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Defect-Controlled Mechanoluminescence: A Theoretical Review of Physical Mechanisms and Emerging Applications

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Abstract

Mechanoluminescence (ML) is a unique luminescence phenomenon in which materials emit light under mechanical stimulation without requiring continuous optical or electrical excitation. Among the various mechanisms proposed to explain ML, defect-controlled carrier trapping and release is considered the most widely accepted. Crystal defects create localized energy states that trap charge carriers and regulate their release during mechanical deformation, leading to radiative recombination and light emission. This review presents a theoretical perspective on the fundamental role of crystal defects in governing mechanoluminescence. The electron trap model, piezoelectric effects, defect engineering, trap-depth optimization, and dopant-induced luminescence are discussed to explain the relationship between defect structure and emission performance. Emerging applications in structural health monitoring, biomedical imaging, and wearable sensing are also highlighted, together with current challenges including weak emission intensity, limited reproducibility, and the incomplete understanding of defect-controlled mechanisms. This review provides a conceptual framework for the rational design of efficient mechanoluminescent materials through defect engineering.

Keywords: *Mechanoluminescence; Crystal defects, Defect engineering, Electron trapping, Trap depth, Mechanically induced luminescence.*

1. Introduction

Mechanoluminescence (ML) is a luminescence phenomenon in which materials emit light in response to mechanical stimulation such as rubbing, scratching, compression, bending, or fracture [1–3]. Unlike photoluminescence and electroluminescence, mechanoluminescence does not require continuous optical or electrical excitation, making it a unique process for directly converting mechanical energy into visible light [2–4]. Owing to this distinctive property, mechanoluminescent materials have attracted considerable attention for Crystal

defects play applications in stress sensing, structural health monitoring, wearable electronics, anti-counterfeiting technologies, and biomedical imaging [1,4–8].

The origin of mechanoluminescence has been extensively investigated, and several mechanisms have been proposed, including piezoelectric polarization, triboelectric effects, fracture-induced charge separation, and defect-mediated carrier release. Among these, the defect-controlled electron trap model is considered one of the most widely accepted explanations for mechanoluminescence in inorganic phosphors. In this model, crystal defects act as electron or hole trapping centers that store charge carriers. Under mechanical stimulation, these trapped carriers are released, migrate through the crystal lattice, and recombine at luminescent centers, resulting in light emission. Therefore, the concentration, distribution, and energy depth of defects largely determine the intensity and efficiency of mechanoluminescence.

Defects play a fundamental role in controlling the optical performance of mechanoluminescent materials. Intrinsic defects, such as vacancies and interstitials, together with extrinsic defects introduced through dopant ions, regulate charge trapping, carrier transport, and radiative recombination. Appropriate defect engineering can optimize trap depth and luminescence efficiency, whereas excessive or poorly controlled defects often increase non-radiative recombination, leading to luminescence quenching.

Although numerous studies have reported new mechanoluminescent materials and their applications, comparatively few reviews have focused specifically on the role of defects in governing mechanoluminescence. Most existing reviews emphasize material synthesis or applications rather than the underlying defect physics. This review presents a theoretical perspective on defect-controlled mechanoluminescence by discussing the fundamental mechanisms, the role of crystal defects and trap engineering, emerging applications, and current challenges. The objective is to provide a conceptual framework for the rational design of efficient mechanoluminescent materials through defect engineering [1,9–13].

2. Principal of Physical Mechanisms of Mechanoluminescence

Mechanoluminescence is generally explained by the conversion of mechanical energy into optical emission through the movement and recombination of charge carriers. Although several mechanisms have been proposed, the electron trap model is considered the most widely accepted explanation for mechanoluminescence in inorganic materials **[1–6]**. According to this

model, crystal defects create localized energy levels within the band gap that trap electrons or holes during excitation. When an external mechanical force is applied, these trapped carriers gain sufficient energy to escape from the defect states, migrate through the crystal lattice, and recombine at luminescent centers, producing visible light **[1,4–8]**. Consequently, the nature and distribution of defects largely determine the efficiency of mechanoluminescence.

Mechanical stimulation can be introduced through compression, friction, bending, stretching, fracture, or ultrasonic excitation. These mechanical actions generate local lattice deformation and internal electric fields that facilitate the release of trapped carriers **[4–8]**. The released electrons subsequently recombine with holes at activator ions such as Cu^{2+}, Mn^{2+}, or rare-earth dopants, resulting in characteristic luminescence **[5–8]**. The emission intensity depends not only on the applied mechanical stress but also on the concentration of trapping centers and the probability of radiative recombination.

Trap depth is another important factor governing mechanoluminescence. Shallow traps release carriers easily but cannot retain them for extended periods, often resulting in weak emission. In contrast, excessively deep traps retain carriers too strongly, making mechanical release difficult. Therefore, an optimum trap depth is essential to achieve efficient mechanoluminescence. Defect engineering through suitable dopants and controlled synthesis conditions has become an effective strategy for tailoring trap depth and improving luminescence performance **[1,6–10]**.

Besides the trap-controlled mechanism, piezoelectricity also contributes to mechanoluminescence in certain non-centrosymmetric materials. Mechanical deformation generates an internal electric field that accelerates charge carriers and promotes radiative recombination **[5,9–12]**. Although the relative contribution of piezoelectricity varies among different materials, many researchers consider mechanoluminescence to arise from the combined effects of defect-mediated carrier release and stress-induced polarization rather than from a single mechanism **[1,5,9–12]**. A deeper understanding of these physical processes is essential for the rational design of high-performance mechanoluminescent materials.

3. The Importance of the Role of Defects in Mechanoluminescent Materials

Crystal defects are fundamental to the generation of mechanoluminescence because they create localized energy states within the band gap that act as trapping centers for charge carriers. In contrast to conventional luminescent materials, where defects are often considered

undesirable, mechanoluminescent materials rely on controlled defect formation to achieve efficient light emission. The type, concentration, and distribution of these defects strongly influence carrier trapping, release, and recombination, thereby determining the overall luminescence performance **[1,4–8]**.

Defects in mechanoluminescent materials can be broadly classified into intrinsic and extrinsic defects. Intrinsic defects, including vacancies, interstitial atoms, and antisite defects, are naturally formed during crystal growth and influence the electronic structure of the host lattice. Extrinsic defects are intentionally introduced through dopant ions such as Cu^{2+}, Mn^{2+}, Eu^{2+}, and Dy^{3+}. These dopants not only serve as luminescent centers but also modify the defect structure by creating additional electron or hole traps. The interaction between intrinsic and extrinsic defects plays a crucial role in controlling mechanoluminescence efficiency **[1,6–10]**.

An important parameter governing defect-controlled mechanoluminescence is trap depth. Trap depth represents the energy required for trapped carriers to escape from defect states during mechanical stimulation. Shallow traps release carriers readily but often produce weak and short-lived emission, whereas excessively deep traps retain carriers too strongly, limiting their mechanical release. Consequently, materials with an optimum trap depth generally exhibit stronger and more stable mechanoluminescence. Tailoring trap depth through defect engineering has therefore become an effective strategy for improving material performance **[1,7–12]**.

Dopant selection is another critical factor in defect engineering. Different activator ions produce distinct trapping characteristics and emission properties depending on their electronic configuration and interaction with the host lattice. For example, Cu-doped ZnS remains one of the most extensively studied mechanoluminescent systems because copper ions simultaneously create suitable trapping centers and efficient luminescent sites. Similarly, rare-earth ions such as Eu^{2+} and Dy^{3+} have been widely employed to optimize trap distribution and enhance emission intensity in various phosphor materials **[1,8–13]**.

Overall, defect engineering provides a practical approach for controlling carrier dynamics and optimizing mechanoluminescence. A detailed understanding of defect formation, trap distribution, and dopant-induced modifications is therefore essential for designing next-generation mechanoluminescent materials with improved brightness, stability, and reproducibility **[1,9–15]**.

4. New Applications of Mechanoluminescent Materials

The unique ability of mechanoluminescent materials to directly convert mechanical energy into light has enabled their application in several emerging technologies. Unlike conventional optical materials that require external light sources or electrical power, mechanoluminescent materials respond directly to mechanical stimuli, making them attractive for real-time sensing and self-powered optical devices [1,2,9–13].

One of the most important applications of mechanoluminescence is structural health monitoring. Mechanoluminescent coatings and composites can visualize stress distribution and detect the initiation of cracks in engineering structures. The emitted light provides a direct indication of mechanical deformation, allowing early identification of structural damage without the need for complex electronic sensors. Such systems have been investigated for monitoring bridges, buildings, aircraft components, and other critical infrastructures where continuous stress evaluation is essential [3,19,20].

Mechanoluminescent materials have also attracted considerable attention in biomedical imaging. Mechanical stimuli, particularly focused ultrasound, can penetrate deep biological tissues more effectively than visible light, enabling the activation of mechanoluminescent nanoparticles within the body. The localized light generated by these materials has shown potential for bioimaging, drug delivery, and ultrasound-mediated optogenetics. Their ability to produce light without external optical excitation makes them promising candidates for minimally invasive diagnostic and therapeutic applications [1,10–18].

Another emerging application is in wearable and flexible sensing devices. Mechanoluminescent materials incorporated into flexible polymers or textiles can detect body movement, pressure, and deformation through visible light emission. These self-powered sensors offer advantages such as simple operation, low energy consumption, and real-time monitoring, making them suitable for healthcare monitoring, sports analytics, and human–machine interaction [12–18].

Although these applications continue to expand, further improvements in emission efficiency, mechanical stability, and material durability are required before mechanoluminescent materials can achieve widespread practical implementation. Continued advances in defect engineering and material design are expected to further enhance their performance and broaden their application potential [1,14–18].

5. A critical Challenges and Future Options

Despite significant progress in mechanoluminescent materials, several challenges continue to limit their practical applications. One of the major limitations is the relatively weak emission intensity observed in many mechanoluminescent phosphors, which restricts their use in large-scale sensing and biomedical imaging. In addition, repeated mechanical loading often leads to gradual degradation of luminescence performance, raising concerns regarding long-term stability and reproducibility [1,10–18].

Another important challenge is the incomplete understanding of the underlying luminescence mechanisms. Although the defect-controlled electron trap model provides a widely accepted explanation, the contributions of piezoelectric effects, triboelectric charge generation, and stress-induced polarization remain under investigation. The interaction between these mechanisms is likely to vary among different material systems, requiring further experimental and theoretical studies [1,4–10].

Future research should focus on rational defect engineering to optimize trap distribution, carrier transport, and luminescence efficiency. The development of new host materials, advanced synthesis techniques, and computational approaches for predicting defect behavior may further improve mechanoluminescent performance. Such advances are expected to accelerate the development of efficient and reliable mechanoluminescent materials for sensing, biomedical, and optoelectronic applications [1,9–18].

6. Conclusion

Mechanoluminescence represents a unique luminescence phenomenon in which mechanical energy is directly converted into visible light, offering significant advantages for sensing, imaging, and smart material applications. Crystal defects play a fundamental role in this process by creating electron traps that govern charge storage, release, and radiative recombination. Consequently, defect engineering has emerged as an effective strategy for optimizing mechanoluminescence intensity, stability, and reproducibility through the control of trap depth and dopant distribution. Although considerable progress has been achieved, challenges related to emission efficiency and the incomplete understanding of underlying mechanisms continue to limit practical applications. Future research should emphasize rational defect design, advanced material synthesis, and theoretical modeling to develop high-

performance mechanoluminescent materials for next-generation sensing, biomedical, and optoelectronic technologies.

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