PPE AND PPAE IN II-VI SEMICONDUCTORS BASED ON PEIRLS BARRIER MODEL

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Abstract

In the past, two modelshave been proposed to explain the photoplastic effect (PPE)in II-VI semiconductors. These models are: (i) Peierls barrier model and (ii) photo-obstacle dislocation pinning model. The dislocation mobility in II-VI semiconductors is governed by a kind of Peierls potential that originate in the electrostatic interaction between charges at the dislocation core with rows of like charged lattice ions past which the dislocation moves.The interaction between charged dislocations and electron photoionized from F-centres gives rise to what is known as the photoplastic effect. This is a reversible change in the stress necessary to produce further plastic deformation in a strained crystals containing F-centres when F- light is shown on it. The effect is observed in norminally pure and in doped crystals.

1. Introduction

The photoplastic effects differ from the usual point defect hardening in crystals in which they are caused by changes in electronic state rather than by atomic or ionic lattice defects. In photoplastic effect, due to absorption of light radiation, flow stress is altered. This effect is almost reversible, it can be either positive or negative. This effect is also known as photomechanical effect. On the other hand, the photoplastic aftereffect has also been observed. It is a phenomenon revealing a flow stress peak after certain time duration, due to short pulse of light. A photomechanical effect has also been observed in semi-conductor. This effect appeared to be a surface phenomenon which required the presence of either n or p-type impurities. Incident light always caused softening in case of semi-conductors. The mechanical effects of ionic defects are reversible only in the sense that the defects can be removed or redistributed by annealing or other treatments. In pure crystals a hardening is produced at all temperatures whatever be the F-centre concentration, but in crystals doped with divelent impurities a softening is observed.

In pure coloured crystals the proposed mechanism is that on illumination electrons are photoionised from F-centres and attracted to charged dislocations. An electron cloud is then formed around the dislocation core and is trapped at impurities or other defects. The potential barrier generated by the electron cloud oppsses dislocation motion and produce hardening.

2.Mechanism

The II-VI compounds exhibit a large PPE. Osip'yan and Petrenko (1978) proposed that dislocation motion is limited by some form of Peierls stress, and found very significant observations in the interpretation of the photoplastic effect. These results on all the II-VIcompounds except CdTe and CdSe show that dislocation charge is increased by illumination and that there is a direct linear relationship between the flow stress and the dislocation charge.

The Peierls barrier model is more suitable as compared to photo-obstacle dislocation pinning model which can be understood with respect to the following steps.

(i) The dislocation mobility in II-VI semiconductors is governed by a kind of Peierls potential that originate in the electrostatic interaction between charges at the dislocation core with rows of like charged lattice ions past which the dislocation moves.

(ii) The illumination of crystals enhances the dislocation charge owing to the capture of charge carriers and consequently the barrier height.

(iii) The positive PPE is caused by the reduction of dislocation mobility due to an increase of the Peierls potential height caused by illumination.

2.1 Photoplastic Effect In II-VI Semiconductors Based OnPeierls Barrier Model

The rate of generation of free electrons can be expressed as

$$g = \eta A I_L \qquad (1)$$

The rate equation for the change in the number of free electrons at any time t can be written as

$$\frac{d\Delta n}{dt} = \eta A I_L - \alpha_1 \Delta n - \alpha_2 \Delta n \qquad (2)$$

The change in the number of free electrons at any time $t = t_0$, is given by

$$\Delta n = \frac{\eta A I_L}{(\alpha_1 + \alpha_2)} \left[1 - \exp\{-(\alpha_1 + \alpha_2)(t - t_o)\}\right] \qquad (3)$$

Thus, the rate of generation of filled electron traps may be given by

$$g_t = \frac{\alpha_2 \eta A I_L}{(\alpha_1 + \alpha_2)} \left[1 - \exp\{-(\alpha_1 + \alpha_2)(t - t_o)\}\right] \qquad (4)$$

In equilibrium, the rate of generation of filled electron traps may be expressed as

$$g_t = \frac{\alpha_2 \eta A I_L}{(\alpha_1 + \alpha_2)} = \mathrm{p}\,\eta \mathrm{A I_L} \qquad (5)$$

Where p = $\alpha_2/(\alpha_1+\alpha_2)$, is the efficiency for trapping of electrons.

The change in the number of traps filled with electrons at any time t is given by

$$\Delta n_t = \frac{p \eta A I_L}{\beta} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] \qquad (6)$$

The rate of generation of light-generated interacting filled traps may be expressed as

$$g_i = \frac{\dot{\varepsilon} V \eta r_i p A I_L}{b\beta} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] \qquad (7)$$

The transfer of electrons from the filled traps to the core of the dislocations, may be written as rate euation

$$\frac{d\Delta n_i}{dt} = \frac{\dot{\varepsilon} V \eta r_i p A I_L}{b\beta} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] - \gamma \Delta \mathrm{n_i} \qquad (8)$$

If $1/\gamma = \tau_i$, is the lifetime of electrons in the interacting filled traps then the change in the number of interacting filled traps at any time $t = t_0$, is given by

$$\Delta n_i = \frac{\dot{\varepsilon} V \eta r_i p A I_L}{b\beta\gamma} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] \qquad (9)$$

Thus, the rate of capture of light generated carriers in the dislocation core may be written as

$$g_d = \frac{\dot{\varepsilon} \gamma_2 V \eta r_i p A I_L}{b\beta\gamma} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] \qquad (10)$$

If $\tau_d = 1/\delta$ is the lifetime of electrons captured at the core of the dislocations, then we write the following rate eqation

$$\frac{d\Delta n_d}{dt} = \frac{\gamma_2 \dot{\varepsilon} V \eta r_i p A I_L}{b\beta\gamma} \left[1 - \exp\{-\beta(t - t_o)\}\right] - \delta \Delta n_d \qquad (11)$$

Since δ should increase with the strain-rate therefore τ_d decreased with increasing value of the strain-rate $\dot{\varepsilon}$.

For deformation of the crystal at high strain rate, δ will be large and thus taking δ>>β, the change in the number of electrons captured at the dislocation core at any time $t = t_0$ is expressed as

$$\Delta n_d = \frac{\gamma_2 \dot{\varepsilon} V \eta r_i p A I_L}{b\beta\gamma\delta} \left[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}\right] \qquad (12)$$

For deformation of crystals at very slow strain-rate, δ will be less and thus taking β>>δ, we find

$$\frac{d\Delta n_d}{dt} = \frac{\gamma_2 \dot{\varepsilon} V \eta r_i p A I_L}{b\beta\gamma} \left[1 - \exp\{-\beta(t - t_o)\}\right] - \delta \Delta n_d \qquad (13)$$

The electrons captured at the dislocation cores will increase the charge on the dislocation and consequently the barrier height. Thus, the change in flow stress will increase linearly with Δn_d and PPE may be expressed as

$$\Delta \sigma = D \Delta n_d \qquad (14)$$

$$\Delta\sigma = \frac{D\gamma_2\dot{\varepsilon}V\eta r_i pAI_L}{b\beta\gamma\delta}[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}] \quad (15)$$

(forhigh $\dot{\varepsilon}$)

And

$$\Delta\sigma = \frac{D\gamma_2\dot{\varepsilon}V\eta r_i pAI_L}{b\beta\gamma\delta}[1 - \exp\{-\delta(\mathrm{t} - \mathrm{t_o})\}] \quad (16)$$

(forlow $\dot{\varepsilon}$)

Equation (15) and (16) show that when a crystal will be deformed at a fixed strain-rate and it will be exposed to light at $t = t_0$ then, the PPE should initially increase linearly with time and then it should attain saturation value given by the following equation.

$$(\Delta\sigma)_s = \frac{D\gamma_2\dot{\varepsilon}V\eta r_i pAI_L}{b\beta\gamma\delta} \quad (17)$$

2.2Photoplastic After-EffectIn II-VI Semiconductors Based OnPeierls BarrierModel

During the exposure of a semiconductor material, t_0 light electrons absorb energy and they jump to the conduction band. For the intensity I_L, the rate equation for the change in the number of free electrons at any time t can be written as

$$\frac{d\Delta n}{dt} = \eta \mathrm{AI_L} - \alpha_1\Delta\mathrm{n} - \alpha_2\Delta\mathrm{n} \quad (18)$$

The change in the number of free electrons at $t = t_0$ is given by

$$\Delta n = \frac{\eta AI_L}{(\alpha_1 + \alpha_2)}[1 - \exp\{-(\alpha_1 + \alpha_2)(t - t_o)\}] \quad (19)$$

In equilibrium, the rate of generation of filled electron traps may be expressed as

$$g_t = \frac{\alpha_2\eta AI_L}{(\alpha_1 + \alpha_2)} = \mathrm{p}\eta AI_L \quad (20)$$

If $\tau_t = 1/\beta$, then we can write the following rate equation

$$\frac{d\Delta n_t}{dt} = \mathrm{p}\eta AI_L - \beta\Delta\mathrm{n_t} \quad (21)$$

The change in the number of traps filled with electrons at any time $t = t_0$ may be expressed as

$$\Delta n_t = \frac{p\eta AI_L}{\beta}[1 - \exp\{-\beta(\mathrm{t} - \mathrm{t_o})\}] \quad (22)$$

If the light source is turned off at $t = t_c$ and if the duration of light pulse $(t_c - t_0) << \tau_t$ (=1/β), then from Eq. (22) may be expressed as

$$(\Delta n_t)_o = p\eta AI_L\,(\mathrm{t_c} - \mathrm{t_o}) \quad (23)$$

When the light source will be turned off at $t = t_c$, then the number of electrons filled in the traps will decrease with time. The change in the number of filled electrons in traps at any time t may be given by

$$(\Delta n_t)_d = p\eta AI_L\,(\mathrm{t_c} - \mathrm{t_o})\exp[-\beta(\mathrm{t} - \mathrm{t_c})] \quad (24)$$

The rate of generation of light-generated interacting filled traps in the crystal having volume V may be expressed as

$$g_i = \frac{\dot{\varepsilon}V\eta r_i pAI_L(t_c - t_o)}{b}\exp\{-\beta(t - t_c)\} \quad (25)$$

$1/\gamma = \tau_i$, then the change in the number of interacting filled traps at $t = t_0$ is given by

$$\Delta n_i = \frac{\dot{\varepsilon}V\eta r_i pAI_L(t_c - t_o)\exp[\beta(t_c - t_o)]}{b(\gamma - \beta)}. \left[\exp\{-\beta(t - t_o)\} - \exp\{-\gamma(t - t_o)\}\right] \quad (26)$$

Thus, the rate of capture of light-generated carriers in the dislocation core may be written as

$$g_d = \frac{\gamma_2\dot{\varepsilon}V\eta r_i pAI_L(t_c - t_o)\exp[\beta(t_c - t_o)]}{b(\gamma - \beta)}. \left[\exp\{-\beta(t - t_o)\} - \exp\{-\gamma(t - t_o)\}\right] \quad (27)$$

If $\tau_d = 1/\delta$ is the lifetime of electrons captured at the core of the dislocation,then the change in the number of electrons captured at the dislocations core at $t = t_0$ is given by

$$\Delta n_d = \frac{\gamma_2\dot{\varepsilon}V\eta r_i pAI_L(t_c - t_o)\exp[\beta(t_c - t_o)]}{b(\gamma - \beta)}. \left[\frac{\exp\{-\beta(t - t_o)\}}{(\delta - \beta)} + \frac{\exp\{-\gamma(t - t_o)\}}{(\gamma - \delta)} - \frac{\exp\{-\delta(t - t_o)\}}{(\delta - \beta)(\gamma - \delta)}(\gamma - \beta)\right] \quad (28)$$

Since $\gamma >> \beta$ and $\gamma >> \delta$. Thus, Eq. (28) may be expressed as

$$\Delta n_d = \frac{\gamma_2\dot{\varepsilon}V\eta r_i pAI_L(t_c - t_o)\exp[\beta(t_c - t_o)]}{b(\gamma - \beta)(\delta - \beta)}. \left[\exp\{-\beta(t - t_o)\} - \exp\{-\delta(t - t_o)\}\right] \quad (29)$$

The electrons Δn_d captured at the dislocation cores will increase the charge on the dislocation and according to Peierls barrier model this will ultimately increase the flow stress. Thus, the PPAE may be expressed as

$$\Delta\sigma = \frac{D\gamma_2 \dot{\varepsilon} V \eta r_i pAI_L (t_c - t_o)\exp[\beta(t_c - t_o)]}{b(\gamma - \beta)(\delta - \beta)} . \left[\exp\{-\beta(t - t_o)\} - \exp\{-\delta(t - t_o)\}\right] \tag{30}$$

Equation (30) indicates that Δσ should be zero at $(t - t_0) = 0$, and at $(t - t_0) = \infty$. Thus, Δσ should be maximum for a particular value of time.

For shorter value of $(t - t_c)$, from Eq. (30) rise of PPAE may be expressed as

$$\Delta\sigma = \frac{D\gamma_2 \dot{\varepsilon} V \eta r_i pAI_L (t_c - t_o)\exp[\beta(t_c - t_o)]}{b\gamma} .(t - t_0) \tag{31}$$

The above Eq. (30) indicates that when a sample is exposed to light at $t = t_0$, then initially Δσ should increase linearly with $(t = t_0)$

3. Results and Discussions

The main conclusions drawn from the photoplastic effect, photoplastic after-effect in II-VI semiconductors are as given below:

(i) During the plastic deformation of a crystal movement of dislocations takes place. A moving dislocation approaches the filled traps lying in undeformed region of a crystal, then the rate constant β for the release of electrons from the filled traps increases to γ and consequently the transfer of electrons from the filled traps to the conduction band and to the dislocation core takes place. The capture of electrons in the dislocation core enhances the dislocation charge. Thus, the illumination of semiconductors under deformation may enhance the dislocation charge and consequently positive PPE may occur due to increase in the Peierls barrier height.

(ii) The PPE, depends on different parameters like charge on dislocations, strain-rate, radius of interaction of dislocation with the traps, absorption coefficient, light intensity, lifetime of electrons in the traps lying in undeformed region of the crystals and lifetime of the electrons captured at the moving dislocation core.

(iii) This effect is closely correlated with an increase of the dislocation charge due to illumination. Illumination of a sample results in the formation of a certain concentration of dislocation inhibiting centres, which decreases exponentially after the light is shut off, i.e. if the lifetime of the electronic excitations is sufficiently long, moving dislocations can continue to “pick up” charges and the stress continues to grow even in darkness.

4. Conclusion

Some properties have only been studied in one or two of the II-VI compounds. Therefore further investigation of Photoplastic effect in II-VI semiconductors is required.

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