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X-ray induced radiation damage in segmented p$^+$n silicon sensors

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Experiments at the European X-ray Free Electron Laser (XFEL) require silicon pixel sensors which have to meet extraordinary requirements for experiments at the XFEL. This paper shortly describes the requirements and challenges for silicon sensors at the European XFEL and addresses the efforts made by the detector group of Hamburg University for the sensor development. In particular, the main results on the X-ray induced radiation damage are presented.

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1. Requirements and challenges for silicon sensors at the XFEL

The next generation light source, the European X-ray Free Electron Laser (XFEL) [1], is now being constructed at DESY, Hamburg and its commissioning is scheduled for 2015. Then, studies will be performed in physics, chemistry, life sciences, materials research and other disciplines with X-ray beams of unique quality. Some unique applications include the structural analysis of single complex organic molecules, the investigation of chemical reactions at the femtosecond-time scale and the study of processes that occur in the interior of planets.

At the European XFEL, silicon pixel detectors will be used for imaging experiments. One of the ongoing detector developments is the Adaptive Gain Integrating Pixel Detector (AGIPD) Project, which has to fulfil extraordinary performance specifications [2]: Single-photon sensitivity and a dynamic range of up to more than 10^4 photons of 12.4 keV per pixel of 200 μm $\times$ 200 μm arriving within less than 100 fs, a frame rate of 4.5 MHz, and a radiation tolerance for doses up to 1 GGy for 3 years of operation. To address these challenges, radiation-hard silicon pixel sensors and electronic components with outstanding performance need to be developed.

The complete AGIPD Project has been presented in [3]. In this paper, the work of the detector group of Hamburg University on understanding the X-ray induced radiation damage, its influence on silicon pixel sensors, and the design of a radiation-hard sensor for AGIPD are shortly summarized. In addition, the main experimental results on X-ray induced radiation damage are presented.

2. Activities of the detector group of Hamburg University for the XFEL

To meet the requirements of silicon sensors for experiments at the European XFEL and to design a radiation-hard silicon pixel sensor for the AGIPD Project, the detector group of Hamburg University has studied the following topics:

Plasma effect: The densities of electrons and holes in silicon sensors created by the high intensity X-rays at the European XFEL produce the so-called plasma effect. The neutral plasma formed by the high densities of electrons and holes dissolves slowly. The boundary of the plasma shields the electric field created by the external bias voltage. Thus the pulse shape changes significantly and the time needed to collect all charges is increased. Two processes are involved in the separation of electrons and holes from the plasma: Diffusion and repulsion. Before electrons and holes are separated ambipolar diffusion is the dominant process. Once electrons and holes are separated, the electrostatic repulsion increases the spread of the electrons and holes. We have extensively studied this topic [4, 5, 6, 7]. As expected, the plasma effect decreases as the electric field increases. From the study we conclude: An operating voltage above 500 V of the AGIPD sensor should be used in order to reduce the influence, especially the charge-collection time, due to the plasma effect.

Surface damage: X-rays with energies below 300 keV only cause surface damage in silicon sensors, whereas hadrons, gamma-rays and high energy electrons mainly cause bulk damage. Thus, the X-rays at the European XFEL only induce surface damage: Oxide charges and interface traps will build up with time in the SiO_2 and at the Si-SiO_2 interface, respectively. The net oxide charges are positive, thus they induce electrons which accumulate in the silicon below the Si-SiO_2 interface (electron-accumulation layer). The interface traps increase the surface current. The presence of the oxide charges and interface traps induced by X-rays influences the electrical properties of segmented p^+n sensors [8, 9, 10]: Increase of the leakage current, the full depletion voltage and the interpixel/interstrip capacitance; decrease of the interpixel/interstrip resistance and the mobility of minority carriers below the interface; reduction of the breakdown voltage; and charge losses close to the interface. Using measurements on X-ray-irradiated test structures from different vendors, we have observed that the densities of oxide charges and interface traps, which are responsible for the surface current, saturate at high doses. In Section 3 of this paper previous results together with new measurements are presented.

Charge losses and stability of silicon sensors: The charge losses close to the Si-SiO_2 interface of segmented p^+n sensors have been studied using multi-channel time-resolved current measurements (multi-TCT). Depending on the applied bias voltage, biasing history and environmental conditions like humidity, incomplete electron or hole collection and both electron- and hole-accumulation layers at the Si-SiO_2 interface with different lateral extensions have been observed. Results on this study and their relevance to the stability of silicon sensors are discussed in [10, 11]. From the studies we conclude that the effect of charge losses is small if the X-rays enter the sensor through the face opposite to the segmented read-out electrodes, as is the case for AGIPD.

Optimization of the AGIPD sensor: The AGIPD sensor has to satisfy the following specifications to meet the requirements at the XFEL: Interpixel capacitance of less than 0.5 pF, a maximal leakage current per pixel of 1 nA, and an operating voltage of above 500 V in order to reduce the plasma effect. To guarantee safe operation the design goal has been set at a minimal breakdown voltage close to 1000 V. A complete list of the AGIPD sensor specifications is described in [12]. The specifications should also be met after 3 years of operation with an accumulated dose up to 1 GGy non-uniformly distributed over the sensor. To design the AGIPD sensor, experimental data on the dose dependence of the oxide-charge density and the surface-current density obtained from surface-damage studies, have been implemented in the Synopsys TCAD simulation program in order to optimize the layouts of the pixel and the guard-ring structure. The methodology of the sensor design, the optimization of the most relevant parameters and the simulated performance, like breakdown voltage, leakage current and interpixel capacitance, as function of the X-ray dose are reported in [12, 13]. A design which according to simulations meets the specifications of the AGIPD sensor for X-ray doses between 0 and 1 GGy, in particular with respect to inter-pixel capacitance, dark current and breakdown voltage, has been achieved.

3. Studies of X-ray induced radiation damage (surface damage)

We have studied the X-ray induced radiation damage in silicon sensors and extracted the damage-related parameters like oxide-charge density and surface-current density from test structures. For details, we refer to [8, 14, 15, 16]. Below we just summarize the main results of the work:

For the investigation of X-ray induced radiation damage up to an X-ray dose of 1 GGy, MOS capacitors and gate-controlled diodes built on high-resistivity n-type silicon with crystal orientations <100> and <111> produced by four vendors, CiS, Hamamatsu, Canberra and Sintef, have been irradiated with 12 keV X-rays at the DORIS III synchrotron of DESY. Using

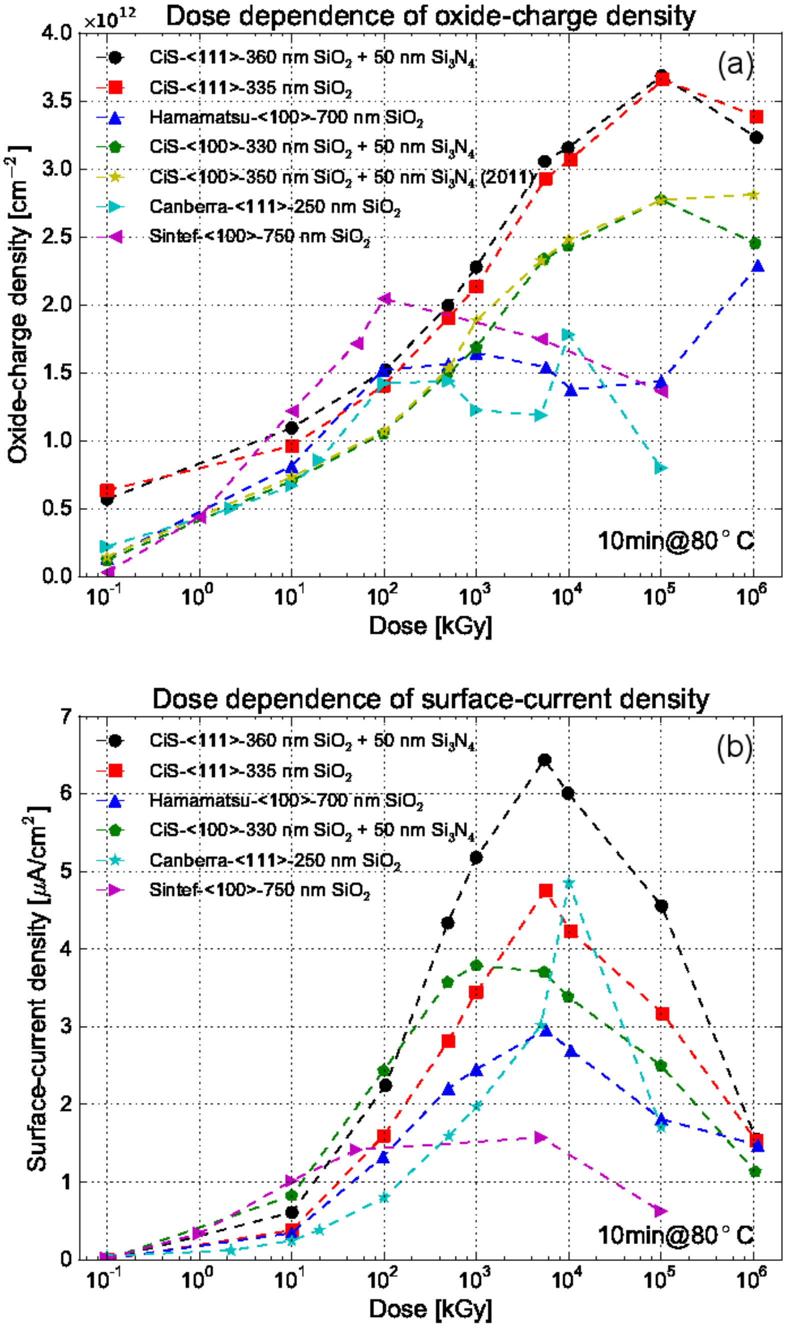

Figure 1: Dose dependence of the oxide-charge density N_{ox} and the surface-current density J_{surf} scaled to 20°C after annealing at 80°C for 10 minutes. (a) N_{ox} vs. dose. (b) J_{surf} vs. dose. Results of N_{ox} and J_{surf} before irradiation are plotted at a dose of 10^{-1} kGy in the figures.

capacitance/conductance-voltage, current-voltage and thermal dielectric relaxation current measurements, the oxide-charge density, the densities of interface traps at the Si-SiO_2 interface, and the surface-current density have been determined as function of dose. Figure 1 shows the dose dependence of the oxide-charge density and the surface-current density after annealing at 80°C for 10 minutes. A short-term annealing has been done before the measurements in order to obtain consistent results [14], however measurements immediately after irradiation have also been performed. The gate lengths of the gate-controlled diodes are: 50 μm for CiS and Hamamatsu, 100 μm for Canberra, and 210 μm for Sintef. In addition, the shapes of the gates are ring for CiS, Hamamatsu and Sintef, and rectangular figures for Canberra. We note that in the analysis we have just divided the surface current by the area of the gate and not taken into account gate-length dependent effect [17, 18]. Studies of the gate-length dependence are underway. They indicate that the surface-current density for the diode with longer gate length may well be under estimate by 20% - 50%. From the measurements, it is found that:

- N_{ox} and J_{surf} for <100> silicon before irradiation are lower than for <111> silicon.
- There is no obvious dependence on the SiO_2 thickness.
- Little difference in N_{ox} is observed for the MOS capacitors with an insulating layer made of SiO_2 and an insulating layer made of SiO_2 and Si_3N_4.
- The values found for samples fabricated by the four vendors differ by a factor of 2 or 3, which indicates some dependence of radiation-induced defects on technology.
- N_{ox} and J_{surf} either saturate or decrease at high X-ray doses. The reason why J_{surf} decreases at high doses is still an issue to be understood.

In addition, the influence of the voltage applied to the gates of the MOS capacitor and the gate-controlled diode during X-ray irradiation on the oxide-charge density, the interface-trap density and the surface-current density has been investigated for doses of 100 kGy and 100 MGy. It is found that the values of the oxide-charge density, the interface-trap density and the surface-current density strongly depend on the gate voltage if the electric field in the oxide points from the surface of the SiO_2 to the Si-SiO_2 interface; however little difference is observed if the direction of the electric field is opposite. Annealing studies have also been performed at 60°C and 80°C on MOS capacitors and gate-controlled diodes irradiated to 5 MGy, and the annealing kinetics of oxide charges and surface currents determined: They can be described by functions predicted by the "tunnelling model" for the oxide-charge density and the "two reaction model" for the surface-current density. Details on the gate-voltage dependence and annealing temperature and time dependence of the damage-related parameters are documented in [15].

4. Summary

The requirements and challenges of silicon sensors at the European XFEL have been presented in this paper and the studies of the detector group of Hamburg University on how to meet these challenges have been summarized. To reduce the spread in space and time of the signal due to the plasma effect, it has been found that operating voltages for a 500 μm thick sensor in excess of 500 V are desirable. Charge losses close to the Si-SiO_2 interface have been observed, however

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their influence on measurements at the XFEL are minor and can most probably be ignored. A selection of results on the X-ray dose dependence of the oxide-charge density and the surface-current density from MOS capacitors and gate-controlled diodes built on high-resistivity n-type silicon with different orientations produced by different vendors have been presented. The influence of the electric field in the oxide on the formation of oxide charges and interface traps, and the annealing of oxide charges and surface currents have also been shortly summarized. Using above information, the AGIPD pixel sensor has been optimized with the help of detailed TCAD simulations. The simulations show that the challenging requirements for the AGIPD sensor, e.g. the breakdown voltage of $\sim$ 1000 V, interpixel capacitance of 0.5 pF and leakage current of 1 nA/pixel after irradiation to 1 GGy, can be met.

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