Performance and Design Optimization of Graphene Field-Effect Transistors for Radiation Detection

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INTRODUCTION

The two-dimensional material graphene 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 [1]. 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 results of our experimental program to develop a new type of radiation detectors based on graphene.

DETECTOR DESIGN AND PRINCIPLE OF OPERATION

Detection of radiation using GFETs is based on the sharp dependence of the graphene resistance on the local electric field [2]. 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. This field can be abruptly altered by the ionization induced in the absorber. 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 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. The operation of GFET as a radiation sensor, including its numerical modeling, is described in more detail in [3,4].

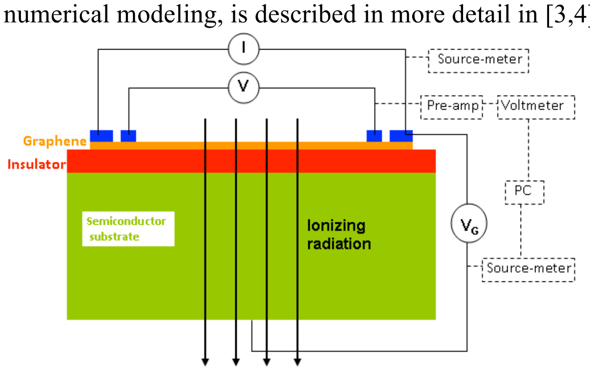

Fig. 1. The GFET structure and electrical interface for radiation detection [5]

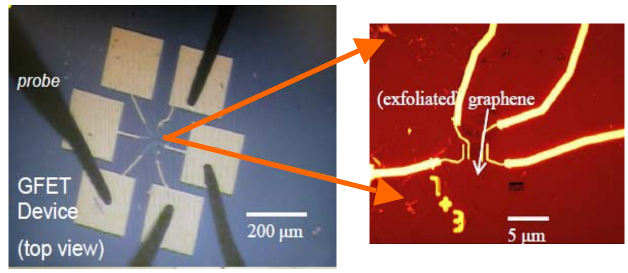

Fig. 2. Representative GFET device based on exfoliated graphene [5]

In typical fabricated devices (Fig. 2), four electrodes are instructed on graphene in order to allow accurate 4-probe measurement of graphene resistance by eliminating the contact resistance, although a 2-probe measurement could be used in many practical situations. The two outer electrodes are used to supply the current through the graphene, while the inner two electrodes are used to measure the voltage drop across the graphene. Resistance measurements are usually performed using a lock in amplifier.

SUMMARY OF EXPERIMENTAL RESULTS

In our experimental program we have demonstrated fabrication and operation of GFETs on a variety of substrates, including Si, SiC, CdTe, and GaAs. We have employed the fabricated devices to detect photons with a wide range of energies, including visible light, X-rays, and gamma rays. In the experiments with X-rays it has been demonstrated that the response of epitaxial GFETs [5] decreases at gate voltages of one polarity and increases at gate voltages of the other polarity due to X-ray exposure, and the higher the X-ray energy or flux at a fixed gate voltage, the larger the change in graphene resistance. The relative change in graphene resistance due to X-ray irradiation has been measured to be as high as 70% at a gate voltage of -50 V at room temperature.

Here we provide more detail on the room light response of chemical vapor deposition (CVD) graphene FET on undoped SiC substrate at room temperature (Fig 3). Graphene resistance increases by ~200% when the device is exposed to light at a gate voltage of 50 V [5]. Moreover, a negligible response was measured at zero gate bias, proving that the response of gated GFET to light is a field effect. This device suffers from a low response speed when the radiation source is turned off. In other words, graphene resistance is restored to its original value (before radiation exposure) over a relatively long period of time. This slow restoration of resistance is associated with the fact that our current devices lack a mechanism to effectively remove the ionized charges which are drifted to the top surface of the semiconductor substrate (due to the gate voltage applied across the absorber) and accumulated there. This has been experimentally confirmed by applying a short voltage pulse across the sensor thickness with opposite polarity to the gate voltage simultaneously with turning off the radiation source. In this case, graphene resistance has been observed to return to its original value before any radiation exposure considerably faster.

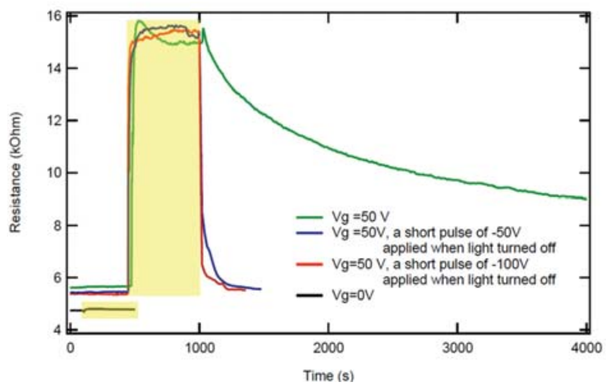

Fig. 3. Light response of CVD graphene FET on undoped SiC. Exposure intervals for different curves are shown in yellow boxes [5]

Typical operating devices have relatively small surface areas of <100 μm^2, but larger (~1 cm^2) devices have also been demonstrated. We have recently also used GFETs to detect alpha particles, where we unambiguously demonstrated the volumetric nature of the GFET detector response 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 based on neutron conversion to heavy charged particles.

IMPROVED DESIGNS AND CONCLUSION

We have demonstrated that gated GFETs fabricated on undoped semiconductor substrates can be used as radiation sensors featuring a novel detection concept with potentially improved capabilities. In addition to the relatively small size of typical devices fabricated to date, the challenges we encountered include the hysteresis effect and the relatively slow recovery of the device following irradiation. We attribute this long recovery time to the absence of a mechanism for ionized charge removal in the present proof-of-concept device architecture. A promising approach to solve this problem is the use of a somewhat more complex device design, akin to that of the depleted p-channel field effect transistor (DEPFET). Some details of our design and simulation work to develop graphene-based DEPFET [5] is illustrated in Figs. 5 and 6.

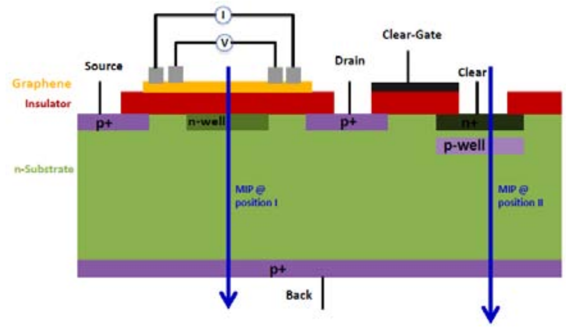

Fig. 4. Graphene DEPFET device architecture optimized with TCAD simulations [5]

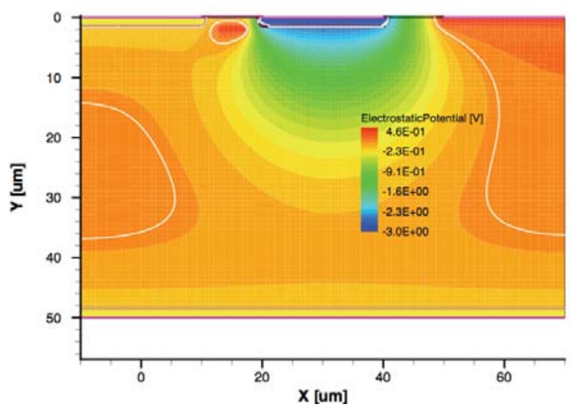

Fig. 5. Electrostatic potential distribution in GFET operating in detection mode [5]

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