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Impact of plasma effects on the performance of silicon sensors at an X-ray FEL

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ABSTRACT

The impact of electron hole plasmas on silicon sensor performance was studied with a multi-channel Transient Current Technique (mTCT) setup. Electron hole densities of up to $10^{16}\,\mathrm{cm}^{-3}$ (equivalent to 10^5 focused 12 keV photons) were created with sub-ns lasers (660 and 1015 nm) and the time resolved current pulses of segmented sensors (4 channels simultaneously) were read out by a 2.5 GHz oscilloscope. Measurements for strip sensors of 280 μm thickness and 80 μm pitch as well as 450 μm thickness and 50 μm pitch were carried out showing an increase of the charge collection time and an increase of the charge spread (charge cloud explosion) with increased charge carrier density. These effects were studied as a function of the applied bias voltage and electron hole density. It was shown that for the current AGIPD sensor design plasma effects in p-in-n sensors of 450 μm thickness are negligible if at least 500 V bias is applied.

1. Introduction

The European XFEL [1] will push the limits of brilliance further than any light source today. The expected dynamic range, from single photons to 10^5 12 keV photons per pixel per pulse, is a challenge to the design of silicon sensors and front end electronics [2–5].

At the European XFEL the photon energy will be tunable from 12.4 to 0.8 keV. The XFEL pulses will be of short duration (<100 fs) and have a bunch repetition rate of 5 MHz (200 ns spacing). A super-cycle of 3000 bunches is followed by 99.4 ms idle time (10 Hz) [6].

The high number of photons per pixel per pulse will create charge carrier densities exceeding the bulk doping of the sensor which will influence among others the linearity, point spread function and response time of the detector.

The main physical effect of these so-called electron hole plasmas is the change of the electric field inside the sensor. In the low density case this change is small and can be neglected, whereas in the case of high densities the changed electric field plays a dominant role in the charge collection process.

Due to self-shielding effects inside the plasma ambipolar diffusion becomes the dominant transport process, changing the induced current pulse of the sensor and increasing the charge collection time by a so-called plasma time [7]. Plasma effects have shown to decrease as the electric field increases [8]. Using incident ions of varying mass and energy, the influence of sensor properties on plasma effects has been studied in detail in Ref. [9].

However, the plasma effects observed for heavy ions are not expected to be observed at the European XFEL, as the created charge carrier densities will be orders of magnitude lower than those created by high-Z ions.

The plasma effects change the charge collection process. Carriers will drift apart laterally due to two processes: diffusion and electrostatic repulsion. At first diffusion is the dominant process as electrons and holes are not separated. Once the charges are separated mutual electrostatic repulsion, which increases with charge carrier density, increases the lateral spread.

These two effects will result in an increased lateral spread of the collected charge and thus in increased charge sharing between pixels, as shown recently in Ref. [10] for α−particles. It was shown in Ref. [11] that this spread is a strong function of the electric field inside the sensor and thus of the bias voltage. High bias voltages reduce the self-shielding effects of high charge carrier densities.

All measurements in this work have been performed using light with perpendicular incidence. Results for oblique incidence are expected to show less plasma effects and asymmetric charge spreading as shown in Ref. [12] for light ions.

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2. Experimental setup

To study the impact of the electron hole plasma a multichannel Transient Current Technique (mTCT) setup was built. Charge carrier densities up to $10^{16}\,cm^{-3}$ (corresponding to 10^5 12 keV photons in a small spot) were created with sub-ns lasers (660 and 1015 nm) and the time resolved current pulses of the investigated sensors (4 channels simultaneously) were read out by Miteq AM-1309 wideband amplifiers and a Tektronix DPO 7254 2.5 GHz oscilloscope. The transfer function of the whole setup has been checked and was found to introduce distortions on the sub-ns level, which were considered insignificant.

The samples were mounted on a special substrate that allowed light injection from both sides while cooling them to 20 °C and simultaneously providing the high voltage to the rear side of the sensor.

The sample holder and optics were mounted on translation stages controlling the position of light injection with 0.1 μm accuracy.

2.1. Laser properties

The laser system was manufactured by Picoquant GmbH [13] and provided short and intense laser pulses with a FWHM <100 ps. The system uses exchangeable laser heads, each head providing light of different wavelength. For this study laser light with an average wavelength of 660 nm (± 2 nm) and 1015 nm (± 6 nm) was used. The maximum pulse energy is 140 and 260 pJ for the 660 and 1015 nm laser, respectively.

In silicon the number of optical and X-ray photons decreases exponentially with thickness. The attenuation length of 660 nm light and 1 keV photons is 3 μm. One thousand and fifteen nm light and 12 keV photons have an attenuation length of roughly 250 μm (calculated from the mass energy absorption coefficient of 12 keV photons).

It should be noted that is a statistical process involving secondary process like Compton scattering and fluorescence. Thus the energy transferred to the silicon lattice (and therefore the initial electron hole distribution) can only be described by an exponential function with an infinite number of impinging photons. However, the statistical fluctuations of deposited energy per unit path length become negligible when a few hundred photons are absorbed simultaneously. So lasers can only be used to simulate the energy distribution of many X-ray photons, not the absorption of individual X-ray photons.

The laser beam was focused to a spot with Gaussian profile with $\sigma \leq 3$ μm. In air the Rayleigh length (distance from focal point to the point where the beam radius increases by $\sqrt{2}$) is approximately 90 μm. This guarantees a focused laser beam for 1015 nm light through the entire thickness of the silicon sensors used in this work, as the high refractive index of silicon effectively increases the Rayleigh length inside the silicon by a factor of approximately 3.6. Different pulse energies have been created by using optical attenuation, which has no influence of the spot size and pulse duration.

2.2. Investigated sensors

Two microstrip sensors have been investigated. The overall size (substrate) of the microstrip sensors was 10 mm $\times$ 10 mm, the strip length about 8 mm. Both sensors are p-in-n sensors (structured p+ implant (front) in n-type silicon (bulk), continuous n+ implant(rear)).

The sensor of 280 μm thickness, which has a strip pitch of 80 μm and a p + implantation width of 20 μm, was produced by CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH [14]. The silicon used is high resistivity n-type diffusion oxygenated float zone silicon with ⟨1 0 0⟩ orientation manufactured by Wacker. The effective doping, determined from a diode test structure on the wafer is $8 \times 10^{11}\,cm^{-3}$. The depletion voltage for the 280 μm strip sensor is 63 V.

The sensor of 450 μm thickness, which has a strip pitch of 50 μm and a p + implantation width of 11 μm, was produced by Hamamatsu Photonics [15]. The silicon used is high resistivity n-type silicon with ⟨1 1 1⟩ orientation. The depletion voltage for the 450 μm strip sensor is 155 V.

The 280 μm sensor has an aluminum grid on the back contact that allows laser light injection opposite to the strips. The aluminum on the rear contact of the 450 μm sensor was removed to allow light injection from the rear side.

The readout electronics was on ground potential. To ensure proper working conditions five strips on both sides of the readout strips were also connected to ground potential. The bias voltage was applied to the rear side.

3. Results

All results presented were obtained with rear side illumination.

The generated charge is given as equivalent photons by dividing the number of electron hole pairs by the number of electron hole pairs created by a photon of 1 keV (278 e,h pairs) or 12 keV energy (3333 e,h pairs).

There is a difference in the number of absorbed and incident 12 keV photons, as the conversion probability of a 12 keV photon in 280 and 450 μm of silicon is roughly 0.73 and 0.88, respectively.

3.1. Increase of charge collection time

From the measured transients the charge collection time is determined as a function of bias voltage and charge carrier density. A few selected transients for 660 and 1015 nm light are shown in Figs. 1 and 3.

Without plasma effects the charge collection times range from 6 to 20 ns (500 and 100 V, respectively) for the 280 μm sensor and from 12 to 30 ns (500 and 200 V, respectively) for the 450 μm sensor.

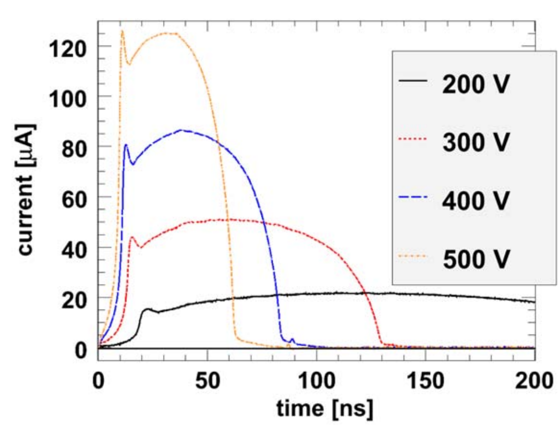

Fig. 1. Transients obtained for the 450 μm sensor. Focused 660 nm light of high intensity (≈ 3 μm rms, 3.24×10^5 1 keV photons) was injected from the rear side, centered to the readout strip. Transients are presented for different applied bias voltages, showing an almost rectangular shape, plasma delays and very long charge collection times for low voltages. The depletion voltage of this sensor is 155 V.

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