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Graphene Quantum Dots

Springer

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Preface

When one of us, PH, arrived at the University of Kentucky to start his Ph.D. with K. Subbaswamy in 1981, graphene in intercalated graphite (GIC) was all the rage. He was given a paper by Wallace describing electronic properties of graphene and graphite and told to go and talk to Peter Eklund's group who was measuring optical properties of intercalated graphite next door. The next 4 years were exciting, with the standing room only at the graphite sessions at the March Meetings, it seemed that future belonged to graphene. However, the excitement did not last forever, and after completing Ph.D. PH went on to work on another class of artificially made materials, semiconductor heterostructures. The last 30 years has seen the ability of controlling semiconductors moving from heterojunctions and superlattices to three-dimensional control and making semiconductor quantum dots. Today, semiconductor quantum dots enable, for example, transistors based on spins of single electrons, sources of single and entangled photons, efficient quantum dot lasers, biomarkers, and solar cells with improved efficiency.

In this monograph, we describe a new class of quantum dots based on graphene, a single atomic layer of carbon atoms. Since the isolation of a single graphene layer by Novoselov and Geim, we became interested in using only graphene, instead of different semiconductors, to create graphene quantum dots. By controlling the lateral size, shape, type of edge, doping level, sublattice symmetry, and the number of layers we hoped to engineer electronic, optical, and magnetic properties of graphene. Our initial exploration started in 2006, but came into focus later after we became aware of a beautiful work by Ezawa and by Palacios and Fernandez-Rossier on triangular graphene quantum dots. This work emphasized the role of sublattice symmetries and electron-electron interactions in engineering magnetic properties of graphene nanostructures, opening the possibility of creating an interesting alternative to semiconductor spintronics. The second intriguing possibility offered by graphene is that it is a semimetal with zero-energy gap. By lateral size quantization the gap in graphene quantum dots can be tuned from zero to UV. By contrast, in semiconductors, the energy gap can only be larger than the energy gap of the bulk material. In principle, graphene quantum dots allow for design of material with the desired energy gap. The exciting possibility of convergence and seamless integration of electronics, photonics, and spintronics in a single material, graphene, could lead to a new area of research, carbononics.

These were some of the ideas we embarked to explore when two of us, ADG and PP joined the Quantum Theory Group led by PH at the NRC Institute for Microstructural Sciences in 2008. The monograph is based largely on the Ph.D. thesis of one of us, Pawel Potasz, shared between NRC and Wrocław University of Technology.

After Introduction in Chap. 1, Chap. 2 describes the electronic properties of bulk graphene, a two dimensional crystal, including fabrication, electronic structure, and effects of more than one layer. In Chap. 3 fabrication of graphene quantum dots is described while Chap. 4 describes single particle properties of graphene quantum dots, including tight-binding model, effective mass, magnetic field, spin-orbit coupling, and spin Hall effect. The role of sublattice symmetry and the emergence of a degenerate shell of electronic states in triangular graphene quantum dots is described. The bilayers and rings, including Möbius ring with topology encoded by geometry, are described. Chapter 5 introduces electron-electron interactions, including introduction to several tools such as Hartree–Fock, Hubbard model and Configuration Interaction method used throughout the monograph. Chapter 6 discusses correlations and magnetic properties in triangular graphene quantum dots and rings with degenerate electronic shells, including existence of magnetic moment and its melting with charging, and Coulomb and Spin Blockade in transport. Chapter 7 focuses on optical properties of graphene quantum dots, starting with tight-binding model and including self-energy and excitonic corrections. Optical spin blockade and optical control of the magnetic moment is described. Comparison with experimental results obtained for colloidal graphene quantum dots is also included.

We hope the monograph will introduce the reader to this exciting and rapidly evolving field of graphene quantum dots and carbononics.

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