Open Access

Recent Progress in Materials

LIDSEN Publishing Inc.

Review

Advances in Quantum Properties of Graphene and Derivatives Applied to Functional Nanomaterials and Metamaterials

A. Guillermo Bracamonte [1, 2, 3, *]

1. Departement de chimie et Centre d'optique, photonique et laser (COPL), Université Laval, Québec (QC), G1V 0A6, Canada; E-Mails: gbracamonte@fcq.unc.edu.ar; guillermobrac@yahoo.ca
2. Instituto de Investigaciones en Físicoquímica de Córdoba (INFIQC), Departamento de Química Orgánica, Facultad de Ciencias Químicas, Universidad Nacional de Córdoba. Ciudad Universitaria, 5000 Córdoba, Argentina
3. University of Akron, Institute of Polymer Science and Engineering; and NASA Astrobiology Institute, Ohio, United States

* **Correspondence:** A. Guillermo Bracamonte; E-Mails: gbracamonte@fcq.unc.edu.ar; guillermobrac@yahoo.ca

Academic Editor: Vardan Apinyan

Special Issue: Quantum Mechanics in Solid State Systems

Recent Progress in Materials
2023, volume 5, issue 1
doi:10.21926/rpm.2301008

Received: December 30, 2022
Accepted: February 06, 2023
Published: February 13, 2023

Abstract

In the present work we describe the most important quantum properties of graphene and derivatives recently published. We discuss how these properties were incorporated into varied hybrid materials such as substrates for specific tuning of matter to track varied quantum signals. Their potential applications were analyzed from nanomaterial and nanotechnology. In particular graphene, its derivatives and other carbon-based allotropes were chosen due to their special chemical structure and properties from the nanoscale to larger lengths, according to specific applications. As expected, these carbon-based and related materials' highly ordered and condensed electronic configuration showed particular electronic properties below the nanoscale. Thus, we discussed the generation of pseudo-

© 2023 by the author. This is an open access article distributed under the conditions of the Creative Commons by Attribution License, which permits unrestricted use, distribution, and reproduction in any medium or format, provided the original work is correctly cited.

electromagnetic fields and conduction bands. This particular property could also interact with different quantized energy levels and quantum properties, such as those focused on: i) Dirac electron interaction and conduction, ii) anomalous quantized hall effects, iii) magnetic effects, iv) excitons, v) polaron generations, d vi) Fermi and Landau levels. These different phenomena were discussed about the particular topological states of graphene by tuning their 3D chemical structures. Therefore, quantum phenomena and their possible modifications such as quantum interference, potential improvements and encrypted signal transduction were considered for applications.

Keywords
Topological states of graphene; quantum states; dirac electron conduction; fermi level interaction; polaron; exciton; electronic conductions; pseudo-electromagnetic fields; enhanced energy mode coupling

1. Introduction

In this short review we discuss a high-impact research field related to quantum properties where graphene could participate in developing variable quantum properties with potential applications and high technological perspectives such as quantum computing, encryption and non-classical light generation. Thus, graphene with its high-ordered 2D material could be tuned within 3D nanomaterials where electronic confinement could generate non-classical phenomena explained by quantum physics and chemistry [1-3].

Hence, quantum properties proved interesting for a large variety of themes, such as quantum chemical calculations, particularly in astrochemistry [4], quantum computers [5], quantum memories [6], encryption [7, 8], quantum light-emitting devices [9], and even quantum communications on a global scale [10]. In the examples, different implications of hybrid materials were shown on different scales, with the generation of quantum properties from sub-atomic scales to macroscale and beyond. Therefore, the importance of developments on shorter scales should be underlined, including coherent electrical control of a single high-spin nucleus in silicon for quantum memories [11] and the interference of quantum states that could affect the quantum information processing [12], detection and resolution of macroscopic objects [13]. Different theoretical models were used for these quantum applications, such as quantum particles, photons and quantum states, in addition to multidisciplinary fields that allowed advances in quantum optics, nano-optics, micro-circuits and higher macroscale optical designs and engineering. Here, graphene and carbon allotropes could participate differently based on properties such as condensed electronic matter [14] combined with free electron orbitals [15] and pseudo-electromagnetic properties available. Thus, graphene formed by little atomic thickness showed stable chemical structures and films with semimetal properties. Their tiny overlapped valence and conductance bands showed a strong ambipolar electric field effect such as electrons and holes in high concentrations per cm square with room temperature mobility when voltage-gating increased [16]. Such properties are based on the particular electronic sp^2 orbitals that could interact among them within free spacer lengths of around 0.335 nm producing pseudo

electromagnetic fields. New electronic properties could be controlled and generated with the right excitation from 2D structures towards 3D. For example, strong pseudo-magnetic fields could be theoretically calculated in graphene more than 300 T within confined bubbles in carbon-based material [17]. Likewise, Pseudo-electromagnetic fields were recorded in 3D topology based on other semimetals [18].

Confined properties from the Nanoscale to tunable electronic properties and further developments and uses within quantum nanomaterials were discussed. Thus, on the micro-scale, we could include the control of the multi-layered deposition of graphene chemical structures on modified silica substrates for electron shuttle applications within optical and electroactive chips and devices (Figure 1) [19]. In this example, graphene was embedded in a double-gated structure enabling the system-on-chip approach. This device allowed the development of relativistic tunneling experiments such as: i) single-layer graphene, ii) gate tunable bands gaps in bi-layers and iii) tunable band overlaps by tri-layered depositions. As could be observed from the modified silica substrate many different materials are interacting in close contact from where is required proper Optical setups to stimulate the systems and record targeted interferences and signal modifications. In this manner, the control in the Nanoscale of reduced-sized Graphene structures on a highly conductive silica substrate and between gold Nanostructures led to a confined quantum set up close to the molecular level control where varied materials and properties were joined. Thus, proper excitation and detectors coupling was afforded to the different measurements recorded. In this context, the tunneling signal generated was based on the electronic interactions between all the mentioned materials; such as electromagnetic fields from graphene, gold Plasmonics, and Semiconductive properties of Silica that afforded a different material behavior non showed in comparison to the absence of some of these components. Similiarly, it could be mentioned the generation of metamaterials and new properties within varied scales dependes on the targeted study and coupled Optical set up. And in this regard, as mentioned previously, the use of different Optical setups to record varied signaling opens a huge window to propose new materials and related studies and developments based on accurate joined materials controlling from the Quantum to the Nanoscale and beyond. From another point of view and thinking on functional materials it could be proposed Nano-tools be incorporated within miniaturized instrumentation as well. So, it is just mentioned in the middle of quantum highlights and optical Quantum properties.

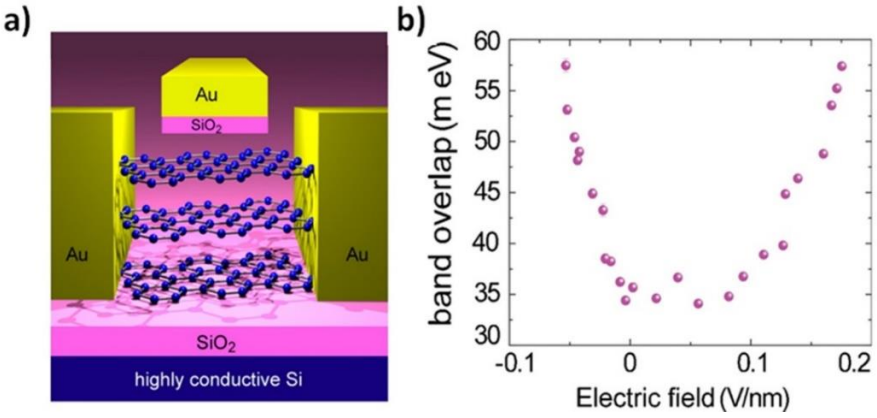

Figure 1 Scheme of modified silica substrate for gate-tunable band gaps in multi-layered graphene, b) band gap overlap (meV) vs electric field (V/nm) plots. Reprinted with permissions from S. Tarucha et al. 2011 [19], Nanotoday, Elsevier.

Accordingly, in this review we discuss a selection of the quantum properties mentioned, with potential implications and applications in nanomaterials. The main factors associated with carbon-based matter constitution and 3D architecture directly impacting the study and tuning of different quantum properties were presented and discussed. Thus, their perspectives and potential uses in the design of new nanomaterials were opened, in addition to discussing the basis of quantum graphene implications, and future perspectives in quantum and nanotechnologies [20].

2. Graphene Quantum Properties and Implications for Nanomaterials

Due to their intrinsic chemical structure associated with highly conjugated and confined electronic states, graphene and its derivatives have gained increasing interest in the field of quantum. Optical set-ups were applied to different carbon-based nanomaterials and metamaterials given the properties studied. As a result, varied resolution in quantum signaling was achieved in different potential applications. Control from the atomic level to longer distances in the nanomaterial structure could stimulate different quantum phenomena and effects. In this context, it should be mentioned that the capability to tune and incorporate electromagnetic fields and electronic densities within heterojunctions and hybrid materials could affect the quantum properties of Graphene and materials in their close surrounding. In this manner, the generation of new chemical species with different quantized energy levels could be of interest from the quantum point of view. Hence, in this section we discussed a selection of the most recent publications on the topics referred to.

Graphene showed particular electronic properties thoroughly explained by classical theoretical and experimental methodologies, such as Dirac electron interaction and conduction through different media. Dirac particles are described as similar electrons with spin-1/2 massive particles studied with interacting free electrons. Monte Carlo simulations of graphene were developed on different substrates to do that. Important information on short to long Dirac electron interactions was gathered based on Coulombic resonances within the Fermi level such as an electro-active band of conductions [21]. The faster Fermi velocity recorded and not explained by classical ab initio calculations was described. Moreover, we predicted that interactions on metallic substrates could be enhanced rather than suppressed. These mechanisms could not be applied to all systems

due to lattice-scale physics that depends on experimentally tunable parameters like strain and substrate that regularize the Dirac theory. So, structural constraints, coulombic interactions, and electromagnetic fields produced resonances within high energy-gaining media that led to enhanced velocities of quantum particles. In addition, these expectations could not be applied to UV as predicted by the Dirac theory; however, it was extended for the IR interval, opening up a new field of research and development. These interactions were evidenced in different phenomena such as the excitation of antiferromagnetic materials with varied degrees of an order [22]. Organic carbon-based materials with a highly ordered chemical structure and electronic density in 2D were compared to inorganic materials.

Twisted bilayers of graphene showed anomalous quantum behavior in the Hall Effect. In this context, for neophytes, the Hall effect of the quantum regime is related to an electronic effect within a confined space in the presence of a high-energy electromagnetic field. Therefore, in this study the phenomenon was evaluated by the external electromagnetic field of graphene. This effect was described as a precise quantized Hall resistance at zero magnetic field application in topological insulators of Bi_2Se_3 doped with magnetic atoms [23]. However, this phenomenon was produced by combining the right topology and magnetic properties from twisted bilayer graphene aligned with hexagonal boron nitride. As a result, strong intrinsic interactions of polarized electrons were developed into a single spin and valley-resolved moiré mini-band. The band interactions of inter-double layers controlled and tuned the electronic properties. Note that Moiré structures are associated not only with carbon-based metamaterials, as their nomination is associated with homogeneous and periodic atomic patterns [24]. Thus, electrical currents as small as 1 nanoamper were generated within these high electronic densities between both twisted bilayers, switching the magnetic order between different polarization states. These modifications in opposite polarization states could form electrical rewritable magnetic memories. This effect resulted from the highly ordered moiré structures with periodic layer superposition whose effect and phenomena could vary depending on the interacting properties [25]. For example, strongly correlated electrons and hybrid excitons in moiré heterostructures were recently reported [26]. These properties were generated from the collective electron dynamics and interactions in atomically thin semiconductors that formed exciton-polarons [27]. In this field new nano-optical studies could be developed with graphene and its derivatives, based on electron and energy transfer where excitons could be present [28, 29]. Electronic properties could generate new ones interacting from below the nanometer resolution and within the atomic level, particularly with these 2D carbon-based chemical structures. Strongly interacting dipolar polaritons were recently reported waveguiding through micrometer lengths [30]. Even if this phenomenon was not achieved in the presence of graphene, it should be highlighted to develop similar studies to infer its potential participation in related phenomena.

In addition, it is important to underline the relation between electronic confinement and topological spaces for tuning electronic interactions. For example, strain engineering of giant pseudo-magnetic fields, valley polarization and topological channels were developed in graphene within the nanoscale, influencing electromagnetic properties and quantum energy levels [31]. An accurate deposition of graphene obtained this nanosystem on modified substrates with Pd nanocrystals (NCs). The deformation of the deposed graphene modified the electronic strains (Figure 2 a), leading to energy variation within pseudo-electromagnetic fields (Figures 2 b, and c). The sensed variations were at Landau and Fermi levels of energies and electronic conductions

(Figures 2 d and e). In this context, the high sensitivity of Graphene interactions between inter-layers manipulating van der Waals heterostructures to manage nontrivial topology, and electron-electron interactions [32]. So, to achieve Graphene deformations and tune distortion-induced strain in graphene lattices, we considered the generation of strain-induced and scalar gauge potentials related to a distribution named Berry connection (Figures 2 f and g) [33]. Due to structural distortions, these modified gauge potentials resulted from the differences in the distances or angles between the electronic orbitals (Figure 2h). The excess scalar potential caused by these interactions could generate scattering of Dirac fermions and modifications in the local charge densities.

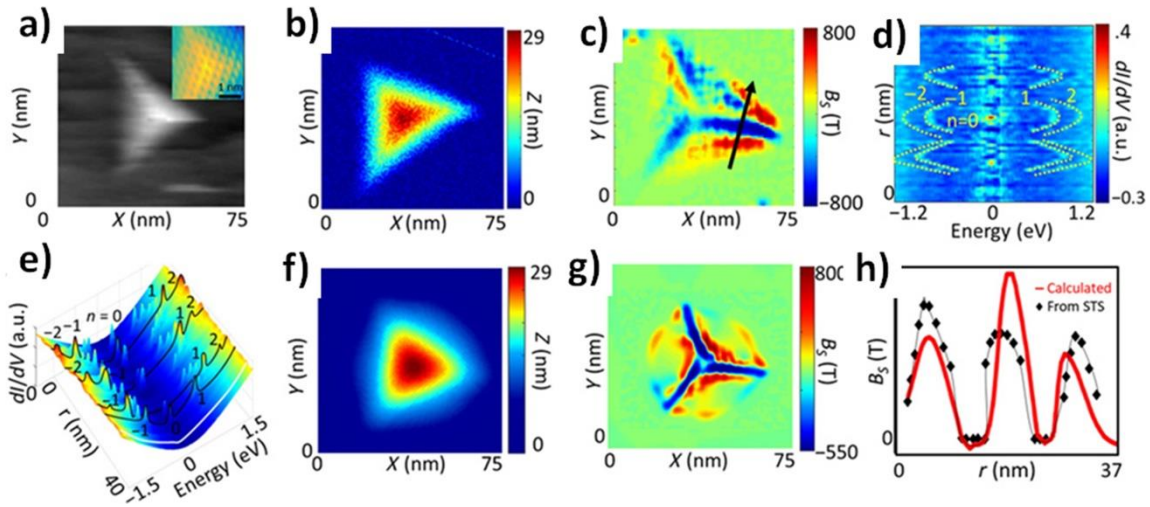

Figure 2 Topographic and spectroscopic studies of strain-induced effects on graphene at room temperature due to one Pd tetrahedron NC. a) 3D topographic images of the distorted graphene taken by AFM (main panel) and STM (inset, zoom-in image with atomic resolution). b) 3D topographic image of the distorted graphene taken by STM. c) Pseudo-magnetic field map calculated from the topography over the same area as shown in (b). d) Tunneling conductance spectral difference relative to the Dirac spectrum of strain-free graphene shown along the line cut indicated by the black arrow in (c), revealing spatially varying strengths of strain-induced pseudo-magnetic fields as found by the variations in the Landau-level separation. a.u., arbitrary units. e) Representative spectra of tunneling conductance versus energy of strained graphene along the black line cut in (c), showing quantized conductance peaks in strained regions and V-shape Dirac spectrum in strain-free regions as exemplified by the white curve located at $r \sim 36$ nm. f) 3D topographic map of graphene/h-BN deformation on an ideal tetrahedron, as computed from MD simulations described in the Supplementary Materials. g) Pseudo-magnetic field map computed from the topographic distortion in (f). h) Comparison of the absolute values of pseudo-magnetic fields $|B_S(r)|$ derived from topographic studies (red line) and from Landau-level separations in STS (black diamonds), showing overall satisfactory agreement. Here, r denotes the distance measured from the lower-left end to the upper-left end of the black arrow shown in (c). Reprinted with permissions from N. C. Yeh et al. 2020 [31], Science Advances, Sci.

In contrast, the excess of gauge potential led to pseudo-magnetic fields related to curvatures in the Berry surfaces. Therefore, through accurate control of the graphene layer interactions, variable strong electromagnetic fields could be tuned such as those greater than 300 Tesla in graphene nanobubbles [34]. Hence, via a small 3D configuration control, a highly sensitive electro-active response was produced at different levels. These phenomena showed implications such as anomalous quantum Hall effect in monolayer graphene, topological zero modes in molecular graphene assemblies, topological valley transports and across graphene wall domains [35].

Quantum Landau particles considered electronic packages of different energies according to the number of electrons [36] that could interact with electromagnetic fields. It was shown that, at room temperature, pseudo-magnetic fields, from graphene through a wafer-scale epitaxial platform, generated strain-induced Landau levels detected by angle-resolved photoemission spectroscopy [37]. In this research, two-dimensional Dirac materials are shown on wafer-scale platforms potentially applied to new designs of quantum devices. The sensitivity of these phenomena was demonstrated by the control and tuning of valley polarization, inversion in strained graphene via pseudo-Landau levels and valley splitting of real Landau levels [38]. Thus, these electronic interactions confined in quantized energy levels showed potential applications in metamaterial designs.

Electromagnetic fields from carbon-based materials within short spacer length intervals of 0.2-0.5 nm could affect additional material intercalated and coupling with other energy modes generated by materials such as tiny metallic and quantum particles. Small sizes below 5 nm diameters show particular and different properties non-explained by traditional physics; and explained by Quantum theory from Eigenvalues of varied energy modes. These types of studies at the moment there are not so many due to the major quantity being focused on the Nanoscale. Thus, non-local quantum models of the permittivity for the propagation of Plasmonic waves in quantum-confined silver nanoparticles and other types of inorganic materials are of high interest and impact on their close surrounding [39]. And in this context close interaction with other electronics, quantum behaviors, and associated phenomena such as from grapheme and highly conjugated are potential materials to generate new and different properties [40]. Thus, to study these potential metamaterials, the chemistry of surfaces joining proper excitation and detection optical systems should be controlled to track targeted quantum signaling.

To conclude this section, it is important to note that the topics discussed could be extended to other systems such as chemical modification of regular patterned structures by incorporating single atoms and molecules that could modify their quantum properties. Here we can include the design and synthesis of graphene derivatives [41] and topological engineering of molecular Graphenoids [42] and theoretical calculations such as the Density Functional Theory of atoms and molecules [43]. Hence, a focused multi-disciplinary approach could be adopted.

3. Design of Hybrid Graphene and Metamaterials with Quantum Implications

Quantum properties from graphene-based materials also need to be addressed here. In this perspective, it should be led to the know-how to control carbon-based materials by wet chemistry methods and coupled to high-impact technological set-ups for targeted applications with laser-assisted techniques. Thus, quantum implications could be transferred from the nano- and micro- to the macroscale by designing new high-impact nanomaterials and metamaterials. Many of these

developments have not yet been achieved, although recent reports suggest potential developments of approaches to address targeted applications. To design a bottom-up approach, the chemical surface modification of graphene should be considered. Hence, their relatively highly stable and inert chemical structure could be modified by wet chemical synthesis of reduced graphene oxide. For example, controlling the exfoliation of multi-layer from graphite could be achieved with strong oxidant agents [44]. Reduced graphene oxide was obtained directly from graphite in a solution of potassium permanganate and concentrated sulfuric acid with ultra-sonication assistance. A 0.36 nm thickness of graphite oxide was achieved, allowing acceptable dispersion in aqueous solutions; this was attained by combining variable strong oxidant solutions such as HNO_3/H_2SO_4 and implementing thermal or microwave methodologies [45]. Thus, from the synthesis of graphene, surfaces could be modified by covalent and non-covalent interactions in the design of advanced and functional nanomaterials, as in 2D modifications of electrodes with a direct impact on the next generation of energy conduction and storage devices [46, 47]. It should also be noted that considering oxide graphene layers as versatile chemical surfaces could be their surfaces with additional conductive molecules, such as polythiophene [48], and semi-conductive materials [49]. The incorporation of nanoparticles [50, 51] showed particular properties from the nanoscale with different developments such as single electron transfer detection [52, 53] towards improved hybrid materials and metamaterials for energy applications. And in this context in order to understand the particular electronic behavior of Graphene; it should be highlighted the capability of this highly ordered chemical structure to interact with its close surrounding such as between two electrodes for low electronic conductions at the level of single electron detection. This phenomenon was possible due to Graphene containing a large number of rings having a zero energy gap between the conduction and valence bands showing by this manner a semimetallic behavior with a weak gate effect (Figure 3). Proper chemical modifications could also tune these particular properties from 2D structures. Thus, hybrid-modified materials could improve already developed and existing properties in the graphene market. In this context it is possible to design chemical modifications to incorporate multi-material compositions. These different materials could also be considered from the molecular level to the quantum and Nanoscale. Here, it is important to note the importance of wet and solid state chemistry applying different methodologies such as within colloidal dispersions and Laser based Lithography techniques.

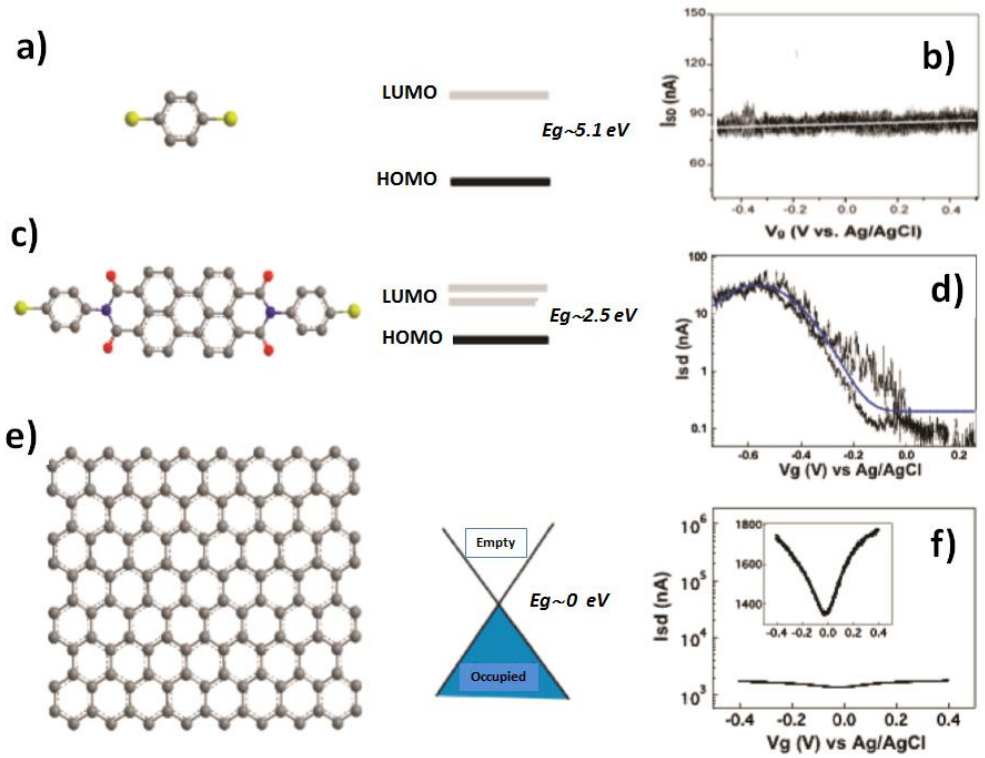

Figure 3 Molecular structures, energy diagrams, and electrochemical gate effects of benzenedithiol, PTCDI, and a graphene sheet: a) Benzenedithiol (containing a single benzene ring) has a large LUMO-HOMO gap (5.1 eV) and is "insulating" with a weak gate effect (b). c) The LUMO-HOMO gap of PTCDI (containing seven rings) is 2.5 eV, and the molecule is "semiconducting" with a large gate effect (d). e) Graphene (containing a large number of rings) has a zero energy gap between the conduction and valence bands and shows semimetallic behavior with a weak gate effect (f). Reprinted with permissions from Chen et al. 2009 [52], Accounts of Chemical Research, RSC.

In addition, Ferroelectrics [54], carbon allotropes [55] and chemical modifications such as dehydrogenation [56] were also added to graphene layers. From all these modifications, implicit quantum properties could be studied beyond these scales. Laser-assisted techniques could also allow the design of micro-patterning on graphene surfaces to develop electronic and photonic devices such as waveguides for chip applications [57]. Different laser techniques enabled the nano-patterning of modified 2D chemical surfaces and 3D materials to design electronic devices, and nano-electronic circuits, and the possibility of developing these patterned designs according to the specific needs of graphene oxides.

Therefore, special patterns for micro-supercapacitors, flexible electrodes, field effect transistors, and sensors, among others, could be devised. Patterned surfaces could also be tuned and modulated as sensitive for particular modifications of energy band gaps applied to enhanced conductions. In addition, by the appropriate patterned surfaces, [comma] Single Molecule Detection (SMD) approaches could be developed [58, 59].

In this context of high-impact applications, the possibility of affording new designs of quantum [60] and nanoelectronics circuits [61] for a variety of uses, such as smart responsive photonic surfaces [62], should be opened up. These are just some examples that show the importance of

developments incorporating graphene-based optical meta-materials. Despite available research into these topics, further studies are still required to develop approaches and new matter properties.

4. Future Perspectives and Discussion

As shown in previous examples, confined electrons and interactions from graphene, its derivatives and highly conjugated carbon chemical structures could lead to variable quantum states and modification of their properties. Quantum properties and related parameters could be used as valuable information to handle, tune, control, translate, transfer, store, and encrypt, with many feasible applications. This is possible due to control from the atomic, and molecular level toward higher dimensions, in addition to the appropriate instrumentation that detects and evaluates variable quantum energy states. Moreover, these quantum states and properties could interact with other materials in their surroundings, causing other effects. The modifications reported were made within quantized levels that could be transduced and measured to larger size lengths and dimensions. With the right design of materials, it is possible to develop quantum devices. By accurately tuning graphene bandgaps [63], properties such as voltage-gated electronics, photon conductions and pseudo electromagnetic fields could be generated through nanomaterials. These electronic bandgaps showed high sensitivity against different stimulations such as voltage, photon, electrical and magnetic applications. Therefore, there is great potential depending on targeted functionalities, as in the development of nanosensors [64], smart responsive photonic surfaces [65, 66], chips [67], waveguides [68], luminescence waveguiding [69-71], transistors [72], computers [73] and screens [74]. In this manner, the factor shared by all the examples discussed should be noted related to a high sensitivity by the right tuning of the material. Thus, considering how sensitive quantum states and energies were in the different studies, the capacity of graphene and its derivatives to provide concentrated electronic densities is already seen/has already been evidenced, in addition to particular physical and chemical properties such as pseudo-electromagnetic fields and conduction band. These two phenomena could be tuned in different ways and with diverse strategies, and could be added to nanomaterials to interact with and produce new properties (Figure 4). Graphene is incorporated into many applications thanks to the development of chips, and miniaturized instrumentation, especially those developed on a macro scale. The issue raised about the quantum impact should be addressed with current and ongoing research developed from technology aimed at quantum supremacy within communication, electronics, energy and computer manufacturing. Therefore, it is highlighted the main idea in the use of graphene hybrid quantum and nanomaterials, as high electron-dense material with the capability to produce electronic waves that from their movement generate electromagnetic fields; and by this manner interact with photons, varied quantum states, and quantum bits could modify their properties.

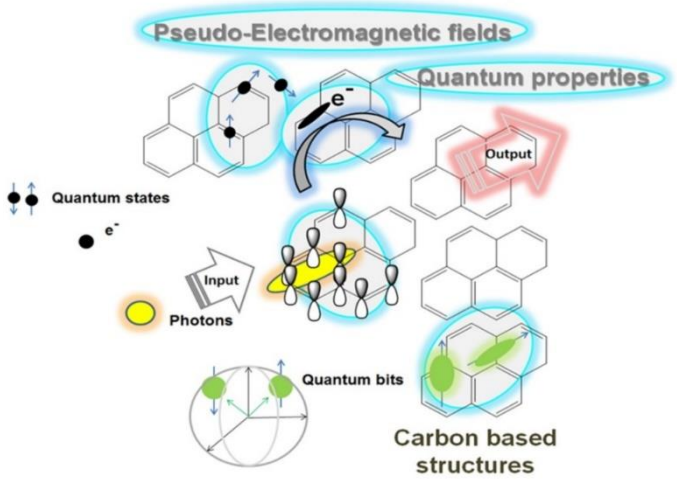

Figure 4 Schema of perspectives of quantum state and particle interaction with pseudo-electromagnetic fields, electronics and quantum properties developed from highly conjugated carbon-based nanomaterials such as graphene and its derivatives. Reprinted with permissions from G. Bracquemont and W. Hutchinson et al. 2020, Bentham publishers.

This way, pseudo-electromagnetic fields generated from single and multilayered graphene could interact in their surroundings. Plasmonic properties from the near field, within closer nanometer lengths, towards the far field within longer lengths could also be analyzed. Quantum properties could be affected by these new energy modes. Graphene showed interesting properties for strong light-matter interactions (Figure 5) [75], such as graphene-based plasmonics for varied signal modulation and sensing [76]. Their optical and electrical properties could be coupled to obtain resonators for measurements of varied modes of plasmonic signal translations, such as from photonics, phonons, excitons, quantum phenomena and enhanced emissions [77, 78]. In this context it should be highlighted the particular interest in the resonance of nano-structured and quantum dots arrays to generate different and new enhanced properties. It is known for its varied design with the incorporation of the concept of cascades, coupling, shuttling, and resonances where the phenomena are different. But, there is a factor in common with translation through space, enhancement, and energy mode transfers. These are just keywords, concepts, and ideas that could open new ones in the next generation of experiments, studies and applications.

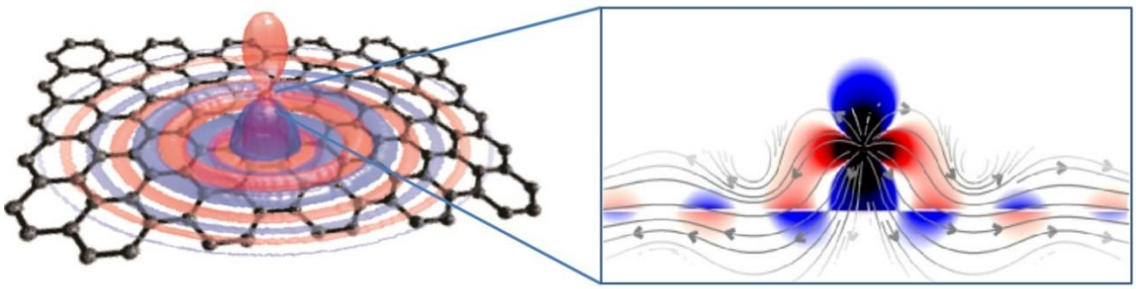

Figure 5 Scheme of long-distance graphene plasmons generated on single-layered graphene. Reprinted with permissions from Koppens et al. 2011 [75], Nano Lett.

5. Conclusions

Different quantum implications of graphene were already shown in different designs and approaches to quantum nanomaterials and metamaterials. However, combining chemical graphene modification and other quantum nanomaterials and semiconductors offers new opportunities for other types of studies. Incorporating varied optical setups could also lead to the study and development of new properties. Thus, a large number of experimental designs could be created. Shortly, new advances in the quantum and metamaterial research will be made.

From the discussed topics we could highlight that pseudo-electromagnetic fields have promising potential applications not only within quantum material. In this manner, it could also lead to plasmonic interactions in their close surrounding with molecules and other types of materials. These interactions could be generated from the high electron density of graphene and derivatives. Thus, the conjugated *sp*-orbitals could produce abnormal electronic conductions and quantum states through and across their 2D structures; for instance, gated voltage control and electron shuttling allowed graphene incorporation into varied substrates for the design and fabrication of devices. Likewise, variable quantum properties were developed and studied depending on the optical set-up applied. For instance the following properties and effects were produced by applying graphene and derivatives: i) anomalous quantum Hall effects such as topological quantum transports along the valley of twisted graphene, and across graphene surfaces; ii) strained Landau quantum energy packages; iii) tuning of quantum polarization properties; iv) localized and waveguiding plasmonics; v) Q-bits interactions and transport; and vi) quantum photonics. These results should highlight their potential uses for quantum materials, metamaterials, and nanomaterial design where quantum properties coupled to other phenomena could lead to smart responsive materials for varied targeted studies and applications. In this context it should be mentioned quantum luminescent materials such as quantum dots and meta-Nano-emitters [79]. Similarly, encryption, quantum computing developments, and communications [80] are of high interest. While within Life-Sciences the incorporation of biological media and coupling with active optical biostructures are closely related with high impact quantum biology studies [81, 82]. So, there is a huge potential in varied Research fields based on Hybrid Nanomaterials incorporating and tuning quantum properties. In this way, it is up to the Researchers, the design new materials to develop new or modified properties accompanied with insights of prototyping functional materials thinking from the molecular level towards higher sized materials depending on needs such as nano-, and micro-devices.

Acknowledgments

We are particularly grateful to University of Akron, Institute of Polymer Science and Engineering, NASA Astrobiology Institute, Ohio, United States, and to Département de Chimie and Centre d'Optique, Photonique et Laser, Québec, Canada. We also acknowledge Professor and Certified Translator Carolina Mosconi from the UNC for being part as Invited Guest Co-Editor in this ongoing special set of communications entitled "Design and Synthesis of Hybrid Graphene based Metamaterials" proposed by the author A. G. B.. Finally, we would like to acknowledge the different grants and funds which have allowed us to develop Research within Nanomaterials Science. In particular, special thanks to SECyT (Secretary of Science and Technology from the National University of Cordoba, UNC, Argentine) for the completion of the second payment of the

first Grant for Young Researchers awarded to A.G.B. at INFIQC, Dep. of Organic Chemistry, Faculty of Chemical Sciences, UNC, Argentine.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

References

1. Katsnelson MI. Graphene: Carbon in two dimensions. Mater Today. 2007; 10: 20-27.
2. Ji Z, Dervishi E, Doorn SK, Sykora M. Size-dependent electronic properties of uniform ensembles of strongly confined graphene quantum dots. J Phys Chem Lett. 2019; 10: 953-959.
3. Torres LEFF, Roche S, Charlier JC. Introduction to graphene based nanomaterials: From electronic structure to quantum transport. Cambridge: Cambridge University Press; 2020.
4. Baiano C, Lupi J, Tasinato N, Puzzarini C, Barone V. The role of state-of-the-art quantum-chemical calculations in astrochemistry: Formation route and spectroscopy of ethanimine as a paradigmatic case. Molecules. 2020; 25: 2873.
5. Bennett CH, DiVincenzo DP. Quantum information and computation. Nature. 2000; 404: 247-255.
6. Pang XL, Yang AL, Dou JP, Li H, Zhang CN, Poem E, et al. A hybrid quantum memory–enabled network at room temperature. Sci Adv. 2020; 6: eaax1425.
7. Yin J, Li YH, Liao SK, Yang M, Cao Y, Zhang L, et al. Entanglement-based secure quantum cryptography over 1,120 kilometres. Nature. 2020; 582: 501-505.
8. Asaad S, Mourik V, Joecker B, Johnson MA, Baczewski AD, Firgau HR, et al. Coherent electrical control of a single high-spin nucleus in silicon. Nature. 2020; 579: 205-209.
9. Yan Y, Gong J, Chen J, Zeng Z, Huang W, Pu K, et al. Recent advances on graphene quantum dots: From chemistry and physics to applications. Adv Mater. 2019; 31: 1808283.
10. Diamanti E. A step closer to secure global communication. Nature. 2020; 582: 494-495.
11. Asaad S, Mourik V, Joecker B, Johnson MA, Baczewski AD, Firgau HR, et al. Coherent electrical control of a single high-spin nucleus in silicon. Nature. 2020; 579: 205-209.
12. Stobińska M, Buraczewski A, Moore M, Clements WR, Renema JJ, Nam SW, et al. Quantum interferences enables constant-time quantum information processing. Sci Adv. 2019; 5: eaau9674.
13. Sequino V, Bawaj M. Quantum fluctuations have been shown to affect macroscopic objects. Nature. 2020; 583: 31-32.
14. Katsnelson MI, Novoselov KS. Graphene: New bridge between condensed matter physics and quantum electrodynamics. Solid State Commun. 2007; 143: 3-13.
15. Neto AC, Guinea F, Peres NM, Novoselov KS, Geim AK. The electronic properties of graphene. Rev Mod Phys. 2009; 81: 109.
16. Novoselov KS, Geim AK, Morozov SV, Jiang DE, Zhang Y, Dubonos SV, et al. Electric field effect in atomically thin carbon films. Science. 2004; 306: 666-669.

17. Atanasov V. Pseudo-magnetic fields in graphene in excess of 300 T: Theoretical framework. Annuaire de l'Université de Sofia "St. Kliment Ohridski", Faculté de Physique. 2011; 104: 63-70. Available from: https://www.arxiv.org/ftp/arxiv/papers/1303/1303.7373.pdf.
18. Ilan R, Grushin AG, Pikulin DI. Pseudo-electromagnetic fields in 3D topological semimetals. Nat Rev Phys. 2020; 2: 29-41.
19. Craciun MF, Russo S, Yamamoto M, Tarucha S. Tuneable electronic properties in graphene. Nano Today. 2011; 6: 42-60.
20. Lauk N, Sinclair N, Barzanjeh S, Covey JP, Saffman M, Spiropulu M, et al. Perspectives on quantum transduction. Quantum Sci Technol. 2020; 5: 020501.
21. Hesselmann S, Lang TC, Schuler M, Wessel S, Läuchli AM. Comment on "The role of electron-electron interactions in two-dimensional Dirac fermions". Science. 2019; 366: eaav6869.
22. Sen A, Suwa H, Sandvik AW. Velocity of excitations in ordered, disordered, and critical antiferromagnets. Phys Rev B. 2015; 92: 195145.
23. Serlin M, Tschirhart CL, Polshyn H, Zhang Y, Zhu J, Watanabe K, et al. Intrinsic quantized anomalous Hall effect in a moiré heterostructure. Science. 2020; 367: 900-903.
24. Le Ster M, Maerkl T, Kowalczyk PJ, Brown SA. Moiré patterns in van der Waals heterostructures. Phys Rev B. 2019; 99: 075422.
25. Admidror I. The theory of the moiré phenomenon: Volume II aperiodic layers. Springer; 2007.
26. Shimazaki Y, Schwartz I, Watanabe K, Taniguchi T, Kroner M, Imamoğlu A. Strongly correlated electrons and hybrid excitons in a moiré heterostructure. Nature. 2020; 580: 472-477.
27. Sidler M, Back P, Cotlet O, Srivastava A, Fink T, Kroner M, et al. Fermi polaron-polaritons in charge-tunable atomically thin semiconductors. Nat Phys. 2017; 13: 255-261.
28. Yankowitz M, Chen S, Polshyn H, Zhang Y, Watanabe K, Taniguchi T, et al. Tuning superconductivity in twisted bilayer graphene. Science. 2019; 363: 1059-1064.
29. Lu X, Stepanov P, Yang W, Xie M, Aamir MA, Das I, et al. Superconductors, orbital magnets and correlated states in magic-angle bilayer graphene. Nature. 2019; 574: 653-657.
30. Rosenberg I, Liran D, Mazuz-Harpaz Y, West K, Pfeiffer L, Rapaport R. Strongly interacting dipolar-polaritons. Sci Adv. 2018; 4: eaat8880.
31. Hsu CC, Teague ML, Wang JQ, Yeh NC. Nanoscale strain engineering of giant pseudo-magnetic fields, valley polarization, and topological channels in graphene. Sci Adv. 2020; 6: eaat9488.
32. Yang Y, Li J, Yin J, Xu S, Mullan C, Taniguchi T, et al. In situ manipulation of van der Waals heterostructures for twistronics. Sci Adv. 2020; 6: eabd3655.
33. Novoselov KS, Mishchenko A, Carvalho OA, Castro Neto AH. 2D materials and van der Waals heterostructures. Science. 2016; 353: aac9439.
34. Levy N, Burke SA, Meaker KL, Panlasigui M, Zettl A, Guinea F, et al. Strain-induced pseudo-magnetic fields greater than 300 tesla in graphene nanobubbles. Science. 2010; 329: 544-547.
35. Xu F, Chou PH, Chung CH, Lee TK, Mou CY. Strain-induced superconducting pair density wave states in graphene. Phys Rev B. 2018; 98: 205103.
36. Mikhailov SA. A new approach to the ground state of quantum-Hall systems. Basic principles. Phys B. 2001; 299: 6-31.
37. Nigge P, Qu AC, Lantagne-Hurtubise É, Mårsell E, Link S, Tom G, et al. Room temperature strain-induced Landau levels in graphene on a wafer-scale platform. Sci Adv. 2019; 5: eaaw5593.

38. Li SY, Su Y, Ren YN, He L. Valley polarization and inversion in strained graphene via pseudo-landau levels, valley splitting of real landau levels, and confined states. Phys Rev Lett. 2020; 124: 106802.
39. Moaied M, Ostrikov K, Palomba S. Non-local quantum plasmon resonance in ultra-small silver nanoparticles. Plasmonics. 2021; 16: 1261-1267.
40. You C, Nellikka AC, De Leon I, Magaña-Loaiza OS. Multiparticle quantum plasmonics. Nanophotonics. 2021; 9: 1243-1269
41. Liu J, Tang J, Gooding JJ. Strategies for chemical modification of graphene and applications of chemically modified graphene. J Mater Chem. 2012; 22: 12435-12452.
42. Lombardi F, Lodi A, Ma J, Liu J, Slota M, Narita A, et al. Quantum units from the topological engineering of molecular graphenoids. Science. 2019; 366: 1107-1110.
43. Parr RG. Density functional theory of atoms and molecules. In: Horizons of quantum chemistry. Dordrecht: Springer; 1980.
44. Gebreegziabher GG, Asemahegne AS, Ayele DW, Dhakshnamoorthy M, Kumar A. One-step synthesis and characterization of reduced graphene oxide using chemical exfoliation method. Mater Today Chem. 2019; 12: 233-239.
45. Singh RK, Kumar R, Singh DP. Graphene oxide: Strategies for synthesis, reduction and frontier applications. RSC Adv. 2016; 6: 64993-65011.
46. Kumar R, Sahoo S, Joanni E, Singh RK, Tan WK, Kar KK, et al. Recent progress in the synthesis of graphene and derived materials for next generation electrodes of high performance lithium ion batteries. Prog Energy Combust Sci. 2019; 75: 100786.
47. Kumar R, Joanni E, Singh RK, Singh DP, Moshkalev SA. Recent advances in the synthesis and modification of carbon-based 2D materials for application in energy conversion and storage. Prog Energy Combust Sci. 2018; 67: 115-157.
48. Yadav SK, Kumar R, Sundramoorthy AK, Singh RK, Koo CM. Simultaneous reduction and covalent grafting of polythiophene on graphene oxide sheets for excellent capacitance retention. RSC Adv. 2016; 6: 52945-52949.
49. Kumar R, Sahoo S, Joanni E, Singh RK, Yadav RM, Verma RK, et al. A review on synthesis of graphene, h-BN and MoS_2 for energy storage applications: Recent progress and perspectives. Nano Res. 2019; 12: 2655-2694.
50. Kumar R, Matsuo R, Kishida K, Abdel-Galeil MM, Suda Y, Matsuda A. Homogeneous reduced graphene oxide supported NiO-MnO_2 ternary hybrids for electrode material with improved capacitive performance. Electrochim Acta. 2019; 303: 246-256.
51. Kumar R, Macedo Jr WC, Singh RK, Tiwari VS, Constantino CJ, Matsuda A, et al. Nitrogen–sulfur co-doped reduced graphene Oxide-Nickel oxide nanoparticle composites for electromagnetic interference shielding. ACS Appl Nano Mater. 2019; 2: 4626-4636.
52. Chen F, Tao NJ. Electron transport in single molecules: From benzene to graphene. Acc Chem Res. 2009; 42: 429-438.
53. Kawasaki JK, Sharan A, Johansson LI, Hjort M, Timm R, Thiagarajan B, et al. A simple electron counting model for half Heusler surfaces. Sci Adv. 2018; 4: eaar5832.
54. Cortes-Arriagada D, Sanhueza L, Bautista-Hernandez A, Salazar-Villanueva M, Chigo Anota E. Chemical and physical viewpoints about the bonding in fullerene–graphene hybrid materials: Interaction on pristine and Fe-doped graphene. J Phys Chem C. 2019; 123: 24209-24219.

55. Escobar JC, Villanueva MS, Hernández AB, Cortés-Arriagada D, Anota EC. Interactions of B12N12 fullerenes on graphene and boron nitride nanosheets: A DFT study. J Mol Graph Model. 2019; 86: 27-34.
56. García-Hernández E, Salazar-García E, Shakerzadeh E, Chigo-Anota E. Effect of dehydrogenated hydrocarbon doping on the electronic properties of graphene-type nanosheets. Phys Lett A. 2020; 384: 126702.
57. Kumar R, Singh RK, Singh DP, Joanni E, Yadav RM, Moshkalev SA. Laser-assisted synthesis, reduction and micro-patterning of graphene: Recent progress and applications. Coord Chem Rev. 2017; 342: 34-79.
58. Sathe C, Zou X, Leburton JP, Schulten K. Computational investigation of DNA detection using graphene nanopores. ACS Nano. 2011; 5: 8842-8851.
59. Zhao S, Wu Q, Pi J, Liu J, Zheng J, Hou S, et al. Cross-plane transport in a single-molecule two-dimensional van der Waals heterojunction. Sci Adv. 2020; 6: eaba6714.
60. Schmidt FE, Jenkins MD, Watanabe K, Taniguchi T, Steele GA. A ballistic graphene superconducting microwave circuit. Nat Commun. 2018; 9: 4069.
61. Ueda K, Matsuo S, Kamata H, Baba S, Sato Y, Takeshige Y, et al. Dominant nonlocal superconducting proximity effect due to electron-electron interaction in a ballistic double nanowire. Sci Adv. 2019; 5: eaaw2194.
62. Sheibani S, Capua L, Kamaei S, Akbari SS, Zhang J, Guerin H, et al. Extended gate field-effect-transistor for sensing cortisol stress hormone. Commun Mater. 2021; 2: 10.
63. Sealy C. Nanoscale carving tunes graphene's bandgap. Nano Today. 2019; 26: 1-2.
64. Kim JT, Choi H, Shin E, Park S, Kim IG. Graphene-based optical waveguide tactile sensor for dynamic response. Sci Rep. 2018; 8: 16118.
65. Kamysbayev V, Filatov AS, Hu H, Rui X, Lagunas F, Wang D, et al. Covalent surface modifications and superconductivity of two-dimensional metal carbide MXenes. Science. 2020; 369: 979-983.
66. Riis-Jensen AC, Deilmann T, Olsen T, Thygesen KS. Classifying the electronic and optical properties of Janus monolayers. ACS Nano. 2019; 13: 13354-13364.
67. Garrido Alzar CL. Compact chip-scale guided cold atom gyrometers for inertial navigation: Enabling technologies and design study. AVS Quantum Sci. 2019; 1: 014702.
68. Azami D, Abdulkareem SS, Hassanzadeh A. Resonant enhancement of evanescent waves with graphene and double-negative materials in the visible regime. J Nanophotonics. 2020; 14: 036003.
69. Liu H, Lu Z, Zhang Z, Wang Y, Zhang H. Highly elastic organic crystals for flexible optical waveguides. Angew Chem Int Ed. 2018; 57: 8448-8452.
70. Grégoire A, Boudreau D. Chapter 28: Metal-enhanced fluorescence in plasmonic waveguides. In: Nano-Optics: Principles enabling basic research and applications. Dordrecht: Springer; 2017. pp. 447-447.
71. Zhao G, Dong H, Liao Q, Jiang J, Luo Y, Fu H, et al. Organic field-effect optical waveguides. Nat Commun. 2018; 9: 4790.
72. Pradhan B, Das S, Li J, Chowdhury F, Cherusseri J, Pandey D, et al. Ultrasensitive and ultrathin phototransistors and photonic synapses using perovskite quantum dots grown from graphene lattice. Sci Adv. 2020; 6: eaay5225.
73. Thomas S. CMOS-compatible graphene. Nat Electron. 2018; 1: 612.

74. Kong W, Kum H, Bae SH, Shim J, Kim H, Kong L, et al. Path towards graphene commercialization from lab to market. Nat Nanotechnol. 2019; 14: 927-938.
75. Koppens FH, Chang DE, García de Abajo FJ. Graphene plasmonics: A platform for strong light-matter interactions. Nano Lett. 2011; 11: 3370-3377.
76. Grigorenko AN, Polini M, Novoselov KS. Graphene plasmonics. Nat Photonics. 2012; 6: 749-758.
77. Papasimakis N, Luo Z, Shen ZX, De Angelis F, Di Fabrizio E, Nikolaenko AE, et al. Graphene in a photonic metamaterial. Opt Express. 2010; 18: 8353-8359.
78. Rascol E, Villette S, Harté E, Alves ID. Plasmon waveguide resonance: Principles, applications and historical perspectives on instrument development. Molecules. 2021; 26: 6442.
79. Moody G, Chang L, Steiner TJ, Bowers JE. Chip-scale nonlinear photonics for quantum light generation. AVS Quantum Sci. 2020; 2: 041702.
80. Arun G, Mishra V. A review on quantum computing and communication. Proceeding of 2014 2nd International Conference on Emerging Technology Trends in Electronics, Communication and Networking; 2014 December 26-27; Surat, Gujarat, India. IEEE.
81. Engel GS, Calhoun TR, Read EL, Ahn TK, Mančal T, Cheng YC, et al. Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. Nature. 2007; 446: 782-786.
82. Nie L, Nusantara AC, Damle VG, Sharmin R, Evans EP, Hemelaar SR, et al. Quantum monitoring of cellular metabolic activities in single mitochondria. Sci Adv. 2021; 7: eabf0573.