Editorial

Quantum physics and photoluminescence: contribution of the SPQEO journal

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Abstract. This article explores the potential applications of photoluminescence (PL) spectroscopy in analyzing the atomic and electronic structures of modern materials, with a specific focus on the rapidly evolving fields of quantum science and nanotechnology. Photoluminescence is a powerful spectroscopic tool for the comprehensive investigation of energy states in semiconductors, dielectrics, organic compounds and a variety of nanoscale structures. Articles published in SPQEO journal showcases progress in nanocomposites, nanoclusters, luminescent nanostructures, and defect-related emission mechanisms. Key findings include the role of electron–phonon interactions in aluminum nitride, the controlled formation and enhanced emission of silicon nanoclusters, impurity-induced modification of luminescence in SiOx-based materials, and defect- and dopant-related PL behaviour in A^2B^6 semiconductor nanocrystals. PL spectroscopy also sheds light on intricate energy transfer processes in hybrid nanocomposites, molecular donor–acceptor complexes, and emission channels related to vacancies in CdS-based materials. Studies concerning structural defects, phase transformations and impurity diffusion utilizing PL method further substantiate its value in understanding the microstructure, recombination pathways and defect evolution in technically important materials such as SiC, amorphous Si–C films and II–VI semiconductors. Together, these results conclusively demonstrate the versatility and diagnostic power of PL spectroscopy in characterizing materials and enabling advances in quantum technologies, optoelectronic devices and nanoscale engineering.

Keywords: quantum physics, photoluminescence, SPQEO journal.

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1. Photoluminescence as a tool to study atomic and energy structure of materials

The 2025 International Year of Quantum Science and Technology is coming to a successful end. We previously informed you that the UN Resolution emphasized on the critical importance of quantum science and technology for economic development. Their potential applications can provide solutions to global challenges such as food security, health care, sustainable cities and communities, advanced communications, clean water, and energy generation, thereby supporting climate action [1]. Additionally, we have curated a selection of highlights from this year's numerous events for your review [2].

Our focus here will be on photoluminescence (PL), a powerful diagnostic tool for studying energy structures of various materials, ranging from semiconductors and dielectrics to organic materials, including nanoscaled structures [3-6]. Numerous studies have been focused on investigating quantum dots (QDs) of different structure and composition, including single QDs [7], 2D QDs [9] and arrays of QDs made of various materials InAs/GaAs [10], graphene [11], InP [12], type-II QDs [8], *etc*. For in-depth analysis of QDs a variety of advanced luminescence techniques has been applied: time-resolved PL spectroscopy [13], micro-PL spectroscopy [14], PL microscopy [15], ultrafast PL spectroscopy [16], and others.

2. Luminescent properties of nanocomposites and nanoclusters

In [17] a characteristic low-energy (less than 2.02 eV) PL spectrum containing a series of equidistant maxima was observed in AlN. Theoretical analysis has shown that the observed PL features may be caused by strong electron-phonon interaction that probably leads to the appearance of quasi-particles, “elions”, which are a bound state of an electron with an ion in the crystal lattice.

Review [18] systematically organizes the results of the studies related to the main methods of creating silicon nanocrystals (nc-Si) and various approaches for achieving luminescence effects in traditionally non-luminescent silicon materials (typical indirect bandgap semiconductors). It is particularly emphasized that the presence of C, N, and Al elements significantly accelerates the nucleation and growth of silicon nanoclusters during the formation of nc-Si in SiO_2 matrix at high temperatures (1100–1200 °C). By controlling dopant concentration (0.1 to 2 atomic percent), the size and concentration of nanoclusters can be adjusted, thereby altering the spectral characteristics of the luminescent structure. By combining multiple stimuli that promote nanocluster formation, modification of the Si-nc/SiO_2 interface, non-radiative recombination centers, *etc*., the photoluminescence intensity efficiency can be significantly enhanced (up to 17 times) compared to conventional luminescent structures (*i.e*., the ones obtained by thermal decomposition of non-stoichiometric SiO_x films, where $x \approx 1.5$).

Michailovska *et al.* [19, 20] studied the effect of Sm and Ni impurities on PL spectra. In the samples with Sm impurity concentrations approaching 2 wt.%, emission bands from Sm^{3+} and Sm^{2+} ions appeared in the PL spectrum. The concentration dependence of these emission bands exhibits threshold behavior: PL of Sm impurities is not observed at low Sm concentrations [19]. The reduced PL decay rate and enhanced PL intensity observed in SiO_x/Ni/Si samples can be attributed to the coating effect of nickel silicide on the dangling bonds at the interface between Si nanoparticles and the SiO_x matrix [20].

Nanocrystals of A^2B^6 materials were investigated in [21-24]. PL properties of undoped CdS nanocrystals reveal nonlinear behavior of the intensity of near-band-edge and defect-level emission lines vs. excitation power, accompanied by a blue shift in the peak emission of defect-level emission. The origin of red emission was ascribed to intrinsic defects such as sulfur vacancies or twin interfaces [21]. The variety of micro- and nano-sized A^2B^6 powders were obtained by self-propagating high-temperature synthesis and studied in [22-24]. Analysis of PL and thermoluminescence spectra of microcrystalline ZnS:Cu revealed the influence of annealing parameters on the intensity of the “blue” and “green” PL bands. It was shown that heat treatment leads to the formation of the centers responsible for the glow in the “green” spectral region (Cu ions in the positions of Zn ions) [22]. The two-phase ZnS-$Cu_{2-x}S$ system exhibited [23] maximum radiative wavelengths of 515 nm for both photoluminescence and electro-luminescence. Additional annealing and introducing the Ga co-activator lead to more non-uniform distribution of impurities within microcrystals. It causes the increase in the intensity of the blue band in photoluminescence spectra and shift of the maximum of electroluminescence toward longer wavelengths due to the formation of Cu_i-Cu_{Zn} radiative centers [23]. In the case of ZnS:Ag application of self-propagating high-temperature synthesis produces simultaneously two fractions with different particle sizes. The maximum concentration of Ag was achieved in the micrometer-sized fraction as is seen from the ratio of the intensities of Ag-related and self-activated PL bands. PL band at ~450 nm (Ag band) in the spectrum of ZnS:Ag grown by self-propagating high-temperature synthesis appeared to be narrower and almost symmetric as compared with the one of ZnS:Ag obtained using the thermal doping method, however, the latter samples exhibited an additional PL band with λ_{max} ~ 505 nm, indicative of high intrinsic defects concentration [24].

Photoluminescence studies were also applied to nanocomposites containing molecular compositions and nanoparticles [25,26]. The observed influence of gold nanostructures on the PL spectral characteristics of the nanocomposite material “polycarbonate matrix – gold nanostructures – HTTH dye” [25] elucidated the interplay of the concentration of HTTH molecules and gold nanostructures, on the one hand, and the efficiency of the FRET and PRET resonance energy transfer phenomena, on the other hand. Understanding of these factors paves the way to the targeted optimization of luminescence properties of these composites. Experimental data obtained in [26] indicate that the PL spectra of natural melanin and the electron acceptor PCBM in acetone-nitrile solutions reveal the formation of a weak conjugated transfer complex between melanin and PCBM molecules. Specifically, the properties observed at the 705 nm band in the melanin-PCBM solution can be attributed to the formation of this conjugated transfer complex. Meanwhile, the appearance of an intense 400–430 nm band in the two-component system of melanin and PCBM, along with the quenching of the 460–480 nm exciton melanin emission band, can be attributed to the formation of a weak conjugated transfer complex between the monomeric constituents of the melanin oligomer and PCBM.

Application of the density functional method revealed that neutral cadmium vacancy in CdS and $Cd_{0.5}Zn_{0.5}S$ forms local states near the valence band top, whereas the zinc vacancy produces the local state at 0.9 eV in the energy gap. With the account of experimental PL spectra of CdS and CdS:Zn QDs in 2.1…2.3 eV region, it was shown that cadmium vacancies are the possible channels of radiative recombination in $Cd_{1-x}Zn_xS$ QDs [27].

3. Luminescence spectroscopy study of defects, vacancies, and structures

In [28], optical properties of electron excitation, transport dynamics, and relaxation pathways in cyanoamine-based supramolecular D–π–A complexes were investigated. Two components in the transfer of charge, corresponding to different conformational states of the carbon chain in merocyanines, were found. The PL of the studied molecular solutions of merocyanines was interpreted as an exciplex luminescence, being a manifestation of resonant and charge transfer interaction in an excited state.

PL investigation of SiC structures elucidated mechanisms of phase transformations in as-grown 3C-6H polytypes junction [29-33]: (i) low-temperature PL of crystals β-SiC with joint polytypes transformation shows the same spectra as those inherent to pure β-SiC crystals after plastic deformation or after high temperature annealing. This type of spectra is indicative of the formation of intermediate (3C-6H) metastable micro- and nanostructures involving the stacking faults [29]; (ii) phase transformation started exactly from lamella between polytypes, β → α SiC transformation propagates from lamella as from nuclear [29]; (iii) the peculiarity of the PL spectra related to the zones of disorder to a great extent depends on the impurity concentration in the matrix as a whole; in pure samples at low temperatures the stacking faults spectra are dominant, whereas the intensity of the deep-level spectra is very low [30]; (iv) in the doped samples the deep-level spectra are dominant and overlap with a broad band of donor-acceptor emission, while stacking faults spectra are practically invisible [30]; (v) all deep-level spectra have the same logic of construction and demonstrate identical behavior of the thin structure elements, deep-level and stacking faults spectra have different nature and character, even when they follow the nanostructure transformations together [32, 33]. The article [34] deals with the PL properties of oxidized stochiometric and carbon-rich amorphous $Si_{1-x}C_x$:H films. Near-stochiometric and carbon-rich a-$Si_{1-x}C_x$:H thin films were deposited using the magnetron sputtering of Si target in Ar/CH_4 gas mixture. As-deposited near-stochimetric ($x = 0.5$) films showed weak blue PL, while the PL of as-deposited carbon-rich ($x = 0.7$) sample was white in color and 20 times stronger. The strongest oxidation and strongest white light emission were observed in carbon-rich samples ($x = 0.7$) after the annealing in oxidizing atmosphere.

Quality and transformation of A^2B^6 materials were studied by PL spectroscopy in [35-38]. Main results can be summarized as follows: (i) defect PL in CdS nano-whiskers grown by vapor-solid method correlates with the deficiency of sulfur and rises with increasing of the surface; slower growth produces more qualitative crystals due to more effective recovery of defects, that needs some time [35]; (ii) doping of ZnSe<Al> by Yb impurity from vapor phase in a closed volume causes “quenching” the yellow-green band and appearance of intensive blue luminescent band that has exciton nature [36]; (iii) the luminescence spectra of ZnSe <Al> crystals doped with Gd from the vapor phase exhibit two bands: luminescence edge band and the low-energy G-band.The latter is caused by incomplete filling the Zn vacancies with Gd atoms [37]; (iv) Variation of the low-temperature (T=2 K) PL in single crystals CdTe:Cl under the influence of microwave irradiation (2.45 GHz, 24 GHz) have revealed modification of defect structure in the irradiated material; the microwave treatment (duration ≥10s) leads to the increasing of the distance between the components of donor-acceptor pairs responsible for the recombination radiation near 1.455 eV; the microwave treatment leads to quenching the band near 1.478 eV associated with extended defects, which indicates effective interaction of microwave fields with dislocations [38]. Complex study of polymer-based nanocomposites containing CdS QDs using PL and optically detected magnetic resonance (ODMR) methods revealed the participation of four paramagnetic centers in radiative recombination and one center related to non-radiative recombination, among them the oxygen-related interfacial center in CdS/PVA and sulfur vacancy center in CdS/PEI were identified [39].

4. Conclusion

Photoluminescence spectroscopy continues to assert itself as one of the most informative and versatile methods for investigating the electronic, structural, and defect-related properties of modern materials. The reviewed studies collectively demonstrate how PL enables the identification of quasiparticle formation, defect states, impurity-related recombination channels, and nanoscale structural transformations across a wide range of material systems — from silicon nanoclusters and organic D–π–A complexes to II–VI semiconductor nanocrystals and complex SiC polytype interfaces. Recent advances in PL methodologies, including time-resolved, micro-PL, ultrafast PL, and PL microscopy, have significantly enhanced the ability to resolve dynamic processes and spatially localized phenomena. These capabilities make PL a strategic tool for guiding the development of luminescent nanomaterials, optimizing dopant incorporation, tailoring defect landscapes, and elucidating fundamental mechanisms that govern emission efficiency and spectral behavior. As quantum technologies and nanoscale engineering continue to evolve, PL spectroscopy will remain a key technique for bridging atomic-scale interactions with macroscopic optical properties, supporting both fundamental research and the development of advanced optoelectronic and photonic applications.

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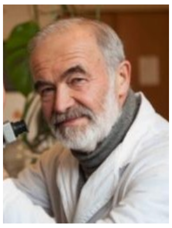
Authors and CV



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Maksimenko Z.: resources, data curation, writing – review & editing.
Rudko G.: verification, formal analysis, writing – review & editing.
Belyaev A.: supervision, writing – review & editing.

Квантова фізика та фотолюмінесценція: внесок журналу SPQEO

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Анотація. У статті досліджено потенційні застосування спектроскопії фотолюмінесценції (ФЛ) для аналізу атомної та електронної структур сучасних матеріалів з особливим акцентом на швидкозростаючі галузі квантової науки та нанотехнологій. Фотолюмінесценція є потужним спектроскопічним інструментом для всебічного вивчення енергетичних станів у напівпровідниках, діелектах, органічних сполуках та різноманітних наноструктурах. Велика кількість статей, опублікованих у журналі SPQEO, демонструє прогрес у вивченні нанокомпозитів, нанокластерів, люмінесцентних наноструктур та механізмів випромінювання, пов'язаних з дефектами. Ключові результати включають роль електрон-фононних взаємодій та еліонних квазічастинок в AlN, контрольоване формування та посилене випромінювання кремнієвих нанокластерів, модифікацію люмінесценції, зумовлену домішками, у матеріалах на основі SiO_x, а також поведінку ФЛ, пов'язану з дефектами та легуючими домішками, у напівпровідникових нанокристалах A^2B^6. Спектроскопія ФЛ також висвітлює складні процеси перенесення енергії у гібридних нанокомпозитах, молекулярних донорно-акцепторних комплексах та каналах випромінювання, пов'язаних з вакансіями в матеріалах на основі CdS. Дослідження структурних дефектів, фазових перетворень та дифузії домішок за допомогою методу фотолюмінесценції додатково підтверджують його значення для розуміння мікроструктури, шляхів рекомбінації та еволюції дефектів у технічно важливих матеріалах, таких як SiC, аморфні плівки Si–C та напівпровідники II–VI груп. Разом ці результати однозначно демонструють універсальність та діагностичний потенціал фотолюмінесцентної спектроскопії для характеризації матеріалів, що дозволяє досягти успіхів у квантових технологіях, оптоелектронних пристроях та нанорозмірній інженерії.

Ключові слова: квантова фізика, фотолюмінесценція, журнал SPQEO