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Systematic Analysis of The Potential for Graphene Electronics

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Abstract:
Graphene, a one-atom-thick carbon hexagonal layer has been earning increasing attention from scientist in almost every area by virtue of its extraordinary electronic and thermal properties under low energy circumstances. In this paper: the intrinsic electrical properties of high-purity graphene under experimental conditions are introduced and explained in details; Chemical vapor deposition method (CVD), one of the most advanced methods for the manufacturing of graphene of high quality, a method that uses carbon-containing gases as the precursors, which will decompose at high temperatures to release carbon elements, and metals that have appropriate catalytic activity such as copper, nickel, and platinum as substrates to enhance the adsorption and diffusion of carbon elements on the substrate surface is analysed in terms of both of its advantages and disadvantages the other challenges that the production of graphene is currently facing is given as well; The applications of graphene in superconductors and semiconductors, which are both one of the most characteristic use of graphene’s remarkable properties, are introduced in terms of their potential, recent breakthroughs, and estimated future. Estimations about the future development of graphene will be elaborated.

Keywords: Graphene, electrical properties, challenges

1. Introduction

It was claimed 80 years ago by Landau and Peierls that purely 2D crystals could not exist because they were thermodynamically unstable. The mold was broken in 2004 when 2D atomic crystals were discovered experimentally by exfoliation. In addition to existing at different temperatures, the 2D layers might also have excellent crystal quality and low rates of doping and vacancy [1]. In particular, graphene has demonstrated remarkable physical properties in comparison. Nowadays, with some modern methods in producing graphene, high quality graphene can be produced. The applications of graphene are of quite a wide range from solar panels to transparent touching screen, because graphene is a magical material that has marvelous properties and astonishing potential in electronics. In this case, the future of graphene is still replenished with hope and reward if creative ideas, proper research strategies and hard work can be paid. The study will examine graphene’s inherent electrical characteristics, expound on its primary techniques of manufacturing, and provide a prospect of graphene.

2. Graphene electrical properties

Graphene has special physical properties compared to other materials, such as high thermal conductivity (5000 Wm−1 K−1), high electron mobility (250,000 cm2V−1 s−1), large surface area (2630 m2 g−1), and better electrical conductivity and optical transmittance [2-5]. In this paper, we are going to focus on analyzing the reason graphene has such high electron mobility.

2.1 Band structure and electron mobility in graphene

By solving the tight bonding dispersion model of graphene using Fourier transform, the energy dispersion of graphene could be calculated and simulated into 3D models which is shown in Fig.1 [6].

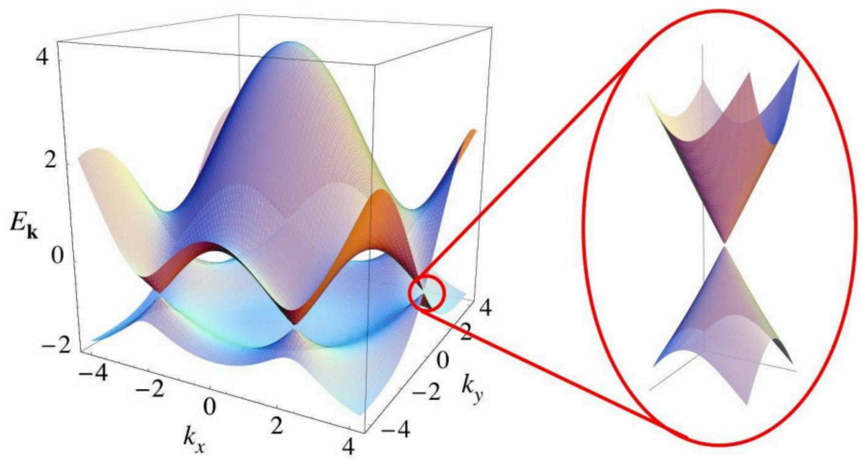

Fig.1 Band structure of graphene [6]

In the band diagram, there are six points of intersection between conducting and valency bands, by definition, they are Dirac points. Around the Dirac points, the Brillouin zone is conelike, indicating that the energy of the electrons in the material varies linearly with the wave vector in a particular direction. This conelike shape is often called a "Dirac cone" where energy dispersion is governed by the linear dispersion relation.

For graphene, it recognizes this as massless Dirac dispersion, where electrons in the cone are considered as Dirac fermions (fermions are particles with odd half-integral angular momentum) that are relativistic, have no stationary mass and have their energy linearly varies with their momentum. This symptom could lead to various properties such as quantum hall effect and high mobility of electrons.

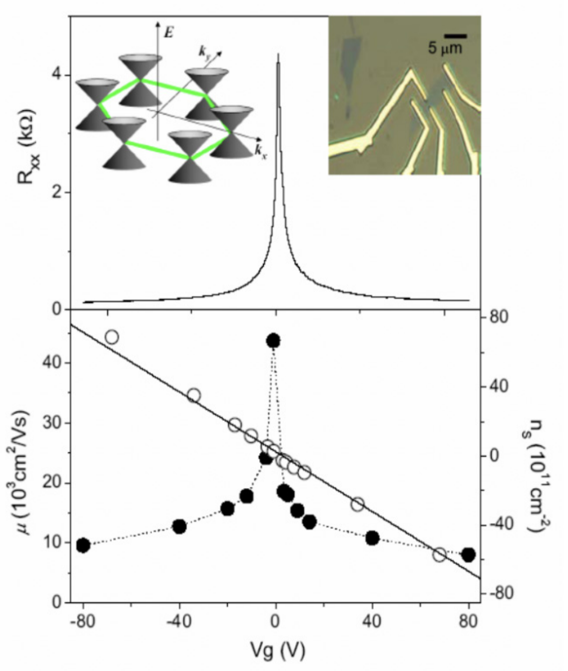

Fig.2 Resistance, carrier density, and mobility of graphene measured at 1.7 K [7]

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The upper half session of Fig.2 shows the gate modulation of Rxx at zero magnetic field. A sharp peak whose value is on the order of 4 kΩ is observed at Vg = 0 [7]. The existence of such a sharp peak is consistent with the reduced carrier density as the energy level approaches the Dirac point of graphene where the density of states vanishes. For the lower half, the research assumed the graphene behaved ideally, following the Drude model. The mobilities are higher than 10**4 cm2 /Vs for the entire gate voltage range [7].

2.2 Electron scattering in graphene

One of the things that lowers some materials' mobility is electron scattering. Phonon scattering occurs when an electron moves via the internal channels that exist between the lattice's layers. Because of the contact between electrons and vibrating lattices, that could result in an energy loss. Additionally, electrons can scatter as a result of the opposing static electric forces through coulomb scattering.

In the case of electrical conduction, electronic scattering is a dominant factor. Impurities, defects, or lattice vibrations and scattering are all determining factors for electronic scattering. Defect-less graphene has lower impurity or vacancy concentration. Because electrons in defect-less graphene may go farther without scattering, they have a greater mean free path (MFP), which increases conductivity. The electron channel in graphene layer, showing single layer graphene has only two surface channels, hence having a greater conductivity is shown in Fig.3 [8].

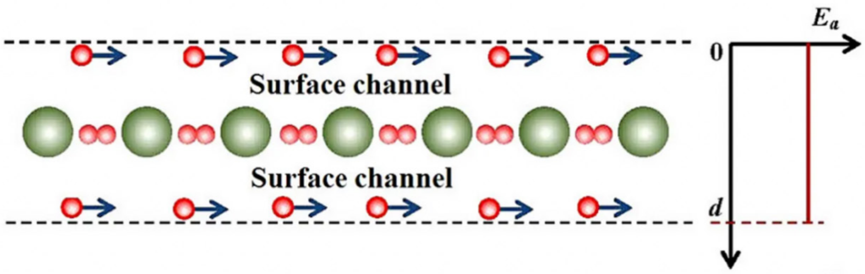

Fig.3 The electron channel in graphene layer, showing single layer graphene has only two surface channels, hence having a greater conductivity [8]

2.3 Quantum Hall effect in graphene

Under strict experimental conditions, the graphene had quantum hall resistance varying in a quantized way against continuously changing applied voltage. Moreover, the value of the quantized resistance is accurate even when materials contain impurities. Because of this, the quantum Hall effect is used to confirm the accuracy of the ohm and may also be used as a resistance sensor. The Quantum Hall resistance under changing effective voltage, 1.6K is shown in Fig.4 [7].

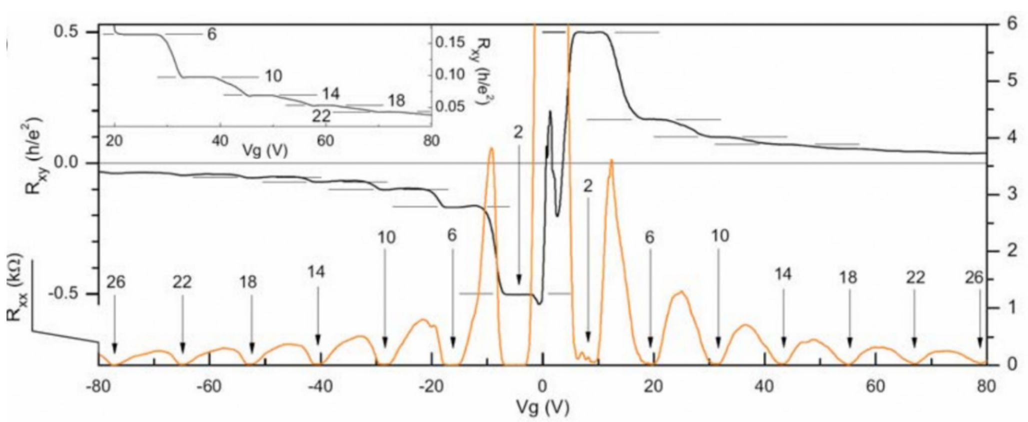

Figure 4. Quantum Hall resistance under changing effective voltage, 1.6K [7]

3. Methods of producing graphene

Because of the great interest in graphene, the method, chemical vapor deposition method, uses carbon-containing gases as the precursors, which will decompose at high temperatures to release carbon elements, and metals such as copper, nickel, and platinum as substrates. These metals have appropriate catalytic activity and will enhance the adsorption and diffusion of carbon elements on the substrate surface. At high temperatures, the precursor gas decomposes and releases carbon elements. Free carbon atoms will be adsorbed on the surface of the substrate, gradually grow and merge with each other on the surface of the substrate, and eventually form a continuous single-layer graphene. Li et al. produce the graphene under the situation of 1000 °C, using a mixture of methane and hydrogen as the precursor and copper as the substrate. Using a scanning electron microscopy (SEM) image, as a result, the produced graphene showed to be continuous and high-quality (about 95% of graphene are one-layer) [8]. Also, after transferring this graphene to alternative substrates, such as SiO2/Si, the date from using Raman spectroscopy shows that one-layer graphene's proportion is still about 95%, and there is only a small fraction of tripayer or bilayer graphene [9]. This shows that the transfer of graphene is effective. The feature of a high-quality product is also proven by Bhaviripudi et al. [10]. With Cu foils placed in the furnace and hydrogen gas into the system, under 1000 °C and 325 mTorr, the methane gas was introduced (pressure came to 625 mTorr). Using Raman spectroscopy, the result also shows the high quality of graphene with the low defect density. The process of chemical vapor deposition methods is shown in Fig.5 [11].

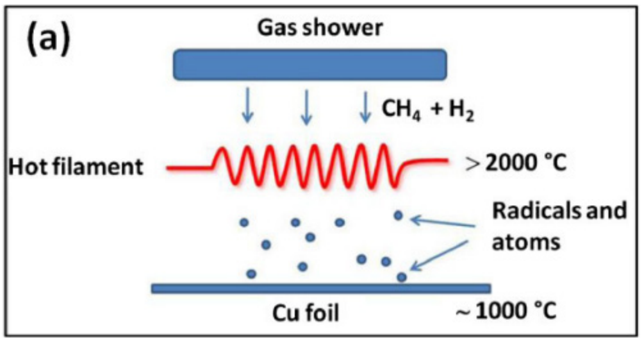

Fig.5 the process of chemical vapor deposition methods [11]

The reason for CVD to be widely used is that CVD is ideal to deposit graphene on complex geometry and control over film thickness [12]. Also, by using CVD, the component of the film can control the composition of graphene [13]. Under the situation of 1000 °C, 33 sccm CH4, 20 sccm H2, and 50 to 300 sccm N2/NH3 gas mixture for 30 min, Recep Zan and Ali Altuntepe's group Use two groups of dopants: The first group is composed of pyridine, and the second group is composed of 95 percent nitrogen with 5 percent ammonia. Using 200 sccm Ar flow as the carrier for the first group dopant for 30 minutes, this group later used the second group for the nitrogen-doped graphene growth. By spinning PMMA onto the graphene on the copper, the layer with PMMA can be transferred to the Si/SiO2 wafer to be determined to be pristine or doped. Then the group uses SEM (scanning electron microscope), EDS (energy dispersive x-ray spectroscopy), AFM (atomic force microscope), and a four-point probe for the characterization of the graphene films. The result of this is that about 93% of graphene was doped, and it will decrease to 83% with only pyridine. By being doped, graphene's resistance decreases, which makes it very desirable to use in optoelectronic devices.

4. Applications of graphene

4.1 Graphene in semiconductors

A semiconductor is a sort of materials that has different performances of conducting electricity under different conditions. A semiconductor has a valence band in which electrons cannot move freely and a conduction band in which electrons can move freely (can conduct electricity). What stops the electrons moving between these two bands is a band gap, and to jump from the valence band to the conduction band, an electron must have enough energy to overcome the band gap between the two bands. This is exactly why the electrical conductivity of a semiconductor changes with the conditions. Unlike normal conductors whose resistance does not change dramatically under different conditions, a semiconductor can be used to control the current flowing throwing it by changing the conditions that determine the resistance of the semiconductor. This unique property gives semiconductors an important role in modern electronics, and semiconductors can be often found in microprocessors, transistors and a lot of other electronic devices.

When graphene is used to create a semiconductor, its excellent properties including high electrical conductivity, chemical stability, thinness and flexibility would make it extremely appealing when it is used in many applications like transistors. However, graphene cannot be used as a semiconductor directly for a reason that seems to be very hard to be tackled. Graphene has no band gap. Nevertheless, standing in the way that human beings move forward, this problem is taken care of any way.

Scientists now have developed many methods to insert a band gap into grapheme and to make graphene a semiconductor, including cutting graphene into specific shapes, chemical doping, combining graphene with other semiconductor materials and so on [14-16].

However, it turns out all of these methods would finally reduce the electron mobility or limit the performance of the grapheme semiconductors in other ways, and there are still factors like cost preventing graphene semiconductors

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from being produced in a large scale. Developing a way to make graphene semiconductors of better performance and more suitable for wider use is still an issue that deserves attention.

In the January of 2024, the world's first 2D semiconductor that meets all the necessary requirements for being used in nanoelectronics is created, and its electrical properties are much better than any other 2D semiconductors that are currently in development. It even has the mobility that is 10 times of silicon [17]. It seems that graphene is now having a great chance to take over the position of silicon in electronics, and lead electronics into a brand-new era.

4.2 Graphene in supercapacitors

Supercapacitors are capacitors that can store a paramount amount of energy and give out electricity in a very rapid speed compared with regular capacitors. A supercapacitor has two metal plates as well just like the normal capacitors, but unlike the normal capacitors, a super capacitor also has electrolyte that does not usually get electrolyzed in addition to the electrodes. When a voltage is applied to the electrodes, the ions in the electrolyte move to different electrodes, and the electricity is stored in this way. When the voltage is moved, the ions move back to the electrolyte, and the electricity is given out in this way [18]. During the process, an electrical double layer is formed on the surface of the electrode, giving the supercapacitor higher capacitance then the other normal capacitors [19].

When graphene is used in a super capacitor by itself, multiple advantages can be gained: Since graphene has a very large surface area relative to the mass and volume, when graphene is used in a super capacitor, a greater amount of charge per unit volume can be kept on the electrode of the capacitor, equipping the super capacitor with a higher capacitance [20]. As graphene has a very high electrical conductivity, the supercapacitor would be able to charge and discharge more rapidly, and have higher power density in this way [21]. Because graphene is chemically stable, a super capacitor can have longer life span [22].

However, supercapacitors that use electrodes made purely by graphene are still facing some serious challenges: Since graphene has a strong tendency to restack due to the Van der Waals' force, the accessible surface area of graphene and the transporting speed of ions may be reduced over time, limiting the capacity and power density of the super capacitor [23]. Due to the limit of mature techniques that can produce high quantity of graphene of high quality at low cost and many other factors, it is hard to produce super capacitors using purely graphene at a large scale [22].

Scientists are now trying to overcome these problems by combining graphene with other materials that also have many excellent properties like Ni-based materials, which have high theoretic specific capacity, high thermal stability, and high resource reserves, developing better electrode structure to make better use of the large surface area of graphene and so on. Progresses have been made indeed, and the supercapacitors that now make use of graphene are all having much better performances then before. However, the world is still moving forward, and apparently, the requirements for super capacitors are still rising. Hence, staying still at where they are now is clearly not expected for super capacitors, and the performances of the super capacitors that use graphene are still expected to be improved by combining graphene with other materials, and designing electrodes of better structure and better quality.

5. Conclusion

By using the chemical vapor deposition method, graphene of high quality can be acquired, but how to conduct the production of high-quality graphene in a more efficient way that can be used in a large scale at low cost is yet still a question left unsolved.

When graphene is used in super capacitors, the performances of the super capacitors would have a rise dramatically, but better results are still expected, and scientists are still trying to enhance the super capacitors by combing graphene with other materials, designing more reasonable electrode structure and so on; When graphene is used to create semiconductors, its talented electrical properties and other unique physical properties would make it very competitive, but scientists are still trying to reach higher goals by introducing a band gap into graphene in a better way to get semiconductors that are more suitable for massive production and of better capability.

In conclusion, Graphene is a material that has an incredible potential for its unique properties, and has a hope to start a new era in human society just like silicon dioxide. But despite of the appealing properties of graphene and current accomplishments in developing the potential of graphene, the methods for producing graphene, the applications and potential of graphene mentioned in this essay are still far from enough, and the methods for production, applications and potential of graphene are still expected to bear further progresses that are more monumental with efforts devoted by scientists with dreams and strength.

6. Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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