes and anode was 1 μm. A cross section of the detector is shown in Fig. 2.

2.3 Readout ASIC and FPGA

The ASIC was designed by the University of Tokyo based on Time-over-Threshold method and fabricated using a 0.25 μm Taiwan Semiconductor Company complementary metal oxide semiconductor (TSMC CMOS) process. Each channel of the ASIC consists of a charge-sensitive preamplifier with a gain of 5 V/pC and a comparator whose threshold is controlled by a 12-bit digital-to-analog threshold (DAC).

Each of the digital outputs from the ASIC are fed into an FPGA through a single line for multiplexing to the data acquisition (DAQ) system, which counts the number and measures the width of the signals.

3. Operational characteristics

One detector was placed in the Apollowave MBP-55 probe station for optical and electromagnetic shielding, and we measured the bias voltage dependence of leakage current and junction capacitance with the Keithley 4200-SCS semiconductor characterization system. One sample channel was connected with a commercial preamplifier and a shaper to measure the ³²⁴Am and ⁵⁷Co spectra.

3.1 Leakage characteristics

We measured the leakage current of all 50 channels at four typical bias voltages at 20°C.
The 50-channel detector has a homogeneous leakage performance when the bias is lower than 120 V except for the two edge channels. The average leakage current of the central 48 channels is 2.9 nA and the leakage current density is calculated to be 0.06 nA/mm² at 120 V bias. However, one channel showed higher leakage current when the bias was 150 V.

3.2 Capacitance characteristics

The junction capacitances of five channels at typical bias voltages were measured and the depletion depths were estimated accordingly (Fig. 4). A bias of 120 V guarantees depletion of over 90% of the whole wafer and homogeneous leakage performance of all central 48 channels. The working bias of the detector was 120 V.

3.3 Energy spectrum characteristics

A CLEARPULSE 5005H charge-sensitive preamplifier and an ORTEC 571 shaper were used to evaluate the noise of the detector. The performance of the preamplifier was 1.25 keV (FWHM) +20 eV/pF (FWHM) for silicon at a
2.0 $\mu$s shaping time.

Pulse height spectra of $^{241}$Am and $^{57}$Co measured by the second channel of the detector are shown in Fig. 5 and 6, respectively. The FWHM of the 59.5 keV photopeak is 2.8 keV (Fig. 5) and the FWHM of the 122 keV photopeak is 2.9 keV (Fig. 6). The shaping time was set to 1.0 $\mu$s, the bias was set to 120 V, and the temperature was kept at 18°C during the measurement.

4. Position sensitivity and gamma-ray image

An identical threshold of 50 times the DAC value above baseline was applied to the comparator of each channel, and each of the digital outputs from the ASIC was fed into an Altera Cyclone III FPGA for multiplexing to the data acquisition (DAQ) system, which counts the signals.

4.1 Edge scan of a lead brick with a $^{137}$Cs gamma-ray source

Fig. 7 shows the setup for the edge-on position sensitivity measurement. The intensity of the $^{137}$Cs gamma-ray source is 1 MBq. The count distribution of 48 channels was measured with irradiation from the $^{137}$Cs gamma-ray source for 2 500 s(Fig. 8). The average count over 48 channels is 623. The lead brick was then inserted and moved thrice, each time by 1 mm. The measured counts were normalized with the flood-field data and are shown in Fig. 9. We can clearly see the movement of the scanned edge with the movement of the lead brick. The distance between scanned adjacent edges is about twice the strip pitch, because the distance between the gamma-ray source and the detector is about twice the distance be-
between the gamma-ray source and the lead brick.

4.2 Edge-on imaging of a tungsten object with a $^{137}$Cs gamma-ray source

We stacked two silicon strip detectors to perform a 2D scan experiment. The distance between the two detectors was 9.6 mm. The object to be scanned was a tungsten cylinder with dimensions of $R_1$ cm $\times$ 2.0 cm and a conical hole in the center. Setup of the scans is shown in Fig. 10.

The $^{137}$Cs source was placed 12.0 cm in front of the 2 detectors, and we measured the flood-field image data when the object was not inserted. The average of counts over 48 channels was about 900. Then the tungsten object was inserted 5.0 cm from the $^{137}$Cs source and moved perpendicular to the detector surface in 9 increments of 1.2 mm. Counts of each step were normalized by the flood-field image data and are shown in Fig. 11. From the figure, the central hole and the outer edge of the tungsten cylinder are clearly visible. We can also see that the image obtained with the second detector cannot be spliced above the 8th data of the first detector, because photons are not incident parallel to the detector. We can expect this splice when the photon source is placed far enough from the object, indicating that we can image an object in a single irradiation when tens of strip detectors are stacked. As a result, the dose to environment and imaging time can be greatly decreased. We are now constructing
a compact imaging system consisting of 20 stacked silicon strip detectors.

5. Conclusion

We developed a high-energy X-ray/gamma-ray imaging system for nondestructive testing of concrete structures. The detector module consists of 20 stacked a-Si/c-Si heterojunction strip detectors and 48-channel ToT ASICs. Benefitting from the stacked edge-on geometry, a 2D image can be obtained with a single irradiation. Time consumption and radiation dose to the environment can be greatly decreased using this system.

We fabricated an a-Si/c-Si heterojunction strip detector, which greatly simplifies the fabrication procedures and is suitable for mass production at low cost. The detector has an energy resolution of 2.8 keV FWHM at 59.5 keV. We stacked two edge-on detectors and obtained images of a tungsten object using a $^{137}$Cs source.

Acknowledgements

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References

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