Challenges for Silicon Pixel Sensors at the European XFEL

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The high instantaneous intensity and the high repetition rate of 4.5 MHz of the European X-Ray Free-Electron Laser - XFEL pose new challenges for imaging detectors. The specific requirements for the detectors are a dynamic range of 0, 1 to more than 10^4 photons of e.g. 12.4 keV per pixel for a XFEL pulse duration of < 100 fs, and a radiation tolerance for doses up to 1 GGy for 3 years of operation. In addition, the sensors should have good detection efficiencies for X-ray energies between ~7 and ~20 keV, and minimal inactive regions at the edges. Within the AGIPD Collaboration the Hamburg group has systematically studied the consequences of these requirements for p^+n silicon sensors and is now presenting an optimized p^+n-sensor design.

High instantaneous photon intensities cause the so-called plasma effect, which results in a significant change of the pulse shape of the signals from the electrodes and of the spatial distribution of the collected charges, compared to single photon detection. The plasma effect has been studied using a p^+n strip sensor read out by a multi-TCT system (Transient Current Technique) for charge carriers generated by sub-nanosecond focused light with absorption lengths between 3.5 µm and 1 mm (660 to 1060 nm wavelengths). Results on the pulse shape and point-spread function as function of charge-carrier density, and their impact on the choice of the resistivity of the silicon and the operating voltage will be presented.

The high X-ray dose results in an increase of the oxide charge density, N_{ox}, and in the formation of traps at the Si-SiO_2 interface, Nit. Detailed I-V, C/G-V and TDRC (Thermal Dielectric Relaxation Current) measurements on Gate Controlled Diodes and MOS capacitors from two vendors can be described by 3 dominant interface traps. Their location in the band gap, their capture cross sections and densities Nit and N_{ox} as function of X-ray dose have been determined. In addition, the annealing behavior has been measured and described by a model. The results of these studies will be presented.

The X-ray radiation damage has a major impact on the dark current, the charge densities and the electric field in the vicinity of the Si-SiO_2 interface and of the p^+ implants. They in turn influence sensor parameters, like breakdown and depletion voltage, inter-electrode capacitances and charge-collection efficiency. The latter has been studied on sensors before and after irradiation to 1 MGy (SiO_2) with ~10 keV X-rays using I-V and C-V measurements, and the multi-channel TCT using focused light of 3.5 µm absorption length (660 nm wavelength) from a sub-nanosecond laser. From these measurements the charge collection efficiencies and the extensions of the accumulation layers under the Si-SiO_2 interface as function of dose, biasing history and ambient humidity have been determined. The experimental findings are explained with the help of detailed simulations using SYNOPSYS TCAD. A summary of these fairly complex results will be given.

Finally, with the help of extensive TCAD simulations, which use the results of above measurements, the AGIPD sensor (1024 x 1024 p^+ pixels; 200 µm x 200 µm pixel size; 500 µm thick n-type silicon) has been designed for operation at radiation doses between 0 and 1 GGy. The strategy and the results of the optimization, and the expected sensor parameters like dark current, breakdown voltage and inter-pixel capacitance will be presented.