

Chapter 8

Mechanisms of Electrical Conductivity in Carbon Nanotubes and Graphene

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ABSTRACT

There is enormous interest in carbon nanomaterials due to their exceptional physical properties, from the perspective of science and engineering of materials applied to the electronics industry. Significant progress has been made towards understanding the mechanisms of electrical conductivity of carbon nanotubes and graphene. However, scientists around the world continue studying these mechanisms to exploit them fully in different electronic applications with a high technological impact. This chapter discusses the mechanisms of electrical conductivity of both nanomaterials, analyzes the present implications, and projects its importance for future generations of electronic devices. In particular, it is important to note that different mechanisms may be identified when these nanomaterials are used individually, when they are incorporated as fillers in composite materials or hybrid materials, or even when they are doped or functionalized. Finally, other electrical variables with important role in electrical conductivity of these materials are also explored.

INTRODUCTION

In the search for alternative materials to semiconductor materials used commonly in electronics such as silicon, germanium, gallium arsenide, gallium phosphide, etc., researchers around the world have been developing carbon-based materials with ideal electrical properties to operate with high efficiency in nanoelectronics. Carbon nanotubes (CNTs) and graphene represent two technological options for these innovative materials, which can be used either individually, or in composite or hybrid materials as electrical filler. They offer electrical properties such as high electrical conductivity and high dielectric permittivity, which can be tuned by synthesis, doping, functionalization, etc. These qualities can be exploited in applications such as interconnects, electronic devices such as field-effect transistors, batteries, fuel

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cells, supercapacitors (Yusoff, 2015), electrodes for touch screens (Zheng, 2015), flexible transparent memory circuits, materials for electrostatic discharge (ESD) and electromagnetic interference (EMI) shielding (Vargas-Bernal, 2015c), etc.

This chapter will review the most important electrical transport mechanisms associated with the electrical conductivity of carbon nanotubes and graphene, since these can be used in individual way or within composite or hybrid materials, with the aim of discovering the origin of their extraordinary electrical properties than have been used, are being used, and will be used in diverse technological applications. The effect of a set of technical variables related with electrical behavior of carbon nanotubes and graphene, and associated with the electrical conductivity such as band gap, intrinsic mobility, percolation threshold, electrical conductivity, and dielectric permittivity, are also discussed.

BACKGROUND

Electrical conduction can be defined as the movement of electrical carriers through a transmission medium. A transmission medium is a material substance that transmits or guides through of itself electromagnetic waves. This movement of carriers generates an electrical current in response to an electrical field. Moreover, in each type of material, different mechanisms of electrical conduction are presented. For example, electrons are electrical carriers in metals, and the Ohm's law is the mathematical relationship used to determine the mathematical expression between the electrical current (I) and the applied potential difference (V) between a pair of ends of the material (Bird, 2014):

$$I = \frac{V}{R} = VG, \quad (1)$$

where R and G are electrical resistance and electrical conductance, respectively. Thus, one or more electrons from each atom can move freely within the metal, since they are loosely bound to the atom in the higher level of the valence band. These electrons are incorporated to the conduction band as electrical carriers due to the potential difference, and therefore, an electrical current is generated. An electrical current is a flow of electrical charge carried out regularly by moving electrons through a medium.

Electrical conductivity (σ) also called specific conductance can be defined as the ability of a material for conducting an electrical current. In three-dimensional conductor materials, the electrical conductance can be mathematically expressed as:

$$G = \frac{A}{\rho L} = \frac{Wt}{\rho L} = \frac{Wt\sigma}{L}, \quad (2)$$

where A is the cross-sectional area, L is the length, W is the width, t is the thickness, and, ρ and σ are electrical resistivity and electrical conductivity of the material, respectively. Two different types of electrical conductivities can be found in materials: surface conductivity and bulk conductivity. Surface conductivity or sheet conductance quantifies the electrical conductance of thin films with uniform thickness nominally. This represents the rate between the electrical conductivity of the material, and the thickness of the thin film. Therefore, it is mathematically expressed as:

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