

Review Paper

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Mechanoluminescence of Rare-Earth Doped Aluminate Phosphors-A Review

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Abstract - Luminescence	based on the rare-earth doped alur	minates has been reported in this	paper. The luminescence
increases on the application of	of mechanical energy to these mater	ials and this phenomenon is called th	ne Mechanoluminescence.
Since a few materials show	persistent luminescence, the number	of persistent luminescent materials	is still less and the work
done on the mechanism behi	nd the phenomenon is still not conve	eniencing. The study reveals that the	y are persistent phosphors
and the persistence remains	for minutes to few days. It has be	en pointed out that these materials	possess phosphorescence
without doping. However, do	pping enhance their efficiency and h	ence persistence in their emission. T	The emission is so intense
that it can be seen in day lig	ght with naked eye. It has been rep	ported that their sensitivity to stress	or any other mechanical
energy attract the researche	rs as potential materials for sensiti	ve sensors. Also the preparations a	and applications of these
phosphors are discussed.			

Keywords: persistent luminescence; Mechanoluminescence; aluminates and rare-earth doped Strontium Aluminates

Introduction

Luminescence represents the emission of light, i.e. typically light emitted by sources other than a hot incandescent body. A luminescent material converts certain types of energy into electromagnetic radiation. While most phosphors emits radiation in the visible range, they may also emit in the UV and infrared regions. The source of excitation energy dictates the classification of luminescence: Cathodoluminescence, Photoluminescence, Mechanouminescence etc.

Any material that emits light after being irradiated by the excitation source is called a Phosphor. A phosphor is a

substance that absorbs energy in photon form and emits visible light. The term 'phosphor' was invented in the early 17^{th} century in Italy by an Italian alchemist, Vincentinus Casciarolo when he fired the Bologanian stone or Litheophosphorus in an oven to obtain gold [1]. He found that the sintered stone emitting red light in the dark after exposure to sunlight. The first object of the scientific study of luminescence phenomena was invented. It is now known that the Bologna stone was BaSO₄ and the fired product was BaS (BaSO₄ + 2C \rightarrow BaS +2CO₂) which is a host for phosphor materials. Later phosphor developments occurred in 1768 when Canton obtained CaS and then in 1866 when Sidot formed the first ZnS, green emitting luminescent material.



Fig.1.1. Jablonski diagram of fluorescence and phosphorescence mechanism

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'Phosphorescence' derived from The word word 'phosphor' means the persisting light emission from a substance after the excitation source has stopped. On the other hand, fluorescence refers to the emission of light from a substance exposed to the source of excitation. The term 'Luminescence' includes both fluorescence and phosphorescence and is the radiative recombination of excited electrons and holes to emit light at varying wavelengths [1]. The process is depicted as

Mechanoluminescence

Mechanoluminescence (ML) is caused by the deformation of the luminescent material. ML is the emission of phosphors caused by the application of mechanical energy to a solid [2]. The phenomenon of ML has been known for centuries but attracted researchers only in recent years by virtue of its potential applications for sensing structural damage, fractures and damages [3]. It is ML sensor that senses the environmental stress by emitting light and because of this sensitivity it is expected to be used widely in highly appreciated applications like the prediction of earthquakes, damage detection for air planes or cars and mostly in the study of human diseases [4].

Since elastic mechanoluminescence is the cause of stress at elastic region, the EML materials are non-destructive and effectively convert the applied mechanical energy into the detectable signal. ML based materials are non-destructive, reproducible, wireless, small size, reliable, real-time, stress sensing etc. In ML, every particle of the phosphor acts as the sensor.

Mechanoluminescence includes the elastic deformation, plastic deformation and fracture of solids. A wintergreen Candy glows when it is chewed or bitten in dark. Similarly, a sugar crystal emits light when it is fractured or crushed in dark. These phenomena of light emission induced by the fracture of solids are known as fracto mechanoluminescence. Materials that emit light when they are plastically deformed and no fracture is required like in ZnS:Cu,Cl single crystals, MgO etc. This phenomenon of light emission is called plastico mechanoluminescence. Another class of ML is elastico mechanoluminescence where neither plastic deformation nor fractures are required. Here the solids such as alkali halides, ZnS: Mn, SrAl₂O₄:Eu, etc. are irradiated by X- or γ -rays and emit light when they are plastically deformed.

The various examples of EML materials are: ZnS:Mn, SrAl₂O₄:Eu, SrAl₂O₄: Ce, SrAl₂O₄ :Ce, Ho, SrAl₂O₄:Er, SrAl₂O₄:Eu,Er, SrMgAl₆O₁₁:Eu, SrCaMgSi₂O₇:Eu, SrBaMgSi₂O₇:Eu, Sr₂MgSi₂O₇:Eu, Ca₂MgSi₂O₇:Eu,Dy, CaYAl₃O₇:Eu etc. The investigation of new intense EML materials with repetitive EML intensity and self-recovery and the investigation of new applications of EML materials are still the challenges for researchers. These materials when irradiated with excitation source, there is sharp increase in their intensity which then reaches a saturation value and decreases slowly. In the emission process, the intensity initially increases, reaches a maximum and then decays. The phenomenon is depicted in the Fig. 2.1.



Fig.2.1. Excitation and emission spectra of $SrAl_2O_4$:Eu nanoparticles (after Xu et al., ref [43]).

ML is actually a phenomenon whereby light is emitted by a solid as a response to mechanical stimuli [5]. The intensity of the emitted light depends upon large number of factors including stress, strain, strain rate pressing rate, temperature, atmospheric pressure, particle/crystal side, sample mass, dopant type and concentration, annealing temperature etc[6]. The stress (load) dependence of the ML is found to be linear as depicted in Fig.2.2. Recently, intense ML materials have been prepared whose ML emission can be seen in day-light with naked eye. These materials are finding applications in novel self-diagnosis systems, optical stress sensors, stress imaging devices[7], wireless fracture sensor systems [8] and in damage sensors[9], stress distribution in solids and visualization of stress near the tip of the crack[10]. The instruments used to produce the ML are shown below. The stress (load) dependence of the ML is found to be linear as depicted in Fig.2.3.



Fig.2.2. Dependence of EML intensity on the applied load



Fig. 2.3. Schematics of the devices used for EML measurements: (a) a material testing machine for inducing EML by compression [44], (b) impulsive deformation technique for inducing EML, and (c) friction technique for inducing tribo ML[44].

Aluminates

The group of compounds consisting of Eu^{2+} doped and rareearth (R^{3+}) co-doped alkaline earth aluminates (MAl₂O₄:Eu²⁺, R^{3+} ; M: Ca, Sr, Ba) are by far the most studied family of persistent luminescent materials and are considered the first generation of the modern persistent luminescence materials [11]. This classification was possible after an article by Matsuzawa et al. on $SrAl_2O_4$: Eu^{2+} , Dy^{3+} [11]. Since then the aluminates have been at the centre of attention in persistent luminescent research. Some of the specific outstanding achievements of this era include the bright green luminescence of the monoclinic [12] $SrAl_2O_4$: Eu^{2+} , Dy^{3+} , which was discovered in 1966 [13] and described by Blasse and Bril two years later, together with that of $CaAl_2O_4$: Eu^{2+} and $BaAl^2O^4$: Eu^{2+} [14].

The promising results shown by these phosphors led to a search for a method to synthesize co-doped MAl_2O_4 :Eu²⁺ in an efficient, cheap and simple way. The methods include, solid-state reaction combustion [16,17], Pechini [15], microwave [18], laser heated pedestal growth (LHPG) [19], and sol-gel [20,21], which have been used to varying degrees of satisfaction. These investigations revealed that not all the techniques lead to identical crystallographic and luminescent properties. For example, SrAl₂O₄:Eu²⁺,Dy³⁺prepared by microwave synthesis shows a decreased initial brightness of the afterglow, together with a small blue shift of the emission spectrum, possibly due to the small grain size [18]. A similar blue shift has been reported for sol-gel prepared SrAl₂O₄:Eu²⁺,Dy³⁺ [20,21]. During the preparation of $CaAl_2O_4$ by combustion or a solgel method, Hölsä and co-workers obtained an unusual hexagonal crystal structure instead of the expected monoclinic one [22]. Other researchers have been able to create grains with orthorhombic structure [11]. These observations imply that care should be taken when comparing luminescence of compounds prepared using different procedures. Similarly, the exact composition of the starting mixture has important consequences for the afterglow behavior. A deficit of alkaline earths has been found to enhance the afterglow [23], while an excess of barium in BaAl₂O₄:Eu²⁺,Dy³⁺ has been observed to completely annihilate the persistent luminescence in the phosphor [24]. The influence of the borate (B_2O_3) on $SrAl_2O_4:Eu^{2+}$, Dy^{3+} has been the subject of interest to various researchers. Though this material is usually added to the starting mixture as a fluxing agent [11], it has been observed to have other influences. For example, samples prepared without borate showed only very weak [25] or no persistent luminescence at all [26] even though perfect SrAl₂O₄ phase formation was achieved. A probable explanation for this effect is that the boron is incorporated in the host as BO_4 , where it forms substitutional defect complexes with Dy^{3+} . This decreases the depth of the charge trapped in SrAl₂O₄ from 0.79eV to 0.65eV, making it suitable for persistent luminescence at room temperature [25].

Host material	Dopants	Fluorescence maximum (nm)	Afterglow maximum (nm)	Afterglow duration
SrAl ₂ O ₄	Eu ²⁺ ,Dy ³⁺	520 (green)	idem	>30 h
CaAl ₂ O ₄	Eu ²⁺ ,Nd ³⁺	440 (blue)	430 (blue)	>5 h
$BaAl_2O_4$	Eu ²⁺ ,Dy ³⁺	500 (green)	idem	>2 h
Sr ₄ Al ₁₄ O ₂₅	Eu ²⁺ ,Dy ³⁺	490 (blue)	idem	>20 h
SrAl ₄ O ₇	Eu ²⁺ ,Dy ³⁺	480 (blue)	idem	>3 h
SrAl12O19	Eu ²⁺ ,Dy ³⁺	400 (blue)	idem	>3 h
Ca12Al14O33	Eu ²⁺ ,Nd ³⁺	440 (indigo)	idem	>10 min
Sr ₃ Al ₂ O ₆	Eu ²⁺ ,Dy ³⁺	510/610 (disputed)	idem	(disputed)
SrMgAl ₁₀ O ₁₇	Eu ²⁺ ,Dy ³⁺	460 (blue)	515 (green)	>3 min
BaMgAl ₁₀ O ₁₇	Eu ²⁺ ,Co ³⁺	450 (blue)	idem	>5 min

Table.1. Various luminescent materials based on aluminates

The aluminate phase $Sr_4Al_{14}O_{25}:Eu^{2+}$, Dy^{3+} , is a blueemitting persistent phosphor with emission around 490 nm and an afterglow that has been reported to remain visible for over 20 hours [26,27]. A small deficit of strontium enhances the persistent luminescence [27], and preparation without borate strongly reduced the afterglow. The addition of silver (Ag+) ions in this phosphor has been observed to have a positive effect on the afterglow, and has been attributed to an increase in the trap density [28]. Other interesting results on aluminates involve the Sr₃Al₂O₆:Eu²⁺,Dy³⁺ phase. The emission colour from the triboluminescence [29] and photoluminescence [30] measurements on this phosphor is bright green with a spectrum peaking around 510 nm. However, when the same material was prepared using either microwave or sol-gel processes [31], red Eu2+-emission around 612 nm was observed. These conflicting reports have led to the emission colour of $Sr_3Al_2O_{6s}$: Eu²⁺, Dy³⁺ being indicated as 'disputed'.

Persistent Luminescent Phosphors

Persistent phosphors are a type of phosphors that possess long afterglow emission after the source of excitation has been stopped. These phosphors are irradiated by UV, visible light, X-ray, Y-radiations etc. The mechanism of long persistent phosphors is a basically three-level electronic transition mechanism, including an excited state, a ground state and a meta-stable trapping state for active electrons. The electrons that are trapped or the holes that are produced during the excitation, cause the afterglow effect. Phosphorescence lifetime is usually longer than the lifetime at the excited state and it depends on the trap depth and trapping/detrapping mechanism.



Fig. 4.1. Three level model showing the mechanism of long persistent phosphorescence.

As shown in fig.4.1. Ct and Cd are the trapping and detrapping rates respectively, while A and B represent the excitation and emission rates respectively. Phosphorescence life time usually depends on the trap depth, trapping and de-trapping rates and are therefore longer than the life times of the excited state [1]. On the other hand fluorescence is based on the two level electron transition mechanism, ground and excitation state and its decay time depends on the transition strength between the two states.

The long lasting afterglow phenomenon has been intriguing to the people for long time. In August 1996, Matsuzawa et al. published an article [32] of persistent luminescence. He demonstrated that the long lasting luminescent materials SrAl₂O₄:Eu²⁺ [33]when co-doped with the rare earth element dysprosium (Dy^{3+}) , can create a material that can emit bright light for hours after ending the excitation. These results were confirmed by Takasaki et al. reported similar results [34]. They found an afterglow with both a far higher initial intensity and a much longer lifetime compared to ZnS:Cu,Co. Comparative studies showed that Strontium Aluminate doped by Dysprosium and Europium are the efficient ones and possess long lasting persistence. A typical comparative study by C.N Xu for the persistence of luminescence of aluminate based phosphors has been shown in Fig 4.2 Their discovery marked the beginning of a renewed search for different and better persistent luminescent materials. After the discoverv of $SrAl_2O_4:Eu^{2+},Dy^{3+}$, the research for new persistent luminescent compounds has become increasingly popular. These strontium aluminates are the special members of persistent phosphors.



Fig.4.2. Comparison of afterglow characteristics measured after 10 min exposure to 200 lx of D_{65} light. A: SrAl₂O₄:Eu²⁺, B: SrAl₂O₄:Eu²⁺, Dy³⁺ C: SrAl₂O₄:Eu²⁺, Nd³⁺, D: ZnS:Cu,Co [43].

Preparation

Solid State Reaction

Strontium aluminate phosphor doped with Eu²⁺and co-doped with Dy³⁺(SrAl₂O₄:Eu²⁺, Dy³⁺) are prepared by solid state reaction approach using strontium carbonate (SrCO₃),

aluminum oxide (Al_2O_3) , europium oxide (Eu_2O_3) and dysprosium oxide (Dy_2O_3) as the starting materials. Small amount (0.2 mol %) of H₃BO₃ was used as a flux. Prior to heating at 1250°C, the reagents were grinded using a ball mill to form a homogeneous mixture. First, the dry milling was used for 30 min and then continued by wet-mixing machine for 30 min. The resulting slurry was dried at 150°C for 3 hrs to remove the water content. After fully dried, the mixed white powder was placed in a small alumina crucible and then fired at 1250°C for 2 hrs under a mild reducing atmosphere. Graphite crucible was used to create the reducing atmosphere and to ensure complete reduction of Eu³⁺ to Eu²⁺ and to crystallize and form the luminescence centers. Usually the particle size in this process is about 10-20µm. The mixing-milling process was used after calcination to prepare smaller particle size and homogenous mixture.



Fig. 5.1 Flow chart of the preparation of REE doped $SrAl_2O_4$ phosphor powders

Chemical Combustion Synthesis

The solution-combustion method is based on the preparation of mixture of nitrates of metal cations $(Sr(NO_3)_2 \cdot 4H_2O, Al(NO_3)_3 \cdot 9H_2O)$ and dopants such as Eu_2O_3 with organic fuel (urea, $CO(NH_2)_2$). Europium Oxide is first converted into nitrate as per equation (1).

$$\operatorname{Eu}_2O_3 + 6\operatorname{HNO}_3 \rightarrow 2\operatorname{Eu}(\operatorname{NO}_3)_3 + 3\operatorname{H}_2O \tag{1}$$

The temperature ranging from 60 to 80 °C is mostly used for this operation. The continuous stirring, lasting from several minutes to one hour, ensures the homogenization of mixture. The evaporation and re-crystallization of the product provide the solution, gel, foam or fine powder for subsequent thermal treatment. The combustion is a fast process (a few minutes) which takes place after introducing the sample into the furnace heated to the temperatures from 400 to 600 °C. The temperature during the combustion may reach 1100 °C. The voluminous foamy ash after the combustion is then grinded and used as a precursor for the flame-pyrolysis of oxide powder for the synthesis of strontium aluminates.

The chemical equation of combustion is complicated and not yet verified; however, the brief equation can be shown as below: $2Al(NO_3)_3.9H_2O + Sr(NO_3)_2 + CO(NH_2)_2 + Eu(NO_3)_3 + 1.5O_2 \rightarrow SrAl_2O_4: Eu^{2+} + 20H_2O + 5N_2 + 14.5O_2 + CO_2$ (2)



Fig.5.2 Scheme of the combustion method.

Applications of the Phosphorescent materials

The luminescence of the ZnS:Mn and SrAl₂O₄: Eu, crystals can be used for the following purposes:

Stress Sensor

As the ML intensity of ZnS:Mn and $SrAl_2O_4$: Eu, Dy phosphors mixed in a resin increases with increasing stress or the applied pressure, the stress or the pressure can be determined by measuring the EML intensity and hence they can be used as stress sensors.

Real -Time Visualization of the Stress Distribution in Solids

SrAl₂O₄: Eu phosphor of 1.00 g is mixed with an optical epoxy resin of 4.00 g to form a composite disc of 25 mm in diameter and 15 mm in thickness. Now stress is applied on the sample by a normal material testing machine or by a vise with a force gauge [35]. The ML intensity distributions observed by an intensified CCD (ICCD) camera which increases exponentially with increasing r/a (where 'r' is the distance from the centre, and 'a' is the radius of sample). As it is consistent with that obtained from the simulations based on elastics, it demonstrates that EML from stressed SrAl₂O₄: Eu provides obvious view of stress distribution in solids.

Impact sensor: After the application of load or stress to the ML smart material, its impact initially increases the intensity

of the of ML, attains peak value at a particular time an then decays with the passage of time[36]. This mechanical impact can be remotely sensed using efficient ML material via detection of impact ML intensity.

Real-Time Visualization of the Stress Field Near the Tip of a Crack

Sohn et al., [37] prepared the compact test (CT) specimen (19 mm x 20 mm x 3 mm) from a mixture of epoxy resin and 10wt. % of SrAl₂O₄:Eu, Dy, Nd, phosphor for the direct observation of crack tip stress field using ML. Using a very sharp blade for providing a crack initiation poin, an acute notch tip of radius 50µm was introduced into the CT specimen. The specimen was placed on a specially designed CT type loading machine and exposed to 365 UV light for 10 minutes and then aged in a dark room for 5 minutes for the phosphorescence to relax down to a certain level before loading. Using a digital camera with shutter open at each loading step, the notch tip area was photographed making it possible to investigate the stress field formation in front of a stationary crack- tip in terms of ML for a stress intensity factor of 1.7 M Pa m1/2, whereby the formation of circleshaped stressed area was evident. This observation is believed to be the result of fracture mechanics.

EML-Based Safety-Management Monitoring System

EML-based safety-management monitoring system has been developed [38] that includes: (i) EML sensors (ii) image sensors (iii) wireless photo-detector nodes, (iv) a data-base for diagnosing the stress anomaly in the structure on the basis of the EML intensity, and (v) a network system that coordinates the operation of these components. Using this system the appearance of a crack that occurs in the concrete of bridges and buildings can be visualized.

ML-Driven Photocell System

A novel ML-driven photocell system was successfully demonstrated by Terasaki et.al.[39] where $SrAl_2O_4$:Eu, micro size particles are used as light source and a commercial silicon solar cell as photoelectric converter.

Determination of the Crack-Growth Resistance and other Parameters of Crack- Propagation

Crack growth resistance curve (R–curve), crack velocity, crack-length dependence of crack-velocity, crack-tip stress field, bridging stress distribution, wake width etc can be suitably determined using the ML technique as it is much simpler, cheaper and more suited to the detection of fast cracks [40].

Visualization of Internal Defect in a Pipe

In a pressurized pipe, the defect can be visualized by using ML sensor [41]. There is agreement between the hoop strain distribution obtained from the ML intensity and that obtained from the strain gauge measurement and the FEM calculation. On the defective pipe, the hoop strains have

maximum and minimum values around the defect that increases with depth of the defect and hence the location and depth of the defect in a pipe can be easily estimated by using the ML sensor.

The main advantages and the ultimate objective of ML exhibiting Strontium Aluminate Phosphors

Unless and until the ML material is not fractured actually, no light is emitted and hence no false alarms are generated. As increase in the compressive load leads to corresponding increase in ML intensities in materials like SrAl₂O₄:Ho,Ce (Zhang et.al, Appl. Phys. Lett. 91, 081905 2007) and SrAl₂O₄:Eu,Dy, the relation between ML and compressive load is almost linear. These properties indicate that this sample can be used for smart-skin and self-diagnosis applications. The ultimate objective is to fit an airplane with this "pain sensitive skin" containing a "nervous system" of embedded optical fibers. When an impact cracks the doped resin, it sends a tiny flash of light through these fibers. Thus the intensity of the light of ML directly gives the magnitude of the damage and the wavelength of the light emitted indicate the location of damage

Conclusions

In last few decades, many new aluminate based EML and FML materials having intense ML intensity have been investigated. Also the ML has attracted the attention of a large number of researchers because of its potential in different types of mechano-optical devices such as damage sensors, stress sensors, fracture sensors, visualization of stress distribution in solids, visualization of quasidynamic crack-propagation in solids, safety- management monitoring system, etc. The investigation of ML-based damage sensor and ML-based safety management monitoring system are considered to be a great achievement in the field of ML.

Perspectives for Aluminate based ML Research

The desire of new ML materials, new instrumentation for ML and new applications of ML needs further determination and focussed investigation. The understanding of elastic deformation, plastic deformation and fracture using ML are possible, but it has been least studied till now. Furthermore, the design of ML-based low pressure touch screen, wearable sensors, light sources, ML sensors, displays, amusement instruments, ML toys, etc. may be important. It will be interesting to extend the uses of ML to earthquake prediction and in understanding the earthquake lights. The ML-based safety-management monitoring system and different types of MLbased sensors need further investigation. The microscopic theories of EML, PML and FML still need further investigation. Research in EML, PML and FML is therefore rich with many possible experiments and applications.

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References

- [1]www.isbc.unibo.it/Files/10_SE_BoStone.htm [Accessed 26 November 2011]
- [2]. Xu C.N., in Encyclopedia of Smart Materials, edited by M. Schwartz Wiley, New York, 2002 Vol. 1, p. 190.
- [3]. Sage I, Badcock R, Humberstone L., Geddes N., Kemp M., and Bourhill J, J. Intell. Mater. Syst. Struct. 8,504 1999.
- [4]. Xu C.N, Wantanabe T., Akiyama M., and Zheng X.G., Mater. Res. Bull.34, 1491 1999.
- [5]. Chandra B.P., in: D R Vij(Ed), Luminescence of Solids, ,Plenum Press, New York, 1998, p.361.
- [6]. Chandra V K & Chandra B P,J. Lumin, 132(2012)1382.
- [7]. Xu C N, Watanabe T, Akiyama M,Sun P & Zheng X G, J Am Ceram Soc, 82(1999)2342.
- [8].Akiyama M, Xu C N, Matsui H, Nonaka K & Watanabe T, Appl Phys Lett, 75(1999)2548.
- [9]. Sage I, Badcock R, Humberstone I,Geddes N,Kemp M & Bourhill G, Smart Mater Struct, 10(2)(2001)332.
- [10]. Li C, Xu C N, Zhang L, Yamada H & Imai Y, Journal of Visualisation, 11(4) (2008)329.
- [11]. Matsuzawa, T. Aoki, Y. Takeuchi, N. Murayama, Y. J. Electrochem. Soc., 143: 2670, (**1996**).
- [12]. Chander, H. Haranath, D. Shanker, V. Sharma, P. J. Cryst Growth., 271: 307, (2004).
- [13]. Lange, H. US patent 3, 294, 699, (1966).
- [14]. Blasse, G. Bril, A. Philips Res. Rep., 23: 201, (1968).
- [15]. Aitasalo, T. Hölsä, J. Jungner, H. Lastusaari, M. Niittykoski, J. Parkkinen, M. Valtonen, R. Opt. Mater., 26: 113, (2004).
- [16]. Peng, T. Yang, H. Pu, X. Hu, B. Jiang, Z. Yan, C. Mater. Lett., 58: 352, (2004).
- [17]. Qiu, Z. Zhou, Y. Lü, M. A. Zhang, Ma, Q. Acta Mater., 55: 2615, (2007).
- [18]. Geng, J. Wu, Z. J. Mater. Synth. Proces., 10: 245, (2002).
- [19]. Jia, W. Yuan, H. Lu, L. Liu, H. Yen, W.M. J. Cryst. Growth., 200: 179, (1999).
- [20]. Peng, T. Huajun, L. Yang, H. Yan, C. Mater. Chem. Phys., 85: 68, (2004).
- [21]. Tang, Z. Zhang, F. Zhang, Z. Huang, C. Lin, Y. J. Eur. Ceram. Soc., 20: 2129, (2000).
- [22]. Aitasalo, T. Hölsä, J. Jungner, H. Lastusaari, M. Niittykoski, J. J. Alloy. Compd., 341: 76, (2002).
- [23]. Sakai, R. Katsumata, T. Komuro, S. Morikawa, T. J. Lumin., 85: 149, (1999).
- [24]. Nag, A. Kutty, T.R.N. Mater. Res. Bull., 39: 331, (2004). 81
- [25]. Nag, A. Kutty, T.R.N. J. Alloy. Compd., 354: 221, (2003).
- [26]. Lin, Y. Tang, Z. Zhang, Z. Mater. Lett., 51: 14, (2001).
- [27]. Lin, Y. Tang, Z. Zhang, Z. Nan, C.W. Appl. Phys. Lett., 81: 996, (2002).
- [28]. Suriyamurthy, N. Panigrahi, B.S. J. Lumin., 128: 1809, (2008).
- [29]. Akiyama, M. Xu, C. Nonaka, K. Watanabe, T. Appl. Phys. Lett., 73: 3046, (1998).

- [30]. Chang, C. Li, W. Huang, X. Wang, Z. Chen, X. Qian, X. Guo, R. Ding, Y. Mao, D. J. Lumin., 130: 347, (2010).
- [31]. Zhang, P. Xu, M. Zheng, Z. Sun, B. Zhang, Y. Mater. Sci. Eng. B Solid State Mater. Adv. Technol., 136: 159, (2007).
- [32]. Matsuzawa, T.; Aoki, Y.; Takeuchi, N.; Murayama, Y. A new long phosphorescent phosphor with high brightness, SrAl2O4:Eu2+,Dy3+. J. Electrochem. Soc. 1996, 143, 2670–2673.
- [33]. Abbruscato, V. Optical and electrical properties of SrAl2O4:Eu2+. J. Electrochem. Soc. 1971, 118, 930– 933.
- [34]. Takasaki, H.; Tanabe, S.; Hanada, T. Long-lasting afterglow characteristics of Eu, Dy codoped SrO-Al2O3 phosphor. J. Ceram. Soc. Jpn. **1996**, 104, 322–326.
- [35] Akiyama, M.; Xu, C.N.; Taira, M.; Nonaka, K. Visualization of stress distribution using mechanoluminescence from Sr3Al2O6: Eu and the nature of the luminescence mechanism. Philos. Mag. Lett., **1999**, 79, 735.
- [36]. Chandra B.P., Chandra V K, Mahobia S.K, Jha P,Tiwari R, Haldar B, Real time mechanoluminescence sensing of the amplitudeand duration of the impact of stress, sensors and Actuators A 173(2012)9-16.
- [37]. Sohn, K.S.; Seo, S.Y.; Kwon, Y.N.; Park, H.D. Direct observation of crack tip field using the mechanoluminescence of SrAl2O4: Eu, Dy, Nd. J. Am. Cream Soc., 2002, 85, 712.
- [38]. Xu, C.N. Monitoring system for safety management of structures using elastico-luminescent materials- Realtime visualization of the shape distribution and propagation of cracks using elastico-luminescent sensors. AIST Today, **2010**, 10, 18.
- [39]. Terasaki, N.; Xu, C.N.; Imai, Y.; Yamada, H. Photocell System Driven by Mechanoluminescence. Jpn. J. Appl. Phy., 2007, 46, 2385.
- [40]. Kim, J.S.; Kwon, Y.N.; Shin, N.; Sohn, K.S. Visualization of frac-tures in alumina ceramics by mechanoluminescence. Act. Matr., 2005, 53, 4337.
- [41]. Ono, D.; Xu, C.N.; Li, C.; Bu, N. Visualization of Internal Defect of a Pipe Using Mechanoluminescent Sensor. J. Jpn. Soc. Exp. Mech. (JSEM), 2010, 10, 152.
- [42]. Xu, C. N.; Li, C.; Imai, Y.; Yamada, H.; Adachi, Y.; Nishikubo, K. Development of elastico-luminescent nanoparticles and their appli-cations. Adv. in Sci. and Tech., 2006, 45, 939.
- [43]. Matsuzawa, T.; Aoki, Y.; Takeuchi, N.; Murayama, Y. A new long phosphorescent phosphor with high brightness, SrAl2O4:Eu2+,Dy3+. J. Electrochem. Soc. **1996**, 143, 2670–2673.
- [44]. Xu, C.N. In Encyclopedia of Smart Materials, M. Schwart, ed.; John Willey & Sons, Inc.: New York , 2002; vol. 1, pp 190-201.