Graphene Field Effect Transistor as Radiation Sensor

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***Abstract*–A novel radiation sensor based on a graphene field effect transistor (GFET) is experimentally demonstrated. The detection relies on the high sensitivity of the resistivity of graphene to the local change of electric field that can result from ionized charges produced in the underlying semiconductor substrate. We present the experimental results of our study on the response of graphene-based radiation detectors to X-rays, gamma-rays, and light photons. We observed increasing resistance change of graphene with increasing X-ray flux in an electrically biased GFET based on Si, SiC, and GaAs substrates. We have measured the temporal characteristics of our detector, along with the sensitivity of the device at high (40 keV, 80 μA) and low (15 keV, 15 μA) X-ray fluxes. Furthermore, we demonstrate room-temperature operation of a GFET based on a SiC absorber and explore new architecture for a faster response.**

I. Introduction

The development of high performance detectors for the use in detection of special nuclear material (SNM) is a topic of considerable current interest. Based on the exceptional electrical properties of graphene [1,2], we are developing high-performance graphene-based sensors for detection of radiation emitted by SNM. Our prototype device (Fig. 1a) is an electrically gated graphene field effect transistor (GFET), which uses a semiconductor substrate as a radiation absorber. Unlike other semiconductor detectors with rely on charge collection, GFET uses a sharp change in resistance of graphene (Fig. 1b) to detect the ionization produced by absorbed radiation [3]. The induced charges due to the ionizing radiation cause a change in local electric field near graphene and subsequently a change in its conductivity, which could then be detected without charge drift and the associated charge collection time. The effect of local field-induced change in graphene conductivity is significant even at room temperatures, which offers prospects for the use of graphene in detectors for a wide variety of applications like nuclear security, medicine, and basic research.

Manuscript received November 14, 2011. This work has been funded by National Science Foundation, Department of Homeland Security, and Department of Defense under awards 0833689-ECCS, 2009-DN-077-ARI036- 02, and HDTRA1-09-1-0047 respectively.

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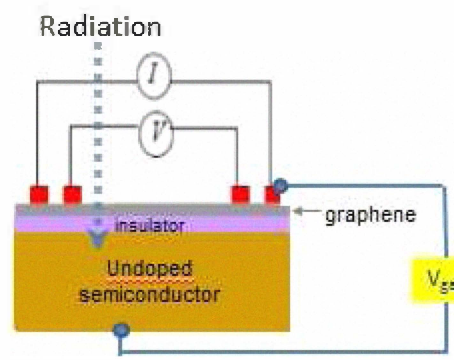
a.



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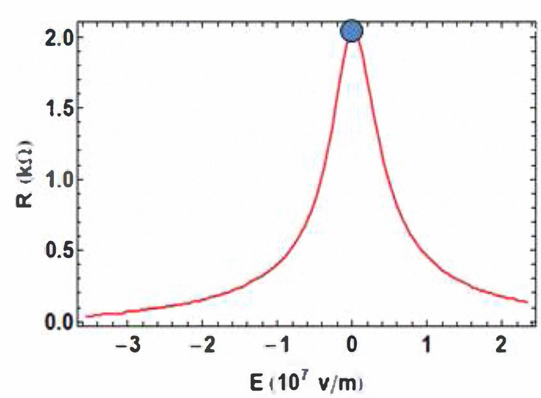
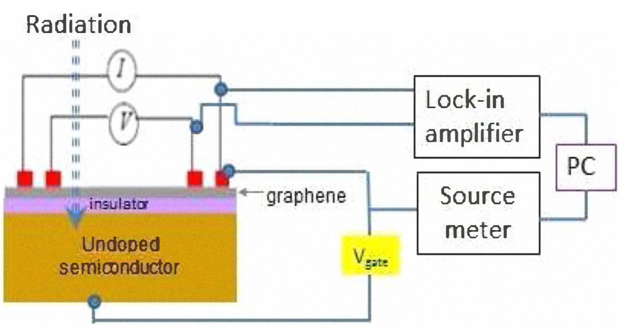


Fig. 1. a. A prototype graphene field effect transistor (GFET); b. graphene exhibits a sharp change in resistance as a function of applied field, near the charge neutrality point ("Dirac point"). Data shown are measured in a representative GFET with doped Si as substrate and 300nm-thick SiO_2 as buffer layer at room temperature [4].

II. Measurement Scheme

Our prototype GFET sensor (Fig. 1a) comprises graphene on an electrically gated, undoped Si as the radiation absorbing substrate, separated by an insulating SiO_2 layer. Applying a gate voltage between the graphene and the back of the absorber results in 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. There are four electrodes on the graphene for accurate 4-terminal resistance measurements, while 2-terminal measurements could be employed in the sensor in many practical situations. The drain and source electrodes supply the current through the graphene and are used to measure the voltage drop across the graphene. Figs. 2a and 2b depict the simplified schematic of the experimental setup and four probe connection on a graphene flake, respectively.

a.



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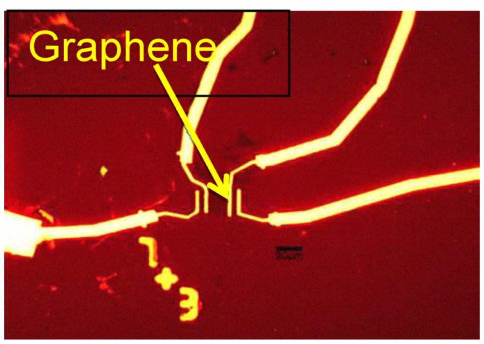

Fig. 2.a. Experimental schematic for X-ray irradiation on GFET and four-probe measurement with graphene [4]; 2b. Optical microscope image of a graphene device with 4 metal electrodes.

To validate our concept, we present the results of the experiments conducted on our GFET at cryogenic and room temperatures with X-ray source in the range of energies of up to tens of keV. We discuss the results obtained with two different absorbers (Si and SiC).

III. Silicon Absorber Based GFET

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. Also, the X-ray source was characterized to obtain its X-ray spectrum at different voltage and current settings. As a proof of concept, we test the field effect at zero back gate voltage and show no change in resistance in graphene due to the lack of electric field (Fig. 3a). We further show the effect of changing energy and flux, which results in corresponding changes in the resistance in graphene (Fig. 3b). 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. 3c).

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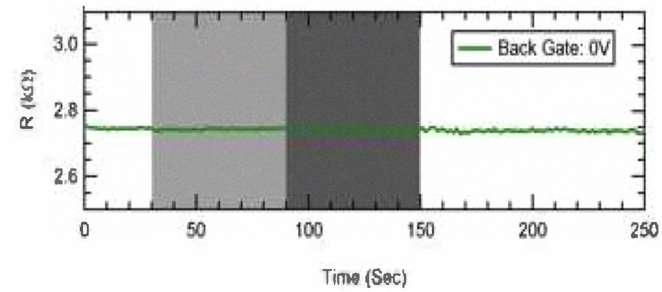

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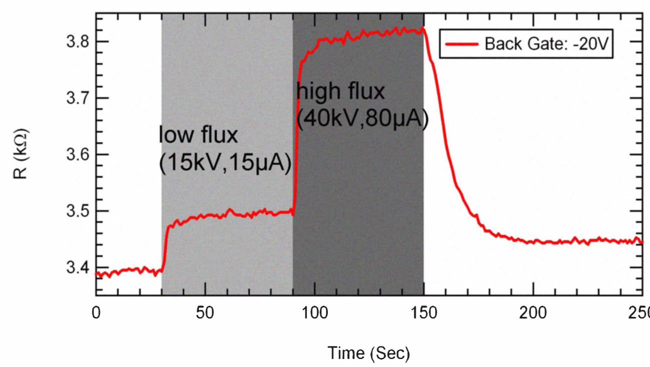

Fig.

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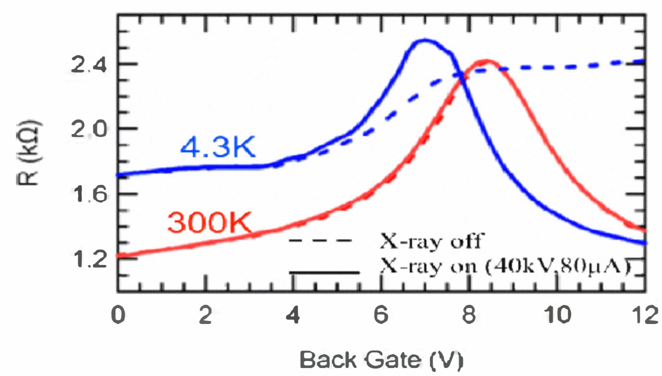

Fig. 3. a. Demonstration of proof of concept: Field effect is what causes a change in graphene resistance [4]; b. GFET response to low (15 keV, 15 μA) and high (40 keV, 80 μA) X-ray flux [4]; c. response of Si-based GFET at 4.3K and 300K [4]

IV. Silicon Carbide Absorber-Based GFET

The incoming radiation interacts with the absorber, which induces ionization. In conjunction with graphene, we are making use of various semiconductor absorbers, with potentially relaxed temperature, carrier mobility, purity, and lifetime constraints. High-density SiC and CZT absorbers have been chosen for the current studies for X-ray and gamma-ray detection. The SiC absorber-based GFET has shown good response to X-rays, gamma-photons, and light photons at room temperature. We observe up to 70% change in graphene resistance with X-ray irradiation on our SiC-based GFET at room temperature. Further, we have also studied the back gate voltage relationship to the graphene response, which is also shown in Fig. 5.

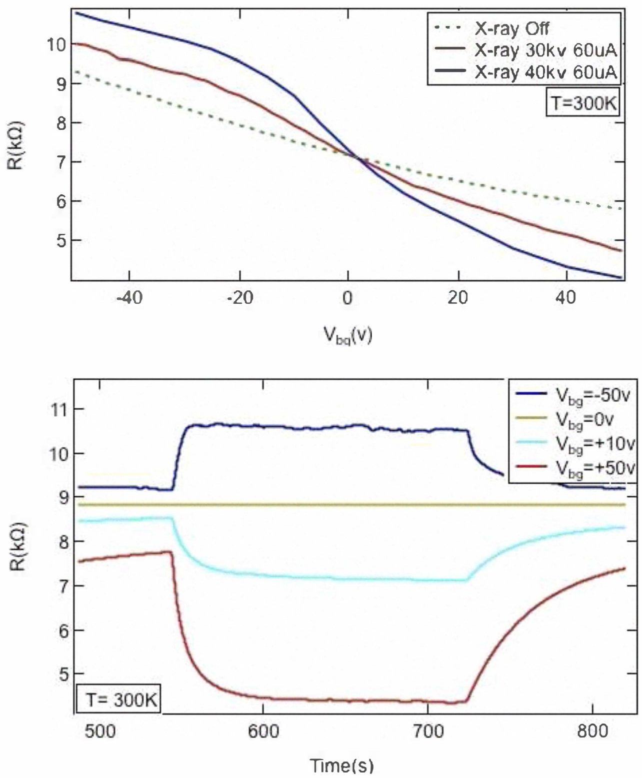

Fig. 5. Response of SiC based GFET to X-rays at 300 K

The Si and SiC 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 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. 6.a. We also tested the SiC device with gamma-rays. A 4.5 mCi ^{137}Cs source was used for the gamma-photon response (Fig. 6b).

We are also testing the GFET device with other absorbers like CZT, CdTe and GaAs. Undoped GaAs absorber was tested at 4.3 K and showed a faster response with X-ray radiation than the Si or SiC based devices. Presumably due to a lower RC in these devices, the charges quickly flow towards the respective electrodes and hence the response is quicker (Fig. 6c).

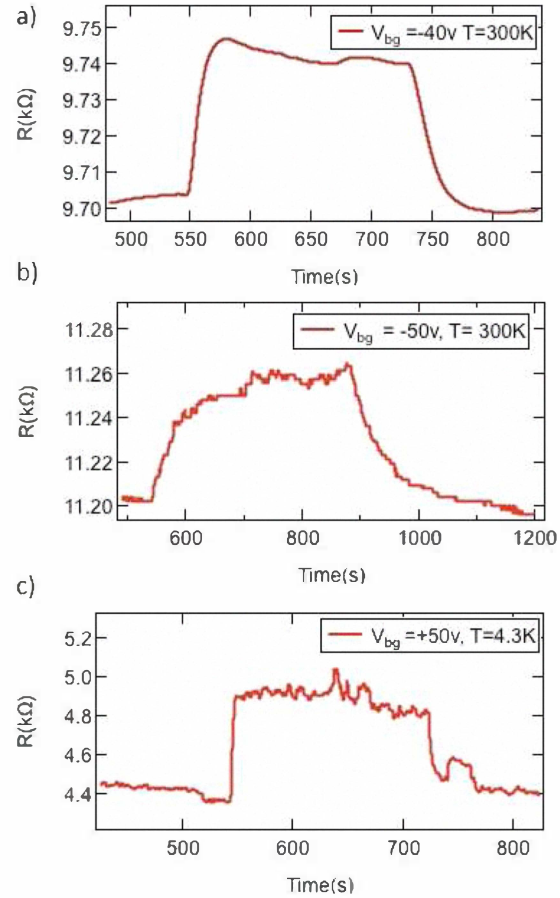

Fig. 6 Typical response of SiC-based GFET to a) light photons, b) gamma rays. Also shown in c) is the response of a GaAs-based GFET to X-rays.

V. Conclusion and Future Work

We are currently investigating methods to improve the GFET speed, which will require draining the accumulated charge under graphene. The charge drain mechanisms that are being considered resemble those used in a Depleted P-channel Field Effect Transistor (DEPFET) device. Our experimental results have shown that a relatively low response speed is obtained with graphene sensors based on a simple FET structure. The slow increase of graphene resistance due to radiation is associated with long overall drift time of carriers to the vicinity of graphene, while the slow decay is attributed to the lack of a mechanism to drain the charges accumulated below graphene. The latter has been experimentally confirmed by applying a short voltage pulse with a sign opposite to the gate bias voltage simultaneously with the turn off of the radiation source. In this case, graphene resistance has been observed to immediately restore its original value before any radiation exposure. Low detection speed is obviously a major issue that needs to be resolved for graphene sensors to compete with other well-established detector technologies. In order to achieve fast graphene sensors, we are investigating more advanced device structures that give rise to higher carrier drift speed and facilitate the removal of the electrons accumulated at the top surface of the semiconductor substrate.

Graphene on DEPFET [5] and high mobility AlGaAs/GaAs 2D electron gas structures are two promising solutions that are under consideration.

DEPFET, a detector composed of a field effect transistor incorporated into a fully depleted substrate, provides simultaneous radiation detection and signal amplification, resulting in a very low noise and high resolution. In fact, our graphene sensors exhibit a similar principle of operation to DEPFET in terms of combining detection and amplification, except that the transistor channel is a p-type inversion layer in case of DEPFET, while it is graphene in case of GFET. The response time of DEPFET is in the order of nanoseconds, and the low response speed of GFET compared to DEPFET can be a consequence of the differences in device architecture, such as the absence of (1) the p-n junction to deplete the substrate in GFET, (2) potential minimum to confine electrons near the transistor channel (graphene), and (3) "Clear" contact to drain the electrons from the potential well after readout. When all these components are incorporated into our graphene FETs, a DEPFET-like graphene FET structure would result, as depicted in Fig. 7. It is expected that this architecture could increase the detection speed.

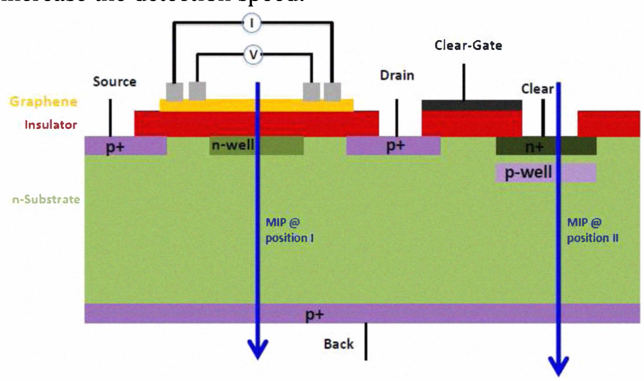

Fig. 7. DEPFET-like GFET structure. An n-well is implanted underneath graphene to accumulate the electrons in this region for readout. The electrons are then drained by applying a positive voltage to the "Clear" contact. All electrons generated in the left side of the detector drift to the n-well, while the majority of the electrons generated on the right side are lost to the "Clear" contact. In order to prevent this loss, a p-well is implanted under the "Clear" contact. Existence of p-well under the "Clear" contact gives rise to a potential barrier which makes the process of clearing more difficult. In order to control this potential barrier and the potential of the substrate neighboring the internal gate (n-well), a "Clear-gate" electrode is introduced.

We are also fabricating graphene on AlGaAs/GaAs HEMT (High Electron Mobility Transistor) as another possible option to reduce the response time. A sketch of a graphene HEMT is shown in Fig. 8. The hetero-junction of heavily n-type doped wide-band gap material $Al_{0.3}Ga_{0.7}As$ (E_g=1.80 eV) and undoped lower band gap material GaAs (E_g=1.42eV) results in transfer of electrons from AlGaAs region to the GaAs region, accumulating near the interface, due to the band gap offset of the two materials. This electron accumulation layer, called 2D electron gas, becomes the channel of the transistor. The band diagram of AlGaAs/GaAs hetero-structure (Fig. 9) provides a good visualization of the formation of the 2D electron gas. Since GaAs is undoped and, therefore, there are no impurities to scatter electrons, the electron mobility in a HEMT channel is higher than the electron mobility in a doped conventional MOSFET channel, making HEMTs faster than MOSFETs. The electrons generated by ionizing radiation move to the low potential 2D electron gas and modulate the graphene resistance. After readout, the electrons can be drained by the use of ohmic source and drain contacts to the 2D electron gas as shown in Fig. 8.

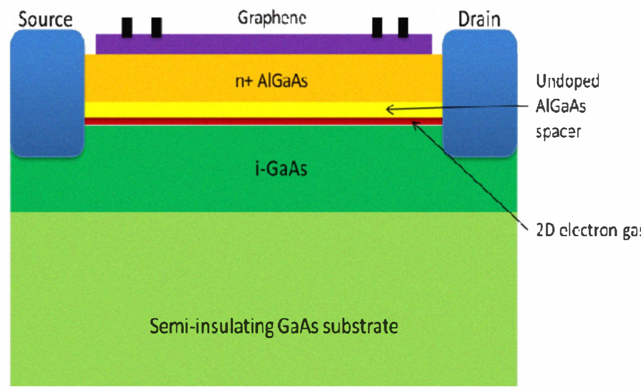

Fig. 8. Graphene on AlGaAs/GaAs HEMT

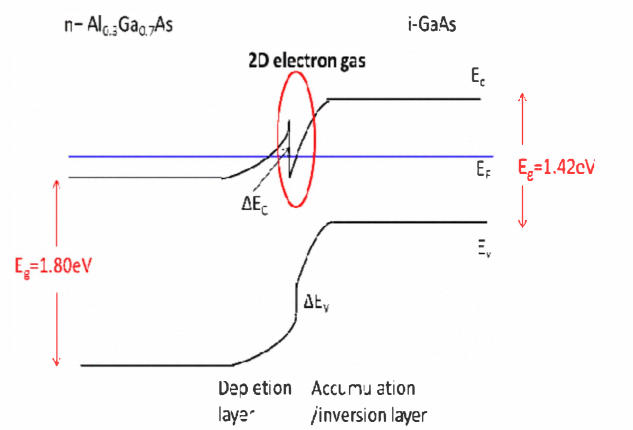

Fig. 9. Band diagram of AlGaAs/GaAs heterojunction

We have used Si, SiC and GaAs absorbers to fabricate GFET devices and experimentally demonstrated their sensitivity to X-rays, gamma-rays, and visible light. The operating principle of these detectors is based on detecting a local change in the field produced by incoming radiation through ionization, unlike detectors that utilize charge collection. The room temperature operation of SiC based GFET has also been demonstrated.

We are also fabricating a CZT, CdTe, GaAs, and AlGaAs absorber-based GFETs to study their performance in a range of operating conditions. We also have demonstrated through simulations [6] that neutron detection is possible with larger graphene devices. Experiments are in progress to test the neutron sensitivity of SiC based GFET. Such neutron sensors could find use in applications such as portal monitors. We also plan to demonstrate single-photon response of a GFET, along with demonstrating and measuring its energy resolution.

ACKNOWLEDGMENT

We are thankful to the Department of Homeland Security (DHS), Defense Threat Reduction Agency (DTRA), and National Science Foundation (NSF), who have supported us on this 'high risk – high pay off' project to construct a graphene-based sensor for SNM detection.

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