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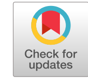
A novel graphene field-effect transistor for radiation sensing application with improved sensitivity: Proposal and analysis



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ABSTRACT

In this paper, a new radiation sensitive field-effect Transistor (RADFET) dosimeter design based on armchair-edge graphene nanoribbon (AGNR), for high performance low-dose monitoring applications, is proposed through a quantum simulation study. The simulation approach used to investigate the proposed nanoscale RADFET is based on solving the Schrödinger equation using the mode space (MS) non-equilibrium Green's function (NEGF) formalism coupled self-consistently with a two dimensional (2D) Poisson equation under the ballistic limits. The responsiveness of the proposed RADFET to the modulation of radiation-induced trapped charge densities is reflected via the threshold voltage, which is considered as a sensing parameter. The dosimeter behavior is investigated, and the impact of variation in physical and geometrical parameters on the dosimeter sensitivity is also studied. In comparison to other RADFETs designs, the proposed radiation sensor provides higher sensitivity and better scalability, which are the main requirements for futuristic dosimeters. The obtained results make the suggested RADFET dosimeter as a viable and attractive replacement to silicon-based MOS dosimeters.

1. Introduction

Radiation dosimeter is a device used to measure the absorbed or exposure dose of ionizing radiation and to monitor its time derivative (dose-rate) [1]. Nowadays, the radiation dosimetry becomes increasingly more important process due to dimensions of its valuable information. The dosimeters are used in many major fields such as space, nuclear industry, modern medicine, and environment monitoring [1–3]. Over the past decade, the use of radiation sensitive field-effect transistor (RADFET) dosimeters has remarkably increased because of their suitable characteristics such as small size, high sensitivity, non-destructive and immediate readouts, ultra-low power consumption, easy calibration, reasonable reproducibility, compatibility with microprocessors, and the possibility of wireless operating mode [1–10]. The dual-dielectric MOS dosimeter that was developed in the 1990s is considered one of the most attractive RADFET due to the particularity of its insulation structure, which consists of a silicon nitride layer (Si_3N_4) deposited on a layer of very high quality thermal oxide (SiO_2) [11]. The major benefits of this type of RADFET are attributable to its main trapping operation that occurs at the Si_3N_4-SiO_2 interface away from the channel/SiO_2 interface, leading to a minimization of hole neutralization by tunneling and interface-trap buildup. This significantly enhances the annealing and fade characteristics of the RADFET output response [11]. However, the scaling and sensitivity limitations of such dosimeters remain the major obstacles that prevent their broader use especially in radiotherapy [2–6]. Therefore, new theoretical approaches, materials, and designs which capture and improve the sensitivity behavior and figure of merit of such RADFETs should be developed in order to give new impetus to the development of these detectors as well as to pave the way for the fabrication and industry [8,9]. Graphene is among the promising materials that can substitute the silicon channel for such an application due to its unique and fascinating properties such as the low manufacturing costs, large surface-to-volume ratio, tunable band gap, high carrier velocity, linear energy dispersion relation, very high sensitivity to the local electrostatics, and high mobility in excess of 10^5 $cm^2/V\,s$ [12–14].

In this paper, a new nanoscale dosimeter design based on dual-dielectric double gate graphene nanoribbon field-effect transistor (DDDG GNRFET) has been proposed. The GNR-based RADFET is simulated by self-consistently solving the Schrödinger equation using the mode space (MS) non-equilibrium Green's function (NEGF) formalism with two-dimensional (2D) Poisson equation, under the ballistic limit [15–21]. The sensitivity behavior of the novel dosimeter has been analyzed in function of its dimensional and physical parameters. The

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obtained results cover several required features for futuristic dosimeters making the proposed GNR-based RADFET as a promising candidate for high-performance medical dosimetry and environment monitoring applications.

The outline of the paper is organized as follows. Section 2 introduces the structure, geometry, and operating principle of the proposed GNR-based RADFET. In Section 3, we present a brief description of the used quantum simulation approach. In Section 4, we present and discuss the simulation results. The conclusions will be drawn in the last section.

2. Dosimeter structure and working principle

Fig. 1(a) shows an armchair-edge single-layer graphene nanoribbon (AGNR) with 12 carbon atoms ($n = 12$) along the y-direction, which correspond to a bandgap of $E_G \approx 0.60$ eV and a width (W) equal to 1.35 nm [14]. Note that there are two conformations of GNRs, zigzag and armchair-edge GNRs [13,14]. We used the last conformation because the bandgap collapses at a finite source-drain bias in the case of zigzag GNR, which is not appropriate for the MOSFET-type device [19,20]. Fig. 1(b) shows the 2D cross-sectional view of the DDDG GNRFET-based dosimeter, where the whole AGNR is embedded between two silicon dioxide (SiO_2) layers. The source and drain reservoirs are heavily n-type doped (N^+) to ensure ohmic contacts [20,21]. Note that a highly controllable doping with foreign atoms can be performed to get n-type GNRs [21]. Two other low pressure CVD Si_3N_4 layers are deposited on the mentioned SiO_2 layers for acting as insulators and passivation layers. The Si_3N_4 material is used due to its high trapping efficiency and its moderate dielectric constant [22], which are very appropriate to such applications. The gates are attached to the Si_3N_4 over and under the intrinsic AGNR without overlap with the source and drain extensions. The gate bias (V_{GS}) is applied equally to the top and bottom gate. The traps located at the SiO_2/Si_3N_4 interfaces can be created intentionally by special annealing steps or ion implantation techniques for the radiation detection [11,22]. The dimensions t_1 and t_2, L_S, L_C, and L_D are the thickness of SiO_2 and Si_3N_4 layers, and the length of source, channel, and drain, respectively.

When the DDDG GNRFET-based dosimeter is under radiation, the electron–hole pairs at SiO_2 and Si_3N_4 layers are stimulated and released. The generated electrons and holes within nitride layer will be trapped at numerous electron and hole traps existed in the same Si_3N_4 layer, producing a negligible net charge [22]. In the silicon dioxide region, the generated electrons will move towards GNR channel out of the silicon dioxide layer due to a negatively applied gate bias during the radiation [11,22,23], as shown in Fig. 1(c). In contrast, the holes move towards the gate side and will be trapped at SiO_2/Si_3N_4 interface traps, forming the so-called radiation-induced trapped charge densities (N_f). It is to note that the amount of radiation-induced trapped holes can be controlled by tuning the negative gate biases during irradiation [22], and thus avoiding the saturation issue, which is attributed to the unavailability (eventual filling) of interfacial traps. Nevertheless, the provision of a sufficient amount of traps during the elaboration processes by considering the targeted range of radiation-induced trapped charge density is still important. The trapped holes modulate the electrostatic gating and change the threshold voltage V_{TH}, which is considered as a sensing parameter in this work. Therefore, by tracking the threshold voltage shifts, the radiation dose and the dose rate can be monitored successfully [22–24]. It is worth noting that the electrostatic mechanism of the proposed nanoscale GNR-based RADFET can be affected by short channel effects (SCEs), which occur at ultra-scaled FET-based devices due to the rapprochement of reservoirs. Therefore, the overlap effect of several electrostatic modulations (electrostatic gating, radiation-induced variations, SCEs) on quantum transport is expected.

3. Simulation approach

3.1. Quantum transport

The calculation of charge density in the GNR channel is performed by solving the Schrödinger equation using the non-equilibrium Green's function formalism in mode space representation, where the ballistic transport is assumed [17]. The MS approach is mainly used for saving the computational cost while maintaining the same degree of accuracy with respect to the real space (RS) method, which is more beneficial to deal the non uniform electrostatic effects and several quantum features [16–19]. Based on the Hamiltonian matrix of the armchair GNR channel H [19], the retarded Green's function can be written as follows [16]

$$G(E) = [(E + i0^+)I - H - \Sigma_S - \Sigma_D]^{-1} \tag{1}$$

where E is the energy, I is the identity matrix, 0^+ is an infinitesimal positive value, and Σ_S and Σ_D are the self-energies of the source and drain contacts, respectively, which couple the channel to the reservoirs, as shown in Fig. 2(a). The scattering self-energy Σ_{SCAT} is not taken into account ($\Sigma_{SCAT} = 0$) because the transport is assumed ballistic [16–20]. In the mode space approach, the self-energy of the source (drain) for the qth mode can be calculated analytically using the following equation [19]

$$\Sigma_{Sq(Dq)} = \frac{\alpha_{1(M)} + \sqrt{[\alpha_{1(M)}]^2 - 4(E - U_{1(M)})^2 b_{1q}^2}}{2(E - U_{1(M)})} \tag{2}$$
$$\alpha_{1(M)} = (E - U_{1(M)})^2 + b_{1q}^2 - b_{2q}^2$$

where

$$b_{1q} = t_0 + 4\Delta t_0 \sin^2[q\pi/(n+1)]/(n+1)$$
$$b_{2q} = 2t_0\cos(\pi q/(n+1)).$$

In the above relations, $b_{1q(2q)}$, $\Delta = 0.12$, $t_0 = 2.7$ eV, n, and $U_{1(M)}$ are the hopping parameter between B-A (A-B) nearest neighboring carbon lines [15], the edge bond relaxation parameter, the nearest neighbor tight binding parameter, the number of dimer lines that defines the AGNR width and its family (i.e., $n = 3p$, $n = 3p+1$, and $n = 3p+2$, where p is an integer) [14], and the electrostatic potential at the first (last) GNR column, which couples to the source (drain) contact, respectively. The self-energy matrices possess the same size as Hamiltonian $M \times M$, where M is the number of carbon atom lines in transport direction, noting that only *(1,1)* entry of Σ_S and *(M,M)* entry of Σ_D are nonzero elements [15]. Within the device, the local density of states (LDOS) ensuing from the source (drain) injected states is given by

$$D_{S(D)} = G\Gamma_{S(D)}G^+ \tag{3}$$

where $\Gamma_{S(D)}$ is the energy level broadening owing to the source (drain) contact and it can be written as

$$\Gamma_{S(D)} = i(\Sigma_{S(D)} - \Sigma_{S(D)}^+). \tag{4}$$

Once we get the above equations, the electron and hole density in any position of the GNR channel can be given by following equations [15,19,20]

$$n = \int_{E_N}^{+\infty} dE[G\Gamma_S G^+ f(E - E_{FS}) + G\Gamma_D G^+ f(E - E_{FD})] \tag{5}$$
$$p = \int_{-\infty}^{E_N} dE[G\Gamma_S G^+[1 - f(E - E_{FS})] + G\Gamma_D G^+[1 - f(E - E_{FD})]] \tag{6}$$

where E_N is the partial Fermi level in AGNR, and $f(E - E_{FS(D)})$ is the source (drain) Fermi function corresponding to the Fermi level $E_{FS(D)}$.

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