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Radiation Monitoring with Diamond Sensors in BaBar*

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Abstract

In order to safeguard the silicon vertex tracker in the BaBar detector from excessive radiation damage, cumulative dose and instantaneous dose rates are continuously monitored. As an upgrade to the current radiation monitoring system which uses silicon PIN-diodes, we are examining the possible use of single-crystal and/or polycrystalline chemical vapor deposition (CVD) diamonds. The radiation responses of several CVD diamonds have been tested on time scales from tens of nanoseconds to thousands of seconds in order to determine their integrity in monitoring accumulated dose and their response to large sudden changes in dose rates. Two polycrystalline CVD diamonds have been installed near the silicon vertex tracker near existing silicon PIN-diodes for comparative studies. CVD diamond radiation sensors have also been tested using ^{60}Co and in various magnetic field configurations.

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I. INTRODUCTION

IN the *BABAR* [1] detector at the Stanford Linear Accelerator Center, the silicon vertex tracker (SVT)[2] is the nearest instrument to the interaction point of a 3.1-GeV positron beam and a 9-GeV electron beam in the PEP-II storage ring. The first layer of silicon being at a radius of 3.3 cm from the interaction point, the SVT is susceptible to high levels of radiation. The silicon wafers in the SVT and their front-end readout electronics can be damaged and/or made inoperable by both chronic exposure to and sudden bursts of radiation. Inside the SVT, twelve silicon PIN-diodes are used as part of the SVT's radiation monitoring and protection system (SVTRAD)[3]. These diodes are reverse biased at 50 V and their current is monitored. Ionizing radiation incident upon the diodes causes an increase in current proportional to the dose rate. SVTRAD monitors the accumulated dose absorbed by the PIN diodes. It also aborts the positron and electron beams, in less than a millisecond, if the dose rate becomes too high. By using the SVTRAD system, the SVT is expected to accumulate less than 4 MRads of electromagnetic radiation by the summer of 2005.

The twelve silicon PIN-diodes in SVTRAD are themselves damaged by radiation, making monitoring difficult. Based their size and the amount of energy needed to create electron-hole pairs in silicon, the diodes give a 1 nA signal current for every 5.2 mRad/s. The unirradiated diodes had leakage currents on the order of 1 nA. However, diodes that have received approximately 1 MRad dose, originating from the positron and electron beams, now have leakage currents above 1μA. This gives a radiation signal current to intrinsic leakage current ratio of about $1/1000$. In addition, the leakage current varies by 10% per $^\circ$C change in temperature. Fluctuations in leakage current must be closely monitored so they do not obscure the changes in the signal current. In order to correct for these temperature variations, thermistors monitor each silicon PIN-diode's temperature to within 0.01 degrees. These temperatures are then used in calculating the portion of total current that is due to radiation. It is expected that the leakage current will continue to increase at its present rate of 1 nA per kRad of radiation. At this rate the SVTRAD system will become inoperable years before the *BABAR* experiment is planned to end.

The difficulty of measuring radiation-induced signal current arises from the fundamental properties of the silicon PIN-diodes. In order to overcome these difficulties an alternative radiation sensor technology, chemical-vapor-deposition (CVD) diamond, is being studied.

II. CVD DIAMOND

Polycrystalline CVD (pCVD) diamond has been produced for many years[4,5]. pCVD diamond quality for radiation sensors is typically measured by its charge collection distance (CCD)[6,7]. The CCD is the average separation distance of electron hole pairs under an electric field before they recombine. Current technology allows the growth of pCVD diamonds with CCD of hundreds of microns. A diamond sensor's CCD is dependent on the bias voltage applied to it and increases with the applied bias voltage. For pCVD diamonds, the CCD typically saturates at approximately 1 V per micron.

Recently, single-crystal CVD (sCVD) diamonds have become available[8]. These diamonds offer two major advantages over pCVD diamond. Their CCD is substantially larger than pCVD diamonds and their CCD saturates at lower electric fields, approximately 0.2 V per micron. The elimination of crystal grain boundaries may also improve other aspects of CVD diamond sensor performance.

III. CVD DIAMOND SENSORS

In *BABAR*, CVD diamond sensors are operated in the same manner as the silicon PIN-diodes. A bias is applied across a diamond and the DC current in the circuit is measured. When ionizing radiation passes through the diamond, the electrons and holes drift in the applied electric field. The moving charge induces a signal current that is measured in addition to any small leakage current in the diamond sensor. The signal current is proportional to the amount of radiation incident on the diamond.

Tests have shown that diamonds need to be pumped [6,7] in order to obtain maximum efficiency. This is a process during irradiation in which potential trap sites for electrons and holes are filled. Using a ^{60}Co source, we pumped and calibrated our diamond sensors before their installation into *BABAR*. We also observed that both florescent and sun light can induce nanoamps of current in the pCVD diamond sensors.

The main advantage of CVD diamond over silicon is its radiation hardness[9,10,11,12]. Accumulated radiation dose causes a significant increase in the leakage currents of the silicon PIN-diodes in *BABAR*. For CVD diamond sensors, the leakage currents remain small even after accumulating high doses of radiation. Our packaging of CVD diamond gives leakage currents from a few picoamps to a few tens of picoamps. For diamond sensors, there is also no variability of signal or leakage current due to temperature fluctuations.

Two pCVD diamonds were installed inside *BABAR* in August of 2002[13]. They were placed in the horizontal plane of the detector, one on either side, about 15 cm from the beams' interaction point and about 5 cm from the beam line. Their position is similar to that of the silicon PIN-diodes. The diamonds are $1\text{cm}\times 1\text{cm}$ and 500μm thick. Metal electrodes are deposited on the two faces of the diamonds making ohmic contacts. The metal contacts are $\sim 9\text{mm}\times 9\text{mm}$. Coaxial cables are connected to the ohmic contacts using Indium solder. The diamonds and cable are electrically shielded and insulated. The two diamonds reach a maximum CCD of approximately 200 μm at a bias voltage of 500 V. Both diamonds are biased at 500 V in order to ensure a maximal signal.

The same custom electronics and software designed for the SVTRAD system and the silicon PIN-diodes[14] is used to monitor the two pCVD diamonds in *BABAR*. The system has 20-pA current resolution. The signals from the diamonds can also be passed into the same beam-abort-logic circuitry as the silicon

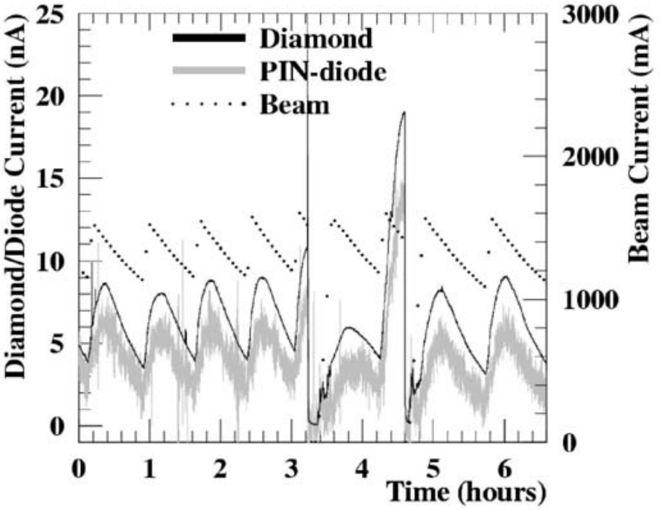


Fig. 1. This is a comparison of a pCVD diamond sensor and a silicon PIN-diode monitoring radiation in the SVT. Radiation levels in the SVT roughly track the electron beam current. The beam current gradually decreases between successive fills of the PEP-II storage ring. The diamond sensor current is comparable to that of the silicon PIN-diode. At two points the beam is aborted. The first abort is due to an acute spike in the dose rate; the second abort is due to a smaller but longer lived increase in the dose rate. Both aborts are seen in the diamond sensor and the silicon diode sensor.

diodes. One of the pCVD diamonds is currently operational in the SVTRAD beam abort system. The response of the diamond sensors installed inside *BABAR* is 1 nA of current for every 7 mRad/s of radiation.

IV. DIAMOND SENSOR PERFORMANCE IN *BABAR*

We have monitored the response of the two pCVD diamonds to radiation in *BABAR* for approximately ten months and compared them with the signals from the 12 silicon PIN-diodes in the SVTRAD system. Over this period of time we have observed that the diamond sensors provide a reliable and consistent response to radiation. Fig. 1 shows that a diamond sensor and a silicon diode with similar location in the SVT have comparable responses to dose rates over the course of several hours. This is due to the similar sensor sizes, sensitivities, and radiation environments for the two types of sensors. Leakage currents in the diamonds sensors have remained negligible (below the sensitivity of the monitoring electronics) and with no detectable temperature sensitivity. After exposure to hundreds of kRads, both diamonds have not shown any degradation in signal. The dose rates calculated from similarly located diodes and diamonds have been observed to be proportional to each other over a wide range of signal sizes. The signal currents from both diamond sensors are currently being used to provide prompt feedback to *BABAR* and PEP-II operators.

The response of the two pCVD diamond sensors to radiation in *BABAR* has also been studied at nanosecond time scales. This is to ensure that the diamonds can provide a signal in a short enough time to be able to abort the positron and electron beams before severe SVT damage. Using a custom fast amplifier and an oscilloscope, we have observed that the diamond sensors respond to radiation within 20 nanoseconds which is the limit imposed by the speed of the readout electronics. This is well below our required response time.

Over the course of several months we have recorded the signals from silicon PIN-diodes and diamond sensors during radiation bursts. Fig. 2 shows an example of the signals from a diamond and a diode during the same large radiation event. Comparisons of the two types of sensors during such events have shown that the diamond sensors can consistently provide signals suitable for use in the SVTRAD system. With both diamond signals and silicon PIN-diode signals supplied to the same SVTRAD abort circuitry, 90% of the time when a diode gave an abort signal a diamond did as well. We do not expect all radiation incidents to trigger an abort in both sensors because of their different locations.

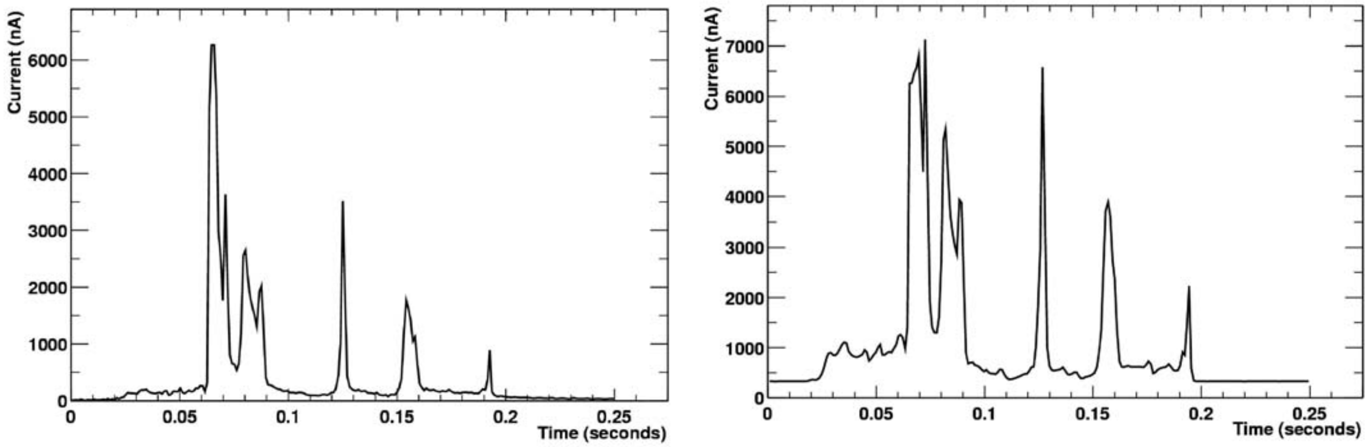
We observe that when dose rates change suddenly, the diamond signal promptly changes by about 90% of its full response, followed by a nonexponential approach to its final value. This dynamic response to instantaneous radiation changes is shown in Fig. 3 over a time interval of minutes. A tail is also observed at millisecond time scales. The slow component of the response empirically fits a $1/\sqrt{t}$ curve. The origin of the slow component of the response is under study. Fortunately it accounts for a negligible error for our monitoring purposes. It also does not affect the diamond's ability to protect the SVT in the event of a sudden increase in the radiation level.

We have also observed a response in diamond sensor leakage current due to changes in magnetic field. During normal operation of the *BABAR* detector, the sensors are in a 1.5-T magnetic field with the magnetic field lines approximately perpendicular to the electric field lines due to the bias voltage. When the magnetic field is turned off, the leakage currents in both diamond sensors increase over the course of several minutes. As seen in Fig. 4, these spurious currents are erratic and large. Once the magnetic field is turned on, the leakage currents in the diamond sensors return to their stable and low values. While the origin of this magnetic effect is undetermined, it does not affect the normal operation of diamond sensors in *BABAR*.

V. ^{60}CO TESTS OF CVD DIAMONDS

Although the origins of the tails shown in Fig. 3 and currents shown in Fig. 4 are not known, their presence has been verified in laboratory tests. The dynamic response in signal currents after a reduction in dose rate is seen outside *BABAR* in tests with ^{60}Co with pCVD diamonds.

Irradiation tests using ^{60}Co have shown that, in pCVD diamonds, spurious currents similar that those seen in *BABAR* arise. These currents seen after ^{60}Co irradiation are ~ 100 to ~ 1000 times less than those seen in *BABAR*. These smaller spurious currents have been observed in various magnetic field strengths and orientations. In the same field orientation as the diamonds in *BABAR* (electric field perpendicular the the magnetic field), we observe that these smaller spurious currents are also removed. At magnetic field strengths around 0.2 T



(a) Diamond sensor current during a large radiation event.

(b) Silicon PIN-diode current during a large radiation event.

Fig. 2. During the same large radiation event in the SVT, both (a) a diamond sensor and (b) a silicon PIN-diode show comparable responses. It is important for the protection of the SVT that such events be accurately and consistently measured so that beam abort decisions may be made.

to 0.5 T, the spurious current is enhanced. Intermediate field strengths and various field orientations reveal a complex and history-dependent response.

VI. CONCLUSION

CVD diamond radiation sensors are a viable alternative to silicon PIN-diodes for the measurement of ionizing radiation in BABAR. The SVTRAD system must have the ability to monitor large amounts of accumulated dose and also respond quickly to any sudden increases in dose rate. The pCVD diamonds tested in BABAR have shown that they are able to fulfill these requirements. They have also shown to have advantages over the use of silicon PIN-diodes; namely their radiation hardness, their low leakage currents, and their insensitivity to ambient temperature changes. Based on nearly a year of operation in BABAR, we have demonstrated that pCVD diamond sensors can provide fast, reliable, and accurate measurements of the SVT's radiation dose.

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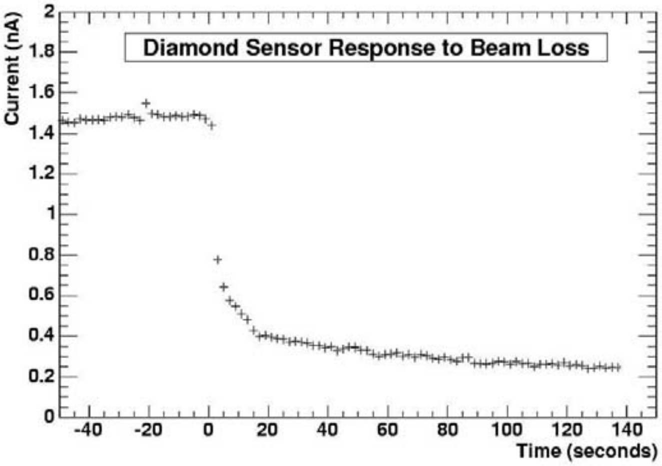

Fig. 3. Response of a diamond sensor in BABAR to loss of positron and electron beams: At time zero PEP-II loses both positron and electron beams. The radiation level immediately drops to zero (as verified by the silicon PIN-diodes). DC current from the diamond sensor, however, shows a slow response to the change in dose rate after an initial fast response.

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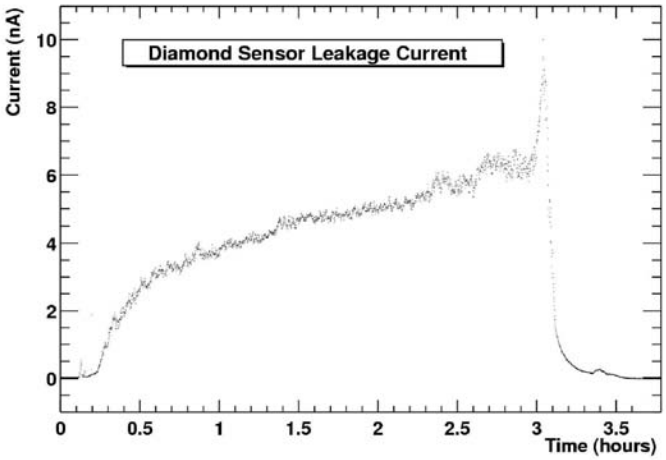

Fig. 4. Diamond sensor response to magnetic field changes in BABAR: At approximately 0.1 hours, the 1.5 T magnetic field in BABAR is turned off. A leakage current in the diamond sensor appears within minutes and increases to several nanoamps. From about 3 hours through 3.6 hours, the magnet field is increased linearly from 0 T back up to its nominal value of 1.5 T. At a low magnetic field during this transition, the diamond sensor leakage current is seen to increase even further. This phenomenon has been reproduced outside the BABAR detector.

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