Analele Universităţii de Vest din Timişoara
Vol. L, 2007
Seria Fizică

SENSOR DEVELOPMENT FOR THE BEAMCAL AT THE ILC

A. Rosca

West University of Timisoara, Timisoara, Romania

Abstract

Sensors used for calorimeters near the beam pipe at an ILC detector, e.g. the BeamCal must be very radiation hard due to the high level radiation exposure of this calorimeter. Polycrystalline diamonds, gallium arsenide (GaAs), radiation hard silicon and small samples of single crystal diamond have been investigated. Results of the charge collection efficiency measurements as well as of the measurements of the current and capacitance of the samples as a function of the bias voltage are summarized.

1. Introduction

At the future International Linear Collider (ILC) the detectors and the electronics in the region of low polar angles of the experiment will have to withstand an extreme environment. In beam-beam interactions a large number of electron-positron pairs of low energy are created by beamstrahlung and will hit the detectors. The deposited energy by ionization can be as high as 10 MGy per year of operation. Thus, radiation hardness is required for both detectors and electronics to survive in these severe conditions. The very forward region of the detector at the ILC will be equipped with three calorimeters. These are: the LumiCal for luminosity measurement, the BeamCal for fast luminosity feedback and for detector hermeticity and the GamCal for luminosity monitoring. The BeamCal covers polar angles down to 5 mrad with respect to the beam line and is composed of segmented sensor layers of 500 μm thickness made of a radiation hard material, interspersed between 0.35 cm thick tungsten disks. The need for radiation hard detectors can be satisfied with materials which are inherently more radiation hard than silicon. We investigated several options for possible sensor materials for the BeamCal: polycrystalline and single crystal CVD diamonds, gallium arsenide (GaAs) and the so-called radiation hard silicon.

2. Material properties

The basic properties of the materials investigated, which are important for sensor applications, are compiled in Table 1.

Diamonds are produced by industry in a low pressure, low temperature chemical vapor

deposition process. CVD diamonds grow in a polycrystalline columnar structure along the growth direction. The material starts with small grain sizes of about 1 μm on the substrate side which grow in size reaching diameters of about 100 μm on the growth side. The thickness of the sample ranges from 300 μm up to almost 3 mm. CVD diamond is not homogenous throughout the material and consequently also the electronic properties vary with the thickness. This material is under investigation since several years for the experiments at the Large Hadron Collider [1].

A diamond consists of carbon atoms in a diamond lattice structure having the highest atomic number density of 1.75×10^{23} atoms/cm^3. A unique feature of carbon atoms in the diamond lattice is the strength of their bonds which leads to a cohesive energy in diamond of 3.62 eV/bond. The band gap between the valence band and the conduction band of CVD diamond is 5.47 eV, about five times higher than the one of silicon. Consequently, there are very few free charge carriers present in CVD diamond at room temperature, the resistivity is very high and the leakage currents are very small. These properties mean that diamond detectors need not to be depleted. However, the large band gap leads to a high energy necessary to create an electron-hole pair of 13 eV, compared to only 3.6 eV for silicon. Consequently, a minimum ionizing particle traversing a diamond detector of 300 μm thickness will release in average about 10800 electron-hole pairs. For a given amount of material, one has a smaller signal produced in diamond than in either silicon or gallium arsenide. The electrical properties of diamond, namely the charge carrier mobility and the charge carrier lifetime are important for particle detection. The mobility of electrons and holes in diamond is high, enabling faster charge collection in diamond sensors than in silicon. The pCVD samples we investigated are about 500 μm thickness and a 1 x 1 cm^2 size, while the sCVD sample has a thickness of about 340 μm and a round sensitive area of 3 mm in diameter.

GaAs is a semi-insulating material, doped with Sn and compensated with Cr to make a high resistivity material. The resistivity is about $2.5 \times 10^7 \Omega$m. Its band gap is much larger compared to silicon, suggesting that it will be more radiation tolerant. The amount of free charge carriers induced by ionization in GaAs is about a factor of two higher than for silicon. The prototype sensor we used was produced by the Siberian Institute of Technology in Tomsk as part of a 3 inch wafer. The thickness of the material is 500 μm.

Table 1: Material properties of several sensor candidates for the BeamCal.

Material	Silicon	CVD diamond	GaAs
Band gap [eV]	1.12	5.47	1.43
Mass density [g/cm^3]	2.33	3.5	5.32
Dielectric constant [As/Vm]	11.9	5.7	13.1
Resistivity [Ωm]	2.3×10^5	$>10^{11}$	1×10^8
Breakdown field [V/μm]	30	1000	40
Electron mobility [cm^2/V s]	1350	1800	8500
Hole mobility [cm^2/V s]	480	1200	400
Saturation velocity [km/s]	82	220	80
Thermal expansion coeff. [10^{-6}/K]	2.6	0.8	6.86
Thermal conductivity [W/cm K]	1.5	10…20	0.46
Radiation length [cm]	9.4	12	2.3
Specific ionisation loss [MeV/mm]	0.321	0.469	0.56
Energy to create eh-pair [eV]	3.6	13	4.2
Ave. no. of eh-pairs/MIP [e/0.1 mm]	9200	3600	13000
Ave. no. of eh-pairs/MIP [e/0.1 % X_0]	8900	4500	3000

3. Charge collection

The charge collection distance in a homogenous semiconductor material is proportional to the mobility and the lifetime of the charge carriers and it is an important quantity that determines the induced charge on the electrodes of the sensor. It is defined as the average distance that electrons and holes drift apart in an electric field before they are trapped. The CCD is lower than the material thickness if traps or recombination centers in the material prevent the charge carriers to reach the electrodes, as for instance it is the case for the pCVD. It is known that the exposure of diamonds to ionizing radiation and UV-light can substantially increase the CCD. This phenomenon is called pumping [2]. Traps are passivated by the radiation, allowing the electrons and holes to move further apart. Due to the inhomogeneous columnar structure of pCVD diamonds, the CCD is not constant throughout the detector. It has been shown [3] that the local collection distance grows linearly from zero at the substrate side towards a maximum at the growth side.

The charge collection distance of sensors is measured using a ^{90}Sr source with a collimator and filter, which delivers β electrons ranging up to an energy of 2.28 MeV. The sample under test and a scintillator are aligned under the collimated Strontium source. When a reasonably high threshold is applied to the trigger detector in this setup, the low-energy part of the source spectrum does not give a trigger signal. Only electrons passing the sample and the scintillator are used for the spectroscopic measurement, thus their energy loss will be a good approximation to the energy loss of a minimum ionizing particle (MIP). The detector is

connected to a low-noise charge-sensitive amplifier, which is calibrated by injecting a well-defined voltage step pulse over a capacitance.

4. Radiation hardness

The main radiation damage phenomena in semiconductor detectors are: the increase of the leakage current with the irradiation dose due to the creation of traps or recombination centers, the change in the effective doping concentration at large doses, leading to an increased depletion voltage, and finally a shortening of the carrier lifetimes due to increased trapping at radiation-induced defects, with corresponding loss of charge.

The above mentioned sensors were irradiated with 10 MeV electrons at the S-DALINAC facility, a linear accelerator of the Technical University of Darmstadt, Germany during beam tests in 2006 and 2007. The beam current has been varied between 2.5 nA and 50 nA, corresponding to dose rates between 20 kGy/h and 300 kGy/h. In intervals of about one hour the charge collection distance of the sample was measured using the ^{90}Sr source setup described in section 3. The dose rate during the source measurement was about 0.1 Gy/h. The samples were biased with HV, typically of 100-200 V, for the whole duration of the experiment.

Two pCVD diamond samples, labeled E6_B1 and E6_B3, were irradiated at beam currents up to 50 nA and one sCVD diamond sensor was irradiated up to a dose of 5 MGy. Preliminary results obtained [4] are shown in Figures 1 and 2. Both pCVD diamond samples show an initial increase of the CCD by a factor of 2 due to pumping. For higher absorbed doses the CCD decreased as a function of dose, reaching a value of 100 μm for an absorbed dose of 4.5 MGy (sample E6_B1), respectively 80 μm for 5.5 MGy, sample E6_B2. The CCD of the cSVD sample before the irradiation is about 340 μm, corresponding to an efficiency of 100%. After about 1 MGy the CCD decreased to 50% of the initial value, as can be seen on Figure 2, reaching 60 μm for an absorbed dose of 5 MGy. The leakage current of all diamond samples stayed very low, with no change due to irradiation.

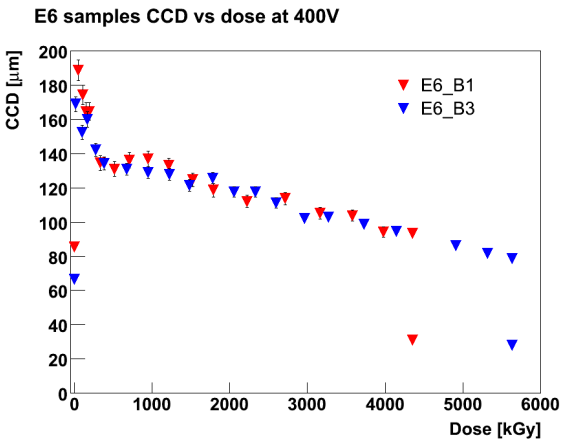

Figure 1. Charge Collection Distance (CCD) of two pCVD diamond sensors as a function of the absorbed dose, from ref. [4].

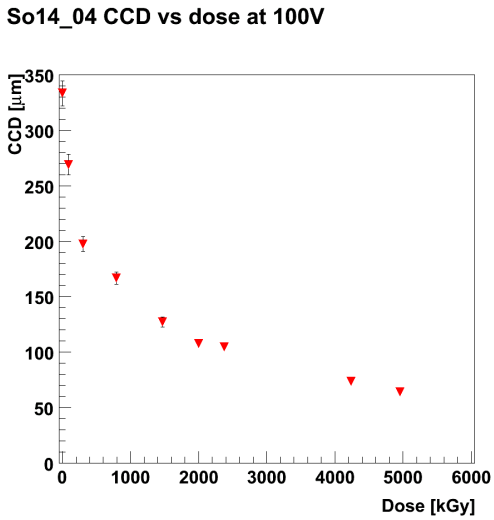

Figure 2. The CCD as a function of the absorbed dose for a sCVD diamond sensor, ref [4].

Two GaAs sectors of a sensor prototype, called GaAs1 and GaAs2 have been irradiated with 10 MeV electrons up to doses of 850 kGy the GaAs1, respectively of 1.5 MGy, the GaAs2. The result of the investigation of the sensor response to MIPs as a function of the absorbed dose is shown in Figure 3. The initial charge collection efficiency of the sensor is about 50%, corresponding to a CCD of about 240-250 µm for the two samples. During the irradiation the CCD of the GaAs sensors decreased significantly, to about 50% of its initial value after 100 kGy of absorbed dose. In addition, the GaAs samples showed an increase in their leakage currents, which reached about 1 µA for a bias voltage of 200 V.

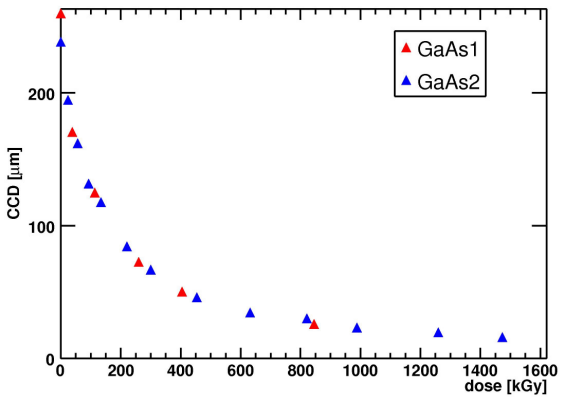

Figure 3. The CCD as a function of the absorbed dose for the two GaAs sectors, from reference [4].

One sample of radiation hard silicon has been investigated. Although the CCD value did not change after an absorbed dose of 90 kGy, the irradiation procedure was stopped when the noise level became too high for performing further a CCD measurement.

4. Conclusions

We investigate the properties of possible sensor materials for the beam calorimeter BeamCal of the detector at the ILC. The materials under investigation are subject to a reduction of their charge collection distance during irradiation with 10 MeV electrons up to several MGy. PCVD diamond shows an expected pumping behavior during the first phase of the irradiation, followed by a decrease of the CCD. No significant increase of the leakage currents of the sensors was observed. SCVD has a CCD equal to the sensor thickness before the irradiation and decreases to about 18% of its initial value after 5.5 MGy. No change in the leakage current was measured. GaAS has an high response to ionizing radiation which compensates its efficiency of only 50% before the irradiation. The CCD after absorbing 1.5 MGy provides still a detectable signal, but the increase of the leakage current might require special treatment in the final system.

Acknowledgements

The author would like to thank the FCAL Collaboration for a collaborative spirit and the S-DALINAC group of the TU-Darmstadt, Germany for their support during the usage of their facility. Part of this work was supported by the CEEX Program of the Romanian Ministry of Education, Research and Youth, contract 118/01.08.2006.

References

1. C. Bauer *at al.*, Nucl. Instr. and Meth., A383 (1996) 64.
2. R.J. Keddy, T.L. Nam and R.C. Burns, Phys. Med. Biol., Vol. 32, No 6 (1987) 751.
3. M.A. Plano *et al.*, Appl. Phys. Lett., Vol. 64, No 2 (1994) 193.
4. Ch. Grah, A. Rosca, *et al.*, Radiation Hard Sensors for the Beam Calorimeter of the ILC, Proceedings of the Nuclear Science Symposium and Medical Imaging Conference, Oct. 27 – Nov. 3, 2007, Hawai, USA; Ch. Grah, *et al.*, Polycrystalline CVD Diamonds for the Beam Calorimeter of the ILC, Proceedings of the Nuclear Science Symposium and Medical Imaging Conference, Oct. 29 – Nov. 4, 2006, San Diego, USA;