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Developments for Radiation Hard Silicon Detectors by Defect Engineering -Results of the CERN RD48(ROSE) Collaboration-

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SUMMARY

The RD48(ROSE) collaboration has succeeded to develop radiation hard silicon detectors, capable to withstand the harsh hadron fluences in the tracking areas of LHC experiments. In order to reach this objective, a defect engineering approach was employed resulting in the development of Oxygen enriched FZ silicon (DOFZ). Systematic measurements have been carried out with various standard and oxygenated material in fluence ranges between 5×10^{10} and 5×10^{14} cm^{-2} (1MeV-n-equivalent). The defect generation on a microscopic scale was also studied, gaining invaluable insight in the underlying physics. Only macroscopic effects of the O-enrichment with direct relevance for LHC detector application are summarized in the following:

- ***Leakage current:*** the damage parameter α is material independent (no dependence on conduction type, crystal orientation, resistivity and impurities) and is scaling almost ideally with NIEL (non ionizing energy loss) independent of particle type and energy.

- ***Effective doping concentration (depletion voltage):*** the damage induced change in N_{eff} is considerably improved after charged hadron irradiation. Short term annealing (10 days at RT) leads to $\approx$3 times less increase in the depletion voltage as compared to standard silicon and the reverse annealing even shows an unexpected saturation at higher fluences. This amounts to a decrease in the N_{eff}-change by as much as a factor of 4 and together with the additional effect of a 5 times larger annealing time, thus offering an additional safety margin for detectors kept at room temperature during maintenance. To present knowledge these improvements hold only for proton irradiation (in accordance with existing checks for pions), for neutrons a beneficial effect was observed by using low resistivity material (e.g. 1 kΩcm instead of the standard 5 kΩcm silicon decreases the change in N_{eff} after 2×10^{14} n/cm^2 by a factor of $\approx$2).

- ***Charge collection efficiency:*** while the measurements for N_{eff} have mostly been performed on test pad diodes using C/V methods, these results have been checked both with test and silicon strip detectors measuring the charge collection efficiency as function of bias voltage. The results show a good agreement between both techniques also revealing that the systematic analysis done with test diodes can reliably be used for strip detectors.

- ***Model description for macroscopic damage effects and projection to LHC:*** For the above described effects the "Hamburg-model" had been applied for the O-enriched silicon detectors and relevant parameters were extracted. The application of the model to LHC operational scenarios indicates that by using oxygenated instead of standard silicon the lifetime of e.g. the sensors in the B-layer of the ATLAS pixel detector would be extended to almost 10 years. In fact, the ATLAS pixel group had meanwhile decided to use the RD48 developed technique.

- ***Optimization of the DOFZ technique:*** So far feasibility studies with various companies have shown that the oxygenation of the silicon bulk by prolonged tempering after normal oxidation (diffusion of O from the SiO_2-Si interface) does not result in any problem. Optimization experiments are presently carried out with O-diffusion in the range between 6 days at 1200^0C and 8 hours at 1150^0C.

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