Simulation, Fabrication and Measurement of Graphene Based Passive Guided Devices

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Science & Engineering

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By

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Abstract

Motivated by the few work has done on the performance measurement of graphene passive devices compared to graphene active devices, several different types of passive devices are fabricated and measured. In general, the fabricated devices are divided into two parts: the DC devices and the RF devices, which based on the different electrical properties we measure in Chapter 7.

For the DC devices, attention has been given to the resistance of CVD graphene that we later use in all the RF devices. The Dirac point seems only appears in the exfoliated graphene measurement, which is caused by the doping concentration difference between the exfoliated and CVD graphene. Meanwhile, the sheet resistance of graphene is calculated based on the four-point measurement. The sheet resistance of CVD graphene is around 291 Ω/sq.

For the RF devices, the measurement is conducted on the two types of graphene passive devices from 0-110 GHz. The first type of graphene devices is the graphene CPW resonator. We measure the input impedances of the graphene resonators on different substrates (Si/SiO$_2$ and GaAs) and with different graphene lengths (440 µm, 500 µm and 1415 µm). For the graphene resonators on Si/SiO$_2$ substrate, the input impedance does show the resonance shift compared to the graphene-removed structure. The frequency position of the resonance that appears is consistent with the theoretical calculation result. Besides, the influence of the external conditions such as temperature on the performance of graphene resonators has been investigated. The input impedance resonance shows the shift when the external temperature varying from 40° C (313K) to 160° C (433K). This measurement is undertaken with the graphene resonator on GaAs substrate.
The second type of graphene devices is the graphene CPW transmission line on Si/SiO$_2$ substrate. The S-parameters measured from VNA reveal that graphene within the transmission line acts as the transmission channel, which is a little lossy at the microwave frequency range. The poor transmission is also partially caused by the mismatching of the parasitic impedance, as well as the substrate loss, which is verified by the comparison result between the graphene transmission line and the graphene-removed transmission line. Similarly, the concern on the signal line coupling is also eliminated by using the graphene-removed structure.
Declaration

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# Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>ADS</td>
<td>Advanced Design System</td>
</tr>
<tr>
<td>AFM</td>
<td>Atomic Force Microscope</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapour Deposition</td>
</tr>
<tr>
<td>CPW</td>
<td>Coplanar Waveguide</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analogue Converter</td>
</tr>
<tr>
<td>DDC</td>
<td>Digital Down-Converter</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FETs</td>
<td>Field Effect Transistors</td>
</tr>
<tr>
<td>GICs</td>
<td>Graphite Intercalation Compounds</td>
</tr>
<tr>
<td>HIS</td>
<td>High Impedance Surface</td>
</tr>
<tr>
<td>MA</td>
<td>Metamaterial Absorbers</td>
</tr>
<tr>
<td>MLG</td>
<td>Multi-layer Graphene</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl Methacrylate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RIS</td>
<td>Reactive Impedance Surface</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SiO2</td>
<td>Silicon Dioxide</td>
</tr>
<tr>
<td>SPP</td>
<td>Surface Plasmon Polarity</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>THz</td>
<td>Terahertz</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Line</td>
</tr>
<tr>
<td>TEM</td>
<td>Transverse Electromagnetic</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
</tr>
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</table>
Chapter 1 Introduction

Graphene is a two-dimensional (2D) planar layer of carbon atoms packed in a honeycomb lattice. It has been drawing a great attention from both research institutes and industry due to its potential applications since it was firstly peeled from graphite in 2004 [1]. Graphene is the building material of carbon nanotube (CNT), which is a folded strip of graphene in fact. Thus, graphene has many excellent properties similar to CNT such as ultra high electron mobility, ballistic transport, thermoelectric current effect and controllable energy gap. However, unlike CNT, graphene is of a 2D structure, the property which can be used to make planar components and easily placed on a dielectric substrate.

1.1 Motivations

Graphene has attracted lots of attentions as new design material for next generation high-speed electronic integrated circuits due to its excellent electronic properties including high electrical [1] and thermal conductivity [2], and high electron mobility [3]. With a thickness of only 0.34 nm graphene can be easily integrated into or can replace any exist circuit components without changing the design dimensions. The microwave propagation performance for graphene integrated transmission lines have been investigated [4]. It has been reported by Novoselov and Geim [3], Craciun and Russo[5] that the electrical properties of graphene can be tuned using transistor structure applying gate voltage. Cismaru and Dragoman [6] have designed CPW phase shifter with graphene, and have proved applying the DC between the signal electrode and the ground of the CPW cannot tune graphene.
effectively. Hence new work is still needed to explore the new structure of tunable devices using graphene. In this paper, a transmission line with built-in transistor structure in the center of the line is introduced. A tunable TL is modelled and built utilizing the tunability of graphene in transistor structure. The tunable devices and circuits are essential to the adaptive system. These tunable components are necessary for improving the performances of wireless or wired systems [7].

Graphene has attracted extraordinary intensive research in electromagnetic and optical applications such as tunable cloaks, metasurface etc. for the tunability of its conductivity [8]. However, these works mainly focus on applications at higher bands such as THz/infrared, the applications of microwave band are rarely reported. One of the main reasons is that the available high quality graphene is pretty small compared with wavelength in this band. For another, the loss of graphene in microwave band is large [9]. In previous studies, graphene has ever been used as radiation units of tunable antennas. However, the radiation efficiency is very low because of large loss; therefore effective radiation is hard to achieve [10].

1.2 Aims and Objectives

This aims of the PhD research are simulation, fabrication and measurement of graphene passive guided devices. This project was technically supported by the Manchester Centre for Mesoscience and Nanotechnology, University of Manchester. With graphene applied on the passive devices, the amazing electrical properties of graphene could be measured with RF methods. The transport properties at DC and RF region and the tunability of graphene’s conductivity are the most concerned in the research.

There are five objectives expected to achieve in my PhD research:

Establish the accurate surface impedance model of graphene in CST Microwave
Studio according to the MATLAB simulation data;
Based on the tunability of graphene, design and simulate different types of passive devices at microwave frequency region including: graphene transmission lines, graphene resonators, graphene antennas, and graphene switches.
Learn and master the preparation method of exfoliated graphene and the identification of the monolayer graphene;
Through the training of the Manchester University graphene laboratory, complete the fabrication of the desired graphene electronic devices;
Measurement and evaluation of the fabricated graphene devices based on Vector Network Analyzer (VNA) within 0-110 GHz region;

1.3 Structure of Thesis

This thesis consists of 8 chapters, and the content of each chapter is described as below:
Chapter 1 - Introduction: The motivations of the PhD research are presented, as well as the aims and objectives;
Chapter 2 - Literature Review: The study work concerned on the structure, transport properties and preparation of graphene are presented. Published paper related to graphene passive devices are reviewed;
Chapter 3 - Electromagnetic Modelling Simulations of Graphene: Two approaches for graphene electromagnetic modelling simulation are discussed;
Chapter 4 - Electromagnetic Modelling Simulations of Graphene Based Passive Devices: Four different types of graphene passive devices are simulated in CST;
Chapter 5 - Device Fabrication: The procedures of graphene devices fabrication are detailed explained;
Chapter 6 - Characterization techniques and Experiments Descriptions: describes
three characterization techniques for graphene identification and equipment setting for Chapter 7;

Chapter 7 - Measurements Results and Analysis: Analyze the measurement results of graphene resonators and graphene transmission lines;

Chapter 8 - Conclusions and Future Work: Gets conclusions of fabricated graphene passive devices and proposes the future research interests.
Chapter 2 Literature Review

Graphene is a very thin, almost transparent slice, with only one atom thickness formed of pure carbon. It is significantly stronger than many other materials (stronger than steel in two orders of magnitude [11]) with its nearly negligible weight, and its thermal conductivity and electric efficiency are very outstanding [12]. While the researchers have developed their study on graphene for a long time, it was firstly peeled from graphite in the Manchester University in 2004 [13]. Because it can actually be viewed as a two-dimensional structure, it achieves very different interactions with other materials, as well as light. These days researchers have gained very good result in the fields such as bipolar transistor effect, quantum oscillation and the ballistic transport.

This chapter is organized as follows. In section 2.1, the band structure of graphene is described, as well as the amazing properties and its preparation methods. In section 2.2, the research on the applications of graphene on the different types of passive guided devices are reviewed, which including the graphene antennas, graphene transmission lines, and graphene absorbers.

2.1 Graphene

2.1.1 The band structure of graphene

Graphene is a two-dimensional (2D) honeycomb lattice that filled with the carbon atoms [14], which is in the form of sp2 hybridized carbon atoms sheet. In graphene, there is a strong interaction between two electrons and two electrons and between the electron and the honeycomb grid. Like the surface of graphite, graphene can be adsorbed and desorbed various atoms and molecules. In the form of two-dimensional honeycomb lattice, the
carbon atoms are knitted like in the Figure 2.1.

**Figure 2.1 Honeycomb lattice of (monolayer) graphene (left) and its Brillouin zone (right) [15].** Left: The A and B area delineates the unit cell of graphene with its two non-equivalent ato, where $a_1$ and $a_2$ are the vectors of the unit cell. Right: The points $M$, $K$ and $K'$ (high symmetry points) and $b_1$, $b_2$ (unit cell vectors) in the form of a reciprocal lattice are illustrated within the first Brillouin zone in graphene.

In the honeycomb lattice, carbon atoms are bonded together by $sp^2$ hybridization orbitals which can be generally viewed as a 2px, 2py and 2s mixture (the schematic illustration of the three sp2 orbitals formed in a plane as σ bonding is shown in Figure 2.2). These three kinds of bonds are separated by the same angle of 120° in three different directions (here represented by $\delta_1$, $\delta_2$ and $\delta_3$ in Figure 2.1, and illustrated in the Figure 2.2 (c) and Figure 2.2 (d)). And in this way, every one single carbon atom accompanied by three valence electrons form together the $\zeta$ bond. The last electron left remains in its orbit $2pz$, which sharing with the neighbor carbon atom to form together the $\pi$ bond. Because of the weaker orbital overlap, the $\pi$ bond is not that strong as a covalent bond $\zeta$. Furthermore, normally the $\pi$ bond electrons contribute most to its transport properties in nearly all of the carbon allotropes (the simple illustration can be found in the Figure 2.3). That’s why we only take into account the $\pi$ wave function when deriving the formula of the conductivity of graphene in [16].
As shown in Figure 2.1 (a), there are two inequivalent atoms A and B forming together as a unit cell in graphene’s two-dimensional honeycomb lattice. These two inequivalent atoms A and B are with different hybrid orbitals the wave function. In this way, they contribute to a sub-lattice within the whole honeycomb lattice, respectively (shown in Figure 2.1). These two sub-lattices work together with nearest areas with only the 1.42Å distance. When taking into account the other honeycomb lattice structure, these inequivalent atoms A and B are vital for carrier hopping.

![Figure 2.1](image1)

\[ \mathbf{a}_1 = \left( \frac{a}{2}, \sqrt{3}, 1 \right), \quad \mathbf{a}_2 = \left( \frac{a}{2}, \sqrt{3}, -1 \right) \] (2.1)

**Figure 2.2** The schematic illustration of the three sp² orbitals formed in a plane as σ bonding [17].
where, \( a \) is the graphene 2-D lattice constant: \( a = |\vec{a}_1| = |\vec{a}_2| = 1.42 \times \sqrt{3} = 2.46 \text{Å}. \)

As we know, the unit vectors in a reciprocal lattice (shown in Figure 2.1 (b)) can be derived from the equation above as long as this reciprocal lattice is also in the form of honeycomb. Thus, we can get the unit cell vectors in a reciprocal honeycomb lattice:

\[
\vec{b}_1 = \left( \frac{2\pi}{\sqrt{3}a} \right) \left( 1, \sqrt{3} \right), \quad \vec{b}_2 = \left( \frac{2\pi}{\sqrt{3}a} \right) \left( 1, -\sqrt{3} \right) \tag{2.2}
\]

In the Equation (2.2), we can find that not only the values of unit vectors have changed, but also the direction of them have rotated by 30°. This can be found in the Figure 2.1(a) and 2.1 (b).

Figure 2.1 (b) demonstrates graphene’s first Brillouin zone. There are three kinds of high symmetry points located at the corner, the center, and the center edge, respectively. Here we use symbols \( \Gamma \), \( M \), \( K \) and \( K' \) to represent them. In all of them, \( K \) and \( K' \) are playing an important role quite similar to the atoms A and B, which are also inequivalent points and contribute to the formation of unit cell in a reciprocal honeycomb lattice of graphene. In this way graphene exhibits some unique properties.

To study the band structure of graphene, tight binding method is a good choice, which is suitable for many different types of solid materials. In this method, electrons are assumed that they are tightly bonded to their central atom and also ignore the interaction with the other atoms.

A few decades ago, P.R.Wallace firstly used the tight binding method to investigate the band structure of the graphite crystal structure in the paper [18]. Since graphene can be viewed as the 2-D structure of the graphite crystals, the tight binding model adopted by P.R.Wallace is even more appropriate for graphene. Thus, the energy dispersive relationship can be derived from [18]:

\[
E(\vec{k}) = t f'(\vec{k}) \mp t \sqrt{3 + f'(\vec{k})} \tag{2.3}
\]
where \( f'(k) = 2\cos(k, a) + 4\cos\left(\frac{\sqrt{3}k, a}{2}\right)\cos\left(\frac{k, a}{2}\right) \).

In the Equation (2.3), when the negative symbol is applied, it means that it is anti-bonding orbital. The corresponding band structure is the upper section (the conduction band) of Figure 2.3. And if the positive symbol is applied, it indicates the bonding orbital (the valence band).

The Figure 2.3 shows the band structure of graphene with the numerical results. That is very obvious that the conduction band and the valence band are separated. On the contrary, the \( \pi \) and \( \pi^* \) are approaching each other when near the K point. At this point, no energy gap is existed. For Figure 2.3, the Fermi level is 0 eV and the dotted curve represents the vacuum Fermi level. \( \Phi \) is the work function.

![Figure 2.3](image-url)  
**Figure 2.3**  
Electronic band structure of (monolayer) graphene.

Now if we derive the Equation (2.3) further considering the situation of two Dirac points and the momentum vector symbolled with \( q \) are given. This equation can be expanded in the form of the second-order and conclude the following \([15]\):

\[
E(\vec{q}) \approx 3t' \pm \nu \bar{q} - \frac{3t'a^2}{4} + \frac{ta^2}{8}\sin\left(3\theta_{\vec{q}}\right)|\vec{q}|^2
\]  
(2.4)
where

\[ \theta_q = \tan^{-1}\left( \frac{q_x}{q_y} \right) \]

and

\[ \nu_f = \frac{\sqrt{3}a}{2} \]

\( \nu_f \) is the Fermi velocity and normally with value of \( 10^6 \) m/s [18].

Equation (2.4) describes the energy dispersion in graphene. When assume graphene within the area nearing the Dirac point K, we can derive a more direct equation (2.6):

\[ E(\vec{q}) = \pm \nu_f |\vec{q}| \]

Equation (2.6) can well explain the energy dispersion of graphene when approaching the Dirac point, which really plays such an important role in the field of graphene electronics. With this equation, we can enhance our understanding of the many unique properties of graphene.

2.1.2 Transport properties of graphene

The unique band structure of graphene makes itself exhibit many novel electronic properties. One of the most striking properties is the high carrier mobility. The first graphene-based electronic device exhibited 10,000 cm\(^2\)V\(^{-1}\)s\(^{-1}\) (with the SiO\(_2\) over the substrate) [19], it was considered at that moment a relatively high mobility. Since then, the mobility on the SiO\(_2\) substrate graphene devices has improved up to 15,000 cm\(^2\)V\(^{-1}\)s\(^{-1}\) [20] Also, if the SiO\(_2\) substrate is removed, and the suspension graphene can exhibit \( 2 \times 10^5 \) cm\(^2\)V\(^{-1}\)s\(^{-1}\) mobility at low temperatures (with the carrier density below \( 5 \times 10^9 \) cm\(^{-2}\) ) [21 ]. This result is really close to the graphene mobility limit value derived by the Chen et al. [22]. In addition, the mobility can be maintained at \( 1.2 \times 10^5 \) cm\(^2\) V\(^{-1}\)s\(^{-1}\) with the carrier density \( 2 \times 10^{11} \) cm\(^{-2}\) [23].

The high mobility of graphene is not unexpected from the theoretical point of view. As how we describe Linear dispersion relation in Equation (2.6) in the last section, the
behavior of massless Dirac Fermion carriers can share the same manner in the performance of graphene carriers with the value of $V_F 10^6$ m/s. This important parameter will determine the longitudinal velocity of the acoustic scattering mechanism, which is considered as the limitations origin of the mobility of graphene. This limitation is estimated by Chen et. al. [22], where indicates that in a low carrier concentration system, the mobility of graphene can reach up to $2 \times 10^5$ cm$^2$V$^{-1}$s$^{-1}$. The requirement for this limitation is that carrier density $n = 1 \times 10^{12}$ cm$^{-2}$ (which can be specified by a gate voltage of 14V and SiO$_2$ in a thickness of 300nm is used as the substrate) [22].

High mobility is a prominent aspect of the semiconductor material. Despite the lack of band gap, which makes graphene rarely replace silicon in digital circuits [24, 25] as the next generation of the substrate, it is still a good choice for frequency transistor or a light detector [26]. All of these fields make graphene a very promising material for applications. Expect these important aspects, the high mobility of graphene can also apply to the Hall sensor, expecting to achieve the higher sensitivity and lower noise. In this field, graphene is viewed as a better resolution.

Clearly, the mobility of suspended graphene devices is higher, or even close to the theoretical limit of graphene which is determined by the longitudinal phonon scattering mechanism. The limit of mobility increases in the suspended graphene devices compared to the one of devices fabricated on SiO$_2$ substrate. The main external factor that causes decrease of carrier mobility in graphene devices is the scattering mechanism.

There are already a lot of factors proposed to cause the scattered mechanism. Until now the most widely accepted view is that the charged impurity scattering may result in relatively low carrier mobility on the SiO$_2$ substrate. This conclusion agrees with the theoretical and experimental results using this model [22, 26, and 27]. In particular, this theory offers a simple explanation of $\sigma - n$ linear relationship in graphene devices [28, 29]. S. Das Sarma et al., who developed the widely cited model in [30], attempts to use
the combination of long-range Coulomb scattering effect (disorder charged from various sources) and the short-range scattering disorder to explain the transmission characteristics. There are also many other reasons (except charged impurity) that can cause the long distance scattering. They include the roughness when transforming graphene to SiO$_2$ substrate and the inherent microscopic corrugations of graphene [31, 32]. Besides, the remote interface phonon [22, 33] may also result in the scattering. Although some short-range disorder scattering has also been considered in Salma Das et. Model [30], the origin of the phenomenon is still far away truth up to now. Under normal circumstances, the short-range disorder scattering is imported by a point defect or dislocation. But this is not a good explanation since graphene has very high quality crystal structure. Thus, the impact of these impurities should be even negligible for graphene [34].

2.1.3 Preparation of Graphene

Normally, there are five methods of the preparation of graphene [35]:

1. Micro-mechanical exfoliation of graphite (Scotch tape or peel-off method).
2. Creation of colloidal suspensions from graphite oxide or graphite intercalation compounds (GICs).
3. Chemical vapour deposition (CVD) of hydrocarbon.
4. Epitaxial growth on electrically insulating surface such as SiC.
5. Total organic synthesis.

![Schematic models of chemical strategies towards graphene from different...](image)

*Figure 2.4 Schematic models of chemical strategies towards graphene from different...*
Table 2.1: The advantages and disadvantages of recently used graphene produce methods [35].

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Exfoliation</td>
<td>Low cost and easy, No special equipment needed.</td>
<td>Serendipitous, Uneven films, Labor intensive</td>
</tr>
<tr>
<td>Epitaxial Growth</td>
<td>Most even films (of any method), Large scale area</td>
<td>Difficult control of morphology and sorption energy, High temperature process</td>
</tr>
<tr>
<td>Graphene Oxide</td>
<td>Straightforward up-scaling, Versatile handling of the suspension, Rapid process</td>
<td>Fragile stability of the colloidal dispersion, Reduction to graphene is only partial</td>
</tr>
</tbody>
</table>

Comparing these methods above, mechanical exfoliation has the advantages of low cost and easy to prepare. No special equipment is needed and better contrast can be got by tuning the thickness of SiO₂. But the disadvantages are the uneven films and intensive labor, which is not suitable for large scale production. On the contrary, epitaxial growth method can get most even films and large scale area. But it is difficult to control the morphology and adsorption, which also requires high temperature during preparation. As for the graphene oxide method, it has straightforward up-scaling, versatile handling of the suspension and rapid process. However, the fragile stability of the colloidal dispersion and only partial graphene out of graphene oxide are the drawbacks.

2.2 Application of Graphene on Passive Guided Devices

2.2.1 Graphene Antennas

Due to the unique chemical, thermal, mechanical, electronic and optical properties of graphene [43], many studies on its application for RF, microwave/millimeter-wave and THz devices and circuits have been reported. For example, the field effect transistors (FETs) and frequency multipliers and mixer [37] - [44]. Graphene can also be used as
passive components, such as transmission lines to guide electromagnetic waves or as antennas to act as interface between the free space wave and signal source [45] - [48]. The beauty of graphene is that its conductivity can be tuned electromagnetically, showing a potential of designing and realizing a new class of reconfigurable THz antennas [44]. In addition, the graphene exhibits slow wave property which can be highly desirable for graphene circuit applications [48].

The unique graphene electronic property allows the existence of surface plasmon polarity (SPP), which can lead to realization of highly miniaturized graphene-based millimeter-wave and THz antennas and passive guided components. However, work on the application of graphene in antennas and other passive guided devices are still in its infancy [49]-[53]. For example, a reconfigurable loop antenna on switchable high-impedance surface using graphene is proposed in [52], whereas graphene is applied for designing the fixed-beam reflect array antennas in [53]. In all these antenna works, only graphene dipole or patch antennas were reported.

We have demonstrated that graphene is a promising material to apply in the miniaturized terahertz resonance antenna. In [48], working as the radiation unit of antenna, an initial study of the electromagnetic wave propagates on graphene within the free space and radiation area. With a very simple geometry layout, an optical mixer working at the THz region can achieve the very good matching. Another good step is the integrated all-graphene transceiver system composed of graphene THz antennas. Since graphene is transparent with 97% transparency, this integrated system can be developed on the transparent screen. On the other hand, the plasmonic property of graphene make itself functioned as metals in terms of the return loss and radiation efficiency. In this case, the research on graphene based THz antennas has been developed. A new beam reconfigurable antenna is proposed in [52] based on graphene, where graphene explores its terahertz applications as the high impedance surface (HIS). A terahertz antenna is
designed over the HIS and the reflection coefficients of performance and radiation patterns were studied in this paper. With applying the different voltages to different cells of graphene HIS, the antenna is reconfigurable with the beam deflection angle changes within $\pm 30^\circ$ at 860 GHz, which is verified through the simulation numerically. This research makes graphene based structures strongly possible to be implemented in the future THz reconfigurable system. The configuration and the schematic design of the reconfigurable THz antenna based on graphene HIS are shown in Figure 2.5 and Figure 2.6, respectively. Inspired by this paper, a new design is proposed in Chapter 4.

*Figure 2.5 Configuration of the switchable graphene-based HIS. [52].*

*Figure 2.6 Schematic of the antenna with HIS: (a) cross-sectional view and (b) top view [52].*
In [54], the electromagnetic properties of graphene at different frequency ranges and their potential use in antenna applications were discussed. Based on reviews of the graphene modeling and the characteristics of the associated surface conductivity and impedance, simple graphene-based antennas operating at different frequencies were proposed in the aim of highlighting the potential interest and limitations of using graphene for antennas applications.

The concept and analysis of a terahertz (THz) frequency-reconfigurable antenna using graphene were presented in [44]. The antenna exploited dipole-like plasmonic resonances that can be frequency-tuned on large range via the electric field effect in a graphene stack. In addition to efficient dynamic control, the proposed approach allowed high miniaturization and good direct matching with continuous wave THz sources. A qualitative model was used to explain the excellent impedance stability under reconfiguration. These initial results are very promising for future all-graphene THz transceivers and sensors.

A first important step towards reconfigurable THz reflectarrays using graphene electric field effect was made in [53], where the use of graphene for fixed-beam reflectarray antennas at Terahertz (THz) was proposed. Graphene’s unique electronic band structure lead to a complex surface conductivity at THz frequencies, which allowed the propagation of very slow plasmonic modes. This lead to a drastic reduction of the electrical size of the array unit cell and thereby good array performance. The proposed reflectarray has been designed at 1.3 THz and comprises more than 25 000 elements of size about. The array reflective unit cell was analyzed using a full vectorial approach, taking into account the variation of the angle of incidence and assuming local periodicity. Good performance was obtained in terms of bandwidth, cross-polar, and grating lobes suppression, proving the feasibility of graphene-based reflectarrays and other similar spatially fed structures at Terahertz frequencies.
2.2.2 Graphene Transmission Lines

In [55], the use of graphene for microwave integrated circuit transmission lines was proposed, where a modified procedure to etch graphene involved the use of Au on top of graphene was adopted. The proposed procedure enabled the etching process to be performed with the presence of PMMA masking layer. The etchant was made of 3HCl:HNO$_3$:8H$_2$O. Co-planar transmission lines of various widths and lengths were constructed on graphene to ensure compatibility with microwave wafer probes used in the measurements. The lines and the underlying SiO$_2$ layer were modeled using CST Microwave Studio electromagnetic simulator. The center conductor width was 30 μm, while the spacing varied from 30 to 100 μm. The graphene parameters were subsequently subtracted out from measurements by curve-fitting the experimental results with simulation. Low frequency I-V measurements revealed conductivity of the order of 2.89 × 10$^7$ S/m, but scattering parameter measurements of the samples conducted over 1 to 20 GHz revealed much lower conductivity, an effect which we think was the result of poor quality thermally grown SiO$_2$ substrates used in this experiment.

In [56], the effective surface conductivity of chemical vapor deposition-grown graphene were quantitatively evaluated through a full-wave electromagnetic method and the intrinsic characteristics of the transmission line (TL) of the graphene at frequency ranging from 0.5 to 40 GHz were also investigated. According to the simulated data based on the measured S-parameters, the effective conductivity of single- and multi-layer graphene (MLG) was about 4.3×10$^6$/m and 1.2×10$^6$/m, respectively. Furthermore, it was confirmed that the multi-layer graphene was more suitable for use in transmission lines compared to single-layer graphene in the observed frequency region. The configuration and the schematic design of the reconfigurable THz antenna based on graphene HIS are shown in Figure 2.5 and Figure 2.6, respectively. Inspired by this paper, a new design is proposed in Chapter 4.
Figure 2.7 The magnitude of measured (solid) transmission, $S_{11}$, and reflection, $S_{12}$, over the frequency range 10 MHz–50 GHz and 65 GHz–110 GHz for open gap and series graphene transmission lines on quartz [57].

Figure 2.8 The magnitude of measured (solid) transmission, $S_{11}$, and reflection, $S_{12}$, over the frequency range 10 MHz–50 GHz and 65 GHz–110 GHz for through and shunt graphene transmission lines on quartz [57].
To measure the high frequency transmission performance of graphene, the graphene transmission lines based on the quartz substrate are simulated in [57]. In this paper, CVD graphene is used for its large size grown on copper, and then transferred to quartz. Microwave measurements were performed from 0.01 to 110 GHz. Simple microwave models were used to extract graphene impedance parameters. It is shown that contact resistance was effectively shunted above 3 GHz. Atomically thin large area graphene behaved as a wideband resistor with negligible kinetic inductance and negligible skin effect. The configuration and S-parameters of the four models of graphene transmission lines are shown in Figure 2.7 and Figure 2.8, respectively. Inspired by this paper, a new graphene based transmission line on the Si substrate is proposed in Chapter 4 and measure results are presented in Chapter 7.

2.2.3 Graphene Absorbers

Recently, graphene has been introduced in designing THz absorber for its tunability of conductivity [58]-[60]. With tunable conductivity of graphene sheet, propagation and absorption of electromagnetic wave could be controlled conveniently [61][62]. Based on graphene micro-ribbons, a Far-infrared region absorber with wide-angle high absorption was contributed in [60]. In [58], employed with effective surface conductivity approach, both narrow-band and wide-band absorbers were designed with graphene wire medium and fishnet metamaterials. Except for pattern graphene, continuous graphene sheet is also used to design absorber. Xu proposed a narrow-band tunable terahertz absorber based on a stack of graphene and dielectric slabs. With method of cascading, the absorption bandwidth was expanded [59]. Concluding with the above most recent absorber research, it can be found that most designs are with narrow absorption bandwidth [59][60], and with the changes of biased voltage or chemical potentials, the absorption peak decreased dramatically, which acts more accurately as an absorption switch [58][59].
To get a wideband absorber with tunable but high absorption peak, we proposed a THz absorber design with double-layered graphene. With the introduction of two tunable varieties, the high absorption could be maintained even the peak absorption frequency is changed in a certain range. Besides, the absorption bandwidth could be drastically expanded with two resonances.

The configuration of the graphene based absorbers proposed in [59] is shown in Figure 2.9. Inspired by this paper, a novel graphene based triple band absorber is proposed in Chapter 4.

*Figure 2.9 Configuration of the graphene based absorber with dielectric separation. (a) 3D view and (b) cross-section view. [59].*
Chapter 3 Electromagnetic Modelling Simulations of Graphene

Graphene is a two-dimensional (2D) planar layer of carbon atoms packed in a honeycomb lattice. It has been drawing considerable attention from both research institutes and industry due to its potential applications since it was firstly peeled from graphite in 2004 [63]. Conductivity is one of the most significant electromagnetic parameters of graphene, which is vital for our further research work.

However, the first challenge to design a graphene device is how to model graphene in the simulation software. In this chapter, we discuss two approaches to graphene modeling in the commercial software CST Microwave Studio 2015 in section 3.1 and section 3.2. In the last section, the tunability of graphene will be discussed.

3.1 Complex Surface Conductivity of Graphene

Graphene with only one-atom thickness can be modeled as an infinitely thin surface with the compound surface conductivity $\sigma$. In the THz band, the intraband contribution of graphene dominates. Thus, the surface conductivity can be calculated using Kubo formulism [64]:

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$  \hspace{1cm} (3.1)

$$\sigma_{\text{intra}}(\omega,\mu_c,\Gamma,T) = -j \frac{e^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left( \frac{\mu_c}{k_B T} + 2 \ln(e^{\mu_c/k_B T} + 1) \right)$$  \hspace{1cm} (3.2)

$$\sigma_{\text{inter}} = \frac{e^2}{4\hbar} \left[ H\left(\frac{\omega}{2}\right) + i \frac{4\omega}{\pi} \int_0^\infty \frac{H(\Omega) - H(0)}{\omega^2 - 4\Omega^2} d\Omega \right]$$  \hspace{1cm} (3.3)

where

$$H(\Omega) = \frac{\hbar}{k_B T} \left[ \text{cosh} \left( \frac{\hbar \Omega}{k_B T} \right) + \text{cosh} \left( \frac{E_F}{k_B T} \right) \right]$$  \hspace{1cm} (3.4)
\( \sigma \) is determined by temperature \( T \), chemical potential \( \mu_c \), radiation frequency \( \omega \) and scattering rate \( \Gamma = 1/\tau \), where \( \tau \) is the relaxation time. It is shown that graphene's surface conductivity could be efficiently controlled by changing its chemical potential \( \mu_c \), which \( \mu_c \) can be changed via doping or changing density of the carrier. Values of \( T \) and \( \tau \) are set to 300 K and 1 ps, respectively.

In order to numerically study the electromagnetic response of graphene, it is necessary to self-consistently couple the phenomenological conductivity model (3.1) with the three-dimensional Maxwell’s equations. The major complication here is that a typical numerical scheme to solve Maxwell’s equations involves finite-size discretization of space, which makes modeling of the infinitesimally thin graphene layer a challenging task. In what follows, we propose and compare two different approaches to solving this problem. In the first method, graphene is approximated by a thin, but finite, slab with an effective tensor conductivity

\[
\bar{\sigma} = \begin{pmatrix}
\frac{\sigma}{\Delta} & 0 & 0 \\
0 & \frac{\sigma}{\Delta} & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

(3.5)

where \( \Delta \) is the thickness of an equivalent slab, and the graphene layer is located in the x-y plane. The tensor structure of the conductivity (3.5) together with the relation

\[
\lim_{\Delta \to 0} \frac{1}{\Delta} = \delta(z)
\]

ensures that, in the infinitesimally thin slab limit, the induced current is purely two-dimensional.

The main disadvantage of the proposed method is the high mesh densities and hence high computational costs. To simplify the problem, we propose to model graphene as an equivalent impedance surface. The surface impedance \( Z_s \) connects the tangential component of the electric field on the surface with the surface electric current. Taking into account that the current induced in the graphene layer is purely superficial, and it is related to the tangential component of the electric field via surface conductivity as

\[
J_{\text{surf}} = \sigma E_{\perp} \bigg|_{z=0} = 0,
\]

one can define the boundary conditions at the graphene interface:
\[ \hat{n} \times \left[ \frac{d}{dz} \left| \frac{d}{dz} \right|_{z=0} - H \right]_{z=0} = J_{\text{surf}} = \frac{1}{Z_s} E_1 \left|_{z=0} \right. \] (3.6)

where \( Z_s = \frac{1}{\sigma} \) is the equivalent surface impedance of the graphene.

This figure 3.1 shows the complex conductivity of graphene from microwave to the visible frequency range. It is worth mentioning that to simulate graphene using the software CST; it is modeled by the frequency-dependent surface impedance \( Z_s = \frac{1}{\sigma} \).

![Figure 3.1: Surface conductivity of graphene under different chemical potential.](image)

![Figure 3.2: Surface impedance of graphene under different chemical potential.](image)

Figure 3.1 shows the complex surface conductivity of graphene from 0.1 THz to 10 THz with values of \( \mu_c \) setting to 0 eV and 0.5 eV. It is evident that the conductivity is
frequency-dependent and varies as the change of $\mu_c$. By applying an external field or modifying the type and density of carriers, a reconfigurable graphene device can be realized.

In the simulation, graphene is modeled as an equivalent impedance surface. The surface impedance $Z_s$ of graphene is inversely corresponding to its complex surface conductivity, that is, $Z_s = 1/\sigma = R_s + j\omega L_s$. Here $R_s$ and $L_s$ are the real loss and inductive impedance components, respectively. Figure 3.2 shows the complex surface conductivity of graphene from 0.1 THz to 10 THz with values of $\mu_c$ setting to 0 eV and 0.5 eV. As the frequency increases, the inductive behavior of graphene dominates, which leads to the highly inductive nature of graphene at THz. Thus, it allows the SPP exist in the THz region, where only TM surface wave propagates between graphene and the air interface [65].

3.2 Drude Model of Graphene’s Permittivity

For the Terahertz frequencies, where the photon energy, the interband part (3.3) is negligibly comparing with the intraband. Therefore, the surface conductivity from the Drude model (3.2) can be used to describe graphene. For the conductivity depends linearly on the Fermi energy [66]

$$\sigma = \frac{e^2 E_F}{\pi h^2} \frac{i}{\omega + i\tau^{-1}}$$ (3.7)

Assume graphene with a thickness $\Delta$

$$\varepsilon_{\text{eff}, n} = 1 + \frac{i}{\varepsilon_0 \omega \Delta}$$ (3.8)

The normal component of the effective permittivity $\varepsilon_{\text{eff}, n} = 1$.

In other words, we can say that graphene is represented by a thin metal with the plasma frequency depending on the Fermi level

$$\omega_p = \left[ \frac{2e^2 k_B T}{\pi h^2 \varepsilon_0 \Delta} \ln(2\cosh \frac{E_F}{2k_B T}) \right]^{1/2}$$ (3.9)

If we compare the surface conductivity and plasma frequency method of graphene
modeling, we can get nearly the same simulation result for the same graphene device structure. Thus, when we are setting the graphene model in CST, we can choose an appropriate Drude model to describe the electromagnetic properties of graphene based on variable temperatures and chemical potentials.

On the other hand, according to Maxwell equations, the permittivity can be derived from the conductivity. Now we will have some study on graphene's permittivity based on its conductivity. Given the time-harmonic electromagnetic wave, from

\[ \nabla \times H = J + \frac{\partial D}{\partial t} = J - i\omega E = \sigma_{3D} E - i\omega E = -i\omega \left( \varepsilon - \frac{\sigma_{3D}}{i\omega} \right) E \]  

(3.10)

And

\[ \sigma_{2D} = \sigma_r + i\sigma_i \]  

(3.11)

we can conclude

\[ \varepsilon_{\text{eff}} = \varepsilon - \frac{\sigma_{3D}}{i\omega} = \varepsilon + \frac{\sigma_{2D}}{\omega\Delta} = \varepsilon - \frac{\sigma_r}{\omega\Delta} + i\frac{\sigma_i}{\omega\Delta} = \varepsilon' + i\varepsilon'' \]  

(3.12)

According to Equation (3.12), we can see that the real part and imaginary part of graphene’s permittivity can be presented in form of conductivity:

\[ \varepsilon' = \varepsilon - \frac{\sigma_r}{\omega\Delta} \]  

(3.13)

\[ \varepsilon'' = \frac{\sigma_i}{\omega\Delta} \]  

(3.14)

Thus, the imaginary part of graphene’s conductivity determines the real part of permittivity and the real part of graphene’s conductivity determines the imaginary part of permittivity. Since graphene is very thin, \( \Delta \to 0 \), \( \varepsilon' \) can be presented approximately as:

\[ \varepsilon' \approx -\frac{\sigma_r}{\omega\Delta} \]  

(3.15)

Thus, the loss tangent of graphene can be presented as:

\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} = \left| \frac{\sigma_r}{\sigma_i} \right| \]  

(3.16)
We can see that the loss tangent value of graphene is determined by the ratio of the conductivity's real part over the imaginary part. According to the relationship between permittivity and conductivity, we can change graphene's permittivity by varying its conductivity. Since the conductivity of graphene is controlled by the externally applied gate voltage, the permittivity of graphene can also be tuned by the gate voltage. Meanwhile, the loss of graphene is affected by gate voltage as well.

![Graph showing the relationship between gate voltage and permittivity](image.png)

*Figure 3.3: The relationship between the gate voltage $V_g$ and the permittivity $\varepsilon$, of graphene with temperature $T=3K$ and frequency $f=50 THz$."

From Figure 3.3, we can find that the permittivity of graphene is varying within a relatively wide range under the particular gate voltage control, which could be either positive or negative. Different values of gate voltage can be applied to graphene, which will achieve the tunability of graphene.

### 3.2 Tunability of Graphene’s Conductivity

#### 3.2.1 Tunability of graphene’s conductivity controlled by the gate voltage

Generally, the chemical potential of graphene is controlled by the applied gate voltage, which means that the conductivity of graphene can be tuned by the gate voltage.
Now we will have some study on the relationship between the chemical potential of graphene and the applied gate voltage. For the monolayer graphene, the values of chemical potential are determined by the density of the corresponding carriers [64]:

\[
\mu_z = \frac{2}{\pi \hbar^2 v_F^2} \int_0^\infty \epsilon [f_d(\epsilon) - f_d(\epsilon + 2\mu_z)] d\epsilon
\]

(3.17)

where \( v_F \) is the Fermi velocity of graphene, normally as \( 10^6 \text{ m/s} \). Take \( f_d(\epsilon) \) into Equation (3.2) and after calculation, we can get:

\[
n_z = \frac{2}{\pi \hbar^2 v_F^2} \int_{-\mu_z/\epsilon_d}^{\mu_z/\epsilon_d} x e^x + 1 dx + k_BT \mu_z \ln \left( e^{\frac{-\mu_z}{k_BT}} + 1 \right) + \frac{\mu_z}{k_BT} \ln \left( e^{\frac{\mu_z}{k_BT}} + 1 \right)
\]

(3.18)

On the other hand, considering the monolayer graphene on the SiO\(_2\)/Si substrate, the surface carrier density of the monolayer graphene can be expressed as:

\[
n_z = \epsilon_0 \epsilon_d V_g / 4\epsilon
\]

(3.19)

where \( V_g \) is the applied gate voltage. \( \epsilon_0 \) and \( \epsilon_d \) represent the permittivity of vacuum and the SiO\(_2\) layer, respectively. \( T \) is the thickness of the SiO\(_2\) layer, which normally is 300 nm. Combining the Equation (3.18) and Equation (3.19), we can derive the relationship between the gate voltage and the chemical potential of graphene:

\[
V_g = \frac{n_z}{\alpha} = \frac{2\epsilon}{\pi \hbar^2 v_F^2 \epsilon_0 \epsilon_d} \int_{-\mu_z/\epsilon_d}^{\mu_z/\epsilon_d} x e^x + 1 dx + k_BT \mu_z \ln \left( e^{\frac{-\mu_z}{k_BT}} + 1 \right) + \frac{\mu_z}{k_BT} \ln \left( e^{\frac{\mu_z}{k_BT}} + 1 \right)
\]

(3.20)

We can draw the relationship curve of the chemical potential corresponding to the gate voltage when \( T = 300K \), which is shown in Figure 3.4.
Figure 3.4: The relationship between the gate voltage $V_g$ based on the thickness of the isolation layer and the chemical potential of graphene with temperature $T=300K$.

From Figure 3.4 we can conclude that each value of the chemical potential corresponds to a unique gate voltage. Thus, the chemical potential increases as the applied gate voltage go up. To verify the calculation above, we will compare them with those in the reference paper [67]. In this article, when $T = 3K$, the thickness of SiO$_2$ $t = 300nm$ and $\mu_c = 0.15eV$, the corresponding gate voltage $V_g = 22.84V$. Under the same conditions, we can calculate to get the gate voltage $V_g = 22.9V$. In the paper [68], when $T = 300K$, the thickness of SiO$_2$ $t = 1.56um$ and $\mu_c = 0.13eV$, the corresponding gate voltage $V_g = 98.6V$. Under the same conditions, we can calculate to get the gate voltage $V_g = 101V$. From here we can verify that our calculation consists of the reference paper results. Therefore, we can conclude that the chemical potential can be changed by varying the applied gate voltage, which further impacts the conductivity of graphene. The tunability of graphene’s conductivity controlled by the gate voltage is one of the key properties of graphene, which is vital for the application of many new types of the reconfigurable devices.
### 3.2.2 Tunability of graphene’s conductivity affected by the frequency

In the application area, the working frequency of graphene devices is one the important factors that people are concerned. For this concerning, we need to discuss the effect of different frequency fields on the graphene’s conductivity.

In the different frequency fields, the intraband and interband of graphene contribute differently to the conductivity, which includes the real part and imaginary part. Now we assume $T = 300K$ and $\Gamma = 0.11meV$, then the response of graphene’s conductivity to the chemical potential under different frequency points are presented in Figure 3.5. The conductivity here is expressed as: $\sigma = \sigma_{\text{int, a}} + \sigma_{\text{int, e}}, \quad \sigma_{\text{int, a}} = \sigma'_{\text{int, a}} + i\sigma''_{\text{int, a}}, \quad \sigma_{\text{int, e}} = \sigma'_{\text{int, e}} + i\sigma''_{\text{int, e}}.$

In the application area, the working frequency of graphene devices is one the important factors that people are concerned. For this concerning we need to discuss the effect of different frequency fields on the graphene’s conductivity.

We need to mention that the conductivity in Figure 3.5 is actually the surface conductivity, and the bulk conductivity of graphene can be derived from the surface conductivity over the thickness of graphene: $\sigma_{3D} = \sigma_{2D}/\Delta$, where $\Delta$ is the thickness of graphene. From Figure 3.5 we can conclude that:

(a) At lower frequencies ($f < 1\text{THz}$), the intraband contribution of graphene dominates to the conductivity. Compared with the interband contribution, there is a difference up to several orders of magnitude. Thus, the interband conductivity is negligible.

(b) As the frequency increases, the interband contribution becomes comparable to, or even more than the intraband contribution of graphene to the conductivity. In this region, we need to take into account the influence of the interband conductivity.

(c) When the frequency is further increased ($f > 100\text{THz}$), we can only consider the contribution of the interband conductivity of graphene, ignoring the intraband contributions.
(d) Either for the interband conductivity or the intraband conductivity, the imaginary part of the conductivity of graphene becomes dominated as the frequency increases. When the frequency goes beyond 1THz, we can only consider the impact of the imaginary part of the conductivity of graphene and ignore the real part.

Based on the conclusions above, when our study is concerned on the microwave or millimeter wave band characteristics of our study graphene, we can only consider the intraband conductivity of graphene. In this way, the conductivity can be simplified as Equation (3.2), which is quite straightforward.

Figure 3.5: The relationship between the graphene’s conductivity and the chemical potential under different frequency points when $T = 300K$ and $\Gamma = 0.11meV$. 
3.2.3 Tunability of graphene’s conductivity affected by the magnetic field

In many cases, the conductivity of graphene in the nanophotonic devices electrically controlled (e.g. the gate voltage) also involves the impact of the interaction interface between the electrodes and the graphene [69]. In addition, with the Fermi energy of graphene goes up, we also need to consider its nonlinear electronic band structure [70].

For controlling graphene plasmons, an alternative way is to apply an external static magnetic field. The electrons’ small cyclotron mass and relatively low concentrations of graphene are affected by the external magnetic field [71]. The plasmon modes of graphene have been demonstrated in the applied magnetic field [72]. Large Faraday rotation has also been predicted in arrays of graphene microribbons through the excitation of the magnetoplasmons of individual ribbons [73]. Compared with the tunability of graphene controlled by the electrical method, applying the static magnetic field to the graphene microstructure gets rid of the direct electrical contact to tune its optical response.

Now we assume that the static magnetic field is perpendicular to the graphene plane, then the tensor of graphene’s permittivity can be expressed as [74]:

\[
\varepsilon_8 = 1 + \frac{i}{\omega \varepsilon_0} \begin{pmatrix}
\sigma_{xx} & \sigma_{xy} & 0 \\
-\sigma_{xx} & \sigma_{yy} & 0 \\
0 & 0 & \sigma_d
\end{pmatrix}
\]

(3.21)

where \( t \) is the thickness of graphene in the \( z \) direction set as 0.5 nm, and \( \varepsilon_0 \) is vacuum permittivity. The value of \( \sigma_d \) keeps the same, which is independent of the external magnetic field \( \sigma_d = \sigma_{xx}(B = 0) \). Thus we can derive the graphene’s conductivity tensor written as [75]:

\[
\sigma_{xx} = \sigma_{yy} = \frac{e^2 |E_f|}{\pi \hbar^2} \frac{i(\omega + i/\tau)}{(\omega + i/\tau)^2 - \omega_c^2}
\]

(3.22)

\[
\sigma_{xy} = -\sigma_{yx} = \frac{e^2 |E_f|}{\pi \hbar^2} \frac{\omega}{(\omega + i/\tau)^2 - \omega_c^2}
\]

(3.23)
where \( E_f \) is the Fermi level, and \( \tau \) is the relaxation time \( \tau = \mu E_f / eV_f^2 \) is the intrinsic relaxation time with carrier density \( \mu = 10^5 \text{ cm}^2/\text{V.s} \). \( \omega_c = eBV_f^2/E_f \) is the angular frequency of the collision frequency of electrons. \( v_F \) is the Fermi velocity of graphene, normally as \( 10^6 \text{ m/s} \).

The simulation model is built using the finite element method (FEM) method in CST MW Studio 2015. Figure 3.6 shows the simulation results of the real and imaginary parts of graphene under the external magnetic field from 0 T to 10 T with Fermi energy of 0.1 eV and 0.3 eV.

![Simulation results](image)

**Figure 3.6:** The spectra of the real part of graphene's permittivity ((a)and (c) \( \varepsilon_{xx} \), (b)and (d) \( \varepsilon_{xy} \)) under the external magnetic fields \( B=0 \text{ T}, 4 \text{ T}, 8 \text{ T}, \text{ and } 10 \text{ T} \) with the chemical potential (a)and (b) 0.1 eV, (c)and (d) 0.3 eV.

The Figure 3.6 (a) and Figure 3.6 (b) show that when the chemical potential is 0.1 eV graphene is strongly dependent on the change of the external magnetic fields. Especially the real part of \( \varepsilon_{xx} \), which changes from negative values into positive ones under \( B= 8 \text{T}, \text{ and } 10 \text{T} \). For the real part of \( \varepsilon_{xy} \), it also reaches the maximum value at the similar wavelength points. On the other hand, as the chemical potential increases, the dependence between the
permittivity and the external magnetic field is weakened. As shown in the Figure 3.6 (c) and Figure 3.6 (d), the chemical potential is 0.3 eV, and the real part values of $\varepsilon_{xx}$ and $\varepsilon_{xy}$ keep the nonlinear increase in the negative area and positive area, respectively. However, the external magnetic field still has an influence on the permittivity when varying from 0 T to 10 T.

To further investigate influence of the external magnetic field on the graphene microstructure, the parameter setting of graphene in CST can be achieved using the dielectric dispersion fit in the isotropic form (Figure 3.7). With different datasheets imported, we can simulate the graphene nanophotonic devices with different external magnetic fields.

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**Figure 3.7:** The parameter setting of graphene in CST dielectric dispersion fit in the isotropic form under the external magnetic fields $B=0$ T with the chemical potential 0.1 eV.
Chapter 4 Electromagnetic Modelling Simulations of Graphene Based Passive Devices

These days, researchers have gained very good result in the fields such as bipolar transistor effect, quantum oscillation and the ballistic transport. On the other hand, the research of graphene’s application on the passive guided devices is still in its infancy. Section 2.2 has already reviewed the achievement published by other scientists and this chapter would like to propose our novel design for a series of types of graphene based passive devices. By analyzing the simulation results of these devices, we could make the determination for the designs worthy fabrication and measurement.

This chapter is organized as follows. In section 4.1, a triple-band graphene absorber is proposed. In section 4.2, the research on the graphene transmission line is conducted with the tenability of graphene applied. The graphene antennas are simulated in section 4.3. The section 4.4 in Chapter 4 includes the design of a RF graphene switch controlled by the external gate voltage, which achieves a novel reconfigurable antenna at the microwave frequency region in the last section.

4.1 Simulations of the Graphene THz Triple-band Metamaterial Absorber

4.1.1 Simulations of the graphene triple-band metamaterial absorber
To begin, we first recall briefly some fundamentals and principle physics that have been established for metal-dielectricmetal metamaterial absorbers (MA). To date, several theoretical approaches attempting to illustrate the underlying physics have been reported, including the excitation of the localized EM resonance, TL circuit model analysis, Fabry-
Pérot resonance, cavity resonance, and interference theory. Despite these progressive developments, this issue is still under debate. In this regard, we do not address this issue but focus on identifying a specific region associated with specific operating frequencies, which is the main concentration in this work and which is extremely essential for independent control and flexible design. Here, we will follow the mostly accepted absorption mechanism by relating multiband impedance matching to simultaneous electric and magnetic resonances and use the TL theory to further validate the specific localized resonances that have been drawn from the field analysis. It will be demonstrated that the conclusions drawn from these two approaches are reasonably consistent. These approaches are rational, based on the fundamental aspect that the proposed element is electrically very small, which enables the resulting periodical structure to be appropriately described as an effective bulk medium.

A typical triple-band absorber is a sandwiched structure composed of three layers. The back layer is normally a metallic thick plane as the ground and the front layer is commonly made of periodically patterned metallic subwavelength electric resonators. A dielectric middle layer is put between the two metallic layers. For the front metallic layer, its structure with appropriate dimensions can be defined through an equivalent TL circuit model analysis shown in Figure 4.1.

Figure 4.1 Equivalent TL circuit model of proposed MA with three resonant frequencies.
In Figure 4.1, we assume that both the higher-order resonance of the interdigital capacitors and the parasitic resonances of additional structures can be neglected. Given that the ground back layer transmission can be neglected, a single port system is adequate. $L_s$ and $L_m$ are the self-inductance. $Z_{ei}$ is the equivalent impedance and $d_i$ is the electrical length of TL. The back layer of MA is also presented in Figure 4.1 as the ground. The two side inductors, a parallel tank with two subring inductors as each branch, and two interdigital capacitors define the fundamental first resonant frequency $f_1$ as

$$f_1 = \frac{1}{2\pi\sqrt{(2L_m + L_s)C_i}}$$

The coupling efficient modeling the edge effect of two side interdigitals of $k_1$ and $k_2$, and two identical branches, where there are two $L_s$, one $C_i$, a coupling capacitor $k_1 C_i (0 < k_1 < 1)$, and a coupling inductor $k_2 L_s (0 < k_2 < 1)$ at both ends, respectively contribute to the second resonant frequency $f_2$. Therefore $f_2$ can be represented as

$$f_2 = \frac{1}{2\pi\sqrt{[2(k_1/L_1 + 1)](k_2/2 + 1)L_s C_i}}$$

Similarly, the third resonant frequency can be calculated as $f_3 = \frac{1}{2\pi\sqrt{L_s C_i / 2}}$.

To engineer a triple-band absorber with three arbitrary resonant frequencies, the capacitance and inductance can be tuned, which makes a nearly unity absorptivity achievable. One way of implement is properly adjusting the front and substrate layer with constant thickness and dielectric constant, and back ground layer to be equivalent. Such a design can modulate the electric and magnetic resonances to coincide at the same frequency, resulting in an impedance-matched absorber with free space. Moreover, because of the shielding of the back ground layer, no transmission ($S_{21} = 0$) exists in a MA through the whole frequency range, which makes nearly unity absorption of incident waves achieved.
The design procedure can be divided into three steps.

1) Derive and adopt the equivalent circuit model in the circuit simulator advanced design system (ADS). Calculate groups of possible L, C, and R based on the target operating frequencies and other electrical characteristics (e.g. bandwidth and absorptive efficiency), using TL analysis and a refined optimization in ADS.

2) Select a prescription from the possible solutions and guarantee that the lumped elements are accessible through standard printed circuit board (PCB) technology. Synthesize a rough physical layout based on the analytic equations from circuit elements.

3) Optimize the draft layout in the EM simulator in order to achieve maximized absorption at specific frequencies.

Following the design procedures shown above, we can engineer the proposed graphene MA in Figure 4.2. To characterize, the unit cell template in CST is chosen associated with the Floquet boundary conditions. The frequency domain solver is used. The dielectric substrate is made of F4B, which has the dielectric constant of 2.65 and loss tangent of 0.002. The thickness of the substrate is 0.03mm. The material used to build the front layer is graphene under the chemical potential of 0.5 eV, which is set as the ohmic sheet 50 Ω/□ and the thickness of 0.34 nm. Figure 4.2 shows the optimized dimensions of proposed MA: a = 106 µm, b = 50 µm, l = 24 µm, w = 12 µm, \(d_1 = 2\) µm, \(d_2 = 3\) µm, and \(d_3 = 13.2\) µm, where a transverse electromagnetic (TEM) wave is supported. In this paper, four subrings with self-inductance \(L_s\) are put on the dielectric plane and four capacitors \(C_i\) are loaded respectively into the concaves formed by each two subrings. Four meandered arms with the self-inductance \(L_m\) are connected with each capacitor. In this way, the neighboring unit cells are also connected.
Figure 4.2 The structure of the triple-band graphene metamaterial absorber (0.4 eV chemical potential applied to graphene in this structure).

To test the performance of proposed MA, we use the structure and dimension setup in Figure 4.2 and get the numerical simulation result Figure 4.3 in CST. It can be obviously observed that three resonance peaks exist at frequency $f_1 = 0.22$ THz, $f_2 = 0.68$ THz, $f_3 = 1.13$ THz respectively. The material’s dielectric constant of the substrate affects the absorptivity of MA. Higher absorption rates can be reached by choosing the substrate with higher dielectric loss. In addition, we can also improve the resonance by increasing the chemical potential of graphene, which makes graphene functioned more metal-like. Once off the resonant frequencies, the absorption rate becomes very low. This frequency-sensitive feature of proposed MA can be applied in many areas such as spectrum filters and bolometric pixel elements.
4.1.2 Simulations of multi-layer triple-band metamaterial absorber

Although the absorbers in the subsection 4.1.1 can be tuned and optimized to achieve comparably high absorptivity, polarization insensitivity, and wide angles of incidence, most of them are confined to the only few-band absorption response, there is still a lack of sufficient progress toward the design and implementation of multiband (>3) MAs. A solution for this is to place the triple-band metamaterial absorber in a stack. Two layers and Three layers in a stack are designed and simulated. Figure 4.4 and Figure 4.5 show the layout of the two layers and three layers triple-band metamaterial absorber, respectively.
Figure 4.4  Two layers triple-band THz metamaterial absorber simulation setup in CST (perspective view). The front layer has the thickness of the substrate $t_h = 15 \, \mu m$ and the front layer has the thickness of the substrate $t_b = 30 \, \mu m$.

Figure 4.5 Three layers triple-band THz metamaterial absorber simulation setup in CST (perspective view). Each layer has the same thickness of the substrate $t = 30 \, \mu m$.

In Figure 4.6 and Figure 4.7, six absorption peaks and nine absorption peaks below -10 dB are show, respectively, which demonstrates the feasibility of designing a multi-band THz metamaterial absorber in the method of stacking. Further work on this direction is expected.
4.2 Simulations of the CPW transmission line using the graphene sheet

This section presents the design of a tunable transmission line with under-layer graphene, where its transmission properties can be adjusted electrically. Its tenability comes from the varying conductivity of graphene biased by external voltage. The forward transmission varies more than 60% when voltage is applied to change chemical potential in the range 0-0.8eV. The promising results provide an alternative using graphene for tunable transmission lines.

The coplanar waveguide (CPW) with the graphene center is shown in Figure 4.8. The structure is built on 200μm thick Gallium Arsenide substrate, with 80μm signal trace width and 53μm gap between signal and ground traces on each end of the line having characteristic impedance around 50Ω. In the middle of the line, step taper structure is used for impedance matching purpose to reduce the reflection. In the middle the signal electrode width is 190μm and 78μm gap, and in the center of the signal electrode, a 30μm
gap filled with 1um thickness of gold, below is 0.3um polyimide, and graphene sheet is laid under the polyimide layer. Graphene is connected with one side of the electrode to build the transistor structure. External voltage is applied between both sides of signal electrode to tune the conductivity of graphene. Full-wave electromagnetic simulation using CST 2012 is performed in the frequency range 0-110GHz.

Figure 4.8 (a)The structure model of the constructed CPW TL with graphene under-layer and its dimentions (b)The transistor strcture in the centre of the signal electrode.
The magnitude of measured transmission $S_{12}$ over the frequency range 0–110 GHz under 0, 0.2, 0.4 and 0.8 eV, respectively.

The simulation results of $S_{21}$ of the constructed model using CST Microwave Studio is shown in Figure 4.9. The tunability of the designed transmission line can be observed, the $S_{21}$ increases with higher chemical potential, namely the applied voltage; With $U_c = 0.4$ eV, the transmission is above -3dB and $U_c = 0.8eV$, the transmission is around -1.5dB which is acceptable loss in transmission line. It can be seen that without applied external voltage, i.e. under 0-ev chemical potential, the $S_{21}$ curve shows a different tendency from the results with applied voltage; The $S_{21}$ increases with frequency in the case voltage is applied while the parallel impedance of the add-in capacitance of the transistor structure is considered to be much smaller. Parallelism in $S_{21}$ is observed when voltage is applied. Only 1dB change is observed for all curves over 0- 110GHz due to the fact that the surface resistivity of graphene is with negligible changes over frequencies.

4.3 Simulations of the Reconfigurable Terahertz Patch Slot Antenna Based On Graphene with Metamaterial Structures

In this section, graphene terahertz (THz) patch slot antenna is proposed and analyzed. The
reconfigurable resonance of the graphene is investigated for efficient THz radiation. Thanks to graphene unique electric band structure, the two-dimensional (2D) graphene is modeled by the complex surface conductivity at THz. The proposed antenna is loaded with a reactive impedance surface (RIS), which significantly reduces the size of the antenna. It has the reconfigurable resonance from 1.56 THz to 1.6 THz with the applied external DC voltage and radiation efficiency over 75% around the central frequency of 1.562 THz. Parametric study on the antenna performance with the material properties have been carried out. The results reveal that the graphene-based antenna can find its applications for future graphene multi Terabit wireless data transmission and transparent all-graphene THz sensing systems.

The design and geometry of the proposed patch slot antenna is shown in Figure 4.10. A coaxial probe feeding is adopted. The patch surface on the top is copper. The slot and the four short-circuiting stubs are graphene. In this way graphene can act as the extension of the copper patch antenna, and therefore, change the resonant frequency by applying DC bias. A 11 by 11 array of RIS using copper is located under the patch slot surface. The RIS array is coated as a sandwiched structure, where the upper layer is the silicon dioxide with the thickness of 300 nm and the lower layer has a dielectric constant of 4.02 with the loss tangent of 0.009. The thickness of the lower substrate is 2600 nm. The ground plane is copper as well, following after the lower substrate. Figure 4.10(a) shows the optimized dimensions of proposed antenna: a1 = 5.4 μm, a2 = 6.2 μm, h1 = 0.4 μm, h2 = 2.6 μm, l1 = 3.05 μm, and w1 = 3.05 μm. The thickness of copper is 40 nm and the width of the gap between the patch and the slot is 0.8 μm. Figure 4.10(b) shows the side view of the layout of the proposed antenna, where a transverse electromagnetic (TEM) wave is supported.

The gate voltage applied is determined by the thickness of the isolation layer silicon dioxide between the graphene slot and the copper RIS. When reducing the thickness of silicon dioxide, the gate voltage required decreases correspondingly.
To test the performance of proposed patch slot antenna, we use the structure and dimension setup in Figure 4.10 and get the numerical simulation result Figure 4.11 in CST.

The reflection coefficient of the graphene patch slot antenna with a 11 by 11 array of RIS and without RIS are shown in Figure 4. In the case that without RIS, the -10 dB return loss bandwidth is from 1.61 THz to 1.66 THz and the minimum return loss is located at 1.64 THz with the value of -39.2 dB. In the case that with RIS, the resonant frequency shifts towards lower frequency band. The -10 dB return loss bandwidth moves to from 1.54 THz to 1.58 THz. The bandwidth seems less sensitive to the applied RIS structure although the return loss seems having degraded. The fact that the resonant frequency of the proposed antenna can be lowered by applying the RIS structures provides an efficient
way to realize the design of the miniaturized THz antenna.

To study how the external DC voltage can affect the resonant frequency of the proposed graphene patch slot antenna, we vary the chemical potential of graphene in the slot and four short-circuiting stubs. Then we compare the simulation results of the proposed antenna under the different chemical potential that shown in Figure 4.12.

It can be obviously observed that four resonant peaks occur at frequency $1f = 1.562\text{THz}$, $2f = 1.58\text{THz}$, $3f = 1.585\text{THz}$ and $4f = 1.6\text{THz}$ respectively with $c\square$ of $0.8\text{eV}$, $0.2\text{eV}$, $0.1\text{eV}$ and $0\text{eV}$. In the case that applying a low DC bias such as $0\text{eV}$ and $0.2\text{eV}$, the resonant peaks appear at $1.6\text{THz}$ and $1.585\text{THz}$, which are mainly affected by the size of the patch unit. When the applied DC bias increases such as $0.2\text{eV}$ and $0.8\text{eV}$, the graphene acts more metallic, which allows more current flow through the slot. In this case, the electrical length under higher chemical potential ($0.8\text{eV}$) is longer than the one under lower chemical potential ($0\text{eV}$), which causes the resonant frequency lower. On the other hand, when the applied DC bias decreases, for example, the chemical potential changes from $0.8\text{eV}$ to $0\text{eV}$, Figure 5 shows the degraded minimum value of the resonant peak. This is due to the lossy performance of graphene when unbiased. In this case, the proposed patch slot antenna acts more like a single patch antenna since nearly all the current flow in the central patch unit.

![Figure 4.11](image)

*Figure 4.11 Magnitude of reflection ($S_{11}$) of the proposed graphene patch slot*
antenna with and without RIS.

Figure 4.12 Magnitude of reflection (S11) of the proposed graphene patch slot antenna under different chemical potentials.

4.4 Simulations of A Graphene-based Electromagnetic Switch at Microwave Frequencies

In this section, the concept, design, and analysis of a graphene based switch at microwave frequencies are presented. Switching is achieved by using graphene’s tunable conductivity to allow good transmission or high reflection, respectively. The structure of the proposed switch is modeled as a coplanar waveguide transmission line in the CST Microwave Studio 2015. The performance of the switch’s on and off state is evaluated. With combining with other passive guided devices, the graphene based RF switch can find a lot of applications in developing guided graphene-based devices at microwave frequencies.

The design and geometry of the proposed switch is shown in Figure 4.13. A CPW transmission line structure is adopted as the source, grain and top gate of graphene stripes. Between the GaAs substrate and the silicon dioxide layer, one layer of gold electrodes is deposited as the bottom gate. In this way graphene can be applied a DC bias, which acts as
the essential part of on/off state. To reduce the required gate voltage level, the thickness of the silicon dioxide is changed from the standard 300 nm to 20 nm. The thickness of the bottom gold electrodes is 40 nm and the top transmission line is 100 nm.

Figure 4.13 (a) shows the optimized dimensions of proposed switch: \(a = 1400 \text{ μm}, b = 600 \text{ μm}, a_1 = 200 \text{ μm}, s = 80 \text{ μm}, g = 53 \text{ μm}, \) and \(w = 60 \text{ μm}.\) The thickness of graphene is 0.34 nm and the width of the gap in the center position is 87.5 μm. Figure 4.13 (b) shows the side view of the layout of the proposed switch.

To test the performance of proposed switch, we use the structure and dimension setup in Figure 4.13 and get the numerical simulation result Figure 4.14 in CST. The reflection coefficient \(S_{11}\) and transmission coefficient \(S_{21}\) of the graphene switch are shown in Figure 4.14. In the case of the off state, the minimum value of the transmission coefficient is -18.2 dB. In the case of the on state, the insertion loss is 1.4 dB at low frequencies and increases to around 3 dB at higher frequencies. The reflection becomes very obvious in the off state when the graphene is applied by the DC bias voltage. On the other hand, the transmission dominates in the on state when the graphene unbiased. The difference between the on and off state can be enhanced by applying the higher gate voltage. In this structure, the chemical potential of graphene in the off state is 0.2 eV, that is, around 24 V as a gate voltage.
Figure 4.13 The structure of the graphene-based switch: (a) top view and (b) side view.

Figure 4.14 Magnitude of reflection ($S_{11}$) and transmission ($S_{21}$) of the proposed graphene switch with on/off state.
4.5 Simulations of the Reconfigurable Monopole Antenna Based on a Graphene at Microwave Frequencies

As mentioned at the beginning of this chapter, we can combine a common monopole antenna with the RF graphene based switch at microwave frequencies that proposed in section 4.4. In this way we can easily build a reconfigurable monopole antenna based on graphene.

The structure of the proposed tunable antenna is shown in Figure 4.15. As shown the main part is a common CPW monopole antenna made of gold placed on the isolation SiO$_2$ layer. Under the isolation layer, a GaAs substrate is located. The structural parameters of the antenna are shown as follows, $w=0.42$ mm, and $l=2.26$ mm.

![Figure 4.15 Structure top view of the CPW monopole antenna connected to a graphene-based switch.](image)

To test the performance of the proposed switchable antenna, we use the structure and dimension setup in Figure 4.15 and get the numerical simulation result Figure 4.16 in
CST.

The reflection coefficient S11 of the proposed monopole antenna connected to the graphene switch is shown in Figure 4.16. In the case of the off state, the reflection coefficient of the proposed antenna easily reaches the maximum value, which is close to 0 dB. In the case of the on state, there is an obvious resonance peak at 18.2 GHz with the minimum value of -32.4 dB at the peak frequency point. The off state is achieved when the graphene is applied by the DC bias voltage. On the contrary, the antenna works normally in the on state when the graphene unbiased. The difference between the on and off state can be enhanced by applying the higher gate voltage. In this structure, the chemical potential of graphene in the off state is 0.2 eV, that is, around 24 V as a gate voltage.

![Figure 4.16 Magnitude of reflection (S11) of the proposed monopole antenna connected to the graphene switch with on state.](image)

The radiation patterns of the antenna at $\theta = 0^\circ$ and $\phi = 90^\circ$ are illustrated in Figure 4.17 (a) and (b), respectively. The frequency of interest is at 17.5 GHz, where the return loss is -32.3 dB. It can be seen that the graphene antenna has demonstrated very good omnidirectional radiation patterns. Both the gain and radiation efficiency reach the maximum values of 3.05 dBi and 60.8% respectively around the center resonant frequency.
frequency of 17.5 GHz, then decrease in the other frequencies. We need to mention that the low radiation efficiency here is caused by the insertion loss of the graphene switch, which is -2 dB at 17.5 GHz. In other words, only 63% power has been transmitted into the gold antenna.

![Radiation patterns](image)

(a)  
(b)

*Figure 4.17 Radiation patterns of the proposed monopole antenna connected to the graphene switch with on state at 17.5 GHz in terms of (a) H-plane, (b) E-plane.*
Chapter 5 Device Fabrication

Device fabrication is a critical step to investigate the physical properties and electrical properties of graphene based devices. Based on the different performance expectations for graphene devices, a large amount of variable factors need to be considered in the device fabrication process. Taking the limit to working frequency of graphene based passive devices into account, exfoliated graphene is given up. Chemical Vapor Deposition (CVD) graphene is adapted in the fabrication.

The whole fabrication process of graphene based passive devices is divided into three stages. In fact, each stage involves in the huge amount of equipment, material and sample treatment. However, each main stages can be viewed as the partial success of the final devices. Even the fabrication requirements for different graphene based passive devices differ, the fabrication could be completed effectively and efficiently. These three stages are: section 5.1 - the preparation of graphene, section 5.2 - flake transfer, and section 5.3 - lithography. Each stage requires a lot of small steps, which will be detailed introduced in each section.

5.1 Preparation of Graphene

Graphene has a unique structure and excellent performance in recent years in chemistry, physics and materials research, which attracted the wide interests. The preparation of graphene has made a lot of progress and there are many methods for preparing graphene, which can be divided into the physical and chemical categories. Physical methods usually
use inexpensive graphite or expanded graphite as raw materials with mechanical cleavage, epitaxy method [88, 89]. These methods easily obtain raw materials and the operation is relatively simple.

For the chemical method, graphite oxide reduction becomes the most potential and promising method [90]. In addition, chemical vapor deposition (CVD) and epitaxial growth method can also be used for large-scale production of high purity graphene [91]. Although CVD graphene has been commonly used for the research activities, the significance of mechanical cleavage method still dominates. Even CVD is chosen to fabricate our graphene based passive devices due to the size issue, the outstanding physical properties make exfoliated graphene worthy being introduced here.

5.1.1 Wafer cleaning

The silicon wafer needs to be cleaned before the graphene flake taping on the top. Firstly, the wafer is put into acetone and isopropyl alcohol so that the large particles could be removed. This step may take 20 minutes in an ultrasonic machine. After that, O2/Ar plasma will be used to clean the remaining organic residue. The purpose of this step is to strengthen the adhesion of graphene flake to the silicon wafer.

5.1.2 First peel from graphite

First, we need to prepare some tapes ready for putting the bulk graphite on. The tapes are specially chosen with the properties of high tack and low stain. Slowly locate the bulk graphene on the tape, then use the tweezer to generally moved from the tape. It is easy to find some shining pieces left on the tape, which are much smaller than the bulk graphite. We call this step as first peeling. Keep repeating this step until enough area of graphite
pieces covered the whole silicon wafer. Figure 5.1 shows the steps included in the whole process of mechanical cleavage.

![Figure 5.1: The procedure of mechanical cleavage for graphene.](image)

5.1.3 Tape removal

As mentioned in the subsection 5.1.1, the surface of silicon wafer should be clean enough to enhance the adhesion of graphene to the substrate. So O2/Ar plasma is used in the cleaning step, which requires us to press the first peeled tape on the clean wafer soon after the cleaning step finished. The tape should be firmly pressed on the substrate until all the graphite pieces fully grown on top.

5.1.4 Second peel from the tape

The first peel is far way enough to let us obtain graphene. The graphite pieces still need the second peel after removing the tape. Before the tape removal, the sample will be baked
with the temperature of 105 degrees. The baking time should be more 10 minutes, which is beneficial for moving water molecules contained away and increasing adhesion of graphite pieces. The tape should be removed in the MIBK solution, which is quite helpful to obtain the large size graphene. The second feeling is undertaken with a low angle method using the same type of tape. After that, the identification of graphene can be achieved by optical microscopy. We will discuss of these characterization techniques later in Chapter 6.

5.1.5 Requirements for graphene flakes

Figure 5.2 Photos captured of graphene flake with different drawbacks: (a) Size of flake is not big enough; (b) The edge of flake is scrolled; (c) The flake is surrounded by the graphite piece. Only the graphene flake in (d) satisfies all the requirements.

With the purpose of fabricating graphene based passive devices, the size of graphene flakes is always the most urgent requirement. Unlike CVD graphene, the mechanical cleavage method traps exfoliated graphene with the size issue. Normally, the size of exfoliate graphene cannot beyond 1mm by 1mm in the clean room. However, there are
some other factors also impact the choosing of graphene flakes. One scrolling graphene flake with even a large size is possibly a bad choice since it is much easier to be damaged by photoresist in fabrication. The last factor is the graphene flake surrounded by the thick graphite piece. This type of graphene always brings in more work to get rid of graphite in fabrication.

5.2 Flake Transfer

Due to the design considerations, sometimes we need to transfer the graphene flake from the original substrate onto the other one. For the graphene based passive devices, there are plenty of choices for the substrate as long as they are flat enough.

Up to now, there are two popular transfer methods that often in use, that is, wet transfer and dry transfer. We can easily understand that the wet transfer method should involves the chemical solutions. As for the dry transfer, since no chemical contamination imported in the transfer process, the possibility of chemical residue on the surface of graphene flake is zero.

![Figure 5.3 The illustration of wet transfer process of the graphene flake from Si substrate to GaAs substrate. There are 7 steps included in this process: (i) target graphene flake (ii) PMMA layer coating (iii) applying window tape (iv) SiO2 etching (v) graphene flake separation (vi) baking and (vii) PMMA removal.](image-url)
Dry transfer method is rarely used in the fabrication process of graphene passive devices, so we will only give a brief introduction in the subsection 5.2.2.

5.2.1 Wet-transfer technique

Wet transfer method is taken when fabricating graphene based devices on the GaAs substrate, which is not as lossy as the standard silicon substrate in the RF measurement conducted in Chapter 7.

Figure 5.3 is the illustration of wet transfer process of the graphene flake from Si substrate to GaAs substrate. There are 7 steps included in this process: (i) target graphene flake (ii) PMMA layer coating (iii) applying window tape (iv) SiO2 etching (v) graphene flake separation (vi) baking and (vii) PMMA removal.

5.2.1.1 The preparation of the PMMA membranes

PMMA is really a good choice that the film it formed is robust enough. With the high adhesion to graphene, PMMA is also easy to be removed from graphene. As shown in Figure 5.4, so when we are trying to transfer graphene to another substrate, the window tape together with the target graphene are all on the PMMA membrane.
As shown in Figure 5.5, it is the illustration of the graphene membrane preparation process: After the whole sample coated with PMMA, we will locate the window tape on top of the target graphene. To make sure that the PMMA membrane could separate from the surrounding coating, and in the last step, we will the sharp tweezer to scratch out along the edge of the window tape. In this way, after one night (at least four hours for KOH reacting with SiO2), the PMMA membrane on the tape automatically separates from the Si substrate in KOH.
Figure 5.5 Illustration of the graphene membrane preparation process: (a) coated with PMMA, (b) locate the window tape on top of the target graphene, (c) separation PMMA membrane from the surrounding coating, and (d) PMMA membrane on the tape separates from the substrate in KOH after one night.

5.2.1.2 Mask aligner

The common use of one mask aligner is quite different from we will do for PMMA membrane locating. Lithography / UV Exposure Machine, this is just what we called as Mask Aligner here, generally helps to transfer the pattern on the mask onto the photoresist during the photolithography. In this process, the pattern such as device or circuit configuration is temporarily "Copy" to the surface of silicon wafers. However, for the membrane locating, only a few components of the mask aligner will be involved. All the components needed are marked in Figure 5.6: the objective lens, the tape window holder and the movable stage.

The whole transfer procedures are described as follows: Put the tape window on the tape
holder, which is a steel disk with a hole in the center. The PMMA membrane together with the window tape should just cover the hole. Then turn over the holder disk and let the PMMA membrane facing to the side of the target substrate. Moving down the holder to the stage with the target substrate on, the situation of membrane can be observed from the objective lens. The observation in the lens will help us to confirm the contact situation between the membrane and the target substrate. The detailed procedure can be found in Figure 5.7.

Figure 5.6 Components involved in the PMMA membrane locating process of the MJB4 Mask Aligner: (a) and (b) are the same images of the side view of the mask aligner but with different components marked. From top to the bottom, there are objective lens(observing the location of PMMA membrane), tape window holder (the window tape with PMMA membrane will be put on) and the movable stage(adjust the target substrate close to PMMA membrane). (c)A PMMA membrane has been put on the center of the holder disk.
Figure 5.7 Illustration of locating the PMMA membrane towards the target substrate under the objective lens. (i) Lens position adjusting, (ii) coarse stage adjusting, (iii) fine stage adjusting and (iv) stage lifting.

After the PMMA membrane transferred onto the new substrate, at least 10 minutes baking is essential. This step is to make sure the membrane tightly grown on the new substrate. Then PMMA will be removed in acetone.

5.2.2 Dry transfer

The dry transfer method is significantly different from the wet transfer. The KOH solution used in wet transfer to react with SiO2 is definitely denied in the dry transfer. An illustration of procedures of dry transfer is shown in Figure 5.8.

The graphene flake ready for transfer are grown on the Si substrate with bilayer coating: PMMA and PMGI. Use the sharp tweezer to scratch on the two layers on top to separate the window tape from surrounding coatings. Then the PMGI layer will be dissolved in MF-319 and the PMMA membrane float automatically. In the fishing step, a metal ring is used to pick up PMMA membrane out of DI water and locate it on the target substrate with mask aligner. After baking and PMMA dissolving steps, the graphene flake has been transferred onto the BN substrate.
Figure 5.8 The illustration of dry transfer process of the graphene flake from Si substrate to Si/BN substrate. There are 8 steps included in this process: (i) target graphene flake (ii) PMMAPMGİ bilayer coating (iii) dissolving PMGI (iv) floating the membrane (v) metal ring fishing (vi) PMMA scratching (vii) baking and (viii) PMMA removal.

5.3 The Lithography

The lithography is a quite critical part especially for fabricating graphene based passive devices.

The lithography may be required several times in the fabrication up to the structure of the fabricated device. There are two main types of lithography frequently required in the process: the alignment cross and the metal structure. Both of these two steps are undertaken with the laser writer, which could figure out the minimum size of 1 um. This precision is more than enough to the dimension of our devices.
5.3.1 Alignment crosses

Coping with such tiny size of graphene in the lithography is really a challenge, compared with the dimensions of the metal structure in graphene passive devices. Considering the requirement for accurate positioning, drawing alignment crosses is the best choice. Before starting the lithography, we need to pay attention to the photoresist lift-off.

5.3.1.1 Photoresist Lift-off

The most popular choice in our clean room for the photoresist coating is the bilayer photoresist. To understand why the two layers of photoresist are necessary, we compare the bilayer method with the single layer method. The different results in lift-off is presented in Figure 5.9. From this figure, we can clearly find the advantages of bilayer photoresist, which shows the perfect lift-off eventually. On the contrary, the rabbit-ear sidewalls are left in the single layer method.

5.3.1.2 Photoresist coating

The common choice for the bilayer photoresist is PMGI/PMMA. The main consideration when choosing the photoresist is the sensitivity to the UV light of laser writer. The bottom photoresist should be more active to the UV light than the top one. Thus, PMGI is first coated and PMMA follows. After finishing the whole coating process, the sample normally needs baking for 1 minute at 105 degrees.
5.3.1.3 Patterning alignment crosses

A square or rectangular shape of 4 by 4 or 6 by 6 alignment crosses are the most popular pattern. All the alignment crosses are surrounding the target graphene flake in the center. The distance between each cross should be decided according to the size of graphene, which is also applied to the crosses’ size. The metal used for the crosses is gold and the thickness deposited should be no less than 40 nm. In Figure 5.10, the 6 by 6 alignment crosses are deposited surrounding the graphene flake with distance between each other 100 um.

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Figure 5.9 Difference in lift-off between the bilayer photoresist method and the single layer method.
5.3.2 Fabricating metal structures

When fabricating the metal structures, the two steps of both patterning and metal deposition are requirement. The common metal we use is gold since it has low contact resistance with gold and high conductivity itself [92, 93]. Besides, one layer of 8 nm Cr is also required. The Figure 5.11 is one photo of the graphene transmission line after developing in MF-319. We can see that very clean and clear patterning is achieved. The performance of this graphene based transmission line will be discussed in Chapter 7.
Figure 5.11  Photos of the graphene based transmission line after developing. Very clean and clear lithography is achieved.
Chapter 6 Characterization techniques and Experiments Descriptions

Various characterization techniques are required in the fabrication process, and the measurement process. The working principle, practical application and the advantages and disadvantages of each characterization technique are outlined in this chapter. We need to figure out that what kind of characterization techniques is suitable for graphene’s fabrication process. The reason is that, in some cases, it is tough to distinguish from the bilayer or trilayer graphene normally just closed located to what we need - only a single layer of graphene. In section 6.1, three characterization techniques (optical observation, atomic force microscopy and Raman spectroscopy) are introduced. And in section 6.2, the measurement method and the equipment setting will be briefly explained.

6.1 Characterization for graphene

In 2007, graphene has got a simple definition as "monolayer of carbon atoms" from Andre Geim and Konstantin Novoselov in a published paper [76]. Therefore, the monolayer graphene should be viewed as the meaningless repeat. However, affected by some initial graphene-related materials and publications, the terms such as "bilayer graphene" and "trilayer graphene" results in a large number of papers referring these two terms to describe the double-layer or triple-layer graphite sheet [77,78] is use. However, in this chapter, the term "graphene" is used only to represent monolayer graphene unless on the issues about the layer number.

The widely used technology to easily identify graphene is the optical microscope, where the graphene sheets need to be deposited on two particular thickness of silicon dioxide (SiO₂) on a Si wafer. Nevertheless, optical recognition is largely dependent on the experience of an observer. This kind of experience-based method should be replaced by other more accurate characterization techniques. Generally, there are two techniques often
chosen: atomic force microscope (AFM) and Raman spectroscopy. AFM is a quite satisfying choice because it does not require any specific working conditions or sample processing. However, using AFM may report errors about the thickness of the sample. In contrast, the Raman spectra is the best option for the graphite and graphene with several layers.

In the common situation, we can adapt two or three of existing characterization techniques together to identify graphene. But the optical observation always comes prior to the other techniques. In any case, we would conduct the optical observation first, because no other method could complete the graphene identification work within 20 minutes. This is how long an experienced researcher need to checking graphene on a standard 6-inch wafer, although the beginners may cost much more time.

Scanning electron microscopy (SEM) is also one way for characterization of submicron or atomic level, as well as transmission electron microscopy (TEM). However, in the identification process, contamination and damage may be brought to the graphene sheet in the SEM imaging process [79]. From this view, SEM is not a good choice for graphene identification. As for TEM, TEM imaging requires very careful transformation to the TEM grid and the electron beam used may bring the damage to the graphene sample [80]. As a result, TEM is not suitable for our identification of graphene either.

6.1.1 Optical identification

Graphene is one kind of the material with the transparency more 97% [81]. The optical microscope is an efficient method for rapid characterization of graphene layer numbers. Using oxide-coated silicon wafer as a substrate, adjust the thickness of silicon dioxide to 300nm [82], in the light of a particular wavelength irradiation, we can use color and contrast differences between substrates and graphene to distinguish different numbers of layers. This is due to a certain interference to light caused by graphene and the substrate,
respectively. The certain contrast can be then used to distinguish graphene under an optical microscope. Also, the substrate for observation can also use other materials, such as Si3N4, Al2O3, and PMMA, etc. And color contrast between graphene and the substrate under light can also be processed with many other image processing methods to achieve the accurate resolution purpose. Optical microscopy to characterize the monolayer and multilayer graphene is the most direct characterization way, but it cannot accurately distinguish the layer numbers of graphene.

Figure 6.1 One large piece of graphene/graphite flake on Si/ SiO2 substrate. The thickness of SiO2 layer is 290 nm. The picture on the left side is captured in green light and the right side one is in white light. This flake is clearly divided into four regions according to the different contrast to the substrate in light, which are symbolled with numbers 1, 2, 3, and 4, indicating the layer number of each region.

Figure 6.1 shows one large piece of graphene/graphite flake on Si/ SiO2 substrate. The thickness of SiO2 layer is 290 nm. The picture on the left side in Figure 6.1 is captured in the green light and the right side photo is in white light. From these two pictures, this flake can be easily divided into four regions according to the different contrast to the substrate in light. These four regions are symbolled with numbers 1, 2, 3, and 4, indicating the layer number of each region. We could also find that the contrast becomes clear in green light.
6.1.2 Atomic force microscopy (AFM)

AFM is considered one of the most powerful techniques for characterizing graphene, which is normally used to confirm the thickness of multi-layer graphene. AFM uses the atom probe slowly approaching until in contact with the sample surface. When the distance is reduced to a certain extent, the force between atoms will increase rapidly. Therefore, the force on the atom probe can be converted directly to the sample surface height, thus obtaining a sample’s surface topography information [83].

Figure 6.2 The working schematic of an AFM. The structure of AFM system can be divided into three parts: the force detecting section, the position detecting section, a feedback system.
The working schematic is described in Figure 6.2: AFM uses tiny cantilever to sense an interaction between the tip and the sample, which would force the cantilever swing, and then irradiated with laser light at the end of the cantilever. When the swing formed, the position of the reflected light will change, which causes the offset. Then the laser detector will record this offset, feedback the signal to the system at the same time, which helps the system to make the appropriate adjustments. Finally, the system presents the sample's surface topography information in the form of images.

6.1.3 Raman spectroscopy

Raman spectroscopy is the mostly used technique to characterize the carbon material, which is fast, non-destructive and with high resolution [84]. Raman spectrum looks very simple, usually just composed of a few very strong characteristic peaks with the wave-number range in 1000-2000cm\(^{-1}\) and a few modulation structures. However, even small changes in peak shape, intensity and location are related to the structure information of the carbon material. Since the electronic structures of graphene, multilayer graphene and graphite are different. The shape, position and intensity in the Raman spectrum will correspondingly change with increasing number of layers. Based on these changes, we can preliminary analyzing the layer number of graphene.

There are three peaks in the Raman spectra of graphene, respectively: D, G and 2D peak. D peak generally appears at near 1350cm\(^{-1}\) (1300-1400cm\(^{-1}\)), which is caused by symmetric stretching vibration of sp\(^2\) carbon atoms in the aromatic ring. Generally D peak is activated by a defect, so the intensity of D peak is usually used to measure the disorder in the material’s structure. G peak appears near 1580cm\(^{-1}\) (1560-1620cm\(^{-1}\)), which is caused by stretching vibration of sp\(^2\) carbon atoms, corresponding to the E2g optical phonon vibration in Brillouin zone center. The 2D peak appears near 2680cm\(^{-1}\) (2660-2700cm\(^{-1}\)), is caused by the phonons resonance transitions of two carbon atoms with reverse momentum. The movement and shape of 2D peak are closely related to graphene
layer numbers [85–86]. The oscillation modes of three peaks are illustrated in Figure 6.3 (a) and (b).

Figure 6.3 The oscillation modes of (a) G peak and (b) D and 2D peak.

Figure 6.4 Raman spectra of regions of different atomic-layer numbers on one graphitic flake [87]. The image of the taken flake is the embedded picture in (a). Four regions are marked with the number1, 2, 3, and 4 indicating different layer numbers of graphene, respectively. Spectra correspond to different number layers’ graphene from (a)to (d). E peak in (b) is an artifact peaks.
As seen from Figure 6.4, Raman spectra distinguish the single layer from the other number of layers corresponding to the peak shapes. Raman spectroscopy can be taken as our first choice to identify graphene. In Chapter 7, we will use Raman spectroscopy to help us confirming the quality of graphene devices fabricated in Chapter 5.

6.2 The Measurement Method and Equipment Setting

The graphene devices have been fabricated in Chapter 5. Before starting the measurement and results analysis for these devices, the brief introduction to the measurement method and the equipment setting will be given in this section since both the DC and RF properties need to be investigated in the next chapter.

6.2.1 Four-point method in the DC measurement of graphene’s resistance

![Diagram of four-point method](image)

*Figure 6.5 The principle picture of four-point method used to measure the resistance of graphene.*
Figure 6.5 illustrates the principle of four-point method that used to measure the resistance of graphene in Chapter 7. The basic characteristic of the four-point method is constant current power supplied to a resistor with the relatively small resistance through two current wires. And the digital voltmeter is connected to the resistor for potential difference measurement through another two wires. In this way, the contact resistance and intrinsic resistance of the two current wires are canceled. On the other hand, due to the extremely high input impedance of digital voltmeter, the contact resistance and intrinsic resistance of the two voltage wires is negligible for the measurement results. 

As shown in Figure 6.5, the derivation steps are presented as follows:

The voltage between point 2 and point 3:

\[ V_z = I_g (R_{c2} + R_{c3}) + I_g R_g \]  

(6.1)

The voltage between point 2 and point 3 can also be expressed as:

\[ (I_g - I_g) R_g \]  

(6.2)

The display value on the digital voltmeter:

\[ V_v = I_g R_g \]  

(6.3)

And if

\[ R_g \gg R_{c2}, R_g \gg R_{c3}, R_g + R_{c2} + R_{c3} \gg R_z, I_g \gg I_g \]  

(6.4)

where \( R_{c1}, R_{c2}, R_{c3}, R_{c4} \) are all contact resistance.

Then we can get

\[ V_v \approx V_z \]  

(6.5)

The measured resistance value of the resistor:

\[ R = \frac{V_v}{I_z} \approx \frac{V_z}{I_z} = R_z \]  

(6.6)

To apply the four-point method on the resistance measurement of graphene, we will use the four-probe work station and the semiconductor characterization system (Keithley 2000). The exfoliated and CVD graphene deposited on Si/SiO2 substrate ready for measurement will be put on the wafer stage shown in Figure 6.6(a). The measurement
parameter of four-point method will be set in Keithley 2000 shown in Figure 6.6(b) and (c).

6.2.2 RF measurement with the Vector network analyzer (VNA) system

There are two types of graphene devices need to be measured in Chapter 7: graphene resonators and graphene transmission lines. To investigate their performance, the data of 1-port or 2-port S-parameters are required. So the vector network analyzer (VNA) up to 110 GHz is necessary, which is shown in Figure 6.7 (a). What shown in Figure 6.7 (b) is the wafer holding stage where the devices will locate and the vacuum will be switched on during the measurement. In Figure 6.7 (c), a graphene transmission line is ready to measure, where 2-port S-parameters will be exported later.

Figure 6.6 The DC Measurement Equipment Setting: (a) four-probe work station, (b) the semiconductor characterization system (Keithley 2000), and (c) the model of four-point method in Keithley for parameters setting.
Figure 6.7 The RF Measurement Equipment Setting: (a) the vector network analyzer (VNA) 8510 XF up to 110 GHz, (b) the wafer holding stage, and (c) the graphene passive device ready for measurement (the graphene based transmission line).

6.2.2.1 Calibration

The accuracy of the network analyzer is very much dependent on this error-correction technique; therefore, the analyzer must be calibrated before it is used to make measurements.

During measurement calibration, a standard device with known characteristics is
measured, and the results of the measurement are used to create a set of error coefficients. During subsequent measurements, the network analyzer uses the error coefficients to correct for its own measurement errors.

The first step of calibration is to align the planarity of the probes using the contact substrate. The contact substrate is an alumina substrate with a soft gold top layer, which is used to align the planarity of the probes. The planarity of the probes ensures that all three probe contacts come down onto the device at the same time. The procedures of the planarity alignment include:

1) Raise the lever of the probe station to raise the probes to a maximum height with this adjustment.

2) Slowly lower the Z adjustment lever (also called the platen handle). The probes will come more and more into focus. Make sure the probes do not touch the contact substrate when the Z lever is fully down by using the Y adjustment micrometers if necessary.

3) Use the Z micrometer to lower the probe until it contacts the substrate and slides forward slightly.

4) Withdraw the probe from the substrate by using the Z micrometer.

5) Observe impressions in the gold where the probe fingers have made contact with the gold. If there are three contacts, one for each finger, the planarity alignment is finished. If not adjustment to the planarity of the probe will be necessary.

6) With the probe raised off the substrate use the planarity adjustment micrometer to adjust the tilt of the probe. This is a trial and error exercise where an adjustment is made and the probe is brought down onto the contact substrate to recheck the planarity and further adjustments made, if necessary.

After finishing the planarity alignment we need to align the Impedance Standard Substrate (ISS). The Impedance Standard Substrate (ISS) is used to calibrate the system. Position the ISS, the two probes and the microscope so that the probes can be viewed coming down
onto the ISS. The procedures of the ISS alignment include:

1) Slowly lower the Z adjustment lever (also called the platen handle). The probes will come more and more into focus. Make sure the probes do not touch the contact substrate when the Z lever is fully down by using the Y adjustment micrometers if necessary.

2) Position the probes with the X and Y micrometers and the ISS position with chuck adjusters so that the probes will come down onto the ISS at one of the alignment marks on the ISS. Finely adjust the probe station and lower the probes using the Z position micrometers so that the probes first contact the substrate at position X (dashed line) shown in Figure 6.8.

3) Lower the probes further until the probe tip reaches position Y (dashed line) shown in Figure 6.8.

4) Using the Z adjustment lever raise the probes fully off the substrate.

Figure 6.8 Alignment marks.

A variety of calibration techniques can be used with the VNA 8510XF, including the following:

• SOLT (Short-Open-Load-Thru)

• Offset Shorts (Shorts with different offset lengths)

• TRL (Thru-Reflect-Line)
• TRM (Thru-Reflect-Match)
• LRRM (Line-Reflect-Reflect-Match)

In our measurement, we have adopted the method of calibrating across the entire frequency range of the VNA, using the Line-Reflect-Reflect-Match technique, without differentiating the range into separate frequency bands. The procedures of the LRRM calibration include:

1) Launch the on-wafer RF measurement calibration tool WINCAL 3.1.
2) With the probes still raised off the substrate, measure the “open port 1” and “open port 2”.
3) Using the X-axis knob move the substrate so that the probes will land on a load when lowered and using the Z adjustment lever (platen handle) lower the probes onto the loads. Measure “load port 1” and “load port 2”.
4) Raise the probes using the Z adjustment lever (platen handle).
5) Using the X-axis knob move the substrate so that the probes will land on a short when lowered and using the Z adjustment lever (platen handle) lower the probes onto the shorts. Measure “short port 1” and “short port 2”.
6) Raise the probes using the Z adjustment lever (platen handle).
7) Using the X-axis knob move the substrate so that the probes will land on a through when lowered and using the Z adjustment lever (platen handle) lower the probes onto the through. Measure “thru”.
8) Using the Z adjustment lever raise the probes fully off the substrate.
9) Compute and the Cal line should be within two guidelines (-0.1 dB ~ +0.1 dB).
10) Save the calibration results to VNA. VNA accepts calibration coefficients and switches calibration correction on.
11) The VNA is now well calibrated and ready to measure a device.
6.2.2.2 External conditions impact measurement

The external conditions impact the measurement results sometimes very significantly. With equipment shown in Figure 6.9 and Figure 6.10, we can develop the study on the external temperature and the bias voltage influence on S-parameters. By connecting the DC power supply to VNA, graphene devices can be investigated under different gate voltages. As for the temperature controller, the input impedances of graphene resonators are measured with external temperatures varying from 40°C to 160°C.

![Figure 6.9 Temptronic TP03200 Thermal Chuck System Controller TP03200A-2300-2 with -65°C to 200°C temperature range.](image)

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Figure 6.10 DC power supply up to 60 V (Agilent E3641A).
Chapter 7 Measurements Results and Analysis

In this chapter, the measurement results of the graphene devices fabricated in Chapter 5 are presented. The measurement results are divided into two parts: the DC measurements and the RF measurements, which are based on the different electrical properties we want to get.

For the DC part, the measurement results of the DC conductivity of the monolayer graphene are presented. Both the exfoliated graphene and CVD graphene are included. This measurement is conducted on the graphene devices (one piece of graphene sheet between two gold electrodes) with Si/SiO\textsubscript{2} substrate. It is found that the Dirac point appears at the quite different locations depending on the type of graphene we used to fabricate the device, which is caused by the doping concentration difference between the exfoliated and CVD graphene. Meanwhile, the sheet resistance of graphene is calculated based on the measurement data so that we could make essential corrections to our simulation design in Chapter 4.

For the RF part, the measurement is conducted on the two types of graphene passive devices from 0-110 GHz. The first type of graphene devices is the graphene CPW resonator. We measure the input impedance of the graphene resonators with different substrates (Si/SiO\textsubscript{2} or GaAs) and different graphene lengths. The measurement results are consistent with the numerical calculation using the sheet resistance we measured in the DC part. Besides, the influence of the external conditions such as temperature on the performance of graphene resonators has been investigated. The input impedance resonance shows the shift when the external temperature varying from 40° C (313K) to 160° C (433K).

The second type of graphene devices is the graphene CPW transmission line on Si/SiO\textsubscript{2} substrate. The S-parameters measured from VNA reveal that graphene
within the transmission line acts as the transmission channel, which is a little lossy at the microwave frequency range. The poor transmission is also partially caused by the mismatching of the parasitic impedance, as well as the substrate loss, which is verified by the de-embedded structure of the graphene transmission line.

This chapter is organized as follows: Section 7.1 presents the DC measurement results including the resistance characteristics of exfoliated and CVD graphene. Section 7.2 presents the RF measurement results of graphene resonators. In the last section, RF measurement results of graphene transmission lines are presented.

7.1 DC Characteristics Measurement of Graphene

7.1.1 Resistance characteristics of exfoliated graphene

Figure 7.1 shows the exfoliated graphene viewed under a microscope (Nikon Eclipse LV100D with a 5x and a 20x, respectively. The exfoliate graphene locates between two gold electrodes (source and grain) and on Si/SiO2 substrate. The exfoliated graphene is surrounded by one large piece of graphite sheet as shown in Figure 7.1. The size of exfoliated graphene is 50 μm by 30 μm. The thickness of SiO2 is the standard 300 nm and Si substrate of 500 μm.

Figure 7.1 Exfoliated graphene viewed under a microscope (Nikon Eclipse LV100D with a 5x and a 20x, respectively). The exfoliate graphene locates between two gold electrodes (source and drain) and on Si/SiO2 substrate.
As introduced in Chapter 6, the four-probe method is used to measure the resistance of the exfoliated graphene. Resistance dependence on the back gate voltage $V_g$ of the exfoliated graphene is shown in Figure 7.2. The back gate voltage is applied within the range 0-25 V and the measurement current is set to 100 nA. Measurement is taken under room temperature $T=290$ K. In the Figure 7.2, we find that the Dirac point does not appear at 0 V as supposed. Instead, The Dirac point moves to 9.2 V, which should be resulted by two factors: the contamination of the remaining photoresist used in the fabrication process and the air doping.

![Resistance Vg Graph](image)

Figure 7.2 Resistance dependence on the back gate voltage $V_g$ of the exfoliated graphene. The back gate voltage is applied within the range 0-25 V and the measurement current is set to 100 nA. Measurement is taken under room temperature $T=290$ K.

7.1.2 I-V characteristics of CVD graphene

Figure 7.3 (a) shows the top view of CVD graphene on Si/SiO2 substrate, and Figure
7.3 (b) shows CVD graphene under a microscope (Nikon Eclipse LV100D with a 5x). The CVD graphene locates between two gold electrodes (source and drain). The size of CVD graphene is 1000 μm by 70 μm. The thickness of SiO2 is the standard 300 nm and Si substrate of 500 μm.

Figure 7.3 (a) The top view of CVD graphene on Si/SiO2 substrate, and (b) CVD graphene under a microscope (Nikon Eclipse LV100D with a 5x). The CVD graphene locates between two gold electrodes (source and drain).

For the CVD graphene, we repeat the procedure used to measure the resistance of the exfoliated graphene. However, since the appearance of Dirac point of CVD graphene often requires very high gate voltage applied, no sudden change on the measurement curve is detected. In this case, the resistance dependence on the back gate voltage Vg of CVD graphene seems a flat line. The back gate voltage is only possibly applied up to 35 V due to the measurement equipment setting. Thus, instead of drawing the resistance dependence curve, we would prefer the I-V characteristics curve. In the Figure 7.4, we find that the slope of the I-V curve can be observed with slightly change. Actually, the resistance of CVD graphene has doubly changed when the gate voltage varying from -8 V to 35 V. After calculation, the sheet resistance of CVD
graphene is around 291 Ω/sq. This value will be involved in the following results analysis for the RF measurement of graphene resonators and transmission lines.

![Graphene I-V Characteristics](image)

*Figure 7.4 I-V characteristics curve of the CVD graphene. The back gate voltage is applied within the range -8-35 V and the measurement voltage is set to 0.1 V. Measurement is taken under room temperature T=290 K.*

### 7.2 RF Characteristics Measurement of Graphene Resonators

#### 7.2.1 RF characteristics measurement of graphene resonators on Si/SiO2 substrate

As we mentioned in subsection 7.1.2, one piece of 1 cm by 1 cm CVD graphene is used to fabricate a series of graphene resonators and transmission lines, which is shown in Figure 7.5 (a). Figure 7.5 (b) shows the graphene shaped by the laser writer. The stub in the center position is graphene, and the surrounding metal is gold. The graphene stub after shaping, and one of the CVD graphene resonators after final fabrication are exhibited in Figure 7.5 (c) and (d).
Figure 7.5 (a) CVD graphene on Si/SiO2 substrate used to fabricate the graphene resonators, and (b) graphene shaped by the laser writer. The stub in the center position is graphene, and the surrounding metal is gold. (c) The graphene stub after shaping, and (d) one of the CVD graphene resonators fabricated in Chapter 5.

Before starting the fabrication, we need to use Raman spectroscopy to confirm the layer number of our CVD graphene. This is quite essential since the electrical properties are quite different for monolayer and multi-layer graphene. Figure 7.6 shows the laser point of Raman spectroscopy on CVD graphene during measurement. The wavelength of laser is 523 nm. And one of the measurement results of six random positions on CVD graphene is presented in Figure 7.7, which is convinced that it is mostly covered by the monolayer graphene.
Figure 7.6 The laser point of Raman spectroscopy on CVD graphene before the fabrication. The wavelength of laser is 523 nm.

Figure 7.7 Raman spectra of CVD graphene that shows the monolayer graphene detected.
After finishing the fabrication, we need to use Raman spectroscopy again to detect the existence of graphene. This is even more important because graphene may be ruined in the fabrication process, especially in the photoresist step. Figure 7.8 shows the well fabricated devices ready for Raman spectroscopy. The wavelength of laser is 523 nm. And one of the measurement results of all the graphene devices is presented in Figure 7.9, which is convinced that each device is covered by the patterned monolayer graphene.

![Image](image.png)

*Figure 7.8* Raman spectroscopy taken after final graphene devices fabrication. The wavelength of laser is 523 nm.

It is so easy to cause damage to graphene during the measurement process because graphene is so fragile. So we need to use Raman spectroscopy again to detect the existence of graphene after completing the measurement. This will be helpful to determine if any further action should be taken. Figure 7.10 shows the graphene devices after RF measurement ready for Raman spectroscopy. The wavelength of laser is 523 nm. And one of the measurement results of all the graphene devices is presented in Figure 7.9, which helps us to find out the undamaged device.
Figure 7.9 Raman spectra of patterned graphene in the graphene devices that shows the monolayer graphene detected.

Figure 7.10 Raman spectroscopy taken after RF measurement on all the graphene devices. The wavelength of laser is 523 nm.
Figure 7.11 Raman spectra of patterned graphene in the graphene devices after RF measurement that shows the monolayer graphene detected.

In the Figure 7.12, the $I_{SD}$-$V_{SD}$ characteristics curve of CVD graphene in the graphene resonators is presented, which shows the linear dependence. $I_{SD}$ is the current between the source and drain and $V_{SD}$ is the voltage between the source and drain. There is no gate voltage applied. From this figure we can obtain the resistance between the source and drain is around 70 $\Omega$.

There are two graphene resonators with different length of graphene stub are measured using VNA. The first type of resonator is designed with the 440 $\mu$m graphene stub, where has been shown in Figure 5 (d), called as the graphene short resonator. We need to measure the 2-port S-parameters of the graphene short resonator using VNA. Then we keep the structure of the short resonator fixed, only removing the graphene stub, and conduct the same measurement. Based on the S-parameters we can compute the input impedances of the short resonators with and
without graphene respectively. It is easy to find in Figure 7.13 that there is the big shift for the input impedance resonance peak between the resonators with graphene and without graphene. For the graphene short resonator, the resonance peak appears at 35.2 GHz. And for the short resonator without graphene, the resonance peak moves backwards up to 37.5 GHz. When the graphene stub is removed, the current flows cannot flow through graphene any more. Thus, the electrical length of the whole resonator is reduced, resulting in resonant frequency moving to the higher region. However, since the ordinary Si wafer other than the high resistivity Si is used in this resonator as the substrate, the performance of the resonator becomes very poor.

![Graphene Resonators](image)

**Figure 7.12** The $I_{SD}$-$V_{SD}$ characteristics curve of CVD graphene in the graphene resonators. $I_{SD}$ is the current between the source and drain and $V_{SD}$ is the voltage between the source and drain. There is no gate voltage applied.
The second type of resonator is designed with the 1415 μm graphene stub, which has the same structure as the graphene short resonator. Here we call the second type as the graphene long resonator. We will also measure the 2-port S-parameters using VNA and compare the input impedances of the long resonators with and without graphene.

In the Figure 7.14, there is also the resonance shift between the long graphene resonators with and without graphene. For the 1415 μm graphene resonator, the resonance peak appears at 20 GHz. And once removing the graphene stub, the resonance peak moves backwards up to 26 GHz. Obviously, the difference between two resonance peaks is highlighted. This is because that the graphene stub plays a more active role in the long graphene resonator. However, the input impedance performance of this resonator degrades since graphene is quite lossy in the low frequency region.

Figure 7.13 Input impedance of the short-ended graphene resonator and the de-embedding with 440 μm graphene stub within 25-45 GHz.
Figure 7.14 Input impedance of the short-ended graphene resonator and the deembedding with 1415 μm graphene stub within 12-28 GHz.

7.2.2 RF characteristics measurement of graphene resonators on GaAs substrate

Now we will measure the temperature influence on the performance of the graphene resonator. The resonator we measure keeps the same geometry as the one shown in Figure 5 (d). The graphene stub has the length of 500 μm and the substrate has changed into GaAs. The measurement is conducted under the variable external temperatures: 40°C, 80°C, and 160°C. As we can observe from Figure 7.15, when the temperature is increased every 40°C, the input impedance resonance peak moves backwards 1 GHz. At 40°C, the resonance appears at 38 GHz. At 80°C, the resonance moves to 37 GHz, and continues moving until 36 GHz at 160°C. As we discussed in Chapter 3, the conductivity of graphene is affected by many factors.
One of them is the temperature. So when the external temperature rises, graphene becomes more metal-like. In this situation, more current could flow through the graphene stub, which causes the resonance frequency decreases. This kind of resonance shift should be enhanced if we extend the graphene stub in the resonator.

![Graphene Resonator Input Impedance Graph](image)

*Figure 7.15 Input impedance of the short-ended graphene resonator on GaAs substrate with 500 μm graphene stub within 30-50 GHz. The external temperatures are variable as 40°C, 80°C, and 160°C.*

**7.3 RF Characteristics Measurement of Graphene Transmission Lines**

There are two graphene transmission lines with different length of graphene stub are measured using VNA. In the Figure 7.16, the 2-port S-parameter measurement on the graphene transmission line is taken using VNA. The distance between each probe is 100 μm.
In the Figure 7.17, the firstly measured graphene transmission line has the 20 μm graphene channel. The transmission line is made of gold with the 20 μm gap in the center and graphene locates on the gap as a channel. The measured S parameters (S11, S22, S21, and S12) of the graphene transmission line with the 20 μm graphene stub are presented in Figure 7.18. For clarity, the values of S22 and S12 are reduced by 5 dB. The measurement frequency range is 0-50 GHz. In this figure, we find very poor transmission performance in the graphene transmission line. Although graphene is quite lossy with the sheet resistance of 291 Ω/sq, most of the power is reflected other than being wasted inside the material. With the improved dimension design, better matching could be achieved to reduce the reflection.
Figure 7.17 The graphene transmission line with the length of the graphene stub 20 μm. The transmission line is made of gold with the 20 μm gap in the center and graphene locates on the gap as a channel.

Figure 7.18 The measured S parameters (S11, S22, S21, and S12) of the graphene transmission line with the 20 μm graphene stub. For clarity, the values of S22 and S12 are reduced by 5 dB. The measurement frequency range is 0-50 GHz.
In the Figure 7.19, the secondly measured graphene transmission line has the same structure as the last one with the 60 μm graphene channel. All the other dimensions of the second transmission line keep fixed except the graphene channel length.

The measured S parameters (S11, S22, S21, and S12) of the graphene transmission line with the 60 μm graphene stub are presented in Figure 7.20. For clarity, the values of S22 and S12 are reduced by 5 dB. The measurement frequency range is 0-50 GHz. In this figure, we find that the transmission performance degrades compare to the first one. The only difference between two transmission lines is the length of the graphene channel. In the first transmission line, the gap on the gold signal line is only 20 μm, which indicates that the strong coupling exists. The contribution of metal coupling is as significant as the transmission performance of graphene. Thus, when the length of the gap increases, the transmission performance could even be treated as the open circuit.

![Figure 7.19 The graphene transmission line with the length of the graphene stub 60 μm. The transmission line is made of gold with the 60 μm gap in the center and graphene locates on the gap as a channel.](image)
Figure 7.20 The measured S parameters ($S_{11}$, $S_{22}$, $S_{21}$, and $S_{12}$) of the graphene transmission line with the 60 μm graphene stub. For clarity, the values of $S_{22}$ and $S_{12}$ are reduced by 5 dB. The measurement frequency range is 0-50 GHz.

In the Figure 7.21, the graphene transmission line with the length of the graphene stub 20 μm will be compared with the open graphene transmission line without graphene filling in the gap.

Because of the coupling issue we discussed above, the transmission coefficient $S_{21}$ of the graphene transmission line and the open transmission line are compared in Figure 7.22. The measurement frequency range is 0-18 GHz. In this figure, we can clearly see the near 15 dB difference between the graphene transmission performance and the open circuit performance. This strongly verifies the contribution of graphene to the transport properties in the transmission line.
Figure 7.21 (a) The graphene transmission line with the length of the graphene stub 20 μm. (b) The open graphene transmission line without graphene filling in the gap, which keeps all the other parts as same as the 20 μm graphene transmission line.

Figure 7.22 The measured transmission coefficient $S_{21}$ of the graphene transmission line and the open transmission line. The measurement frequency range is 0-18 GHz.
Chapter 8 Conclusions and Future Work

8.1 Conclusions

Motivated by the very few work has done on the performance measurement of graphene passive devices compared to graphene active devices, several different types of passive devices are fabricated and measured. In general, the fabricated devices are divided into two parts: the DC devices and the RF devices, which based on the different electrical properties we measure in Chapter 7.

For the DC devices, attention has been given to the resistance of CVD graphene that we later use in all the RF devices. The Dirac point seems only appears in the exfoliated graphene measurement, which is caused by the doping concentration difference between the exfoliated and CVD graphene. Meanwhile, the sheet resistance of graphene is calculated based on the four-point measurement. The sheet resistance of CVD graphene is around 291 \( \Omega/\text{sq} \)

For the RF devices, the measurement is conducted on the two types of graphene passive devices from 0-110 GHz. The first type of graphene devices is the graphene CPW resonator. We measure the input impedances of the graphene resonators on different substrates (Si/SiO\(_2\) or GaAs) and with different graphene lengths. For the graphene resonators on Si/SiO\(_2\) substrate, the input impedance does show the resonance shift compared to the graphene-removed structure. The frequency position of the resonance that appears is consistent with the theoretical calculation result. Besides, the influence of the external conditions such as temperature on the performance of graphene resonators has been investigated. The input impedance resonance shows the shift when the external temperature varying from 40\(\degree\) C (313K) to 160\(\degree\) C (433K). This measurement is undertaken with the graphene resonator on GaAs substrate.
The second type of graphene devices is the graphene CPW transmission line on Si/SiO$_2$ substrate. The S-parameters measured from VNA reveal that graphene within the transmission line acts as the transmission channel, which is a little lossy at the microwave frequency range. The poor transmission is also partially caused by the mismatching of the parasitic impedance, as well as the substrate loss, which is verified by the comparison result between the graphene transmission line and the graphene-removed transmission line. Similarly, the concern on the signal line coupling is also eliminated by using the graphene-removed structure.

### 8.2 Future Works

Obviously, either exfoliated graphene or CVD graphene exhibited very lossy performance in the measurement period. This indicates that graphene maybe more suitable for applying in the absorber, especially the structure discussed in Chapter 4. As seen from the Figure 8.1, we could use CVD graphene to replace copper in the patterns. Once the external bias voltage is applied to the graphene pattern, the nine resonant peaks may degrades each other, which achieving a novel broadband absorber.

Another promising research direction in the future is to complete the fabrication of the RF graphene based switch, as shown in figure 8.2, which is also proposed in Chapter 4. The dimension and layout of the switch proposed in Chapter 4 are the results after optimization with considering the practical trouble may face in the fabrication and measurement (such as how to apply the bias voltage to graphene). After this optimization the measurement results can be well anticipated.
Figure 8.1 Three layers triple-band THz metamaterial absorber simulation setup in CST (perspective view). Each layer has the same thickness of the substrate $t = 30 \mu m$. 
Figure 8.2 The structure of the graphene-based switch: (a) top view and (b) side view.
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