Properties of GaAs as detector material for BeamCal

Petty Bernitt
CTH Göteborg, SWEDEN
e-mail: petty_bernitt@web.de
Supervisor: Dr. Wolfgang Lohmann

This report was done during the DESY summer student program in 2007. The performance of irradiated GaAs being a probable material for BeamCal at the ILC detector will be measured and discussed. The irradiation took place in Darmstadt at the end of June in 2007 in the framework of the project "TestBeam07". The report considers I-V characteristics as well as results from CCD (Charge Collection Distance) measurements.

1. Introduction

The following paper discusses electrical and geometrical properties of GaAs detectors which might be used in the International Linear Collider (ILC) that is planned to probably be built in the near future.

1.1 ILC

The ILC will accelerate electrons and positrons - each on a length of approximately 15 km - to a center-of-mass energy of about 500 GeV at the interaction point. A general layout of the ILC can be seen in Fig. 1.

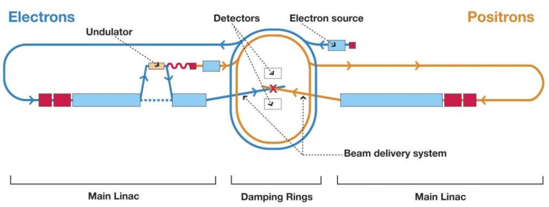

Fig 1: General layout of ILC

The fact that point-like elementary particles are collided at the ILC is advantageous in comparison to the Large Hadron Collider (LHC) at CERN since the produced final states have a clearer signature and are therefore simpler to analyse. The ILC will be important for precision measurements of the properties of particles that might be discovered by the LHC. The aim of the ILC will be to analyse e.g. the properties of the Higgs boson and investigate probable super-symmetric (SUSY) particles which present just one good candidate for dark matter.

1.2 BeamCal

The Very Forward Region of the ILC is shown in Fig. 2. To match the physics it is required to have two different types of calorimeters in this region – one to determine the luminosity (LumiCal) precisely by using Bhabha scattering and one for measuring the huge amount of particles that occur at small polar angles (~ 3…20 mrad): BeamCal. Those particles have their origin in the beamstrahlung: two incoming beams penetrate one another so that the electrons and positrons are deflected from their initial trajectory. The interaction of their dynamic magnetic fields leads to the emission of Beamstrahlung photons. These in turn produce e^+e^- pairs which deposit energies of up to 20 TeV in the BeamCal per bunch crossing. In units of radiation dose this means that the detector materials used for the BeamCal at ILC have to withstand radiation doses of up to 10 MGy/year and even more. At the moment the FCal group at DESY Zeuthen considers materials like CVD-diamond, radiation-hard Si and GaAs [1].

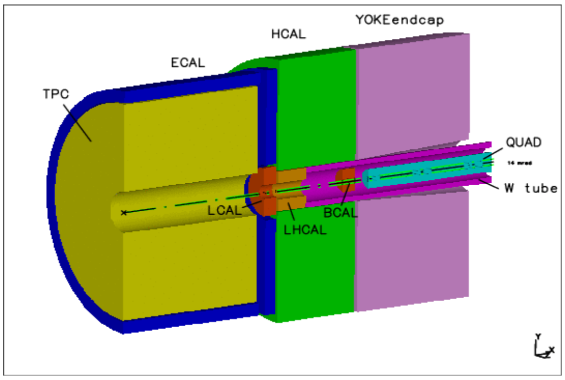

Fig. 2: Very forward region of the detector for ILC

2. Theory

Here some theoretical aspects mostly on the Charge Collection Distance (CCD) will be explained in a short manner.

2.1 Charge Collection Distance (CCD)

A charged particle that enters a material loses a part of its energy as described by the Bethe-Bloch formula [2]. Its exemplarily illustration is shown in Fig. 3.

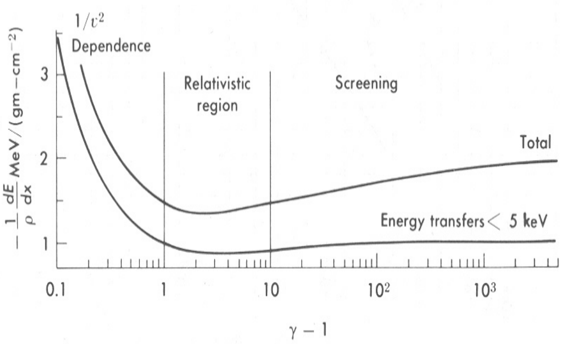

Fig. 3: The Bethe-Bloch curve
The energy loss dE/dx is shown as a function of the momentum.

Particles that have their momentum in the range of the minimum of the Bethe-Bloch curve are considered as MIPs (Minimum Ionizing Particles). They create a minimum signal which is of interest when determining the sensitivity of materials with respect to the minimum energy deposition. The produced electron-hole pairs drift to the electrodes when an electrical field is applied to the sensor and ionize the material. Finally the CCD is defined as the drift distance the electron and the hole move apart until they are trapped by lattice imperfections. The charge that is induced on the electrodes during this drift process can be quantified by the Shockley-Ramo theorem [3, 4, 5]. For this experiment ^{90}Sr serves as source for the MIPs. The ionization energy they deposit in the sensor is approximately 0.5 MeV and this equals the minimum of the Bethe-Bloch curve for the considered materials.

3. The Experimental Setup

The aim of the project was to measure the I-V characteristics and the CCDs of GaAs sensors in order to observe how their properties changed after being irradiated by electrons of 10 MeV. The samples named “GaAs 1” and “GaAs 2” had to withstand a radiation dose of 500 kGy and 900 kGy, respectively. Each sensor is 500 µm thick and originates from a 3-inch-wafer where the pad structure is realised through the metallization of GaAs with Au.

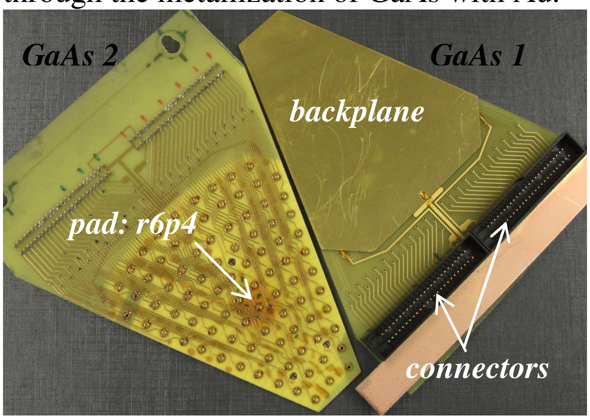

Fig. 4: Image of the GaAs sensors

In Fig. 4 it is clearly to see that the central pad "r6p4" (row 6, pad #4) has been irradiated. The following measurements will concentrate on this pad and those lying directly next to it. For every measurement a KEITHLEY will be used as high voltage supply.

3.1 *I-V characteristics*

To measure the I-V characteristics the pad of interest was fed by high voltage through a needle that sat directly at the contact. The voltage varies between +500 V and –500 V and is controlled by a LabView program. The backplane of the sensor was placed on a metallic table so that the current through the pad could be measured.

Fig. 5 is an image of how the applied setup for this measurement looked like.

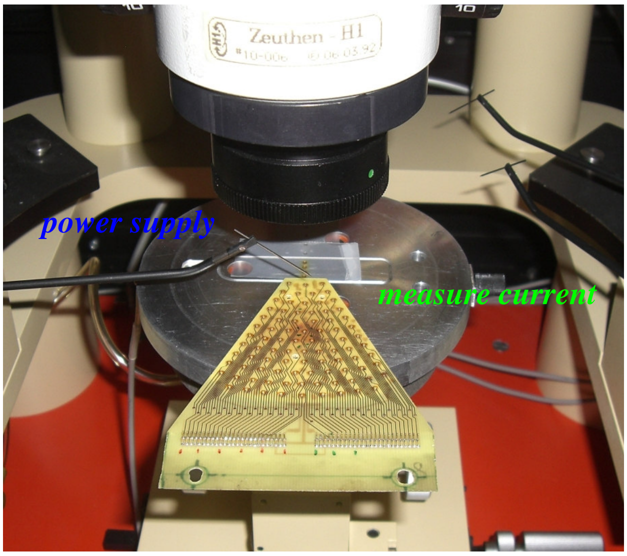

Fig. 5: Setup for measuring I-V characteristics

3.2 *CCD measurement*

For measuring the CCD the sensor was placed in the so-called pre-amplifier box where a voltage of +200 V or -200 V was applied to the pad of interest. A ^{90}Sr source is situated above the pre-amplifier box and β^- particles which can be regarded as MIPs are collimated into the sample and create a signal. If the same particle also enters the scintillator under the sample the ADC finally records the signal. All used devices for measuring the CCD are visualized in Fig. 6.

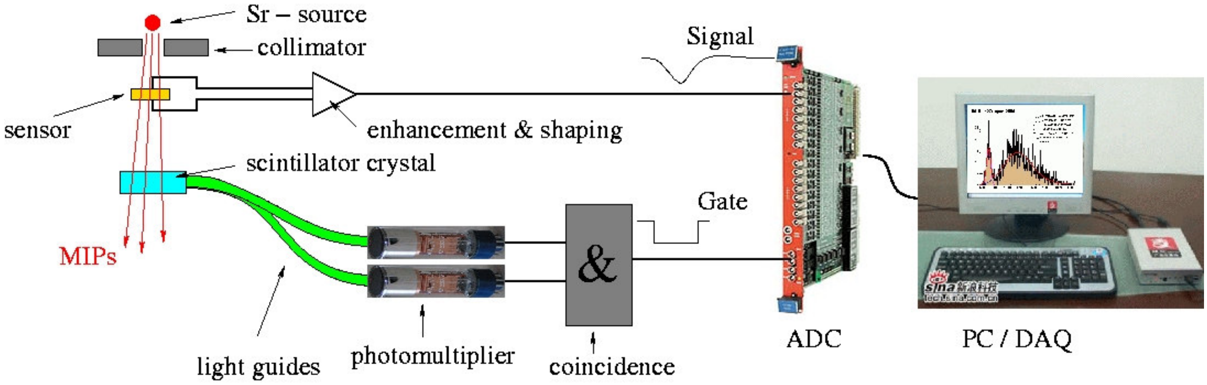

Fig. 6: Setup for CCD measurement

4. Experimental Results

4.1 I-V characteristics

Fig. 7 shows the I-V characteristic for the central pad of the sensor.

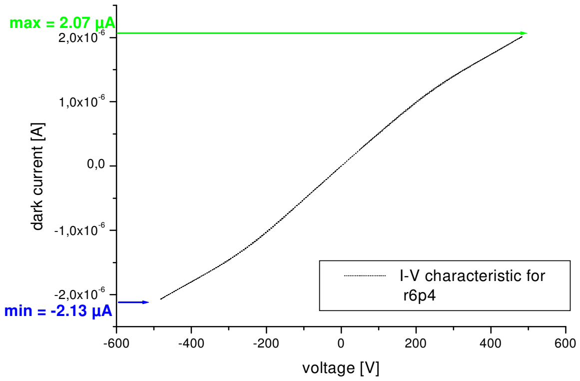

Fig 7: I-V characteristic for irradiated pad "r6p4"

Even though GaAs is an intrinsic semi-conductor its I-V curve mostly behaves Ohmic. The semi-conducting properties become apparent when experimental conditions, especially temperature, change. The temperature was not recorded but it could still be observed that higher temperatures increase the dark current slightly. This can be seen in Fig. 8. A quantitative study of the dependency between dark current and temperature was done in a previous project [6].

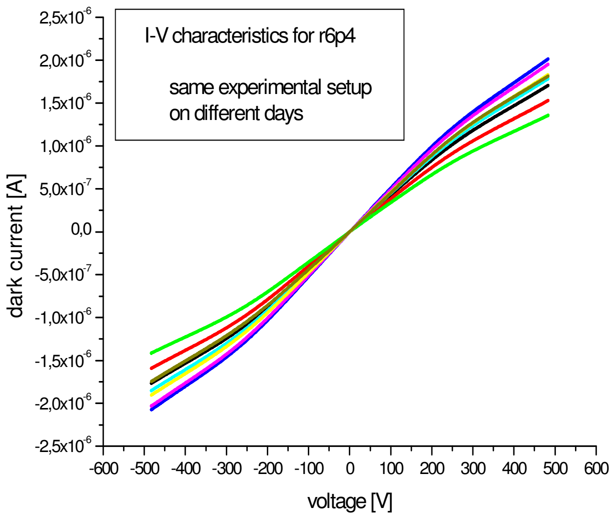

Fig. 8: I-V characteristics of "r6p4" at slightly different temperatures

I-V measurements for the pads around the central pad "r6p4" were performed for GaAs 1 and GaAs 2 to see how the dark current changes with increasing distance from the point of irradiation. Its distribution can be seen in Fig. 9 and 10:

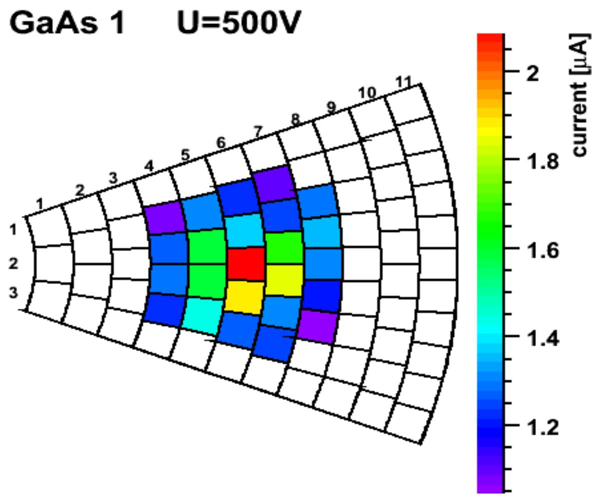

Fig. 9: Dark current distribution at 500 V for GaAs 1

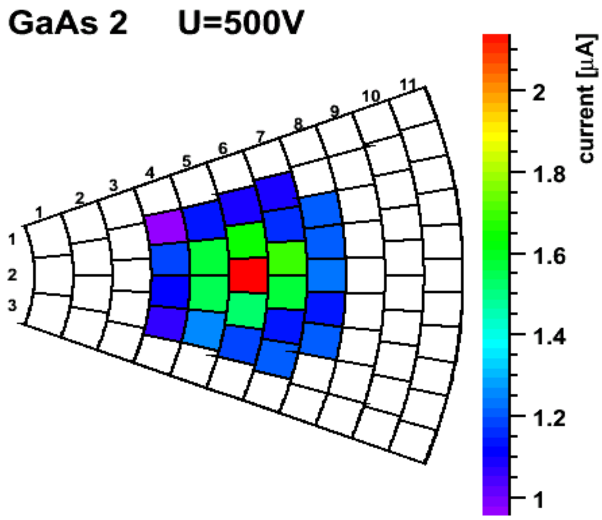

Fig. 10: Dark current distribution at 500 V for GaAs 2

Obviously the dark current is highest at the point of irradiation (r6p4). Fig. 9 shows clearly that the electron beam did not just hit the central pad "r6p4" of GaAs 1 but also the pads lying next to it. This is because the beam was not directly focussed on the central pad as it was done for GaAs 2.

Additionally it was of big interest to see how the dark current of other pads changed after being irradiated. A reproducible comparison of the data before and after irradiation could not be made since at that time the temperature was not recorded. It is recommended to monitor the temperature in future measurements.

4.2 CCD measurements

First of all a calibration of the setup was performed in order to assign the amount of charges to an ADC channel. This information is necessary for calculating the CCD. To obtain the necessary calibration curve the sensor in Fig. 6 is replaced by a capacitor with given capacity. A pulse generator is connected to it and provides the capacitor with voltage. The induced charge is well known and calibration factors can be calculated. An overview is given in Tab. 1.

	inverted signal	*non-inverted signal*
6 dB	42.1 ± 0.7 e^-/ch	40 ± 0.7 e^-/ch
12 dB	78.8 ± 1.1 e^-/ch	79.2 ± 1.4 e^-/ch

Tab. 1: Calibration factors for different attenuation

The typical image of a signal can be seen in Fig. 11. It was recorded by an oscilloscope and is a good example for a clear sensor signal.

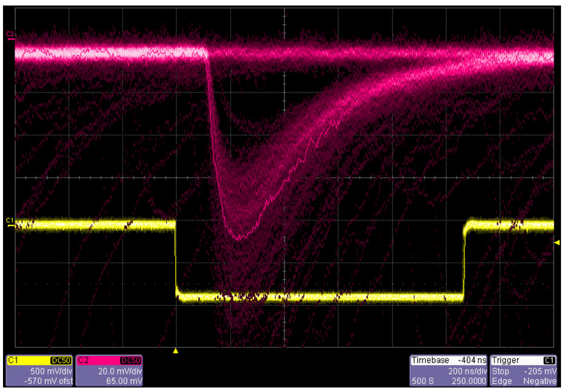

Fig. 11: Image of signal for GaAs 2 (time scale: 200ns);
yellow line: trigger with scale 500mV/div
pink line: signal peak with scale 20mV/div

Here the straight part of the pink line corresponds to the pedestal or baseline. The pedestal is simply the electronic noise and is considered to be a constant quantity. Integrating over the time gives the area below which is Gaussian distributed. The program used to visualize the obtained data counts the events per channel.

In Fig. 12 the signal spectrum for the pad "r7p4" is shown. It lies next to the irradiated one and three distinguishable peaks can be seen: the first one is the pedestal whose fit is clearly Gaussian (pink line). The other two peaks are interpreted as signal peaks (blue and green line). Their actual Landau distribution is convoluted by a Gaussian since the signal also contains noise.

The fit parameters make it possible to calculate the CCD by using:

$$CCD = \frac{Q_{collected}}{Q_{induced}} \cdot d = \frac{Q_{coll.}}{\rho_{ind.}} . \qquad (1)$$

$Q_{coll.}$ (= collected charge) is directly obtained from the fit and resembles the amount of collected charge:

$$Q_{coll.} = \left(MPV_{signal}^{i=1,2} - \mu_{pedestal} \right) \cdot k . \qquad (2)$$

$\rho_{ind.}$ is a theoretical value for how many free charge carriers are created per µm. This number is $\rho_{ind.}$=146.87 e^-/µm for GaAs. The constant k is the calibration factor.

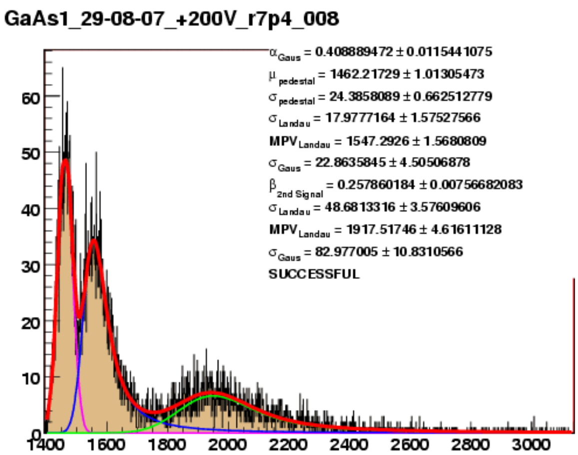

Fig.12: Fitted plot of the r7p4-spectrum (GaAs 1)

The appearance of two signal peaks was not predicted but can be explained in the following manner: GaAs 1 has been irradiated by a very sharp collimated electron beam which was not completely focussed on the central pad “r6p4” (cf. I-V characteristics, Fig. 9). Therefore the pads lying directly next to the central one were partly irradiated by high energy electrons. Obviously the diffusion process of traps is not a very strong one in this case so that a sharp border between areas of high and low trap densities was created. This fact might cause the production of more lattice imperfections in one part of the pad than in the other one and two different CCD values could be obtained for one pad. The CCD results for both GaAs samples are summarized in Fig. 13 and 14.

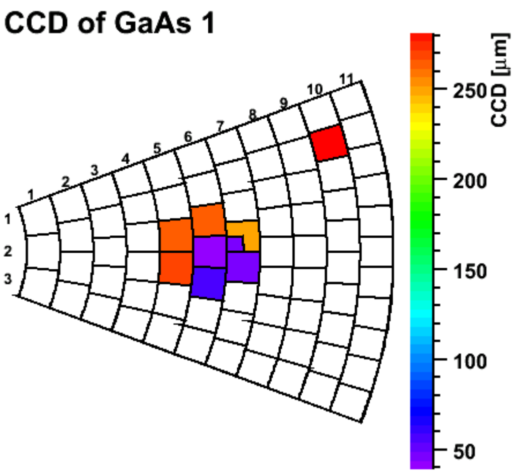

Fig. 13: CCD distribution over the GaAs 1 sensor

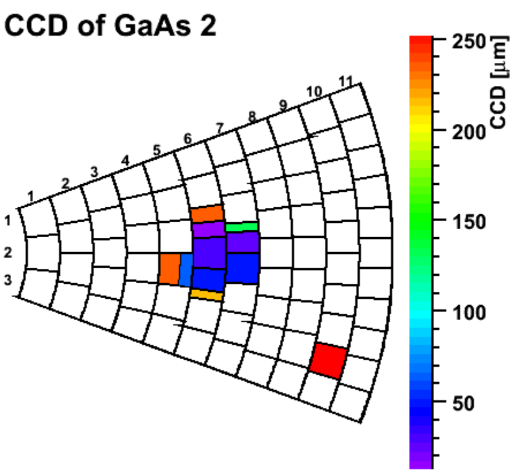

Fig. 14: CCD distribution over the GaAs 2 sensor

The few pads that show two CCD values are those that have been partly irradiated. Their values are comparable to those of irradiated and non-irradiated areas. As it was expected the CCD is smallest at the point of irradiation and increases when moving further away from it. Furthermore it was seen that the extreme values for the CCD of GaAs 1 and 2, given in Tab. 2, differ from each other. This is because the radiation dose on GaAs 2 was higher than the one on GaAs 1.

	GaAs 1	*GaAs 2*
r6p4	(39 ± 0.8)µm	(27 ± 0.6) µm
r10p2	-	(247 ± 4.1) µm
r10p9	(275 ± 4.5) µm	-

Tab. 2: Collection over extrema of the measured CCDs
r6p4: minimum CCD for irradiated pad
r10p*: maximum CCD since furthest away

The CCD values for “r10p2” and “r10p9” are highest in both cases. They agree with the CCD measured before irradiation. This can be seen in Fig. 15 (dose = 0 kGy). The plot was made during the “TestBeam07” measurements and shows the preliminary results of measuring the CCD vs. dose while GaAs 1 and 2 were irradiated.

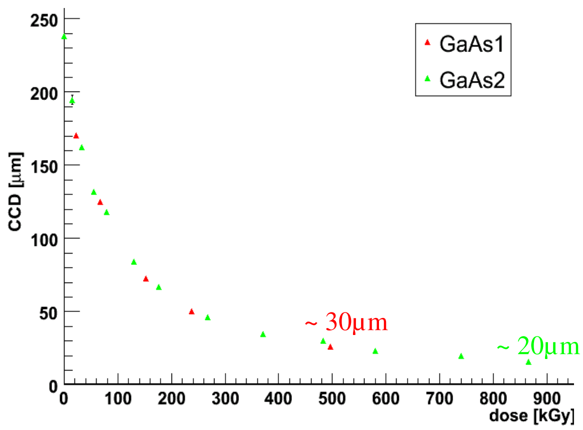

Fig. 15: CCD vs. dose measurement of “r6p4” while irradiating GaAs 1 (red) and 2 (green)

The CCDs at the end of irradiation are slightly lower than the values measured a few weeks after irradiation. The reason for this increase lies most likely in the fact that the sensors recover so that the trap density might decrease a little.

It is not yet understood why the minimum CCD for GaAs 2 of approximately (15 ± 2.2) µm was measured next to the central pad “r6p3” but one probable reason could be that this part of the crystal contains more lattice imperfections than others.

5. Summary

The distribution of the dark current over irradiated GaAs crystals behaves as it was expected: the resistance is smallest at the point of highest irradiation and increases with the distance. In the range of -300 V and +300 V the current is directly proportional to the voltage, i.e. the resistance is Ohmic even though GaAs is a semi-conducting material. Its temperature dependence could be seen and is of special importance at higher voltages (absolute value). This should be considered in future measurements. The highest current was measured for “r6p4” and is about 2 µA. Measurements before irradiating the sensor gave a value for the dark current of the central pad of about 1 µA. But since the temperature was not monitored those values should be handled with care because they might vary in a range of a few hundred nA.

It is assumed that the Charge Collection Distance depends on the trap density and increases therefore with further distance from the point of irradiation. Since the CCD is distributed in a very distinct manner it gives an insight in the sharpness and of the beam collimation. In conclusion one can say that not only from observing the sensor by eye and measuring the I-V characteristics but also through calculating the CCD it is possible to find out where the electron beam hit the material and created lattice imperfections. The conclusions derived from the comparison of the CCD data before, while and after irradiation comply with the expected results. The small differences in the CCD value for the central pad “r6p4” probably originate from the material’s recovery. Important numbers of the CCD measurements are listed in Tab. 3.

	GaAs 1	*GaAs 2*
r10p2 *r10p9*	270 µm -	- 250 µm
r6p4	39 µm	27 µm
r6p4, before	?	240 µm
r6p4, dir. after	30 µm	20 µm

Tab. 3: Survey of important CCD values for GaAs 1 and 2

The CCD for GaAs 1 and 2 was maximally decreased by 85 % and 90 %, respectively.

6. Acknowledgements

First of all I would like to thank DESY for arranging the Summer Student Program in 2007. The participation was a great opportunity to get closer insights into scientific work and research projects. The friends I made will be friends for a lifetime and the experience I got in working will influence my future. But most of all I got to thank all the people who introduced me to my work, helped me with fixing the measurements and giving timeless explanations to make me understand the details of my project: Martin Ohlerich, Wolfgang Lohmannn, Wolfgang Lange, Christian Grah, Sergej Schuwalow, Szymon Kulis, Ringo Schmidt.

7. References

[1]: E. Kuznetsova, Design Studies and Sensor Tests for the Beam Calorimeter of the ILC Detector (PhD thesis), Humboldt University Berlin, 03/2007

[2]: www.physics.uoregon.edu/~torrence/490/radintro/

[3]: W. Shockley, Currents to conductors induced by a moving point charge, Journal of Applied Physics 9 (1938)

[4]: S. Ramo, Currents induced by electron motion, Proceedings of the I.R.E. (09/1939)

[5]: www.sciencedirect.com, Zhong He, Review of the Shockley-Ramo theorem and its application in semiconductor gamma-ray detectors, University of Michigan, 11/2000

[6]: I. Sadeh, Measurements performed on GaAs – a possible sensor material for the forward region of the ILC, ISSP 2006, DESY – Zeuthen (09/2006)