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Luminescence: An Overview

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Abstract :

Luminescence is the emission of light from a substance not due to heat, differing from incandescence. This light emission starts with energy input and stops once excitation ceases, as seen in light bulbs, campfires, and fireworks. It includes various physical forms and applications in citizens services. Key types are photoluminescence, chemiluminescence, bioluminescence, electroluminescence, thermoluminescence, and radioluminescence. In citizens services, luminescence aids lighting and signaling in homes, offices, tunnels, and theaters. The excitation source differentiates types; for example, photoluminescence uses light for excitation, while cathodoluminescence involves electron bombardment. Chemiluminescence emerges from chemical reactions, and radioluminescence occurs due to radioactive particle bombardment. Bioluminescence is a form of chemiluminescence in living organisms. Mechanoluminescence includes triboluminescence and piezoluminescence, while thermoluminescence parallels sunlight excitation through thermal heating.

Keywords: Luminescence, photoluminescence, chemiluminescence, bioluminescence, electroluminescence, thermoluminescence. Etc.

1. Introduction to Luminescence

Luminescence is the emission of light generated by electronic excitation and subsequent radiative decay. This phenomenon is utilized in a wide range of scientific, technical, and commercial fields. Consequently, various specialized luminescence techniques have become prominent in resource prospecting, environmental monitoring, solid-state physics, and device characterization. Luminescence originates from excited states created by processes unrelated to heating; hence, it is not a form of incandescence. The majority of luminescence processes result from the transformation of some pre-existing form of energy into photons. The most common forms of energy that may be transformed into luminescence include electromagnetic radiation, charged particles (e.g., electrons and alpha particles), electrical fields, chemical reactions, and mechanical action such as friction collisions.

2. Types of Luminescence

Luminescence is the emission of light by a substance not resulting from heat; it is a form of cold-body radiation. The major types of luminescence are photoluminescence, chemiluminescence, bioluminescence, electroluminescence, thermoluminescence, and radioluminescence. Photoluminescence occurs when electrons produced by photon absorption return to the ground state by radiative emission. Chemiluminescence is caused by chemical reactions. Bioluminescence is light production by organisms. Electroluminescence is produced by an electric current or a strong electric field. Thermoluminescence occurs when previously absorbed energy from ionizing radiation is reemitted as light upon heating. Radioluminescence happens when energetic ions excite luminescent centers (L. Fritzen et al., 2020).

2.1. Photoluminescence

Photoluminescence (PL) typically involves the excitation of atoms or molecules through the absorption of photons. Fundamentally, PL comprises two principal steps. First, electromagnetic radiation is absorbed by electrons in the ground state (initial state), leading to excitation to higher energy levels (excited state). Second, the excited electrons return to lower energy levels within the band gap, releasing energy as photons of longer wavelength than the initial incident radiation (Varkentina et al., 2022). Delayed PL (persistent luminescence) continues light emission after the excitation source has been removed, with decay lasting from seconds to hours (Tan et al., 2019). The photoluminescence yield strongly depends on temperature and is frequently used to characterize the internal quality of semiconductor materials (Kurtulik et al., 2021).

2.2. Chemiluminescence

Chemiluminescence involves light emitted from chemical reactions that excite electrons to higher energy states. This process can result in light production, such as bioluminescence and light emission during phosphorus oxidation. The intensity of light is generally proportional to the reaction strength, though some require catalysts for better sensitivity. Reactions between organic and inorganic compounds can lead to luminescent effects. Chemiluminescence can be used to identify substances and coordinate reactions, with detection capabilities in ultraviolet to near-infrared ranges, linked to the energy states of luminescent materials. Key sources include phosphorus oxidation and organic peroxides like luminol and luciferin. Applications include bio-labeling, disease diagnosis, food safety, environmental protection, military security, and crime investigation. Inorganic chemiluminescence often occurs with H_2O_2 reactions, such as with Na_2MoO_4 or Na_2WO_4, emitting primarily blue-violet light around 430 nm from charge transfer transitions.

2.3. Bioluminescence

Bioluminescence is a natural light-emission phenomenon driven by the enzyme luciferase, which catalyzes the oxidation of luciferin with oxygen. Various bioluminescent systems include D-luciferin, coelenterazine, Cypridina luciferin, tetrapyrrole, bacterial, and fungal types, each emitting light at specific wavelengths. These systems are applied in drug discovery, protein interaction monitoring, in vivo imaging, and neuronal control. Bioluminescence assays leverage luciferase expression and luciferin permeation, crucial for biomedical research. The process begins with luciferase-mediated oxygenation of luciferin, which produces an excited intermediate that emits light when relaxing to its ground state. Some luciferases directly oxygenate luciferin, while others need cofactors for efficient light production, and certain mechanisms rely on divalent metal ions for stabilization. (N. Dunuweera et al., 2024)

2.4. Electroluminescence

Electroluminescence (EL) refers to the phenomenon of light emission from a material upon the application of an electric field. The process begins with carrier injection from electrodes, where injected electrons and holes move through the luminescent media. They eventually encounter luminescent centers or combine to form excitons; the subsequent radiative decay of these excitations produces light. EL offers a method to obtain optical output with convenient electrical inputs. It has appealed to lighting and display technologies with broad commercial applications. A classic EL device comprises a thin phosphor pellet, such as zinc sulphide doped with copper, placed between two electrodes. When a constant voltage is applied, the irradiated pellet exhibits an intense field-emission spectrum within the blue–green wavelength range (Sentić et al., 2015).

2.5. Thermoluminescence

Thermoluminescence (TL) occurs in crystalline materials subjected to ionizing radiation or heat in a closed system. TL intensity follows a Komov-type kinetic equation, relating to the recombination and trapping rates of electrons and holes, determined by activation energy and frequency factors. The recombination rate depends on trapped electron concentration. With a steady trap concentration, the probability of occupying a trapping center corresponds to the capture frequency of thermally emitted electrons. During excitation, intensity moves from the crystal structure's shell to the entrance center. Electrons and holes migrate to traps and luminescent centers, affected by the types of recombination centers and trapping probabilities, resulting in characteristic luminescent radiation. TL is often linked to RL, considering thermal excitation rather than external radiation. The TL response of calcite is influenced by impurities like manganese and lead, seen in samples from Santa Bárbara and Picher, where low impurity samples showed no luminescence under long-wave UV, while those with 0.04 atom% manganese and 0.03 atom% lead exhibited bright luminescence. Lead-manganese calcite's heightened sensitivity is due to the lead-oxygen complex acting as an effective hole trap near manganese. Materials with TL present distinct peaks; for example, gamma-irradiated zircon has a significant TL peak at 165°C from electron recombination with Dy{sup 3+} related shallow hole traps, and after short preheating, its TL glow curve displays additional peaks at 300–320 °C and ~420 °C linked to Tb{sup 3+} related hole traps. OSL in zircon shows emissions from Tb{sup 3+} ions and

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[SiO{sub 4}]{sup 4–} groups, with deep traps affecting OSL emissions associated with both TL peaks. (Schrope, 1975)(Secu et al., 2007)

2.6. Radioluminescence

Radioluminescence is the optical and ultraviolet radiation produced when charged particles or electromagnetic radiation bombard a material. A typical luminescent system includes an energy source, like ultraviolet radiation or radioactive decay, and an emitter that absorbs the energy and emits photons. High-energy particles or photons from a radioactive source excite electrons in the phosphor's atoms or molecules, providing enough energy to remove an electron or elevate it to a higher energy level. When the electron returns to a lower energy state, it emits a photon characteristic of the atom or molecule. Radioluminescent materials include platinum, manganese, rhodium, copper, saline compounds, organic salts, and supermolecules. These phosphors are essential in nuclear instrumentation, radioisotope-powered lights, and geological and archaeological dating.

3. Mechanisms of Luminescence

Electroluminescence enables visualization of surfaces in electrical contact with an electroluminescent device and is widely applied in lighting technology and flat-panel displays (Hananya & Shabat, 2019). Thermoluminescence arises when a previously irradiated and illuminated material emits visible light upon heating. Radioluminescence results from high-energy radiation. Although each luminescent phenomenon boasts distinct characteristics, the underlying mechanisms remain similar.

Photoluminescence involves the emission of light by a substance irradiated with photons. Chemiluminescence requires chemical agents that excite the luminophore; luminescent phenomena produced in biological media are termed bioluminescence (Feng & Smet, 2018). Electroluminescence is obtained by injecting electric charge into the luminophore; thermoluminescence occurs during the progressive heating of the irradiated material. Radioluminescence results from the excitation of luminophores by high-energy electromagnetic (e.g., X-rays) or particulate (e.g., electrons) radiation.

3.1. Excitation and Emission Processes

Luminescence involves the emission of light from a material following excitation by a suitable source. Various excitation sources elicit the emission of photons from luminescent materials through different mechanisms. For instance, photoluminescence involves absorption of photons, whereas chemiluminescence proceeds via a chemical reaction (Varkentina et al., 2022). Electroluminescence results from the electrical excitation of atoms or molecules, which may be part of an electron-hole recombination process in semiconductors. Exposure of luminescent materials to ultraviolet radiation, heating, or ionizing radiation can also establish atomic and molecular electronic configurations that relax with photon emission, producing phenomena such as fluorescence, thermoluminescence, and radioluminescence, respectively. These kinetic

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processes govern the excitation and emission events that underlie all luminescence types respectively (Varkentina et al., 2022).

3.2. Energy Transfer Mechanisms

The energy transfer concept explains interactions of energy flow in luminescent systems. Various processes act as excitation mechanisms for photoluminescence, including direct light excitation, vibrational relaxation, intersystem crossing, energy transfer, or photoinduced electron transfer. Energy transfer is categorized as either radiative or non-radiative. This process typically involves two luminescent centers: a sensitizer that captures excitation energy and an activator that emits a photon. Efficient energy transfer occurs with good spectral overlap between the sensitizer's emission and the activator's absorption, as well as proximity. The rate of radiative energy transfer can be calculated using Einstein coefficients. Non-radiative mechanisms include resonance energy transfer (FRET), Dexter energy transfer, and charge-assisted energy transfer. FRET relies on dipole–dipole interaction, dependent on the inverse sixth power of molecular distance, while Dexter transfer involves electron exchange, rapidly decaying with distance and relying on molecular orbital overlap. Detailed mechanisms for these transfers are reviewed elsewhere.

4. Applications of Luminescence

Luminescence encompasses distinct physical phenomena in which electromagnetic radiation is emitted by a substance following absorption of energy. There are several types of luminescence, each characterized by a particular mechanism for the conversion of the input energy into radiation (or light emission) (L. Fritzen et al., 2020). Photoluminescence arises from the absorption of electromagnetic radiation and includes fluorescence and phosphorescence as subtypes. Chemiluminescence originates from a chemical reaction, while bioluminescence is a type of chemiluminescence occurring in biological systems. Electroluminescence is induced by an applied electric field or current. Thermoluminescence emerges upon heating of a previously irradiated substance, and radioluminescence is excited by ionizing radiation.

4.1. Lighting Technologies

Lighting Technologies Lighting technologies have undergone extensive development in parallel with advances in luminescent materials and devices. Different lighting technologies are suited to diverse illumination scenarios and have enabled a wide variety of applications. Among consumer lighting devices and systems, incandescent lamps and fluorescent lamps remain the most popular options, closely followed by light-emitting diodes (LEDs). Incandescent lamps generate optical radiation through the heating of a metal wire, which rapidly increases in temperature when connected to a power source. Traditional ("desktop") fluorescent lamps consist of mercury vapour in an enclosed tube and are designed to provide wavelength-specific radiation (typically centred at a wavelength of 254 nm) from an inner glass wall, as emission is absent in a free-space regime due to aluminium atoms adsorbed on the tube walls. By direct comparison, LED-based lighting offers integrated photoelectric features and exceptionally long lifetimes (>10 000 h) of

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operation; such persistence is unreachable by traditional incandescent and fluorescent devices (L. Fritzen et al., 2020).

4.2. Biological Imaging

Luminescence imaging is favored in biological analysis for its simplicity, non-destructive nature, and shorter measurement times compared to fluorescence. It provides a lower background signal, making it useful for in vivo imaging. Research continues vigorously into bioluminescence imaging reagents and substrates. Numerous caged luciferin-based probes and 1,2-dioxetane chemiluminescence probes have been developed for in vivo use. This indicates that bioluminescence and chemiluminescence imaging will remain influential in biological discoveries. The rapid feedback, high sensitivity, and spatiotemporal resolution of biomedical luminescence imaging facilitate real-time detection of physiological and pathological processes. Various luminescence probes, including organic dyes and quantum dots, are being studied as contrast agents. Significant attention is directed towards developing agents operating within the near-infrared window (700–1700 nm), particularly the second near-infrared window (NIR-II, 1000–1700 nm), which ensures high spatial resolution and deep tissue penetration due to reduced scattering and autofluorescence. Autofluorescence diminishes with increasing wavelength and is negligible beyond 1500 nm; however, few probes can image at this range. Detecting and imaging within deep tissue is challenging due to signal attenuation from tissue absorption and scattering, necessitating alternative detection methods. Luminescence lifetime imaging is a key technique for identifying specific biomarkers or physiological processes, operating independently of contrast-agent concentration and less affected by tissue-related artifacts. (Takakura, 2021)(Li et al., 2022) .

4.3. Security and Safety Applications

Security and safety have gained considerable attention in recent decades, and luminescent materials can provide excellent features in several areas. Radioluminescent information storage systems can significantly improve data safety by offering unique security keys based on radiation intervals or repetitive radiation. For instance, microwave devices including clocks, oscillators, and filters for phase-shift keying signals, as well as self-calibrated brightness shielding, have been designed to support these applications. Because ^4f ^–^4f and ^4f ^–^5d inner electronic transitions can produce spectrally, temporally, and thermally resolved photoluminescence, luminescence spectroscopy becomes a powerful approach for particle sensing and can even assist in anti-counterfeiting and antimission. Scintillation detectors—utilizing radioluminescent oxides, such as Tb-doped Gd_2O_3/Y_2O_3 powders or (Y,Gd)_2SiO_5 single crystals—can effectively perform near-real-time neutron radiography to monitor and visualize radioactive sources (YANAGIDA, 2018). By employing thermally and optically stimulated luminescence materials to aggregate radioactive sources, security personnel can efficiently locate them; these materials also help minimize false alarms, as the excitation and luminescence are highly specific to nuclear emissions (L. Fritzen et al., 2020).

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4.4. Environmental Monitoring

Environmental monitoring is a crucial aspect of luminescence applications. Fluorescence has been employed to track pollution, fertilizer efficiency, and toxic materials in air, water, and soil formulations. Both natural and artificial light emissions enable the monitoring of emission dispersion and accumulation. By exploiting fluorescent nanomaterials, agents with high sensitivity and selectivity can be designed to detect active molecules and environmental toxicants in living organisms. A notable example is the luminous bacteria test, which detects exposure to ecotoxicological agents by measuring changes in bacterial bioluminescence intensity and luminescence induction time (Lebel et al., 2024).

5. Luminescent Materials

Luminescence encompasses a diverse range of optical phenomena permitting the design of materials that respond to various external stimuli with a broad spectrum of observable colors and temporal profiles.

For fundamental research and to meet the demands of specific applications, the ability to generate, sustain, adjust, and inhibit characteristic luminescence is crucial.

These capabilities depend critically on both the excitation method and the luminescent material employed (Sharma et al., 2024) (Tan et al., 2019).

5.1. Organic Luminescent Materials

Organic luminescent materials encompass small molecules, polymers, and macrocycles, many of which exhibit aggregation-induced emission (AIE). These materials play essential roles across lighting and display devices, biological sensing and imaging, antimicrobial and antiviral agents, solar concentrators, security inks, and luminescent solar concentrators (Sharma et al., 2024). Light-emission efficiency critically influences the performance of devices incorporating organics. Photoluminescence is pivotal in detecting and understanding structural features within solid-state materials including semiconductors, metals, and insulators. Long persistent luminescence (LPL) in organic materials stems from mechanisms such as triplet-triplet annihilation, delayed fluorescence, and thermally activated delayed fluorescence. The appeal of organic LPL compounds lies in their adaptability, facile solution-phase processing, and adjustable emission colors. Although the majority of organic persistent-emitter systems are based on phosphorescent compounds, a limited number of organic systems are capable of exhibiting prolonged phosphorescence under ambient conditions despite competition from various non-radiative decay pathways.

5.2. Inorganic Luminescent Materials

Inorganic luminescent materials date back to the 15th and 16th centuries, initially serving as phosphors in lamp mantles. The 1990s introduction of blue LEDs sparked renewed interest in these phosphors, leading to their use in energy-efficient lighting and displays. Inorganic luminescent systems consist of a host lattice, an emitting center, and other components. Typically, the host is a semiconductor with heavy elements to promote electronic transitions,

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creating high band gaps or low phonon energy. Emitting centers can be rare-earth ions or transition metal ions, while luminescence may arise from defects or intrinsic properties. Commercial fluorescent lamps mainly use Hg-i lamp and light-conversion phosphors for LEDs, with other uses including particle radiation, X-ray scintillation, lasers, plasmonics, and dosimeters. (Ishida et al., 2019)(Sharma et al., 2024)

5.3. Nanomaterials

Nanomaterials are organic or inorganic materials with dimensions below 100 nm, and luminescent types are valued for their optical and electrical properties, photochemical stability, large surface area, and ability to be functionalized. They significantly improve the performance of polymer matrices by enhancing conductivity and thermal stability. Research focuses on synthesizing novel luminescent nanomaterials, such as nanoparticles, quantum dots (Qdots), and carbon nanomaterials, for luminescence detection and studies. Recent advancements include magneto-plasmonic Qdots and semiconductor heterostructures, crucial for analytical luminescence techniques like electroluminescence and X-ray detection. Functionalized nanoparticles' high photoluminescence benefits bioimaging and cancer therapy.

6. Measurement and Characterization Techniques

Measurement and characterization of luminescence employ various techniques that provide insight into luminescent materials and their emission phenomena. Central to studies are luminescence excitation and emission spectra, utilizing methods like photoluminescence spectroscopy, chemiluminescence, bioluminescence, electroluminescence, thermoluminescence, and radioluminescence. The excitation and emission processes, along with energy transfer, are vital to luminescence phenomena. Technologies including photoluminescence, chemiluminescence, and electroluminescence have significant applications, such as in lighting, environmental detection, monitors, dosimetry, and archaeological dating. Effective material preparation and characterization are essential, along with addressing challenges related to stability and degradation for practical implementation.

6.1. Spectroscopy Techniques

Luminescence experiments yield high information content, and probing luminescence spectra from solids, liquids, or single molecules in steady-state or time-resolved modes is common in radiation science. These techniques are widely implemented in biological, chemical, and physical research for analysis and measurement. Key emission time regimes guide technique selection and experimental setup. Important luminescence techniques include photoluminescence, which often uses selective excitation via a monochromatic light source. Steady-state experiments ascertain the emission lineshape, while time-resolved ones offer decay data. Excitation sources comprise mercury and xenon arc lamps, lasers, LEDs, and discharge lamps, with directional laser sources favored. Steady-state fluorescence/photoluminescence is pivotal for environmental sensing, as the emission lineshape, Stokes' shift, and lifetime are influenced by environmental and chemical factors. Photoluminescence is valuable for analyzing defects in crystals and organic

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materials, and integrated luminescence intensity measurements can reveal molecular organization. (Ishida et al., 2019)

6.2. Microscopy Techniques

Luminescence microscopy techniques remain at the forefront of innovative imaging methods in biological and materials research. Microscopic techniques, based on luminescence processes, are routinely used for the imaging of cells, tissues, and molecules. In organic molecules, luminescence is excited using light. Inorganic or hybrid materials (mainly inorganic phosphors or quantum dots) can also be excited using electrons to generate cathodoluminescence for detailed imaging of the surface layers of a sample. Electron microscopy with cathodoluminescence detection has been employed in materials science, yet offers unexplored opportunities in life sciences.

Different types of luminescence microscopy are established for super-resolution imaging, three-dimensional sectioning of deep tissues, single-cell in situ monitoring, and several other fields that are impossible or challenging for traditional imaging techniques. The wealth of information provided by luminescence is accompanied by challenges, however, including stability, durability, and intensity. Continuous efforts in fundamental photophysics and photochemistry aim to overcome these issues.

7. Challenges in Luminescence Research

Durability, stability, and cost represent the principal challenges of luminescence and persistent luminescence materials (L. Fritzen et al., 2020). For persistent luminescence materials, improved formulation strategies investigated as a route to enhanced chemical stability should precedent the improvement of afterglow intensity. Despite the decrease in afterglow intensity observed with enhanced stability, continued improvement of the formulation ensures increased intensity. Previous studies have resorted to enhancing both external and internal quantum efficiencies to improve afterglow intensity.

7.1. Stability and Durability

Luminescent materials such as phosphors and quantum dots serve various applications, including lighting, displays, sensors, and bioimaging. Luminescent emission typically requires continuous excitation, yet persistent luminescence materials can store excitation energy and release afterglow upon cessation of excitation. The phenomenon of phosphorescence, describing long-lasting afterglow, has been studied since the 17th century, making PL one of the oldest photophysical phenomena. Luminescence validity in materials generally requires a balance between brightness and afterglow duration. Effective utilization calls for persistent phosphors and luminescent nanoparticles with tunable optical properties, stability, durability, reproducibility, efficiency, and spectral range.

7.2. Efficiency Improvements

Luminescence efficiency is an essential factor for the commercialization of luminescent devices. Various techniques have already been developed and applied to enhance this capability. For

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example, according to Sharma et al. (Sharma et al., 2024) , an organic blend such as a luminescence-tetramethylbenzidine-polyphenylene terephthalamide (TMB-PPT) system can enhance solar cell performance because it absorbs the ultraviolet part of the solar spectrum and emits visible luminescence, which is readily absorbed by the solar cell. However, empirical investigations demonstrated that a luminescence blend exhibits a short-lived organic luminescence effect and a negligible net enhancement of energy conversion.

8. Future Trends in Luminescence

Luminescence is the light emitted by a material without heat, encompassing various subcategories like photoluminescence, electroluminescence, and bioluminescence. It occurs when an electric, magnetic, or electromagnetic field excites an atom or molecule, resulting in the emission of photons as the excited state relaxes. The use of luminescence is rapidly increasing, attracting significant research interest. Different excitation mechanisms influence luminescence behavior. Its sensitivity and versatility allow applications in diverse fields. Improvements in light sources, such as efficiency and brightness, are advancing many sectors. Despite being known for over 4000 years, luminescence's true potential is just beginning to be acknowledged. (L. Fritzen et al., 2020)

8.1. Advancements in Material Science

The field of luminescence is advancing rapidly due to innovations in material science, resulting in new materials and improved characterization techniques. Long persistent phosphors and organic afterglow materials are shifting toward host–guest architectures. Research into organic long-persistence luminescence in molecular crystals shows that duration depends on the energy gap between singlet and triplet states, while efficient room-temperature phosphorescence is emerging in amorphous organic materials due to host–guest interactions. Practical applications include rare earth doped phosphors like $SrAl2O4:Eu,Dy$, which improve photovoltaic performance and are being integrated into solar cells. Luminescent silica nanoparticles (LSNs) have also made significant strides, combining brightness and stability with the versatility of silica for various applications such as bioimaging, chemosensing, and nanomedicine, with potential in solar energy conversion. Challenges include enhancing selectivity and signal-to-noise ratios and refining synthesis methods. However, interactions between phosphors and localized surface plasmon resonance (LSPR) metals present promising research avenues. (Sharma et al., 2024)(Li et al., 2019)

8.2. Integration with Nanotechnology

Nanomaterials compatible with luminescence are increasingly valued for their unique properties compared to bulk materials. Nanostructures display distinctive physical behaviors that enhance luminescence, aided by high dispersity, purity, and adjustable surfaces. Photo-excited electrons and holes, as minority carriers, can transfer energy more readily before recombination. This fusion of luminescence and nanostructures is compelling, with lanthanide-doped upconversion nanoparticles (Ln-UCNPs) showing remarkable near-infrared (NIR)-to-visible upconversion

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luminescence. These offer promising uses in bioimaging, photodynamic therapy, drug delivery, and sensors. Other luminescent nanomaterials include NIR-II molecular fluorophores with Au clusters, halide perovskites, and phenothiazine-based polymers. Control over type, shape, size, and surface chemistry aids in designing tailored luminescent nanostructures. Quantum dots (QDs) can also produce visible light through electron and hole recombination. Integrating nano- and micro-technologies is essential for on-chip light sources, linking luminescent research to real-world applications. (Yang et al., 2021)

9. Conclusion

Luminescence is the spontaneous emission of light from external stimulation, demanding a multi-disciplinary approach to ensure its qualitative and quantitative analysis across various fields. It plays a crucial role in contemporary science and technology, attracting substantial attention during recent decades and spurring fast-developing materials-research activities. Its continued importance necessitates an overview covering essential concepts, types, mechanisms, luminescent materials, applications, key characterization techniques, challenges, and future trends.

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