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Effect of Ultrasonic stress in Semiconductor Materials and Devices

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Abstract:**-- Effect of Ultrasonic Stress in solid state devices and materials have been discussed with the help of electromagnetic wave theory. Ultrasonic stress (radiation pressure) changes the characteristics of solid state devices and materials. Analytical treatment of changed characteristics of solid state devices and materials have been discussed.**

Index Terms**— Maxwell's wave equation, Poisson's equation, Space Charge density, Attenuation and Dispersion of Stress Wave, Ultrasonic Radiation Pressure.**

I. INTRODUCTION

Effect of ultrasonic stress is known in pure materials. Further, a systematic study has been made in solid state devices made from pure materials defined as Acoustoelectic effect. [1-13] due to ultrasonic radiation pressure effect when a sound wave propagates through a material containing free electrons, its momentum, as well as energy is attenuated. The momentum attenuation acts a dc force, causing the electrons to drift in the direction of force. When there is a closed circuit in this direction, a direct current is produced called "Acoustoelectric current" which is proportional to the sound intensity, as the momentum attenuation itself is. If on the other hand, the circuit is open, the drifting electrons produce a space charge whose electric field cancels the dc force due to the sound wave momentum attenuation. This back electric field is the "Acoustoelectric Effect" due to ultrasonic radiation pressure effect. The resistance of the material is changed due to acountic stress. There is a simultaneous bunching of electrons and holes in the solid state devices under the action of deformation potential of the travelling ultrasonic wave.

The phenomenon of phonon drag contributes to the thermometric power due to the momentum transfer to electrons from thermal phonons streaming down temperature gradient. It is qualitatively equivalent to the acoustoelectric effect, while quantitatively, it is different, since the ralations between typical wave length, mean free times and frequencies are entirely changed. For the propagation of acountic wave in piezoelectric semiconductor, there is a possibility of achieving acoustic gain by applying a dc electric field which causes the interacting charge carriers to drift in the direction of wave propagation faster than the sound. Ultrasonic wave carries a flux of momentum. A loss in energy from wave is equivalent to a proportional loss in momentum. This loss in momentum constitute a constant force acting on the object absorbing the energy (radiation pressure). The absorbers are the free charged carriers, and the ultrasonic radiation pressure is the acoustoelectric effect.

There is a simultaneous bunching of electrons and holes in a solid state devices under the action of deformation potential of the travelling acoustic wave. A sound wave in a solid gives rise to electric fields which accelerate electrons in much the same way as an electromagnetic wave. An analytical treatment of ultrasonic radiation pressure effect has been discussed.

II. ANALYTICAL TREATMENT: DESCRIPTION

Stress waves and Electrical Phenomena in Piezoelectric Semiconductors

For a one dimensional approximation, Electric field E produces a stress in the x_1 direction as follows:

$$\sigma = c\varepsilon - eE \quad (1)$$

$$D = eE + pE \quad (2)$$

c = elastic constant, E = electric field
D = electric displacement
ε = permitivity of a medium
σ = surface charge density
e = piezoelectric constants relating electric field to stress

p = magnitude of the elastic displacement component
Expressing E in terms of ε and differentiating (1) with respect to x leads to a wave equation. If D is assumed constant, this equation takes the form

$$\rho \frac{\partial^2 S}{\partial t^2} = c\left(1 + \frac{e^2}{cp}\right)\frac{\partial^2 S}{\partial x^2} \quad (3)$$

S is the displacement. The change in c due to the presence of the electric fields is thus obvious. The condition of constant D further leads to a zero space charge density through Poisson' s equation

$$\frac{\partial D}{\partial X} = Q \quad (4)$$

where as the continuity relation

$$\frac{\partial J}{\partial X} = -\left(\frac{\partial Q}{\partial t}\right) \quad (5)$$

For an extrinsic semiconductor in thermal equilibrium, the total space charge density Q may be expressed in terms of the energy levels and densities of the impurity states in the forbidden band, and the concentration of electrons in the conduction band. The condition of electrical neutrality corresponds to Q=0, and the acoustically produced space charge is the periodic variation of Q about zero.
J is the current density, indicates that in this case the varying current density due to the piezoelectric fields is zero, which corresponds to a very low conductivity in the medium.
In the case of very high conductivity, the field E accompanying the wave will be zero, and the elastic constant C will remain unaffected (Equation 1), whereas the stress wave will be accompanied by D fields, currents and varying space charge.
The case of specific interest here is that corresponding to intermediate values of conductivity, in the range encountered in semiconductors. In this range, equation (4) and (5) are used, together with an appropriate expression for J, to obtain values of D and E. These, in turn permit one to eliminate E from the wave equation.
For an extrinsic semiconductor (assumed to be n type), the current density may be expressed by

$$J = q\,(n + fn_s)\mu E + (\mu KT)f\left(\frac{\partial n_s}{\partial X}\right) \quad (6)$$

where the first term is due to drift and the second term is due to diffusion, q is the electronic charge, K is Boltzman's constant, T is the temperature, n is the mean density of electrons in the conduction band, and f is the fraction of acoustically produced space charge density n_s which is mobile.
Thus, $(n + fn_s)$ is the instantaneous local density of electrons in the conduction band. Equation (1) to (4) combined with plane wave representations of D and E

$$D = \frac{-i(nq\,\mu/\omega)E}{1 + i\omega\left(\frac{k}{\omega}\right)^2(\mu fKT/q)} \quad (7)$$

In the case of small conductivity modulation $(fn_s \ll n)$, equation (7) may be further simplified and written in the form

$$D = \frac{-i(b/\omega)E}{1 + i\omega\left(\frac{k}{\omega}\right)^2(\mu fKT/q)} \quad (8)$$

$b = nq\mu$represents the average conductivity.
The condition of small conductivity modulation $(fn_s \ll n)$ is satisfied when the effective drift velocity of the carriers in the piezoelectric field $f\mu E$ is much less than the velocity of the stress wave v. This imposes a limitation on the strain value:

$$\varepsilon \ll pv/f\mu e \quad (9)$$

In order to determine the attenuation and dispersion of stress waves, use is made of the conductivity frequency, defined by $\omega_c = \frac{b}{p}$, and the diffusion frequency, defined by,

$$\omega_D = \frac{q}{f\mu KT}\left(\frac{\omega}{K}\right)^2 \approx \left(\frac{q}{f\mu KT}\right)v^2$$

From equation (1), (2) and (8), one obtains

$$E = -\frac{e\varepsilon}{p}\left[\frac{1 + i(\omega/\omega_D)}{1 + i(\omega/\omega_D) + i(\omega_c/\omega)}\right]$$

In the case of negligible charge carrier diffusion ($\omega_D \gg \omega c$ equation (9) may be simplified to:

$$E = -\frac{e\varepsilon}{p}\left[\frac{1 - i(\omega_c/\omega)}{1 + \left(\frac{\omega_c}{\omega}\right)^2}\right] \quad (10)$$

and the effective elastic constant is obtained by substitution into (1)

$$\sigma = C\left[1 + \frac{e^2}{cp}\frac{1 - i\left(\frac{\omega_c}{\omega}\right)}{1 + \left(\frac{\omega_c}{\omega}\right)^2}\right]\varepsilon \quad (11)$$

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The velocity and attenuation are obtained in terms of the real and imaginary parts of the complex elastic constant

$$V = V_0\left[1 + \frac{\frac{e^2}{2Cp}}{1+\left(\frac{\omega_c}{\omega}\right)^2}\right] \quad (12)$$

$$\alpha = \frac{\omega}{V_0}\frac{e^2}{2Cp}\left[\frac{\frac{\omega_c}{\omega}}{1+\left(\frac{\omega_c}{\omega}\right)^2}\right] \quad (13)$$

This expression show that at very low frequency V tends to V_0 and α tends to zero, whereas in the high frequency limit the become.

$$V = V_\propto = V_0\left[1 + \frac{e^2}{2Cp}\right] \quad (14)$$

$$\alpha = \alpha_\propto = \frac{\omega_c e^2}{V_0 2Cp} \quad (15)$$

$\omega_D$is the frequency above which the wave length is sufficiently short for diffusion to smooth out carrier density fluctuations associated with the periodicity of the stress wave.

Expression (11) and (12) are obtained on the assumption that $\frac{e^2}{Cp}$ is small.

In the vicinity of $\omega = \omega_c$, a simple relaxation –type dispersion occurs. It should be emphasized that the relaxation frequency is given by the conductivity of the material.

When carrier diffusion is taken into account, the complete expression for velocity and attenuation become

$$V = V_0\left[1 + \frac{e^2}{2Cp}\frac{1+(\omega_c/\omega_D)+\left(\frac{\omega}{\omega_D}\right)^2}{1+2\left(\frac{\omega_c}{\omega_D}\right)+\left(\frac{\omega}{\omega_D}\right)^2+\left(\frac{\omega_c}{\omega}\right)^2}\right] \quad (16)$$

$$\propto = \frac{\omega}{V_0}\frac{e^2}{2Cp}\left[\frac{\omega_c/\omega}{1+2(\omega_c/\omega_D)+\left(\frac{\omega}{\omega_D}\right)^2+\left(\frac{\omega_C}{\omega}\right)^2}\right] \quad (17)$$

In this case, for $\omega_D \gg \omega_c$, expression (12) and (13) retain their validity for all frequencies, except that $\propto$ approaches a constant value $\left(\frac{\omega_c}{V_0}\right)\left(\frac{e^2}{2Cp}\right)$ in the frequency range between ω_C and ω_D, and drops to zero as ω becomes larger than ω_D. For $\omega_C \gg \omega_D$, the velocity and attenuation may be expressed by:

$$V = V_0\left[1 + \frac{e^2}{2Cp}\frac{(1+\omega^2/\omega_D\omega_C)}{2+(\omega^2/\omega_D\omega_C)+(\omega_D\omega_C/\omega^2)}\right] \quad (18)$$

And

$$\propto = \frac{\omega}{V_0}\frac{e^2}{2Cp}\left(\frac{\omega_D/\omega}{2+(\omega^2/\omega_D\omega_C)+(\omega_D\omega_C/\omega^2)}\right) \quad (19)$$

The maximum velocity change occurs at the frequency $\omega = \left(\frac{\omega_D}{\omega_C}\right)^{1/2}$, whereas the frequency corresponds to maximum attenuation is

$$\omega = \left(\frac{\omega_D\omega_C}{3}\right)^{\frac{1}{2}}$$

Ultrasonic radiation pressure has been discussed analytically [13].

III. CONCLUSION

Discussion of the interaction of ultrasonic waves with lattice vibrations or with defects in a solid follows a pattern very close to that of thermal conductivity theory. The interaction or coupling between ultrasonic waves and conduction electrons proceeds through the absorption and emission of phonons. At sufficiently low temperature there is also energy transfer from ultrasonic waves to conduction electrons.

Electrons are coupled to the lattice and interact with stress waves in at least two distinct ways. Lattice waves interact with ultrasonic stress waves, and nuclear quadrupole coupling link the nucleus with the lattice and hence with ultrasonic stress waves.

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