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Recent developments in graphene based field effect transistors

B. Vamsi Krsihna^a, S. Ravi^b, M. Durga Prakash^{a,c,*}^a Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Guntur 522502, Andhra Pradesh, India^b Department of Electronics and Communication Engineering, Gudlavalleru Engineering College, Gudlavalleru 521356, Andhra Pradesh, India^c Department of Electronics and Communication Engineering, Velagapudi Ramakrishna Siddhartha Engineering College, Vijayawada 520 007, Andhra Pradesh, India

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ABSTRACT

This paper presents a comprehensive survey on the recent developments in Graphene Field Effect Transistor (G-FET), considering various aspects such as fabrication, modelling and simulation tools and applications especially in sensors, highlighting the future directions. Complying with the Moore's law, to increase the transistor density of an Integrated Circuit, new alternate materials for fabrication have been tried, instead of silicon due to its limitations in reducing transistor dimensions. Graphene, one such material, proves to be a suitable alternate for silicon due to the factors like superior carrier mobility and very high *trans*-conductance gain, etc and G-FET is becoming the most suitable choice for high-speed analog VLSI, RF, and bio- sensor circuits.

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1. Introduction

Graphene is the name given to a flat monolayer of carbon atoms firmly pressed into a two-dimensional (2D) honeycomb cross section, furthermore, is an essential structure hinder for graphitic materials of all other dimensionalities shown in Fig. 1 [1]. It tends to be wrapped up into 0D fullerenes, folded into 1D nanotubes or stacked into 3D graphite. Theoretically, graphene (or '2D graphite') has been read for a long time [2–4], furthermore, is generally utilized for portraying properties of different carbon-based materials. After forty years, it was understood that graphene additionally gives a magnificent consolidated issue simple of (2 + 1)-dimensional quantum electrodynamics [5–7], which moved graphene into a flourishing hypothetical toy model. Then again, albeit known as a necessary piece of 3D materials, graphene was assumed not to exist in the free state, being portrayed as a 'scholarly' material [6] and was accepted to be flimsy regarding the arrangement of bended structures, for example, sediment, fullerenes and nanotubes. Out of nowhere, the vintage model transformed into the real world, when unattached graphene was startlingly discovered three years prior [8,9] and particularly when the subsequent trials affirmed [10,11] that its charge bearers were

in reality massless Dirac fermions. In this way, the graphene 'dash for unheard of wealth' has started.

The Fig. 2 shows one of the possible implementation of dual gate G-FET. The Fig. 2(a) shows the 2-dimensional view and the Fig. 2(b) shows the corresponding 3-dimensional view. In this structure, the graphene channel is fabricated in between two gate oxide layers namely one is the top gate and second is back gate oxide (substrate) as a layer. The SiO₂ acts as the dielectric for back gate. The bottom layer is made by Si wafer, which act as the back gate. The bilayer graphene channel is fabricated by depositing on a thick SiO₂ layer, which in turn made to grow on a thickly doped back gate which is the Si wafer. By applying a proper back gate bias voltage, channel inversion can be done in order to operate G-FET as a switch that changes its state between ON and OFF. The back gate is used to control source and drain resistance of the GFET.

G-FET based transistors have several merits as listed below:

- High electron mobility ($\mu_n = 2 \times 10^5 \text{ cm}^2/\text{V.s}$)
- High transconductance gain (g_m)
- High velocity saturation ($6.3 \times 10^7 \text{ cm/s}$)
- High carrier density (10^{12} cm^{-2})
- High intrinsic cut-off frequency ($f_T = 427 \text{ GHz}$)
- Large surface to volume ratio and
- Smaller band gap (about 200 meV).

* Corresponding author.

E-mail address: mdprakash@vrsiddhartha.ac.in (M.D. Prakash).<https://doi.org/10.1016/j.matpr.2020.07.678>

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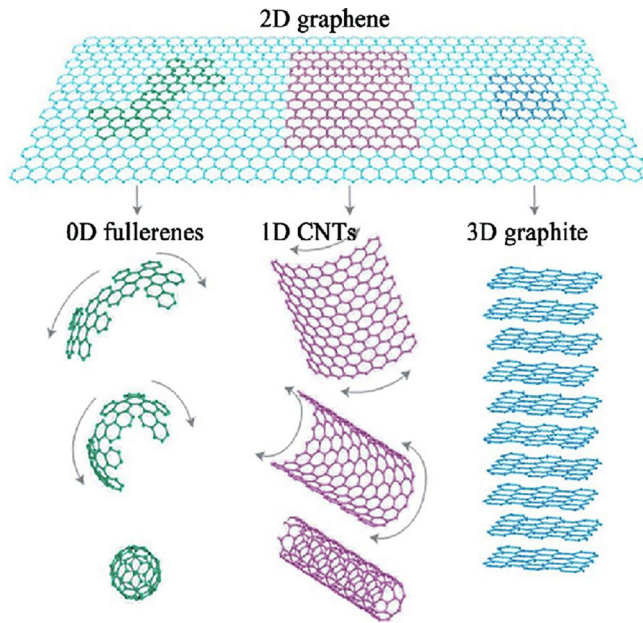


Fig. 1. Birth of all graphitic structures. Graphene is a 2D building material for carbon materials of all other dimensionalities. It can be wrapped up into 0D Bucky balls, rolled into 1D nanotubes or stacked into 3D graphite.

Graphene has also other specific qualities which are given hereunder:

- Tensile strength ten times that of the steel,
- Excellent thermal conductivity, high selectivity,
- High sensitivity,
- Optical transparency and
- Highest ballistic electronic speed.

Based on the above merits of graphene, G-FETs are being used in several nanometer sized circuits such as high speed analog circuits – voltage controlled current sources, radio frequency devices – frequency doubler, frequency tripler, mixer, frequency multiplier, sensors – G-FET based DNA sensors, and gas sensors, etc [12].

Organization of the paper: The Section 2 presents some of the related surveys done by the researchers in the domain of graphene based FET. The Section 3 presents the developments in modelling, design, and fabrication of GFET. The Section 4 presents the popular software tools for modelling and analysis of GFET circuits. The Section 5 presents some of the possible research directions in GFET followed by conclusion in the Section 6.

2. Related surveys

A recent survey in developments in gas sensing technologies is presented [13] in which classified the sensors, based on the methods used for sensing, such as electrical variations in materials such as Metal-oxide-semiconductor (MOS), Carbon nanotubes, polymer, and moisture absorbing materials. It also discussed other methods like optic methods, acoustic method etc. This paper also reviewed various methods of improving sensitivity and selectivity of sensors. However, the Graphene based FET sensors, which are the special types of sensors under carbon nanotubes based sensors, are not discussed much in detail. Another survey based on applications of GFET in bio-sensing applications is presented in [14], which focused on the applications of GFET in sensing bio-molecules like DNA, neuro transmitters, and proteins. A survey paper on graphene manufacturing techniques and metrology is presented in [15], which reviewed some of the techniques on establishing switching behaviour in Graphene based FETs. It also presented the details of fabrication techniques such as exfoliation, epitaxial graphene from Silicon carbide substrate, and chemical vapour deposition. Our paper, considering the above mentioned surveys, focuses on the development in G-FET from the mentioned directions, and also surveys the other major aspects such as tools used for G-FET design and analysis.

3. Recent developments

There are three major categories as listed below, on which, this survey/review paper is written and presented. The materials presented here are the latest update of the developments in the field of GFET based research.

- (i) Fabrication Methodologies
- (ii) Modelling and Simulation tools for GFET and
- (iii) Applications of GFET.

3.1. Fabrication methodologies

There are four commonly used fabrication methods for Graphene as listed below:

- (i) Exfoliation by Mechanical means
- (ii) Epitaxial growth
- (iii) Chemical vapour deposition
- (iv) Chemical Derivation.

The following subsections present the details pertinent to each of the above mentioned fabrication methodology.

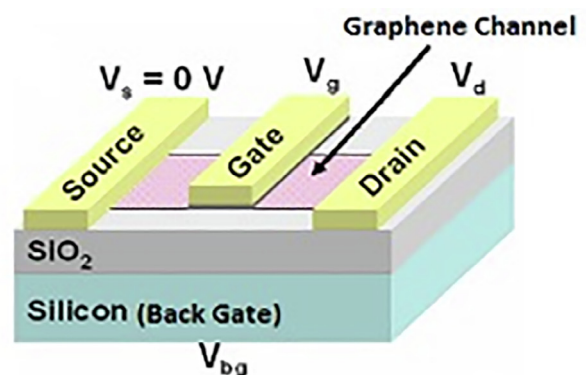
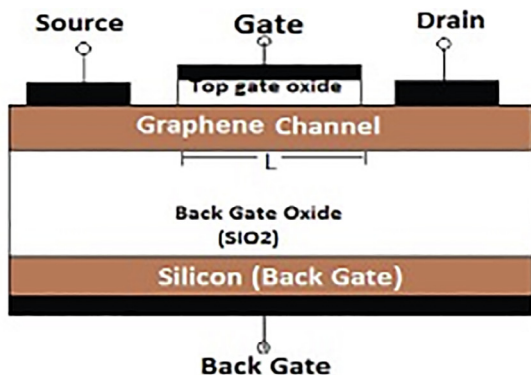


Fig. 2. (a) 2-D view of dual gate GFET; (b) 3-D view of dual gate GFET.

3.1.1. Exfoliation by mechanical means

This methodology, exfoliation, is one of the fabrication methodology to get the graphene layers (one and several) and done mechanically [16], from Graphite. The Graphite consists of sheets of graphene which are bonded together through Van der Waals forces due to which the atoms get attracted and repulsed each other. This fabrication methodology employ adhesive tape to peel off the graphite repeatedly. It is brought to the required thickness by further strips of tape. The final required Graphene material is obtained by rubbing it against silicon dioxide on silicon surfaces. The graphene flakes formed through this approach can be observed through an optical microscope.

3.1.2. Epitaxial growth from Silicon carbide substrates

This is another fabrication methodology, which make the graphene layers, by epitaxial growth from the Silicon Carbide substrates [17]. The epitaxial growth is done thermally at 1250 °C and 1450 °C temperatures by absorbing Silicon. This methodology is more industrially relevant and can be controlled. G-FET can be fabricated from graphene on a wafer scale. The graphene fabricated from this methodology and its layers can be observed by optical microscope and by Raman spectroscopy. The fabrication cost is extremely high compared to the CMOS technologies, which is the disadvantage of this fabrication technology.

3.1.3. Chemical vapour deposition of hydrocarbons

This fabrication method employs the Chemical Vapour Deposition (CVD) methodology for Graphene transistor manufacturing. The chemical vapour deposition is done on metallic surfaces like ruthenium, nickel, etc [15]. This methodology applies dissolving the carbon on metal substrates like nickel and allow to get precipitated by forced cooling techniques. There can be yet another approach of this kind to make the graphene sheets to grow on metals like copper or iridium [18,19]. There are two kinds of substrate materials used as substrate for GFET fabrication. One is rigid materials such as Silicon, dimethyl-siloxane coated Silicon [20], etc. The limitations of using rigid substrates include mechanical property mismatch between structures, signal instability, etc. Fabrication of GFET on a Microbial Cellulose (MBC), a flexible substrate structure, is done using CVD approach [21] and it provides very high mobility ($>1700 \text{ cm}^2/\text{Vs}$). In addition to that it provides improved ohmic resistance, transconductance, and Drain current. However, such flexible structures also having the limitations of performance degradation due to manufacturing issues such as shrinkage, delamination, and deformation. A detailed survey on the developments GFET fabrication approaches using flexible and rigid structures is presented in [22].

3.1.4. Chemical derivation

This is also one of the fabrication methodologies, where chemical derivation methodology applied to manufacture G-FET. Graphene Oxide peeled off using adhesive tape under water to make sheets of layers. Then sodium boro-hydrate or hydrazine are made to get precipitated as insoluble graphene sheets. These sheets are not soluble in water.

3.2. Software tools for G-FET modelling and simulation

This subsection compares some of the commonly available modelling and analysis tools for G-FET and the comparison between these tools.

3.2.1. GFET tool

The tool, GFET tool, used to simulate to do the behavioural study pertinent to electrical and thermal behaviour of a GFET. This tool can estimate the G-FET's voltage / current behaviour keeping

the temperature of the G-FET consistently. The tools employs the approach of drifting and diffusion method for this study. This tool can also estimate and generate the study of the following on the G-FET

1. Carrier density
2. Temperature profile studies
3. Drift velocity and
4. Electric field studies

3.2.2. Silvaco from cadence

Silvaco, a CAD tool, is used to develop the models in ATLAS simulator (a device simulator for 2D and 3D structures) to investigate the performance of GFET [20]. This simulator helps to simulate the electric characteristics, optical and thermal characteristic study of the electronic circuits. These simulation studies makes it easy to comprehend the device behaviour and its performance. These also help in making accurate estimation of the devices, which are fabricated with compound materials like binary, ternary and quaternary.

3.2.3. Cadence Virtuoso spectre circuit simulator

This tool used to model the large signal GFET for high frequency electronic circuits of ambi-polar graphene. This large signal model is widely used in applications like multiplier phase detector, radio frequency sub harmonic mixer and frequency doubler [23]. A dedicated version of Virtuoso spectre for RF applications is available. The tool is named Virtuoso Spectre RF, which can be used to analyse the DC, AC characteristics, RC extraction for delay estimation, and Electromagnetic (EM) analysis of GFET based circuits [24].

3.2.4. Sentaurus

It is one of the popular EDA tool to simulate the behaviour of Graphene FET based sensors used in sensing of single strand DNA (in short, ssDNA) and complementary DNA (cDNA) [25]. It is a state of the art tool for design and optimization of GFET based circuits. This can help generating the device simulations in multidimensional ways. The simulation can be of characteristics study of electric, optic and thermal in nature. The electronic devices can be of semiconductor based or its combination kind.

3.3. Applications – sensors

One of the major application of the G-FET based technology is its ability to develop sensors especially bio-sensors [26]. Even the fast spreading virus disease like Covid-19, can be better diagnosed using G-FET based Bio-sensors. GFET based biosensors have important qualities like high sensitivity, selectivity, fast detection, and large surface to volume ratio that are essential qualities of ideal sensors. The sensors developed using G-FET are far superior over the sensors developed using the other technologies. Some of G-FET based sensors are given hereunder [27] shown in Fig. 3.

3.3.1. Gas sensor

The unique characteristic feature of the G-FET and carbon nanotube based materials possess the ability to manufacture the gas sensors of superior quality than the gas sensors manufactured out of the existent technologies. These gas sensors using the graphene and carbon nanotube are of very high sensitive to the environment [28].

3.3.2. DNA sensor

One of the other major advantage of the G-FET based devices, is its ability to manufacture the DNA sensors. The gate electrode is fabricated with bio-molecules in G-FET, which is unlikely in the conventional FET devices. The DNA probes are fabricated in the G-FET in either the covalent or non-covalent bond. The DNA sen-

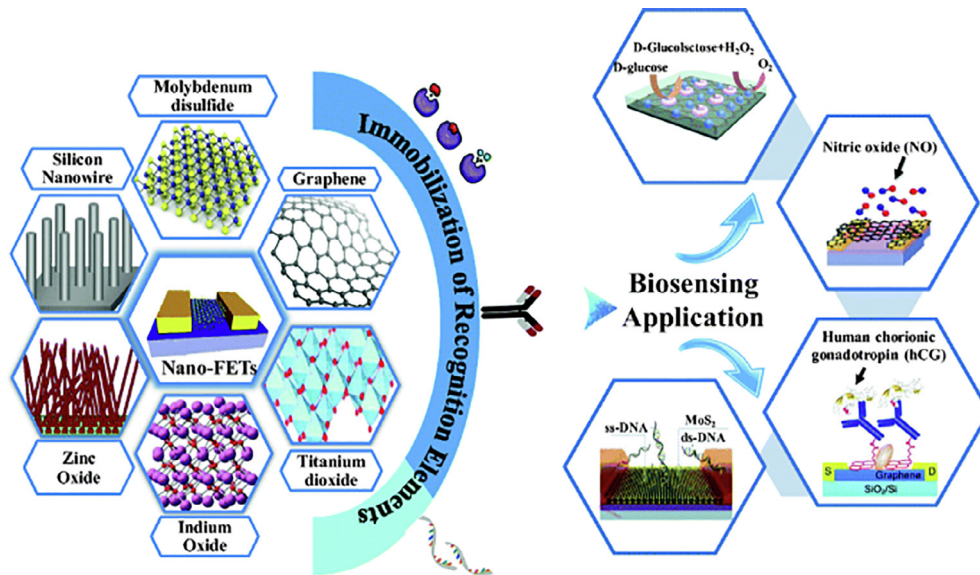


Fig. 3. A schematic illustration of the different nanomaterial-based FET technology, for detection of biomarkers.

sors of G-FET are of superior quality and better of DNA related applications [29]. The alternate for using Silicon-di-oxide, for G-FET is Graphene Oxide (GO). Single-stranded DNA can be absorbed with ease on GO [30] in spite of them negatively charged.

4. Future directions

This section presents on some of the possible research directions pertinent to the development of G-FET based electronic circuits.

(i) Modelling the G-FET behaviour

There are several analytical models like Shichman Hodges, Ebers-Moll models, etc., available for analysis of G-FET based Bipolar and CMOS circuits. A simplified GEFT model that can determine various small signal parameters like Drain-to-Source capacitance, gate capacitance, output resistance, output conductance (g_{ds}), etc., is proposed in [30]. This model enables the identification of various physical parameters. However, an analytical model that gives minute details can be developed which will help in identifying the complete electrical behaviour of the circuits designed using G-FET.

(ii) Development of G-FET based sensors

G-FET has some of the outstanding physical properties like biocompatibility, excellent sensitivity, greater surface to volume ratio, greater mobility, less power consumption, etc. Hence they find applications in design and development of gas sensors and DNA sensors. The electrical behaviour of the GFET can be analysed so that it can be used to realize the motion of Bio molecules and that leads to the identification of pH and protein absorptions. This will pave way for development of applications in biomedical diagnostics, chemical industries, automotive industries, etc.

(iii) Developing techniques for interface resistance and contact resistance reduction

Normally, transit frequency (f_T) of intrinsic GFETs is higher when compared nanometer CMOS devices of equal size. However, in practical aspects, G-FET has lower f_T due to Ohmic resistance [31]. This Ohmic resistance poses a major issue in GFET technology,

and hence finding solutions to these problems can also be taken as a new research direction.

(iv) Fabrication Materials

The GFET can be designed with high field mobility (μ) so that it can even outperform CMOS technology in several high analog circuit applications. Since mobility of carriers varies depending on the semiconductor material used, identifying material that gives high mobility is an open problem.

(v) Development of Energy gap in GFET

The Zero energy band gap in Graphene brings a major hurdle to use it in switching logic applications. This is due to the fact that it produces low values of on/off currents. To overcome these limitations, several appropriate techniques [15] are proposed as listed below:

- Quantum confinement in Graphene Nano Ribbons and
- Substrate induced asymmetry in double layer graphene.

Developing the new techniques in Graphene material towards the development of energy gap without sacrificing mobility can be considered as an issue to be addressed in future. Present days, many RF circuits and sensors have been designed using G-FET. However, new manufacturing techniques have to be evolved in order to develop band gap in Graphene, so that it can be used in digital applications.

(vi) Applications

GFET based devices are mainly used in Optical communication, Bio-sensor applications, solar cells, and electrical circuit design [31]. Each application area requires the different properties of the GFET, in terms of physical structure, electrical parameters, and packaging techniques. Researchers can choose one of the applications areas and develop GFET for the chosen applications.

(vii) Power reduction techniques for G-FET

One of the major problems with G-FET transistors is that it consumes more power due to high off currents. Current Mode Logic

(CML) styles based GFET are used in the fabrication of Logic gates such as OR, AND, and XOR gates [31]. GFET based CML logic circuits are less sensitive to frequency of operation, hence it is preferred in high performance circuits. However, the static power consumption increases as the supply voltage increases. Hence, more novel techniques have to be evolved to reduce the static power consumption in G-FET so that it can compete with its technological counterpart, CMOS technology.

5. Conclusion

Due to its better performance in RF based applications, Graphene-based Field-Effect Transistors find a tremendous growth in recent times and it can even go beyond CMOS technology in future if there is improvement in some of its physical and electrical parameters. Due to its very small channel thickness (one atom) high sensitivity, it is being popularly used in magnetic sensors, bio-sensors and solar cells. There has been research work carried out in G-EFT considering several aspects like modelling, design, fabrication, performance improvement, etc. This paper presented various such developments and highlighted the possible research directions.

CRediT authorship contribution statement

B. Vamsi Krsihna: Investigation, Resources, Data curation, Writing - original draft, Visualization. **S. Ravi:** Data curation, Writing - original draft, Writing - review & editing, Visualization. **M. Durga Prakash:** Conceptualization, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further Reading

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