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for Space Flight*

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THE UTILITY OF DIAMOND SENSORS FOR SPACE FLIGHT

by

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ABSTRACT

Los Alamos National Laboratory has developed diamond sensors with interdigitated electrodes that operate in a photoconducting mode. The specific application for this work was for the Department of Energy's instruments flown on the Global Positioning System satellites. Sensors have been fabricated and tested for their response to low-energy x-rays. These sensors can be operated to extremely high volumetric radiation doses. We find that the sensors are extremely useful for situations where the surface radiation dose is not excessive, but that this limit is exceeded for the GPS orbit. It is possible that further studies and special detector arrangements or auxiliary heating of the sensor may push this limit to higher values.

I. INTRODUCTION

This report summarizes several years of activity on developing diamond sensors for use as low-energy x-ray sensors for space flight. The work was done as a joint program between Groups MST-11 and NIS-2 at the Los Alamos National Laboratory (LANL). Sensors have been fabricated and tested for their response to low-energy x-rays. Diamond sensors can be operated to extremely high volumetric radiation doses. We find that the sensors are extremely useful for situations in which the surface radiation dose is not excessive. This surface limit seems to be exceeded for the Global Positioning System (GPS) program; however, it is possible that further studies and special detector arrangements or auxiliary heating of the sensor may push this limit to higher values. As part of the sensor development activity, NIS-2 has constructed a soft x-ray calibration facility*. This is described briefly here, and some test results for diamond sensors are presented. The report concludes with an optimistic assessment of the utility of diamond sensors for space activities and with recommendations for future work on diamonds.

I.A. GPS PROGRAM

The use of diamond sensors for the GPS program has been seriously considered. The GPS consists of a constellation of 24 satellites in near-circular, 12-hour orbits around Earth, with an orbital radius of 4.1 Earth radii. There are six orbital planes inclined at 55°, with four satellites per plane equally spaced in longitude. The principal mission of the GPS is to provide precise navigation support for U.S. military and international civilian

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* Donald E. Casperson is the Principal Investigator for this facility.

operations. In addition, the GPS hosts a set of nuclear detection instruments (Higbie and Blocker, 1994). Work on the diamond sensors was performed to support this activity.

I.B. REQUIREMENTS

Since the GPS is an operational system, the instruments and parts that are flown must meet stringent reliability requirements. The lifetime of parts must exceed 7.5 years in orbit and an unspecified time for ground processing and storage.

I.B.1. Energy Range

The typical detector design is a sensor/filter combination with the low-energy threshold determined by the material and thickness of the filter through which the x-rays pass to the sensor. This filter can be directly deposited on the diamond sensor. The high-energy cutoff is determined by the sensor efficiency for absorption of x-rays and can be controlled to some extent by selecting the thickness of the sensor. Diamond's intrinsic threshold of 10 eV for photons was judged to be excellent for the particular application required. In order to provide discrete energy windows, it would be desirable to have very thin diamond sensors; but thicker diamond sensors can be used by selecting sensors with identical thicknesses and differing filters. Differential energy channels can then be constructed by subtracting a measurement by one sensor from that of the other.

I.B.2. Spacecraft Constraints

The principal constraints are temperature extremes and vibration. The temperatures range from +71 °C to -34 °C during qualification ground testing; but only from +29 °C to -24 °C in orbital operation. Vibration specifications are available in the Lockheed Martin AstroSpace (LMAS) Interface Control Document, ICD-320. Diamonds are expected to be extremely rugged.

I.B.3. Space Environment

The orbital parameters for the GPS satellites discussed above place the instruments near the heart of the trapped electron radiation belts four times per day. Figure 1 shows the electron fluence for one year in the GPS orbit; Figure 2 is a similar figure for the proton fluence. As discussed below, the major concern turns out to be low-energy protons. Unfortunately, below 100 keV these fluences are not well known from existing data.

I.C. PROGRAMMATIC CONCERNS

I.C.1. Mechanical Ruggedness

Diamond sensors/filter combinations are intrinsically rugged since the filter material, used to provide an energy threshold for the incident x-rays, can be directly and securely deposited on the entrance side of the diamond sensor (see Figure 3). An alternative to diamond sensors is a vacuum x-ray diode (XRD). An XRD relies on the photoelectric effect to eject electrons from a cathode. The photoelectrons are collected by a wire-grid anode, having greater than 80% transparency, placed in front of the cathode. The filter material, in the form of a thin foil, is attached to the grid. This arrangement is less rugged than the arrangement for diamonds since the support is much less than 100%, but it has been acoustically tested by the manufacturer.

Figure 1 Electron fluence for one year in the GPS orbit.

I.C.2. Radiation Hardness

The proton fluxes at the GPS orbit are not well known for proton energies below about 100 keV. For an open sensor or one with a very thin x-ray filter, these fluxes can cause surface radiation damage to the sensor. Since we are interested in making measurements for very soft x-rays, this is a serious concern.

I.C.3 Conservative Design

The GPS program is an operational program rather than a research program that could admit some degree of risk in achieving its goals. One consequence is that the sensors and other equipment flown on the satellite should have very conservative designs inherited from instruments flown on previous satellites or very well understood designs analytically proven to have an extremely high probability of success. The design lifetime of instruments needs be in excess of 7.5 years in orbit, according to the requirements developed by the Air Force and the GPS community.

II. SENSOR CONCEPT

The sensor is based on radiation-induced modulation of electrical conductivity, commonly known as photoconductivity. Energy is imparted in the sensor by the incident radiation. The absorbed energy then ionizes atoms in the sensor, thereby creating free electron-hole pairs which act as the charge carriers. These externally created charge carriers then drift under the influence of an externally applied electric field. The motion of the charge carriers induces a current in the external circuit until the charge carriers are trapped or recombined.

Figure 2 Proton fluence for one year in the GPS orbit.

Figure 3 Cross section of diamond sensor.

Photoconductor operation is fundamentally different than XRD operation. An XRD has a photocathode, where the incident photon causes electrons to be ejected from the cathode into vacuum to be subsequently collected at an anode. But a photoconductor does not require any electrons to be emitted from the surface. It requires, rather, that the incident photons generate carriers in the photoconductor which then drift under the influence of an applied electric field. Therefore, a photoconductor is a volumetric device rather than a surface device. Furthermore, with the electrical contacts placed as shown in Figure 3, the electric field lines fully penetrate to the side opposite the contacts, although the intensity of the field will be attenuated. This allows for the complete protection of the electrode surface from any harsh external environment as well as being an efficient sensor for radiation. Also, the surface contact design results in a large-area, high-sensitivity radiation sensor.

II.A. DIAMOND PROPERTIES

Diamond has been used for various radiation detection purposes such as the detection of x-rays (Kania et al., 1990), γ -rays (Keddy et al., 1987; Fallon et al., 1990), high-energy charged particles (Franklin et al., 1992), and neutrons (Miller, 1966). It also has been shown to be an efficient UV imager (Plano et al., 1993). The primary advantages of diamond over the conventional semiconductor detector materials such as silicon or germanium are the following:

- Diamond is radiation hard;
- Diamond is an excellent insulator with a high breakdown voltage, allowing the application of a large electric field to attain a saturated drift velocity while maintaining a very low leakage current;
- Diamond can operate at high temperatures because of its large band gap;
- Diamond has very high response speed because of large carrier mobilities for both electrons and hole;
- Diamond has a smaller dielectric constant than silicon that leads to lower noise and faster response;
- Diamond is the best known thermal conductor at room temperature and has one of the lowest known coefficients of thermal expansion;
- Diamond is physically robust because of its material strength;
- Diamond requires processing which is relatively simple because of the chemical inertness of the material.

II.B. DIAMOND MATERIALS CONSIDERATIONS

There are several methods available for growing diamond. The first method is of course the "Earth" method leading to natural single-crystal diamond. For these crystals, there are several types: (1) Type Ia, which has large amounts of nitrogen in platelet form. (2) Type Ib, which is usually a man-made material but is also available in nature. It has a large amount of nitrogen in substitutional form. (3) Type IIa, which has nominally 50 ppm of

nitrogen in substitutional form and is known to be the purest of the natural types. And (4) Type IIb, which is a semiconducting form of diamond with boron being the main dopant. The type of natural single-crystal diamond that is used for the sensor applications is usually type IIa.

The second method is the high-pressure/high-temperature (HPHT) growth of single-crystal diamond. This is the traditional method of growing diamond and is done by simulating the way that Earth grows diamond. There have been some efforts in the past to reduce the nitrogen incorporation to a level below natural type IIa diamond, because nitrogen is an impurity that decreases carrier recombination time.

The third method is to employ chemical vapor deposition (CVD). This method of growth for diamond was discovered in the early 1980s. The method is based on a feed gas mixture of carbon and hydrogen with an energy source. At present, heteroepitaxy is not possible. Therefore, all CVD diamond films are polycrystalline with a preferred texture of (110). Primary advantages of the CVD method are possible low cost, large area, and integrated-circuit compatibility. The latest available CVD diamond films have electrical properties that are superior to natural type IIa diamond.

II.B.1. Dimensions

The dimensional issues are critical in diamond. This is primarily due to the cost. Natural type IIa single crystals are readily available with areas up to 1 cm² by a few hundred microns thick. The same can be said for HPHT single crystals. But the cost of these large-area single crystals is extremely high and the possibility for their use becomes unfeasible. However, detector-quality CVD diamond films are available in wafer form with a diameter of 4 in. The cost of these films at current prices is about \$750/cm², with the thickness being a few hundred microns.

II.B.2. Material Availability

Natural single-crystal diamond can be purchased through a commercial diamond supplier. The delivery time of the material is 6-8 weeks. HPHT diamond crystals can take longer for delivery because they are grown after the order is placed. CVD diamond films, on the other hand, can be purchased through a variety of commercial suppliers with the delivery time similar to the natural diamond. The electrical quality of the films from various suppliers, however, can vary widely. It is not expected that the availability of diamonds will disappear in any foreseeable future.

II.C. INTERDIGITATED ELECTRODES

The electrical contact structure for the proposed sensor (or detector) is shown in Figure 4. The idea of interdigitated electrodes is not a new one. This type of electrode configuration has been effectively used in surface acoustic wave (SAW) devices and in ultraviolet detector applications. One of the primary advantages of this configuration for x-ray detection is that the detector sensitivity is only limited by the photolithography limitations rather than device structure limitations. This is due to the fact that the sensitivity is a function of channel width. Furthermore, the active area of the sensor can be arbitrarily large while preserving the detector sensitivity.

Figure 4 Layout for the interdigitated electrode structure that is deposited on one surface of the diamond sensor.

II.D. FABRICATION DESCRIPTION

As-received diamond samples were first cleaned with hot chromic acid which was prepared as a saturated solution of chromium trioxide in sulfuric acid. This procedure has been shown to eliminate any graphite or nondiamond material, such as amorphous carbon from the surfaces of diamond (Pan et al., 1992; Grot et al., 1990A and 1990B; and Mori et al., 1991) as well as any inorganic residues on the sample surface. After this step, the samples were rinsed in deionized water followed by rinses in 0.1-M NH_4OH and 0.1-M HCl . Then, the samples were rinsed in deionized water and dried. At this point, the samples were considered ready for processing into sensors.

The interdigitated electrodes were fabricated using photolithography with photoresist used to define the contact structure. This technology permits the fabrication of a large active area which results in a very good detector sensitivity. Photolithography was accomplished using a contact aligner. Once the electrode pattern was developed, an evaporative deposition system was used to deposit 400 Å of titanium, followed by a 2500-Å gold overlayer. The metal deposition could be also done with sputter deposition. Unwanted metal from the deposition step was lifted off by eliminating the underlying photoresist with organic solvents and de-ionized water. The contacts were then annealed at 600 °C for

approximately 15 min.

III. CALIBRATION RESULTS

III.A. BROOKHAVEN NATIONAL LABORATORY

Prototype diamond sensors (18 mm thick, 4 mm diameter) were tested at the National Synchrotron Light Source at the Brookhaven National Laboratory during July 1991. Extensive data was collected on sensors with 12.5- and 25-mm-pitch electrodes that confirmed the operation of the sensors. The energy range of the tests were from approximately 35 eV to 1500 eV, data was collected as a function of energy with about 1-eV resolution and compared with measurements using an XRD calibrated by the NBS. The results of these tests confirmed the functioning of the diamond sensors and were in accord with estimates of their performance.

III.B. LAWRENCE BERKELEY NATIONAL LABORATORY (LBNL)

Diamond sensors were tested along with prototype carbon XRDs in LBNL's soft laser plasma test facility at energies between 50 and 100 eV. An XRD consists of a thin filter through which the incident x-rays pass, a mesh anode behind the filter with good transmissivity, and a photocathode, carbon in this case. A fraction of the photoelectrons generated by the x-rays in the top layer of the photocathode are captured by the anode to produce the observed signal. Figure 5 shows the response of a bare diamond sensor as a function of wavelength. Figure 6 shows the response with a boron filter directly deposited on the diamond entrance window. Figure 7 shows the response of a windowless XRD as a function of wavelength.

Figure 8 compares the sensitivity between the two sensors as a function of photon energy. The falloff in the sensitivity of the XRD is expected. The effective thickness of the photocathode is about 100 Å, and the photoelectric absorption cross section of carbon from 50 to 100 eV decreases, resulting in a falling conversion efficiency in the photocathode layer. The peak sensitivity is about 2.75 mA/W at 20 eV.

The diamond sensor response is practically flat through this energy region. No rolloff occurs until the photon energy exceeds 2 keV. The high rolloff is due to an effective thickness of about 25 microns and the photoelectric absorption cross section of carbon.

IV. LANL SOFT X-RAY CALIBRATION FACILITY

In support of the nuclear detonation detection (NUDET) sensor development program, the Astrophysics and Radiation Measurements Group, NIS-2, has constructed a pulsed soft x-ray calibration facility based on a laser plasma source. X-ray pulse widths of a few tens of nanoseconds and selectable photon energies ranging from 31 eV to greater than 1.0 keV are characteristic of the system, which is currently in its initial stage of operation.

IV.A. LASER SOURCE

The driver of the source is a Q-switched ruby laser which generates intense optical pulses at 6943 Å. Output energy of the laser is presently 2.5 J per pulse, but it will eventually be operated at 4 to

5 J per pulse for increased x-ray production. Optical pulses are monitored on every laser shot, and are typically 60 ns full width at half maximum (FWHM). The laser beam is transmitted through a

Figure 5 Sensitivity of diamond sensor with x-ray entering on the same side as the electrode surface as a function of soft x-ray wavelength. The spectral independence of the sensor sensitivity is about 10%.

vacuum window onto a lens which focuses the beam down onto a metal target plate with a spot size that is estimated to be a few hundred microns in diameter. Peak irradiance on target is estimated to be between 10^{11} and 10^{12} W/cm², resulting in rapid heating of the target material and generation of a plasma that emits x-ray line radiation characteristic of the target material as well as broadband thermal emission.

IV.B. PLASMA DIAGNOSTICS

Inside the target chamber a set of four XRDs with aluminum photocathodes, each having a different thin filter, views the target plasma directly. Convolution of the aluminum photocathode response with each thin filter transmission enables us to sample different spectral regions, and thus to estimate a plasma temperature. These diagnostic diodes monitor x-ray production on a shot-to-shot basis and so generate a measure of reproducibility. In addition they provide a method by which we are able to optimize the laser focus on the target, and they serve as a reference or normalization signal for the x-rays transmitted from the laser plasma through the x-ray monochromator onto the detector under test.

Figure 6 Sensitivity of diamond sensor with a layer of boron filter deposited on the x-ray entrance side as a function of soft x-ray wavelength. Spectral independence of the sensor sensitivity is about 10%.

IV.C. SOFT X-RAY MONOCHROMATOR

X-rays in a chosen wavelength band are selected from the broadband laser plasma with the use of a grazing-incidence vacuum x-ray monochromator, manufactured by Hettrick Scientific, Inc. This instrument houses a grazing-incidence focusing mirror to relay a small sample of the broadband plasma x-rays through the entrance slit of the instrument onto one of five selectable x-ray diffraction gratings. These gratings have overlapping photon energy ranges and together provide continuous coverage from 31 eV to more than 1.5 keV. Individual gratings can be very simply selected externally without breaking vacuum. This particular Hettrick instrument (the In-Focus-Monochromator, or IFM) provides a range of selectable entrance and exit slit widths, such that the x-ray output can be adjusted for high throughput with moderate spectral resolution (average $\lambda/\Delta\lambda = 50$), or higher spectral resolution ($\lambda/\Delta\lambda = 400$) at reduced throughput, and so is well suited to the needs of our NUDET sensor program.

Figure 7 Sensitivity of aluminum XRD as a function of soft x-ray wavelength. The spectral dependence of XRD sensitivity is clearly seen.

Figure 9 displays a two-channel oscilloscope trace of an incident laser pulse and the corresponding x-ray monochromator throughput onto an interdigitated diamond sensor biased at -200 V. At this bias level all the charge generated by the x-rays is recorded. No preamplifiers were used in collecting these data; signals were coupled through a bias tee directly into the 50-ohm input of a Tektronix Model 2440 digitizing oscilloscope. As seen from the simultaneous traces, x-ray production follows the incident laser pulse quite closely in time and shape. We have observed laser shots in which the temporal structure inherent in the driving pulse is reflected in similarly structured x-ray output.

This diamond sensor has a nominal responsivity of 8 mA/W at x-ray energies of 126 eV, based on earlier synchrotron calibrations. Our observed peak signal of 26 mV into 50 ohms thus corresponds to a peak photon flux of 3×10^{15} photons/s at the exit slit of the monochromator, an integrated flux of $>10^8$ photons, and a deposited energy of 1.5×10^4 MeV in the detector. Most of the diamond sensor data have been taken at the lower end of the x-ray energy range available in the Hettrick monochromator.

Figure 8 Data taken at LBNL. The diamond was 25 μm thick; the XRD had a carbon cathode.

IV.D. SYSTEM CAPABILITIES

Table 1 summarizes the present capabilities of the source. The pulsed soft x-ray source has just recently been completed, and so the results shown here are preliminary. One of our near-term goals is to install a calibrated reference silicon photodiode (AXUV Sensor from International Radiation Detectors, Inc., Torrance, CA), which will become our reference standard and will expand the role of our soft x-ray source to a fully operational calibration facility.

V. RADIATION HARDNESS

The atomic displacement energy for diamond is about 43 eV (Koike et al., 1992) compared with 20 eV for silicon. Based on this energy, diamond should be much more radiation resistant than silicon. In fact, diamond has been shown to be about 1-2 orders of magnitude more resistant to fast neutrons than silicon (Kozlov et al., 1975). In this section, the extent of radiation resistance to low-energy protons is discussed.

Figure 9 A two-channel oscilloscope trace of incident laser light and a plasma-generated x-ray signal through the monochromator, observed on the interdigitated diamond sensor. Channel 1: Soft x-rays @ 126 eV onto the diamond sensor; vertical scale is 10 mV/division. The FWHM of the x-ray signal is 36 ns. Channel 2: Fast vacuum photodiode sample of the Q-switched ruby laser pulse incident on the metal target plate; vertical scale is 2 V/division. The common time scale is 100 ns/division.

Table 1 Laser-Driven Pulsed X-Ray Source Characteristics

Laser Source:	Q-Switched Ruby
Wavelength:	6943 Å
Energy:	2.5 J
Pulse Width:	50 ns
Target Material:	Type 304 Stainless Steel
Monochromator Tuning Range	31 eV – 1.5 keV
Resolution ($\lambda/\Delta\lambda$):	>50 available
X-Ray Pulse Width:	40 ns nominal
Deposited X-Ray Energy:	>10 ⁴ MeV @ 0.1 keV

V.A. THEORY

There are two primary manifestations of radiation damage in solid-state detectors. One is an increase in leakage current, and the other is a decrease in pulse height. The increase in leakage current, in silicon detectors for example, arises from radiation-induced defects such as atomic displacements that produce energy states within the band gap. Because the silicon band gap is only 1.12 eV, these states can act as current generation centers, emitting electrons into the conduction band and holes into the valence band through thermal agitation. These charge carriers are immediately swept out of the depletion region by a combination of built-in and external applied electric fields. The generation current is proportional to the intrinsic carrier concentration (Sze, 1985). Because of diamond's high resistivity,

any detector made of intrinsic diamond would be depleted of free carriers, thereby eliminating the need for a *pn*-junction to create a depleted region. In diamond detectors, the carrier concentrations are in equilibrium, and the recombination rate is, therefore, equal to the generation rate with no net generation/recombination current. As a result, the magnitude of radiation-damage-induced leakage current is negligible for diamond detectors.

The other effect of radiation damage is a decrease in the observed pulse height. This is due to the production of trapping/recombination centers which result in a decrease in mean carrier lifetime. These centers can be produced by charged particles or neutrons through atomic displacements in the lattice. Diamond, with its large cohesive energy and tight lattice structure, should also be resistant to this type of damage.

V.B. TEST RESULTS

Electron irradiation is not a concern from a radiation damage point of view. From Figure 1, the total expected electron fluence at an energy of 2 MeV for the duration of the satellite operation of 10 years is about 10^{14} cm^{-2} . It has been shown that 2 MeV electrons do not cause any damage that hinders detector operation beyond a fluence level of 10^{15} cm^{-2} (Geis n.d.). Therefore, any concerns regarding electron bombardment can be eliminated.

The real concern is with low-energy protons. The total expected proton fluence at an energy of 1 MeV or below is 10^{16} cm^{-2} . The proton ranges at this energy range is $8 \mu\text{m}$ from the detector surface—the same surface facing the soft x-ray source. Therefore, measurements were done to measure the decrease in the response of diamond soft x-ray detectors after the low-energy proton bombardment.

Diamond samples were irradiated with 1-MeV protons from a tandem Van de Graff accelerator. The diamond response is measured with a picosecond UV laser and is shown as a function of fluence in Figure 10. The excitation intensity of the UV laser is expressed as the integral response of the InP:Fe calorimeter used to monitor the UV pulses. It is clear that at the highest fluence, the integral response is reduced by approximately an order of magnitude. This is due to about a factor-of-3 reduction in peak time-resolved response and another factor-of-3 reduction in the carrier lifetime. But one needs to remember that the most damaged region is at the end of the mean range ($\approx 8 \mu\text{m}$), and the laser is only sampling the first micron or so. Therefore, if we had sampled the region around the end of the proton track, the reduction in response would be even worse. But this is not a problem because the soft x-ray spectral region of concern will only penetrate about the penetration depth of the laser.

On the other hand, 100-keV protons may be a greater concern. From Figure 11, it is clear that the integral signal is reduced by a factor of about 8 at the fluence level of 10^{16} cm^{-2} . In this case, all of the damaged region is sampled by the laser because the range of a 100-keV proton is about $0.5 \mu\text{m}$. Therefore, this can be the expected reduction for the response to soft x-rays. Also, the average vacancy production per proton at this energy is about 0.5 that of a 1-MeV proton. Therefore, it is reasonable to expect that the reduction in response should be consistent for even lower-energy protons because the expected vacancy production per proton will be less.

There is one caveat, however. All fluence levels were reached in a very short period of time (approximately 1 h of irradiation time for the highest fluence level). In the real situation, irradiation would be done over a period of 10 years. Therefore, the damage caused by any protons will have time to anneal. The annealing can be enhanced by elevating the temperature of the detectors during the daily instrument calibration cycle. In this manner, the effect of proton damage can be eliminated altogether.

Figure 10 Integrated response of the diamond detector as a function of 1-MeV proton fluence and UV excitation intensity.

VI. ALTERNATE DETECTOR DESIGN CONCEPT

An alternative design would be to use a beryllium or multilayer mirror to reflect the x-ray source onto a diamond sensor. The sensor would be shielded from directly incident protons. This may be very useful for some applications. Moreover, the collecting electrodes could be arranged to provide some imaging capability.

VII. CONCLUSIONS

The diamond sensor is a rugged, highly radiation resistant device that has excellent response to very low energy photons. It can be used for space flight in those space environments in which surface damage from very intense, low-energy protons is not a problem. Thin filters to define thresholds for soft x-rays can be placed on the entrance side

of the sensor. Charge carriers produced by primary interactions in the diamond may be collected by electrodes on the back side. The electrodes used in this work were an interdigitated pair of electrodes, but other novel geometries might be used to provide some position information.

VIII. RECOMMENDATIONS

One of the unknowns in this experiment is the effect of heavy-ion induced damage annealing over a long period of time, say 10^{16} cm^{-2} in 10 years. It is likely that some of

Figure 11 Integrated response of the diamond detector as a function of 100 keV proton fluence and UV excitation intensity.

the damage will be annealed over time because interstitials are believed to be mobile even at room temperature. If this is true then damage effects on the diamond detector will be minimal over long operational times. Furthermore, periodic operation of the detector at an elevated temperature may assist in reducing the effects of damage. This could be accomplished by the deposition of a heating element (e.g., tungsten) on part of the sensor.

We recommend further study of this promising technology.

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