

## Lorentz shift measurements in heavily irradiated silicon detectors in high magnetic fields

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An external magnetic field exerts a Lorentz force on drifting electric charges inside a silicon strip sensor and thus shifts the cluster position of the collected charge. The shift can be related to the Lorentz angle which is typically a few degrees for holes and a few tens of degrees for electrons in a 4 T magnetic field. The Lorentz angle depends upon magnetic field, electric field inside the sensor and temperature. In this study the sensitivity to radiation for fluences up to  $10^{16}$   $n_{eq}/cm^2$  has been studied.

The Lorentz shift has been measured by inducing ionization with 670 nm red or 1070 nm infrared laser beams injected into the back side of the irradiated silicon sensor operated in magnetic fields up to 8 T. For holes the shift as a function of radiation is increasing, while for electrons it is decreasing and even changes sign.

The fact that for irradiated sensors the Lorentz shift for electrons is smaller than for holes, in contrast to the observations in non-irradiated sensors, can be qualitatively explained by the structure of the electric field in irradiated sensors.

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## 1. Introduction

The Lorentz shift  $\Delta x$  for the silicon strip detector of thickness  $D$  with a magnetic field  $B$  perpendicular to the electric field  $E$  inside the sensor can be written as [1]:  $\Delta x = D \tan(\Theta_L) = D r_H \mu B$ , where  $r_H$  is the Hall factor ( $\approx 0.7$  for holes and  $\approx 1.15$  for electrons at room temperature [2]) and  $\mu$  is the drift mobility. The drift mobility is known to increase strongly with decreasing temperature and is proportional to the electric field until saturation is reached [3]. The drift mobility is a factor two to three larger for electrons than for holes and together with the different Hall factors  $r_H$  the Lorentz shift for electrons is a factor of four larger than the one for holes, at least in non-irradiated sensors.

The radiation is not expected to change the mobility significantly up to  $10^{16} \text{ n}_{eg}/\text{cm}^2$ , but the E-field will because of the space charge being trapped in the defects caused by irradiation. This space charge leads to strongly non-uniform electric fields with a double peak structure [4], which makes it difficult to predict the Lorentz shift, so in this study the shift has been measured experimentally using different silicon sensors. The sensors have been irradiated at the proton cyclotron of KIT, Karlsruhe with 25 MeV protons and studied using laser beams inside the superconducting JUMBO magnet in the magnet lab of KIT, Karlsruhe, which features a warm bore [5].

## 2. Experimental setup

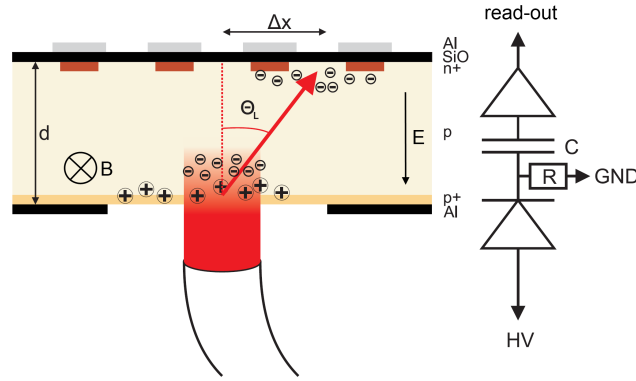
The detailed description of the laser setup can be found in several previous publications [6, 7, 8, 9, 10] and the principle is shown in Fig. 1. Two lasers have been used: a) the red one with a wavelength of  $670 \text{ nm}^1$  penetrates only a few  $\mu\text{m}$  inside the backplane of the sensors, b) the infrared  $1060 \text{ nm}$  laser<sup>2</sup> creates a trajectory inside the whole volume. Both lasers had a maximum power of  $1 \text{ mW}$  adjustable by the pulse height and width of the input pulse to the laser diode. The laser pulse with a width of  $\sim 1 \text{ ns}$  was generated and transmitted to the sensor via a single-mode fiber with an inner diameter of a few microns. The beam spot on the detector can be varied from a few  $10 \text{ micron}$  onwards by changing the distance between fibre and sensor. The setup was located inside the JUMBO magnet operating with the  $B$  field up to  $8 \text{ T}$ . The temperature of the sensor was controlled and kept nearly constant throughout the measurements by flux of cold nitrogen.

The readout electronics include Premux128-Chip with a shaping time of  $45 \text{ ns}$  [11] has a built-in common mode suppression by a double correlated sampling technique. The analog signals of the 128 Premux channels are multiplexed and digitized by an external ADC. The time delays have been adjusted to deliver a maximum signal from the laser. The high voltages and leakage currents were controlled by a Keithley 2410 with a maximum voltage of  $1100 \text{ V}$ . The cabling limits the studied range of depletion voltages to  $1000 \text{ V}$ .

Three types of sensors have been measured: Float Zone (FZ) n-type from STMicroelectronics and p-type from Micron, and Chochalski (MCz) n-type from Helsinki Institute of Physics (HIP), see Table 1. The p-type sensors with n-strips have been used for studying the electrons and the n-type sensors with p-strips for holes, since the charge is integrated on the n-strips for electrons and on the p-strips for holes in reversely biased diodes. Before irradiation all n-type sensors were

<sup>1</sup>The laser QFLD-670-2S from QPhotonics

<sup>2</sup>LD-1060 from Fermionics Lasertech Inc.



**Figure 1:** The principle of the Karlsruhe setup to measure the Lorentz angle of holes and electrons: charge is locally generated at the backplane by a laser pulse and the Lorentz shift is measured by the shift in distance compared with the position at zero magnetic field.

**Table 1:** List of sensors with strips on one side (the p-side (n-side) for n-type (p-type) bulk material) and their parameters. The sensors were irradiated at the proton cyclotron of KIT, Karlsruhe with different fluences  $\Phi$  (25 MeV Protons, hardnessfactor 1.85). The depletion voltage  $U_{dep}$  was derived from the knee in the  $I/C$  over  $U$  plot.

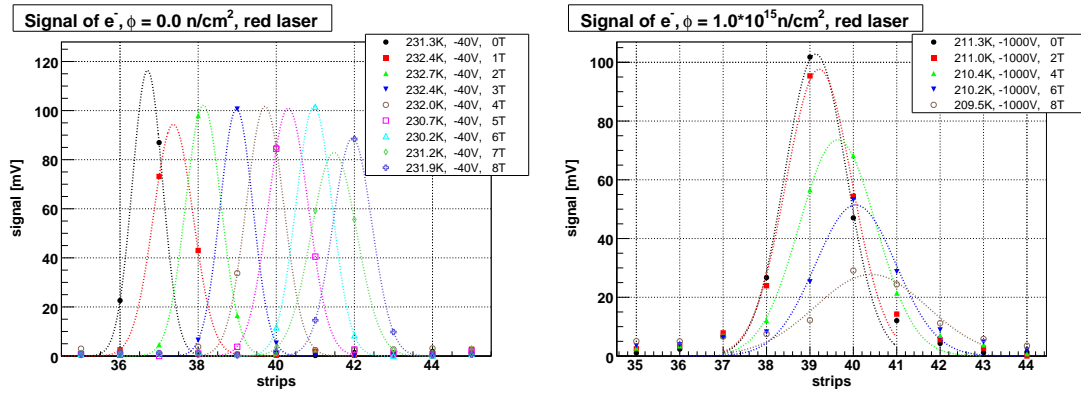
| Sensorname  | Manufacturer | Material   | d [ $\mu m$ ] | Pitch [ $\mu m$ ] | $U_{dep}$   | $\Phi$ [ $n_{eq}/cm^2$ ] |
|-------------|--------------|------------|---------------|-------------------|-------------|--------------------------|
| CMS01 Mini  | ST           | FZ n-Type  | 500           | 120               | 154         | 0                        |
| RD50 28-3-1 | Micron       | FZ p-Type  | 300           | 80                | 12          | 0                        |
| RD50 27-3-2 | Micron       | FZ p-Type  | 300           | 80                | $\sim 1000$ | $1 \cdot 10^{15}$        |
| RD50 28-7-3 | Micron       | FZ p-Type  | 300           | 80                | $> 1000$    | $9.6 \cdot 10^{15}$      |
| MCz 0802-1  | HIP          | MCz n-Type | 300           | 50                | 169         | $7.1 \cdot 10^{14}$      |
| MCz 0802-5  | HIP          | MCz n-Type | 300           | 50                | 272         | $7.1 \cdot 10^{14}$      |
| MCz 0802-3  | HIP          | MCz n-Type | 300           | 50                | $> 1000$    | $7.2 \cdot 10^{15}$      |
| MCz 0802-9  | HIP          | MCz n-Type | 300           | 50                | 347         | 0                        |

fully depleted at a bias voltage of  $\leq 347$  V, the p-type sensor already at 12 V. After irradiation with  $\Phi > 1.0 \cdot 10^{15} n_{eq}/cm^2$  all depletion voltages exceed 1000 V and a full depletion was not possible.

### 3. Results

The signals for different sensors and B-fields are shown in Figs. 2, 3 and 4. The sensor temperatures (around 200 K) have been more accurately indicated in the figures. The width of the signals is determined by the width of the laser beam. The Lorentz shift of the signal with increasing B-field is clearly visible. The measurements confirm that the Lorentz shift increases linearly with the magnetic field up to 8 T [9].

The averaged signal position  $\bar{x}$  was computed from either a Gaussian fit or from the center of gravity of the pulse heights  $p_i$  on neighboring strips  $x_i$ , i.e.  $\bar{x} = \sum p_i \cdot x_i / \sum p_i$ ; both methods



**Figure 2:** Left: the signal for electrons in a non-irradiated sensor using a red laser. Right: as left for a fluence of  $\phi = 1.0 * 10^{15} n_{eq}/cm^2$ . One observes the strong reduction in Lorentz shift, which is largely due to the higher bias voltage needed to reach depletion. Note that the shift is in the same direction for both, the unirradiated and irradiated sensor, i.e. it has the same sign.

gave comparable results. The dependence of the Lorentz shifts on fluences for different sensors is summarized in Fig. 5.

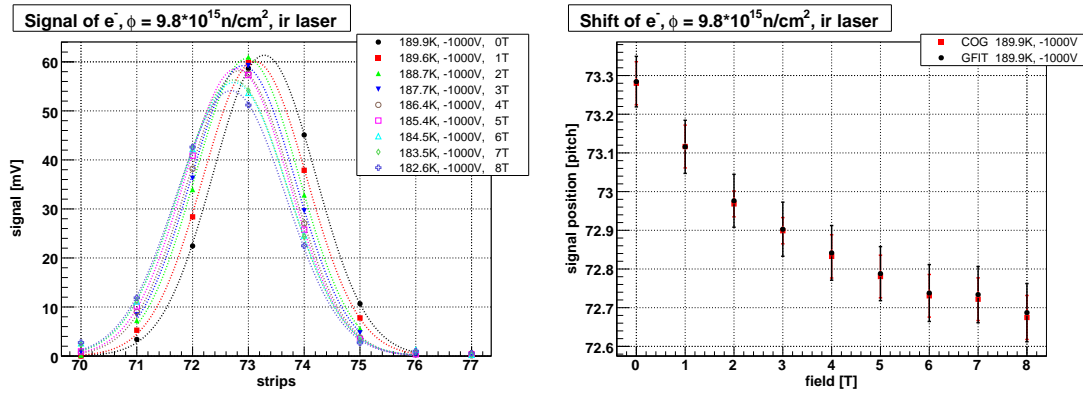
The surprising result is that for holes the Lorentz shift increases with fluence, while for electrons it decreases, so at high fluences the Lorentz shift for holes is significantly larger than for electrons in contrast to the shifts for non-irradiated sensors. This dependence can be qualitatively explained by the expected redistribution of the electric field into a double peak structure in highly irradiated sensors, as will be discussed in the next section.

Although the shifts for the non-irradiated sensor could only be measured to the breakdown voltage of about 300 V, the dependence on voltage has been estimated for zero fluence using the model given in Ref. [12]. These estimates for different voltages are shown for zero fluence on the left hand side of Fig. 5, which allows to see the dependence of Lorentz shift versus fluence for a constant bias voltage.

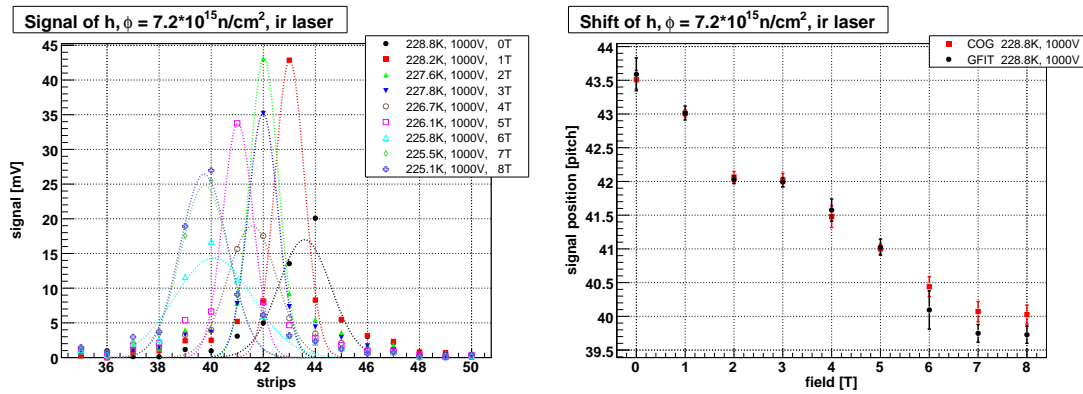
Interestingly, for electrons the Lorentz shift changes sign after a fluence of about  $1. * 10^{15} n_{eq}/cm^2$ . The signal has still the same amplitude as for non-irradiated sensor, so one still observes electrons, but shifted against the direction expected from the Lorentz force. This shift was found to be hardly dependent on temperature, which means it is not sensitive to the drift mobility  $\mu$ . A possible qualitative explanation is discussed in the next section.

#### 4. Discussion and summary

The observed difference in the electrons and holes shifts can be related to the structure of the E field in irradiated sensors. After enough irradiation the bulk of the sensor is always p-type, since the irradiation induces acceptor-type defects at a high rate. So the pn-transition is always near the n-side of the diode, even if the initial material of the bulk was n-type. Type inversion from n-type to p-type depends on the initial doping concentration, but typically happens at a fluence of a few times  $10^{13} n_{eq}/cm^2$ . After a high fluence the detector cannot be fully depleted anymore for bias

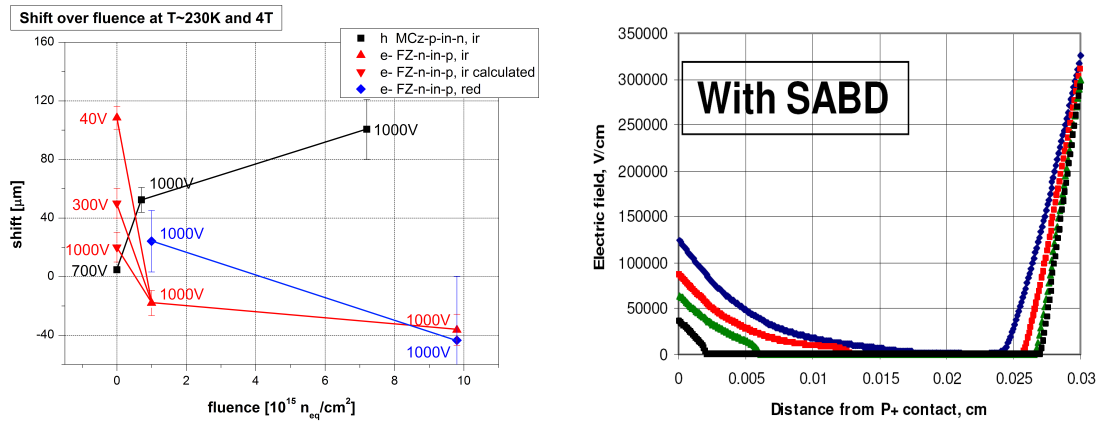


**Figure 3:** The raw  $n+$  strip signals (collecting electrons) in different magnetic fields with the fitted gaussian curves (left) and the peak position of the fitted gaussian curve (GFIT) or center of gravity (COG) as function of  $B$ -field (right). The sensor was irradiated with a fluence of about  $10^{16} \text{ n}_{eq}/\text{cm}^2$  and the signals were generated with the infrared laser. The shift is given in units of the pitch between the strips, which is  $80 \mu\text{m}$ .



**Figure 4:** The raw  $p+$  strip signals (collecting holes) in different magnetic fields with the fitted gaussian curves (left) and the peak position of either the fitted gaussian curve (GFIT) or center of gravity (COG) as function of  $B$ -field (right). The sensor was irradiated with a fluence of about  $10^{16} \text{ n}_{eq}/\text{cm}^2$  and the signals were generated with the infrared laser. The shift is given in units of the pitch between the strips, which is  $50 \mu\text{m}$ .

voltages up to 1000 V, so the voltage drop mainly occurs on the undepleted layer near the  $n$ -side, which causes a high  $E$ -field near the  $n$ -side. Here soft avalanches can occur, which send holes back into the bulge, thus reducing the high electric field. This current stabilization and softening of the electric field around the electrodes in heavily irradiated sensors was discussed already in 1977 [13] and explains why irradiated sensors can sustain much higher bias voltages than non-irradiated sensors. At high bias voltages the electric field develops a significant field also near the  $p+$  contacts, as shown on the right hand side of Fig. 5, which explains, why one can see signals from lasers shining from both sides of a heavily irradiated diode, i.e. one can study the movement of both, electrons and holes, in heavily irradiated sensors in spite of the fact that the detector is

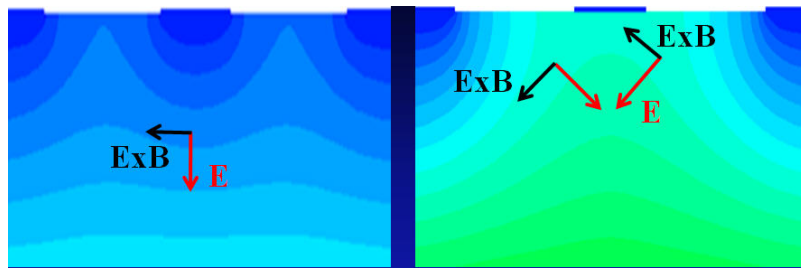


**Figure 5:** Left: the Lorentz shift dependence on the fluence for electrons (triangles ir-, diamonds red-laser) and holes (rectangles). Right: the electric field distribution for bias voltages of 1500, 1000, 750 and 500 V, respectively, in a sensor irradiated with  $10^{16}$   $n_{eq}/\text{cm}^2$ , as calculated by the PTI model including Soft Avalanche Breakdown (SABD), as shown by V. Eremin at the RD50 meeting [14]. The increase in Lorentz shift for holes for higher fluences can be explained by the reduced electric field near the collecting p+ electrodes, while the decrease for electrons can be explained by the increased electric field near the n+ electrode, where charge multiplication may additionally lead to charge sharing preferably in the opposite direction, thus causing "negative" Lorentz shifts.

operated below the depletion voltage. On the p+ side the electric field is much lower than on the n+ side, so the holes collected on the p+ side will experience a higher Lorentz shift than electrons collected on the n+ side, because the Lorentz shift is proportional to  $B/E$ . This is in agreement with the data in Fig. 5.

To explain the "negative" Lorentz shift for electrons at high fluences, one has to explain simultaneously that: i) the collected charge is still high, although the sensor is not fully depleted anymore; ii) the shift is in the opposite direction compared with the expectation from the Lorentz force, as measured in the non-irradiated sensor; iii) the shift does not depend on temperature; iv) the shift for a red and infrared laser at intermediate fluences for which the detector is just depleted at 1000 V, have opposite signs, as is visible in Fig. 5. This means that a mechanism different from the Lorentz shift expected from the simple drift in  $E \times B$  fields is operative.

A hint for an explanation may come from the fact, that the same mechanism, which is responsible for the high breakdown voltage after irradiation, namely the occurrence of charge multiplication mentioned above, is also responsible for the negative Lorentz shift. Indeed, a lot of evidence for charge multiplication has been collected recently, as discussed at the RD50 meeting [14]. Most notably, one observes with an infrared laser shining from the edge of the detector the occurrence of an increased current as soon as the electron cloud reaches the n+ contact and one observes a charge higher than expected from the induced ionization. Note that charge multiplication is a common phenomenon in silicon devices; it occurs when the electric field is typically above  $15 \text{ V}/\mu\text{m}$  and is e.g. responsible for the avalanches in silicon photomultipliers or avalanche photo diodes. Fields above these values are indeed expected in heavily irradiated sensor under high reverse bias voltage,



**Figure 6:** Potential lines in a non-irradiated sensor (left) and irradiated sensor with a reduced electric field on the central strip (right), which might be caused by charge multiplication (calculation with SYNOPSIS TCAD 2007 [15]). The electric field direction is perpendicular to the potential lines, as indicated by the arrows. The Lorentz force is in the direction of the  $E \times B$  arrows. The horizontal electric field components from the neighboring strips can enhance the charge multiplication in an asymmetric way, namely more charge is produced on the side, where the electrons are driven back to the strip by the Lorentz force (the right hand side of the central strip in the irradiated sensor). This leads to asymmetric charge sharing, thus causing the weighted charge distribution to shift in the direction opposite to the one expected from the Lorentz force.

as shown on the right hand side of Fig. 5.

How such a charge multiplication may lead to a Lorentz shift in the "wrong" direction can be qualitatively understood as follows. The reduced electric field on the strip with the highest charge multiplication leads to horizontal electric field components from the neighboring strips, as indicated on the right hand side of Fig. 6. These horizontal components in the reduced electric field below the strip cause an asymmetry in the avalanche, because the Lorentz force, indicated by the  $E \times B$  vector on the right hand side (rhs) of Fig. 6, drives electrons back to the strip on the right hand side and away from the strip on the left hand side (lhs). This means that the charge multiplication is stronger on the rhs than lhs, thus providing a "negative" Lorentz shift by the charge sharing between the strips. For the red laser the electrons have to drift through the whole sensor and the Lorentz shift remains positive, as shown before in Fig. 2 on the rhs. The charge multiplication on the  $n+$  contact may shift it to the opposite direction again, thus explaining why the total shift is so low. To obtain a quantitative understanding of the negative Lorentz shifts would require a detailed simulation of a heavily irradiated sensor, which is difficult and beyond the scope of the present paper.

In summary, the Lorentz shifts have been measured for holes and electrons in heavily irradiated sensors. After heavy irradiation the sensors have a break down voltage well above 1000 V and at these high voltages signals from both  $n+$  and  $p+$  strips can be observed in spite of the fact that the sensors are not depleted anymore. This can be explained by the well-known double peak model of the electric field in such sensors originating from charge multiplication at the  $n+$  strips which reduces the electric field below the breakdown voltage by the so-called soft-avalanche breakdown mechanism. The double peak structure in the electric field leads to a low electric fields near the  $p+$  strips where holes are collected and high electric fields near the  $n+$  electrodes where electrons are collected. Consequently, electrons experience a lower Lorentz shift (proportional to  $B/E$ ) than holes in heavily irradiated sensors in contrast to non-irradiated sensors, where the opposite is true.



## 5. Acknowledgment

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- [15] <http://www.synopsys.com/tools/tcad/Pages/default.aspx>