Graphene Field Effect Transistor-Based Detectors for Detection of Ionizing Radiation

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***Abstract*—We present the results of our recent efforts to develop novel ionizing radiation sensors based on the nanomaterial graphene. Graphene used in the field effect transistor architecture could be employed to detect the radiation-induced charge carriers produced in undoped semiconductor absorber substrates, even without the need for charge collection. The detection principle is based on the high sensitivity of graphene to ionization-induced local electric field perturbations in the electrically biased substrate. We experimentally demonstrated promising performance of graphene field effect transistors for detection of visible light, X-rays, gamma-rays, and alpha particles. We propose improved detector architectures which could result in a significant improvement of speed necessary for pulsed mode operation.**

***Index Terms*—radiation detection, graphene field effect transistor**

I. Introduction

THE two-dimensional material graphene [1,2] has attracted considerable attention in the scientific and engineering community over the recent period. A wide range of applications for this new material have been proposed or realized, motivated primarily by its electronic properties such as the exceptionally high charge mobility, even at room temperature. We introduce a new approach to detect ionizing radiation using low-voltage, room-temperature sensors based on the graphene field effect transistor (GFET) and review the some results of our experimental program to develop a new type of radiation detectors based on graphene.

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II. Principle of Operation

GFETs (Fig. 1) fabricated by mechanical exfoliation and chemical vapor deposition (CVD) have been used in this work. Graphene is deposited on an electrically gated, undoped radiation absorbing substrate (Si, SiC, and CdTe have been used, with potential for other materials). Making use of various semiconductor absorbers, with potentially relaxed temperature, carrier mobility, purity, and lifetime constraints. In Si-based GFETs an insulating SiO_2 layer has also been used between graphene and the substrate. A gate voltage is applied between the graphene and the back of the absorber, producing an electric field across the device. The field can be varied to set the optimum point on the Dirac curve for a sharp change in graphene resistance with the change of electric field. The drain and source electrodes supply the current through the graphene and are used to measure the voltage drop across the graphene. Fig. 1 [3] depicts the simplified schematic of the experimental setup and four probe connection on a graphene flake.

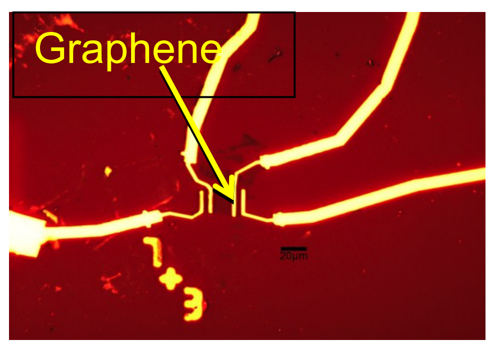


Fig. 1. Optical microscope image of a graphene device with 4 metal electrodes

Detection of radiation using GFETs is based on the sharp dependence of the graphene resistance on the local electric field [4,5]. In GFET, an electric field is established across graphene and an underlying absorber material in contact with graphene, or separated from graphene by a thin insulating layer (Fig. 2). This field can be abruptly altered by the ionization induced in the absorber (Fig. 3). The change of graphene resistance is measured and correlated to the change in electric field, thereby establishing a convenient method to detect the ionization produced in the absorber, even without requiring charge collection. The use of charge separation and drift (Fig. 4) can be beneficial for establishing a definite correlation between the magnitude of ionization induced in the substrate and the graphene resistance, resulting in spectroscopic capability.

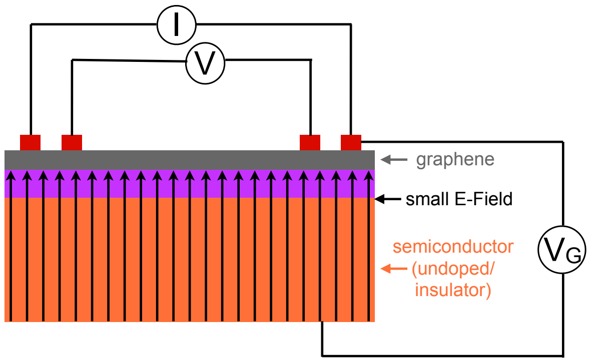


Fig. 2. When the absorber acts as an insulator, the gate voltage drops across both the absorber and the insulator, resulting in a small electric field. With an electric field strength corresponding to the Dirac point, the graphene resistance is at a maximum [5].

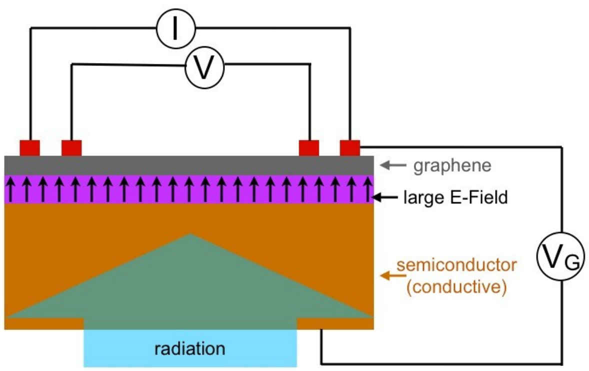


Fig. 3. The incoming radiation ionizes the charges within the (intrinsic) semiconductor to create a conducting absorber. The gate voltage is now effective "transferred" through the absorber and only drops across the insulator (thinner purple region). This results in an increased electric field to be detected by the graphene and the resistance changes according to the increased electric field [5].

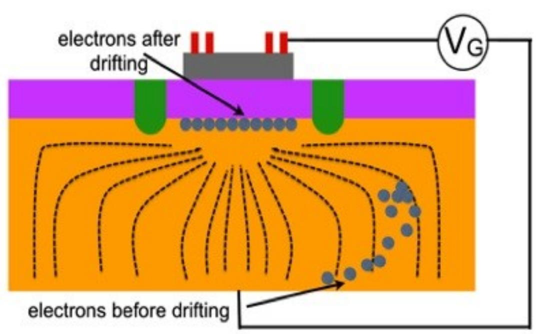
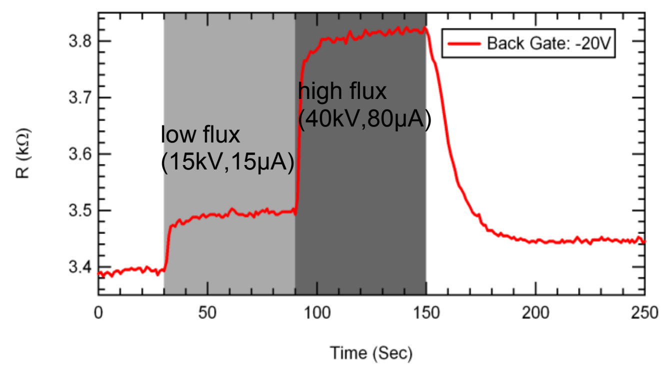


Fig. 4. A cross section of a GFET showing electrons both before and after they are drifted. The path the electrons take is determined from the electric field lines, which are signified by the dotted lines [5].

III. GFET Response to X-Rays,, Visible Light, and Gamma-Rays

We first review our experimental results in detecting ionizing electromagnetic radiation at a variety of energies [6]. Our initial experiments were conducted using a Si absorber-based graphene FET. A mini X-ray source (Amptek) was used to irradiate the GFET and four probe measurements were carried out at cryogenic and room temperatures to measure the device response. We show the effect of changing energy and flux, which results in corresponding changes in the resistance in graphene (Fig. 5a). Further, we have observed more that 50% change in the resistance between the high (40 keV, 80 μA) and low (15 keV, 15 μA) X-ray flux at 4.3 K. In the case of Si absorber we did not observe any response from the device at room temperature as the undoped sample does not completely freeze out and conducting charge carriers still exist. Thus the experiments carried out with Si based GFET were done at liquid helium (4.3 K) temperature (Fig. 5b).

a.



b.

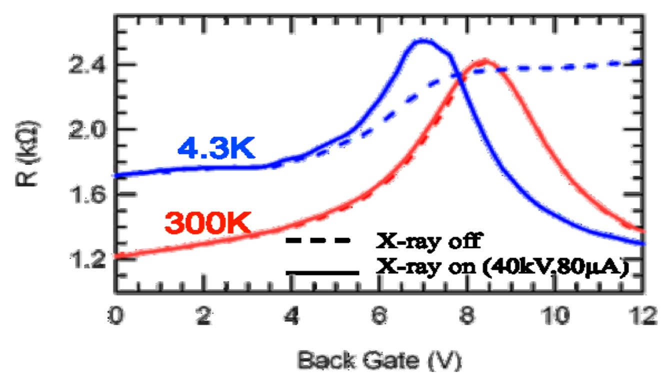


Fig. 5. a. Demonstration of proof of concept: a. GFET response to low (15 keV, 15 μA) and high (40 keV, 80 μA) X-ray flux [4]; b. response of Si-based GFET at 4.3K and 300K [4]

The SiC absorber-based GFET has shown good response to X-rays, gamma-photons, and light photons at room temperature. We observed up to 70% change in graphene resistance with X-ray irradiation on our SiC-based GFET at room temperature (Fig. 6). Further, we have also studied the back gate voltage relationship to the graphene response, which is also shown in Fig. 6.

Si- and SiC-based GFET devices have also been tested for their response to intermittent irradiation with a He-Ne laser and white light. The photons produced by the laser penetrate through the graphene layer and partially ionize the underlying substrate to generate an observable change of conductivity. Thus these devices could also be used in photo-resistor applications. A typical on/off response to white light is shown in Fig. 7a. We also tested the SiC device with gamma-rays. A 4.5 mCi ^{137}Cs source was used for the gamma-photon response (Fig. 7b).

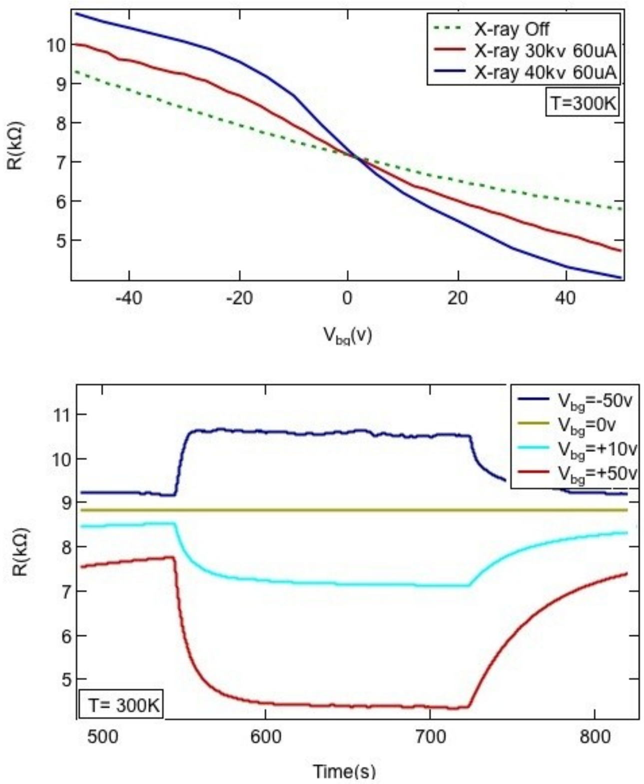


Fig. 6. Response of SiC based GFET to X-rays at 300 K [6]

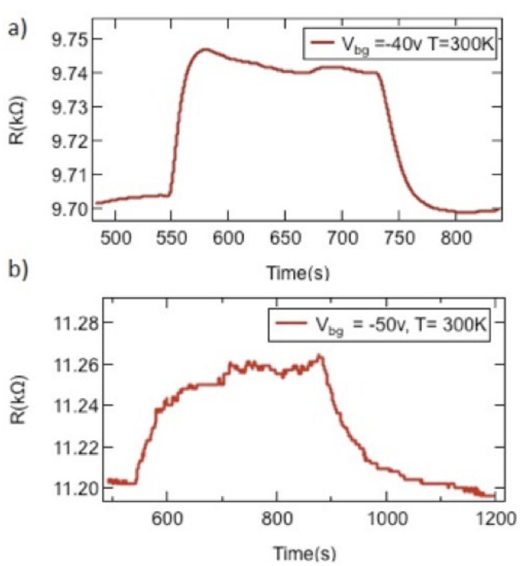


Fig. 7. Typical response of SiC-based GFET to a) light photons, b) gamma rays. [6]

IV. Alpha and Neutron Detection

We investigated the response of graphene field effect transistors to alpha particle irradiation. Alpha particles are particularly useful for characterizing GFETs due to their predictable range and energy deposition. Additionally, the understanding of alpha response is a necessary step in building a graphene-based detector sensitive to thermal neutrons, which may use a boron- or lithium-loaded absorber material to achieve conversion of neutron to heavy charged particles.

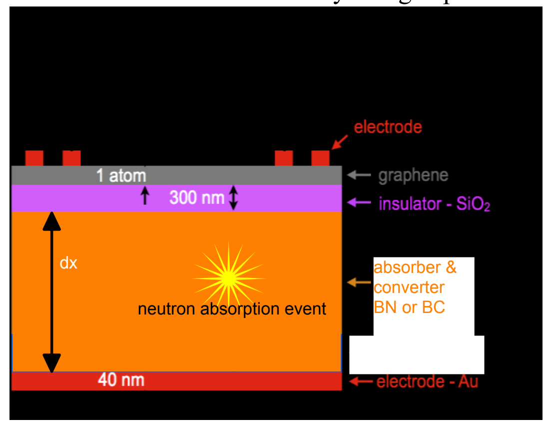


Fig. 8. Design of a boron nitride or boron carbide based GFET for neutron detection [7]

A neutron detector utilizing graphene could be very similar in its design to a gamma-ray detector . A boron layer will be deposited on the bottom of the SiC wafer to act as a neutron-sensitive converter, with the alpha particle or Li ion being absorbed and detected in the SiC. This approach, as with most neutron detectors, requires detectors on the order of a few μm thick, which severely limits the intrinsic efficiency. Alternatively, a design in which converter also serves as a converter (for example, boron carbide or boron nitride, Fig. 8) could offer superior performance due to full energy deposition in the neutron capture reaction [7].

Our approach which uses graphene as the pre-amplifier, combined with recent advances in graphene production, could allow for the mass production of inexpensive neutron detectors with integrated pre-amplifiers. These devices could then be used in a large variety of applications ranging from discrete single detectors to large arrayed configurations. As an intermediate step, we are working on using graphene as an alpha detector.

Experiments have been conducted with direct and indirect irradiation of the GFET with alpha particles (Figs. 9 and 10) [7]. Direct irradiation involves the passage of alpha particles through the graphene film and subsequent energy deposition into the substrate material, whereas indirect irradiation allows energy deposition into the substrate without passage through the graphene. Indirect irradiation response is of primary interest, as this type of irradiation is more consistent with volumetric interactions occurring between the substrate and neutral particles (photons and neutrons).

In our experiments the volumetric nature of the GFET detector response has been unambiguously demonstrated by inducing ionization in the substrate at a significant distance from graphene. Detection of alpha particles represents an important step for developing a graphene-based neutron detector.

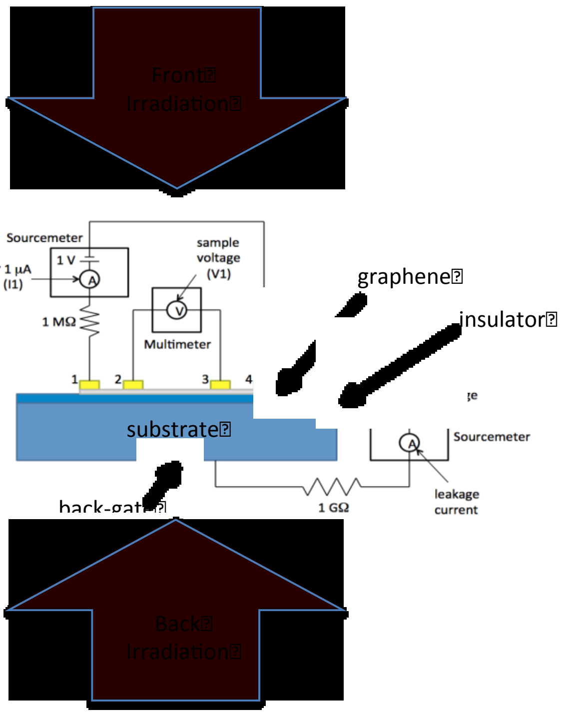


Fig. 9. Electrical setup for GFET measurements and directions of 'direct' and 'indirect' irradiation. The contacts (numbered 1-4) allow resistance reading of graphene. The substrate contains an insulator, semi-conductive, and gate layers placed in a back-gate arrangement relative to the graphene. The current labeled at "I1" is the typical current through the graphene film, which is limited to avoid device damage. Leakage current is also limited to avoid damage and noise. Ideally, resistances are measured by Kelvin (4-terminal) contacts with a multimeter and voltage "V1".[7]

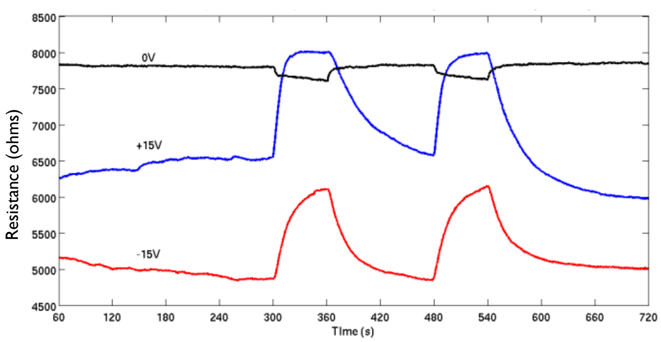


Fig. 10. GFET resistance responses to direct alpha irradiation from the front of the device, for different back gate voltages. [7]

V. Advanced Graphene-Based Detector Designs

In addition to the relatively small size of typical devices fabricated to date, one of the challenges we encountered is the relatively slow recovery of the device following irradiation. This is evident in Fig. 11 in which a graphene FET fabricated by CVD on an undoped SiC substrate has been tested for visible light response at room temperature [8]. When the radiation source is turned off, the graphene resistance is restored to its value prior to exposure over a relatively long period of time. We attribute this long recovery time to the absence of a mechanism for ionized charge removal in the present proof-of-concept device architecture. Specifically, ionized charges drifted to the top surface of the semiconductor substrate are accumulated and cannot be removed. When applying a short voltage pulse across the device with opposite polarity after turning off the radiation source, graphene resistance has been observed to return to its original value much faster, as shown in Fig. 11.

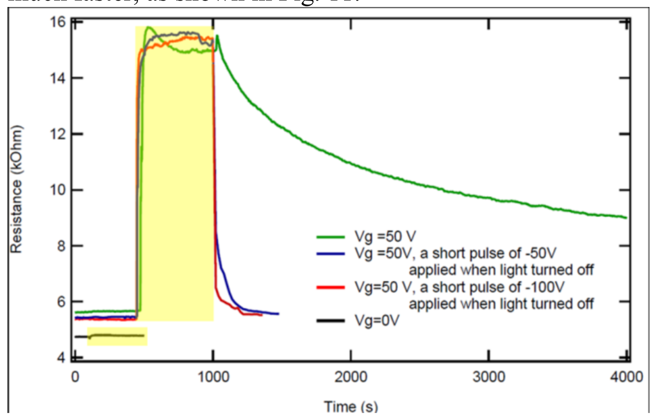


Fig. 11. Light response of CVD graphene FET on undoped SiC. Exposure intervals for different curves are shown in yellow boxes. When turning off the light illumination is accompanied by a short voltage pulse with opposite sign to the gate voltage applied, resistance returns to its initial value much faster. [8]

A promising approach to solve this charge draining problem is the use of a somewhat more complex device design, akin to that of the depleted p-channel field effect transistor (DEPFET) [9]. DEPFETs exhibit low noise, high resolution, and can be read out multiple time, similar to our design. Some key differences between DEPFET and the simple GFET design presented here is that the GFET does not utilize a semiconductor junction and a "Clear" contact to drain charges. Adopting some key DEPFET design features in a GFET has a potential to overcome some of the limitation of the present design.

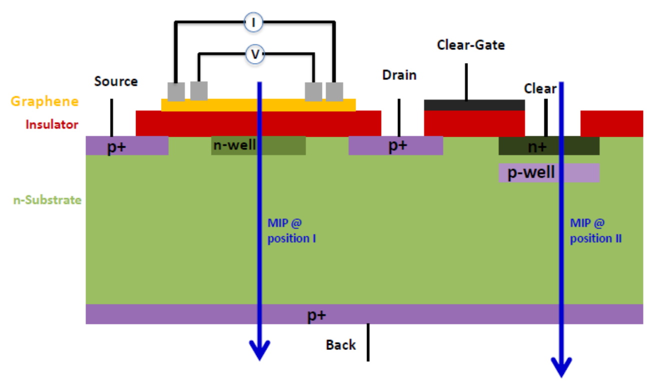


Fig. 12. Graphene DEPFET device architecture optimized with TCAD simulations [8].

We conducted TCAD [10] simulations to develop an improved DEPFET-inspired structure, which is shown in Fig. 12 [8]. In this design, the transistor channel is graphene deposited on the gate dielectric. In a normal DEPFET, the n-well is implanted a little below the p-channel so that electrons accumulated in the n-well can induce inversion p-channel at the semiconductor/oxide interface. However, in case of graphene DEPFET, this inversion channel is not needed. The n-well is therefore implanted right at the semiconductor/oxide interface to confine charges as close as possible to graphene, which results in stronger modification of graphene resistivity.

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