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Diamond detector for beam profile monitoring in COMET experiment at J-PARC

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ABSTRACT: We present the design and initial prototype results of a proton beam profile monitor for the COMET experiment at J-PARC. The goal of COMET is to look for charged lepton flavor violation by direct $\mu$ to $e$ conversion at a sensitivity of $10^{-19}$. The 8 GeV proton beam pulsed at 100 ns with $10^{10}$ protons/s will be used to create muons through pion production and decay. In the final experiment, the proton flux will be raised to $10^{14}$ protons/s to increase the sensitivity. These requirements of harsh radiation tolerance and fast readout make diamond a good choice for constructing a beam profile monitor in COMET. We present first results of the characterization of single crystal diamond (scCVD) sourced from a new company 2A SYSTEMS Singapore. Our measurements indicate excellent charge collection and high carrier mobility down to cryogenic temperatures.

KEYWORDS: Diamond Detectors; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors)

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1 Motivation and test setup

Diamond has emerged as an attractive alternative to silicon for detection of ionizing radiation [1–5]. Properties that make diamond a superior sensor material are summarized in Table 1. Diamond detector structures require no dopants and can be operated at higher fields for faster charge collection. By far the most attractive property of diamond is its high radiation tolerance.

| Property (units) | Diamond | Silicon | Benefit                                      |
|------------------|---------|---------|----------------------------------------------|
| Bandgap (eV)     | 5.5     | 1.12    | Low thermal carrier density                  |
| Breakdown field (V/cm) | $10^7$ | $10^9$ | High field operation                         |
| Mean energy to create e-h pair (eV) | 13     | 3.6     | Small detector capacitance, less noise       |
| Dielectric constant | 5.7    | 11.9    |                                              |
| Displacement energy (eV/atom) | 43     | 13-20   | High radiation tolerance                     |

This paper presents first results of the study of single crystal diamond properties from a new supplier: 2A SYSTEMS, Singapore [7]. The sample received from 2A SYSTEMS (2A) is 460 µm thick with a cross-section area of 5.3 mm × 5.3 mm. For comparison, we have used a second sample from ELEMENT 6 (E6) [8] of comparable area and thickness 538 µm. 2A is metallized with 50 nm Cr + 200 nm Au contacts on both sides. DC tests on 2A indicate a capacitance of 2.2 pF.

We performed two types of tests to determine the signal characteristics in diamond:

1. We measure the current induced as a function of time by a stopping α particle with the transient current technique (TCT) [9]. This is done as a function of temperature down to 4 K.

2. We measure the charge collection from passage of $^{90}$Sr β particles as a function of the bias voltage.
Figure 1. Test setup

Figure 1a shows the setup used to perform TCT measurements. Bias voltage (with a current limiting MΩ resistor) is provided as pull-up in the signal path. The setup is arranged so that α particles enter from the opposite, grounded side of the sample. The penetration depth of α in diamond is ≈ 10 µm. The profile of current induced by e-h pairs as they traverse the bulk can be measured as a function of time on a digital oscilloscope with multi-GHz bandwidth.

The readout scheme for measuring the charge collection shown in figure 1b is similar. A collimated 90Sr β source is aligned with the diamond and a trigger silicon diode. A charge shaping amplifier integrates the deposited charge and measures $dE/dx$ in the sample. The 90Sr β with an energy end-point of 2.3 MeV provides an approximation to the charge deposited by a minimum ionizing particle (MIP) in diamond that is good enough for this measurement.

Figure 2. TCT measurement of electron current at room temperature
Figure 3. TCT results. Figures in the left column are for electrons, in the right column for holes.

1.1 Results: TCT current profile

Figure 2 highlights the TCT results for electrons at room temperature. Figure 3 shows the TCT current results for electrons and holes as a function of temperature and bias voltage.
The signal rises fast due to the plasma of primary e-h pairs created by the $\alpha$, followed by a flat phase during which charge carriers drift in the uniform electric field, inducing a constant current in the signal electrodes. There is an exponentially decaying tail when the charge carriers are collected at the electrode. At lower temperatures, there is a pronounced slope in the drift phase of the signal indicating the presence of space charge. High carrier mobility and carrier recombination in the charge cloud at low temperature [10] reduces the pulse duration and amplitude.

1.2 Comparison with TCAD calculations

We have performed TCAD calculations in the Sentaurus tool suite [11] to cross-check our experimental measurements. Three simplifications were made to allow convergence of the calculation. A two dimensional cross-section as shown in figure 4a was used. The calculation was performed at 0 K temperature. Diamond material thickness was set to 300 $\mu$m for the highest mesh resolution. With a space charge of $+3 \times 10^{11} \text{cm}^{-3}$ specified in the input, the results obtained are shown in figure 4b.

![Figure 4. Sentaurus TCAD signal calculation geometry and results](image)

The TCAD calculation results are in agreement with the trend of the TCT measurements in figure 3. The signal magnitude has to be scaled by $2\pi$ to account for azimuthal symmetry. The slope of the current in the drift phase is opposite that shown by experimental data indicating that the space charge in our sample at low temperatures has negative sign.

1.3 Results: signal distribution, charge collection

Figure 5a shows a characteristic Landau distribution [12] of signals recorded from passage of $\beta$ particles through the diamond. We have shown a comparison of signals recorded in the 2A sample and the E6 sample in the same setup.

Our measurements give the following results for the collected charge in the two samples:

- $2A(460 \mu m)$: $Q_{MP} = 15429e \pm 1235e$; $Q_{avg} = 18636e \pm 6376e$

- $E6(538 \mu m)$: $Q_{MP} = 18331e \pm 1398e$; $Q_{avg} = 21616e \pm 6097e$

where the $\pm$ figures are the 1$\sigma$ standard deviations. With $\rho_{MIP} = 36 \text{ e-h pairs/}\mu\text{m}$, we can in principle infer full charge collection distance in the two samples. However, the charge collection
distance thus determined suffers from two sources of uncertainty that we cannot resolve in our setup. First, the energy deposition by $^{90}$Sr $\beta$ is slightly higher than a MIP. Secondly, due to the finite size of the trigger diode and the diamond sample, there is a variation of up to 15 degrees in the angle of the track through the sample. The component of uncertainty due to the equivalent noise charge of the preamplifier ($\approx 100\ e$ measured in a calibration setup) is negligibly small. When measured, the signal offset at zero bias is indistinguishable from the intrinsic noise of the preamp.

Our measurements of the charge collection as a function of the bias voltage shown in figure 5b indicate that the sample reaches close to maximum charge collection already at 0.2 V/$\mu$m bias.

2 COMET: coherent muon to electron detection experiment at J-PARC

The COMET experiment at J-PARC [13] will look for physics beyond the Standard Model through charged lepton flavor violation (CLFV). Figure 6a shows a functional layout of the COMET experiment. The 8 GeV proton beam is slow-extracted from J-PARC in 100 ns bunches. The protons create pions in a stopping target. Pions decay in flight to muons. Muons are captured in an aluminum target to create muonic atoms. The allowed $\mu \rightarrow e$ decays lead to a continuum of electron energies (figure 6b) since the balance energy is carried away by the undetected neutrino. After $\approx 1.2\ \mu$s, the lifetime of captured muons, the experiment looks for the emission of an electron with kinetic energy exactly equal to the rest mass of the muon minus its (small) binding energy in the aluminum atom. This would indicate a coherent conversion of the muon to an electron — a CLFV process.

2.1 Radiation and timing requirements

The sensitivity of the experiment is determined by the muon statistics. Hence a beam profile monitor is necessary to ensure the purity and time structure of the beam. The beam time structure is indicated in figure 6c. At startup, we expect to have an 8 GeV beam of intensity $10^{10}$ protons/s.
In stable operation, the beam intensity is ramped up to $10^{14}$ protons/s to increase muon flux and improve the sensitivity of the experiment.

Recent tests on the CMS PLT [14] indicate a dependence of the signal magnitude on the rate of particle flux in highly irradiated single crystal diamond. This trend does not adversely impact the objectives of the proton beam monitor for COMET, which will likely have a coarse pixellization. During the 100 ns period of bunch passage with large flux of protons, it is necessary to monitor the cross-section profile of the beam (centroid, lateral spread) to steer it and maximize π production in the target. It is further necessary to ensure that the beam is completely extinguished after 100 ns. Any stray protons entering the beamline outside the 100 ns bunch would contribute to background during the detection period highlighted in red in figure 6c. Both these objectives can be accomplished using multiple detectors with different specifications for dynamic range and timing. Fast signal timing in diamond as discussed in section 1 make it an ideal choice for this application.

3 Conclusions

We have measured the signal time profile and charge collection in scCVD diamond from a new vendor 2A SYSTEMS. The TCT current response is excellent with no indication of space charge at room temperature, i.e. absence of any charge trapping centers. The charge collection studied with a shaping amplifier gives promising results with maximum charge collection being reached already at 0.2 V/µm bias.

Both these properties combined with the high radiation tolerance make this scCVD diamond an excellent choice to construct a beam profile monitor for the COMET experiment at J-PARC.
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