Development of a Novel Silicon Stripixel Detector for RHIC-PHENIX Detector Upgrade

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***Abstract*—A new single-sided silicon strip detector has been developed for the silicon vertex tracker of the PHENIX detector at the Relativistic Heavy Ion Collider in Brookhaven National Laboratory (BNL). The novel "stripixel" detector concept developed by the BNL Instrumentation Division was applied to the first prototype silicon sensor. The novel feature of the stripixel concept is two-dimensional (2-D) position sensitivity with single-sided processing achieved by charge sharing between two interleaved electrodes in one pixel. Signals are read out projectively by double layers of aluminum strips. The first prototype stripixel sensors with the size of 34.3 $\times$ 64.6 mm and thickness of 250 and 400 μm were fabricated. The detector with readout electronics was constructed to evaluate the prototype sensor performance by using an analog multiplexer chip with charge sensitive preamplifier-shaper circuits (VA2 chip of IDEAS). The sensor performance on charge sharing, detection efficiency, signal-to-noise ratio, and position resolution has been tested with a radioactive source and a GeV particle beam at KEK-PS. The stripixel detector concept, the specification of the first prototype stripixel sensor, and the test results are presented.**

***Index Terms*—PHENIX, Relativistic Heavy Ion Collider (RHIC), silicon detector, stripixel detector, vertex detector.**

I. Introduction

THE PHENIX detector [1] at the Relativistic Heavy Ion Collider (RHIC) [2] in Brookhaven National Laboratory (BNL) has shown its physics capability of the baseline detector system since its operation started in 2000. The physics goals are to study a deconfined state of nuclear matter called the Quark Gluon Plasma (QGP) and its properties with heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV and to elucidate the spin structure of the proton with polarized proton collisions at $\sqrt{s} =$ 200–500 GeV.

To enhance the physics capability, a silicon vertex tracker (VTX) has been proposed as one of the major upgrades of the PHENIX detector [3]. The expected detector performances with the VTX are heavy flavor (charm and bottom) tagging with displaced decay vertices and better jet reconstruction with large acceptance charged particle tracking. The VTX consists of four cylindrical layers of silicon detectors, which are hybrid silicon pixel detectors in the innermost layer and silicon strip detectors in the outer three layers. A new single-sided silicon strip detector has been developed for the three outer layers in the VTX.

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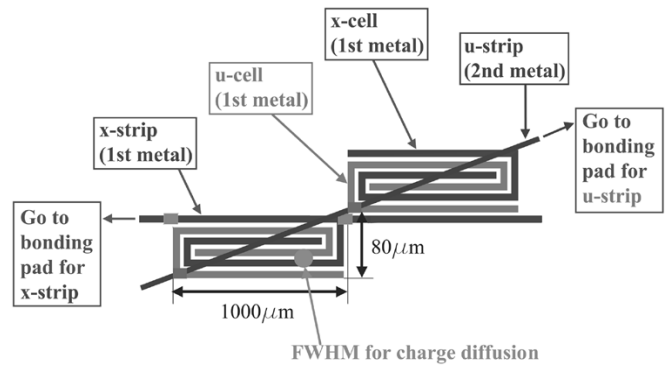

Fig. 1. Stripixel detector concept (top view, not to scale). Only two diagonally adjacent pixels with the corresponding two strip (x-strip and u-strip) readout lines are shown.

II. Novel Silicon Stripixel Sensor

A. Stripixel Detector Concept

The "stripixel" detector concept [4], [5] developed by the BNL Instrumentation Division was applied to the first prototype sensor for the PHENIX VTX strip detector layers. A novel feature of the stripixel concept schematically illustrated in Fig. 1 is two-dimensional (2-D) position sensitivity with single-sided processing achieved by charge sharing between two interleaved electrodes in one pixel. Collected charges are projectively read out by double layers of strips. The n-bulk silicon sensor with $p^+ - n - n^+$ diode structure has an array of pixels in the p^+ side (junction side). Two independent electrodes, x-cell and u-cell, are interleaved in one pixel and are DC-coupled to aluminum lines in the first metal layer. The x-cells are connected by a readout line, x-strip, in the first aluminum layer and the u-cells are connected by a readout line, u-strip, in the second aluminum layer. The two aluminum layers are separated by a polyimide layer. Two-dimensional position sensitivity is

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TABLE I
THE SPECIFICATION OF THE FIRST PROTOTYPE STRIPIXEL SENSOR FOR THE PHENIX VTX STRIP DETECTOR LAYERS

Silicon bulk	n-type
Resistivity	$4-6\,\mathrm{k\Omega\cdot cm}$
Silicon wafer size	4" in diameter
Thickness	400 μm and 250 μm
Sensor diode structure	p^+-n-n^+
Sensor size	34.3 mm $(r\phi)\times$ 64.6 mm (z)
Active area	30.7 mm $(r\phi)\times$ 30.0 mm $(z)\times 2$
Edge dead space	1.8 mm
Pixel pitch	80 μm $(r\phi)\times$ 1000 μm (z)
Number of pixels	384 $(r\phi)\times$ 30 $(z)\times 2$
Electrode (cell) shape	Spiral, 3 turns
Electrode (cell) lines	7 μm line, 6 μm gap
Number of cells per strip	30
Polyimide layer thickness	$2-4\,\mu$m
x- and u-strip stereo angle	4.6°
x-strip line width	20 μm
u-strip line width	16 μm
Number of strips	384×2 (x-strip), 384×2 (u-strip)
Number of bonding pads	384×2 (x-strip), 384×2 (u-strip)
x-strip bonding pad size	120 μm $(r\phi)\times$ 205 μm (z)
u-strip bonding pad size	125 μm $(r\phi)\times$ 105 μm (z)
Bonding pad pitch	80 μm

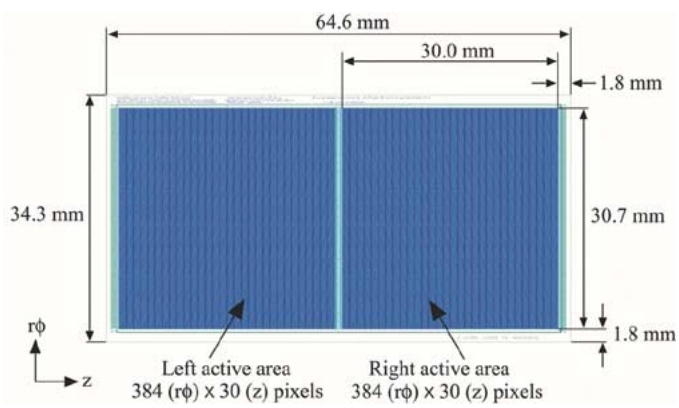

Fig. 2. A layout of the prototype stripixel sensor for the PHENIX VTX strip detector layers.

achieved by sharing of collected charges between x-cell and u-cell, which are projectively read out by x-strip and u-strip.

B. Prototype Stripixel Sensor for the PHENIX VTX Strip Detector Layers

The first prototype stripixel sensors for the PHENIX VTX strip detector layers were fabricated [6]. The specification is summarized in Table I. Layouts of the sensor are shown in Figs. 2–4. The sensors were processed on 4–in-diameter n-type high-resistivity (4–6 k$\Omega\cdot$ cm) silicon wafers with thickness of 400 μm and 250 μm. The sensor has the size of 34.3 mm $(r\phi)\times$ 64.6 mm (z) and has two left-right mirror symmetric active areas of 30.7 mm $(r\phi)\times$ 30.0 mm (z). Each active area is composed of 384 $(r\phi)\times$ 30 (z) pixels with 80 μm $(r\phi)\times$ 1000 μm (z) pitch. Two interleaved spiral-shaped electrodes (x-cell and u-cell) have the line width of 7μm and the line gap of 6 μm. The x-strip readout line connects 30 x-cells in z-direction and the u-strip readout line connects 30 u-cells diagonally. A

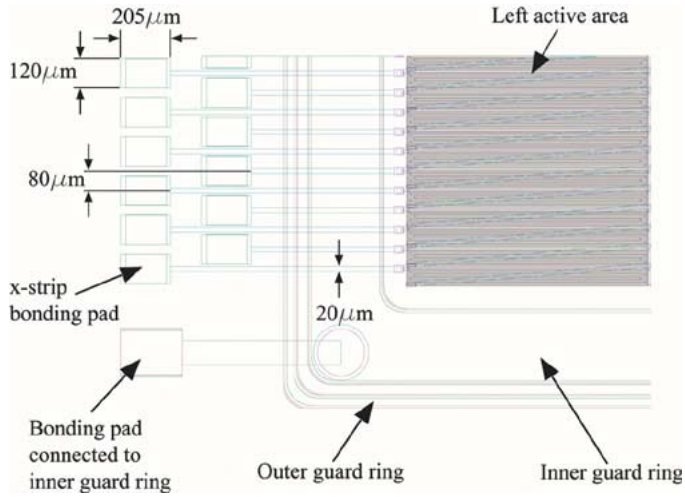

Fig. 3. A layout enlarged in the left-bottom side of the prototype sensor.

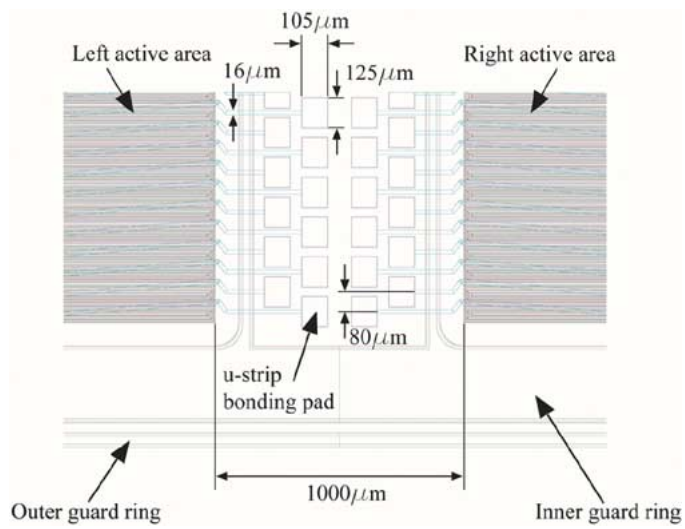

Fig. 4. A layout enlarged in the center-bottom side of the prototype sensor.

stereo angle between x-strip and u-strip is 4.6°. There are 384 x-strips with wire-bonding pads in the left (right) side and 384 u-strips with wire-bonding pads in the right (left) side in the left (right) active area. The wire-bonding pad pitch is 80 μm.

Both I–V and C–V characteristics of single strips have been measured on the wafers in the initial electrical tests to check the leakage current, full depletion voltage, and the capacitance at full depletion [6]. The strip current stayed at about a few nA up to a bias voltage of 400 V. The strip capacitance was about 10 pF at the full depletion voltage of about 80 V.

III. PROTOTYPE DETECTOR

A prototype detector has been fabricated to evaluate the performance of the stripixel sensor. The detector was designed for reading out signals from only the half of the sensor. Fig. 5 shows a picture of the prototype detector.

The detector consisted of the stripixel sensor, six analog readout chips, a base board, two fanout boards (pitch adaptors), and two SMT boards. The sensor was mounted on the base board made of BT resin. The left half of the sensor back plane (ohmic side) was glued with a silver-filled conductive epoxy

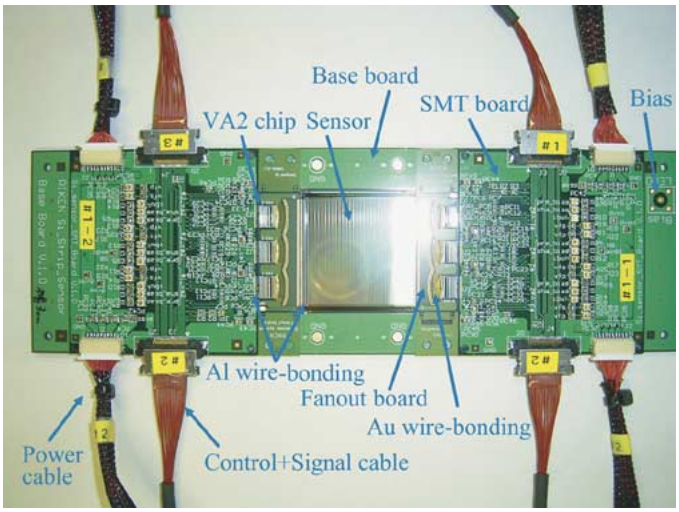

Fig. 5. Prototype detector with read out of the right half of the stripixel sensor.

(Loctite 3888) to one of layers of the base board to apply a positive bias voltage. The sensor was wire-bonded to the fanout board with aluminum wires (30 μm in diameter). The fanout board was made of BT resin. It was designed to electrically connect the sensor and the readout chips with a gold wire (23 μm in diameter) by matching the difference between the pitch of the sensor (80 μm) and that of the readout chip (45.6 μm). The VA2 chip of IDEAS[1] , an analog multiplexer chip with 128-channel charge sensitive preamplifier-shaper circuit, was used to read out a signal from the sensor. The preamplifier has a 1–3-μs peaking time and a nominal gain of 30 mV/pC. Three VA2 chips were wire-bonded to the four-layer SMT board with aluminum wires (30 μm in diameter). The SMT board was designed to operate the VA2 chips and read out multiplexed analog signals. Six VA2 chips (three chips for 384 x-strips and three chips for 384 u-strips) in one detector were sequentially read out with the VME-based data acquisition system, using a set of modules, CAEN V550 and V551B, suitable for dealing with analog multiplexed signals.

Seven detectors with three 400 μm thick sensors and four 250 μm thick sensors were constructed for testing the sensor performance.

IV. Performance Tests

The sensor performance on charge sharing, detection efficiency, signal-to-noise ratio, and position resolution has been evaluated with a ^{90}Sr β-source (2.283 MeV) and a test beam at KEK. In the source test, a three detector telescope was operated with the source located upstream of the first detector and a plastic scintillator for the trigger located downstream of the third detector. The beam test was performed at T1 beam line in KEK-PS, which delivered a positively charged particle beam with momentum of 0.50–2.00 GeV/c. A seven detector telescope operated with trigger plastic scintillators placed upstream and downstream of the telescope. One detector in the middle of the telescope could be rotated with respect to the vertical direction (z-direction in Fig. 2) to change the beam incident angle.

[1]http://www.ideas.no/

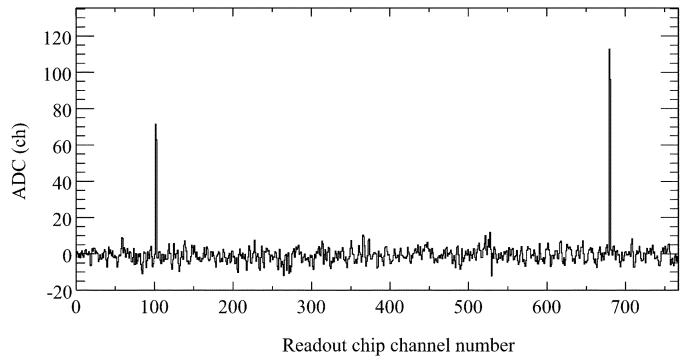

Fig. 6. Collected charges [ADC (ch)] for a typical event detected by one detector as a function of readout chip channel number (1–768).

A. Charge Sharing

Charge sharing between the x- and u-cells can be characterized by the asymmetry, $\mathcal{A}_Q = (Q_x - Q_u)/(Q_x + Q_u)$, where Q_x and Q_u represent collected charges in x-strip and u-strip, respectively. With a good charge sharing, the $\mathcal{A}_Q$ distribution should be a narrow peak with the mean at zero. Its width depends on the incident particle angle θ. The widest distribution is expected for perpendicular crossings $\theta = 0°$ and it becomes narrower as θ increases.

Fig. 6 shows collected charges [ADC (ch)] for a typical event detected by a one detector telescope as a function of readout chip channel number (1–768). The channel number 1–384 correspond to x-strips and the channel number 385–768 correspond to u-strips. Two-dimensional position sensitivity by charge sharing can be seen as one peak in the x-strip range and the other peak in the u-strip range. The Q_x and Q_u were obtained by clustering those two peaks.

Fig. 7 shows the $\mathcal{A}_Q$ distributions and the correlations between Q_x and Q_u measured in the beam test and in the source test. The θ-dependence has been observed in the beam test measurements presented in three upper rows of Fig. 7. In the test with the radioactive source, the $\mathcal{A}_Q$ distribution was effectively smeared with the electron incident angle, resulting in its shape and width as for nonzero θ. The quite narrow distributions for $\theta = 15°$ and 30° in the beam test represent the evidence that the stripixel principle is working and that a good 2-D position sensitivity is achievable. However, the broad distribution for $\theta = 0°$ with two peaks at $\mathcal{A}_Q \sim \pm 0.2$ is a clear indication that, for perpendicular crossings, quite frequently, almost all charge is collected either at x-cell or u-cell with little charge sharing. Improvement of the charge sharing is expected by making the finer stripixel structure with the smaller center-to-center distances between x- and u-cells.

B. Detection Efficiency and Signal-to-Noise Ratio

Detection efficiencies and signal-to-noise (S/N) ratios were measured in the beam test. The detection efficiencies were $\sim 97\%$ for the detectors with 400 μm thick sensor and $\sim 60\%$ for those with the 250 μm thick sensor. The S/N ratios were ~ 17 for the 400 μm thick sensor and ~ 9 for the 250 μm thick sensor.

The poorer detection efficiency and the S/N ratio of the detector with 250 μm thick sensor, compared to 400 μm, were

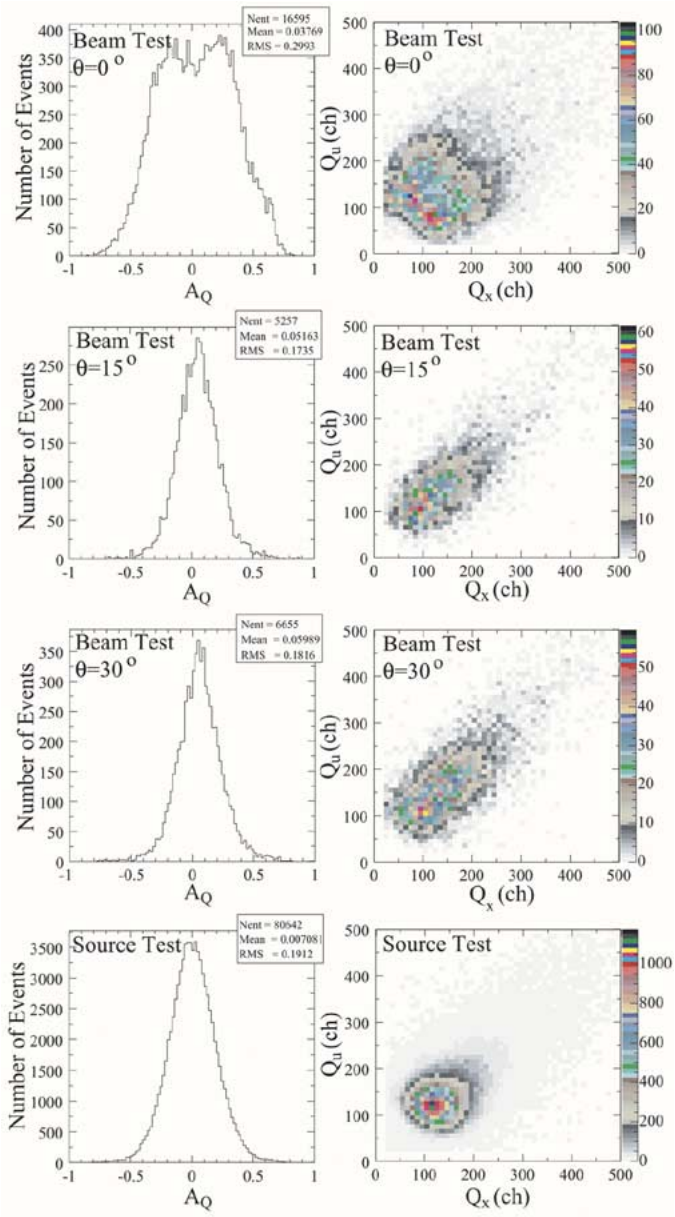

Fig. 7. The $\mathcal{A}_Q$ distributions and correlations between Q_x and Q_u measured in the beam test (three upper rows) and with the radioactive source (bottom row).

mainly due to lower ionization and larger electronics noise. In respect to electronics noise, there is still room for improvements by optimizing the operation condition. The better charge sharing between x-cells and u-cells in the finer structured detector will also contribute to the improvement of the detection efficiency and S/N ratio.

C. Position Resolution

The position resolutions were determined in the beam test by using the measured hit residuals for reconstructed particle trajectories. The expected position resolutions from the pixel pitch of 80 μm $(r\phi)\times$ 1000 μm (z) are $\sigma_x = 80\ \mu\text{m}/\sqrt{12} = 23\ \mu\text{m}$ in x-strip from the $r\phi$-direction pixel pitch, $\sigma_z = 1000\ \mu\text{m}/\sqrt{12} = 289\ \mu\text{m}$ from the z-direction pixel pitch and $\sigma_u = \sigma_x \cos\alpha \oplus \sigma_z \sin\alpha = 33\ \mu\text{m}$ in u-strip, where α and $\oplus$ represent the stereo angle between x-strip and u-strip and the quadratic-sum, respectively.

After deconvoluting contributions of the setup geometry and multiple scattering, the measured position resolutions of the detector were $\sigma_x \simeq 23\ \mu\text{m}$ for x-strip and $\sigma_u \simeq 31\ \mu\text{m}$ for u-strip. These results are in the good agreement with the expectations.

V. Conclusion

The stripixel detector concept developed by the BNL Instrumentation Division was applied to the development of the silicon strip detector for the PHENIX VTX upgrade. The first prototype stripixel sensors of the thickness 400 μm and 250 μm have been fabricated and have been integrated with readout electronics for the performance tests. The performance tests carried out by using the radioactive source and the beam showed the stripixel principle of 2-D position sensitivity by charge sharing is working. The second prototype stripixel sensors with the finer center-to-center distance between x-cell and u-cell lines, which are expected to show the better performance, are currently under processing.

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