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Study of high-dose X-ray radiation damage of silicon sensors

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ABSTRACT

The high intensity and high repetition rate of the European X-Ray Free-Electron Laser, presently under construction in Hamburg, will require pixel sensors which can stand X-ray doses up to 1 GGy for 3 years of operation. Within the AGIPD Collaboration the Hamburg group has systematically studied X-ray damage in silicon sensors for the dose range between 1 kGy and 1 GGy using strip sensors and test structures fabricated on high-ohmic n-type silicon from four different vendors. The densities of oxide charges, interface traps and surface current as function of dose and annealing conditions have been determined. The results have been implemented in TCAD simulations, and the radiation performance of strip sensors and guard-ring structures has been simulated and compared to experimental results. Finally, with the help of detailed TCAD simulations, the layout and technological parameters of the AGIPD pixel sensor have been optimized. It is found that the optimization for silicon sensors exposed to high X-ray doses is significantly different from that for non-irradiated sensors, and that the specifications of the AGIPD sensor can be met.

1. Introduction

The European X-Ray Free-Electron Laser (EuXFEL) [1,2], planned to start operation in 2016, will provide X-ray beams with unique features: a brilliance which is 8 orders of magnitude higher than the most brilliant synchrotron-radiation beams for wavelengths in the Ångström region, full transverse coherence, a pulse length of about 10 fs, and pulse trains of 2700 pulses with 220 ns spacing every 100 ms. These unique features pose major challenges for imaging detectors, in particular Refs. [3,4]: a dynamic range of 0, single photon to more than 10^4 photons of typically 12.4 keV per pixel, a radiation tolerance for doses up to 1 GGy for 3 years of operation, a good detection efficiency for X-rays with energies between 3 and 20 keV, and minimal inactive regions at the edge of the sensors.

Within the AGIPD (Adaptive Gain Integrating Pixel Detector) Collaboration [5,6] the Hamburg group has studied the consequences of these requirements for p^+n-silicon sensors and optimized the design of the AGIPD sensor. From the study of the plasma effect, which occurs at high instantaneous X-ray densities [7–9], it has been concluded that, for a sensor of a thickness of 500 μm, an operating voltage above 500 V is needed to achieve a sufficiently high electric field to limit the spatial spread of the charge carriers and to achieve a charge-collection time compatible with the 220 ns spacing of the EuXFEL pulses. Studies of the charge collection in segmented sensors after irradiation with different X-ray doses [10,11] have shown that, depending on X-ray dose, biasing history and environmental parameters like relative humidity, losses of holes or electrons occur. However, these effects have little relevance for the EuXFEL applications.

In this paper we summarize the results on the main effects of X-ray radiation damage, in particular the increase of oxide-charge density, the formation of Si–SiO_2-interface traps, their impact on dark current and breakdown voltage, and the optimization of the design of the AGIPD sensor for high operating voltages for X-ray doses between 0 and 1 GGy.

2. X-ray radiation damage of p^+n-silicon sensors

The X-ray energies at the EuXFEL are well below the threshold energy for the formation of defects in the silicon bulk, and only defects in the dielectric, at the Si–SiO_2 interface, and interfaces between dielectrics are generated. The effects of X-ray radiation damage are discussed in detail in Refs. [12,13]. Here we give only a very short summary. In SiO_2 X-rays produce on average one *eh* pair every 18 eV of deposited energy. Depending on ionization density and electric field, a fraction of the eh pairs recombine. The remaining charge carriers move in the SiO_2 by diffusion and, if an electric field is present, by drift. Electrons, due to their high mobility and relatively low trapping probability, leave the SiO_2.

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However holes, which move via polaron hopping, are typically captured by deep holes in the SiO_2 or at the $Si–SiO_2$ interface, which results in fixed positive charge states. We denote the density of oxide charges by N_{ox}, the surface-current density by J_{surf}, and the density of interface traps as function of their energy E relative to the conduction band by $D_{it}(E)$ with units $1/(\mathrm{eV\,cm^2})$. The interface traps, if exposed to an electric field, act as generation centers and generate a surface current.

For a realistic simulation and optimization of sensors, values of N_{ox}, N_{it}, the effective number of interface traps, and J_{surf} as function of dose are required. We therefore have irradiated test structures from 4 different vendors (Canberra [14], CiS [15], Hamamatsu [16], Sintef [17]) built on high-ohmic n-type silicon (3–14 kΩ cm), with different crystal orientations (⟨111⟩ and ⟨100⟩), and different dielectra (SiO_2 and SiO_2+Si_3N_4). The structures used were MOS Capacitors, MOS-C, and Gate-Controlled Diodes [18], GCD. The irradiations were performed at the "white" X-ray beam F4 at DORIS III, which had a mean energy of 12 keV and dose rates between 1 and 200 kGy/s [19,20]. Irradiations were performed for dose values between 1 kGy and 1 GGy.

In order to determine $D_{it}(E)$, Thermal Dielectric Relaxation Current measurements, TDRC, on the MOS-C were made. In these measurements the MOS-C, biased in accumulation, was cooled down to a temperature of 10 K to freeze the electrons in the interface traps. Then the MOS-C was biased to deep depletion, heated up with a constant heating rate $\beta = 0.183$ K/s to 290 K, the current $I_{TDRC}(T)$ due to the release of the trapped electrons measured, and $D_{it}(E)$ extracted. To obtain quantitative results, the $D_{it}(E)$ spectrum was fitted by 3 Gauss functions [20]. From measurements with different heating rates β, the charge-carrier cross-sections for the three levels were estimated. Following Ref. [21], this information was fed into an equivalent RC-circuit model and the voltage dependence of the capacitance/conductance, C/G–V, for different frequencies evaluated, assuming acceptor-like interface traps.

In order to determine N_{ox}, C/G–V measurements on the MOS-C for frequencies between 1 and 1000 kHz were made. N_{ox}, which just shifts the C/G–V curves along the V axis, has been derived from the voltage shift of the calculated 1 kHz C–V curve with respect to the data. After this shift the calculated C/G–V curves provide a fair description of the measurements for all frequencies and radiation doses.

Fig. 1 shows the results for the thus determined values of N_{ox}. The CMOS-C had been annealed for 10 min at 80 °C to reach a stable state with respect to short-term annealing. Up to an X-ray dose of approximately 100 kGy N_{ox} increases, and values of about 2×10^{12} cm^{-2} are reached. Above this dose for some MOS-Cs N_{ox} saturates, for others it continues to increase. We have verified that the spread in N_{ox} for different MOS-Cs from the same producer is small, so that the large spread is attributed to the different technologies and crystal orientations.

For determining the surface-current densities, I–V measurements on Gate Controlled Diodes, GCD, were performed. The diodes were biased to −12 V, the voltage on the gate varied from accumulation via depletion to inversion, and the diode current measured. The surface-current density, J_{surf}, was obtained by dividing I_{surf}, the difference in current between depletion and accumulation, by the gate area. For the calculation of J_{surf} it has been assumed, that the entire gate area is depleted, which may not be correct for all GCDs at high currents. It has been estimated that in this way the value of J_{surf} could be underestimated by at most 50%. Fig. 2 shows the results for J_{surf}. As for N_{ox}, the values of J_{surf} saturate at dose values between 1 and 10 MGy. The maximal values of J_{surf} vary between 1.5 and 6.5 μA/cm^2, which we again attribute to differences in technology. At higher doses J_{surf} decreases, which is not yet understood.

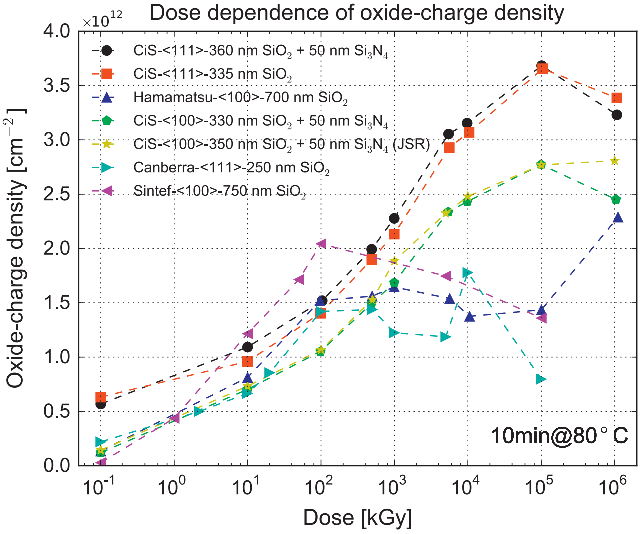

Fig. 1. Dependence of the surface-charge density, N_{ox}, on X-ray dose obtained from measurements on MOS capacitors from four different vendors after annealing for 10 min at 80 °C.

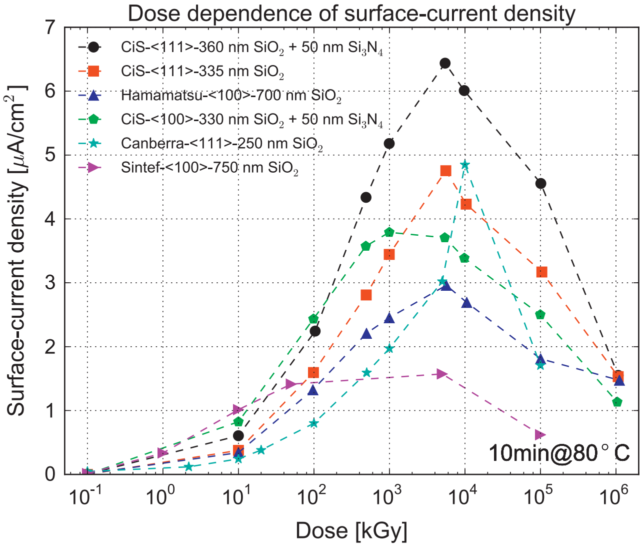

Fig. 2. Dependence of the surface-current density J_{surf} on X-ray dose obtained from measurements on Gate Controlled Diodes from different vendors after annealing for 10 min at 80 °C.

3. Sensor optimization

The results of the studies of the plasma effect have shown that for experiments with high instantaneous X-ray intensities, e.g. 10^4 X-ray photons per pulse in a 200 μm × 200 μm pixel, operating voltages well above 500 V are required for 500 μm thick sensors. The problem of reaching a high breakdown voltage for high radiation-induced oxide-charge densities is illustrated in Fig. 3, which shows the electric field close to the $Si–SiO_2$ interface from a 2D TCAD simulation of a p^+n-strip sensor biased at 500 V for two values of N_{ox}. Whereas the maximal electric field 10 nm below the $Si–SiO_2$ interface is 50 kV/cm for $N_{ox} = 10^{11}$ cm^{-2}, it is 450 kV/cm for $N_{ox} = 2 \times 10^{12}$ cm^{-2}. The reason for this difference is, that the voltage difference between the readout strip and the accumulation layer increases with increasing oxide-charge density, and at the same time the width of the accumulation layer increases and extends below the metal overhang. The result is a high electric