Silicon Sensor Developments: Material Design and Characterisation

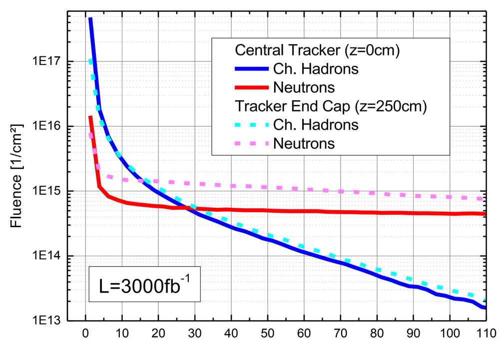
Common effort of the Institut für Experimentelle Physik, Universität Hamburg, and the Institut für Experimentelle Kernphysik, KIT

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Introduction

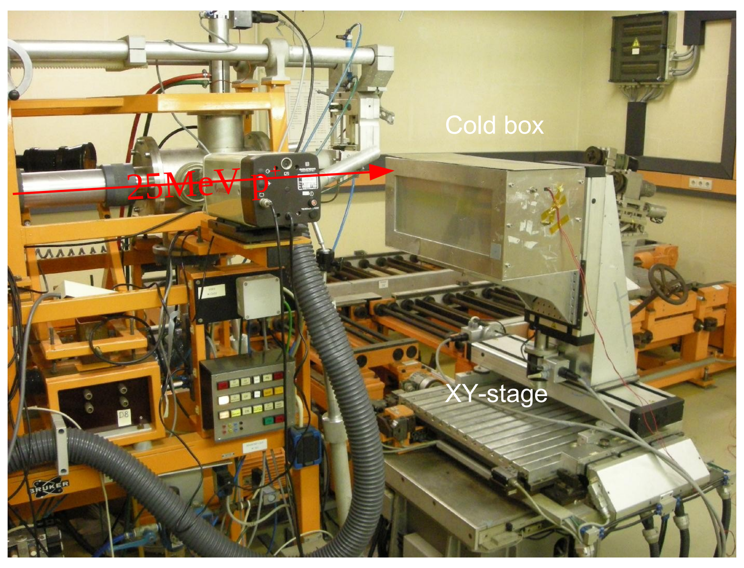
This work package combines the infrastructure and expertise needed to develop radiation hard silicon detectors for future high energy particle physics experiments.
Especially, the upgrade of the LHC (sLHC) to a luminosity of $10^{35}cm^{-2}s^{-1}$ requires to increase the radiation tolerance of the silicon tracking devices up to fluences of 10^{16} cm^{-2}.
With the help of the Helmholtz Alliance (HHA) the two institutes could improve their experimental setups. They are prepared to measure all relevant microscopic and macroscopic parameters of silicon sensors as they are needed for further developments.
The infrastructure is accessible for all Alliance members and comprises:

- Proton irradiation facility (25MeV)
- X-ray irradiation facilities (1keV and <60keV)
- Manual and semi-automatic probe stations
- Thermally Stimulated Current (TSC) Setup
- Deep Level Transient Spectroscopy (DLTS) Setup
- Transient Current Technique (TCT) Setups
- Multi-channel TCT
- Read-out system for strip sensors
- Cosmic Telescope



Expected particle fluence in the CMS Tracker after 3 years at sLHC

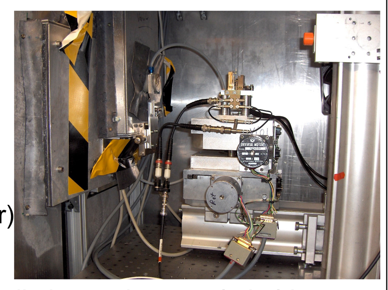
Proton Irradiation Facility



The compact cyclotron, run by the Zyklotron AG, is made available to Alliance members through the IEKP at Karlsruhe. The infrastructure for the irradiations and the dosimetry is maintained and irradiations are performed by one scientist and one technician funded by the Alliance.
The samples can be cooled with cold nitrogen gas and the beam can be scanned over a maximum area of 150mm x 400mm. To prevent heating of the samples the beam current is limited to 1.5μA, which still allows to irradiate to high fluences in short times, e.g. a sensor of 40mm x 40mm can be irradiated to 10^{15} n_{eq}/cm^2 in 50 minutes.
Expenses for the irradiations by Alliance members are mostly covered by the HHA.
The facility has been used so far by the universities Bonn, Dortmund, Freiburg, Karlsruhe and the HLL München, which results in a total of 150 hours of beam time.

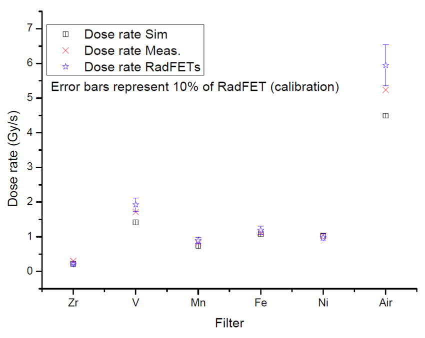
X-Ray Irradiation Facilities

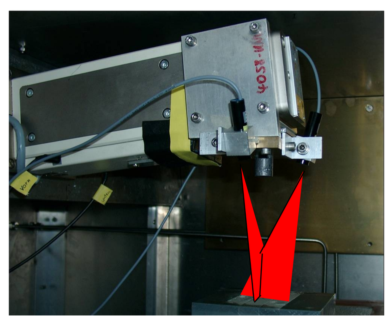
Synchrotron source at Hamburg



The X-Ray irradiation facility is set up in the "white beam" F4 at HASYLAB. The beam energy is about 10 keV with a width of ±5 keV and dose rates between 0.75 and 150 kGy/s (selectable with a chopper) and a spot size of 2x5mm². A manually adjustable x-y collimator can be used do define the field of irradiation and a sample holder allows easy exchange of samples, up to four biasing lines and temperature control between 10 and 30°C. Larger areas can be irradiated by computer controlled scanning. The source has been used by HLL München, DESY, Hamburg and the AGIPD Collaboration.

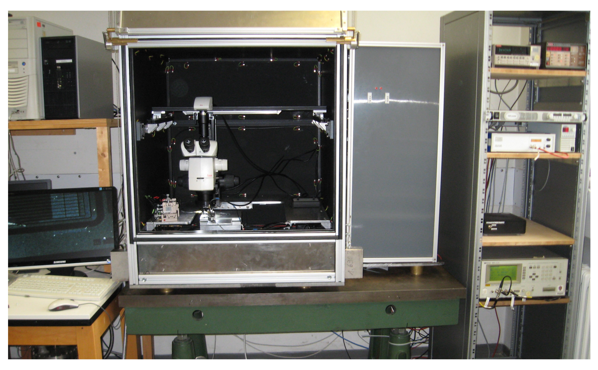
X-Ray source at Karlsruhe



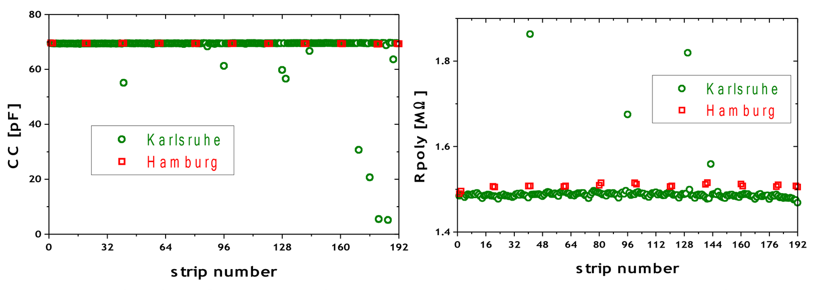


The X-ray tube in Karlsruhe comes with a tungsten target, a maximum voltage of 60kV at 33mA and several filter materials. The hardest spectrum is produced by a zirconium filter with a dose rate of about 80kRad/h (0.22Gy/s). This can be increased to about 720kRad/h (2Gy/s) using a Vanadium filter.
The source has been used so far by Darmstadt, HLL München, Heidelberg and Karlsruhe for about 600 hours.

Probe stations for sensor characterisation



Karlsruhe has build a new, second probe station for silicon sensor characterization [1]. Special care was taken to allow easy measurements of irradiated samples, which have to be cooled and biased to high voltages. The use of probe needles results in a flexible setup, which can access wafers up to 8 inch. The placement of the needles requires a good microscope with a long focus, which was funded by the HHA together with power supplies.
Further cooled manual probe stations are available in Hamburg.
These probe station have been cross-calibrated using test-structures and showed measurements of good agreement.



Example plots from the calibration measurements showing coupling capacitance and poly-recistances on a mini strip sensor

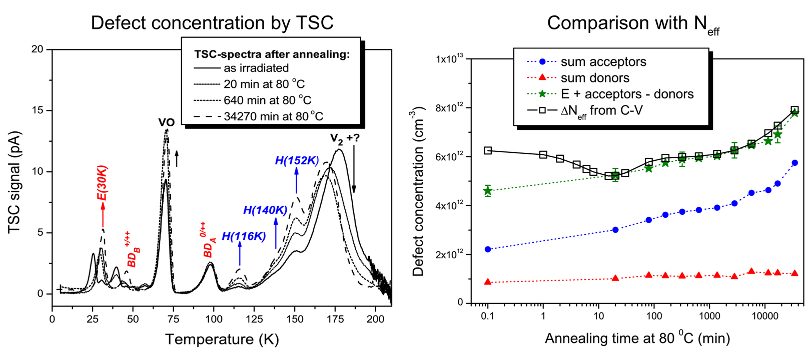
[1] J. Erfle, "Entwicklungen für neue Siliziumstreifensensoren und deren Qualitätskontrolle", Universität Karlsruhe (TH), 2009, IEKP-KA/2009-27

Thermally Stimulated Current

The Concept

Defects in silicon have energy levels in the band gap. At very low temperatures (5K) the defects are filled with charge carriers. With increasing temperature the charge carriers are activated and the corresponding current measured. Energy levels and concentrations can be extracted from the current vs. temperature diagram.

Impact of microscopic defects on the effective doping concentration



The results from the TSC defect investigations were used to predict the annealing effects of N_{eff} which are then compared with those from C-V measurements at RT. There is a striking agreement between prediction and results for the annealing effects in neutron irradiated epitaxial material (EPI) (see figures) and Magnetic Czochralski (MCz) material and for 23 GeV proton irradiation. Those measurements have proven to be a powerful tool for the characterization of irradiated sensors. Experiments and analysis were performed in Hamburg [2].

[2] I. Pintilie, E. Fretwurst, A. Junkes, G. Lindström; DOI:10.1016/jnima.2009.09.065

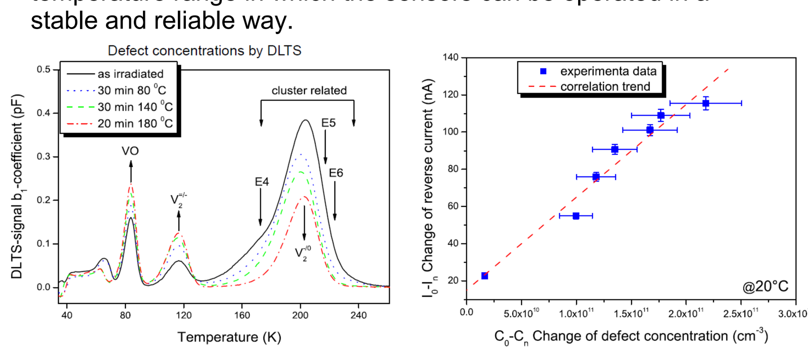
Deep Level Transient Spectroscopy

The Concept

Deep level defects are filled with charge carriers by modulating the Fermi level and measuring the capacitance transient (C-DLTS) caused by the emission of the charge carriers. The sign of the transient identifies the type of defect as hole or electron traps.

Defect clusters: Understanding of radiation induced dark current

The generated dark current after heavy irradiation is limiting the temperature range in which the sensors can be operated in a stable and reliable way.



A correlation between the generation of the dark current and vacancy-like defect clusters [3] is found. This DLTS study was performed on F_{eq} = 3 × 10^{11} cm^{-2} neutron irradiated MCz material in Hamburg.
These results present a breakthrough in the understanding of radiation induced dark currents in silicon sensors.

[3] A. Junkes, 2008th RADECS conference proceedings, Jyväskylä, Finland

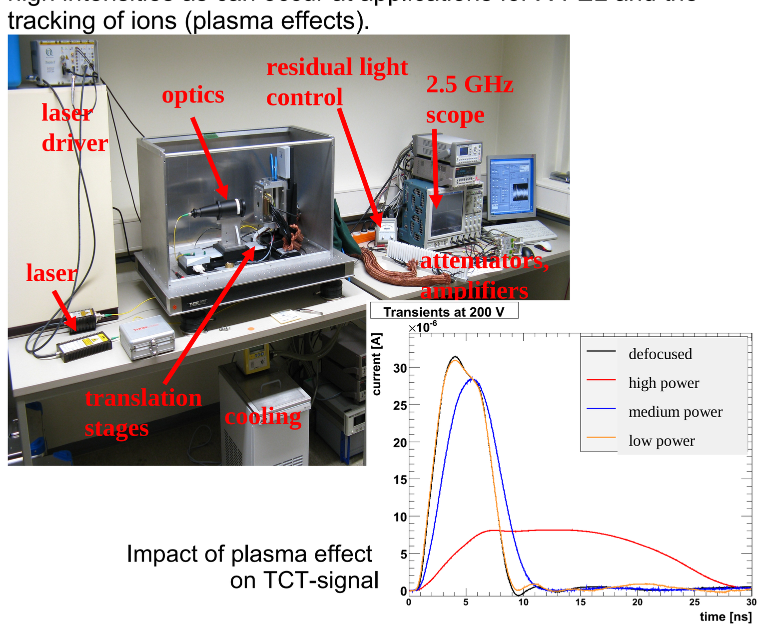
Transient Current Technique

The Concept

Charge carriers are generated on one side of the biased diodes with a short (<1ns) laser pulse or alpha source. The signal current response is acquired with a fast scope.
This current response is measured for several applied bias voltages at several temperatures to extract trapping times, drift times, electric field profiles, ...

Multi-channel TCT

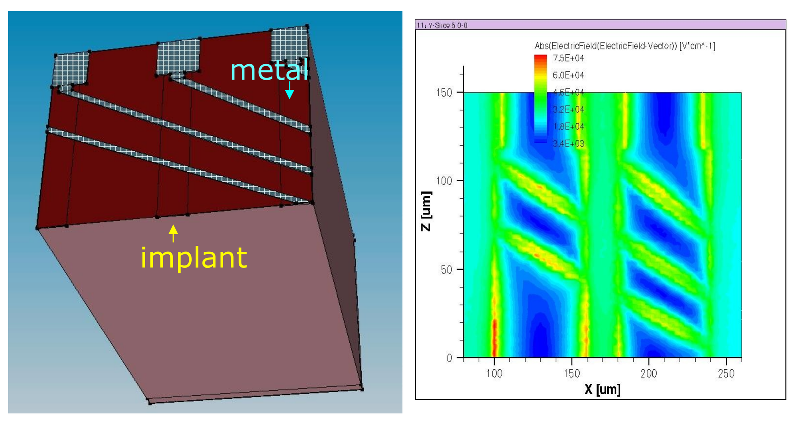
In Hamburg the TCT concept was expanded to measure the current response of several channels on a strip sensor. Fast (≤100ps) laser pulses with wavelengths of 660nm, 1015nm and 1052nm can be focused to a spot of ≤ 3μm, which can be moved with submicron accuracy. The setup is temperature (-30°C – 50°C) controlled. It is suited to investigate charge transport up to very high intensities as can occur at applications for X-FEL and the tracking of ions (plasma effects).



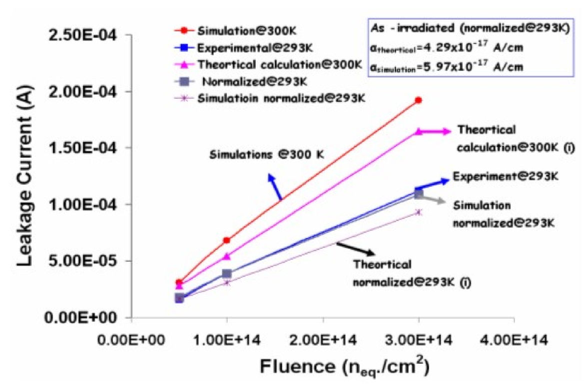
Impact of plasma effect on TCT-signal

Device Simulation

The design of radiation tolerant sensors is assisted by numerical simulation with Synopsis TCAD in which we implement the experimental results of the radiation damage studies. The topics reach from calculation of the electric field in pitch adapter on sensor designs and their break down and coupling behavior to current estimations and electric field profiles in irradiated sensors.

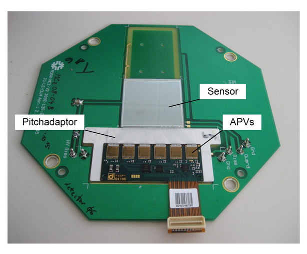


3d simulation of electric field close to the Si/SiO2 interface in the pitch adaptor region

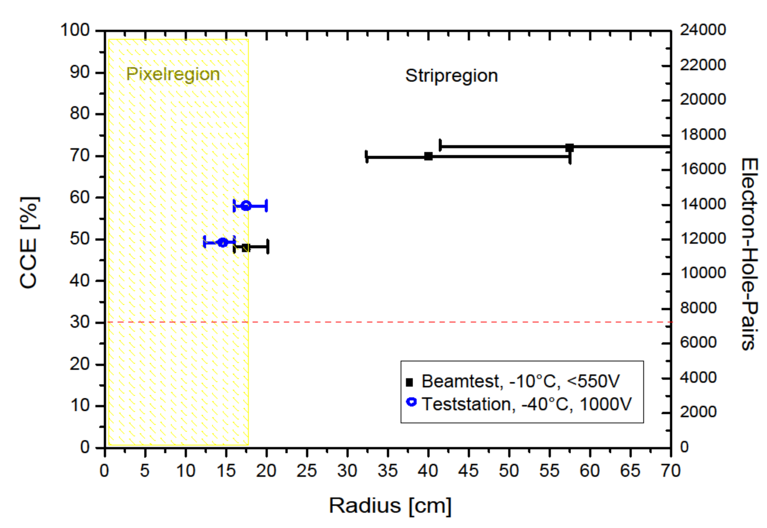


2d simulation of the leakage current in irradiated silicon diode and comparison to experimental values

Beam test with n-type MCz strip sensors



Strip sensors produced at the Helsinki Institute of Physics were characterized, irradiated and assembled into modules in Karlsruhe.
The beam test demonstrated that highly irradiated n-type MCz silicon sensors can be operated down to a radius of 15cm in the upgrade of the CMS Tracker at sLHC [4,5].

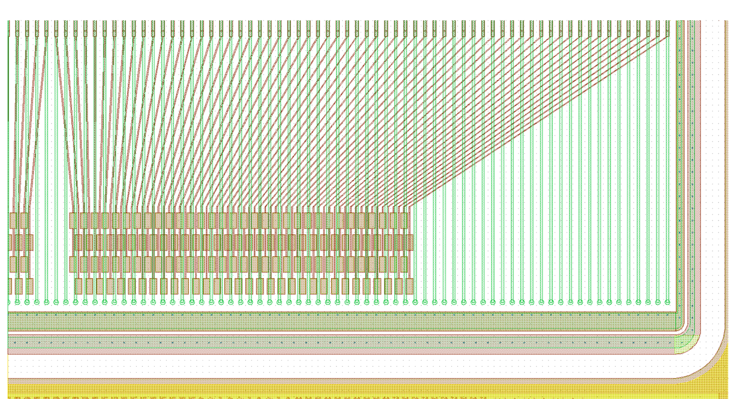


[4] M. Frey, "Entwicklung von hoch strahlenharten Silizium-streifensensoren für den Einsatz am Super Large Hadron Collider", Universität Karlsruhe (TH), 2009, IEKP-KA/2009-18
[5] P. Luuka et. al., "Test beam results of heavily irradiated magnetic Czochralski silicon (MCz-Si) strip detectors", NIM A (2009) doi:10.1016/j.nima.2009.08.017, in Press

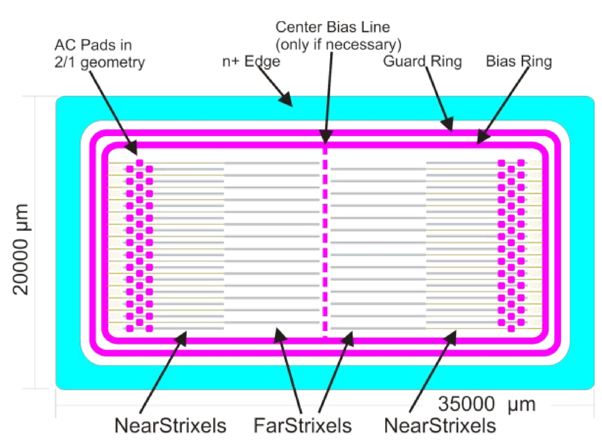
Participation in the CMS Tracker Upgrade Project: the Central European Consortium

The Central European Consortium (CEC) is a collaboration of 9 institutes, which have the goal to find a single material and module design for the outer tracker and to determine the minimum radius for which the modules can be operated. The Consortium is coordinated by members of the Hamburg and Karlsruhe groups.
This Alliance workpackage participates by investigating the radiation hardness of sensor materials as there are n- and p-doped Magnetic Czochralski (MCz), Float zone and epitaxial silicon.
Of special interest for the CMS Tracker is the investigation of sensors with short strips (to reduce occupancy) and integration of pitch adaptors in the sensor (to reduce material budget), which is conducted by Hamburg and Karlsruhe. Several possible pitch adaptor layouts have been designed, simulated and will be produced at two fabrication sites, which work in close collaboration with the CEC.

Within the CEC optimised test-structures were developed, which can be (and are) added to any wafer submission to have a common parameter set for comparing the quality of different processes and vendors.
To make sure that the setups at all institues being involed in CMS sensor qualification are well calibrated, the CEC has planned and is conducting a calibration campaign. For this, unirradiated and irradiated test-structures are characterised in Karlsruhe and sent out to all the participating institutes (12 at the moment).
Within the CMS Tracker upgrade program a wafer production with Hamamatsu Photonics has started. Test-structures on these wafers were designed by the CEC and a detailed irradiation and test program has been developed. This production will make a variety of silicon materials available to the consortium and this workpackage. First versions of a mini sensor with integrated pitch adaptor and a short strip sensor have been designed and integrated in the wafer layout.



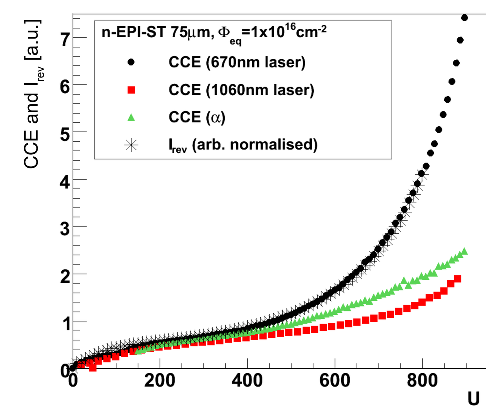
Possible pitch adaptor layout on a mini strip sensor



A first version of a short strip mini sensor

Outlook

The harsh radiation environment and the high particle density at future high energy accelerators require to find new materials and designs, which guarantee a reliable operation over many years.
The radiation hardness of new materials like MCz and epitaxial silicon has to be exploited.
Recently, unexpected high charge collection efficiency in epitaxial diodes irradiated to fluences above $10^{15}n_{eq}/cm^2$ point to avalanche multiplication. This effect is under detailed investigation.
Measurements show different behaviour of n- and p-type MCz silicon when exposed to mixed radiation fields (neutrons and charged hadrons). These findings need some more systematic investigations.
An interesting option for radiation hard material is p-type silicon with electron read-out, since electrons show less trapping than holes.
Still, new features appear and the optimal material for the inner tracking devices at future collider experiments has to be found.
With the help of the HHA we could build new setups, which are needed for sensor characterisation and development, and are used by several groups of the HHA.



Charge collection efficiency was measured in HH to increase beyond 100% in thin highly irradiated diodes

Created by A. Dierlamm, IEKP, KIT
Hamburg material from A. Junkes