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Radiation-Hard Active Pixel Sensors for HL-LHC Detector Upgrades Based on HV-CMOS Technology

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Currently deployed silicon sensors in particle tracking detectors of the Large Hadron Collider (LHC) experiments will not withstand the augmented radiation levels in the foreseen High-Luminosity upgrade of the LHC (HL-LHC). Therefore, improved radiation hard sensors are necessary for HL-LHC experiments. We have developed several prototypes of High-Voltage CMOS (HV-CMOS) sensors compatible with the current read-out chip of the ATLAS pixel detector, FE-I4, and compatible with various analog and digital strip read-out systems.
This paper shows results of spectrum measurements with a Strontium-90 radioactive source of a sensor irradiated to $10^{15}\,(1\,\mathrm{MeV}\,\mathrm{n}_{eq})/\mathrm{cm}^2$. Preliminary data analysis yields a charge signal decrease as much as 31% due to irradiation. An outlook on measurements with an enhanced setup to confirm the number stated above is given.

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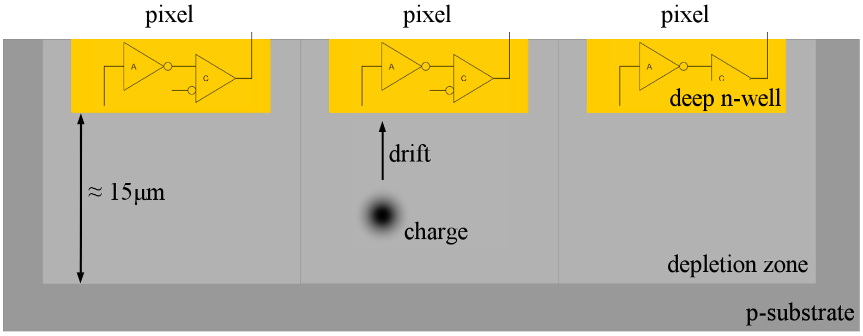

Figure 1: Schematic cross-section of the pixel sensor. The charge generated in the depletion zone by a passing ionizing particle is brought to the pixel electrode by drift. There it is amplified (and treated further) by the in-pixel electronics. The required CMOS-logic is embedded in a deep n-well and a subsequent additional p-well (not shown in the figure).

1. Sensor Prototypes

Tracker detectors are the parts of high-energy-physics collider experiments which are the closest to the particle collisions. Therefore they receive large amounts of particle flux and radiation dose. The innermost part of the tracking detector in the ATLAS experiment at CERN's LHC is composed of silicon semiconductor detectors. Currently the two technologies used (pixel and strip detectors) are designed to withstand a particle flux up to 10^{15} and 10^{14} (1 MeV n_{eq})/cm^2 respectively. These figures are significantly lower than the radiation levels that will be reached in the HL-LHC [1]. This is why new radiation hard technologies are required for HL-LHC tracking detectors. One promising candidate for HL-LHC silicon detectors is the HV-CMOS technology. First, it is expected to withstand high non-ionizing particle fluxes due to a very short charge collection time as well as high ionizing radiation doses thanks to the deep sub-micron process [2]. Second, it features a list of properties advantageous for its use as a silicon particle tracking detector, like high spatial resolution, low operation voltage, easier thermal management, and cheap production costs (a more exhaustive list is discussed in [3]).

In this paper we discuss results obtained with prototype sensors manufactured in a commercial 180 nm HV-CMOS process by AMS [4]. Key feature of these sensors is simple in-pixel electronics together with high-voltage capability on a bulk with moderate resistivity ($\approx 20\,\Omega$cm). The depletion depth is estimated at only 15 µm. With a high electric field applied, the charge collection by drift is very fast (≈ 1 ns) and therefore nearly insensitive to trapping by irradiation-induced bulk defects. The diffusion part of the charge signal is affected by bulk defects and will decrease the total signal after irradiation. The relatively low drift charge signal of about 1000 electrons generated by a minimum ionizing particle (MIP) is still reliably detected thanks to the in-pixel electronics, which includes pre-amplification of the signal (figure 1).

The sensor is designed to match the existing and well-known FE-I4 pixel readout chip [5]. In addition, the on-sensor electronics makes it possible to also use it as a strip-like detector and connect it to strip read-out systems of both the analog and digital kind. More information on the sensor can be found in [6], [7], [8], [9].

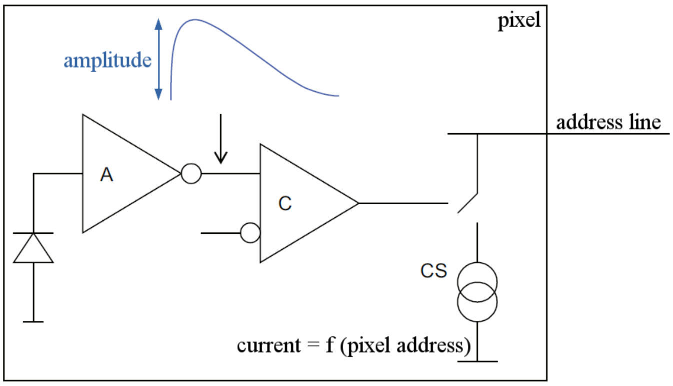

Figure 2: Schematic of the in-pixel electronics. The charge signal created in the depletion zone (depicted as a diode) is amplified by a charge sensitive pre-amplifier (A). The resulting signal is then treated by a comparator (C) and sent to the address line. The current source (CS) level is set in a manner so that different pixels can be identified by the signal height in the address line. The arrow indicates where we measure the amplitude for the spectrum measurements.

2. Spectrum Measurements

Although we expect the sensor to show high radiation hardness due to its design and process properties, it still suffers from signal degradation caused by irradiation effects. The first effect is the reduction of the initial charge signal. We measure this effect by recording the spectrum of a strontium-90 radioactive source with the sensor under test. Having the source emitting MIP-like electrons, the spectrum follows a Landau-distribution with the Most Probable Value (MPV) as characteristic value. Comparing the calibrated MPVs of different spectra puts in relation the charge created by a passing MIP. We obtain the spectrum by measuring the amplitudes of the particle signals directly after the pre-amplifier in one pixel (figure 2). These values (in mV) are then translated into charge units by performing a calibration measurement with an iron-55 source. Figure 3 shows the spectrum measured with a first generation prototype that was neutron irradiated to 10^{15} (1 MeV n_{eq})/cm^2 at the JSI TRIGA Mark II research reactor in Ljubljana, Slovenia. The fit of the Landau-distribution to the data outside the noise region gives an MPV of 67 to 72 mV. Using the conversion factor from a calibration measurement this corresponds to 1100 to 1190 electrons. The same measurement with an unirradiated sensor yields a value of about 1600 electrons. We deduct a value for the charge signal degradation due to irradiation between 26 and 31 %.

3. Perspectives

The method of taking all signals of the pre-amplifier above a certain threshold into account is actually biasing the Landau-distribution of the spectrum. All electrons from the source that reach the sensitive volume are taken into account. However, only the electrons near the upper limit of the source spectrum (2.28 MeV for strontium-90) act as MIP-like particles. A more exact measurement would include a scintillator trigger "behind" the sensor in order to measure only signals from particles with a high enough energy to traverse the sensor and arrive at the scintillator. Such a setup has been built and we are currently taking data in order to give a more exact result.

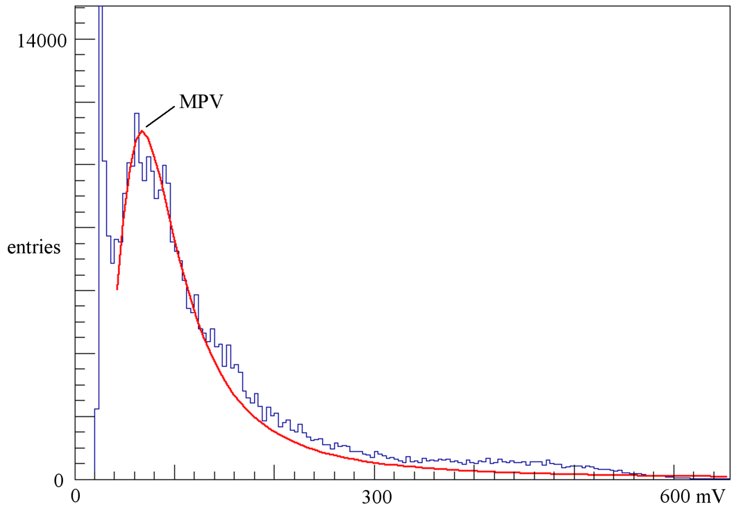

Figure 3: In blue, the spectrum of a strontium-90 radioactive source recorded with the neutron irradiated sensor. On the abscissa the amplitude heights measured after the pre-amplifier are plotted. In red the fit of a Landau distribution to the data is shown. The MPV serves as characteristic value for the spectrum. At larger amplitudes the measured spectrum shows more entries than expected from the Landau distribution. This is due to low-energy non-MIP-like electrons from the source. Future measurements will include an enhanced setup, which is only selecting high-energy particles in order to get more accurate results.

In addition, the described measurement has only been done with the first generation sensor prototype. The second and third generation have been produced and will also be measured within this year. These results will be published elsewhere.

References

[1] ATLAS Collaboration, *Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*, CERN Technical Report, Dec. 2012, CERN-LHCC-2012-022, LHCC-I-023.

[2] I. Perić et al., *Particle Pixel Detectors in High-Voltage CMOS Technology - New achievements*, *NIMA* **650** (2011) 158-162

[3] S. Feigl, *Performance of Capacitively Coupled Active Pixel Sensors in 180 nm HV-CMOS Technology After Irradiation to HL-LHC Fluences*, 2014 *JINST* 9 03 C03020.

[4] AMS, *0.18 µm High-Voltage CMOS Process*, accessed July 2014.

[5] ATLAS IBL Collaboration, J. Albert et al., *Prototype ATLAS IBL Modules Using the FE-I4A Front-End Readout Chip*, 2012 *JINST* 7 P11010 [arXiv:1209.1906].

[6] I. Perić, *Hybrid Pixel Particle-Detector Without Bump Interconnection*, *IEEE Transactions on Nuclear Science* **56** (2009) 519-528.

[7] I. Perić, *Hybrid Pixel Detector Based on Capacitive Chip to Chip Signal-Transmission*, *NIMA* **617** (2010) 576-581.

[8] I. Perić, *Active Pixel Sensors in High-Voltage CMOS Technologies for ATLAS*, 2012 *JINST* 7 C08002.

[9] I. Perić et al., *High-Voltage Pixel Detectors in Commercial CMOS Technologies for ATLAS, CLIC and Mu3e Experiments*, *NIMA* **731** (2013) 131-136