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Review of Ph.D Thesis
New pixel detectors in SOI technology for particle physics applications
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General description

The dissertation consists of four chapters, preceded by the introduction, summary and conclusions, the bibliography followed by the glossary of symbols, list of figures and list of tables. The thesis is written on 123 pages altogether.

The structure of thesis conforms generally to principles and requests to the structure of scientific thesis.

The Author declares that the main objective of the dissertation was to validate the performance and characterization of the prototype of integration type pixel detectors designed in Silicon-On-Insulator (SOI) technology. The SOI pixel detector prototypes were tested to verify their usefulness for future high energy, nuclear physics, satellite and medical applications, where ionizing particle imaging is required. Author focuses his research on the most recent prototypes representing two families designed in SOI technology: *Integration type pixel* (INTPIX3) and *Dual mode integration type pixel* (DIPIX2).

The scientific topic of the dissertation represents the forefront of high granularity semiconductor detectors dedicated to precise tracking of secondary charged particles in high energy collisions, aiming at precise detection of secondary vertices.

Semiconductor position-sensitive detector modules which are used in current HEP experiments are of a hybrid design, consisting of two parts: the sensor wafer and the readout electronics chip. The advantage of this structure is that characteristics of each part can be optimized individually due to independent fabrication of high-resistivity wafer material and low-resistivity electronic readout chip material. The drawback of such design is relatively high "material budget" – significant amount of the passive material in the system what affects the tracking precision due to the multiple scattering of charged particles traversing a multilayer hodoscope. Monolithic active pixel sensors - proposed recently by several groups of developers, allow to expect a significant progress in the technology of solid state detectors of high granularity. One of the main advantages of such a design is lower material budget of a single module with higher granularity of the pixel matrix. One of the options is to fabricate Complementary Metal-Oxide-Silicon (CMOS) device on a SOI wafer. The SOI structure consists of low resistivity material layer for readout which is directly fused via a thin silicon oxide layer with high resistivity wafer of the ionization sensor.

There are several technological developments in the SOI technology that may constitute the standard detection modules used to construct complex tracking systems for future experiments. The study and further development in the field of SOI pixel sensors - if successful - could contribute to the significant progress in the experimental techniques.

CMOS monolithic active pixel sensors which are characterized by the Author in the dissertation have been developed at KEK and fabricated by Lapis Semiconductor Co. Ltd, using 200 nm SOI technology.

The topic of thesis is current and relevant in the context of up-to-date research and development in high granularity radiation sensors for experimental particle physics.

Summary of results

In the dissertation the author presents an interesting class of solid state pixel detectors in SOI technology. Their properties are summarized in the first two chapters of the dissertation. The Author also provides the context of his work in the field of the particle physics experiments.

The state-of-art of SOI pixel detectors at the origin of the research work presented in the dissertation was the design of 2006 by Y. Arai at KEK named INTPIX2. Characterization process of INTPIX2 revealed a severe drawback of the design called by the Author a *back gate effect* (BGE). This effect was the main issue which had to be remediated by the developers as it did not allow the front-end electronics to operate at back bias voltage large enough to assure full depletion of the sensor layer. The issue of BGE was the critical aspect in further development of the SOI pixel technology. The solution proposed for the BGE mitigation was to add the *buried p-well* (BPW) layer in the SOI technology process. This modification should provide a shielding of the sensor electric field by placing lightly doped p-type layer underneath the insulating layer which separates the sensor and the readout transistor. Characteristics of the new structure were studied by Mr Ahmed using numerical simulation tools.

Technology Computer Aided Design (TCAD) simulation, mainly using ENEXSS package, was used to study the impact of BPW parameters on the effect of back gate mitigation. The transfer characteristics of NMOS and PMOS transistors for different BPW sizes and variety of BPW placing with respect to the pixel center were simulated. It was found that it is possible to stabilize fully the transfer characteristics of the IO pixel transistor for bias voltages in the range of 100V if the size of the BPW is large enough. Also the optimization of the BPW position with respect to the pixel center was found to be a critical issue. Mr Ahmed points out that a tradeoff between the BPW size and the pixel size in order to reduce the signal losses caused by increased pixel capacitance with larger BPW. Also the surface distribution of the electric field due to the detector back bias voltage was simulated. In the ideal case, the electric field on the electronic-side face of the Buried Oxide insulating layer should be uniform regardless the voltage applied. It was clearly not the case of the INTPIX2 structure. Mr Ahmed demonstrates in the dissertation the reduction of the field nonuniformity by a factor of four for the BPW size increasing from 1μm to 8μm even for bias voltages as high as 150 V across 250μm sensor of 700Ωcm resistivity. The modelling of the INTPIX pixel structure shows that the BPW technological improvement may allow to cure the main limitation found with INTPIX2 monolithic structure.

The INTPIX3 monolithic sensor family was designed to study the impact of a proposed BPW implementation on the sensor operation. Mr Ahmed investigated characteristics of two prototypes: INTPIX3a and INTPIX3b. Both detectors consist of several pixel topologies which differ in the dimensions of p^+ implant and BPW size/geometry. In total 16 sections of different pixel type layout topologies were designed what allowed verification of the initial hypotheses. The sensors were fabricated on 700Ωm Czochralski n type wafer of 250μm thickness using SOI 200nm process. Precise measurements of signal characteristics done with ^{241}Am source (with a shielding against alpha impact on the sensor) allow to compare performances of different layouts. It is convincingly demonstrated by the Author that the region number 8 of the INTPIX3b allows highest ionization charge collection efficiency and the lowest equivalent noise charge (ENC) among all the structures under investigation. The results confirm that the small BPW area covering both, the p+ charge collecting implant and IO transistors, allows the best performance in terms of charge collection efficiency and the energy resolution. Signals corresponding to 8keV X-ray energy deposit can be separated from the electronic background.

That is very interesting and important result confirming that the designers have deep understanding of the charge transfer processes in the complex structure of a monolithic detector and the technological process of a sensor production is controlled with high precision.

Successful results obtained with INTPIX3 developmental sensor made it possible to construct prototypes of the fully operational multipixel sensor family called by the developers DIPIX. DIPIX detectors were fabricated using three different wafers with different resistivity and conduction type: Czochralski n-type (Cz-n), Float Zone n-type (FZ-n) and Float zone p-type (Fz-p). The Cz-n wafer had similar characteristics as the one used for INPIX3 family, whereas the FZ detectors' wafers were thicker (500μm) and with resistivity of ~2kΩcm and ~7kΩcm for FZ-n and Fz-p, respectively. The long term stability test of the sensors shows that the dark current signals change less than 5% during the 1 hour measurement. It is not clear whether the improvement with respect to the INPIX3 behaviour should be attributed to the pixel layout structure or to the rearrangement of the sensor board with respect to the main readout board. These studies need to be continued in the systematic manner, as the long term stability issue is a fundamental aspect of a successful application of the technique. The drawback of the FZ-n DIPIX2 structure called "hallo effect" limited the detector bias voltage to 80V, hence the full characterization of this prototype could not be performed, but, for bias voltages below 80V, both FZ type structures exhibit similar characteristics.

The most impressive results are achieved for the FZ-p wafer DIPIX2 structure. It has been demonstrated that the full depletion is achieved at the bias voltage of 80V and it remains stable up to the highest voltage of 130V applied. The threshold bias voltage for full detector depletion is consisted with the calculated value for the detector specification. The energy spectra measured for ^{241}Am source X-rays demonstrate that the lowest energy signals corresponding to 8keV can be distinguished from the detector noise. The detector response show good linearity for the whole range of deposited X-rays energies between 8keV and 59.5keV used for the tests. Comparison of the leakage currents measured for Cz-n and FZ-p detectors is confusing as the dark current measured for higher resistivity wafer is by an order of magnitude larger than the one measured for a thinner Cz-n wafer of lower resistivity. Mr Ahmed correctly points on this observation and attributes the effect to the increased current leak at the higher resistivity chip edges. The attempt of the explanation is quite straight-forward. Also the evolution of leakage current and ENC with temperature is not consistent if one assumes pixel leakage only. Nevertheless the leakage current and ENC characteristics should be studied further, as a better understanding of these processes may result in optimization of the DIPIX2 detector layout.

The results of characterization of the FZ-p type DIPIX2 detector presented in the dissertation confirm a very significant progress in monolithic SOI sensor technology. Not all effects observed are fully understood but the developers demonstrate good understanding of the ionization charge transport and are on good track to construct a SOI monolithic pixel detector which should fulfill requirements of particle physics experiments.

<u>Critical remarks</u>

The dissertation is very reach of technical information related to the monolithic pixel detectors developed at KEK and fabricated at Lapis Semiconductor Co., Ltd using improved technology originally developed by OKI Electric Industry. Very large numbers of acronyms in the text does not facilitate reading and understanding of the research and development process described. Some editorial processing of the text would provide better readability and clarity. It would also reduce unnecessary repetitions of information. Also directing a reader to the information which is located later in the text should be avoided. Visible are evidences that the dissertation was edited in a big hurry.

The vocabulary of symbols on pages 101-103 is in my opinion redundant, as it does not list all the symbols used in the text, some symbols are obvious and some of them are listed with different meaning eg. L as distance between planes or length. Instead, the glossary of acronyms used in the text with brief definitions would certainly make the reading easier. Some acronyms used, eg ENC, are not explained in the text leaving the reader to find the meaning of the acronyms by himself.

The link in the text to the Table 4.1 to find the thicknesses of the wafers used is confusing as this data is not presented in the table. There is quite a number of typo errors I noticed in the text, but I'll not list them here.

The notion of an output gain is not correctly employed as the semiconductor detectors do not exhibit the feature of an internal charge gain. The concept of charge sensitivity with a conversion factor in [Volts/unit of charge] should better correspond to the parameters measured.

The general discussion of the detector parameters and the operation criteria which would match specificity of ionization charge detection in particle physics experiments is missing in the dissertation. What values of parameters of the SOI pixel detector performance, in terms of ENC, leakage current, charge sensitivity, charge collection efficiency and SNR, should be achieved to fulfill requirements of an operational detector for HEP experiment? Mr Ahmed reports in the dissertation a successful attempt of thinning a high resistivity FZ-n wafers down to 50 μm, but the loss of the primary charge by a factor of 10 and the issue of much worse SNR expected are not discussed. I'd like to have this issue deeply discussed during the public defense of the dissertation. It would be interesting to present some predictions concerning this topic in the dissertation

Conclusions

Despite some general criticism mentioned above, the dissertation of Mohammed Imran Ahmed describes very interesting and important research work towards designing an operational detection module of high granularity pixel readout with low "material budget". The results presented in the dissertation open new and promising directions for practical implementations of pixel detectors using SOI technology. In particular, this may be a significant step in development of a new generation 2-dimensional detectors for inner layers of tracking systems for future particle physics experiments

The results are original and should encourage other researchers to follow this promising development.

The thesis reaches standards of quality required for PhD thesis. Therefore I recommend Mohammed Imran AHMED to be admitted to further stages of the procedure of awarding degree of Ph.D in physics.

Wojciech Dominik