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Modelling of Graphene Field-Effect Transistor for electronic sensing applications

Abstract. *A top-gated Graphene Field-Effect Transistor (GFET) suitable for electronic sensing applications was modelled. The applied simulation method reproduces correctly the output transfer GFET characteristics and allows to investigate doping effect caused by different physical, chemical or biological factors. The appearance of additional charge in the system results in the shift of the current-voltage characteristic. This feature could be employed to measure the external factor intensity.*

Streszczenie. *Przedstawiono model grafenowego tranzystora polowego (GFET). Zastosowana metoda symulacyjna pozwala poprawnie odtworzyć charakterystyki tranzystora GFET i badać efekt domieszkowania wywołanego przez czynniki fizyczne, chemiczne i biologiczne. Pojawienie się w układzie dodatkowego ładunku powoduje przesunięcie charakterystyki prądowo-napięciowej, co może być wykorzystane do pomiaru wielkości działającego czynnika zewnętrznego. (**Modelowanie grafenowego tranzystora polowego do zastosowań w sensorach elektronicznych**).*

Keywords: graphene, Field-Effect Transistor, GFET, sensor.
Słowa kluczowe: grafen, tranzystor polowy, GFET, sensor.

Introduction

Graphene is a two-dimensional material consisting of thin monolayer sheets of carbon atoms arranged in a honeycomb crystal structure. Due to its outstanding properties, such as large surface-to-volume ratio, excellent electrical conductivity, high carrier mobility and density, high thermal conductivity, unique optical properties and so on, graphene can be considered as a promising base for electronic sensing. What is more, graphene is thought to enable practically endless design possibilities of sensors that are smaller, lighter, more sensitive, exhibiting better selectivity, working quickly and being even less expensive than traditional sensors. The majority of graphene-based sensor designs utilize a Field-Effect Transistor (FET) devices with a graphene channel (GFET) (Fig. 1).

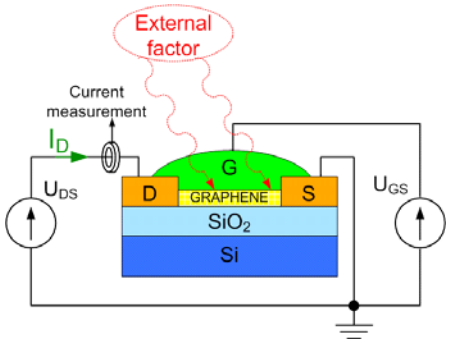

Fig. 1. Illustration of Graphene Field-Effect Transistor sensor circuit.

Generally, FET is a three-electrode device which is commonly in use in electronic applications. The principle of its operation is based on the so-called field effect which enables to control the conductivity of the semiconducting material in the channel region by an electric field generated by the applied external voltage. More precisely, the shape of the channel and the flow of electrons (or holes) from the source (S) to drain (D) is influenced by the voltage applied across the insulated gate (G) and the source. Thus, in the typical Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) the drain current I_D depends on the U_{GS} voltage applied between the gate and the source terminals [1]. In a word, MOSFET transistors are easily controlled by changes of the U_{GS} voltage without power consumption by a control circuit in the static on-states.

The FET technology is still under development and the research work is mainly focused on either the miniaturization of the devices or the improvement of their parameters (see e.g. Refs [2-4]). At the same time, the intensive investigations of graphene-based transistors are carried out and one can suspect that GFETs could compete with the conventional MOSFET devices which have been developed for decades. Previously, a 300 nm SiO_2 layer underneath the graphene served as a dielectric material and a highly doped Si substrate acted as the back-gate. Such devices, however, suffered from unacceptably large parasitic capacitances and could not be integrated with other components. Because of that limitation, a practical GFET needs a top-gate [5]. It is worth to note at this stage, that the high carrier mobility and the unique band structure of graphene make it very promising for various FET applications [5-7], especially in the field of detection of different physical, chemical and biological factors which strongly influence electrical properties of the graphene layer.

Estimation of properties of a newly designed device is always an essential issue during the development process because the realization of a prototype (especially in the case of a transistor) may be often difficult due to the complicated technological process and the requirement of the specialized equipment. It is why the simulation should be always performed at this stage of the investigation. The aim of this work was to study the performance of the modelled Graphene Field-Effect Transistor suitable for electronic sensing applications.

Physical model and computational details

Graphene is a zero-gap semiconductor with a linear dispersion near the Fermi level. It has been observed during various measurements that large-area-graphene transistors exhibit a unique current–voltage (I-V) transfer characteristic. The type of carriers (electrons or holes) and carrier density in the channel depend on the potential differences between the channel and the gate. Positive gate voltages lead to n-type conductivity whereas negative gate voltages promote p-type conduction mechanism in the channel. As a consequence, the two branches of the transfer characteristics, separated by the so-called Dirac point (charge neutrality point), appear. At the Dirac point the minimum conductivity and maximum resistance are visible. The value of the Dirac point voltage depends on several factors, such as: type of electric contacts, the quality of the substrate and the graphene layer, the type and density of

the charges at the interfaces at the top and bottom of the channel and any doping of the graphene sheet. The last listed feature is of great importance in the context of electronic sensing because many external factors (e.g. adsorbed molecules or ions on the graphene surface) could be regarded as dopants which are responsible for the Dirac voltage shift [8-10]. Therefore, when the Dirac point is at negative (positive) voltage on an *I-V* graph, graphene is doped with electrons (holes).

Our calculations were performed with the use of the GFET Tool program [11] which enabled simulation of the electrical characteristics of a top-gated Graphene Field-Effect Transistor. The drift-diffusion approach was employed to calculate self-consistently the current vs. voltage behavior of the simulated GFET for the different initial temperatures. Also the carrier density in the channel could be evaluated in this program. The velocity saturation, charge inhomogeneity ("puddle" charge density distribution caused by impurities in the SiO_2 layer and on the graphene surface or to thermally excited carriers), Seebeck effect and device breakdown due to thermal self-heating are taken into account in the code, as well.

In this study we assumed the GFET device with 1μm x 1μm graphene channel geometry, the top-gate dielectric thickness of 10nm and the 300 nm SiO_2 layer. The simulated initial temperature was 293 K. The mobility of the both type of carriers (electrons and holes) was 3000 cm^2/Vs. We decided to investigate the performance of the device at three Dirac voltages U_0 = 0 V, -5 V and +5 V to simulate different types of doping.

Results of simulation

Generally, output $I_D(U_{DS})$ characteristics of the modelled GFET (Fig. 2) are similar to the typical FET I-V characteristics. The linear and saturation regions are noticeable especially for U_{GS} voltages much higher than the Dirac voltage U_0. The drain saturation current I_{Dsat} depends directly on the gate-to-source voltage U_{GS}, which is a characteristic feature of the Field-Effect Transistors.

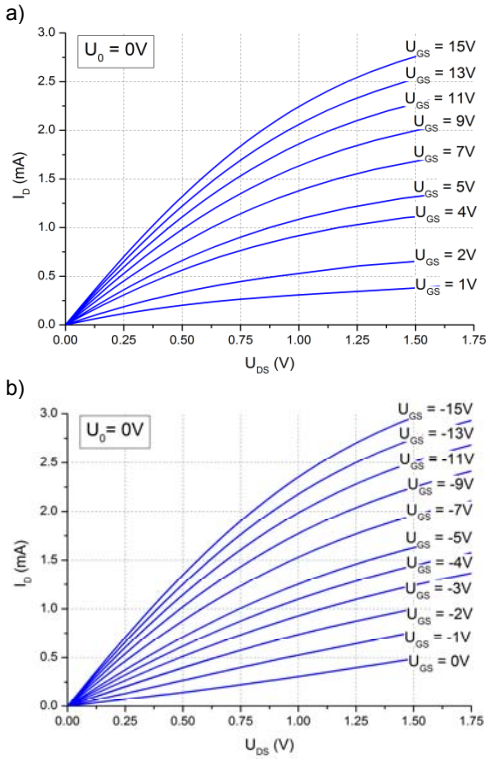

Fig. 2. Output characteristics $I_D(U_{DS})$ of a modelled GFET for U_0 = 0 V: a) for $U_{GS} > U_0$, b) $U_{GS} \leq U_0$.

However, there are also some noticeable differences between the both types of transistors. It is visible from Fig. 3 that the transfer characteristic $I_D(U_{GS})$ of GFET differs from the typical one of MOSFET. The threshold voltage $U_{GS(th)}$ is not observed so the GFET is in a conduction state in all the range of U_{GS} voltage [5]. The I_D current reaches the minimum for U_{GS} close to the Dirac point voltage used in the program set-up for the simulation (U_0=0V). One can also see a shift of the Dirac voltage, evaluated from the output characteristics (i.e. the point of the minimal conductance), towards positive values with increasing drain voltage. This effect can be explained by the influence of the drain voltage on the channel potential [7].

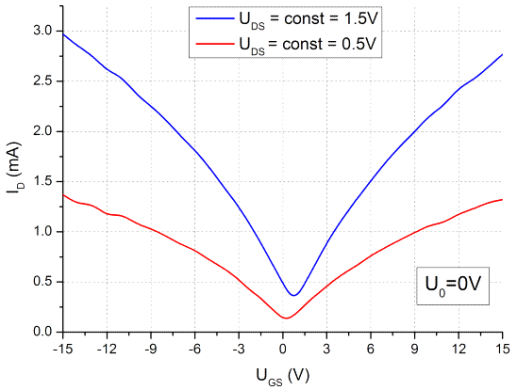

Fig. 3. Transfer characteristic $I_D(U_{GS})$ of the modelled GFET for U_O = 0 V, U_{DS} = 0.5 V and U_{DS} = 1.5 V.

It should be pointed out, that the conduction of GFET is ambipolar, that is, exhibits an electron character for $U_{GS} > U_0$ and hole character for $U_{GS} < U_0$. It means that the graphene-based transistor behaves, to some extent, similarly to the *n*-FET for $U_{GS} > U_0$. The drain current I_D increases with decreasing U_{GS} for $U_{GS} < U_0$ but in contrast to the *p*-FET the direction of current flow is the same as for the *n*-FET.

The drain-to-source resistance R_{DS} plots are presented in Fig. 4. The maximum of R_{DS}, corresponding to the previously-mentioned minimum of the conductivity, is visible for U_{GS} close to U_0 and it is about few kΩ - much less than for typical FETs (the order of tens of kΩ). The value of R_{DS} also depends on the U_{DS} voltage. The smallest dynamic resistance is in the linear region of $I_D(U_{DS})$ characteristics (U_{DS} = 0.5 V), which is typical for FETs. The minimal value of R_{DS} equals 370 Ω and is comparable with the value used in the GFET Tool input (350 Ω).

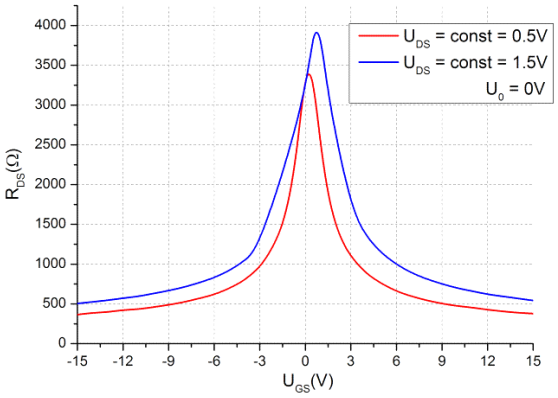

Fig. 4. The drain to source resistance R_{DS} of the modelled GFET for U_0 = 0 V, U_{DS} = 0.5 V and U_{DS} = 1.5 V.

Next, we simulated different doping by applying various Dirac point voltage in the set-up to analyze its influence on the $I_D(U_{GS})$ and $Q_G(U_{GS})$ characteristics. At first glance the

shape of the examined $I_D(U_{GS})$ characteristics does not change significantly and can be assumed not to depend on the U_0 changes (Fig. 5). This effect may be employed in practical sensor applications, where the external factor impacts on the Dirac voltage as it was recently demonstrated for GFET gas sensors [8,9].

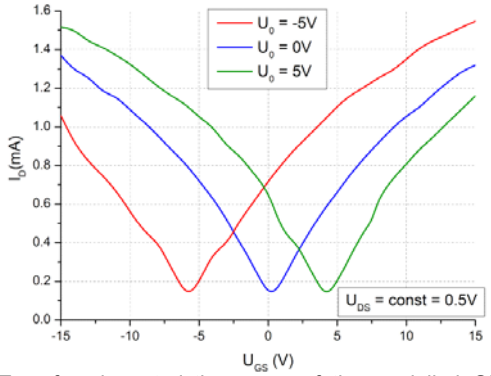

Fig. 5. Transfer characteristic $I_D(U_{GS})$ of the modelled GFET for U_0 = 0V, -5V and 5V, U_{DS} = 0.5V.

The simulated characteristics of the total charge Q_G, accumulated in the gate layer, for different Dirac voltages are shown in Fig. 6. In all the cases electron and hole conduction mechanisms can be distinguish above (right side) and below (left side) the charge neutrality point, respectively. The performed simulation indicates, that the presented $Q_G(U_{GS})$ characteristics can be assumed to exhibit linear character in the whole range of U_{GS}. The slopes of these characteristics also remain constant during the different doping (the U_0 voltage change). Hence, the estimated value of the gate capacitance (C_G = 35 pF), defined as $C_G = dQ_G/dU_{GS}$, is constant, too.

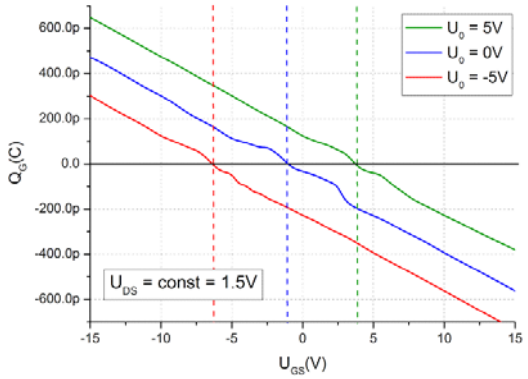

Fig. 6. The gate charge characteristics $Q_G(U_{GS})$ of the modelled GFET for U_0 = 0 V, -5 V and 5 V (U_{DS} = 1.5 V). Dashed lines indicate charge neutrality points.

Conclusions and perspective

In this paper the results of the simulation of a top-gated Graphene Field-Effect Transistor (GFET) were presented. We succeeded in reproducing typical for a graphene-based transistor characteristics. The applied method enables simulation of different types of doping influencing the position of the charge neutrality point in practical GFET applications, as well. From our investigation, it appears that at various Dirac point voltages all the characteristics exhibit practically the same character.

The GFET devices could be successfully employed in the widespread electronic sensing applications due to their simplicity of design, ease of mass production in high-density array and inherent capability of signal amplification. One of the possible methods of electronic sensing to be utilized in practical devices is to set the GFET operating point at the minimum of the conductivity when the external factor is not present and the determined U_{GS} and U_{DS} voltages should be kept constant. The appearance of additional charge in the system due to the influence of the external factor must result in the shift of the current-voltage characteristic and, consequently, in the change of the operating point. In this situation the drain current I_D is modulated and could be treated as a measure of the external factor intensity (see Fig. 1).

Despite the great progress in the field of GFET sensor design, there are still numerous challenges, such as controlling the graphene surface and the number of layers, limiting substrate-derived effects and enhancing the overall performance. Different GFET architectures and gate materials should also be taken into consideration. Furthermore, there is an urgent need for intensive investigation aimed at the output signal analysis and, especially, the processing of signals from arrays of GFET sensors to enable precise measurements of different kinds of factors. In the nearest future the measurements of output characteristics of the real GFET sensors are planned what will allow for the direct comparison between the simulation and the experimental data.

REFERENCES

[1] Tsividis Y.P., Operation and Modelling of MOS Transistor, (1999) *Oxford University Press, New York*

[2] Wong H.-S. P., Beyond the conventional transistor, *Solid-State Electron.*, 49 (2005), No. 5, 755–762

[3] DasGupta A., Multiple gate MOSFETs: The road to the future, *International Workshop on Physics of Semiconductor Devices*, (2007), 96–101

[4] Rossum M.V., MOS Device and Interconnects Scaling Physics, *Advanced Nanoscale ULSI Interconnects: Fundamentals and Applications*, Shachma-Diamand Y., Osaka T., Datta M., Ohba T. (Eds.), (2009), Springer, 15-38

[5] Schwierz F., Graphene transistors, *Nat. Nanotechnol.*, 5 (2010), No. 7, 487–496

[6] Bae M.-H., Islam S., Dorgan V. E., Pop E., Scaling of High-Field Transport and Localized Heating in Graphene Transistors, *ACS Nano,* 5 (2011), No. 10, 7936–7944

[7] Rodriguez S., Vaziri S., Ostling M., Rusu A., Alarcon E., Lemme M. C., RF Performance Projections of Graphene FETs vs. Silicon MOSFETs, *ECS Solid State Lett.*, 1 (2012), No. 5, Q39–Q41

[8] Inaba A., Yoo G., Takei Y., Matsumoto K., Shimoyama I., A graphene FET gas sensor gated by ionic liquid, *IEEE 26th International Conference on Micro Electro Mechanical Systems,* (2013), 969–972

[9] Inaba A., Yoo K., Takei Y., Matsumoto K., Shimoyama I., Ammonia gas sensing using a graphene field–effect transistor gated by ionic liquid, *Sens. Actuators B Chem.*, 195 (2014), 15–21

[10] Zhan B., Li C., Yang J., Jenkins G., Huang W., Dong X., Graphene Field-Effect Transistor and Its Application for Electronic Sensing, *Small*, 10 (2014), Iss. 20, 4042–4065

[11] Eric Pop, Feifei Lian (2014), *GFET Tool*, https://nanohub.org/resources/gfettool (DOI: 10.4231/D3QF8JK5T).

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