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R&D activities of FAZIA upgrade in Korea

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Summary. — The FAZIA detector is designed to identify charges and masses of fragments from heavy-ion collisions within an energy range of several tens to a hundred MeV per nucleon. One basic unit of FAZIA consists of three layers: the first two layers are Si sensors with different thicknesses of $300\,\mu$m and $500\,\mu$m, respectively, while the third layer is a 10 cm CsI(Tl) scintillator coupled with a photodiode detector read out. The detector signals are analyzed using digital signal processing based on the FPGAs. The current module enabled the charge identification of nuclei with Z up to 54 and the isotopic nuclei discrimination with Z up to 25 by using the ΔE-E information and the pulse shape analysis. The FAZIA upgrade project aims to extend the beam energy coverage and increase the acceptance capabilities. The Korea FAZIA team is going to develop thicker and thinner Si sensors and make the compact and versatile FEE card to meet upgrade goals. This paper describes the R&D process for the Si sensors and FEE card.

1. – Introduction

FAZIA, which stands for "Forward-angle A and Z Identification Array", consists of a three-layer structure, including two Si sensors with thicknesses of $300\,\mu$m (Si1) and $500\,\mu$m (Si2), along with a 10 cm CsI(Tl) scintillator coupled with photodiode detector (CsI). The FAZIA telescope is designed to detect the charges and masses of fragments emitted in heavy-ion reactions at Fermi energy levels. The telescope has an active area of $20 \times 20\,\mathrm{mm}^2$ in the forward direction. A single FAZIA detector module is composed of 16 telescopes arranged in a 4×4 matrix, referred to as a FAZIA block. The block covers a forward polar angle from 1.4° to 12.6° and is located one meter away from the heavy-ion reaction target. The detector's frame behind sets up eight front-end electronic (FEE) cards for data processing, which interprets detector signals using digital signal processing implemented on the FPGAs [1], and the detector operates with a copper cooling plate in vacuum. Outside the vacuum, the electronic system additionally consists of a regional board and block card for data transfer. The current FAZIA detector can discriminate nuclei up to $Z \sim 54$ and masses up to $Z \sim 25$ thanks to the ΔE-E technique [2] and the pulse shape analysis [3].

This paper describes the research and development efforts by the Korean research team to fabricate both thinner and thicker Si sensors, as well as the progress of the next version of FEE [4]. The production process for 750 μm and 115 μm thick sensors is also discussed.

2. – The Si sensor development

2˙1. *Sensor fabircation*. – To investigate 750 μm and 115 μm thickness Si sensor, we used Synopsys TCAD simulation to design a silicon PiN diode. The structure consists of highly doped p-type region and n-type regions on either side of intrinsic silicon, with one main guard ring and eight sub guard rings doped with boron, as well as a channel stop structure doped with phosphorus at the edges. As shown in fig. 1, the blue regions indicate boron doping, the red regions indicate phosphorus doping, and the green region represents low-concentration phosphorus doping. The simulation provides a leakage current of a few tens of nA per cm^2. Additionally, the electric field within the silicon structure was confirmed to be influenced by design of the guard rings and channel stop. We also confirmed the breakdown voltage, which could be optimized by adjusting the design of the guard rings.

Based on the TCAD simulation, we optimized the process parameters, including doping concentration, the growth and deposition of insulators and metal layers, and etching thicknesses. Photomasks were also designed to create patterns on the silicon wafer (fig. 2 (left)) using CAD software. The production was carried out by the Electronics and Telecommunications Research Institute (ETRI) in Korea. Two types of silicon wafers were used, with thickness of 750 μm and 625 μm, respectively. The 625 μm wafer with highly doped substrate include two variations, each with high-resistivity epitaxial layers of 100 μm and 50 μm thickness. The production was successfully completed (fig. 2 (right)). In the case of the 100 μm epitaxial wafer, we removed the substrate, leaving a 100 μm epitaxial layer and a thin substrate layer, targeting a final thickness of 115 μm to minimize the effects of thickness non-uniformity during fabrication. For the fabricated

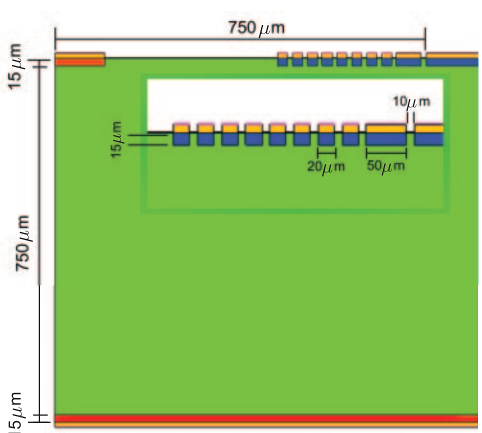

Fig. 1. – The sensor schematic in TCAD tool.

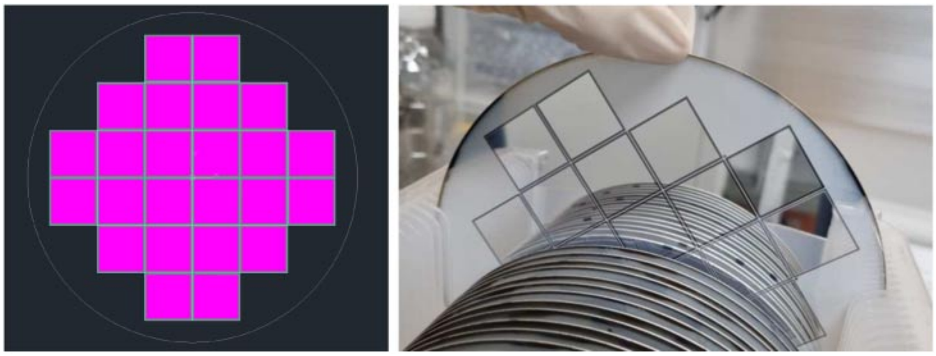

Fig. 2. – Left: the photomask layout for the sensor patterning in CAD design. Right: the processed wafers.

Si sensors, dark current was measured using probe stations, and it remained in the range of a few nA until the full depletion was reached.

2˙2. *Sensor performance*. – The fabricated Si sensors were mounted on a frame designed to minimize dead zone, which was made of Ergal aluminum alloy. The four sensors were grounded by attaching them to the frame with silver conductive epoxy paste. Wire bonding was then used to connect the sensors to four flexible printed circuit cables attached to an appropriate bonding surface. This surface was patterned with thicker metal in certain areas to facilitate connections (fig. 3). The assembly process was carried out at MEMSPACK in Korea.

The Si sensors were connected to a charge-sensitive preamplifier (Cremat's CR-110-R2.2), which was further connected to an Ortec's 671 spectroscopy amplifier. The sensor was kept in a vacuum environment. To measure its energy resolution, an americium-241 (Am-241) coin source, primarily emitting alpha particles, was placed on the sensor. A reverse bias voltage of 100 V was applied to the sensor, achieving an energy resolution of 0.49% Full Width at Half Maximum (FWHM) (fig. 4). Additionally, the energy separation of alpha particles from different energy levels of Am-241 was well discriminated.

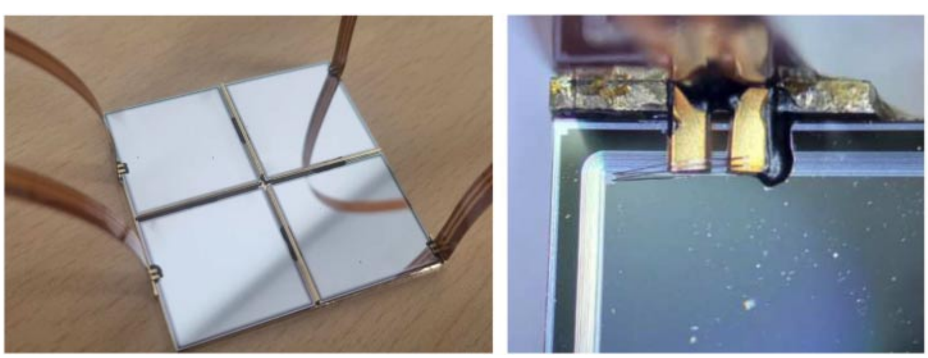

Fig. 3. – Left: gluing one frame to Si sensors using conductive epoxy. Right: wire bonding pad to flexible cable.

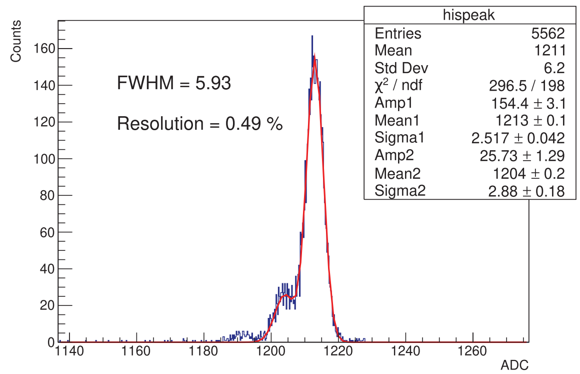

Fig. 4. – Peak distribution of detection signal from Si sensor with Am-241 source.

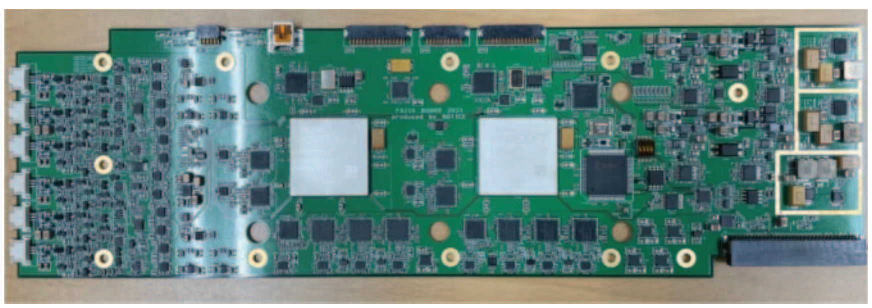

Fig. 5. – The prototype board produced by NOTICE.

Radiation hardness tests were performed on the sensors. The sensors were irradiated with a proton beam at a fluence of the order of $10^{11}/\text{cm}^2$ at Korea Multi-purpose Accelerator Complex (KOMAC). After irradiation, the leakage current of the sensors increased to several tens of μA.

3. – The front-end electronic development

The single FEE card, which contains a variety of components, including charge-sensitive preamplifiers, ADCs, high-voltage regulators, and FPGAs, is capable of connecting a total of six signals, consisting of two Si1, two Si2, and two CsI. For the FAZIA upgrade, the FEE system is essential for processing signals from the Si sensors and ensuring accurate charge and mass identification of detected fragments. The FEE card design replaced outdated elements with a FPGA chip that provides the same functionality and was simplified in collaboration with the company NOTICE (fig. 5).

4. – Conclusion

In this paper, we described the successful completion of the design and production process for the 750 μm and 115 μm Si sensors developed by the Korean team in collaboration with ETRI. Additionally, the process of the wafer of 50 μm is also in progress. Performance measurements for these sensors are currently ongoing and show promising results in terms of energy resolution and radiation hardness. Furthermore, the prototype FEE board was produced in collaboration with NOTICE.

In the future, the Korean team will focus on the production of sensors and FEE cards to construct a complete FAZIA block. The next version of the FEE board is in the design phase, and we plan to further optimize the system to achieve even better performance. These developments will contribute to the overall goal of the FAZIA upgrade project, which aims to extend energy coverage and improve the acceptance capabilities of the detector.

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