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Characterisation of “n-in-p” pixel sensors for high radiation environments

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ABSTRACT

This work presents the first held at Liverpool University measurements of pixel sensors with n-type readout implant in the p-type bulk before and after irradiation of samples by 24 GeV protons to doses 7×10^{15} and 1.5×10^{16} protons/cm^2. A comparison is given for two measurement techniques; one based on the FE-I3 readout chip designed for the ATLAS and the other using the Beetle chip developed for the LHCb experiments at CERN.

1. Introduction

In the future luminosity upgrade of the Large Hadron Collider at CERN pixel sensors are anticipated to occupy a larger volume to satisfy the need of increased granularity imposed by the much higher track density. The total surface covered by pixel sensors would go from present ~ 1.8 to 10 m^2 in the upgraded ATLAS detector. This significant increase in area can justify the use of cost-effective p-type silicon bulk instead of present n-type for the n-type readout pixels needed for enhanced radiation tolerance. Savings up to 50% come from avoiding double-sided photolithography required for the backplane of n-type silicon to implant a diode structure there.

The much larger area short strip detectors have already adopted such an approach as a default with 10×10 cm^2 detectors now being delivered. It has been proven that “n-in-p” (n-type readout implant in the p-type bulk) segmented silicon sensors offer radiation tolerance similar to the “n-in-n” ones, fully satisfying the requirements for all pixel layers of the upgraded experiments. On the other hand, the bias voltage required to operate heavily irradiated sensors has to be remarkably high (up to 1000 V for the innermost layers). It must be demonstrated that “n-in-p” silicon pixel detectors can be biased to this level without electrical breakdown or discharges through the overlapping readout chip.

Novel technologies resulting from research and development programmes (R&D) on radiation-tolerant detectors need planning for being transferred to large scale applications for optimisation of performance and expenses. Pixellated detector assemblies (where the electronics is hybridised by bump-bonding to the sensors themselves) are particularly valuable due to high production costs. At the system level, engineering of the front-end services, i.e. power feed, cooling, etc. should provide reliable operation of sensors throughout their lifetime. Having long traditions in design and construction of the silicon tracking detectors [1,2], the Oliver Lodge Laboratory of the Liverpool University can contribute substantially to the ATLAS upgrade.

The “n-in-p” planar technology is being evaluated at Liverpool University as a candidate for the future strip and pixel detectors. It has already been shown [3] that after expected dose of 2×10^{16} neq/cm^2 they still produce signals compatible with 99% efficient tracking. Variety of vendors, low manufacturing costs (the DC-coupled pixel sensors require 3 or 4 mask levels only) and high production yield are evident advantages of the “n-in-p” process in the entire class of semiconductor particle detectors. The paper describes the development programme of planar pixel sensors at Liverpool University in collaboration with the Micron Semiconductor Ltd.[1]

2. Pixel sensor design

Studies of pixel detectors at Liverpool University have started with the preparation of a new wafer containing devices reproducing the geometry of standard ATLAS pixel sensors [4] for a single chip assembly (SCA) based on the FE-I3 chip [5]. The SCA detector with its 2800 pixels has been redesigned to be read out by only two Beetle chips [6]. The new sensor has eight interleaved pixels per column connected to one wire bond pad at the die boundary, Fig. 1. Such a geometry allows for the cluster size measurements up to 7 pixels with 50 μm pitch. In the second version of that detector every other pixel (400 μm long) in the row is connected to the same wire bond pad. The readout pixel matrix consists of 128×16 implants grouped for the column-parallel (APC) or row-parallel (APR) readout. The second metal was needed for the pixel interconnect.

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Fig. 1. Sensor with interleaved readout pixels. Second metal layer provides their interconnect and routing to the wire bond pad. Shuffling of readout channels minimises their cross-talk.

A possibility of wire bonding at room temperature is one major advantage of these detectors for irradiation and annealing studies. Re-use of their bonding pads makes it possible to irradiate them without the readout chip. Furthermore these devices facilitate measurements of the punch-through voltage, inter-strip resistance and capacitance before and after irradiation.

APC and APR devices were manufactured in 2009 by Micron Semiconductor Ltd. on 300 μm thin 6-in. wafer in the double-metal "n-in-p" process on float-zone silicon with 13 kOhm cm bulk resistivity and the p-spray isolation [7]. The wafer includes also strip detectors with bias options and pads for testing the high voltage performance of guard structures and dicing schemes. In addition the RD50 collaboration[2] has provided prototypes of the ATLAS pixel sensors (produced by Micron Semiconductor Ltd. on float-zone p-type silicon with 10 kOhm cm bulk resistivity) which were used for populating the SCAs.

3. Characterisation of sensor layout components

A detailed analysis was needed to characterise the new detector structures including the matrix of readout implants, high voltage termination (multiple floating guard rings) and dicing options. Their influence on the readout electronics (before and after irradiation), their operating limits and tolerance to layout variations were investigated.

Prior to measurements all sensors underwent several HV cycles to the breakdown point with the current limitation at 1 μA. Most of detectors could stand the maximum voltage of Keithley 2410 source-measure unit of 1100 V. For some other devices the HV training (burn-in) has helped to improve the breakdown voltage by almost 30% up to 900 V after which the IV and CV characteristics of pixel sensors were obtained to check that the reverse bias voltage could be applied safely for the full bulk depletion. However, the HV performance of SCA detectors had degraded (probably due to excessive thermal and mechanical stress) after their bump bonding at the Fraunhofer Institute.[3]

The silicon sensors, the SCAs and some test structures were irradiated by protons at IRRAD-1 facility [8] at CERN to doses 7×10^{15} and 1.5×10^{16} protons/cm^2.

3.1. Measurements of readout implants

Each pixel features a punch-through biasing circuit that connects the readout implant to the bias grid through a narrow gap of an accumulation layer. The build-up voltage between the grid and readout implants, called "punch-through voltage" U_{pt}, was measured using a Keithley 6517A electrometer for gap lengths ranging from $L=3$ to 50 μm. The voltage across the gap for unirradiated sensor follows one-to-one the reverse bias voltage applied either to pixels or to the grid. For the APC irradiated to 7×10^{15} protons/cm^2 this dependence is about 50 times weaker. After reaching the value $U_{pt}\approx 1\ \mathrm{V}/\mu\mathrm{m}\times L\ (\mu\mathrm{m})$ the punch-through voltage becomes independent of further increase of the bias voltage for both measurement samples. The readout electronics connected to the pixel sensor has to cope with this voltage. To comply with absolute maximum ratings of deep-submicron CMOS process the potential of the bias grid bump bonded to the FE-I3 chip on the SCA was controlled to be equal to an average potential of pixels. For measurements with the Beetle chip the bias grid of the APC was left floating.

Isolation of pixels from the bias grid (gap resistance) was parameterised as an inverse slope of the IV characteristics with the voltage differential (smaller than U_{pt}) applied between the readout implants and the grid. The number of joined pixels was increased to eliminate the systematic error and for all pixels in parallel their gap resistance at room temperature and before irradiation was in the TOhm range, independent of the bias voltage above 50 V. For the APC irradiated to 7×10^{15} protons/cm^2 the gap resistance of all pixels in parallel at $-25\,^{\circ}$C was 100 kOhm, independent of the bias voltage above 1 kV. Similarly, the inter-strip resistance was measured between two groups of implants (even and odd columns of the APC). It equals to 200 GOhm/cm for the non-irradiated sensor at room temperature with the bias voltage above 50 V and 10 MOhm/cm at $-25\,^{\circ}$C and 1 kV bias for the APC irradiated to 7×10^{15} protons/cm^2.

The IV and CV scans were made for the entire pixel matrix through its bias grid. The full depletion voltage amounts to 80 V for unirradiated APC detectors as found from the $1/C^2$ plot. However this technique cannot be used for irradiated sensors and therefore one relies on the charge collection measurements. The reverse leakage current density at 600 V amounts to 25 nA/cm^2 for the unirradiated APC detector at room temperature and 60 and 100 μA/cm^2 for doses 7×10^{15} and 1.5×10^{16} protons/cm^2 at $-25\,^{\circ}$C. The breakdown voltage of all APC samples exceeds 1100 V.

3.2. Studies of the guard structures

The breakdown voltage of a bare implant with 600 μm distance to the cut edge is about 150 V before irradiation that is well above the full depletion voltage of 80 V. However, the ratio between the full depletion and breakdown voltages becomes worse for irradiated implant in this geometry. The optimum HV range could be significantly extended by using guard rings. Several diodes with different guard structures: varying gaps

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[2] http://rd50.web.cern.ch

[3] Fraunhofer IZM Gustav-Meyer-Allee 25, D-13355 Berlin, Germany.

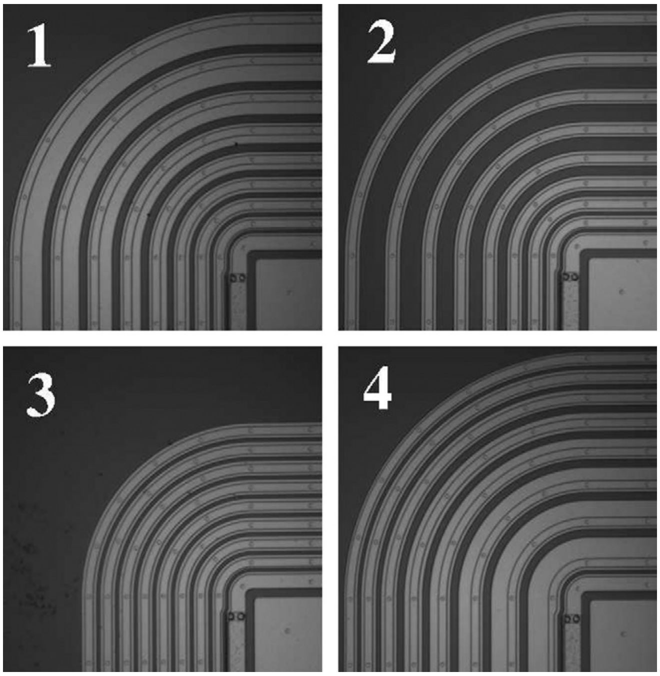

Fig. 2. Four types of evaluated guard structures. Each has four dicing options. Type 1 is the standard RD50 layout, types 2 and 3 are used for the CMS and ATLAS pixel sensors and type 4 with reverse orientation of metal plates and steps between implants was needed to prove the tolerance of the first three designs. Central implant is 600 μm away from the cut edge on the left and top.

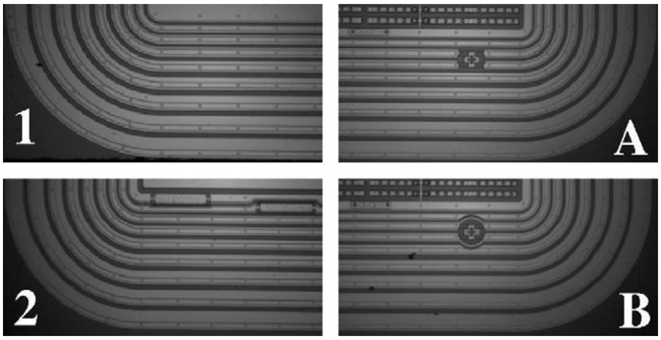

Fig. 3. Probe pads (design 2) and reference marks (designs A, B) on the guard structure. Layouts 1 and A are preferable over 2 and B.

between implants, varying metal width, reverse orientation of the field plates have been evaluated as shown in Fig. 2.

All devices had a good HV performance with an average breakdown voltage of 900 V. It is not as good as for the APC and APR detectors due to locating wire bond pads on the guard rings for test purposes. The new pixel sensors for the ATLAS upgrade [9] have their alignment marks on the guard rings, Fig. 3. It has been shown that the HV properties of such detectors do not degrade if the guard structure remains uniform throughout.

The surface current has been measured for all diodes before irradiation by connecting an amperemeter between any pairs of adjacent guard rings. This current was the same everywhere: close to the central implant and near the cut edge and it contributed up to 80% to the total leakage current before breakdown. It has been shown [10] that after irradiation the ratio between the surface and the bulk currents changes and it depends on the bombarding particle type. In case of protons the surface current can still be sizeable.

3.3. Evaluation of the dicing schemes

One major role of guard rings in the planar technology is to make the surface current isotropic and therefore the guard structure has to be on the depleted, i.e. on the readout side. This reduces the active detector area. To find the minimum number of guard rings, the pad detectors with all guard types were stretched to have the cut line going through the 8th, 4th and the 2nd innermost guard rings. The IV curves were scanned after their dicing before and after irradiation. The breakdown voltage versus distance from the readout implant to the cut edge for unirradiated samples has the same slope of 1 V/μm as for the punch-through voltage measurements meaning that the breakdown occurs when the bulk depletion in lateral direction reaches the cut edge. Diodes with one remaining guard ring show a 10-fold increase in the breakdown voltage after doses 7×10^{15} and 1.5×10^{16} protons/cm^2. Sensors with 3 and 7 rings do not break down under 1100 V.

4. Charge collection measurements

The charge collection in pixel detectors was measured using a ^{90}Sr radioactive source. The SCA with its FE-I3 chip was read out by the ATLAS pixel "Turbo-DAQ" system.[4] The FE-I3 chip utilises the time over threshold (ToT) technique to digitise the input charge [13].

The cross-calibration of charge collection for the pixel detectors becomes possible with APC and APR devices using a newly developed ALiBaVa system [11]. The signal source is either ^{90}Sr or movable infra-red laser (980 or 1060 nm wavelength) with a variable focus distance, light intensity and exposure time. The analogue ALiBaVa readout allows for accurate charge cluster analysis taking into account small amplitudes that are not available in the ToT technique due to its readout threshold.

The pixel efficiency and spatial resolution measurements require track information from the particle telescope. Irradiated samples have been tested with 24 GeV protons at CERN in October 2010. The SCAs were readout by the "Turbo-DAQ" integrated into EUDET tracking system [12]. The beamtest data analysis is ongoing.

4.1. Measurement system

Two dedicated test cards were designed for the SCA and APC detectors. The cards feature low-dropout voltage regulators to protect against the noise the FE-I3 and Beetle analogue supplies fed through the long mixed-signal cables. A collimated scintillation trigger mounted underneath each test card provided small variation in the incidence angles and reasonably high energies of beta particles crossing the silicon.

To avoid thermal runaway of heavily irradiated sensors at high bias voltages and moderate cooling temperatures, each sensor is being cooled from its backplane by a heat sink with a soft thermal interface. The heat sink and the test card have holes to let through the particles from the radioactive source to avoid energy loss in front of the SCA and APC sensors.

Each test card is placed inside the electromagnetic shielding box in a freezer whose temperature is controlled down to −25 °C with 2 °C accuracy using a K-type thermocouple attached to a dummy heat sink. Two blowers provide cold air flow through each shielding box. ALiBaVa and "Turbo-DAQ" log temperature of

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[4] http://physik2.uni-goettingen.de/~jgrosse/TurboDAQ/

the Beetle and FE-I3 chip which differ from the temperature of sensor on the heat sink by approximately 3 °C.

4.2. Measurements of single chip assemblies

Prior to their irradiation the SCAs were temporarily mounted on test cards for the chip tuning and calibration as described in Ref. [13]. It has been found that the current consumption of the FE-I3 pixel chips with conventional 1.6 V analogue supply voltage has dropped from 110 mA down to 40 mA after irradiation and the minimum analogue voltage of 1.8 V was required for both SCAs to operate. Similarly the minimum bias voltage of 300 V was required for DC-coupled pixel sensors after irradiation to get any response from the pixel chip. The high voltage becomes unstable above 700 V for both irradiated sensors: their bias currents drop and the trigger circuit starts to register electromagnetic spikes whose frequency correlates with HV with approximately 10 Hz/V slope. For a safe long-term operation the bias voltage of 600 V was chosen at which the leakage currents without annealing of 60 and 100 μA/cm^2 for doses 7×10^{15} and 1.5×10^{16} protons/cm^2 were measured at −25 °C (same as for APC at 600 V) that agrees with expectations for the given detector volume, accumulated dose, the bias voltage and annealing time [14].

The sub-threshold signals could not be read out in the ToT method which introduces an offset into the formula for measured charge:

$$Charge[ToT] = Gain\left[\frac{ToT}{e}\right](Charge-Threshold)[e]. \qquad (1)$$

The gain is related to the chip tuning parameters: 60 ToT counts should match by convention 20 000 electrons, reduced by 3200 electrons threshold. An inverse function to Eq. (1) describes the physical charge produced by beta particles and collected in sensors that gives roughly 7200 and 6400 electrons at 600 V for corresponding doses of 7×10^{15} and 1.5×10^{16} protons/cm^2. These results originate from the “Turbo-DAQ” fitting algorithm based on the χ^2 minimisation and, if understood as mean values of the Landau distribution and recalculated to most probable values (MPV) [15], are consistent with data presented in Ref. [3]. The maximum estimate of the systematic uncertainty due to non-linearities in the FE-I3 calibration, amplification and threshold circuits is 10%.

4.3. Measurements of APC with analogue readout

All pixels of the APC sensor have a DC-coupling to the Beetle chip. The leakage current of detector diodes is drained by the input amplifiers. The test with laser pulses has shown that each input of the Beetle chip can tolerate, without degradation of gain, up to 1 μA leakage current using current generated by an additional constant infra-red light source.

Measurements with the ^{90}Sr source of the charge collection efficiency (CCE) for the irradiated to 7×10^{15} protons/cm^2 APC device as a function of its bias voltage are shown in Fig. 4. The two lines differ in the event selection: the upper shows amplitudes for single hits only (one pixel at a time has a signal above threshold) the lower contains all events including multi-pixel clusters for which the cluster seed (central pixel) amplitude is presented. All values are normalised to non-irradiated detector at 250 V whose full depletion voltage of 80 V is taken from its $1/C^2$ characteristics. The most probable value (MPV) of 6000 electrons at 600 V and 8000 electrons at 900 V agrees with data in Ref. [3]. The systematic uncertainty has been eliminated by calibrating the Beetle chip with a pulse generator and by measuring the charge collection with 140 and 300 μm thin unirradiated sensors. The statistical errors on MPV are negligibly small for data samples of 100k events. Results are being published as preliminary since more detectors need to be analysed.

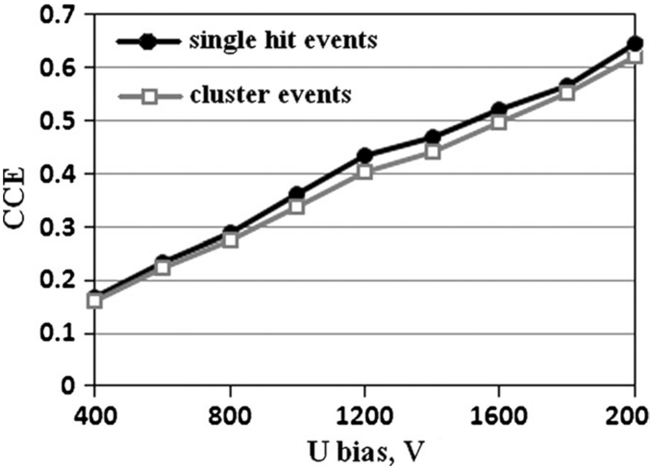

Fig. 4. Charge collection efficiency for the 300 μm thin APC detector irradiated by 24 GeV protons to dose 7×10^{15} particles/cm^2.

5. Summary

This manuscript describes briefly the properties of planar silicon pixel detectors designed at Liverpool University and methods for their evaluation. Two measurement techniques: the time-over-threshold of the FE-I3 pixel chip and analogue pipeline of the Beetle chip were compared for the charge collection from heavily irradiated planar pixel sensors.

The silicon wafer with analogue readout pixels was designed at Liverpool University and manufactured by Micron Semiconductor Ltd. Layout rules for improved HV performance of the “n-in-p” planar detectors were finalised during the workflow. This knowledge was implemented in the second 6-in. wafer produced by Micron Semiconductor Ltd. for the IBL ATLAS pixel project [9].

The beam telescope based on the ALiBaVa readout with an integrated “Turbo-DAQ” is currently under construction in collaboration between Valencia, Liverpool and Barcelona Universities. The plan is to extend laboratory measurements of charge collection with different beam types and to complement them by characterisation of spatial efficiency and coordinate resolution of pixels.

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