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SOI pixel sensor opens a new era of particle and nuclear physics

A pixel detector plays an important role in particle physics to study decay of short lived particles involving heavy quarks or the τ lepton with excellent time and spatial resolution under harsh radiation environment in a high luminosity particle accelerator.

In silicon-on-insulator (SOI) technology, CMOS (complementary metal oxide semiconductor) circuits are fabricated on a thin SiO_2 insulating layer (buried oxide, BOX) on the silicon substrate. As each circuit element like a transistor is isolated on BOX, parasitic capacitance and leakage current are minimized in an SOI circuit realizing an ideal characteristic beyond that of a normal CMOS. A pixel sensor using SOI technology (SOIPIX) would, therefore, serve as an excellent particle detector, where charges induced by radiation in the silicon substrate (bottom) are collected and processed in the CMOS circuit (top) on the BOX (Fig. 1). The small feature size of CMOS helps to realize high performance, monolithic pixel sensors.

The SOIPIX collaboration was formed in 2005 to develop generic SOI pixel sensor technology [1] when the KEK Detector Technology Project (KEKDTP) [2] was founded. With the KEKDTP support, an intensive R&D program for pixel sensor was initiated using the SOI CMOS technology of Lapis Semiconductor Co., Ltd., a leading company that provides foundry services for SOI devices. Development of a large area X-ray 2D image sensor was the first goal of this project, which has since been achieved and the device widely used in experiments of material science.

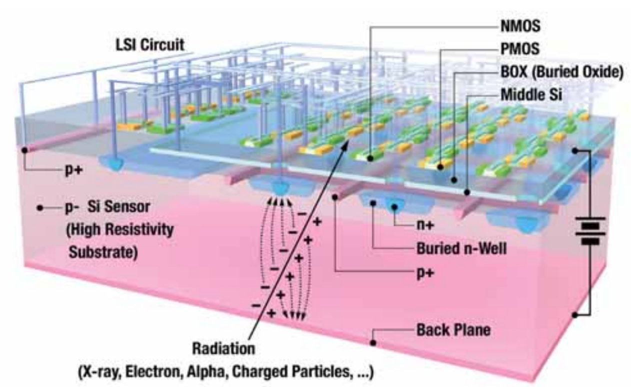

Fig. 1. Concept of the SOI pixel sensor.

Recent improvement of the SOIPIX structure with an additional silicon layer on BOX enables to compensate the effect of accumulated charge due to radiation and makes the sensor radiation-tolerant, even in a harsh environment as high as 1 MGy at a collision point of high luminosity collider experiments like SuperKEKB [3].

In January 2017, a group in the SOIPIX collaboration working for particle physics (*) performed a beam test with 120 GeV protons at the Fermi National Accelerator Laboratory (Fermilab), USA [4] (**),

Fig. 2. SOIPIX sensor stack involving four FPIX2 and two SOFIST1 sensors used for the beam test in Fermilab.

(*) KEK, Tohoku University, University of Tsukuba and Osaka University. Work supported by JSPS (Japan Society for the Promotion of Science) KAKENHI Grant Number JP25109006.
(**) Supported by Japan-US cooperative program in High Energy Physics.

to demonstrate the capability of SOIPIX sensors for particle detection. Two types of sensors, FPIX2 [3] and SOFIST1 [5] were tested. FPIX2 is characterized by an ultra small pixel size (8 μm × 8 μm). SOFIST1 is designed with a pixel size of 20 μm × 20 μm for good measurements both in charge and timing for the International Linear Collider (ILC) [5]. Four FPIX2 and two SOFIST1 sensors were integrated into the test setup (Fig. 2). A total of 5.6M proton tracks were recorded during the data acquisition period of three weeks. After careful and fine alignment of the sensors, the proton trajectories were reconstructed using FPIX2 sensors; here, the impact points were precisely calculated in a charge centroid algorithm among several pixels. Accuracy of spatial measurement is evaluated in terms of residual distribution, which is defined as the shift of the proton impact point from the measured value by the target sensor to that traced by other sensors. Figures 3 shows

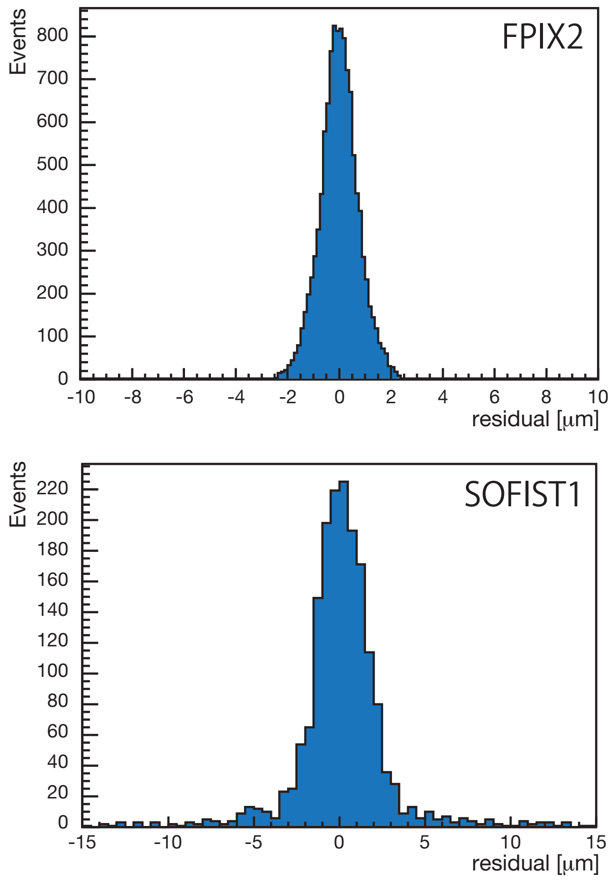

Fig. 3. Residual distribution for FPIX2 (top) and for SOFIST1 (bottom). Residual is defined as a measure of spatial resolution by a shift from the proton incident position measured by the target sensor to that traced with the other sensors. FPIX2 clearly demonstrates the world's best resolution significantly better than 1 μm.

such a residual distribution demonstrating the positioning accuracy of better than 0.89 μm and 1.4 μm in chip FPIX2 and SOFIST1, respectively. A Monte-Carlo simulation confirmed that the above distributions could be reproduced with an intrinsic spatial resolution of 0.7 μm in FPIX2.

The sub-micron (<1 μm) spatial resolution achieved by the SOIPIX group in KEKDTP signifies a first time achievement in the history of particle detectors. Realization of ultra small pixel size and extreme level of accuracy in spatial measurement is likely to open a new era of particle and nuclear physics research.

References

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