The Compact Muon Solenoid Experiment

Conference Report

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

10 September 2012 (v3, 11 September 2012)

Lorentz angle measurements as part of the sensor R&D for the CMS Tracker upgrade

Andreas Nürnberg and Theo Schneider on behalf of the CMS Tracker collaboration

Abstract

The CMS detector is one of the main experiments at the LHC accelerator at CERN. Its $200m^2$ silicon strip tracker was designed to withstand the radiation of 10 years of LHC operation. The foreseen high luminosity upgrade of the LHC imposes even higher demands on the radiation tolerance and thus requires the construction of a new tracking detector. To determine the properties of different silicon materials and production processes, a campaign has been started by the CMS Tracker Collaboration to identify the most promising candidate material for the new CMS tracker.

The silicon sensors of the CMS tracker are operated in a 3.8 T magnetic field. Charges created by traversing ionizing particles inside the active sensor volume are deflected by the Lorentz force. The Lorentz angle, under which the charge drifts through the sensor, is strongly dependent on the mobility, which in turn depends on the electric field and may depend on the radiation damage created by the particles produced by the LHC. Studying this is part of the campaign mentioned above.

This contribution summarizes the Lorentz angle measurements at magnetic fields of up to 8 T performed on small strip sensors after mixed irradiation with protons and neutrons to fluences of up to $5.8 \times 10^{15} n_{eq}/cm^2$ and gives a comparison to a simple simulation model.

Presented at *iWoRID 2012: 14th International Workshop on Radiation Imaging Detectors*

Lorentz angle measurements as part of the sensor R&D for the CMS Tracker upgrade

Andreas Nürnberg^{*a} and Theo Schneider^b

*^aInstitut für Experimentelle Kernphysik (IEKP), Karlsruhe Institute of Technology (KIT),
Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany*

*^bInstitut für Technische Physik (ITEP), Karlsruhe Institute of Technology (KIT),
Hermann-von-Helmholtz-Platz 1, 75045 Eggenstein-Leopoldshafen, Germany*

E-mail: andreas.nuernberg@kit.edu

ABSTRACT: The CMS detector is one of the main experiments at the LHC accelerator at CERN. Its 200 m² silicon strip tracker was designed to withstand the radiation of 10 years of LHC operation. The foreseen high luminosity upgrade of the LHC imposes even higher demands on the radiation tolerance and thus requires the construction of a new tracking detector. To determine the properties of different silicon materials and production processes, a campaign has been started by the CMS Tracker Collaboration to identify the most promising candidate material for the new CMS tracker. The silicon sensors of the CMS tracker are operated in a 3.8 T magnetic field. Charges created by traversing ionizing particles inside the active sensor volume are deflected by the Lorentz force. The Lorentz angle, under which the charge drifts through the sensor, is strongly dependent on the mobility, which in turn depends on the electric field and may depend on the radiation damage created by the particles produced by the LHC. Studying this is part of the campaign mentioned above.

This contribution summarizes the Lorentz angle measurements at magnetic fields of up to 8 T performed on small strip sensors after mixed irradiation with protons and neutrons to fluences of up to $5.8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and gives a comparison to a simple simulation model.

KEYWORDS: Si microstrip and pad detectors; Radiation-hard detector; Particle tracking detectors (Solid-state detectors).

^{*}On behalf of the CMS Tracker collaboration. Corresponding author.

Contents

1. Motivation	1
2. Investigated Materials	1
3. Lorentz angle	2
3.1 Measurement method	2
3.2 Simulation	3
4. Results	3
5. Outlook	5

1. Motivation

The present silicon strip tracker of the CMS detector was designed to withstand 10 years of LHC operation. The foreseen high luminosity upgrade of the LHC imposes even higher demands on the radiation tolerance of the silicon sensors that will be used to build a new tracking detector. To determine the properties of different silicon materials and production processes, a campaign has been started by the CMS Tracker Collaboration to identify the most promising candidate material for the new CMS tracker [1]. The silicon sensors of the CMS tracker are operated in a 3.8 T magnetic field. Thus, charges created by traversing ionizing particles inside the active sensor volume are affected by the Lorentz force, which leads to a deflection of the drifting charge that may decrease the detector performance, if it is not taken into account during track reconstruction. This deflection angle is called Lorentz angle. It is strongly dependent on the drift mobility, which depends on the electric field and may depend on the radiation damage.

2. Investigated Materials

A large number of wafers from different bulk materials and production processes and with different thicknesses have been purchased. Several mini strip sensors in a standard layout are implemented on the wafers [1]. A subset of these sensors is dedicated to Lorentz angle studies. In particular, n-bulk and p-bulk float-zone silicon sensors with different active thicknesses have been investigated, where either p-spray or p-stop strip isolation is implemented on the p-bulk sensors. The physical thickness of the sensors used in this study is always 320 μm , the reduction of the active thickness to 200 μm on the thin sensors is performed by deep diffusion of dopants on the sensor backside.

The test sensors have been irradiated with neutrons and protons to fluences of up to $5.8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. All structures have been electrically characterized before and after each irradiation step by measuring current-voltage (IV) and capacitance-voltage (CV) characteristics.

3. Lorentz angle

An external magnetic field, as it is present in the CMS detector, exerts a Lorentz force to the drifting charge carriers inside a silicon strip sensor. On the one hand, the magnetic field leads to a systematic shift of the read out charge in comparison to the hit position of the particle. This shift is typically of the order of ten to up to over 100 microns, depending on operation conditions. On the other hand the shift promotes the sharing of charge between neighbouring strips and by that may increase the resolution as the analogue readout of the CMS tracker allows the estimation of the center of gravity of the charge distribution more precisely if the charge is shared among multiple strips.

The Lorentz angle depends on several parameters. Besides the strength of the magnetic field and the temperature of the sensor, radiation induced damage created by non ionizing interactions of the detected particles with the sensor material can have a strong impact on the Lorentz angle.

3.1 Measurement method

The irradiated and characterized sensors are assembled onto a PCB and connected to a CMS tracker readout electronics board, as shown in figure 1. By that, up to six sensors of one type can be read out simultaneously.

Figure 1. The irradiated and characterized sensors are mounted onto a PCB and connected to a CMS tracker readout electronics board. By that, up to six sensors of one type can be read out simultaneously, while being operated inside a magnetic field.

Figure 2. Principle of the Lorentz angle measurement. Charge is induced by a short laser pulse on the sensor backside using two different wavelengths.

In order to measure the Lorentz angle, charge is induced by a short laser pulse on the backside of the sensors, which are operated inside the coil of the superconducting magnet JUMBO at the Institute for Technical Physics at KIT at magnetic fields of up to 8 T. By the use of an insulating tube, the sensors are thermally decoupled from the liquid helium and are operated at temperatures between 233 K and 293 K. Two different laser wavelengths with different absorption lengths are used, as shown in figure 2.

Light with a wavelength of 1055 nm penetrates the whole sensor thickness and ionizes charge carriers along the whole path (figure 2, right). This is similar to a traversing particle, while light with a wavelength of 880 nm penetrates only a few microns and thus creates charge only close to the sensor surface (figure 2, left). One type of charge carriers is then collected at the nearby backside electrode within ~ 1 ns while the other type drifts through the whole sensor volume. This allows studying the Lorentz angle of electrons and holes separately. However, the use of the 880 nm laser is only possible on the 320 μm thick sensors, as the absorption length is too low to reach the active volume of the deep diffused 200 μm thick sensors from the backside.

The Lorentz angle Θ_L and Hall mobility μ_H can be obtained from the measured Lorentz shift Δx and the sensor thickness d by

$$\tan(\Theta_L) = \frac{\Delta x}{d} = \mu_H B$$

3.2 Simulation

Following [2], a simulation model of the Lorentz angle that is reflecting the laser measurements has been implemented. In contrast to the integration over the whole sensor thickness as described in [2], 2500 virtual charge carriers are placed inside the active volume of the sensor and are propagated to the sensor strips individually. This extension makes it possible to take the gaussian beam profile and the absorption length of the laser light into account. The drift of these charges due to the electric field is then evaluated stepwise, taking the field dependend drift mobility and the deflection due to the Lorentz force into account. The type of charge carriers which drifts towards the sensor strips and thus contributes mainly to the read out signal (electrons in a p-bulk sensor, holes in a n-bulk sensor) is considered only.

Figure 3. One dimensional parametrization of the electric field and the drift mobility of electrons vs. the sensor depth in a 300 μm thick p-bulk sensor.

Figure 4. Two dimensional placement of charges as created by a 1055 nm laser in the sensor bulk. The absorption length at -30°C is almost 1 mm.

Figure 5. Projection of charge towards the sensor strips as created by the laser (in blue, dashed) and after the drift to the readout strips (in red, solid).

Figure 3 shows the one dimensional linear parametrization of the electric field and the derived drift mobility of electrons in a 300 μm thick p-bulk sensor which is operated at a bias voltage of 300 V. As an example, the placement of charge carriers as induced by a 1055 nm laser in the sensor bulk is shown in figure 4. The absorption length of the light at -30°C is over three times the sensor thickness, thus charges are created along the whole path of the laserlight. After the propagation towards the sensor strips in a 4 T magnetic field, the center of gravity of the charge has been shifted by around 50 μm , as it is shown in figure 5. The blue, dashed curve shows the distribution of the charge as it is created by the laser while the red, solid curve depicts the position of the charge after being propagated towards the strips. Besides the shift, the expected broadening of the distribution is visible.

4. Results

Figure 6 shows the Lorentz shift obtained in several sensors with different type of bulk doping

and different active thickness as a function of the magnetic field. The electrons (p-bulk) and holes (n-bulk) are deflected in different directions and the shift is reduced for thin sensors. Due to the higher mobility and larger Hall factor, the Lorentz shift for electrons is about a factor four larger. The solid lines show the expected Lorentz shift obtained by the simulation model outlined in 3.2. Except for some minor deviations at magnetic fields larger than 6 T, the model describes the data-points very well. The dependence of the Lorentz shift of electrons on the bias voltage is shown in figure 7 for three sensors of the same type at different irradiation fluences. The shift rises with the applied bias voltage until the sensor is fully depleted, since the active thickness of the sensor grows with increasing bias voltage. After that point, the shift is decreasing again, because of the stronger electric field in an overdepleted sensor which leads to a lower mobility of the drifting charge carriers. Again, the simulation model is in good agreement to the data points.

Figure 6. Lorentz shift as a function of the magnetic field obtained in unirradiated sensors with different bulk doping and different active thickness. For electrons, sensors with either p-stop or p-spray strip isolation are shown. The solid lines show the shifts obtained by the simulation model outlined in 3.2.

Figure 7. Lorentz shift of electrons in 320 μm thick sensors as a function of the applied bias voltage for three different irradiation fluences. The solid lines are representing the simulation model.

Figure 8. Lorentz shift of electrons (left) and holes (right) as a function of irradiation fluence and annealing time.

The evolution of the Lorentz shift with irradiation fluence is shown in figure 8 after three different states of annealing at a bias voltage of 600 V and a magnetic field of 8 T. At fluences lower than $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at which the sensors are still fully depleted, the shift of holes rises, while it decreases for electrons. At higher fluences this difference gets overcompensated by the fact that the sensor cannot be fully depleted anymore. This leads to a reduced active thickness of

the sensors and thus to a reduced Lorentz shift. The full depletion voltage of the sensors increases also during long-term annealing, which leads to a further reduction of the Lorentz shift.

A comparison of the Hall mobility of holes obtained in this study to the mobility obtained by the analysis of CMS tracker data as a function of the applied bias voltage is shown in figure 9. Using the CMS tracker, the Hall mobility can be estimated by studying the average cluster size as a function of the track incident angle [3]. The results of the two measurement methods agree very well and the decreasing trend of the Hall mobility with the applied bias voltage is similar in both datasets.

Figure 9. Comparison of Hall mobility μ_H of holes obtained with 880 nm laser to values obtained from CMS Tracker data.

5. Outlook

Up to now, the study covers silicon sensors of a physical thickness of 320 μm . The reduction of the active thickness to 200 μm in the thin sensors is obtained by the deep diffusion of dopants to the sensor backside. However, the deep diffused backside of the sensors makes it impossible to use the 880 nm laser and to investigate electrons and holes separately as the absorption depth is too low to reach the active sensor volume from the backside. Therefore, the irradiation of sensor material with a physical thickness of 200 μm is currently ongoing.

Acknowledgments

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025. This work is supported by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 ("Physics at the Terascale").

References

- [1] K.-H. Hoffmann, *Campaign to identify the future CMS tracker baseline*, Nucl. Instrum. Meth. A, Vol. 658, Issue 1, 30-35 (2011).
- [2] V. Bartsch, W. de Boer et al., *An Algorithm for calculating the Lorentz angle in silicon detectors*, Nucl. Instrum. Meth. A 497 (2003) 389-396.
- [3] B. Henrich, R. Kaufmann, *Lorentz-angle in irradiated silicon*, 2002, Nucl. Instrum. Meth. A 477 (2002) 304-307.