

Review



Nanocluster Luminophores for Electrogenenerated Chemiluminescence Imaging

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Abstract: Electrogenenerated chemiluminescence (ECL) imaging has emerged as a powerful visual analytical technique that integrates electrochemistry and optical detection, and finds extensive applications in immunosensing, single-cell analysis, and single-particle behavior investigation. Its exceptional capacity to realize in situ visual observation of microscale targets endows this method with irreplaceable practical value in frontier analytical research. Luminophores act as the core determinant of ECL imaging emission, while the limited types and inherent defects of conventional luminous materials severely restrict the further development and practical application of ECL imaging. As a newly developed class of functional materials, nanoclusters offer outstanding advantages, including low toxicity, good biocompatibility, tunable optical performance, and high structural uniformity, making them promising innovative luminophores for advanced ECL imaging. This review systematically summarizes the basic equipment of ECL imaging and comprehensively discusses the advantages and limitations of mainstream ECL luminophores. More importantly, it emphatically reviews the unique properties, photon emission-enhancing strategies, and diversified imaging applications of nanocluster-based ECL systems. Additionally, the current technical bottlenecks of nanocluster ECL imaging are discussed, and future research directions, including structure-activity relationship exploration, synergistic performance modification, application expansion, and intelligent equipment integration, are prospected. This review aims to provide a systematic and insightful reference for the rational design of high-efficiency ECL luminophores and the development of novel high-performance ECL imaging platforms for bioanalysis and environmental monitoring.

Keywords: ECL imaging; nanoclusters; performance enhancing strategies; applications

1. Introduction

Electrogenenerated chemiluminescence (ECL) refers to a luminescence phenomenon in which luminophores undergo high-energy electron-transfer processes at electrode interfaces to form excited states, which subsequently relax to the ground state accompanied by photon emission [1–4]. Integrating the merits of electrochemistry and optical readout, ECL represents a unique subset of luminescence where reactive intermediates are generated via electrochemical redox reactions at electrode surfaces through electrical excitation, fundamentally differing from photoluminescence such as fluorescence and phosphorescence [5,6]. As early as the 1920s, Dufford and Harvey independently observed light emission during electrolysis using Grignard reagents and luminol (5-amino-2,3-dihydro-1,4-phthalazinedione), respectively [7,8]. It was not until the mid-1960s that comprehensive investigations into the electron-transfer mechanisms of ECL were reported by research groups led by Hercules, Chandross, Bard,



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and other pioneers, laying a solid foundation for the rapid advancement of ECL technology thereafter [9–12]. Benefiting from the synergy between electrochemical and spectroscopic methodologies, ECL exhibits prominent superiorities over chemiluminescence and photoluminescence: (1) External excitation light sources are not required, yielding ultralow background signals and an ultrahigh detection sensitivity down to the $\text{pmol}\cdot\text{L}^{-1}$ level; (2) Both the temporal and spatial resolution of luminescence can be precisely controlled; (3) An extremely broad linear detection range spanning more than six orders of magnitude and ultrafast signal acquisition within several seconds. To date, ECL has evolved into a robust analytical technique with tremendous achievements across diverse research areas, including bioanalysis [13,14] and immunoassays [15,16]. Moreover, commercialized bioassays based on ECL have been widely applied in clinical diagnosis [17]. Supported by continuously emerging technical approaches, ECL-based analytical methods are undergoing fast-paced innovation and expansion.

In the 1990s, Amatore [18] and Bard [19] pioneered the integration of microscopic imaging techniques with ECL. Taking advantage of the intrinsic spatial resolution of microscopy, they visualized the molecular concentration gradients generated by ECL redox reactions in the vicinity of electrode surfaces [20]. Since then, ECL imaging has attracted extensive research interest owing to its unique merits, including the absence of interference from external excitation light sources, favorable spatial resolution, and high-throughput detection capacity [21,22]. Its representative applications cover latent fingerprint visualization [23], colorimetric ECL sensors [24], enzymatic activity quantification [25], single-cell bioanalysis [26–28], and single-particle characterization [29–31]. Among these branches, investigations targeting single-cell physiological events and single-particle interfacial behaviors stand out as the most prominent, which have greatly accelerated the advancement of ECL imaging and established this technique as a powerful platform for exploring cellular physiological activities as well as the physicochemical properties of functional materials.

Despite the substantial progress and broad application prospects of ECL imaging, its further development is still severely restricted by the limited variety of available ECL luminophores. Currently, ECL imaging overwhelmingly relies on two classical mature systems, namely the $\text{Ru}(\text{bpy})_3^{2+}$ /tripropylamine (TPA) and luminol/ H_2O_2 reaction pairs. Nevertheless, these conventional ECL systems still suffer from inherent drawbacks that limit their analytical performance and imaging applicability. In this regard, the exploration and development of novel ECL luminophores with enhanced luminous efficiency, tunable photon emission, and superior stability are critically important for advancing and broadening the practical utility of ECL imaging technology.

In this review, we systematically summarize the basic equipment configuration of ECL microscopy, as well as the categories, advantages, and inherent limitations of currently available ECL luminophores (Figure 1). Specifically, we emphatically focus on emerging nanoclusters as a novel class of ECL luminophores for ECL imaging. The unique superiorities of nanocluster-based ECL emitters, the feasible strategies for ECL intensity enhancement, and their diverse imaging applications are comprehensively elaborated. Furthermore, the current challenges and future development prospects of nanocluster-based ECL imaging technology are prospected, aiming to provide a systematic reference and insightful perspective for the design, optimization, and extended application of advanced ECL imaging platforms.

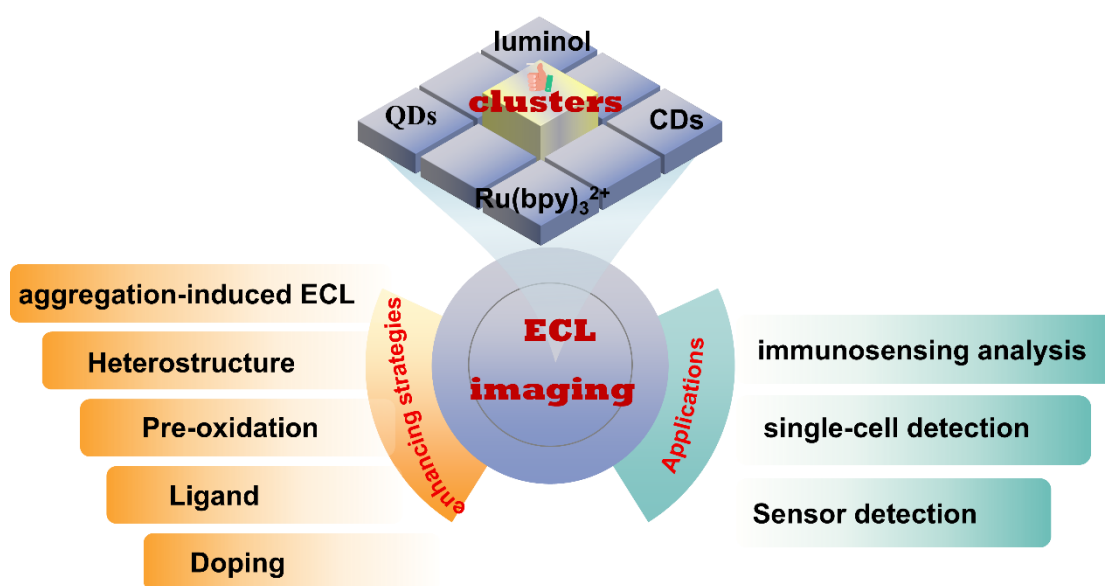


Figure 1. Schematic diagram of nanocluster luminophores for electrogenerated chemiluminescence imaging.

2. The ECL Microscopy Setup

As illustrated in Figure 2, the ECL imaging system consists of an electrochemical cell, a voltage generator (or electrochemical workstation), a simple optical imaging assembly, and a computer terminal [32–34]. Conventional electrochemical cells adopt a three-electrode configuration, comprising a working electrode (WE), a reference electrode (RE), and a counter electrode (CE) [35]. Analytes are either immobilized on electrode surfaces or uniformly dispersed in electrolyte solutions. Widely utilized working electrodes can be categorized into four major groups: (1) Noble metal electrodes [36] (Pt, Au) feature rapid electron-transfer kinetics, yet they are susceptible to electrochemical oxidation and surface passivation, resulting in compromised ECL sensitivity and inferior operational stability; (2) Carbon-based electrodes [37,38], including the conventional glassy carbon electrode as well as emerging carbon nanomaterials such as carbon nanotubes and graphene, exhibit fast heterogeneous electron-transfer dynamics, despite the difficulty in achieving consistent structural quality of carbon substrates; (3) Transparent electrodes fall into two subcategories: glass-supported metal oxide electrodes [39] (e.g., indium tin oxide (ITO) and fluorine-doped tin oxide (FTO)), and carbon-based electrodes supported on glass or polymeric substrates [40], both of which are cost-effective and user-friendly; (4) Boron-doped diamond [41,42] (BDD) electrodes possess distinct merits including a broad electrochemical potential window, strong resistance to high applied potentials, and outstanding chemical and mechanical stability. As depicted in Figure 2, electrochemical reactions are triggered by the voltage generator or electrochemical workstation. Upon activation, luminophores undergo redox reactions at the working electrode interface to generate ECL emission. The emitted optical signals are captured by a charge-coupled device (CCD) or an electron-multiplying CCD (EMCCD), followed by signal readout and data recording via matched computer software.

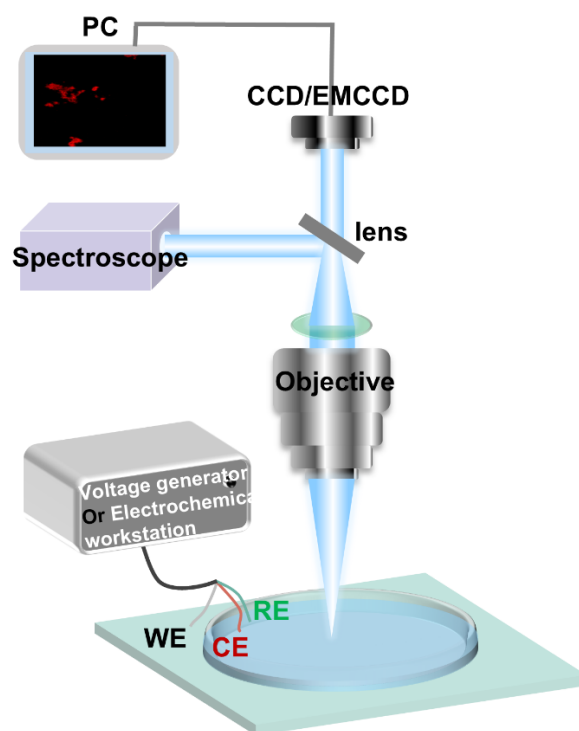


Figure 2. Schematic illustration of the ECL microscopy setup.

3. Luminophores for ECL Imaging

ECL luminophores play a leading role in ECL imaging systems, which react with different co-reactants or their intermediates to generate ECL emission [43]. Figure 3 illustrates common luminophores, along with their advantages and limitations. Representative traditional organic small-molecule ECL luminophores, including $\text{Ru}(\text{bpy})_3^{2+}$ and luminol, possess high luminescence quantum yields and constitute well-established and mature ECL systems that have been widely applied in conventional ECL analysis and imaging [15]. Nevertheless, these classic luminophores still suffer from several inherent limitations. Ruthenium complexes are costly and exhibit unsatisfactory ECL stability under long-term detection, while both ruthenium and luminol systems exhibit narrow and non-tunable emission bands, which greatly restrict their multiplexed imaging and in-depth analytical

applications [44,45]. With the rapid advancement of nanostructures, a variety of nanomaterial-based luminophores, including quantum dots (QDs) [46,47], carbon-based quantum dots (CDs) [48,49], and perovskite [50,51] have been successively introduced into ECL imaging to address the shortcomings of traditional small molecules [3,52]. These nanoluminophores exhibit tunable optical properties, improved surface modifiability, and enhanced ECL performance, effectively compensating for the fixed emission wavelength and poor functional expandability of conventional organic luminophores. However, nanomaterial ECL emitters inevitably present new challenges. Most QDs and perovskite materials suffer from high biological toxicity, poor aqueous stability, and complicated synthetic procedures [53]. In addition, uncontrollable particle size distribution and severe batch-to-batch inconsistency further hinder their reproducibility and practical application in high-precision ECL imaging and bioanalysis. Therefore, exploring novel ECL luminophores with high stability, low toxicity, uniform structure, and facile synthesis is urgently required for the further development and application of high-performance ECL imaging technology.

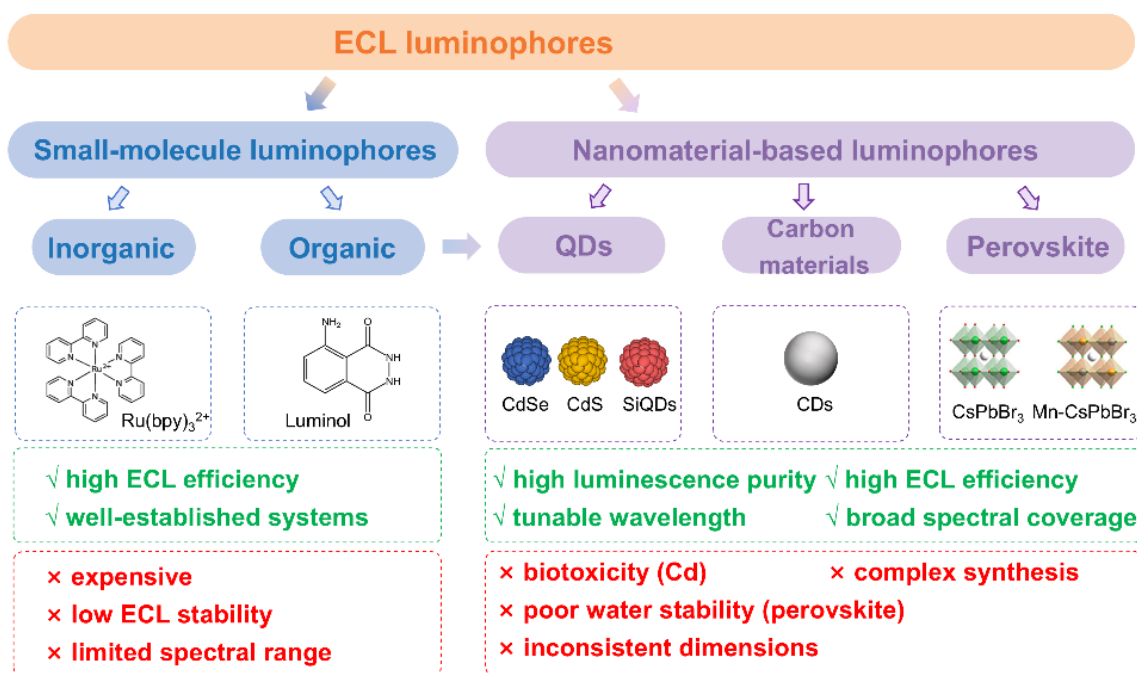


Figure 3. Luminophores for ECL imaging and their advantages and limitations.

To address the limitations of traditional luminophores, the use of nanoclusters as ECL emitters has developed rapidly since ECL properties were first detected in gold nanoclusters [54]. Nanoclusters are a class of ultra-small nanomaterials composed of a limited number of atoms or molecules, with sizes typically ranging from a few angstroms (Å) to several nanometers (nm), bridging the gap between single molecules and conventional nanocrystals [55,56]. Compared with traditional ECL emitters, nanoclusters possess inherent advantages in ECL imaging: (1) Nanoclusters have precise molecular formulas and structures, ensuring consistency between batches of synthesised products and reproducibility of their ECL properties, which is crucial for demanding applications in bioassays and clinical diagnostics; (2) The synthesis of clusters often involves simply mixing precursors; the conditions are straightforward and the process is easy to carry out; (3) Clusters typically measure less than 2 nm in size, which is significantly smaller than traditional nanocrystal luminescent materials, enabling them to reflect the original position and distribution of target molecules with greater precision and achieve higher-resolution imaging; (4) Noble metal clusters, typically gold clusters, can be metabolized by the human body without causing biological toxicity, endowing them with unique superiority for life-health-related ECL bioanalysis and in situ biological imaging; (5) The emission wavelength of the clusters can be precisely tuned within the visible to near-infrared spectrum, laying the foundation for the application of cluster-based ECL imaging systems. Nanoclusters show distinctive strengths in ECL imaging beyond their common advantages in ECL sensing. Their near-infrared emission reduces biological background noise and achieves deep penetration for intracellular and tissue imaging. Their ultrasmall size ensures high resolution and favorable cell permeability. In addition, facile surface functionalization supports specific targeted imaging. Tunable electrochemical properties also enable multi-mode ECL imaging. With low phototoxicity and good photostability, they are ideal for long-term dynamic imaging of living samples.

4. The ECL Enhancing Strategies of Nanoclusters

Although nanocluster luminescent materials possess inherent advantages, their ECL efficiency is inherently lower than that of traditional inorganic metal complexes and organic ECL probes. This inefficiency stems from two main factors [57]: (i) Emission limitation: the surface ligands of nanoclusters, through their rotational and vibrational movements, facilitate non-radiative energy dissipation from the excited state back to the ground state, which diminishes the efficiency of radiative transitions [58–61]; (ii) Excitation limitation: the generation rate of active free radicals and the electron transfer rate between them are slow, adversely affecting the ECL efficiency of nanoclusters [62–65]. A series of established performance enhancement strategies, including doping, ligand, heterostructure, pre-oxidation, and aggregation-induced ECL, elevate the ECL efficiency of nanoclusters by improving emission efficiency, excitation efficiency, or both. The ligand strategy acts solely on emission efficiency, while heterostructures and pre-oxidation only promote excitation efficiency. In contrast, doping and aggregation-induced ECL are capable of enhancing the two efficiencies simultaneously. The representative strategies are summarized as follows: (1) Doping strategy: Metal ion doping typically involves the generation of bimetallic or polymetallic nanoclusters through the strategic substitution or replacement of metal atoms without disrupting their structural integrity [56,66,67]. The doping enriches the electronic properties and catalytic activity, ultimately resulting in improved luminescent performance [68]. As shown in Figure 4a, Ag was doped into Au NCs to prepare Au-Ag bimetallic nanoclusters. On the one hand, the formation of Au-Ag alloy in the core layer exhibited a synergistic effect in enhancing ECL, and on the other hand, the formation of Ag-N bonds in the shell layer restricted the free movement of surface ligands. Consequently, these two interactions collectively improved the emission efficiency of Au NCs [69]. (2) Ligand strategy: Nanoclusters are luminescent materials with a core-shell structure; they also possess a high specific surface area, which means that surface ligands have a significant influence on their properties [63,70,71]. Chen and his team systematically compared the ECL intensity of Au-Ag NCs stabilized by Met, BSA, MUA, NAC, l-Pro, and GSH, and found that Au-Ag NCs protected by the Met ligand exhibited the best performance (Figure 4b) [72]. Met balances lattice mismatch and reduces surface-state defects, increasing the ECL efficiency by up to 163%. Furthermore, it narrows the bandgap, facilitating electron transfer and significantly enhancing the ECL response. (3) Heterostructure: As shown in Figure 4c, Pd nanocubes (Pd NCs), serving as a co-reaction accelerator, formed a heterostructure with Au NCs on the working electrode surface [73]. This structural design enhanced the ECL signal of the Au NCs-TEA system via two mechanisms. On one hand, Pd NCs acted as efficient “electron traps” to capture electrons injected from TEA into the lowest unoccupied molecular orbital of Au NCs, thus significantly promoting the oxidation of TEA. On the other hand, the incorporation of Pd NCs effectively improved the electrochemically active surface area of Au NCs, thus providing more active sites to catalyze the oxidation of TEA. Together, these two mechanisms accelerated the generation of TEA free radicals and the subsequent excited state of Au NCs, thereby enhancing the ECL of the system. (4) Pre-oxidation: The pre-oxidation process accelerates the formation of radical cation intermediates and co-reactant promoters. Subsequent low-potential treatment activates these promoters, thereby accelerating the formation of excited-state NCs and enhancing the electrochemiluminescence response. For example, research by Shen and his colleagues shows that the ECL of Met-AuEu NCs was enhanced 24.3-fold via pre-oxidation in 100 mM triethanolamine at the potential step of 1.0 V for 60 s, obtaining a high ECL quantum yield of 143% [68]. The pre-oxidized Met-AuEu NCs retained a 20.1-fold ECL enhancement ratio after storing for 12 h and generated intense self-ECL in the absence of co-reactant (Figure 4d). (5) Aggregation-induced ECL: The aggregation of luminophores can reduce free rotation and vibration, suppressing non-radiative decay for enhanced ECL [74]. Zou et al. found that Zn^{2+} -induced aggregation of Au NCs can result in 1690-fold enhanced ECL [75] (Figure 4e). Two coupled pathways contribute to this multiplicative enhancement effect. Improved ligand rigidity occurs upon Zn^{2+} -induced aggregation of Au NCs, as the Zn^{2+} can reduce the vibration and rotation of ligands to suppress non-radiative decay. Meanwhile, Zn^{2+} -ligand bonds promote electron transfer, which can enhance charge annihilation with the assistance of energy level alignment between Au NCs and the Zn^{2+} -ligand bond. The dual-enhanced Aggregation-induced ECL strategy can be utilized to design even brighter ECL luminophores.

The improved ECL performance further promotes the application of nanoclusters in ECL imaging. Yuan's group developed an agmatine/6-aza-2-thiothymine templated gold nanoclusters (Agm/ATT-Au NCs) as a novel ECL illuminant [76]. The electrochemical redox reaction of Agm/ATT-Au NCs was enhanced owing to the boosted electron transfer kinetics of the illuminant by the positively charged Agm-triggered surface charge redistribution of ATT-Au NCs, resulting in an ~110-fold higher ECL signal of Agm/ATT-Au NCs than ATT-Au NCs. Building on this, a faint, diffuse ECL emission of Agm/ATT-Au NCs was observed with a potential sweep from 0 V to 1.0 V in PBS containing 10 mM TPrA (Figure 5), representing the first ECL imaging achieved from these nanocomposites and suggesting their promising prospects in this field.



Figure 4. The ECL enhancement strategy of nanoclusters: (a) Doping [69], Copyright 2025 Elsevier; (b) Ligand [72], Copyright 2025 American Chemical Society; (c) Heterostructure [73], Copyright 2026 Elsevier; (d) Pre-oxidation [68], Copyright 2025 Elsevier; (e) Aggregation-induced ECL [75], Copyright 2025 the Royal Society of Chemistry.

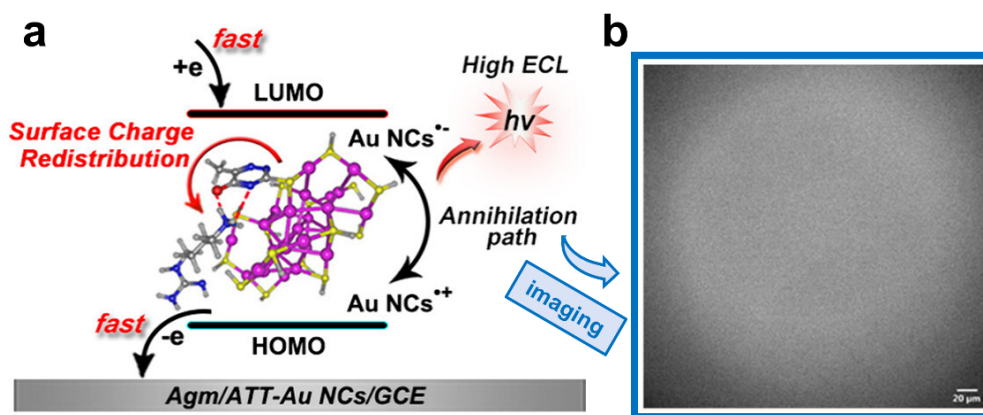


Figure 5. (a) ECL path; (b) ECL images of Agm/ATT-Au NCs [76], Copyright 2025 American Chemical Society.

The above-mentioned work focuses on developing single-wavelength ECL emission enhancement strategies for Au NCs, which are unable to achieve spectrally continuous tunability, thereby hindering their progress in multispectral ECL imaging, optoelectronic devices, and spectrum-resolved multiplexed biosensing systems. In contrast, near-infrared-I (NIR-I) NCs, as light sources, offer advantages including near-zero background interference, deep tissue penetration, and low light damage [77–79], showing great potential in optoelectronic devices (such as solid-state lasers [80], light-emitting diodes [81], and waveguides [82]) as well as multispectral ECL imaging [83]. Yuan's research team achieved a comprehensive enhancement of the ECL emission of Au NCs across the entire NIR-I window by continuously tuning the plasmon resonance absorption wavelength of gold nanorods (Au NRs) to precisely match the ECL emission wavelength of the gold nanoclusters (Au NCs) [84] (Figure 6a). Within the wavelength range from 670 nm to 820 nm, the ECL intensity of Au NCs/Au NRs is 3–4 times higher than that of individual Au NCs due to the acceleration of electron-hole recombination and radiation transition rate by the high-energy electromagnetic field. In contrast, compared with Au NCs, the ECL imaging of Au NCs/Au NRs exhibits distinct characteristics, with clearly visible bright spots uniformly distributed across the field of view, indicating that NIR-I ECL imaging of the nanoclusters has been achieved (Figure 6b).

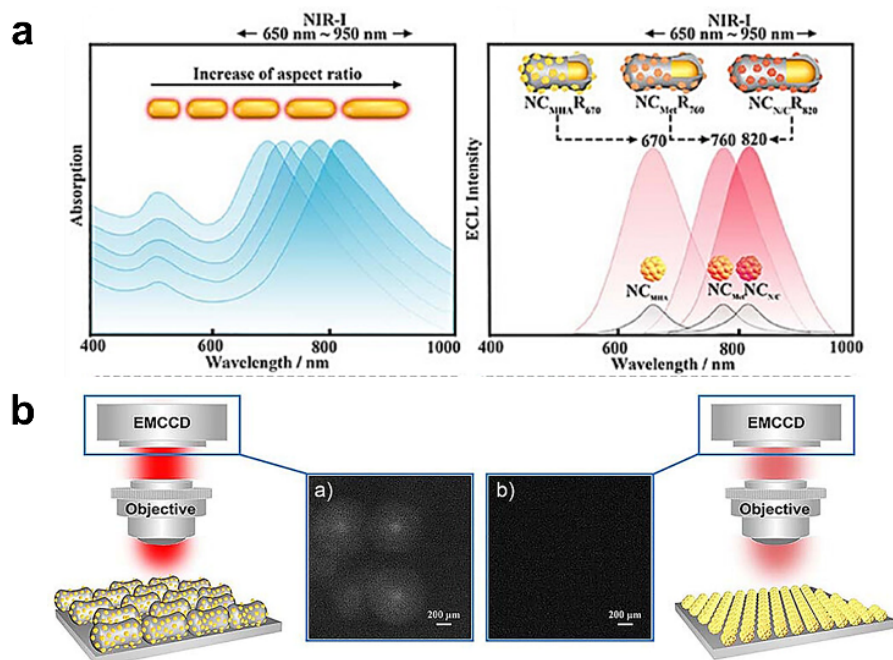


Figure 6. (a) The entire NIR-I ECL enhancement strategy of Au NCs; (b) ECL images of Au NCs/Au NRs and Au NCs [84], Copyright 2025 Wiley.

5. Applications of ECL Imaging in Nanoclusters

The previous section has developed various strategies for enhancing the ECL performance of nanoclusters and has further demonstrated ECL imaging, thereby laying the groundwork for the application of nanocluster-

based ECL imaging systems. As a new technology that integrates electrochemistry and optical imaging, ECL imaging offers a number of unique advantages [83,85–87]. ECL imaging requires no external excitation light source, thereby eliminating autofluorescence and scattering background [88]. The improved signal to noise ratio and sensitivity allowing high-sensitivity analysis of subtle signal variations in the systems [6]. These characteristics endow ECL imaging with considerable potential for development in biological analysis [89,90].

5.1. Sensor Detection and Analysis

Given the aforementioned advantages of ECL imaging, it has emerged as a highly effective sensing and detection method [2,91]. Wei and her colleagues employed the nanocluster-based ECL imaging system for the sensitive visual detection of the insecticide acetamiprid (ACT) [92]. Met-Au NCs served as efficient near-infrared-emitting nanoclusters, with triethylamine (TEA) as the co-reactants, to construct an ECL imaging sensor for the detection of ACT (Figure 7a). The ZnS-ZnIn₂S₄-In₂S₃ (Z-Z-I) semiconductor material, synthesized by vulcanization of ZIF-8@MIL-68(In) as a template, not only provided a large specific surface area for the loading of aptamers but also accelerated the generation of triethylamine radicals, thereby enhancing the ECL signals. Moreover, the sensor provided anodic near-infrared ECL emission, which was harmless to active materials such as aptamers. On this platform, ECL imaging was utilized to image different concentrations of ACT. In the detection range from 100 fM to 1 μ M, the linear equation was $C = 1211 \lg c + 16561$ ($R^2 = 0.98$), and the detection limit was 42 fM, demonstrating superior performance compared to other ACT detection methods. This work provides some valuable insights into the development of highly sensitive sensors and visualized ECL sensors.

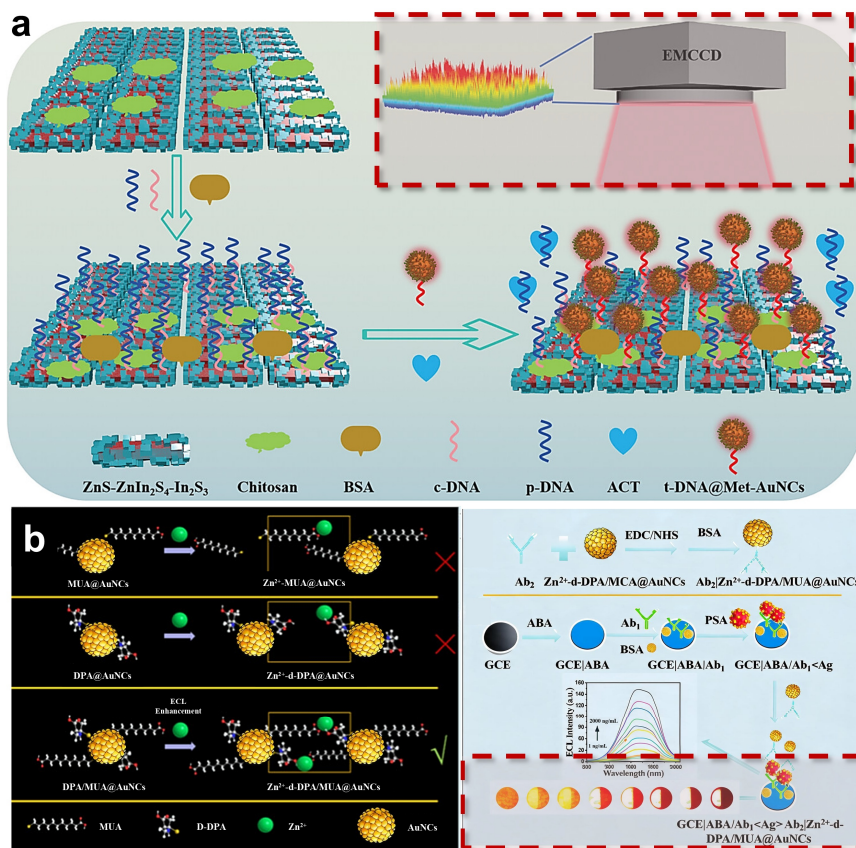


Figure 7. (a) ECL imaging sensor construction process of Z-Z-I/Met-Au NCs [92], Copyright 2024 Wiley; (b) The fabricating procedures of NIR ECL sensor with Zn²⁺-d-DPA/MUA@Au NCs as tags [93], Copyright 2026 American Chemical Society.

Guo's group has further extended the nanocluster ECL imaging system to the field of immunosensing analysis. They designed a simple strategy for developing an enhanced NIR ECL system with Au NCs as luminophores via introducing Zn²⁺ into d-penicillamine/11-mercaptopundecanoic acid (d-DPA/MUA) capped Au NCs and triethanolamine (TEOA) as a coreactant (Figure 7b) [93]. Thanks to a combined strategy of the short/long chain ligands with less steric hindrance and aggregation-induced effect, the coordination of Zn²⁺ to Au NCs caused the rigidity of ligand motion by cross-linked NCs aggregates, which induced the disappeared vibration of the –CH₂– structure from MUA. Moreover, the enhanced carrier concentration and electron–hole recombination at

the interface of Au NCs along with the addition of Zn^{2+} could considerably increase the ECL intensity by around 9-fold compared with Au NCs without Zn^{2+} . By combining this nanocluster with the corresponding antibody to construct an immunosensor, they were able to detect prostate-specific antigen (PSA). ECL images were captured using an ECL imaging instrument, as shown in Figure 7c, revealing that ECL intensity increased with rising PSA concentration. This approach enables the visualization and detection of biomolecular substances. Each image showed the prepared immunosensor (left) and blank control (right). This blank control validated the immunosensor's response specificity and enabled semiquantitative visual discrimination of PSA concentration ranges.

5.2. Single-Cell Detection

The superiority of ECL imaging over conventional ECL lies in its ability to observe micro-region changes, rendering it widely applicable in single-cell analysis [94–96]. However, conventional ECL imaging typically relies on luminescent layers ranging in thickness from hundreds of nanometres to micrometres (originating from $\text{Ru}(\text{bpy})_3^{2+}$ or luminol), which reduces spatial resolution and obscures fine details within cells. Consequently, there is an urgent need for ultra-micro ECL emitters capable of forming strong and stable near-zero-thickness ECL layers in situ to enable high-resolution ECL imaging. Ultrasmall luminescent nanoclusters have emerged as promising candidates for this purpose. Zhu's group reported ultrabright Au NCs protected by Cys-Arg-Arg-Arg-Arg peptides and 6-aza-2-thiothymine (CR_4/ATT -Au NCs) as next-generation ECL emitters [97]. Intra-cluster hydrogen bonding between neighboring ligands rigidifies their conformation and promotes ordered π - π stacking, significantly enhancing photoluminescence quantum yield (~ 60 -fold) and electron transfer efficiency (~ 4.8 -fold). This synergistic enhancement activates a previously unreported reduction-oxidation ECL pathway of Au NCs, resulting in over 250-fold improvement in ECL intensity (Figure 8a). Upon immobilization on electrodes with cells (Figure 8b), CR_4/ATT -Au NCs generate a robust, near-zero-thickness ECL layer visible to the naked eye, directly enabling high-resolution ECL microscopy that clearly resolves fine subcellular structures down to ~ 170 nm. This work extends the nanocluster-based ECL imaging system into the field of life sciences. In addition, Yuan's team prepared Met/NAC dual-ligand copper nanoclusters (Met/NAC-Cu NCs) [98]. As a surface defect regulator, Met connects NAC through -S-S bonds. Continuous adjustment of the Met/NAC molar ratio enables modulation of the surface defects and maximum ECL emission of Cu NCs. Using Met/NAC-Cu NCs as near-infrared ECL emitters along with signal amplification, they constructed an ultrasensitive ECL biosensor for MMP-2 detection. Its LOD reaches 1.65 fg/mL, and it has been successfully applied to detect MMP-2 in HeLa and MCF-7 cells. This study offers an excellent approach to tuning the optical properties of metal nanocluster-based ECL emitters and paves the way for their applications in ECL imaging.

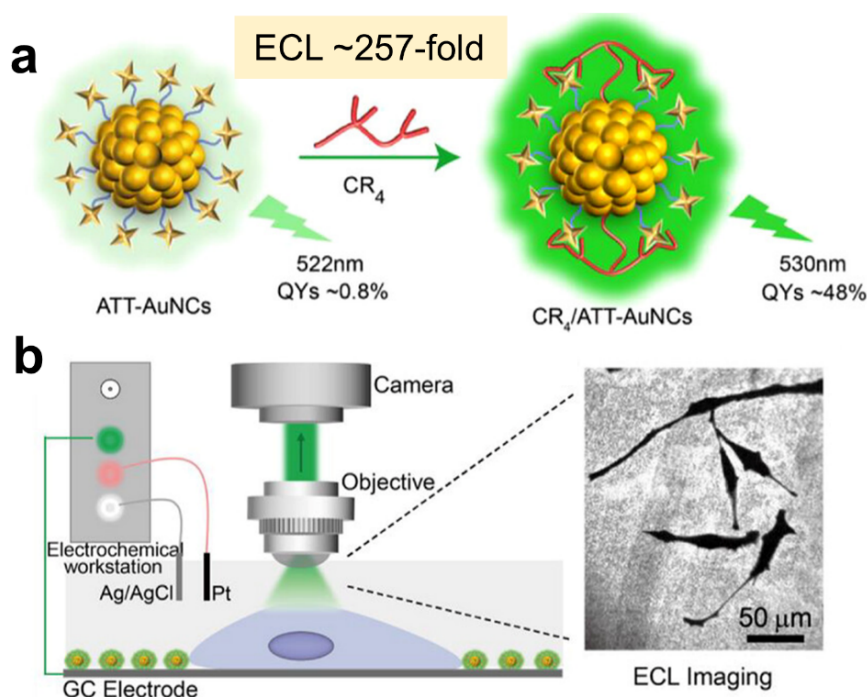


Figure 8. (a) ECL of ATT-Au NCs and CR_4/ATT -Au NCs; (b) ECL imaging of single HeLa cells based on CR_4/ATT -Au NCs [97], Copyright 2025 Wiley.

6. Conclusions and Outlook

This review summarizes the fundamental device composition for ECL imaging and sorts out mainstream ECL emitters applied in current systems. The merits and existing defects of traditional small molecule luminophores and conventional nano luminophores are fully discussed. In particular, this work highlights the research progress of nanoclusters as innovative ECL imaging materials. The distinct properties, performance improvement methods, and typical imaging applications of nanocluster-based ECL systems are summarized in detail. Meanwhile, the existing bottlenecks in this field are analyzed thoroughly. On this basis, several future research directions and outlooks are proposed to promote the further development of high-performance ECL imaging technology:

- (1) In-depth exploration of the structure-activity relationship of nanocluster ECL systems is essential. It is critical to clarify the internal correlation between the geometric structure, electronic configuration, and surface chemical state of nanoclusters and their ECL luminous behavior. Establishing clear structure-activity rules can provide theoretical guidance for the rational design and targeted optimization of high-performance nanocluster ECL luminophores, and break the empirical design limitation of existing ECL materials.
- (2) Multi-strategy synergistic modification is expected to be developed to further elevate ECL luminous efficiency. Combined means of surface engineering, heteroatom doping and dielectric environment regulation can effectively reduce non-radiative recombination and enhance electron transfer capability, which helps achieve ultrasensitive and high-contrast ECL imaging.
- (3) The application scope of nanocluster ECL imaging holds promise to be expanded toward complex biological and environmental systems. More functional modification and recognition modules can be integrated on nanocluster surfaces to realize selective imaging analysis of biomarkers, pollutants and interfacial microenvironments.
- (4) The integration of nanocluster ECL imaging with advanced micro fabrication and intelligent detection technologies warrants in-depth investigation. The combination of microfluidic chips, electrochemical micro devices, and image algorithm analysis will promote the development of miniaturized, high-throughput and intelligent ECL imaging platforms for practical detection scenarios.

Author Contributions

J.G.: conceptualization, data curation, writing—original draft preparation; R.L.: data curation, writing—original draft preparation, investigation; Y.W.: data curation, writing—original draft preparation, investigation; H.Z. and C.M.: supervision, writing—reviewing and editing, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All data graphs in this manuscript are reproduced from previously published literature with corresponding citations provided.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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