Instytut Fizyki Molekularnej Polskiej Akademii Nauk

Praca doktorska

# Właściwości magnetyczne czystego i modyfikowanego grafenu

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Poznań 2017

## Abstract

The presented PhD dissertation contains findings from the research of the magnetic properties of pure graphene, thermally and chemically reduced graphene oxides, graphene oxide and partially hydrogenated graphene. The main purpose of this research was to determine the conditions in which graphene magnetism occurs, observation of theoretically predicted magnetism of graphene and its derivatives and to prove that magnetism is an intrinsic property of the studied materials. Another purpose was to determine the nature of magnetic ordering for each material and to define stability of the observed phenomena.

To study magnetic properties we used Ferromagnetic Resonance, recording spectra on Electron Paramagnetic Resonance spectrometer, and vibration magnetometry VSM and SQUID (Superconducting Quantum Interference Device). Magnetometric measurements allowed us to establish dependencies of magnetization on temperature and external magnetic field. Additionally, based on the analysis of the ferromagnetic resonance spectra recorded in the temperature range between 4.2 and 300 K the temperature dependencies of ferromagnetic resonance signal intensities were obtained. Intensity of this signal is directly proportional to magnetic susceptibility. The magnetic research was complemented with several other methods (Scanning Electron Microscopy, X-ray Photoelectron Spectroscopy, Infrared Spectroscopy, Atomic Force Microscopy in topographic and Kelvin probe modes) to properly characterize studied materials.

High purity of the studied materials confirmed by various methods and internal consistency of the results allowed us to establish that the observed magnetism is an intrinsic property of those materials. Comparison of results of both ferromagnetic resonance and magnetometric methods provided us with a complete picture of magnetic orderings in graphenic materials. Observation of one-dimensional edge magnetism requires not only vacuum but also spatial separation of the graphene flakes. The edge ferromagnetism of graphene oxide paper exists only due to unsaturated edge states in closed pores of this material. Relative stability of two-dimensional ferromagnetic ordering in partially hydrogenated graphene is associated with low efficiency of RKKY (Ruderman-Kittel-Kasuya-Yoshida) interactions due to appearance of magnetic defects in the unhydrogenated regions.

Magnetic properties of studied materials are generally in agreement with theoretical predictions. However, in some cases, the observed phenomena have not been earlier foreseen. For example, diffused paramagnetic centers on the surface of chemically reduced graphene oxide or partially hydrogenated graphene tend to order ferromagnetically. Additionally, we were able to demonstrate that surface disorder (defects and functional groups) stabilizes ferromagnetic ordering.