Graphene Review: A Future for Electronics Applications

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***Abstract*—Graphene has recently attracted great interest among the researcher in the field of material science and nanotechnology. Some of unique properties of graphene with new device concepts and nanotechnology can overcome some of the main limitations of traditional radio frequency electronics in terms of maximum frequency, linearity, and power dissipation. However, graphene devices may not be ideal for all electronics, but may have advantages over silicon in many applications. Numerous experts already see it as the successor of silicon. Many groups around the different parts of the world are fabricating graphene transistors, and graphene MOSFETs with record cutoff frequencies 300 GHz have been reported. In this paper, we highlight the recent research done on graphene. We also attempt to discuss the possible use of graphene in future electronics applications.**

***Index Terms*—graphene-FET, carbon electronics, microwave electronics, microwave materials.**

I. INTRODUCTION

The consensus in the semiconductor industry is that CMOS technology, the ruling technology currently in use, cannot be scaled down much longer. The limitations come from the fabrication technology and the material properties of silicon (Si). Herein lies the motivation to develop new kinds of electronics, that is often referred to as beyond-CMOS [5]. Graphene devices may not be ideal for all electronics, but may have advantages over silicon in many applications.

Graphene is a hexagonally organized form of carbon atoms that is only one atomic layer thick [1][Fig.1]. Andre Geim and Konstantin Novoselov received the Nobel Prize for Physics in 2010 for their discovery of the electrical conductivity of graphene. It is the thinnest material ever known to man so far, and the atomic structure gives rise to exceptional electrical, optical, mechanical and thermal properties [2]. The most interesting electrical properties are high electron mobility and ballistic transport of charge carriers. Graphene displays an ambipolar field-effect which means that it can conduct both electrons and holes without impurity doping. The charge carrier type can be changed with the gate voltage. This phenomenon gives more freedom in designing applications where in-field tunability is desired.However, graphene cannot be turned off, and this presents complications for electronics.

Nonetheless, there are cases when low power consumption is not as important as high performance. One such example is radio frequency (RF) applications. Graphene nanoribbons (GNR) have been suggested for use as RF low noise amplifiers [3], though the plan is still in simulation phase. The first graphene integrated circuit was demonstrated in 2011 by IBM [4]. Transistors are not the only application, in which graphene can be used; others include graphene thin film electrodes, using graphene as sensing material or as a photodetector to name a few. An interesting application of graphene is as a material for nanoelectromechanical systems (NEMS) such as resonators.

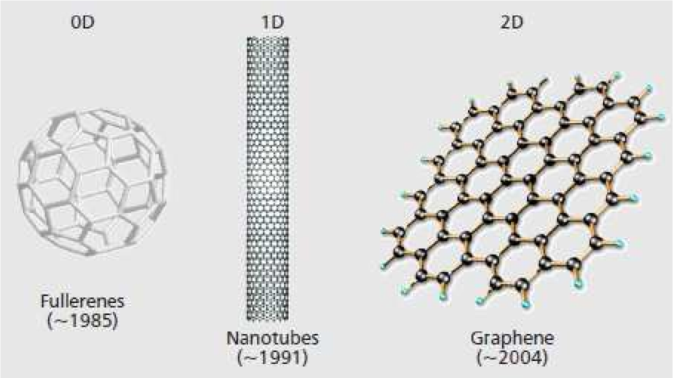

Fig. 1. *Diagram of different low-dimensional carbon structures and the year of their discovery/isolation.*

II. PROPERTIES OF GRAPHENE

Graphene is a zero band gap semiconductor,or a semimetal. The lack of a band gap in intrinsic graphene is perhaps, together with large scale manufacturing, the most difficult engineering issue. The zero band gap means that graphene cannot be switched from conductive state to nonconductive state. The lack of a band gap is a problem, if graphene is to be used in logic circuits in much the same way as silicon is used today as the material for CMOS logic circuits. The high mobility of electrons in graphene arises from the fact that they are confined to the hexagonal lattice. At room temperature in undoped graphene, the number of thermally excited electrons is ~$10^{11}$$cm^{-2}$ (along with an identical number of holes)[6].For RF electronic applications considered, grapheme exhibits the highest carrier mobility: >100,000 cm^2 V^{-1} s^{-1} at room temperature [7]. This is not only ~100 times greater than that of Si, but about 10 times greater than state-of-theart semiconductors lattice-matched to InP, currently regarded the best high-speed materials. The saturation velocity (vsat) of graphene has not been determined clearly yet, but it is estimated to be ~5 times greater than that for Si MOSFETs [8]. With expected large on-state current density and transconductance per gate capacitance compared to Si, graphene has the potential to offer excellent switching characteristics (capacitance/on-state current) and short circuit current gain cut-off frequency [9]. The following table showing comparison of characteristics of graphene with other material used in VLSI;

TABLE I
COMPARISION OF CHARACTERISTICS OF DIFFERENT MATERIAL

Characteristics	Si	AlGaAs/ InGaAs	InAlAs/ InGaAs	SiC	AlGaN/ GaN	Graph-ene
Electron mobility at 300K(cm^2/V-s)	1500	8500	5400	700	1500 - 2200	>100,000
Peak Electron Velocity(x 10^7 cm/s)	1.0	1.3	1.0	2.0	1.3	5-7
Thermal Conductivity(W/cm-K)	1.5	0.5	0.7	4.5	>1.5	48.4 -53

(*Courtesy: National University of Singapore,Graphene Research Centre*)

III. GRAPHENE FIELD EFFECT TRANSISTOR[GFET]

The first graphene FET (GFET), reported in 2004, was fabricated on an HOPG graphene flake deposited on top of a SiO2/Si substrate [10]. In graphene-based field-effect transistors (graphene FETs), the carrier channel mobility is strongly influenced by substrate and gate dielectric materials. For transistor fabrication, currently exfoliated, epitaxial, and CVD(Chemical Vapor Deposition) graphene are most popular. Exfoliation is inexpensive and simple, while graphene epitaxy and CVD are more attractive for the industry. Graphene MOSFETs (GFETs) with different graphene modifications, namely large-area monolayer graphene (gapless), bilayer graphene(semiconducting) and graphene nanoribbons (GNR, semiconducting) have successfully been realized.

In many RF circuits, FETs are continuously operated in the onstate so that switch-off is not necessary. Several groups achieved excellent RF performance in terms of cutoff frequency *f*T as indicated in Fig. 2 showing *f*T vs. gate length for different types of RF FETs. Currently, the fastest graphene transistor is a 144-nm gate GFET from UCLA showing a *f*T of 300 GHz [11]. Similarly remarkable are GFETs reported by IBM showing 100 and 53 GHz *f*T for gate lengths of 240 and 550 nm [12].Regarding *f*T, GFETs clearly outperform competing carbon nanotube FETs and the 300-GHz GFET is as fast as the best III-V HEMTs (with comparable gate length) [13].

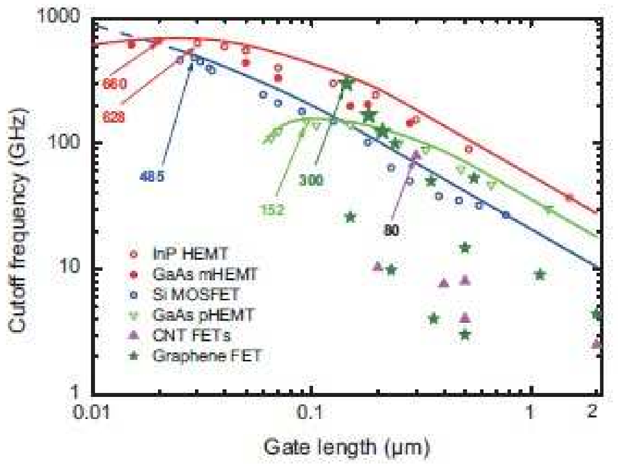

Fig. 2. *Cutoff frequency of RF FETs vs. gate length.*[13]

IV. POTENTIAL APPLICATIONS OF GRAPHENE

Since large-area graphene is gapless and behaves like a semimetal, it may be used for interconnects. This would open the possibility of all-graphene ICs with both the active devices and the wiring made of graphene [14-15]. This vision has stirred more detailed investigations on the potential of graphene for use as interconnect. It has been shown that graphene interconnects show comparable or even better performance compared to copper interconnects at room temperature [16-18] and that graphene can support current densities in excess of 108 A/cm2 [19]. Note that this is two orders of magnitude more than the current density supported by copper and comparable with that supported by carbon nanotubes.

Graphene devices for sensing applications look also promising. Graphene virtually consists only of surface without a bulk and therefore should be very sensitive to its environment. Graphene sensors able to detect single gas molecules have been reported [20]. Another possible class of sensor devices is graphene-based NEMS (nano electromechanical system) that benefit from the superior mechanical properties and the extremely small mass of graphene [21].

V. FUTURE OF GRAPHENE

This GNR back-gate MOSFETs with narrow semiconducting channels (width down to less than 5 nm) have been reported [22, 23]. These transistors showed excellent switch-off and on-off ratios up to 106. Recently also the first GNR MOSFET with top-gate has been demonstrated [24]. The on-off ratio of this transistor (around 70) significantly exceeds the on-off ratios of MOSFETs with large-area graphene channels (typically 2…20) but is still too low for logic application where on-off ratios of 104 to 107 are required [25]. The GNR channel of this transistor was about 10-20 nm wide and apparently did not offer a bandgap wide enough to sufficiently suppress the off-current. However, a by further reduction of the ribbon width we can expect much better on-off ratios of top-gated GNR MOSFETs in the near future. So far, experimental data on the dynamic behavior (e.g., on the cutoff frequency or the switching delay) of GNR MOSFETs is not available.

In spite of the impressing performance obtained with experimental devices, these "conventional" graphene MOSFETs suffer from several fundamental problems. Some of these are: (i) the loss of mobility in narrow GNRs, (ii) the need of extremely narrow GNRs (only a very few nm wide) to open a gap useful for switch-off, (iii) the unsatisfying drain current saturation of graphene MOSFETs with large-area graphene channels. This has motivated research on novel graphene-based FET concepts. Two examples, that have already gathered considerable attention in the device community, are the graphene tunnel FET [26] and the graphene BiSFET (Bilayer PseudoSpin FET) [27].

VI. CONCLUSION

During the last two years, various research communities have done immense research work in graphene. Graphene has attracted more attentions of RF chipmakers. The future success of the RF circuit applications depends on high-quality material growth on large-wafer scale, vertical and lateral scaling of graphene MOSFETs to minimize parasitics and improved gate modulation efficiency in the channel, a bandgap engineering of graphene channels in the MOSFETs, and innovative circuit concepts. However, seeing graphene as the successor of silicon is not correct. Though, graphene has many advantages over silicon but still graphene cannot replace silicon in most of the applications.

When assessing the prospects of graphene in electronics, it is important to recognize that all other options considered as possible successors of the conventional mainstream transistors also face serious problems. The chances for electronic graphene devices are promising but optimistic. In near future, We may see the use graphene based integrated circuits in consumer electronics.

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