Numerical Model of Graphene-Based Radiation Detector Response

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***Abstract*—Graphene-based radiation detectors (GRDs) have a potential to provide new and improved capabilities when compared to more conventional detectors. The unique electrical properties of graphene can result in a GRD response that resembles that of a transition edge sensor. We have modeled the interaction of gamma rays with a variety of GRD absorber materials using GEANT4. The transport of the charge carriers through the detector is then modeled using an electric field calculated by the COMSOL multiphysics model. During the drift of the electrons to the graphene, the Shockley-Ramo theorem is used to calculate the time-resolved detector response. We present the calculation of the expected time-resolved signal from a gamma ray interaction. Additionally, we present a preliminary analysis of expected energy resolution and noise analysis for GRDs.**

I. Introduction

GRAPHENE is a single atomic layer of carbon, which exhibits unique electrical properties [1]. When approaching the charge neutrality point, the resistance of the graphene sample increases dramatically, theoretically to an infinite resistance at the charge neutrality point. As the density of either holes or electrons begins to decrease, the resistance increases, resulting in a peak, called the Dirac point, Fig. 1. It has been shown that graphene samples are extremely low electronic noise devices which have the ability to sense miniscule changes of the electric field, such as those resulting from adsorption of a single molecule [2][3].

In the field of radiation detection, particularly when attempting to detect special nuclear material, efficient gamma ray and neutron detectors are required. In addition, it is usually required that the energy of the incoming particle be known with a high level of accuracy (e.g. 1%). For these reasons, we explore the use of a graphene-based radiation detector (GRD) in hopes of taking advantage of its unique electrical properties to produce a radiation detector with performance exceeding that of more conventional radiation detectors. The relevant detector characteristics we would like to improve include the energy resolution, efficiency, cost, and power requirements.

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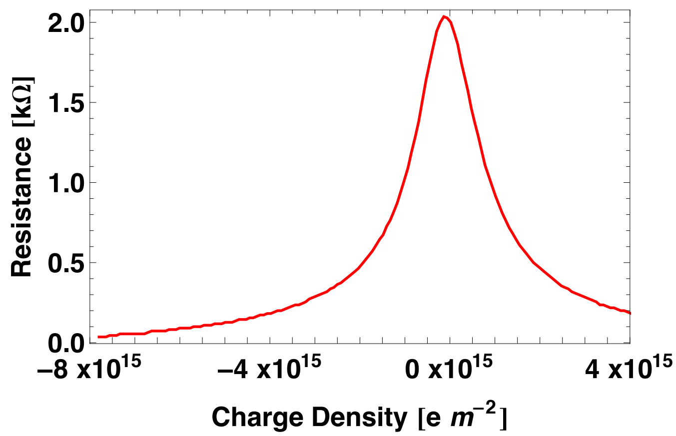

Fig. 1. Graphene exhibits a sharp peak in resistance at the charge neutrality point (Dirac point).

Here we present a possible GRD architecture for detection of gamma rays, which drifts electrons to the buffer layer under the graphene, where they are detected remotely by the graphene. We provide a simulation for calculating the detector response in two steps. The interaction of the radiation with the GRD is modeled with GEANT4. The charge transport is modeled using the electric field generated from COMSOL as input. Lastly, we present a preliminary calculation of the inherent energy resolution of a GRD.

II. Device Architecture

A GRD, Fig. 2, consists of three main components: the absorber, the buffer layer, and the graphene. The absorber is an undoped semiconductor which serves as the medium of interaction for the radiation. The buffer layer serves a few different purposes: firstly, it insulates the graphene from the semiconductor. Secondly, the buffer layer prevents the electrons from reaching the graphene and draining out before they are cleared by the side electrodes. The graphene senses the electric field induced by the charges, and the resistance

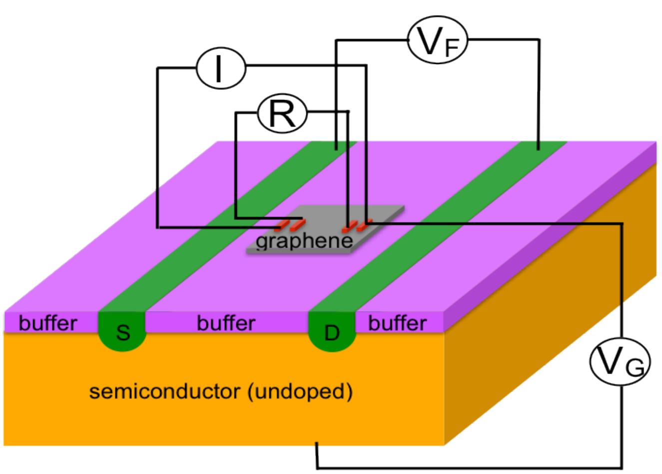

Fig. 2. Schematic of our GRD design. The applied gate voltage, V_G, produces an electric field which is focused to the graphene sample. A gamma ray interacts within the semiconductor absorber and the ionized electrons are then drifted to the buffer layer, where they collect directly under the graphene. As the electrons approach the graphene, the effective electric field experience by the graphene increases and the resistance, R, is read out with a constant current, I. To drain the electrons, a drain voltage V_F is applied either at a constant small voltage, or a large pulsed voltage.

changes proportionally. Source and drain electrodes serve to clear all of the electrons that collect at the buffer layer, and reset the detector for continued operation.

A gate voltage, V_G, of -100 V is applied between the back gate and the graphene sample (Fig. 3). The difference in size of the electrodes results in the electric field lines funneling towards the graphene. In the current device, based on commercially available parts, we use a SI wafer of thickness 500 μm and 1 cm x 1 cm area. The buffer layer is SiO_2 of thickness 300 nm, and the graphene is 10 μm on the side. The drain voltage, V_F, is applied between the source and drain electrode. The voltage depends on the mode of operation and the drift time of the charges.

III. Radiation Interaction

Using GEANT4, we modeled the interaction of gamma rays from a ^{60}Co source with the GRD. Fig. 4 shows the GRD, along with sample gamma-ray tracks which either pass through the detector (green) or scatter (red). Once an interaction occurs, if it is a Compton scatter, the Compton electron is tracked as it produces secondary electrons. All electrons are tracked to energies as low as 1 keV by GEANT4, and the remaining energy is manually broken up to evenly distributed electrons along the final part of the trajectory. The electron cascades, 30 events being shown in Fig. 5, are then used as an input to the charge transport code to predict the pulse shape and in the end predict the energy resolution expected.

IV. Charge Transport

With the electric field output from COMSOL, Fig. 3, the charges are transported throughout the absorber. As the charges are transported towards the graphene, the weighting potential is used to calculate the induced charge on the graphene via the Shockley-Ramo theorem [4]. The calculated

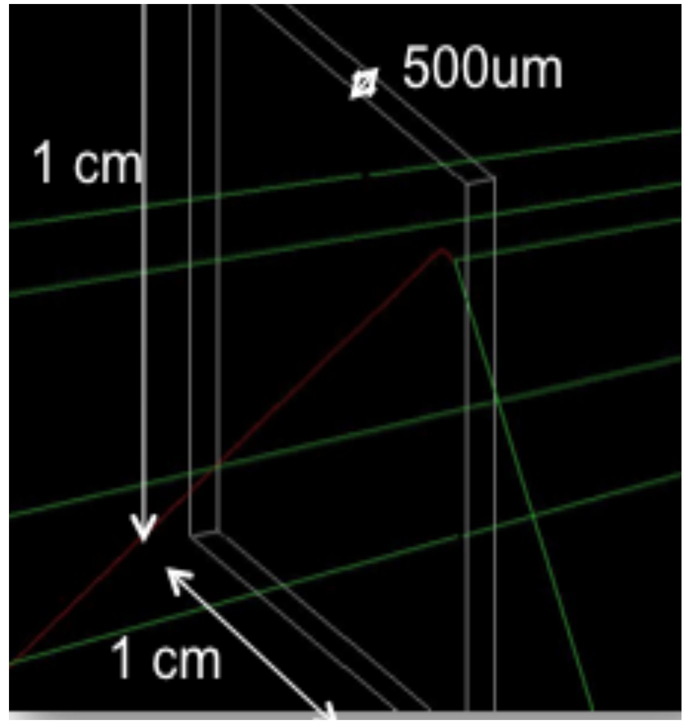

Fig. 4. The interaction of ^{60}Co gamma rays with a GRD is modeled with GEANT4.

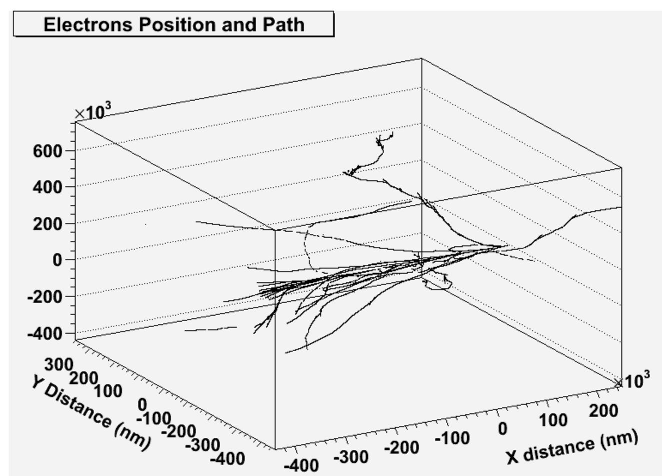

Fig. 5. The path of a Compton electron is tracked throughout the GRD, and the final position of the secondary electrons are plotted.

pulse, Fig. 6, has two distinct portions. The early rapid rise is from the drift of the electrons to the buffer layer, with the slow gradual rise being from the drift of the holes to the back electrode. When the electrons reach the buffer layer, they produce a relatively uniform layer of charge underneath the graphene, which allows consistent resistance measurements. When calculating the pulse for 100 electrons and assuming an initial charge density of 0.2×10^{15} electrons/m^2, we predict a drop in resistance of $\sim$0.2 Ω per electron.

Another important piece of information to take from the pulse shape is the drift time of the electrons. In the instance of the electrons generated at (5000,0) μm, the drift time is $\sim$40 ns. As we begin to move along the x-axis away from the

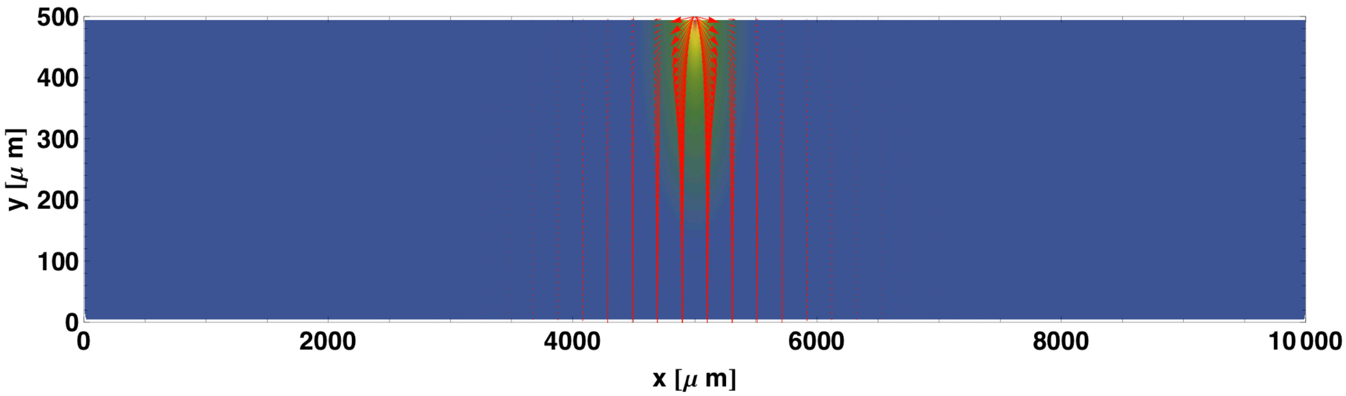

Fig. 3. Voltage profile as calculated by COMSOL Multi-Physics, with the electric field lines in red. The back gate is at a voltage of -100 V, while the graphene, located at (5000, 500) μm in our model, is grounded. The electric field lines focus towards graphene, funneling the electrons towards the graphene.

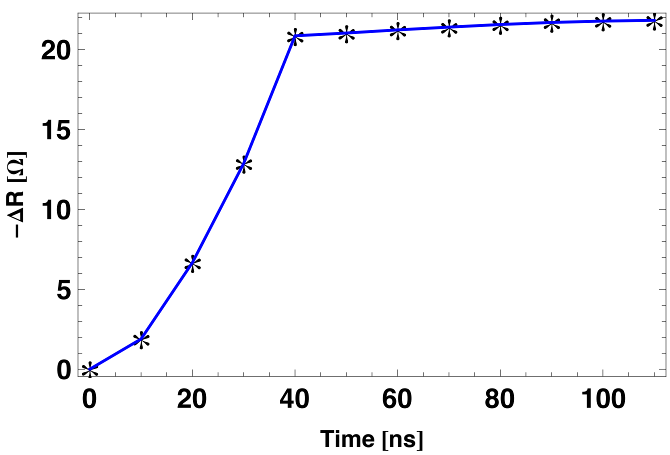

Fig. 6. Using the Shockley-Ramo theorem, we calculate the induced charge on the graphene as the electrons drift, which allows us to calculate the time dependent resistance change expected during the electron drift. When all the electrons are present at the buffer layer directly under the graphene, a resistance change of $\sim$0.2 Ω per electron is calculated, given a starting charge density of 0.2×10^{15} electrons/m^2. The slow increasing slope after 40 ns is a result of the holes drifting to the back electrode.

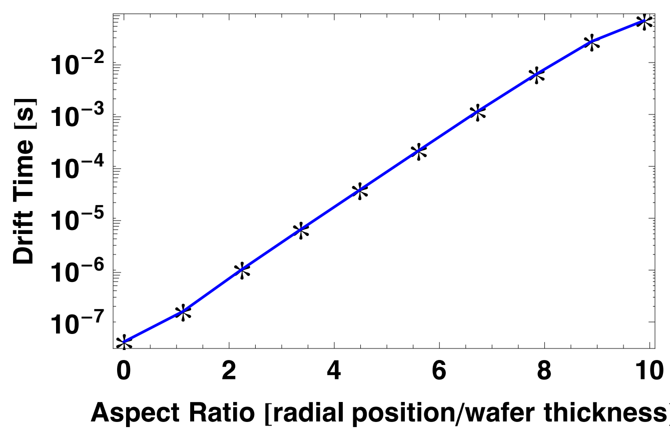

Fig. 7. The drift time of an electron is plotted as a function of the radial distance away from the center of the graphene projection. When the electron is directly under the graphene, it takes approximately 40 ns to drift from the opposing surface to the graphene sample. This drift time increases rapidly with the aspect ratio.

detector axis, the drift time starts to increase since the electric field intensity decreases as the radial distance increases. When we plot the drift time for the electrons as a function of the absorber thickness away from the detector axis, a significantly longer time is required for electrons to reach the graphene, Fig. 7. This large increase of drift time suggests that the ratio of graphene width to the absorber thickness should be kept as close to unity as possible to obtain a drift time shorter than $\sim$100 ns.

V. Noise Analysis

In a preliminary analysis of the noise in a GRD, we consider three factors. The first factor are the statistical limitations of the absorber. Secondly, noise is present in the resistance measurements of the graphene. Lastly, noise is associated with resetting of the detector. We assume Poisson distribution of charge carriers with a Fano factor of 0.115 for Si [5]. For graphene, the resistance fluctuations have been measured [6], and are shown in Eqn. 1. The noise attributed to the device reset is similar to that in a DEPMOS, which has been previously measured to 3.6 electrons. This noise arises from incomplete charge removal or pre-emptive charge removal. While the GRD architecture is not identical to DEPMOS, the reset noise in DEPMOS does not contribute significantly to the overall noise, and thus we conjecture that it is not likely to be a significant contributor to GRD noise either. Fig. 8 shows the energy resolution as a function of the deposited energy: the statistical noise is the red dashed curve, graphene noise is the green dash-dot curve, and the reset noise is the blue dashed curve. One important thing to note is the effect of the size of the graphene. The smaller the graphene, the lower the energy of peak sensitivity for the device. Once the charge density is saturated, the resistance starts to change non-linearly, resulting in a larger noise contribution of the graphene itself.

$$N_R = \frac{\delta R^2}{R^2} = 15 \times 10^{-8} \tag{1}$$

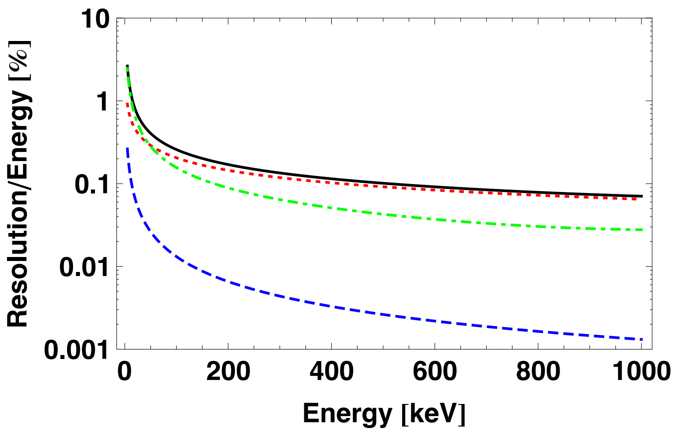

Fig. 8. The expected resolution curve (black) starting at 0.2×10^{15} elec m^2 calculated by adding the statistical noise (red-dotted), graphene device noise (green-dot-dashed), and the reset noise (blue-dashed) in quadrature.

VI. Speed of Operation

The detection rate limit is determined by the drift time, which depends on the aspect ratio of the absorber. Desired drift time is <200 ns, resulting in a maximum detection rate of 5 MHz. If the drain voltage is pulsed to clear the charges under the absorber, no significant reduction of the detection rate is expected, but either (1) a real time data analysis will be needed, or (2) an uncorrelated drain voltage pulse needs to be used. Alternatively, if a constant drain voltage is applied, it must be sufficiently low to maintain the additional loss in resolution below 0.1%, Fig. 8. Dividing the drift time by 0.1%, we get a minimum drain time of 200 μs to keep the drain noise from dominating the device resolution limits. When operating at a drain time of 200 μs, we get a maximum device operating speed of 5 kHz. Next we calculate the drain voltage V_F for a separation 20 μm, twice the length of the graphene and obtain a drain voltage of 16 μV.

VII. Conclusions

We have developed a device architecture for detecting ionizing radiation by drifting the charges produced toward the graphene and detecting the change in resistance which is proportional to the energy deposited in the detector. Our preliminary models show a resistance change of ~0.2 Ω per electron. Noise estimates show that the GRD should be able to operate at the statistical limit of the absorber at various energy ranges.

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