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Neutralizing the polarization effect of diamond diode detectors using periodic forward bias pulses

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ABSTRACT

A new technique for neutralizing the polarization effect of diamond detectors has been demonstrated. The technique, which relies on the diamond detector to be configured as a diode, is to periodically pulse the diamond diode with forward bias. A ^{210}Po alpha source was used to induce the polarization effect for a thin PIN diamond radiation detector. Results show that for a single forward bias pulse, a forward current of about 60 nA applied for 1 s removes the polarization buildup. The benefits of using this technique add significant value to the diamond diode configuration.

1. Introduction

To date, fabricating diamond detectors to have diode electrical properties has been seen as a mostly unnecessary step. Silicon detectors are made into diodes so that an electric field can be placed across the device without generating a current. Diamond, thanks to its wide bandgap, has a resistivity large enough that an electric field can be placed across the diamond without generating a current, allowing for a simple metal-insulator-metal (MIM) structured detector. The advantages of using diamond diode as a detector include the following: external bias for thin devices is not required allowing for more compactness and lower noise, a reduction of leakage current at high temperatures [1], and medical applications where close proximity to patients or in vivo devices is required [2]. Thin diamond detectors are of particular interest in slow neutron detection since they are nearly insensitive to gamma-rays [3]. Another reason for using a diamond diode detector, which is presented in this work, is that it allows for a new technique for addressing a common problem with diamond detectors, the so called polarization effect.

One of the major limitations of diamond detectors is the polarization effect. During irradiation, electrons and holes are created and begin traversing the diamond, some being trapped by defects resulting in a buildup of negative net charge near the (+) electrode and positive net charge near the (−) electrode leading to a reduction in the field strength across the diamond. Polarization buildup is a relatively slow process that depends on the detector flux [4], the diamond quality [5], and the electric field across the diamond, usually occurring over seconds or minutes until finally stabilizing once the rate of trapping matches the rate of detrapping. Also, the polarization effect becomes more pronounced as diamond detectors are damaged by radiation [6]. The polarization effect in diamond and many other wide bandgap semiconductors, including for example CdTe [7] [8] and CdZnTe [9] [10], will play an important role in the viability and implementation of these detectors.

Polarization can be minimized in an MIM diamond detector using a variety of techniques previously mentioned in other studies including: heating the detector [1] [11], alternating the bias polarity [12] [13], setting the bias off and waiting [14], and illuminating the detector with light [15] [16]. These methods for reducing the effect of polarization can be effective depending on the application, but may be difficult to implement requiring careful observation of the signal returning to pre-polarized levels, a knowledge of pre-polarized signal levels, and a time period of minutes or tens of minutes to complete. For diamond diode detectors, a new method for removing polarization is introduced: periodically pulsing the diamond diode with forward bias. By forward biasing the diode, charge that has been trapped in the diamond is quickly swept away. The purpose of this work is to demonstrate a new technique: Using periodic forward bias pulses to neutralize the

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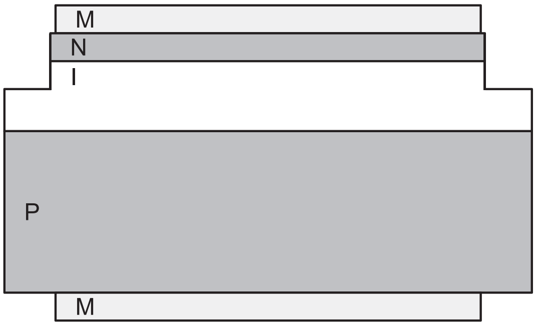

Fig. 1. The diamond PIN device structure (not to scale). M: metal, N: n-type layer, I: intrinsic, P: p-type layer.

polarization effect in a thin diamond PIN detector. This device is currently being developed as a thermal neutron detector [3].

2. Diamond PIN diode

A diamond PIN detector was fabricated with a 4.5 μm thick intrinsic layer. A 4.5 μm intrinsic layer was grown on top of a heavily doped p-type diamond (111) substrate using the CVD process. A 400 nm phosphorus doped diamond n-layer was grown onto the intrinsic layer. A partial mesa etch was used to restrict the perimeter of the n-type layer to be slightly beyond the metal contacts, thus preventing leakage current around the device during operation. The metal contacts are made from Ti(50 nm)/Pt(50 nm)/Au(150 nm) and have an area of about 2.5 mm × 2.5 mm. Fig. 1 shows a schematic of the diamond detector. An I-V measurement of the device, shown in Fig. 2, found the turn-on voltage to be about 4 V. A more complete description of the fabrication process and characterization of the diamond PIN detector is described in a previous work by J Holmes et al. [3].

3. Setup and methods

A ^{210}Po alpha source sealed with a gold foil was used for studying the polarization effect of the detector. Because the ^{210}Po is sealed within a gold foil with thickness 1.778 μm, the 5.3 MeV α-particles leave the source with about 4.5 MeV. The 4.5 MeV α-particles then pass completely through the 4.5 μm intrinsic layer depositing about 1.6 MeV into the intrinsic layer [3]. The alpha source was placed about 3.3 cm away from the detector inside a vacuum with about 50 mTorr pressure. The detector flux for each measurement in this work was approximately 460 cps. No collimation was used in order to have a sufficient flux, however the large distance from the detector helped to reduce the acceptance of α-particles with large angles. The detector was operated in

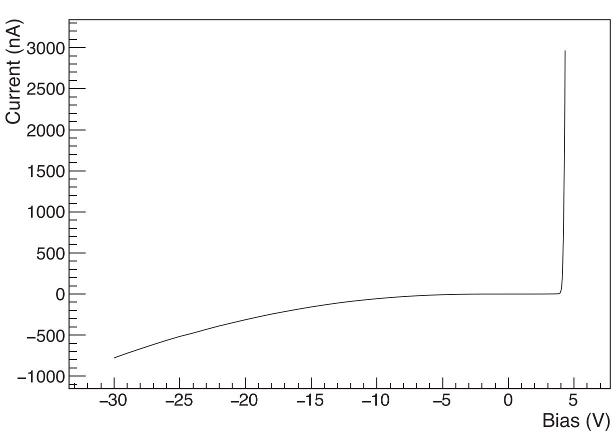

Fig. 2. The current vs. bias across the device with no radiation [3]. This diamond configuration has electrical properties consistent with a diode.

pulse-mode using an Ortec 142A charge integrating preamplifier and signals were fed into an Amptek 8000D MCA. See Fig. 3 for a schematic of the experimental setup.

For each measurement, as the diamond PIN detector was irradiated, a pulse height spectrum was collected in 6-second increments repeated 600 times giving a total measurement duration of 1 h. Fig. 4 shows a typical pulse height distribution for the sample diamond used in this study and the corresponding fit to a Gaussian curve to extract the most probable pulse height (charge deposited per α-particle). For constant bias, a Keysight U80002A power supply was used. For the periodic forward bias pulses, a Rigol DG1022U signal generator was used. The signal generator has a square pulse option where the period, duty cycle, and peak to peak amplitude are highly selectable. The n-side of the diamond diode was biased between 0 V and 30 V relative to the p-side (reverse bias is positive). The bias is coupled to the detector through an RC network located inside the Ortec 142A which has a resistance of 101.8 MΩ. The p-side was biased to ground and the response to the α-radiation from the ^{210}Po source was also measured from the n-side.

4. Forward bias pulse

The forward bias pulses in this work were implemented by setting the signal generator to periodically apply 10 V for 1 s. At all other times, the signal generator is set to a constant reverse bias. Since the signal generator is coupled to the detector through the bias filter, during a forward bias pulse the voltage across the diamond diode is equal to the turn-on voltage. The forward bias pulse current was measured using an Agilent 34410A multimeter to be 59 nA ± 2 nA. The current can be calculated as well, $(V_{supply} - V_{diode})/(R_{filter})$ = (10.0 V − 4.0 V)/(101.8 MΩ) = 60 nA. From the I-V data for the diamond diode, the forward bias at 60 nA is between 4.00 V and 4.05 V. Since each forward bias pulse has a 1-second duration and the current is 60 nA, the total number of electrons flowing through the diamond is approximately 3.7 x 10^{11} for each forward bias pulse. Pulses with a 1-second duration were chosen because the duration is long enough to not be filtered by the bias filtration circuit. A solution for using shorter forward bias pulse durations and higher forward current would be switch between circuits, one for reverse biasing the detector with a strong filter, and another for forward biasing the detector through a more direct coupling.

5. Results and discussion

Fig. 5 demonstrates the effect of polarization for various reverse bias values. Moving the radiation source closer (increasing flux), the polarization effect was observed to be more rapid. The axis on the top of Fig. 5a is the accumulated number of electron-hole (e-h) pairs generated by the α-irradiation (found by assuming an average energy deposit from each alpha of 1.6 MeV at a rate of 460 cps). Each curve in Fig. 5a was fit to a 3rd order polynomial, $y = \{C_0\} + \{C_1\}x + \{C_2\}x^2 + \{C_3\}x^3$. The fitted curve for 10 V reverse bias is $y = \{135.3\} + \{-4.778\text{E-}11\}x + \{-2.370\text{E-}22\}x^2 + \{7.991\text{E-}34\}x^3$, where x is the number of e-h pairs. For a 10-Volt reverse bias, a 1% reduction in the signal occurs after 2.54 × 10^{10} e-h pairs have been generated in the detector (330 GeV of accumulated energy deposit); or equivalently for this setup, a 1% signal loss occurs after 448 s. The polarization results measured for reverse biases of 0 V, 2 V, 5 V, 10 V, 15 V, 20 V, and 30 V are summarized in Table 1.

Fig. 5b demonstrates the effect of polarization on the charge collection efficiency of diamond after 1 h(3600 s) of irradiation. As the diamond is irradiated, the charge buildup creates an effective internal potential which counteracts the external reverse bias, thus reducing the charge collection efficiency. In Fig. 5b, the distance between curves along the x-direction reveals the effective internal potential reached after 1 h of irradiation. Dashed arrow indicators in Fig. 5b reveal points where the internal potential built up to 5 V after 1 h. It is this gradually decreasing total field strength caused by the polarization effect that

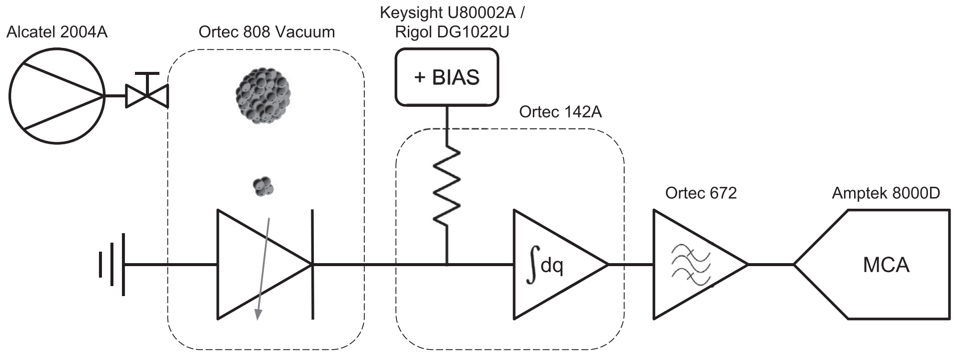

Fig. 3. A diagram outlining the main components of the pulse-mode detector system.

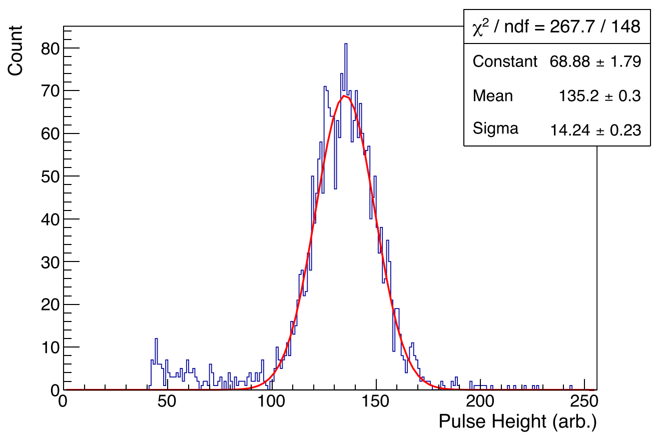

Fig. 4. A pulse height distribution taken over 6 s for a 10-Volt reverse bias with the source at 3.3 cm away. The detector flux is approximately 460 cps.

Table 1
Each curve shown in Fig. 5a was fit to a 3rd order polynomial to extract when the signal reduces by 1%. The time for a 1% drop in signal, $t_{-1\%}$, is for this particular setup. The reduction of the signal by 1% in time-independent terms are given by the number of e-h pairs generated by the α-particles, $e-h_{-1\%}$, and the energy deposited in the diamond, $E_{dep,-1\%}$. The uncertainty in $t_{-1\%}$, $e-h_{-1\%}$, and $E_{dep,-1\%}$ is less than 1% except in the case of 30 V where the uncertainty may be up to 5%.

V_{bias}	$t_{-1\%}$ (s)	$e-h_{-1\%}$ (10^{10})	$E_{dep,-1\%}$ (GeV)
0	71	0.40	52
2	93	0.53	69
5	152	0.86	112
10	448	2.54	330
15	1162	6.58	855
20	2083	11.8	1530
30	4860	27.5	3580

reduces the detection signal over time.

By introducing a periodic forward bias with an appropriate frequency, the polarization effect is mitigated completely. As shown in Fig. 6, three different periodic forward bias modes were used to demonstrate the technique for the diamond PIN detector: 1 s out of every 24 s, 1 s out of every 192 s, and 1 s out of every 1800 s. Because periods of 24 s and 192 s are less than the 1% signal reduction time of 448 s measured for a 10-Volt bias, no noticeable drop in the signal is measured. In the case of 1 s out of every 1800 s, measurement shows that the polarization is reset from a single forward bias pulse. Unlike methods used to reduce the polarization in MIM diamond detectors, the periodic forward bias method can reset the diamond with every forward bias pulse even after a large amount of polarization has built up. For cases where polarization occurs more rapidly due to a higher flux, the forward bias pulse frequency can be increased. In addition, with circuitry as described in Section 3, the pulse duration can be shortened to reduce the amount of dead time to an acceptable level. To mitigate the effect of polarization, the forward bias pulsing period needs to be much less than the time where polarization has reduced the signal to unacceptable levels.

An attempt was made to reduce the polarization effect when biased at a constant 10 V by removing the alpha source periodically for 10 s out of every 192 s for a measurement lasting 1 h, the same frequency as one of the measurements done with periodic forward bias pulses.

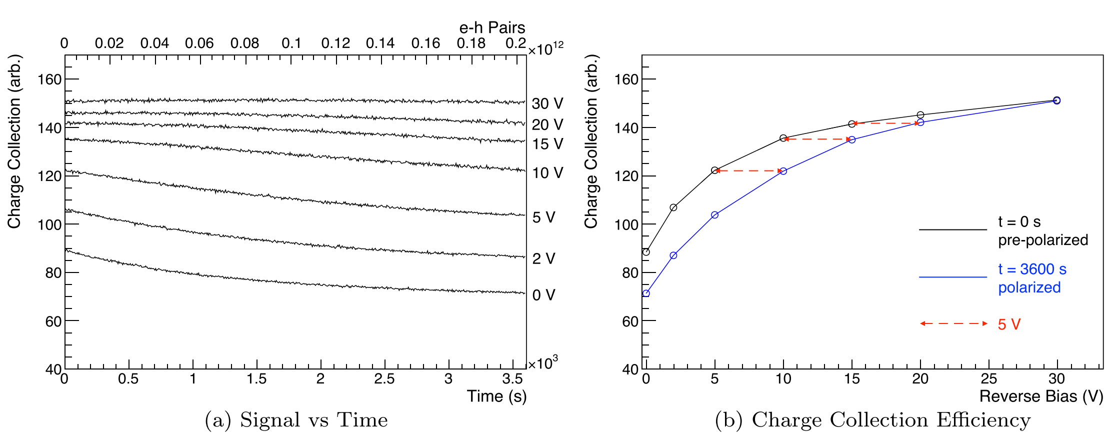

Fig. 5. Irradiated by ^{210}Po, the polarization effect is shown versus time (a) and versus reverse bias (b). In both plots, the y-axis is the same. In (a), the signal strength is observed to reduce over time as a result of the polarization effect for different reverse bias values (labeled to the right of the plot). In (b), the charge collection efficiency is observed to degrade over the course of 1 h starting from a pre-polarized state, a result of the polarization effect.

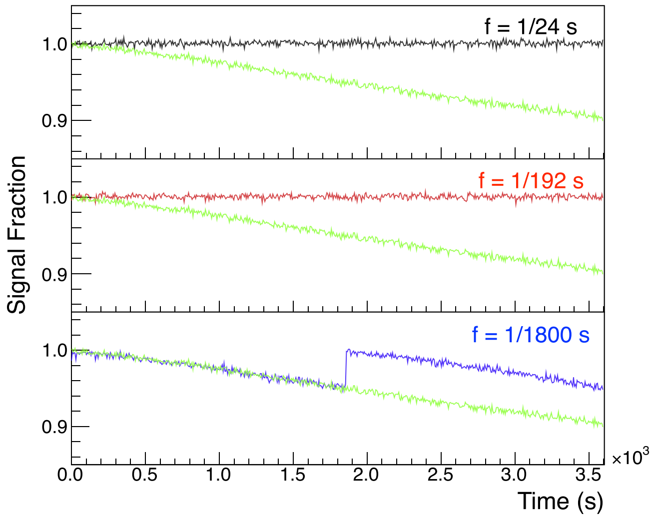

Fig. 6. While irradiated by ^{210}Po, the diamond diode was pulsed periodically with forward bias. The frequency of periodic forward bias pulses was changed and the results are shown. The frequencies used: 1 s out of every 24 s (black, top), 1 s out of every 192 s (red, middle), and 1 s out of every 1800 s (blue, bottom). For a constant reverse bias of 10 V (green), the polarization effect is observed and shown in each plot for comparison.

Unlike the forward bias results of the same frequency, no noticeable reduction of the polarization effect was observed by removing the radiation. The rate of polarization when removing the radiation for 10 s out of every 192 s remained nearly identical to the previous polarization measurements.

6. Summary

A new technique for neutralizing the polarization effect has been shown effective for a thin diamond PIN detector. The technique, periodic forward bias pulses, uses short pulses of duration and frequency chosen for the application. These results provide motivation for using a diode configuration as an alternative to the MIM configuration for diamond detectors. Future work might include characterizing the effectiveness of this new method for various thicknesses of the intrinsic region, different diode configurations, and for polycrystalline diamond or other semiconductor materials.

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