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Graphene Based Electronic Device

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***Abstract*—**The semiconductor industry is placing an increased emphasis on emerging materials and devices that may provide improved performance, or provide novel functionality for devices. Recently, graphene, as a true two-dimensional carbon material, has shown fascinating applications in electronics. In this paper detailed discussions are introduced for possible applications of grapheme Transistor in RF and digital devices.

***Keywords*—**Graphene, GFET, RF, Digital.

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I. Introduction

GRAPHENE is a two-dimensional plane of carbon atom arranged in a honeycomb lattice [1], [2], which has a linear electronic dispersion and possesses outstanding transport properties such as a high Fermi velocity, excellent carrier mobility and a high carrier saturation velocity[2]-[6],Moreover, the outstanding thermal conductivity [7], the ultimate thinness and the stability of graphene are also very attractive. These characteristics make graphene a promising material for application in future electronic devices.

Graphene transistors, a fundamental building block of graphene electronic devices, have been subject to intensive research in the analog/radio frequency (RF) transistor [8]-[11], nanoelectronics [12]-[20], fields.

Graphene research has been focused on transistors and thin film applications, but the interest in different applications of graphene is growing rapidly. Some articles have been published about graphene photodetectors and sensors. It has been suggested that graphene sensors could be used to detect gas molecules through the change in conductivity that the gas molecule causes by doping the graphene layer [21]. Another interesting application of graphene is as a material for nanoelectromechanical systems (NEMS) [22]. A piece of graphene suspended on source and drain electrodes with the gate below the graphene layer can act as a RF NEMS. The NEMS can be used as radio frequency electrical transducer with oscillation frequency in the mega Hertz range. Graphene optoelectronic research is gathering speed with the recent discovery that graphene opacity is dictated only by the fine structure constant $\alpha = 1/137$[23].

Of all of the suggested applications of graphene, the use of graphene as a thin electrode seems the one most closest to emerge [24]. Graphene has excellent properties in the visible region of light, because the transparency is higher than 80%. The currently used material for optically transparent thin film electrodes is indium tin oxide (ITO). ITO is expensive, brittle and has relatively large sheet resistance. The need for another material to replace ITO comes mainly from the limited indium resources and hence its price. Carbon nanotubes (CNT) are at the moment the most promising technology along with graphene to replace TO. CNT sheet large scale production is being developed by several companies, such as Finnish Canatu. Transparent electrodes are required in a large variety of applications, such as touch screen and liquid crystal displays.

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II. Electronic Band Structure

Graphene has a honeycomb (hexagonal) structure of sp^2-bonded atoms. The electronic band structure of graphene can be solved with tight binding approximation (TBA) or the similar linear combination of atomic orbitals (LCAO), which is more commonly used in chemistry.

The honeycomb lattice has 2 atoms per unit cell; hence the π bands of graphene have 2x2 Hamiltonian. The diagonal elements of the Hamiltonian describe the nearest neighbour interactions, while the off-diagonal elements describe the three nearest neighbor interactions in different sublattices.

Graphene is a 2D material, but distinctions can be made between bi-layer graphene andfew-layer graphene (FLG). Bilayer graphene has two layers, but the electronic band structure is already quite different from single layer graphene. Band gaps of some hundreds of millielectron volts have been achieved with bilayer graphene by applying a perpendicular electric field to the bilayer [24]. The gap in Bernal stacked bilayer graphene arises from the forming of pseudospins between the layers, thus making it possible to electrically induce a band gap [25].

There are still many properties of graphene that have not been thoroughly investigated. Eventhe existence of a band gap in large area graphene is controversial. In addition to band gap opening in bilayer graphene by applying an electric field, it is possible to create band gapby quantum confinement, i.e. by fabricating graphene nanoribbons [26]. Edges may have significant influence on electrical properties, especially with GNRs [27]. The edge effects are still being actively researched. Numerical modeling shows that strain induced band opening is also a possibility, though there is no experimental verification of strain induced band opening [28]. Band engineering of graphene is essential if graphene is ever to compete with silicon CMOS technology. The energy gap is important for logic gate purposes to keep the power consumption at minimum i.e. going to a non-conductive state.

The band-structure of graphene differs from the band-structures of semiconductors in that the energy dispersion around the band edges is linear instead of quadratic [29]. The

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mobility of charge carriers is limited by defects in the supporting material or defects in graphene. The previous claim is backed up by the much higher mobilities achieved with suspended grapheme sheets. Electronic transport that is limited by scattering is called ballistic transport. Ballistic transport is possible in very pure and defect free graphene. Naturally, obtaining clean and defect free graphene is difficult and is often not achieved. The linearity of band dispersion in graphene means that the velocity of electrons is independent of energy or momentum.

Furthermore, the velocity of electrons in graphene is at maximum the Fermi velocity, which is 1/300 of the speed of light. Another intriguing property is that backscattering through phonons or charged impurities is forbidden and the mean free path is in the range of hundreds of nanometres.

Fig. 1 shows the electronic band-structure of graphene. The figure was plotted with Matlab using the equation and values given in [30]. The linear dispersion around the Diracpoint, the part where the conductance and valence bands meet, can be seen from the band diagram.

The electrical properties of graphene have been studied extensively, but much is still unknown about the mechanical and thermal properties. Mechanical and thermal properties of graphene are similar to those of carbon nanotubes. Measurements show that the breaking strength of graphene is around 40 N/m, and thermal conductivity in the range of 5000 W/mK,and yet the thermodynamic properties of graphene are largely unknown [31].

The chemistry of graphene is in early phases, but shows much promise. Graphene can absorb and desorb different atoms and molecules, such as K and OH. Adsorbates can affect the electronic properties of graphene. There is even the possibility of localized doping. In addition, the stability of graphene under various circumstances has not received much attention.

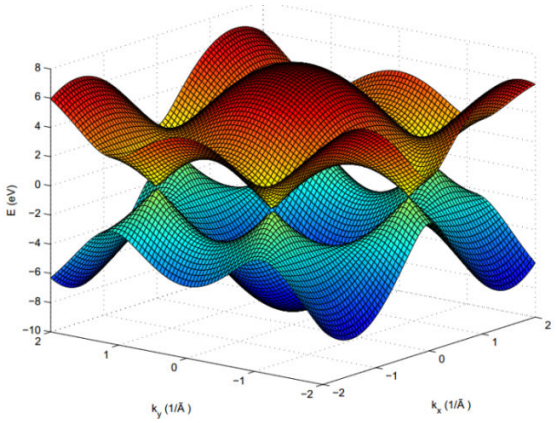


Fig. 1 The electronic dispersion in graphene

III. Graphene Synthesis

It may be beneficial tobriefly discuss the most commonly used graphene synthetization methods in order to understand the challenges in fabricating graphene devices. After the discovery of graphene by mechanical exfoliation, often called the 'Scotch tape method', serious attempts have been made to produce large areas of top quality graphene [25]. The importance of high quality grapheme with few or no defects cannot be emphasized enough. The investigations into electron transport in graphene and current saturation show that defects are the most important factor in hindering the transport of electrons (holes). The best graphene quality is still achieved with mechanical exfoliation. However, two synthetization methods with great potential for large scale manufacturing of graphene have been developed, namely graphene grown with chemical vapor deposition (CVD) and silicon carbide (SiC) desorption method [25].

Mechanical exfoliation works, to a large extent, as the name suggests. First, a piece of bulk graphite is repeatedly peeled with tape to separate layers of graphene, whichis then transferred onto a substrate, usually silicon dioxide SiO_2 [26]. This technique has become a form of art. The problem is in finding those single layer graphene samples and finding one with the right size for further studies. Novoselov and Geim discovered that the invisible graphene flakes become visible on (SiO_2) substrate that is of a certain thickness. The phenomenon is due to optical interference at the graphene-substrate interface. Raman spectroscopy can be used to find out if the graphene flakes are single, few- or multilayer.

Graphene can be synthetized by sublimation of silicon from SiC in high temperature (1200°C) in ultra-high vacuum [32]. The benefit of this method is that the SiC provides an insulating substrate and no transfer of the graphene layer is needed in order to fabricate top gated FETs. Yet, the disadvantage of this method may outweigh its advantages; the high temperature is cost-ineffective, and thus may not be suitable for large scale manufacturing.

The grapheme layer has different properties depending on the crystal growth face. Graphene grown on Si-terminated face has poor homogeneity and crystal quality and is subject to unintentional doping. Graphene grown on C-terminated SiC is often called 'turbostatic' graphene, because of the rotational disorder. Graphene grown on C-face has higher mobility than on Si-face and has less doping.

Growing graphene with CVD is an attractive solution, because it is compatible with existing semiconductor industry processes [25]. Graphene has been grown with CVD on metal substrates, such as nickel (Ni) and copper (Cu). With CVD, the graphene layer needs to be transferred to a substrate, which is somewhat difficult, and may degrade the quality of the layer and lead to folding of the layer. However, CVD synthetized graphene has larger grain size. Researchers are optimistic about extending CVD growth to silicon wafer sizes.

Other suggested methods of large scale graphene synthetization are direct chemical synthetization [26], ion implantation [33], crystal sonification [26] and even unzipping carbon nanotubes to form graphene sheets [34].

IV. Graphene Field-Effect Transistor Structure

Graphene FET research was fueled by the discovery of the ambipolar electric field effect in graphene by nobelists Novoselov and Geim in 2004. They showed that the electronic

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properties of few layer graphene (FLG) greatly differed from those of bulk graphite, a 3D structure.

The sheet resistivity of graphene was found to have a peak of a few kOhms and decays to some hundreds of Ohms with changing the gate voltage [1]. The resistivity peak, often called dirac point or minimum conductance point, is located approximately at zero gate voltage in pure graphene. The location of the Dirac point depends on the difference between the work functions of the gate and the graphene, doping (electrical or chemical), and type and density of charges at the interfaces at the top and bottom of the channel. The Dirac point changes with adsorbed water or other ambient adsorbing molecules [35]. Positive gate voltages promote n-type, electron, conduction and negative voltages give rise to p-type channel (hole conduction). Fig. 2 shows an example of a measured gate- voltage drain-current curve for a SiC GFET fabricated at Micronova. This particular transistor has the Dirac point quite far from zero gate bias, which is most likely due to unintentional doping during the fabrication and storage in room temperature. The transport curve in Fig. 2 is quite symmetric, but often the transport is asymmetric due to charged impurities or graphene-electrode contact. Asymmetry in this case means that electrons and holes have different mobilities [36].

Novoselov and Geim explain the ambipolar field effect by a 2D metal with a small overlap between valence and conductance bands [1]. The electric field induces doping in grapheme by changing the Fermi energy, which should not be confused with the context of doping in semiconductors.

Graphene is unique as a channel material, because unlike other semiconductors, grapheme does not require impurity doping to conduct electricity. Graphene displays a phenomenon that is often called self-doping. Self-doping refers to the electric field effect in graphene, which allows the charge carrier type and concentration to be controlled with an outside electric field, or rather gate voltage.

The doping levels of graphene can be monitored with Raman scattering [37]. The raman peak intensity and displacement varies according to the applied gate voltage. The ambipolarity of graphene makes it possible to operate a graphene transistor with either electrons, holesor both simultaneously. The graphene band structure allows the conduction to shift from electrons to holes by changing the Fermi level. Das et al. [37] estimated the doping concentration in an electrochemically top gated GFET as

$$V_{TG} = \frac{\hbar|v_F|\sqrt{\pi n}}{e} + \frac{ne}{C_{TG}} \quad (1)$$

where v_F is the Fermi velocity, n the doping concentration, and C_{TG} is the top gate capacitance calculated as a parallel plate capacitor.

The Hall coefficient R_H changes sign at dirac point [1]. The resistivity ρ of graphene is described by the classical equation

$$\rho^{-1} = \sigma = ne\mu \quad (2)$$

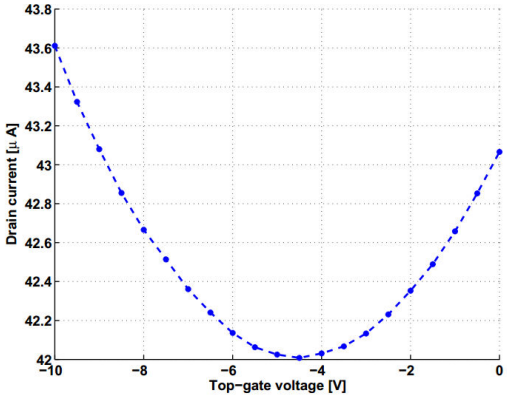


Fig. 2 The Dirac point of a SiC GFET with 0.5 V drain-source voltage and W=10 μm and L=4 μm

where n is the doping concentration, σ conductivity and μ the mobility of graphene.

According to Banerjee et al. [25], the transport properties of graphene are affected by the quality of the graphene layer, the interface with insulators and the metal contacts. The quality of the graphene is mostly affected by the fabrication process [23].

A graphene field effect structure is constructed from bottom to top as follows: substrate, graphene layer as the channel, dielectric layer and source-drain electrodes and top gate electrode. An example of a GFET is shown in Fig. 3 It shows a two gate-finger structure that is used when making S-parameter measurements. It is common that GFETs are often misleadingly referred to as dual-gate transistors, when the devices have both a top gate and a heavily doped bulk substrate working as a back gate, whereas dual-gate transistor commonly means a transistor with two top gates.

A structure with substrate contact and a top gate is used to allow more control in electronic properties [38]. The reason for using both back gate and top gate is that it allows more freedom in adjusting the doping by gate voltage, thus allowing more precise control in device resistance. The idea is that when the channel resistance is minimized, the transconductance is maximized. SiC substrate is insulating, and therefore SiCGFETs must naturally have a top gate.

It is often simpler to fabricate a transistor with only a back gate for research purposes, because the layer under the substrate is often chosen as heavily doped silicon that can be directly used as a back gate.

V. Graphene RF Devices

Radio frequency transistors are a key component in wireless communication devices. RF transistors amplify signals and provide gain at very high frequencies. The high mobilities achieved with graphene FETs have shown much promise for RF transistor development. Let us define cut-off frequency as the frequency f_t at which the device current gain drops to unity, and the maximum frequency of oscillation as the frequency f_{max} at which the power gain becomes unity. The recent progress in RF-GFETs is mapped in Fig. 4 [36].

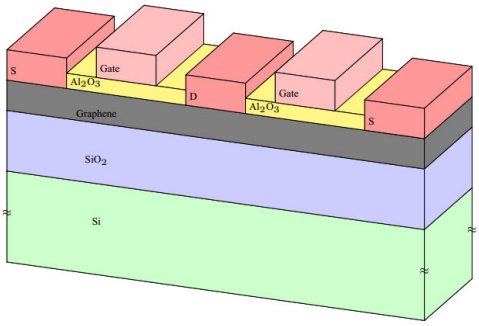


Fig. 3 3D view of a GFET with two top gates

It shows that though there has been progress in RF GFETs these past few years, the GFETs are still outperformed by In P and GaAs mHEMTs. Graphene FETs show quite high cut-off frequencies, but the maximum frequency of oscillation is another interesting parameter that is often disappointingly low. Unfortunately GFETs have low value of f_{max}.

Currently, the fastest reported GFET has the cut-off frequency of 170 GHz with 90 nm channel length [39]. Cut-off frequency of around 600 GHz, has been achieved with GaAs metamorphic high electron mobility transistor (mHEMT) with a 20 nm gate or InP HEMT. Graphene as a large area sheet may offer higher mobility than semiconductor crystals, but the very weak or non-existent current saturation of GFETs limit the highest achievable cut-off frequency, intrinsic gain and other properties of interest in RF devices.

Constant progress has been made in improving GFET cut-off frequency, and the devices are limited by the series resistances. GFET cut-off frequency could be improved to 350 GHz, if the series resistances can be minimized and a self-aligned gate structure is used.

Lin et al. from IBM demonstrated a 100-GHz GFET using epitaxial SiC process. GFETs were fabricated on a 2 inch graphene wafer. For perspective, current silicon processes allow wafer sizes up to 16 inch. The gate dielectric was a spin-on dielectric poly-hydroxystyrene and HfO_2 on top. Lin et al. had promising results with the uniformity of the graphene; the dirac point was consistently at -3.5V gate bias. Despite the extrapolated 100 GHz cut-off frequency, the devices failed to show current saturation.

The improved performance of Lin et al. [40] transistors can be attributed to reduction in access resistances and enhanced mobility due to better dielectric deposition and high-κ material. The significance of access resistance grows as the channel length shrinks. Lin et al. report that they used a back-gate to modulate the access resistance through electrostatic doping. The back-gate was used to provide electrostatic doping in areas where the top gate does not reach, and thus lower access resistance. The total resistance of the graphene device was modelled by Lin et al. as the sum of ideal graphene channel resistance modulated by the top gate, and a series resistance R_s

$$R_{Total} = R_S + \left[\frac{e\mu W}{L_G}\sqrt{n_0^2 + \left(\frac{C_{tot}}{e}(V_{TG} - V_{TRC})\right)^2}\right]^{-1} \quad (3)$$

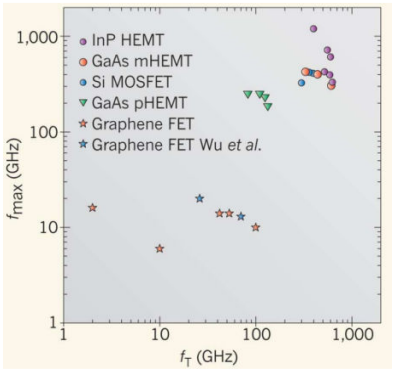


Fig. 4 The maximum frequency of oscillation as a function of cut-off frequency

C_{tot} is the total capacitance of the top gate consisting of top gate capacitance and grapheme channel quantum capacitance. The top gate dirac voltage is denoted as V_{DRC} and n_0 is the minimum sheet carrier density, determined by disorder and thermal excitation.

Graphene based FETs have been found to operate much the same way as their MOSFET counterparts. The GFET intrinsic current gain follows the 1/f frequency dependence and the cut-off frequency f_T is dependent on the dc transconductance g_m of the device and is given by

$$f_T = g_m/(2\pi C_g) \quad (4)$$

where C_g is the gate capacitance. The cut-off frequency was deduced from S-parameter measurements by Lin et al [41]. The cut-off frequency is also found to be inversely proportional to the square of the gate length.

VI. Graphene Digital Devices

Digital graphene devices have been intensily researched ever since graphene was first discovered. Alas, graphene's lack of band gap has turned out to be an issue that is yet to overcome.

The results in graphene digital devices have been so disappointing, that IBM, the company leading the graphene research, has already stated that it is unlikely that graphene would ever replace silicon technology [42].

Yang et al. [43], proposed a triple mode single-transistor graphene amplifier in 2010. The operation is made possible by the ambipolarity of graphene, which enables different points of operation. This device can be considered as proof of concept, though the properties of the proposed graphene amplifier are yet inferior to conventional MOSFET technology. Single-transistor graphene amplifiers have several advantages over the current technology. Single-transistor amplifiers take less space, and thus use less components and materials. In addition, it is beneficial that the transistor can be configured in-field, which in infeasible with MOSFETs. It has

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also been suggested that the 1/f noise is quite low in graphene transistors. At the moment, the small transconductance and very low current saturation limit the operation.

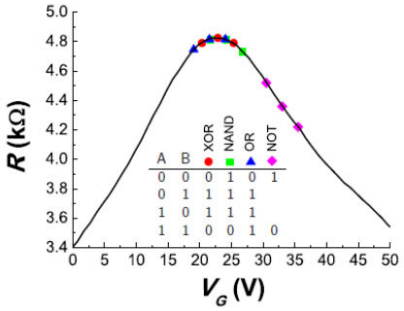


Fig. 5 The four logic gates

Sordan et al. [44], have demostrated four basic input logic gates with a single grapheme transistor. Needless to say, it is desirable to have fewer transistors. Their idea is similar to the triple mode transistor of Yang et al. Sordan et al. grapheme logic gate uses the charge neutrality point to implement boolean logic. The gate values are decoded with resistance values as shown in Fig. 5.

The logic gates demonstrated, showed promise in the possibility of a configurable logic gate [44]. Alas, there are issues with the proposed design. The fact that graphene cannot be turned off, makes the power consumption unacceptably high. Sordan et al. suggest that the transistor resistance could be increased to lower the static power usage. Then again, a higher resistance would slow the response time of the transistor. Furthermore as the input and output logic voltage levels are not the same, cascading the gates would require additional transistors [44].

VII. Summary

Graphene is an interesting new material that is relatively easy to produce. It has so many interesting potential applications that it could become the 'new silicon'. The many electrical and mechanical properties of graphene make it a 2D wonderland of physics, not to mention the bountiful chemical properties that have only just began to be researched. It is no surprise then, that graphene is researched in several fields and new findings are reported almost every week.

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