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Microelectronics Reliability 45 (2005) 1202–1207

MICROELECTRONICS RELIABILITY

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Monolithic active pixel sensor realized in SOI technology—concept and verification

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Received 1 September 2004; received in revised form 6 October 2004
Available online 2 December 2004

Abstract

The paper presents the concept and the verification of a novel silicon monolithic active pixel detector realized in the SOI technology. The reliability and the basic electrical characteristics of the sensor are studied and the sensor sensitivity to the ionising radiation is investigated in details.

1. Introduction

Silicon active pixel detectors, which consist of a matrix of sensing diodes connected to readout electronics, are modern tools of high-energy physics, medicine, space science and many other disciplines. At present most of the large scale applications relies on hybrid active pixel detectors, in which the sensor and the readout circuit are realized as separate entities [1]. Such approach requires however complicated and expensive bump-bonding process [2] for the connection of these two structures. For this reason nowadays a common trend in the field of highly segmented ionising radiation detectors is the development of monolithic active pixel detectors, that integrate the readout electronics and the particle detector in one entity. This solution of pixel detectors allows not only elimination of the hybridisation process but also enables obtaining thinner devices suitable for inner layers of vertex detectors in particle physics experiments. One of the well-established approaches to the monolithic detectors relies on bulk CMOS technologies and thermal diffusion of the charge generated in a lightly doped epitaxial layer towards collecting N-wells. In such detector however due to the small active volume the charge generated by a minimum ionising particle is small (of order of few hundreds up to 1000 electrons) and only NMOS circuitry may be implemented in the front-end electronics [1,3]. This paper addresses the development of an alternative solution of the monolithic active pixel detector, which exploits a Silicon on Insulator (SOI) substrate for the integration of the particle sensor and the readout electronics. The proposed in the paper method of the sensor realization offers not only an electrical separation of the detector and front-end electronics active volumes,

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doi:10.1016/j.microrel.2004.10.014

but also effective ionising radiation detection and a short charge collection time due to the use of high resistive detector substrates.

The possibilities of the SOI technology use in particle detectors were extensively studied in the nineties [4,5] but the works were not followed by successful implementation in practical applications. Taking advantages of the dynamic progress in the field of the SOI wafers production a novel concept of the SOI sensor, which relies on the commercially available wafer-bonded substrates, has been proposed. The developed method of the detector and readout electronics integration in the SOI substrate together with the sensor reliability and performance tests will be discussed in the following.

2. Concept of the SOI sensor

The concept of the SOI sensor relies on the utilization of both silicon layers (device and support layers) of a wafer-bonded SOI substrate [6]. The cross-section of the SOI pixel sensor is illustrated in Fig. 1. The detector is realized in 300 μm thick, high resistive (>4 kOhmcm) support layer and it has the conventional form of p^+–n junctions. The readout electronics is created in 1.5 μm thick, low resistive device layer and is separated from the detector sensitive volume by 1 μm thick buried oxide (BOX). Both parts of the active sensor are DC coupled by the connection that passes through the silicon film and the buried oxide. Constructed in this way sensor from the functional point of view is similar to the hybrid detectors but does not require any hybridisation process since the electronics and particle detector integration is included in the production steps of the SOI sensor. More detailed description of the SOI detector concept and its fabrication process may be found in [7].

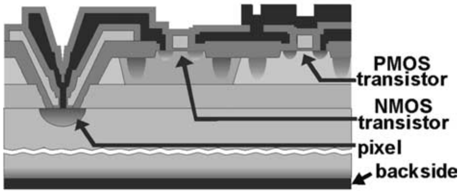


Fig. 1. Cross-section of the SOI pixel sensor.

3. Verification of the SOI sensor concept

3.1. Integration reliability of the pixel diodes and readout electronics in the SOI substrate

In the proposed SOI sensor relatively thick device and buried oxide layers are used to reduce possible cross-talk between the electronics and the detecting volume. Therefore the metal path between both parts of the active sensor has to pass through the steps of significant height and the reliability of the connection becomes an important issue. The solution of the problem together with the microscopic photograph of the realized connection to the pixel is presented in Fig. 2. As it is illustrated, in order to ensure continuous electrical paths, the pixel cavity has V-shape created by anisotropic etching of silicon with $\langle 100 \rangle$ orientation. In addition the surface of the cavity walls is smoothed out by the polysilicon coating, which also prevents the detecting diode from possible contamination during the subsequent technological processes.

In order to investigate the reliability of the pixel-readout channel connection special test structures, which consist of a chain of 100 contact windows to pixel diodes and metal1 serpentine over 100 deep detector contact windows, were designed. The microscopic photographs of the produced test structures are presented in Fig. 3. The performed tests indicated the yield of the proper connections close to 100% and proved the very high reliability of the sensor integration.

3.2. Basic electrical characteristics of the SOI sensor

One of the first steps of the SOI sensor verification was the evaluation of the pixel junction leakage current as the basic parameter of the particle detector. For these measurements a dedicated test structure consisting of pixels with dimensions of $105 \times 105\,\mu m^2$ was used. The obtained results for the best processing are presented in Fig. 4. As it is illustrated satisfactory leakage current values of order of $10\,nA/cm^2$ for a completely depleted detector were achieved.

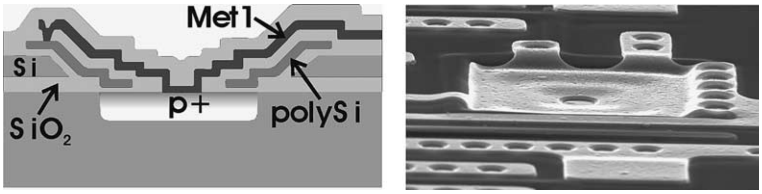


Fig. 2. The cross-section of the connection between the pixel and readout channel together with its microscopic photograph.

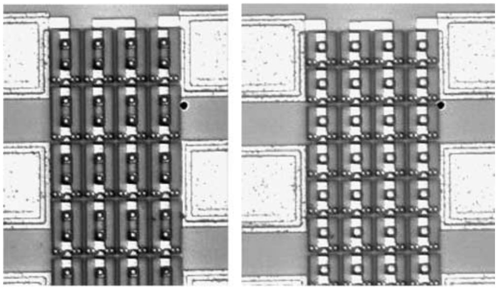


Fig. 3. Fragments of the reliability test structures—a chain of the contact windows to the detector diodes and a metall serpentine over the deep detector cavities.

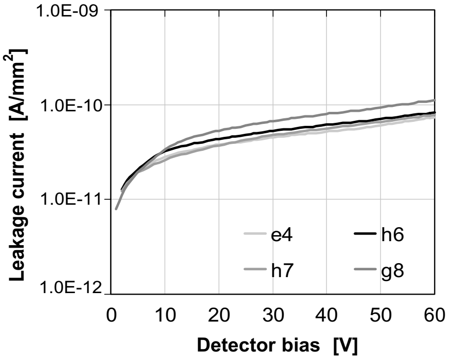


Fig. 4. Detector leakage current per mm^2 versus detector biasing voltage for the best processing and different localization on the wafer.

Further validation of the concept of the SOI detector was performed with more complex test structures, including small matrices of readout channels both with input pads for an external signal source and monolithically integrated detector diodes. These test structures allowed characterization of bare front-end electronics realized in non-standard SOI technology and extensive tests of the complete structure of the SOI sensor. The schematic views of the readout channels implemented on the test structures are presented in Fig. 5. Both presented configurations have the structure similar to the typical three transistor cells [3], but in contrary to the conventional solutions, widely used in the CMOS sensors, the reset transistors of the opposite type than the input transistors are used to achieve faster discharging of integrating capacitances. Moreover additional diodes are added to protect the readout channel from the excessive input voltage coming from the detector bias. For the channel configuration presented in Fig. 5(a), the single-transistor row-selection switch is also replaced by the transmission gate to improve the linearity of the sensor response. The dimensions of the sensor cells on the test structures are 140 µm by 140 µm and 140 µm by 122 µm for the schemes presented in Fig. 5(a) and (b) respectively. The proposed sensor cells allow measurements of the charge generated in the detector volume and integrated on the pixel capacitance during a given time period and they are optimised for high particle fluxes, as it is required in some imaging applications of the SOI detector [8]. The tests of the readout channels with external voltage pulse signal indicated the input dynamic range corresponding to the charge generated by 180 and 85 minimum ionising particles (MIPs) for the structures with transmission gate and single-transistor switch respectively.

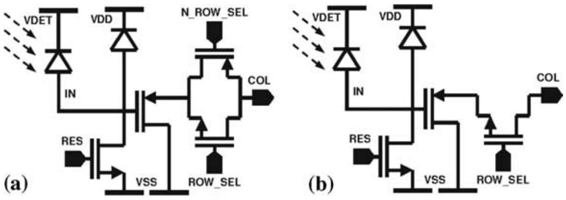


Fig. 5. Schematic views of the detector cells implemented on the SOI detector test structures.

Complementary linearity and dynamic range measurements for the complete SOI sensor (with integrated sensing diodes) were performed for the matrix of the cells designed as illustrated in Fig. 5(b). The applied test method relied on the measurements of the average value of the sensor output signal for the charge generated by a different number of the infrared laser pulses, simulating the particles passing through the detector volume. During these tests the backplane of the completely depleted detector was exposed to the laser light of the 850 nm wavelength. The detector was biased via a metal mesh with rectangular holes to avoid light reflections. For every number of 4 µs wide light pulse injected during integration time (1 ms) 10000 events was recorded and the results were averaged. The chart presented in Fig. 6 shows the relation between the input charge and the measured values of the output signals after correlated double sampling processing (CDS) and a pedestal subtraction. The detector sensitivity for the ionising radiation and the linear response as a function of the generated charge in the investigated range of 45 MIPs can be observed.

3.3. Measurements of the SOI senor performance with radioactive source and DAQ system

More advanced tests of the SOI sensor were performed with a multifunctional data acquisition (DAQ) system with implemented advanced analogue electronics and algorithms. The system (called SUCIMA Imager) was developed at the Institute of Nuclear Physics in Krakow for the purpose of "Silicon Ultra-fast Cameras

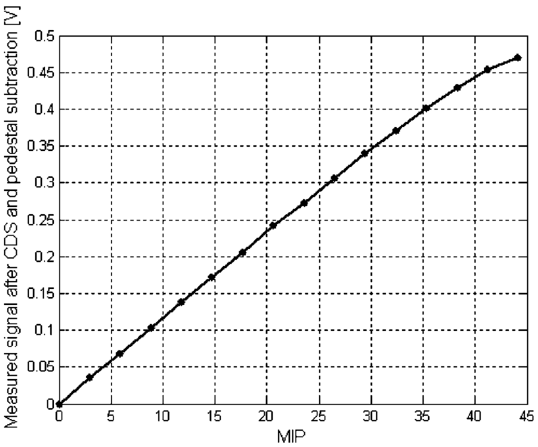
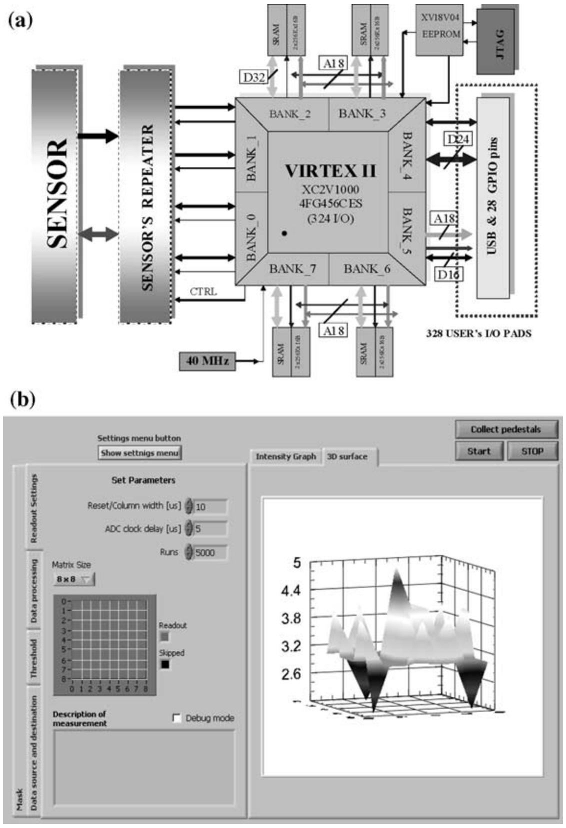


Fig. 6. Output signal (after CDS and pedestal subtraction) from the test structures of the SOI sensor versus generated charge.



Reset/Column width [us] 10
ADC clock delay [us] 5
Runs 5000
Matrix Size 8x8

Fig. 7. (a) Architecture of the SUCIMA Imager board, (b) graphical user interface for SOI detector readout.

for Electron and Gamma Sources in Medical Applications" project [8]. The block diagram of the SUCIMA Imager is presented in Fig. 7(a). As it is illustrated the system is equipped with four independent analogue input channels (each with 12 bit analogue-to-digital converters and a 1MB fast Static RAMs), the FPGA Virtex II XC2V1000 chip for advanced algorithms and the high speed USB 2.0 port for a fast data transfer to and from a PC computer. The SUCIMA board may perform and supervise all the functionalities required for the fast analogue data readout, sampling, digitisation, signal processing, data selection and compression, storage and fast data transmission to a PC computer [9]. The DAQ system is connected to the graphical user interface (GUI) program via the Dynamic Link Library with the USB2.0 port service. The presented in Fig. 7(b) GUI is developed in LabVIEW environment and according to the requirements of the SOI detector it allows a number of settings: the matrix size to be readout, the pulse width of the readout clock, the ADC clock delay, the number of the readout runs and the operation mode of the DAQ system (last frame or CDS readout). The interface enables also masking noisy pixels, subtracting pedestals, suppressing signals bellow threshold and exporting data to the ASCII file.

The SUCIMA Imager was used for the SOI sensor tests with alpha and beta particles from the Americium 241 (Am241) and Strontium 90 (Sr90) radioactive sources. During the tests with Am241 the source of alpha particles with initial energy of 5.5 MeV was positioned at the distance of 1 cm from the detector backplane. For the given detector-source distance and the initial energy of the particles the most probably particles range of 22 μm and energy deposited in silicon of 4.5 MeV were simulated with the SRIM software [10]. The alpha emission spectrum was measured at the detector bias of 70 V (above full depletion) and the integration time of 720 μs. An example of the recorded events in the detector is presented in Fig. 8 and the spectrum of alpha particles after the pedestal subtraction, the common mode suppression and the cluster search is presented in Fig. 9(a). As it is illustrated a broad spectrum was obtained due energy straggling in air and the large distant between the detector and the source. The typical

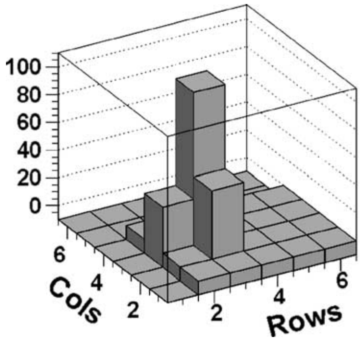


Fig. 8. Recorded event in the detector. Tests performed with alpha source.

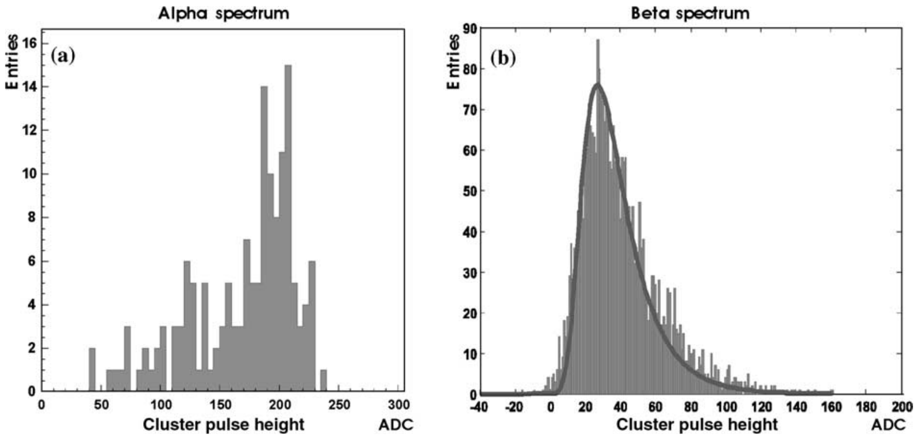


Fig. 9. (a) Alpha particle emission spectrum obtained with Am241 source positioned at the distance of 1 cm from the detector backplane. (b) Landau distribution of beta particles from Sr90 source. Spectra obtained for different DAQ settings.

value of 200 ADC was measured at the signal to noise ratio of about 130. The obtained results of the measurements of the alpha particles spectrum proved high dynamic range of the sensor and its sensitivity for particles with limited range in silicon.

The SOI detector sensitivity for minimum ionising particles was studied with the Strontium 90 (Sr90) beta source. Like for the tests with americium source, the beta energy spectrum was measured for completely depleted detector at the integration time of 720 μs. During these tests however the sensor output voltage was amplified before digitalisation (different DAQ settings than in the previous paragraph), since the sensor is optimised for high particle fluxes and the output signal for a MIP is low. The obtained histogram after the CDS processing, the pedestal subtraction and the cluster calculation is presented in Fig. 9(b). As it was expected a Landau distribution of the recorded signals was obtained and the most probably value of 27 ADC counts corresponding to the MIP signal was measured at the signal to noise ratio for the clusters of about 4.5.

4. Conclusions

The paper summarised the concept and the verification process of a novel monolithic active pixel sensor realized in SOI technology. The large dynamic range, sensitivity for minimum ionising radiation and particles with limited range in silicon were demonstrated for the new detector is series of measurements with radioactive sources and infrared laser spot. The obtained results show that the proposed solution of the monolithic sensor may be attractive option for the future particle physics experiments and medical equipment. Currently the production of fully functional and large area ($2 \times 2\,\mathrm{cm}^2$) SOI sensors is in progress. These sensors may find a use in various applications and their characterization will be a next step of the development.

Acknowledgment

The authors would like to thank the team of the Institute of Nuclear Physics in Krakow—A. Zalewska, A. Czermak, B. Dulny and B. Sowicki—for making available the SUCIMA Imager DAQ system for the tests of the SOI sensor.

Development of the SOI pixel detector is supported by the European Union GROWTH Project G1RD-CT-2001-000561.

References

[1] Wermes N. Trends in pixel detectors: tracking and imaging. IEEE Trans Nucl Sci 2004;51/3:1006–15.
[2] Broennimann Ch, Horisberger R. Bump bonding technology, 12th International Workshop on Vertex Detectors VERTEX 2003, Low Wood, Lake Windermere, Cumbria, UK, 14–19 September 2003.
[3] Berst JD. Monolithic Active Pixel Sensors for High Resolution Vertex Detectors, Proceedings of 6th Workshop on Electronics for LHC Experiments, Krakow, Poland, 2000. p. 535–9.
[4] Colinge JP. An Overview of CMOS-SOI Technology and Its Potential Use in Particle Detection Systems. Nucl Instrum Meth Phys Res A 1991;305:615–9.
[5] Dierickx B, Wouters D, Willems G, Alaerts A, Debusschere I, Simoen E. Integration of CMOS-Electronics and Particle Detector Diodes in High-Resistivity Silicon-on-Insulator Wafers. IEEE Trans Nucl Sci 1993;40:753–8.
[6] Marshall A, Natarajan S. SOI Design: Analog, Memory and Digital Techniques. Dordrecht, MA: Kluwer; 2001.
[7] Niemiec H, Klatka T, Koziel M, Kucewicz W, Kuta S, Machowski W, et al., Technology Development for Silicon

Monolithic Pixel Sensor in SOI Technology, Proceedings of the 10th International Conference MIXDES 2003, Lodz, Poland, 2003. p. 508–11.

[8] Caccia M, Airoldi A, Alemi M, Amati M, Badano L, Bartsch V et al.. Silicon Ultra Fast Cameras for Electron and Gamma Sources in Medical Applications. Nucl Phys B 2003;125:133–8.

[9] Czermak A, Zalewska A, Dulny B, Sowicki B, Jastrzab M, Nowak L. Data Acquisition System for Silicon Ultra Fast Cameras for Electron and Gamma Sources in Medical Applications (SUCIMA Imager), 8th ICATPP Conference on Astroparticle, Particle, Space Physics, Detectors and Medical Physics Applications, Como, Italy, 2003.

[10] Available from: <www.srim.org>.