Graphene Field Effect Transistors for Detection of Ionizing Radiation

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***Abstract*–A novel radiation detector based on a graphene field effect transistor (GFET) is experimentally demonstrated. The detection in GFET 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 graphene-based radiation detector response to X-rays. We observed increasing resistance change of graphene with increasing X-ray flux in an electrically biased GFET based on a Si substrate. We have measured the temporal characteristics of our detector, along with the sensitivity of the device at high (40 kV-80 µA) and low (15 kV-15 µA) X-ray fluxes. Furthermore, we demonstrate room-temperature operation of a graphene radiation sensor based on a SiC absorber.**

I. INTRODUCTION

The development of high performance detectors for the use in detection of special nuclear material (SNM) has been a topic of interest for many researchers. Based on the exceptional electrical properties of graphene [1], [2], we are developing graphene-based sensors with high performance for detection of radiation emitted by SNM. Our prototype device (Fig. 1a) is an electrically biased 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 (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.

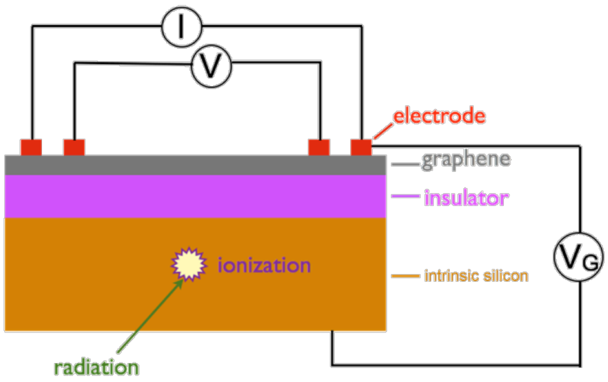

Fig. 1a. A prototype graphene field effect transistor (GFET)

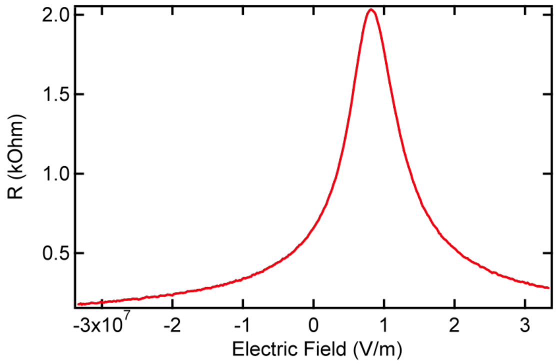

Fig. 1b. Graphene exhibits a sharp change in resistance as a function of applied field, near the charge neutrality point ('Dirac point'). Data shown are measured in a representative GFET with doped Si as substrate and 300nm-thick SiO2 as buffer layer at room temperature [4].

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 to the back of the absorber produces electric field which is varied to find the optimum point on the Dirac curve for a sharp change in graphene resistance. 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

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and source electrodes supply the current through the graphene and are used to measure the voltage drop across the graphene. The following (Fig. 2a and 2b) show the basic schematic of the experimental set-up and four probe connection on a graphene flake.

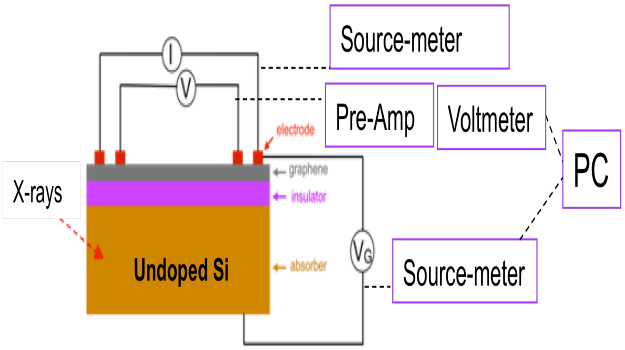

Fig. 2a Experimental schematic for X-Ray irradiation on GFET

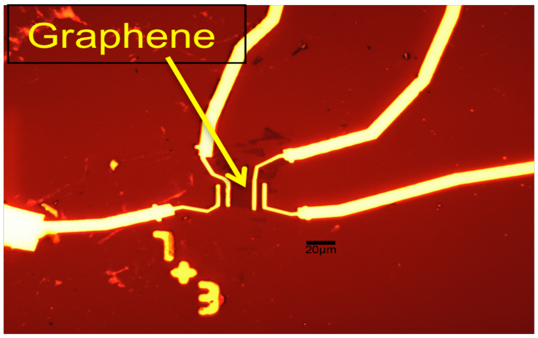

Fig. 2b Four-probe measurement with graphene [4]

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 up to tens of keV. We have used two different absorbers for radiation, i.e., Si and SiC based GFET, and show in the following section the results obtained thereof.

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 see the device response. Also, the X-ray source was characterized for the X-ray spectrum it produced at different voltage and current settings. As a proof of concept, we test the field effect at zero back gate voltage and show that the change in resistance in graphene is due to the local variation of field (Fig. 3a). We further show the effect of changing energy and flux, which has a corresponding change in the resistance in graphene (Fig. 3b). Further, we have observed more that 50% change in the resistance between the high (40 kV-80 μA) and low (15 kV-15 μA) X-ray flux at 4.3K. In the case of Si absorber we did not observed any response from the device at room temperature as the undoped sample does not completely freeze out and there still are charge carriers in motion. Thus the experiments carried out with Si based GFET were at liquid helium (4.3K) temperature (Fig. 3c).

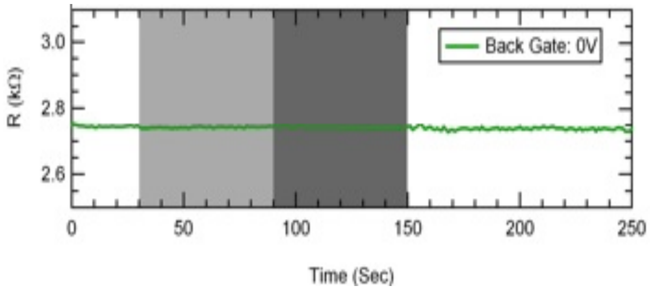

Fig. 3a Demonstration of proof of concept: Field effect is what causes a change in graphene resistance [4]

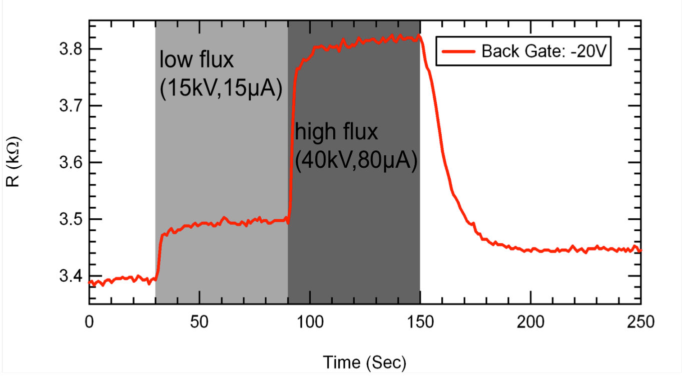

Fig. 3b GFET response to low (15 kV-15 μA) and high (40 kV-80 μA) X-ray flux [4]

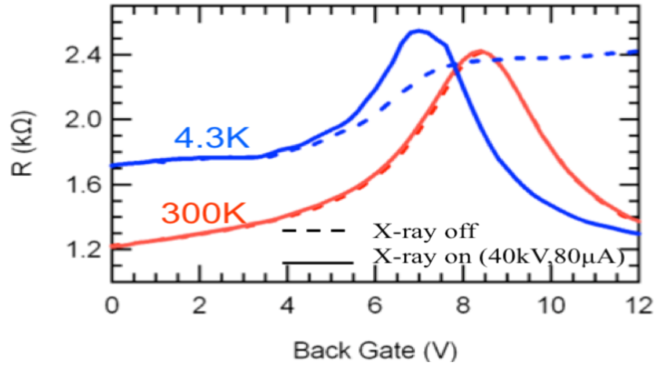

Fig. 3c The response of Si based GFET at 4.3K and 300K [4]

IV. SILICON CARBIDE ABSORBER BASED GFET

The absorber used in GFET interacts with the incoming radiation, 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 9% change (Fig. 5a) in graphene resistance with X-ray irradiation on our SiC based GFET at room temperature. Moreover, the observed change in graphene resistance is ever higher, approximately 72% (Fig. 5b) at 4.3K. Further, we have used higher X-ray energies and observed corresponding increase in the resistance change in graphene (Fig. 5c).

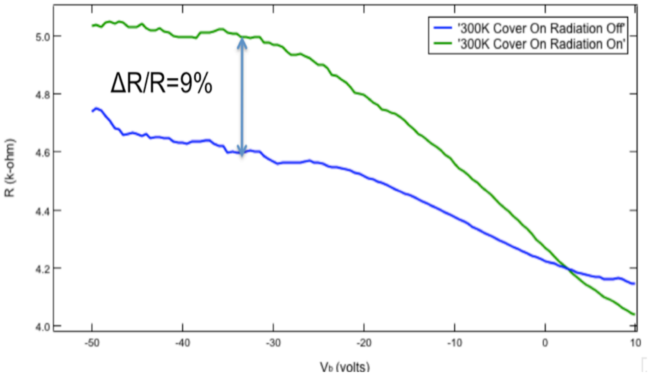

Fig. 5a Response of SiC based GFET to X-rays at 300K

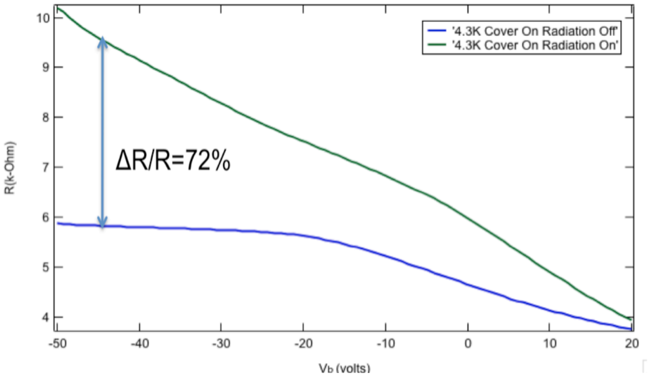

Fig. 5b Response of SiC based GFET to X-rays at 4.3K

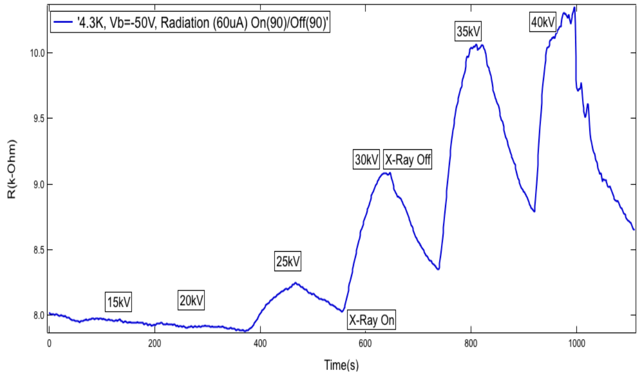

Fig. 5c SiC Based GFET response to increasing X-ray energies

GFET as Photo-resistor device:

The Si and SiC GFET devices have also been tested for their response to intermittent irradiation with He-Ne laser and light (white) photons, respectively. The photons produced by the laser penetrate through the graphene layer and ionize the underlying substrate to generate a change in the conductivity. Thus these devices could also be used in photo-resistor application. A typical On/Off response to a typical room light is shown in Fig. 6.

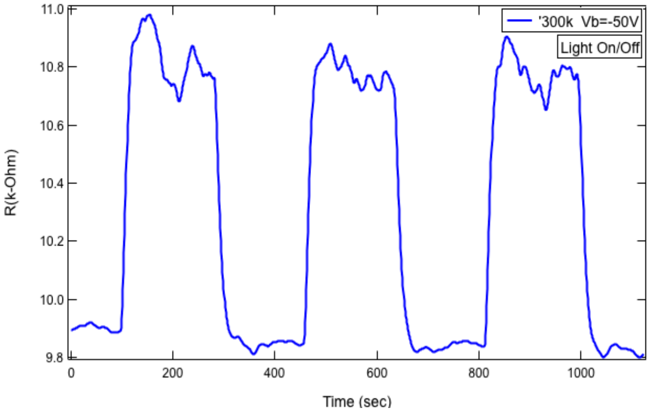

Fig. 6 Typical response of SiC based GFET to light photons

V. CONCLUSION AND FUTURE WORK

We have experimentally demonstrated the sensitivity of a GFET to X-rays. This detector works on the principle of a local change in the field produced by incoming radiation through ionization, unlike detectors that utilize charge collection. We have used Si and SiC absorbers and have observed response from X-rays and light photons. The room temperature operation of SiC based GFET has also been demonstrated.

We are currently investigating methods to improve the GFET speed, which will require draining the charge. The charge drain mechanisms that are being considered resemble those used in a DEPFET device. We are also fabricating a CZT absorber-based GFET. We are in the process of testing the GFET with gamma-rays. In near future we plan to demonstrate single-photon response of a GFET, along with demonstrating and measuring the energy resolution. Lastly, we are also considering applying graphene to neutron detection, which could be effectively used in applications such as portal monitors at national borders.

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