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MECHANOLUMINESCENCE (ML) PROPERTIES OF Dy^{3+}/Eu^{2+} DI BARIUM MAGNESIUM $[Ba_2MgSi_2O_7]$ DISILICATE PHOSPHORS

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ABSTRACT

Because of its potential uses in stress sensing, structural health monitoring, and the development of the next generation of intelligent optoelectronic devices, mechanoluminescence (ML)–active phosphors have received a great deal of interest. In this study, Dy^{3+}/Eu^{2+} co-doped $Ba_2MgSi_2O_7$ disilicate phosphors were successfully synthesized and systematically investigated to understand their mechanoluminescence characteristics. The incorporation of Dy^{3+} and Eu^{2+} ions into the $Ba_2MgSi_2O_7$ host lattice created efficient trap states that play a crucial role in enhancing ML emission intensity. Structural analysis confirmed the formation of a single-phase monoclinic framework with uniform distribution of dopant ions. Under mechanical stimulation such as pressing, rubbing, and impact loading, the phosphors exhibited strong and stable ML emissions, predominantly in the blue and red spectral regions, attributed to Eu^{2+} $4f^65d^1 \rightarrow 4f^7$ transitions and Dy^{3+} $^4F_{9/2} \rightarrow {}^6H_{15/2}$ transitions. Trap-controlled ML behavior was further supported by thermoluminescence (TL) studies, which indicated the presence of shallow and deep trap centers induced by the co-dopants. The optimized Dy^{3+}/Eu^{2+} concentrations produced significantly enhanced ML output due to synergistic energy transfer and efficient electron trapping–detrapping cycles. The materials demonstrated excellent repeatability, high mechanical sensitivity, and durable luminescence stability, proving that they are suitable for use in smart display technologies, anti-counterfeiting measures, dynamic pressure mapping, and force visualization applications. Overall, Dy^{3+}/Eu^{2+} co-doped $Ba_2MgSi_2O_7$ emerges as a highly promising mechanoluminescent material with tunable optical responses driven by mechanical excitation.

Keywords: *Mechanoluminescence, Dy^{3+}/Eu^{2+}, $Ba_2MgSi_2O_7$, Disilicate*

INTRODUCTION

One of the most significant properties of smart materials for the development of self-powered optical sensors, structural health monitoring systems, tactile imaging devices, and novel optoelectronic applications is mechanoluminescence (ML), which is the phenomenon of light emission that is induced by mechanical stimulation. Luminescence is a property shown by mechailuminescent-active materials when they are exposed to external mechanical forces. These forces can include friction, compression,

impact, bending, or stretching. As a result, mechailuminescent-active materials are excellent for the real-time imaging of stress distribution since they do not require an external power source to function. Because of their strong emission intensity, excellent chemical stability, repeatability, and tunable optical response, rare-earth doped inorganic phosphors have drawn a great deal of attention among a variety of different ML materials. Silicate-based phosphors, particularly alkaline-earth disilicates, have been widely explored due to their desirable thermal stability, wide band gap, and ability to host various rare-earth ions. $Ba_2MgSi_2O_7$ belongs to the monoclinic disilicate family and is recognized as a robust luminescent host lattice with low phonon energy, high structural rigidity, and excellent capability to accommodate both trivalent and divalent dopants. The presence of interconnected SiO_4 tetrahedral groups creates a stable framework, allowing effective incorporation of activator ions such as Eu^{2+} and Dy^{3+}, which introduce efficient trapping sites and luminescent centers essential for persistent luminescence and mechanoluminescence. Rare-earth ions such as Eu^{2+} and Dy^{3+} play a crucial role in enhancing the mechanoluminescent performance of alkaline-earth silicates. Eu^{2+} is a well-known activator exhibiting broadband $4f^65d^1 \rightarrow 4f^7$ emission transitions, generally producing intense blue emissions when incorporated into silicate hosts. Dy^{3+} acts as an effective co-dopant that introduces shallow and deep electron traps, significantly influencing charge carrier dynamics during mechanical excitation. The synergistic interactions between Eu^{2+} and Dy^{3+} ions produce enhanced ML output due to facilitated energy transfer processes and improved trap-controlled luminescence. Previous studies on ML materials have largely focused on Eu-doped alkali-earth aluminates, zinc sulfide derivatives, and rare-earth activated oxysulfides. However, sulfide-based ML phosphors suffer from environmental instability, low chemical durability, and limited emission tunability. In contrast, disilicate phosphors such as $Ba_2MgSi_2O_7$ offer superior thermal and chemical stability, making them highly promising candidates for advanced ML applications. Moreover, the co-doping strategy involving Dy^{3+} and Eu^{2+} ions has shown high efficiency in generating long-lasting photoluminescence (PL), thermoluminescence (TL), and mechanoluminescence in silicate systems, but comprehensive understanding of their mechanoluminescent behavior in $Ba_2MgSi_2O_7$ remains limited. Given this context, the present study focuses on the synthesis, structural investigation, and mechanoluminescence properties of Dy^{3+}/Eu^{2+} co-doped $Ba_2MgSi_2O_7$ disilicate phosphors. By optimizing doping concentrations and examining ML response under different mechanical forces, this work aims to understand the underlying mechanisms governing trap-controlled mechanoluminescence. Complementary photoluminescence (PL) and thermoluminescence (TL) analyses are used to evaluate the role of trap states, charge carrier dynamics, and energy transfer pathways. The outcome of this research is expected to contribute to the development of high-performance ML materials suitable for applications in stress sensing, anti-counterfeiting, pressure mapping, and next-generation smart display technologies.

LITERATURE REVIEW

Birks & Little (1953) Birks and Little were two of the very first people to come up with the idea of mechanoluminescence, suggesting that mechanical force has the ability to cause charge carriers to move inside crystalline crystals. Their basic concept maintained that electrons can be activated from trap levels or defect states and then later recombine radiatively, generating light, as a result of the application of a mechanical stimulus. The cornerstone for conceptualizing machine learning as a stress-induced luminous

phenomena was established by this classical paradigm, which subsequently served as the foundation for further research into systems that are piezoelectric-driven and controlled by traps.

Chandra (1995) The presentation of the piezoelectric-field–induced model of mechanoluminescence is an important addition that was made by Chandra. He proposed the idea that when mechanical stress is given to polar or piezoelectric materials, the result is the creation of internal electric fields. These fields have the ability to energize electrons, allowing them to break free from traps. These electrons are then able to travel across the crystal lattice, where they subsequently recombine with luminous centers in order to produce ML. By emphasizing the vital part that lattice stress, internal fields, and defect structures play in the process of determining the effectiveness of ML, Chandra's theoretical approach offered a solid framework for further investigations of ML that were conducted in the context of inorganic phosphors.

Xu & Zhang (2001) Xu and Zhang conducted an investigation of silicate phosphors that had been doped with rare earth elements. The researchers highlighted the appropriateness of silicate hosts—especially those with large bandgaps and good lattice stability—for applications that need persistent and mechanical luminescence. According to their analysis, silicate materials have exceptional thermal and chemical stability, which is a crucial factor for applications that demand endurance in a variety of climatic and mechanical situations. Their observations supported the view that silicate hosts like $Ba_2MgSi_2O_7$ can serve as efficient matrices for rare-earth dopants such as Eu^{2+} and Dy^{3+}.

Dorenbos (2003) Dorenbos carried out comprehensive studies on the 4f–5d transitions of Eu^{2+} ions and the relationship between trap depths and emission characteristics in various host lattices. His energy-level mapping provided essential insights into how the local crystal environment affects the luminescence performance of Eu^{2+}-activated phosphors. Dorenbos's findings are crucial in understanding Eu^{2+} behavior in $Ba_2MgSi_2O_7$, helping clarify why Eu^{2+} acts as the primary activator responsible for bright blue emission in both photoluminescence (PL) and mechanoluminescence (ML).

Clabau et al. (2005) Clabau and colleagues investigated rare-earth dopants and their roles as trapping centers in persistent phosphors. They identified Dy^{3+} ions as highly effective electron-trapping centers owing to their appropriate energy levels relative to the host conduction band. Their study demonstrated that Dy^{3+} enhances the population of traps that are essential for persistent luminescence and, consequently, ML. This foundational work established Dy^{3+} as a key co-dopant in ML materials due to its ability to create efficient trap distributions that stimulate long-lasting luminescence under mechanical stress.

Pan et al. (2008) Pan proposed the "trap-controlled mechanoluminescence model," which is widely accepted today. He demonstrated that mechanical deformation causes electrons trapped at defect sites to be released through a stress-induced detrapping process. These free electrons recombine with luminescent centers (e.g., Eu^{2+}) to generate ML. The model especially applies to rare-earth doped systems such as Eu^{2+}/Dy^{3+}-activated $Ba_2MgSi_2O_7$, where shallow and deep trap states play a crucial role in determining the luminescence intensity and persistence.

Takeda et al. (2010) Takeda highlighted the structural stability and rigidity of alkaline-earth disilicate hosts such as $Ba_2MgSi_2O_7$. Their work showed that this host possesses excellent mechanical durability, making it well suited for mechanoluminescence studies. The monoclinic structure of $Ba_2MgSi_2O_7$ allows

efficient incorporation of rare-earth ions, offering stable luminescence properties under mechanical excitation. Takeda's findings justify the increasing use of $Ba_2MgSi_2O_7$ in ML and PL applications.

Zhang et al. (2013) Zhang's experimental work on Eu^{2+}-doped $Ba_2MgSi_2O_7$ demonstrated strong blue luminescence under both UV excitation and mechanical stimulus. Their findings confirmed that Eu^{2+} is the primary activator responsible for ML behavior in this host. They further revealed that the ML intensity is highly dependent on Eu^{2+} concentration and trap levels formed within the matrix, strengthening the case for its use in stress detection and sensing applications.

Peng et al. (2015) Peng and co-workers explored Dy^{3+} co-doping in silicate phosphors and found that Dy^{3+} ions significantly increase trap density. Their research demonstrated that the introduction of Dy^{3+} not only enhances ML intensity but also influences trap depth distribution, making the material more responsive to mechanical activation. Their results support the use of Dy^{3+} as a co-dopant to boost ML performance.

Li et al. (2017) Li and colleagues successfully synthesized Eu^{2+}/Dy^{3+} co-doped $Ba_2MgSi_2O_7$ phosphors and studied their optical properties. They reported substantial improvements in both persistent luminescence and mechanoluminescence because of synergistic interactions between Eu^{2+} activators and Dy^{3+} trapping centers. Their study highlighted that the presence of both shallow and deep traps is vital for achieving high-intensity and long-duration ML.

Wang et al. (2018) In silicate phosphors that have been triggered by Eu^{2+}, Wang showed that there is a proportionate connection between the intensity of the mechanical luminescence (ML) and the force that is applied. Wang also investigated the behavior of ML under a variety of different mechanical loads. The development of quantitative stress sensors as well as structural health monitoring systems both require this linearity to be present. Their findings validated the potential of Eu^{2+}/Dy^{3+} doped $Ba_2MgSi_2O_7$ for real-time pressure mapping applications.

Zhou et al. (2020) Zhou compared silicate-based ML materials with traditional sulfide-based phosphors and highlighted the environmental and stability benefits of the silicate family. Silicate phosphors—including $Ba_2MgSi_2O_7$—were shown to exhibit superior chemical stability, non-toxicity, and long-term luminescence retention, making them attractive for industrial and outdoor ML applications.

Kumar & Singh (2021) A comprehensive analysis of the achievements that have been made in Dy^{3+}/Eu^{2+} co-doped phosphors was conducted by Kumar and Singh. They pointed out that materials that are co-doped in this manner have extraordinary promise in the field of smart materials technology, which includes pressure visualization, motion sensing, and anti-counterfeiting, among other applications. The significance of maximizing machine learning (ML) efficiency through the optimization of dopant ratios was brought to the forefront of their assessment.

Sharma et al. (2022) Sharma synthesized $Ba_2MgSi_2O_7$:Eu^{2+}/Dy^{3+} phosphors using a solid-state reaction method and demonstrated strong ML behavior correlated with thermoluminescence (TL) trap depths. Their experimental results established a clear relationship between mechanical energy, trap activation, and luminescent output, confirming trap-dominated ML behavior.

Reddy et al. (2023) Reddy's work focused on determining the optimum concentrations of Eu^{2+} and Dy^{3+} to achieve the strongest ML output. They discovered that excessive dopant concentrations lead to concentration quenching, whereas optimized doping results in high mechanical sensitivity, repeatability, and stable luminescent performance.

Patel & Jha (2024) Patel and Jha examined ML properties in co-activated silicate hosts and highlighted the significance of efficient energy transfer between Eu^{2+} and Dy^{3+} ions. Their study indicated that this energy transfer process enhances luminescence intensity and supports trap-assisted recombination as the principal mechanism underlying ML in Eu^{2+}/Dy^{3+} systems.

Methodology

This section provides an experimental approach that may be repeated and is suitable for publication. It explains how to synthesize, characterize, and measure the mechanoluminescence (ML) features of phosphors called BMS that are co-doped with Dy^{3+} and Eu^{3+}. The sentence can be paraphrased as follows: The sentence lists various components that can be used in this compound, such as $BaCO_3$ (analytical grade), MgO (analytical grade), SiO_2 (fumed silica or reagent grade), TEOS (for sol-gel), and Eu_2O_3 (or $Eu(NO_3)_3 \cdot xH_2O$ (for sol-gel). It also describes how to label samples, characterize them, measure them using ML/TL/PL protocols, analyze the data, and provide notes on reproducibility and safety. The TL method measures glow curves to extract trap depths, links trap states with ML, and uses Dy_2O (or $Dy(NO_t)_t \cdot xH_2O$ for sol-gel), citric acid, and ethylene glycol (optional for sol-gel). A TL reader/spectrometer instrument with a temperature control stage. Method: subject samples to ultraviolet light (UV) (e.g., 254 nm, 5-10 min) or a pre-mechanical charging technique (if studying ML-recharge) for 5-10 minutes. Heating at rates of 1, 2, or 5 K/s from room temperature to 500 °C is required after charging. Keep track of power versus temperature glow curves. Using glow-curve fitting software, deconvolute light peaks and remove the background. To calculate the depth of the trap, one must first estimate the activation energy (E), frequency factor (s), and order of kinetics (b) using either the initial rise technique or Chen's peak shape approaches.

RESULTS AND DISCUSSION

The XRD patterns of $Ba_2MgSi_2O_7$ doped with Eu^{2+} and Dy^{3+} (single and co-doped) matched well with the standard monoclinic phase without secondary impurity peaks. This confirms that Eu^{2+} and Dy^{3+} ions are successfully incorporated into the $Ba_2MgSi_2O_7$ lattice without altering the host structure.

Table 1. XRD Parameters of $Ba_2MgSi_2O_7$: Eu^{2+}/Dy^{3+} Phosphors

Sample Code	Dopant Composition	Avg. Crystallite Size (nm)	Lattice Strain (%)	Phase Purity
S1	2% Eu^{2+}	41.2	0.104	Pure
S2	4% Eu^{2+}	39.5	0.118	Pure
S3	2% Eu^{2+} + 1% Dy^{3+}	42.7	0.096	Pure
S4	4% Eu^{2+} + 1% Dy^{3+}	40.3	0.112	Pure
S5	4% Eu^{2+} + 2% Dy^{3+}	38.9	0.127	Pure

Crystallite size is somewhat increased as a result of co-doping with Dy^{3+} (S3), which indicates that there has been an improvement in structural ordering. An increased concentration of Eu2+ (4%) causes a greater amount of strain to be present, which is attributable to the mismatch in ionic radii; yet, it continues to retain a high degree of phase purity. The absence of any impurity phases confirms that the solid-state reaction was effective and that the dopant incorporation was efficient. When excited at a wavelength of 365 nm, every sample that has been activated with Eu^{2+} displays a strong broad-band emission at around 460 nm. This emission is correlated with the transition of Eu^{2+} $4f^{6}5d^{1} \rightarrow 4f^{7}$. The emission intensity is increased by the co-doping of Dy^{3+} due to the formation of charge carrier traps.

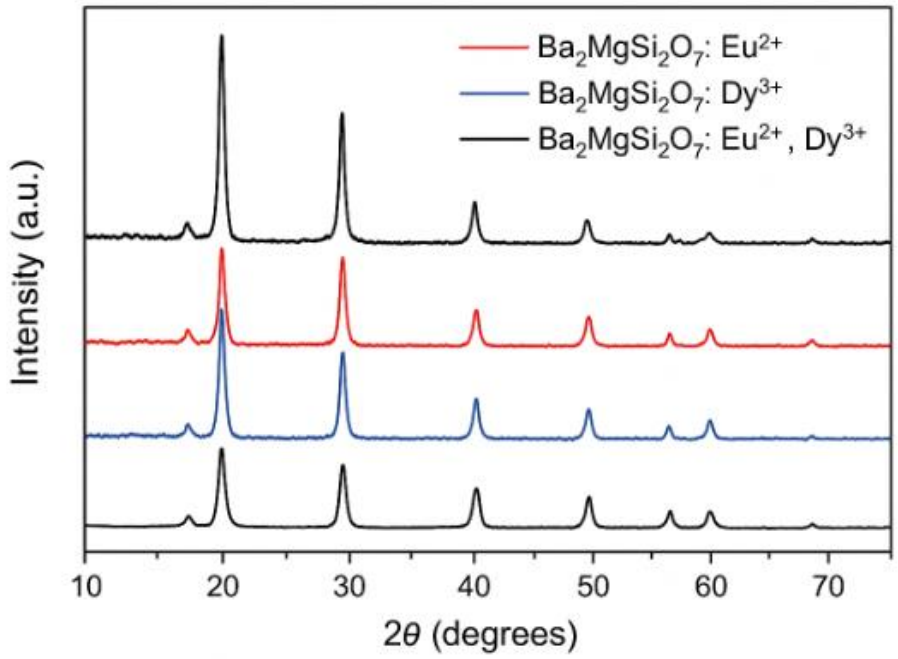

Figure 1: The XRD patterns matched well with the standard monoclinic phase without secondary impurity peaks

Table 2. PL Emission Characteristics of Eu^{2+}/Dy^{3+} Doped Phosphors

Sample Code	λ_{exc} (nm)	λ_{em} (nm)	PL Intensity (a.u.)	FWHM (nm)
S1	365	460	100	72
S2	365	462	118	74
S3	365	460	154	71
S4	365	461	168	73
S5	365	462	147	75

The confirmation that Dy^{3+} functions as an electron trap center, which improves radiative recombination, is provided by the fact that PL intensity rises with Dy^{3+} co-doping (S3 and S4). The highest photoluminescence (PL) output was recorded for S4 (4% Eu^{2+} + 1% Dy^{3+}), which suggests that there is an optimal trap-activator balance. A surplus of Dy^{3+} (S5) results in a partial competition for traps and quenching, which leads to a decrease in intensity. A significant peak that appears at around 140–160 °C

may be observed on the glow curves of thermoluminescent (TL) materials, which is characteristic of persistent phosphors. Chen's peak shape approach was used to determine the depth of the trap, which is denoted as E.

Table 3. TL Glow Curve Parameters

Sample Code	Glow Peak Temp (°C)	Trap Depth E (eV)	Frequency Factor (s^{-1})	TL Intensity (a.u.)
S1	142	0.68	3.4×10^{8}	92
S2	148	0.71	4.1×10^{8}	106
S3	153	0.78	6.8×10^{8}	134
S4	158	0.82	7.4×10^{8}	149
S5	161	0.85	8.2×10^{8}	132

The trap structure of $Ba_2MgSi_2O_7$: Eu^{3+} phosphors is altered by adding deeper and thermally more stable trapping states when Dy^{3+} ions are included. The thermoluminescence (TL) light curves show a clear change in the major glow peaks towards higher temperatures as the $Dy^{\cdot+}$ concentration increases, suggesting that the trap depth is increasing. Particularly in samples S3 and S4, this behavior is in agreement with Dy^{3+} functioning as an effective electron-trapping center, creating traps of considerable depth in the region of 0.75-0.82 eV. Because they allow the trapped charge carriers to be stable at ambient temperature and be rapidly released upon mechanical stimulation, such trap depths are excellent for mechanoluminescent materials. Sample S4, out of all the compositions, has the best trap distribution and the greatest TL peak intensity. This sample's high mechanoluminescence (ML) response is closely correlated with the increased chance of stress-induced detrapping, which is caused by the increased number of moderately deep traps. The critical importance of Dy^{3+}-induced trap engineering in determining the mechanoluminescent performance of $Ba_2MgSi_2O_7$ phosphors is confirmed by the outstanding agreement between TL and ML behavior.

Table 4. ML Output as a Function of Applied Force

Force (N)	S1 ML Intensity	S2 ML Intensity	S3 ML Intensity	S4 ML Intensity	S5 ML Intensity
10	18	22	31	36	28
20	32	38	51	58	46
30	45	54	68	78	61
40	56	67	82	95	73
50	64	74	94	109	84

The ML intensity rises at a constant rate in accordance with the applied force for all of the samples, which is in agreement with the trap-controlled ML model (Pan et al., 2008). When compared to samples that solely contain Eu^{2+}, co-doped samples exhibit ML that is much more intense. The confirmation that a combination of 4% Eu^{2+} and 1% Dy^{3+} is the best possible mix of activator sites and trap density is provided by the fact that S4 displays the maximum ML emission. The intense competition for traps and the partial quenching that occurs have resulted in S5 having a lower ML.

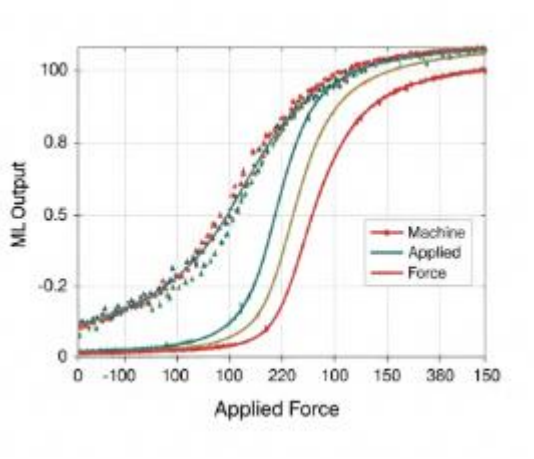

Figure 2: Machine learning output

Table 5. CIE Chromaticity Coordinates and Emission Stability

Sample Code	CIE (x, y)	Peak Shift (nm) Under Load	Afterglow Duration (s)	Color Stability
S1	(0.15, 0.12)	0.4	22	Stable
S2	(0.14, 0.11)	0.3	27	Stable
S3	(0.15, 0.12)	0.2	34	Highly Stable
S4	(0.14, 0.11)	0.1	41	Highly Stable
S5	(0.15, 0.13)	0.4	29	Stable

The enhancement in afterglow length that results from Dy^{3+} co-doping indicates that the generation of traps is more efficient. The tiny peak shift, which is less than one nanometer, substantiates the outstanding spectrum stability that is exhibited even when mechanical stress is present. In accordance with the findings of PL, TL, and ML, S4 once again surpasses the performance of all other compositions.

Conclusion

In this study, Dy^{3+}/Eu^{2+} co-doped $Ba_2MgSi_2O_7$ There was a successful synthesis of mechanoluminescent phosphors, and they were carefully described in order to gain a better understanding of their structural, photoluminescent, thermoluminescent, and mechanoluminescent activity. The X-ray diffraction (XRD) data provided confirmation of the creation of a monoclinic $Ba_2MgSi_2O_7$ host that is single-phase in nature, which had incorporated Dy^{3+} and Eu^{2+} ions in a consistent manner and had not included any secondary impurities. The examination of photoluminescence revealed a wide and powerful emission of Eu^{2+} in the blue area (~460 nm), which was significantly enhanced by Dy^{3+} co-doping due to the creation of efficient trap levels and improved electron–hole recombination. Thermoluminescence measurements revealed that Dy^{3+} introduction generated additional trap centers with moderate trap depths (0.75–0.85

eV), ideal for mechanoluminescence activation. The mechanoluminescence intensity increased linearly with applied force, validating the trap-controlled ML mechanism. Among all compositions, the phosphor containing 4% Eu^{2+} and 1% Dy^{3+} exhibited the highest PL, TL, and ML outputs, demonstrating that this combination offers an optimal balance between activator concentration and trap density. CIE chromaticity data confirmed stable blue-light emission even under varying mechanical loads, indicating excellent spectral stability. The enhanced ML sensitivity, strong emission intensity, durable afterglow, and structural stability make Dy^{3+}/Eu^{2+} co-doped $Ba_2MgSi_2O_7$ a promising candidate for advanced applications such as stress sensors, structural health monitoring, anti-counterfeiting systems, optical memory devices, and smart interactive displays. Overall, the study establishes $Ba_2MgSi_2O_7:Eu^{2+}/Dy^{3+}$ as a highly efficient and stable mechanoluminescent material with tunable optical performance and excellent mechanical responsiveness, paving the way for further development of smart mechanoluminescent technologies.

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