Measurements of CVD Diamond properties for the ILC Forward Beam Calorimeters

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In the frame of the DESY Summerstudent program 2005 the suitability of several CVD diamond samples for a forward calorimeter for the ILC has been investigated. This was done by measuring IV-characteristics and the Charge Collection Distance in dependence of applied voltage, time and irradiation dose with a ^{90}Sr source. The samples E64 and FAP5 looked promising, while the FAP7 series proved unsuitable as their signal in the CCD measurement was not stable under irradiation.

1. Introduction

In an international design effort the particle physicists are developing the International Linear Collider (ILC). The e^+/e^- collider with an energy range of 500 GeV to 1000 GeV is expected to start operation around 2015. The physics program of the ILC is complementary to the Large Hadron Collider (LHC) at Cern. Its main aspects are the search for electroweak symmetry breaking via exploration of the Higgs boson properties and the search for super-symmetry. Since for these new particle searches hermeticity is essential, calorimetry down to polar angles of about 5 mrad is required[1].

For parts of the ILC, like the superconducting cavities, the former TESLA design proposed by DESY is used. Another example of research being carried over from TESLA to the ILC is the forward calorimetry, which is being developed by the FCAL collaboration[6].

2. Forward Calorimetry

Two calorimeters are planned: the LumiCal and the BeamCal. The ILC will measure cross sections of interesting processes and therefore it is essential to know the luminosity to convert a number of events in a given process into the corresponding cross section. A precise luminosity measurement is necessary for a small error of the final result.

A possible layout is shown in Fig. 1, where the LumiCal is used for the precise luminosity measurement. It uses the well known Bhabha scattering, which can be calculated precisely.

This work is focused on the BeamCal which covers lower polar angles and measures e^+/e^- pairs generated by beamstrahlung at the interaction point. This way the BeamCal can provide a fast feedback on the luminosity and may be used to measure beam parameters. Additionally it shields the inner parts of the detector against backscattered radiation and detects particles of high energies.

The BeamCal is a "sandwich" structure of an absorbing material, preferably tungsten, and a detector material. This is conventionally made out of silicon in a reverse biased diode structure.

Since the expected dose in the forward region of the ILC is up to 10 MGy per year[1] serious problems with radiation damage in Si occur. The option to exchange a Si-calorimeter in intervals of less than a year is not very appealing. A possible way around this is to use diamond as the detector material, with the economical choice being CVD-diamond (chemical vapor deposition[2]). It's radiation hardness has been proven up to 10 MGy with 1MeV photons, which is promising for the ILC[3], but it's use in a calorimeter is a novelty.

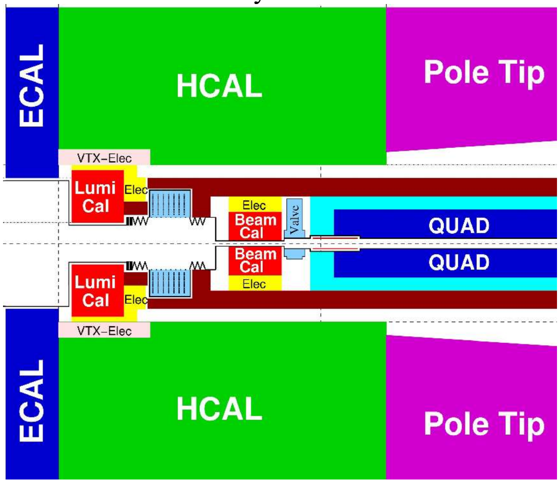

Fig. 1: planned layout of forward calorimeters for the ILC

3. Characterizing Diamond performance

With a bandgap of 5.45 eV[4] diamond is normally considered to be an insulator at room temperature. But since the CVD growth produces polycrystalline structures, these diamonds feature a considerable amount of defects at the grain boundaries. In combination with possible impurities this leads to an amount of free charge carriers with a negligible temperature dependence at room temperature. Therefore the expected I-V dependence is ohmic and diamonds with few defects and impurities will feature a very low current.
A very important characteristic of diamonds for a calorimeter is the charge collection distance (CCD). The energy deposited by a charged particle in diamond is well known from the Bethe-Bloch formula. It is measured by applying a high electric field (e.g. 1 V/μm) to the diamond and integrating the current over a short time, giving the charge. In a pure monocrystalline crystal the liberated charge carriers would drift to the electrodes and one would measure the complete signal. In a typical CVD diamond the charge carriers are trapped by defects after an average distance referred to as CCD, thus reducing the flowing current with time. Therefore it is crucial to know about the CCD and its time-, voltage- and dose-dependence for the particular diamond to get an accurate measurement in a detector. The CCD is the major parameter to judge the suitability of CVD diamonds for calorimeter applications.
Another way of getting information about the diamonds is via thermally stimulated currents (TSC). If diamonds are exposed to radiation some of their defects will trap charge carriers and get saturated. This increases the CCD. For deeper states the potential barrier is high enough so that the charge carriers stay trapped until the diamond is heated up. One can learn about these states if the radiated diamond is heated up with an applied voltage and the current is measured. If the procedure is repeated, the background / intrinsic current can be measured and the difference is the TSC.
Additionally PL- and Raman-spectra can be taken and can be used to identify the kind and amount of defects in the diamonds.

4. Set-up

Several CVD diamond samples have been investigated:

- FAP7 1b, FAP7 2b (IV, CCD)
- FAP5 (IV, CCD, TSC)
- E64 (IV, CCD)
- FAP7 6a, FAP7 9, FAP7 2 (CCD)

The FAP diamonds are produced by the Fraunhofer institute IAF in Freiburg. All series 7 samples originate from the same wafer; FAP5 is one of the best Fraunhofer samples. The E64 was bought from Element 6 and was remeasured now with its 3rd metalization. All diamonds have one metal pad on the side where the negative high voltage (HV) is normally applied ("normHV") and 4 pads covering most of the surface on the other side. These 4 pads were connected to the readout for CCD measurements. This way pads which draw a considerably higher current than the other ones can be disabled for the read-out. This was done with pad 2 of the FAP5 for all measurements.

4.1. IV-characteristics

For these measurements the diamond was put into a black box, providing electromagnetic and optical shielding, and inside that put into a small plastic box which was flooded with nitrogen to keep the humidity nearly at 0%. The current measurement and high voltage supply was done with a Keithley 487 Picoammeter / high voltage source. The voltage was ramped up in 50V steps up to 500V and then reduced to 0V with the same step size. This was done and monitored by a custom Labview program.

The current in the diamonds declined with time, so it was chosen to measure for 300s and then average over the last 20% to get a reproducible value of the current. If measured repeatedly the current will continue to decline[5]. This was avoided by a delay of several hours between successive measurements.

4.2. Charge Collection Distance

The set-up is shown in Fig. 2. A ^{90}Sr β-source was placed over a metalized box with the diamond and the preamplifier (PA). A window covered with aluminium mylar foil was cut into the box above and below the diamond sample. The e^- beam was defined by brass collimators. A lead collimator below the diamond absorbed particles that otherwise might have hit the scintillator without traveling through the diamond. The scintillator was placed under the diamond and was observed by two photomultiplier tubes (PMT). The threshold setting of the discriminators (DISCR) determined whether a signal was detected by the corresponding PMT. The output of both discriminators was combined using an AND-gate and in case of a coincidence the dual timer (not shown) applied a gate to the ADC. The ADC read out the signal from the PA and sent it to the connected PC. This way the noise rate without the ^{90}Sr source was always below 0.1Hz, compared to data rates of 10 to 50 Hz.
The high voltage was provided by an ISEG 222M or Keithley 6487 and the current was measured by the Keithley. The temperature was measured with a Keithley 2000 multimeter. These devices were controlled and read out using serial or GPIB interfaces and a Labview program.

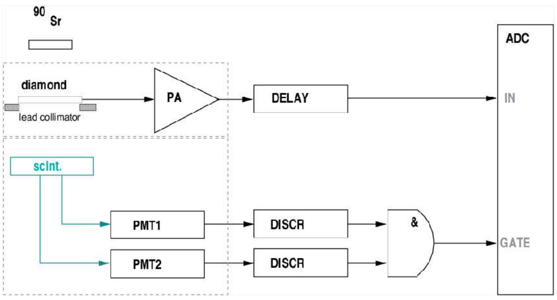

Fig. 2: setup for CCD measurements

Pedestal spectrums were taken to measure the electronical noise, mainly caused by the preamplifier. To do this a pulse generator applied a random trigger signal to the ADC. It turned out that for these measurements to be accurate the sample had to be irradiated by the ^{90}Sr source (see 5.4.).

4.3. Thermally stimulated currents

Here the diamond was taken out of its plastic enclosure and put between two pieces of metal, to which a voltage of 50V was applied. This construction was thermally coupled to a heating plate by a diamond and surrounded by a black metal box to get an even temperature distribution inside. The Keithley 487 served as voltage supply and current monitor, a Keithley 2000 multimeter measured the temperature with a Voltcraft temperature adapter. After the measurement the wirebonds have to be renewed.
The placement of the thermocouple is critical for the absolute values obtained in this measurement, as experiments showed that the real diamond temperature may be 1.6 times higher than measured with the standard placement of the thermocouple.

5. Experimental Results

5.1. IV-characteristics

Typical IV-curves for the "good" diamonds are shown in Fig. 3. The maximum current is 2pA and the curve corresponding to increasing voltage is almost linear, showing ohmic behavior. A hysteresis is seen for decreasing voltage, which is normal for CVD diamond and supposedly causes the reduced current in subsequent measurements as well. So one can reasonably assume that this is caused by trapped charges which oppose the electric field.
Typical curves for the FAP7-series are shown in Fig. 4. The current approaches the order of nA and increases strongly at 500V for these samples. The high current means that these diamonds have considerably more defects than the E64 and FAP5 and it is therefore expected that they have a comparatively small CCD.
One feature clearly observed with pad 4 of FAP7 1b is breakthroughs, as shown in Fig. 5. The resulting current is not huge in absolute terms, but the logarithmic scale shows an increase of two orders of magnitude at the step from 300V to 350V. When the measurement was repeated the next day the same happened going from 50V to 100V. This is probably caused by localized defects (possibly micro cracks), which can be seen in Fig. 6. The otherwise very good FAP5 has them as well, therefore its pad 2 is not connected to the read out.

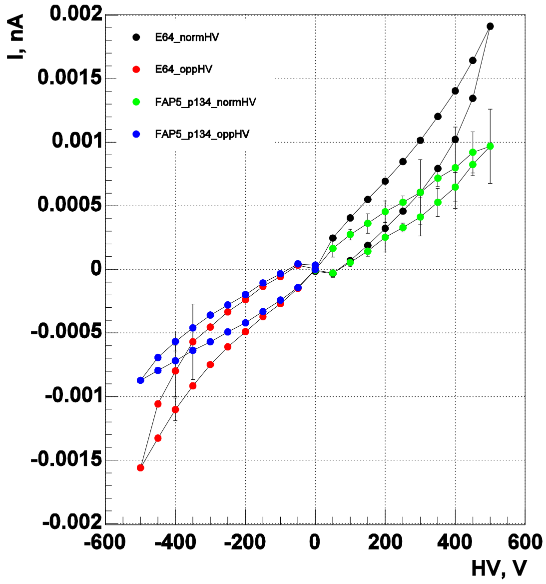

Fig. 3: I-V curves for E64 and FAP5, higher current while ramping up

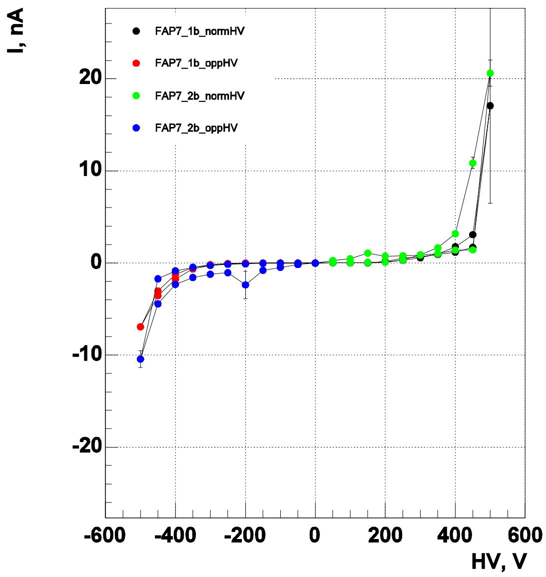

Fig. 4: I-V curves for FAP7 1b and 2b

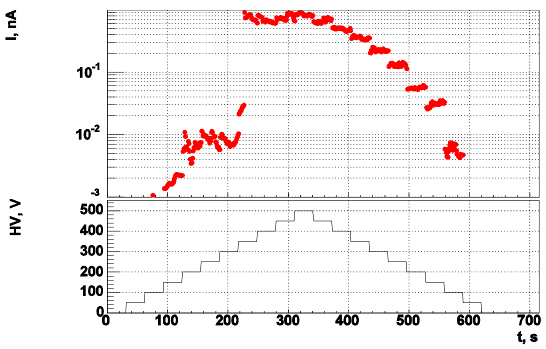

Fig. 5: FAP7 1b pad 4, measured current while ramping up the voltage

Fig. 6: photo of a diamond

5.2. Charge Collection Distance

Since a lot of CCD measurements have been done only some results will be presented with graphs, the rest is given in table 1. For a CCD vs t measurement the voltage was applied to the diamond and then the CCD was measured typically 10 to 15 times, distributed over 3 hours. For CCD vs HV the voltage was ramped up in steps corresponding to 0.2V/ µm. 4 measurements with 10 minutes in between were done for each voltage step. For the FAP7 6a and FAP7 9 existing measurements were analyzed, the other data was obtained from new measurements.

Diamond	**CCD vs t, 1V/µm [µm]**	**CCD vs HV, 1V/µm [µm]**
FAP7 1b	14.2	14
FAP7 2b	15.6	16
FAP7 6a	10.9 (0.8V/µm)	10
FAP7 9, pad 1	7.0	7
FAP5, without pad 2	18.9, 23.7, 25.1	33
E64	130	145

Tab. 1: CCD measurement results

The diamonds of the FAP7 series behaved rather similar. They all produced a weak signal, which was difficult to separate from the pedestal noise using a curve fit. So every single fit is not very trustworthy, but since the provided numbers are averages of several measurements, the accuracy should be good enough. There was no clear time dependence observed for these diamonds, which could be attributed to the fact that their signal was too small to see that. Their CCD vs HV plots showed a linear scaling with the applied voltage.

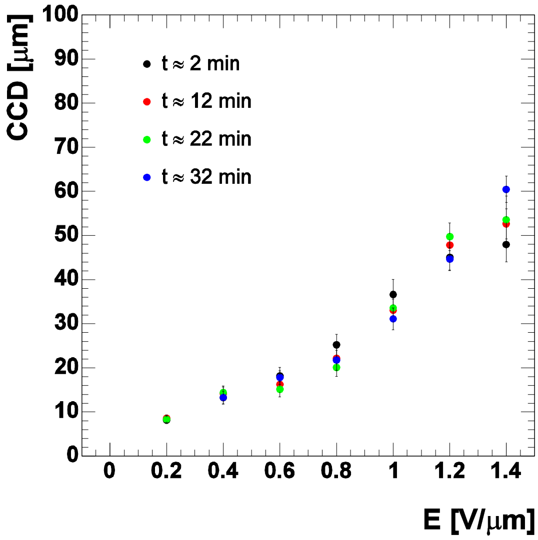

Fig. 7: CCD vs HV for FAP5, t = time after voltage was applied

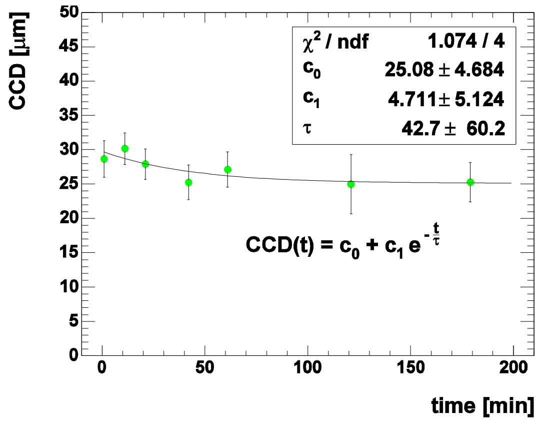

Fig. 8: CCD vs t for FAP5

The FAP5 showed much better results with a CCD as high as 47 μm at 1.2 V/μm (Fig. 7), giving a signal which could clearly be distinguished from the pedestal. This diamond was the only one from Freiburg (FAP) showing a weak time dependence of the CCD (Fig. 8). This can partly explain the difference in the CCD obtained by "CCD vs t" and "CCD vs HV", as the CCD value did not stabilize in the 30 minutes of the "CCD vs HV" measurement. The 3 values for "CCD vs t" originate from:

- the initial measurement, pad 2 floating
- pad 2 grounded
- pad 2 floating, but with better background measurement → more accurate fit

It is clear from this comparison that the status of pad 2 had no visible influence on the measurements.

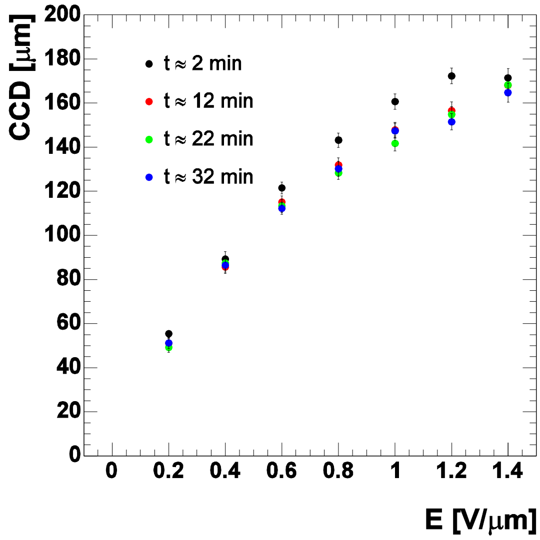

Fig. 9: CCD vs HV for E64, t = time after voltage was applied

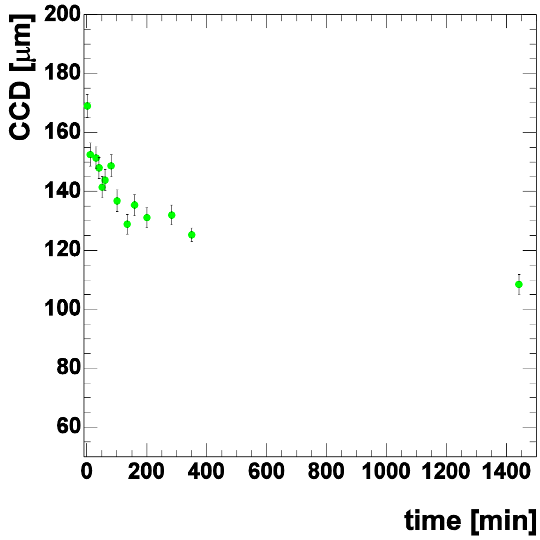

Fig. 10: CCD vs t for E64

The Element 6 diamond E64 has by far the highest CCD of the examined samples (Fig. 9). From 0.2 to 0.6 V/μm the CCD scales linearly with the voltage, from 0.8 V/μm on a saturation can be seen. This diamond showed a rather strong time dependence (Fig. 10) and additional measurements after 1400 minutes would have been good to see whether there was a real drop in the CCD.

5.3. CCD vs dose

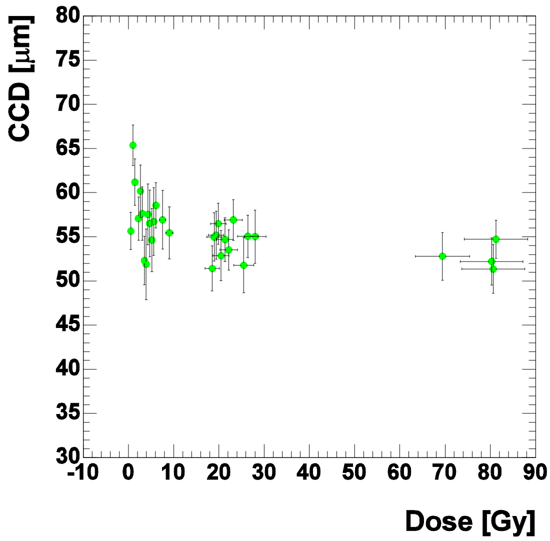

Fig. 11: CCD vs dose for FAP5 with preamplifier 1

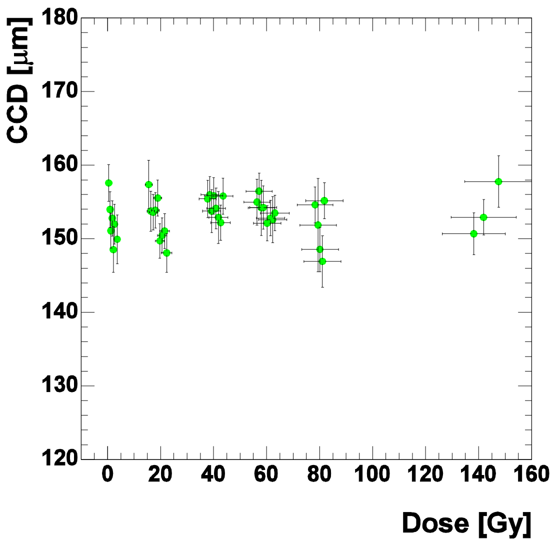

Fig. 12: CCD vs dose for E64

The CCD vs dose was measured for FAP5, E64 and FAP7 2b (300 μm), 7 (690 μm) and 2 (300 μm). All 3 measured FAP7 series diamonds showed a similar behavior: after 1 to 2 hours the current increased to a point (i.e. ~100nA) where the noise was getting so high that a measurement of the CCD was no longer possible. The current kept rising so the measurements were aborted. This is considered to be characteristic for the FAP7 series diamonds, as they showed rather similar behavior in other measurements.

The measurement of FAP5 had to be done with a different preamplifier with a much smaller amplification. Due to that the signal could not be distinguished from the pedestal as clearly as before, so the error of single measurements was considerably higher than for the other measurements. Nevertheless the overall result in Fig. 11 shows that the signal was stable under irradiation, measured up to 80 Gy. The different preamplifier explains the difference in the value of the CCD compared to the other measurements.

The E64 was measured up to 150Gy and showed no long term time dependence (Fig. 12). What can be seen is a reduction of the CCD over each well measured day. A temperature increase of ~3K was observed during that time. This increased the pedestal noise as well, but this can not cause a signal shift of 10 μm. The radiation was done at minimal distance between the diamond and the ^{90}Sr source, whereas the measurement was done at an additional 2cm to reduce the double pulse rate while still maintaining a convenient data rate. This means that during the day the dose rate was lower than over night. A "CCD vs dose rate" dependence has been observed for the E61 (Element 6, one pad) before, so a measurement of the E64 at different dose rates is being done now.

5.4. CCD vs height

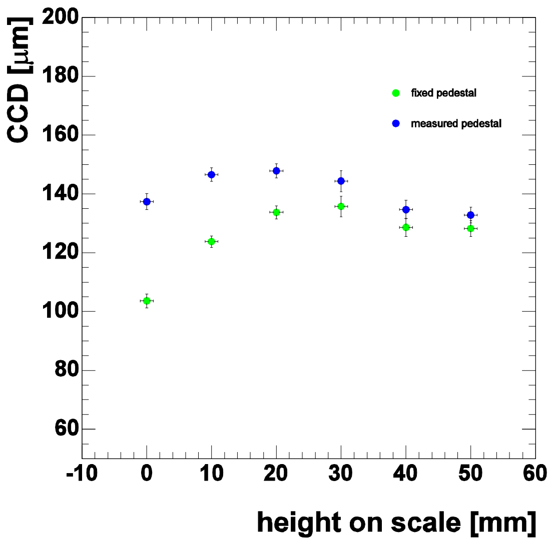

Fig. 13: CCD vs height, distance between diamond and source: height on scale + 26 mm, 2 calculation methods: blue / top curve for measured pedestal, green / bottom curve for fixed pedestal

If the distance between the source and the diamond is too low, the amount of double pulses during one gate length will become too high and the measurement will not represent the energy deposition of one particle any more. Additionally after very strong pulses there is a long lasting overshot effect, which can be considered as a positive offset for triggered signals after that. Since negative currents are measured, this reduces the corresponding ADC values, shifting the entire spectrum to lower values.

It was found empirically before that 4 cm is a safe distance for measurements. An examination of this effect is shown in Fig. 13. The green points are CCD values calculated with the pedestal measured without irradiation. Since this pedestal is constant, the CCD points represent the most probable values of the measured spectra. The shift to lower ADC channels is clearly visible.

The blue points are calculated with noise spectra taken under irradiation, so the shift applies to the pedestal as well. Here the calculated CCD value changes less with distance, but the deviation from the values at high distances is still significant.

This effect is less pronounced for diamonds with a lower CCD than this E64, so if the count rate is high enough, the measurements can safely be done at 4 cm. If one has to go closer, the second calculation method has to be used together with noise spectra under irradiation.

5.5. Thermally Stimulated Current

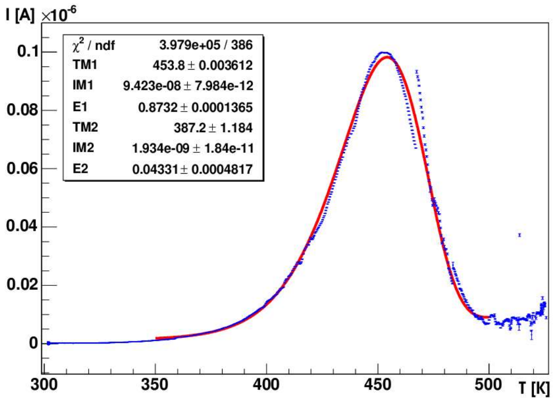

Fig. 14: TSC of FAP5 after 80 Gy of irradiation

The TSC has only been measured for FAP5. In Fig. 14 the difference between the current in the irradiated diamond and the unirradiated case is plotted against the temperature. The heating clearly released trapped charges. To calculate the corresponding energy level(s), a curve fit was done assuming the existence of 2 discrete energy levels . The main peak is found at 454 K with an energy level of 0.87 eV. The second level is located at 43 meV has an approximately 50 times smaller current than the first one, so it can't be seen in the graph.

These absolute values are certainly incorrect because the measured temperature has been shown not to be the real temperature of the diamond. To get accurate results the calibration to account for this error has to be done over the whole temperature range.

6. Summary and future work

The major result of these measurements is that the FAP7 series is not suitable for calorimeters, whereas the E64 and FAP5 are very promising. Further investigations in other facilities are planned to find the reason for this difference between FAP7 and FAP5. A theory exists that it may be caused by a higher boron concentration in the FAP7 series.

Another observation is the daily CCD dependence of FAP5, which is being checked whether it is caused by a CCD - dose rate dependence. The CCD vs dose measurement will be repeated for FAP5 with the standard amplifier to get more accurate values. In addition to this the effect of measuring at small distances was quantified.

To do further studies new samples are needed. It is planned to acquire samples which have less of the localized defects shown in Fig. 6 and discussed in 5.1.

7. Acknowledgements

I'd like to thank DESY and especially DESY Zeuthen for making the Summerstudent program possible and all people involved in the organization, furthermore all the people who helped me with my work, especially my supervisor Wolfgang Lohmann, Christian Grah and Ekatherina Kouznetsova.

8. References

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