Journal of Engineering for THERMAL ENERGY AND POWER

ISSN: 1001-2060
Vol. 26 No. 1, 2023

QUANTUM TRANSPORT IN GRAPHENE: MECHANISMS AND DEVICE APPLICATIONS

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Abstract

Received: 26/11/2022

Revised: 19/12/2022

Accepted: 15/01/2023

DOI:
10.12060/jet-ep-v26.i1-1

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Graphene, a monolayer of carbon atoms arranged in a hexagonal lattice, exhibits exceptional electronic properties, including high carrier mobility, ambipolar conduction, and ballistic transport over submicron distances. These unique quantum transport characteristics make graphene a promising material for next-generation nanoelectronic and optoelectronic devices. This paper reviews the fundamental mechanisms of charge transport in graphene, examines the effects of scattering and substrate interactions, and explores recent advancements in graphene-based electronic devices. The challenges and future prospects of integrating graphene into practical systems are discussed.

Keywords: Graphene, Quantum Transport, Carrier Mobility, Ballistic Conduction, Nanoelectronics.

1. INTRODUCTION

Graphene has attracted significant attention since its experimental isolation in 2004 (Novoselov et al., 2004). Its two-dimensional structure and linear energy dispersion near the Dirac points result in charge carriers that behave as massless Dirac fermions, giving rise to extraordinary electronic properties. Understanding how electrons transport through graphene is crucial for leveraging its full potential in high-frequency transistors, sensors, and quantum devices.

Quantitative insights into graphene's transport phenomena arise from both theoretical models—such as the Dirac equation for massless fermions—and experimental studies using advanced fabrication and characterization techniques. This paper systematically reviews quantum transport mechanisms in graphene and their implications for device performance.

2. THEORETICAL BACKGROUND

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2.1. Graphene Band Structure

Graphene's honeycomb lattice produces a unique band structure with conduction and valence bands meeting at the Dirac points (K and K′). Near these points, the energy–momentum relationship is linear, leading to energy:

E(k)=ℏvF|k|E(k) = \hbar v_F |k|E(k)=ℏvF|k|

where vFv_FvF ≈ 10610^6106 m/s is the Fermi velocity (Castro Neto et al., 2009). The lack of a bandgap is responsible for its ambipolar behavior, where both electrons and holes contribute to conduction.

2.2. Quantum Conductance

Quantum conductance in ballistic graphene relates to the Landauer formula:

G=2e2hT(E)G = \frac{2e^2}{h} T(E)G=h2e2T(E)

where T(E)T(E)T(E) is the transmission probability at energy *E*. In ideal graphene, conductance scales with the number of channels and transmission approaches unity over short distances (Tworzydło et al., 2006).

3. CHARGE TRANSPORT MECHANISMS

Graphene's charge transport is governed by competing scattering mechanisms:

3.1. Ballistic Transport

At low temperatures and short channel lengths (<1 μm), carriers may undergo ballistic transport with minimal scattering. Mobility (>200,000 $cm^2/V \cdot s$) demonstrates near-ballistic behavior at low defect densities (Du et al., 2008).

3.2. Phonon Scattering

At room temperature, phonons—lattice vibrations—dominate scattering. Acoustic phonons contribute to charge carrier relaxation, reducing mobility. Optical phonons become significant at high bias conditions (Sarma et al., 2011).

3.3. Impurity and Substrate Effects

Graphene supported on SiO_2 suffers from charged impurities and surface roughness that scatter carriers. Encapsulation in hexagonal boron nitride (h-BN) reduces such effects, enhancing mobility (Dean et al., 2010).

4. EXPERIMENTAL TECHNIQUES FOR MEASURING TRANSPORT

4.1. Four-Probe Measurements

Four-probe configurations reduce contact resistance effects, enabling accurate measurement of sheet resistance and mobility. Gate voltage sweeps reveal ambipolar conductance and Dirac point shifts.

4.2. Quantum Hall Effect

At low temperatures and high magnetic fields, graphene exhibits an unusual half-integer quantum Hall effect:

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σxy=±4e2h(n+12)\sigma_{xy} = \pm \frac{4e^2}{h}(n + \frac{1}{2})σxy=±h4e2(n+21)
This reflects spin and valley degeneracy and massless carrier behavior (Zhang et al., 2005).

5. GRAPHENE DEVICES: DESIGNS AND PERFORMANCE

5.1. Graphene Field-Effect Transistors (GFETs)

GFETs exploit ambipolar conduction for high-speed switches. While lacking a bandgap limits ON/OFF ratios compared to silicon, GFETs exhibit superior cutoff frequencies (>300 GHz) due to high carrier mobility (Schwierz, 2010).

5.2. Sensors and Photodetectors

Graphene's surface sensitivity enables ultra-low concentration detection of gases and biomolecules. Graphene photodetectors benefit from broadband absorption and fast response times (Xia et al., 2009).

6. CHALLENGES AND FUTURE DIRECTIONS

Despite its promise, graphene faces key challenges:

- **Absence of bandgap:** Limits logic applications. Methods like nanoribbon patterning and doping have been explored to induce gaps (Han et al., 2007).
- **Scaling and fabrication:** Reliable, low-defect large-area graphene remains a manufacturing challenge.
- **Integration with existing technology:** Interfacing with CMOS platforms requires engineered heterostructures.

Emerging directions include twisted bilayer graphene exhibiting correlated phases and superconductivity, promising novel device paradigms.

7. CONCLUSION

Graphene's quantum transport properties—ballistic conduction, high mobility, and ambipolar behavior—make it a foundational platform for future electronic and photonic devices. Continued advancement in synthesis, substrate engineering, and heterostructure design will propel graphene from experimental systems to commercial technologies.

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