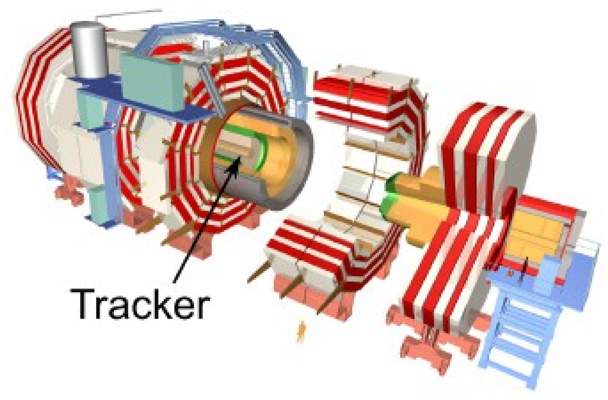
Silicon Strip Sensor Simulations for the CMS Phase II Tracker Upgrade

Thomas Eichhorn, CMS Upgrade Week at DESY, 3rd – 7th June 2013

The CMS Phase II Tracker Upgrade

Plans exist to upgrade the Large Hadron Collider LHC to a high luminosity LHC in the year 2020. This is also the designed lifetime of the currently installed CMS silicon tracker, which consists of 15148 detector modules arranged in a barrel and an end cap configuration. The position of the tracker within the CMS detector is shown below:



In the course of this upgrade, the instantaneous luminosity will be raised tenfold, leading to increased radiation damage and a higher track density. For these needs, a new tracker is needed, requiring senors that are more radiation hard, withstanding fluences of up to $2 \cdot 10^{16}\ n_{eq}/cm^2$ and that also can cope with a higher occupancy though higher granularity.

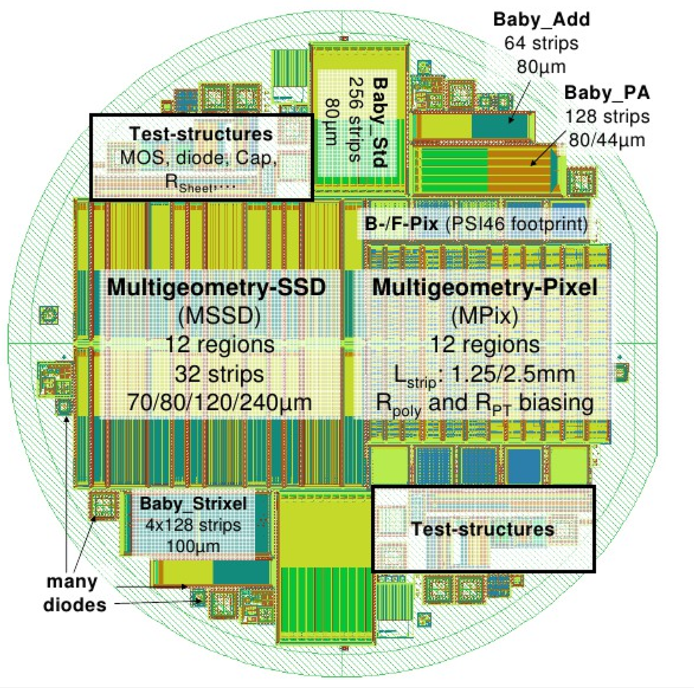
It is also aimed to reduce the material budget and use information from the tracker in the first level trigger of CMS.

The HPK Campaign

In order to identify the technological baseline for the CMS Phase II Tracker Upgrade, a campaign has been started to study radiation damage effects, annealing behavior and evaluate different geometries and materials.

To ensure overall comparability, a single producer was chosen and a common measurement procedure between participating institutes has been agreed on.

The picture below shows the structural layout of a produced wafer containing various regions. Each of these dedicated areas are then used to investigate specific sensor properties, before and after irradiation.



Simulation Software: Synopsys Sentaurus

How does the simulation work?
Synopsys Sentaurus is a commercially available software package for semiconductor simulations and is used not only in academia, but also in related industries. The simulation process is divided into the following steps:

> Structure generation – A structure is created by TCAD design, specifying for example geometry, material and semiconductor doping of the sensor. A lattice is then generated, so that the structure is characterized by mesh points.

> **Physical environment** – The physical models and conditions to be used during the simulation process are then selected and can be further parameterized These can include temperature, electric field generation, charge carrier recombination, trapping and carrier lifetime.

> External effects – A variety of external effects can be added to the simulation. Examples are an electrical circuit via a SPICE network (useful for comparison with experimental measurements), laser illuminations or traversing particles.

> Simulation type selection – Three basic simulation modes can be combined: current-voltage ramps, capacitive analysis and time transient simulation.

> Simulation run – With all parameters specified, the actual finite-element simulation is done. At all previously generated mesh points Poisson's equation

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{1\varepsilon_r \cdot \varepsilon_0}$$

and the carrier continuity equations

$$\nabla \cdot \vec{J}_n = q \cdot \left(R_{eff} + \frac{\partial n}{\partial t}\right) \qquad -\nabla \cdot \vec{J}_p = q \cdot \left(R_{eff} + \frac{\partial p}{\partial t}\right)$$

are solved. The desired physical properties, such as electric fields, current flows and charge distributions are then derived.

The Sensor Simulation Working Group in CMS

To streamline and coordinate tasks, a simulation group has been formed, with members coming from various other institutes beside DESY:

> Delhi University

> Karlsruhe Institute of Technology

> University of Helsinki

> University of Pisa

Aims of the group
To provide input to the HPK campaign and the CMS Phase-II Upgrade, the following points are under investigation:

> Comparison of simulation tools – There are various simulation packages available and in usage. An understanding of how different programs work, knowing their benefits and also their disadvantages is important.

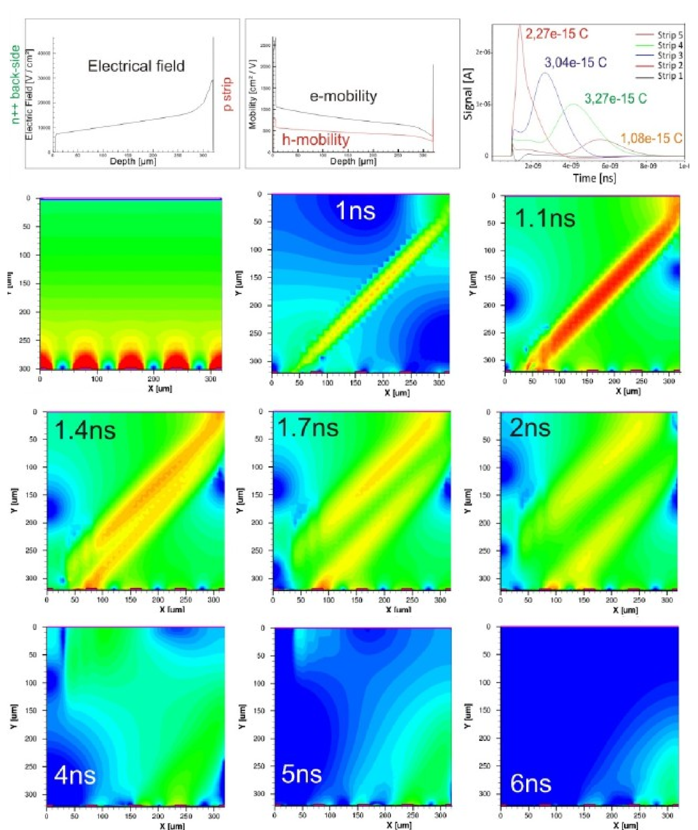
> Device design – Simulate sensor capacities, verify isolation techniques for p-type silicon devices.

> Radiation damage – Create a list of known defects and their properties. Can a trap model be derived and how does it change important sensor characteristics?

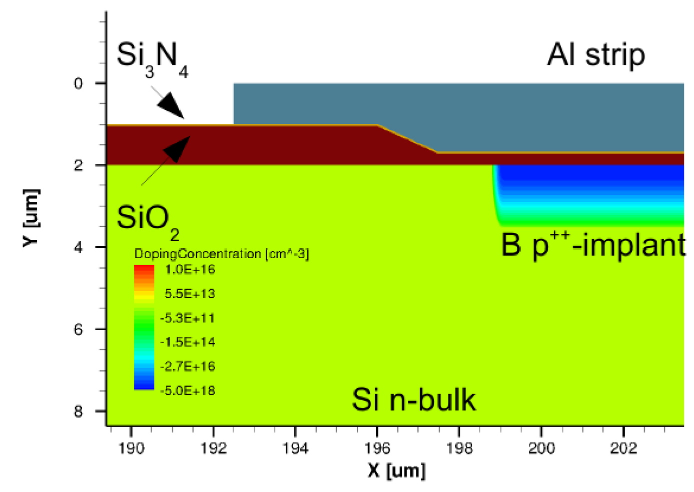
> Charge collection and readout – Research optimal layout, how does radiation damage effect charge collection efficiency?

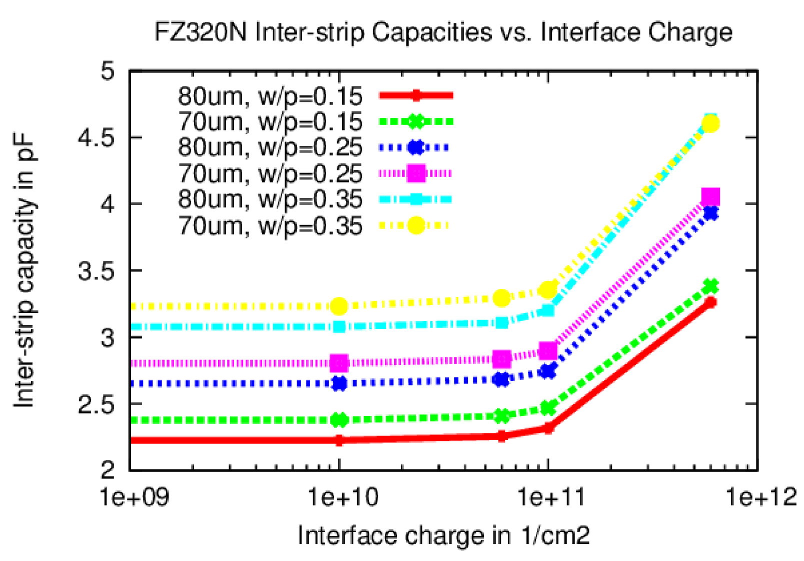
Charge Collection in a Silicon Strip Sensor

The picture below depicts a simulation of a 5-strip sensor. The first three subsets show profiles of the electric field and the carrier mobility though the sensor bulk, followed by the signals gathered at every strip from a traversing particle. An overview of the electric field, peaking at the strips, is shown in the fourth subset. The charges generated by the particle, their separation, drift and collection at the strips can be seen in the following time-resolved images.



Sensor Properties in Simulation and Measurement





MSSD sensor capacity
Strip capacitance is one of the most important reasons for electronic noise. This property is investigated in detail on so called Multi-geometry Silicon Strip Devices, containing 12 regions of different strip pitches (70µm, 80µm, 120µm and 240µm) and different ratios of strip implant width to pitch (0.15. 0.2. 0.3).

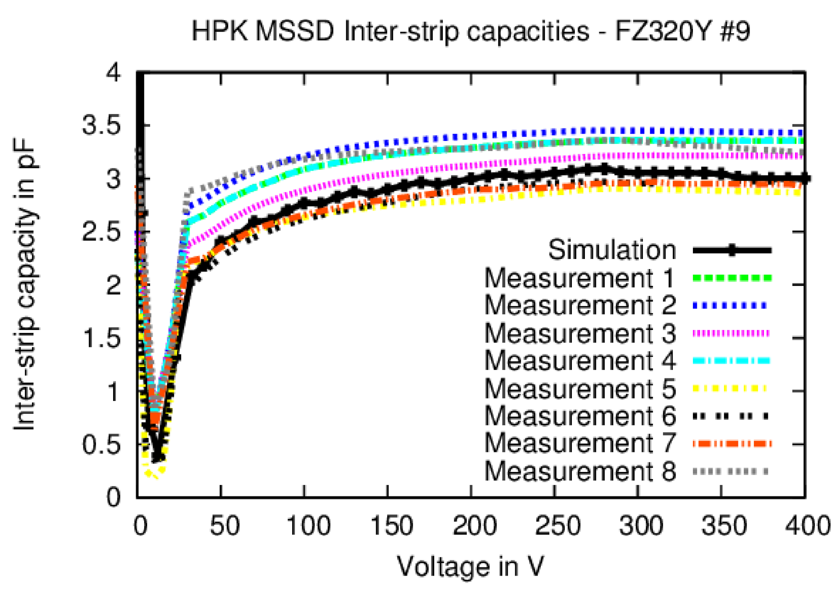
The performed simulations aim to reproduce measurements undertaken on MSSD sensors before and after irradiation. By tuning the simulation parameters, various sensor properties which are yet unknown can be extracted. Examples are the implant depths, the doping profiles and the exact geometry of the aluminum strips.

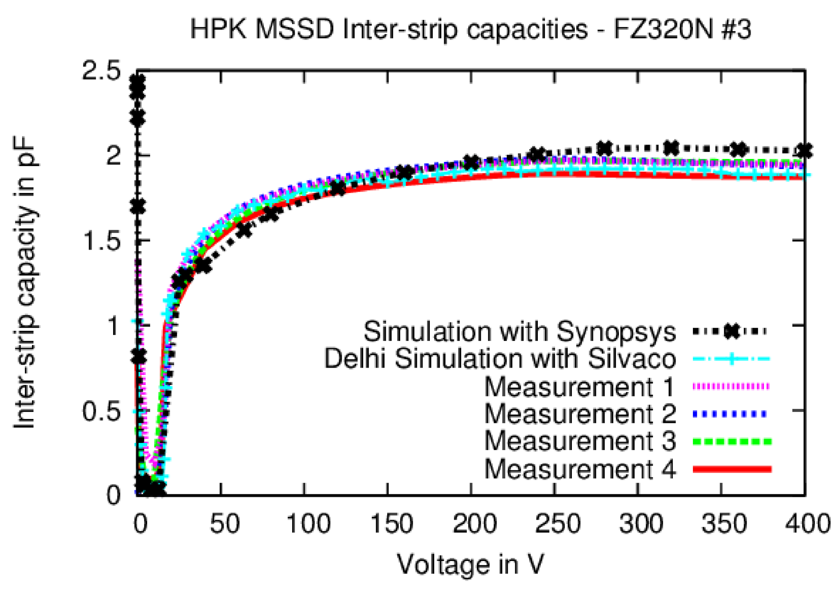
In addition, novel concepts and ideas, such as p-stop isolations can be tested in simulations and their feasibility can be tested before production commences.

The approximated structure used for simulations can be seen on the top at the right. The aluminium strip in gray is separated from the silicon bulk and boron implant by a layer of silicon nitride and silicon oxide.

One of the most sensitive sensor properties is the interface charge between silicon bulk and silicon oxide. The influence of the charge on C_{int} is shown bottom left for various width-to-pitch ratios. For the following simulations the interface charge was set to $1e11 cm^{-2}$.

On the right, the inter-strip capacitance C_{int} is displayed against the bias voltage for two different materials and geometries. Both simulations are in good agreement with measurements.





Modeling Radiation Damage

Understanding radiation damage and correctly implementing it in simulations is a major issue. Experimental data shows that damage effects on a silicon sensor can be categorized into the formation of point- and cluster defects. Vacancies, combinations with oxygen, the silicon doping and carbon complexes are thought to be point defects. Examples of cluster defects are the E30K, H116K, H140K and H152K defects. The type and concentration of defects are dependent on silicon material and irradiation type.

Point defects can be included in simulation by the means of traps – energy states in the silicon band gap. Important parameters are:

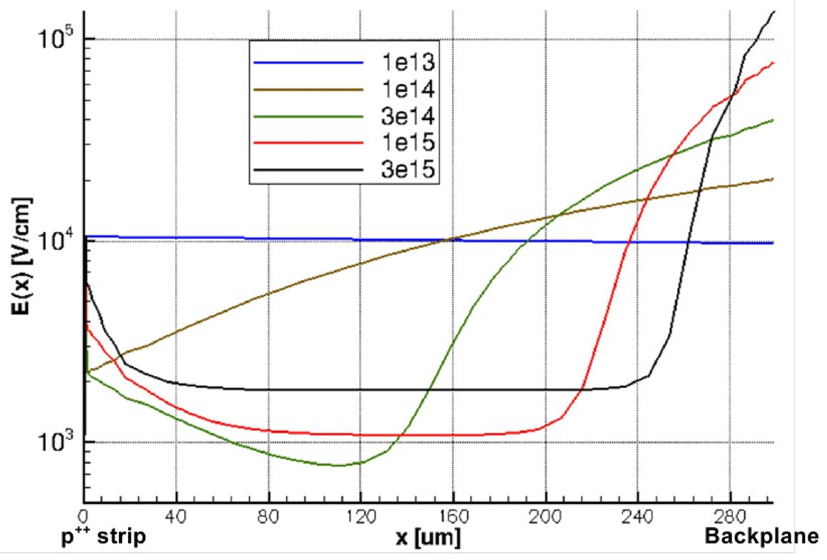
> particle fluence and trap **introduction rate**
> capture cross sections for electrons / holes
> energy level (i.e. position in the band gap)
> charge sign → acceptor or donor?

The simulation then calculates the number of occupied traps, resulting in a change of the charge density and then computes the capture and emission rate. This carrier movement between conduction band, trap and valence band increases leakage current and changes the depletion voltage and the charge collection efficiency.

A first trap model used for approximating proton and neutron damage is the EVL-4 model, which consists of two traps, a donor and an acceptor:

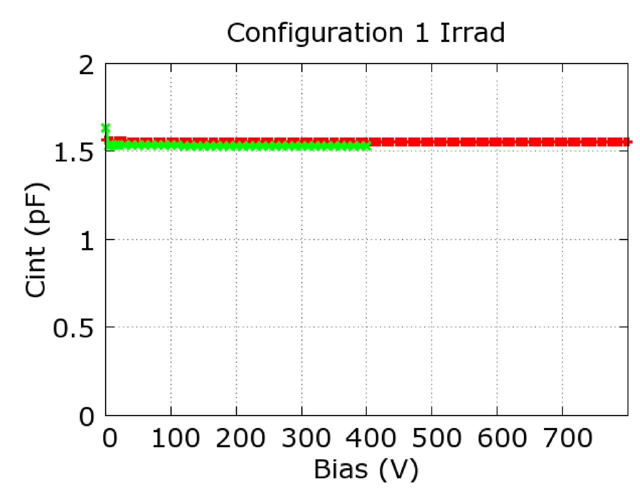
Defect	Energy [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	g [cm]
Acceptor	$E_C - 0.525$	4e-14	4e-14	0.8
Donor	$E_V + 0.48$	4e-14	4e-14	0.8

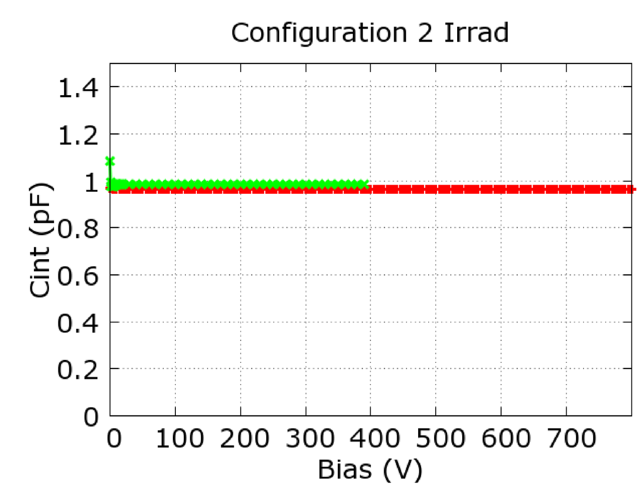
Radiation Damage in Sensor Simulations



Electric Field
A first test for a trap model is to see how the electric field in a sensor changes with increasing irradiation. Experimental measurements have shown that that irradiated sensors have a characteristic double peak in the electric field. This should be reproducible by simulations.

The above image shows a cut through a simple diode from strip to backplane with the simulated electric field for various fluences. The electric field shows linear behaviour for fluences of $1 \cdot 10^{14}\ n_{eq}/cm^2$ and below, but gets double peaked with increasing radiation. The flatness for high fluences can be attributed to the sensor no longer being depleted at the used bias voltage of 300V.



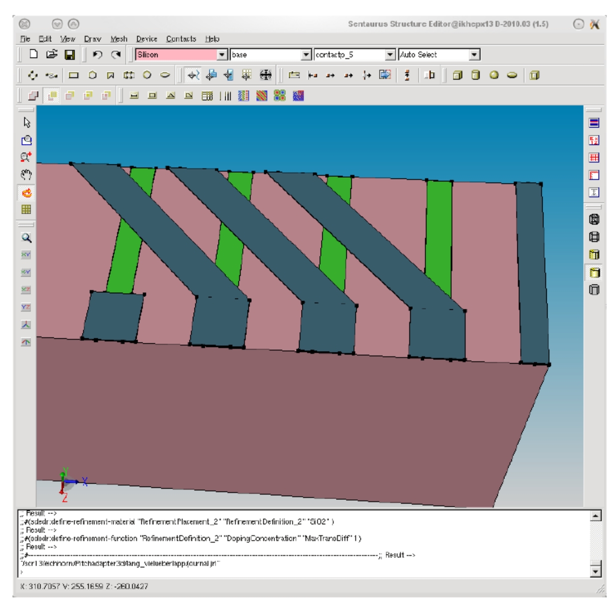


MSSD Sensor Capacitances
The inter-strip capacitance C_{int} changes with radiation damage.
The above two plots show that simulations (in green) can reproduce measurements (in red).

Ongoing and Future Work

TCAD simulations can provide an important insight into the future development of silicon sensors for particle physics experiments.

Sensor geometry
Currently, various design schematics are being simulated and their performance evaluated. The feasibility of new materials and layouts will be investigated. An example of a three-dimensional structure for a routing simulation can be seen below.



Radiation damage
The CMS sensor simulation group is currently investigating various defect models in order to reproduce measurements of irradiated sensors. A long-term goal is to be able to predict the radiation damaging a sensor will experience during its operational lifetime.

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