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Development of CVD diamond tracking detectors for experiments at high-luminosity colliders

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Summary. — Diamond was studied as a possible radiation hard technology for use in future high radiation environments. With LHC upgrades expected, all LHC experiments are planning for detector upgrades which require radiation hard technologies. Chemical Vapor Deposition (CVD) diamond has now been used extensively in beam conditions monitors as the innermost detectors in the highest radiation areas of BaBar, Belle and CDF and is installed in all LHC experiments. As a result, this material is now being discussed as an alternative sensor material for tracking very close to the interaction region of the super-LHC where the most extreme radiation conditions will exist. RD42 Collaboration continued making progress in diamond detector technology. Polycrystalline and single-crystal chemical vapor deposition (pCVD and scCVD) diamond detectors were constructed, irradiated and tested. Irradiated diamond detectors showed that both pCVD and scCVD follow a single damage curve allowing one to extrapolate their performance as a function of dose.

PACS 81.05.ug – Diamond.
PACS 29.40.-n – Radiation detectors.
PACS 29.40.Gx – Tracking and position-sensitive detectors.
PACS 29.40.Wk – Solid state detectors.

1. – Introduction

While the Large Hadron Collider is collecting data, the design luminosity of the planned Super Large Hadron Collider (SLHC) of $10^{35}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ poses a serious challenge for future vertex detectors close to the interaction region, in particular due to the harsh radiation environment. In SLHC scenarios the total expected fluence at a radius of about 4 cm will exceed 10^{16} particles/cm^2 [1]. A number of studies are currently being performed to find solutions for detectors that can operate in such environments. Chemical Vapor Deposition diamond, in either single-crystal (scCVD) or polycrystalline (pCVD) form, is a material which is being considered for such detectors. Besides being radiation tolerant, diamond is also an attractive material, since it is an excellent thermal conductor and it exhibits no leakage current, fast collection times and a small input capacitance.

Recently pCVD diamond material has become available in the form of wafers produced by ElementSix [2]. The charge collection distance is a measure of the quality of material and normally exceeds 300 μm. After characterizing wafers, all indications are that Element Six can reproducibly grow and process high quality detector-grade CVD diamond material. Advances in the production of scCVD diamonds have led to the production of sensors with sizes larger than 1 cm^2 and thicknesses of up to 700 μm. The production process is still in its development. scCVD detector material is superior in terms of charge collection and homogeneity than pCVD diamond sensors [3, 4]. The RD42 Collaboration has developed and characterized diamond detectors [5, 6], constructed several pixel diamond detectors, and in cooperation with the Fraunhofer Institute for Reliability and Micro integration(IZM) [7], performed fine-pitch flip-chip bump bonding on diamond sensors. Single-chip devices and also multi-chip module detectors have been assembled and tested in particle beams. Radiation tolerance studies [8] are presented in this paper.

2. – CVD diamond

The properties of diamond and, for comparison, those of silicon that are of interest when considering the material for use as a detector are reported in [9]. The most distinctive feature of diamond is its large band gap, 5.5 eV. This large band gap along with the associated large cohesive energy are responsible for much of the radiation hardness of diamond. The large band gap also makes diamond an excellent electrical insulator. As a result, a large electric field can be applied without producing significant leakage current. Thus, there is no need for a reverse biased pn-junction and the diamond detector functions much like a solid-state ionization chamber. Diamond has two additional properties that compare favorably to silicon. Its smaller dielectric constant yields, for a given geometry, a lower detector capacitance and thereby, lower noise performance of the associated front-end electronics. In addition, even though diamond is an electrical insulator, it is an excellent thermal conductor with a thermal conductivity exceeding that of copper by a factor of five at room temperature. This is important since a common problem with large detector systems is the management of the thermal load generated by the large number of electronic channels used in the detector readout. The handling of this thermal load would be simplified if the detectors were constructed from diamond since the diamond would act as a heat spreader. Although diamond appears ideal in many respects it does have a limitation: the large band gap which produces many of its outstanding properties also means that its signal size is at most half with respect to the one of silicon for a given detector thickness in radiation lengths. This is somewhat compensated by lower front-end electronic noise. The discovery of the growth of diamond using the Chemical Vapor Deposition (CVD) process allowed the consideration of large-scale use of diamond detectors. The detailed structure (polycrystalline or single-crystal) depends on the substrate employed during growth. For the last ten years the RD42 Collaboration at CERN has worked to develop detectors based on pCVD diamond [10]. They have succeeded in constructing detectors with feature sizes from μm to cm. They have measured the radiation hardness up to fluences greater than 10^{15} hadrons per cm^2 and have found it to be sufficient to allow diamond detectors to operate for several years at the highest design luminosity of the LHC. The basic principle of using diamond as a particle detector is applying a voltage across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms in crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3600 electron-hole pairs are created per 100 μm of diamond traversed

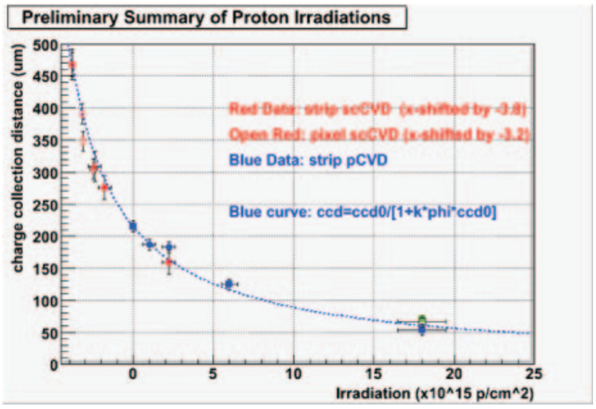

Fig. 1. – (Colour on-line) Summary of proton irradiation results for pCVD (blue points) and scCVD (red points) material at an electric field of 1 V/μm and 2 V/μm (solid green square point) to a fluence of $1.8 \cdot 10^{16}\, p/\text{cm}^2$. The blue curve is the damage curve $1/ccd = 1/ccd_0 + k\phi$. The scCVD data has been shifted to the left by a fluence of $-3.8 \cdot 10^{15}\, p/\text{cm}^2$ where its unirradiated collection distance falls on the curve. With this shift the pCVD and scCVD data fall on a single curve indicating the damage due to irradiation is common to both. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by a minimum ionizing particle. These charges drift across the diamond in response to the applied electric field producing a signal that can be measured. Since there may be traps in pCVD material we use the term collection distance to denote the average distance the electron-hole pair drift apart [9]. From the mean value, $\langle Q_i \rangle$, of the signal spectrum one derives the charge collection distance $ccd = \frac{\langle Q_i \rangle}{36e/\mu\text{m}}$ where $36\, e/\mu$m is the mean number of electron-hole pairs generated by a minimum ionizing particle along 1 μm in diamond.

3. – Radiation hardness

The RD42 irradiation program consists of testing each sample prepared as a detector in a CERN test beam before and after a range of irradiations. Most recently we irradiated the highest quality polycrystalline CVD diamond with 24 GeV protons from CERN PS to a fluence of $1.8 \cdot 10^{16}\, p/\text{cm}^2$. Figure 1 shows the signals observed in various pCVD and scCVD diamond sensors after a range of irradiations. The scCVD diamond is expected to be representative of the next generation high quality material. A single damage curve given by the equation $ccd^{-1} = ccd_0^{-1} + k\Phi$, with ccd_0 the initial collection distance and k the damage constant can accommodate for the different measurements shown, with one universal constant k. In particular, also the measurements on the scCVD fall on the same curve if shifted by $3.8 \cdot 10^{15}\, p/\text{cm}^2$. The interpretation is that, owing to the intrinsic crystalline structure, the unirradiated pCVD material behaves as effectively having the same number of trapping centers as the scCVD material after a dose of $3.8 \cdot 10^{15}\, p/\text{cm}^2$. After 10 years of SLHC running typical fluences of $2 \cdot 10^{16}\, p/\text{cm}^2$ are anticipated for vertex detectors at 4 cm.

Therefore the diamond pCVD sensors were shown to be rather radiation hard in high energy proton beams, although with a signal level an order of magnitude below the signals in silicon sensors, that improves by a factor around 3 with the advent of scCVD diamond. The radiation damage causes two effects: the change of dark current and the

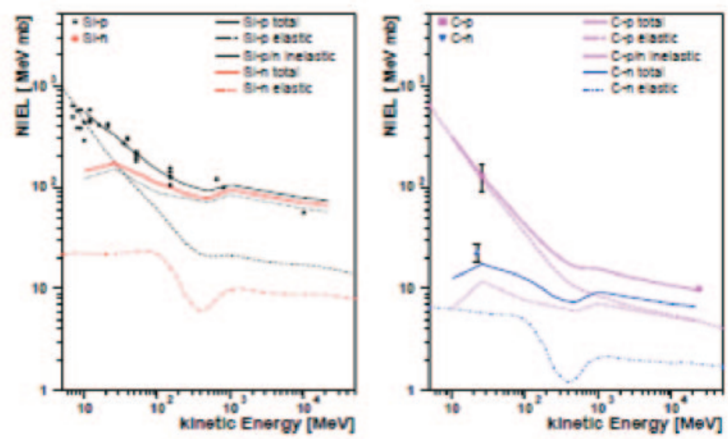

Fig. 2. – NIEL damage cross section of Si (left) and Diamond (right) for protons and neutrons (solid lines: upper one for p, lower one for n) as function of the incident energy. The different cross section contributions from elastic and inelastic scattering have been indicated as well.

signal decrease with increasing fluence of the detected particles. For silicon sensors the strong increase of dark current requires a cooling of the detectors in order to avoid reverse annealing and thermal runaway, while in diamond sensor the leakage current even at room temperature is negligible and usually decreases after irradiation. The signal decrease in silicon has been studied at various particle energies and fluences and was found to be in most cases proportional to the Non-Ionizing Energy Loss (NIEL) damage cross section, which is closely related to the creation of lattice defects. At low beam energies E the NIEL cross section is dominated by the long-range Rutherford scattering, which falls like $1/E^2$ and creates many small-scale lattice displacements. At intermediate energies (above a few MeV) the anomalous elastic Rutherford scattering from the nuclear interactions between the incoming beam and the nuclei in the sensor starts to play a role, while at energies above a few hundred MeV the inelastic cross section, which is almost energy independent, dominates. Impurities like oxygen, can reduce the signal losses by forming stable non-trapping defects with the vacancies [11], thus leading to a deviation from the NIEL scaling hypothesis, which states that the radiation damage is proportional to the NIEL damage cross section. In diamond the expected increase in radiation damage by Rutherford scattering at low energies has never been measured. This study was triggered by the observation that the ionization signal in diamond sensors decreases surprisingly fast after irradiation with 26 MeV protons. After a fluence of $(4.5 \pm 1.5) \cdot 10^{14}\, p/\mathrm{cm}^2$ the ionization signal or CCD is reduced by a factor of 2 [8]. The NIEL cross section in diamond has been calculated and compared with data for the radiation damage from protons and neutrons at low energies for the first time [10]. The NIEL cross sections for Silicon (Diamond) are shown on the left (right) panel of fig. 2 The silicon data were taken from [12], but scaled to fit the present calculation at low energies. The RD42 results at 24 GeV with $\Phi_{1/2} = (6 \pm 2) \cdot 10^{15}\, p/\mathrm{cm}^2$ were used as normalization for the diamond results and the NIEL calculation was used to determine the energy dependence. For the neutrons the normalization at 24 GeV was taken to be 0.69 times $\Phi_{1/2}$ of protons, as expected from theory, see fig. 2 Both, the large increase in cross section for the charged particles and small increase for the neutrons, are reproduced by the data. Comparing the left- and right-hand side shows that for low energies the difference in radiation damage cross section between silicon and diamond is a factor of a few, while at high energies the difference is an order of magnitude. Note that only the shape of the energy dependence is relevant here, since the data were scaled to fit the data at low energy for silicon and high energy for diamond.

4. – Conclusions

The development of CVD diamond is progressing rapidly and as a result diamond sensors are finding widespread applications in high-energy physics. Their radiation resistance is beyond that required for 10 years of SLHC operation. The next few years should yield the development of larger scCVD diamond devices. It is shown that for Si and diamond sensors, the NIEL hypothesis, which states that the radiation damage and the corresponding signal loss is proportional to the Non-Energy-Energy-Loss (NIEL), is a good approximation to the present data. The smaller inelastic nucleon-carbon cross section and the light nuclear fragments imply that at high energies diamond is an order of magnitude more radiation hard than silicon, while at energies below 0.1 GeV the difference is significantly smaller. New measurements are planned for next year with proton beam at low energies at the 15 MV Tandem accelerator of the National Southern Laboratories (LNS) of National Institute of Nuclear Physics (INFN) in Catania (Italy). These studies are important even at high energy hadron colliders, because the underlying events from the soft collisions of spectator partons and secondary interactions in the detector material yield an appreciable fraction of particles in this energy range. Finally, the fast response and radiation tolerance of pCVD material has also proven ideal for beam condition monitors. The Belle, ATLAS and CMS experiments are following the BaBar lead and developing their own diamond-based beam condition monitors. Now a CMS Precision Luminosity Telescope Project is nearly ready.

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