Chapter 5

SYNTHETIC DIAMOND AS A RADIATION SENSING ELEMENT FOR MAMMOGRAPHY X-RAY BEAM DOSE MEASUREMENTS

Abstract

The desirable properties of diamond have made the mineral a material of choice in radiation measurements and are currently used extensively in high-energy physics. Its use in the low energy beam such as mammography X-ray beam however, has not been fully investigated. In this presentation a diamond probe has been constructed using both chemical vapour deposited (CVD) synthetic diamond as well as diamond produced under high-pressure high-temperature (HPHT) as the radiation sensing materials. An investigation into the exposure geometry of the diamond sensor that will give maximum absorption of the incident X-ray beam was also conducted in this study by calculations. The diamond samples were characterized to obtain information about the level of impurities especially nitrogen levels and consequently establish the material quality. Nitrogen quantities in the diamond lattice have been shown to have a profound effect on the radiation detection properties of diamond (Nam et al., 1991). The diamond sample surfaces were metallized with titanium, platinum and gold to provide ohmic contacts. The probe was connected to both the Wellhöfer Dosimetrie (model CU 500) and the PTW Unidos E commercial electrometers. In all the measurements, the incident radiation beam was perpendicular to the edge of the CVD diamond plate to optimize absorption of the X-ray beam by the sensing material. The probe was calibrated against PTW Diados secondary standard dosimeter. The results of the study are presented in both tabular and graphical forms.

5.1. Introduction

Diamond is the cubic form of crystalline carbon. Carbon is the sixth element of the periodic table, with a proton number of 6 and atomic number of 12. With atomic number density of 1.75×10^{23} atoms/cm^3, which corresponds to a molar volume of 3.44 cm^3/mol., the carbon atoms in the diamond lattice structure has thus one of the highest atomic number densities.

The mass density of diamond is 3.515 g/cm^3. With these physical properties, diamonds, with a size of a few cubic millimeters can be used in radiation measurements. The small size allows for 'pin point' measurements to be made which has an advantage over large volume detectors where average values are obtained. The lattice structure of diamond consists of single elements of carbon in sp^3 bonded form i.e. in the stable four-atom coordination state. Silicon and germanium are elements in the same group as carbon in the Periodic Table of the Elements. Silicon and germanium have the diamond structure and are also used for the construction of wide range of electronic devices of varied applications hence forming the basis for the comparisons between them and diamond. Table 5.1 is presented comparison of some of the properties of diamond and silicon.

Table 5.1: Comparison of some of the properties of diamond and silicon.

Property	Diamond	Silicon
Band gap	5.47	1.12
Mass density [g/cm3]	3.515	2.33
Dielectric constant	5.7	11.9
Resistivity [Wcm]	>1011	2.3 x 105
Breakdown field [kV/cm]	103 - 2 x 104	300
Electron mobility [cm2/Vs]	1500 - 2400	1450
Hole mobility [cm2/Vs]	1000 - 2100	480
Thermal conductivity [W/ cm K]	10 – 20	1.3
Radiation length [cm]	12	9.4
Energy to create an electron-hole pair [eV]	13	3.6

References: Pan et al., 1993

The major setback to the application of natural diamond as a radiation detector has been the lengthy selection process for a good stone and the fact that natural diamond crystals differ one from another. Lightowlers and Dean (1965) noted that no two natural diamond crystals can be guaranteed to produce similar responses to radiation without extensive initial testing of each stone. The development of synthetic diamond has created enthusiasm to the possible commercial exploitation of the crystal in radiation detection instruments. With the present synthesizing techniques, it is believed that batches of diamond crystals containing controlled amounts of impurities and having good detection characteristics can be produced in a reproducible manner. The application of synthetic diamond crystal as dose measuring instrument has since been reported. Diamond has been used as radiosensitive resistor (Burgemeister, 1981; Keddy et al., 1987); as a thermoluminescence dosimeter (Nam et al., 1987; Nam 1989); as a near tissue-equivalent probe in electron radiation therapy (van der Merwe, 1994); as a sensor for measuring low dose-rates (Grobbelaar et al., 1991).

Fallon et al. (1990) has found that as a pulse-counting gamma-ray detector, synthetic diamond has a linear response for over five orders of magnitude of dose. Fallon et al. (1990) also found that priming diamond with a large γ-ray dose gave best response. For a chemical vapour deposited (CVD) diamond however, Bruzzi et al. (2000) has found linearity for a range of 1-11 Gy/min. CVD diamond dosimeters have been found to have the highest dose sensitivity compared to natural diamond and silicon diode dosimeters. CVD diamond was found to exhibit priming behaviour in which the output increases slowly with the delivered dose (Whitehead et al. 2001).

5.2. Selection of exposure geometry for the diamond sensors

An investigation into the exposure geometry of the diamond sensor that will produce maximum absorption of the incident X-ray beam was conducted in this part of the study. The absorption levels of two CVD diamond samples of equal surface area but different thicknesses were calculated for both edge-on[1] and flat-on radiation exposures. Mass attenuation coefficient data as well as the densities of diamond and those of the metals used to form ohmic contacts on the diamond samples where applicable were taken into consideration. The study was carried out using spectral data measurements obtained at 25 and 30 kVps. For the calculations, both the absorption depths and absorption areas of the exposure geometries were taken into consideration.

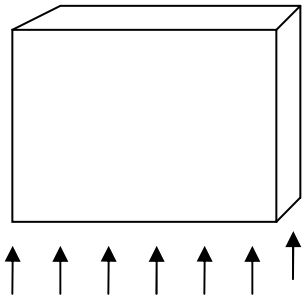
The percent total absorption for the entire energy spectrum as well absorption percent at different segments of the energy spectrum (arbitrary chosen) were calculated for both sets of spectral data. The percent of total photon flux incident on the diamond samples based on the exposure geometry as well as the percentage incident photon flux absorbed by the diamond sample were determined. The percentage absorption from the two geometries considered is presented in Tables 5.2 and 5.3 for the 25 and 30 kVps spectral data respectively.

For the two selected kVps, the percentage of the total photon flux incident on the diamond samples in the edge-on geometry was found to be much lower due to the relatively smaller area of the diamond sample available to the X-ray beam than that of the flat-on geometry. It can be concluded from the data that at the lower energy segment of the spectrum, the

[1] In the flat-on exposure geometry impinging radiation is to the largest surface area of the specimen but has smaller depth, whereas in edge-on exposure geometry the impinging radiation is on the smallest surface area of the same specimen but having greater depth. Cf. Figures 5.1 and 5.2.

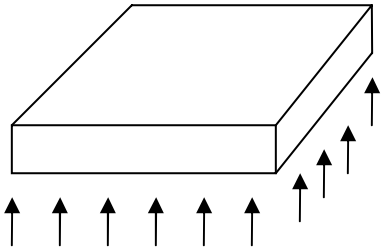
absorption levels of both exposure geometries are similar. At intermediate and higher energy segments of the spectrum however, the percentage incident photon flux absorbed by the diamond samples was much higher in the edge-on geometry than the flat-on geometry even though the incident photon flux was comparable in both geometries.

Figure 5.1: Edge-on geometry



Incident X-ray beam direction

Figure 5.2: Flat-on geometry



Incident X-ray beam direction

The edge-on geometry was found to be about four times more absorbing than the flat-on geometry at the intermediate and higher energy segments considered for the study. The observation is in agreement with the fact that as X-ray energy increases, mass attenuation coefficients of materials decreases hence larger thicknesses are required for appreciable attenuation of the X-ray beam. Mali et al. (2004) found similar results in their investigations.

The results of this study indicated that generally, the edge-on exposure geometry has higher absorption levels than the flat-on geometry and ought to be the X-ray exposure geometry of choice in radiation dose measurements especially in the mammography X-ray energy range. Because both edge-on and flat-on geometry have comparable absorption levels at lower X-ray

energies, flat-on exposure geometry will be appropriate for use in lower X-ray beam energies (less than 10 keV) as a higher response for the same crystal size can be expected.

5.3. Construction of Test Probe (Mark I)

A sketch of the diamond probe used for selection of diamond specimens is shown in Figure 5.3. To provide ohmic contacts, the diamond sample (5) surfaces were metallized with titanium, platinum and gold. These were evaporated under vacuum onto both surfaces of the sample. Care was taken throughout the metallization process of the diamond surfaces to ensure that the edges of the diamond were not coated with any of the metals. This was found necessary to prevent electrical shorting and spark over. The diamond probe housing consisted of a Teflon (polytetrafluoroethylene, PTFE) (4) core. Electrical connections to external electronics were carried out through the use of a standard triaxial connector (1). Three carbon fibre rods (3) were used to provide contacts to the diamond. The central carbon fibre electrode and the metallic disc shaped electrode that is connected on both sides with two carbon fibre electrodes were used to complete the circuit. To reduce spurious noise, the outer aluminium (2) casing was earthed. For measurements, the probe was connected to a Wellhöfer Dosimetrie (model CU 500) commercial electrometer. In all the measurements, the incident radiation beam was perpendicular to the length of the probe. The probe was calibrated against PTW Diados secondary standard dosimeter.

5.4. Sample preparation

Two single crystal and four polycrystalline synthetic diamond samples of volume ranging from 2.7 mm^3 to 100mm^3 were used for the study. The samples were mechanically polished with diamond paste of grain size 1 μm placed on a cast iron scaife and rotating at about 2800

revolutions per minute. The polished samples were boiled in 1:3:4 mixtures of nitric, perchloric and sulphuric acids for 30 minutes. The samples were further cleaned in a 1:4 solution of "Contrad" (a surface cleaning reagent) and deionised water in order to remove any metallic impurities as well as non-diamond carbon atoms. This was followed by triple ultrasonic rinsing with deionised water at different time settings (Makau and Derry, 2003).

No.	Description	Material	No.	Description	Material
1	Triaxial connector	Steel	5	Active sensing material	Diamond
2	Detector outer housing	Aluminium	6	Probe cover	Aluminium
3	Electrodes	Carbon fibre rods	7	Sample disc positioner	Aluminium
4	Insulator	Teflon	8	Flexible wire	Insulated copper wire

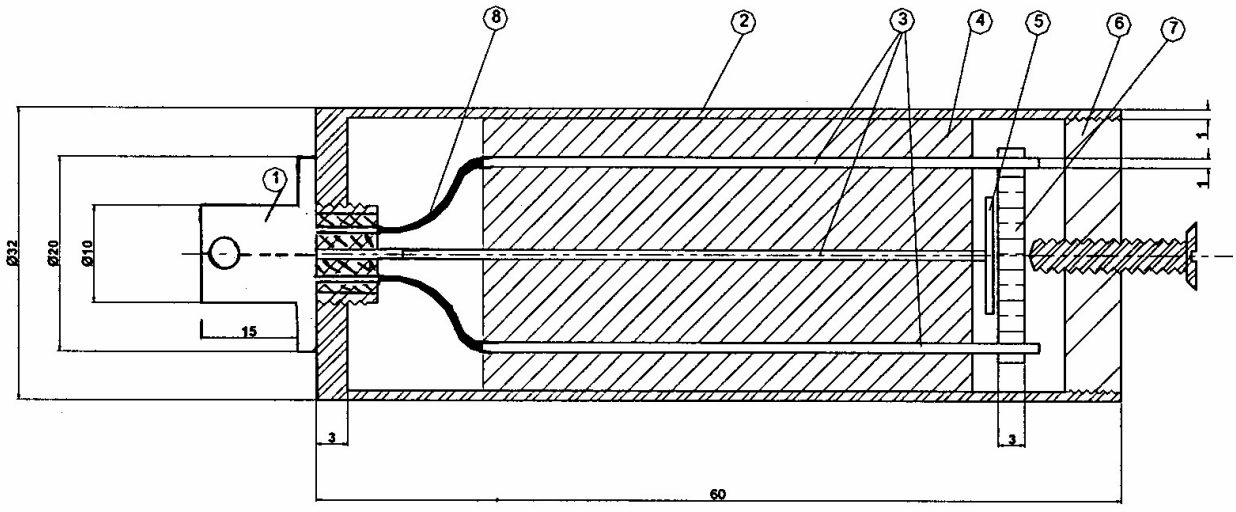


Figure 5.3: A constructed Test Probe with diamond as sensing material (Mark I).

5.5. Sample characterization

It has been established that the response of a diamond sample is dependent on the types of impurities and their levels or concentrations. Nitrogen is the most important impurity in diamond. Nitrogen in diamond determines the optical properties and also influences thermal,

electrical as well as mechanical properties of diamond (Field, 1992). Nitrogen is also the principal factor responsible for many performance characteristics of diamond as a radiation detector (Nam et al., 1991). Diamonds with high nitrogen concentration tend to have much lower shallow trap concentrations than those synthesized with lower nitrogen levels (Nam, 1989). Diamond crystals with high concentration of nitrogen have been found to exhibit low specific conductance (Nam, 1989). Nam also observed that diamonds with single substitutional nitrogen have high recombination efficiency to the detriment of response due to the presence of a dipole. With diamond as a TLD (thermoluminescence dosimeter), it has been reported that about 5 orders of magnitude reduction in the response could occur as the paramagnetic nitrogen content increases from 10 ppm to 150 ppm (Keddy et al., 1987). It is therefore imperative to characterize the diamond samples to obtain information about the level of impurities especially nitrogen levels and consequently establish the material quality. The following standard characterization techniques for crystals were carried out on the samples: Raman spectroscopy, electron spin resonance (ESR) measurements, current-voltage (I-V) characteristic measurements, polarizing voltage, response with and without UVR and response with time after exposure.

5.5.1. Raman spectroscopy

The diamond samples were analyzed using Raman spectroscopy to determine the type of carbon atoms present in the diamond films. Raman spectroscopy was carried out before and after the samples were polished and cleaned. Spectra were acquired using the micro-Raman attachment of a Jobin-Yvon T64000 Raman spectrometer operated in single spectrograph mode, with the 514.5 nm line of an argon-ion laser as excitation source. The 20x objective of the Raman microscope was used for observation of typical beam diameter on the sample of

just over 1 micron. In the measurement, light from the argon-ion laser beam was focused onto the diamond sample and the backscattered light from the sample collected. Five different spots were selected on the surface of each sample: one in the centre and 4 near the corners of the rectangular samples. The sampling depth of the beam was approximately 5 microns. The Raman spectral calibration was done using the green emission line of a mercury lamp at position 1122.47 cm^{-1}.

The results of the Raman measurements were fitted with a Lorentzian function to determine the Raman peak position and peak width at half height for each measured spot. The Raman line of all the diamond samples (before and after they were polished and cleaned) occurred at 1331.6 ± 0.5 cm^{-1}. The peak width at half height for the diamond samples ranged from 2.25 ± 0.01 to 2.56 ± 0.01 cm^{-1}. The Raman line peak intensities of the cleaned samples were higher than those of the uncleaned samples. This was proposed to be due to the removal of graphitic and other non-diamond atoms and enhancement of the diamond atoms during the polishing and cleaning process. The 1st order Raman scattering for diamond in an sp^3 bonded form is known to be 1332 cm^{-1} and has a half-width of about 3 cm^{-1} (Field, 1992). The measured Raman peak positions of the diamond films used in this study compare favourably with the established values indicating that the diamond samples used for the study were of good quality. The Raman peak positions and the half-width values measured at different spots of a sample were found to be similar for the same sample. These similarities show that there was little variation within the crystal structure of a sample. Raman spectrum of diamond sample A is shown in Figure 5.4.

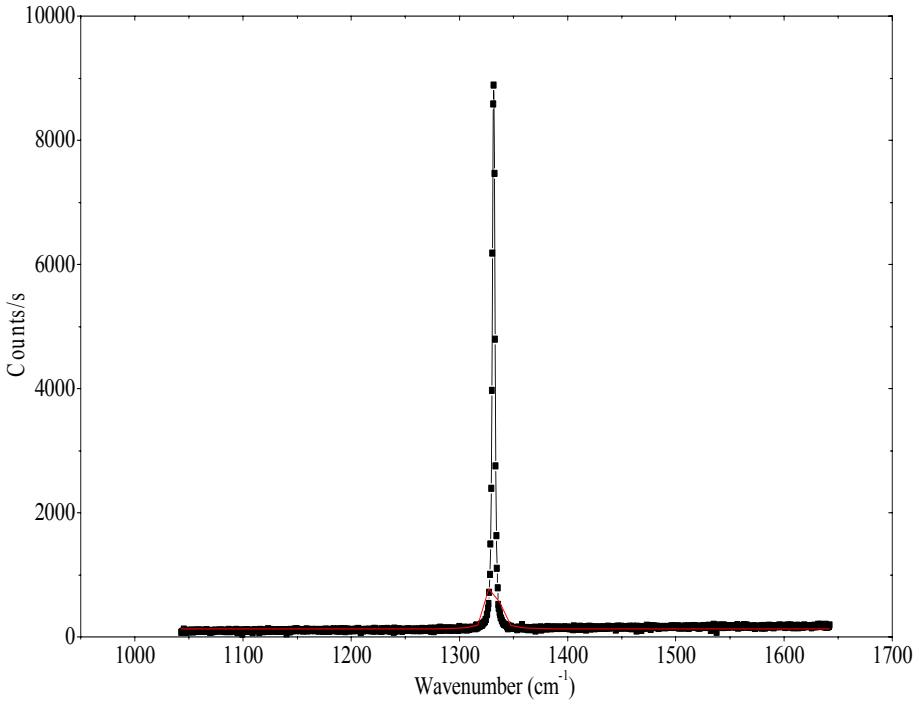


Figure 5.4: Raman spectrum of diamond sample A.

5.5.2. ESR measurements

Nitrogen in synthetic diamond occurs as isolated atoms in substitutional lattice sites at concentrations up to 500 ppm (Field, 1992). In the substitutional position, four of the five valence electrons of the nitrogen atom form tetrahedral bonds with four surrounding carbon atoms. The remaining lone electron forms a C-N antibonding orbital that is evenly distributed over the four surrounding bonds resulting in the paramagnetic nature of the diamond (Fallon, 1989). Electron spin resonance measurements (ESR) were carried out on the diamond samples to determine the concentration of nitrogen. ESR techniques depend on the interaction between the spin angular momentum of an unpaired electron and an external magnetic field. In the presence of a magnetic field, the degeneracy of the spin states of the unpaired electron

characterized by the quantum number $m_s = \pm½$ is lifted and transitions between the spin levels are induced by radiation of the appropriate frequency.

The ESR measurements were carried out with a Bruker ESP300E ESR spectrometer, operated at a frequency of 9 GHz. The diamond sample was placed in a cavity resonator and variable magnetic field was applied perpendicularly to the microwave magnetic field. In the magnetic field, the electron spin levels are separated by an amount, which depends on the magnetic field. At equilibrium, there is a small difference in the populations of the two levels. When the magnetic field is adjusted so that the energy difference between the two spin levels equals the energy of the microwave photons, transitions induced between the two levels occurs, giving rise to an ESR signal.

The observation of the ESR signal relies on maintaining the population difference between the spin levels, which in turn depend on the relaxation times. For high nitrogen concentrations these relaxation times are short and ESR transitions are detected readily. For low nitrogen concentrations, the relaxation times become long and the population difference between the spin levels become smaller and it becomes more difficult to observe the ESR transitions. A technique, known as the rapid scan technique, in which the magnetic field is scanned repetitively through resonance at a rate comparable to the relaxation time, can be used to detect the resonance. For both the conventional and the rapid scan technique, the concentration in any sample is determined by comparing it with a signal from a calibrated reference sample. A typical ESR spectrum of the high-pressure high-nitrogen (HPHT) diamond sample (Sample F) with high concentration of nitrogen is shown in Figure 5.5. The clearly visible and equally

spaced triplets in the figure indicate that the applied magnetic field was parallel to the [100] direction of the sample. The triplets occur at 3409.73g, 3443.45g and 3478.25g and had a line width of ≈1.46g.

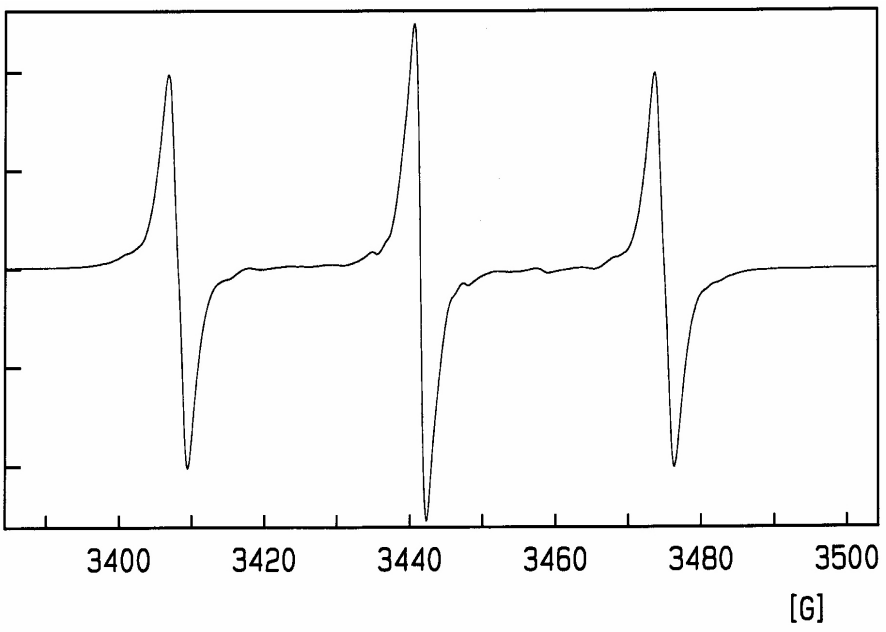


Figure 5.5: Typical ESR spectrum of a high nitrogen diamond sample.

The electron spin resonance measurements of the polycrystalline CVD diamond, Samples A and B had nitrogen concentration of 20 and 10 atomic ppb respectively. The two single crystal HPHT diamond samples, Suite 2 No. 2 and Sample F, had nitrogen concentrations of 16.9 and 130 atomic ppm respectively.

5.6. Metallization of sample

The polished and cleaned diamond samples were metallized following the method established by Hayes and da Costa, 2003. Metal contacts were applied by thermally evaporating onto the diamond surface using an electron beam system, successive metals: titanium (200 Å)/platinum

(200 Å)/gold (2000 Å), in an ultra high vacuum chamber at a pressure of about 10^{-7} torrs. The metal in contact with the diamond generally determines the electrical properties of the contact (Pan et al., 1993). Titanium and other transition metals that form carbides produce ohmic contact to diamond. The metallized diamond was annealed (Tachibana et al., 1992). Platinum was deposited next followed by gold at the surface. The chemically inert nature of gold prevents oxidation from occurring and thus protects the contact from any chemical reaction with oxygen. Post-deposition annealing of the samples was carried out in a ceramic furnace in a high vacuum environment of about 10^{-6} torrs. The annealing temperature was 500°C.

5.7. Sample grouping

Operationally for ease of use and wide usage, an ideal detector should have both high sensitivity to the incident radiation, an extended range of linearity of response, and relatively fast response. This study has shown that both response and sensitivity are susceptible to the presence of defects within the crystal. In addition some diamonds due to the presence of trapping centers are light sensitive. Two forms of trapping centres, shallow or deep traps, have been identified. The shallow traps are believed to occur at energy level of less than 1.55 eV and are believed to be responsible for the slight initial increase in count rate after the diamond has been pre-irradiated with a high dose of γ-radiation. The pre-irradiation has been found to populate these traps and depopulation occurs during pulse counting by exposure to light energy of at least 1.55 eV, or by heat even at room temperature (Fallon, 1990).

The deep traps located at energy levels greater than 2.2 ± 0.1 eV are believed to be responsible for the large decrease in response of the diamond detector after exposure to light. Populating of the deep traps has also been found to be responsible for the increase in response when

diamonds, with low concentrations of single substitutional nitrogen, have been pre-irradiated (Fallon, 1992). The depopulation of the trapping levels however, occurs when the diamond is exposed to light resulting in a lightly populated state, which acts as a carrier trap with consequent reduction of pulse-counting response (Fallon, 1992).

To reduce the effect of traps and increase the performance of the CVD diamond sensor, it has been reported that diamond samples with low nitrogen concentrations should be irradiated or primed by exposure to γ-, X-rays or ultraviolet radiation and should not be exposed to any other light afterwards (Burgemeister, 1982; Keddy et al., 1987; Fallon et al., 1992; Vaitkus et al., 1993). Beta radioactive sources such as strontium-90 have also been used to prime CVD diamond samples (Borchi et al., 1998; Marinelli et al., 2001). Irradiation of diamond with ultraviolet radiation has been found to have the same effect as pre-irradiation with γ-radiation sources (Fallon, 1992, Vaitkus et al., 1993).

Each diamond sample metallized on opposite faces for electrical contacts was carefully tested in order to identify working stones amongst them for use as the radiation sensor in mammography X-ray beam dose measurements. The tests consisted of: response to progressive X-ray irradiation or dose; response with applied voltage; linearity with X-ray tube loading and linearity with X-ray tube energy or tube voltage. From the test results, 'good' stones (Sample A, F and Suite 2 no. 2) were identified and 'not so good' ones (Sample B) were irradiated with ultra violet radiation and also with strontium-90 radioactive source with the view of improving their performance.

5.7.1. Selection of polarizing voltage

The applied potential for optimal performance and to obviate the dependence of the probe response on variations in applied potential of the diamond probe was established. The probe was connected to a Wellhöfer Dosimetrie (model CU 500) commercial electrometer. The response of the probe at varying applied potentials was recorded for the different diamond samples. Saturation in response occurred at polarizing potential range of +280 V to +480 V, for both the HPHT single crystal diamond (Suite 2 No. 2) and the CVD polycrystalline ones (Samples A and B). The probe was operated at +340 V (6.8 kV/cm) for all subsequent measurements. Figure 5.6 shows a response versus applied electric field curve for diamond sample A.

5.7.2. Detector response to tube loading and tube voltage variations

The response of the diamond samples used for the study was each measured. The sample performance testing was to gather baseline information about the samples i.e. to assess their behaviour with dose or with progressive X-ray irradiation. In order to establish the optimum time needed for the probe to collect all the charges produced, the response of the probe at a specific X-ray tube setting was measured with different electrometer time settings. The response of the diamond samples with varying nominal X-ray tube voltage at a constant tube current time product (tube loading, mAs) was carried out to determine the linearity of the diamond probe with energy. The linearity of the probe with tube loading was also measured at a constant tube voltage. Graphs of the linearity measurements are presented in Figures 5.7 and 5.8. The linearity of the diamond probe was also checked against the response of IC10 ionization chamber (Figure 5.9).

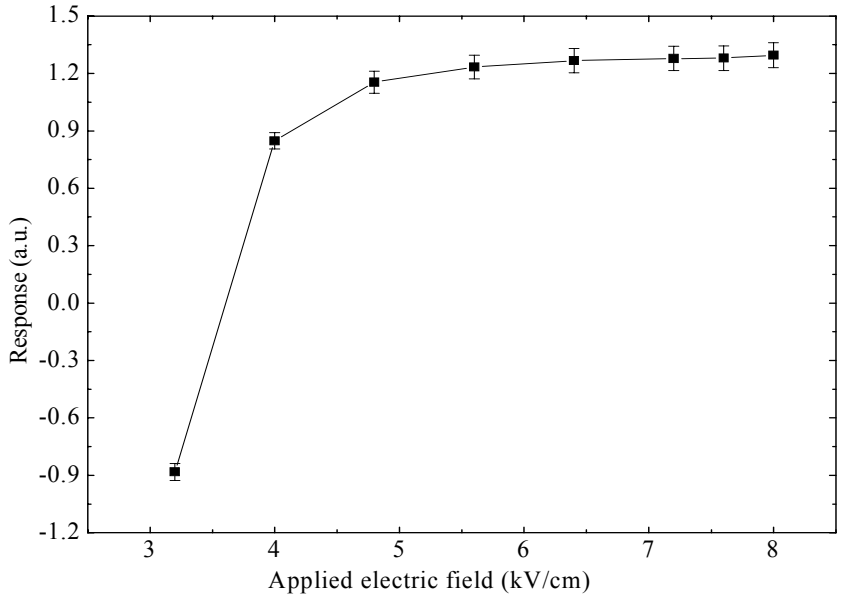


Figure 5.6: Response of diamond sample A with applied electric field at an X-ray tube setting of 30 kVp and 200 mAs.

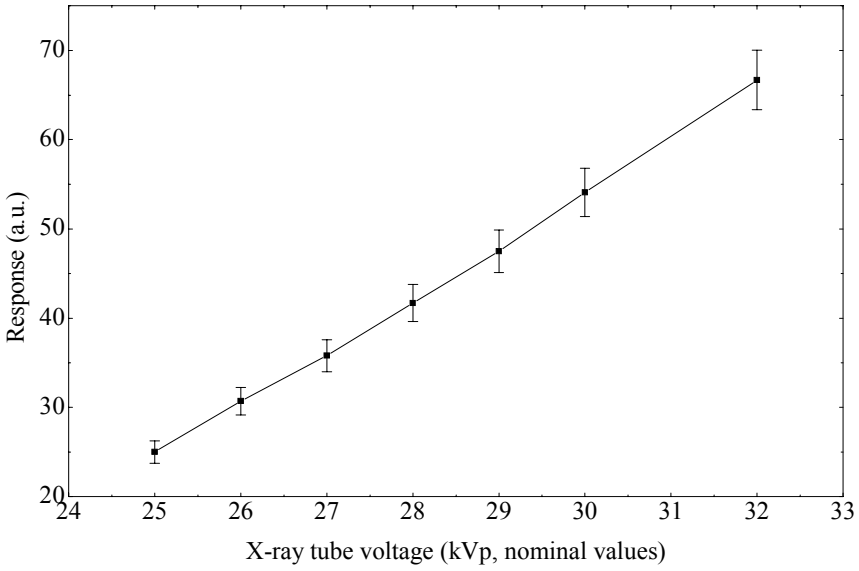


Figure 5.7: Response of diamond sample A with varying X-ray tube voltage. Tube loading setting was 200 mAs and applied electric field was 6.8 kV/cm.

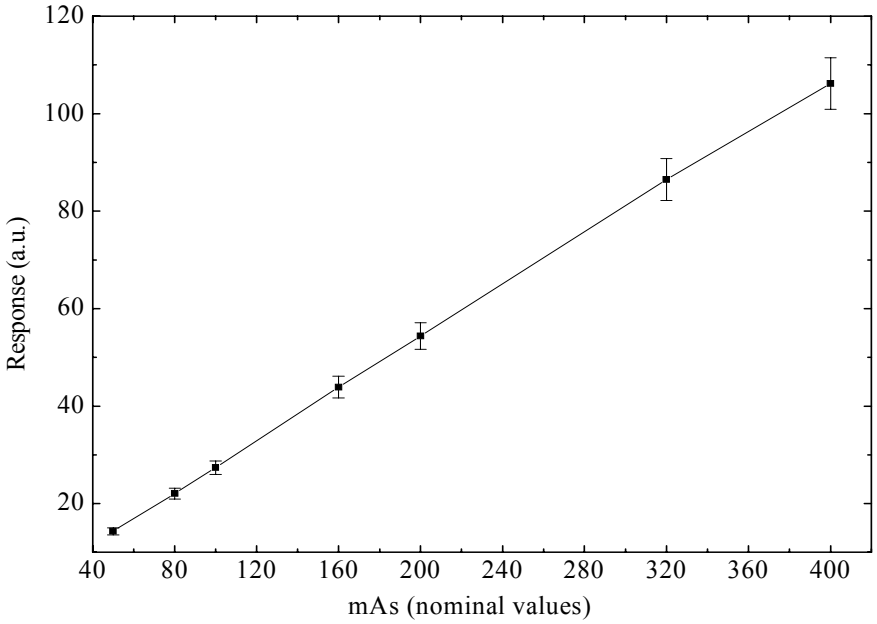


Figure 5.8: Response of diamond sample A with varying mAs. X-ray tube voltage used was 30 kVp. The electric field applied to the diamond sample was 6.8 kV/cm.

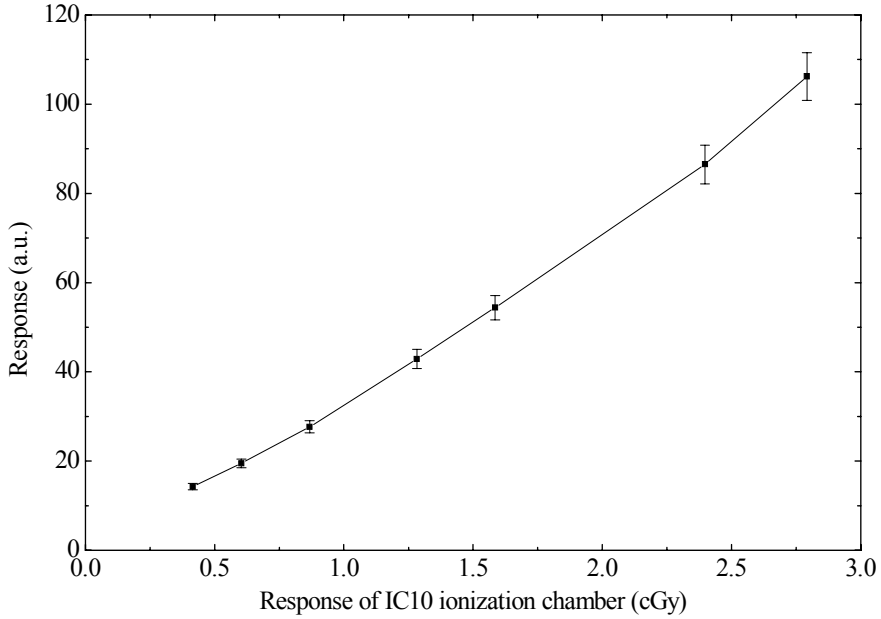


Figure 5.9: Correlation of the response of diamond sample A with the response of IC10 ionization chamberset at same tube settings.

The response of the HPHT single crystal diamond (Sample F) and the CVD polycrystalline diamond (Sample A) with varying applied voltage, nominal X-ray tube voltage and tube loading have been compared. The response with X-ray tube voltage was carried out at a constant tube loading of 200 mAs whiles that with tube loading was done at a constant tube voltage of 30 kVp. Graphs showing the performance comparisons are presented in Figures 5.10, 5.11 and 5.12. The measurements were carried out using PTW-Unidos E electrometer system. The samples showed similar response patterns with varying applied voltage, X-ray tube voltage and tube loading (Figures 5.10, 5.11 and 5.12 respectively). The response of Sample A was however, found to be higher than that of Sample F by a factor of 1.3 to 1.5 with the higher factor occurring at higher applied voltage.

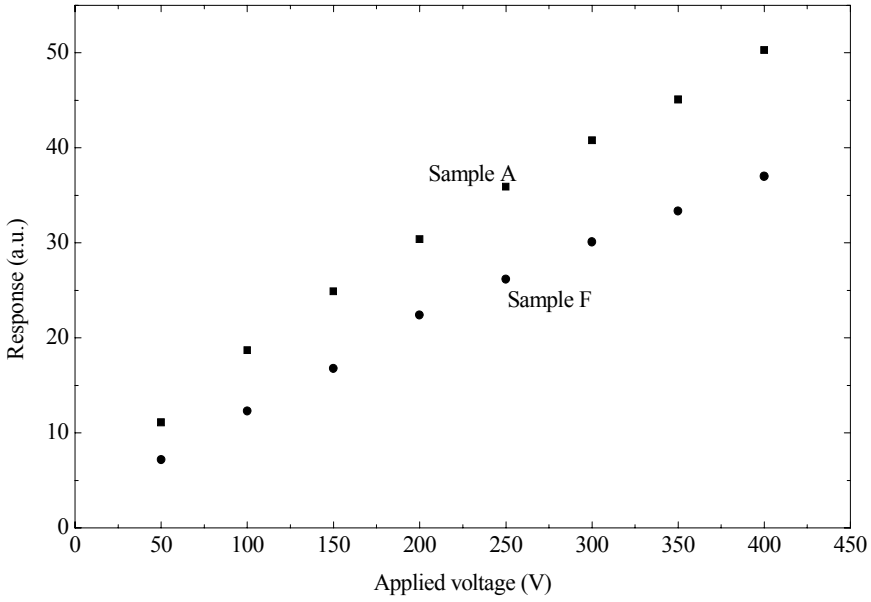


Figure 5.10: Response of diamond sample A and F with varying applied potential using PTW-Unidos E electrometer system. X-ray tube setting used for measurement was 30 kVp and 200 mAs.

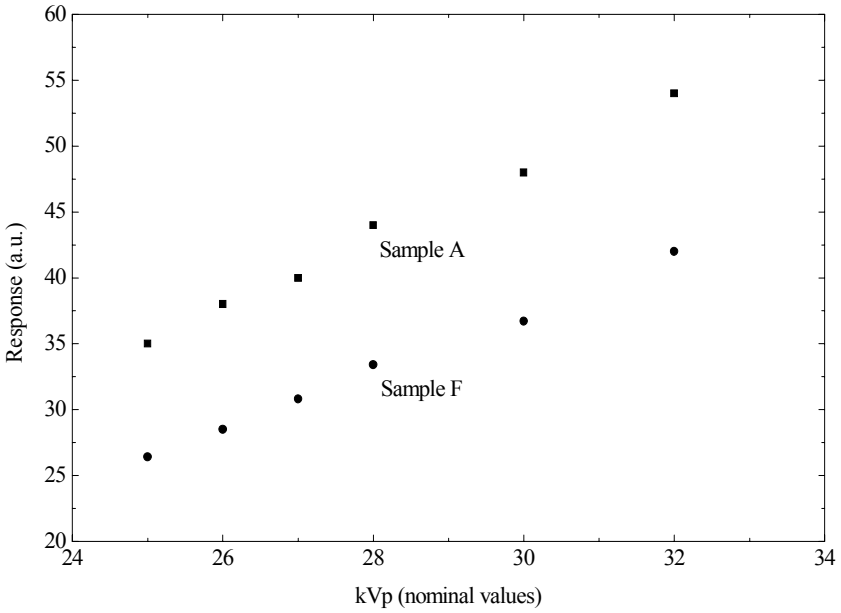


Figure 5.11: Response of diamond sample A and F with varying X-ray tube voltage. X-ray tube loading used for measurement was 200 mAs and applied voltage to the diamond samples was 400 V. Measurements were carried out with PTW-Unidos E electrometer system.

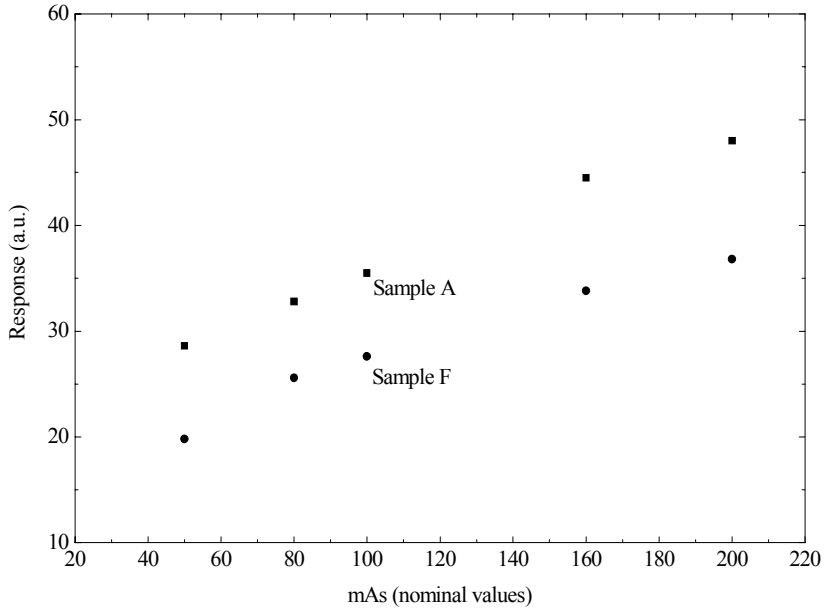


Figure 5.12: Response of diamond sample A and F with varying X-ray tube loading. X-ray tube voltage used for measurement was 30 kVp and applied voltage to the diamond samples was 400 V. Measurements were carried out with PTW-Unidos E electrometer.

5.8. Priming of diamond samples

The sensitivity of one of the diamond samples (Sample B) was found to increase with progressive X-ray irradiation (Figure 5.13). This observation was assumed to be due to the filling of trapping centres within the crystal by charge carriers. To test the 'trapping filling gives rise to higher sensitivity to radiation exposure' hypothesis, the diamond sample was irradiated with ultra violet radiation (UVR) for two hours. After the irradiation, the sample was shielded from direct exposure to light. An increase in the response values of the sample after the UVR irradiation (Figures 5.14) with much lower applied voltage needed for measurements was observed. The response of such sample was monitored for some time in order to assess the temporal efficacy of the priming. The response was stable up to a point

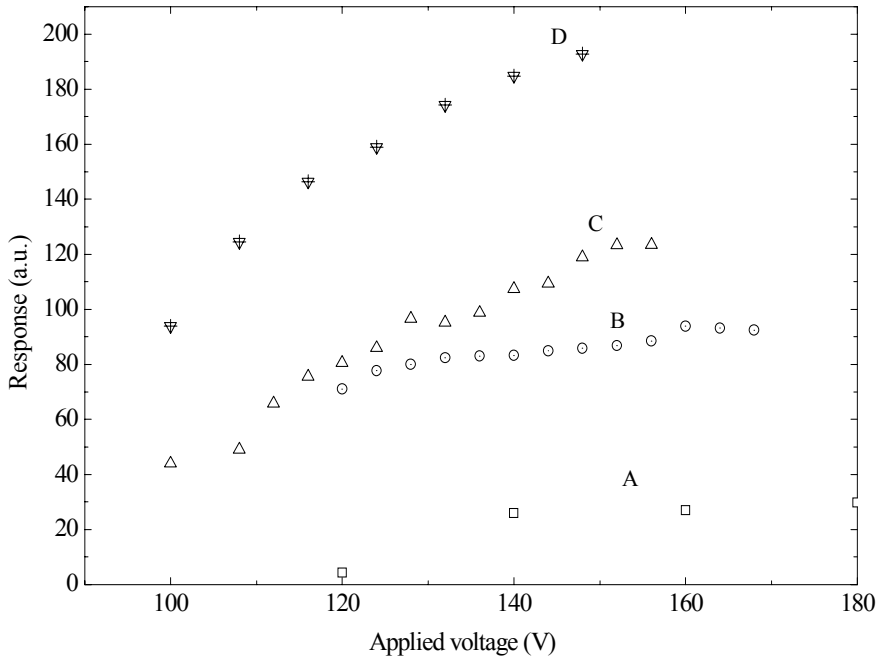


Figure 5.13: Sensitivity of diamond sample B with progressive X-ray irradiation.
A, B, C and D represent the first, second, third and fourth measurements respectively.

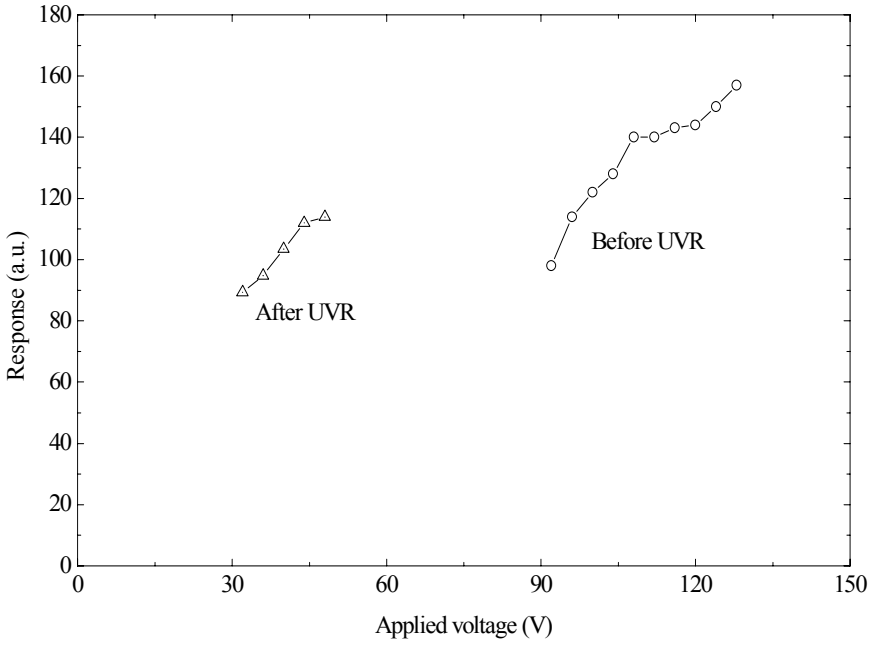


Figure 5.14: Comparison of the response of diamond sample B before and after UVR irradiation with applied voltage. The X-ray tube settings used were 30 kV, 200 mAs.

(Figure 5.15) and thereafter showed an increase in response with dose indicating that not all the trapping centres in the sample were filled, suggesting therefore that the 2-hour UVR was insufficient and that a longer irradiation time was needed.

To further test the hypothesis that the diamond sample contains trapping centres the presence of which gave rise to reduced response, the sample was annealed at 450°C for 30 minutes to empty as many of the shallow to medium level traps as possible. The diamond samples showed lower response values (Figure 5.16) compared to the response values before annealing (Figure 5.16). Much higher voltages could be applied to the diamond samples for a fixed exposure. The observation supports the results made after UVR irradiation. The response of the sample increased with accumulated dose (Figure 5.17) needing consequently a lower

voltage for the same response to exposure. The response of the diamond sample did not show initial drop, contrary to the response values before the UVR irradiation. This observation suggests that the annealing process adopted did not empty all the filled traps during the heating cycle implying that only partial annealing of the sample was achieved.

Furthermore where an annealed diamond sample was irradiated with UVR for 5 hours, a comparison of the response of the diamond samples from the two UVR irradiation times (Figure 5.18) with a fixed applied voltage showed that the 2-hour UVR irradiation gave higher response values than the 5-hour UVR irradiation. The observation suggests that the UVR has not been successful in improving the performance of the diamond sample. The decay times (Figure 5.19) of the sample after irradiation also confirm the presence of traps.

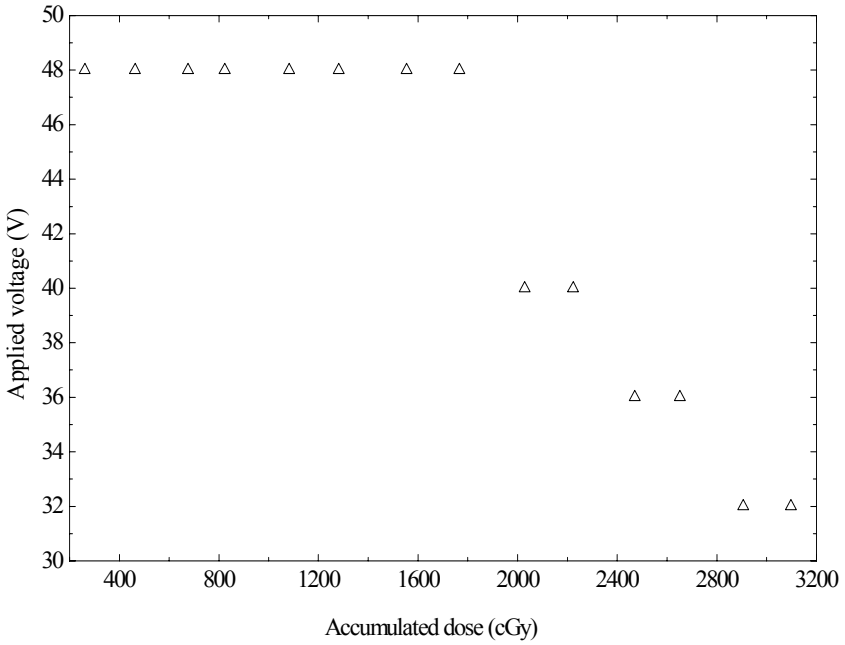


Figure 5.15: Variation of applied voltage required for fixed response with accumulated dose values. Sample has been UVR irradiated for 2 hours. The X-ray tube settings used were 30 kV, 200 mAs.

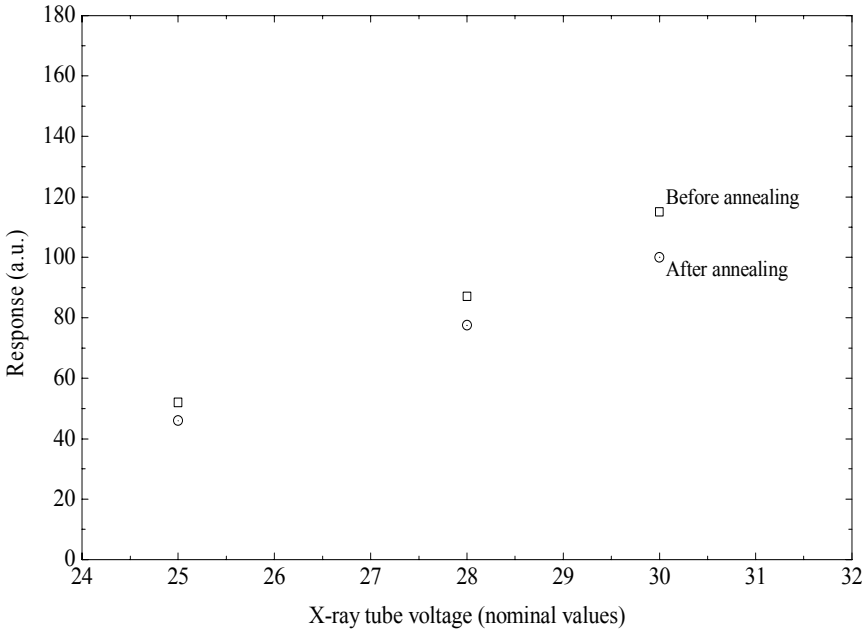


Figure 5.16: Comparison of the response of diamond sample B before and after annealing at 450 C. Before annealing measurements were carried out at 32 V while the after annealing measurements were done at 300 V.

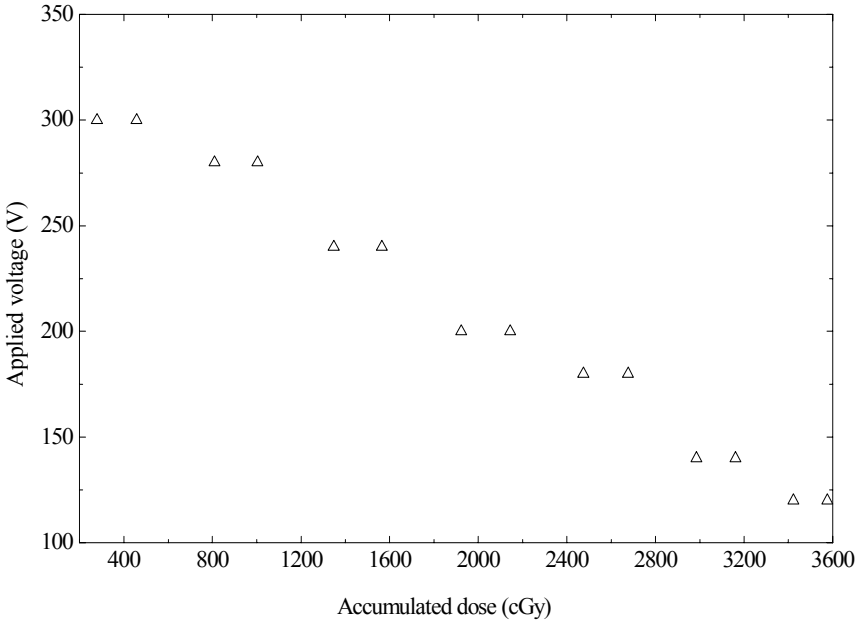
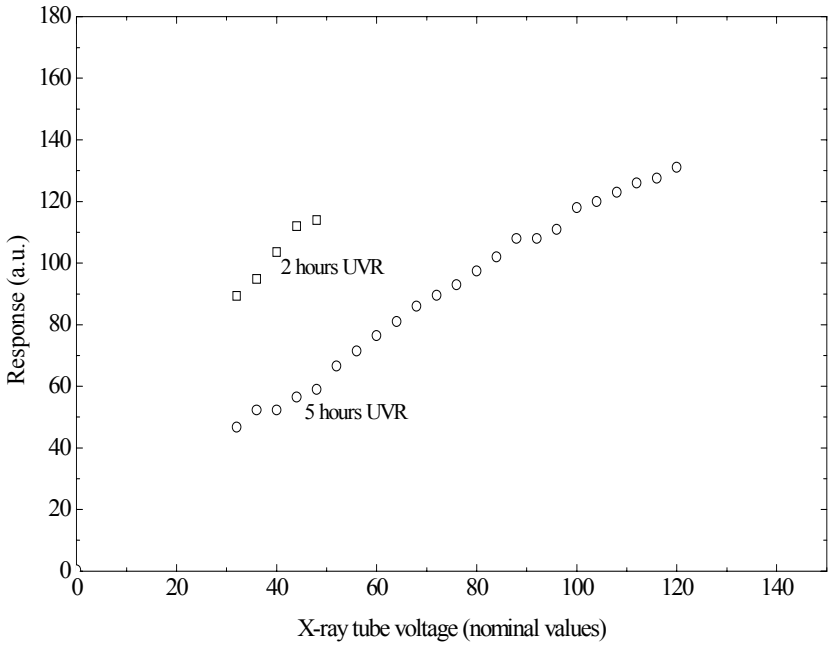


Figure 5.17: Variation of applied voltage required for fixed response with accumulated dose values. Measurements were taken after sample annealing. The X-ray tube settings used were 30 kV, 200 mAs.

The presence of traps in the diamond detector has been found to give rise to slow decay time after a pulsed excitation with a consequent rise in baseline level (Bergonzo et al., 2003). The diamond sample was further irradiated with strontium-90 source for 60 hours (Marinelli et al., 2001). It was expected that because of its higher intensities and energies the strontium-90 source would be able to penetrate the entire diamond thickness with increased probability of trap filling in a shorter time as compared to UVR. A fully primed sample was expected to function more efficiently than previously observed. The diamond sample response after the strontium-90 irradiation was higher than before the strontium-90 irradiation. However, like earlier observations made in previous measurements, the response of the sample increased with accumulated dose.



5.18: Comparison of the response of diamond sample B irradiated at different times with applied voltage. The X-ray tube settings used were 30 kV, 200 mAs.

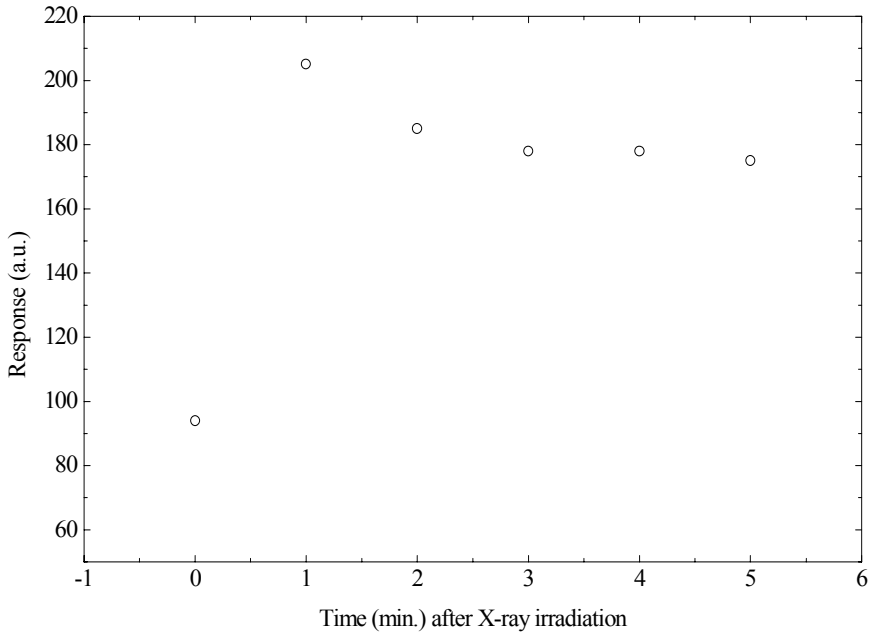


Figure 5.19: Decay time of diamond sample B after exposure.
Response at zero represents before irradiation level.

It is apparent from the results above that UVR and strontium-90 irradiations which are usually used to prime low nitrogen CVD diamonds have not been successful in improving the performance of this particular diamond stone. Other forms of sample passivation techniques have to be considered and employed. This however, is beyond the scope of the present study.

5.9. Construction of diamond probe

Following the performance of the constructed Test Probe (Mark I), two more diamond probes have been constructed with similar electrical connections as in Mark I. The two probes named as Mark IIA and IIB (Figures 5.20 and 5.21 respectively) were constructed using entirely tissue equivalent materials with carbon fibre providing both electrical contacts and shielding. Electrical insulation was provided by Teflon tubes. The outer casing of the probes was

Perspex and it has removable split Perspex cap or window, which allows for the direct measurements of incident photons. The outer casing of the probes was earthed with 3 microns thickness of aluminium in order to reduce electronic noise. Mark IIA (Figure 5.20) are designed for diamond stone of volume 52 mm^3 (10 x 10 x 0.52 mm^3) (Sample A) and is intended for total dose measurements while Mark IIB (Figure 5.21) with a crystal of volume 2.7 mm^3 (Suite 2 no. 2) is targeted for routine dose monitoring. Mark IIA has been constructed to allow for both edge-on and flat-on exposure measurements. Photographs of Mark IIA are shown in Figures 5.22 and 5.23.

Some salient features of and anticipated advantages that could arise from the specially designed and constructed diamond probes and with preselected crystals are:
(1) Dose response values are not susceptible to changes in ambient temperature, pressure and humidity unlike air ionization chambers. (2) Diamond is near tissue-equivalent thus it has similar attenuation properties as tissue therefore its response in dose measurements would not require some of the conversion factors needed to convert air kerma measurements to mean glandular dose values. The number of variables used in dose evaluation quantities is reduced hence reduction of possible sources of error or uncertainty in dose measurements. (3) High sensitivity of diamond implies that thinner diamond samples could be used and hence reduction in total cost of construction. (4) With its customized Perspex phantom, tissue depth dose can easily be measured. (5) The constructed probes are easily adaptable to existing commercial electrometers and thus do not need special electrometer systems for operation. (6) The construction design of the probes allow for radiation detection in both “edge-on” and “flat-on” sensor geometry profiles without firstly unseating the diamond sensor element from its original position within the probe housing before taking measurements. This feature makes

the probe physically more robust than the currently available ionization chambers. (7) The constructed probe is expected to find use for charged particles detection in the flat-on geometry and therefore may find application in electron and proton therapy as well. The probe with diamond as a sensing material thus has a further possibility of being able to replace the different ionization probes, currently needed to provide dose evaluation information.

5.10. Dose measurements

To determine radiation dose in Perspex material and hence the dose to glandular tissue, the constructed probe was inserted into the custom-made Perspex phantom. Varying thicknesses of Perspex were placed on top of the Perspex phantom and each time X-ray tube exposure was taken and the diamond probe response recorded. Exposure of the diamond probe with zero Perspex was also taken. The difference between the response with and without Perspex was calculated as the radiation dose to the Perspex material. In this measurement the diamond sensor was in "edge-on" geometry configuration. The calculated radiation dose for varying thicknesses of Perspex from the measurement has been plotted and compared with calculated radiation dose obtained from simulated studies. The results are presented in Chapter 6.

5.11. Effect of a breast compression plate on patient dose

The extent to which breast compression plate influences the radiation dose to patient has been assessed in this part of the study. Response of the diamond sensor to direct incident of photons was carried out with the Perspex cap or window of the probe removed. Varying thicknesses of Perspex were placed on top of the diamond; exposures were taken and the responses recorded. The assessment was conducted for different X-ray tube settings. It was observed that the 3 mm Perspex thickness commonly used as breast compression plate in mammography X-ray

examination reduces radiation dose to the patient significantly. For a 25 kVp examination, the reduction in radiation dose was found to be 23%. The radiation dose reduction for 26, 28 and 30 kVp examinations were found to be 21%, 16% and 14% respectively. The result from the evaluation is presented in Figure 5.24. The results obtained highlights the often forgotten role that a breast compression plate has in reducing the dose to patients and the degree to which it is reduced as a function of the tube voltage setting.

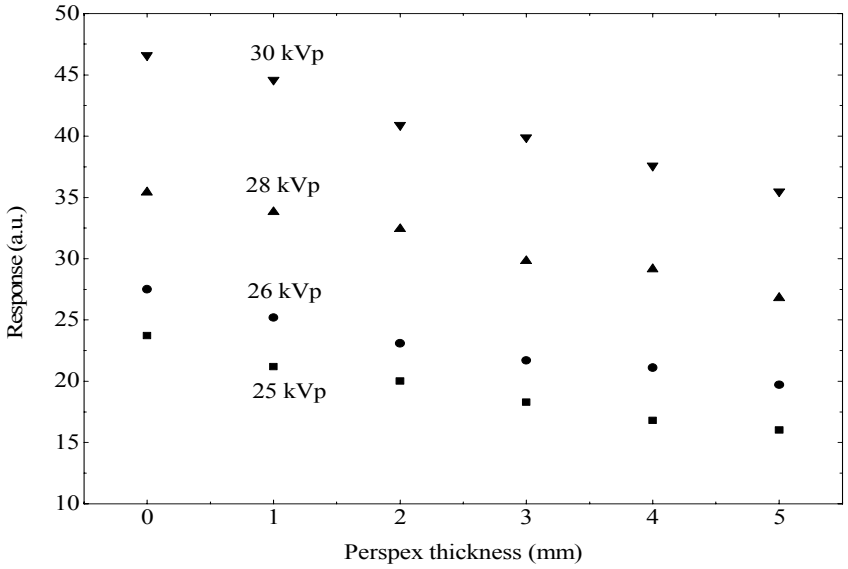


Figure 5.24: Response with small increment of Perspex thickness for different tube voltage settings. A tube loading of 200 mAs was used in all the measurements. Graph demonstrates the importance of breast compression plate in dose reduction.

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