GRAPHENE: INTRODUCTION AND APPLICATIONS IN NEXT-GENERATION ULSI TECHNOLOGY AN OVERVIEW

Shiromani Balmukund Rahi, Priyank Rastogi and Rahul Kumar
Department of Electrical Engineering, IIT, Kanpur, U.P, India

ABSTRACT

The continuous device scaling and performance improvements required by the International Technology Roadmap of Semiconductors (ITRS) are facing a great challenge as conventional Si CMOS scaling comes to its fundamental physical limits. Remarkable development can observe in the field of CMOS technology. This paper presents a review of the latest research and development in this field in the last few years. We review the recent research progress in CMOS technology in graphene due to very large mobility and some unique material properties and new device architecture such as graphene FET (G-FET).

INDEX TERMS *- MOSFET, Graphene, Nanoelectronics, transistor scaling, Graphene-FET (G-FET), Dirac point, ballistic transport.*

I. INTRODUCTION

The continuous scaling of the silicon transistors has been the driving engine for the exponential growth of digital information processing systems for last few decades. The Si transistor in production today is below the 100-nm scale and has entered the nanoelectronics regions [1]. With the scaling limit of Si field effect transistors (FETs) in sight, large groups of emerging research devices are being extensively studied. Among them, carbon – based nanostructure FETs are the forerunners due to their excellent carrier transport properties of Graphene's high intrinsic mobility, high current densities as well as it is compatible with silicon, which makes graphene- based circuits has been considered promising for next generation field - effect transistors (FETs) [2,3].
The paper is organized as, section-1, gives the introduction about research progresses in the technology, section-2 gives the detail about their material properties and band structure and section - 3&4 gives the introduction about newly proposed idea about Graphene MOSFET (G-FET). Conclusion and future work is given in section-5.

II. GRAPHENE

Graphene is newly discovered material with unusual electrical and optical properties [4]. The high field effect mobility of ~120 000 $cm^2V^{-1}s^{-1}$1has been extracted from a "suspended" graphene field effect transistor (FET) made by mechanical exfoliation of bulk graphite at 240 K [4, 5]. Although practical application of graphene FET requires a reliable substrate, the mobility of graphene FET on the SiO_2/Si substrate is limited to ~10 000 $cm^2\ V^{-1}s^{-1}$ [5].With promising progress on fabricating and pattering a Graphene layer, Graphene electronics has been a topic of strong research, i.e. Graphene Nanoribbon (GNR) can be either metallic or semiconducting, depending on its structure. An exceptionally high mobility (~ 10000 cm^2/V s) of Graphene and GNRs has been experimentally and theoretically demonstrated, which lead to a promising near- ballistic transport in Nanoscale GNRFET [2, 9, 10, 15]. Graphene mobility : > 100, 00 $cm^2V^{-1}s^{-1}$ at room temperature, this is not only ~100 times greater than of Si, but about 10 times greater than that state-of-the art semiconductors lattice-matched to InP, regarded the best high-speed materials. The saturation velocity (v_{sat}) of graphene has not been determined clearly yet, but it is estimated to be ~ 5 times greater than that for Si MOSFETs [6, 7, 8].

Note: Mechanical exfoliation is fabrication technique used in fabricating graphene, it performed upon a wafer, which is composed of many stacked layers of graphene.

Graphene is a two- dimensional allotrope of carbon. It is made of carbon atom arranged on a honeycomb structure hexagons and can be thought of as a composed benzene rings strips out from their hydrogen atom as shown in Fig.1. In 1946 P. R. Wallace in first wrote on the band structure of graphene and showed the unusual semi metallic behavior in this material [11].

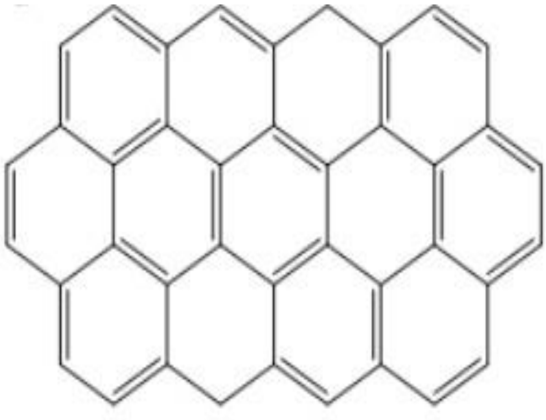

Fig.1: Chemical Structure of Graphene [honeycomb structure of graphene]

Electron in graphene behaves as massless Fermions and travel through the lattice with long mean free path as by high mobility. Graphene is a zero-gap material, with linear dispersion in corresponding Fermi energy, which makes it particular unsuitable for transistor applications [12].

2.1. Intrinsic and extrinsic graphene

Graphene has unique properties, so it is necessary to distinguish between intrinsic and extrinsic Graphene. Gapless graphene (either monolayer {MLG} or bilayer {BLG}) has a charge neutrality point (CNP) i.e., the Dirac point, where its character changes from being electron like to being hole like as shown in Fig.[2(a)& 2(b)] respectively. Note: Density of states of graphene is close to the Dirac point. Such a distinction is not meaningful for a 2DEG (or BLG with a large gap) since the intrinsic system is simply an undoped system with no carriers (and as such is uninteresting from the electronic transport properties perspective) [13].

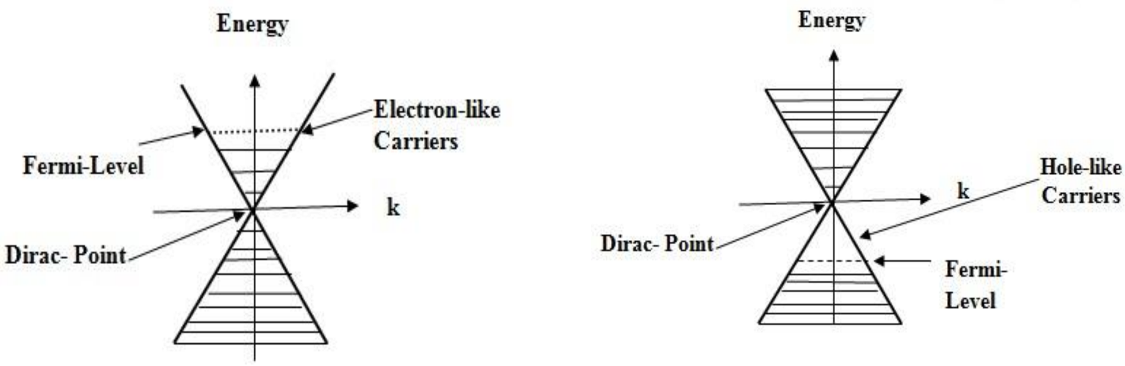

Fig.2 (a): Dirac point **Fig.2 (b):** Dirac point

Fig.2: Dirac point in Graphene [Note: case 2(a), 2(b) electron and hole respectively].

In monolayer and bilayer graphene, the ability to gate (or dope) the system by putting carriers into the conduction or valence band by tuning an external gate voltage enables one to pass through the CNP where the chemical potential (EF) resides precisely at the Dirac point. This system, with no free carriers at T "0", and EF precisely at the Dirac point is called intrinsic graphene with a completely filled (empty) valence (conduction) band. Any infinitesimal doping (or, for that matter, any finite temperature) makes the system ''extrinsic''with electrons (holes) present in the conduction (valence) band. Although the intrinsic system is a set of measure zero (since EF has to be precisely at the Dirac point), the routine experimental ability to tune the system from being electron like to being hole like by changing the external gate voltage, manifestly establishes that one must be going through the intrinsic system at the CNP. If there is an insulating regime in between, as there would be for a gapped system, then intrinsic graphene is not being accessed [14].

2.2. Band Structure

The band of graphene is very peculiar, and the dispersion relation E (k_x, k_y) is represented by a conical surface defined in 2-D reciprocal lattice [k_x, k_y]. Besides, being the graphene lattice formed by two sublattices A and B as shown in fig-3, its wave function has two components and the single–electron Hamiltonian in graphene exhibits an analogy with the Hamiltonian of massless Dirac fermions, with the group velocity v_f playing the role of the speed of light c(i.e. 10^8cm/s) in quantum electrodynamics (QED) and the two sublattices playing the role of pseudo-spin [10,15].
The energy bands derived from Hamiltonian have the form

$$E_{\pm}(k) = \pm t\sqrt{3 + f(k)} - t' f(k) \tag{1}$$

The value of t' is not well known but initio calculations find 0.02t ≤t'≤0.2t depending on the tight binding parameterization. Experimentally t' is find as t'≃0.1eV, where

$$f(k) = 2\cos\left(\sqrt{3}\,k_y\,a\right) + 4\cos\left(\sqrt{\frac{3}{2}}\,k_y a\right)\cos\left(\frac{3}{2}k_x\,a\right) \tag{2}$$

The band structure of graphene emphasizing the linear dispersion relation at k-points.

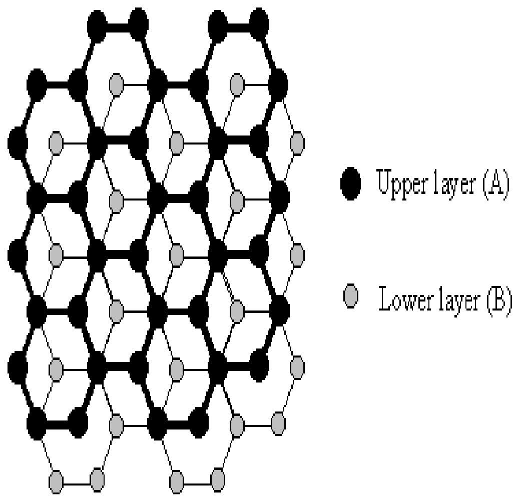

Fig.3: Graphene Lattice structure

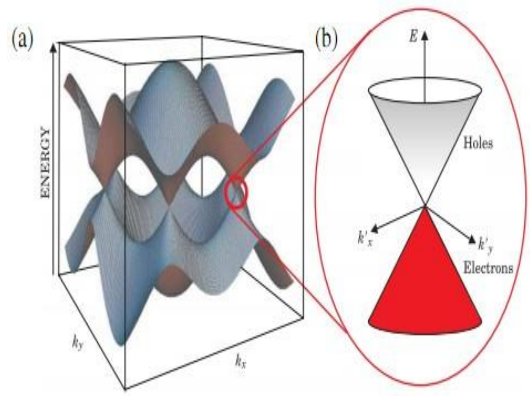

Fig. 4 (color online). (a) Graphene band structure. (b) Enlargement of the band structure.

2.3. Material Properties of GRAPHENE [15, 17, 18]

- Graphene is a semimetal (zero gap semiconductors) with charge carriers behaving as massless Dirac fermions.
- Under charge neutrality conditions, the Fermi level is at the interception of the valance and conduction bands, but can be shifted with the application of a vertical electric field to create a majority of holes or electrons. A transition of the Hall coefficient from positive to negative values is observed.
- Graphene exhibits very high carrier motility at room temperature due to a weak electron phonon interaction.
- Electrons travel ballistically in graphene over long distance (of the order of one micrometer) which for exceed the length of advanced FETs.
- Graphene is more than 100 times stronger than strongest steel.
- Mechanical properties of graphene include an exponential Young's modulus of~ 1 TPa and elastic stretchability of up to 20%. As structure is changed when graphene is strained, graphene could be a potential material for electro- mechanical transducers.
- Graphene can sustain current densities exceeding those of copper at comparable dimensions.

- Saturation velocity(cm/sec)≃4-5×10^7
- Current density(A/cm^2) ~ 10^9
- Thermal conductivity(W/m-K)≃4800

Table.1: Summery of Intrinsic Material properties of Graphene

S.N.	Property	Value
1	Saturation Velocity(cm/Sec)	4-5X10^7
2	Carrier mobility(cm^2/Vs)	>100,000
3	Current density(A/cm^2)	~10^9
4	Thermal conductivity(W/m-k)	4800
5	Optical opacity (%)	2-3%per layer
6	Young' modulus(Pa)	0.5-1 tera
7	Mechanical stretchability	Up to20%

III. GRAPHENE MOSFET (G-FET) DEVICE STRUCTURE

Graphene transistors are getting more attention and various device structures could be investigated for many possible applications. The cross-sectional view of graphene based transistors is shown in Fig.5, 6 &7. In graphene based devices channel is Graphene. Graphene field–effect transistors (GFETs) have been under continuous development because of their high mobility and carrier velocity, excellent scaling properties, configurability as electron or hole channel devices and their potential CMOS and RF application compatibility [16].

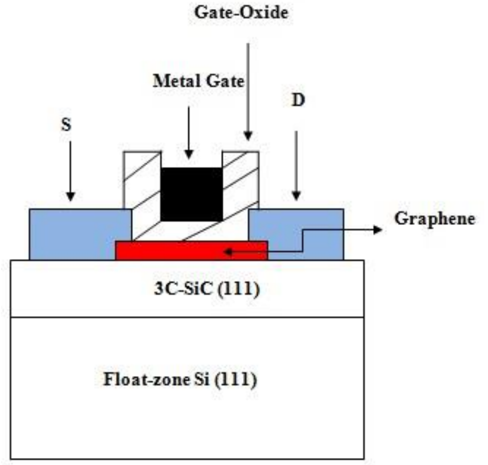

Fig.5: A schematic of top-gated graphene FET (TG-GFT)

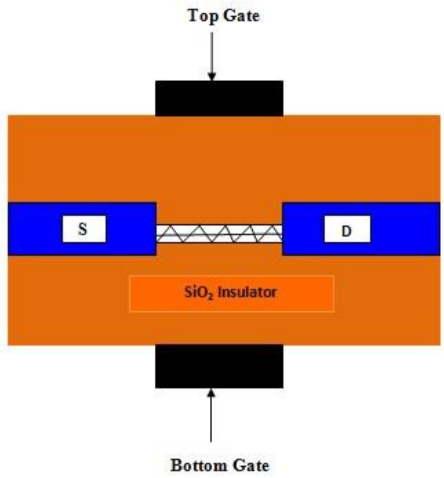

Fig.6: Double-gate Graphene based MOSFET (DG-GFT)

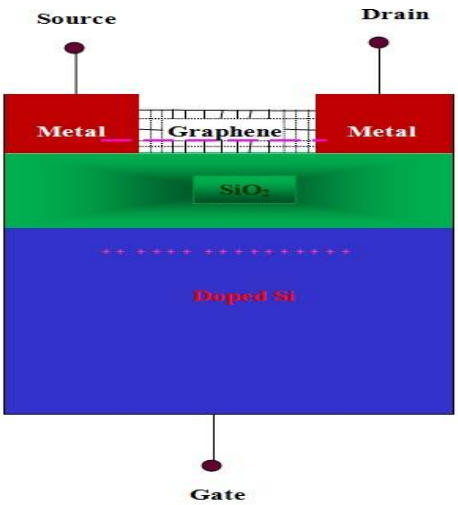

Fig.7: Device structure of Graphene based bottom-gate MOSFET

IV. EPITAXIAL GRAPHENE ON SIC TRANSISTORS

Epitaxial graphene FETs are in early stages of development, though several key device parameters have been demonstrated. For example, the epitaxial graphene RF FETS have been demonstrated in top-gated layout with the highest ever on-state current density of 3 A/mm, the extrinsic speed performance (f_t/f_{max} of 5 GHz/14GHz) is reported with a 2 μm gate length. Also I_{on}/I_{off} ratio was ~ 4 with field-effect mobility below 200 cm^2/Vs. While graphene field-effect mobility as high as 5400 cm^2/Vs for electron has been demonstrated, it was achieved using six to seven layers of epitaxial graphene on C- face SiC substrates, resulting in I_{on}/I_{off} ratio of<2. In the case graphene FETs fabricated on the Si face of SiC substrates, field effect mobility has been limited below 1200cm^2/Vs, but with an improved I_{on}/I_{off} ratio of~ 10 [20,21].

V. CONCLUSION AND FUTURE SCOPE

The objective of this paper is to review the latest research and development in the CMOS technology. In this work we observe that Graphene is an emerging electronic material, provides promising properties for next –generation CMOS technology as well as for future nanoelectronics applications. The fundamental current- carrying capacity is found to be much higher than traditional FETS (MOSFETs, HEMTs). Due to large thermal conductivity, graphene devices is more to suitable ultra large scale (ULSI) application and less pron to self-heating effect(SHE).

Finally, graphene research includes large-scale and high throughput solution based processing for low- cost electronics and compatible with silcon, which makes graphene based circuits a potential candidate for the above emerging applications.

ACKNOWLEDGEMENT

The authors wish to thank all individuals who have contributed directly or indirectly in completing this research work.

REFERENCES

[1] ITRS, International Technology Roadmap for Semiconductor. [Online] Available: www.itrs.net

[2] Yijian Ouyang, Youngki Yoon and Jing Guo, *"Scaling Behaviors of Graphene Nanoribbon FETs: A Three –Dimensional Quantum simulation Study"* IEEE Trans. Electron Device vol 54 no 9, September 2007.

[3] Omid Habibpour, , JosipVukusic, and Jan Stake, "*A 30-GHz Integrated Subharmonic Mixer Based on a Multichannel Graphene FET*" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 61, NO. 2, FEBRUARY 2013.

[4] Ama! Kasryl,, George Tulevski, Marcelo A Kuroda, Ageeth A Bo1, Glenn. Martyna, Berhard Menges, Saoshi Oidi, Mostafa El Ashry, Matthew Copd, Libor Vlick *"Electrical and Optical properties of graphene Mono-and Multi layer: Towards graphene based optoelectronics"* IEEE 2010.

[5] K. Nagashio, T. Yamashita, T. Nishimura, K. Kita, and A. Toriumi, *"Electrical transport properties of graphene on SiO2 with specific surface structures"*, J. Appl. Phys.2012.

[6] J.S Moon, M, antcliffe, H.C. Seo, S.C. Lin, A Schmitz, I Milosavlevic, K. McCalla, D. Wong, D.K.Gaskill,P. M. Campell, K-M. Lee, and P. Asbeck "Graphene Review: An Emerging RF Technology", IEEE 2012.

[7] Jeong-Sun Moon and D. Kurt Gaskill "Graphene*: Its Fundamentals to Future Applications"* IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 59, NO. 10, OCTOBER 2011.

[8] Dong- Wook Park, Tzu- Hsuan Chang, Solomon Mikel, Jung- Hun Seo, Paul F. Nealey and Zhenqiang Ma *"Graphene RF transistors with Buried Bottom Gate"* IEEE. 2013.

[9] B. Obradovic, R. Kotlyar, F. Heinz, P. Matangne, TRakshit, M. D. Giles, M.A. Stettler, and D. E. Nikonov, " *A* Analysis of graphene nanoribbons *as a* channel material for field *–effect transistors,* Appl. Phys. Lett. , vol.88, no.14, pp.142 101.1-142 101.3, Apr.2006.

[10] J.K. David, L.F.Register, and S.K. Banarjee, *"Semiclassical Monto Carlo Analysis of Graphene FETs"* IEEE Trans. Electron. Devices, vol.59, no.4 April2012.

[11] A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov and A. K. Geim *"The electronic properties of graphene"* Rev. Mod. Phys., Vol. 81, No. 1, January–March 2009.

[12] Young Yoon, Gianluca Fiori, Seokmin Hong, Giuseppe Iannaccone, and Jing Guo*," Performance Comparision of Graphene nanoribbon FETs with Schottky Contacts and Doped* Reservoirs*"*, IEEE, Trans.Electron Devices, vol.55, no.9, September 2008.

[13] S.Das Sarma, Shaffique Adam, E.H. Hwang, Enrico Rossi *"Electronic transport in two-dimensional graphene"* REVIEWS OF MODERN PHYSICS, Vol. 83, APRIL–JUNE 2011.
[14] Yuanbo Zhang, Yan-Wen Tan , Horst L. Stormer & Philip Kim1 "Experimental observation of the quantum Hall effect and Berry's phase in graphene." NATURE, Vol 438, 10 November 2005.
[15] Matthew Yankowitz, Jiamin Xue1, Daniel Cormode, Javier D. Sanchez-Yamagishi, K.Watanabe T. Taniguchi, Pablo Jarillo-Herrero , Philippe Jacquod and Brian J. Le Roy, "Emergence of super lattice Dirac points in graphene on hexagonal boron nitride" NATURE PHYSICS, VOL 8,MAY 2012.
[16] J.C. Moon, H.- C Seo, M. Antcliffe, S.Lin, C. McGuire, D.Le,L.O. Nyakiti, D.K. Gaskill P.M.Campbell, K..-M. Lee, and P. Asbeck, *"Graphene FET-Based Zero- Bias Rf to Millimeter – Wave Detection*" IEEE, Electron Device Lett.vol.33, no.10, October 2012.
[17] Robertto Grassi, Antonio Gnudi, Elena Gnani, Susanna Reggiani, Giorgio Baccarani, *"Graphene nanoribbons FETs for High- Performance Logic applications: Perspectives and challenges"* IEEE 2008.
[18] Peide D. Ye "InGas and Graphene as High mobility Channels for Post Si- CMOS applications" IEEE 2008.
[19] M.C. Lemme, S. Vaziri, A.D. Smith, J. Li, S. Rodriguez, A Rusu, M. Ostling "*Graphene for More More and More Than Moore Applications"*.
[20] Jeong-sun Moon, D. Kurt Gaskill, Paul Campbell and Peter Asbeck, *"Graphene -on- SiC and Graphene –on-Si Transistors RF Applications",* IEEE, 2011.
[21] J.S. Moon et al., *"Epitaxial Graphene RF Field –Effect Transistors on Si- face 6H-SiC Substrates*", IEEE Electron De.Lett., vol.60, pp650-652, 2009.

BIOGRAPHY

Shiromani Balmukund Rahi received the B.Sc. degree (PCM) in 2002 and M.Sc. (Electronics) from DDU Gorakhpur, U.P, India in 2005, M.Tech (Microelectronics) from Panjab University Chandigarh India in 2011.He has one-year teaching experience in undergraduate program in SIIT Gorakhpur U.P. Currently he is pursuing Ph.D in IIT Kanpur U.P. India in Microelectronics. His current research interest is in physics and modeling of advanced nano scale MOSFETs and novel devices.

Priyank Rastogi was born in India in 1985. He received his B.Sc. (PCM) in 2006 and M.Sc (Physics) in 2008 from Chaudhary Charan Singh University, Meerut, India. He received his M.Tech (Microelectronics) degree in 2011 from Indian Institute of Information Technology, Allahabad, India. He is currently pursuing PhD in Microelectronics from Indian Institute Of Technology, Kanpur, India. His area of interest is in physics and modeling of advanced nano scale MOSFETs and novel devices.

Rahul Kumar was born in Gorakhpur 1991.He receieved the B.Tech degree with honors in 2012 from Madan Mohan Malaviya Engineering College in Gorakhpur. Current he is pursuing his M.Tech in IIT Kanpur.