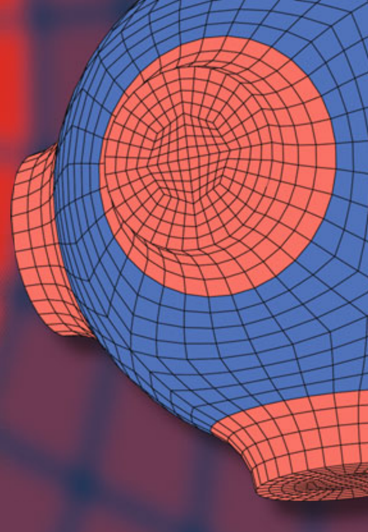
Advanced Structured Materials



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Nanomaterials for Healthcare, Energy and Environment

Springer

Advanced Structured Materials

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Common engineering materials reach in many applications their limits and new developments are required to fulfil increasing demands on engineering materials. The performance of materials can be increased by combining different materials to achieve better properties than a single constituent or by shaping the material or constituents in a specific structure. The interaction between material and structure may arise on different length scales, such as micro-, meso- or macroscale, and offers possible applications in quite diverse fields.

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Dedicated to my Grandmother and Mother,
both of whom have been my great Inspiration

Preface

Nanotechnology has emerged as an important field of modern scientific society due to its diverse range of applications in the area of electronics, material sciences, biomedical sciences, energy science, food, environmental detection and monitoring and other applications. The advantages of the use of nanomaterials, which are related to their properties that are completely different from the bulk materials, make them extremely attractive and give them enormous potential. Various nanomaterials like titanium dioxide, nanoclays, nanotubes, nanodendrimers, graphene, ferritin, porphyrinogens, noble metals, etc., find their applications in various fields.

Although there have been extensive interdisciplinary activities, major collaborative efforts are needed to jointly address some of the most challenging issues in life and medical sciences. Nanomaterials also find great deal of applications in environmental control and remediation. The biosynthetic route of synthesis of nanomaterials is taking a central stage nowadays. Nanomaterials lead to new-generation devices for more efficient, cost-effective and reliable solar energy conversion.

Therefore, realizing the importance of nanomaterials with their application in these three major sectors, this edited book is hoped to fill the gap of knowledge in the field of nanotechnology. Generally, conventional materials find their use in the fields of energy, health and environment, but the nanomaterials often have properties that are significantly different and efficient from the properties of the same matter at the bulk scale and also have an enormous potential economic impact. Nanomaterials are used in a variety of, manufacturing processes, products and healthcare including paints, filters, insulation and lubricant additives. High-quality filters may be produced using nanostructures; these filters are capable of removing particulate as small as a virus. Nanomaterials are being used in modern and human-safe insulation technologies; in the past, they were found in asbestos-based insulation. As a lubricant additive, nanomaterials have the ability to reduce friction in moving parts. This book is basically intended to address the holistic approach in terms of nanomaterial applications by taking into consideration various stakeholders using nanomaterials. It is hoped that publication of this book will provide the readers new knowledge and understanding on the broad range of nanomaterials and their applications.

Last but not least, we are highly thankful to all the authors who contributed chapters and provide their valuable ideas and knowledge in this edited book. We attempt to gather all the scattered information of authors from diverse fields around the world (Malaysia, Portugal, Japan, India, Saudi Arabia and Oman) in the areas of nanomaterials and finally complete this venture in a fruitful way. We greatly appreciate contributor's commitment for their support to compile our ideas in reality.

We are highly thankful to Springer Nature Team, Heidelberg Platz, Berlin, Germany, for their generous cooperation at every stage of the book production.

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About the Editors

Dr. Aamir Hussain Bhat is currently working as assistant professor at Department of Applied Sciences, Higher College of Technology, Muscat, Oman. He was born on 4 June 1980 in Baramulla, India. He received his highest degree of doctorate from Indian Institute of Technology Kharagpur, which ranks among the prestigious institutes of India. He has four years of postdoctoral experience at Universiti Sains Malaysia and around five years of teaching experience in the capacity of assistant professor in chemistry at Universiti Teknologi Petronas, Malaysia. He was awarded Prime Ministerial Postdoctoral Fellowship by the Ministry of Higher Education, Malaysia, for his excellence in the field of research. His research interests include polymer bio-nanocomposites and techniques to characterize them, nanofluids for oil well-drilling applications, isolation and application of nanocellulosic materials, nanomaterial synthesis using top-down and bottom-up approach, nanocoating using geopolymers and wastewater treatment using bio-sorbent-based die removal and micro-algae for heavy metal adsorption. He has been principal investigator of many government-funded projects. The prominent among them are Fundamental Research Grant Scheme (FRGS) entitled "New Malaysian Green Nano fluid for drilling at high temperature and pressure", YUTP Grant on "Biopolymer blend of Poly (lactic acid) and Poly (hydroxybutyrate co-valerate) based nano bio-composites reinforced with nanocrystalline cellulose with potential application in packaging" and Graphene Oxide Additives in Water Based Drilling Fluid for Enhanced Performance of Fluid Loss Control again funded by YUTP. He has also worked on joint industrial project with PRSB based on "Synthesis and Characterization of Nanoparticles for Enhanced Oil Recovery". His research group includes four Ph.D. and two MS students and has mentored 13 final-year undergraduate students. He has served as an international/national examiner for many research dissertations. He is also a member of various scientific chemical societies, prominent among them is American Nano Society. He has published 39 full-length research papers in highly reputed international scientific journals with a citation of more than 1350 and 23 chapters with highly reputed publishers. He is serving as a reviewer for several high-impact ISI journals of Elsevier, Springer, Wiley, Taylor and Francis, Sage, etc.

Dr. Imran Khan is currently working an assistant professor in Department of Chemistry, Sultan Qaboos University, Muscat, Oman, and earlier worked as post-doctoral fellow in the group named as Process and Product Applied Thermodynamics (PATh), in the Associated Laboratory Center for Research in Ceramics and Composite Materials (CICECO), Department of Chemistry, University of Aveiro, Portugal. Also, he was the principal investigator of Exploratory Research and Development Projects, funded by Fundação para a Ciência e a Tecnologia (FCT), Portugal, on development of a sustainable technology for the extraction and purification of chlorophylls from biomass in year 2014. His area of research interests includes solution chemistry, study thermophysical behaviour of pure liquids and liquid mixtures with ionic liquids, surfactant and polymer, as well as extraction and separation using ionic liquid. He worked as a visiting scientist for three months in the Department of Chemistry, University of Delhi, India, to study the effect of polymer on the ionic liquid solution funded by FCT, Portugal, to expand the collaboration between India and Portugal. Previously, he worked on the effect of filler on pressure-sensitive adhesive as postdoctoral fellow at Universiti Sains Malaysia, Penang, Malaysia, in the year 2011–2013, and published many research articles. He also worked in the Department of Chemistry, Durban University of Technology, Durban, South Africa, in the year 2010 in the area of solution chemistry. He has published more than 51 scientific papers in international peer-reviewed journals and 16 chapters, and has an h-index of 16. He also presented many scientific research papers in various international conferences and is also a member of various scientific chemical societies.

Dr. Mohammad Jawaid is currently working as a fellow researcher (associate professor), at Biocomposite Technology Laboratory, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, Serdang, Selangor, Malaysia, and also a visiting professor at Department of Chemical Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia, since June 2013. He is also a visiting scientist to TEMAG Laboratory, Faculty of Textile Technologies and Design at Istanbul Technical University, Turkey. Previously, he worked as a visiting lecturer, Faculty of Chemical Engineering, Universiti Teknologi Malaysia (UTM), and also worked as a expatriate lecturer under UNDP project with Ministry of Education of Ethiopia at Adama University, Ethiopia. He received his Ph.D. from Universiti Sains Malaysia, Malaysia. He has more than 10 years of experience in teaching, research and industries. His area of research interests includes hybrid-reinforced/filled polymer composites, advanced materials: graphene/nanoclay/fire retardant, lignocellulosic-reinforced/filled polymer composites, modification and treatment of lignocellulosic fibres and solid wood, nanocomposites and nanocellulose fibres, and polymer blends. So far he has published 8 books, 17 chapters, and more than 140 international journal papers and 5 published review papers under top 25 hot articles in ScienceDirect during 2013–2015. He is also the deputy editor-in-chief of Malaysian Polymer Journal, guest editor of special issue—Current Organic Synthesis and Current Analytical Chemistry, Bentham Publishers, UK, and editorial board member—Journal of Asian Science Technology and Innovation. Beside that, he is also a reviewer of several high-impact ISI journals of Elsevier, Springer, Wiley, Saga, etc. Presently, he is supervising 15 Ph.D. students and 5 master students in the fields of hybrid composites, green composites, nanocomposites, natural fibre-reinforced composites, etc. Four Ph.D. and three master students graduated under his supervision in 2014–2016. He has several research grants at university and national levels on polymer composites of around RM 700,000 (USD 175,000). He also delivered plenary and invited talks in international conferences related to composites in India, Turkey, Malaysia, Thailand, and China. Beside that, he is also a member of technical committee of several national and international conferences on composites and material science.

Prof. Fakhreldin O. Suliman obtained an M.Sc. (1992) and a Ph.D. (1996) in analytical chemistry from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. He was awarded a Science and Technology Agency (STA) Fellowship at the National Institute for Environmental Studies, Japan, in 1998. He joined the Department of Chemistry at Sultan Qaboos University in Sultanate of Oman, in 1999, where he is now professor and head of department. His research interests include developing fluorescent probes for sensing, miniaturization and automation of analytical techniques, supramolecular chemistry and molecular modelling. He has a teaching experience of more than twenty years in tertiary education. He has supervised and co-supervised more than thirty postgraduate students. His publication record in international peer-refereed journals exceeds hundred papers with an h-index of 21. Recently, he became a fellow of the Royal Society of Chemistry (RSC). He has been involved as a principal and co-principal investigator in many research projects and served as a reviewer to many high-impact journals of well-known publishers such as RSC, Elsevier and Wiley.

Dr. Haider Al-Lawati is an associate professor in the Department of Chemistry, Sultan Qaboos University, Sultanate of Oman. He completed his degree of doctorate from University of Hull, UK, in 2007. After obtaining his Ph.D., he started planning to establish a new research group in microfluidics area.

In May 2009, he successfully obtained His Majesty (HM) Grant for a project entitled "Developing Microfluidic Systems for Routine Analysis of Pharmaceutical Samples" with a budget of 207,254 $ RO. He was able to establish the first research laboratory in the field of microfluidics at SQU and in the Gulf region. Additionally, the grant helped a great deal in creating an excellent research environment and a strong research group. The group participated in Oman innovation fair in 2011 and received award for the best innovation in the exhibition. These heavy research activities requested further investment, and an extension for a year was granted with a budget of 26,316 $.

In June 2011, a new research proposal was submitted to The Research Council (TRC), Oman. The research utilizes microfluidics as an efficient mixing device as a chemiluminescence detection system for a capillary HPLC. The project was highly appreciated by the referees, and based on their comments, the TRC accepted to fund the project with a budget of 372,020 $ for three-year duration (2012–2015). Since 2015, he was able to attract additional two research funds: one from TRC and the other was funded by His Majesty Grant Funds with total budget of 628,109 $, in addition to some other funds like internal grants and few external funds. He published around 50 articles in refereed journals and presented many papers in various international conferences. He also supervised a number of Ph.D. and master students. He received several awards among these: first, GCC award of excellence in chemistry, 7 December 2015. This award is the most prestigious award in GCC. The awards cover areas such as science, medicine, industry, literature, politics and diplomacy, economics, youth and sports, security and philanthropy which are of crucial importance to the progress and welfare of the GCC states, the Arab world and humanity at large. A candidate is eligible to vie only once for these awards. The awards are given once every five years at a ceremony held under auspices of the leader of the host country of the GCC Supreme Council session.

A GCC state can nominate seven scholars for a prize through a formal letter to the GCC Secretariat. The GCC Secretariat and the secretariat of each competition assess the achievements of the nominees before selecting the winners and then table a name list of the winners to the GCC Ministerial and the GCC Supreme Council for final endorsement. He also received the National Research Award in the research area Culture, Basic and Social Sciences, 5 October 2016, TRC, Oman. In May 2014, his student received Marlene DeLuca Award in the 18th International Symposium on Biochemiluminescence and Chemiluminescence. Finally, he was heading the Department of Chemistry for three years from September 2014.

Prof. Salma Muhamed Al-Kindy is currently the dean of the College of Science, and a professor of analytical chemistry. She obtained her B.Sc. (Honours, 1982) in chemistry from American University of Cairo, Egypt, and Ph.D. in chemistry from Loughborough University, UK, in 1987. She started her academic career in 1989 at SQU where she became the first female professor in the university's history, and the first Omani national with a doctorate to join the Department of Chemistry. She was awarded a Matsumae International Fellowship by the Matsumae International Foundation in 1996, where she spent time at the Department of Bioanalytical Chemistry in Tokyo University, Japan, working on developing methods for the analysis of enantiomeric drugs. Her research interest has been in developing analytical protocols for the monitoring of analytes in complex matrices. She focuses her research on the development of analytical methodology and instrumentation for drug analysis in pharmaceutical and biological matrices, monitoring of organic pollutants and toxic metal ions in water using luminescence techniques in combination with HPLC, and flow systems such as, FIA and SIA and in developing sensitive and selective method for the essay of pharmaceutical components using microfluidic systems. Currently, she is developing methods to remove hazardous chemical by-products from wastewater using green chemistry approach. In April 2010, she became the first Omani national elected as a member of the prestigious World Academy of Science for Sustainable Development (TWAS). She was Oman's recipient of the United States Department of State's Award for outstanding female scientist in 2013 and has been inducted into the State Department's Middle East and North Africa (Mena) Women in Science Hall of Fame. She was recently awarded a Fellowship of Royal Society of Chemistry (FRSC). In 2014, she was awarded a medal by The World Academy of Science for Sustainable Development (TWAS) for her contribution to science, and she delivered a medal lecture during TWAS general meeting in Muscat last October. She recently received a "Lifetime Achievement Award in Chemistry" by the Venus International Foundation (VIF), in recognition for her contribution, research excellence and accomplishments in the field of chemistry. Furthermore, she has published more than 88 scientific papers in reputable scientific journals and has contributed to many international scientific conferences and seminars worldwide. She was recently invited to attend the General Assembly and Conference of Organization for Women in Science for the Developing World (OSWD) where she gave a presentation on research which was well received. Her recent paper was chosen as a cover page for Analytical Methods Journal published by Royal Society of Chemistry.

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Optical Applications of Nanomaterials

Pankaj Bharmoria and Sónia P. M. Ventura

Abstract Riding on their size tunable properties, "*Nanomaterials*" have emerged as darling materials of 21st century for plethora of practical applications including optical. The nonlinear optical properties and optical emission of nanomaterial's, enhances with the decrease in particle size due to the "*quantum confinement effect*." Therefore, the quantum mechanical effects emerge at the nanoscale which ultimately dictates the optical properties of nanomaterials. This book chapter will delineate the conceptual basis of optical applications of nanomaterials, subject to their size and material specific optical properties, including examples for conceptual demonstration. Considering the broad width of applications this book chapter is particularly focussed on biosensing and photovoltaic applications of nanomaterials.

Keywords Nanomaterials · Optical applications · Quantum confinement effect · Biosensing · Photovoltaics

1 Introduction

Nanomaterial is any particle, aggregate or agglomerate (natural or manufactured) with one or more than one dimensions in the size range of 1–100 nm (European Commission 2011). Historically, nanomaterial's, are being used by humans since 600 BC, in the form of carbon nanotubes and cementite nanowires in Hindvi steel developed in Southern India (Sanderson 2006). However, the modern world witnessed their scientific revolution for practical utility after the invention of scanning tunnelling microscope (STM) in 1981 by Gerd Binnig and Heinrich Rohrer (awarded Nobel prize in 1986) (Binnig and Rohrer 1986; Nobelprize.org. 1996 and discovery of fullerenes in 1985 by Richard Smalley, Robert Curl, and Harold Kroto (awarded Nobel Prize in 1996) (Kroto et al. 1985). Thereafter, in early 2000, the research on nanotechnology picked up impetus and growing unabated till date with a plethora of practical applications (Bhagyaraj et al. 2018; Guo and Tan 2009). Thanks to their

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unique physical, chemical, mechanical and optoelectronic properties which offer tunability as *per* size and dimensions (Guo and Tan 2009). Among these, the optical properties have gained a lot of interest, namely because of the advanced optical applications of nanomaterials. This is due to the fact that the optical properties are a function of their internal electronic structures, which can be tuned by altering their size and dimension as *per* the required optical application. However, before going deep into details we must understand the basics of material optics and *quantum confinement effect* of nanomaterials, responsible for their exceptional optical properties required for optical applications.

Material optics generally deals with the interaction of light with matter which results in manipulation of the flow of light involving reflection, refraction, absorbance, fluorescence, dispersion, frequency alterations and focusing or splitting of an optical beam (McGraw-Hill 1993). The characteristics of the optical material are a strict function of the light wavelength used. Since the dimensions of nanomaterials are defined in the nanoscale, which is sometimes lower than the wavelength of light, the understanding of the light matter interaction becomes a key step under the scope of optical applications of nanomaterials. Thus, the optical properties of materials may be categorized in two main sets, the linear and non-linear properties.

Linear optics and linear optical properties: The linear optics deals with "weak light", which upon interaction with medium is deflected or delayed but does not undergoes to a frequency change, thus following the superposition principle (Zhang and Wang 2017). According to the superposition principle when two waves undergo overlap in a space time then the optical property of resulting wave would be an algebraic sum of individual wave. In simple algebraic equation if the wave A gives signal X and the wave B gives signal Y, then upon superposition of A and B (A + B) the resulting wave would give the signal X + Y (i.e. A + B = X + Y). In linear optics, the light wave induces vibration in the molecules followed by the emission of the light, having the same frequency of the incident light, then interfering with the original light (Fig. 1). The optical response of materials scales linearly with the amplitude of the electric field of light when electric field associated with the radiation is small as shown in Eq. (1) (Suresh and Arivuoli 2012).

$$\vec{P} = \varepsilon_o \chi \vec{E} \tag{1}$$

Here, P is induced by dipole moment *per* unit volume, which defines polarization, ε_{o} is the permittivity of free space, χ is polarization susceptibility and E is electric field amplitude. The arrow above P and E is indicating their vector nature. The general linear optical properties of materials are reflection, refraction and diffraction, which are utilized for practical optical applications such as in phase shifters, beam splitters and recently, in quantum computing (Turner et al. 2013; Wu et al. 2017; Pittman et al. 2004). Lenses, mirrors, wave-plates and diffraction gratings are some examples describing the well-known linear optical materials.

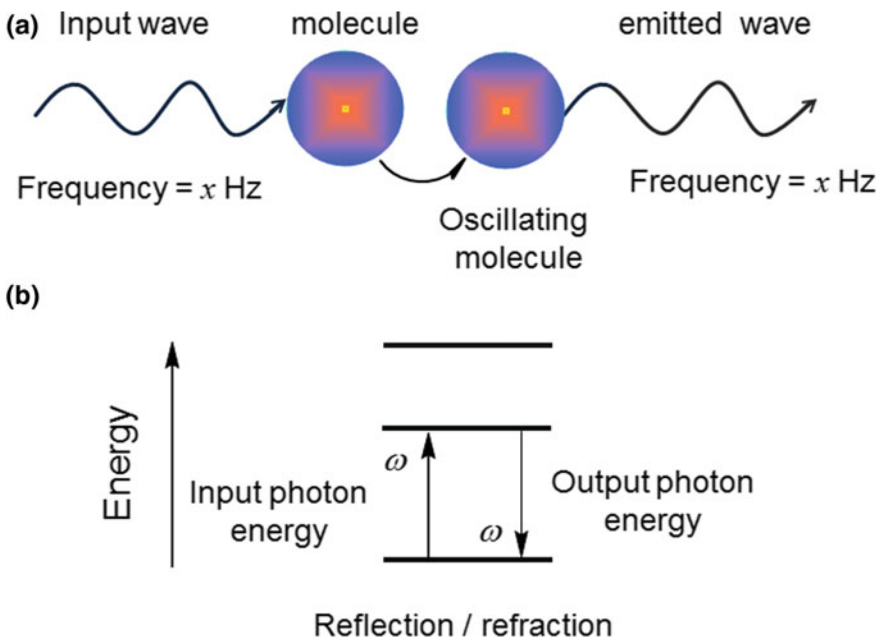

Fig. 1 Presentation of linear optical system; **a** showing no change in frequency of input light wave after being emitted by vibrating the molecule with whom it interacted and **b** no change in the photon energy after the same event

Non-linear optics and non-linear optical properties: The non-linear optics deals with the "intense light", which upon interaction with material changes its optical properties (Luca 2010; Lewis et al. 1941). Unlike linear optical systems the non-linear optical systems does not follow superposition principle (i.e. A + B ≠ X + Y). As a result of non-linear effect the incident light undergoes a change in optical properties like polarization, frequency, phase or path of incident light because the polarization density of medium responds non-linearly to the electric field of light (Zhang and Wang 2017). This behaviour is observed when the optical electric field strength of light is very high and comparable to that of intra-atomic electric field. In this case, the induced polarization is given by Eq. (2) (Agrawal 2013).

$$\vec{P} = \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2\chi^{(3)}\vec{E}^3 + \cdots \tag{2}$$

$\chi^{(1)}$ is the linear polarization susceptibility of materials which is applicable for lenses. $\chi^{(2)}$ and $\chi^{(3)}$ are non-linear polarization susceptibilities of the materials, which defines second order effects like a second harmonic generation and third order effects such as third harmonic generation, stimulated Raman scattering, four wave mixing and intensity dependence of the index of refraction. In non-linear optics, the light does not follow superposition principle. At high irradiance many molecules are excited to a high energy state, which are excited further to another higher energy states (the first excited state act on a low energy state for a high energy states). This causes vibrations at all frequencies corresponding to energy differences between populated states which, upon mixing, generate light with different frequency. The typical non-linear optical system is presented in Fig. 2.

The non-linear properties of materials are susceptible to change at higher powers inducing nonlinear effects like self-focusing, solitons and high-harmonic generation. The most common non-linear processes involves second harmonic generation, third harmonic generation, optical parametric amplification, optical rectification, optical Kerr effect, multi photon absorption and cross polarised wave generation (Franken et al. 1961; Heinz et al. 1982; Ciriolo et al. 2017; Zhong and Fourkas 2008; Palese et al. 1994).

Since the electronic structure of atom changes with the decrease in size of nanomaterials, its optical properties are highly prone to alterations. Based on the dimension of nanomaterials, they have been classified into various types as shown in Fig. 3 (Tiwari et al. 2012; Cha et al. 2013).

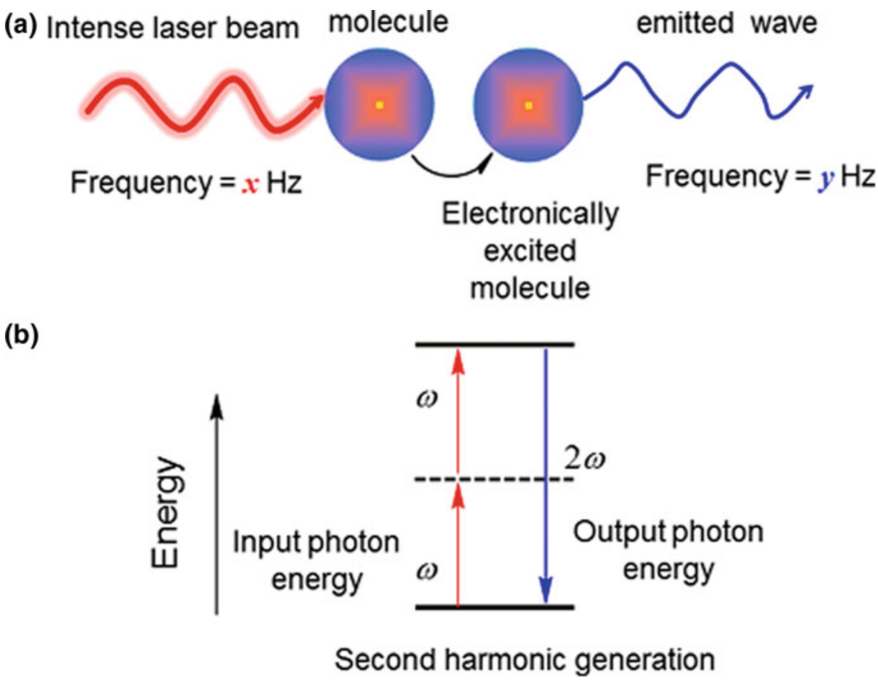

Fig. 2 Presentation of the non-linear optical system; **a** showing change in frequency of input light wave after being emitted by vibrating molecule with whom it interacted and **b** change in the photon energy after same event, exemplified by a second harmonic generation

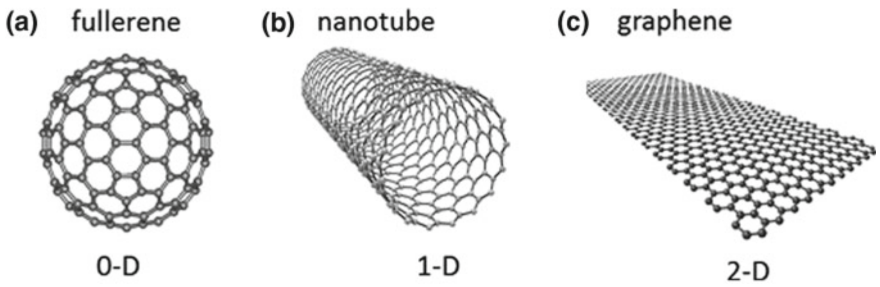

Fig. 3 Nanomaterials of various dimensions **a** 0-dimension (fullerene); **b** 1-dimension (nanotube) and **c** 2-dimension (graphene)

(i) **Zero dimension nanomaterials** (confined into three dimensions), e.g. *nanoparticles, nanoshells, nanocapsules, nanorings, fullerenes and quasi crystals*.
(ii) **One dimension nanomaterials** (confined into two dimensions), e.g. *nanorods, nanofilaments, nanotubes, quantum wires, and nanowires*.
(iii) **Two dimension nanomaterial** (confined into two dimensions), e.g. *discs, platelets, ultrathin films, super lattices, graphene and quantum wells*.

The alterations in optical properties of nanomaterial with reduced dimensionality are usually defined by "*quantum confinement effect*."

Quantum confinement effect: The increase in energy difference between band gap and energy states of a material due to the origin of discrete energy spectrum, when one of its dimension approaches the size below 5 nm, is called as "*quantum confinement effect*" (Zorman et al. 1995; Takei et al. 2011) (Fig. 4). Consequently, both optical and electronic properties of nanomaterials deviates compared to the bulk material, where the energy levels remain continuous. The '*quantum confinement effect*' arises due to the spatial confinement of electrons in the conduction band, and holes in the valence band when diameter of the particle approaches de Broglie wavelength of electron ($\lambda_{electron} = 1.23$ nm). This will cause the quantization of their energy and momentum with restricted motion since in such a situation they follow the principle of quantum mechanical motion rather than classical mechanics (Anas et al. 2014). The situation becomes similar to the particle in one dimension box. In this situation it becomes very intriguing to confine the probing light for measuring the optical property of a single nanoparticle or nanowire, since the surrounding substrate is always going to interfere with the optical measurement. If the substrate is not photo-luminescent and its absorption range doesn't lie on the frequency range of the probing light, then its effects on the measurement of non-linear optical properties are automatically discarded. However, it affects the linear optical properties like transmission and reflection, just to mention a few. Therefore, the correction of linear optical measurements is inevitable, which can be performed by subtracting the linear optical properties of the substrate alone from the nanomaterial laden substrate.

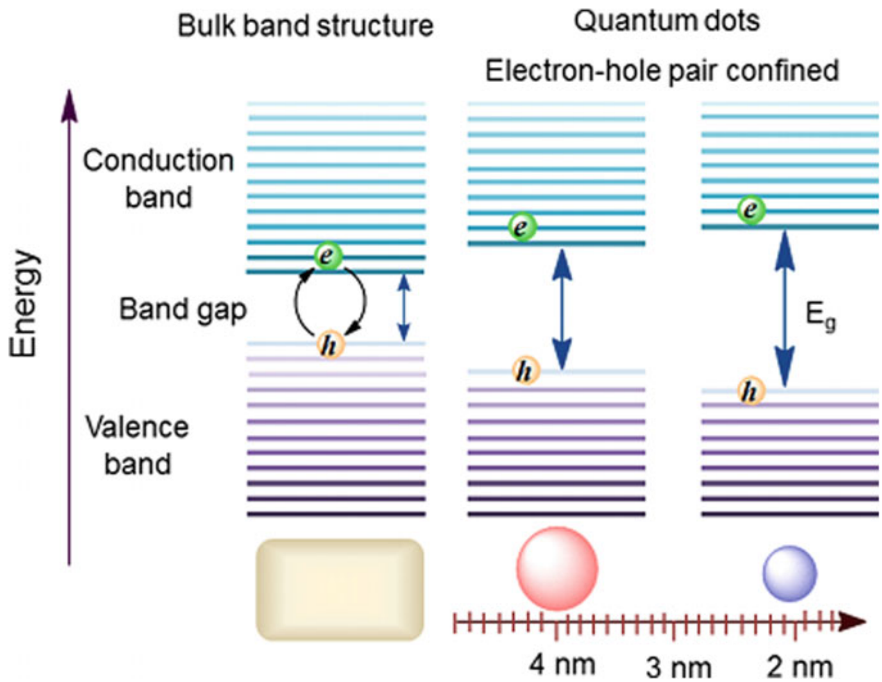

Fig. 4 Presentation of *quantum confinement effect*, wherein the band gap between valence and conduction band increases while decreasing the material size to quantum level due to electron-hole confinement. The holes remain confined in the discrete valence band and electrons remain confined in the discrete conduction band

The "*quantum confinement effect*" has been exploited immensely by tailoring the optical properties of the nanomaterials by tuning their crystal dimensions and the chemistry of their surfaces (Clancy et al. 2018). However, developing technologies for the utilization of these nanomaterials becomes the key factor to achieve their practical applications. The optical applications of nanomaterials include bio-sensing, solar cells, photovoltaics, imaging, non-linearity, photonics and optoelectronics (Keshea and Khakpoor 2017; Jang et al. 2016; Carey et al. 2015; Joarder et al. 2018; Zheng and Zhang 2016). Therefore, in the following section, the optical applications of nanomaterials specifically in Biosensing and Photovoltaics shall be discussed.

2 Optical Applications of Nanomaterials

2.1 Nanomaterials in Optical Biosensing

The high optical sensitivity leading to lower detection limits of analytes by nanomaterials is pointed out as an advantage favouring their application for biosensing applications. Their highly specific surface along with their large surface area could enable the increase in immobilization rate of different types of bio-receptors. In fact, a typical biosensor is composed of a bio-receptor, a transducer, a signal processor and an interface (Li and Liu 2017; Wen et al. 2015; Borisov and Wolfbeis 2008), as depicted in Fig. 5. By its turn, an optical biosensor is comprised of an optical transducer and a bio-receptor. The bio-receptors at the surface senses physical or chemical change when 'in natura', which are transported/transduced to the transducer resulting in changes of the properties of light, namely absorption, fluorescence, transmission, reflection, refraction, phase, amplitude, frequency and polarization (Lara and Perez-Potti 2018).

As observed, nanomaterials perform the function of a transducer in a biosensor, providing a high electrical conductivity and optical sensitivity to a very small detection limit. The biomolecules can be immobilized on the nanomaterial surface either via non-covalent interactions such as electrostatic, H-bonding and π-π stacking, or via covalent cross-linking, e.g. amide coupling reactions. The covalent binding is particularly useful in terms of stability and reproducibility of the surface functionalization. However it has a major drawback of uncontrolled functionalization, consequently changing the principal recognition site, whereas the non-covalent immobilization possesses advantages regarding the maintenance of the properties

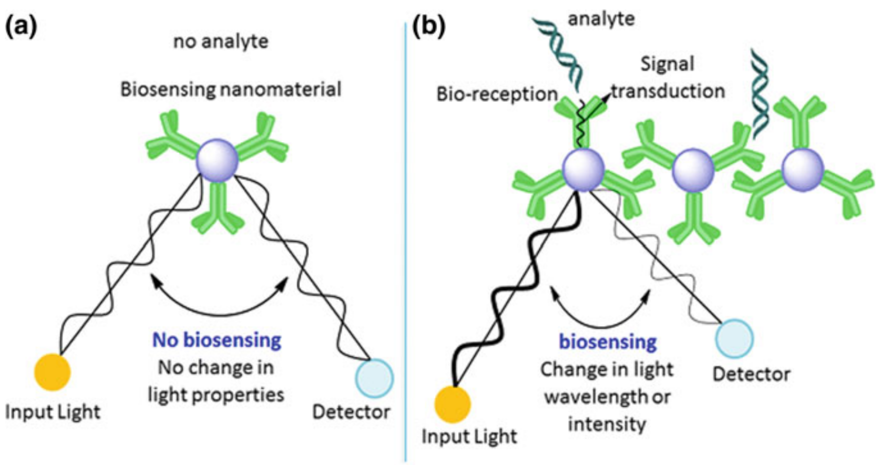

Fig. 5 Schematic representation of optical bio-sensing by using a nanomaterial **a** without and **b** with an analyte, thus demonstrating characteristic changes in the properties of light