Diamond Radiation Detectors

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1. Introduction

The purpose of this technical memorandum is to summarize the research on diamond radiation detectors. The use of these detectors in various applications is also discussed.

2. Principle of the Diamond Radiation Detector

The use of diamond in photoconductivity experiments began in 1923.[1] Since then advances in the technology used to metallize the diamond at the edges to enable electrical contacts has promoted the use of diamond as a photoconducting detector of radiation.[2-5] Extremely rapid turn-on and turn-off times (<100 ps) have been demonstrated with the use of fast x-ray excitation of the diamond detectors.[4,6] Recent advances in chemical vapor deposition (CVD) technology have enabled the production of diamond films of the quality (at least in terms of the electrical and thermal properties) of natural diamond.[6] Diamond has a large band gap, radiation hardness, large saturated carrier velocity and low atomic number. This makes diamond a very attractive candidate as a radiation detector. The most common diamond radiation detectors (DRDs) are in the form of two terminal electronic devices with a metal-insulator-metal (MIM) structure.[2] The insulator (diamond) is undoped and the metal caps form Ohmic contacts requiring no p-type or n-type junctions as is common with silicon based radiation detectors. Silicon cannot be operated with this structure because thermally generated leakage currents are high. These leakage currents in silicon are suppressed by the use of reverse biased junctions.

Diamond can detect any radiation (UV, x-rays, gamma rays, charged particles, neutrons, pions and other high energy particles) that generates free carriers (electron-hole pairs) in the diamond. The fundamental mechanism of radiation detection in diamond is independent of the exciting radiation as long as it is more energetic than the band gap in diamond (5.5 eV). Figure 1 shows a schematic of a MIM diamond detector. A high resistivity diamond is sandwiched between two metal electrodes connected to an external voltage to provide an electric field across the device. Mobile charges produced as a result of absorbed radiation drift in this electric field and generate a current in the external circuit. The basic physics of the device is well explained in

Ref. [3]. It is the fact the production of mobile charges in the diamond effectively reduces the resistance of the diamond that distinguishes it from silicon based detectors such as PIN diodes.

Because the sensitivity of the DRD depends linearly on the voltage applied across the device (for a given diamond thickness), DRDs exhibit a very desirable signal amplitude compression as the output signal approaches the DRD bias voltage. A simple algebraic correction can retrieve the effective signal which may be larger than the applied bias:

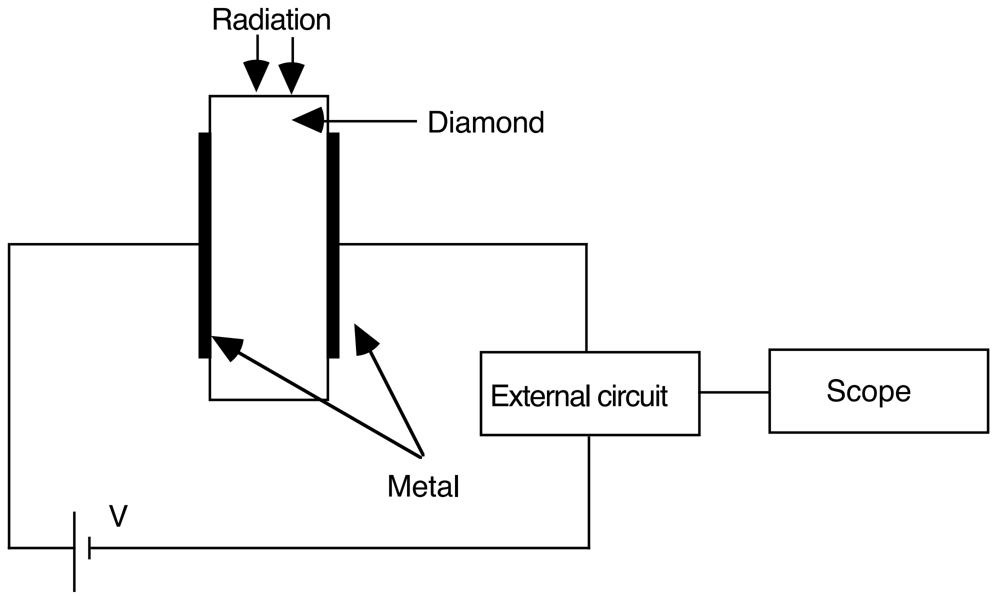

Figure 1: Schematic diagram showing a diamond metal-insulator-metal detector.

$$V_c = V_m / (1 - V_m / V_b) \quad (1)$$

where V_b is the applied bias voltage, V_m is the measured signal, and V_c is the corrected signal.[7] Thus even in cases where a signal may unexpectedly approach saturation, useful and accurate information may still be obtained. If the signal levels are small, sensitivity can be increased by increasing the bias voltage applied across the detector for a given detector thickness. Alternatively, sensitivity might be increased by reducing the detector thickness for a given bias voltage. The latter approach might be preferable since it keeps the bias voltage low and thus the electronics requirement for the dosimeter simple.

3. Applications

Diamond radiation detectors have been used in Nuclear Weapons Effects simulation at Sandia National Laboratory.[4,7] Time resolved measurements of the soft x-ray fluence from plasma radiation sources on Saturn were obtained using calibrated DRDs. These measurements show that the sensitivity of the DRDs is independent of the energy of the photons over a wide range of photon energies ranging from ≈100 eV through ≈5 keV.

DRDs have also been used to measure the intensity of x-rays emitted by synchrotrons.[3] These measurements consisted of both time integrated and time resolved measurements of the x-ray intensity. The time integrated measurements provide a monitor of the x-ray intensity as if it were emitted from a continuous source. The time resolved measurements have resolved the individual bursts of photons emitted with an x-ray pulse full width at half maximum ≈350 ps.

Diamond radiation detectors have also been successfully used to detect charged particles and energetic neutrons.[8] Both time resolved and time integrated (pulse counting) measurements have been made.

Diamond radiation detectors have the distinct advantage of being rugged and radiation hardened and require only a low DC forward bias voltage. Extremely simple circuitry is required to measure the signal generated in the diamond due to the radiation incident on it.

Recently Alameda Applied Sciences Corporation, in collaboration with Atomic Energy Canada Limited (AECL), has used diamond radiation detectors to measure the dose delivered by a 12 MeV electron accelerator at AECL. This accelerator is used at AECL for medical instrument sterilization. The electron beam is scanned to generate a beam size of 18 cm x 3 cm at 50% beam intensity (i.e. full width at half maximum). The dose/pulse was 0.5 kGy with a duration of 200 μs.

The diamond detector was biased positively and negatively with a dc voltage of 45 V. The peak signal produced by the detector (measured across a 50 Ω load) was identical for both bias polarities. Signal strength from the detector was linearly proportional to the accelerator beam current as shown in Figure 2. The beam current is proportional to the beam intensity showing that the diamond detector signal is linearly proportional to the beam intensity.

The dose rate at 95 mA beam current was 2.5 MGy/s. The measured signal of 850 mV across 50 Ω corresponds to 0.017 A. Therefore the sensitivity is 6.8 nA/Gy/s. A 100 Gy/s dose rate would then produce 0.68 μA. The dark current in these detectors at bias voltages ≈100 V is less than 0.1 nA, allowing an accurate measure of a dose rate as low as 100 Gy/s while also accurately measuring 2.5 MGy/s. The dynamic range of these detectors is thus very high. The question that remains is the stability of this response over time and with accumulated dose. It is these questions that the proposed research will answer.

The detector signal was Gaussian as shown in Figure 3 as the beam is scanned. The width of the signal indicates the size of the beam at the detector. Figure 3 shows the beam current (200 µs wide pulse) and the diamond response with a negative bias. The scan voltage was 75 V corresponding to a scan length of 18 cm. When the scanning length was increased from 18 cm to 60 cm the diamond signal full width at half maximum decreased inversely to 9.5 µs (shown in Figure 4).

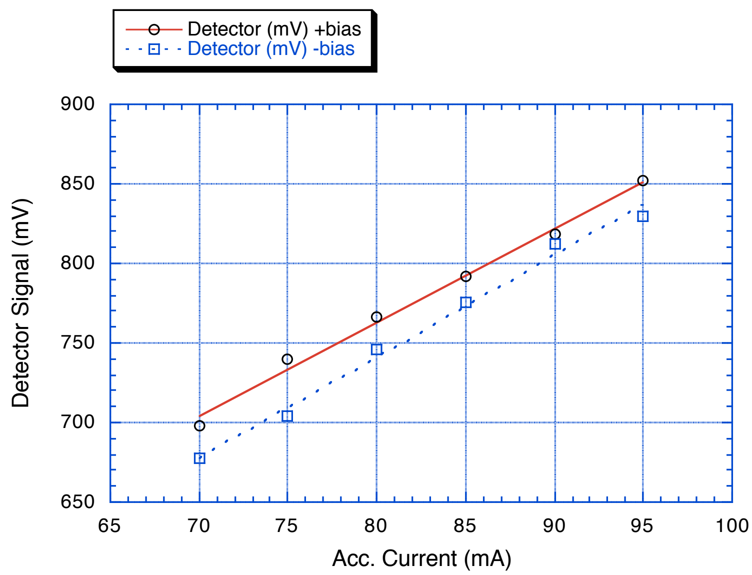

Figure 2: Diamond detector signal as a function of accelerator beam current for both positive (circles) and negative (squares) bias. The lines are the best fit. The signal strength is essentially the same for both positive and negative detector bias.

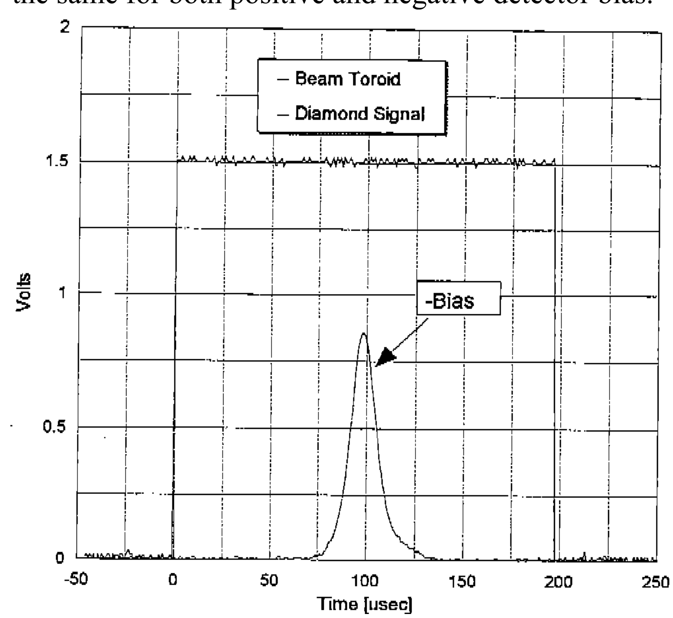

Figure 3: Temporal evolution of the diamond detector signal and beam current.

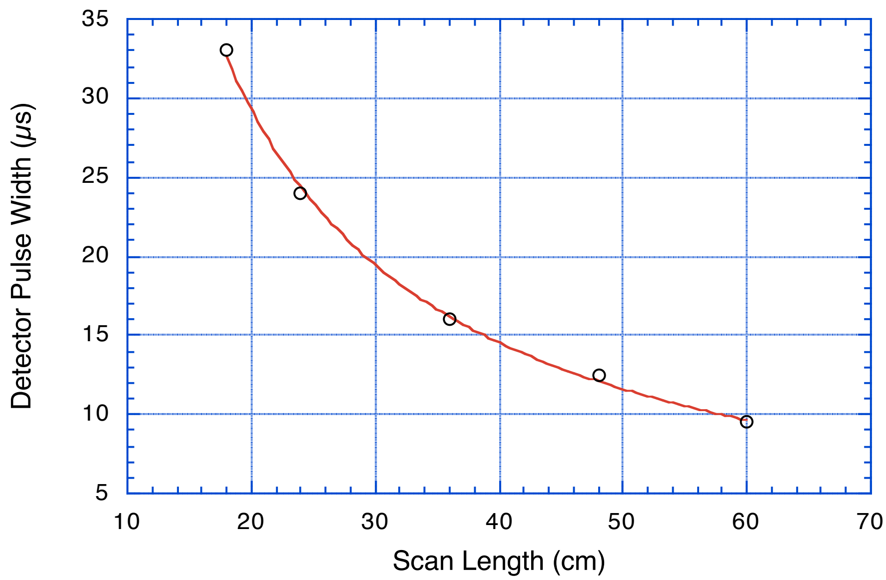

Figure 4: Diamond detector signal full width at half maximum as a function of beam scan length. The width decreases inversely with increasing scan length.

Due to the exploratory nature of these experiments the total dose accumulated on the detector was only 50 MGy. Over this dose the sensitivity of the detector did not change.

4. Comparison of natural and CVD diamond

Until recently the only form of diamond suitable for radiation detectors was natural Type IIa diamond that constitutes a large fraction of the cost of the detectors. However, recent breakthroughs in chemical vapor deposition (CVD) processes have led to the production of economical, large CVD diamond wafers with electronic properties equal to or surpassing natural diamond.[6] AASC has used some of this CVD material instead of natural Type IIa diamond for its soft x-ray radiation detectors. Dr. R. B. Spielman of Sandia National Laboratory agreed to test the response of both CVD and natural DRDs at his calibration facility using 1 keV x-rays. Figure 5 shows the data from both DRDs. The x-ray pulse was a little less than 2 ns wide, showing the fast response of DRDs. *No difference in the sensitivity and temporal response of the detector was measured in the soft x-ray region.* This bodes well for the potential of inexpensive detectors for several diverse applications requiring either time resolved or real time monitoring of the radiation environment.

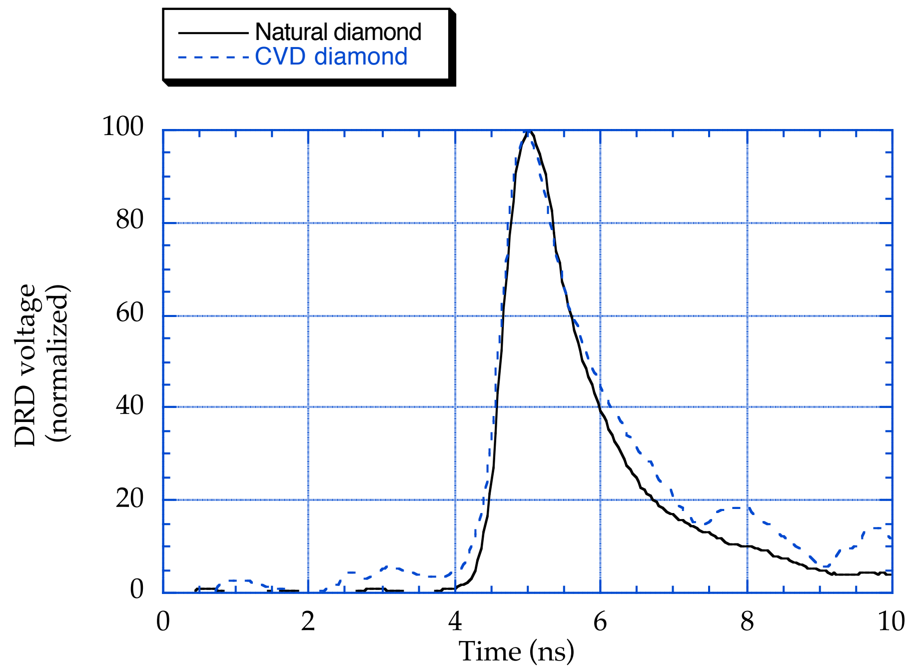

Figure 5: Normalized trace of the voltage developed across a 50 Ω resistor in series with two diamond radiation detectors. The detectors were viewing the same 1 keV x-rays from a laser produced plasma source. Tektronix 5 GHz digitizers were used to capture the traces. These traces are reproduced with the kind permission of Dr. R. B. Spielman of Sandia National Laboratories.

5. AASC Detectors

Figure 6 shows a photograph of an AASC diamond radiation detector used for soft x-ray intensity measurements. The detector is mounted in the MIM configuration shown in Figure 1.

The following are typical specifications of diamond radiation detectors used in UV to soft x-ray (≈4 eV - 5 keV) flux measurement applications. Custom detectors with different specifications can be provided, if needed. Detectors are also available for measuring charged particle and energetic neutron fluxes.

Diamond Radiation Detector property	Value
Area of sensor	3mm x 1mm (Smaller and larger areas can be provided)
Thickness of detector	1 mm
Sensitivity to 100 eV - 5 keV photons	4 - 7 x 10^{-4} A/W (for 100 V bias)
Detector mount	SMA (smaller profile connectors available on request)

Figure 6: Photograph showing a diamond radiation detector. The diamond element is mounted within an SMA connector.

Diamond radiation detectors can be provided with all biasing and digitizing electronics for a complete turnkey system, based upon the customer's needs.

References

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