Graphene-Based Neutron Detectors

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***Abstract*—We are developing detector architectures and devices based on the novel carbon nanomaterial graphene, which has been shown to exhibit unusual electrical properties of potential use for next-generation radiation detectors. Of particular interest is the use of this technology to develop novel neutron detectors. To this end, we are studying architectures based on a neutron-absorbing converter material in conjunction with a graphene field-effect transistor (GFET). As an intermediate step towards the demonstration of GFET neutron detectors we utilize an alpha-source to systematically study the effect of charge deposition on the device response. As an added benefit, this experiment helps us elucidate the important systematics of response to other types of radiation, including the dependence of the magnitude of graphene resistance modulation on the deposited energy and the dependence of device speed on the morphology of energy deposition.**

I. Introduction

GRAPHENE field-effect transistors (GFETs)[1] utilize the unique electrical properties of graphene [2], [3] to detect radiation. The ability of to detect electromagnetic radiation (light, X-rays and γ-rays) has been demonstrated[4]. In applications such as detection of special nuclear material (SNM), neutron detection can be beneficial, in addition to the usual detection of electromagnetic radiation. To this end, we have recently started the development of graphene-based neutron detectors, and we describe our results to date, as well as our future experimental plans.

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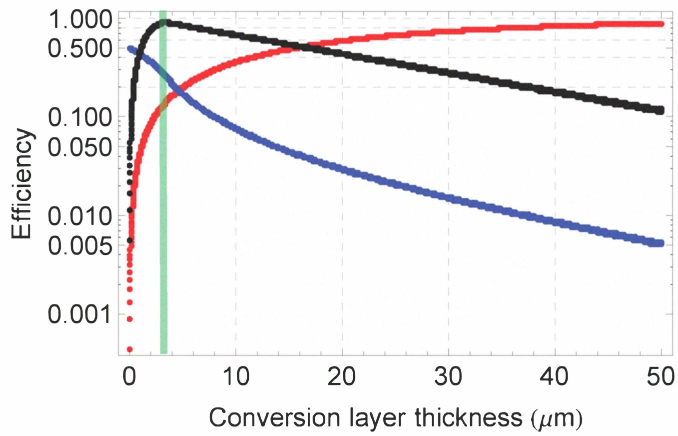

Fig. 1. The calculated optimal thickness for a ^{10}B conversion layer using the Monte Carlo simulation. The neutron conversion efficiency (red) is multiplied by the α-detection efficiency (blue) to get the total detection efficiency (black) which is shown at 25x for scaling. The optimal thickness is calculated to be $\approx 3.4\mu$m.

II. Neutron Detection using Graphene-Based Detectors

In order to detect neutrons using a GFET, a conversion layer needs to be implemented to generate a detectable α-particle signal[5]. We choose ^{10}B due to its cross section for conversion, and ease of fabrication.

$$\begin{aligned} & n + {}^{10}\text{B} \rightarrow \\ 94\% \rightarrow {}^{7}\text{Li}(840\text{ keV}) + \alpha(1.47\text{ MeV}) + \gamma(480\text{ keV}) & \\ 6\% \rightarrow {}^{7}\text{Li}(1.02\text{ MeV}) + \alpha(1.78\text{ MeV}) & \qquad (1) \end{aligned}$$

In order to determine the optimal conversion layer thickness for our design (Figure 1), along with the energy deposited within the GFET (Figure 2), we created a Monte Carlo model of the detector. In this model the α-particle is emitted isotropically with an initial position sampled from neutron interaction locations. While the neutron conversion efficiency increases with increasing conversion layer thickness, the fraction of α-particles that exit the conversion layer and penetrate the GFET substrate decreases. From the calculations, we determine that the conversion layer of ^{10}B, with thickness of 3.4 μm is optimal. The energy deposition shows a rise in counts up to 1.47 MeV, then drops sharply to a shoulder which extends out to 1.78 MeV, which is due to the branching ratios of the neutron conversion process, Equation 1.

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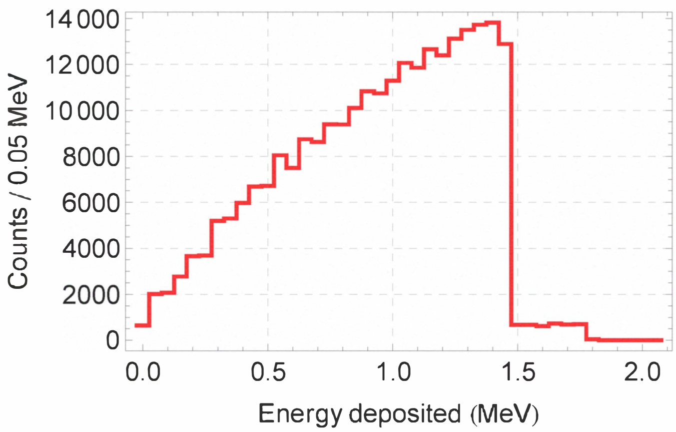

Fig. 2. The energy deposited per α-particle within the substrate. The shoulder from 1.5 to 1.8 MeV is from conversion to the ground state of ^{7}Li.

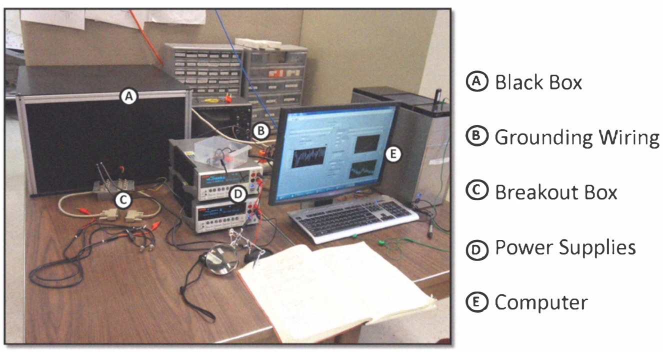

Fig. 3. The experimental apparatus for determining the effect of α-particle radiation consists of a dark box to minimize the effect of environment (ambient light) on the device. Precision voltmeters, current and voltage supplies are used for biasing the device and measuring its response. A computer is used for data acquisition.

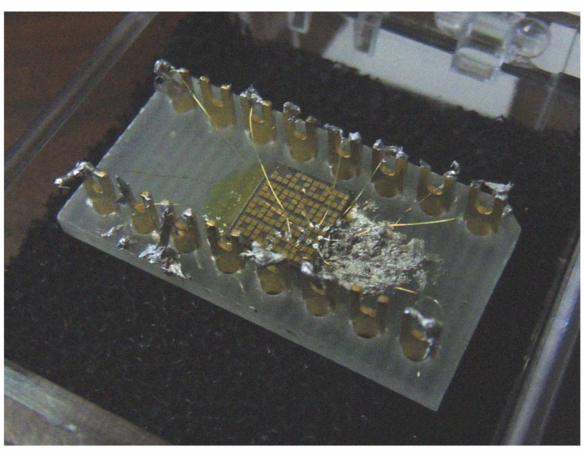

Fig. 4. Multiple GFETs fabricated on the SiC wafer, with one of the devices wire bonded for testing.

III. Alpha Detection Experiment

We have designed and developed an experimental apparatus for testing the response of a GFET in the presence of α-particles, Figure 3. A close-up of the GFET is shown in Figure 4, in which the substrate is SiC and there are multiple devices on the SiC wafer. One device is wire-bonded for operation.

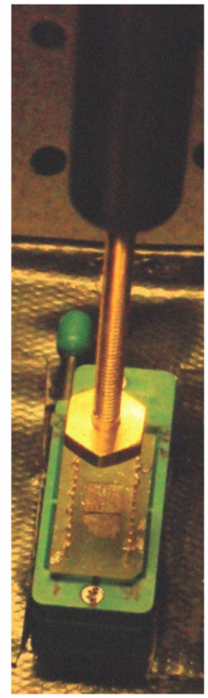

Fig. 5. The α-source irradiates the GFET from the top. Graphene faces the α-source.

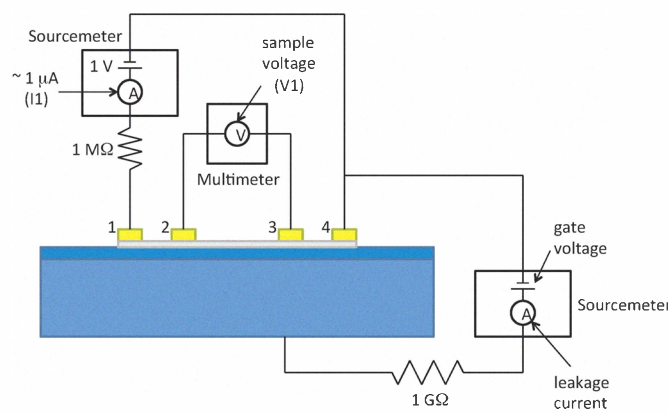

Fig. 6. In order to determine the resistance of the graphene, 1 V is applied in series with a 1 MΩ resistor to produce ∼ 1 μA current. The resulting voltage drop across the graphene is measured, which is directly related to the resistance of the graphene. This resistance changes as a function of the gate voltage which is applied in series with a 1 GΩ resistor to measure the leakage current.

In the present setup we irradiate the graphene-side of the GFET, with α-particles passing through the graphene, Figure 5. This method of irradiation has some drawbacks, such as the possibility for ionization in the air to affect the measurement of graphene resistance and the differences in radiation energy deposition compared to the future neutron detector. However, top irraditation is considerably easier to implement that the irradiation from the back side. Irradiation with α-particles impinging on the back side of the GFET will be pursued in the future to provide a more representative neutron-like response. The schematic of the setup for resistance measurement of the graphene is shown in Figure 6.

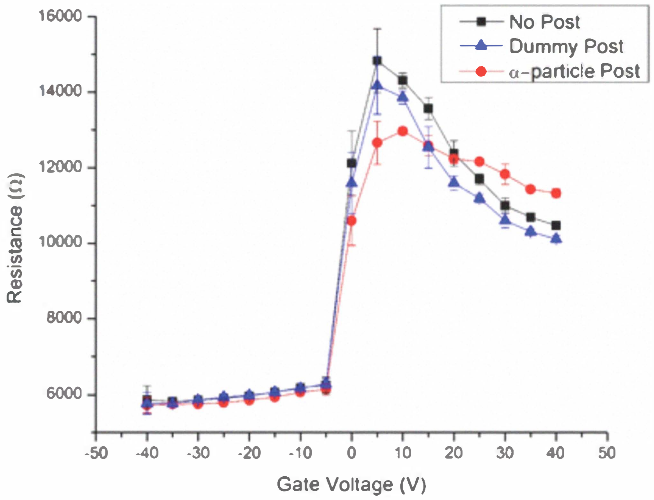

Fig. 7. With the α-source present, the slope of the Dirac curve for n-type operation decreases. A dummy post with identical geometry as the α-source is used to verify that the response differences are due to α activity.

IV. Device Response

We have been able to measure global response of the GFET to the α-particle radiation. With the 20 μCi ^{241}Am source at a distance of 1-3 cm, we measure a decrease in the slope of the operational characteristic of the GFET (Dirac curve) for n-type device operation (gate voltage¿10 V), Figure 7. The measured slope values are shown in Table I. We are working on detecting a pulse due to single-event energy deposition. Based on the results to date, GFET has a potential to detect α-particles and in turn neutrons, but further testing is needed to confirm this preliminary experimental data.

TABLE I
With the α-source present there is a clear decrease in the slope of the Dirac curve.

	Slope [kΩ/V]
No Post	-135 ± 10
Dummy Post	-124 ± 12
α-source	-54 ± 3

V. Neutron Detector Experimental Plans

Following the completed study of the α-particle response, we will focus on fabrication and operation of GFET-based neutron detectors. A GFET will be coupled to a conversion layer as shown in Figure 8 and will be systematically studied (Figure 9). With the GFET-based neutron detector we will be able to study a wide range of operational characteristics, such as speed, intrinsic efficiency, pulse shape, directional sensitivity and robustness to environmental changes (temperature, humidity, ambient light, aging).

In addition, we will be able to use different device substrates such as GaAs or CZT to better characterize the potential performance parameters of a graphene-based neutron detector.

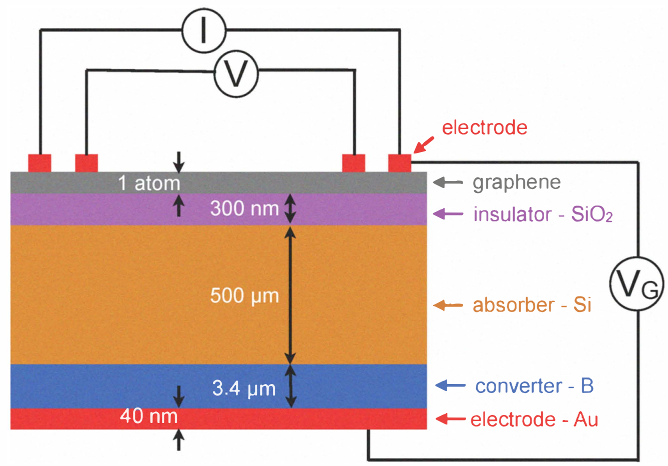

Fig. 8. Schematic of the GFET-based neutron detector utilizing a ^{10}B conversion layer.

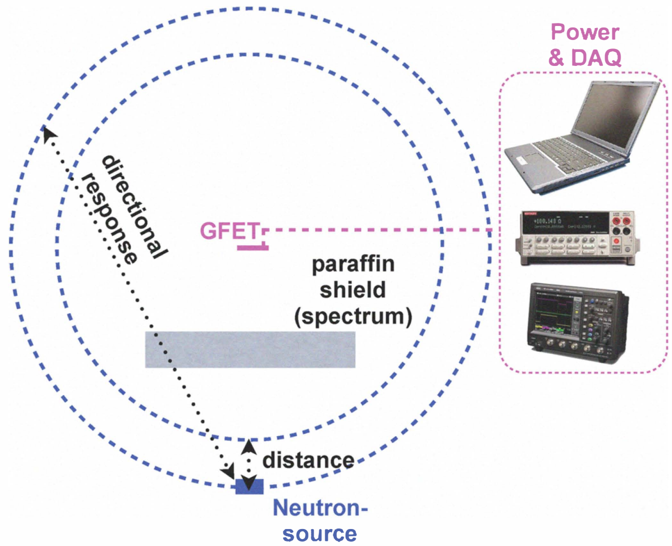

Fig. 9. Schematic of what the experimental setup will be to utilize neutrons in order to study the graphene-based neutron detector.

VI. Conclusions

We have designed a neutron detector based on a GFET and are in the process of proof-of-principle tests for our design that utilize α-particles to simulate interaction with neutron. We have preliminary evidence for GFET response to α-particles, and are in the process of making more refined measurement. Upon complete characterization, we plan several activities. First, we will systematically study the device spatial response using a collimated α-source. Second, we will fabricate graphene-based neutron detectors and study their response to thermal neutrons. Finally, we will explore alternative device architectures that could result in improved performance (particularly speed), such as the DEPFET architecture[6].

Acknowledgments

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