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New developments in CVD diamond for detector applications*

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Abstract. Chemical Vapor Deposition (CVD) diamond has been discussed extensively as an alternative sensor material for use very close to the interaction region of the LHC and other machines where extreme radiation conditions exist. During the last seven years the RD42 collaboration has developed diamond detectors and tested them with LHC electronics towards the end of creating a device usable by experiments. The most recent results of this work are presented. Recently, a new form of CVD diamond has been developed: single crystal CVD diamond which resolves many of the issues associated with poly-crystalline CVD material. The first tests of this material are also presented.

1 Introduction

The experiments at the LHC and SLHC will be exposed to high particle fluxes of O(10^{15} particles cm^{-2}) in the inner regions of the detector during their lifetime. In the regions close to the interaction point and the beam pipe the radiation levels will be even higher. Thus diamond as an alternative radiation resistant detector material is being investigated by the RD42 collaboration since 1995. Some properties of diamond and silicon are listed for comparison in Table 1. The low dielectric constant and the low leakage current of diamond detectors minimizes the noise in the amplifying electronics. Furthermore, the high band-gap of about 5.5 eV allows operation at elevated tempera-

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* presented by A. Oh, on behalf of the RD42 collaboration

Table 1. Comparison of properties of Diamond and Silicon

	Diamond	Silicon
Band Gap [eV]	5.47	1.1
Dielectric Constant	5.7	11.9
Specific Resistance [Ω cm]	$> 10^{11}$	$2.3 \cdot 10^5$
Ionisation Energy [eV]	13	3.6
Ionisation Density MIP [eh μm^{-1}]	36	89

tures. Most importantly, the tolerance to radiation makes diamond an attractive material for detector applications in harsh radiation environments. The disadvantage of the materials are the incomplete charge collection and, associated to this, inhomogeneous charge collection properties. To improve the charge collection properties RD42 has initiated a successful research program in partnership with industry [1].

2 Material studies

Synthetic diamond produced in a Chemical Vapor Deposition process (CVD) can be grown on 6 inch substrate wafers. The deposited films are typically polycrystalline. The crystallites constituting the film grow in a columnar form, widening their diameter with the film thickness leading to the typical columnar structure seen with polycrystalline CVD diamond films (Fig. 1). The charge collection distance, defined as the product of electric field strength, carrier mobility and lifetime, could be increased from a few micrometers to over 250 μm today, corresponding to a charge signal of about 9000 e for a minimum ionizing particle.

Typically, the charge collection properties are not uniformly distributed due to the poly-crystalline nature of the material. The effects on position sensitive devices are non-uniform response, effectively broadening the Landau spectrum for minimum ionizing particles, and systematic deviations in the position reconstruction as a function of the impact position on the detector. Both effect are due to the poly-crystalline structure and have been modeled using a numerical growth simulation and a charge drift simulation taking into account the distribution of trapping centers and the arising polarization fields. Qualitative agreement with test-beam data has been shown [2].

2.1 Radiation tolerance

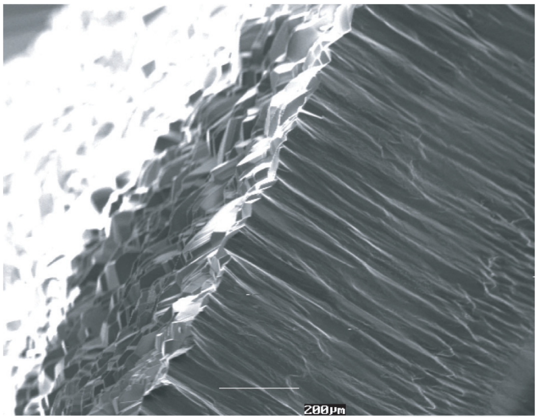

Fig. 1. Side-view of a poly-crystalline CVD diamond

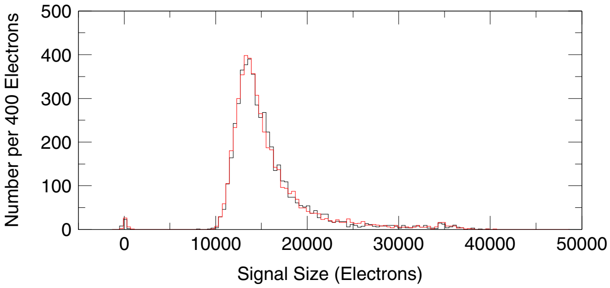

Fig. 2. Landau spectrum recorded with mono-crystalline CVD diamond and ^{90}Sr . Two spectra, differing in the polarity of the electric field, are overlaid

The impact of radiation on the charge collection properties of diamond has been studied with protons [3], pions [3], neutrons [4] and photons [5]. Simple dot detector as well as strip detectors have been studied. The highest loss in the charge signal of about 50% was observed with pion radiation of $2.9 \cdot 10^{15} \pi$ cm^{-2}. With neutrons a loss of 15% was observed at a fluence of $2.2 \cdot 10^{15}$ n cm^{-2}. The resolution of the irradiated strip detectors improved in each case between 20% and 30% after irradiation. Also, the Landau spectrum became narrower, which is attributed to a smoothing of the collection efficiency of crystallites. No radiation damage was observed with photons up to a fluence of 10 MGy [5].

2.2 Mono-crystalline CVD diamond

The development of special substrates allows the homoepitactic growth of CVD diamond with a mono-crystalline structure [8]. The Landau spectrum recorded with a monocrystalline sample (Fig. 2) shows a very narrow distribution (comparable to Silicon) and a clear separation from 0 with an on-set of the signal at 10,000 electrons and an average of about 15,000 electrons indicating an excellent uniformity of charge collection. The corresponding collection distance for this sample is about 420 μm and practically a fully efficient charge collection is observed. The maximum charge collection is attained at an applied field of 0.2 V/μm, which is an order of magnitude lower compared to poly-crystalline material.

Direct studies of the charge collection uniformity and tests of the radiation hardness are envisaged.

3 Particle detector prototypes

Different prototype detectors have been tested with charged particle beams. Simple dot detectors, strip detectors and pixel detectors were deployed in these studies.

3.1 Strip detectors

Strip detectors with 50 μm pitch were tested with slow VA2 electronics and with fast LHC type electronics. As indicated before as part of the irradiation program also irradiated strip detectors were tested [6].

Typically a spatial resolution of $\sigma \approx 50\ \mu\text{m}/\sqrt{12}$ (digital) was obtained with VA2 electronics. With LHC electronics a S/N ration of about 8:1 and digital resolution were obtained. The reconstruction efficiency is about 90%.

It is foreseen to test a device with intermediate strips to facilitate the charge sharing and to gain in resolution.

3.2 Pixel detectors

Pixel detectors have been produced with patterns matching the CMS and ATLAS pixel read-out chip specifications [7]. The CMS pixel prototype had a pixel pitch of 125 μm × 125 μm, Ti-W metalization and was bump-bonded with an Indium process at the UC Davis. A spatial resolution of 31 μm was obtained, and an efficiency of 90%.

The ATLAS pixel prototype had a pitch of 50 μm × 400 μm, an Al metalization and was lead-tin soldered at IZM Berlin. Simular results were obtained, namely digital resolution (14 μm and 114 μm for the small and long pitch resp.) and an efficiency of about 80%.

The pixel prototype studies will continue with radiation hard read-out electronics and improved material and metalization.

4 Applications in HEP

Currently, none of the high energy physics (HEP) experiments is foreseeing vertex detectors with diamond. However, niche applications in HEP exist where diamond is a good candidate. Two examples are a calorimeter application for very low rapidity jets [5] and a beam monitoring device for BaBar at SLAC and possibly CMS at the LHC.

Beam monitoring is crucial for the protection of the most inner layers of multi-purpose detectors. It must reliably and fast signal a beam accident to take protective measures, like actively dumping the beams, or shutting-down detector supplies. While CMS is still investigating the possibilities of diamond for this application, BaBar has already installed a prototype of a beam-monitoring device made of CVD diamond. The device is operated in parallel to the production system with Silicon diodes since 4 month (as of Juli 2003), and demonstrates reliable and reproducible operation. No increase in leakage current has been observed.

5 Summary and outlook

The progress made in fabrication of detector grade CVD diamond is impressive. Polycrystalline CVD diamond material with a collection distances of above 200 μm , corresponding to an average charge signal of 7200 e for a minimum ionizing particle, is available. It is anticipated that 300 μm collection distance material will be available in the future. Furthermore, a new material, mono-crystalline CVD diamond, promises to overcome most of the polycrystalline shortcomings, as there are non-uniformity of the charge signal, and the worse resolution of position sensitive devices compared to devices made with Silicon.

Prototypes of strip and pixel detectors have been successfully tested with LHC electronics. The achieved S/N ration is 8:1 for strip detectors with radiation hard electronics.

The radiation hardness of CVD diamond has been tested with pions, protons, neutrons and photons. The most severe loss of charge signal was observed with pions at a fluence of $2.9 \cdot 10^{15} \pi\ \text{cm}^{-2}$ and a loss of about 50%. No loss was observed with photons up to a dose of 10 MGy. More radiation studies will be pursued with high quality material.

First applications of diamond detectors in high energy physics are upcoming. A beam monitoring system is currently under study for the CMS detector, and another one being already successfully tested in-situ at BaBar.

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