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# Graphene: A new beginning for semiconductor devices beyond silicon

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***Abstract :*** *Currently, graphene is a topic of very active research fields due to its exceptional electronic properties. For various RF circuit applications, including low-noise amplifiers, the unique ambipolar nature of graphene field-effect-transistors can be utilized for high-performance frequency multipliers, mixers, and high-speed radiometers. Direct current (DC) and radio frequency (RF) measurements were performed on graphene field-effect transistors to find out the DC and RF properties. Two sets of GFETs were measured; first chip was fabricated with SiC process and the second with CVD process. The SiC GFET impedance levels were too high to measure RF properties. RF-measurements were performed on CVD GFETs. The CVD GFET cut-off frequency was found to be approximately 80 MHz, which is in the same range as the calculated cut-off frequency. MOSFET small-signal model was used for GFETs and the model parameters are presented .The results of the DC measurements were analyzed and the data was fitted according to an existing device resistance model. The curve-fit to total device resistance gives estimations on parameters such as contact resistance, residual charge carrier concentration and conductivity mobility.*

***Keywords :*** *Ambipolar, Graphene FET, FLG, graphite, nanotechnology, RF circuit*

## I. INTRODUCTION

Graphene has been a purely theoretical form of carbon for decades. It wasn’t until the year 2004 that Andre Geim and Konstantin Novoselov managed to produce graphene flakes with a technique called mechanical exfoliation. Geim and Novoselov were awarded the Nobel Prize in Physics in 2010 for their discovery of graphene. It is, therefore, easy to claim that 2010 has been the year of graphene. In 2010, around 3000 graphene related articles were published and roughly 400 patent applications filed. According to a recent news article in Nature [1], South-Korea is planning to put 300 million US dollars in commercializing graphene. New graphene related discoveries are in nanotechnology news almost every other day. Keeping up with the pace of progress in the graphene research field is getting quite exhausting, and the pace of new discoveries shows only slight saturation .Graphene is a single layer of sp2-bonded carbon atoms, that are packed in a honeycomb lattice [2]. The name graphene is sometimes misleadingly used with multiple layers, even though the variation in properties is quite significant when going from one layer to several. It should be noted that multilayer graphene can have up to ten layers, and still be called graphene. Few layer graphene (FLG) has three to nine layers. The limit where graphene becomes graphite is ten layers. Graphene 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. However, these properties come with a twist; graphene is zero-bandgap semiconductor, or semimetal. The lack of bandgap in intrinsic graphene is perhaps, together with large scale manufacturing, the most difficult engineering issue. The zero-bandgap means that graphene cannot be switched from conductive state to non-conductive 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 in complementary metal-oxide semiconductor logic circuits [3]. Nonetheless, the zero band gap of large area graphene is not an issue in all applications. One such example is radio frequency (RF) applications, where having no energy gap is not an issue. Transistors are not the only field, in which graphene can be used; other applications include graphene thin film electrodes, using graphene as sensing material or as photodetector to name a few. The most studied graphene transistor today is the graphene field-effect transistor (GFET).The operation principle of a GFET is based on the ambipolar electric field effect in single and few-layer graphene [4]. The ambipolar field effect is due to a small overlap in the valence and conductance bands. The structure of a GFET resembles that of silicon FETs.

## GRAPHENE SYNTHESIS

Though the synthetization of graphene is not the focus of this thesis, it may be beneficial to briefly discuss the most commonly used synthetization methods in order to understand the challenges in fabricating graphene transistors. 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 [14]. The importance of high quality graphene with few or no defects cannot be emphasized enough. The investigations into electron transport in graphene and current saturation show, those defects are the most important factor in hindering the transport of electrons (holes). In 2010, the time of writing this thesis, 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 vapour deposition (CVD) and silicon carbide (SiC) desorption method [14].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, which is then transferred onto a substrate, usually silicon dioxide SiO2 [2]. 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 in 2004 that the invisible graphene flakes become visible on (SiO2) 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 synthesized by sublimation of silicon from SiC in high temperature (1200_C) in ultra-high vacuum. 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 graphene layer has different properties depending on the crystal growth face [8]. 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 ’turbo static’ 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 [14].

## II. Background

Graphene is a purely two dimensional material. If graphene is stacked vertically to hundreds of layers, it would form three dimensional graphite. When rolled into a tube, graphene forms 1D carbon nanotubes, and when in a ball shape it forms 0D fullerenes. Since the discovery of graphene in 2004, graphene has been claimed as the savior of Moore’s law. Moore’s law states that the number of transistors in integrated circuits doubles every two years [6]. The consensus in the scientific community is that transistor line width cannot be reduced for much longer without increasing fabrication costs to such a level that the cost of a single transistor would be too high [7]. Graphene research has been focused on transistors and thin film applications, but the interest in different applications of graphene is growing rapidly [8]. Some articles have been published about graphene photodetector 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 [9]. Another interesting application of graphene is as a material for nanoelectromechanical systems (NEMS) [10]. 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. Of all of the suggested applications of graphene, the use of graphene as a thin electrode seems the one most closest to emerge [1]. Graphene has excellent properties in the visible region of light, because the transparency is higher than 80%.

## III. FIGURES AND TABLES

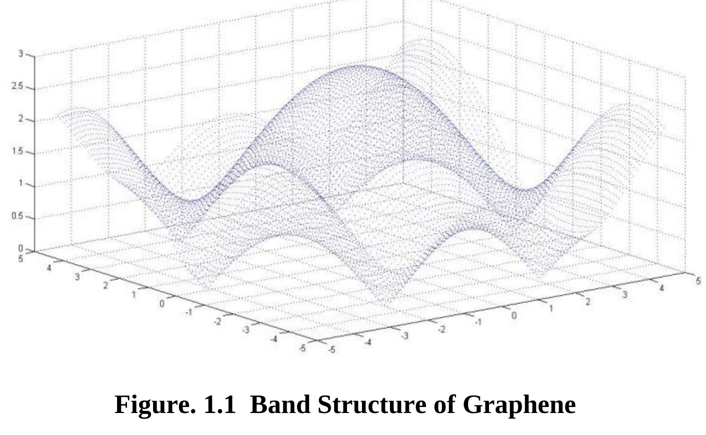

**Figure. 1.1 Band Structure of Graphene**

## IV. CONCLUSION

A Si substrate is used as the global back gate, while the top gate serves as the main gate terminal for regular FET operations. At $V_{BG}$ = 0 V, the GFET exhibits ambipolar transfer characteristics with a current minimum at $V_{TG}$ = 0.7 V. This ambipolar transport reflects the gapless nature of the graphene band structure. The current minimum corresponds to the Dirac point, where the total carrier density of electrons and holes in the graphene channel becomes minimal. Dirac voltage $V_{DRC}$, defined as the top-gate voltage at the Dirac point, is linearly dependent on $V_{BG}$, and the slope ($\Delta V_{BG}/\Delta V_{DRC} \approx 35$) can be used to determine the capacitance $C_{TG}$ of the top-gate dielectrics. This additional resistance is analogous to the access resistance in conventional Si MOSFETs. The total resistance of the graphene device ($R_T$) is modelled as the sum of an ideal graphene channel resistance modulated by the top gate and a series resistance $R_S$

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