Computational and Informatics Research Framework of Transport Phenomenon and devices based on Graphene Material System: for Optical Information processing,Computing & Applications – A Review.

A promising Material System for all valid reasons in the domain of Photonics Industry.

(Information Collected based on my experiences in both hi-tech industry and academia so far)

Nature of implementation : Could be Theoretical,Experimental or a Combination of both.

Description of the research lines for possible implementations for further research:

The special nature of graphene carriers produces transport properties very peculiar. The minimum conductivity [1], absence of localization effects [2], large electron free paths [3], and high mobilities [4] are some of these characteristics. Understanding the transport properties is crucial to improve the graphene performance for various applications.

Disorder has important effects on transport and it is known to be present in all samples. Vacancies, voids, topological defects such as dislocations, pentagons or heptagons, and adsorbed atoms have been experimentally observed [5]. Defects and impurities are sources of scattering processes with important implications on electronic and magnetic properties.

Ripples, corrugation and strain affect the low-energy physics of graphene. In fact , effective gauge fields arise from the topology of the lattice, and modify elementary properties.Recently, spin transport has attracted the attention of several research groups. Spin coherence lengths of the order of micrometers have been measured in graphene-based spin-valves at room temperature [6-17]. Larger coherence lengths can be obtained by improving the spin injection efficiency [7-19].

Graphene is a potential material for spintronics devices due to the weakness of the spin-orbit coupling and near absence of nuclear magnetic moments. Another interesting issue related to the spin-orbit interaction in graphene is the quantum spin Hall effect and the topological insulator state [8-42].

Graphene nanoribbons (GNR), stripes of graphene of width of the order of nanometers and much larger length, present promising potential applications in electronics and spintronics. The shape of the ribbon edges (zigzag or armchair type [9-35]) define the basic behavior of the system. Chemical and structural modifications of graphene edges pave the path to design GNR-based devices.

One of the most active research fields in graphene physics is the study of its properties in presence of magnetic fields. The sequence of transversal conductivity plateaus in the quantum Hall effect (QHE) regime was one of the first evidences of the Dirac-like electronic spectrum [10,11,34-48]. Two main aspects make the integer QHE in graphene different when compared to conventional semiconductor systems.

First, the survival of the QHE plateaus at room temperature [12], attributed to the large cyclotron gap for relativistic fermions. Moreover, the high electronic mobilities, which do not change appreciably as a function of temperature for devices on substrate, imply high quality of Landau quantization, contributing as a positive factor. Second, the existence of a zero-energy Landau level shared by electrons and holes, responsible to the plateaus sequence [13]. Another important aspect is the role of interactions in the presence of magnetic fields, specially after the discovery of the fractional QHE in suspended devices [14,15,23-47].

The elastic and morphological properties of graphene are even more interesting than the electronics. Despite its enormous lattice rigidity, the suspended graphene samples exhibit an apparently random spontaneous curvature that can be visualizedas ripples of various sizes. These have been observed in experiments with transmission electron microscopy [1-3 & 41] and in scanning tunneling microscopy [2,3].

The origin of the ripples remains one of the open problems in graphene up to today. The membrane aspect of graphene has been explored in [4-17].Since the electronic properties of graphene are dictated by the special geometry and topology of the Honeycomb lattice, a very important issue is how the deformations of the lattice affect these.

Topological defects formed by substitution of a hexagon by another polygon (pentagons and heptagons are the most common) as well as dislocations (pentagon-heptagon pairs) and the so called Stone Wells defects are very common in nanotubes and fullerenes. They have been produced in graphene with electron transmisson spectroscopy. The early studies made in [5-27] to model the electronic structure of the fullerenes gave rise to the modern approach of the gauge fields modelling of elastic deformations.

The modelling of C60 as the Dirac equation in a sphere also opened the way of studying the electronic properties of curved samples with the techniques of quantum field theory in curved space,a technique lead by our group.

The Coulomb interaction among the electrons in graphene gives rise to collective modes (plasmons) and screening when the Fermi level is shifted away from the Dirac points [1]. Inter-band polarization effects lead to a screening similar to that of an insulator, while the intra-band processes lead to a metallic-like screening. The situation is different if the graphene electrons are exposed to a strong magnetic field that quantizes their kinetic energy into nonequidistant Landau levels [2,3]. One of the most prominent consequence of this LL quantization is a strong LL mixing which leads to the formation of linearly dispersing plasmon-type modes, specific of graphene and which are absent in a standard two-dimensional electron gas with a parabolic band dispersion [4].

References :

[1] Y.-W. Tan, Y. Zhang,1, K. Bolotin, Y. Zhao, S. Adam, E. H. Hwang, S. Das Sarma, H. L. Stormer, and P. Kim, *Measurement of Scattering Rate and Minimum Conductivity in Graphene*, Phys. Rev. Lett. 99, 246803 (2007).

[2] S. V. Morozov, K. S. Novoselov, M. I. Katsnelson, F. Schedin, L. A. Ponomarenko, D. Jiang, and A. K. Geim, *Strong Suppression of Weak Localization in Graphene*, Phys. Rev. Lett. 97, 016801 (2006).

[3] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, *Electric Field Effect in Atomically Thin Carbon Films*, Science 306, 666 (2004).

[4] K.I. Bolotin, K.J. Sikes, Z. Jiang, M. Klima, G. Fudenberg, J. Hone, P. Kim, and H.L. Stormer, *Ultrahigh electron mobility in suspended graphene, Solid State Communications 146, 351-355 (2008).*

*[5] Jannik C. Meyer, C. Kisielowski, R. Erni, Ma*rta D. Rossell, M. F. Crommie, and A. Zettl, *Direct Imaging of Lattice Atoms and Topological Defects in Graphene Membranes*, Nano Lett. Vol. 8, No. 11 (2008).

[6] Nikolaos Tombros, Csaba Jozsa, Mihaita Popinciuc, Harry T. Jonkman, and Bart J. van Wees,*Electronic spin transport and spin precession in single graphene layers at room temperature*, Nature448, 571 (2007).

[7] Wei Han, K. Pi, K. M. McCreary, Yan Li, Jared J. I. Wong, A. G. Swartz, and R. K. Kawakami,*Tunneling Spin Injection into Single Layer Graphene*, Phys. Rev. Lett. 105, 167202 (2010).

[8] C. L. Kane and E. J. Mele, *Quantum Spin Hall Effect in Graphene*, Phys. Rev. Lett. 95, 226801 (2005).

[9] Mitsutaka Fujita, Katsunori Wakabayashi, Kyoko Nakada and Koichi Kusakabe, *Peculiar Localized State at Zigzag Graphite Edge*, J. Phys. Soc. Jpn. 65, 1920 (1996).

[10] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov, *Two dimensional gas of massless Dirac fermions in graphene*, Nature438, 197 (2005).

[11] Y. Zang, Y.-W. Tan, H. L. Stormer, and P. Kim, *Experimental observation of the quantum Hall effect and Berry’s phase in graphene*, Nature 438, 201 (2005).

[12] K. S. Novoselov, Z. Jiang, Y. Zang, S. V. Morozov, H. L. Stormer, U. Zeitler, J. C. Maan, G. S. Boebinger, P. Kim, and A. K. Geim, *Room-Temperature Quantum Hall Effect in Graphene*, Science315, 1379 (2007).

[13] V. P. Gusynin and S. G. Sharapov, *Unconventional integer quantum Hall effect in graphene*, Phys. Rev. Lett. 95, 146801 (2005).

[14] X. Du, I. Skachko, F. Duerr, A. Luican, and E. Y. Andrei, *Fractional quantum Hall effect and insulating phase of Dirac electrons in graphene*, Nature 462, 192 (2009).

[15] K. I. Bolotin, F. Ghahari, M. D. Shulman, H. L. Stormer, and P. Kim, *Observation of the fractional quantum Hall effect in graphene*, Nature 462, 196 (2009).

[16] P. Esquinazi, D. Spemann, R. Höhne, A. Setzer, K.H. Han, and T. Butz, Induced magnetic ordering by proton irradiation in graphene, Phys. Rev. Lett.91, 227201 (2003).

[17] M. M. Ugeda, I. Brihuega, F. Guinea.and J. M. Gómez-Rodríguez, Missing atom as a source of carbon magnetism, Physical Review Letters 104, 096804 (2010)

[18] R. R. Nair, I-Ling Tsai, M. Sepioni, O. Lehtinen, J. Keinonen, A.V. Krsheninnikov, A.H. Castro Neto, M.I. Katsnelson, A.K. Geim, and I.V. Grigorieva, Dual origin of defect magnetism in graphene and its reversible switching by molecular doping, Nature Commun. 4, 2010 (2013)

[19] Nikolaos Tombros, Csaba Jozsa, Mihaita Popinciuc, Harry T. Jonkman, and Bart J. van Wees, Electronic spin transport and spin precession in single graphene layers at room temperature, Nature 448, 571 (2007)

[20] Kathleen M. McCreary, Adrian G. Swartz, Wei Han, Jaroslav Fabian, and Roland K. Kawakami, Magnetic Moment Formation in Graphene Detected by Scattering of Pure Spin Currents, Physical Review Letters 109, 186604 (2012)

[21] C. L. Kane and E. J. Mele, Quantum Spin Hall Effect in Graphene, Phys. Rev. Lett. 95, 226801 (2005)

[22] Z. Y. Zhu, Y. C. Cheng, and U. Schwingenschlogl, Giant spin-orbit-induced spin splitting in two-dimensional transition-metal dichalcogenide semiconductors, Physical Review B 84, 153402 (2011).

[23] Di Xiao, Gui-Bin Liu, Wanxiang Feng, Xiaodong Xu, and Wang Yao, Coupled Spin and Valley Physics in Monolayers ofMoS2 and Other Group- VI Dichalcogenides, Phys. Rev. Lett. 108, 196802 (2012).

[24] Intervalley Scattering, Long-Range Disorder, and Effective Time-Reversal Symmetry Breaking in Graphene, A. F. Morpurgo and F. Guinea, Phys. Rev. Lett. 97, 196804 (2006).

[25] Spin-orbit coupling in curved graphene, fullerenes, nanotubes, and nanotube caps, Daniel Huertas-Hernando, F. Guinea, and Arne Brataas, Phys. Rev. B 74, 155426 (2006).

[26] Pseudomagnetic Fields and Ballistic Transport in a Suspended Graphene Sheet, M. M. Fogler, F. Guinea, and M. I. Katsnelson, Phys. Rev. Lett. 101, 226804 (2008).

[27] New Type of Vacancy-Induced Localized States in Multilayer Graphene, Eduardo V. Castro, María P. López-Sancho, and María A. H. Vozmediano, Phys. Rev. Lett. 104, 036802 (2010).

[28] M. A. H. Vozmediano, M. P. López-Sancho, T. Stauber, and F. Guinea, Local defects and ferromagnetism in graphene layers, Physical Review B 72, 155121 (2005).

[29] Daniel Huertas-Hernando, F. Guinea, and Arne Brataas, Spin-orbit coupling in curved graphene, fullerenes, nanotubes, and nanotube caps, Physical Review B 74, 155426 (2006).
[30] L. Chico, M. P. López-Sancho, and M.C. Muñoz, Curvature-induced anisotropic spin-orbit splitting in carbon nanotubes, Physical Review B 79 (2009) 235423-1-6.

[31] Maria P. López-Sancho, Fernando de Juan, and María A. H. Vozmediano, Magnetic moments in the presence of topological defects in graphene, Physical Review 79, 075413 (2009).

[32] E. V. Castro, M.P. López Sancho, and M.A.H. Vozmediano, Pinning and switching of magnetic moments in bilayer graphene, New Journal of Physics 11, (2009) 095017-1-9.

[33] A. H. Castro Neto and F. Guinea, Impurity-Induced Spin-Orbit Coupling in Graphene, Physical Review Letters 103, 026804 (2009).

[34] M. M. Ugeda, I. Brihuega, F. Guinea.and J. M. Gómez-Rodríguez, Missing atom as a source of carbon magnetism, Physical Review Letters 104, 096804 (2010).

[35] M. P. López-Sancho and M.C. Muñoz, Intrinsic spin-orbit interactions in flat and curved graphene ribbons, Physical Review B 83, (2011) 075406-1-9.

[36] P. Haase, S. Fuchs, T. Pruschke, H. Ochoa, and F. Guinea, Magnetic moments and Kondo effect near vacancies and resonant scatterers in graphene, Physical Review B 83, 241408(R) (2011)

[37] H. Ochoa and R. Roldán, Spin-orbit-mediated spin relaxation in monolayer MoS2 , Phys. Rev. B 87, 245421 (2013)

[38] B. Wunsch, T. Stauber, F. Sols, and F. Guinea, New J. Phys. 8 (2007) 318.

[39] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov, Nature 438 (2005) 197.

[40] Y. Zhang, Y.-W. Tan, H. L. Stormer, and P. Kim, Nature 438 (2005) 201.

[41] R. Roldán, J.-N. Fuchs, and M. O. Goerbig, Phys. Rev. B 80 (2009) 085408.

[42] “Spin connection and boundary states in a topological insulator”V. Parente, P. Lucignano, P. Vitale, A. Tagliacozzo and F. Guinea,Phys. Rev. B 83, 075424 (2011)

[43] “Tunable Casimir Repulsion with Three-Dimensional Topological Insulators”
Adolfo G. Grushin, Alberto Cortijo, Phys. Rev. Lett. 106, 020403 (2011), See related focus story!

[44] “Topological Fermi Liquids from Coulomb Interactions in the Doped Honeycomb Lattice”
Eduardo V. Castro, Adolfo G. Grushin, Belén Valenzuela, María A. H. Vozmediano, Alberto Cortijo and Fernando de Juan,Phys. Rev. Lett. 107, 106402 (2011)

[45] “Fields radiated by a nanoemitter in a graphene sheet” A. Yu. Nikitin, F. Guinea, F. J. Garcia-Vidal and L. Martin-Moreno,Phys. Rev. B 84, 195446 (2011)

[46] Dynamical polarization of graphene at finite doping, B. Wunsch, T. Stauber, F. Sols, and F. Guinea,New Journal of Physics 8, 318 (2006).

[47] Damping pathways of mid-infrared plasmons in graphene nanostructures, H. Yan, T. Low, W. Zhu, Y. Wu, M. Freitag, X. Li, F. Guinea, P. Avouris, and F. Xia,Nature Photonics 7, 394 (2013).

[48] H. Ochoa, A. H. Castro Neto, and F. Guinea, Elliot-Yafet Mechanism in Graphene,Physical Review Letters 108, 206808 (2012).

Compiled by Dr.Nirmal . Non-Profit Academic R&D Only. Inspire Others. Self Study Purpose. [December-2015]

With Sincere Thanks to all my Mentors + Collaborators + Friends. Refs used : [1] – [48].