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Real-time mechanoluminescence sensing of the amplitude and duration of impact stress

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ABSTRACT

The present paper reports the real-time sensing of the amplitude and duration of impact stress using mechanoluminescence (ML) of the films such as ZnS:Mn and $SrAl_2O_4$:Eu. After the impact of a small ball from a low height onto the film, initially the elastico mechanoluminescence (EML) intensity increases with time, attains a peak value and then it decreases with time, initially at a fast rate and later on at a slow rate. The fast decay time of the EML intensity is related to the rate constant for the rise of impact stress and the slow decay time of EML is equal to the lifetime of electrons in the shallow traps lying in the normal piezoelectric region of the crystals, which get filled during the detrapping of thermally stable traps at the time of the increase of pressure. Both the peaks of EML intensity and total EML intensity increase linearly with the height through which the ball is dropped onto the films. The EML spectra are similar to the corresponding photoluminescence and electroluminescence spectra. On the basis of the localized piezoelectrically induced electron detrapping model, expressions are derived for different parameters of the impact stress-induced EML of the films, whereby a good agreement is found between the experimental and theoretical results. As the EML intensity depends on the impact stress, the impact stress can be sensed by measuring the EML intensity. Furthermore, the duration of stress is related to the time t_m corresponding to the peak of the EML intensity versus time curve; hence, the pulse duration of the impact stress can be monitored by measuring the value of time t_m.

1. Introduction

Mechanoluminescence (ML) is the phenomenon of light emission from a solid as a response to a mechanical stimulus given to it. The light emissions induced by elastic deformation, plastic deformation and fracture of solids are known as elastico ML (EML), plastico ML (PML) and fracto ML (FML), respectively [1,2]. On the basis of the development made in the past, the span of ML research can be divided into the following four generations [3]: (i) pre-PMT (photomultiplier tube) generation of ML (from the beginning to 1950), (ii) early post-PMT generation of ML (from 1951 to 1990), (iii) late post-PMT generation of ML (from 1990 to date), and (iv) future generation of ML (yet to come). It is to be noted that, although PMTs were investigated during 1930s, they were used for ML measurements only after 1950. In the first generation of ML, nearly 500 mechanoluminescent materials were investigated visually and elementary information related to the mechanisms and spectra of ML was obtained. In the second generation of ML, thousands of mechanoluminescent materials were investigated and deep understanding of the mechanisms and characteristics of ML was made and also sophisticated ML instruments were designed. In the third generation of ML, the intense elastico and fracto mechanoluminescent materials are investigated, and applications of mechanoluminescent materials in damage sensors and stress sensors are being made. The fourth generation of ML will be based on the wearable ML sensors, ML laser, ML sensors for getting prior information of the occurrence of earthquakes and mine-failure, etc.

Only limited number of solids exhibit the phenomenon of elastico ML. The examples of elastico mechanoluminescent materials are: x or γ-irradiated alkali halide crystals: ZnS:Mn, $SrAl_2O_4$:Eu, $SrAl_2O_4$:Ce, $SrAl_2O_4$:Ce, Ho, $SrMgAl_6O_{11}$:Eu, $SrCaMgSi_2O_7$:Eu, $SrBaMgSi_2O_7$:Eu, $Sr_2MgSi_2O_7$:Eu, $Ca_2MgSi_2O_7$:Eu, Dy, $CaYAl_3O_7$:Eu, (Ba, Ca)TiO_3:Pr^{3+}, $ZnGa_2O_4$:Mn, $MgGa_2O_4$:Mn, $BaAl_2Si_2O_8$:rare earth element, $Ca_2Al_2SiO_7$:Ce, ZrO_2:Ti and ZnS:Mn, Te [1–15]. The rare earth dopant can be Eu. A few

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polymers [16] and certain variety of rubbers have also been reported to be elastico mechanoluminescent [17,18]. Certain materials, such as $SrAl_2O_4$:Eu, $SrMgAl_6O_{11}$:Eu and $Ca_2Al_2SiO_7$:Ce, ZrO_2:Ti, show such an intense EML so that it can be seen in day light with naked eye. The EML materials have potential for their use in stress sensors [15,19] and visualizations of stress distribution in solids [15], stress field near the tip of crack [20] and quasidynamic crack-propagation in solids [21]. The EML materials have also the potential for developing new generation optical sensors for recording defects and damages and for developing a safety monitoring network system using EML sensor.

Up to 1970, the studies on ML were primarily concentrated on the spectroscopy of ML, mechanisms of ML, investigation of new mechanoluminescent materials, and methods for deforming the materials for ML emission [1,2,22]. In 1972, Chandra et al. fractured the crystals by dropping a fixed load from different heights, in which comparison of the ML intensity of different crystals could be made, rise and decay of ML and fracture-initiation time could be determined, and the ML spectra could be recorded easily [23–26]. Chandra and Zink [27,28] designed an instrument for the impulsive excitation of ML in crystals and reported that the transient ML intensity and total ML intensity of crystals depend systematically on the impact velocity of the piston used to deform the crystals. Recently, Chandra et al. [29] have shown that when a crystal is fractured by a piston having initial velocity v_0, then the time t_m corresponding to the peak of ML intensity versus time curve decreases with v_0, the peak of ML intensity I_m increases with v_0, and the total ML intensity I_T, initially increases with v_0 and then it attains a saturation value for higher values of the impact velocity v_0. It is found that the time t_m increases with the thickness of crystals, the peak ML intensity I_m increases with the area of cross-section of the crystals, and the total ML intensity increases with volume or mass of the crystals. The peak of ML intensity is related to the rate of creation of new surfaces of the crystals and the total ML intensity is related to the new surfaces created during fracture of crystals. Chandra et al. [30,31] have also reported the ML produced during the slow deformation and loading of crystals. Sage et al. [32] have reported that after the impact, initially the ML intensity increases with time, attains a peak value and then it decreases with time. Using a two-stage hypervelocity light gas gun, a projectile was accelerated to approximately 5–6 km/s before striking a ZnS:Mn phosphor-coated aluminium plate and it is found that up to the projectile kinetic energy of nearly 0.20 J, the peak ML intensity I_m increases at a fast rate and then from 0.2 J to 1.60 J, the peak ML intensity increases at a slow rate [33,34]. ML has been found useful in understanding the processes involved in earthquake lights [35–37].

As the ML is produced from a solid as a response to a mechanical stimulus given to it, a systematic correlation between the ML pulse and the associated pressure pulse is expected. Although ML pulse has been reported to appear during the application of pressure pulse onto solids [1,2], the relation between ML pulse and pressure pulse required for the development of ML-based pressure sensors is not satisfactorily known to date. In the present paper the correlation between the ML pulse and pressure pulse produced during impact of a ball onto the film of mechanoluminescent material coated on a substrate is explored and it is shown that, the peak intensity and total intensity of ML are quadratically related to the amplitude of the stress pulse and the time corresponding to the peak of ML pulse is directly related to the pressure pulse duration. Thus, the present paper explores that the ML provides a sensitive optical technique for sensing the amplitude and duration of the pressure pulse produced by an impact. The advantages of ML-based pressure or stress sensors are: (i) no contact electrodes are required, (ii) they can be used remotely, and (iii) they are suitable for small solids even in the range of a nanometer. Furthermore, the present study indicates that, during the impact of a ball, the stress increases nonlinearly with the compression and the volume from where the ML emission takes place increases linearly with increasing value of the contact area of the ball. A good agreement is found between the theoretical and experimental results.

2. Mechanisms of elastico mechanoluminescence

2.1. Mechanism of the elastico ML of ZnS:Mn

The mechanism of the elastico ML in ZnS:Mn can be understood with respect to the following steps:

(i) The deformation of ZnS:Mn crystals produces piezoelectric field because crystal – structure of ZnS is non-centrosymmetric [38], in which the piezoelectric field near Mn^{2+} ions may be high due to the change in local structure.
(ii) Because of the decrease in the trap-depth due to the piezoelectric field or due to the band bending the detrapping of electrons from filled-electron traps takes place, and therefore, electrons reach the conduction band.
(iii) The electrons reaching the conduction band may recombine with the holes trapped in the defect centres or they may jump to the valence band and subsequently energy may be released non-radiatively.
(iv) The energy released non-radiatively during electron-hole recombination may be transferred to the Mn^{2+} ions, whereby Mn^{2+} ions may get excited.
(v) The de-excitation of excited Mn^{2+} ions gives rise to the light emission characteristic of the Mn^{2+} ions.

2.2. Mechanism of the elastico ML of $SrAl_2O_4$:Eu

The appearance of elastico ML only in the piezoelectric-phase of strontium aluminate crystals [9] indicates that the piezoelectrification is responsible for the elastico ML of $SrAl_2O_4$:Eu. The steps involved in the ML emission in $SrAl_2O_4$:Eu crystals are as given below:

(i) The application of pressure produces piezoelectric field in $SrAl_2O_4$:Eu crystals because they are non-centrosymmetric [9], whereby the piezoelectric field near certain defect centres may be high due to the change in the local structure.
(ii) The piezoelectric field reduces the trap-depth of the traps lying near the defect centres.
(iii) The decrease in trap-depth causes transfer of electrons from electron traps to the conduction band.
(iv) Subsequently, the moving electrons in the conduction band are captured in the excited state of Eu^{2+} ions located at the bottom of the conduction band, whereby excited Eu^{2+} ions are produced.
(v) The de-excitation of excited Eu^{2+} ions gives rise to the light emission characteristic of the Eu^{2+} ions.

3. Theory

3.1. Piezoelectrification caused by the impact stress

If a small ball of mass m is dropped onto a film from a height h, then its initial velocity is $v_0 = \sqrt{2gh}$, where g is the acceleration due to gravity. After the impact, the velocity decreases with time. If τ_r is the rise time of the compression x, then we can write the following expression

$$x = x_0 \left[1 - \exp\left(-\frac{t}{\tau_r}\right)\right] = x_0 \left[1 - \exp(-\xi t)\right] \quad (1)$$

where x_0 is the maximum compression and $\xi = 1/\tau_r$.