Recent Research in Science and Technology 2012, 4(8): 124-125
ISSN: 2076-5061
Available Online: http://recent-science.com/

Hypervelocity impact induced mechanoluminescence of phosphors

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Abstract

Phosphors are materials doped with one or more impurities that give cold light emission when excited. When a high velocity projectile strikes the backside of a metal plate whose front side is coated with phosphor, then the light emission takes place from the phosphor. ZnS:Mn is an important phosphor which has many applications. It is observed that, when a projectile moving with a hypervelocity makes an impact on to the metal plate coated with ZnS:Mn phosphors, then intense mechanoluminescence (ML)is produced.. The present paper reports the kinetics of ML induced by hypervelocity impact on ZnS:Mn phosphors ,whereby a good agreement is found between the experimental and theoretical results.

Keywords: Hypervelocity, mechanoluminescence, materials

INTRODUCTION

The luminescence induced by any mechanical action on solids is called mechanoluminescence (ML).The light emissions produced during elastic deformation, plastic deformation and fracture of solids are called elastico ML (EML), plastico ML (PML) and fracto ML (FML), respectively. The mechanoluminescence (ML) phenomenon has generated extensive research interest over the years because of its potential application for damage detection [1]. ML is the emission of light by solid materials when they are under stress or fractured [2, 3]. It has been estimated that about 50% of all crystal compounds exhibits a range of ML [4]. There are number of techniques currently being used for damage detection and monitoring of civil, aerospace and military structures. The major drawbacks of current techniques are that they do not provide in-situ and distributed sensing. ML based sensor systems may be able to overcome the fore mentioned drawbacks. A ML based sensor system comprising highly efficient ML materials could allow simple, real- time monitoring of both the magnitude and location of damage with minimal parasitic influence to the host structure [5]. They can be used as stress, fracture and damage sensors. They have also been proposed for visualizing the stress field near the crack-tip stress distribution in solids and quasidynamic crack-propagation in solids [6]. Although there are still many challenges to overcome, ML based sensing systems promise to significantly enhance the nondestructive evaluation and structural health monitoring of engineering structures because of their potential for wireless intrinsic and distributed sensing. The present paper reports the decay time of mechanoluminescence of ZnS:Mn phosphors induced by hypervelocity impact.

Mechanism of Fracture Induced ML in ZnS:Mn Crystals

The mechanism of the fracture- induced ML in ZnS:Mn crystal may be understood with respect to the following steps:

(i) At the tip of the moving crack movement of dislocations takes place. Intense piezoelectric field is produced near the defect centres.

(ii) The dislocations in ZnS:Mn crystals are charged, hence intense electric field is produced in their surroundings.

(iii) The electric field in the vicinity of the defect centres causes the bending of the bands of the crystals.

(iv) Subsequently the trapped electron tunnel from the electron traps to the conduction band.

(v) The electron-hole radiative recombination gives rise to the light emission.

(vi) In the case of ZnS:Mn either the electrons are accelerated in the field of dislocation, excite Mn^{2+} centers, or the energy released electron hole recombination, excites Mn^{2+} centers and de-excitation of Mn^{2+} centers give rise to the light emission.

THEORY

In the experiment of ML induced by hype velocity impact the phosphor is coated on the surface of metallic plate and a projectile moving at very high velocity makes an impact on the back side of the metallic plate and the shock wave travelling through the metal excites the mechanoluminescence in the coated phosphors. Tthe time dependence of pressure P can be expressed by the following equation

$$P = P_0\left[1 - e^{-\xi t}\right] \tag{1}$$

Where P_0 is the maximum pressure and ξ is the rate constant for rise of the pressure.

If d_0 is the localised piezoelectric constant near defect centres, then the piezoelectric field can be expressed by

$$F = Bd_0P = d_0P_0\left[1 - e^{-\xi t}\right] \tag{2}$$

Where B is a constant.

From Eq. (2) the rate of change of electric field with time is given by

$$\dot{F} = \frac{dF}{dt} = Bd_0 P_0 \xi e^{-\xi t} \qquad (3)$$

In fact the detraping of electrons from traps is proportional to $\dot{F}$. Thus the rate of detraping g is given by

$$g = \alpha \dot{F} = \alpha d_0 P_0 \xi e^{-\xi t} \qquad (4)$$

where α is a proportionality constant.

If the $\bar{x}$ is the mean free path of the free charge carriers then the total distance travelled by the free charge carriers per unit time is given by g$\bar{x}$. Thus the rate of recombination R of charge carriers is given by

$$R = \sigma g \bar{x} n_h \qquad (5)$$

where σ is the capture cross section of electrons and n_h is the concentration of hole centres.

If η is the efficiency of the radiative recombination and $\bar{x} = \mu F \tau$, where μ is the mobility of electron and τ is the lifetime of electrons in the conduction band then the ML intensity can be expressed as

$$I = \eta R = \eta \sigma g \mu F \tau n_h$$

From equation (2) and (4) we get

$$I = \eta \sigma \alpha d_0^2 P_0^2 \tau n_h \mu \xi \left[e^{-\xi t} - e^{-2\xi t} \right] \qquad (6)$$

From Eq. (6) the time t_m and intensity I_m corresponding to the peak of ML intensity versus time curve. The total ML intensity I_T, the slow decay of ML intensity I_{ds} and the fast decay of ML intensity I_{df} can be expressed by the following expressions

$$t_m = \frac{1}{\xi} \ln 2 \qquad (7)$$

$$I_m = \frac{\eta \sigma \alpha d_0^2 P_0^2 \tau n_h \mu \xi}{4} \qquad (8)$$

$$I_T = \frac{\eta \sigma \alpha d_0^2 P_0^2 \tau n_h \mu}{2} \qquad (9)$$

$$I_{ds} = \eta \sigma \alpha d_0^2 P_0^2 \tau n_h \mu \xi \exp(-\xi t_m) \ \exp[-\xi (t - t_m)] \qquad (10)$$

and,

$$I_{df} = \eta \sigma \alpha d_0^2 P_0^2 \tau n_h \mu \xi \ \exp[-\chi (t - t_m)] \qquad (11)$$

where $\chi = \frac{1}{\tau_e}$, the life time of excited Mn^{2+} centres.

Fig. 1 shows the shows the ML intensity versus time curve for ZnS:Mn phosphors coated on metal plate [3]. It is seen that initially the ML intensity increases with time attains a peak value and then it decreases with time. This result is in accordance with Eq. (6).

From the plot between ln I and (t-t_m), the plot is a straight line with a negative slop. Such result is expected from Eq. (10). The value of decay time τ_e comes out to be 300 μs. This value is compared with the lifetime of excited Mn^{2+} ions.

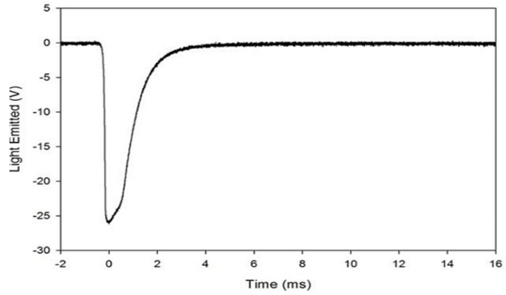

Figure 1. Example PMT potential response for ZnS:Mn. Notice that the luminescence decay appears to follow standard exponential decay.

CONCLUSION

When a pressure pulse is applied on ZnS:Mn phosphor coated metallic plate, then ML is produced, in which initially the ML intensity increases with time, attains a peak value and then it decreases with time. Expressions are derived for different characteristics of the pulsed induced ML, whereby a good agreement is found between experimental and theoretical results. It is shown that the lifetime of excited Mn^{2+} ions and rise time of pressure pulse can be determined from the ML measurements.

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