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Theoretical Study of Infra-red Laser Induced Mechano Luminescence in Alkali Halide Crystals

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ABSTRACT

The present paper reports that when a X or γ-irradiated alkali halide crystals is exposed to 1060 nm infrared pulses of nanosecond duration from Nd-YAG laser, then the shock waves produced in the crystals excites visible luminescence, analogous to the mechanoluminescence (ML) produced due to the mechanical deformation of the crystals. In the ML intensity versus time curve spectra two peaks appear. The first peak appears almost in the presence of shock-wave and the second peak appears after the cessation of shock-wave. The decay time of ML intensity after the first and second peak gives the pinning time of dislocations and the lifetime of electrons in the dislocation band, respectively. The ML excited by invisible laser pulses may be an important optical tool to determine the parameters of dislocations in crystals.

Keywords: Nd-YAG laser, alkali halide crystals, visible luminescence, mechanoluminescence, dislocation.

1. INTRODUCTION

When certain matters absorb energy, then a part of energy may be re-emitted as electromagnetic radiation in excess of thermal radiation. Such cold emission of light is known as luminescence. Thus, luminescence is a non-equilibrium, non-thermal phenomenon. On the basis of energy absorbed, the luminescence has been classified into different types, for example photoluminescence, cathodoluminescence, electroluminescence, chemiluminescence, bioluminescence, mechanoluminescence, etc.

Mechanoluminescence (ML) is a type of luminescence produced during mechanical deformation of solids. It can be excited by cutting, cleaving, compressing or impulsive deformation of solids. So far as

the ML excitation is concerned, the crystals are either deformed slowly at the fixed strain rate, or by applying a statical load on the crystals or by impulsively deforming the crystals[1-12]. Recently, it has been found that infrared laser pulses produce shock-waves in the solids. Thus, ML can be excited by laser pulses instead of direct deformation of solids.

The present paper reports the theory of the kinetics of laser induced ML in alkali halide crystals.

2. THEORY

In a crystal having N_d dislocations of unit length per unit volume, if r_F is radius of interaction of a dislocation with F-centres and v_d is the average-velocity of dislocations, then in unit time, N_d dislocations may interact with the F-centres lying in volume $N_d v_d r_d$. If n_F is the density of F-centres, then for a crystal of unit volume, the rate of interaction of F-centers with dislocations may be given by

$$g_i = N_d v_d r_d n_F = \frac{\dot{\varepsilon}}{b} r_F n_F \qquad (1)$$

where b is the Burger vector and $\dot{\varepsilon} = N_d v_d b$, is the strain rate.

Suppose a alkali halide crystal is exposed to a infra-red laser pulse whose intensity is given to $I = I_0 e^{-t/\tau_L}$ where, I_0 is the maximum intensity and $\tau_L$is the duration of a laser pulse.The Laser pulse will produce strain in the crystal and the time dependence of strain rate $\dot{\varepsilon}$ proposed in the crystal may be given by

$$\dot{\varepsilon} = A I_0 e^{-t/\tau_L} \qquad (2)$$

Thus, from Eq^n.(1) and (2), we get

$$g_i = \frac{A I_0 e^{-t/\tau_L} r_F n_F}{b}$$

$$g_i = g_0 e^{-t/\tau_L}$$

$$\text{where } g_0 = \frac{A I_0 r_F n_F}{b} \qquad (3)$$

In the expansion region of dislocations, the average energy E_i of F-centers interacting with dislocations is higher as compared to the non-interacting F-centres[12]. Thus, E_i will lie between the normal ground state of F-centre and the dislocation band. If α_1 is the rate constant for the jumping of interacting F-centred electrons to the dislocation band, band α_2 is the rate constant for the dropping back to the normal F-level, then we can write the following rate equation

$$\frac{dn_i}{dt} = g_i - (\alpha_1 + \alpha_2) n_i = g_i - \alpha n_i \qquad (4)$$

where $\{1/(\alpha_1 + \alpha_2)\} = \tau_i$, is the lifetime of interacting F-centres and n_i is the number of F-centre electrons at any time t, and $\alpha = (\alpha_1 + \alpha_2)$.

From Eq^n.(3) and (4), we get

$$\frac{dn_i}{dt} = g_0 e^{-\alpha_L t} - \alpha n_i \qquad (5)$$

where $\alpha_L = 1/\tau_L$.

$$\frac{dn_i}{dt} + \alpha n_i = g_0 e^{-\alpha_L t} \qquad (6)$$

Integrating factor (I.F.) = $e^{\int \alpha dt} = e^{\alpha t}$

Solution of Eq^{n}.(6) is

$$n_i e^{\alpha t} = \int g_0 e^{-\alpha_L t} . e^{-\alpha t} dt + C$$

$$n_i e^{\alpha t} = g_0 \int e^{(\alpha-\alpha_L)t} dt + C$$

$$n_i e^{\alpha t} = g_0 \frac{e^{(\alpha-\alpha_L)t}}{(\alpha - \alpha_L)} + C \quad (7)$$

If $n_i = 0$ at $t = 0$, we get

$$0 = \frac{g_0}{(\alpha - \alpha_L)} + C$$

$$C = - \frac{g_0}{(\alpha - \alpha_L)}$$

Putting value of C in Eq^{n}.(7), we get

$$n_i e^{\alpha t} = g_0 \frac{e^{(\alpha-\alpha_L)t}}{(\alpha - \alpha_L)} - \frac{g_0}{(\alpha - \alpha_L)}$$

$$n_i = \frac{g_0}{(\alpha - \alpha_L)} (e^{-\alpha_L t} - e^{-\alpha t})$$

$$n_i = \frac{g_0}{(\alpha_L - \alpha)} (e^{-\alpha t} - e^{-\alpha_L t}) \quad (8)$$

From Eq^{n}.(2) and (8) the rate of generation of electrons in the dislocation band may be written as

$$g = \frac{\alpha_1 g_0}{(\alpha_L - \alpha)} [e^{-\alpha_L t} + e^{-\alpha t}] \quad (9)$$

for $\alpha_L >> \alpha$, Eq^{n}.(7) may be expressed as

$$g = \frac{\alpha_1 g_0}{\alpha_L} e^{-\alpha t} \quad (10)$$

When the dislocation containing electrons are moving in a crystal, then the electrons may recombine with the defect centres containing holes and also with the deep traps present in the crystals. The retrapping of dislocation electrons in the negative ion vacancies may also take place. Suppose N_1, N_2 and $N_3$are densities of recombination centres, deep traps and negative ion vacancies (without trapped electrons), respectively and σ_1 σ_2 and σ_3 are the capture cross-section for the recombination centre, deep traps and negative ion vacancies, respectively, then the rate equation may be written as

$$\frac{dn_d}{dt} = g_0 e^{-\alpha t} - \sigma_1 N_1 v_d n_d - \sigma_2 N_2 v_d n_d - \sigma_3 N_3 v_d n_d$$

$$\text{or} \quad \frac{dn_d}{dt} = g_0 e^{-\alpha t} - n_d / \tau_d$$

$$\text{or} \quad \frac{dn_d}{dt} = g_0 e^{-\alpha t} - \alpha_d n_d \quad (11)$$

where,

$$\tau_d = \frac{1}{(\sigma_1 N_1 + \sigma_2 N_2 + \sigma_3 N_3) v_d}$$

and $\alpha_d = 1/ \tau_d$

As $n_d = 0$ at $t = 0$, the integration of eq. (11) gives

$$n_d = \frac{g_0}{(\alpha_L - \alpha)} [e^{-\alpha t} - e^{-\alpha_d t}] \quad (12)$$

if η is the probability of radiative recombination, then the deformation induced ML intensity for a crystal of volume V containing N_d dislocation of unit length may be expressed as

$$I = \eta \sigma_1 N_1 v_d n_d$$

$$I = \frac{\eta \sigma_1 N_1 v_d A I_0 r_F n_F}{b(\alpha_d - \alpha)} [e^{-\alpha t} - e^{-\alpha_d t}] \quad (13)$$

Eq^n.(11) indicates that I should be maximum for a particular value of time t given by

$$t_m = \frac{1}{(\alpha_d - \alpha)} \ln(\alpha_d / \alpha) \quad (14)$$

for $\alpha_d >> \alpha$, Eq^n.(13) may be expressed as

$$I = \frac{\eta \sigma_1 N_1 v_d A I_0 r_F n_F}{b(\alpha_d - \alpha)} e^{-\alpha t} \quad (15)$$

Eq^n.(15) shows the exponential decay of ML, where the decay time will be controlled by α, i.e., the pinning time of dislocation. Similar results were obtained when rare-earth doped strontium eliminate phosphor mixed in an epoxy resin, is deferred elastically by applying a uniaxial pressure by laser, then initially the mechanoluminescence (ML) intensity increases with time, attains a peak value I_m and later on it decreases with time. (13)

CONCLUSION

It is to be noted that the electrons captured by dislocation have two types of motion, firstly, they move with dislocations, and secondly they also move along the dislocation axis with a very low velocity of the order of 0.1 cm/sec. Thus, initially the ML intensity should decay with a fast rate and then it should decay with a slow rate. The first decay time should give the pinning time of dislocations and the second lifetime of the electrons in the dislocation band.

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