A set-up to study the radiation hardness of silicon sensors for the XFEL

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Imaging experiments at the XFEL pose unprecedented requirements to the detectors in terms of radiation tolerance: Photon fluxes up to 10^{16} photons/cm^2 corresponding to approximately 10^9 Gy in silicon, are expected. An irradiation station has been set up in the DORIS beam line F3, silicon test structures have been irradiated, and first results on the radiation tolerance of Si-structures obtained.

Following effects of high dose irradiation of silicon sensors and electronics may occur: (1) bulk damage, (2) charge build-up at the Si-SiO$_2$-interface and (3) current generation at the Si-SiO$_2$-interface. Given that the photon energy of 12 keV is well below the threshold for bulk damage (~300 keV), no effects are expected for (1). (2) and (3) have been observed at lower doses (~100 kGy) with some evidence for saturation of both effects with increasing dose.

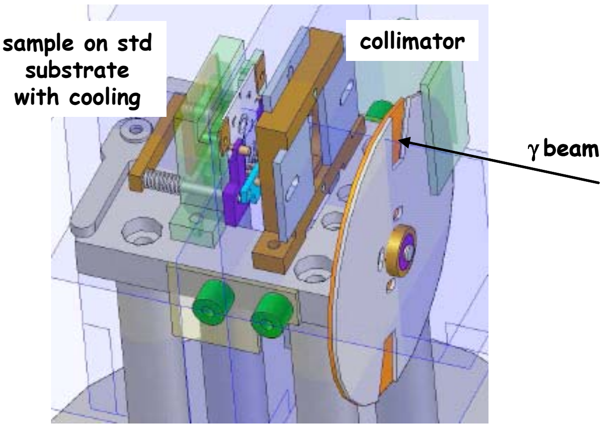

Figure 1: Irradiation set-up in F3 beam

In the DORIS “white beam” F3 an irradiation facility has been set up. As shown in Fig. 1 it consists of a rotating Ta chopper, which can reduce the dose by a factor 50 - 300, a precisely adjustable horizontal and vertical collimator, and a water-cooled sample holder. The device to be irradiated is mounted on a 20 mm·25 mm alumina substrate with five gold contacts which can be used to apply a potential to different parts of the circuit. Spring-loaded contacts allow an easy and quick exchange of the samples. For the determination of the dose and of the beam profile, the current in a planar Si-diode without applied voltage is measured.

The beam profiles, measured by setting the horizontal/vertical slit to 0.5 mm are: horizontal box-shaped with 5 mm width; vertical parabolic with a full width of ~4 mm. The photon energy spectrum has been calculated from the synchrotron spectrum and the absorbers (50 μm Al and 250 μm Be). The energy of the photons absorbed in the silicon peaks at 10 keV with a full width at half height of about 6 keV. Without chopper the dose rate is ~150 kGy/sec. With chopper it can be reduced ~0.5 kGy/sec. A pneumatic beam shutter allows a minimum irradiation time of ~1 sec.

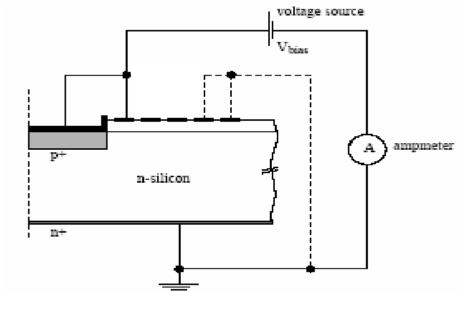

Figure 2: Cross-section of gated diode

To study the charge build-up and the current generation at the Si-SiO$_2$ interface, gate controlled diodes as shown in Fig. 2 have been used [1]. They are fabricated on a 285 μm thick n-doped Si-substrate with a central p$^+$-doped diode and five Al gate on top of about 350 nm of SiO$_2$-Si$_3$N$_4$. Standard C-V measurements in the frequency range 10-800 kHz on gate rings 2 and 3 are used to determine the flat band voltage from which N_{Ox}, the charge density at the interface, is obtained. Fig. 3 shows N_{Ox} versus irradiation dose obtained from the 10 kHz data. Starting at ~$3\cdot10^{11}$/cm^2 for un-irradiated diodes, N_{Ox} increases to a maximum of ~$4\cdot10^{12}$/cm^2 (flat-band voltage shift of about 75 V) and then decreases to about

$2 \cdot 10^{12}/cm^2$. Note that the dose scale is logarithmic. Strong annealing is observed: the measurement results depend on the time between irradiation and measurement. The decrease above 5 MGy is probably due to an insufficient cooling of the substrate for irradiations without the chopper. It is obvious that the large increase of oxide charges has to be taken into account when designing sensors and read-out electronics. Nevertheless, it is comforting that N_{Ox} appears to saturate.

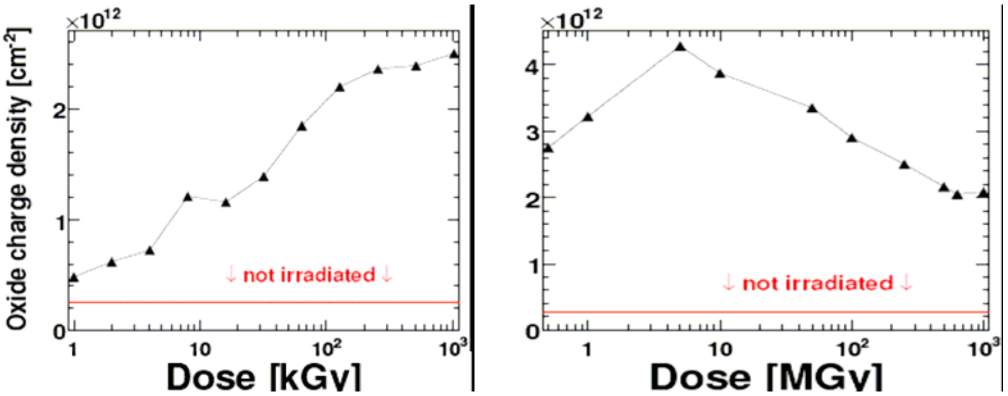

Figure 3: Measured oxide charge density at the Si-SiO_2-interface as function of dose

The surface current from the Si-SiO_2-interface is determined from the change in current when driving the Si-SiO_2-interface from accumulation to depletion. Whereas at low irradiations the I/V curves follow the classical gate controlled diode characteristics [1], they get more complex at higher doses. This still has to be understood. The results on the surface generation current density versus dose are shown in Fig 4 . From an initial current of $6 \cdot 10^{-9}$ A/cm^2 for un-irradiated detectors it rises to about 10^{-6} A/cm^2 at a few MGy, and then decreases at higher doses. Again, we assume that annealing due to insufficient cooling for the irradiations without chopper is the cause. But there is clear evidence that the increase in surface generation current density is limited.

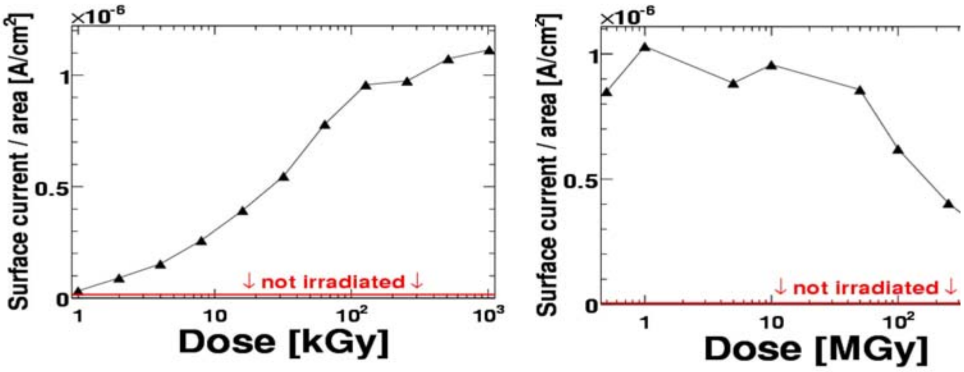

Figure 4: Measured surface generation current density at the Si-SiO_2-interface as function of dose

To summarise: A high dose (up to 150 kGy/s) irradiation stand has been set up in the F3 beam line at DORIS. Gated diode test structures have been irradiated up to doses of 1 GGy. A significant increase in charge density and in generation current at the Si-SiO_2-interface has been observed, which appear to saturate at doses above a few MGy. Other groups have already used the stand.

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References

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