1 Rate Dependence, Polarization, and Light Sensitivity of 2 Neutron-Irradiated scCVD Diamond Sensors

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7 Abstract

We study the dependence of the charge-collection-efficiency, or CCE, on the rate of charged particles impinging on neutron-irradiated single-crystal Chemical-Vapor-Deposition (scCVD) diamond sensors. These effects are not observed in un-irradiated high quality scCVD sensors. The rate dependence appears to be associated with the build-up of an electric field opposing the applied charge-collection field in the sensor. We find that exposure of the detector to red or near-IR light reverses this effect on the CCE during operation.

8 *Keywords:* Diamond detector, Radiation damage, Polarization,
9 Optoelectronic properties

10 1. Introduction

11 Chemical-Vapor-Deposition (CVD) diamond sensors are widely considered
12 suitable for charged particle trackers in environments where the long-term and
13 short-term radiation dose is quite high, such as experiments at the proposed
14 High-Luminosity Large Hadron Collider (HL-LHC) [1, 2]. While some reduction
15 in collected charge is expected due to Non-Ionizing-Energy-Loss (NIEL) damage
16 of the diamond lattice, models and some data [3, 4] indicate that the fractional
17 signal loss will be less for diamond than for similar silicon sensors exposed to
18 the same dose of hadronic radiation.

19 On average 36 electron-hole pairs are produced per micron of diamond sensor
20 traversed by a minimum-ionizing particle (MIP) [1]. For polycrystalline CVD
21 (pCVD) sensors used in typical applications only one-third to one-half of the
22 signal expected from the electron-hole pairs is collected, as charge trapping
23 occurs on domain boundaries and other sites. In contrast, full signal collection
24 is possible from single-crystalline CVD (scCVD) diamonds. Before radiation
25 damage, detector-grade scCVD sensors achieve full signal collection very quickly,
26 with applied fields of $\sim (0.2-0.4 \text{ V})/\mu\text{m}$. As a result there has been considerable

27 interest in scCVD diamond sensors since they became commercially available
28 about a decade ago.

29 Concurrent with the research reported here, the CMS experiment at the
30 LHC reported unexpected degradation of charge collection from pCVD and sc-
31 CVD diamond sensors which were exposed to large particle fluxes near the LHC
32 beam [5]. This was particularly evident in detectors that were placed in regions
33 of the CMS detector with increased albedo neutron contributions to the radi-
34 ation [5]. Since irradiation of diamonds by neutrons is less well studied than
35 that by protons, and the observations by CMS suggest that neutrons are a
36 main source of damage, we study scCVD diamonds irradiated with neutrons
37 from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Labora-
38 tory (ORNL) [6]. We exposed detectors to several well reproduced fluences of
39 neutrons with energies ranging from 0.5 eV to about 10 MeV.

40 Highly energetic particles introduce lattice defects that can trap charge car-
41 riers, thus reducing carrier mean-free-path and the charge-collection-efficiency
42 (CCE). The passivation of these traps is possible through the technique of pump-
43 ing, in which some of the charges liberated by ionization are absorbed by traps
44 and neutralize them [7]. While this passivates the trap from absorbing further
45 charge, this process changes the internal electric field of the diamond [8]. Al-
46 though traps are distributed throughout the lattice, electrons are more likely to
47 fill electron traps near the positive electrode in the presence of an applied elec-
48 tric field. The same applies to holes and hole traps near the negative electrode.
49 This space-charge accumulation creates an internal electric field which opposes
50 the applied electric field. This effect is often referred to in the literature as po-
51 larization¹. We use this terminology throughout the paper. It is also referred
52 to as memory effects in the literature and has been known to cause signal insta-
53 bilities in low quality pCVD diamond [9, 10]. The ionization and recombination
54 rates at trapping centers, which may or may not be in equilibrium, determine
55 the polarization field strength; thus polarization is rate dependent and often
56 dynamic. As such, we probe CCE as a function of the test source's rate.

57 It is difficult to operate a high-energy physics experiment in which a detector
58 is very sensitive to the ambient radiation environment, as this can change very
59 quickly. The detector should have a reasonably constant (and high) efficiency
60 over a continuous data-taking period that might last hours or days. At the
61 HL-LHC, the innermost tracking sensors will need to operate (with degradation
62 in signal) in a hadronic radiation of $\sim 2 \times 10^{16}$ n_{eq}/cm² over a ~ 10 year
63 period. Much of this radiation will be charged protons and pions, so these
64 detectors will see charged particle fluxes of tens of MHz/cm². While such rates
65 are not available in our laboratory, we report significant changes in the CCE of
66 irradiated scCVD sensors of the type proposed for use in, for example, the CMS

¹This is not the “classic” dielectric polarization, also found in diamond, which goes to zero as the applied electric field goes to zero. This polarization is believed to be associated with the filling and emptying of traps. It appears to be dynamic (time and rate dependent) at the same applied external electric field, and can persist when the applied field goes to zero.

67 Pixel Luminosity Telescope (PLT) [11, 12], when exposed to tens of kHz/cm^2
68 or less of ionizing radiation.

69 This paper primarily reports the results from one detector-grade scCVD sen-
70 sor, manufactured by Element Six [13] and polished and first metalized by Dia-
71 mond Detectors Ltd [14]. This sensor, referred to as M4, was well-characterized
72 before its first irradiation of 1.1×10^{14} “broad-spectrum” (between 0.5 eV and
73 10 MeV) neutrons/ cm^2 at the HIFR. After this irradiation, M4 was remeasured,
74 re-polished, and re-irradiated with neutrons at the HIFR, to a total exposure
75 of 4×10^{14} neutrons/ cm^2 . Even unirradiated, no two Element 6 scCVD sen-
76 sors behave exactly the same. However, the behavior observed in the M4 sensor
77 has been qualitatively reproduced with several other neutron-irradiated sensors.
78 The discussion of these results is left for Section 7.

79 Ideal diamond, with a band gap of 5.5 eV, should be visible-light blind. Yet
80 current manufacturing techniques do not produce such an ideal diamond. Hence,
81 there could be defects in scCVD sensors which might be photo-activated [10].
82 The sensitization of pCVD diamond to blue light has been extensively studied
83 in [15], yet a study of light’s effect upon single crystal diamond has yet to be
84 completed. We investigate the CCE of scCVD diamonds as function of light
85 illumination with different wavelengths and intensities before and after neutron
86 irradiation.

87 We use CCE as our standard charge measurement, given in terms of charge
88 collection distance (CCD) as $\text{CCE} = \text{CCD}/t_S$, with t_S the physical thickness
89 of the detector. The CCD is related to the mean-free-path (MFP) of charge
90 carriers in the bulk material: when the MFP is infinite, the CCD is just the
91 thickness of the sensor and thus $\text{CCE} = 1$, while for $\text{MFP} \ll t_S$, the CCD is
92 approximately the MFP. The average charge collected, in number of electrons,
93 is just the CCD (in μm) multiplied by 36 electrons/ μm . If not stated otherwise,
94 the electric field applied to collect the charge (from which the CCE is calculated)
95 is $\pm 1\text{V}/\mu\text{m}$.

96 2. Apparatus and Technique

97 For the irradiation of the diamond detectors at the HIFR, the detectors were
98 positioned in a “rabbit” and delivered close to the reactor core in a pneumatic
99 tube. To achieve well-controlled fluences, the necessary irradiation time was in-
100 creased by operating the reactor at 10% of its nominal power, resulting in about
101 10% of the nominal neutron flux. The neutron energy spectrum was predicted
102 using MCNP code [16] and several activation probes were deployed before, after,
103 and during the actual diamond irradiation to obtain measurements for compar-
104 ison with the simulation. The agreement between the predicted and measured
105 probe activities was found to be within 5%. The neutron energy spectrum was
106 cut off below 0.5 eV by inserting a cadmium lining in the rabbit. The average
107 orientation of the diamond detector was measured from the difference in acti-
108 vation of gold wires placed in four equiangular positions around the diamond
109 with an uncertainty of less than 3 degrees. For the diamond probes presented
110 here, the angle was near perpendicular incidence to within 10 degrees.

Our laboratory setup for measuring CCE follows an established recipe [1, 2]. A collimated ^{90}Sr source is placed above the sensor and a scintillation counter is placed below. The sensor is held in place by copper annular electrodes, so that only highly-energetic electrons, following a direct path from the source to the scintillator through the diamond, register in coincidence between diamond and scintillator. This path is approximately parallel to the diamond's thinnest direction. An external voltage is applied to the sensor through very thin metallic films that have been deposited on both sides of the sensor.

These films are in “press-fit” contact with the annular electrodes. The voltage is applied to the diamond through one electrode, and the signal induced on the other electrode by liberated electrons and holes is capacitively-coupled out of the electrode on the other side, which is nominally at ground. Our typical film pad consists of 50 nm of Chromium evaporated onto the clean diamond surface, followed by 150 nm of Gold evaporated onto the Chromium “dots.” We have also studied sensors that have been “metalized” with similar thin films of Diamond-Like-Carbon/Platinum/Gold (from DDL) and Titanium/Tungsten (the standard PLT metalization) and find negligible difference in the charge collection properties of the sensors, provided that the metal pads have been properly applied.

The scCVD sensors are typically 500 μm thick, so virtually all decays of the ^{90}Sr β -decay electrons stop in the sensor. There are essentially as many ^{90}Y decays as ^{90}Sr decays, and the ^{90}Y β -decay electron has a much higher end-point kinetic energy (2.283 MeV). Calculations based on the ^{90}Sr and ^{90}Y β -decay spectra in [17] and the CSDA Range for electrons in diamond from [18] show that $\sim 80\%$ of the ^{90}Y β 's will pass through 500 μm of diamond. However, some fraction of these will range out in the thin metal pads on the diamond and in the tape and foil covering the scintillation counter.

The ^{90}Sr sources we use have strengths of 0.1 MBq and 30 MBq. Throughout this paper we will refer to these sources as the “weak source” and the “hot source.” The aperture of the annular electrodes at the sensor is 2.3 mm^2 , and the trigger rate from the scintillation counter is ~ 1.5 Hz for the weak source and ~ 420 Hz for the hot source. Thus, the intensities of MIPs at the sensor are about 100 Hz/ cm^2 and 20 kHz/ cm^2 for the weak and hot sources, respectively, with real rates at the sensors about a factor of four higher than this due to stopping ^{90}Sr and ^{90}Y electrons which do not trigger the data acquisition (DAQ). The stopping electrons do not exactly mimic MIPs at the LHC, which deposit charge uniformly throughout the sensor, but they do deposit more charge per β entering the diamond than a MIP.

The individual pulses from the sensors are read out through an ev-5093 charge sensitive preamplifier [19], which produces a voltage step proportional to the charge in the pulse. The preamp output is then shaped by a differential pulse-shaper (ev-5137 or CR-200), so that the area of the pulse output by the combined preamp/pulse-shaper is proportional to the charge deposited in the sensor. The typical calibration of our system is such that 160 nV $\cdot$ sec is equal to 500 μm of CCD, or 18,000 e^- . The gain of the preamp is monitored by a step pulse input through a 1 pF capacitor, and the absolute calibration is given by

unirradiated scCVD diamond sensors which have been cross calibrated against silicon PIN diodes.

Using the scintillation counter as an external trigger, a LabVIEW DAQ program reads in the pulses, integrates the waveform, and records the charge in $\text{nV} \cdot \text{sec}$. The DAQ writes the average (and r.m.s.) charge in 1000-10000 pulses to a disk file and accumulates histograms. To compensate for noise which occasionally appears in the system, we integrate for a time of 2550 nsec after the trigger *and* 2550 nsec before the trigger, and take the charge in the signal as the difference in these integrals. This also compensates for any constant voltage offset from the pulse shapers. Indirect scatters, cosmic rays, and tube noise can cause false triggers from the scintillator. These false triggers are removed by a simple threshold cut prior to data processing and CCE calculation. The average charge without a threshold cut is also retained, so if any change in the false trigger rate is detected, this data (properly corrected) can also be used for the charge measurement.

One advantage of this DAQ is that, if the voltage is reduced to 0 V but the DAQ is left running, and opposite sign pulses due to sensor polarization appear, these pulses are integrated and recorded just as the correct sign pulses are. If nothing else changes in the set-up, the false trigger rate remains the same, so one can compare the (opposite sign) CCE due to polarization with the normal CCE due to the applied electric field. A similar technique for measuring polarization is used in [20].

When the polarization field is still strong enough to influence charge transport, the sensor can retain its polarization field even after removal from the test electrodes. We have observed that reinserting the sensor reversed in the electrodes causes the polarization pulses to flip sign. We have also observed this polarization independent of the type of metal pad used to couple the signal out of the sensor; it has been observed with Chromium-Gold, Titanium-Tungsten, and Diamond-Like-Carbon/Platinum/Gold.

3. Light Sensitivity of Un-irradiated scCVD Diamond

A typical unirradiated scCVD sensor produces close to 100% CCE at applied fields of $1 \text{ V}/\mu\text{m}$, and often even at voltages significantly lower than this. The acceptance criteria for PLT sensors was that they reach their CCE plateau by $0.4 \text{ V}/\mu\text{m}$ for one polarity of applied voltage, they reach CCE plateau for the other polarity by $0.6 \text{ V}/\mu\text{m}$, and they have a leakage current of $< 1 \text{ nA}$ at $1 \text{ V}/\mu\text{m}$.

As an example of the PLT acceptance criteria, the CCE versus Voltage curve for M4 prior to neutron irradiation is shown² in Fig. 1. The original thickness

²In most figures such as Fig. 1, the point-to-point errors are smaller or on the order of the symbol size and so are suppressed. On many of the time series plots, there are many adjacent points and the spread of the data is apparent. The errors quoted on quantities in the text, such as CCE, are dominated by common errors such as the scale uncertainty on the charge calibration.

195 of this sensor was $525 \pm 5 \mu\text{m}$. This sensor easily passes the PLT acceptance
 196 criteria because it had full CCE for both polarities by 50 V.

Figure 1: The CCE vs Voltage curve for the M4 sensor before neutron irradiation (left plot). The blue squares are for positive voltage and the red triangles are for negative voltage. The plot on the right is the CCE of the unirradiated M4 sensor at $+1.0 \text{ V}/\mu\text{m}$ (blue squares) and $-1.0 \text{ V}/\mu\text{m}$ (red triangles) when exposed to different intensities of 473 nm blue laser light. Color versions of the plots are available in the online version of the paper.

197 With such excellent performance as compared to pCVD sensors, it is tempt-
 198 ing to think of detector-grade scCVD sensors as ideal diamond sensors. However,
 199 typical scCVD sensors have a greater density of dislocations than the HPHT
 200 (high pressure high temperature) diamonds on which they are grown, though
 201 they have a much lower nitrogen content than these HPHT “seed” diamonds.

202 These dislocations do not cause a noticeable detriment to CCE in unirra-
 203 diated detector-grade scCVD sensors. They do, however, create energy levels
 204 and trap states within the diamond’s bandgap [10]. Although the arrangement
 205 and density of defects varies greatly between scCVD and pCVD diamonds, the
 206 constituents (Nitrogen-Vacancy centers, etc.) can be the same. For this reason,
 207 past pCVD diamond research could provide useful directions for the study of
 208 scCVD diamond, especially in the case of irradiated scCVD, since irradiation
 209 induces defects.

210 In particular, two groups working to improve pCVD diamond CCE pub-
 211 lished results showing that visible spectrum light illumination (specifically blue
 212 light [15] or white light [9]) could improve detector CCE. Hence, we under-
 213 took a long term investigation of the effects of light on CCE performance for a
 214 monocrystal subjected to stages of irradiation.

215 While the diamond is positioned in the testing apparatus, a light source
 216 illuminates an exposed side of the diamond. For initial light tests we utilized a
 217 473nm blue light laser whose intensity could be varied.

218 The results shown in Fig. 1b are remarkable considering that high quality
 219 scCVD diamond sensors are often advertised as ‘light blind.’ The M4 sensor,

as well as several other Element Six scCVD diamonds we tested, shows a loss in CCE with increasing blue light intensity. This occurs for both polarities of applied voltage. UltraViolet light is also found to cause CCE loss.

4. Irradiation of Samples and Rate Dependence

After characterization in its unirradiated state, the M4 sensor was sent to Oak Ridge National Laboratory for an irradiation of 1.1×10^{14} neutrons/cm². After the irradiation, the sensor CCE was remeasured and as expected, it suffered a CCE loss. However, as not expected, the sensor CCE also acquired a rate and time dependence. As seen in Fig. 2, while CCE prior to irradiation was stable, after irradiation the CCE sagged considerably over the course of a test. The figure also reveals the rate dependence of this CCE reduction. Thus the β 's used to measure CCE appear to “depump” the diamond, taking a couple hours for the hot source, and days for the weak source.

Figure 2: Comparison of M4 detector charge collection before and after irradiation, at a bias voltage of 1 V/ μ m. The green squares represent the stable, $\sim 100\%$ CCE signal under the weak source before irradiation. Both blue triangles (weak source data) and red stars (hot source data) represent the signal after irradiation.

Testing revealed that the irradiated M4 sensor could only be pumped³ without applied voltage. Although this pumping improved the initial CCE at voltage, the diamond began to depump as soon as beta particles traversed the diamond with the voltage applied. However, if this depumping is due to the build-up of a polarization field which opposes the applied field, the polarization

³The terms “pumped” or “fully pumped” imply that the diamond responds with its maximum achievable CCE at a particular voltage. We found this could easily be reached by exposure of the sensor to the hot source for an hour with no applied voltage.

field will be oriented with the applied field once the applied voltage polarity is flipped. We observed that the diamond responded with its fully-pumped CCE after the polarity had been flipped (Fig. 3). Figure 3 also shows that depumping then began immediately at the flipped polarity. This behavior has also been reported in [5]. Since some pixel sensor electronics only operate at one polarity, it is worth noting that oscillations between $1 \text{ V}/\mu\text{m}$ and 0 V also impart a similar effect.

Figure 3: The M4 sensor subjected to voltage cyclings of 10 minute periods between 500 V and -500 V with the hot source. Negative polarity data is shown as positive CCE, and positive polarity data is shown as $-1 \times \text{CCE}$ in this plot. CCE loss occurs until the voltage is flipped.

5. Polarization in Irradiated Diamond

As mentioned in Sec. 2, the “inverted” CCE due to the polarization field can be measured by reducing the applied voltage to zero and allowing the polarization field to influence charge transport. The weak source is always used in these measurements, as the hot source quenches the polarization within minutes. As also mentioned earlier, unirradiated scCVD sensors do not need pumping to reach their full CCE, and polarization does not appear to impact their CCE.

We use the variable CCE^* when referring to the CCE observed during polarization tests. Signal measurements due to an applied field are signed positive. However, when the applied voltage is then set to zero, the polarization signal we observe is of the opposite polarity to that collected when the applied voltage is on. Here the polarization CCE (CCE^*) is signed negative. This implies the polarization field is the opposite polarity of the applied voltage, and thus the movement of carriers is reversed. We use CCE^* in Figures 4, 5, and 7.

Unirradiated sensors typically have a “polarization CCE” of $\leq 10\%$ of the normal full-voltage CCE, and this dissipates in less than a half-hour under the

261 weak source (Fig. 4). However, in post-irradiation tests, both the form and mag-
 262 nitude of the polarization signal show significant change. It can persist for days
 263 and can for short periods even exceed the CCE measured at voltage. Further,
 264 Fig. 4 shows the polarization CCE increases for several hours before diminish-
 265 ing. There also exists a correlation between the length of time the detector is
 266 under test with the hot source at voltage and the maximum polarization CCE
 267 measured after the voltage is removed, as seen in Fig. 5.

Figure 4: An example polarization measurement of the irradiated M4 sensor: up to time 0, CCE data is taken with the hot source, then at time 0, the voltage is turned off and the weak source is used to measure the CCE* (described in text) of the polarization field (blue triangles). The green squares correspond to a run taken before the irradiation of M4, and are included to show the typical polarization of an unirradiated sensor (though here, the weak source is used both before and after time 0).

268 Although polarization builds up quicker with the hot source than with the
 269 weak source, the dissipation of polarization at 0 V is also quicker with the hot
 270 source. Deposited charge will respond to the applied voltage while it is on, but
 271 without voltage, charge responds to the polarization field and acts to neutralize
 272 it. Thus the behavior seen in the voltage cycling test of Fig 3 depends on
 273 the rearrangement of the polarization field which occurs with each flip of the
 274 voltage.

275 6. Polishing and Additional Irradiation

276 It is possible that the rate dependence is due to irradiation-induced surface
 277 defects. To test this, the M4 sensor was sent [21] for a light surface polish ($\sim$
 278 $25\ \mu\text{m}$ was removed from each side), and received a new (Cr/Au) metalization.
 279 As seen in Fig. 6 the CCE still sags under the hot source, though it maintains
 280 a higher depumped CCE. The polishing may have removed radiation-induced
 281 surface defects which are prone to depumping. However, the increase in CCD

Figure 5: Longer operation at voltage (negative voltage on left and positive voltage on right) with the hot source results in a greater polarization build-up, as measured with the weak source. In the plots, the red stars correspond to ~ 10 minutes of hot source exposure, the violet triangles to ~ 20 minutes of hot source exposure, the green dots to ~ 100 minutes, and finally ≥ 1000 minutes for the blue squares. As in Fig. 4, Time=0 is when the applied voltage is set to zero and we begin observing the polarization signal.

due to polishing is so large that other effects, such as annealing of the sensor, may have occurred during polishing.

Polishing did not remove the polarization (Fig. 7). The polarization curves before and after polishing look nearly identical. This is evidence that polarization is in part a bulk effect. In addition, the same amount of polarization build-up does not cause the same amount of CCE loss. Although polarization may be associated with irradiation damage, it does not directly cause depumping susceptibility.

A subsequent irradiation of 3×10^{14} neutrons/cm² (for a total of 4×10^{14} neutrons/cm²) revealed similar results, albeit with even greater CCE degradation (Fig. 8). Given the continuous radiation damage a sensor near the beam line at the HL-LHC will see, the improvement from polishing is only transitory, and so not a practical remediation technique. Polarization after the second irradiation takes the same form as before, though the overall lowering of detector CCE seems to cause an analogous decrease in polarization CCE.

7. Light Sensitivity of Irradiated scCVD Diamond

Polarization-induced CCE loss was the primary motivating factor for the light sensitization studies discussed earlier [9, 7]. Since polarization becomes a noticeable feature after irradiation, it was hypothesized that this same method may work in scCVD diamond.

Colored LEDs were used to measure the response of the M4 sensor's CCE to light illumination. As seen in Fig. 9a, white light only imparted a slight

Figure 6: Comparison of the M4 sensor's CCE under the hot source, after first irradiation (red triangles) and after subsequent re-polishing (blue squares).

Figure 7: The polarization signal, in CCE^* , after operating the M4 sensor at $1 \text{ V}/\mu\text{m}$ with the hot source, measured after the first irradiation (left), post-polishing (center), and after the second irradiation (right). The polarization following negative (positive) voltage is given in red triangles (blue squares). While the polarization is induced with the hot source, the polarization measurement data, as usual, is taken with the weak source, and Time=0 corresponds to the applied voltage being set to zero and the sources swapped.

Figure 8: Comparison of M4 detector charge collection under the weak source before irradiation (green squares), after the first irradiation but before polishing (blue triangles), and after polishing and the second irradiation (red stars).

increase of CCE. The blue band of light previously shown to improve pCVD performance [15] also improved CCE, but not as significantly as red light. The red to near IR wavelength range was found to give the greatest improvement in CCE. The CCE improvement for 645 nm red light plateaus above 1 mW/cm^2 (Fig. 9).

Overall CCE stability is also improved, as evidenced in Fig. 10, although a slight rate dependence does persist. Almost no CCE reduction occurs with the weak source, even with one day of exposure. The hot source still induces a small initial CCE loss followed by signal stability. With red light illumination, the M4 sensor's CCE behaves approximately as NIEL predicts.

These results have also been further corroborated with two other neutron irradiated monocrystal sensors. These sensors are referred to as S122 and S132, and have irradiation doses of $3 \times 10^{14} \text{ n/cm}^2$ and $0.5 \times 10^{14} \text{ n/cm}^2$, respectively. They were irradiated in the same ORNL facility and with the same neutron energy spectrum as seen by M4.

Every significant aspect of the M4 characterization discussed in this paper (polarization, rate dependence, etc) was duplicated with S122 and S132. The decay of CCE in the dark under hot source exposure, and its repeated recovery when the red LED is turned on, is shown in Fig. 11 for S132. The red light effect on M4, S122, and S132 is shown in Fig. 12 as a function of radiation dosage.

8. Discussion and Conclusions

We conclude by stressing the practical features of this research, while noting that much remains to be discovered of the physical mechanisms at work.

Figure 9: (Left) Comparison of the M4 sensor's CCE augmentation due to illumination with different wavelengths of LED light. The symbol for white light CCE is two white squares connected by a line, denoting the spectral range of the white light we used. Intensity was varied for each wavelength; the largest attainable CCE for each wavelength is plotted. (Right) The M4 sensor's CCE as a function of the intensity of the illumination with 645 nm red LED light. Both plots record the M4 sensor's asymptotic CCE under illumination and the hot source, after the sensor is first depumped in the dark with the hot source.

Figure 10: Comparison of M4 detector operation with (red triangles) or without (black squares) red light illumination. Weak source data is at left and hot source is at right. In both cases the red light improves and stabilizes CCE, though a slight rate dependence persists.

Figure 11: The CCE of the 5×10^{13} n/cm² irradiated sensor (S132) under the hot source, exposed to 645 nm, 4 mW/cm² red light (red triangles) and in the dark (black circles). The sensor's CCE drops from the pumped state under the hot source, until the red light is turned on, effecting an increase of CCE back to the pumped level. As soon as the light is removed, the sensor depumps again.

Figure 12: The pumped (black), depumped (green), and red-light-illuminated (red) CCEs for M4 (squares), S122 (triangles), and S132 (circles) are shown at their respective irradiation doses. The data at 11×10^{13} n/cm² are from the first irradiation of M4. Since the red light effect was not known at the time these measurements were taken, there are only pumped and depumped data points at this dosage. All data were taken with the hot source.

Polarization in the M4 sensor has changed dramatically with neutron irradiation. While any polarization in the unirradiated sensor was small and had no apparent effect on its CCE, very large polarization build-up occurs in the irradiated diamond in addition to the expected NIEL CCE loss. In the simplest view, as discussed in [9], polarization is due to the non-spatially uniform distribution of charge in the sensor's traps. New traps have been created by irradiation, and these traps have changed the charge transportation in the monocrystal sensor in a dynamic way, and not merely reduced its CCE.

The next obvious conclusion is that irradiation has impacted pumping behavior, and this has induced a rate dependence in the CCE. Prior to irradiation, the M4 sensor had no need for pumping and no rate dependence (or depumping) at voltage. After irradiation, pumping of the sensor with an applied voltage causes polarization which acts to counter the applied electric field. The neutralization of traps by pumping is still achievable at 0 V, but this pumped state does not persist. The pumped sensor will polarize again when operated at voltage.

However, we have shown that a light source can be used to mitigate these effects. Light proves to be as essential to irradiated scCVD diamond CCE as pumping is for polycrystals. Illumination of the red/near IR wavelength spectrum during operation minimizes the CCE reduction associated with polarization build-up in irradiated diamond. The installation of rad-hard LEDs, or laser light carried by optical fibers, could prove a simple remediation technique, but this, like HV cycling, might prove difficult or impossible to implement at a hadron collider such as the HL-LHC. Surface treatments such as polishing require physical repairs to damaged diamonds. These are only viable if the radiation damage that causes the polarization is a surface damage, and if it does not recur after repair with additional radiation doses.

Due to the discrepancies between the work of Souw [9, 10], Manfredotti [15, 7] and our own, we doubt this research applies to all types of irradiated diamonds. Both the irradiated CCE instabilities and the success of red light are most likely due to the diamond's composition. Others on CMS, testing similar diamonds, have seen effects like the ones we observe [5].

Further improvements in CVD production techniques will be necessary if single crystal diamond sensors are to replace silicon sensors as tracking detectors in experiments where they will be exposed to large hadronic radiation damage. Diamond sensors which do not suffer radiation damage beyond what NIEL predicts, which we can achieve with red light illumination, would be sufficient. The fact remains that the polarization we and others observe is reversible under light illumination, and the optimum wavelength of the light necessary to reverse it is discernible. These are important clues to finding the cause of this behavior and hopefully changing the manufacturing process to improve the sensors.

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