CMS CR -2012/320

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

21 November 2012 (v2, 22 November 2012)

Silicon Strip Sensor Simulations for the CMS Phase-II Tracker Upgrade

Thomas Eichhorn for the CMS Collaboration

Abstract

The future high luminosity upgrade of the LHC will necessitate radiation harder sensors for the CMS silicon strip tracker. CMS has instigated a campaign to identify a possible technology baseline for upcoming sensor generations. In addition to measurements, simulations can give an important insight into specific sensor properties. In this report, the concept of TCAD simulations is briefly explained, followed by sensor simulation results before and after irradiation. These results are then compared to measurements. The focus lies on the inter-strip capacitance $\mathrm{C_{int}}$ of silicon strip sensors.

Presented at *IEEE-NSS-MIC-RTDS2012: 2012 Nuclear Science Symposium, Medical Imaging conference and RTDS workshop*

Silicon Strip Sensor Simulations for the CMS Phase-II Tracker Upgrade

Thomas Eichhorn for the CMS Tracker Collaboration

***Abstract*—The future high luminosity upgrade of the LHC will necessitate radiation harder sensors for the CMS silicon strip tracker. CMS has instigated a campaign to identify a possible technology baseline for upcoming sensor generations. In addition to measurements, simulations can give an important insight into specific sensor properties. In this report, the concept of TCAD simulations is briefly explained, followed by sensor simulation results before and after irradiation. These results are then compared to measurements. The focus lies on the inter-strip capacitance C_{int} of silicon strip sensors.**

***Index Terms*—Silicon radiation detectors, TCAD simulations, CMS upgrade, Radiation damage**

I. INTRODUCTION

THE currently installed silicon strip tracker in the CMS detector was built with a running time of 10 years and a peak instantaneous luminosity of $10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ in mind. The upcoming high luminosity LHC upgrade will not only increase the instantaneous luminosity by a factor of five, but also create an even harsher radiation environment than already present. An upgraded tracker will therefore experience higher detector occupancy and require increased radiation hard sensors. It is planned to use information from the tracker in the first level CMS trigger and to additionally reduce the material budget.

A. The CMS HPK Campaign

The CMS Tracker Collaboration has started a campaign to identify not only properties and production processes of various silicon materials, but also to provide a baseline for a possible future sensor generation [1]. This ongoing campaign focuses on determining radiation damage effects and annealing behavior, as well as evaluating sensor geometries and materials.

For this, a single wafer producer has been selected and common testing procedures between participating institutes have been agreed on. The schematic layout of a produced wafer can be seen in figure 1. The wafers contain various structures, each serving a specific measurement, examples are:

1 MSSD Sensors for the inter-strip capacitance C_{int}
2 Diodes to measure charge collection efficiency, current-voltage (IV) and capacitance-voltage (CV) behavior
3 Short Strip Sensors to evaluate a novel biasing scheme
4 Pitch Adapters and various test-structures

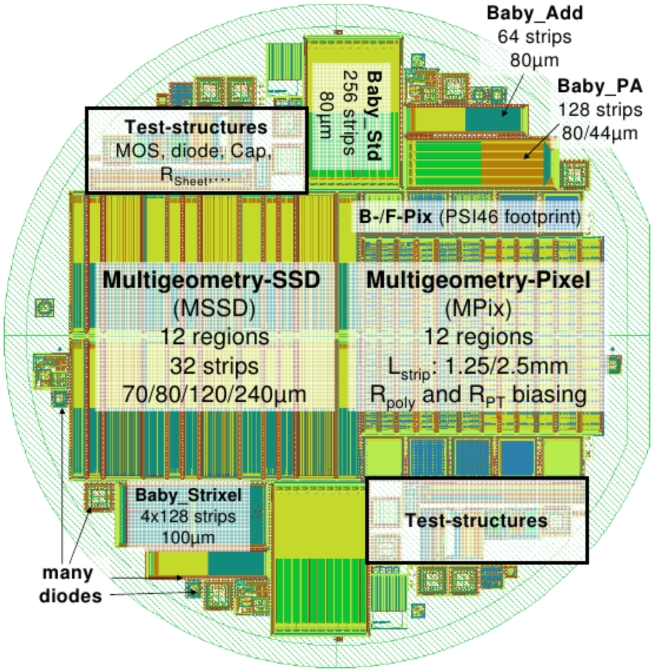

Fig. 1: Layout of the wafer produced for the HPK campaign.

Simulations can provide an important insight into the understanding of silicon sensors. Device simulations allow cross-checks of measured electrical properties, for example leakage currents or depletion voltages, but can also provide additional in-depth information such as field configurations and charge carrier distributions.

B. Simulation Software

In the DESY CMS group the commercially available simulation package Synopsys Sentaurus TCAD [2] is used, although a large variety of similar products are on the market, the most prominent example being Silvaco ATLAS [3]. Both software packages have many applications and enjoy an extensive use in the semiconductor industry. The simulation process follows the usual finite-element analysis procedure:

In a first step, a two- or three dimensional structure is generated and the used materials and their properties, such as the doping of the silicon, are defined. Alternatively, the actual sensor fabrication and processing steps can be simulated to create a device. This structure is now meshed into a lattice for the actual simulation, as can be seen in figure 2.

Thomas Eichhorn is with the Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany (e-mail: `thomas.eichhorn@desy.de`).

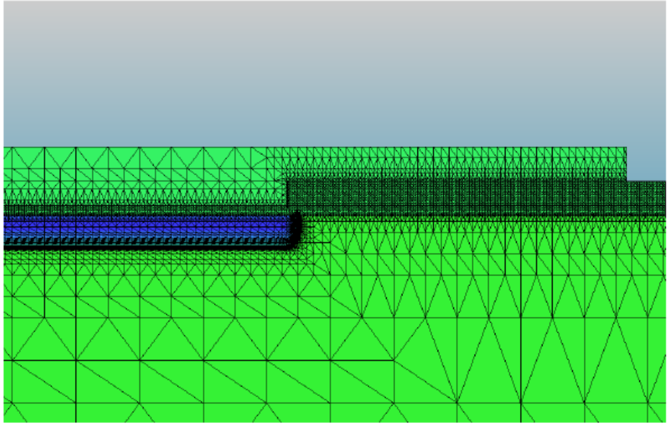

Fig. 2: Close-up view of a mesh generated for a strip sensor structure. The doped implant is displayed in dark blue, the region of fine meshing represents the silicon dioxide isolation underneath the aluminum strip.

Before starting the simulation, environment variables must be set and desired physical models must be activated. These models for example allow the parametrization of charge carrier mobility or electric field saturation. A list of the used physical models can be found in the appendix. Radiation damage is modeled through the usage of multiple carrier traps and basic read-out electronics can be implemented via SPICE to allow for comparison with different measurements. Traversing particles and laser illuminations can also be added and the simulation mode, a simple I-V simulation, a capacitive calculation or a time-dependent simulation can be selected. The finite-element simulation then calculates Poisson's equation

$$\frac{d^2V(x)}{dx^2} = -\frac{\rho(x)}{\epsilon_r \epsilon_0}$$

with the charge density ρ and using the electron and hole current densities $\vec{J_n}$ and $\vec{J_p}$, the electron and hole densities n and p and the effective recombination rate R_{eff} solves the carrier continuity equations

$$\nabla \cdot \vec{J_n} = q \cdot (R_{\mathit{eff}} + \frac{\partial n}{\partial t})$$

and

$$-\nabla \cdot \vec{J_p} = q \cdot (R_{\mathit{eff}} + \frac{\partial p}{\partial t})$$

at each previously generated mesh point and later derives user-specified physical quantities, such as electric fields, capacities, trap occupations or carrier densities. Tools integrated into the software allow an analysis and extraction of simulated data.

C. The CMS Sensor Simulation Group

In order to streamline the simulation efforts ongoing in the CMS collaboration, a working group has been formed to coordinate tasks. At present, there are four other participating institutes beside DESY. These are:

- Delhi University, India
- Karlsruhe Institute of Technology, Germany
- Helsinki Institute of Physics, Finland
- University of Pisa, Italy

The group aims to provide input to the future CMS sensor design and has agreed to investigate the following points:

1) Comparison of simulation tools: To ensure that the simulation software used within the CMS Sensor Simulation Group is comparable, simulation results obtained from different software packages have to be cross-checked. This has been done using previous publications in the silicon sensor simulation field. Both main software packages, Synopsys TCAD and Silvaco ATLAS have been found to give the same results, given the same non-default input parameters.

2) Device design: To find an optimal sensor design, different isolation techniques have to be verified and the inter-strip capacitance of possible devices, a main contributor to strip noise, must be calculated.

3) Radiation damage: In order to include radiation damage in sensor simulations, an adequate trap model is required. This model must not only be able to describe observed radiation effects for multiple sensor materials and designs, but also to predict the impact of future irradiation on silicon sensor properties.

Various efforts have already been undertaken to derive such a model, described for example in [4] and [5]. The CMS Sensor Simulation Group will check such models against measured sensor properties and aims to derive a model valid for the sensors used in the HPK campaign, to the extent that simulations of irradiated sensor properties can compare to the results obtained from measurements.

4) Charge collection and read-out: On finding a valid model capable of describing radiation damage, simulations will be carried out to investigate charge collection efficiency and signal read-out, researching the optimal sensor layout.

II. SIMULATIONS OF UNIRRADIATED SENSORS

Before simulating an irradiated sensor, it must be ensured that the simulation of an unirradiated sensor is in agreement with measurements. When simulating a sensor structure, the issue arises that not all sensor parameters needed for the simulation are known or have been released by the manufacturer. Knowledge of these parameters is nevertheless vital for a comparison of simulation results with measurements. As a first step, the simulated structure must therefore be approximated to the actual sensor geometry.

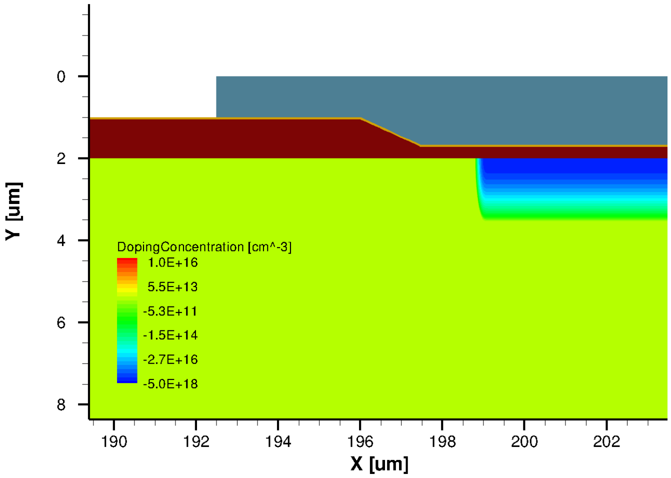

Fig. 3: Section of the simulated structure used as an approximation of the actual MSSD geometry. The aluminium strip top is displayed in grey with an additional diagonal element to model the etching process, the silicon bulk is shown in green and the silicon dioxide in brown. The strip implant has a blue color, depending on concentration. Note the additional silicon nitride oxide in yellow.

A. MSSD sensors

The multi-geometry silicon strip detector sensors (MSSDs) are used to measure the dependence of the inter-strip capacitance C_{int} on the width-to-pitch ratio w/p, C_{int} being a major source of strip noise. The wafers used in the HPK campaign contain twelve distinct MSSD regions, with four pitches (70 µm, 80 µm, 120 µm and 240 µm) and different widths, resulting in three width-to-pitch ratios for the three wafer thicknesses (120 µm, 200 µm and 320 µm). This is summarized in table I. The structure shown in figure 3 is used as an approximation to the MSSD sensor geometry.

The parameters in table I are given by the MSSD sensor specifications. By approximating CV and C_{int} simulations to measurements, the parameters in table II were found and have been used in the following simulations. An example of the dependency of the inter-strip capacitance on the $\mathrm{Si} - \mathrm{SiO_2}$ interface charge can be seen in figure 4 for various w/p ratios of an n-type float-zone (FZ) sensor, the thickness being 320 µm. C_{int} is not sensitive to interface charges below $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$, but increases significantly for charges over $1 \cdot 10^{11}\,\mathrm{cm}^{-2}$.

The main source of noise in strip sensors originates from the inter-strip capacitance C_{int}. Within the HPK campaign, numerous measurements of this property have been undertaken. By using the parameters found in approximating the sensor structure, the simulated C_{int} curves are in very good agreement with the measurements, for all regions, thicknesses and materials used within the HPK campaign. For illustration, two C_{int} comparisons are shown in figures 5 and 6.

Region	Pitch in µm	Implant width in µm	Aluminium width in µm	w/p ratio
1	120	18	26	0.15
2	240	36	44	0.15
3	80	12	20	0.15
4	70	10.5	18.5	0.15
5	120	30	38	0.25
6	240	60	68	0.25
7	80	20	28	0.25
8	70	17.5	25.5	0.25
9	120	42	50	0.35
10	240	84	92	0.35
11	80	28	36	0.35
12	70	24.5	32.5	0.35

TABLE I: Geometrical MSSD sensor properties from the wafer submission.

Property	Size	Obtained by
Si - $\mathrm{SiO_2}$ interface charge	$1 \cdot 10^{11}\,\mathrm{cm}^{-2}$	C_{int} comparison
Implant depth	1.5 µm	CV comparison
Bulk doping concentration in $10^{12}\,\mathrm{cm}^{-3}$	3 for FZ320N & FZ200N 4.5 for FZ120N 3.4 for FZ320Y/P & FZ200Y/P 1.5 for FZ120Y/P	CV comparison

TABLE II: Geometrical MSSD sensor properties found by approximating simulated C_{int} and CV curves to measurements. N stands for n-type, Y for p-spray isolated p-type and P for p-stop isolated p-type material.

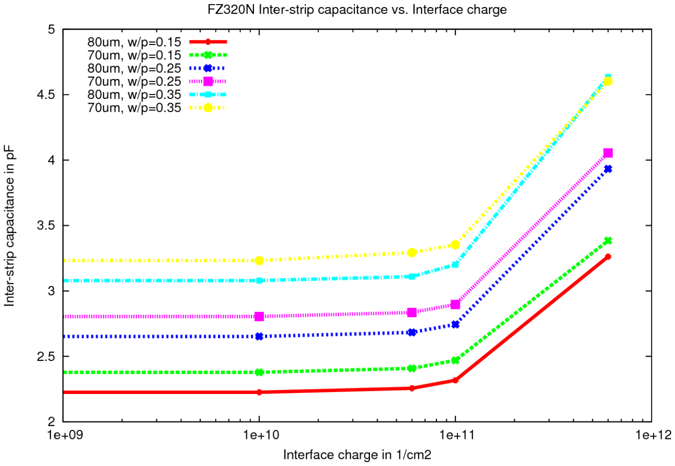

Fig. 4: Dependency of the inter-strip capacitance C_{int} on the interface charge for different pitches and different width-to-pitch ratios. N-type float-zone material with a thickness of 320 µm is used.

The values for C_{int} between two strips i and j were calculated with the following formula, in accordance with [6]:

$$C_{int} = C_{AC_i - AC_j} + C_{AC_i - DC_j} + C_{DC_i - DC_j} + C_{DC_i - AC_j}$$

Here AC-AC denotes the capacitance between two AC-contacts, DC-DC between two DC-contacts and AC-DC between an AC- and a DC-contact.

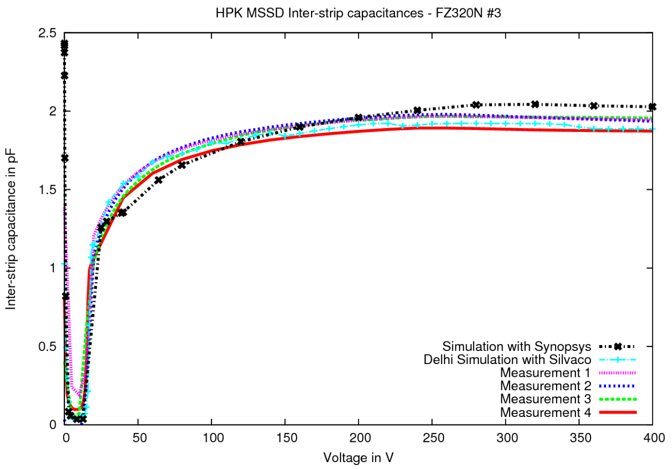

Fig. 5: Comparison of simulated C_{int} curve for a n-type $320\,\mu\text{m}$ thick float-zone sensor (region 3) with measurements. Note also the simulation obtained by Silvaco ATLAS, which gives a result comparable with the Synopsys simulation for the same input parameters.

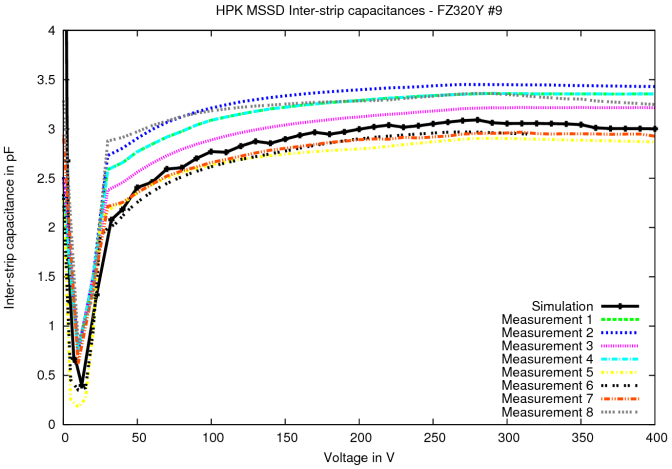

Fig. 6: Comparison of simulated C_{int} curve for a p-type $320\,\mu\text{m}$ thick float-zone sensor (region 9) using p-spray isolation with measurements.

The C_{int}-curves show an initial drop for very low voltages, due to the convergence of the simulation solver. For rising voltages, both simulated and measured C_{int} values rise, until the sensor is fully depleted. C_{int} then remains constant for high voltages.

The spread seen in the measured values can be explained by the different environments the measurements were undertaken in. This concerns temperature, relative humidity and also experimental setup. For comparison, the used simulation parameters are listed in table III.

Simulation parameter	Value
Temperature	$293\,\text{K}$
Interface charge	$1 \cdot 10^{11}\,\text{cm}^{-2}$
Oxide thickness	$270\,\text{nm}$ to $680\,\text{nm}$
Silicon nitride thickness	$50\,\text{nm}$
p-spray isolation	$1 \cdot 10^{16}\,\text{cm}^{-3}$

TABLE III: Simulation parameters used for the C_{int} simulations of MSSD sensors.

III. SIMULATIONS OF IRRADIATED SENSORS

In order to implement radiation damage into TCAD simulations, one must first decide on a trap model. A trap model is a list of defects, which are introduced into the simulation to generate energy states in the silicon band-gap. The number of occupied traps is then calculated, changing the charge densities, as well as the capture and emission rates, which influence the carrier movement between conduction band, trap and valence band, causing the known effects of leakage current increase, shift in depletion voltage and degrading charge collection efficiency.

As already mentioned, there are a variety of trap models in usage within the simulation community. The CMS simulation group has chosen to start out with a modified version of the EVL model, originally proposed by V. Eremin [7] to compare the simulation packages. This approach has also been chosen by the RD-50 collaboration [8].

A. *The EVL-4 trap model*

The EVL-4 trap model is an effective trap model, meaning that it aims not to include all known defects, but rather approximate these into two more generalized traps. The parameters of these traps are listed in table IV and were chosen to model the double peak in the electric field, which is observed in irradiated sensors. The introduction rate g allows a scaling of the fluence to the defect concentration c, with $c = \Phi_{\text{neq}} \cdot g$.

Type	Energy in eV	σ_n in cm^2	σ_p in cm^2	g in cm^{-1}
Acceptor	$E_c - 0.525$	$4 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	0.8
Donor	$E_v + 0.48$	$4 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	0.8

TABLE IV: Parameters of the EVL-4 trap model.

The original EVL model contains an additional trap at an energy position of $E_c - 0.65\,\text{eV}$ with electron and hole capture cross sections of $10^{-13}\,\text{cm}^2$ and an introduction rate g of $1\,\text{cm}^{-1}$. This trap is intended to only generate leakage current. This cannot be modeled in Synopsys TCAD and Silvaco ATLAS, as all specified traps also contribute to the change in space charge and trapping. Therefore, the introduction rates have been modified as to include this effect in the two existing traps.

B. MSSD sensors

As shown previously, simulations can reproduce the inter-strip capacitance measurements very well. Figure 7 shows that when using the modified EVL model, simulations can also describe the $\mathrm{C_{int}}$ behavior of irradiated MSSD sensors. As an example the first four MSSD regions were simulated on $320\,\mu\mathrm{m}$ thick n-type float-zone material, at a temperature of $253\,\mathrm{K}$ and an irradiation fluence of $5 \cdot 10^{14}\,\mathrm{n_{eq}/cm^{-2}}$. The obtained inter-strip capacitance values $\mathrm{C_{int}}$ are in good agreement with the corresponding measurements.

For this simulation, Silvaco ATLAS has been used. Work is being undertaken to reproduce these simulations with Synopsys TCAD, again for all MSSD materials, regions and thicknesses used in the HPK campaign.

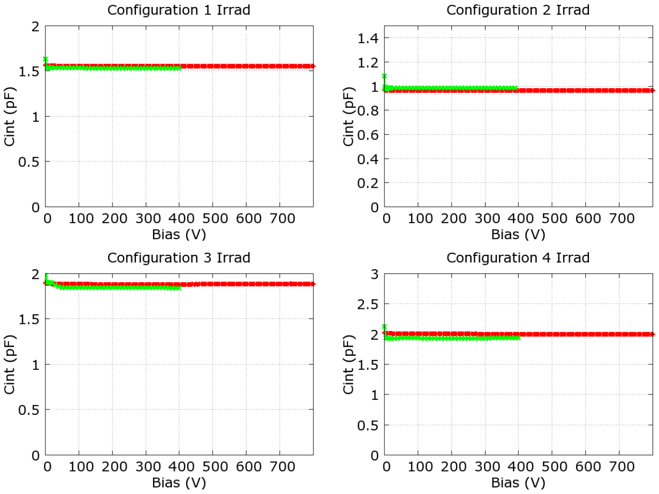

Fig. 7: Simulated irradiated $\mathrm{C_{int}}$ curves for MSSD FZ320N regions 1 to 4 shown in green, compared with the corresponding measurements displayed in red. Both simulations and measurements were performed at a temperature of $253\,\mathrm{K}$ with a fluence of $5 \cdot 10^{14}\,\mathrm{n_{eq}/cm^{-2}}$.

C. Diodes

As previously mentioned, the EVL-4 trap model aims to reproduce the electric field's double peak observed in irradiated sensors. A first test for this model should therefore be if this can be achieved in simulations. To simplify this simulation, a diode has been chosen instead of a full strip sensor, reducing the simulation size and run time. Furthermore, any effects of the read-out strips on the electric field can be ruled out.

Figure 8 shows the result of such a simulation. A $300\,\mu\mathrm{m}$ thick n-type FZ diode was simulated at room temperature for various irradiation fluences up to a value of $3 \cdot 10^{15}\,\mathrm{n_{eq}/cm^{-2}}$. At a bias voltage of $300\,\mathrm{V}$, the electric field through the diode was extracted.

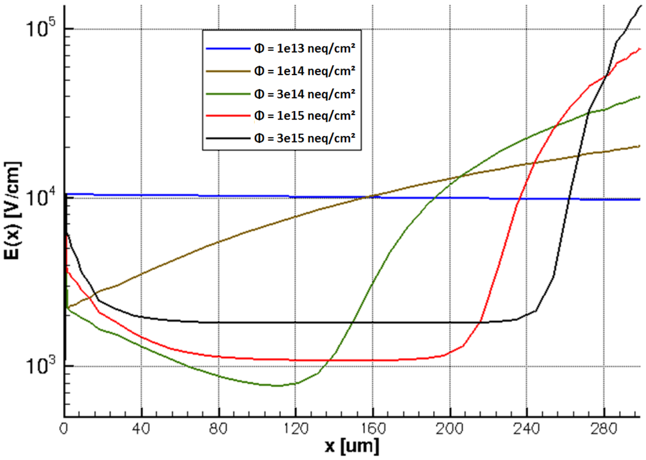

Fig. 8: Simulated electric field profile in a cut through a n-type diode. The $\mathrm{p^{++}}$ strip is located at $0\,\mu\mathrm{m}$ on the left, the backplane on the right.

For fluences of $1 \cdot 10^{13}\,\mathrm{n_{eq}/cm^{2}}$ and below, the electric field shows a linear behavior. As the fluence rises, the electric field at the backplane increases and a double peak is formed. This effect is especially visible at $3 \cdot 10^{14}\,\mathrm{n_{eq}/cm^{2}}$. With higher fluences, the bulk field becomes more and more flat, which can be explained by the fact that the sensor is no longer depleted due to the low bias voltage of $300\,\mathrm{V}$.

IV. SUMMARY AND OUTLOOK

It has been shown that simulations can provide a viable input to the design of future sensors for high-energy physics experiments. A simulation structure representing the MSSD sensors used in the CMS HPK campaign has been constructed and inter-strip capacitance simulations without inclusion of radiation damage show, that results obtained from measurements can be reproduced for all materials, sensor thicknesses and sensor regions.

The EVL-4 trap model has been included into the simulations and first tests show that the observed effect of a double peak in the electric field can be reproduced. The inter-strip capacitances from the first simulations and measurements of irradiated MSSD sensors are in good agreement with each other.

More extensive simulations concerning CV, IV and CCE measurements are forthcoming. Other trap models, for example described in [4] and [5], are also being implemented and simulations of their influence are currently ongoing.

Other long term plans are to provide input to the CMS HPK campaign, in the sense that sensor behavior can be predicted after irradiations and that the feasability of sensor designs and layouts can be assessed without cost-intensive production runs and measurements.

APPENDIX
USED PHYSICAL MODELS

The following physical models were used for all simulations in Synopsys TCAD:

```
Physics {
  Temperature = @temperature@
  AreaFactor = @areafactor@
  Mobility (
    Enormal
    DopingDependence
    eHighFieldSaturation
    hHighFieldSaturation
    CarrierCarrierScattering (
      ConwellWeisskopf ) )
  Recombination (
    SRH (
      DopingDependence
      TempDependence
      ElectricField (
        LifeTime = Hurkx
        DensityCorrection = none ) )
    Auger
    eAvalanche (
      vanOverstraeten
      Eparallel )
    hAvalanche (
      vanOverstraeten
      Eparallel )
    CDL )
  EffectiveIntrinsicDensity (
    Slotboom )
  Fermi }
```

REFERENCES

[1] K.-H. Hoffmann, *Campaign to identify the future CMS tracker baseline*, Nucl. Instrum. Meth. A, 658(1):30 – 35, 2011, RESMDD 2010.

[2] Synopsys, Inc., Synopsys TCAD services, 2009, http://www.synopsys.com/Tools/TCAD.

[3] Silvaco, Inc., Silvaco ATLAS products, 2012, http://silvaco.com/products/tcad/index.html.

[4] F. Moscatelli, A. Santocchia, D. Passeri, G.M. Bilei, B.C. MacEvoy, G. Hall and P. Placidi, *An enhanced approach to numerical modeling of heavily irradiated silicon devices*, Nucl. Instrum. Meth. B, 186(1-4):171 – 175, 2002.

[5] M. Petasecca, F. Moscatelli, D. Passeri, G.U. Pignatel and C. Scarpello, *Numerical simulation of radiation damage effects in p-type silicon detectors*, Nucl. Instrum. Meth. A, 563(1):192 – 195, 2006.

[6] S. Chatterji, A. Bhardwaj, K. Ranjan, Namrata, A.K. Srivastava, R.K. Shivpuri, *Analysis of interstrip capacitance of Si microstrip detector using simulation approach*, Solid-State Electronics, 47(1):1491 – 1499, 2003.

[7] V. Eremin, E. Verbitskaya and Z. Li, *The origin of double peak electric field distribution in heavily irradiated silicon detectors*, Nucl. Instrum. Meth. A, 476(1):556 – 564, 2002.

[8] The RD50 collaboration, *RD50 Status Report 2009/2010 - Radiation hard semiconductor devices for very high luminosity colliders*, CERN-LHCC-2012-010. LHCC-SR-004, 2012.